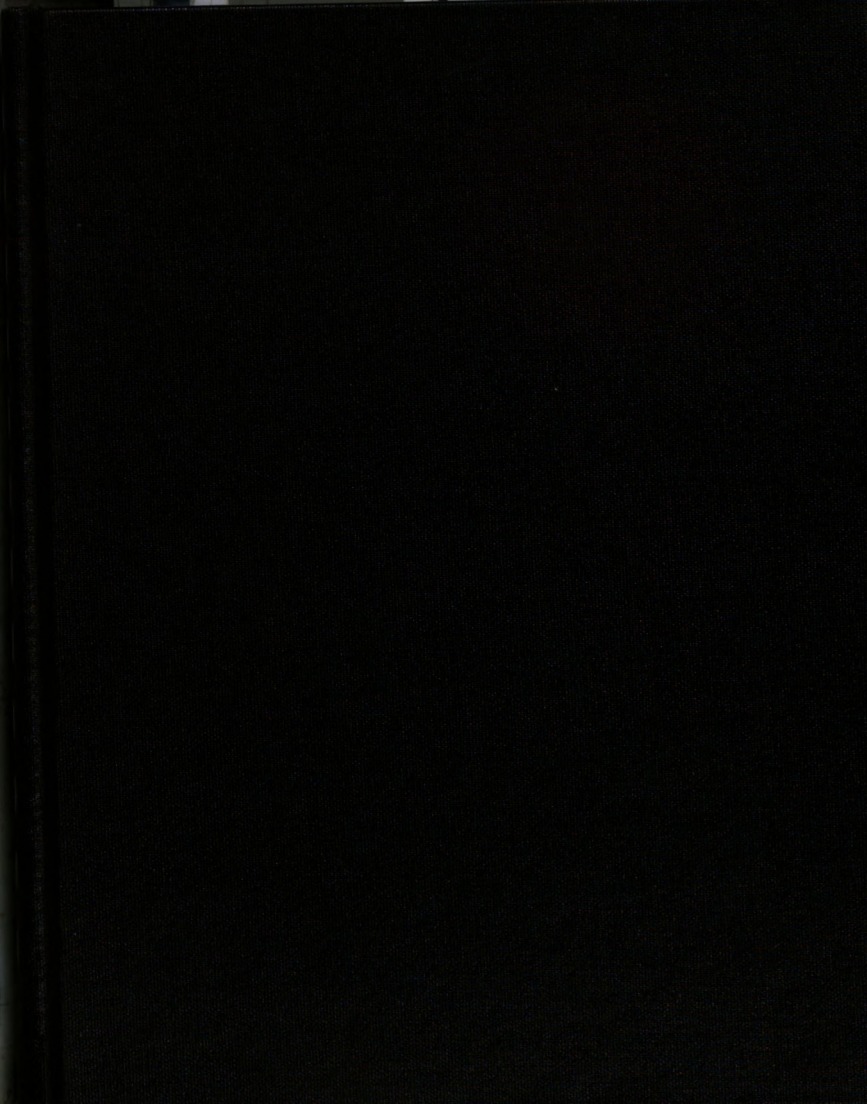






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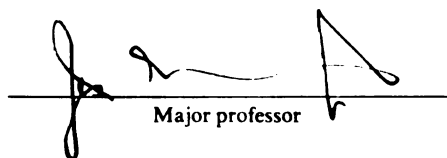
PROPERTIES OF ELECTRON CYCLOTRON RESONANCE
PLASMA SOURCES

presented by

ASEEM KUMAR SRIVASTAVA

has been accepted towards fulfillment
of the requirements for

Doctor of Philosophy degree in Electrical Engineering


Major professor

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**PROPERTIES OF
ELECTRON CYCLOTRON RESONANCE PLASMA SOURCES**

**By
Aseem Kumar Srivastava**

**A DISSERTATION
VOLUME I**

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

**DOCTOR OF PHILOSOPHY
Department of Electrical Engineering**

1995

ABSTRACT

PROPERTIES OF ELECTRON CYCLOTRON RESONANCE PLASMA SOURCES

By

Aseem Kumar Srivastava

Over the past few decades, microwave electron cyclotron resonance (ECR) plasma/ion sources have found use in various divisions of physics and electrical engineering. The design and operating conditions of an ECR ion source is heavily dependent on its eventual application. Experiments in nuclear and atomic physics for example, rely on ECR ion sources (ECRIS) operating at extremely low pressures (about 10^{-7} Torr), and generating multiply charged ions. High energy ion beams are extracted from these ECRIS for injection into particle accelerators.

The emphasis for engineering plasma sources on the other hand, is on the generation of low energy, low charge state ions and reactive radical species. These plasma/free radical sources, operate at relatively high pressures (about 1 mTorr) and are used for substrate processing, like plasma assisted chemical vapor deposition, plasma assisted anisotropic etching, high T_c superconducting film deposition, etc. Such processes require low energy ions since the substrate could be damaged by energetic ion bombardment. ECRIS therefore, must be designed to produce the required plasma species in a wide range of parameters.

This dissertation evaluates several different ECR ion/plasma sources. The MPDR 610 - a commercially available compact, coaxial plasma/free radical

source is comprehensively characterized in terms of the plasma output (ion density, electron and ion energies, etc.) as the input variables (like microwave power, frequency of excitation, discharge pressure, gas type, etc.) are changed. The ion source generates high ion densities (10^{11} cm^{-3}) at sub-mTorr pressures, with low input power levels (less than 200 W).

The design, development and characterization of a 610 like source - the 610-*a* is then described. This source was useful in studying the electric field patterns inside the cavity structure of the MPDR 610. The normal electric field strength at the cavity wall of the 610 are about 30 to 40 kV/m. The existence of TEM standing waves in the coaxial section of the cavity is confirmed.

Another small source - the MPDR 5 is also characterized in this dissertation. While different from the 610, this source too is ECR based operating at 2.45 GHz with permanent magnets, and a tunable resonant cavity structure that sets up TE_{111} field pattern to couple power into the plasma.

The high energy sector of ECRIS is studied using the 6.4 GHz Superconducting ECR ion source (SCECR) at the National Superconducting Cyclotron Laboratory. Several mutual experiments between the Electrical Engineering and the Cyclotron ECR research groups had been identified, and the results are discussed in Volume Two of this dissertation. The performance of the SCECR at 2.45 GHz mimics other high frequency sources, like the 6.4 GHz RTECR. This unique modification of the SCECR has been the basis of an ongoing patent procedure at Michigan State University.

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For my parents,
Mrs. H. K. Srivastava and Dr. P. B. L. Srivastava,
without whose unceasing guidance and extreme sacrifices
this dissertation could never have been written.

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The attainment of knowledge goes well beyond a set of experiments, or a series of lectures and examinations. In my tradition, the teacher is esteemed beyond anyone else in the entire universe (...GUROOR SAAKSHAAT PARAM BRAHMA - Sanskrit for "...the teacher is Brahma himself..."). And so I salute all my teachers from the days of Saint Joseph's Academy in Dehra Dun, The

Modern School in New Delhi, to the dozens of professors at Michigan State University who helped lay the foundation of my professional career. In that capacity, I also acknowledge Dr. J. Hopwood, Dr. M. Dahimene and Mr. D. Cole for their active help and support with my experiments when I needed it most.

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Chapter 1

Prologue to a Dissertation

1.1 Introduction

1.2 ECR - an Introduction to Power Transfer

1.2.1 "Pure" ECR

1.2.2 Power Transfer Through Mechanisms Other than ECR

1.3 Microwave ECR Ion Sources - a Black Box Model

1.4 Organization and Motivation of this Research Effort

Chapter 1

Prologue to a Dissertation

1.1 Introduction

The word “plasma” is derived from the Greek language for “something molded.” It was first applied by Tonks and Langmuir in 1929 to the inner region, away from the boundaries, of a glowing ionized gas produced by an electrical discharge in a tube [Bit-86, Nic-83]. The term is now used to describe any concentration of charged and neutral particles that has a zero net space charge and is internally field free, and where interactions between each charged species are governed by long range Coulomb forces [Bit-86]. For practical purposes, a plasma may in fact be treated as a conductor because of its large population of energetic charged particles (both negative and positive), with its conductivity being defined by the charge density and electron mobility.

If enough energy is imparted to a solid, its internal kinetic energy increases to the point where its binding potential is overcome, converting the solid to a liquid. The solid is then said to have undergone a phase transition. Another such transition occurs when the liquid is heated up to the level beyond

which it changes to a gas. A plasma is often called the fourth state of matter, since it is a superheated, and ionized gas [Nic-83]. This is somewhat misleading, since the phase transitions from solid to liquid, and from liquid to gas occur at a temperature known as the latent heat of that phase transition. For a given pressure the latent heat of these phase transitions is constant. However, the transition from a gas to a plasma is not a phase transition in this thermodynamic sense, because this transition occurs gradually with increasing plasma temperatures.

A plasma discharge is created when sufficient energy is imparted to the neutral discharge gas such that a significant number of the gas molecules (or atoms) lose one or more of their valence shell electrons. Hence the plasma is a mixture of a very large number of neutral gas atoms (or molecules), and individual charged, energetic, metastable and unstable species, with complex interactions occurring between them. Note that the ions generated in the discharge may be singly, or multiply ionized depending on the operating conditions of the discharge. Plasma discharges occur naturally in the universe in many shapes and sizes - the sun's corona, the earth's ionosphere and the Van Allen belts, lightning bolts, etc. Most of intergalactic space is presumed to be a (very low density) plasma where the charged species are spread out over vast volumes. It is in fact estimated that about 99% of the universe is a plasma and cold planets like the earth are rare areas where natural plasmas (like lightening bolts) exist only under severe circumstances.

While there are many artificially generated plasma discharges on earth that are used in everyday life, like fluorescent lighting, a plasma cannot be created on earth at atmospheric pressures except for electrical discharges, or

combustion. Stringent requirements of pressure (or lack thereof) and energy transfer to individual constituents of the plasma need to be satisfied before these artificial discharges can be sustained under the normal atmospheric conditions. These requirements are met through the use of complex systems that incorporate vacuum technology, theory of electromagnetic energy transport, often cryogenics and superconductivity, and many other branches of physics and engineering. Appropriately, the machine that actually generates and sustains a plasma is known as an ion source, or a plasma source. The two terms may in general be used interchangeably (except when an ion beam is extracted from the source, in which case the machine is specifically referred to as an ion, or an ion beam source).

There are many different ways through which energy may be transferred into the plasma, both artificial and natural. The ionosphere of the earth, for example, is sustained due to naturally occurring photo-ionization. A plasma on the earth's surface is generally a gas discharge that has been generated by transfer of electrical power into the gas. For weakly ionized plasma discharges (less than 5% ionization), the neutral (un-ionized) gas is the largest constituent. However, the identification of all the plasma species is a very complicated pursuit, and even the simplest plasma discharges have not yet been completely characterized (other than the exhaustive work done on fluorescent lights by companies like General Electric and GTE).

Initial research into plasma theory in the fifties and sixties was done mainly to satisfy the demands of the controlled thermonuclear fusion program and the magnetohydrodynamic (MHD) conversion of thermal power into electrical energy [Gal-83]. Also about that time, plasma discharges in outer

space and around the hulls of space vehicles were studied by NASA. In recent times, a number of spin off technologies have been spawned, mainly due to the improvements in the ability to create the required plasma species with relative ease, and also due to a better understanding of the plasma chemistry. The success of plasma processing technology for integrated circuit fabrication, plasma assisted chemical vapor deposition, and other applications utilizing some kind of plasma discharge has been amply demonstrated both in the research and industrial environments.

Due to this success, there has been a concerted effort in ion/plasma source research and development. A variety of plasma sources with innovative designs have been developed with their dimensions and characteristics being defined by the end process and application, and by the engineering talents of the designers. To do batch processing of silicon wafers for example, a low energy broad beam ion/free radical source is necessary [Kau-85, Har-89]. Initial research into such a broad beam ion source was actually conducted at NASA for space (electric) engine design. On the other hand, narrow, energetic slit shaped ion beams are extracted from specially designed sources, and these ion beams are rastered over the substrate in ion implantation machines [Ste-92, Kel-89]. Yet other applications require smaller ion sources that can adapt to pre-existing apparatus, or be able to produce the requisite plasma species in the appropriate abundance close to the substrate surface.

This dissertation documents a comprehensive study of a number of plasma and ion beam sources that were designed at the Department of Electrical Engineering (EE) at Michigan State University (MSU). Joint experiments on ion sources with the ion source research group at the National Superconducting

Cyclotron Laboratory (NSCL) at MSU are also detailed. The research detailed in the forthcoming chapters was performed at the EE and the NSCL laboratories at MSU, and encompassed the last five years. In this chapter a brief introduction into the energy transfer techniques from the impressed electric fields to the plasma discharge is presented. A simple black-box model of a generic microwave ion source is also presented, to lay a foundation for understanding concepts developed here, and in later chapters. This is followed by a chapter-wise breakdown of the rest of this dissertation, that will also explain the motivation behind the efforts of the past five years. Individual ion sources that were experimentally evaluated, and all their peripheral systems (like the vacuum stations, the microwave apparatus, etc.) will be introduced and described in detail in the appropriate chapter, along with the results of each sub-study.

1.2 ECR Plasma Sources - an Introduction to Power Transfer

There are several ways of creating an electrical discharge - the simplest of them being a glow discharge in an evacuated tube between two biased electrodes. Ion source construction of course varies in complexity with each new and unique design, the design itself predicated by the end user demands. Probably the most important aspect of ion source design is the method(s) of energy transfer to the plasma load from the impressed electromagnetic fields. One of these methods of power transfer is electron cyclotron resonance (ECR) and the ion sources employing this technique are appropriately known as ECR ion sources (ECRIS). As will be seen, ECR is a very efficient method of power transfer, and takes advantage of the natural cyclotronic resonance of electrons

(hence the name ECR) to selectively transfer power from the impressed electric fields and into the electron gas. From this heated electron gas, the energy is transferred to the other constituents of the plasma through collisions. While the theory of "pure" ECR is simple to understand and a basic ECRIS is not too complicated to design and develop, the actual picture of power transfer to the plasma is much more complex. In the following sub-sections a simplified ECR theory is presented, after which a more complete analysis of microwave power absorption in ECR plasma sources is discussed. This analysis is based on a monograph by Popov [Pop-94a].

1.2.1 "Pure" ECR

In the presence of a static magnetic field, a charged particle resonates around magnetic lines of force at a particular frequency, known as its rotation or cyclotron frequency. For an electron, this is given by $\omega_{ce} = qB/m$, where ω_{ce} is the cyclotron frequency, B is the necessary static magnetic field, and q and m are the electronic charge and mass respectively. While in this static magnetic field, if the particle is then subjected to a time harmonic AC electric field oscillating at the cyclotron frequency of the particle, and a component of the impressed electric field is perpendicular to the static magnetic field, the charged particle will rapidly absorb power from the impressed electric field. This phenomenon of electron cyclotron resonance (ECR) is used to couple energy into the electron gas that constitutes a plasma. A complete analysis of ECR heating (ECRH) is available in several references [Bit-86, Nic-83, Kel-89, Asm-89a, Eld-72, Lie-94], and only a brief introduction is now presented to aid in development

of the forthcoming chapters.

In an ECRIS, neutral discharge gas is incrementally injected into a confined structure (like a quartz, alumina or copper tube) under high vacuum conditions. A static (time constant) magnetic field of specific strength and orientation exists such that all, or part, of the confinement structure is immersed in this field. As mentioned earlier, in the presence of this static magnetic field, the charged particle follows a helical path gyrating about the magnetic field lines. Now if a time harmonic electric field with frequency equal to the cyclotron frequency of the charged particle ($\omega = \omega_{ce}$) is impressed on the confinement structure, if the appropriate magnetic field strength is present at some point, and if there exists a component of the impressed electric field that is perpendicular to this static magnetic field, the charged particle will absorb energy from this impressed electric field.

Based on several assumptions (some of which are actually inaccurate, used only to generate a closed form solution from a complex set of equations - see Reference Pop-94a), this energy absorption by the electron gas may be modelled by the following equation [Asm-89a, Pop-94a]:

$$P = Re(J \times E) = \frac{eN_e E_r^2}{4m} \left\{ \frac{v_e^2}{v_e^2 + (\omega - \omega_{ce})^2} + \frac{v_e^2}{v_e^2 + (\omega + \omega_{ce})^2} \right\} \quad (1.1)$$

Here E_r is the component of the electric field that is perpendicular to the static magnetic field and v_e is the electron-neutral elastic collision frequency. As can be seen, the first term in the right hand part of the equation (curly brackets)

denotes a resonance between the impressed microwave and the electron cyclotron frequencies where the electron rotates around the static magnetic field line in the same direction as the vector of the microwave electric field. Such an electromagnetic wave is called the right hand circularly polarized (RHCP) wave. The second term in the curly brackets denotes an electric field whose vector rotates in a direction opposite to that of the electron rotation in the magnetic field. This is known as the left hand circularly polarized (LHCP) wave. Note that any electric field may be represented as a linear superposition of the RHCP and the LHCP wave.

The energy absorption by the gyrating electron results in an increasing radius of the electron's helical path about the magnetic field line (see Figure 3, Reference Asm-89a). The regions inside the plasma confinement structure that have the required magnetic field strength and the appropriate electric field orientation for ECRH are known as the "ECR zones." For example, the required B field strength for the operating microwave frequency of 2.45 GHz, is 875 gauss, and ECRH of the electron gas would occur in regions of the plasma confinement structure where $B = 875$ gauss, and the electric field has a component perpendicular to this B field. The energetic, or "hot" electrons then transfer this energy to valence electrons of neutral atoms (or molecules) of the working gas through inelastic collisions.

Note that this process involves using the hot electron's kinetic energy to increase the potential energy of the bound electron. Ionization occurs when sufficient energy is transferred from the hot electrons (usually by single, sometimes by multiple collisions) to the valence electron of the discharge gas, such that the valence electron is stripped away from the atom (or molecule). An

ion-electron pair is then formed. Once the loss mechanisms (diffusion and recombination) are balanced by ionization in a steady state, a discharge can be sustained. ECRH is, therefore, a low pressure (m-Torr or lower) phenomenon that relies on collision frequencies that are high enough to sustain the discharge, yet sufficiently low such that the electron gas may gain substantial energy from the high frequency impressed electric field before transferring this energy to the other constituents of the discharge. Typically the electric fields are launched with frequencies in the microwave range - several hundred MHz to about 100 GHz, although some (non-ECR) plasma/free radical sources (notably the inductively coupled devices) operate at the lower radio frequency (rf) of 13.56 MHz.

It has been shown by Popov [Pop-94a] and others (see Figure 13.5, page 418, Reference Lie-94) that real ECR heating occurs only through absorption of the energy from RHCP waves by the discharge. This may happen, however, for a very limited set of circumstances - at microwave breakdown and for very low power absorption levels that generates an over dense (ion density greater than the critical density for that excitation frequency) magnetoactive plasma. (More discussions of critical density, and over dense discharges will be taken up later.) For most ion sources that are used in industrial applications, the external plasma conditions (for example, input power levels, gas flow rates, discharge pressure etc.) vary significantly from this, and mechanisms other than pure ECR for electron momentum transfer are needed to explain the power transfer that occurs in these discharges. Some of these alternate energy transfer techniques are now presented.

1.2.2 Power Transfer Through Mechanisms Other than ECR

Many ion sources currently in use employ electron cyclotron resonance for heating the electron gas which then indirectly heats and ionizes the neutral gas through inelastic collisions. This, of course is not the only method of power transfer to sustain a discharge. A similar phenomenon for ion cyclotron resonance (ICR) also exists that directly couples energy to the ion gas. ICR however, is not a practical method of power transfer for most ion sources. Since the magnetic field requirement scales linearly with the mass of resonating particle, the static magnetic field strength for ICR heating is approximately 1840 times that of the electrons for a given excitation frequency. The only machines that may utilize ICRH in a practical manner are the large toroidal tokamaks used in controlled thermonuclear fusion that have plasma chambers up to two meters high.

There is another, less known method of energy transfer for the generation of a stable discharge - the Penning effect [Ste-92] based on multiple collisions of a discharge species with the other constituents of the plasma. In this case, an energetic atom (or molecule) collides with an atom that is in a metastable state due to energy absorption from prior electron-atom (or molecule) collisions. If the ionization potential of the atom in the metastable state is only slightly higher than its metastable state, even a small amount of energy transfer from the second collision to the metastable atom leads to ionizing the latter. Rare gases, like neon can utilize this effect to sustain a discharge. For instance, neon has a metastable state at 16.5 eV with a long lifetime, while its ionization energy is 21.6 eV. If an atom-metastable collision transfers about 5 eV of energy from the

atom to the metastable, the latter will ionize. Since atoms have large collision cross sections, energy can more easily be transferred through elastic, or inelastic collisions between atoms and/or ions. Hence, for specific rare earth gases that can take advantage of this phenomenon, this seems to be an efficient method of energy transfer.

If the excitation frequency of the impressed electric field is different from the cyclotron frequencies, power transfer can still occur from the electric field to the plasma if the discharge pressure is high enough. This is known as Joule, or collisional, or Ohmic heating. The effective collision frequency at high pressures goes up, and this allows for significant energy transfer to the discharge constituents through these collisions. Many high pressure ion sources (100 mTorr to several tens of Torrs) in the EE Plasma Sciences Laboratories of MSU involved with chemical vapor deposition of diamond and diamond-like thin films employ the principle of Joule heating to create and sustain a plasma.

In his monograph, Popov [Pop-94a] presents an excellent discussion of at least nine mechanisms of microwave absorption in ECR plasma sources, other than "pure" ECRH. These are: (1) Doppler shifted ECR, (2) Whistler waves absorption in overdense magnetoactive plasmas, (3) LHCP wave absorption, (4) Upper hybrid resonance (UHR), (5) Higher harmonic resonance, specifically second (SHR) and third harmonics, (6) Plasma geometrical resonances, (7) Stochastic heating, (8) Non-linear power absorption at high microwave electric fields, and (9) Non-resonant collisional absorption of LHCP waves. Appropriate references in his monograph actively supplement each subtopic.

It is not the purpose here to detail every such method of microwave power transfer, but the point being made is that in general, while designing ECRIS,

only conditions satisfying ECR heating (for example, whether ECR zones exist somewhere in the plasma generation region, or whether the impressed electric field has a component that is perpendicular to the static magnetic field in these ECR zones) are accounted for. However, the actual mechanism of power transfer is very much more complex, and this transfer can occur under conditions that vary significantly from ECR specifications. For example, a high level of microwave power absorption of transverse electromagnetic waves at 2.45 GHz can occur at magnetic field strengths much less than 875 Gauss, as well as for field strengths much greater than 875 Gauss provided the plasma density is not lower than the critical density at that frequency of operation. This power absorption, probably due to Landau damping of whistler waves, was experimentally verified by Musil et al. [Mus-75]. Another method of energy transfer - second harmonic resonance (SHR) has in fact been considered in the near past as a prime candidate for powering the next generation of microwave plasma sources.

Several such deviations from the pure ECRH of microwave plasmas are listed by Popov, leading to an inescapable conclusion: while the design of microwave ECRIS is usually based on satisfying electron cyclotron resonance conditions alone, power absorption into the plasma load is significantly diverse and can occur under conditions atypical for ECR. A total reliance on Eqn. (1.1) is therefore inappropriate. This equation was derived using several assumptions (like the cold plasma approximation, homogeneous plasma density and homogeneous magnetic field, linear electrodynamics [Pop-94a], etc.) which simplify the complex equations and produce a closed form solution. However, over-simplification of the problem may also result in loss of information.

Perhaps that is why ECRIS are generally very robust and characteristically forgiving - even poorly designed ECRIS manage to perform well.

All four plasma sources that are experimentally evaluated in this dissertation are microwave ECRIS. The MPDR 610, the 610- α , and the MPDR 5 were designed at the EE Plasma Sciences Laboratory at MSU, while the Superconducting ECR Ion Source (SCECR) was designed, and is under continuous operation at the NSCL. While all the sources are indeed ECRIS, the differences between the design, the external operating conditions (like frequency of operation, input power levels, discharge pressure, etc.) and the final source output (like ion density, ion beam energy, etc.) will become apparent as this dissertation progresses. For example, the frequency of excitation ranges from 915 MHz to 6.4 GHz for the various ion sources, while the operating discharge pressure ranges from 10^{-7} Torr for the SCECR, to 10^{-4} Torr more typically found in the EE sources.

To enhance the importance of ECR effects, and also to serve as a basis for the review of several ECR (and some non-ECR) plasma sources in the next chapter, a generic model of an electron cyclotron resonance ion source is now presented. It will be seen that this model accounts for satisfying pure ECR conditions only.

1.3 Microwave ECR Ion Sources - a Black Box Model

In practice, an ECR ion source consists of a discharge confinement structure that may be made of quartz, alumina, boron-nitride, stainless steel, or copper. This quartz tube, or copper vessel is surrounded by permanent magnets,

or electromagnetic coils (which might be superconducting) that generate the static magnetic field topology for ECR, and also to control (or restrict) the flow of charged species within, and outside the source. The discharge vessel is sealed to a vacuum system which ensures sufficiently low base pressures (usually of the order of 10^{-8} Torr). These low pressures are created with one or a combination of several types of pumps - diffusion, cryogenic, turbo-molecular, titanium sublimation and the regular mechanical backing pump. Discharge gas (or a mixture of several gases) is fed into the plasma vessel through a controlled leak. Electromagnetic energy at the appropriate AC frequency is impressed on the neutral gas, generally through an applicator that ensures maximum possible power transfer to the gas.

Somewhere inside the discharge confinement structure, the static magnetic field is designed such that it has the correct orientation and strength (with respect to the impressed electric field). ECR zones are thereby formed where the power absorbed by the electron gas is enhanced. Subsequent ionizing collisions between the hot electrons and atoms (or molecules) create and sustain the discharge. In general, some sort of cooling (either air, or water) is necessary for the ion source due to the heat generated from the wall losses of the electromagnetic fields, and also from the energy dissipated by collisions and recombinations on the plasma containment vessel walls. Once the discharge is in a steady state, plasma constituents can diffuse out freely from the generation region and into the processing chamber, or a specific subspecies from the quasi-neutral plasma may be selectively extracted using an appropriate extraction apparatus.

ECR technology has several outstanding advantages over previously

established ion source technologies (like Penning gauges that typically have cathodes, or filaments that generate the hot electrons). Filaments (or cathodes) that are present in the discharge region are bombarded by high energy ions and are liable to degrade over time. This leads to short lifetimes, and also contamination from the sputtered material off the electrodes. ECR sources do not require any electrodes, or filaments to ignite or sustain the discharge. Although there are some ion sources reviewed in the next chapter that do have antennae within the discharge zone, ECR ion sources are typically electrodeless in nature. Hence there is no question of contamination from an electrode, or a filament (although wall collisions might lead to sputtering of the wall material). Also, in a well designed source, the only material that needs continuous replenishment is the working gas - all other components should be relatively unharmed after extended use. There are sources that can operate up to 200 hours without problems - ECR ion sources have long lifetimes, which ultimately leads to lower operational costs.

Another advantage of ECR technology is that the plasma electrons are preferentially heated by the impressed electric field. This contains the thermal ion energy to extremely low levels. Low thermal energy of ions is extremely good for several reasons - ion bombardment of substrates does not cause prohibitive damage if the ion energies are low. Hence the performance of ECR plasma sources is dominated by low plasma temperature chemistry. Also, for ion beam sources, one of the factors that leads to beam divergence is high thermal energy of the ions, which generates radially directed space charge fields and increases the repulsive force between the ions constituting the beam, ultimately causing prohibitive beam divergence.

The purpose of an ion source is therefore two fold. First, the discharge confinement structure isolates the (low pressure) plasma generation region from external atmospheric (high pressure) contamination and from the downstream processing region, while delivering the plasma constituents at a steady rate. And second, energy from the power supply (at an appropriate AC frequency), is normally coupled into the plasma through a specially designed applicator that enables maximum power transfer. The ion sources designed in the EE labs, for example, have a resonant microwave cavity structure that acts as an applicator, in which power resonates before being absorbed by the plasma. More details about these ion source and the plasma applicators are presented in the forthcoming chapters as the ion sources experimentally evaluated for this study are introduced and described.

1.4 Organization and Motivation of this Research Effort

No study is complete without an attempt at relating the obtained results to previous and current developments of the technology. This is best accomplished through a survey of the existing literature. Chapter Two of this dissertation is a review of several compact microwave and radio frequency (rf) ion sources. Practically, it is very difficult to compare and contrast each ion source reviewed in Chapter Two due to the many different figures of merit that researchers employ to characterize their ion sources. This also makes it difficult to compare the experimentally measured results of the various ion sources studied in this dissertation, with the results of the reviewed source of Chapter Two. However, where possible, this comparison is made. It is expected that a

scrutiny of the current technology performed in Chapter Two will also help in understanding the experimental results of the sources that are experimentally evaluated in this dissertation.

Chapter Three explains the various characterization principles and experimental techniques that were used to evaluate the ion sources of this study. This chapter is not meant to provide exhaustive details of each characterization technique, but instead to lay a foundation for a basic understanding of each technique, along with its shortcomings, and exact data acquisition methodology. Several pertinent references for each technique are provided if further study is required. For measurement of some parameters (like the ion energy distribution function), new - and possibly next generation methods of data acquisition are also described.

Chapter Four begins the experimental section of this dissertation. The microwave plasma disc reactor 610 (MPDR 610TM) is introduced and described. (Note that during the course of this dissertation, the terms "MPDR 610" and "610" may be used interchangeably, and neither is to be confused with the "610- α ," which is a modification of the 610, and will be introduced in Chapter Six.) While the characterization of the 610 was conducted on several vacuum systems, the "Yorktown-T" that was used for a majority of the experiments is described in this chapter. Other vacuum systems that were used will be described in the appropriate chapters. Characterization results of operating the MPDR 610 at 2.45 GHz microwave frequency are presented. These results include measurements of ion density, electron temperature, plasma potential, electron and ion energy distribution functions, as these output parameters vary with input pressure, power levels and position downstream from the 610. The

results discussed in this chapter were presented at several conferences, including the International Conference on Ion Sources (ICIS-91) in Bensheim, Germany and subsequently published in the proceedings.

The 610 is a unique ion source that can operate at any of a large band of microwave frequencies due to its coaxial structure (refer to Chapter Four for further explanations). The results of exciting the 610 at 915 MHz are presented in Chapter Five. Similar experiments as those done for Chapter Four were also conducted at the operating frequency of 915 MHz, and the results (similarities and differences) of the two frequencies of excitation are compared in Chapter Five. These results were presented at the American Vacuum Society symposium (AVS-92) in Chicago, USA and subsequently published in the proceedings.

Further characterization of the MPDR 610 necessitated the development of the 610-*a*. As will be inferred from Chapters Four and Five, the MPDR 610 was designed to be inserted deep into vacuum systems to generate a plasma close to the substrate surface, and away from the vacuum seal. The 610-*a* does not extend inside the vacuum chamber as does the MPDR 610. Instead, in the 610-*a*, the plasma is generated close to the vacuum seal. This allows for the entire body of the 610-*a* to stay outside of vacuum. Micro-coaxial probes can then be used to determine the electric field patterns, and the absolute (calibrated) electric field strength on the inner surface of the 610-*a*. All internal dimensions of the 610-*a* are similar to those of the original 610, and the sliding short/center conductor assembly of the latter was interchangeably used for both sources. Chapter Six explores these electric fields that exist inside the 610-*a*, and by inference inside the 610, and how these fields change as the pressure, power and gas type are varied. This chapter also brings together concepts of

loaded, and empty cavity quality factors to determine the coupling efficiency of the “cavity applicator” of the 610. Power loss to the walls is calculated based on the measured absolute electric field strengths, and this provides further information on the coupling efficiency of the MPDR 610 cavity structure. Finally, a lumped circuit model for the 610 emerges, based on the calculation of coupling efficiency. Results of this chapter were presented at the IEEE Conference on Plasma Sciences (ICOPS-94) in Santa Fe, New Mexico, USA and subsequently published in a refereed journal.

Chapter Seven shifts gears slightly when attention is moved from the 610 (and 610-*a*) to another compact ECR microwave ion source that was developed at the EE laboratory several years ago - the MPDR 5. While this source has been evaluated earlier, there were significant gaps in its characterization. Further experimentation on this source was therefore conducted for this chapter in terms of its ion energy distribution functions, ion density, etc. as the usual parameters of pressure, power and position were varied. Results of this chapter were incorporated with prior studies by other researchers, and presented at the International Conference on Ion Sources (ICIS-93) in Beijing, China and subsequently co-published in the proceedings.

Chapters Eight, Nine and Ten depart from the EE Plasma Science laboratory and to the ion source facility of the NSCL, where several interesting joint experiments were conducted. The Superconducting ECR ion source (SCECR) produces multiply charged ions for injection into the two particle accelerators (cyclotrons) at the NSCL. ECRIS that are used to create multiply charged ion beams generally have two stages. The first stage was normally thought to pre-ionize the discharge gas before injection into the main stage of

the multiply charge state ECRIS. Chapter Eight is an applications oriented study of the 610 as an injector stage for the 6.4 GHz SCECR to study the exact effects of the first stage on the performance of the SCECR. The 610 could be positively biased relative to the main stage for ion injection, or negatively biased (again, relative to the main stage) for electron injection into the main stage. Or it could be floated for neutral plasma injection. Hence it could be determined with one set of experiments whether the main stage of the multiply charged ion source requires negative, positive or neutral injection from the first stage. Results of this study were presented at the International Conference on Ion Sources (ICIS-93) in Beijing, China and subsequently published in the proceedings.

Chapter Nine is a study of the 610 as an ion beam source, where the source is set up on a test stand (another vacuum system) at the NSCL, and an ion beam is extracted from it. Description of the new vacuum station is followed by the results of beam extraction from the MPDR 610. The first known photographs of the effects of increasing extraction voltage on the plasma meniscus (the ion emitting surface) are presented. Prior results of the 610 on the analysis magnet of the SCECR beamline are also presented, along with charge state distribution spectra, and emittance measurement results. Results of this study were presented as a late entry to the IEEE Conference on Plasma Sciences (ICOPS-94) in Santa Fe, New Mexico, USA.

Chapter Ten is an analysis of the performance of the SCECR when it is excited at a lower microwave frequency of 2.45 GHz. This rather interesting set of experiments indicated that while the SCECR performance in it's "High-B" mode at 2.45 GHz is not as impressive as the SCECR High-B performance at 6.4 GHz, it is perfectly feasible to design a multiply charged state ion source at the

more abundantly available (and therefore much cheaper) frequency of 2.45 GHz. The surprising results of this chapter also call into question the dependence of the designers of multiply charge state ECRIS on the often quoted "law of frequency squared scaling of the ion density." An invention disclosure for the design of this new multiply charged ECRIS at 2.45 GHz has been submitted to the Office of Intellectual Property of MSU, and an international and US patent is currently pending. Also, results of this study will be presented at the forthcoming International Conference on Ion Sources (ICIS-95) in Whistler, Canada, and subsequently published in the proceedings.

Chapter Eleven then brings to a closure the efforts of the past five years with a recapitulation of the conclusions about the MPDR 610, the 610-*a*, and the collaborative experiments at the NSCL. No experimental work is ever quite complete however, and proposals for further research on this set of ion sources are cited at the culmination of this dissertation as a guide for future researchers.

Chapter 2

Compact Plasma Sources - a Brief Review

2.1 Introduction

2.2 The Review Process

2.2.1 The Kyoto University Microwave ECR Ion Beam Source

2.2.2 The Hitachi non-ECR Microwave Ion Source

2.2.3 Compact ECR Source of Ions and Radicals from Russia

2.2.4 The Japanese ECR Radical Gun

2.2.5 The Compact ECR Ion Source from RIKEN, Japan

2.2.6 The N.C. State/ASTeX Inc. Compact ECR Plasma Source

2.2.7 The N.T.T. LSI laboratories Compact ECR Ion source

2.2.8 The Oxford Applied Research Atom/Radical Beam source

2.2.9 A 2.45 GHz. Compact ECR Source from France

2.2.10 The Microscience, Inc. Ion Beam Source

2.3 Discussion - Ion/Ion Beam/Plasma Sources

2.4 Discussion - Figures of Merit

2.5 Concluding Remarks

Chapter 2

Compact Plasma Sources: A brief review

2.1 Introduction

With the advent of plasma processing technology in the industrial environment, there has been a concerted effort in ion and free radical source research and development stemming from the demands of a varied field of research - including plasma physics, atomic physics, ion accelerators, but most specifically from the semiconductor industry. A variety of innovative plasma source designs have been developed with their dimensions and characteristics being predicated by the process and the application. Plasma sources have been designed to work through a vast range of power (few tens of watts to few hundreds of kWatts), pressure (several atmospheres to sub milli Torr) and for cracking several types of gases or metal vapors.

Of the vast variety of plasma sources that have been developed, one subset consists of the compact microwave ion/plasma sources. Some of these are used as a source of ions, while others as reactive free radical sources, and yet others have energetic ion beams extracted from them. Applications of these

plasma sources range from molecular beam epitaxy (MBE) nitriding of GaN and InN, high T_c superconducting thin film deposition using reactive oxygen radicals, free radical pre-cleaning of GaAs wafers using reactive atomic hydrogen, low temperature etching, oxygen implantation using an energetic oxygen beam among other uses. Plasma technology, and ion source development continues to exert its strong influence on the semiconductor and materials processing industry.

2.2 The Review Process

For a basic understanding of the state of the art in ion source design, and also to provide a platform of comparative information (like source dimensions, diagnostics data, etc.), this chapter reviews several compact plasma sources currently used in the semiconductor industry. While the definition of "compact" is rather subjective, an inner source diameter of about 10 cm or less is considered to be compact in this study. However, the adherence to this "cutoff" criterion during this review process is loose at best, so as to study a variety of interesting and unique compact ion/plasma sources. Based on this somewhat flexible criterion, ten compact plasma sources are reviewed in this chapter. To further specialize this review, the frequency of excitation for these sources is in the S band - the microwave range (several hundred MHz up to 100 GHz) in most ion sources, while one of the sources is excited at radio frequency (rf - some tens of MHz).

Each source is individually described in terms of its physical design, assisted by detailed (though not to scale) figures. These figures are

reproductions from the published literature on that ion/plasma source. During the source description, numbers in parentheses indicate the labelled parts in the accompanying figure. An important aspect that defines each source is the method of power transfer into the discharge gas from the source's power coupling structure. While the specific power coupling structure is relatively easy to describe, the actual mechanism of power transfer is usually not that easy to explain. Where possible, the power coupling mechanisms for each source are discussed, or speculated if suitable information is not specifically provided in the source literature.

Performance characteristics of the source are then presented. While different researchers perform different characterization experiments, certain figures of merit for each ion source are commonly measured, like ion/electron density (in cm^{-3}), electron temperature (in degree Kelvin, or eV; $1\text{eV}=11,604.4\text{ K}$), average ion/electron energy (in eV) and the ion/electron energy distribution functions, and ion saturation current density (in $\text{mA}\cdot\text{cm}^{-2}$). Free radical sources are generally characterized in terms of their atomic flux (in $\text{mA}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$) and film growth analyses, measured indirectly by XPS, reflection high energy electron diffraction (RHEED), or quartz crystal microbalance (QCM) studies of the film. Optical emission spectroscopy (OES) data are also provided by some researchers to identify individual species within the plasma. Ion beam data are generally provided as the total beam current (in mA or μA , assuming 100% beam acceptance by a shielded Faraday cup), or beam current density (in $\text{mA}\cdot\text{cm}^{-2}$) that accounts for the Faraday cup's collection area. The emittance (in $\text{mm}\cdot\text{mRad}$), or the normalized emittance where relativistic effects of the beam are taken into account (also in $\text{mm}\cdot\text{mRad}$), and brightness (in $\text{A}\cdot\text{m}^{-2}\cdot\text{rad}^{-2}$) of the

beam are also characteristic of the ion beam source and its extraction apparatus. These two measurements of the ion beam indicate the efficiency of the extraction apparatus, and the transmission properties of the beam transport system. Mass spectrometry of a discharge, typically using a quadrupole mass spectrometer (QMS), can produce a charge state distribution (CSD) that gives the relative current intensity for each charge state present in the beam. Details of several characterization techniques mentioned above are presented in Chapter Three - these techniques were utilized to evaluate the performance of the four major ECR plasma/ion beam sources studied during the course of this dissertation.

Input power, in all cases implies the net power being absorbed by the discharge and/or the ion source. It is the difference of the total incident power and the reflected power from the plasma source, taking into account all attenuation factors pertaining to power loss in the cables, connectors, source walls, etc.

This review process concludes with a general discussion of compact microwave ion sources that are studied in this chapter, with a brief comparison, where possible, of the figures of merit that define these sources. A discussion of the necessity to standardize certain figures of merit also follows. Many of the sources discussed here have commercial versions available, and all are used for processing applications, or as tools for fundamental plasma physics and chemistry investigations. Where reported in literature, the various applications of the plasma/ion/ion beam sources are detailed.

This review confines itself to compact plasma sources and some ion beam sources used in materials processing and semiconductor applications. A

significant omission from this study, therefore, is the family of microwave ion beam sources used in accelerator laboratories throughout the world. While most of these ion sources used in atomic and particle physics research (including particle accelerators) are large and bulky, some may be classified as "compact." The main difference between accelerator ion beam sources and those used in processing applications is that the former are designed to produce highly charged species with multiply stripped ions, which are then extracted as a very energetic beam (up to several tens of kV extraction potential), and injected into the accelerators for further energy gain. The latter variety on the other hand (the plasma/ion sources used in substrate processing applications), require only singly charged ions to prevent substrate damage from energetic ion bombardment. (The higher the charge state of the ion, the more energy it gains while being accelerated through an extraction potential, or even while falling through the plasma potential within the discharge.) Note that while ion beam sources used in ion implanters do produce multiply charged species (like O^{2+}) to reduce the required acceleration potential, the beam energies and most other operating conditions of ion implanter sources are still very different from high charge state producing ion sources.

While each plasma source discussed in this chapter varies from the other, they have many things in common. Most are electron cyclotron resonance (ECR) based ion sources that require a static magnetic field to create resonant conditions for the electron gas, while some are off resonance devices (non ECR). Non ECR sources employ essentially Joule heating and other mechanisms of power transfer such as stochastic (non collisional) heating - as discussed in Chapter One - to create and sustain the plasma. There are usually some

magnets even in non ECR plasma sources to confine and control the diffusion of charged species out of the source. Some sources use permanent magnets, mainly to simplify the design and reduce overall size and peripheral apparatus costs, while others rely on current coils for better control of field strength while sacrificing some of the simplicity and cost benefits of permanent magnets (current coils require water cooling, and peripheral power supplies to control the magnetic flux).

An important point needs to be made about resonance - a topic that will come up while describing several sources. There are two types of "resonant sources" that will be discussed. The microwave plasma disk reactors (MPDRs) designed at MSU in the EE laboratories have tunable resonant cavities that set up specific electromagnetic resonant modes within the adjustable cavities. This type of resonance has to be differentiated from the electron cyclotron resonance, which all ECR based sources incorporate. Hence, a "resonant cavity" may simply be the source's reliance on ECR, or it may mean that the source has adjustable dimensions that are tunable to appropriate EM modes, as in the case of the MPDR family of sources. This distinction will be pointed out when the sources are discussed during the appropriate sections.

It is expected that once this review is completed, it will provide a better understanding of ion sources (both ECR and non-ECR) in terms of their design parameters, optimal operating conditions and performance characteristics. Also, as awareness grows about these various plasma sources, a basis will be formed to more thoroughly understand and compare the evaluative results obtained during the past five years of research on the four primary plasma sources that are detailed in Chapters Four through Ten of this dissertation.

2.2.1 The Kyoto University Microwave ECR Ion Beam Source

In 1983, Ishikawa et al. at Kyoto University in Japan reported the development of a low power compact ECR microwave ion source with a non resonant cavity structure [Ish-84, Sak-89]. Shown in Figure 2.1 (not to scale), the source has an overall diameter of 5.0 cm, and height of 6.5 cm. The plasma chamber is 1.6 cm in diameter and 5 mm in effective height, ending in a 2 mm non ferro-magnetic aperture. The gap between this aperture and the extraction electrode (5) is 3 mm. The base flange is water cooled, allowing the use of a Viton O-ring for sealing this flange to the rest of the source, although the source itself uses a copper gasket to seal to the vacuum chamber. A sheath heater (2) is wound around the ion source to raise the temperature of the source when a metal vapor is to be ionized.

Design of the axial magnetic field structure is critical to this ion source, and numerical simulation of the beam extraction and magnetic lines of force was used to optimize this magnetic field configuration. The Sm-Co permanent magnet (3) used in this source is donut shaped measuring 50 mm outer diameter, 40 mm inner diameter and 15 mm high. The extraction electrode (5), the magnet and a connecting flange made of ferro-magnetic material forms a closed magnetic circuit from the bottom of the discharge region to the top of the source. This effectively creates a magnetic field residual flux density of about 0.97 kiloGauss, with the field strength varying from 800 G to 1200 G between the antenna (7) and the extraction electrode. The "ECR zones" therefore fall well within the plasma generation region of the source. The field lines are also arranged to enhance ion divergence.

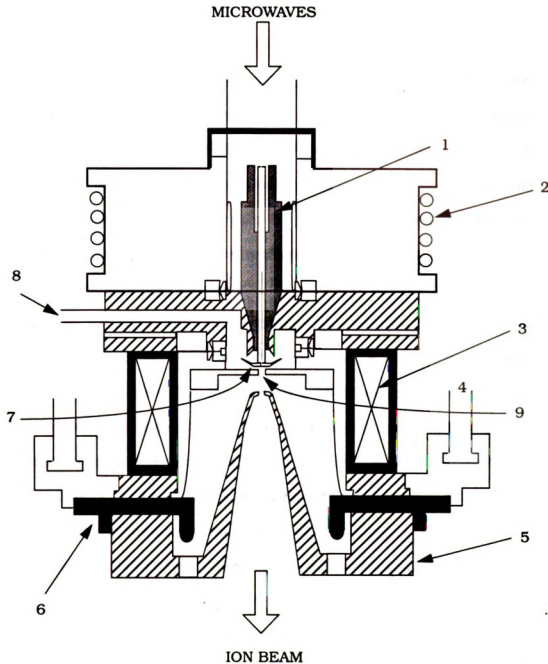


Figure 2.1 Kyoto University Microwave ECR Ion Beam Source

1. Boron Nitride Plug
2. Sheath Heater
3. Permanent Magnets
4. Coolant

5. Extraction Electrode
6. Maycor Insulator
7. Antenna
8. Gas Inlet
9. Aperture

Microwaves at 2.45 GHz are fed through a flexible coaxial cable, to a sealed coaxial connector and into the discharge chamber via a "T" shaped antenna (7). This antenna, made of molybdenum or stainless steel wire of 1.5 mm diameter, protrudes into the plasma production chamber. The unique shape of the antenna maintains a high electric field within the chamber walls, and this electric field is able to sustain a stable discharge even at low pressures (few mTorr). A boron nitride (BN) plug (1) prevents plasma generation near the antenna shank. For input power (incident minus reflected) of about 20 to 30 W, the power coupling has a reflection ratio of about 30-40% for metal vapor, and about 30% for argon, nitrogen, and other gaseous discharges. This reflection ratio is somewhat high, and should be expected because of lack of any tuning mechanism to counteract the changing load impedance as the discharge approaches steady state. It is, therefore, impossible to match the microwaves to the plasma for all operating conditions. However, the high reflection coefficient does not affect the ion source performance.

The performance characteristics of the source were measured using a multi-grid Faraday cup placed 6 cm downstream from the plasma generation region [Ish-84]. Also, mass spectra were analyzed, and emittance measurements were made. The electron suppressor voltage on the first grid of the Faraday cup was kept sufficiently high (negative 150 V) to prevent high energy electrons from entering the cup and polluting the readings with secondary electron emissions. At low input power levels of about 20 - 30 W, and an extraction voltage of 15 kV, the argon ion current density at a relatively low pressure of 1 mTorr is almost 100 mA-cm^{-2} . The ion beam current variation with extraction voltage is less than the maximum current predicted by the classical Child-Langmuir law - a linear

relation between the extraction voltage and the beam current on the log-log scale (assuming a specific ion density in the generation region). The current-voltage characteristics of the source indicate an initial linear increase in beam current with increasing potential, leading to a saturation beyond a certain voltage. Typically, the linear region is ion density limited, while the saturation region is said to be space charge limited.

Similar high current densities are observed for nitrogen, carbon dioxide and oxygen gas, and also for Cs and Rb metal vapors. For a metal vapor (like cesium) at about 20 watts input power and 15 kV extraction voltage, the current density was over 80 mA-cm^{-2} , the total current being 2.7 mA. Plasma density can be controlled by pressure and power variation. QMS analysis showed a high ratio of about 95:5 for the $\text{Ar}^{1+}:\text{Ar}^{2+}$ ions, possibly due to the divergent and non-confining structure of the magnetic field. The ratio of doubly charged ions does increase as the pressure decreases, in part due to the increased lifetime of hot electrons with the falling electron-neutral collision frequency with reduced discharge pressure. Theoretical estimations of the ion density, based on the assumption that the average electron temperature in the plasma is 5 eV are made to be in the low 10^{12} cm^{-3} - note that ion density and electron temperature is not directly measured.

A plasma density of 10^{12} cm^{-3} for a 2.45 GHz discharge at about 1 mTorr pressure is relatively high. This may be explained by the efficient power transfer from the EM fields to the discharge as claimed by the authors. The skin depth, which is defined as the depth at which the attenuating electric field is $\exp(-1)$ of its amplitude before being attenuated by the discharge, is given by the following equation [Ish-84]:

$$\delta = \frac{c}{\left(\omega_p^2 - \omega^2\right)} \quad (2.1)$$

where δ is the skin depth, c is the speed of light, ω_p is the plasma angular frequency, and ω is the frequency of excitation. At 2.45 GHz and with an estimated ion density of 10^{12} cm^{-3} , δ is calculated to be about 5.5 mm; the height of the plasma generation region is 5 mm. Hence, the authors speculate that such high density is probably due to effective penetration of the right hand circularly polarized (RHCP) up to the skin depth in the magnetized plasma.

Emittance calculations were done to characterize the beam extraction and transport for this ion source. The measurement system consisted of a plate with a series of 0.5 mm diameter holes; this plate is separated from the mobile wire detector of 25 μm diameter by a distance of 16.5 cm. With 86.5% of the total ion beam current covered by the fitted emittance contour, the normalized emittance of the beam was estimated to be $3.7 \times 10^{-8} \text{ m-rad}$, or $3.7 \times 10^{-2} \text{ mm-mRad}$. The normalized brightness is calculated to be about $1.8 \times 10^{11} \text{ A-m}^{-2}\text{rad}^{-2}$. Both the emittance and brightness were a function of input power. The ion beam divergence angle measured with the emittance apparatus was estimated to be about 5° . This divergence is relatively high presumably because of the inadequacies of the double grid extraction system and should decrease with the use of a proper accel-decel system.

The ion source can therefore work at extremely low power and low pressure conditions, and can effectively absorb microwave power even though it does not have a resonant cavity structure. Potential applications of the ion source are postulated to be in accelerators, sputtering and ion beam assisted

etching machines. A similar source is currently under construction at the cyclotron laboratory of Catania, Sicily for possible beam injection into the main stage of a multiply charged state ion source [Gam-94].

A scaled up variation of the above source was introduced in 1989 [Tsu-89]. Although not a compact source any more (outer diameter is 22 cm, and height is 10 cm), it is a significant modification - there are three similar helical molybdenum (or stainless steel) antennae instead of one. The scaling is done therefore, by effectively stacking three sources together. The plasma production region is larger - $1.6 \times 6.6 \times 0.5 \text{ cm}^3$. Each antenna is fed via a quasi coaxial line, as in the previous version, using a BN plug as an insulator that prevents plasma from being generated near the antennae shanks. Even with this larger area the source is not a resonant cavity structure. 10 small Sm-Co permanent magnets ($3.0 \times 0.8 \times 2.0 \text{ cm}^3$) are circularly arranged and, along with the ferromagnetic materials of the bottom plate, provided the axially divergent magnetic fields for ECR and ion transport requirements.

Two microwave power sources at 2.45 GHz were used to power the three input lines - one supplying power for the center antenna, and the other source for the two outer antennae. Typical microwave power was about 40 W, with a total of about 27 W reflected. About 80% of the input power from each antenna was absorbed by the plasma, a fact confirmed by alternately switching on individual antenna while keeping the other antennae off. This also indicated that the EM fields from any antenna did not adversely affect the fields of the other antennae. A "sheet beam" was extracted from the ion exit slit ($0.6 \times 60 \text{ mm}^2$), with a $4 \times 70 \text{ mm}^2$ long extraction aperture. An einzel lens (three pairs of plate electrodes with an opening area of $3.0 \times 9.0 \text{ cm}^2$) was used to focus the sheet

beam. Such a sheet beam is typically used in ion implanters.

Performance characteristics were measured using a multigrid Faraday cup placed 27 cm away from the ion exit aperture. An electron suppressor voltage of 1.2 kV is applied to the top grid to prevent contamination of collected current data from secondary electrons. As for the previous version of the source, the plasma density generated within the source is estimated to be about 10^{12} cm^{-3} . At an extraction voltage of 20-25 kV and 100 W input power, a 10-20 mTorr argon discharge produces a total current of 12.5 mA. Note that this is a relatively high pressure discharge, specially if the pressure measurement is conducted downstream - the discharge pressure in that case may be several times higher than the processing chamber pressure. For the same pressure and power conditions, a nitrogen discharge produced an ion current of about 13.5 mA, while the oxygen current was 5.6 mA for an oxygen plasma - a marked increase in the total current production over the previous source design. This modified source, therefore, operates at higher pressure and power levels, while providing higher beam currents.

As can be seen, a major advantage of this source is that for more intense ion currents, or a larger beam area, the plasma source can be easily scaled up because of its quasi-modular design, and also because it is not a resonant cavity structure despite being an "ECR source". Addition of similar antennae and extraction apparatus is possible without sacrificing the source performance in any way. While resonant cavity based plasma sources like the microwave plasma disk reactors (MPDRs) that will be discussed later in the dissertation, may also be scaled up, factors like choice of resonance at specific electromagnetic modes might affect the scaling process. The different "stacking together" method of

scaling used in this source ensures that such problems are not an issue, specifically because the source is not based on a resonating any specific mode in the cavity structure.

Yet another version of this compact ion source was presented at the International Conference on Ion Sources in 1991 in Beijing, China by a research group at the Peking University, PRC [Son-92]. The source design remained essentially the same as the original single antenna source of Ishikawa et al. The total source diameter is 4.6 cm, and its height is 5.0 cm. The copper discharge chamber has a diameter of 2 cm, and is equipped with a 2 mm extraction hole in the bottom stainless steel plate. The ferromagnetic extraction electrode is 3-7 mm away from the ion exit plane, and has a 4 mm diameter hole. A similar annular axial permanent magnet is used create the magnetic fields inside the discharge chamber. The "T" shaped antenna is made of stainless steel with a diameter of 2 mm.

Initial performance characterization of this version of the plasma source has indicated a similar tendency of a high reflection coefficient - about 40% of the power is reflected back. With less than 60% of the power coupling into the plasma, the authors conclude that further research into the plasma impedance matching mechanism needs to be done. A nitrogen discharge was used to obtain preliminary ion extraction data. At a pressure of 10 mTorr, and about 50 watts of power absorbed, the nitrogen discharge produced a total beam current of about 1.2 mA with an extraction voltage of 10 kV. Further experiments to characterize the ion source, and also to improve its design and performance are currently under way.

2.2.2 The Hitachi non-ECR Microwave Ion Source

Another off resonance microwave ion source was developed by Sakudo and associates in the Tokyo laboratories of Hitachi Limited in 1977 [Sak-77] and further reviewed later [Sak-87, Sak-89]. The source, which is shown in Figure 2.2 (not to scale), has a discharge chamber diameter of about 6 cm. The plasma chamber is essentially an extension of the 50 Ohm circular coaxial waveguide (2). Microwaves at 2.45 GHz are fed through a rectangular waveguide (1) - this is intersected by the coaxial waveguide, terminating in a water cooled antenna (4) that extends into the chamber. The discharge chamber is also water cooled so as to prevent the ceramic vacuum window (9) from being over heated, and/or destroyed by particulate bombardment.

A magnetic mirror ratio of about two is created by three electromagnet coils (3). The magnetic field configuration thus generated helps in preventing backstreaming of energetic particles. The main purpose, however, of the magnetic mirror, is to gradually vary the resistivity of the plasma load. The intensity of the field generated by the coils throughout the source length is higher than that required for ECR at 2.45 GHz. Assuming that the plasma is a resistive (lossy) dielectric, a mirror ratio helps in creating a plasma source that terminates in a gradually varying resistive load, which in turn helps in microwave coupling into the plasma for all discharge conditions. With no external tuning mechanisms, this gradually varying resistive load auto-tunes the resistive component of the plasma load to the 2.45 GHz waveguide impedance. This was demonstrated by a test in which the absorption of microwave energy increased from about 60% to over 90% as the magnetic field

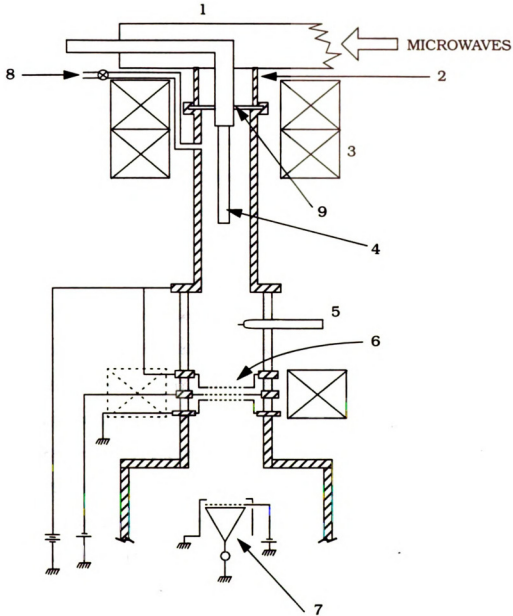


Figure 2.2 Hitachi Non ECR Microwave Ion Source

- | | |
|--------------------------|---------------------------|
| 1. Rectangular Waveguide | 5. Movable Langmuir Probe |
| 2. Circular Waveguide | 6. Multi-aperture Lens |
| 3. Magnet Coils | 7. Multi-grid Faraday Cup |
| 4. Antenna | 8. Gas Inlet |
| | 9. Ceramic Window |

intensity was increased from 40% to 100%.

Note that although there might be regions where the magnetic field conforms to the requirements of ECR, this is not an ECR based source - specifically, the source produces a type of "wave heated" discharge (as discussed in Reference Lie-94). It works on the principle that if the magnetic field inside the source is higher than that required for electron cyclotron resonance, but lower than that for ion cyclotron resonance (ICR), a plasma discharge may be ignited and sustained without relying on ECR [Mus-74]. A three grid (with multiple apertures - 124 holes, each 3 mm in diameter) accel-decel extraction system (6) is used to extract the energetic particle beams, with a negative 300 V suppressor voltage on the middle grid.

Performance characteristics of this source were measured using a cone shaped multigrid Faraday cup (7) placed 15 cm from the extraction grids, and a movable Langmuir probe (5). Electron temperatures for both hydrogen and argon discharges increased slightly with increasing input power ranging from 3 - 4 eV at 200 W, to 5 - 6 eV at 1 kW input power. At 1 mTorr pressure, the argon ion density increased from 10^{12} cm^{-3} to 10^{13} cm^{-3} as input power was raised from 400 W to 1 kW - this source generates densities about 10 to 100 times those in a source that relies on ECR for plasma generation. The source therefore has a very high ionization efficiency. Ion density in hydrogen were typically seen to be a little less than those in an argon discharge. Since the source does not rely on ECR, it need not conform to the critical density development that, theoretically, limits the maximum density of a 2.45 GHz plasma to $7.4 \times 10^{10} \text{ cm}^{-3}$. Over the entire pressure range, the power absorption was noted to be about 75%, which may be increased to 90% by using an external EH stub tuner

between the directional coupler and the ion source. At a pressure of 1.3 mTorr and with 1 kW incident power, a maximum hydrogen ion current of about 380 mA at 4.5 kV extraction voltage, and a maximum argon ion current of about 200 mA at 5 kV extraction voltage was measured with the multi-grid Faraday cup (7) placed downstream from the discharge generation region (see Figure 2.2). As the extraction potential was raised from zero to 5 kV, the argon ion beam current increased monotonically with extraction voltage. The hydrogen ion beam current however, seems to saturate beyond 5 kV bias.

The fundamental advantage of this off resonance ion source over other "ECR sources" seems to be that the ion current intensity and ion densities produced in this source are much higher. Due to the high magnetic mirror ratio, the ceramic window is relatively safe from energetic ion bombardment, hence the source has a long lifetime. However, particulate generation off the antenna that is surrounded by the discharge has not been accounted for by analyzing the plasma constituents, which might lead to problems with UHV applications unless specific ion species are mass separated downstream from the discharge generation region.

2.2.3 Compact ECR Source of Ions and Radicals from Russia

A compact ECR ion and free radical source with a very simple design was introduced in 1991 by the then USSR Academy of Sciences, Moscow [Sha-90, Sha-92]. The source, which is shown in Figure 2.3 (not to scale) has a length of 16.0 cm, and a diameter of 11.3 cm. It may be installed on existing chemical beam epitaxy (CBE) machines and other UHV equipment using a standard CF63

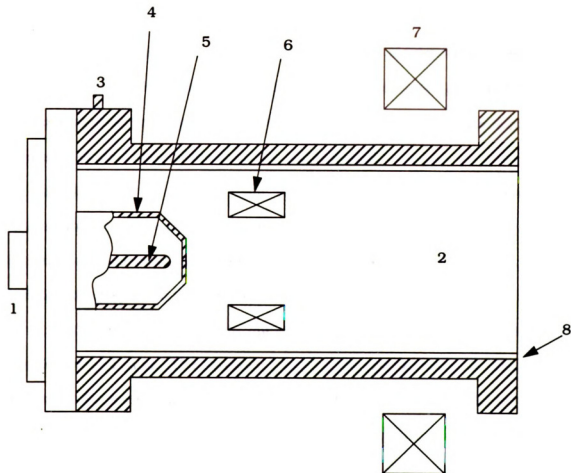


Figure 2.3 Compact ECR source of Ions/Radicals from Russia

1. 50 W Coaxial cable connector
2. Plasma cavity
3. Gas feed
4. Ceramic cup

5. Antenna
6. Ring shaped permanent magnet
7. Electromagnetic coil
8. Quartz tube liner

flange. The source utilizes Sm-Co permanent magnets to create the magnetic fields required for ECR. These ring shaped magnets (6) are placed inside the discharge chamber (2) with special adjusting rods, creating sufficient magnetic field strength for high plasma densities (about 10^{11} cm^{-3}) at a pressure range of 0.1 mTorr to 10 mTorr. An electromagnetic coil (7) is placed outside the source (but in the vacuum chamber) for efficient control of charged particle flux. This variable magnetic field may be used to either extract or deflect the ions away. The stainless steel body of the source is water cooled.

A standard 50 Ohm coaxial cable terminates into an antenna (5), coupling microwaves at 2.45 GHz into the plasma chamber. The antenna is isolated from vacuum via a ceramic cup (4). The diameter of the antenna, and its position with respect to the magnets are critical for stable operation of the ion source; both conditions were determined empirically, and the reported antenna diameter was 4 mm. The variable position of the antenna is the tuning mechanism for matching the load impedance. A quartz tube liner (8) is inserted into the source to reduce losses of radicals and ions to the stainless steel walls. It may also prevent particulate generation (and therefore contamination of the discharge) from the metallic walls, while at the same time providing secondary electrons to the discharge - quartz has a high secondary electron emission coefficient.

Performance characteristics were measured using cylindrical and disc shaped Langmuir probes. These probes were located about 10 cm downstream and were DC biased with a negative potential of 35 volts. Measured saturation ion current density for a 100 W input power hydrogen plasma showed a typical pressure dependence - initially increasing to about 2 mA-cm^{-2} at 1 mTorr, and

then gradually decreasing to about 1 mA-cm^{-2} as pressure was further raised to 4 mTorr. When experiments were conducted over various power and pressure ranges, it was found that the optimal operating pressure range was 0.1 mTorr to 5 mTorr for moderate power levels of 500 W or less. High ion current densities could be obtained at these low powers, and so there was no need for extensive cooling of the source as required for other sources that rely on higher input power levels to generate the high ion densities. At a constant pressure, the saturation current density increased monotonically with increasing power, ranging from 0.5 mA-cm^{-2} at 10 W, to over 3 mA-cm^{-2} at 200 W input power. The electron temperature of a hydrogen discharge, calculated using Langmuir probe I-V characteristics, was estimated to be about 4.7 eV for 50 W, and 4.3 eV for 25 W net input power.

The source has been successfully used for in situ cleaning of GaAs substrate using arsine (AsH_3) and triethylgallium (TEG) in a chemical beam epitaxy (CBE) reactor made by EPIQUIP™ of Sweden. For this process, a hydrogen plasma at 0.2 mTorr was used to bombard the substrate placed about 40 cm away for 10 - 15 minutes. In situ RHEED, XPS and QMS studies confirmed a complete removal of the GaAs native oxide from the substrate surface, and also confirmed the absence of any carbon and oxygen peaks on the surface. Further, film growth experiments demonstrated a significant increase in growth rates of GaAs, and good surface morphology after the substrate was exposed to a hydrogen plasma from this compact ECR ion source. Future applications for this source are foreseen in CBE growth of III-V semiconductors, and as an ion beam source with extraction grids.

2.2.4 The Japanese ECR Radical Gun

The Institute of Physical and Chemical Research (RIKEN), the Toyo University, and the Irie Koken Co. Ltd., all of Saitama, Japan reported in 1991 the development of a compact ECR source [Oke-91a], and also reported on some of its applications [Oke-91b]. The source is sketched in Figure 2.4 (not to scale). Essentially a free radical source, the radical gun has a low ion current density but a high atomic flux, and is therefore most suitable for applications that require high radical species concentration. The simple design of the source consists of a resonant cavity structure made of stainless steel 2.5 cm long, with a 1.0 cm diameter. Note that, as mentioned in the introduction, the "resonant cavity" in this source means only that the source is based on ECR, and not that the dimensions of the cavity change to generate resonant standing electromagnetic waves (as in the case of the MPDR sources). The overall diameter of the plasma source is about 35 mm, and the overall length of the source is variable, depending on the application. It is mounted on a standard 70 mm conflat flange (7).

Microwave power at 2.45 GHz is fed via a flexible coaxial cable (1), the center conductor of which continues into the vacuum creating a variable length, in-vacuum coaxial cavity structure. The center conductor then terminates into an antenna (4) that protrudes into the plasma creation region. The antenna is encased inside a quartz tube (6), and a BN centering ring (3). There are two ring shaped water cooled permanent magnets (5) that provide the static magnetic field for ECR. A beam may be extracted through an orifice of variable diameter - from 1 mm to 10 mm.

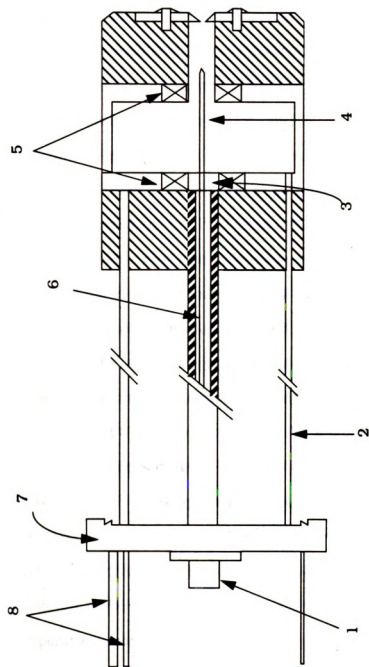


Figure 2.4 Japanese Radical Gun

- | | |
|------------------------------|----------------------------------|
| 1. Microwave Cable Connector | 5. Ring Shaped Permanent Magnets |
| 2. Gas Feedthrough | 6. Quartz Tube |
| 3. BN Centering Ring | 7. 70 mm Conflat Flange |
| 4. Antenna | 8. Coolant Feedthrough |

The performance characteristics of the source were measured using a quartz crystal microbalance (QCM), optical emission spectroscopy (OES), a multi-grid Faraday cup, and Langmuir probes for a variety of gases and under many discharge pressure and input power conditions. For a 0.1 mTorr argon plasma, OES indicated a predominance of the Ar^{1+} ion and $\text{Ar}^{\bullet}$ radicals. The dominant peak in an oxygen discharge at 10 mTorr is the oxygen radical $\text{O}^{\bullet}$, although there are some minor O^{1+} and O_2^{1+} peaks as well. A nitrogen plasma at 1 mTorr has predominantly N_2^{1+} peaks, but $\text{N}^{\bullet}$ and $\text{N}_2^{\bullet}$ radical peaks are also visible. The three Balmer lines of hydrogen are in evidence for a 20 mTorr hydrogen plasma.

A Faraday cup with a negative 80 V electron suppressor grid and an effective area of 12 cm^2 was placed 4 cm downstream from the radical gun to measure the current density produced by the source. For a 0.1 mTorr hydrogen discharge, the ion current increased with increasing power; the maximum current density was $12 \text{ } \mu\text{Amps}\cdot\text{cm}^{-2}$ with 160 W input power, (corresponding to a flux of about $8 \times 10^{12} \text{ cm}^{-2}\cdot\text{s}^{-1}$). Similar ion current density behavior was seen with an oxygen discharge at 10 mTorr - as the input power was increased from 50 W to 150 W the oxygen ion current density increased almost linearly with a maximum of approximately $160 \text{ } \mu\text{amps}\cdot\text{cm}^{-2}$ (and an equivalent ion flux of $10^{15} \text{ cm}^{-2}\cdot\text{s}^{-1}$). For the same range of input power (increased from 50 W to 150 W), Langmuir probe data in a 10 mTorr oxygen discharge indicated that the electron temperature dropped from about 3 eV to about 1.5 to 2 eV, and the oxygen ion density was about 10^{10} cm^{-3} .

QCM analysis was used to obtain quantitative values of radical oxygen flux. When the plasma pressure was decreased from 10^{-2} Torr to 10^{-3} Torr, the

ion flux decreased from $10^{15} \text{ cm}^{-2}\text{-s}^{-1}$ to about $10^{14} \text{ cm}^{-2}\text{-s}^{-1}$, but the radical flux remained almost unchanged at about $10^{15} \text{ cm}^{-2}\text{-s}^{-1}$. So decreasing the pressure increased the radical content of the beam with respect to the ionic concentration. This may be due to the drop in ion density (O_2^+ and O^+) as the pressure is reduced. As an example, for an oxygen discharge pressure of 10 mTorr, the $\text{O}_2^{1+}/\text{O}^+$ percentage was 34%, whereas for a 1 mTorr discharge, this ratio had decreased to approximately 8%.

The radical gun was used in two potential applications: for the in situ oxidation of a superconducting thin film during deposition, and low temperature GaAs substrate cleaning (confirmed by RHEED) using a hydrogen plasma [Oke-91b]. High quality superconducting thin films were produced with the use of this oxygen radical gun. By magnetically deflecting the charged species away and reducing the ion current by as much as 40%, an oxygen radical (O^*) rich beam was created. When the superconducting film was exposed to this oxygen radical beam during deposition, the characteristic temperature of the film increased, and the corresponding properties like the phase transition from normal, to superconducting phase also got better. The improvement in the film properties may be a result of the decrease in the damaging ion bombardment from the beam, once the ions have been magnetically deflected away from the beam that impinges on the film. For the other application, the rate of low temperature (about 100 °C) GaAs substrate cleaning was increased by using higher power. Further applications for this radical gun are expected to include digital integrated circuits etching, surface passivation and semiconductor substrate doping.

2.2.5 The Compact ECR Ion Source from RIKEN, Japan

Collaboration between RIKEN, the University of Tokyo, the Tokyo Institute of Technology and the TOYO University, all of Japan produced another compact high current ECR-type ion source that was reported in 1989 [Tam-89]. The source was designed with a specific application in mind: producing thin oxide layers of composite material. The source is shown in Figure 2.5 (not to scale). The unique and simple design of this non-resonant ECR plasma source consists of a cylindrical pyrex vacuum vessel (8) intersecting a rectangular waveguide (5) that is used to transport the 2.45 GHz microwaves from the magnetron (1) that is placed close to the source. The waveguide terminates into a plunger type tuner whose position is adjusted for optimal power transfer into the ion source. The microwaves are localized in the plasma creation region by a cone shaped structure (2). The outer diameter of the vessel is 7.0 cm, and its height is 5.0 cm.

A modified cusp shaped magnetic field structure is created by two permanent magnets. The first is a water cooled Sm-Co cylindrical magnet (4) with a diameter of 1.0 cm, and length of 3.0 cm. It is placed inside a pipe within the discharge chamber that acts like an antenna (3). The other magnet is a ring shaped structure (6) made of ferritic steel (ID of 6.0 cm, OD of 10.0 cm, and thickness of 1.5 cm), and is placed outside the chamber with its north pole facing the north pole of the cylindrical magnet. This magnet is also water cooled. The magnets are 2.0 cm away from each other and the magnetic field strength inside the source is strong enough to satisfy the ECR condition (875 Gauss at 2.45 GHz operation). The magnetic field structure is such that the field lines also

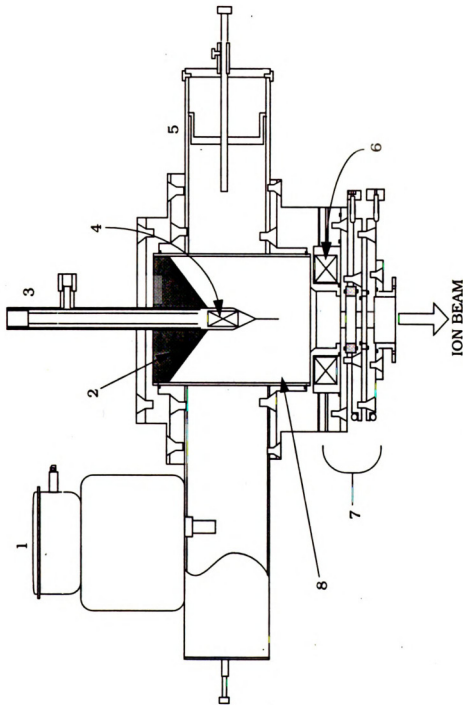


Figure 2.5 Compact Ion source from RIKEN

- | | |
|---------------------------------|---------------------------------|
| 1. Magnetron | 5. Rectangular Waveguide |
| 2. Cone | 6. Ring Shaped Permanent magnet |
| 3. Antenna | 7. Extraction apparatus |
| 4. Cylindrical Permanent magnet | 8. Cylindrical vacuum vessel |

efficiently transport the ions to the bottom of the source where they are extracted by a three electrode accel-decel extraction system (7).

Plasma characteristics were measured using a Langmuir probe, and an ion collector electrode - a single plate placed about 16 cm below the extraction electrodes. The probe was located in the extraction aperture of the first electrode. For a 280 W hydrogen plasma, as the discharge pressure increased from 0.02 mTorr to about 1 mTorr, the ion density increased from $2 \times 10^{10} \text{ cm}^{-3}$ to about $2 \times 10^{11} \text{ cm}^{-3}$. Hence an over dense discharge is achievable in this source. (The critical density at 2.45 GHz is about $7 \times 10^{10} \text{ cm}^{-3}$.) At the same time, electron temperatures fell from about 12 eV to about 3.5 eV. For a 280 W, 0.01 mTorr hydrogen discharge, a beam current of about 4.5 mA was extracted with an accel-decel voltage of 2 kV and negative 200 V respectively. The current density at the output of the discharge chamber could then be calculated to be about 5.7 mA-cm^{-2} since the area of the extraction hole is 0.785 cm^2 . For a 3×10^{-5} Torr hydrogen discharge, the electron temperature and ion density were calculated to be about 11 eV, and about $3 \times 10^{10} \text{ cm}^{-3}$ respectively. A QMS analysis indicated that the proton yield of the source was about 20% from a 3×10^{-5} Torr hydrogen discharge. This source was used to efficiently produce H^+ ions. From a 0.4 mTorr hydrogen discharge at 280 W input power, the H^+ beam had a current of about 0.5 mA-cm^{-2} [Tam-90].

Emittance data was taken for the beam characterization. The measurement system consisted of two plates 75 mm apart, with a 0.5 mm wide slit. The emittance area was estimated to be about $260\pi \text{ mm-mrad}$ with an ion beam divergence half angle of about 8° . This divergence angle is relatively high primarily because of the large ion extraction aperture.

It has been shown that this ECR ion source is very compact, economical and stable, characterized by high electron density and high current intensities for both positive and negative hydrogen ions. The electron temperatures are slightly higher than those obtained with other sources for similar input power levels, probably because the operating pressures are much lower for this source. (As pressure decreases, the electron temperature must increase to sustain the discharge.) The beam characteristics may be improved by using a redesigned extraction apparatus.

2.2.6 The North Carolina State/ ASTeX Inc. Compact ECR Plasma Source

In 1990, ASTeX Inc. of Massachusetts and an engineering team from North Carolina State University reported a distributed, or multicusp ECR ion source [Sit-90a, Dav-90a]. This compact UHV compatible plasma source, shown in Figure 2.6 (not to scale), may be inserted into an existing 2.25 inch diameter MBE effusion cell. The basic structure is similar to that of the Japanese radical gun (Section 2.2.4) - an ECR resonant coaxial microwave applicator, and also to that of the MPDR 610 - detailed later in the dissertation. Note once again, that the "resonant" cavity for this source refers to it being an ECR base source, and not the tunable cavity structure of the MPDR sources (as was mentioned for the Japanese radical gun in Section 2.2.4).

Three small water cooled electromagnets (8) produce the ECR, mirroring and extraction magnetic fields within the source. The magnetic field strength is greater than the 875 Gauss required for ECR at 2.45 GHz throughout the

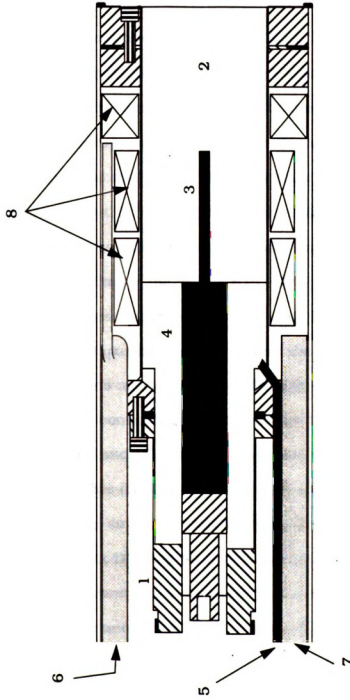


Figure 2.6 N. C. State/ASTeX Compact ECR Plasma Source

- | | |
|---|-------------------|
| 1. N-type 50 Ω coaxial feedthrough | 5. Gas input |
| 2. Plasma cavity | 6. Water inlet |
| 3. Microwave Antenna | 7. Water outlet |
| 4. Boron Nitride insulator | 8. Electromagnets |

plasma generation region, as measured on the axis of the source. Separate position and current controls for each magnet provide flexibility with specific magnetic field configurations, proving specifically useful during the initial design testing and optimization of the source. Due to low input power requirements for plasma ignition (maximum of about 120 W), and an external tuning mechanism for impedance matching, no circulator or dummy load is needed, making the microwave circuitry simple. The body of the source is made of a 13 inch (33.0 cm) long stainless steel tube and has an inner diameter of 2.3 cm, and an outer diameter of about 5.7 cm. Since the discharge generation region is fixed in dimensions, the overall length of the source may be varied, as required by the application, similar to the MPDR 610 - the plasma source that is the main subject of this dissertation.

Like the Japanese radical gun and the MPDR 610, a standard 50 Ohm coaxial cable feeds microwave power through a type N microwave connector (1) into the source, continuing into vacuum as the center conductor of a coaxial cavity structure, and terminating into an antenna (3) that protrudes inside the discharge chamber (2). A sliding slug tuner placed between the source and the microwave power supply is used to match the plasma impedance, and reduce reflected power. A BN plug (4) acts as an insulation window at the top of the source, and also prevents a discharge from being generated there. The diameter and length of the antenna is critical for the characteristics of the discharge, with best results being obtained when the antenna length is between one-quarter and one-half wavelength of the exciting microwave energy (this wavelength is 12.2 cm for 2.45 GHz microwaves). The effects of antenna diameter on plasma characteristics were studied: a large diameter (~ 5 mm diameter) gives a

somewhat "hollow" discharge with a local minimum in the center, while a thin antenna (~ 1 mm diameter) gives a more typical radial profile - maximum current density at the center, falling rapidly across the radial direction.

At MBE conditions, for which this source was tested, no cooling of the antenna was required. The housing tube of the source may be mounted on the test stand, or an existing port of an MBE machine using a standard 4.5 inch conflat flange. Gas breakdown begins at about 0.1 mTorr of pressure and for less than 10 W of power, without any need for pre-ionization of the gas. A stable discharge can be maintained over four decades of pressure ranging from 10^{-5} Torr to 10 mTorr.

Plasma parameters were measured using a cylindrical single Langmuir probe placed 15.0 cm downstream from the source, with an area of 0.1 cm^2 . A Faraday cup with a collecting area of about 1 cm^2 , and a QMS were also used to evaluate the performance of the plasma source. The source was characterized for 2.45 GHz input microwave power of 50 W in a nitrogen discharge at a pressure of 0.1 mTorr. It was observed that the floating potential and current density decreased exponentially with distance downstream, indicating typical ambipolar diffusion in the vacuum processing chamber. At a constant pressure of 0.1 mTorr, the ion current density was about 0.04 mA-cm^{-2} for 10 W input power, and about 0.3 mA-cm^{-2} at 120 W - the ion current therefore increased with increasing input power. For a constant input power of 50 W, the ion current density was 0.2 mA-cm^{-2} at 0.1 mTorr, and about 0.4 mA-cm^{-2} at 1 mTorr - the ion current increased as pressure was raised. At 0.1 mTorr and 50 W absorbed power, electron temperatures of above 100,000 K and ion densities of about 10^{10} cm^{-3} were measured outside the plasma cavity.

When the discharge gas was switched from nitrogen to hydrogen, no further tuning of the source was required to optimize power transfer to the plasma load. Ion current densities for a hydrogen plasma were about 5-6 times higher than those for nitrogen at similar gas flow rates and power conditions. Also, the electron temperature of a hydrogen discharge was lower (about 70,000 K) than that of a nitrogen plasma for the same operating conditions. The floating potential for hydrogen was found to be positive (+5 V), while it was negative for nitrogen (-15 V). QMS studies indicated the presence of N_2^{1+} and N^{1+} ions in a nitrogen discharge, with the N^{1+} concentration constituting about 15% - 20% of the total ionized species. This ratio was seen to be somewhat independent of discharge pressure and input power.

The source has been successfully used in an MBE machine for low temperature (400°-600° C) and low pressure (5×10^{-5} to 1×10^{-4} Torr) epitaxial growth of III-V nitride thin films (like GaN, and AlN) [Sit-90b, Pai-90, Mou-93]. Other potential applications include high T_c superconducting thin film deposition using oxygen radicals, for cracking various molecular gases (like organometallics), and also for in situ substrate cleaning prior to deposition using reactive atomic hydrogen. A commercial version of the source is available from ASTeX Inc. of Woburn, Massachusetts.

2.2.7 The NTT LSI Laboratories Compact ECR Ion Source

The parent design of this high current ion source was developed in 1987 [Tor-87] for mass production of SIMOX substrates in oxygen ion implanters. Since then, very active research and development has led to several variations

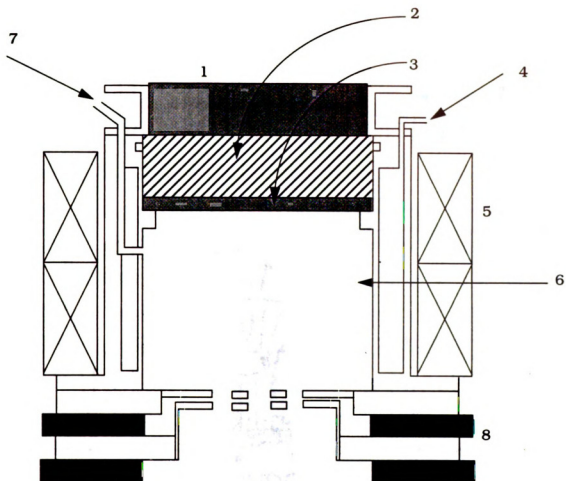


Figure 2.7 NTT LSI Laboratories Compact ECR Ion Source

- | | |
|----------------------------------|--------------------------|
| 1. Waveguide Filled with Alumina | 5. Magnetic Coils |
| 2. Quartz | 6. Plasma Chamber |
| 3. Boron Nitride/Alumina | 7. Gas Inlet |
| 4. Water Cooling | 8. Extraction Electrodes |

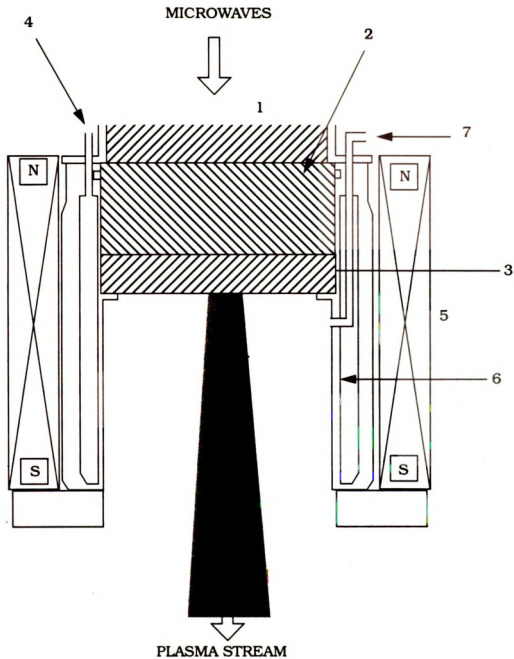


Figure 2.8 NTT LSI Laboratories Compact ECR Ion Source with permanent magnets

- | | |
|----------------------------------|----------------------|
| 1. Waveguide Filled with Alumina | 5. Permanent Magnets |
| 2. Quartz | 6. Plasma Chamber |
| 3. Alumina | 7. Gas Inlet |
| 4. Water Cooling | |

being reported in at least three journals, each with minor modifications to the preceding design along with the operational results of these modifications [Shi-89, Tor-90, Shi-91, Tor-92, Shi-93]. Since this section discusses several versions of essentially the same source, a brief introduction to the original source is first presented. Broader coverage of the compact versions is provided later in this section.

Two of the compact versions are shown in Figures 2.7 and 2.8 (not to scale). The basic design of all the variations of this source consists of essentially four components, as shown in Figure 2.7: a cylindrical plasma chamber (6); a multi-layered dielectric window for microwave transport, vacuum seal and prevention of damage from back-streaming energetic electrons (1, 2, 3); an extraction system (8) when beams are to be extracted; and either some coils, or permanent magnets (5).

In the original report [Tor-87], the plasma chamber had a diameter of 11.0 cm, with a height of 9 cm. Microwaves were transmitted into the source through a rectangular waveguide. A double layered microwave window was used for the electromagnetic wave transmission and vacuum seal, and several combinations of quartz, boron nitride (BN) and alumina were tested. It was found that the highest ion current density was achieved with a quartz and alumina combination, the alumina layer facing the plasma. Three solenoid coils were used to create the magnetic fields required for ECR and ion transport out of the source. A three grid accel-decel extraction structure with seven holes (5 mm diameter) arranged over an area of 2.0 cm diameter was used to extract an ion beam. The beam characteristics were measured with a water cooled copper plate biased positively to suppress secondary electron emission. The plate was placed

about 40 cm downstream of the extraction system. At an extraction voltage of 30 kV, a very high oxygen ion current of about 160 mA, or an equivalent current density of about 120 mA-cm^{-2} was obtained. Mass spectrum studies indicated that the ratio of O^{1+} ions is more than 80%, with an equivalent O^{1+} ion current of more than 125 mA. A disadvantage of this source was that the alumina window facing the discharge was heavily bombarded by back streaming energetic particles, leading to degradation of the window, and a decreased lifetime of the source.

An improvement in the source design was reported in 1989 [Shi-89] when a triple layered window was used. Quartz formed the vacuum seal, alumina helped in microwave transmission and impedance matching of the source, and a BN layer - due to its hardness and better thermal conductivity - was used to prevent damage from energetic back streaming particles. The optimal thickness of the BN layer was determined by studying the reflection coefficient of the source as this coefficient varied for different BN layer thicknesses, the choice being made for a thickness that minimized the reflection coefficient. The window, and hence the source lifetime was increased to over 200 hours, with little damage to the BN layer. An improved extraction system allowed for stable operation over extended periods, with the same high current density as its predecessor was achieved (i.e. 80% O^{1+} ions with over 180 mA total current at 30 kV extraction potential). It was also observed that as the microwave power increased from 100 W to over 600 W, the O^{1+} concentration increased, while the O_2^{1+} density decreased.

The next modification to this source design was reported in 1990 [Tor-90] when the triple layered window was further modified to couple microwaves more

efficiently into a narrow high density plasma mode. The chamber length was optimized relative to magnetic field configuration, which was itself optimized to produce a high density plasma in the center of the source. This allowed highly efficient ion beam extraction, where the extraction region coincided with the highest density plasma confined to the center of the source. The optimized magnetic field configuration also leads to lower impurities concentration in the plasma since wall bombardment by high energy particles is reduced. The O^{1+} ion beam was transported through a commercial NV-200 implanter beam transport system with an efficiency of about 60% indicating low beam divergence, and an efficient use of the extracted current. Just like in its predecessor, the source too can provide over 200 hours of a stable oxygen plasma. Damage to the BN layer is minimized by the centralized location of the plasma generation region, and also by the efficient extraction of ions.

A compact version of the source was introduced at the American Vacuum Society (AVS) symposium, 1990 [Shi-91] with another report soon thereafter [Tor-92]. Shown in Figure 2.7 (not to scale), the compact source has a cylindrical plasma chamber with a diameter of 5 cm, surrounded by two magnetic coils (outer diameter 11 cm). These magnets provide the static magnetic field necessary for ECR, containment of hot electrons, and also ion divergence out of the source. As before, microwave power at 2.45 GHz is fed from the top of the source through a waveguide. However since the plasma chamber diameter is too small for the lowest cutoff wave mode - TE_{11} - to be propagated (which requires a minimum of 7.2 cm diameter for propagation through air/vacuum at 2.45 GHz), the miniaturized rectangular waveguide feeding the microwaves is filled with alumina. Since alumina has a dielectric constant of 9, and the cutoff diameter is

proportional to one over the square root of the dielectric constant, filling the waveguide with alumina effectively decreases the cutoff diameter by about a third of that required for a vacuum, or air filled waveguide. This alumina filled waveguide is now able to propagate microwaves at 2.45 GHz.

The ceramic window used in this modification was the original double layered design - quartz for vacuum seal, and a hard BN layer for protection from hot electrons. The thickness of the two layers was calculated such that for an assumed plasma density of 10^{12} cm^{-3} , the transmission coefficient of the microwave fields is one. A 2 cm diameter double grid extraction system (37 holes, each with a 2 mm diameter) with a 1 mm grid separation was used to extract low energy ion beams.

Plasma parameters were measured using a plane Langmuir probe (6 mm diameter) mounted at the center of the extraction electrode. Also, an ion collector placed 5 cm downstream from the extraction region measured the beam characteristics. The pressure dependence of a 200 W oxygen plasma was studied. As the pressure increased from 9×10^{-5} Torr to about 4×10^{-4} Torr (corresponding to a change in oxygen flow rate from 1 sccm to about 4.5 sccm), the ion density decreased slightly from $4 \times 10^{11} \text{ cm}^{-3}$ to about $2.5 \times 10^{11} \text{ cm}^{-3}$. For the same increase in flow/pressure, the electron temperature decreased from 12 eV to about 7 eV. When the BN layer was replaced by alumina, there was a twenty fold increase in the oxygen ion density, the maximum being about 10^{13} cm^{-3} (200 W absorbed power, 0.24 mTorr pressure). However, the source lifetime suffers with this replacement since alumina is not as resistant to sputtering as BN. An anomalous behavior was observed in the electron temperature dependence on input power for the two types of microwave

windows: T_e increased with increasing power for a quartz-BN window, but T_e decreased when power was raised for a quartz-alumina window. This abnormal temperature dependence on window type has not been explained yet.

Preliminary ion extraction experiments at 1 kV extraction voltage (100 W oxygen plasma, 1 sccm flow), indicated that the source was able to provide a maximum ion current density of about $1.3 \text{ mA}\cdot\text{cm}^{-2}$. Beyond 100 W, the ion current density (measured with a collector placed 5 cm downstream) decreased, although the total current density increased. This may be because as the power was raised, the plasma density increased, and hence, the plasma boundary (the meniscus) began to extend beyond the extraction holes, thereby increasing the species' divergence. The total ion current increased due to the higher ion density, however the current density measured by the collector decreased due to the larger divergence of the beam at higher powers. The radial profile of ion saturation current at 20 cm downstream (6 sccm, 200 W oxygen plasma) shows a relatively flat distribution, with a maximum of about $1.5 \text{ mA}\cdot\text{cm}^{-2}$. Potential applications for this compact version of the source are expected to be in etching, oxidation and plasma assisted deposition.

Yet another version of the original ion source was introduced at the 1992 AVS symposium [Shi-93]. This design is shown in Figure 2.8 (not to scale). This too is a compact source, with most design parameters the same as above, but with one major change - the electromagnetic coils of the previous versions are replaced by permanent magnets (5). This simplifies the source design, although the diameter of the plasma chamber had to be further reduced to 40 mm to accommodate the bulky axially directed Sm-Co magnets (outer diameter 10 cm, inner diameter 6.2 cm, 10 cm high). The magnets successfully produce a

magnetic cusp mirror field, with a mirror ratio of about 2 at the exit of the source. The peak field strength is about 920 Gauss, and is maintained relatively uniform over the entire plasma excitation region. The maximum current density is observed at 920 gauss, rather than the 875 gauss for ECR 2.45 GHz. The multi-cusp mirror configuration effectively confines excited electrons in a donut shaped region at the output of the source, which is then able to generate high density of multiply charged ions.

The resulting high density mode plasma stream was very collimated and directional with a diameter of about 1.8 cm, and a divergence angle of about 3 degrees. Saturation current density measured with a Langmuir probe (6 mm diameter, placed 12 cm downstream) at a bias of negative 80 V was seen to be about 18 mA-cm^{-2} for a 200 W, 10 sccm (about 1.2 mTorr) argon discharge. This current density was higher than that obtained in the previous plasma source design with the magnetic coils. At 5 cm downstream, the saturation current density peaked at about 80 mA-cm^{-2} for a 200 W, 10 sccm argon discharge, decreasing rapidly with radial distance. As the argon flow rate was reduced further, the peak current decreased also, until at about 2 sccm, there was a local minimum at the center of the distribution - a "hollow" beam. This is claimed by the authors to be due in part, to the smaller number of available energetic electrons at such low pressures in the donut shaped confinement region near the output of the source. At a constant power (200W) and flow (10 sccm), the radial profile of the ion beam became more uniform as the probe was positioned further downstream from the generation region. As expected, the saturation current density increased monotonically as input power was raised (at fixed flow rates of 4, 6 and 10 sccm), and also as flow rate/pressure was increased (at fixed

power levels of 50 - 200 W).

QMS measurements indicate a high level of Ar^{2+} ions in the plasma, the ratio of Ar^{2+} to the total ion current ($\text{Ar}^+ + \text{Ar}^{2+}$) increasing with argon flow, and being as high as 50% for a 6 sccm argon discharge. According to the authors, the increase in the 2+ charge state production is probably due to an elevated ion density at higher pressures. This elevated 2+ production may also be due to the confining cusp shaped field produced near the exit of the source. The applications for the various versions of this source are postulated to be for thin film processing such as MBE, and to provide multiply charged ions (oxygen) for high energy ion implantation.

2.2.8 The Oxford Applied Research Atom/Radical Beam Source

An atom/free radical beam source has been developed by Oxford Applied Research of UK and was introduced at the European Vacuum Conference in 1990 [Dav-90b]. Since then, several studies on this source - mostly applications oriented have been conducted [Cla-88, Hok-91, Par-90, Qiu-91, Wat-91]. The electrodeless source, operating at the radio frequency (rf) of 13.56 MHz excitation frequency is shown in Figure 2.9 (not to scale), and is essentially a free radical source due, as claimed by the authors, to the unique electric potentials generated within the discharge tube (6) that prevent most charged particles from escaping the tube. The ion/electron density in the beam is, therefore claimed to be negligible. Note that this is the only inductively coupled rf source that is reviewed in this chapter. The standard body length is 29.0 cm and the vacuum seal is made through a DN63CF flange (3). Similar to the

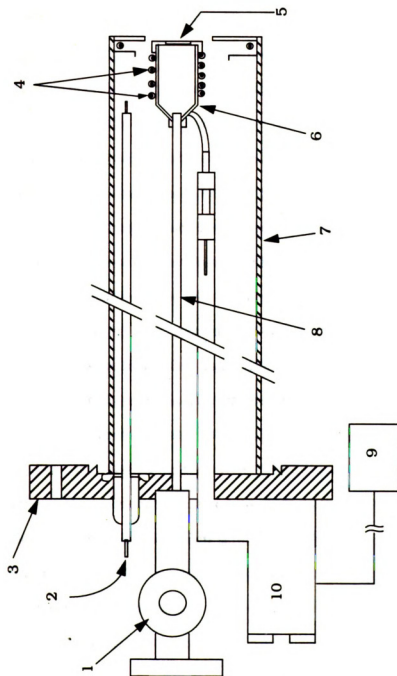


Figure 2.9 Oxford Applied Research Atom/Radical Beam Source

- | | |
|-------------------------|----------------------|
| 1. Gas Inlets | 6. Discharge tube |
| 2. Water Feed | 7. RF Shield |
| 3. DN 63 Conflat Flange | 8. Gas Feed |
| 4. Water Cooled RF coil | 9. RF Generator |
| 5. Beam Exit | 10. RF Matching Unit |

Japanese radical gun, the over-all length of the source is application specific, since the actual discharge producing region is small and at the end of the source. The rf coils (4) around the discharge tube are water cooled, while the material of the tube is dictated by the application- high purity quartz is used when the source is to be used for producing oxygen radicals since quartz has a very low recombination coefficient for atomic oxygen. Ultra-pure pyrolytic boron nitride is used for UHV applications. The discharge gas is fed through a small alumina tube (8) that extends up to the plasma containment tube. The source produces high densities of atomic radicals which have been found useful in oxide/thin film deposition, low temperature etching, hydrogen radical cleaning of wafers, and low temperature nitriding.

Most studies done with this source have been application oriented, with some evaluation data available. Performance characteristics regarding the atomic flux were measured using the quartz crystal microbalance (QCM) for O^* , H^* and N^* radical species. The oxygen atom flux was estimated to range between $10^{14} \text{ cm}^{-2}\text{-s}^{-1}$ and $10^{15} \text{ cm}^{-2}\text{-s}^{-1}$. For a 500 W discharge, and at a pressure of 2×10^{-5} Torr, the radical flux is about $5 \times 10^{14} \text{ cm}^{-2}\text{-s}^{-1}$, increasing to about 4×10^{15} as the pressure is raised to 2×10^{-4} Torr [Loc-91, Dav-90b]. In situ reflected high energy electron diffraction (RHEED) analysis confirmed the QCM oxidation data. XPS spectra of copper films after exposure to an oxygen beam were found to be identical to the Cu(II)O spectrum, while exposure of the film to molecular oxygen was found to produce no significant oxidation. It was therefore confirmed that it is the reactive oxygen radicals that oxidize the film, and molecular oxygen has little or no oxidizing effect. RHEED and Auger Depth profile electron spectroscopy for GaAs substrates passivated by nitriding have

also been used to monitor the performance of the radical source. QCM studies were used to test low temperature etching of GaAs by radicals using a CCl_2F_2 discharge.

A comparison of the atomic radical production between this radical beam source, an ECR source (the Michigan State University/Wavemat MPDR 610TM, to be detailed later in this dissertation), and a microwave source (the Evanson cavity), seems to indicate that the gas flow rate needed to produce approximately the same amount of atomic oxygen (as measured with a QCM) was much lower for the Oxford rf source [Loc-91] than for the other two sources. The cracking efficiency for oxygen in this source is estimated to be about 30%. The source has also been used in MBE growth of InN and GaN films [Hok-91] with a nitrogen discharge, and as a source to incorporate p-type nitrogen acceptor impurities in ZnSe/GaAs epitaxial layers using a nitrogen atomic beam doping during MBE growth [Par-90, Qiu-91]. A hydrogen radical beam from this source has been used in metal organic MBE (MOMBE) to effectively remove the native GaAs oxide layer [Wat-91]. This atomic radical beam source has therefore been extensively characterized and practical applications have been aggressively explored. A commercial version of the source, called the "Oxford Applied Research, Model MPD21" is available from Oxford Applied Research.

2.2.9 A 2.45 GHz Compact ECR Source from France

Preliminary results of a new compact ECR ion source from Paris XI, France were presented at the International Conference on Ion Sources (ICIS-93) at Beijing, China [Bou-94], and subsequently published in the proceedings. This

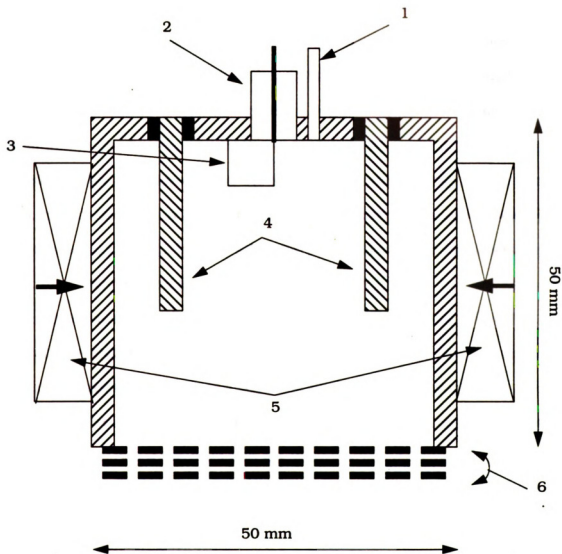


Figure 2.10 Compact ECR ion beam source from France

1. Gas Inlet
2. SMA Connector
3. Excitation loop

4. Lecher lines
5. Permanent Magnets (SmCo)
6. Multi-aperture extraction optics

new source incorporates the unique principle of coupling energy into the discharge through two shielded quarter-wavelength "Lecher line resonators". As can be seen from Figure 2.10 (not to scale), the source is very simple in design and quite compact - only 5.0 cm in diameter (not including the magnets), and 5.0 cm high. The stainless steel discharge chamber is surrounded by four radially magnetized parallelepiped shaped Sm-Co magnets measuring 2.5 X 2.5 X 1.2 cm³. These magnets create a multi-cusp static magnetic field configuration, generating the 875 Gauss field strength for ECR. Discharge gas is leaked through a feedthrough on the top of the source. The two Lecher lines, or pads, are placed 30 mm apart and are coaxially coupled to an off-axis square loop antenna. The Lecher lines fulfill the orthogonality condition between the static magnetic field and the microwave electric field.

Microwave power at 2.45 GHz is supplied to the antenna through a 50 Ω coaxial SMA connector. Depending on the orientation of the loop with respect to the Lecher lines, there are two separate electromagnetic modes that can be excited in the microwave cavity. In the "odd mode," electrical energy is concentrated between the pads and the chamber wall, and in the "even mode," the energy is confined between the two pads. The loop orientation for these two modes is 90° apart. A hybrid dual mode with characteristics of both electromagnetic modes described above can be excited if the loop antenna is part way between the two extreme orientations - that is, at 45°. Initial experiments with the source were conducted with an external tuning mechanism to optimize the source performance. However, this was apparently soon discarded, and source optimization was conducted essentially through selecting the exact Lecher pad length and maximizing the measured current density. The length of

these resonators was restricted to a range from 2.5 cm to 3.5 cm, since a stable discharge ignition was not possible for pad lengths beyond this range. An ion beam was extracted through the bottom of the source using a multi-aperture triple grid electrode system.

A fixed Lecher pad length of 30 mm was used in all source characterization. The hybrid dual mode produced the most ion current density among the three electromagnetic modes, possibly due to the more distributed electric fields through the plasma generation region. Incident power was kept constant at 75 W, and the source was operated at the dual hybrid mode, with an extraction potential of 100 V. As a function of argon discharge pressure, the current density displayed two local maxima - at about 2.5×10^{-3} mbar (2 mTorr) with a current of 0.5 mA-cm^{-2} , and at about 2×10^{-2} mbar (15 mTorr) where the maximum current was 0.7 mA-cm^{-2} . At the lower pressure, the current density maximum is attributed to the resonance of the Lecher lines that produces a maximum ionizing electric field at the end of the line structure. The second maximum at the higher pressure is due to an increase in the collision frequency of the electrons with neutrals in the chamber. This is confirmed by the fact that the maximum at higher pressure is independent of the Lecher pad length, while the maximum at the lower pressure is highly dependent on this length. At 29 mm and 31 mm Lecher line length (optimal length is 30 mm) the low pressure maximum is completely blurred out, while the high pressure maximum is relatively undiminished.

At a constant pressure - 9×10^{-3} mbar (about 7 mTorr) the ion current density increases almost linearly as the power is increased. Plasma ignition occurs with a minimum of about 40 W, producing a current density of 0.4 mA-cm^{-2} .

cm^{-2} , which increases to about $1 \text{ mA}\cdot\text{cm}^{-2}$ as power is raised to 110 W. If the input power is now reduced, a stable discharge can be sustained to power levels as low as 20 W.

Although particulate generation due to ion bombardment on the Lecher lines in the discharge has not been tested, this source is capable of sustaining a high intensity discharge from which high beam currents may be extracted. Applications of the source are expected to be for reactive species cleaning or other surface treatment of substrates, MBE, or as a neutralizer for ion assisted deposition techniques.

2.2.10 The Microscience Inc. Ion Beam Source

Microscience, Inc. of Massachusetts has recently introduced a compact ECR ion beam source capable of producing high intensity beams at medium energies (200 - 1700 V) [Pop-94b]. This source is shown in Figure 2.11 (not to scale). Its design is interesting in that it employs a hybrid technology to inject microwave energy into a plasma cavity that has a diameter below cutoff for 2.45 GHz microwave transmission. Sakudo et al. [Sak-77] used an antenna fed microwave cavity with a high magnetic field (Section 2.2.2), while Shimada et al. [Shi-91] utilized microwave transparent windows for their design (Section 2.2.7), and used alumina as a dielectric that essentially reduced the cutoff diameter of the source (or waveguide) for microwave transmission at 2.45 GHz. The new Microscience Inc., source uses an antenna enclosed inside an alumina cup that also acts as the dielectric window of Shimada's design. This is somewhat similar to the antenna being enclosed by an alumina cup in the Russian design [Sha-90]

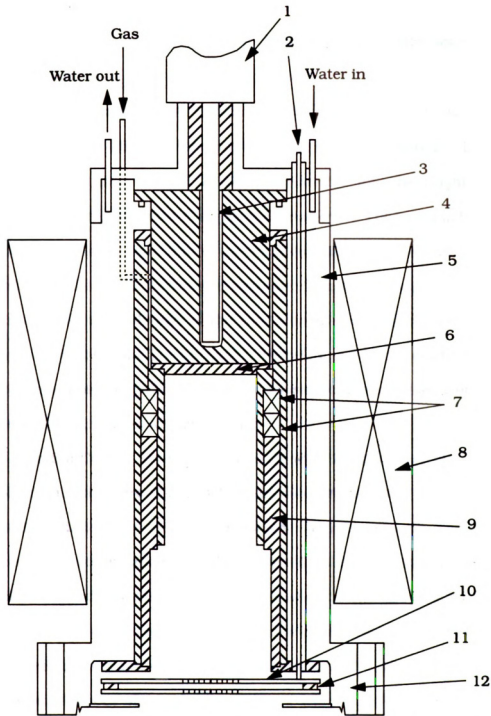


Figure 2.11 Microscience, Inc. Compact ECR Ion Beam Source

- | | |
|----------------------------------|----------------------------------|
| 1. Type N Coaxial Connector | 7. Permanent Magnets |
| 2. High Voltage Bias Feedthrough | 8. Electromagnet coil |
| 3. Half wavelength Antenna | 9. Boron Nitride Encloser |
| 4. Alumina Cup | 10. Bias Grid for Ion Extraction |
| 5. Plasma Chamber | 11. Alumina Spacer |
| 6. Alumina Spacer | 12. 4.5 Inch Conflat Flange |

of a compact ECR ion source (Section 2.2.3) except that here, the alumina fits completely into the quartz chamber. Construction of this source is now described in detail.

The plasma chamber (5) is 5.5 cm in diameter, and 12 cm in length, and is attached to a 4.5 inch Conflat flange (12) on the bottom. Low power microwaves (less than 200 W) at 2.45 GHz are fed into the plasma chamber through an antenna attached to a type N connector (1). The antenna (3) diameter is substantially larger than that of the inner conductor of the cable to retain the continuity of the 50 Ω microwave circuitry. This antenna is enclosed by an alumina cup (4) that fills part of the source body, and also makes the vacuum seal with a Viton O-ring. The antenna is therefore, on the atmospheric pressure side of the alumina cup. This antenna enclosing cup is shielded from the high intensity plasma with an alumina spacer (6).

Two Sm-Co ring shaped magnets (7) with 2.5 cm inner diameter below this alumina spacer are placed a few mm downstream from the alumina cup, with a BN cylinder (9) protecting the magnets from the plasma. These magnets provided the static magnetic flux density for ECR. There is also a large current coil (8) around the outside of the source whose magnetic field strength and relative position can be adjusted. This coil aids in sustaining the plasma and efficiently extracting an ion beam by controlling the divergence of the ions out of the source. The body of the plasma chamber is water cooled. For the low power levels at which this source was used there was no need to cool the antenna, although it is provided with air or water cooling fixtures. Discharge gas is leaked through a feedthrough on the top, and injected into the plasma chamber through tiny holes made in the BN cylinder.

An ion beam may be extracted through two multi-aperture grids (10) about 8 cm downstream from the alumina spacer. Both grids are 1 mm thick pyrolytic graphite, separated from each other by a 1.5 mm thick alumina spacer. Each grid has 65 holes (each hole 2 mm in diameter) leading to a hexagonal beam extraction area of about 2 cm^2 . The body of the ion source is always grounded, while the plasma is placed at a higher potential. Hence the need for the BN cylinder that electrically isolates the grounded cavity from the high potential plasma discharge. The plasma grid (closest to the discharge) is biased positively (DC) at 150 - 2000 V, while the second grid (called the suppressor) is biased at a negative potential of about -50 to -1000 V. Due to this high negative voltage, secondary electrons are repelled from the grid and do not contribute to the total grid (and beam) current.

Different BN liners and other ceramic enclosures are used in this plasma source to prevent shorting or arcing across biased surfaces, and plasma ignition in regions other than the discharge chamber. As mentioned before, these dielectric liners also allow the body of the plasma source to be at ground potential, while the plasma inside the source is raised to the high extraction potentials.

The source normally operates at low power levels (30 - 200 W incident power, with about 10% reflected back from the source), and generates ion beam currents of $0.5 - 3.0 \text{ mA-cm}^{-2}$ with ion beam energies of 200 - 1700 V. Despite the alumina cup that fills the top part of the plasma chamber that should allow microwave transmission, the authors claim that it is the evanescent microwave fields that sustain the plasma. Hence the magnetic field configuration is designed such that the ECR zones are only a few milli-meters away from the

alumina spacer where the attenuating electric fields are strong enough for ECR breakdown. While characterizing the source, the operating pressure ranged from 2×10^{-5} Torr in the beam line, to about $2\text{-}3 \times 10^{-4}$ Torr. This pressure is limited on the low end by the 1 sccm minimum flow rate of the discharge gas, and on the high end by the minimum necessary ratio of ion acceleration grid current to the ion suppression grid current. (If pressure is raised beyond this, no beam can be extracted because the current exceeds the maximum current rating of the power supply. This "problem" will re-surface when the MPDR 610 is used as an ion beam source later in this dissertation.)

It was noticed that the power required to breakdown the gas into a discharge remained almost unchanged as the discharge pressure decreased, up to the minimal pressure of about 2×10^{-5} Torr. The breakdown power (P_{br}) for igniting a discharge was measured to be about 5 - 20 W in this pressure range. If the pressure was reduced further, P_{br} increased dramatically, in part due to the rapidly decreasing collision frequency between electrons and neutrals that sustains the discharge. For example, at a pressure less than 1×10^{-5} Torr, P_{br} is greater than 250 W. A similar dependence of P_{br} was observed with a variation of the magnetic coil current. At 5 - 6 Amps of coil current, the power required to ignite a discharge was several hundred Watts, but as the coil current increased (and the magnetic flux density increased), the break down power requirement dropped dramatically, and ignition occurred at less than 20 W. Note that it is the axial component of the coil magnetic field that is primarily responsible for ECR break down in the plasma chamber near the alumina spacer.

Beam characteristics of the source were measured primarily by studying the current being extracted through the acceleration grid. Although not quite the

same, the ion beam current was taken to be equal to this acceleration grid current. Ion beam current increased as input power was raised. About 8 mA of total current was extracted at a voltage of 1000 V (with a suppression voltage of -220 V) from a 250 W argon discharge (7×10^{-5} Torr). Further increase in the forward power led to a saturation of the extracted current, due in part to a growth in the reflected power. For 100 W incident power, 25 W were reflected for a 7×10^{-5} Torr argon discharge. However, if the power was raised to 250 W for the same discharge, the reflected power rose to about 50 W. Another reason for this saturation may be the de-focussing effects of the beam optics once the ion density begins to increase as the power is raised. The Child's law "3/2" power variance of extracted current with extraction voltage was not observed, which may be because the extracted current is limited by the plasma density, and not the acceleration voltage. For an argon plasma with an estimated electron temperature of about 3 - 5 eV, the ion beam current corresponded to an argon ion density of about $6 - 9 \times 10^{10} \text{ cm}^{-3}$ (assuming that the beam has an extraction cross section of about 3 cm^2).

Once ignited, a plasma discharge of this source could be easily sustained even without magnets. The two ring shaped permanent magnets were pulled from the source, and this did not impede the process of plasma ignition. Once a stable plasma was generated, the current in the external coil too could be reduced to zero. The plasma was still very stable, though at a lower density, switching off once the ion density went below the critical density (about $7 \times 10^{10} \text{ cm}^{-3}$ at 2.45 GHz). As expected, the quenching of the plasma was accompanied by a sharp increase in the reflected power.

The source was used for sputter deposition of various metals (Al, Mo,

SiO₂, Si, etc.). Based on the beam characterization, the following optimal conditions are recommended for these applications: Microwave power of about 100 W, argon pressure of 7×10^{-5} Torr, coil current about 22 A, acceleration voltage 1000 V and suppression voltage about -220 V. Under these conditions, the ion beam current is about 4 mA, and the suppression grid current about 0.05 mA. When a conducting target is placed 17 cm downstream at a 45° angle, the beam divergence angle could be determined from the impact marks of the beam. The minimum half angle of divergence for the beam was measured to be about 4° at 2×10^{-5} Torr discharge pressure and with 1000 - 1500 V extraction voltage. This rose to about 6° at 2×10^{-4} Torr and 200 - 400 V extraction voltage. The divergence angle increased if the target was a dielectric, and also increased when the coil current was raised. Other characterization results, and practical applications of this source are being considered.

2.3 Discussion - Ion/Ion Beam/Plasma Sources

Table 2.1 summarizes all the information pertaining to the design of the ion/plasma/ion beam sources discussed in Section 2.2. For each source, the first column indicates the reported, or most probable application - as an ion beam, free radical, or a plasma source. The next two columns indicate whether the source is ECR based, and if it has a resonant cavity structure. Note that "resonant" cavity does not necessarily mean that the dimensions of the microwave (or plasma) cavity can be changed to tune the source for specific electromagnetic modes - only the MPDR family of sources have "tunable resonant cavities" in which dynamic modification of the cavity height may be

Compact Source	Ion Beam	Type Plasma, Radical	ECR	Resonant Cavity	Dimensions (cm)			Magnets		Energy Transfer		Tuning		Beam Extraction	
					ID	OD	Height	Permanent	Coils	Window	Ant. RF	none	stub Ant. (dimensions)	2 Grid	3 Grid
1. Kyoto University	X		X		5	6.5		X		X		X		X	
2. Hitachi	X				6				X	X		X			X
3. Russia/Epiqueip		X	X	X	11.4		16	X		X			X		
4. Radical Gun from Japan		X	X	X	3.5	1		X		X			X		
5. RIKEN	X		X		7		5	X		X		X			X
6. ASTeX		X	X	X	5.7	2.3	33		X	X			X		
7. NTT LSI (a)	X		X		10.8		7-9		X	X		X			X
(b)	X		X		11	5			X	X		X			X
(c)		X	X		10	4	10	X		X		X			
8. Oxford Radical Source		X					29				X	X			
9. Paris XI	X		X		5		5	X		X			X		X
10. Microscience Inc.	X		X	X		5.5	12	X	X	X		X		X	

Table 2.1 A comparison of compact ion/plasma/ion beam sources

used to match the plasma impedance and decrease the reflected power, thereby increasing power coupling to the plasma load. (This tuning may also be done using external stub, or EH tuners as in the case of the ASTeX compact source.) In several cases, the authors report that their source has a resonant cavity - this may mean just that the source is ECR based, and not the EM resonance which, as mentioned earlier, is a different issue altogether. The source dimensions are provided (where reported) to give an indication of the size, and are followed by the type of magnets employed by the source.

Note that only the Oxford rf source has no magnets, since it is a free radical source, and free radicals do not require ECR, focussing, or diverging magnetic fields. The next column shows the method of energy transfer - via antenna, or microwave transparent ceramic windows, or rf coils, and is followed by information on external tuning mechanisms. For the sources where the antenna is used to inject microwaves into the plasma, and minimize the reflected power (the Russian compact source, or the ASTeX compact source, for example), the dimensions of the antenna, and its relative location to the discharge are important. Some sources, like the Russian compact source have a "static, or discrete antenna tuning," where the antenna dimensions and location are fixed a priori, and once the experiment is under way, the antenna remains fixed. The MPDR sources, on the other hand have "dynamic" tuning where antenna locations may be adjusted during the course of the experiments to match the changing impedance of the plasma load. Finally, for ion beam sources, the type of extraction system is indicated in the last column - whether the beam is extracted from a two grid, or a more typical three grid system.

As the different columns in the table are compared, several interesting

points come to light. Most of these sources have been designed for a specific purpose - to generate an ion beam, or a reactive radical beam, or to create a free flowing quasi-neutral plasma that impinges on the substrate. However, for some sources, like the MPDR 610, the addition of extraction grids can easily convert a plasma source into an ion beam source, as will be seen in Chapter Nine. Also, external magnets, like those for the radical gun from Japan, can bend the ions away from the substrate, generating a reactive radical rich beam. Hence there is flexibility in the applications of some sources.

Almost all the sources employ electron cyclotron resonance for generating the plasma, the significant omissions being the rf coil based Oxford radical source and the Hitachi "non-ECR" ion beam source (the latter falling under the broader, and more recent terminology of "wave heated discharges" [Lie-94]). Hence, for the ECR and ion transport requirements, all sources, other than the aforementioned radical source from Oxford Applied Research, have permanent magnets, or current coils (or a combination of both). Many sources have specifically designed magnetic field configurations that provide the ECR fields, while at the same time helping in efficient ion extraction from the discharge generation region as the ions follow the magnetic lines of force out of the plasma source. In general, current coils (usually solenoids) provide flexibility to modify the magnetic field configuration around the plasma but they are normally bulky, and also lend a degree of complexity to the source design. Power costs, current carrying leads, and heat dissipation are also some other factors that make permanent magnets more appealing to some plasma source designers who want to reduce the complexity of operation and overall size of the source.

As mentioned earlier, of all the sources, only the MPDRs have tunable

resonant cavities, through which microwave power is efficiently coupled to the plasma load. This is usually done by matching the impedance of the load to that of the microwave transport device (either a waveguide, or a coaxial cable). Other plasma sources (like the ASTeX compact source) also match the load impedance by employing stub, or EH tuners. Due to efficient power coupling, tuning allows a source to be operated with less input power, while protecting the cables, waveguides and other microwave apparatus from excessive heating due to large reflected power. Tuning structures also allow the flexibility of dynamically modifying the cavity to match the power as plasma load impedance varies with pressure, power, gas type, or other transient changes without having to switch off the plasma source. Note that some source designs (like the Chinese version of the Ishikawa small source) have no external tuning mechanisms, and have to operate at times with up to 60% reflected power.

Power transfer to the plasma load is an important factor in designing a plasma source. The Oxford rf source of course, employs rf inductive coils to launch the microwaves at 13.56 MHz, but most other sources use some sort of antenna to launch the 2.45 GHz microwave energy. In some sources the antenna is outside of vacuum (like the MPDR 610 - as will be seen in Chapter Four), while sources like the Kyoto University small source immerse the "T" shaped antenna into the plasma. Another method of power transfer is via direct feed from the waveguide through ceramic windows that are transparent to microwaves at 2.45 GHz - this technique is used in all the NTT/LSI sources, where Shimada et al. have designed several versions of their source with multi-layered ceramic windows with specific thickness - allowing a transmission coefficient of 1 for an assumed ion density of 10^{12} cm^{-3} . Indeed, for the compact version of their

source, Shimada et al. filled part of the plasma chamber with alumina (that effectively reduces the minimum diameter required for 2.45 GHz microwave transmission in a cylindrical waveguide - or the plasma chamber - due to the higher dielectric constant of alumina). A significant development was the Microscience Inc. source design which employs a hybrid method of power transfer - a standard antenna launches microwaves into a plasma chamber, the upper part of which is fully filled with alumina (as for the compact Shimada et al. type source) that allows the chamber diameter to be below the empty waveguide cutoff for propagation of microwave fields at 2.45 GHz.

Ion beam sources use either a two grid, or three grid (accel - decel) extraction system. Some ion beams are extracted by simple multiple aperture plates biased at the appropriate potentials, while the design of other extraction systems (like that for the MPDR 610) is based on specialized spherical quasi-Pierce type accel - decel geometry. This will be seen in Chapter Nine, where beam characterization of the 610 is discussed. The main advantage of using the three grid system is that it provides more control over the beam focussing, and also the directed energy of the beam. Most ion beam sources employ grids that have multiple apertures producing a broad beam made by the summation of many small beamlets. These broad beams are important for uniform processing of large diameter substrates. An exception is the MPDR 610 that was tested with a large, centralized single aperture in the three grids.

As mentioned in the introduction of this chapter, many of the sources discussed above have been extensively used in industrial research laboratories. These applications range from nitriding GaN or AlN films (using reactive nitrogen species), high T_c superconducting film growth (using oxygen radicals), reactive

hydrogen pre-cleaning of III-V substrates prior to further operations, to providing ion beams for ion implantation, or injection of plasma species from a compact source (the MPDR 610) into the main stage of a larger ECR ion source for multiply charged species - the SCECR (see Chapter Eight for details). Indeed, the design of several ion/plasma sources discussed here has been predicated by their eventual application. For example, sources like the ASTeX, Inc. compact source, and the MPDR 610 were specifically designed to fit inside existing MBE effusion cell ports, and to create a discharge close to the substrate. Since its inception, the MPDR 610 source has found applications outside of MBE, including possible direct injection of He^{2+} (alpha particles) into cyclotron beam lines [May-95] at the Texas A&M cyclotron facility, and is evidence of the developing requirements and innovations of industrial and academic research.

2.4 Discussion - Figures of Merit

A comment needs to be made about the method of reporting the evaluation results of any ion/plasma/ion beam source. As may be discernible from the details of Section 2.2, different researchers utilize different techniques to measure the same plasma parameter - like using disc shaped, or cylindrical Langmuir probes for ion current density measurements. Often these results are also reported in different ways. This makes a comparative study of the source characteristics very difficult, since the basis for comparing the results is not the same for all sources. A common set of criteria - or figures of merit need to be developed so that the performance of any ion source may be compared to that of others in its class.

As a counter example to this problem, consider the reporting of ion beam currents obtained by multiply charged ion sources: data are presented as the total ion current of a particular charge state extracted from the source, as measured by a Faraday cup placed somewhere downstream (for example, 100 μA of O^{7+}). Since the beam is mass separated and focussed into this collector, the entire beam contributes to the total current. This allows for the performance of a multiply charged state ion source to be compared to that of another such ion source, simply based on the total current produced by that source for that particular charge state. The frequency of operation, the incident and reflected power levels, discharge pressure, type of gas or gases used, extraction apparatus design and the accel - decel potentials, and the very design of the ion source - all of these factors are important. However, ultimately it is the net current output of the ion source for any particular charge state that matters, and a better source is that which can produce the most current.

In industrial plasma sources like the ones reviewed in Section 2.2, the power levels, discharge pressure, etc. are criteria that are more important because they determine the ultimate cost of purchasing the peripheral electronics or microwave apparatus, and of operating the ion/plasma source. A cost-benefit analysis would have to be conducted before a particular plasma source can be chosen over other competing technologies. Indeed this analysis may result in the choice of an ion/plasma source with a slightly lower performance, but a more simplified and cost effective turn key system of operation. Hence the importance of a comparative study.

When reporting the power dissipation in the plasma source, it must be clearly mentioned whether this is the total incident power, or the incident minus

the reflected power (called the net input power throughout this dissertation). Discharge pressure is normally stated, but usually not in conjunction with the flow rate of the operating gas. Sometimes there is a variable conductance valve in the vacuum system that allows more than one pressure in the processing chamber for any one gas flow rate. Also, a particular gas flow rate may produce a significantly different pressure in the chamber for different vacuum stations depending on the pumping capacity of each station. Hence pressure and flow rates for each experiment need to be reported simultaneously.

Perhaps the simplest measurement to characterize the output species of a plasma source, and one that is most often mis-reported is the ion saturation current (or saturation current density). Normally, this data is taken with a Langmuir probe (cylindrical, or disc shaped) biased at a certain "saturation potential". (A shielded Faraday cup may also be used to collect the ion current.) In an ideal plasma, where several assumptions like a Maxwellian electron energy distribution function are presumed true, there is a specific probe bias potential at which the collected current does indeed saturate, with no further increase in the ion (or electron) current as the voltage is raised. However, in a real discharge, many of the assumptions are not valid. Specifically, direct measurements on the MPDRs prove that the electron energy distribution function (EEDF) follows the Druyvesteyn distribution function more closely than the Maxwellian distribution (see for example, data on EEDFs presented in Chapters Four through Six). This departure from theory is reflected in the measurement of the probe current, which still increases beyond the "knee" of the I-V characteristics as the bias potential is further raised, although with a significantly lower slope.

So the question arises, about how to determine this "saturation

potential.” To simply state that the saturation current density is $x \text{ mA-cm}^{-2}$ (total probe current divided by the probe area), is ambiguous. The probe potential at which the current data were taken (for example -50 V), and the specific coordinates of the probe relative to the discharge generation region (like distance downstream), or its radial position from the center axis also need to be reported. Along with information on discharge pressure, gas flow rate and input power, this would present a complete picture of the plasma source, and allow for a more thorough and relevant comparative study, specially in an industrial environment where companies tend to present their products vis-a-vis other competing technologies.

Similar arguments may also be made for reporting ion densities, radical flux densities and electron temperatures. These numbers (in cm^{-3} , $\text{atoms-cm}^{-2}\cdot\text{s}^{-1}$, and eV or degrees K respectively) mean very little unless they are complemented with information regarding method of collection, the location of the collecting instruments, and the exact plasma parameters (like power, pressure, gas flow etc.) while data were taken. Perhaps other figures of merit like Watts per beam amp (or the equivalent eV/ion) that factor out the discrepancies in plasma source designs and measurement techniques need to be considered as important data for reporting on the performance characteristics.

2.5 Concluding Remarks

There are many other “compact” plasma sources that have not been studied here. However, all the sources reviewed in this chapter are excellent examples of the variety of engineering techniques used in designing plasma

sources, and provide a flavor of the intuitive thinking of the “sourcerers” - ion source designers. Many companies like Wavemat Inc., Oxford Applied Research, Applied Science and Technology Inc. (ASTeX), Kimball Physics, etc. offer compact plasma sources as turn key systems, indicating the confidence that these companies have in the maturity of understanding their products and the ability of their products to deliver the required plasma species for specific applications. Success of such companies over the past few years has also demonstrated the high interest of industry and research laboratories in these small plasma sources.

Experimental research is generally used to confirm theoretical predictions. Laboratory measurements can either supplement and support theory, or conflicting results may bring focus to some of the oversights that have been used to derive the currently reigning theory. Some interesting disparities become apparent when the experimentally measured plasma properties are compared to theoretical predictions. For example, at 2.45 GHz, the theoretical “critical density” limit that can be obtained in a plasma is $7 \times 10^{10} \text{ cm}^{-3}$ [Nic-83]. However, state of the art plasma sources that are currently used in the industrial environment routinely exceed this limit, as has been reported in almost all of the ion, or ion beam sources reviewed in this chapter. This so called critical density limit is reached by over simplifying the theoretical analyses.

Without these simplifications, the complex theoretical models of plasma fluid dynamics do not achieve closed form solutions. For example, in order to obtain such solutions the plasma is defined as being a high pass filter, and as being an infinite, homogeneous, cold, and non magnetic. While some of these conditions may hold true for small volumes inside a very large plasma source, or

for the huge tokamak reactors for fusion research, *almost none of the simplifications hold true for the smaller plasma sources*. That the ion density obtained in ECR sources is routinely reported to be higher than the critical density for the frequency of operation is proof of the over simplification that has to date preceded theoretical development. It is therefore obvious that analytical theories derived to date do not adequately explain plasma phenomena, and it is imperative that a next generation of theoretical analysis be developed, based on numerical simulations, if necessary to further explain the secrets of gas discharges.

Chapter 3

Characterization Principles

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Chapter 3

Characterization Principles

3.1 Introduction

In this chapter, some general techniques of characterizing a plasma/ion/ion beam source are discussed, with a purpose to centralize this discussion in this dissertation. Since several plasma/ion beam sources will be evaluated in the forthcoming chapters, this discussion of the actual methodologies of evaluation will provide a foundation for measuring, and studying the characteristics of these sources. This chapter is not meant to provide an exhaustive theoretical analysis of each technique mentioned in the forthcoming sections, but to provide all relevant information (including equations, circuit diagrams, and the appropriate references, etc.) in one location. As was seen in the previous chapter, there are a large variety of compact plasma/ion beam sources. A large number of diagnostics also exist that may be conducted on these sources to evaluate the performance, and to standardize the comparison of these ion sources. Knowledge of the salient features of the plasma or ion beam constituents - like the electron and ion density, their respective energies, the

charge states of an ion beam, etc. - represents an understanding of the fundamental properties of plasma/ion/ion beam sources.

Characterization techniques that are in frequent use today range from the invasive, yet simple Langmuir probes inserted into the plasma, to the non-invasive but more complex optical emission spectroscopy (OES) and laser induced fluorescence (LIF). For a plasma/ion beam source designer it is absolutely imperative to understand these fundamental properties (ion density, electron temperature, etc.), and how they are influenced by varying controlled external parameters like gas flow, pressure, gas type and input power, etc. Such knowledge renders a judgement on the plasma source itself, its design and assembly, its efficiency of transferring power, its resource utilization (like the power and gas feed requirements), and its ability to generate the stipulated plasma species in the required abundance. This in turn, allows for further optimization in the design process, which is inherently facilitated by comparison with previous design versions. On the other hand, under circumstances where plasma sources are used as turn-key systems, the knowledge of plasma properties is necessary since design of peripheral systems (for processing, manufacturing or research) relies on accurately predictable properties of the plasma/ion beam source.

Diagnostic methods exist for characterizing almost any and all species generated in the plasma and a number of these techniques were used to evaluate the four principle plasma sources that were studied during the research for this dissertation. In this chapter, these ion source characterization principles and data acquisition techniques will be discussed in detail. A brief introduction into the theory of each technique, including assumptions and

possible sources of error, is given along with the requisite equations that lead to the measurement methodology. Relevant references are provided to supplement the descriptions given here if further detailed study of any technique is required. The closure of each section is devoted to explaining the exact data acquisition methods as performed in the laboratory for each characterization technique. Also, in Section 3.4 a new method for acquiring data for ion and electron energy distribution functions is proposed. While this method was never used to report the results presented in this dissertation, it may be the next generation of state-of-the-art data acquisition techniques that are a testimony to the continuous evolution of the characterization procedures. This new method needs to be mentioned here so that its applicability (with subsequent acceptance in the battery of characterization techniques in use today) may be tested in the near future as an alternative, and simpler way of acquiring the electron and ion energy distribution functions.

3.2 Theory of Langmuir Probes

One of the most widely used instruments to characterize the plasma discharge are Langmuir probes [Her-89, Sch-68, Dru-30, Lan-23, Joh-49, Coh-1, Swi-69, Pod-71, among many other references]. Simple in design and easy to construct and use, Langmuir probes provide a wealth of information on ion or electron densities (n_i or n_e , typically measured in cm^{-3}), average electron temperatures (T_e , in eV or degrees Kelvin), ion saturation current densities (I_s , in $\text{mA}\cdot\text{cm}^{-2}$), plasma potentials (in eV, or Volts) and electron energy distribution functions (EEDFs). While the complete theory of Langmuir probes is well beyond

the scope of this study, and may be found in several of the references mentioned above, the salient features of two of the most universally used probe techniques - the single Langmuir probe (SLP), and the double Langmuir probe (DLP) are now presented.

In plasma diagnostics, the word "probe" automatically brings to mind some sort of a wire like appendage inserted into the discharge. Although not all probes fit that general description, a majority of probe analysis is done with a thin wire like protrusion into the plasma. As will be seen below, the simplicity of such probes, and also the vast variety of data provided by them, far outweigh the limitations caused by this very simplicity, and the rather complex theoretical developments necessary to attain analytical solutions. It will also be noted below that these analytical solutions rely heavily on assumptions (often inaccurate) to simplify the derivations, which lead to several sources of error inherent to probe analysis.

While the initial work done by Langmuir was confined to low pressure discharges, where collisions in the plasma may be neglected, later work has managed to modify his theory to fit more practical applications of today (like a high pressure plasma, or a discharge under the influence of strong magnetic fields) where Langmuir's original, and relatively simple theoretical developments had failed. Today, Langmuir probes may be successfully operated under a tremendous range of plasma parameters: ion (or electron) densities ranging from 10^0 to 10^{13} cm^{-3} , with electron temperatures ranging from 0.1 eV to hundreds of eV, at plasma potentials of 0.1 V to many kV, and for neutral pressures of less than 10^{-6} Torr, to greater than 1 Torr [Her-89].

3.2.1 Assumptions for a Simplified Probe Theory

Analytical solutions that have led to closed form solutions require many simplifying assumptions to be used. Before going into the details of probe theory, it is desirable that some of these assumptions (and related terminology for probe diagnostics) be understood, with their consequences, and limitations being brought up at appropriate moments in this discussion. A major assumption made while working with gas discharges - upon which a large part of plasma theory is based - is that the electron energy distribution functions are non-drifting Maxwellian in nature. As early as the 1940's it was known that the velocity distributions of electrons, specially in low pressure plasma are not only far from being Maxwellian, but are rarely isotropic, and may also have a drift velocity. A more agreeable analysis may be done with the Druyvesteyn distribution function for electron energies proposed in the early 1930s [Dru-30, Dru-35]. Indeed, it will be seen in the following chapters that the EEDFs in the plasma/ion beam sources like the microwave plasma disk reactors - MPDR 610, and the MPDR 5 are closer to being Druyvesteyn, than Maxwellian.

When a probe is immersed in a discharge, the very presence of a surface creates an electron, or ion rich layer (depending on the probe bias) on the surface called a "sheath". The concept of quasineutrality ($n_e = n_i$) is not valid in this sheath, and the large concentration of positive, or negative, charge can maintain high electric fields near the probe itself, thereby repelling (and attracting) charged species and leading to somewhat erroneous data collection. While the sheath effects are dependent on the very parameters whose calculations they retard - like ion density for example, certain generalized

parametric values may be used to negate some of the error, the real values determined, the sheath effect correction done again, and the process iterated till the margin of error is reasonably reduced. Complete rectification for errors induced by the sheath requires a complex development of the concepts of the plasma sheath the pre-sheath regions, and the establishment of the Bohm criterion [Man-89], and is generally not necessary. The concept of sheath thickness itself remains somewhat vague and undefined (the sheath is supposed to be "several Debye lengths - λ_D " in thickness), and really has no quantitative value that can be exactly estimated. This makes it difficult to correct the probe theory for the sheath effect, although efforts may be made based on estimation of the sheath thickness. Most of the potential drop inside the sheath occurs within five λ_D of the probe surface. However field gradients associated with the pre-sheath may extend out as far as $100 \lambda_D$ [Man-89].

A "weakly ionized plasma" (less than 10% ionization) can easily be perturbed by the presence of a foreign body in the form of a probe and its holder, specially in the plasma generation region where the probe may interfere with the impressed electric field and the static magnetic field. For this reason, in this dissertation research, probe measurements were not taken within the plasma generation region. All probe data were taken downstream from the plasma generation region, although this data may be extrapolated to obtain order of magnitude parametric values within the discharge confinement chamber. Throughout the theoretical development of probe theory, it is assumed that the probes do not "significantly" perturb the downstream plasma, and that all such disturbance is heavily localized.

The ions and electrons created in a plasma are highly energetic, specially

as they are accelerated by the sheath potential on their way to being collected by the probes. Upon striking the probe, these energetic particles might be able to transfer significant energy to the valence electrons of the metal atoms. If this energy is greater than the binding energy of the valence electrons to the atoms, these atoms can get ionized, as the valence electron is expelled from the probe. This is known as secondary electron emission, and may lead to large discrepancies in actual current striking the probe, as compared to the current that has been tempered with secondary electron emission. Although this effect is very difficult to rectify in a probe setup without biased grids, it may be lessened by using a less emissive material for the probe, like platinum. Also, metallic sputtering off the probe tip may locally increase impurity levels to the extent that collisions occur between electrons and the impurity atoms, thereby cooling the electron gas, leading to underestimation of the actual electron gas temperatures, while at the same time interfering with the ionization and excitation processes within that micro-volume of the plasma. Finally, such metallic sputtering may lead to coating of the plasma vessel which might require expensive down time for cleaning the vessel.

3.2.2 Single Langmuir Probes

Although electrostatic probes were used for the investigation of gas discharges as early as the turn of the century, the ground breaking work was done by Irwin Langmuir in the early 1920s and 1930s [Lan-23, Lan-31]. He used a thin cylindrical electrode immersed into the discharge - what is now known as the single Langmuir probe (SLP)- for localized measurement of electron density

and temperature, and developed his technique into one of the most powerful tools of plasma diagnostics. His method involved biasing the immersed probe with respect to some other readily available electrode in contact with the plasma, like the metallic containment vessel. The probe current is then collected as a function of the applied bias and the I-V characteristics analyzed for a wealth of information on the plasma. The exact equations and methodology are now described [Man-89].

A typical SLP I-V characteristic is shown in Figure 3.1. This curve may be divided into three distinct regions, depending on the probe bias. Consider a negative bias on the probe. As this negative voltage is increased, the probe repels electrons and attracts ions, creating a positive sheath around it, till an equilibrium is reached, and any further increase in probe voltage incurs a much smaller increase in the ion current. Region C corresponds to "ion saturation," reached when the probe is biased sufficiently negative and driven into saturation. Also, the ions thus collected are actually accelerated in the sheath, but since the sheath itself is only weakly dependent on voltage, the ion saturation current does not vary much with increasingly negative probe bias.

As the voltage is reversed and made positive beyond region C, the ion current to the probe reduces further, till a voltage is reached at which no current flows through the probe. This bias voltage at which there is zero probe current is called the floating potential V_f of the plasma, and may be positive, or negative depending on the plasma/ion beam source, or the plasma conditions. When the applied voltage is further increased beyond V_f , the positive potential rapidly attracts the fastest electrons from the tail of the electron distribution function. Further increase in the potential leads to more and more of the bulk distribution

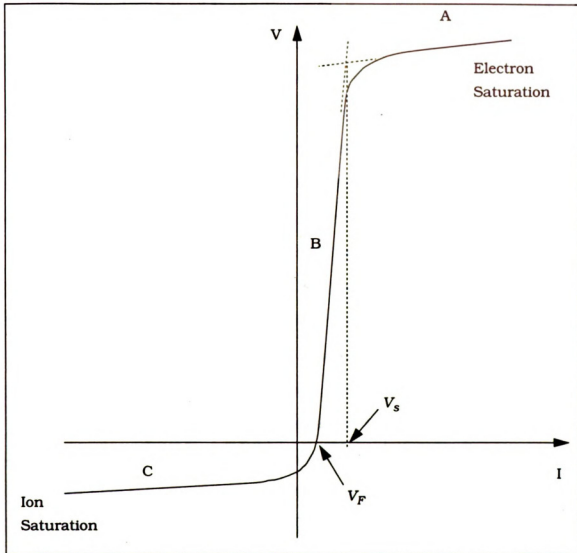


Figure 3.1 An I-V characteristics of a Single Langmuir Probe.

Here, V_F is the floating potential, V_S is the plasma potential. Region C corresponds to ion saturation, while Region A is the Electron Saturation. Note that the electron saturation current is much higher than the ion saturation current.

to be attracted to the probe, and therefore a larger electron current in the probe. This increase in electron current is described by a Boltzman-type equation, somewhat similar to the I-V equations of a diode. There is an almost linear increase of the current versus the applied voltage.

A limit however is reached, when the electron current levels off, and further increase in bias does not affect an equivalent increase in the current, although the current still increases with a smaller slope. This is shown in region A, beyond the “knee” of the curve, and the probe is said to reach “electron saturation”. If the electron energy distribution function in the plasma is exactly Maxwellian, theory predicts that there would be no further increase in current in the saturation region. That the current still increases beyond the “knee” of the curve, albeit with a much smaller slope than in the linear region, is one indication of an off-Maxwellian electron energy distribution.

Whereas the SLP I-V characteristics may be used to provide information on the electron and ion density of the plasma [Man-89], this is more readily available through another technique - the double Langmuir probe method discussed in the next section. Instead, more valuable information is buried in the SLP I-V characteristics. This data may be reduced to get a direct, and more accurate measurement of the average electron temperature, the plasma potential, and the electron energy distribution function (EEDF) [Hop-91]. It was shown by Druyvesteyn [Dru-30, Dru-35] and others [Swi-69] that the second derivative of the probe current with respect to the applied probe potential is directly proportional to the energy distribution function $f(E)$:

$$\frac{d^2 I}{dV^2} = \frac{1}{4} A q n \left(2 \frac{q}{mV} \right)^{1/2} f(E) \quad (3.1)$$

where A is the total collection area of the probe,

n is the neutral gas density, with an ion mass m

V_s is the plasma potential, the potential at which the second derivative of the I-V characteristics is maximum [Run-79, Coh-89],

V is the applied bias, and $E = V_s - V$

While Druyvesteyn himself graphically took the second derivative of the I-V plot, a Princeton Applied Research (PAR-128) lock-in amplifier and other peripheral circuitry may be used to differentially measure the signal proportional to the second derivative in this age of computers. Following Hopwood [Hop-91], Figure 3.2 shows a typical SLP circuit to measure the EEDF. All data acquisition was done using computer controlled apparatus, and the exact methodology will be discussed in a later section of this chapter. A low frequency (1KHz) small AC signal (with an amplitude typically less than $0.5 V_{rms}$) is superimposed on the DC probe voltage. Under certain conditions, the output of the PAR-LIA is proportional to $\frac{d^2 I}{dV^2}$, as shown by the Taylor series expansion of the modulated electron current equation on the next page [Sch-68, Run-79]:

$$I(V + \sin \omega t) = \left[I + \frac{a^2 I''}{4} + \frac{a^4 I'''}{64} + \dots \right] + \left[a I' + \frac{a^3 I'''}{8} + \dots \right] \sin \omega t$$

$$- \left[\frac{a^2 I''}{4} + \frac{a^4 I'''}{48} + \dots \right] \cos 2\omega t + \text{higher order harmonics} \quad (3.2)$$

where primes denote differentiation with respect to V , while a and ω are the amplitude and frequency of the AC signal respectively. Note that the first square

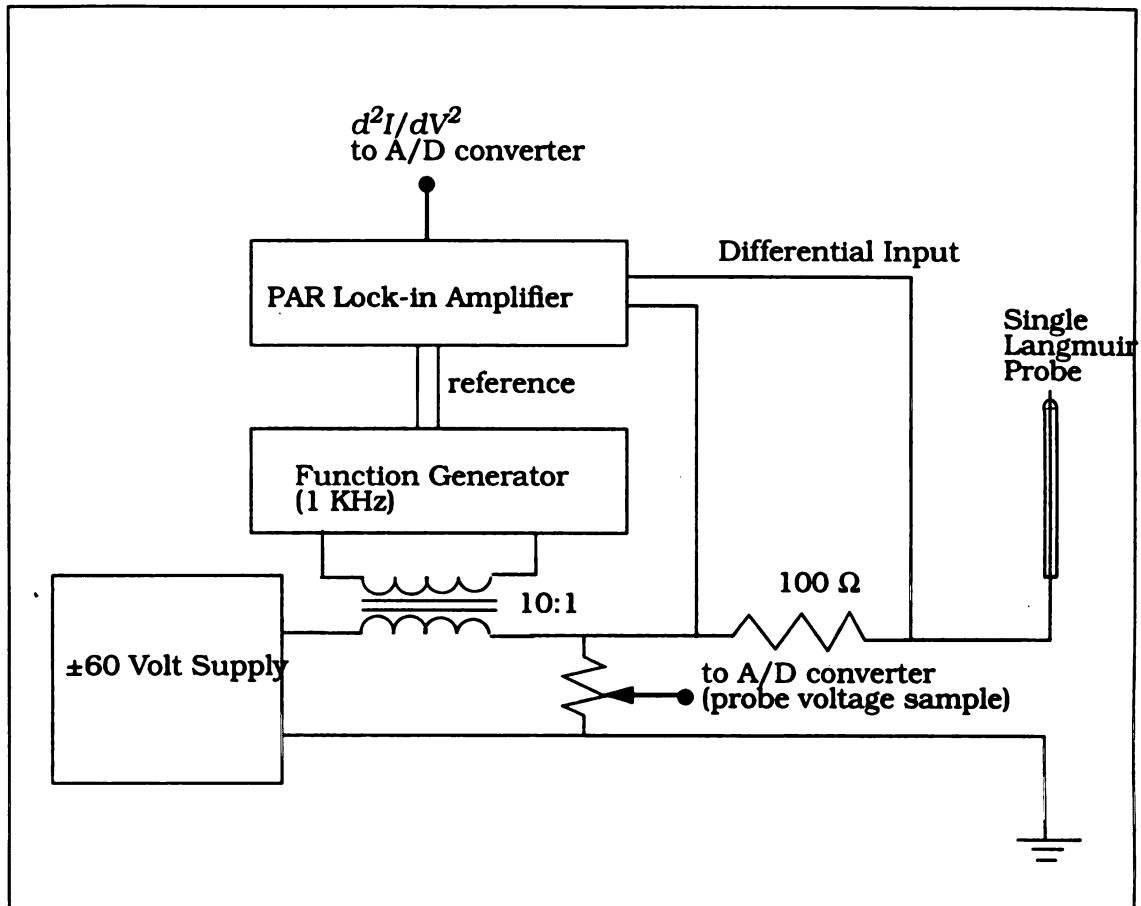


Figure 3.2 The Single Langmuir Probe circuit.

Adapted from Reference Hop-91, this circuit shows the "semi-automated" method of measuring EEDFs, Plasma potential and average electron energies.

bracket contains the DC component of the signal, the second square bracket contains the undistorted AC component, and the third square bracket contains the second harmonic of the signal. Then for sufficiently low values of $a \ll V$, the increase in current can be approximated by [Sch-68]:

$$\Delta i \approx \frac{i}{4} a^2 \Gamma''(V) \quad (3.3)$$

From Eqn. 3.2, it is seen that the second harmonic of the probe current is proportional to the second derivative if the AC signal is small relative to the DC voltage. This information is utilized to measure the second derivative, and hence to directly obtain the EEDF. A small oscillation in the plasma is initiated by the AC signal which is superimposed on the probe voltage, and effects of this oscillation on the plasma are measured by the probe and external circuitry. This is known as the Druyvesteyn method and is valid for all probe types if the plasma may be considered isotropic. However, an anisotropic plasma requires a spherical probe surface for the validity of the result [Sch-68]. It is therefore seen that even with the many simplifying assumptions made, or perhaps due to them, the method yields qualitative results at best and exact plasma parameter values may vary significantly from theory. This is shown clearly on Figure 3.3 which depicts a typical EEDF of the MPDR 5 (that is characterized in Chapter Seven). The experimental curve seems to deviate from the Maxwellian distribution, and is seen to be closer to the Druyvesteyn distribution, as mentioned above. Similar, near-Maxwellian EEDFs have also been reported for non-ECR microwave discharges [Hei-88].

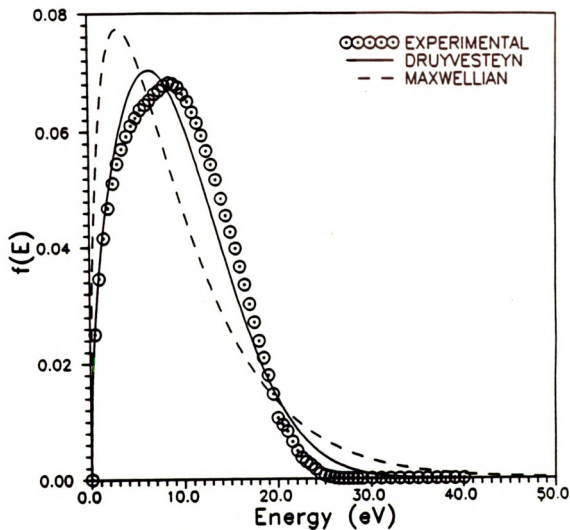


Figure 3.3 A typical EEDF of the MPDR 5

Data taken for an argon discharge at 1.0 mTorr at 100 W input power with the SLP 5 cm downstream (Refer to Chapter Seven).

3.2.3 Double Langmuir Probes

The concept of using two probes was born out of the fact that very often a reference electrode for the SLP is absent, or difficult to define. An example may be measurements in the ionosphere, or a toroidal rf discharge in a glass tube. First proposed by Johnson and Malter [Joh-49, Joh-50], this method employs two similar, single probes with a dc bias applied through an otherwise electrically floating circuit. The double Langmuir probe (DLP) method has been extensively studied [Joh-49, Joh-50, Che-65, Swi-69]. The circuit itself, shown in Figure 3.4(a) is extremely simple and does not require any specialized equipment to operate. Due to this simplicity, and also the very important information it imparts about the plasma, the DLP is widely utilized for plasma diagnostics.

Other than the self contained floating circuit within the plasma, another advantage of the DLP over the SLP system is that the former is limited by the ion saturation current, while the SLP must measure the electron saturation current. As is seen in Figure 3.1, the electron saturation current is much greater than the ion saturation current. Due to these high electron currents specially in intense discharges, the SLP may suffer from over heating, warping or even melting - a problem that does not exist for the DLP.

Figure 3.4(a) shows that the DLP has two small conducting probes immersed in the discharge close to each other. Note the DC isolation of the DLP using transformers. As mentioned earlier (Section 3.2.1), care must be taken in designing the probes so that they are sufficiently far away (several tens of λ_D) and do not reside within the other's sheath, while at the same time are close

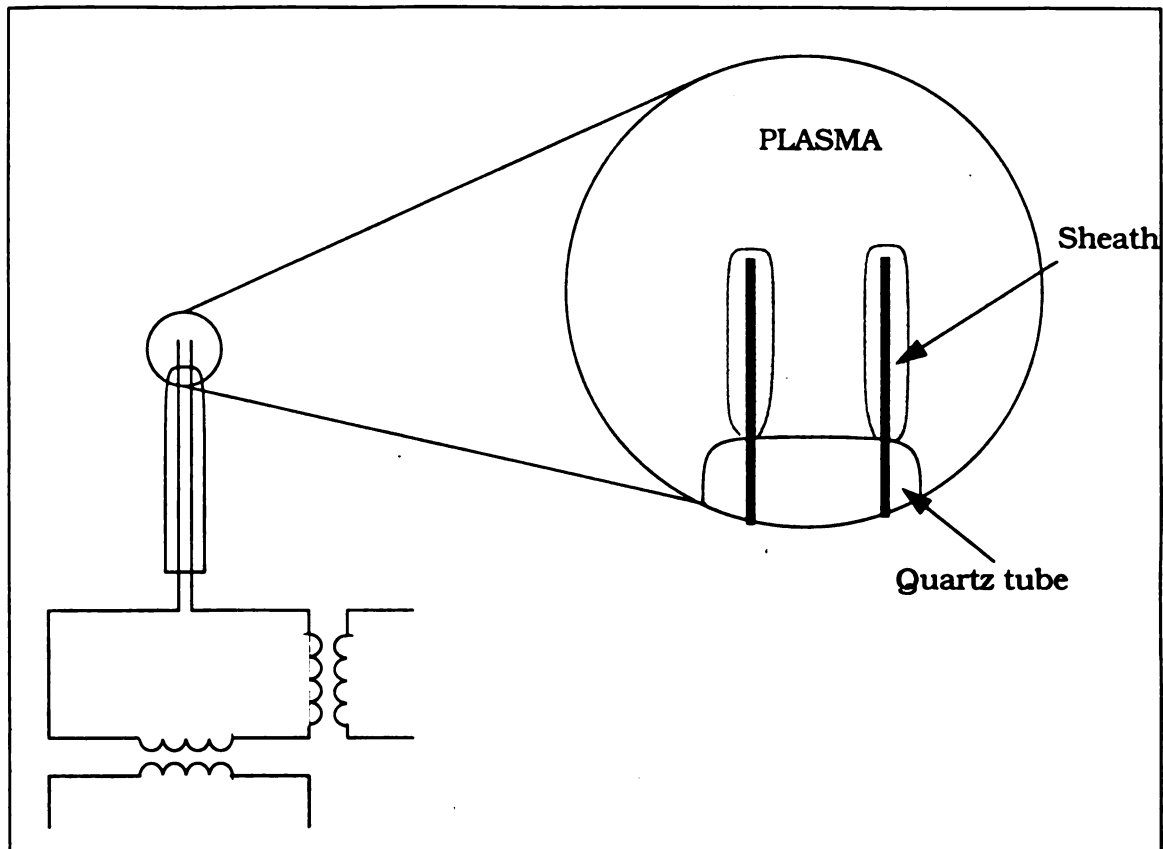


Figure 3.4(a) A DC isolated Double Langmuir Probe circuit.

Inset shows the sheath development around the tungsten wires. Shaded region is the sheath. Note that the quasi-neutral plasma surrounds both probes.

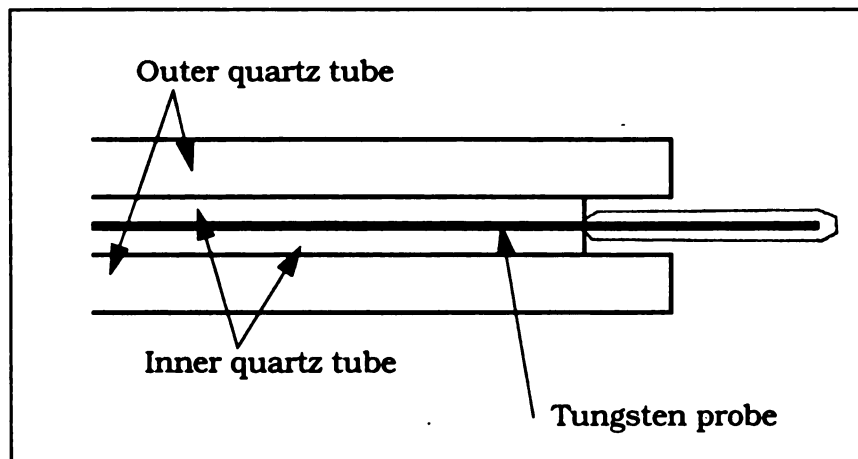


Figure 3.4(b) Recessed Langmuir Probe.

Two such probes glued together with UHV compatible adhesive constitute the Double Langmuir Probe. Note the step like topology that prevents the probes from shorting out. Shaded region is the sheath around the probe tip.

enough such that the plasma potential on both probes is the same. There must exist a quasi-neutral plasma with little or no change in the plasma potential between the sheaths of the two probes. This is shown in the inset of Figure 3.4(a), where the sheath of each probe is comfortably far removed from the other probe, and the plasma encloses each probe completely. Figure 3.5(a) shows the potential drop between the two probes indicating clearly the sheath around the probes. A good explanation of the variation of the plasma sheath and potential drop across the probes as the bias voltage is changed may be found in reference Swi-69 (see, for example Figure 2.3, page 19 of this reference). The probes are floating with respect to ground, and the current circulating between the two probes is measured as a function of applied voltage. A typical DLP I-V characteristics is shown in Figure 3.5(b), and this can be reduced to provide the T_e and n_e . The derivation for extracting the appropriate quantities from the I-V characteristics follows (from Reference Lie-94):

Assuming that the circuit of Figure 3.4(a) is electrically floating with respect to the common ground, the current going into one probe must equal current flowing out of the other, i.e.

$$i_1 = -i_2 \quad (3.4)$$

In terms of the electron and ion components, each probe current may be decomposed into:

$$i_{i1} - i_{e1} = i_{e2} - i_{i2} \quad (3.5)$$

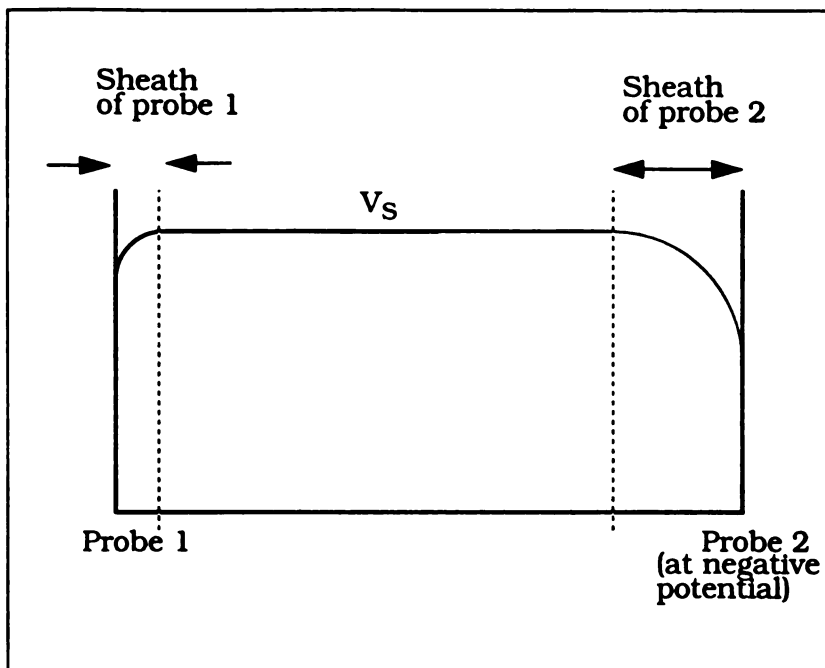


Figure 3.5(a) Potential drops across the Double Langmuir Probes.

Here, V_S is the plasma potential. Note that the potential variation occurs only in the sheath.

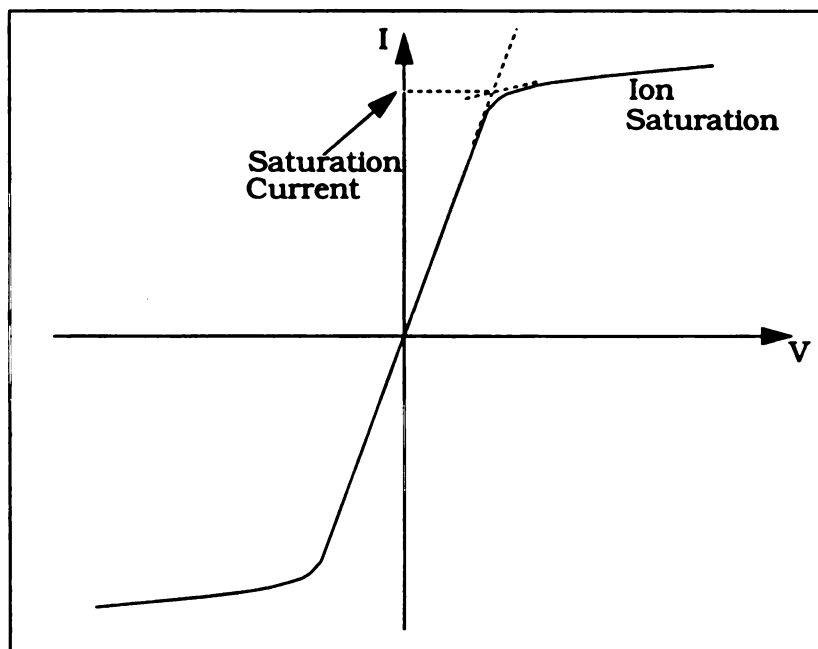


Figure 3.5(b) An I-V characteristics of a Double Langmuir Probe.

The "knee" of the curve indicates where the saturation current value is taken, despite the fact that current still increases with increasing potential beyond this knee.

And a total current expression may be written as:

$$I = i_{i1} - i_{e1} = i_{i2} - i_{e2} \quad (3.6)$$

Now, making use of the Maxwellian electron energy distribution assumption (note, from Figure 3.3 that this assumption may not be exactly valid), the currents can be expressed with Boltzmann like variation with applied potential:

$$i_{e1} = I \cdot \exp\left(V_1/T_e\right) \text{ and} \quad (3.7)$$

$$i_{e2} = I \cdot \exp\left(V_2/T_e\right) \quad (3.8)$$

Here, V_1 and V_2 are the probe potentials with respect to the plasma potential, I is some random electron saturation current, and T_e is the electron temperature. With the assumption that the plasma potential does not vary significantly on the two probes, the relative applied bias is then the sum of the two probe voltages:

$$V = V_1 - V_2 \quad (3.9)$$

Then, using Eqns. 3.6, 3.7 and 3.8, a ratio of currents may be written as:

$$\frac{I + I_{i1}}{I_{i2} - I} = \exp\left(V/T_e\right) \quad (3.10)$$

If $I_{i1} = I_{i2} = I_i$ the above equation may be reduced to:

$$I = I_i \{ \tanh(V/T_e) \}, \quad (3.11)$$

To calculate the electron temperature, an easy method is to obtain the derivative of the above equation at zero potential. Note that the derivative of the hyperbolic tangent function is equal to the square of the hyperbolic secant:

$$\frac{d}{dV} \tanh\left(\frac{V}{T_e}\right) = \left(\operatorname{sech} \frac{V}{T_e} \right)^2 \left(\frac{1}{T_e} \right) \quad (3.12)$$

At the origin ($V = 0$) all terms cancel out and,

$$\left. \frac{dI}{dV} \right|_{V=0} = \frac{I_i}{T_e} \quad (3.13)$$

The above equation may be used to calculate the electron temperature by plotting the DLP I-V characteristics, and equating the derivative of the curve at the origin to the ratio of the saturation current (known) and the unknown electron temperature. Note that the saturation current may be obtained from the I-V characteristics by extrapolation, as shown in Figure 3.5(b). The ion density may then be calculated from the electron temperature and the ion saturation current, using the approximate relation, as shown by Chen [Che-65]:

$$I_i \sim 0.6 n_i e A \sqrt{\left(\frac{kT_e}{m_i} \right)} \quad (3.14)$$

where n_i is the ion density, m_i is the ion mass, and A is the probe collection area. Note that since the sheath surrounds the probes, the area A has to be corrected

for the sheath effect that makes the effective collection area more than the actual surface area of the probe.

3.2.4 Limitations of Probe Analysis

As mentioned earlier, probe theory (specially Double Langmuir probe theory) has some sources of errors. At best, it offers good order of magnitude results that may be used for a comparative study. Exact quantitative data must be obtained from more precise methods, like spectroscopy or laser induced fluorescence. Effects of non-Maxwellian distribution, sheath effect, plasma perturbation etc. have already been considered earlier in Section 3.2.1, and now some other possible sources of error are described.

Other than secondary electron emission, probe surfaces are prone to another problem due to bombardment of high energy particles from the discharge. These high energy particles may also cause sputtering of ions from available metallic surfaces, like the containment vessel (specially if it is made of metallic parts with low sputter thresholds), that may contaminate the probe, leading to inaccurate current values that are measured running through the probe. If such deposition occurs on the insulated part of the probe close to the exposed region, it may actually increase the effective collection area, creating large discrepancies. In the MPDR-610 excited at 915 MHz (see Chapter Five) for example, the plasma at 200 W input power was very intense, and the sputtering off the metallic end of the 610 actually shorted out the probes due to metallic deposition between them. Also, in intense discharges, there may be arcing between the cathodic probe, and the anodic sheath edge. This is called a

“unipolar arc”, and can destroy a probe [Coh-89], or at the very least result in erroneous data. Using metals that are less subject to such arcing, like platinum, or tungsten reduces this problem.

All the above dialogue about probes is limited to collisionless plasma with no magnetic fields acting upon the particles. Some applications of ion sources today not only have strong magnetic fields, but also are sufficiently high in pressure to repudiate the predictions of the rather simplistic analysis done above. It is imperative that corrections be made to incorporate the effects of the magnetic field and pressure variance on the simplified theory presented here (see for example, Reference Her-89 page 142). It may be safely assumed that the ion sources characterized with Langmuir probes during the research for this dissertation have no stray magnetic fields or pressure gradients that may require complex corrections to the simple probe theory discussed here. This will become clear when the designs for the ion source are described in detail in the forthcoming chapters.

From the above discussion it is clear that at best, probe theory is able to present data to plus or minus three to five times the exact values, and to “order of magnitude” calculations at worst. It is nonetheless a most valuable tool in characterizing a plasma. Apart from being almost trivially simple in operation (specially the DLP), electrostatic probes maintain many advantages over other more refined and complex techniques like LIF. The humble electrostatic probe is “distinguished by the possibility of direct local measurement of plasma parameters,” while other techniques often rely on averages over a volume. And so, even though the resolution of the results from probe theory may be no better than order of magnitude (in the worst case), it aptly retains its position as being

a premier plasma characterizing technique.

3.2.5 Data Acquisition using Langmuir Probes

In this section, the actual methodology for Langmuir probes as they were used in the laboratory is explained. All data were taken using computer controlled apparatus, and the relevant peripheral circuitry needs to be explained in detail. For sake of simplicity, DLPs for measuring n_e and T_e are covered before the more complicated SLPs for T_e , V_s and EEDFs.

Care must be taken in constructing the probes. As explained earlier, the probe tips are somewhat invasive. To reduce the plasma perturbation, the probes need to be made as small as possible. However, as explained in Reference Hop-91, if the probe area is made too small, the relative sheath effect around it increases, and to minimize this, the probe's actual area must be increased, which is in direct contradiction with the efforts to minimize perturbation mentioned above. So a compromise must be reached for the probe length and diameter. Also, small non-planar probes may read saturation currents that are orbital motion limited (OML) - a theory covered in References Mor-85 and Sch-68. This may occur if the probe radius is less than one plasma λ_D , and in such a situation, the OML probe current given by Eqn. 3.14 is not valid, and the ion density thus measured is erroneous.

To construct a double probe, therefore, the first order of business must be to determine the length of Debye shielding. This is given by the following equation [Lie-94]:

$$\lambda_D = 743 \sqrt{T_e/n_e} \text{ cm}, \quad (3.15)$$

where, T_e is in eV, or V and n_e is in cm^{-3} . Assuming a typical ion density of $1 \times 10^{11} \text{ cm}^{-3}$ and an electron temperature of about 70,000 K in an ECR MPDR, the Debye length is calculated to be about 60 μm . To avoid OML effects, the radius of the probe needs to be made much greater than a Debye length. The dimensions of each recessed probe is - radius = 0.762 mm, length 0.795 cm, with a total area or about 0.399 cm^2 .

A problem with the DLP that was mentioned in Section 3.2.4 had to do with the sputter deposition on the probe tips from the metallic part of the ion source when the DLP was immersed in a high intensity 915 MHz discharge. The two probes were shorted in a matter of minutes. This problem was rectified using a recessed probe. The design of this probe is shown in Figure 3.4(b). As may be seen, instead of two tungsten wire tips protruding from a closed quartz tube (as seen in Figure 3.4(a)) the recessed probe design used two separate probes, each enclosed in a small quartz tube, into which the tungsten wire was a snug fit. This tube was then enclosed in a larger quartz tube. Both tubes were open at the top. The two probes were then stuck together using a UHV compatible adhesive. This created a staggered quartz structure near the two probes instead of a smooth finish. The probe could then be inserted into intense discharges. While there was some sputtering, the recessed nature of the probes prevented their shorting out, and also kept the probe area from increasing due to deposition of metallic ions onto the quartz. This was confirmed when current values read with this probe were consistent before, and after being immersed in an intense discharge for a period of time.

The first experiments that were performed using DLPs actually involved manual data acquisition, where about 50 - 60 current values were written as the voltage was varied from -60 V to +60 V (a data point every one or two Volts). These data points were then manually entered into the computer, and the appropriate reduction programs (generic) were then used to calculate the electron temperatures and ion densities. Very soon, the monotony of manual data acquisition was replaced by a computer controlled system. The circuit used in this work follows several other researchers' work [Hop-91, Sze-93a, Hop-90a] and is sketched in Figure 3.6, following Hopwood. The explanation presented here for this technique, therefore, borrows heavily from the three references mentioned above.

As mentioned in Section 3.2.3, it is imperative that the two probes of the DLP be electrically isolated from ground. To maintain this isolation, a Metrabyte DAS-8 analog to digital (a/d) converter was isolated from the Langmuir probe using a Metrabyte ISO-4 optical isolation amplifier card in the computer. The ISO-4 allows voltages to be differentially amplified with up to +/- 500 Volt electrical isolation. As shown in Figure 3.6, the bias voltage supplied to the probe is calibrated using a multi-turn potentiometer, channeled through an ISO-4 with no gain, and sent to the DAS-8 a/d converter to be read by the computer. The probe current is sampled as a calibrated voltage signal across some current sampling resistors of a voltage divider circuit. The ammeter and voltmeter shown in Figure 3.6 are used for the initial calibration of the current and voltage readings of the data acquisition system.

The DC voltage is then swept from 0 to +60 V, the I-V data being taken automatically every Volt or so at specific time intervals. A lower sweep rate

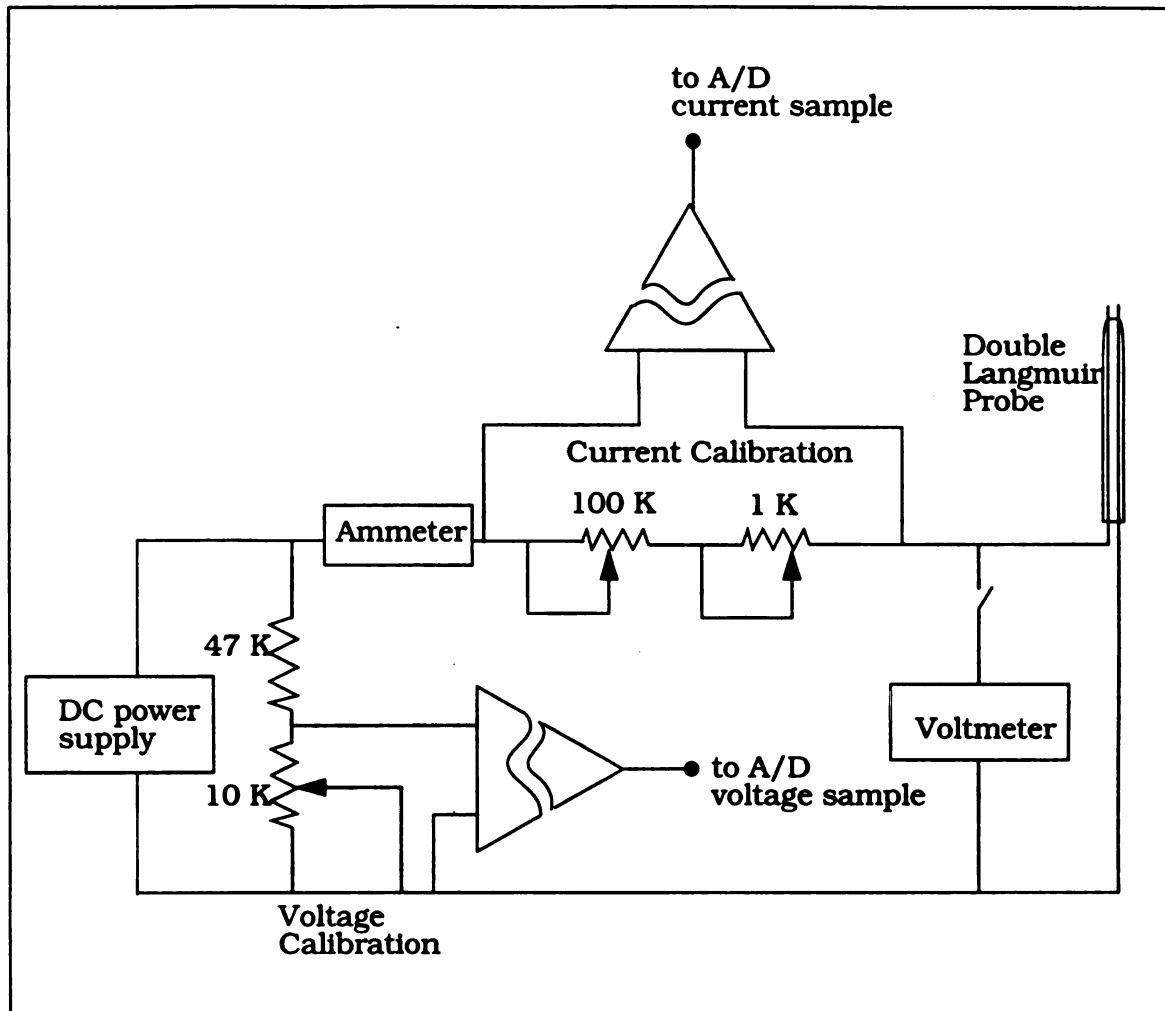


Figure 3.6 Double Langmuir Probe data acquisition circuitry.

The two triangles signify the optical isolators of the ISO card. Adapted from Hopwood [Hop-91].

allows for a higher density of data points to be taken. This is essential near the knees of the I-V characteristics for precise saturation current estimation, as will be detailed below. A double pole double throw switch then exchanges the polarity of the two probes and the subsequent voltage sweep from 0 to 60 Volts is actually converted to be 0 to -60 V. If the two probes are of identical areas, and they are both close enough to sample a volume of the plasma with "similar" plasma potential, the I-V characteristics thus obtained should be mirror images in the 1st and 3rd quadrants, passing through the origin. To minimize random noise, about 60 to 100 samples were taken for each data point, and then averaged by the computer before saving, to provide a smooth I-V characteristics. Control of all data acquisition cards and frequency of current sampling is done through a simple Q-BASIC program.

Data reduction is then carried out by importing the DLP I-V data into another generic program. The electron temperature is found by using Eqn. 3.13, as was discussed earlier. To find the ion density, ion saturation currents need to be determined from the I-V curve. In certain cases, as in low density plasmas, the "knee" of the I-V curve - where the probes are driven into saturation, may be vague and undefined, since real saturation (beyond which the collected current does not change with applied voltage) is never really reached. In such cases, it is necessary to estimate the knees as the intersection of a tangent to the curve passing through the origin, and another tangent to the curve through the "saturation region." This is seen in Figure 3.5(b).

A better method employing a manual selection of the two saturation currents was coded into the generic reduction program. A plot of the data using Eqn. 3.11 is generated. If the plot is linear, then the initial guess of the

saturation points was valid. Two points a little farther may then be tried, till the linear plot shows a discontinuous jump into non linearity near the edges. If the plot is non-linear near the edges, the saturation current values are too large, and must be reduced. The method is iterated till appropriate (maximum) linearity is reached. The current value at this point is picked to be the saturation value. The ion density may then be calculated using Eqn. 3.14. Sheath effects on the probe area, and any other corrections may be incorporated in this equation. Note that Eqn. 3.14 is valid for Maxwellian electron energy distributions only, and for an EEDF that is non-Maxwellian, Eqn. 3.11 will never produce a completely linear plot. Indeed, slightly non-linear plots of Eqn. 3.11 are another indication of the off-Maxwellian EEDFs. In such a case, the validity of Langmuir probe techniques is itself called into question, however the "order of magnitude" results of DLPs are still valid.

As mentioned earlier, the SLP method is more desirable to make average electron temperature measurements than the DLP. This is because of the problems faced while estimating the saturation current values of the DLP I-V characteristics. It has already been stated that the EEDF is not fully Maxwellian, and hence Eqn. 3.11 will only plot a semi-linear curve. Hence the electron temperature data gathered using DLP is suspect. Also, DLPs only measure the high energy tail of the EEDF, and the average electron temperature is calculated from an extrapolated distribution function from this high energy sample. No estimation need be done for the SLP system that directly measures EEDFs, and data on plasma potential, average electron energy (or temperature) are generally more accurate. Hence this direct measurement of the EEDF with no initial assumption of its outcome, and the T_e calculation from this directly acquired

EEDF leads to the accuracy of this so called Druyvesteyn method. Dimensions of the SLP used in for data acquisition are - length = 0.8 cm, radius = 0.5 mm, with an area of about 0.26 cm^2 .

Actual data acquisition was done using two different methods. A semi-automatic system, following Hopwood and Sze [Hop-91, Sze-93a] used the circuit of Figure 3.2. After a low amplitude 1 kHz signal is modulated on the DC carrier bias, the Princeton Lock-In-Amplifier (PAR LIA 128) was used to pick out the second harmonic of the signal, which is proportional to the second derivative of the SLP current (see Eqns. 3.2 and 3.3). The SLP was manually biased at a DC voltage that ranged from 0 to about 40 V, assuming the maximum electron energy in the plasma is about 40 eV. The signal from the LIA then took anywhere from three to 10 seconds to stabilize. Once a stable signal was attained, the key to sample the second harmonic was pressed on the computer, and that data point (d^2I/dV^2 , V) was stored. The DC bias was then increased by about a Volt and the process repeated. The same Metrabyte hardware was used to isolate the SLP from ground as for the DLP system. This was a labor intensive process since the sampling was done by manually pressing the correct key. Also, the amplitude of the small AC signal is dependent on the DC bias. It was therefore necessary to make the appropriate adjustments in the AC signal amplitude after each sampling such that it was the same throughout the experiment. This too meant that the method required constant attention, and increased the total time for the acquisition of an EEDF.

A fully automatic system was developed during the course of these experiments to measure the EEDF, and the ion energy distribution functions (IEDFs). Figure 3.7 shows the block diagram view of this setup. The AC wave

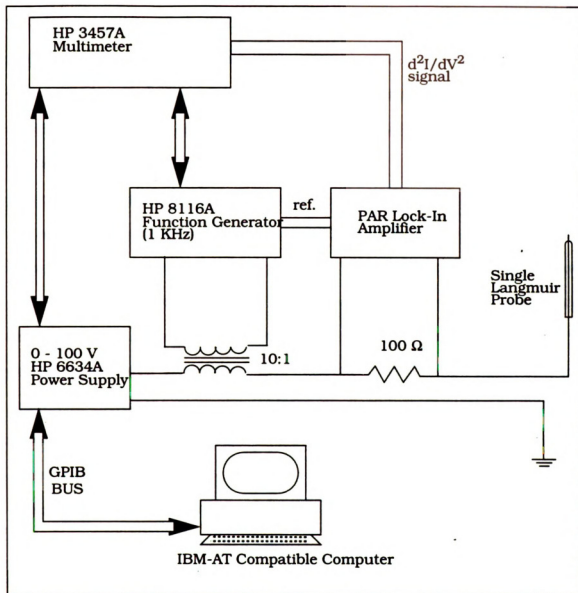


Figure 3.7 A fully automated GPIB controlled single Langmuir probe circuit.

Note that the computer controlled apparatus may be daisy-chained in any order (here, it is shown to be from the computer, to the power supply, to the multimeter and then to the function generator).

generator was replaced by a GPIB controlled Hewlett-Pacard 8116A function generator. The generic DC power supply was also replaced by a HP 6634A, 0-100 V, 0-1 Amp digitally controlled DC power supply. A GPIB controlled HP 3457A multimeter with dual ports was used to measure the AC voltage amplitude, and the second harmonic from the LIA. Finally, a computer program was written in GW-BASIC that would control all the electronics, leading to a sort of turn-key EEDF/IEDF measurement system.

Once the parameters of the experiment (like the AC signal amplitude, the DC voltage sweep range, ΔV which is the incremental increase in voltage after each sample, etc.) are input into the computer, the program sets the digital wave generator and the power supply to the appropriate amplitudes and frequency. Port 1 of the multimeter then reads the AC amplitude and ensures that it is within the required $x\%$ of the input strength (x is also an input into the computer), increasing or decreasing the signal amplitude to conform to the maximum allowed variation. Port 2 then waits from 10 to 30 seconds for the signal from the LIA to stabilize, at which time the second harmonic data is sampled. Once the signal is stabilized, several such samples (up to 50, if necessary) are taken to accurately reduce random noise from the data. The DC bias voltage data is fed to the computer directly from the digital DC power supply. The DC voltage is then incremented by ΔV , typically being 0.5 V, or 1.0 V, as requested by the experimenter, and the process repeated till the user input maximum DC voltage is reached, providing a smooth (d^2I/dV^2 , V) curve.

This system removes all errors relating to manual control of the apparatus, specially the sampling of the second harmonic data, and also all errors related to the initial software calibration that was necessary for the semi-

automatic method of Hopwood and Sze. It was also noticed that while the AC signal amplitude still fluctuated on varying the DC voltage, digital control of the apparatus allowed for much cleaner, faster and easier correction of the AC signal amplitude, and thereby quicker data acquisition. Note that it is no longer necessary to use the optical isolator card, or the A/D converters, since the digital controls automatically isolated and digitized the data. Due to the automation, it is also not necessary to tend to the data acquisition station while the computer is taking the data.

All EEDFs were normalized to one for standardized comparison according to the following equation:

$$\int_0^{\infty} f(E) dE = 1 \quad (3.16)$$

Finally, the average electron energy were calculated using the following equation:

$$\langle E_e \rangle = \int_0^{\infty} (E \cdot f(E)) dE \quad (3.17)$$

The results from this method were seen to be within experimental error of the results original semi-automatic method. Most EEDF and IEDF data reported in this study were acquired using this system. Each EEDF and average energy calculation was carried out a number of times to ensure repeatability, and consistency of the results. The raw data collected using either method (each EEDF normally took 20 - 30 minutes) was fed into another generic program that calculated the plasma potential and the average electron energy. The post

acquisition program (1) determined the plasma potential, (2) plotted the final EEDF, and (3) calculated the average electron energy using Eqn. 3.15, and finally, (4) using the calculated average electron energy, this program plotted the appropriate Maxwellian and Druyvesteyn distributions for comparison with the measured electron energy distribution. All EEDFs presented in this dissertation will therefore have all the three curves.

Another set of Langmuir probes was used in this study to measure the radial profile of ion saturation currents and ion density at a fixed z location, but at various r values (z is taken as the axial direction). While this is best accomplished with a Langmuir probe attached to a computer controlled UHV compatible translation stage, the lack of such a stage necessitated the design of a probe array. Seven recessed single Langmuir probes (0.76 mm radius, 0.8 cm length) were attached 0.5 cm apart using UHV sealant to a pyrex plate. This plate was then attached to two other plates such that the probe array is at the required height, and level with the output of the MPDR 610 (see Figures 4.3 and 4.4 for the 610 mounting position on the vacuum station).

Once the plasma is ignited, the saturation currents, and I-V characteristics across the radius of the ion source may be measured (by alternately switching from probe 1 and 2, to probe 2 and 3, etc.) without having to open the vacuum system to reposition the probes that would invariably involve switching off the plasma source, venting the system, waiting for the system to pump down once again after the probes have been re-positioned, and reigniting the plasma. There is no guarantee that the plasma conditions (pressure, power, etc.) are faithfully reproduced during this prolonged change over. Using the probe array prevents this time consuming and potentially error

filled exercise, and provides accurate measurements of the plasma source output parameters (ion density, saturation current, etc.) at different radial positions across the ion source for any given z location.

3.3 Multi-grid Ion Energy Analyzer

As in the case of electrons, the energy of ions in a plasma also exhibit a distribution function. For a variety of applications, it is extremely important to know this ion energy distribution function (IEDF), and the average ion energy. High ion energies may be detrimental to some substrate processing - energetic ion bombardment on a substrate, for example, may cause damage to the surface. Low energy ions may, on the other hand, catalyze chemical reactions on the surface - it is now believed that while actual anisotropic etching of substrates immersed in a CCl_2F_2 plasma is caused by the atomic chlorine radicals, bombardment of low energy ions on the surface enhances this etch process by providing sufficient energy to the reaction products that are adsorbed on the surface.

While physical effects of high energy ion may be undesirable in most substrate processing experiments, a moderately high energy ion beam is used for implanting ions deep within a substrate. Another application of high energy ion beams is for injection into particle accelerators, where the ions are further accelerated for atomic and nuclear physics fragmentation experiments. A wide range of ion energies, therefore, are in use for various applications, and it is imperative that the energy distributions generated by the plasma/ion beam sources be understood. This section describes the multi-grid ion energy analyzer

(IEA) that was used to measure the IEDFs and average ion energies of the discharge generated in the MPDR plasma sources. The section delves lightly into the theory behind the experimental setup, and also some of the sources of error. It then concludes with the description of the actual experimental technique used with the IEA.

3.3.1 Theory of the Ion Energy Analyzer

Following Hopwood [Hop-91], it may be shown that the IEDF, given by $N(E)$, is proportional to the first derivative of the collector current in the IEA:

$$N(E) = -\left(\frac{d}{dV_{ir}} I_c\right) (V_{ir} - V_{ic})^{-1/2} \quad (3.18)$$

where V_{ir} is the ion retardation potential,

V_{ic} is the ion collector plate potential,

I_c is collected current.

The first derivative of the collected current with respect to the ion retardation potential can, therefore, provide information about the IEDF. As for the SLP experimental system, the PAR 128 lock-in amplifier may be used to differentially sample the magnitude of the fundamental frequency, which is proportional to the first derivative of the collected current, after a 40 Hz small amplitude sinusoidal wave is superimposed on the DC ion retardation grid bias. The theoretical development is now explained.

The current collected in the shielded Faraday cup is given by $I_c = F(\tilde{V}_{ir})$ where F is some energy function, and the ion retardation voltage is the sum of

the DC and AC signals. This may be written as:

$$\tilde{V}_{ir} = V_{ir} + \varepsilon \sin \omega t \quad (3.19)$$

where, V_{ir} is the DC ion retardation bias, and

ε is the small AC signal amplitude superimposed on the DC bias.

The current expression may be expanded in a Taylor series as was shown for the SLP development in Section 3.2.2:

$$I_c = F(V_{ir}) + \frac{d}{dV_{ir}} F(V_{ir}) \varepsilon \sin \omega t + \frac{d^2}{dV_{ir}^2} F(V_{ir}) \frac{1}{2} \varepsilon^2 (\sin \omega t)^2 + \text{H.O.T.} \quad (3.20)$$

Substituting the trigonometric identity $\sin^2 \omega t = (1 - \cos 2\omega t)/2$, the above equation reduces to:

$$I_c = F(V_{ir}) + \frac{d}{dV_{ir}} F(V_{ir}) \varepsilon \sin \omega t + \frac{d^2}{dV_{ir}^2} F(V_{ir}) \frac{1}{2} \varepsilon^2 \left(\frac{1}{2} - \frac{1}{2} \cos 2\omega t \right) + \text{H.O.T.} \quad (3.21)$$

It is seen that there is only one term that is dependent on the fundamental frequency ω , and is also proportional to the ε term of the order of 3 or less. If ε is much less than V_{ir} , all terms ε^3 and above may be ignored. Hence the magnitude of the fundamental frequency may be approximated as being proportional to the $dF(V_{ir})/dV_{ir}$. Once this magnitude is differentially sampled by the lock-in amplifier, the IEDF, written as $N(E)$, as a function of the applied DC bias may be qualitatively obtained. As in the case of EEDFs, all IEDFs are recorded in arbitrary units, and therefore must be normalized to one.

$$\int_0^{\infty} N(E) dE = 1 \quad (3.22)$$

and the average ion energy may then be calculated as the first energy moment:

$$\langle E_i \rangle = \int_0^{\infty} (E \cdot N(E)) dE \quad (3.23)$$

3.3.2 Design of the Ion Energy Analyzer

Initial experimental setup of the IEA followed the work of previous research [Hop-91, Sze-93a, Hop-90a]. Design of the IEA is based on a shielded Faraday cup that collects only the ion current. It has a top membrane with an aperture that severely limits the current flowing into the Faraday cup and into a collector plate. Various grids biased at different potentials between the top membrane and the collector plate allow for accurate collection of the ion current. Design of each part of the IEA is critical to the success of the experiment, and these parts are now discussed. Figure 3.8 shows the IEA, while Figure 3.9(a) shows the potential drops across the grids.

The top membrane, about 50 μm thick, is made of conducting stainless steel chosen to simulate a moderately doped silicon wafer. A tiny aperture in the center of the membrane allows a small percentage of the ions from the quasi-neutral plasma to flow into the Faraday cup. Now, as was the case with Langmuir probes, when the grounded IEA is immersed in the plasma, a sheath forms on top of the membrane - the IEA therefore is a very invasive device. If the

aperture in the top membrane through which the ions fall into the IEA is too large, the sheath will deform around the edges of the aperture, making a teardrop like dip into the aperture. This will allow the neutral plasma meniscus to enter the IEA, thereby emit ions directly inside the Faraday cup and cause large scale errors in the final results. It is absolutely imperative for the success of this experiments that this sheath remain as undisturbed and as parallel to the top surface as possible - otherwise the results of the IEA will be erroneous. Hence the aperture diameter is a critical design parameter - it must be large enough to permit a legitimate signal strength to enter the Faraday cup, however small enough to not disturb the sheath too much.

As calculated in Section 3.2.5 (Eqn. 3.13), the approximate Debye length in a moderately ionized plasma is about $60\text{ }\mu\text{m}$. The aperture diameter should not exceed $10\lambda_D$. For this study, an IEA with an aperture diameter of $250\text{ }\mu\text{m}$ was used. This aperture was drilled into the membrane using an electron beam drill. Hopwood and Sze have used an IEA with a smaller aperture ($50\text{ }\mu\text{m}$) in their experiments [Hop-90a], however the ion sources they characterized were typically more intense than the ones used in this study. Hence the signal to noise ratio for their ion sources was higher to begin with, and a smaller aperture was adequate. For the MPDR 610, it was deemed necessary to use the IEA with a larger aperture so as to retain a high signal to noise ratio.

As may be seen from Figure 3.8, inside the IEA there are two grids and a collector plate, following the work of Matsuoka and Ono [Mat-87]. This IEA was designed and built by co-workers before the research for this dissertation was started, and so it is their design that is described here. Each grid is made of a nickel mesh (100 lines per inch) welded on an aluminum frame, and each grid

has independent and electrically isolated bias leads. The grids and the collector plate are also electrically isolated from each other using Teflon, or Mycor rings. The first grid, nearest to the top membrane is called the electron repulsion grid and is biased at a negative potential high enough to repel the most energetic electrons from the plasma that might enter the Faraday cup. SLP measurements on the MPDR 610 (see Chapter Four) indicated that the EEDF tail may contain electrons of up to 30 eV. Hence a -30 Volt bias may be used on the electron repulsion grid.

The second grid is known as the ion retardation grid, and is positive biased at a variable 0 to +60 Volts to selectively allow ions to fall through. At a low bias potential, most ions are able to get through the retardation grid. As the bias is increased, the ions must travel uphill to overcome the potential, and the rising bias allows only the energetic ions to fall through the ion retardation grid. This decrease in the ion current as the retardation potential is increased determines the energy spectrum of the ions. The third grid, or plate is called the collector plate and is biased at a constant negative potential to attract the ions falling through the ion retardation grid. Note that the double arrow on the ion retardation grid implies a variable potential on that grid.

3.3.3 Limitations of the Ion Energy Analyzer

There are some sources of error that have to be kept in mind when the IEA is used. By far the biggest limitation is that the theoretical development of Section 3.3.2 assumes that all ions entering the Faraday cup have no divergence, i.e. they are all impinging perpendicular to the IEA. For most plasma

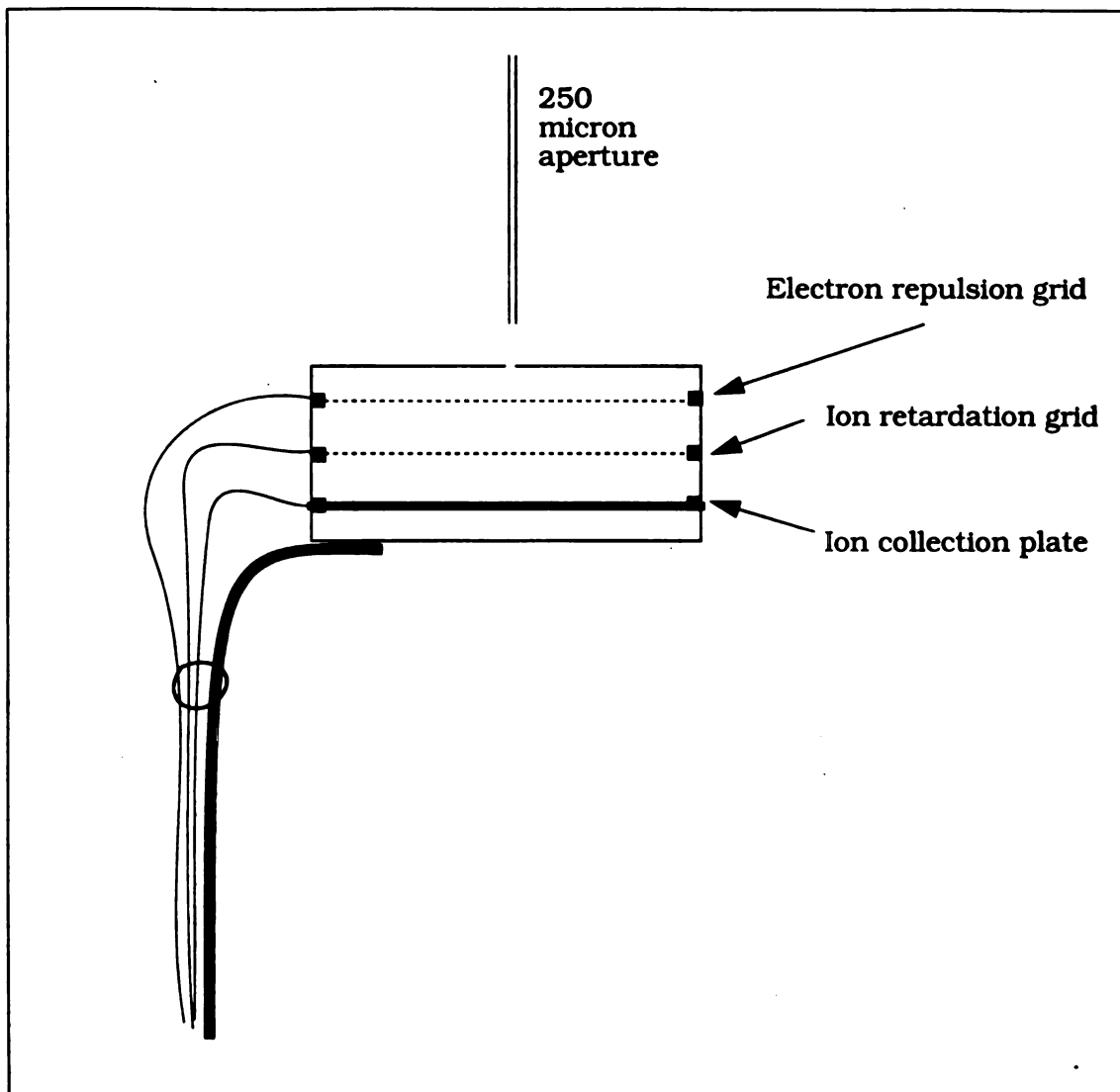


Figure 3.8 The Ion energy analyzer with three grids.

Note that all three grids, and their wiring are electrically isolated from each other, and from the grounded IEA body.

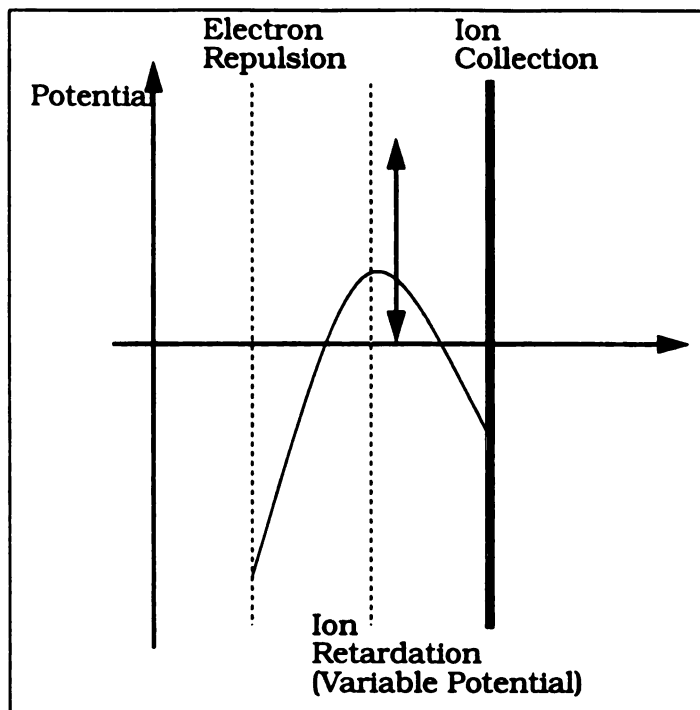


Figure 3.9(a) The potential drops for a three grid IEA.

Note that the potential on the ion retardation is variable (from 0 to about 50 V in most experiments here).

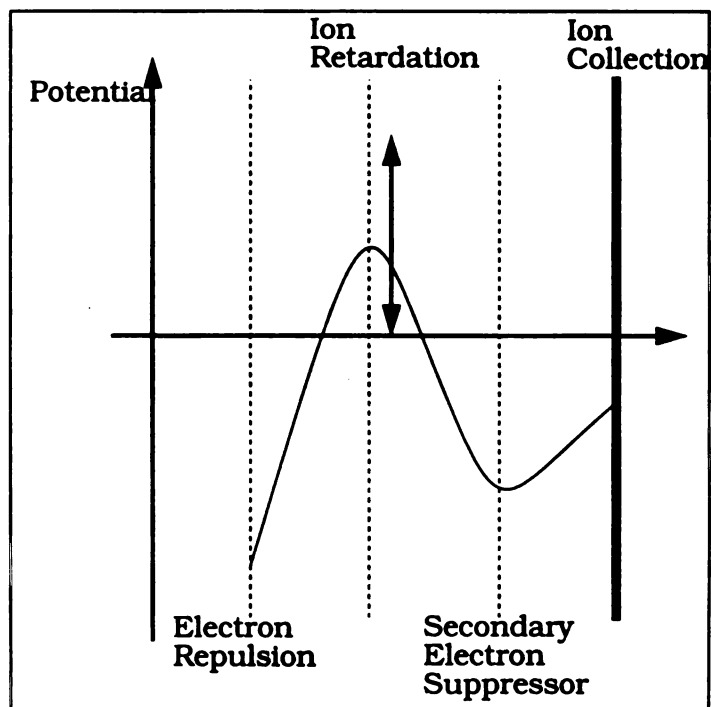


Figure 3.9(b) The potential drops for the IEA with a fourth grid.

Again, the retardation grid has a variable potential.

sources with free diffusion, this is an inaccurate assumption, specially if the IEA is placed in the plasma away from the center axis ($r = 0$) of the plasma source. The radial component of the ion velocity may also be attained if the aperture in the top membrane is larger than the requisite number of Debye lengths. As explained before, the sheath then deforms, dipping the ion emitting plasma meniscus into the IEA and accelerating ions into the analyzer at various angles. The radially directed velocity of the ions is indicated by a broadening of the IEDF, and hence the IEA results must be taken as the upper bound for ion energy measurements.

Another problem that may exist in intense discharges with relatively high ion energies is that of secondary electron emission from the ion retardation grid and the collector plate due to the bombardment of high energy ions. As for Langmuir probes, secondary electrons cause quantitative errors in the actual amount of current that is collected. This may be corrected for to some extent by an additional grid to between the ion retardation grid and the collector plate. Biased negative to ward off electrons, this is known as the secondary electron suppressor grid. The subsequent potential drops across the grids with this new IEA are shown in Figure 3.9(b). As before, the ion retardation grid has a double arrow, implying a varying potential.

3.3.4 Data acquisition using the Ion Energy Analyzer

As with the SLP, two methods were used while collecting IEDFs and average ion energies also. Initial experiments were conducted with the Metrabyte boards and manual sampling of the lock-in amplifier's first harmonic signal once

this signal had stabilized. Following Hopwood, this circuit is shown in Figure 3.10. It must be noted that while the external circuit for using the IEA is more complicated than that of the SLP, there is no dependence of the AC signal amplitude on the variable DC bias. Hence data collection is relatively simpler, and less time consuming.

However, the GPIB control apparatus was again put to good use and a modified SLP program made the IEA system completely automated. Figure 3.11 shows the fully automated IEA measurement circuit, and as may be seen it is similar to the fully automatic EEDF measurement support circuitry of Figure 3.7. With no correction needed for the AC signal (as was needed for the EEDF measurements), the GW-BASIC control program was considerably less complicated, and as for the semi-automatic method mentioned above, the data acquisition for IEDFs was relatively faster. The data obtained with the fully automated GPIB controlled circuitry were consistent with the semi-automated manually sampled data. As in the case of EEDFs, several IEDFs were collected for any given set of experimental conditions to ensure repeatability. The average ion energies reported in this dissertation are therefore the average of the several values measured in the various runs. Figure 3.12 shows a typical set of IEDFs for the MPDR 5 (refer to Chapter Seven).

As in the case of the EEDF measurements, raw data collected using either the automated, or semi-automated method was then imported into another program (different for EEDFs from that for the IEDFs) that reduced the (dI/dV , V) characteristics to generate the ion energy distribution function, normalized it to one, and calculated the average ion energy.

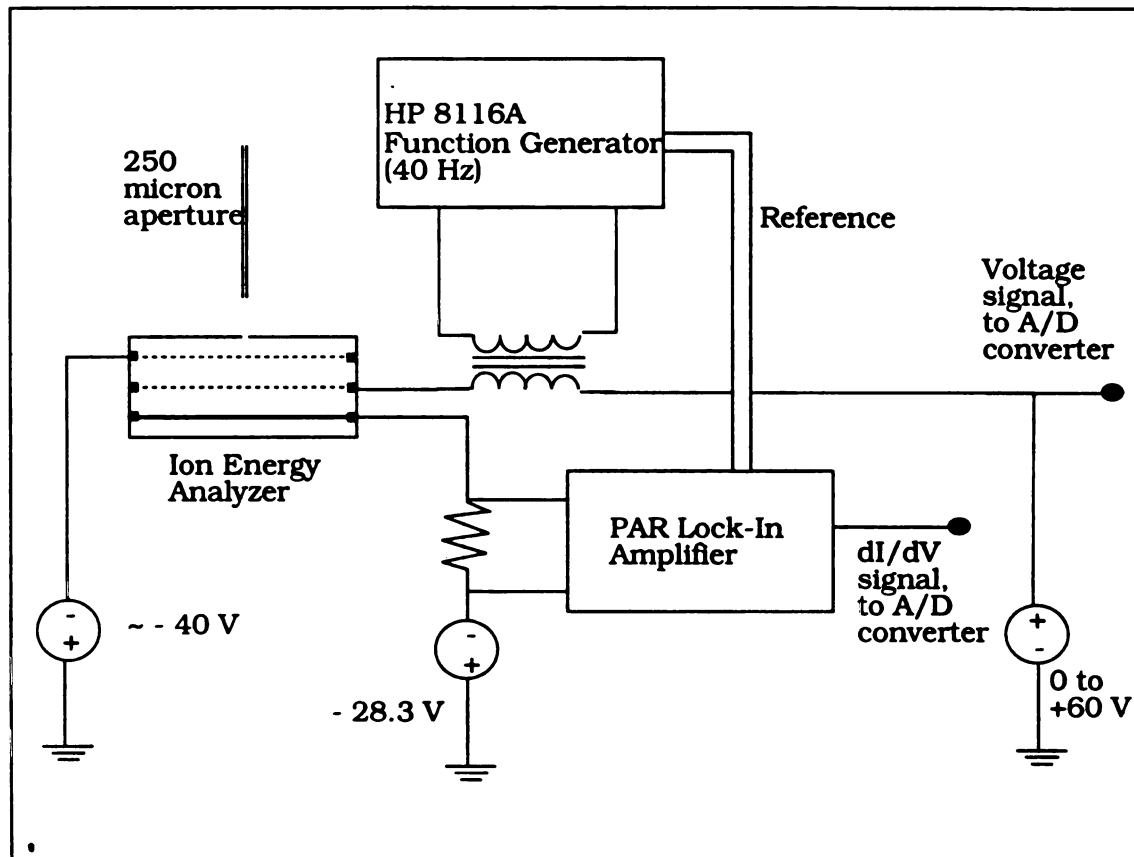


Figure 3.10 Ion Energy Analyzer measurement circuitry.

This is the "semi-automated" method of IEDF measurements, adapted from Hopwood [Hop-91, Hop-90a]

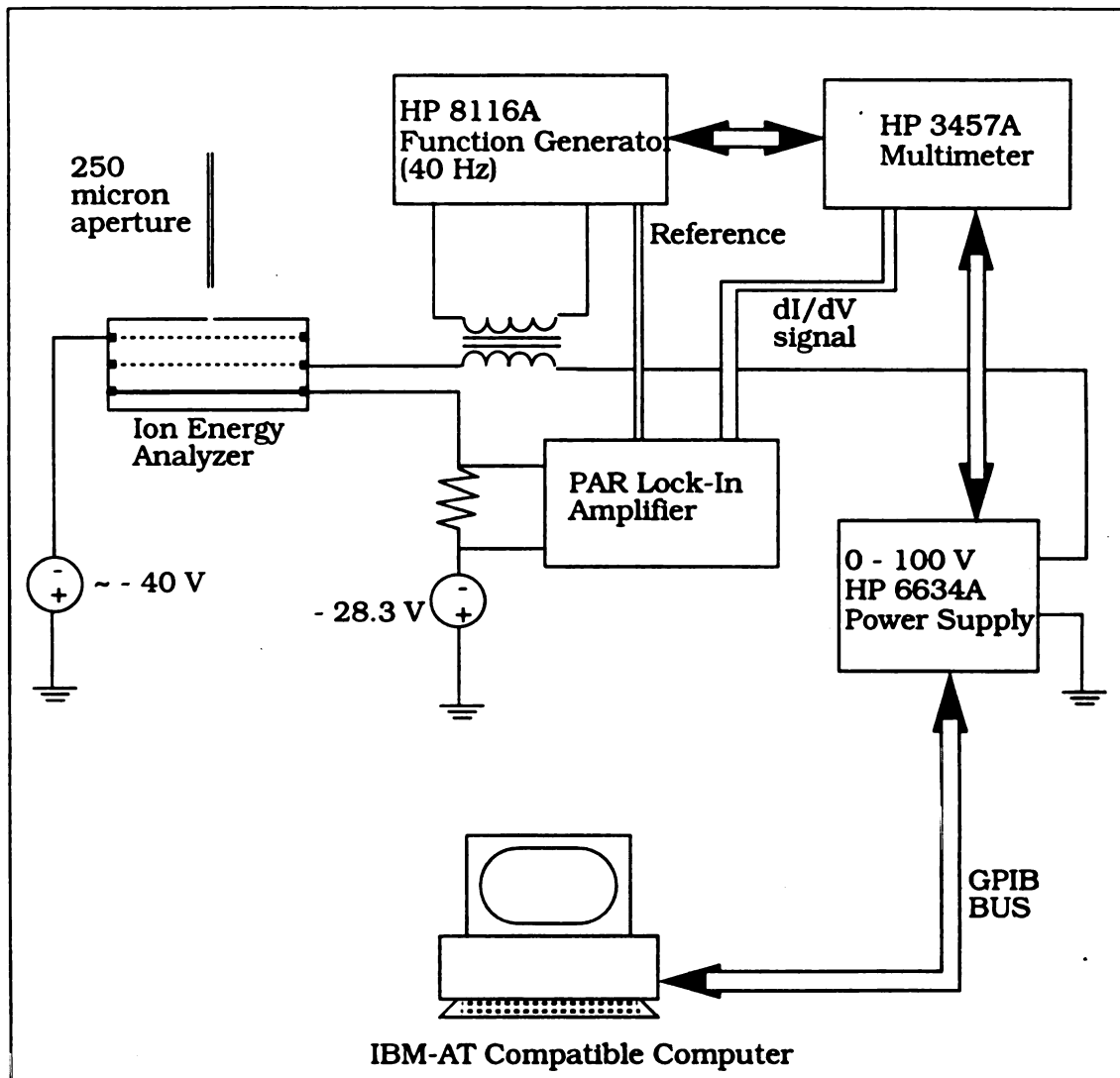


Figure 3.11 Fully automated GPIB controlled IEDF measurement technique. Note the resemblance to the EEDF measurement circuitry of Figure 3.7.

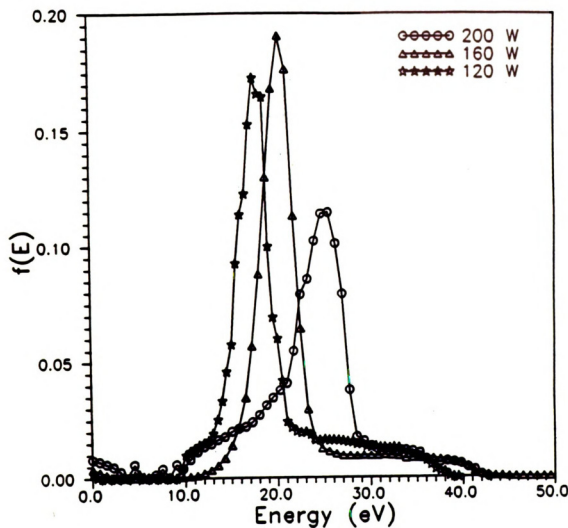


Figure 3.12 Typical IEDFs for the MPDR 5.

Data taken for an argon discharge at 1.2 mTorr, with the IEA positioned 5 cm downstream for various input powers. (Refer to Chapter Seven)

3.4 Energy Distributions - Proposal for a New Method

When Druyvesteyn measured the first electron energy distribution function, he graphically calculated the second derivative of a smooth I-V characteristics of the single Langmuir probe. This "Druyvesteyn" method to measure energy distribution functions that has been described in the sections above, and used throughout this dissertation, is based on indirectly measuring a voltage signal proportional to the second derivative (or the first derivative in the case of ion energy distribution functions) once a small AC signal is modulated over the DC probe (or IEA) bias. While the process is somewhat simplified by using the fully automated system described above (with the GPIB controlled apparatus), there is still some degree of chance involved, specially in sampling the lock-in amplifier signal - when has this signal stabilized enough to be considered a data point?

All this uncertainty, and the very need for the LIA may be done away with by reverting back to directly differentiating the I-V characteristics, but using numerical means rather than graphical. This unique method was tested as an auxiliary acquisition technique but due to time constraints, it was not completely analyzed under varied operating conditions and therefore never incorporated into the battery of characterization principles used during the research detailed in this dissertation. This method is proposed here with the hope that in the near future its applicability may be completely tested.

When an I-V characteristics of the SLP is measured, it becomes obvious why direct differentiation, even if done numerically, would produce erroneous EEDFs. Despite each probe current value being an average of 60 to 100 data

points taken by the computer at every bias voltage, there is some random error, and upon differentiation ($\Delta I/\Delta V$), this error is amplified further, becoming even larger for the second derivative in the case of electron energy distribution functions. It is therefore a practical impossibility to measure an I-V characteristics smooth enough for direct differentiation - this method suffers from successive error propagation.

The new method proposed here incorporates three requirements. First, a computer controlled power supply (like the one used in the GPIB controlled method described earlier) takes as smooth an I-V curve as possible. The frequency at which data are collected determines the ultimate resolution of the results, and a data point every 0.5 Volts is recommended. This I-V characteristics may either be that of the single Langmuir probe, or that of the ion energy analyzer. This I-V characteristics is then fed into a curve fitting program that statistically fits a smooth curve to the data - this fit does not have to pass through every data point. Such curve fitting programs exist in commercially available libraries like NAG, and it is recommended that a routine that fits an n^{th} degree polynomial to the I-V characteristics be used. Note that it is this intermediate curve fitting step that is most crucial to this method of data acquisition, and prevents the errors from propagating. It was noticed during the test runs that the higher the degree (n), the better the computer was able to fit the curve to the data. Finally, when the n^{th} degree polynomial to smoothly fit the measured I-V characteristics is realized, this polynomial may be differentiated any number of times with ease - hence the initial choice of a polynomial fit. It was observed that $n = 9$, or $n = 11$ provided the best fits - lower degrees of polynomials may also work for some cases.

This numerical method completely removes the necessity of the AC function generator (AC small signal), the lock-in amplifier, and most other peripheral circuitry required for energy distribution function measurements. Also there is no error incurred due to the sampling time discrepancy for the lock-in amplifier signal. A fully automated system that incorporates the raw data acquisition, curve fitting and differentiation routines may be set up with the aid of the appropriate computing and electronic support. However, before induction into the characterization techniques, a comprehensive evaluation of this method is required, at various plasma pressure/power/gas type conditions. Also, a comparison of the results obtained from this method, with the "semi-automated" or the fully automated GPIB controlled methods that have been used to date needs to be performed. However, there is no doubt that this new method heralds the next generation of energy measurement methodology, and will soon be incorporated as an alternate way to measure energy distributions.

3.5 Micro-coaxial Probe

Several types of MPDRs have been designed, and they all have one thing in common - they are, or may be operated as single mode microwave cavities. Power is coupled from the waveguide, or coaxial cable and into the plasma through this microwave cavity applicator. Inside the cavity, a single electromagnetic mode is excited, with the plasma acting as the major loss mechanism (small amounts of energy may also be lost to the non-perfectly conducting cavity walls, and also to the coupling apparatus - loop, probe, etc.). The design of these reactors aims at choosing the appropriate transverse

magnetic (TM), transverse electric (TE) or transverse electromagnetic (TEM) mode for the requisite application.

While the EM modes of a perfectly conducting, empty, and lossless cavity are well known and may be found in several references [Har-65, Ram-65], the presence of a plasma, or the brass walls that are not perfectly conducting may significantly alter these modes. Knowledge of the actual EM mode that is excited inside the cavity is therefore essential for understanding the complex dynamics of the cavity. This knowledge aids in further reactor modifications, or design of other reactors that have to satisfy the conditions of ECR that require that the impressed electric fields compliment the static magnetic fields for the power to couple to the electron gas. If the exact electric field structure inside the cavity is known, experimentation with the magnetic field design may lead to a B-field topology that maximizes the ECR “zones” for optimal power transfer. Also, valuable information on the power loss to the cavity walls and the reactor’s coupling efficiency may be obtained through this electromagnetic mode data (see, for example Chapter Six). The relative electric field pattern, and the calibrated electric field strength (in kV/m) inside the microwave cavity can be measured using a semi-rigid micro-coaxial probe, and this diagnostic technique is now described.

3.5.1 Theory and Design of the Micro-coaxial Probes

The simplest way to measure the electric field strength inside the microwave cavity is to sample a small part of the electric fields existing within it [Hop-90b]. This is done by using a semi-rigid micro-coaxial probe inserted into

the side of the cavity through tiny holes (of a diameter such that the probe fits snugly into them, but the microwave power does not radiate out of them). The power collected by the micro-coaxial probe is then read on a standard HP 435A power meter. Since the power being siphoned into the micro-coax comes from the total power resonating inside the cavity, this process can be very invasive, and care needs to be taken to minimize the perturbation of the EM modes inside the cavity. This is ensured by using a micro-coax with a small inner conductor diameter, and a very shallow insertion into the cavity wall. The dimensions of the micro-coaxial cable that was used to construct the probes for this experiment are: inner conductor diameter = 0.6 mm, outer conductor diameter = 2.25 mm., with a TeflonTM dielectric.

Figure 3.13 shows the two different probe designs that were used during the course of these experiments - these are hereafter called the penetrating probe, and the flush probe. In the former, the outer conductor and the Teflon dielectric is peeled back to expose the inner conductor. This probe is then inserted into the small hole made in the cavity such that the inner conductor is penetrating into the cavity, with the outer conductor level with the inner wall of the cavity. As mentioned above, the diameter of the hole drilled in the wall is just large enough so that the probe is a snug fit in the hole, with good electrical contact between the outer conductor of the probe and the cavity wall. The insertion of the inner conductor into the cavity wall creates a monopole over a semi-infinite plane effect, which then samples a fraction of the radial power of electric field existing at that position in the cavity. If a series of holes are drilled in the wall of the microwave cavity, a relative electric field pattern may be measured.

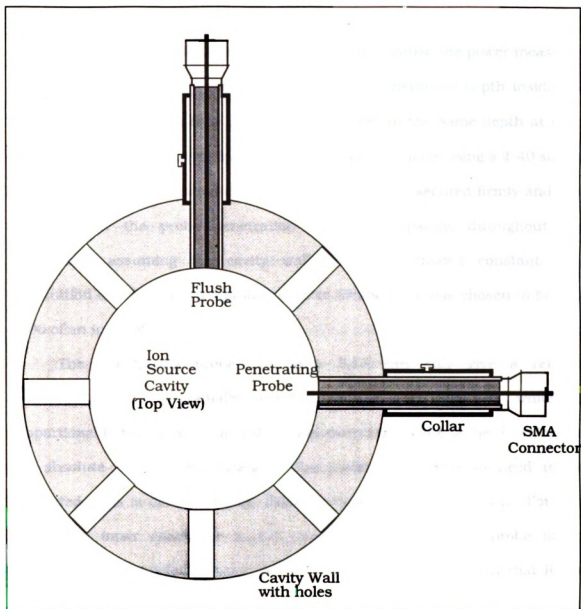


Figure 3.13 Design of the two micro-coaxial probes

These probes were used for measuring electric fields inside the microwave cavity. Note that the figure is not to scale.

For such a measurement however, it is absolutely imperative that the inner conductor protrude into the cavity the exact same distance for each hole to ensure an accurate relative measurement. This is because the power measured by the probe is extremely sensitive to the probe penetration depth inside the cavity. To make certain that the probe is inserted to the same depth at each hole, an adjustable collar is clamped on the outer conductor using a 4-40 screw. Once the desired penetration depth is set, this collar is secured firmly and this ensures that the probe penetration depth is constant throughout the experiment, assuming the cavity wall thickness remains constant. The penetration depth set for the probes used in Chapter Six was chosen to be 30/1000 of an inch (30 mils).

The penetrating probe of Figure 3.13 can only give a relative measurement of the radially directed electric field strength, which is proportional to the square root of the power measured by the probe. To calculate the absolute electric field strength, the power measurements need to be calibrated. This is done using the flush probe shown in Figure 3.13. For this probe, the inner conductor is not exposed, and the entire probe (inner conductor, Teflon dielectric and outer conductor) is inserted such that it are flush with the inner wall of the cavity. Then, the power measured by the probe is related to the electric field by [Bur-85]:

$$E_r = \left(\epsilon_0 K_r \pi a^2 \omega \right)^{-1} \sqrt{2 \frac{P}{Z_0}} \quad (3.24)$$

where, P is the measured power from the probe of Figure 3.12,

Z_0 is the coaxial probe's impedance (50 Ω),

ϵ_0 is the permittivity of free space,

a is the radius of the inner conductor of the coaxial probe,

ω is the microwave frequency (2.45 GHz), and

$K_r = 3.846$ - a constant (as indicated in Reference Bur-85).

During the experiments of Chapter Six, the penetrating probe was used to make the relative field pattern measurements inside the microwave cavity. Due to the penetration of the inner conductor, the signal to noise ratio of this probe was much better than the flush probe. Hence the data could be taken with greater accuracy. The flush probe measurement was then used to calibrate all the field data to give the exact radial electric field strength on the inner wall of the ion source involved in this study (on the 610-a). As will become apparent later in Chapter Six, there were in fact two penetrating probes that had to be built. This was because there were holes drilled through the magnet assembly of the 610-a also to allow for field measurement in the region where the magnets were present - known as the discharge region. It was imperative that the probe penetrating depth in this discharge region be the same as the depth elsewhere, and hence the necessity for the second penetrating probe. This will be discussed in greater detail later in Chapter Six.

3.5.2 Sources of Error with the Micro-coaxial Probes

As mentioned above, care must be taken to insert the penetrating probe only as far into the cavity as necessary. A deep insertion leads to a better signal to noise ratio since more power is captured by the micro-coax, but this may perturb the EM modes that are excited inside the resonating cavity to an extent

that would make the diagnostic tool prohibitively invasive and provide inaccurate field strength data. Also, the size of the probe insertion hole is crucial. A larger than necessary insertion hole could lead to several problems. First, the outer conductor of the probe must be in good electrical contact with the cavity walls. If the insertion hole is too large, the probe will not be snug and will move about inside the hole, making power measurements which are ambiguous and fluctuating, specially when measuring the relative field patterns. Second, the large hole may interrupt the surface currents flowing on the inner wall of the cavity to the extent that the cavity drops the EM mode that is being excited in it. Finally, a large hole may also lead to some microwave radiation specially when operating at high frequencies (low wavelengths) which is not only detrimental to health, but will also act as a secondary power loss mechanism.

3.6 Ion Beam Characterization

All characterization principles that have been discussed up to now assume that the quasi-neutral plasma diffuses freely out of the plasma source. However, as was observed in Chapter Two during the review of several compact sources, several of these sources have extraction grids attached to their output so that energetic ion beams may be extracted from them. This section briefly discusses some of the characterization techniques that are used to evaluate the properties of ion beams.

Once a plasma is ignited in the source, an ion beam may be extracted by using biased grids (or electrodes) that selectively impart a directed velocity (and hence energy) to the ions while retarding electrons. Several applications, like

high energy ion implantation or ion beam injection into particle accelerators, utilize these energetic ion beams. When discussing plasma/ion beam sources therefore, knowledge of ion beam technology is essential. One of the plasma sources studied during the research for this dissertation work (the MPDR 610) was also used as an ion beam source at the National Superconducting Cyclotron Laboratory (NSCL), as will be discussed in Chapters Eight and Nine. The diagnostic methods that were used at the NSCL to characterize the 610 ion beam are now discussed.

3.6.1 Charge State Distribution of the Ion Beam

It is important to know the exact charge state distribution (CSD) of the ion beam, specially for ion beam sources that generate multiply charged ions. This distribution plots a spectrum of the total particle current for each charge state as a function of the charge to mass ratio (Q/M), and hence can give a precise quantitative assessment on the ability of the ion source to produce the desired charge state. The CSD is obtained by bending the ion beam through a 90° analysis magnet, as shown in Figure 3.14. For a specific magnetic field strength that is perpendicular to the velocity of the charged particle, the degree of bending force created by the analysis magnet is specified by the Lorentz force equation: $\mathbf{F} = q(\mathbf{V} \times \mathbf{B})$. This force is directly proportional to the charge state of the ion. Hence, a higher charge state will bend farther than a lower charge state in a give static magnetic field.

To obtain the CSD, the ion beam with all its extracted charge states is allowed to pass through the 90° bending magnet as the current through the coil

is ramped up. A Faraday cup is placed a few meters away at the focus of the ion optics. The Lorentz force selectively chooses the appropriate charge state to strike the Faraday cup. All other charge states are either bent too much, or not enough, and they strike the beam pipe. This is shown in Figure 3.14. A typical CSD of the multiple charge state producing Superconducting ECR (SCECR) ion source at the NSCL is shown in Figure 3.15 [Har-94]. The spectrum is that of a krypton-86 run, with oxygen used as the ballast gas (for super gas-mixing). It clearly indicates the amount of current at each peak, where the peaks represent some ionized species present in the ion beam. For example, the current for Kr^{19+} (at Q/M of about 4.5) is seen to be about 30 particle micro-amps (μA). As can be seen, the exact current of each Q/M species (charge state) may be read and compared to other charge states.

An obvious advantage of the 90° bending magnet is that by setting the bending magnet's current to a specific value the researcher may choose any charge state from all the states that populate the initially extracted ion beam, while rejecting the other states. Only one charge state will then propagate beyond the Faraday cup (once the cup is removed from the beam line).

3.6.2 Emittance of the Ion Beam

The emittance diagram of an ion source gives an indication of the spatial distribution of the beam as it travels through a beamline. It is a measure of the beam volume in a six dimensional phase space defined by x, y, z, p_x, p_y, p_z , where the last three parameters are the three components of the momenta. For a beam travelling in the z direction, the phase volume characterizing the beam is

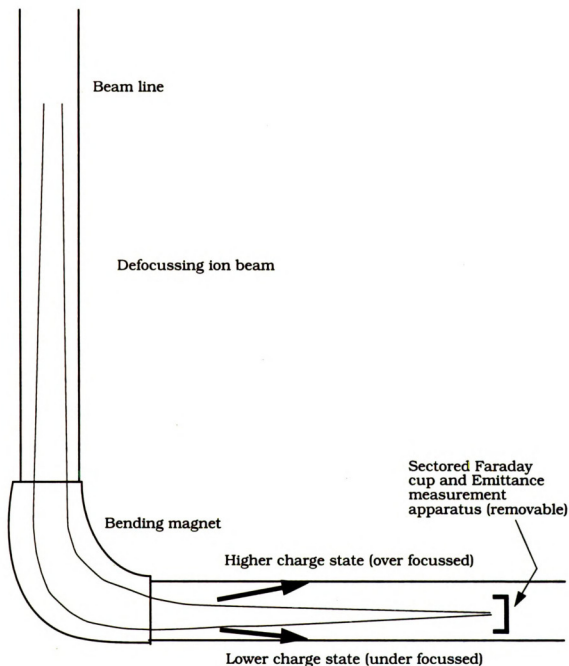


Figure 3.14 Charge state distribution measurement.

Beamline for an extracted ion beam, with a 90° analysis magnet and a removable sectored Faraday cup. Note that at a specific field strength of the analysis magnet, higher charge states are over focussed, and lower charge states are under focussed.

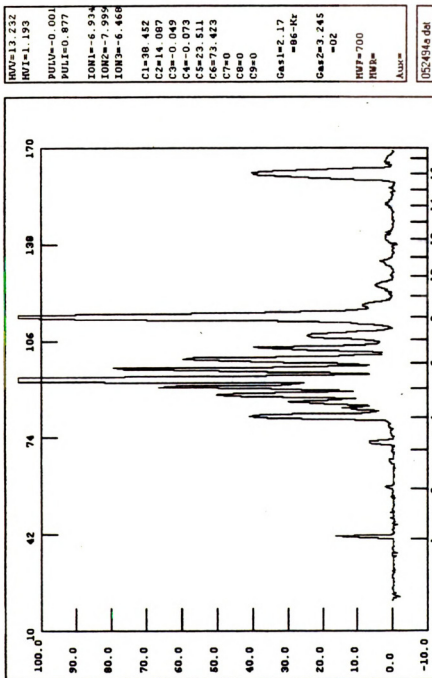


Figure 3.15 A typical charge state distribution of the SCECR at the NSCL.
 The source is producing multiply charged states of krypton 86, with oxygen as the ballast gas. Note that the Kr¹⁹⁺ beam has 30 particle micro-amperes of current.

given by the coordinates x, y, p_x, p_y . This phase volume is the emittance of the beam, and is usually measured in millimeter-milliradians (mm-mrad). In the case of cylindrical symmetry, the emittance may be further simplified and written terms of a 2-dimensional phase space with parameters r, p_r such that $p_r = p_z \alpha$ where α is the half angle of divergence of the ion beam from an axially parallel beam line. Note that a critical factor in beam divergence is that of space charge - the Coulombic radial force on the energetic ions that tends to make the beam diverge. Emittance data can provide information on the space charge effects that the beam is experiencing. For example, if by increasing the extraction bias, the emittance goes down, it may be because of an increase in the ratio of directed velocity to the radial velocity that the energetic ions experience due to space charge effects.

The exact derivation of the emittance formula is very complicated requiring knowledge of Hamiltonian mechanics, canonical momenta, etc., and need not be discussed here. Several references for the various emittance definitions and measurement techniques, and also for the derivation of the emittance formula may be cited for further study [Lej-80, Ste-67, Val-77, Kel-89, Wan-91].

Following Valyi [Val-77], the normalized beam has an ellipsoidal phase space, with its emittance given by: $\varepsilon = r\alpha\sqrt{2meV}$ (in mm-mRad). This equation takes into account the relativistic effects on a fast moving beam. It is to be noted that the net phase volume of the beam that comprises the emittance is not affected by any electric or magnetic fields, even if the beam diverges - emittance is a conserved quantity. Hence it is a useful beam parameter to evaluate the beam's characteristics, and also the extraction optics of the ion source. If the

area on the emittance plot of the beam is larger than the acceptance area of the beam pipe, the beam will diverge, and cannot be transported without substantial losses. Measuring emittance can therefore give an indication of the ion-optical system through which the beam of specific charge state is to be transported. Conversely, emittance data may also provide information on how certain charge states, with specific space charge forces would react to the beam optics.

Another widely used parameter to characterize the beam is its brightness. Defined as the ratio of the particle current (beam current divided by the particle charge) I , and the square of the radial emittance ϵ_r :

$$B = 2 \frac{I}{\pi \epsilon_r^2} \quad (3.25)$$

The larger the brightness of the beam, the more focussed it is and the better it may be transported through the ion optics.

3.6.3 Emittance Measurement Techniques

Several methods exist for measuring the emittance of a beam, the principle of each method being to evaluate the angular deflection of the elementary fractions of the ion beam that have been created using appropriate slits, or a diaphragm with holes. Two such methods are briefly touched on here - the static, and the dynamic detection schemes. Both schemes require the beam to be broken up into tiny beamlets. The static system requires an image of the beamlets some known distance away from the slits (or apertures) - usually several centimeters. This image may be captured by burning a Kapton film, or

on a photographic paper, or even on vacuum grease. The divergence of each beamlet displayed on the image is then studied as a function of the distance separating the slits from the image capture device, and this gives an indication of the emittance of the total beam.

The dynamic method of emittance measurement also involves breaking up the beam into small beamlets, normally by using slits, or gridded diaphragms. A very thin conducting wire (a few mm diameter) is then swept in front of the beamlets measuring the currents of individual beamlets. The broadening of the beamlets as indicated by the ion current peaks then gives an indication of the beam's emittance. As shown in Figure 3.16, by measuring the beamlet's width at the base, and also the distance it travelled from source (the slits), the divergence angle of the beam may be determined, and the emittance then calculated from a phase space plot. Figure 3.17 shows a typical emittance diagram of the SCECR + 610 (see Chapter Eight) taken with the wire scanner method. A similar set of (r, α) measurements may be taken using the static method also, with the Kapton burns.

As may be seen in this figure (bottom sketch), the emittance diagram is generally elliptical. A gross classification of the ion beam may be made based on the shape of the emittance pattern [Kel-89]. If the pattern extends from the third to the first quadrant, the beam is generally divergent. If, on the other hand, it extends from the second to the fourth quadrant, the beam is generally convergent (see Figure 3.5, Reference Kel-89.). Indeed, as the beam travels through the beam pipe, initially focussing to its "minimum skirt," and then defocussing, the emittance ellipse rotates in phase space. However, as mentioned earlier, it is a conserved quantity, and so the total area enclosed by

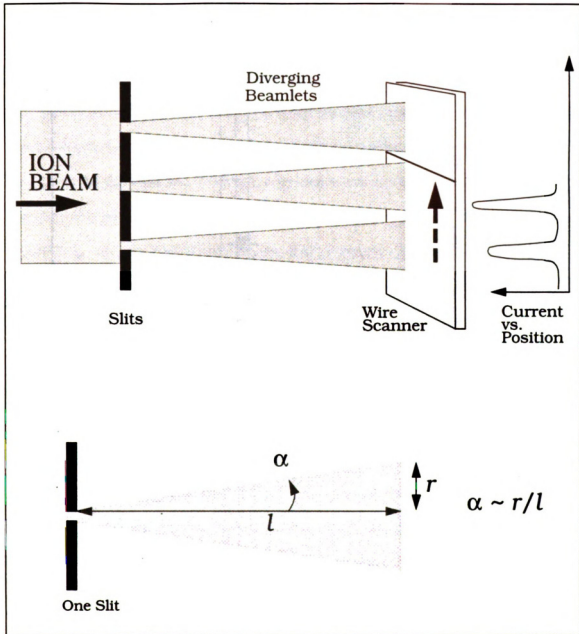


Figure 3.16 The dynamic emittance measurement technique

This method uses a wire scanner. Top sketch shows how wire is scanned across the beamlets, and the current vs. position plot acquired. Bottom sketch isolates one beamlet, and indicates the divergence half angle $\alpha \sim r/l$

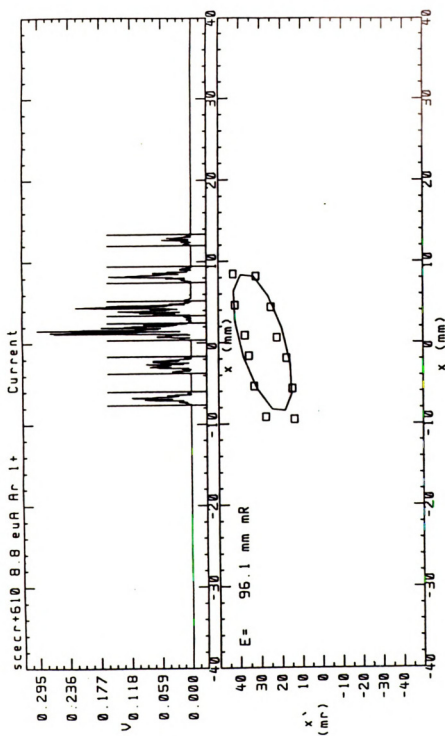


Figure 3.17 Typical emittance diagram of the SCECR-610.
 The wire scanner method was used to obtain the relative currents of each beamlet, and the emittance calculated from this information. (Refer to Chapter Six.)

the ellipse does not change with the focussing-defocussing effects on the beam.

A very important aspect in ion beam characterization is the numerical simulation and modelling of the beam. Several codes exist to perform this simulation (like the BEAM3D developed at the NSCL, and PARMILA, among others). Most codes numerically solve the coupled Poisson-Vlasov equations for ions extracted from a plasma with an equilibrium electron density and for a give charge state distribution. Use of these codes can greatly simplify the design of the ion-optical system for beam transport. When used in conjunction with POISSON, and/or PANDIRA - codes that numerically simulate the magnetic fields, source specific extraction systems can be developed and tested on the computer before expensive models are constructed.

Both the static and dynamic systems were used to study the emittance of the MPDR 610 when it was used as an ion beam source. For the static case, the "pepper pot" method was employed where the beamlet image was captured on a Kapton film after the beam was allowed to pass through the tiny holes in a stainless steel membrane. The dynamic method, whose results are presented in later chapters, was utilized when the 610 was mounted on the beam line of the SCECR (see Chapters Eight and Nine).

3.7 Concluding Remarks

There are several characterization techniques mentioned in this chapter, and all were used to varying degrees for the performance evaluation of the four major ECR ion sources studied in the last five years. Characterization work is never complete, however - there is always more to learn, and techniques other

than those reviewed in this chapter were also attempted. Laser induced fluorescence (LIF) is an example, a complicated technique that was tested on the MPDR 610. For several reasons, the experiments were unsuccessful, and hence no further mention of this method is made in this dissertation. Optical emission spectroscopy (OES) was also used on a nitrogen plasma, but ambiguous results due to the enormous number of emission lines curtailed further experimentation with OES. A more concentrated effort for both LIF and OES needs to be made in the near future.

Other than LIF, several other characterization techniques may be used to further enhance the understanding of the ECR ion sources evaluated here. For example, quartz crystal microbalance (QCM) for measuring the reactive radical species (oxygen and hydrogen) concentration, Fabry-Perot interferometry for an accurate measurement of neutral species temperature, X-Ray analysis using a pin hole camera to further determine the exact location of ECR excitation, and energetic species bombardment on the plasma source walls. It is expected that as performance evaluation of the MPDR 610 and the MPDR 5 is carried further, some or all of the above recommended experiments will be conducted and the results then linked to those obtained using the techniques of this dissertation, ultimately leading to a better understanding of the sources.

Chapter 4

Evaluation: The MPDR 610 at 2.45 GHz.

4.1 Introduction

4.2 Description of the Plasma Source - the "MPDR 610"

4.3 Description of the Vacuum System - the "Yorktown T"

4.4 Description of the Microwave Apparatus

4.5 Discharge Ignition in the 610

4.6 Operational Performance of the 610 - ARGON

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4.7 Operational Performance of the 610 - NITROGEN

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4.9 Concluding Remarks

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Chapter 4

Evaluation: The MPDR 610 at 2.45 GHz

4.1 Introduction

Several types of microwave plasma disc reactor (MPDR) sources have been designed by Asmussen et al. at the Plasma Research Laboratory of the Department of Electrical Engineering (EE). Each plasma source is specific to the application for which it was designed, and these applications range from high pressure diamond thin film deposition, where the sources operate at high power levels (several kWatt) and at several tens of Torr, to low pressure anisotropic etching of silicon wafers where the sources operate at or about mTorr, with no more than a few hundred Watts of input power. MPDR sources therefore have been used for a variety of applications, and under a wide range of pressure and power conditions.

One such semiconductor ultra high vacuum (UHV) application requires a small plasma source capable of producing an intense discharge near the substrate inside molecular beam epitaxy (MBE) machines. Since the substrate may be up to half a meter inside the MBE machines, this stipulates that the

plasma source be inserted deep into the existing MBE machines, and be made of only UHV compatible materials. Such a source was designed by Asmussen et al. and is known as the MPDR 610TM [Asm-90b]. (To re-emphasize from Chapter One, the terms "MPDR 610", and "610" will be used interchangeably in this dissertation. They are not to be confused with the 610-*a*, that is a modified MPDR 610 plasma source and will be discussed in Chapter Six.) Most of the forthcoming chapters are related to the direct, or indirect experimental evaluation of this compact source, with some later sections being devoted to a series of applications oriented studies of the 610.

This chapter begins with a brief history, and a description of the MPDR 610, detailing all the important parts of the source. Next follows a description of the vacuum system where most of the characterization of the 610 was conducted. (Some downstream current density data were taken on the vacuum station at Wavemat, Inc. of Plymouth, Michigan, while the beam characterization of the source was done at the National Superconducting Cyclotron Laboratory - see Chapter Nine for details.) The vacuum station is known as the "Yorktown T" and was put together at the MSU Plasma Research Laboratory (C-16, Division of Engineering Research), and was donated to MSU by IBM Corporation's T. J. Watson Research Center, Yorktown Heights (hence the name). The gas flow system that was designed for the MPDR 610, and the microwave apparatus are then described.

The next several sections are devoted to summarizing the experimental characterization of the 610 at an excitation frequency of 2.45 GHz. Most of the performance evaluation of the 610 was conducted with argon as the discharge gas (in this and other chapters), however some results of helium, nitrogen,

hydrogen and oxygen plasma discharges are also presented. Lieberman and Lichtenberg presented a set of calculations in Reference Lie-94 that may be used to predict the behavior of certain electropositive mono-atomic gas discharges. Based on this, some theoretical calculations of the expected ion density, electron temperature, plasma potential and ion energy generated within a 610-like discharge are compared with the actual measured quantities for a 610 argon discharge - the correlation between theory and practice will be seen to be very close. The chapter ends with some conclusions on the performance of the 610 at the 2.45 GHz excitation frequency. Experimental data provided in this chapter were presented as papers at ICOPS-91 [Sri-91a] and ICIS-91 [Sri-91b] conferences. Some sections discussed in this chapter were also presented at the ICOPS-92 [Sri-92b], while some of the helium data were specifically taken for the computer modelling efforts reported at ICIS-93 [Gro-94a, Gro-93, Gro-94b]. Some of the conference presentations were subsequently published in the proceedings [Sri-92a, Gro-92] of the relevant conferences.

4.2 Description of the Plasma Source - the "MPDR 610"

The MPDR 610 is a compact coaxial electron cyclotron resonance (ECR) plasma/ion source designed at Michigan State University (MSU) specifically for MBE and other UHV applications. With assistance from the research at MSU, this source has been refined and commercialized by Wavemat, Inc. of Plymouth, Michigan. This plasma source was first introduced at the ICIS-89 at Berkeley, [Asm-89b, Asm-90a, Asm-90b] and has since then been used for a variety of applications that include: III-V compound nitriding [Str-91, She-91],

superconducting thin film deposition [Paw-93, Yam-91], pre-cleaning substrates using reactive atomic hydrogen [Abe-92], and as an experimental positive/neutral/negative species injector into the main stage of a high charge state ECR ion source at the National Superconducting Cyclotron Laboratory (NSCL) at MSU (see Chapter Eight). This versatile source, therefore, has been used for several varied applications in over 60 research and industrial laboratories both within the USA, and in Europe and Asia, with more applications on the horizon as an ion beam source.

A sketch of the plasma source is shown in Figure 4.1 (not to scale). The cylindrical source is made of stainless steel, and has an outer diameter of about 5.8 cm with an applications specific overall length; the plasma source that was evaluated in this research is 15 cm long. The vacuum seal at one end is made by a standard 4.5 inch Conflat™ flange (11) with the entire length of the source inserted deep into MBE type vacuum chambers. At the other end (near the discharge), metal-to-metal vacuum seals are made using specially designed UHV compatible ring shaped Helicoflex™ spring loaded seals. The discharge located at this end of the plasma source (12), has a diameter of 3.5 cm. The electromagnetic (EM) cavity excitation region consists of a coaxial coupling section which is terminated at one end with a sliding short (10), and at the other end, by the discharge. The region between the sliding short and the discharge is occupied by a coaxial waveguide section and an evanescent (below cutoff) circular waveguide section. The significance of both the coaxial and evanescent waveguide sections (as well as the significance of their specific dimensions) will become apparent later, and will be discussed in detail in Chapter Six. The diameter of the inner conductor (8) comprising the coaxial section is 1.2 cm.

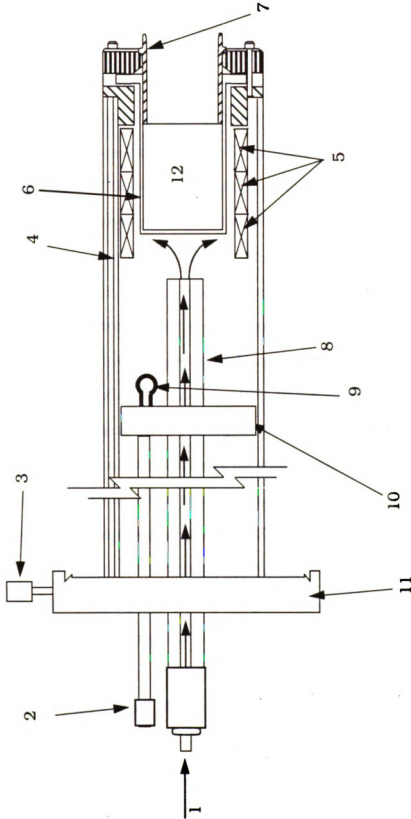


Figure 4.1 MPDR 610

- | | |
|-------------------------------------|------------------------------|
| 1. Cooling Air Feed | 7. Quartz or Alumina chimney |
| 2. Type N Microwave Connector | 8. Center Conductor |
| 3. Gas Feed | 9. Loop Antenna |
| 4. Gas Line | 10. Sliding Short |
| 5. Ring Shaped Permanent Magnets | 11. 4.5 Inch Conflat Flange |
| 6. Quartz or Alumina Plasma Chamber | 12. Discharge region |

A small loop antenna (9) is attached to the sliding short, and this loop excites the EM mode(s) in the microwave cavity. Between the terminus of the center conductor and the discharge is an impedance matching circular waveguide section that has a diameter which is too small to support any electromagnetic propagating modes for the 2.45 GHz excitation frequency (the lowest EM propagating mode - TE_{11} requires a diameter of at least 7.2 cm at a frequency of 2.45 GHz). Evanescent EM waves are therefore set up in this small circular waveguide section of the MPDR 610. The plasma is confined in a quartz or alumina discharge chamber (6) with an inner diameter of 3.76 cm and a height of 4.73 cm. An optional quartz chimney (7) may be used to more efficiently distribute the gas through the discharge generation region. In the initial 610 series, the quartz discharge tube was brazed to a molybdenum ring so that the Helicoflex seals may be used on metallic surfaces. This was discarded in the later designs for a pure quartz or alumina sealing surface, since it was observed that a smooth quartz (or alumina) surface can also be vacuum sealed with the Helicoflex rings if proper care is taken while assembling the ion source. Switching to alumina or quartz reclaims the expense of the brazing process, and also prevented molybdenum sputtering and contamination of the substrate processing regions, thereby making the source completely UHV compatible.

The quartz tube is surrounded by three ring shaped axially magnetized permanent magnets (5) which provide the static magnetic flux density within the plasma chamber for plasma confinement and the 875 Gauss field strength for ECR. These magnets with an outer diameter of 4.95 cm, a height of 1.27 cm, and an inner diameter of 4.32 cm are aligned with like poles facing each other, as shown in Figure 4.2(a). (This figure is not to scale.) While this makes assembling

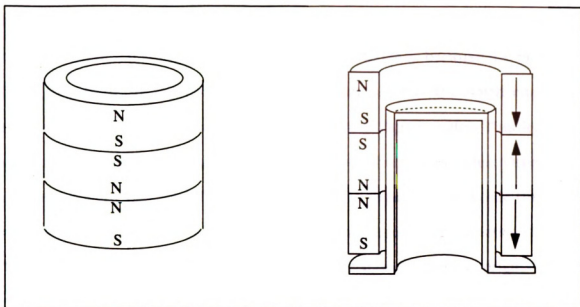


Figure 4.2(a) The magnet design of the MPDR 610 (original).

The right hand sketch indicates the relative position of the quartz (or alumina) discharge confinement structure.

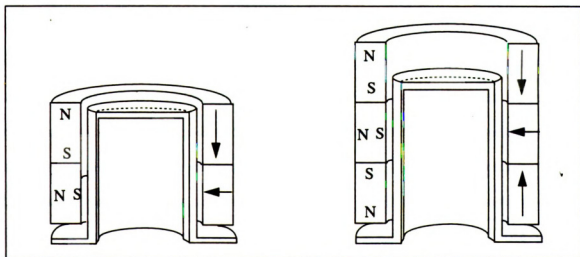


Figure 4.2(b) Other magnet and quartz designs that were also tested.

Note the radial magnets that were used in an effort to push the "ECR zones" further into the discharge chamber.

the magnets rather difficult, this design of the magnetic fields creates a multi-cusp geometry axially, and tends to push the 875 Gauss ECR zones inwards and away from the quartz discharge chamber walls. Some degree of magnetic confinement of the charged particles is also accomplished because the magnetic fields loop from the top north pole to the south cusp, to the north cusp and finally to the south pole in the bottom, following Figure 4.2(a). This leads to regions of high and low magnetic fields that trap charged particles. Other field geometries were also tried, like the ones shown in Figure 4.2(b). While the three rings with a radial magnet in the center also produced high densities (10^{10} to 10^{11} cm^{-3}), the most effective field topology was found to be the original three ring shaped magnets of Figure 4.2(a).

The quartz walls and the magnets are cooled by compressed air (1) flowing through the center conductor and blowing onto the discharge chamber (see Figure 4.1). The positions of the center conductor and the sliding short can be independently adjusted in order to match the discharge load to the input transmission line impedance (50Ω). This discharge load changes as the plasma varies with input power, gas flow/pressure, gas type etc., and appropriate tuning minimizes the reflected power and ensures maximum power transfer to the plasma load. Typically, less than 5% of the power is reflected back when the source is operating in an optimally tuned condition. A discharge can be easily ignited and sustained at sub-mTorr pressures for a variety of gases (oxygen, hydrogen, helium, nitrogen, argon, or a mixture thereof) without the use of ignition filaments, or Tesla coils. Molecular, charged and atomic species diffuse out of the open end of the source, or an ion beam may be extracted by attaching biasing grids or extraction electrodes at the end of the discharge. While the freely

diffusing plasma from the 610 is characterized in this chapter and also in Chapters Five and Six, ion beam characterization of the MPDR 610 will be discussed in more detail in Chapter Nine.

The concept behind using microwave cavities to generate plasma discharges is this: electromagnetic power is coupled into the cavity. Under ideal conditions (the cavity walls are perfectly conducting, the cavity is closed on both sides, etc.) this power resonates between the electric and magnetic fields if the cavity is well tuned. If a load is then introduced in the cavity, like a plasma, the resonating power may be absorbed by the discharge gas (as explained in Section 1.2 of Chapter One). That this is a very efficient method of power transfer will become apparent with the efficiency calculations on the 610 discussed in Chapter Six. The MPDR microwave cavities are designed to excite only one EM mode (or a few modes) to enhance controllability of the discharge. Since the EM modes being excited depend on the frequency of the EM waves, most cavities operate only at one frequency of excitation - 2.45 GHz. Some larger MPDRs are designed to operate at 915 MHz.

Note that for wave propagation in the MPDRs (that are essentially circular waveguides), there is a minimum diameter below which all EM waves are cutoff. To overcome the minimum diameter requirement for propagating (non evanescent) modes, it is expected that a transverse electromagnetic (TEM) wave which has no cut-off is set up in the coaxial section of the 610. This axially symmetric TEM field is excited by the coupling loop attached to the sliding short, and has an azimuthal magnetic field and a radial electric field. Further discussions of the EM modes that are set up in the 610 may be found in Chapter Six where direct measurements of the field patterns confirm the TEM standing

waves being generated in the coaxial section of the 610. Note that due to the coaxial nature of the plasma source the 610 is not limited to one frequency of excitation - a point covered in more detail in Chapter Five.

4.3 Description of the Vacuum System - the "Yorktown T"

The vacuum station on which most of the characterization of the MPDR 610 was conducted is schematically shown in Figure 4.3 (not to scale), along with the mounting position of the 610. The source was inserted into an 18 inch (45.72 cm) diameter by 10 inch (25.4 cm) high cylindrical stainless steel chamber (7) with three 4.5 inch Conflat ports each 90° apart. The 610 (4) could be mounted on any port, while the other two may be used for diagnostics, or as viewing windows. This is seen in Figure 4.4 which is a sketch of the top view of the vacuum chamber (not to scale) and also shows the relative positions of the 610 and the diagnostic apparatus. The fourth end of the vacuum chamber is connected to a 6 inch ASA (10 inch diameter) diffusion pump (12), which is backed by a 27 cubic feet per minute Alcatel mechanical pump (14). A gate valve (9) isolates the vacuum chamber from the diffusion pump stack, so that the chamber may be vented to allow changing samples, or repositioning diagnostic probe without turning off the pumps. Between the gate valve and the diffusion pump is a water cooled cold trap (not shown in Figure 4.3) that helps in keeping stray pump oil away from the vacuum chamber.

Once the sample, or diagnostic probe position change over is completed,
the foreline valve (11) is closed and a secondary pump line from the chamber to
the mechanical pump allows a preliminary rough pump down of the chamber.

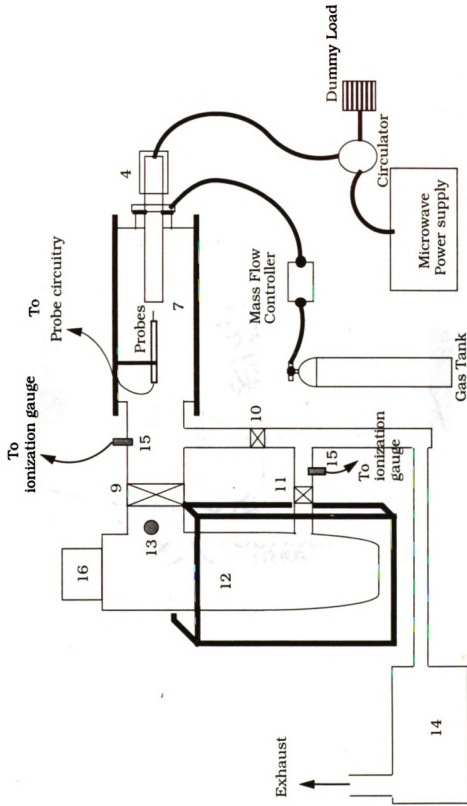


Figure 4.3 Vacuum system - the Yorktown I
Please see the chapter text for definition of numbered parts on this figure.

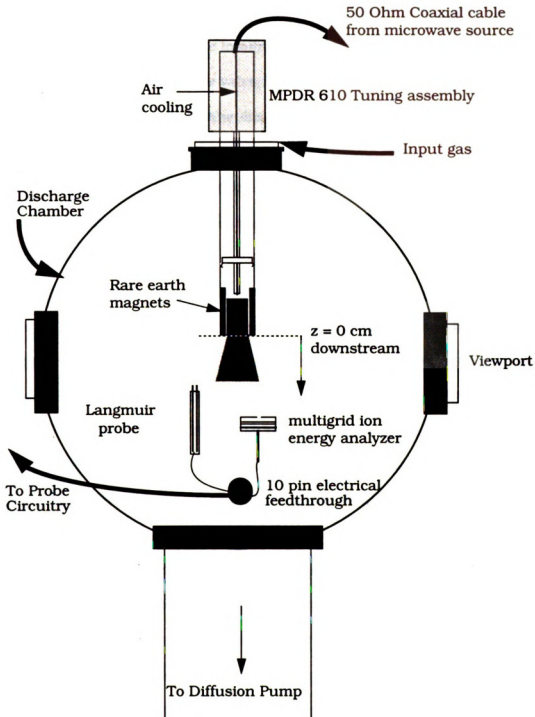


Figure 4.4 Top view of the vacuum chamber

The MPDR 610 may be mounted on any of the three ports. The $z > 0$ region is the downstream (processing) area, away from the discharge generation region.

The "roughing of the chamber" is done till the vacuum chamber pressure is about 100 mTorr, with the gate valve and foreline valve closed and only the roughing valve (10) open. The foreline is then "roughed" by closing the roughing valve and opening the foreline valve. Finally, the gate valve is opened to allow the diffusion pump to evacuate the chamber (final valve settings: gate valve open, foreline valve open, roughing valve closed).

At this point the chamber pressure decreases rapidly (if all seals are vacuum tight) due to the powerful action of the diffusion pump. The three valves (gate valve, roughing valve and the foreline valve) are all pneumatically controlled through a specially designed switch box, and require about 20 pounds per square inch (psi) of compressed air to operate. In case of loss of compressed air, the valves return to their default positions - the gate valve, for example, is normally closed and returns to that position if compressed air pressure drops. Note that the roughing valve and the gate valve must NEVER be open simultaneously due to the danger of oil being sucked out of the diffusion pump and into the vacuum chamber and the vent line. Normal base pressures under optimal pumping conditions were less than 10^{-7} Torr, meeting most UHV application requirements. Two thermocouples (15) and an ionization gauge tube (13) were used to track the pressures in the chamber, the foreline and in the diffusion pump stack respectively. Another ionization tube was later attached to the chamber and it was noticed that the pressure in the chamber is about twice that in the pump stack. All pressures reported in this dissertation are the pump stack pressures.

The diffusion pump stack is also equipped with a titanium sublimation pump (16) on the top to enhance pumping speed. However, due to the constant

requirement of liquid nitrogen for the sublimation pump, and the several drawbacks of sequestering pumps, the TS pump was never used while operating the vacuum station. The diffusion pump is filled with Krytox oil - a perfluoro polyether and the mechanical pump is filled with Fomblin. Both oils are expensive relative to normal pump oils, however they are more resistant to corrosive and reactive species like atomic oxygen, fluorine, etc.

The gas flow system is detailed in Figure 4.5(a) (not to scale). Gas flow into the MPDR 610 is controlled through an MKS 247C four channel readout/controller (21). Two MKS flow meters (22, 23) are installed, one with a maximum flow rate of 20 standard cubic centimeter (sccm) and the other with 50 sccm maximum flow. This allows for an accurate control at very low flow rates using the first flow meter, and an accurate higher flow rate using the second flow meter (or, if necessary an even higher flow rate if both flow meters are used simultaneously). Under molecular flow (as is the case for the mTorr range of operation for the 610), pressure conditions inside the vacuum chamber are controlled entirely by the gas flow rate due to the absence of a variable conductance valve. All components of this system are made of UHV compatible stainless steel. Flexible stainless steel bellows (25) with a 0.25 inch diameter connect the compressed gas bottles (through regulators) to the flow meters. Two needle valves (26), one on each side of the flow meter ensure isolation of the vacuum system in case of a leak in the bellows. The two lines then connect to a stainless steel "T" (24) that leads up to the single bellows which connect to the 610's stainless steel VCR gas feedthrough. This allows either flow controller to be used independently, or both to be used simultaneously to increase gas pressure, or for gas mixing.

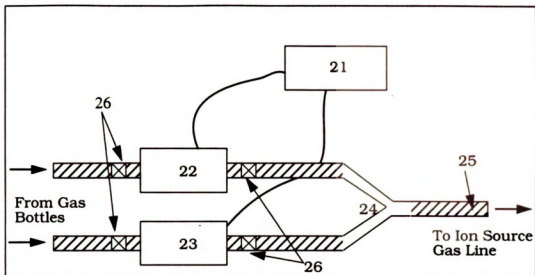


Figure 4.5(a) Gas Flow system for the YorkTown T vacuum station

21. 4 Channel MKS Readout
 22. 20 sccm Flow Controller
 23. 50 sccm Flow Controller
 24. Stainless steel T

25. Flexible 1/4 inch bellows (all shaded regions)
 26. Needle Valves

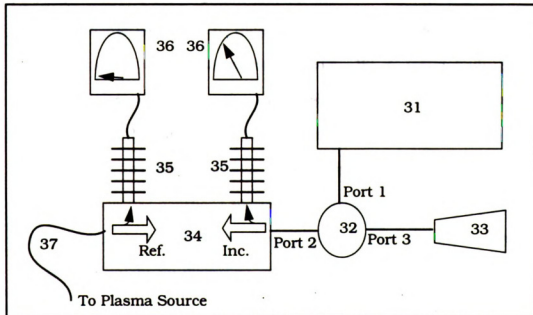


Figure 4.5(b) Microwave Apparatus for Ion Source Characterization

31. Microwave Power Supply
 32. Circulator
 33. Dummy Load
 34. Bi-Directional Coupler

35. Attenuators
 36. Power Meters
 37. 50 Ω Coaxial Cable

Several points of safety must be mentioned while using compressed gas cylinders. (1.) The regulator for each gas (or a set of gases like nitrogen and argon) is different from the other gases. This means that a nitrogen/argon regulator cannot be used for oxygen. This prevents an inadvertent use of an oxygen regulator on, say, a hydrogen bottle, that may cause an explosion if sufficient ratios of the two gases are mixed. (2.) All connections must be made with leak tight VCO or VCR metal fittings (stainless steel VCR fittings with nickel gaskets are used in the current vacuum system). This prevents contamination from the fittings materials like vacuum grease which might also cause insufficient base pressures due to severe outgassing.

(3.) Finally, hydrogen is a highly dangerous gas due to its explosive nature and extreme caution must be exercised while using this gas. It also has a property that with prolonged use, it will adsorb into the metal atomic lattice structure of the gas lines. If, then, the same gas line is used to run oxygen, conditions may be created for an explosion. When using hydrogen for long periods of time, the gas line must be flushed by running compressed nitrogen long enough so that any adsorbed hydrogen may be removed. Also, the exhaust of a hydrogen discharge (specially a high pressure hydrogen plasma that may contain hot reactive hydrogen species) must be flushed with adequate quantities of nitrogen gas before being emitted out. Compressed gas bottles are quite safe to use if the safety conditions are met. However, if the bottles are dropped, or mis-handled in any way, they may become explosive, and extremely dangerous high pressure missiles. As a rule, ALL safety precautions must be adhered to when using high pressure gas bottles and corrosive gases. Only some of the safety regulations are presented in this discussion, but further information on

these safety precautions may be obtained from the relevant OSHA authorities, or from the health and safety personnel of the laboratory.

4.4 Description of the Microwave Apparatus

The apparatus for transmitting electrical energy to the plasma source is now described. This setup, shown in Figure 4.5(b) remains essentially the same for most experiments, with minor modifications made for appropriate tests. Microwave energy is generated at a fixed frequency (or in a very narrow band close to the center frequency) of 2.45 GHz with the MicroNow™ 0 - 300 W power supply (31). A circulator (32) is attached to the output of the power supply. This is a three port network that shunts power from port one, to port two and from port two to port three. Port one of the circulator is connected to the power supply. Port two goes to the plasma source and so all the power out of the power supply is incident on the plasma source. Any power reflected from the source is incident on port two of the circulator, and is shunted to port three, which is connected to a matched dummy load (33) that completely absorbs this reflected power from the plasma source. In this manner, the magnetron of the power supply is protected from the power reflected back from the plasma source. In the case of high reflected powers, a cooling fan might be necessary to prevent the dummy load from burning out.

Between port two of the circulator and the plasma source, a NARDA bi-directional coupler (34), or two uni-directional couplers with proper attenuation (like the NARDA model 3330-20 with 20 dB attenuation) samples about 1% of the incident and reflected power which is measured on HP 435A power meters

(36). Since these power meters are limited to several mW maximum, the sampled power must be further attenuated. For example, the 20 dB ($\times 10^{-2}$) attenuation of the bi-directional coupler is further augmented by 30 dB attenuators (35). This 50 dB ($\times 10^{-5}$) attenuation allows 100 W to be registered on the power meters as 1 mW, allowing for accurate incident and reflected power measurement. Note that throughout this dissertation, "input" power is the difference between the incident and the reflected power.

A 50 Ω coaxial cable (37) with type N connectors and a Teflon dielectric filling material transfers power from the bi-directional couplers to the plasma source. The coaxial structure of the cable is continued into the source body, terminating in the loop antenna (9) shown in Figure 4.1. This loop excites the TEM mode in the coaxial cavity that stretches from the end of the sliding short (where the loop is attached) to the terminus of the center conductor, beyond which several evanescent EM modes are excited in the circular waveguide section of the source (refer, for example, to Chapter Six). Note that some amount of power loss in the bi-directional coupler and the coaxial cable is inevitable. Hence the net input power at the plasma source end is about 85% of the actual power indicated on the power meter's readout, and this is accounted for in all power levels stated in this dissertation.

4.5 Discharge Ignition in the 610

Once the 610 and the vacuum chamber has been evacuated to a sufficient base pressure (usually less than 10^{-7} Torr), the working gas is leaked into the plasma chamber of the 610 through the flow meters. An optional quartz,

or alumina "chimney" may be installed at the end of the quartz tube to channel the gas towards the ECR regions for easier ignition. Pressures of about 1 mTorr (plus or minus one decade of pressure) are best for discharge ignition in the 610, although the plasma generation is not a problem at even lower pressures. Once the pressure in the chamber has stabilized, microwave power is injected into the plasma source, and if the center conductor and sliding short positions are appropriately set, plasma ignition occurs with no problems. This initial ignition is accompanied by a high reflected power (up to 80%) - signifying that the ignition itself does not require too much power, and that once ignited, the plasma de-tunes the cavity. The plasma source must then be tuned to reduce this reflected power

This tuning of the source is done by adjusting the center conductor and sliding short positions such that the cavity dimensions are optimal for power to resonate in a manner best suited to energy transfer into the discharge gas. Heuristic experience shows that once the sliding short is accurately positioned, only the center conductor needs to be adjusted (less than a few mm) for plasma ignition and subsequent optimal tuning. As a corollary, the center conductor position may be fixed and tuning of the 610 done using the sliding short only. Indeed, commercial versions of the MPDR 610 that are sold by Wavemat, Inc. have a fixed center conductor position, with a micrometer control on the sliding short position. Both adjustments complement each other with the ultimate goal being to minimize the reflected power. Under normal operating pressures, once the 610 is tuned to optimal conditions, less than 5% of the incident power is reflected back to the circulator, and this reflected power is then shunted to the dummy load. However, in case of a discharge at extremely low pressure (less

than 10^{-5} Torr), the reflected power may increase to about 10 - 20%, and no amount of tuning is then able to reduce the level of reflected power.

Figure 4.6 shows the center conductor and sliding short assembly of the 610 (not to scale), along with the appropriate dimensions for a steady state argon discharge, where the plasma source has been tuned to minimum reflected power (usually less than 5% of the incident power). Note that the center conductor has to be pulled back about 2.5 cm from the quartz discharge confinement chamber - this is the length of the "evanescent circular waveguide" section of the source. The length of the coaxial section of the source is simply the length of the center conductor beyond the sliding short, and this is about 8.2 cm, about 0.67λ (λ being 12.24 cm for 2.45 GHz). These center conductor and sliding short positions are measured for an argon discharge. In Chapter Six, it will be seen that for a nitrogen discharge, the coaxial length of the source remains unchanged but the length of the evanescent circular waveguide changes in order to match the load of a nitrogen plasma. The 610 operations vary significantly for a nitrogen discharge from its operations in argon, and this will be verified in a later section of this chapter also. This implies that almost no inference may be made of the 610's performance in any other gas (specially diatomic gases) based on its operation in argon - a crucial conclusion considering that most plasma sources are characterized in argon (specially the reactors designed and characterized at the EE Plasma Research Laboratory), while most industrial applications of ion sources use gases other than argon - like nitrogen, oxygen or hydrogen.

A point needs to be made about the center conductor position relative to the discharge. Electric fields are launched off the end of the center conductor

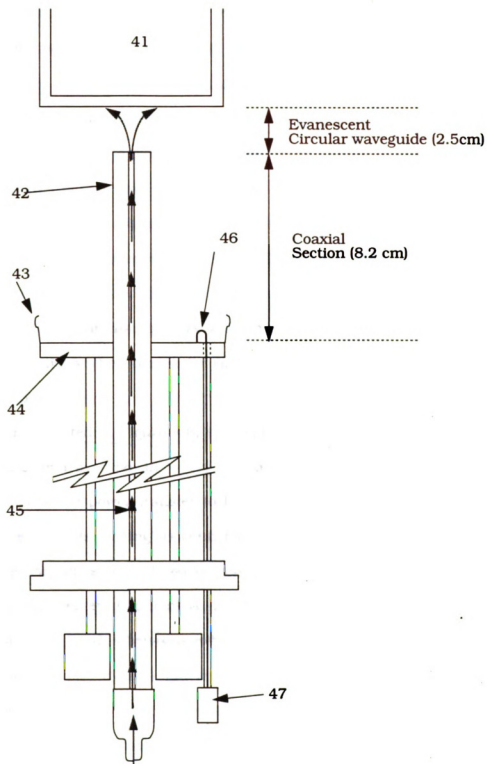


Figure 4.6 Sliding Short and Center Conductor Assembly (argon plasma)

41. Quartz (or
Alumina) Plasma
Chamber

42. Center
Conductor
43. Finger Stock

44. Sliding
Short
45. Air Cooling

46. Loop Antenna
47. Type N connec-
tor

where the coaxial section of the cavity terminates. To satisfy the boundary conditions at that point, several evanescent modes are set up in the 2.5 cm long circular waveguide section (since its diameter is too small for any propagating EM modes at 2.45 GHz). For these decaying modes, electric field strength should decrease exponentially as the distance from the center conductor increases (as will be verified in Chapter Six). It would seem appropriate then, that if the ignition and subsequent sustenance of the discharge is occurring through evanescent modes, the closer the center conductor to the quartz plasma chamber, the stronger the electric fields will be, and the easier it would be to couple power into the discharge. This was, in fact the thinking behind the original 610 operations when the center conductor was placed as close to the quartz tube as possible.

However, as noted in Figure 4.6, the center conductor has to be pulled away from the quartz tube in order to minimize reflected power (and subsequently maximize power transfer to the plasma). That power transfer is indeed increased by this "tuning" is confirmed by the measured output of the source, where ion density and saturation current density values go up dramatically as the center conductor is tuned to optimal operating position. A possible explanation for this behavior (where the source is more efficient with the center conductor pulled back) may be because the impedance of the coaxial section of the source must be matched to the plasma load. This matching is performed by the evanescent circular waveguide section of the 610. A more precise discussion on this topic is covered in Chapter Six, where the exact electric fields inside the 610 are inferred from direct measurement of the fields on the 610-a and a lumped circuit model of the 610 is proposed to explain the

operation of the source.

Due to electron-ion recombinations on the quartz walls that release energy, and also due to bombardment of energetic plasma species on the walls, much heat is deposited on the quartz. This is specially true for plasma conditions that generate highly energetic species (like high power discharges, or a very low pressure discharge where the electron temperature is comparatively higher). The quartz, and the surrounding magnets are cooled using a compressed air line that passes through the center conductor (as indicated by the shaded arrows in Figure 4.6). From the hot exhaust of this cooling gas, the body of the 610 also gets quite warm (40° to 50° C).

4.6 Operational Performance of the 610 - ARGON

The operational performance of the MPDR 610 for an argon discharge at 2.45 GHz is now presented. All characterization techniques are in accordance with the discussions of Chapter Three. Saturation current values are taken with a double Langmuir probe biased at negative 50 V. Figure 4.4 shows the $z = 0$ location, and the "downstream" region ($z > 0$) where the diagnostics are conducted. No probe or energy analyzer characterization is done for $z < 0$ positions (inside the quartz discharge confinement structure) so as not to perturb the generation of the plasma with the invasive diagnostic tools. Subsections 4.6.3 and 4.6.4 compare the measured parameters like ion density, electron temperature, etc. with some theoretically calculated values for a discharge similar to the MPDR 610.

4.6.1 Argon Ion Density Analysis

Figure 4.7 shows the transient behavior of an argon plasma. The saturation current data is taken 2 cm downstream (from $z = 0$ plane) for a 0.58 mTorr, 123 W discharge. As the source warms up (specially the quartz tube upon which heat is deposited through recombinations and collisions) and the pressure eddies within the generation region die down, the saturation current density attains its steady state value. While the data indicates some degree of fluctuation, the general trend of the best fit curve is obvious, as is the premise of this experiment: the plasma source must be allowed to stabilize and reach steady state before further experiments are conducted. During the course of this stabilization process, the plasma source has to be tuned several times to minimize the reflected power. This is because, after ignition, as the transients in the plasma load die down, the load itself changes its impedance and the tuning of the plasma source has to adjust accordingly to match this changing load. This re-tuning is usually very minor - less than a mm change in the center conductor (for a fixed sliding short) or the sliding short (for a fixed center conductor) position. Such a transient effect has been observed in other, larger MPDRs also (see for example, Figure 5.4 in Reference Hop-91).

Figure 4.8 shows the argon ion density variation with the discharge pressure for four different incident powers (164 W, 123 W, 82 W and 66 W) measured with a DLP located 2 cm downstream and centered on the z axis of the 610. At each data point, the 610 is perfectly matched - that is, each time the power or pressure is changed, the 610 is optimized to minimum reflected power. As mentioned before, the gas flow (bottom axis) alone controls the pressure (top

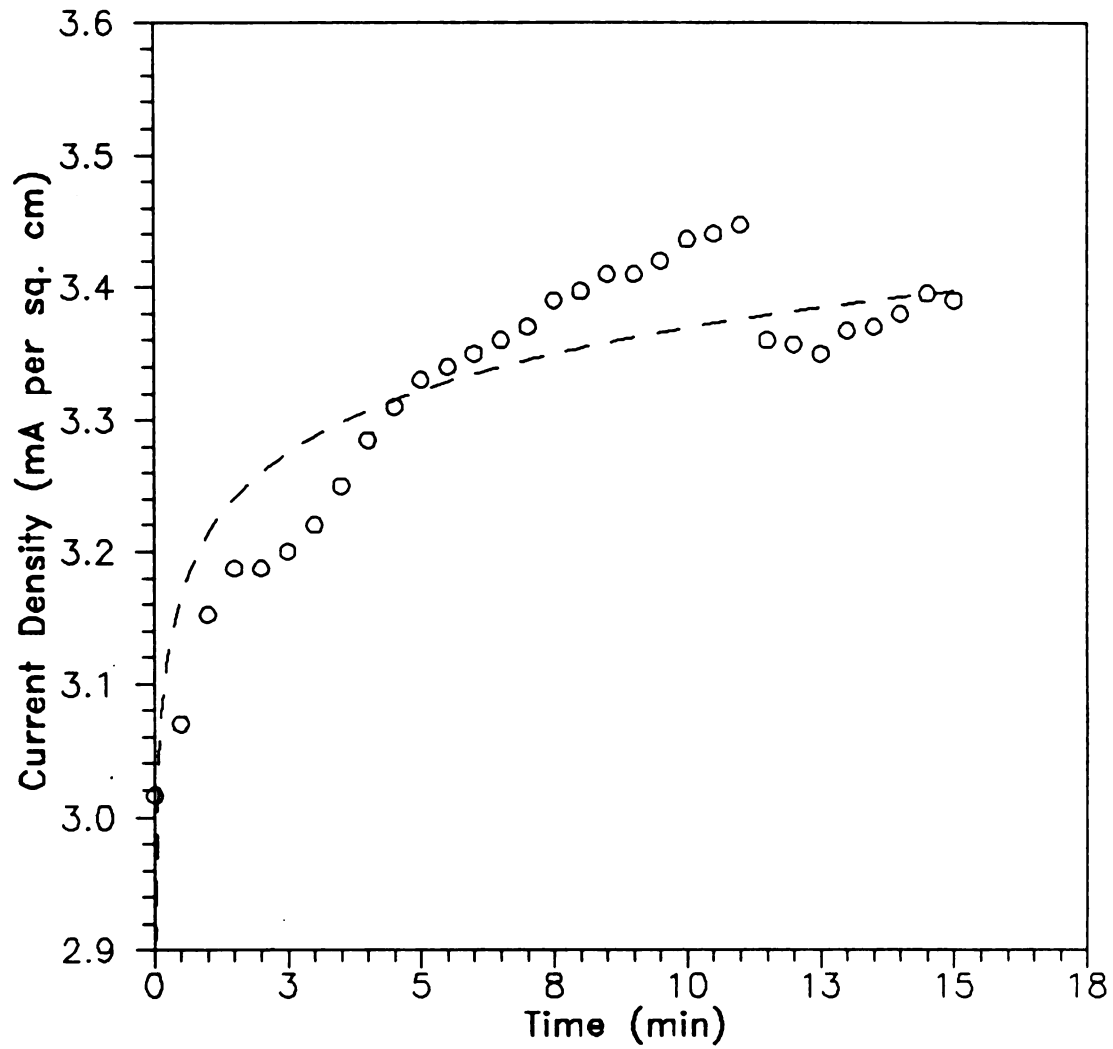


Figure 4.7 Transient Analysis of an argon discharge in the 610.
Incident power is 123 W and the pressure is 0.58 mTorr. Saturation current data are taken at negative 50 V bias.

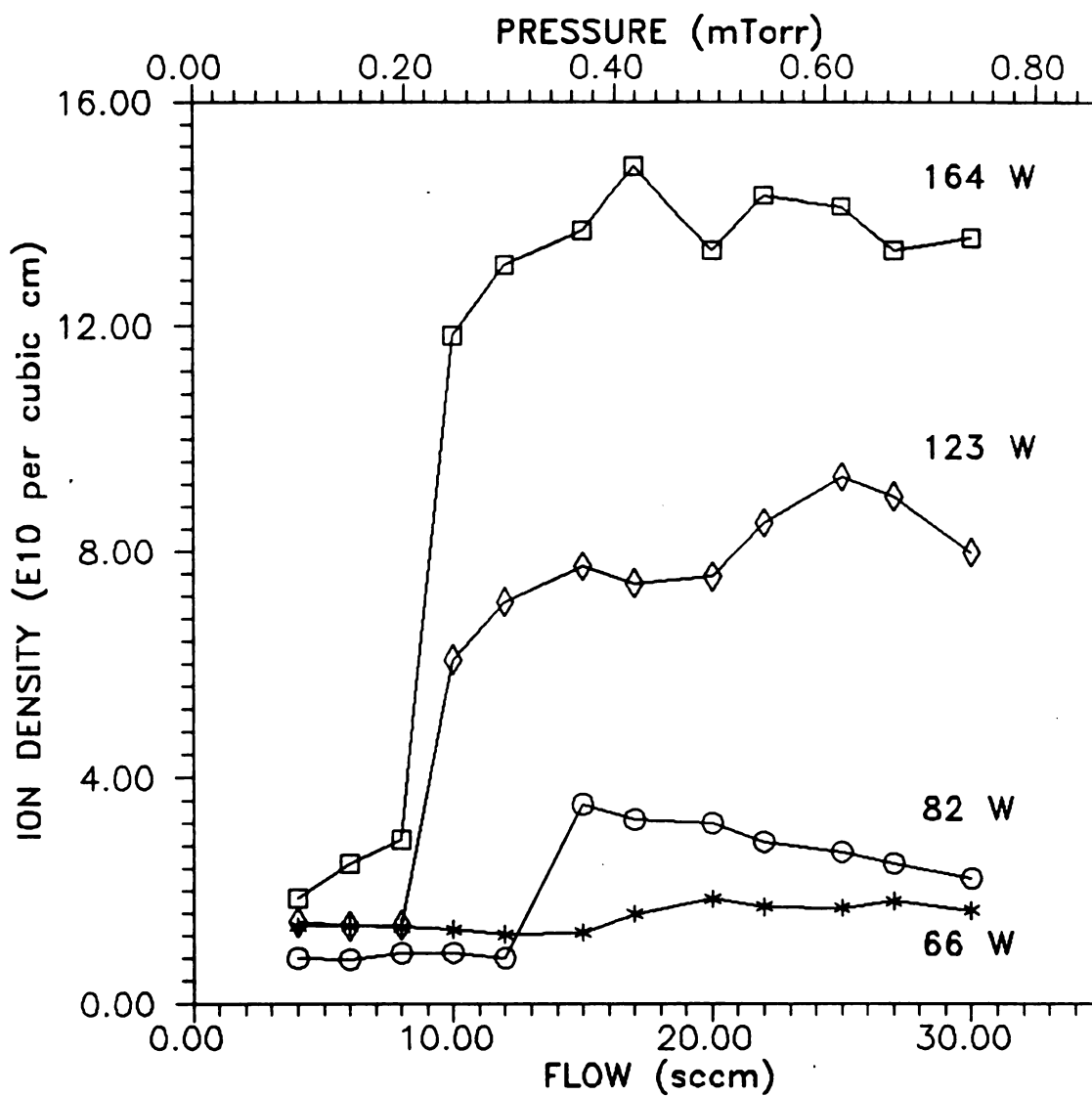


Figure 4.8 Argon Ion Density variation with Pressure.

Double Langmuir Probe data of ion density for four different power levels (164 W, 123 W, 82 W and 66 W). Note that the pressure conditions are dependent on flow rates.

axis) due to the absence of a variable conductance valve in the vacuum system. Several salient features of this figure need to be discussed. For any given power level, the plasma source exhibits a discontinuous "mode jump" as the pressure (and hence the neutral density) increases. The discharge pressure at which this jump occurs is dependent on the input power - the higher the power, the lower the pressure necessary for this change in mode. For example, this mode jump occurs at about 0.2 mTorr for the 164 W incident power curve, and at about 0.3 mTorr for the 82 W curve. The mode jump is accompanied by a change in the brightness of the discharge - the "high density mode" is much brighter than the "low density mode." A minor re-tuning (less than one mm variation in the center conductor position) is required to minimize the reflected power as the source changes its mode of operation.

Also note that the 610 is capable of producing very high ion densities, specially in the high density mode - this mode may produce up to 10 times the ion density (see the 164 W curve that maximizes at about $1.5 \times 10^{11} \text{ cm}^{-3}$) than the low density mode. This increase in brightness when the mode jump occurs suggests an increase in electron-neutral, or electron-ion collision frequency during which the electrons revert to lower energy levels while at the same time emitting energy, some of which is in the form of visible light. A hysteresis loop is observed in this mode jump whereby the ion source jumps to the high density mode at a higher pressure when the flow rate is increasing (from a low initial flow rate), while the source jumps down to the low density mode at a lower pressure when the flow rate is decreasing (from a high initial flow rate). At the center of this hysteresis loop, the 610 can exist at either of the two modes, depending on the initial conditions of the source. This ambiguous state of

operation is typically observed as an unstable plasma that flickers back and forth from the bright high density mode to the dimmer low density mode, accompanied by fluctuations in the amount of reflected power.

The discontinuous mode jump is unique to an argon discharge. This is seen in Figure 4.9 which compares the ion density dependence on pressure for argon and oxygen discharges. Again, data are taken with a DLP 2 cm downstream, for 164 W input power (for both argon and oxygen discharges). Within the range of pressure tested for the oxygen discharge, there is no evidence of the "mode jump." Also, as expected, the oxygen ion densities are much lower, ranging around 10^{10} cm^{-3} , compared to argon densities that can be as high as 10^{11} cm^{-3} in the high density mode. This may be in part because of the many more inelastic collisions and attachment processes that occur in an oxygen discharge, and also because of the higher ionization energies of oxygen. The large data point "error bars" used in this figure for the oxygen data indicate the two ion density extremes if all the oxygen ions in the plasma were either O^+ or O_2^+ . The actual ion density, which is expected to be made up of a mixture of the two species (atomic ions, or molecular ions), will fall somewhere in between the two extremes of the data error bars. Note that the pressure axis on the top corresponds to the argon data, and not the oxygen data - the two gases have different masses, and so a specific flow rate results in a different discharge pressure. The data reported in Figure 4.9 are based on the same flow rate for both the oxygen and the argon discharge.

It seems that knowing the operation characteristics of the plasma source for argon gas does not seem to give any indications to the 610's performance for an oxygen discharge, except perhaps the ease of operation of the 610 - the

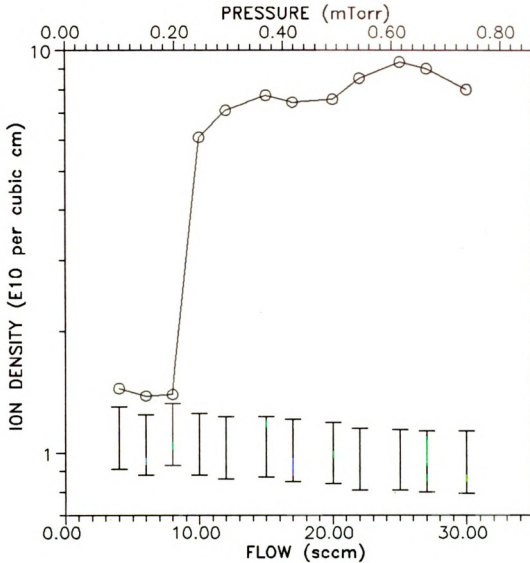


Figure 4.9 Ion density dependence for argon and oxygen pressure.

Double Langmuir Probe data of ion density for argon compared to that for oxygen. Data are taken 2 cm downstream for 123 W input power. Note the absence of the mode jump for oxygen plasma, as is evident for an argon discharge. The "data error bars" on the oxygen plasma signify atomic ions (O^+) or molecular ions (O_2^+). Top axis denotes pressure for argon discharge only, while bottom axis is the actual flow rate for both argon and oxygen discharges.

source showed no operational problems when the gas was switched from argon to oxygen. Only minor repositioning of the center conductor was required. This point will be re-enforced in a later section where the energy analysis is conducted for a nitrogen plasma.

Figure 4.10 shows the electron temperature dependence on pressure for two of the argon discharges of Figure 4.8 (2 cm downstream, 164 W and 82 W input power). These data are also taken with the DLP. As explained in Chapter Three, electron temperature data taken with a double probe is inherently flawed since the DLP only samples the high energy electrons that can pass through the negatively charged sheath on the surface of the probe. However, the general trends of the electron temperature variation is clear. For the 164 W curve, the temperature ranges from 65,000 C (about 5.5 eV) at low pressures to about 40,000 C (about 3.5 eV) at higher pressures - the average electron temperature decreases as the pressure increases.

The drop in electron temperatures may be because as the pressure decreases, so does the neutral density. Within a differential volume of a steady state discharge (in the generation region), the ionization rate must be balanced by the diffusion rate - that is, as the charged species diffuse out of this differential volume, there must be sufficient ionization to sustain the discharge. As the discharge pressure drops, the diffusion of charged species out of this differential volume increases, and hence the ionization rate within this volume must increase to compensate for this increased loss of charged species to sustain the discharge. This increase in ionization rate inherently predicates a higher electron temperature to sustain the plasma, and may indeed explain the depleted high energy tail of the electron energy distribution function of this

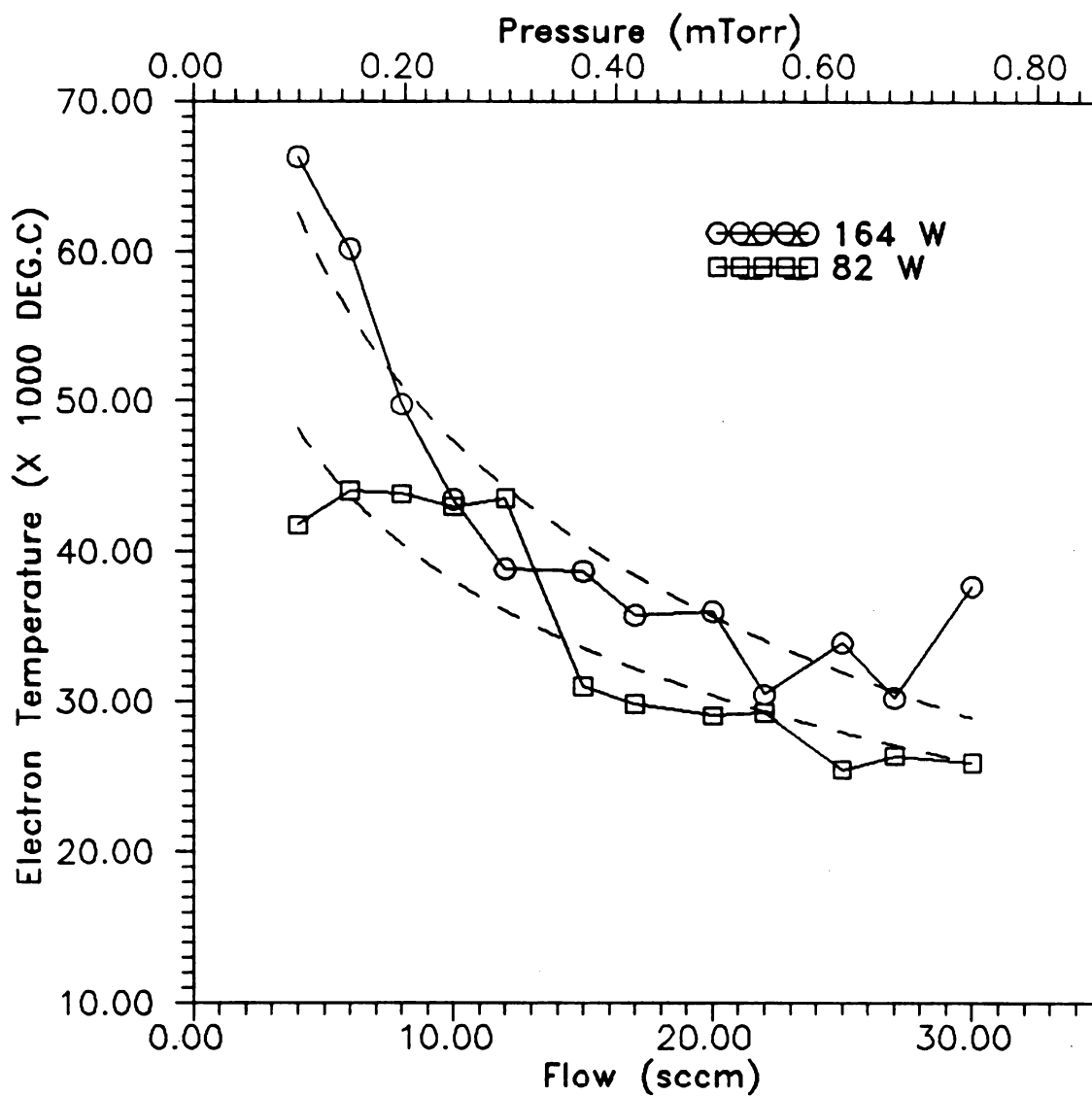


Figure 4.10 Electron Temperature variation with pressure

Double Langmuir Probe data for electron temperatures in an argon discharge as the pressure is varied. Data are taken 2 cm downstream, with 164 W and 82 W input power.

plasma source - see for example, Figure 4.15 where the high energy end of the measured EEDF drops below the theoretical Maxwellian distribution. This increase of electron temperature with decreasing pressure is in accordance with ambipolar diffusion of charged species out of the discharge generation region, for an electropositive, mostly singly ionized discharge like the argon plasma in the MPDR 610. This behavior has been observed in larger ECR ion sources also - as noticed in Figures 3.11 and 4.15 of Reference Mah-89a, and Figure 6.3 of Reference Sze-93a.

The second curve on Figure 4.10 shows the electron temperature variation with pressure for 82 W input power. At about 0.35 mTorr, where the ion density exhibits the mode jump (compare with the 82 W input power curve of Figure 4.8), the electron temperature jumps down from about 45,000 C to the low 30,000 C. So despite a four fold increase in the ion density, only a 1.5 times decrease is seen in the average electron temperature. This may be directly attributed to a large, discontinuous jump in the ion current density also when the plasma source goes through the mode jump. This saturation current variation with pressure is shown in Figure 4.11 According to Eqn. 3.14 (Chapter Three), the ion density is directly proportional to the saturation current, but inversely proportional to the square root of the electron temperature. So the four fold discontinuous change in the ion density may be attributed almost solely to the five fold discontinuous jump in the saturation current values, with only a minor change in the electron temperature. Hence the small "mode jump behavior" of the electron temperature compared to the ion density jump. This brings to light a very important point - due to the small dependence of the ion density on the electron temperature, the saturation current variation of the 610

argon discharge may be used as a rough qualitative assessment of its ion density variation in most cases.

The next two figures show the spatial variation of the saturation current. Figure 4.12 shows the radial position dependence of the ion saturation current at -50 V bias. Position 0 is the center axis of the ion source ($r = 0$, $z = 0$). Data are taken with a DLP for a 0.4 mTorr argon plasma at two different downstream positions - the solid lines at 1 cm downstream and the dashed lines at 3 cm downstream from the $z = 0$ plane. Also, the saturation currents are taken at two different powers (164 W indexed by circles and 123 W indexed by diamonds). At both downstream positions, the current density data indicates a strongly non uniform "Gaussian type" dependence for both power levels. A strong peak in the center tapers off as the probe is moved to the edge of the plasma source. While the current density at 3 cm downstream is seen to be about half of that at 1 cm, the radial profile is more uniform as the distribution of charged species "smears out" once they are within the large vacuum chamber and the chamber walls then control the diffusion rates.

Figure 4.13 shows the downstream variation of the argon ion saturation current density at two different pressure levels, with the input power being 123 W. Data are taken at the center axis ($r = 0$) of the ion source. Note the almost linear drop in the density on a semi-log scale. This indicates a rapid exponential decay of charged species as the distance from the plasma generation region ($z = 0$) increases. This is also observed in other gases, as is indicated in Figure 4.14 which shows the same linear fall of saturation current density with increasing downstream position for four different discharge gases (argon, hydrogen, nitrogen and oxygen).

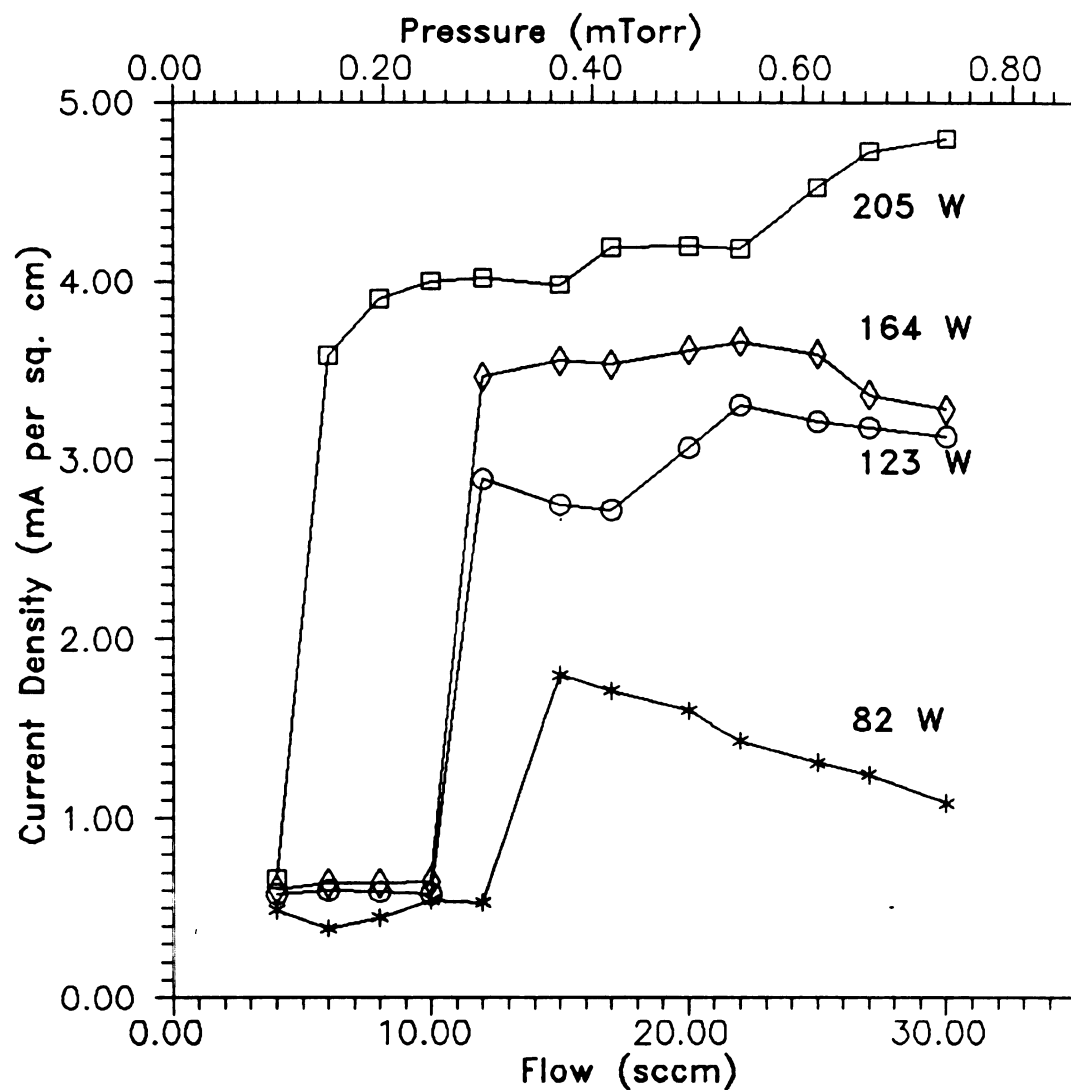


Figure 4.11 Ion saturation current variation with pressure

Double Langmuir Probe data for ion saturation current in an argon discharge as the pressure is varied. Data are taken 2 cm downstream for four power levels (164 W, 123 W, 82 W and 66 W). Probe bias is - 50V.

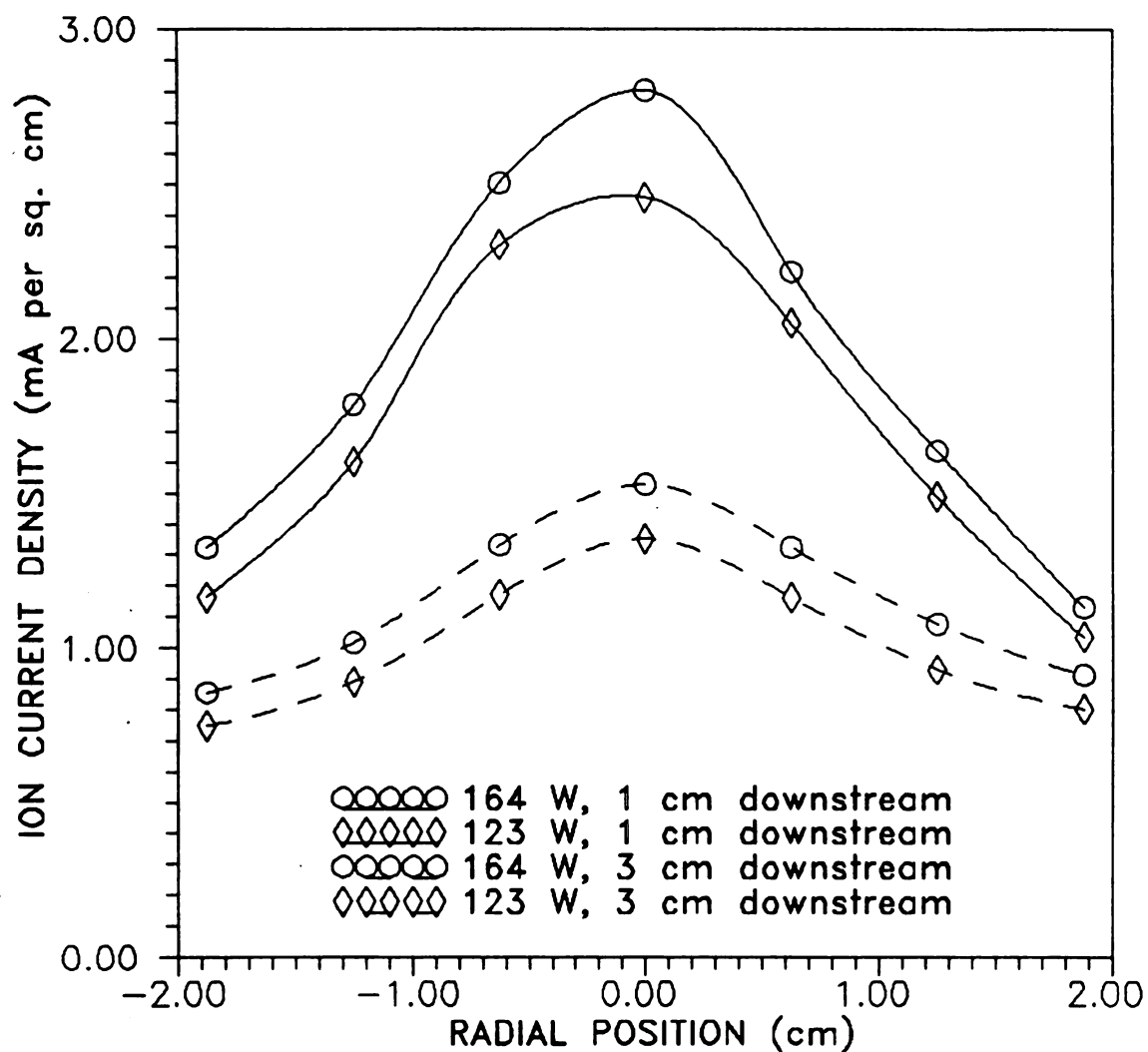


Figure 4.12 Ion saturation current variation with radial position

Double Langmuir Probe data for ion saturation current density in an argon discharge as the radial position is varied at $z = 1$ and $z = 3$ cm downstream. Data are taken for two different power levels (164 W and 123 W) for a 0.4 mTorr pressure.

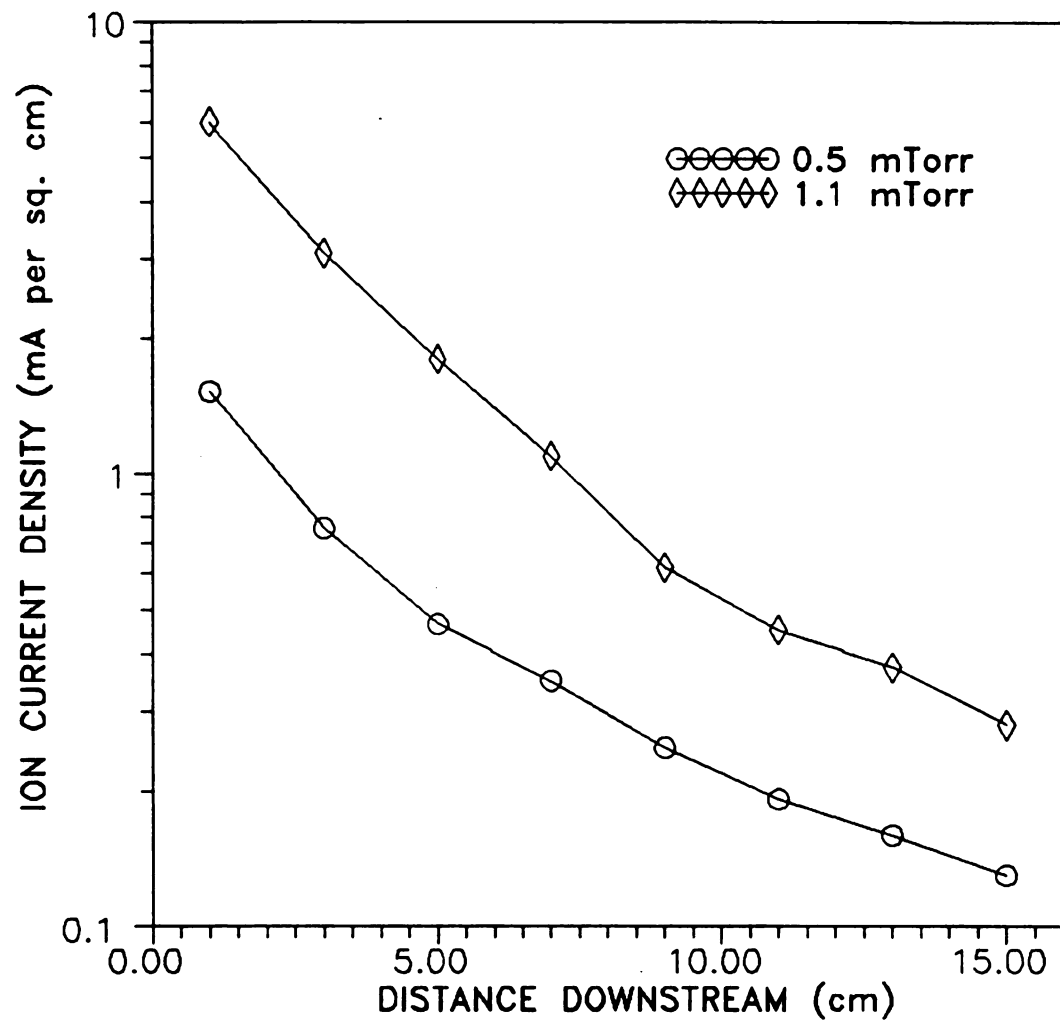


Figure 4.13 Ion saturation current variation with position downstream. Double Langmuir Probe data for ion saturation current in an argon discharge as the position downstream is varied. Data are taken for two pressures (0.5 mTorr and 1.1 mTorr), for a 123 W power level. The DLP is centered at the $r = 0$ position.

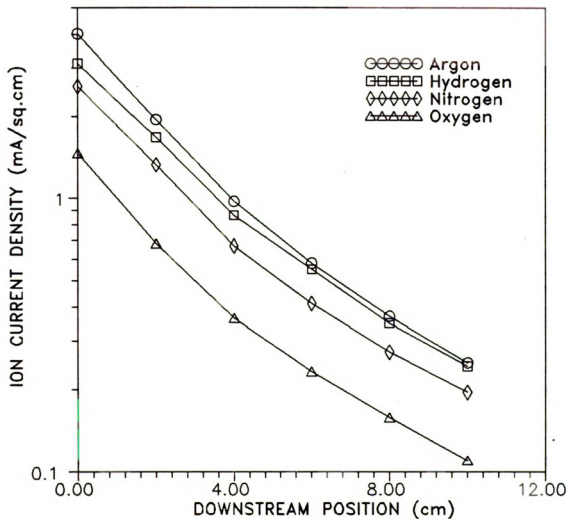


Figure 4.14 Ion saturation current variation with position downstream for four different discharge gases.

DLP data for ion saturation current for four gases is shown - argon, hydrogen, nitrogen and oxygen. Note the linear dependence of the saturation current with downstream position on the semi-log scale - this indicates an exponential decay in the charged species concentration.

Figures 4.12, 4.13 and 4.14 display the rapid decrease of charged species as the probes are moved away both radially ($z = 1, 3$ cm and $r = \pm 3$ cm) and longitudinally ($r = 0, z > 0$) from the source output. This rapid diffusion of the charged species is similar to density variations observed in larger ECR plasma sources also [Hop-88], and can be related to normal ambipolar diffusion processes within the large vacuum chamber outside of the discharge generation region ($z < 0$).

4.6.2 Argon Electron and Ion Energy Analysis

This section of the chapter is devoted to ion and electron energy measurements for an argon discharge at 2.45 GHz. All data are taken using a single Langmuir probe (for the electron energies) and a grounded ion energy analyzer (for the ion energies) in accordance with the techniques described in Chapter Three. Figure 4.15 is a typical electron energy distribution function for an argon discharge in the MPDR 610. This data is taken with an SLP located 2 cm downstream, for 123 W input power and a 20 sccm (equivalent to a 0.58 mTorr) discharge. Note that while the experimental curve follows the general trend of the Maxwellian distribution, it varies substantially from the Maxwellian distribution function and seems to better fit the Druyvesteyn function - a point that was brought up in Chapter Three while discussing SLP theory. Once the EEDF has been directly measured, the average electron energy is determined from Eqn. 3.17 (Chapter Three). The Maxwellian and Druyvesteyn theoretical curves are then plotted using this calculated average energy value. The plasma potential is the knee of the SLP I-V characteristics (see Figure 3.1, Chapter

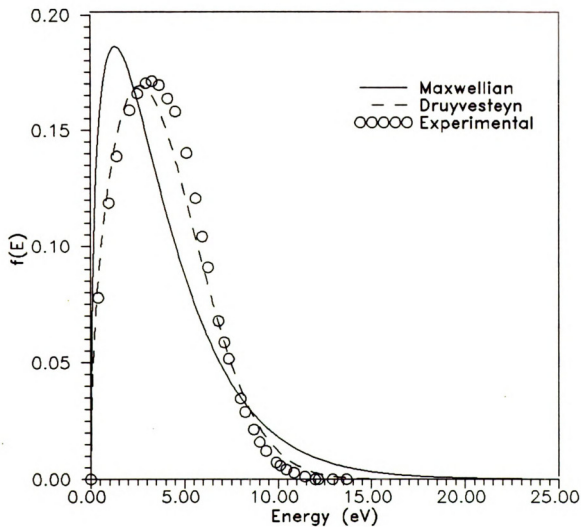


Figure 4.15 A typical EEDF for an argon discharge.

Single Langmuir Probe data, taken at 2 cm downstream for a 123 W input power, 20 sccm = 0.58 mTorr argon discharge. Note that the experimental curve varies somewhat from the Maxwellian and Druyvesteyn curves for the same average electron energy.

Three), and is therefore the local maximum of the d^2I/dV^2 curve. For Figure 4.15, the average electron temperature is about 3.9 eV (46,000 K), and the plasma potential is 11.2 V.

Note that using Eqn. 10.2.9 from Chapter Ten of Reference Lie-94, theoretical analysis indicates that for an average electron temperature of 3.9 eV in an argon discharge, the plasma potential should be approximately $4.7(3.9) =$ about 18.33 V. The discrepancy in the measured plasma potential value (11.2 V) and the analytical value calculated above may be due to two factors. First, theory assumes a Maxwellian distribution which is clearly not the case as may be seen from Figure 4.15. And second, the theory is accurate for a volume of discharge where diffusion and ionization losses are equal - that is, in the discharge generation region. Experimental data of Figure 4.15 was taken 2 cm downstream of the generation region, where there is no ionization. Another point about the experimental curve in Figure 4.15 is the evidence of a depleted high energy tail, which may be because the hot electrons are being used to ionize the gas and sustain the discharge, thereby cooling the overall temperature of the electron gas.

Variation of the plasma potential of an argon discharge with pressure is shown in Figure 4.16. As was seen in Figure 4.10, the electron temperature falls with increasing pressure - the plasma potential also decreases with increasing discharge pressure. These two figures of merit are in fact coupled together. The average electron temperature is a measure of the random kinetic energy of the electron gas. The plasma potential is set up inside the large stainless steel vacuum chamber (for $z > 0$ locations) when the more energetic electrons (compared to the ions' random kinetic energy) rapidly diffuse away to some

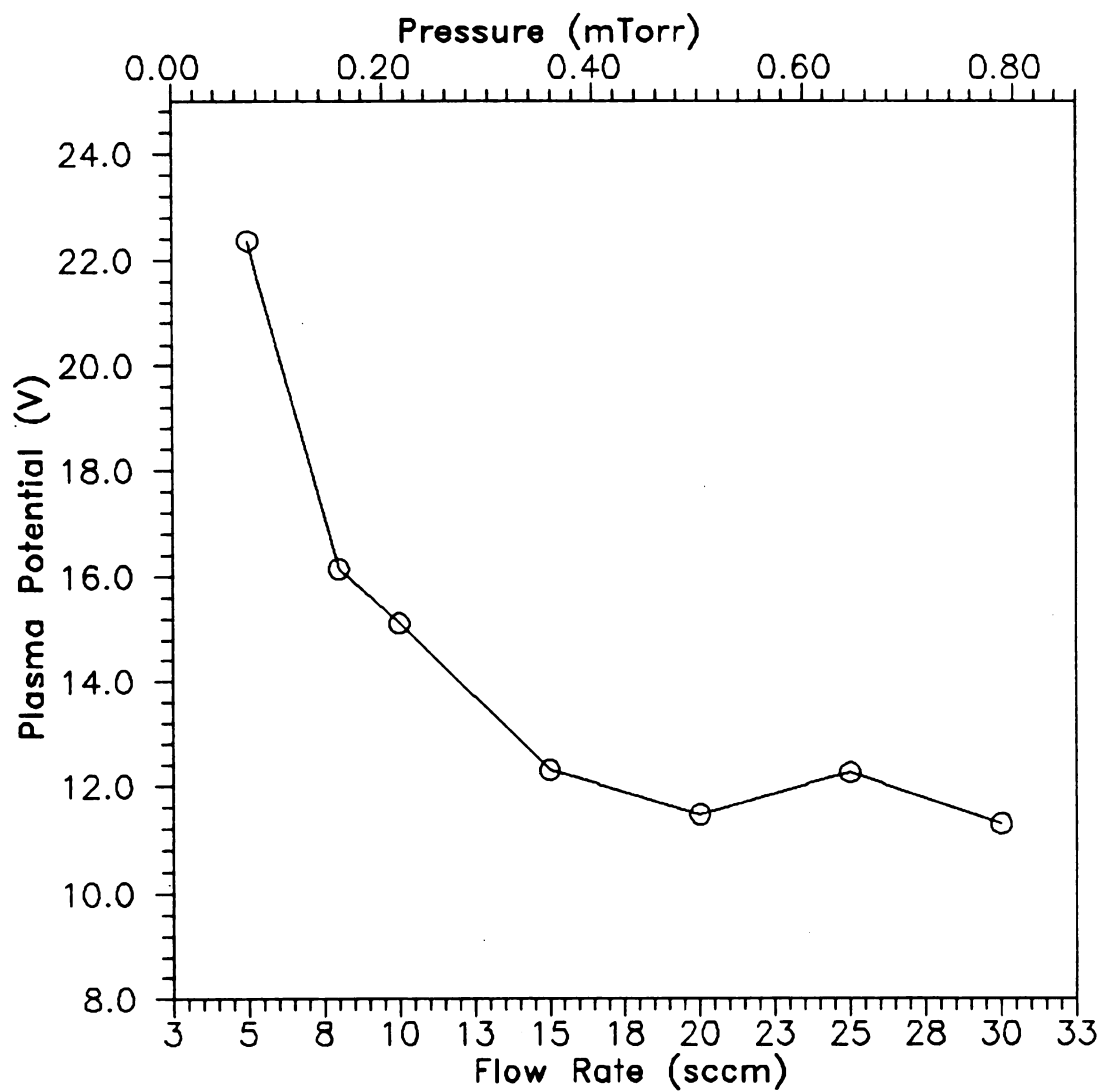


Figure 4.16 Argon Plasma potential variation with pressure.
Single Langmuir Probe data on plasma potential variation with the argon discharge pressure. Data are taken 2 cm downstream for 82 W input power.

conducting surface, like the vacuum chamber walls. At steady state, there is a potential set up to counter this separation of the electrons and ions, and retard the electron drift to the walls. This is known as the plasma potential. The electrons and ions then diffuse together through the vacuum chamber in the presence of this potential as dictated by typical ambipolar diffusion.

As the discharge pressure increases, the electron gas cools (which is seen in Figure 4.10 and is explained by the ionization-diffusion balance theory of Section 4.6.1) and the diffusion of the electrons to the chamber walls is reduced somewhat by their lower kinetic energy - hence the lower plasma potential at higher pressures. In general therefore, the plasma potential variation closely follows the electron temperature variation, which is in turn coupled to the average ion energies. This topic will be encountered again in the following sections that exhaustively discuss ion and electron energy distributions in a nitrogen plasma.

The next two figures show the ion energy distribution functions for an argon plasma as they vary with input power and discharge pressure respectively. Data were taken using the grounded multi-grid ion energy analyzer placed 2 cm downstream. Figure 4.17 shows the IEDF variation for different incident powers at a fixed pressure of 0.31 mTorr (with a corresponding gas flow of 15 sccm). As input power increases, the IEDF shifts to higher ion energies. The average ion energy changes from 16.57 eV at 82 W to 33.95 eV at 123 W, and to 41.51 eV at 164 W of incident power. The full width half maximum (FWHM) also increases from 8.5 eV to 10.3 eV, for a change in input power from 82 W to 164 W. Note that this is a large increase in average ion energies with increasing power, as compared to other (albeit larger) MPDRs - see for example,

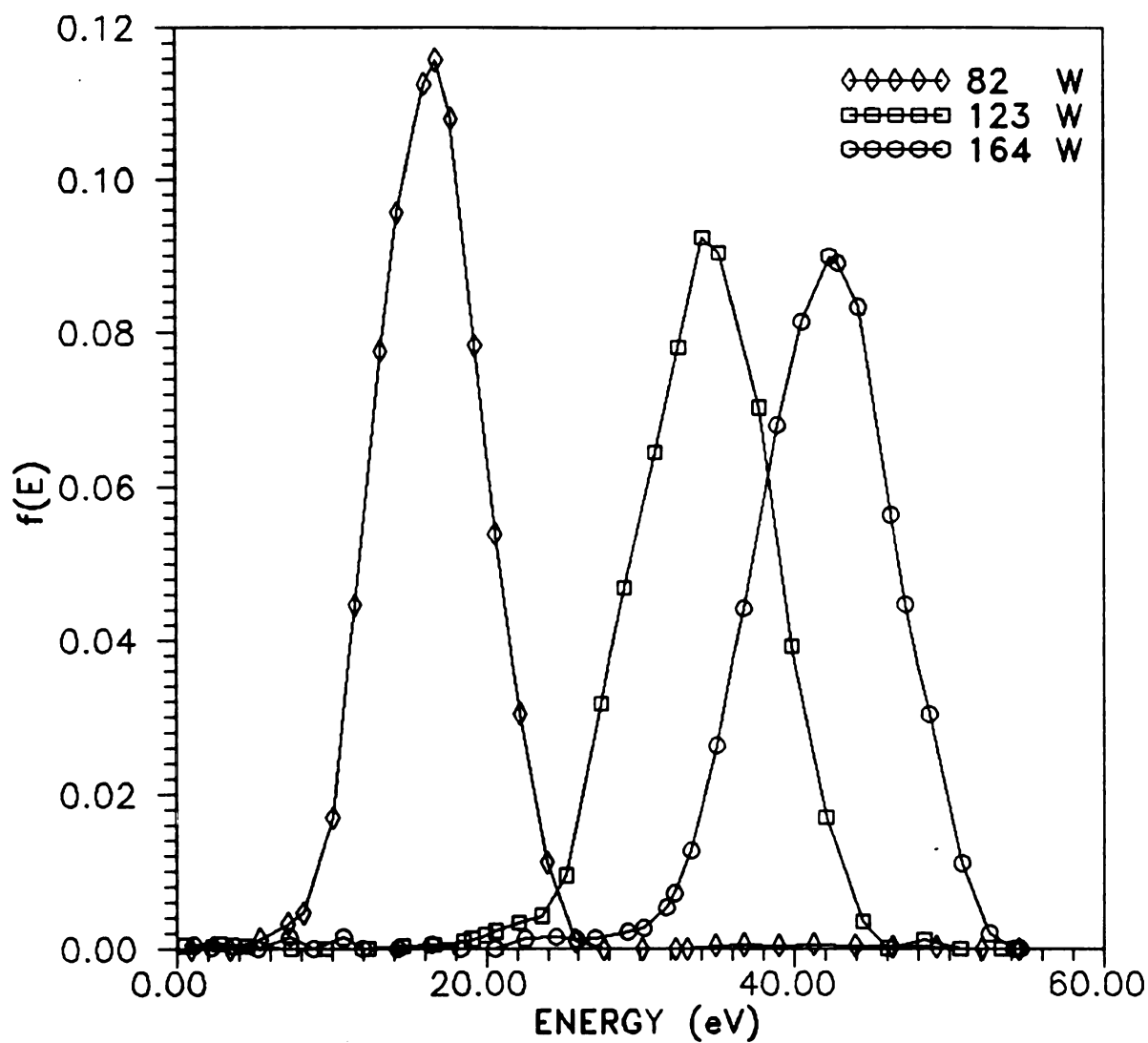


Figure 4.17 Argon IEDF variation with power.

IEDFs are taken with the ion energy analyzer 2 cm downstream for a 0.31 mTorr argon discharge for three input powers: 82 W, 123 W and 164 W. Note the shift towards higher energy as power is increased. Also, the FWHM increases with input power.

Figure 7.4 of Reference Hop-91. Such a large increase in average ion energies (and a corresponding shift of the IEDFs towards higher energies) as input power is raised means that the plasma potential (and therefore the electron temperature also) of the discharge is increasing as the input power is raised, since ions gain some directed energy by falling through the plasma potential set up in the vacuum processing chamber.

The pressure dependence of the IEDFs is seen in Figure 4.18. Over an argon pressure range of 0.24 mTorr to 0.72 mTorr, the FWHM changes from 9 eV to 11 eV, while the average ion energy drops from 35.57 eV to 30.85 eV. This may be explained in part by the decrease in plasma potential with increasing pressure, as was seen in Figure 4.16. While most of the directed energy of the ions may be attributed to the sheath potential formed over the surface of the ion energy analyzer, the ions gain further energy as they fall through the equipotential surfaces of the plasma potential. This was also mentioned above while discussing the ion energy variation with input power. Since this plasma potential decreases with increasing pressure, the ions gain lesser energy at higher pressures, hence the decreasing average ion energy with rising discharge pressures.

As the discharge pressure increases, the collision frequency of ions with other plasma species increases - which is indicated by the rise in the FWHM, which is a measure of the random (not directed) energy of the ions. The increase in FWHM is also observed when input power is raised - and this is known as gas heating. The decrease in ion energies with increased pressure has also been observed in larger ECR sources [Hop-91]. Figures 4.17 and 4.18 are indicative that the 610 can produce low average energy ions with narrow and peaked ion

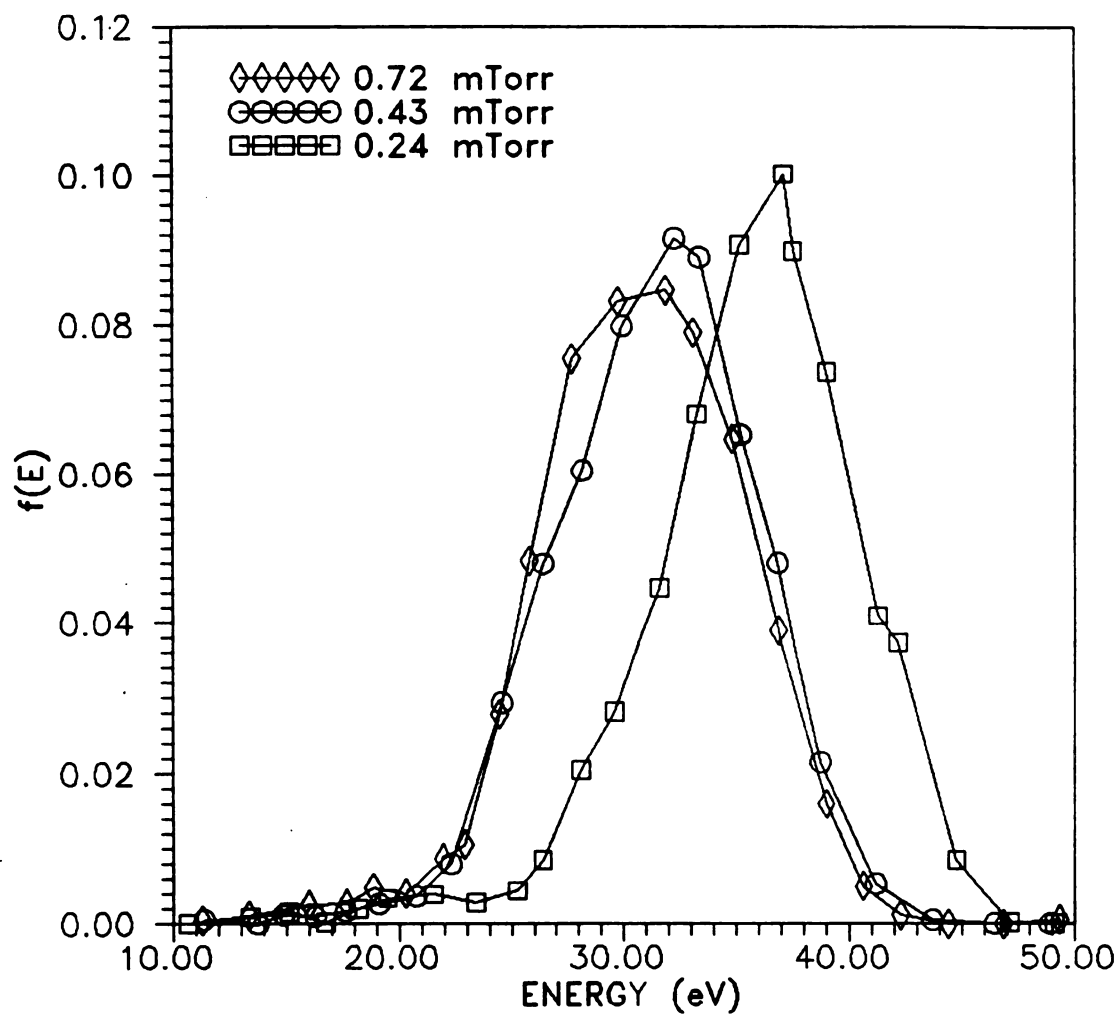


Figure 4.18 Argon IEDF variation with pressure.

IEDFs are taken with the ion energy analyzer 2 cm downstream for 123 W argon discharge for three pressures: 0.72 mTorr, 0.43 mTorr and 0.24 mTorr. Note the shift towards lower energy as pressure is increased. Also, the FWHM increases as pressure goes up.

energy distributions which may be controlled by power and pressure variations, or with the application of DC or RF bias to the substrate [Hop-90a].

4.6.3 Comparison of Measured Data with Theoretical Predictions

Theoretical analyses predicting the behavior of gas discharges have been covered in several books. One of the more important theories that arise out of these analyses is that about the diffusion of charged and neutral species within and out of the discharge chamber. Following the concepts of diffusion theory introduced in Reference Lie-94, some calculations may be done to predict the operational performance of an argon discharge similar to the MPDR 610. As will be seen, the calculations generate results that are the same order of magnitude (or close) when compared to the measured characteristics discussed in Sections 4.6.1 and 4.6.2, and provide a useful ratification of the measured data with theory. Several new terms will be used during these calculations, and a brief nomenclature of these terms is now presented.

The discharge generation region simulated in these calculations is cylindrical with a length (l) of 4.7 cm and a radius (R) of 1.8 cm - both these dimensions correspond to the quartz cup of the MPDR 610. The pressure of the discharge (P) is 1.0 mTorr. The discharge gas temperature (T_g) is 450 K - an approximation. The progression of this calculation is as follows: the neutral gas density (n_g) for the above temperature and pressure is calculated followed by calculation of the ion mean free path (λ_i) which is dependent on the discharge pressure. The "effective plasma size" as defined by Lieberman (d_{eff}) is calculated, based on two parameters corresponding to the radial and axial diffusion (h_r and

h_l respectively). These parameters ("fudge factors") are necessary for closed form solutions for the complex equations arising out of the diffusion theory that fits the pressure regime of the MPDR 610. Here, h_l is defined as the ratio of the density at length $l/2$ to that at the center, while h_r is defined as the ratio of the density at radius R to the density at the center. The first set of calculations conducted in this section will have both radial and axial losses through diffusion. However, for the MPDR 610, where magnetic fields prevent some amount of radial losses, another set of calculations will be conducted with zero radial diffusion losses. This limiting case may be simulated by setting h_r to zero, i.e. the ion density at radius R is zero.

The electron temperature (T_e) of the discharge is then predicted using Figure 10.1 of Reference Lie-94 from the product of the effective diffusion length and the neutral gas density ($n_g \cdot d_{eff}$). This T_e may then be used to approximate the plasma potential (V_p) and the average ion energy (E_i) of the discharge. For the calculation of the ion density, several other sub-calculations must first be conducted. The total energy lost to the discharge (E_l) is first calculated - a sum of the collisional energy (E_c , estimated from Figure 3.17 of Reference Lie-94) required for the production of an ion-electron pair, twice the electron temperature ($2 \cdot T_e$) and the ion energy (E_i). The Bohm velocity (u_B), which is the ion velocity at the plasma sheath is then calculated, as is the effective area of diffusion (A_{eff}). The ion density (n_i) is then calculated taking into account the actual power absorbed within the discharge, the Bohm velocity, the effective area of diffusion loss and the total energy absorbed by the discharge.

For a specific gas temperature and pressure, the neutral gas density (n_g) may be calculated using the density at 1 mTorr, which is $3.3 \times 10^{19} \text{ m}^{-3}$. At 1.0

mTorr and 450 K, n_g is calculated to be $3.3 \times 10^{19} \times \frac{298}{450} \approx 2.18 \times 10^{19} \text{ m}^{-3}$.

The ion mean free path (λ_i) is dependent on the pressure and is given by:

$$\lambda_i = \frac{1}{330P} \text{ cm}, \quad (4.1)$$

where P is the discharge pressure in Torr. From this equation, the mean free path for a 1.0 mTorr pressure is about 3 cm.

The two parameters that correspond to the radial and axial diffusion of charged species out of the generation region - h_r and h_l respectively, are dependent on the ion mean free path and the dimensions of the discharge chamber. Following Reference Lie-94, the coefficients may be approximated as:

$$h_l \approx 0.86 \left(3 + \frac{l}{2\lambda_i} \right)^{-1/2} \text{ and} \quad (4.2)$$

$$h_r \approx 0.8 \left(4 + \frac{R}{\lambda_i} \right)^{-1/2}. \quad (4.3)$$

For the length, radius and ion mean free path used in this calculation, h_r is about 0.37 and h_l is 0.44.

Then the effective plasma size (d_{eff}) is given by:

$$d_{eff} = \frac{1}{2} \cdot \left(\frac{Rl}{Rh_l + lh_r} \right) \text{ m}. \quad (4.4)$$

When the appropriate numbers are substituted, the value of d_{eff} is calculated to

be 1.67 cm, or 1.67×10^{-2} m.

The electron temperature of such a discharge (with the given dimensions, at the given pressure and neutral gas density, and with the appropriate diffusion characteristics) is plotted versus the product of the gas density (n_g) and the effective plasma size (d_{eff}) in Figure 10.1 of Reference Lei-94. This product ($n_g \cdot d_{eff}$) is calculated to be about $2.18 \times 10^{19} \cdot 1.67 \times 10^{-2} \text{ m}^{-2}$ or, $3.64 \times 10^{17} \text{ m}^{-2}$.

Then from Figure 10.1 of Reference Lei-94, the estimated electron temperature (T_e) is about 8 V (or eV). Note that some extrapolation of the curve in Figure 10.1 is necessary, since this curve has a limited range on the abscissa.

The plasma potential V_s is then estimated by the following:

$$V_s \approx 4.7 (T_e) \text{ V} \quad (4.5)$$

And the average ion energy E_i is estimated as:

$$E_i \approx 5.2 (T_e) \text{ V} \quad (4.6)$$

For T_e equal to 8 V, V_s is calculated to be about 37.6 V, while the ion energy is about 41.6 V.

The energy lost to collisions (E_c) for each ion-electron pair that is created may be approximated from Figure 3.17 of Reference Lei-94 that plots E_c versus T_e . From this figure, E_c is about 28 V for the 8 V T_e .

As mentioned earlier, the total energy being absorbed by the plasma (E_t) is then given by the following equation:

$$E_t = E_c + 2T_e + E_i \text{ V} \quad (4.7)$$

Using the numbers from above, E_t is calculated to be about 85.6 V.

The Bohm velocity of ions (u_B) is now calculated:

$$u_B = \sqrt{\frac{eT_e}{m}} \text{ m/s} \quad (4.8)$$

which for argon may be reduced (using the electron charge e , and the ion mass for argon m) to

$$u_B = 1.545 \times 10^3 (T_e)^{-1/2} \text{ m/s.} \quad (4.9)$$

For the given electron temperature (about 8 V), the Bohm velocity is about $4.37 \times 10^3 \text{ m/s}$.

The effective area through which the diffusion losses occur, (A_{eff}) must now be calculated. This is necessary because the value of the ion density at the sheath edge may be different for the radial and axial sheaths. This is given by:

$$A_{eff} = 2\pi R (R \cdot h_l + l \cdot h_R) \text{ cm}^2 \quad (4.10)$$

For the appropriate dimensions and diffusion coefficients, is calculated to be 28.62 cm^2 , or $2.862 \times 10^{-3} \text{ m}^2$.

From Chapter Six, it will become apparent that 87% of the input power is actually absorbed by the plasma (the remaining 13% is lost to the walls, and the loop antenna). For 123 W input power (a common power level for the 610 experiments), this gives P_{abs} of about 107 W. The ion density (n_i) may then be calculated:

$$n_i = \frac{P_{abs}}{eu B^A_{eff} E_t} \text{ m}^{-3}. \quad (4.11)$$

For the appropriate substitutions, this gives the ion density to be about $6.24 \times 10^{17} \text{ m}^{-3}$, or $6.24 \times 10^{11} \text{ cm}^{-3}$.

Note that the calculations above assume that there is no confinement of charged species. With the multi-cusp magnetic field structure of the MPDR 610, there is bound to be some radial confinement of electrons. To simulate this radial confinement, all the above calculations may be conducted in the limit of zero radial loss (complete radial confinement), by setting h_r to zero. This essentially means that the ion density at radius R is zero.

For such a case, Eqn. (4.4) gives $d_{eff} \approx \frac{l}{2h_l}$ which is calculated to be about $5.34 \times 10^{-2} \text{ m}$. The product of this effective plasma size and neutral gas density is $n_g \cdot d_{eff} \approx 1.16 \times 10^{18} \text{ m}^{-2}$, and the electron temperature for this product from Figure 10.1 or Reference Lei-94 is estimated to be about 5.2 eV. Note that unlike the previous calculation, no extrapolation of the curve in Figure 10.1 is needed

for this case. For this T_e , the plasma potential V_s is then about 24.4 V from Eqn. (4.5), and the average ion energy is about 27.04 V from Eqn. (4.6). The collisional loss energy E_c is about 31 V from Figure 3.17 of Reference Lie-94, and the total energy loss E_t is about 68.4 V from Eqn. (4.7). The Bohm velocity for this electron temperature is calculated from Eqn. (4.9) to be about 3.5×10^3 m/s and the effective area of diffusion loss $A_{eff} \approx 2\pi R^2 h_l$ is calculated to be about 8.96×10^{-4} m². The ion density may then be calculated from Eqn. (4.11). It is seen that for zero radial losses, $n_i = 3.12 \times 10^{18}$ m⁻³, or 3.12×10^{12} cm⁻³.

4.6.4 Discussion of Theoretical and Measured Data

The theoretical calculations of Section 4.6.3 are now compared with the measured data for an argon discharge in the MPDR 610. To recapitulate, the above calculations are for a 1.0 mTorr argon discharge of dimensions similar to that of the 610, with an approximate neutral gas temperature of about 450 K and with 123 W input power. Table 1 below compares three sets of data. The measured data in column three are numbers that are approximated for 123 W input power and 1.0 mTorr discharge pressure from figures presented in Sections 4.6.1 and 4.6.2 - ion density data from Figure 4.8, electron temperature data from Figure 4.10, plasma potential data from Figure 4.16, and the ion energy data from Figure 4.18. Note that these numbers are approximated because data presented in Figures 4.6.8, 4.6.10, 4.6.16 and 4.6.18 are for different operating conditions than the calculated data.

Table 1: Comparison of theory and measured data

	Theoretical, with radial diffusion losses	Theoretical, with no radial diffusion losses	Measured data (taken 2 cm downstream)
$n_e (10^{11} \text{ cm}^{-3})$	6.24	31.2	0.8
$T_e (\text{V})$	8	5.2	3
$V_s (\text{V})$	37.4	24.4	12 - 14
$E_i (\text{V})$	41.6	27.04	28

Several things need to be discussed in the above table. First, the numbers of the actual measured data correspond well with the theoretical predictions of the first two columns. The discrepancy between the theoretical predictions (with or without radial losses) and the measured data may be directly attributed to the fact that the theory used to predict the numbers of the first two columns is valid only where the ionization, and diffusion losses balance each other - that is, in the discharge generation region. The measured data are taken at 2 to 3 cm downstream from this generation region, so an exact match in numbers is not to be expected.

As seen from Figures 4.13 and 4.14, the ion saturation current density falls exponentially as distance downstream increases - such an exponential fall is also expected for the ion density variation with downstream distance, and hence the ion density at 2 cm downstream should be well below that predicted in the generation region. If this 2 cm downstream data is extrapolated up to the discharge generation region, the ion density is seen to be in the mid 10^{11} cm^{-3}

range - much closer to the theoretical calculations. A similar argument may be made to explain the discrepancies in electron temperature, plasma potential and the ion energy numbers compared in the three columns above. It is therefore observed that the theoretical developments of Lieberman/Lichtenberg (Reference Lie-94) come close to accurately predicting the behavior of an argon discharge in the MPDR 610 and may indeed be used in the future as the basis for active source design and development.

4.7 Operational Performance of the 610 - NITROGEN

When the ion density variation with gas flow (and hence pressure) was discussed in Figure 4.9, the difference between the 610's performance in argon was strikingly contrasted with its performance in oxygen. No mode jump is exhibited by the plasma source for an oxygen discharge in the range of gas flow that was tested, while this jump is a significant aspect of the argon ion density variation with pressure. The 610 seems to operate differently for diatomic gases. To test this further, exhaustive energy analysis was conducted with nitrogen as the working gas. Nitrogen was chosen because of its importance in the nitrating experiments on semiconductor applications (such as epitaxial growth of GaN or AlN), as is evidenced by the 1992 Workshop on Wide Bandgaps, where some of the nitrogen energy data obtained for the MPDR 610 were presented [Asm-92]. In the next two sub-sections, the dependence of the average electron and ion energies, and the IEDFs on input power, discharge pressure of a nitrogen discharge are presented. The downstream variation of the energies is also discussed. The energy analysis of a nitrogen discharge is then contrasted with

the argon energy measurements that were presented in Section 4.6.2.

4.7.1 Nitrogen Electron Energy Analysis

Figure 4.19 is a typical EEDF of a nitrogen plasma. Note the similarity between this, and Figure 4.15 which is an EEDF of an argon discharge. As before, the theoretical Maxwellian and Druyvesteyn distribution functions are also plotted. Data is taken with an SLP placed 5 cm downstream, with 164 input power, and at 25 sccm (with a corresponding 0.25 mTorr pressure). Again, it is seen that the experimental EEDF fits the Druyvesteyn distribution better than the Maxwellian distribution.

The pressure dependence of the average electron energy (dashed curve, on right Y axis) and plasma potential (solid curve, left Y axis) for the nitrogen discharge are shown in Figure 4.20. Data are taken at 123 W input power, 5 cm downstream. Both the plasma potential and average electron energy increases with increasing pressure, with the former increasing more strongly than the latter in the range of pressures tested. As a direct contradiction, Figures 4.9 and 4.16 are the electron temperature (or average electron energy) and plasma potential variation with pressure for an argon discharge, both of which decrease with increasing pressure.

In larger ion sources, the electron energy remains mostly constant with increasing input powers [Hop-91]. This is seen to be true for the nitrogen discharge in the 610 also, as is evident from Figure 4.21, where the discharge pressure is kept constant at 25 sccm flow, 0.25 mTorr, but the input power is varied. Data are taken with the SLP 5 cm downstream. While the average

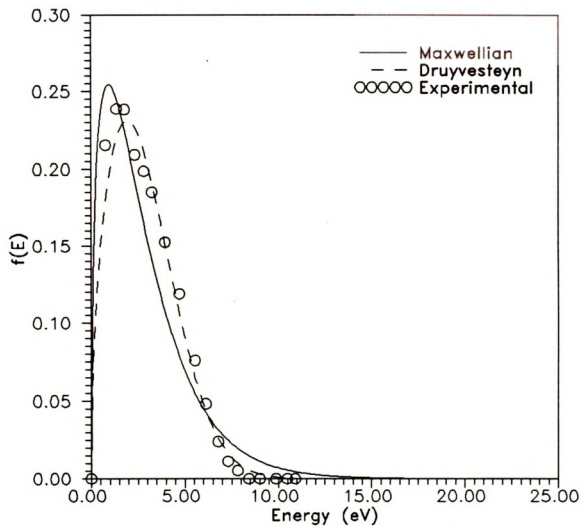


Figure 4.19 A typical EEDF for a nitrogen discharge

Single Langmuir Probe data, taken at 5 cm downstream for a 164 W input power, 25 sccm, 0.25 mTorr argon discharge. Note that the experimental curve matches better with the Druyvesteyn distribution function than with the Maxwellian curve.

Plasma potential (V)

Fl
Sing
pow
plas

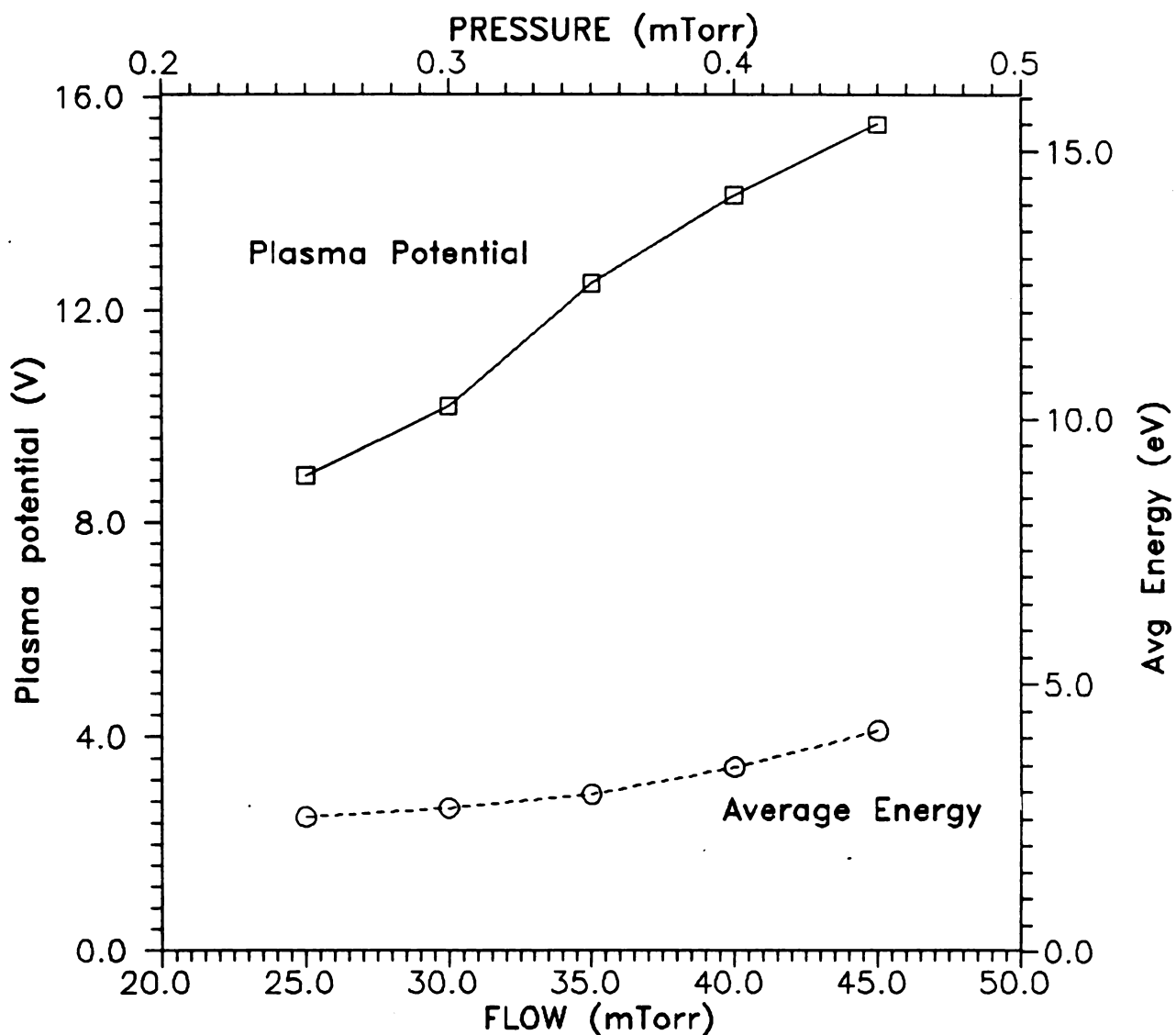


Figure 4.20 Nitrogen electron energy and plasma potential variation with pressure

Single Langmuir Probe data for a nitrogen discharge, taken at 123 W input power, 5 cm downstream. Note the increase in average electron energy and plasma potential with increasing pressure.

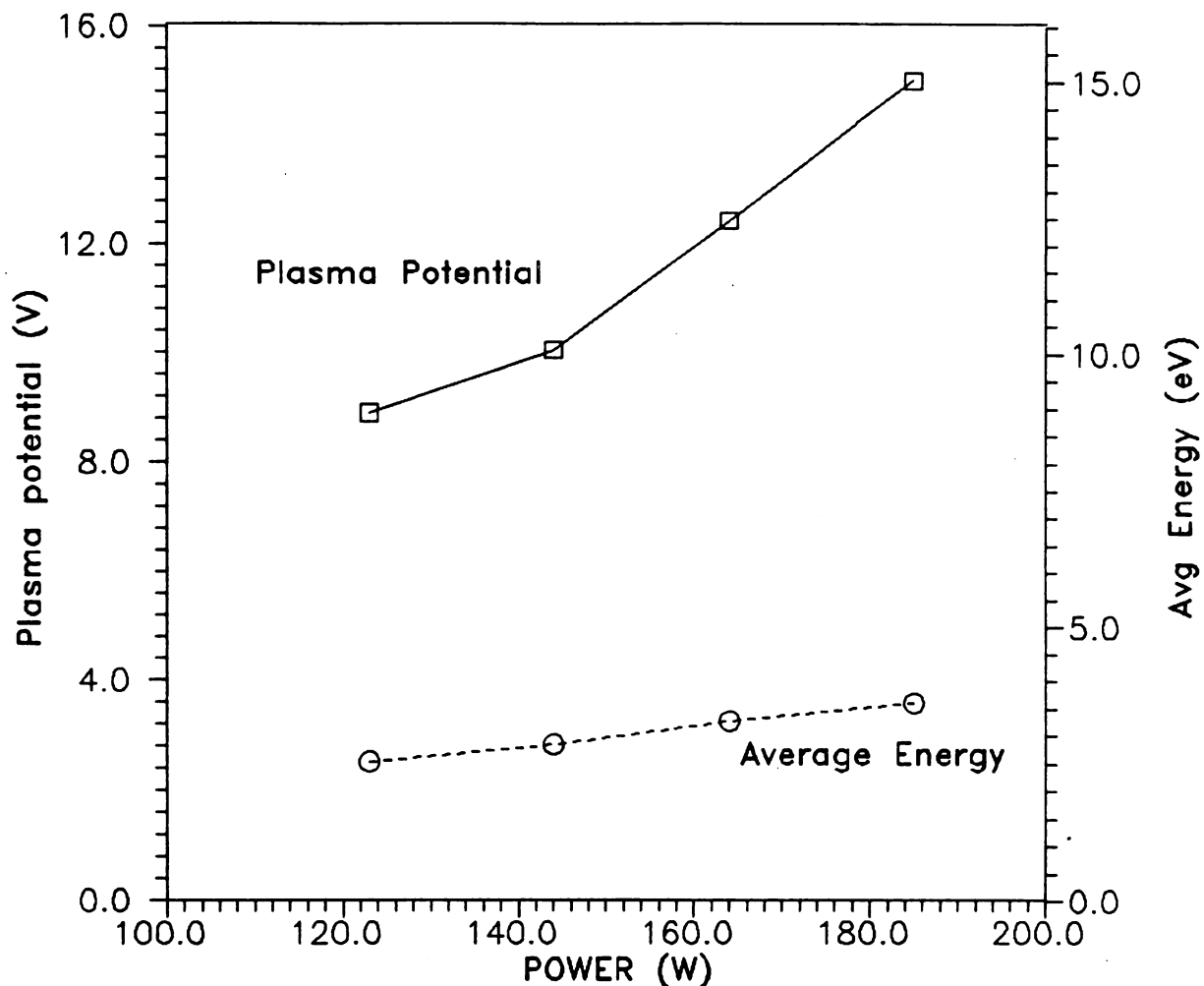


Figure 4.21 Nitrogen electron energy and plasma potential variation with input power

Single Langmuir Probe data for a nitrogen discharge, taken at 25 sccm flow, 0.25 mTorr, 5 cm downstream. Note that the average electron temperature remains somewhat constant, but the plasma potential increases with increasing input power.

electron energy remains almost constant - varying only between 2 and 4 eV for the four power levels (123 W, 144 W, 164 W and 182 W), the plasma potential increases from about 9 V at low power, to about 15 V at 182 W. As was seen in Figure 4.20, the plasma potential increases faster with increasing input power than the average electron temperatures.

Figure 4.22 shows the average electron energy and plasma potential of a nitrogen discharge as the SLP is moved downstream. Data are taken at a fixed pressure of 25 sccm flow, 0.25 mTorr and at two different power levels (123 W and 164 W). The plasma potential is again seen to increase monotonically (solid curves) at both power levels as the downstream position increases. And as was observed in Figures 4.20 and 4.21, the average electron energy increases only slightly with downstream distance.

4.7.2 Nitrogen Ion Energy Analysis

It was mentioned earlier that the ion energy variation typically follows the variation of plasma potential and electron temperature. Further evidence that the MPDR 610's performance in diatomic gases is different from that in argon is presented here as the ion energy distributions are discussed for a nitrogen discharge. Figure 4.23 shows the IEDF variation with power. Data are taken 2 cm downstream at a constant flow of 25 sccm nitrogen, and for four different power levels: 123 W, 144 W, 164 W and 182 W. As in argon, there is a shift of the IEDFs towards higher energies as the input power increases. Also note that there is some increase in the FWHM of the distribution functions with increasing power levels. Figure 4.24 shows this increasing average ion energy with input

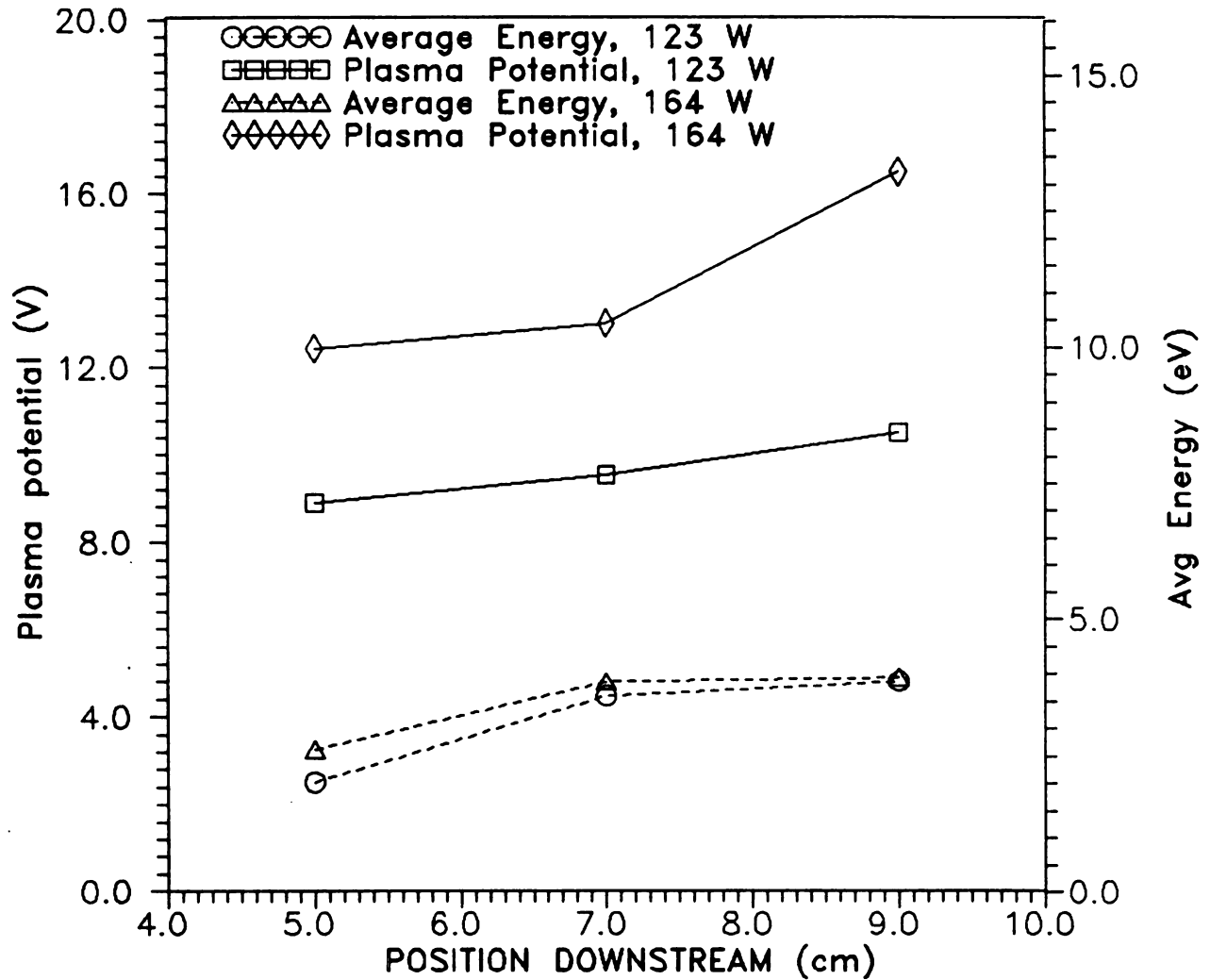


Figure 4.22 Nitrogen electron energy and plasma potential variation with position downstream

SLP data for a nitrogen discharge, taken at 25 sccm flow, 0.25 mTorr, at 124 W and 164 W input powers, as the probe is moved downstream. Note the slight increase in electron temperature, but a larger increase in plasma potential with downstream position.

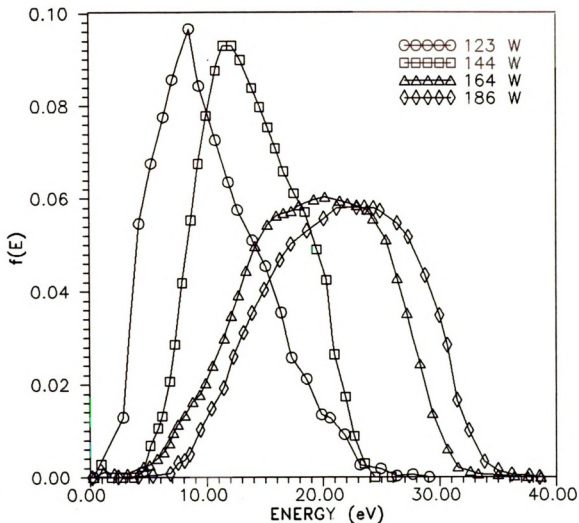


Figure 4.23 Nitrogen ion energy distribution variation with input power
IEA data, taken 2 cm downstream at a constant flow of 25 sccm nitrogen for four power levels: 123 W, 144 W, 164 W and 182 W. Note the shift towards higher energies as input power increases.

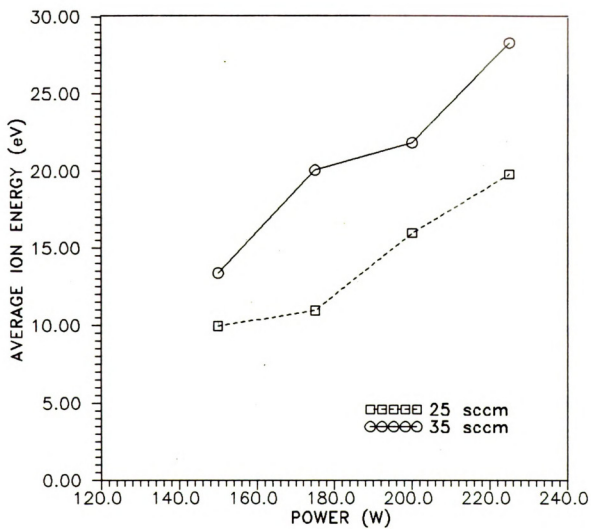


Figure 4.24 Nitrogen average ion energy variation with input power
IEA data taken 2 cm downstream at two different pressure levels (25 sccm nitrogen flow, and 35 sccm nitrogen flow). Note the increase in average ion energies with input power.

power for two different gas flow conditions (25 sccm and 35 sccm). A similar variation of IEDFs and average ion energies with input power was also observed in argon also.

The next two figures show the ion energy distribution function variation with nitrogen discharge pressure (or flow rate), where the crucial difference between an argon and a nitrogen plasma resurfaces. Figure 4.25 shows three IEDFs at 25 sccm, 35 sccm and 45 sccm of nitrogen flow. Unlike the argon discharge, the nitrogen IEDFs shift towards higher energies as the pressure increases. This corroborates the data of Figure 4.20 which showed that the plasma potential of a nitrogen discharge increases with increasing pressure. Since the variation in ion energy seems to follow the variation of plasma potential, through which the ions fall on their way to being collected by the IEA, an increase in the plasma potential with rising pressure leads to a corresponding increase in the directed velocity of the ions. Also note the broadening of the IEDFs as the flow rate goes up - an indication of a rising random velocity, in part due to gas heating at higher pressures. Figure 4.26 shows this increase in average ion energy with pressure at two different power levels (123 W and 164 W). Both curves increase monotonically as the nitrogen discharge pressure increases.

Figure 4.22, presented earlier, showed the plasma potential variation with downstream position for a nitrogen discharge - the potential increases as the SLP is moved away from the $z = 0$ plane. That the ion energies and IEDF are inherently coupled to the fall of ions through plasma potential is indicated in the next two plots. Figure 4.27 shows the IEDF variation with downstream position. Data are taken at 123 W input power for a 25 sccm nitrogen discharge. As the

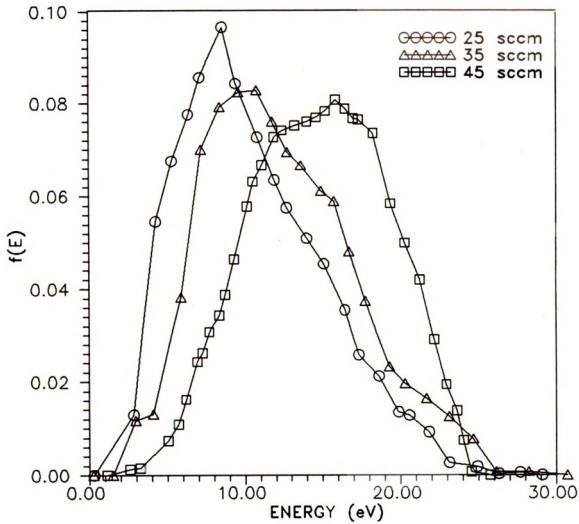


Figure 4.25 Nitrogen ion energy distribution variation with pressure

IEA data taken 2 cm downstream at 123 W input power and at three pressure levels: 25 sccm nitrogen flow, 35 sccm nitrogen flow and 45 sccm nitrogen flow. The IEDFs shift towards higher energies with increasing pressure.

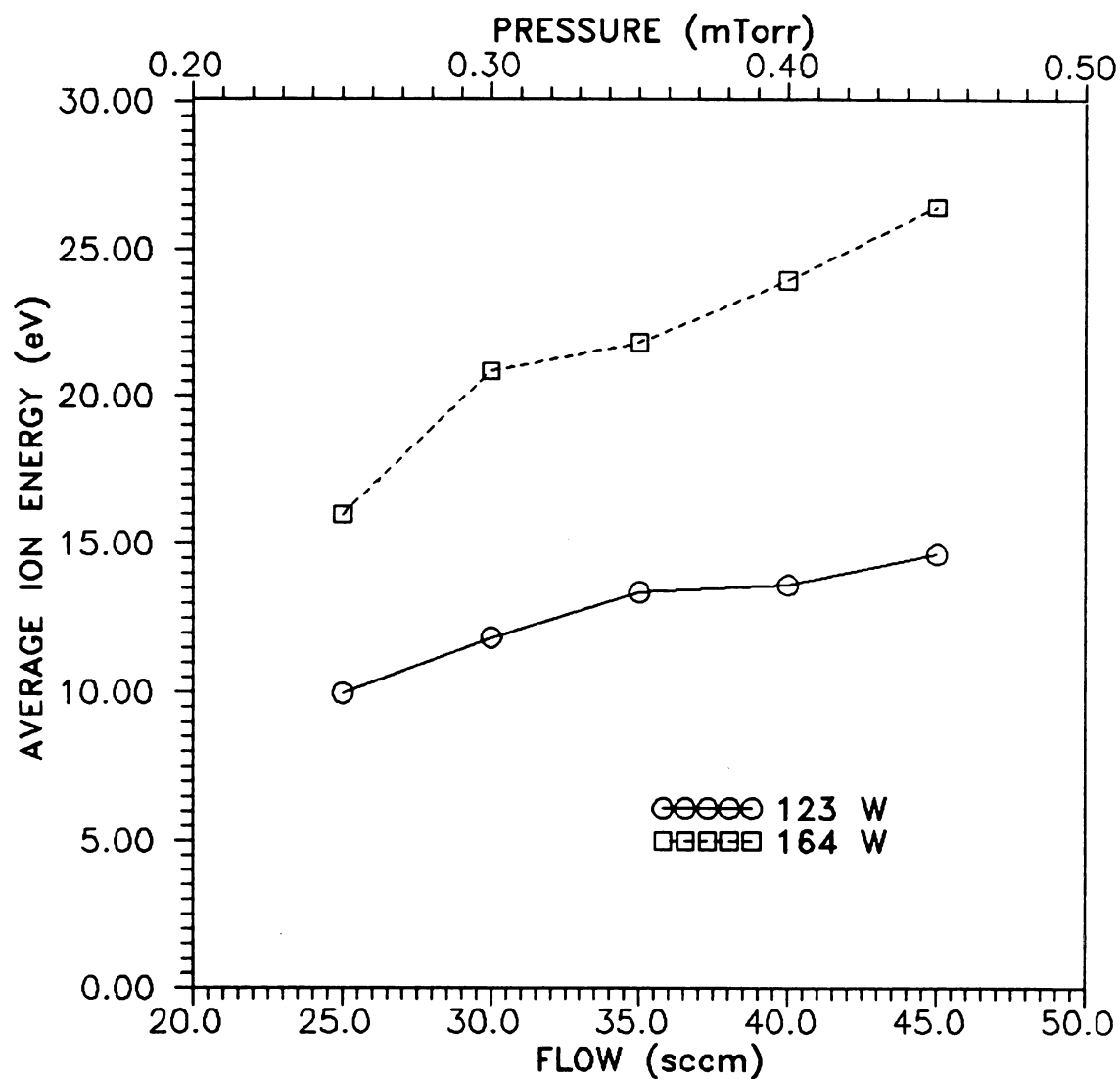


Figure 4.26 Nitrogen average ion energy variation with pressure
IEA data taken 2 cm downstream at two different power levels (123 W and 164 W), as the average ion energy changes with gas pressure. Both curves show a monotonic increase in average ion energy with gas pressure, unlike argon.

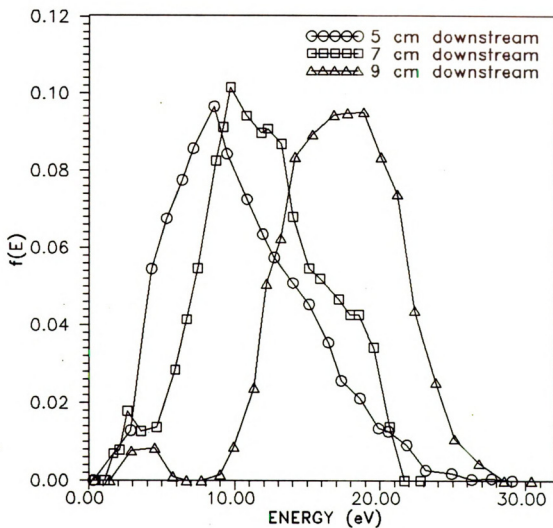


Figure 4.27 Nitrogen ion energy distribution variation with downstream distance

IEA data taken at 123 W input power with 25 sccm nitrogen flow, as the IEA is moved downstream. Note the smaller secondary distribution curve at low energies. This may be due to charge exchange.

IEA is moved downstream and away from the discharge generation region ($z = 0$ plane), there is a shift of the IEDFs towards a higher energy. And Figure 4.28 shows the average ion energy variation for two flow rates (25 sccm indexed by circles and 35 sccm indexed by squares), and at two input powers (123 W indexed by a solid line, and 164 W indexed by a dashed line). The shift in IEDFs is confirmed in this figure where the average ion energies increase with increasing downstream distance for all the nitrogen discharge pressure and power conditions.

From Figure 4.27, it is evident that as this shift towards higher energy with distance downstream occurs, there is a rise of a low energy peak away from the main IEDF. This is secondary peak, occurring about 4 - 5 eV, is first seen when the IEA is 7 cm downstream, and becomes more prominently separated from the main curve when the IEA is 9 cm downstream. The small peak is not seen 5 cm downstream, presumably because the main IEDF curve at 5 cm downstream is too close to the 4 - 5 eV range of the smaller secondary curve. The exact reason for this low energy secondary curve is not known. However it is speculated that this may be the effect of charge exchange downstream from the discharge generation region, where a high energy ion collides with a low energy neutral. If appropriate conditions are satisfied, the charge of the high energy ion is transferred to the low energy neutral, thereby resulting in a low energy ion and a high energy neutral. Such resonant charge exchange has been observed in both other compact, and larger sources also [Sze-93a, Kau-87], and will also be discussed when the MPDR 5 (another compact ECR source) is studied in Chapter Seven.

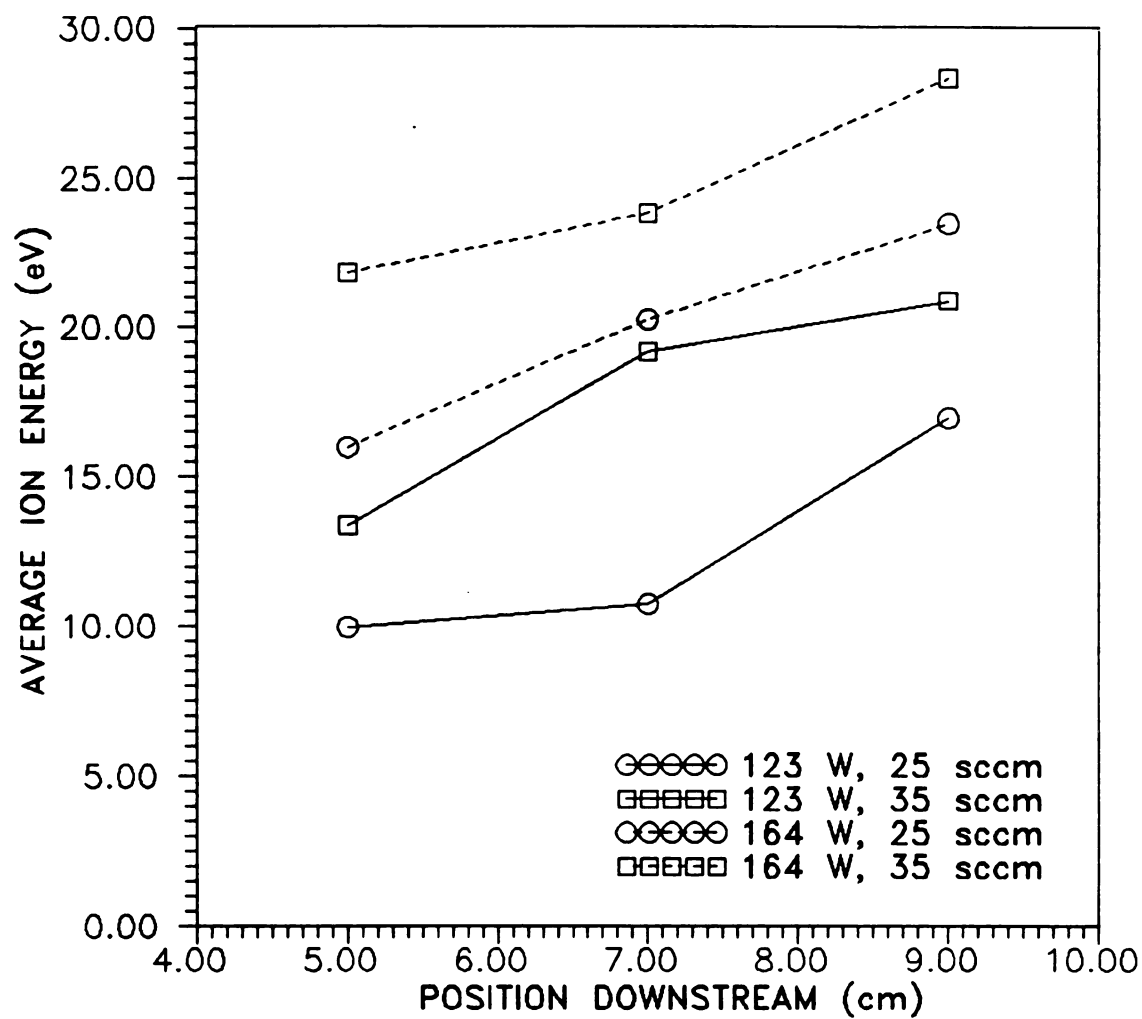


Figure 4.28 Nitrogen average ion energy variation with downstream distance

IEA data taken for a nitrogen discharge at 25 sccm and 35 sccm, and at two different power levels (123 W and 164 W).

4.7.3 A Summary of the Anomalies of a Nitrogen Discharge

From the above section, it is evident that a nitrogen discharge behaves in a manner very unlike an argon plasma. For the 610, an argon discharge seems to follow theoretical predictions relatively well, as is evidenced with the calculations of Sections 4.6.3 and 4.6.4, and also from the plasma potential, average electron and ion energy variation with pressure and power. In a nitrogen discharge however, the plasma potential increases with increasing discharge pressure (as seen in Figure 4.20). This is confirmed when the IEDF variation with pressure is studied in Figures 4.25 and 4.26, where both the IEDFs and the average ion energies shift towards higher energy with increasing pressure.

Further evidence of the anomalous behavior of a nitrogen discharge emerge in Figure 4.22, where the plasma potential and electron energy increases with downstream position, contrary to theoretical predictions. This data too is corroborated with IEDF measurements, as seen in Figures 4.27 and 4.28 where the average ion energy and the IEDFs shift towards higher energy as the downstream distance is increased.

Some speculations may be made regarding this anomalous behavior of a nitrogen discharge. Being a diatomic gas, nitrogen has a very different dissociation phenomenon as compared to argon. The molecule might produce atomic nitrogen, and atomic or molecular ions upon collisions with energetic electrons. Several metastable species may also exist in the discharge. Also, atomic nitrogen is electronegative, and there may therefore be negative ions in the discharge. Further, the molecular ion and molecular gas energies may be distributed not only into random and directed kinetic energies, but also into

vibrational and rotational energy states. As mentioned earlier, this discussion is purely speculation, and further testing of the nitrogen discharge needs to be conducted, so as to explain the anomalous behavior of a nitrogen discharge in context with theoretical predictions of the various diffusion theories.

4.8 Operational Performance of the 610 - HELIUM

A small set of helium experiments were conducted to compliment the numerical modelling effort on the 610 currently under way as part of improving the understanding of MPDRs [Gro-94a, Gro-93, Gro-94b]. Helium was specifically chosen by the modelling group because it is easier to simulate than argon (which might generate multiply charged ions - see Chapter Eight), or nitrogen (which is a diatomic gas). The helium characterization results are now presented here. While the plasma ignition was not a problem for helium, there was usually up to 10% reflected power at optimal tuning conditions, and this reflected power level remained high with no amount of further tuning. This may be directly attributed to the gas being much lighter than argon or oxygen, and hence the pressure at maximum possible gas flow was not high enough for optimal operation of the 610. The input power levels quoted here take into account this large reflected power, i.e. input power is the difference of incident power and reflected power.

Figure 4.29 shows the helium ion density variation with input power. Data are taken with a DLP placed 2 cm downstream at a helium flow rate of 50 sccm (equalling a discharge pressure of 2×10^{-4} Torr). Note that due to the lower weight of the gas, it is necessary to increase the flow rate significantly to reach

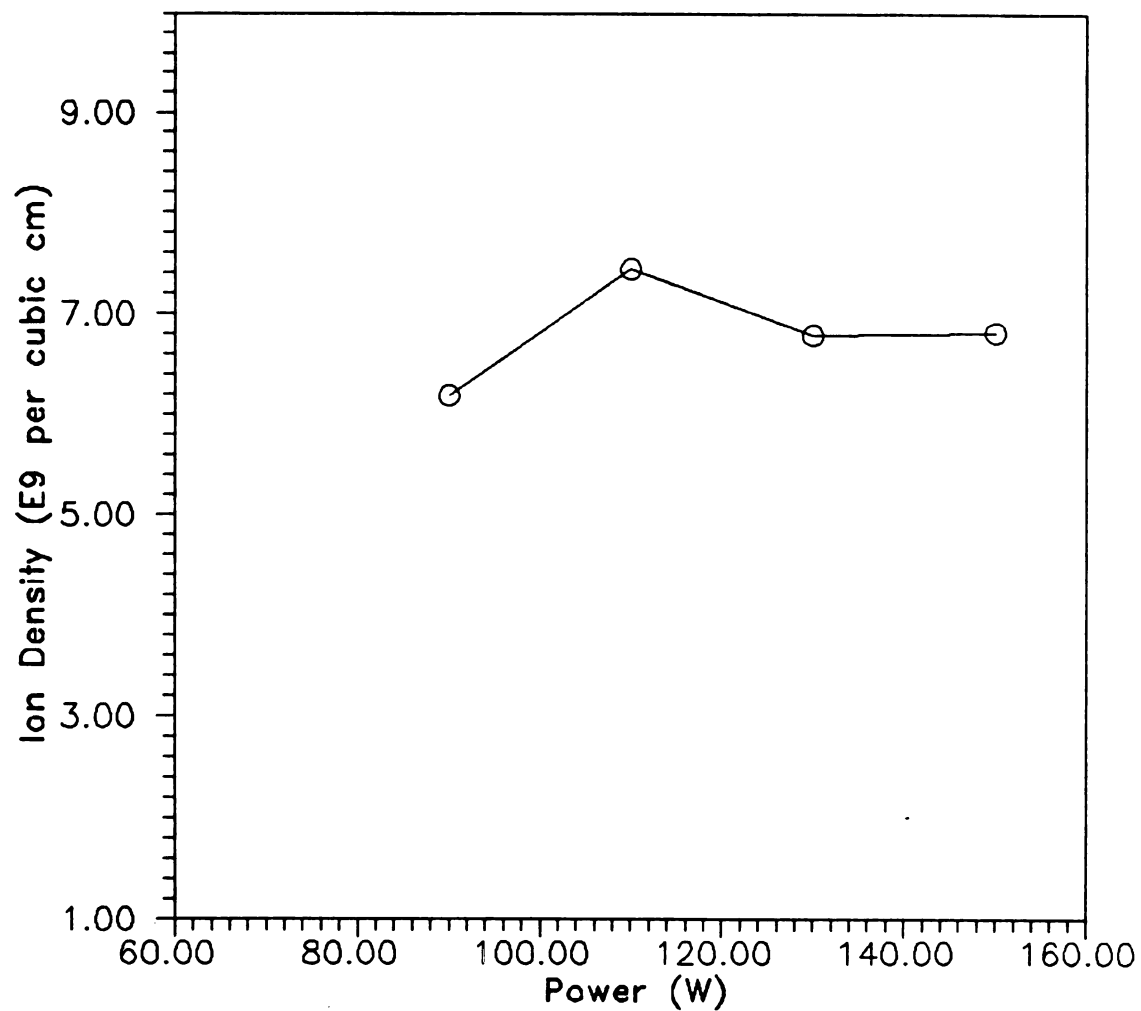


Figure 4.29 Helium ion density variation with input power
DLP data taken 2 cm downstream at 50 sccm helium flow (corresponding to 2×10^{-4} Torr pressure). Note that there is no mode jump, and the helium ion densities are much lower than those observed in argon or even oxygen.

the desired pressure levels. As input power increases, there is seen to be no variation in ion densities - there is no mode change for helium either. Ion densities in a helium discharge are around $7 \times 10^9 \text{ cm}^{-3}$ - much lower than those observed in oxygen or argon discharges. This may be due to inefficient power coupling from the EM fields and into the helium gas (as evidenced by the relatively high reflected power). The ionization potential of helium (about 25 eV) is higher than that of argon (15 eV), or nitrogen (about 14 eV). Hence the ionization efficiency in a helium discharge is probably not as good as that for argon, leading to a lower helium ion density.

Ion density does increase somewhat with increasing pressure, as seen in Figure 4.30, which shows data taken with a DLP at a constant input power of about 110 W. As the helium flow increases from 20 sccm, to 28 sccm and to 40 sccm (with a corresponding increase in pressure from 7.2×10^{-5} Torr, to 1×10^{-4} Torr and to 1.5×10^{-4} Torr respectively), the helium ion density increases from $3.8 \times 10^9 \text{ cm}^{-3}$ to about $6 \times 10^9 \text{ cm}^{-3}$, and the DLP measured electron temperature declines from 70,800 K to 61,887 K and to 65,700 K. As in the case of argon, the increase in ion density, and the cooling of the electron gas with rising pressure may be directly attributed to the ionization-diffusion loss theory of Section 4.6.1.

4.9 Concluding Remarks

The operational performance of the 610 at 2.45 GHz has been presented in this chapter. Several different gas types were used (although argon was the main operational gas), and the data were taken for a variety of input control

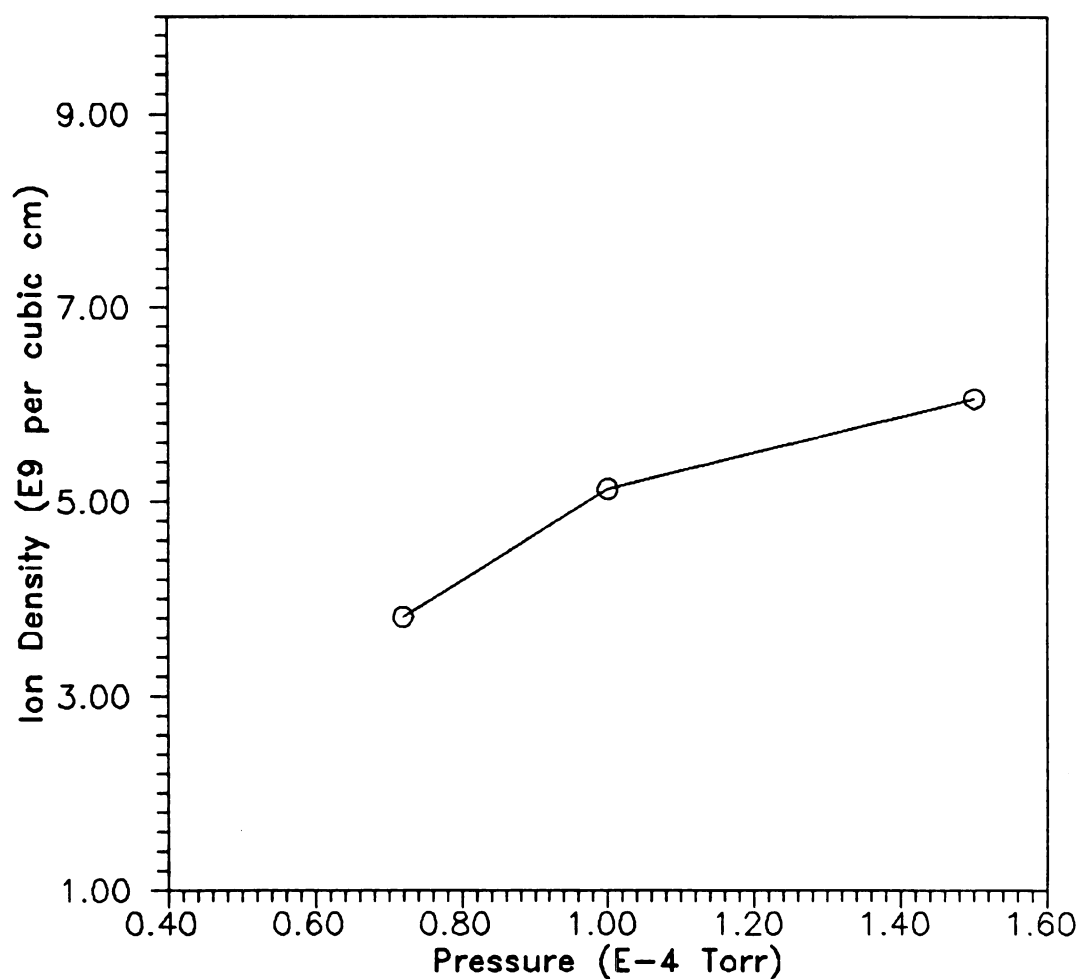


Figure 4.30 Helium ion density variation with pressure

DLP data taken 2 cm downstream, at a net input power of 110 W. The ion density increases with gas pressure, presumably because the rise in flow rate leads to a higher neutral density. This rise in ion density is accompanied by a decrease in electron temperatures - as in an argon discharge.

parameters (i.e. pressure, flow, power and position downstream and radially away from the discharge generation region $z \leq 0$). While discharge ignition was never a problem for any gas (oxygen, nitrogen, hydrogen, helium, or a combination thereof), the degree of tuning that was necessary for each gas type varied, as did the operational performance of the 610 in terms of the ion density and electron, and ion energies.

The argon discharge in the 610 was capable of generating high densities (10^{10} to 10^{11} cm⁻³) at low pressure (sub-mTorr) and input power (less than 200 W). The 610 is therefore "over dense" in the classical (critical density) sense. The ion energies were low (20 to 40 eV) and easily controllable through pressure, power or substrate bias. Note that these ion energies are optimal for most semiconductor processing - they are low enough so as to not damage the wafers by energetic bombardment, but high enough to catalyze surface reactions that might need some kinetic energy from low energy ion bombardment. The electron energy distribution functions seemed to agree better with the theoretical Druyvesteyn distribution, with some evidence of a depleted high energy tail. However, for theoretical developments, an assumption of Maxwellian electron energy distribution in the 610 would not be too far from the reality.

It has been conclusively shown here that while the argon performance of the 610 is interesting to study, it does not necessarily give much indication about the performance of the source in other gases, specially diatomic gases (other than the ease of operation). Several differences exist between the operation of the ion source with argon, and with nitrogen or oxygen. For example, while the argon ion energy variation with pressure exhibits a strong mode jump and hysteresis loop, no such effect is seen for an oxygen, nitrogen or

helium discharge within the range of pressures that were tested. While the plasma potential decreases with increasing argon discharge pressure, the plasma potential increases as the nitrogen discharge pressure is increased - this was also confirmed by the nitrogen IEDF variation with pressure.

Up to now, the theoretical development of plasma dynamics has been somewhat independent of the discharge gases. It is seen here, however, that common diffusion (ambipolar, Schottkey, etc.) theories tend to fit the argon discharge better than any other gas, as is evident from the plasma potential and ion energy variation summarized above. That these diffusion theories do indeed predict the behavior of argon (or other electropositive non-molecular gas) well is seen through the theoretical calculations of Sections 4.6.3 and 4.6.4 where measured data compared well with the theoretical predictions. However, further characterization of MPDRs (or other types of ECRIS) may corroborate or contradict more theoretical dogmas, and hence the importance of continued experimental evaluation cannot be over stated.

This continued evaluation may be undertaken through any of the several techniques mentioned during the process of reviewing compact sources in Chapter Two - optical emission spectroscopy, quartz crystal microbalance, laser induced fluorescence, etc. As more knowledge about the MPDR 610 is collected and analyzed, its operation, and also the theoretical background of ECR plasma sources may be better understood.

Chapter 5

Evaluation: Operation of the MPDR 610 at 915 MHz vs. 2.45 GHz.

5.1 Introduction

5.2 Experimental Description.

5.3 Operational Performance: Density and Temperature Comparisons

5.4 Operational Performance: Ion Energy Comparisons

5.5 Concluding Remarks

Errata

Chapter 5

Evaluation: Operation of the MPDR 610 at 915 MHz

vs. 2.45 GHz

5.1 Introduction

In Chapter Four the operational performance of the MPDR 610 was presented in terms of the output of the plasma source as the external parameters were varied. These external control parameters included the discharge gas flow/pressure, gas type and input power, while the source output was monitored by the ion density, electron temperature, and ion and electron energy distribution functions. The spatial variation of the output was also studied as data were taken at various positions away from the $z = 0$ and $r = 0$ coordinate. (As mentioned in Chapter Four, $z < 0$ is the discharge generation region inside the quartz containment vessel, and $z > 0$ is the free diffusion region in the vacuum processing chamber, and away from the plasma source.) These data were compiled for several gas types, and conclusions were then drawn on the performance characteristics of the MPDR 610 when operated at 2.45 GHz microwave power.

However, one factor that remained unchanged in the sub-study of Chapter Four was the frequency of operation - being set at 2.45 GHz. An important unanswered question relates to the performance of the 610 at a different excitation frequency. As will be seen later (in Chapters Eight and Ten), the development of a class of ion sources that produce multiply charged ions has depended heavily on the so called "frequency squared scaling" law that relates the ion density to the square of the frequency of operation. Following Reference Jon-89, this "law" may be written as:

$$f_p = 8.91 \times 10^3 \sqrt{n_e} \quad (5.1)$$

where f_p is the frequency of operation (in Hz) and n_e is the ion density (in cm^{-3}). While the derivation of the law, based on modelling the plasma as a high pass filter is somewhat simplistic (using a multitude of assumptions), in the past several years multiply charged ECRIS have indeed shown enhanced production of ion density (with a related increase in the intensity of higher charge state ion currents) when operated at higher frequencies (6 GHz to 18 GHz, and up to 35 GHz). Whether the improvement in ion density (and charge state) production in these ECR ion sources is due to higher frequency of operation will be discussed in more detail in Chapters Eight and Ten. For now, it remains to be seen whether such a "frequency squared scaling" is applicable for low charge state ECR ion/plasma sources like the MPDR 610.

It has been stated in Chapter Four that the MPDR 610 is a coaxial plasma source. This means that electromagnetic (EM) energy is propagated through the source body in a coaxial mode, known as the transverse electromagnetic (TEM)

mode. In such a mode, the electric field, the magnetic field and the direction of propagation are all mutually perpendicular to each other, forming an orthogonal set. It is speculated that in the coaxial section of the 610, the electric field is radial, the magnetic field is azimuthal (ϕ directed), while z is the direction of propagation of the microwave energy. If the appropriate derivations are conducted, a major advantage of this coaxial, or TEM mode comes to light - the TEM mode has no minimum cutoff diameter for propagation of electromagnetic energy. Of the other two mode types through which energy can propagate - the transverse electric (TE) or transverse magnetic (TM) modes, the lowest cutoff diameter is for the TE_{11} mode. This mode requires that the plasma source (or any circular waveguide) have an inner diameter of about 7.2 cm or more for wave propagation in the TE_{11} mode at 2.45 GHz. A diameter less than that cannot propagate either a TE or a TM mode. Since the TEM mode has no cutoff, a compact coaxial plasma source (or a circular waveguide) with a diameter less than 7 cm can be designed to propagate TEM wave.

Indeed, it was this property that was exploited during the initial development of the 610 to make it a small, compact ion source. Note that this property was also employed by the designers of the Japanese radical gun and the ASTeX, Inc. small ion source (see Sections 2.2.4 and 2.2.6, Chapter Two) to build sources below the cutoff diameter of the TE and TM modes. In the coaxial section of the 610, a resonant standing wave of electric field is set up. However, the body of the 610 also consists of a circular (below cutoff) waveguide between the terminus of the center conductor and the plasma (confined by a quartz tube, or cup). Due to its small diameter, only evanescent modes may be set up in this small circular waveguide section. (See Figure 4.6 of Chapter Four for the

definition of coaxial and circular waveguide sections of the plasma source.) That the standing wave is indeed generated in the coaxial section of the source, which is then attenuated in the circular waveguide section will be verified later in Chapter Six with direct measurements of the radial component of electric field patterns in the 610-*a* (an adapted version of the MPDR 610).

A corollary to the above mentioned advantage of the coaxial structure of the plasma source is that EM fields at any frequency may be propagated through the structure. This means that since there is no cutoff diameter for wave propagation, and coaxial source may be operated at any frequency of excitation both higher and lower than 2.45 GHz. This chapter details some experiments in which the 610 was excited at 915 MHz instead of the standard 2.45 GHz. The performance of the source is evaluated, as in Chapter Four, by compiling data on (1) electron temperatures, (2) absolute values and the spatial variation of electron and ion densities, (3) saturation current densities, (4) ion energy distribution functions, and (5) ion production costs. All data are taken for argon gas, (although some ion density data in oxygen is also discussed) with independent variation of the input power and discharge pressure, and then compared to similar results obtained for 2.45 GHz excitation. All data are taken with the 610 mounted on the Yorktown T (see Figures 4.3 and 4.4, Chapter Four. The discharge pressure is once again dictated by the gas flow rate due to the lack of a variable conduction valve. The results of this comparison study were first presented at the American Vacuum Society symposium (AVS-92) in Chicago, USA [Sri-92c], and subsequently published in the conference proceedings [Sri-93a].

Other than testing the "frequency squared scaling" law, another reason to

undertake this comparison study is this: as the frequency of operation decreases, the requirement of the ECR magnetic field strength goes down linearly. (See Section 1.2.1 of Chapter One that discusses power transfer through “pure” ECR to the discharge.) The static magnetic field configuration for the 610 has been discussed in detail in earlier investigations [Asm-90, Gro-91, Gro-92]. In particular, the geometry of the magnets and the associated ECR absorption volume for 2.45 GHz have been simulated, and are displayed in Figures 2 and 3 of Reference Gro-92. The field strength required for ECR at 2.45 GHz is 875 Gauss. By linearly scaling down this number, it may be seen that at 915 MHz this field strength requirement for ECR is reduced to about 325 Gauss. If electromagnetic coils are used, this would mean that a lesser current is needed in the coils to generate the requisite magnetic fields, and hence a saving in power costs. In the case of permanent magnets - as for the MPDR 610 - this means that the “ECR zones” are pushed in towards the center of the quartz plasma cup and away from the walls. So if the source operates well at 915 MHz, it might also mean that cheaper, less powerful magnets may be used in the source to sustain an ECR plasma at this lower frequency. The effects of a more pronounced set of ECR zones (within the discharge region of the source) on the output of the 610 are, therefore studied in this chapter.

5.2 Experimental Description

As should be expected, most of the experimental setup for these tests at 915 MHz remains exactly the same as that described for the 2.45 GHz operation of the 610 in Chapter Four. As mentioned earlier, the same Yorktown T (see

Figures 4.3 and 4.4) vacuum system was used for experiments in this chapter, and the gas flow system remains the same also (as in Figure 4.5(a)). The only major difference is in the microwave apparatus. Individual microwave components are calibrated to perform only over a limited range of frequencies. While the set up of the bidirectional coupler/circulator/dummy load/attenuators/power meters, etc. remains the same conceptually (as in Figure 4.5(b)), a completely different set of apparatus needs to be used that is rated for use at or about 915 MHz frequency. A CheungTM 0 - 500 W power supply producing microwaves at 915 MHz was used in this case to power the ion source. And of course the same plasma source - the MPDR 610 is used for both frequencies of operation. The only difference in the source structure is that the resonance position of the center conductor/sliding short assembly at 915 MHz is slightly different from that at 2.45 GHz due to the different EM wavelength at the two frequencies.

Several problems were encountered while compiling data for the AVS-92 symposium. The Cheung power supply was often very erratic in its power output and finally it did break down irrecoverably. A new 915 MHz magnetron with a maximum of 400 W power output and a 300 hour lifetime had to be placed in the power supply, after which the output was very stable, albeit centered at about 918 MHz. Also, it was found that a 20 dB attenuator through which incident power was being sampled to the power meter was actually 23 dB. An additional 3 dB of attenuation reduced the power readout by 50%. So when the incident power meter was reading 100 W, the actual power going to the ion source was 200 W. This discrepancy was resolved immediately by replacing the malfunctioning attenuator with a new one that is rated to operate with precisely

20 dB attenuation at 915 MHz. Before further data acquisition, all other cables and attenuators were tested using a network analyzer and it was found that they conformed to specifications.

Finally, the argon plasma generated by a 915 MHz microwave excitation is very intense. As will be seen from the data that are presented in the forthcoming sections, the electron and ion temperatures at this frequency of operation are higher than those found in a 2.45 GHz excited discharge. This leads to a much higher energy transfer to the quartz walls during collisions and recombinations. It might also be, as some evidence will indicate in a later section, that the diffusion of charged species out of a 915 MHz excited discharge is different from particle diffusion in a 2.45 GHz excited discharge. During the course of data acquisition at 915 MHz, the 610's quartz cracked due to the intense bombardment of energetic particles. The hairline fracture created sufficient problems with vacuum such that the base pressures were several decades higher than normal (which is less than 10^{-7} Torr), and so the quartz had to be replaced. Once the replacement quartz was sealed into place using the HelicoflexTM rings, data compilation proceeded smoothly for the duration of the experiments. All data reported in this chapter are taken in accordance with the procedures discussed in Chapter Three.

5.3 Operational Performance: Temperature and Density Comparisons

Figure 5.1 plots electron temperatures (T_e) as pressure/flow changes in an argon plasma of 160 W input power. Data are taken with a double Langmuir probe (DLP) placed 3 cm downstream ($z = 3$, $r = 0$). As mentioned in Chapters

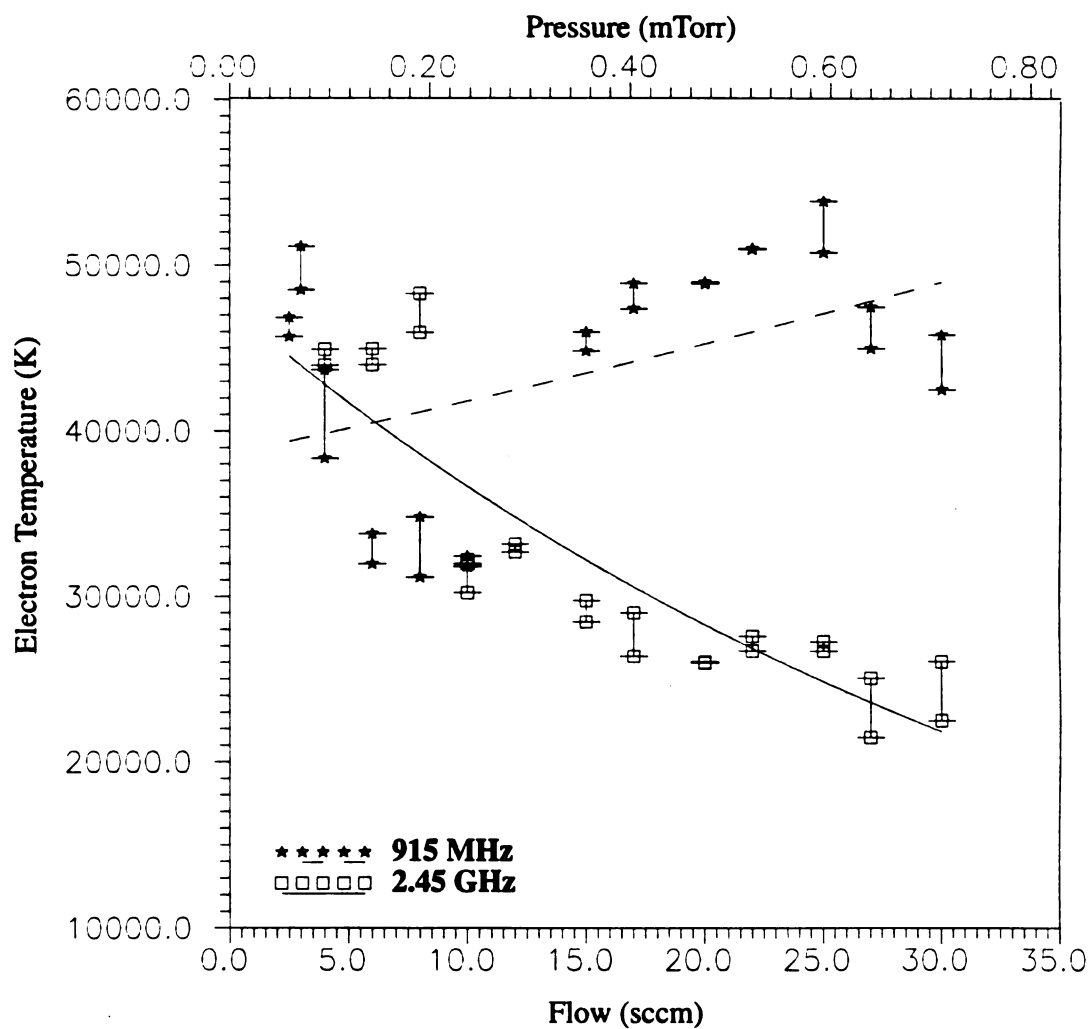


Figure 5.1 Electron Temperature variation for the two frequencies
 The incident power at both frequencies is 160 W. Electron temperature data are taken 3 cm downstream with a double Langmuir probe.

Three and Four, at each point the data were taken several times to ensure repeatability, and for each data point the 610 was tuned to optimal operating conditions (less than 5% reflected power) as the flow/pressure was changed. The error bars in Figure 5.1 are the lowest, and highest T_e values from the several sets of data that were taken at each flow rate. T_e for the discharge at 2.45 GHz excitation frequency goes down as pressure increases. As was mentioned in Chapter Four, there is a sudden dip in the electron temperature when the plasma source undergoes the discontinuous "mode change." This sudden decrease in the electron temperature is seen in the 2.45 GHz curve of Figure 5.1 (also see Figure 4.10, Chapter Four) at about 0.2 mTorr. While discussing Figure 4.10, it was stated that the gradual increase in the T_e as pressure falls is a response of the discharge to sustain itself - specifically (see Section 4.6.1 of Chapter Four) that the ionization-diffusion loss out of a differential volume must be balanced in steady state, and as the pressure falls, the diffusion losses within the discharge generation region increase. Hence the ionization must increase to sustain the plasma, and this in turn predicates an increase in electron temperature. The 2.45 GHz curve in Figure 5.1 reflects this elevated electron temperature at lower pressures.

Within the span of pressures tested, the general trend of the electron temperature at 915 MHz excited discharge is that the electron temperatures are higher than those at 2.45 GHz, specially at higher pressures (> 0.4 mTorr). Later in this chapter, data on ion density variation with discharge pressure are presented, which will indicate that a discontinuous mode jump occurs even at 915 MHz. However, at 915 MHz, there is no sudden drop in T_e when this mode jump occurs, as observed in the discharge operating at 2.45 GHz. Indeed, there

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seems to be a sudden rise in the T_e in a 915 MHz excited discharge at about 0.3 mTorr. This elevated electron temperature at higher pressures is the key difference in the operation of the 610 at 915 MHz, and is probably due to the more pronounced ECR zones that have been pushed inwards (towards the center of the quartz) because of the lower magnetic field strength requirement for ECR at 915 MHz. It may be possible that with this new placement of ECR zones, the diffusion of charged species out of the discharge generation region is higher for a 915 MHz excited discharge from that of a discharge at 2.45 GHz. The higher diffusion losses must be balanced by an increase in electron temperature. The charged particles might in fact be accelerated out of the quartz at both ends, which might explain the hairline fracture of the quartz cup alluded to earlier in Section 5.2, and also might explain the "hollow beam" effect to be discussed later when Figure 5.6 is introduced.

It is re-iterated here, as was noted in Chapter Three, that the DLP only samples the temperature of the high energy tail of the electron energy distribution, rather than the bulk temperature [Her-89]. Thus, the measured electron temperatures presented here are indicative of the temperatures of a Maxwellian (or near-Maxwellian) electron energy distribution which has the same high energy distribution as the fast electrons in the 610 discharge at 915 MHz. The electron temperature data of Figure 5.1 therefore only provide a general trend of the electron temperature variation with input parameters. A more accurate average electron temperature measurement is possible through single Langmuir probe (SLP) technique as described in Chapter Three. However, it has been observed in larger ion sources [Hop-91] that the actual electron temperatures as measured directly with a single Langmuir probe, by sampling

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the complete distribution function vary by at most 15% when compared to the electron temperatures measured with a double Langmuir probe. This variation cannot explain the differences observed in the electron temperature and ion density data between the discharges at the two frequencies of excitation, and so these differences must be inherent to the operation of the source at two separate frequencies.

Figure 5.2 displays the argon ion density variations versus flow/pressure, under the same conditions as Figure 5.1 (DLP positioned 3 cm downstream, 160 W input power). At both excitation frequencies, there is a discharge mode change where the density quadruples for 2.45 GHz (from 2 to $9 \times 10^{10} \text{ cm}^{-3}$) excitation, and doubles for 915 MHz (from 3 to $6\text{-}7 \times 10^{10} \text{ cm}^{-3}$) excitation. This sudden change of density is dependent on the absorbed power and pressure of the discharge such that a hysteresis loop versus pressure, power and density is observed for either frequency of operation (as mentioned in Chapter Four, for 2.45 GHz excitation of the 610). Hence, this hysteresis phenomenon allows two possible ion densities at the same power and pressure conditions, depending on the initial conditions of the plasma source.

As discussed for Figure 5.1, the electron temperature decreases for a 2.45 GHz excited plasma when the discharge undergoes the mode jump to the high density mode, but there is no comparable measurable decrease in electron temperatures for a 915 MHz discharge. This phenomenon is mirrored in Figure 5.3, where the saturation current density for 915 MHz is compared to 2.45 GHz current density, plotted for the same conditions as before (160 W input power, DLP 3 cm downstream). The saturation current is higher at 915 MHz, even though the ion density for the same pressure/power is lower, than that at 2.45

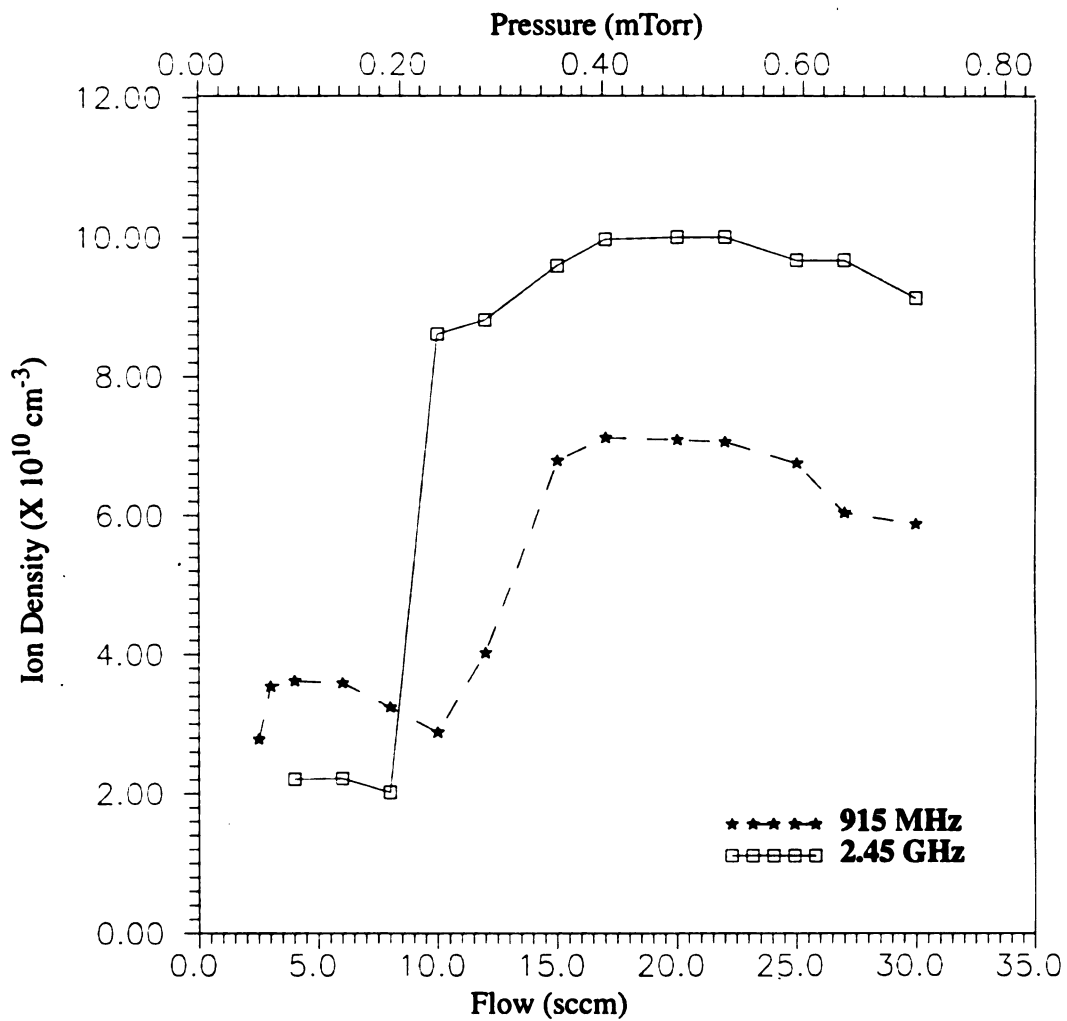


Figure 5.2 Ion density variation with pressure for the two frequencies. The incident power is 160 W for the argon discharge. Data are taken with a double Langmuir probe 3 cm downstream.

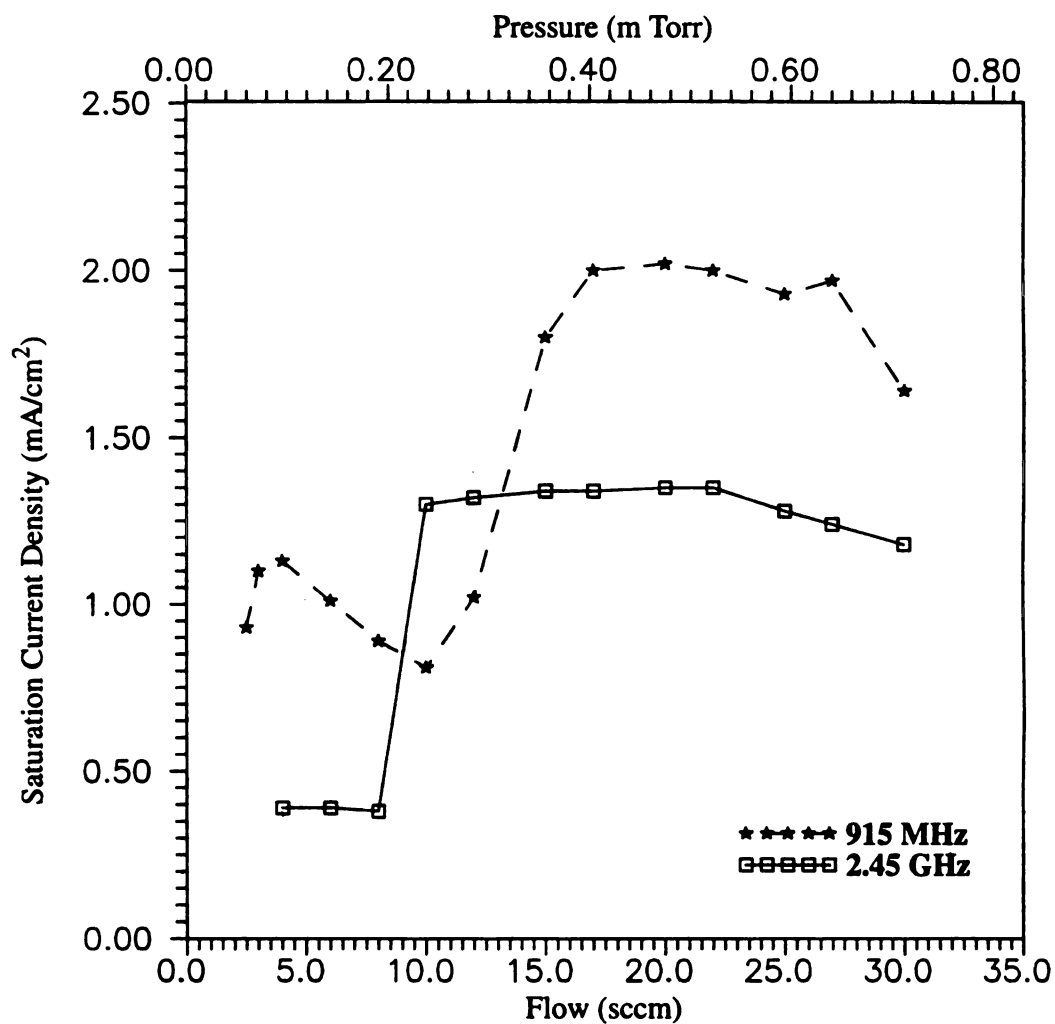


Figure 5.3 Saturation current density variation with pressure for the two frequencies

Ion saturation current density is measured with a double Langmuir probe placed 3 cm downstream for 160 W input power in an argon discharge. Data are taken at a negative 50 volt bias.

GHz. This apparent discrepancy may be explained by revisiting Eqn. 3.14 (Chapter Three), where it is seen that ion density is directly proportional to saturation current density, but inversely proportional to the square root of electron temperature. Indeed, the theoretical development of Section 3.2.3 (Chapter Three) on double Langmuir probes shows that the three parameters (ion density, electron temperature and saturation current density) are inherently inter-related. So even though there is a slight increase in the saturation current density at 915 MHz, the ion density at that frequency is lower because T_e is higher at 915 MHz than at 2.45 GHz.

The same trend (higher saturation current density, but lower ion density) is observed in Figure 5.4, where the ion density and the saturation current density are plotted versus absorbed power for both frequencies. Data are taken 5 cm downstream with a DLP for a 0.7 mTorr argon discharge. While both the saturation current density and ion density increase with increasing input power, it is seen that the saturation current is slightly higher for 915 MHz, but the ion density is comparable at both frequencies. This is probably due once again to the higher T_e at 915 MHz excitation.

The spatial variation of ion density and saturation current density is presented in the next two figures. The downstream characteristics of the discharge at the two excitation frequencies is shown in Figure 5.5, where data are taken with a DLP for a 120 W input power, 0.55 mTorr argon discharge. The discharge at both frequency of excitation indicates the exponential decay as distance away from the generation region ($z > 0$) increases. A similar exponential decay was observed in Chapter Four at 2.45 GHz (see Figures 4.13 and 4.14) for several different gases. Figure 5.6 shows the radial variation of the ion density

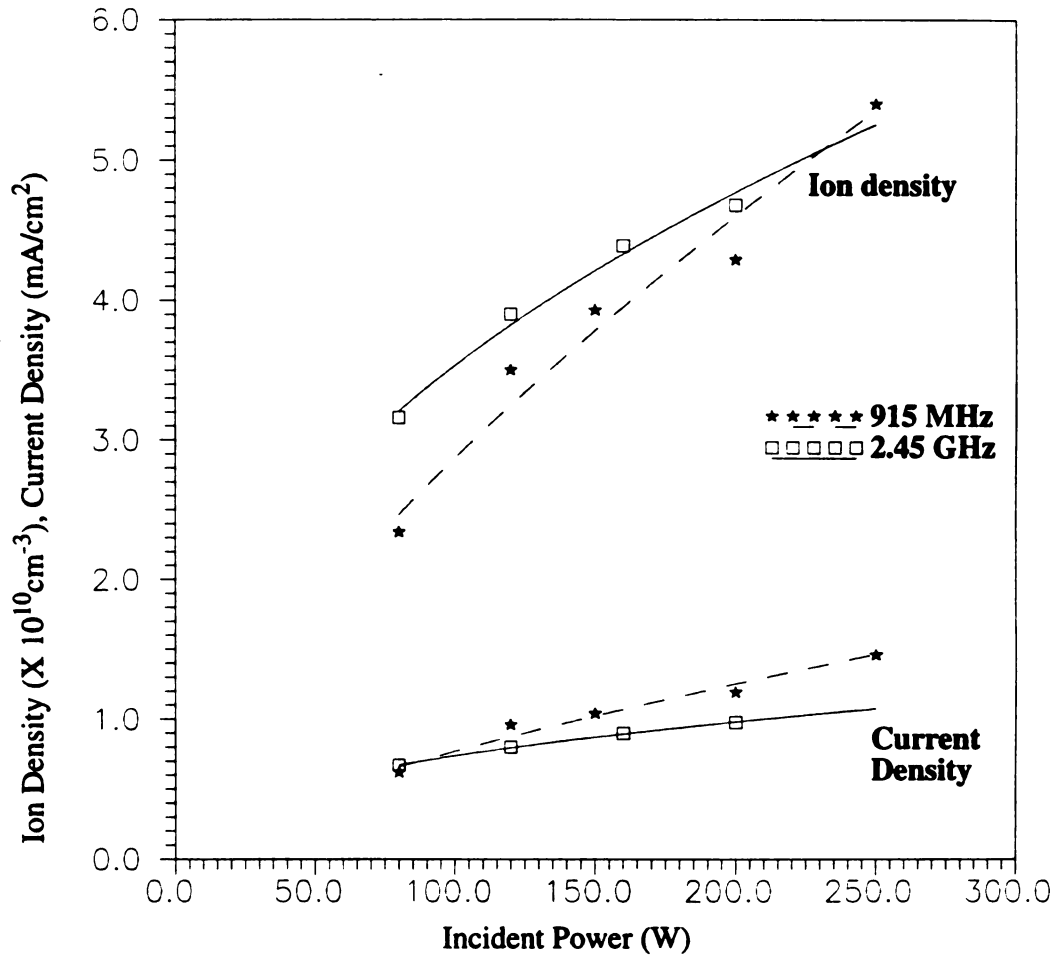


Figure 5.4 Ion density and saturation current density variation with input power for the two frequencies

Data are taken 5 cm downstream at 0.7 mTorr argon discharge pressure. (See Errata note at the end of the chapter.) Saturation current data are taken at a negative 50 volt bias.

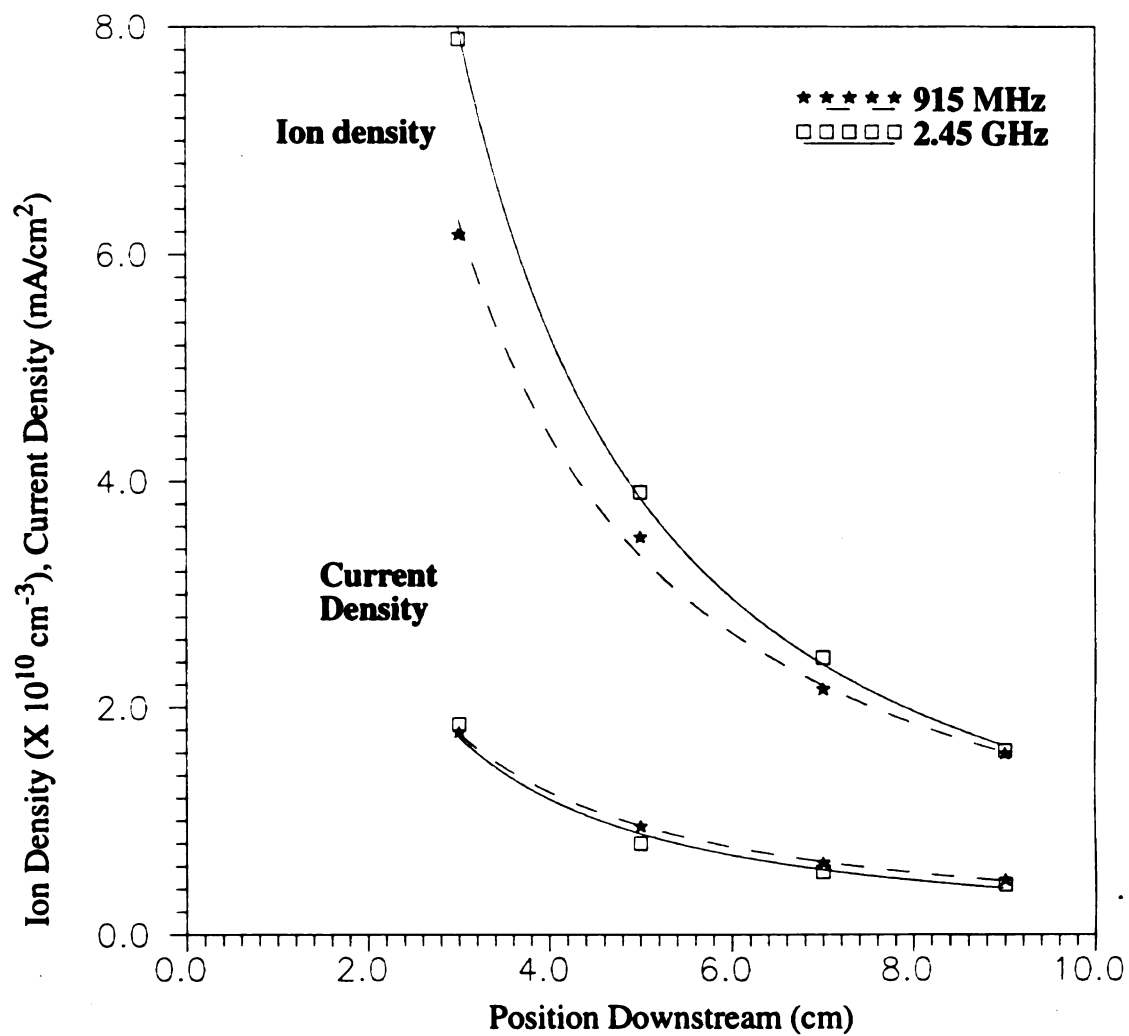


Figure 5.5 Ion density and saturation current density variation with distance downstream for the two frequencies

Incident power is 123 W, pressure is 0.55 mTorr. Data are taken with a double Langmuir probe. Saturation current data are taken with a negative 50 volt bias.

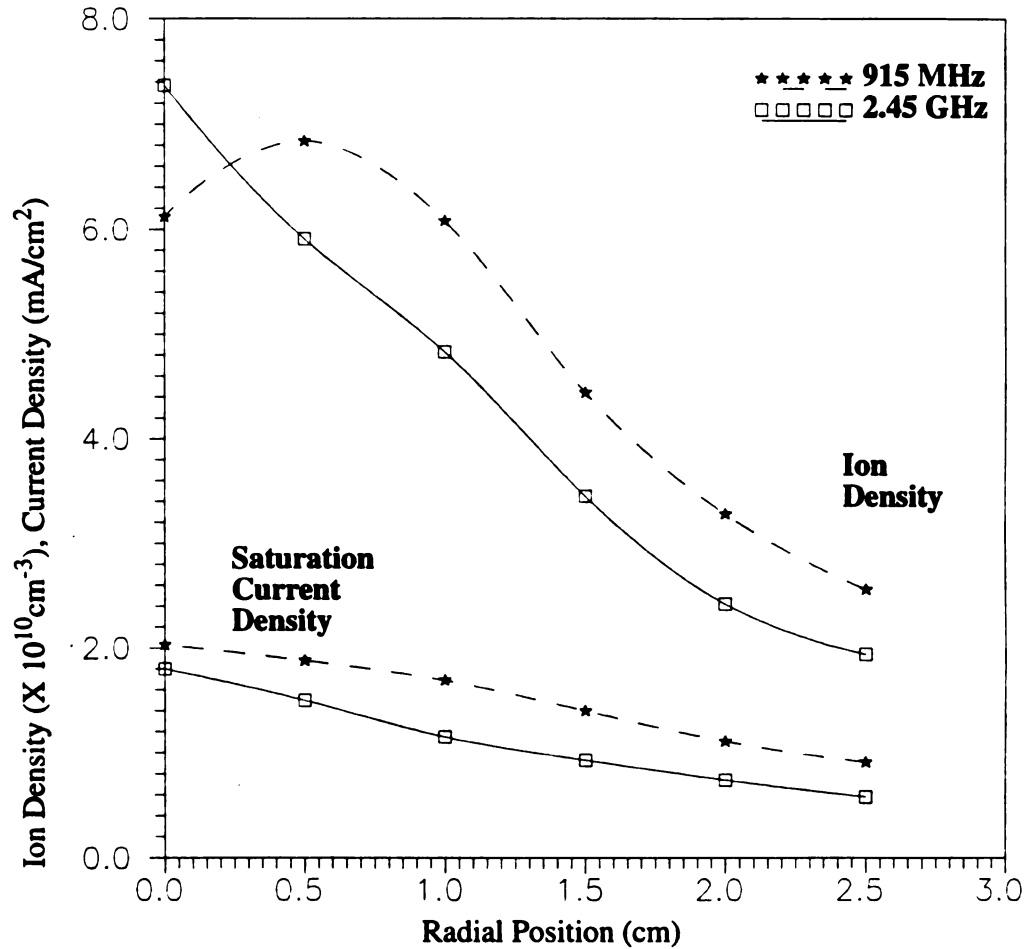


Figure 5.6 Ion density and current density variation with radial position at the two frequencies 3 cm downstream.

Incident power is 200 W, pressure is 0.55 mTorr. Data are taken with a double Langmuir probe. Saturation current density data are taken at negative 50 volt bias.

and saturation current density, where the data are taken 3 cm downstream ($z = 3$, $r \geq 0$) with 200 W input power, and for a 0.55 mTorr argon discharge. ($r = 0$ is the center axis). Both figures indicate that the discharge at either of the two frequencies of operation has comparable ion densities and saturation current densities. Also, the diffusion of charged species at both frequencies of operation follows similar characteristics outside the discharge excitation region (downstream from the generation region).

For Figure 5.6, note that while the saturation current density for both frequencies of operation drops steadily as the radial position increases, at $z = 3$ cm the 915 MHz ion density data indicates a hollow beam discharge. This means that the argon ion density at the exact center of the discharge generation/diffusion region ($r = 0$, $z \leq 3$) is lower than for some $r > 0$ positions for the same z coordinates. Note that due to the unknown variation of the third factor in Eqn. 3.14 of Chapter Three - namely the electron temperature, the ion density at 3 cm downstream may indicate a hollow beam, but the saturation current need not vary in the same manner. This may mean that the electron temperature has a unique radial variation over the cross section that compensates for the "hollow ion beam" effect. This important result needs to be studied further, possibly with a single Langmuir probe (that would be more accurate in measuring the average electron temperatures).

Figure 5.7 shows the radial characteristics with the DLP positioned 5 cm downstream, and a more typical profile is seen, where the "hollow" center has disappeared due to the charged species diffusion into the large vacuum chamber and away from the generation region. Also, the uniformity is slightly greater at 5 cm downstream than at 3 cm downstream (note that the Y axis has different

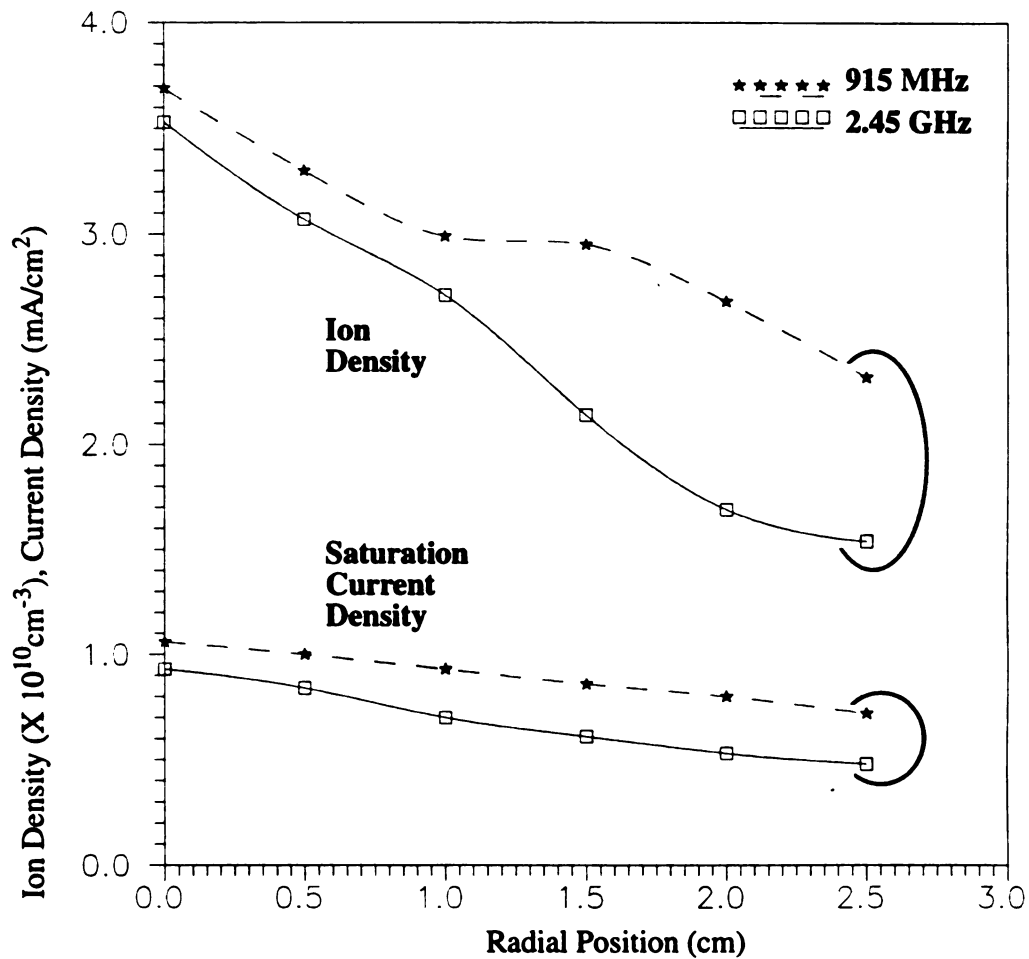


Figure 5.7 Ion density and current density variation with radial position at the two frequencies, 5 cm downstream.

Incident power is 200 W, pressure is 0.55 mTorr. Data are taken with a double Langmuir probe. Saturation current density data are taken at negative 50 volt bias.

ranges for Figures 5.6 and 5.7), as expected in the case of ambipolar diffusion of charged particles out of the generation region.

This phenomenon (of a hollow beam) may be explained in part due to the magnetic field configuration within the discharge generation region. While the magnetic fields themselves do not change (for both 2.45 GHz or 915 MHz operation, the same ion source with the same permanent magnets is used in each case), the position of the ECR zones does change. In fact, the 915 MHz "ECR volume" does not contact the discharge walls, forming an undulating, axially symmetric cylindrical surface that passes out of the end of the discharge, while the 2.45 GHz ECR volume strikes the quartz walls at several locations (see simulated magnetic field figures in Reference Gro-92). Thus at low pressures, many of the ECR accelerated electrons may easily diffuse out of the discharge and it is this difference in the position of the ECR surfaces that is speculated to create this hollow beam for the 915 MHz plasma. As mentioned earlier, the hollow beam is not found further downstream - 5 cm and 7 cm away from the plasma source since the charge density variation is then defined by ambipolar diffusion process, and the boundary conditions of the large process (vacuum) chamber walls.

Data were also taken using oxygen as the discharge gas at 915 MHz (200 W input power) as the discharge pressure was varied. When compared to the oxygen density data at 2.45 GHz (Figure 4.9 of Chapter Four, 123 W input power), it was noted that the 915 MHz oxygen ion density was somewhat higher (mid 10^{10} cm^{-3} , as compared to high 10^9 cm^{-3} for 2.45 GHz). The ratio of input powers at the two frequencies is clearly lower than the ratio of the ion densities at the two frequencies, so a 915 MHz oxygen discharge does indeed produce a

slightly higher ion density than a 2.45 GHz oxygen discharge. However, a similar trend was noted for the oxygen discharge at both frequencies of operation: within the range of pressures tested, there is no evidence of the mode jump for an oxygen plasma that characterizes an argon discharge at either excitation frequency.

5.4 Operational Performance: Ion Energy Comparisons

The next several figures show typical ion energy distribution functions (IEDF) for an argon discharge, measured with a grounded multigrid energy analyzer in accordance with the technique described in Chapter Three. The IEDFs are acquired 3 cm downstream, and Figures 5.8 and 5.9 show their variation at various input powers (100 - 250 W) for a fixed pressure of 0.55 mTorr. Note that at both frequencies of operation, the curves shift towards higher energies as the input power increases. This is due to the higher electron temperatures at the higher absorbed powers, which is a characteristic of this small ECR ion source. A more energetic electron gas indicates a higher plasma potential, since the high energy electrons diffuse to the walls faster. The ions then have to fall through this higher plasma potential, thereby gaining more energy as they enter the plasma sheath of the ion energy analyzer (IEA). Figure 5.10 shows that the average ion energies at 915 MHz are about twice as much as those at 2.45 GHz, in part because the electron energy (and hence the plasma potential) at 915 MHz is higher than that at 2.45 GHz. For both frequencies of operation, there is a monotonic increase in the average ion energy as input power increases.

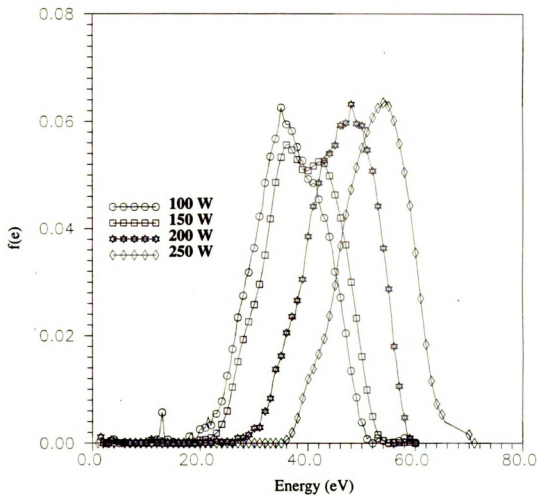


Figure 5.8 Ion energy distribution function variation with input power at 915 MHz

Data are taken with the ion energy analyzer 3 cm downstream for a 0.55 mTorr argon discharge at various input power levels.

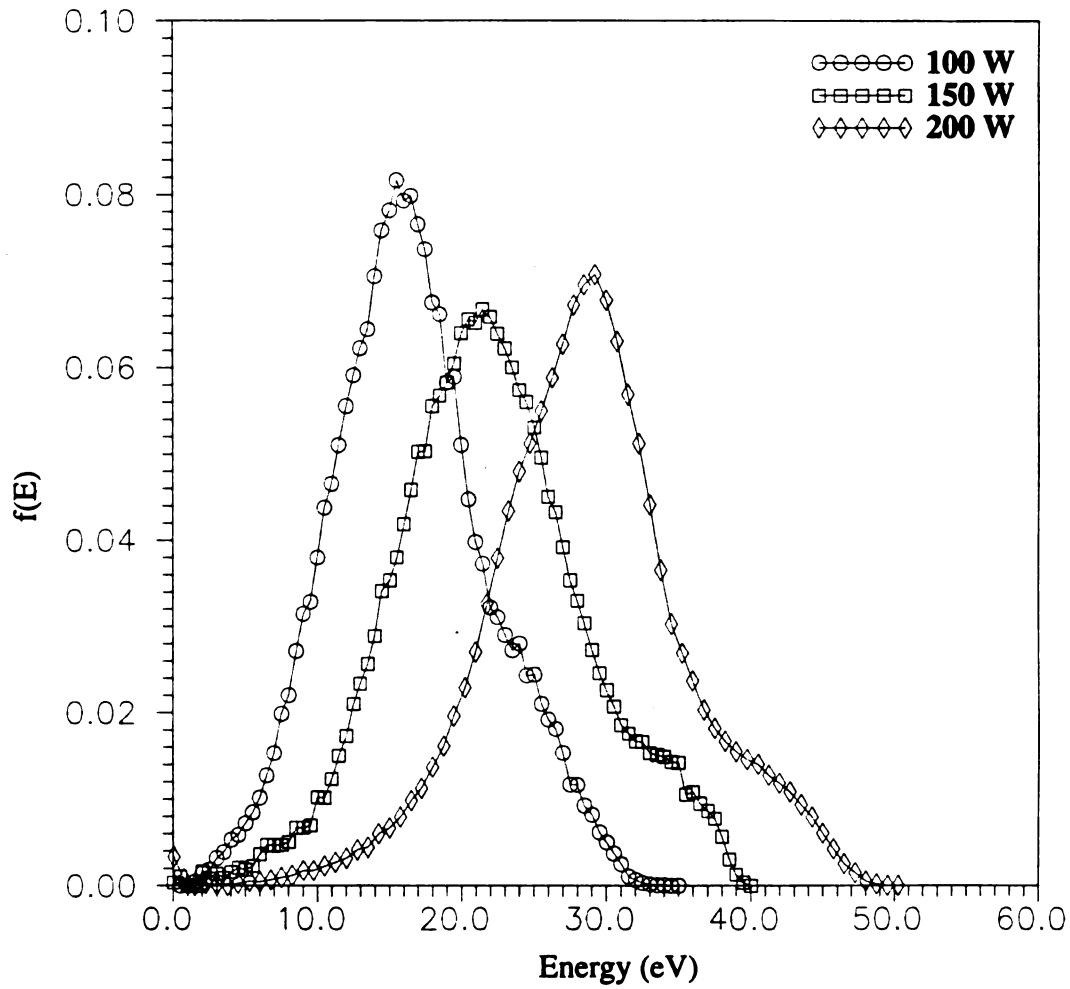


Figure 5.9 Ion energy distribution function variation with input power at 2.45 GHz

Data are taken with the ion energy analyzer 3 cm downstream for a 0.55 mTorr argon discharge at various input power levels.

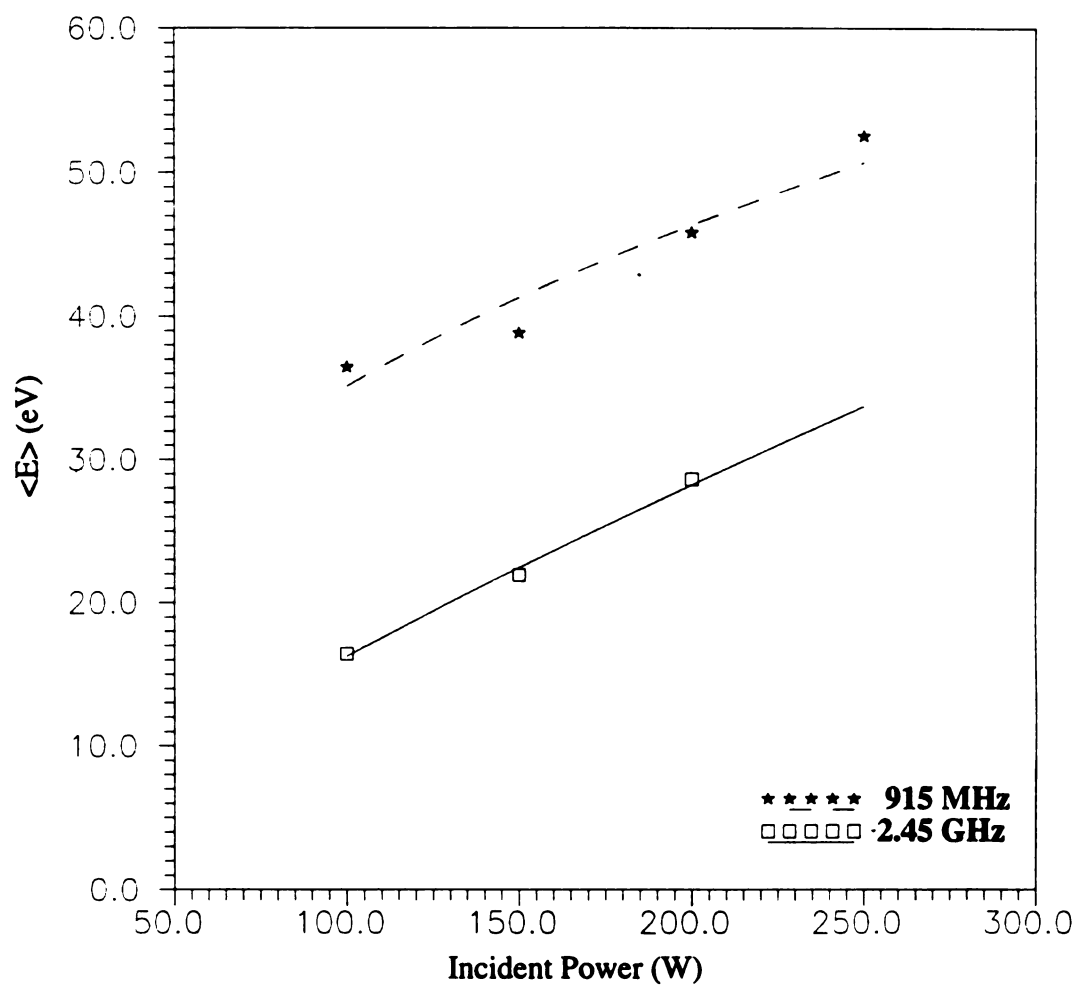


Figure 5.10 Average ion energy variation with input power for the two frequencies

Data are taken with the ion energy analyzer placed 3 cm downstream for a 0.55 mTorr argon discharge.

Figures 5.11 and 5.12 show the IEDF variation with discharge pressure (0.25 mTorr - 0.8 mTorr) at a fixed input power of 150 W. Data are taken, as before, with the IEA located 3 cm downstream for an argon plasma. At both frequencies of operation, the curves are seen to move towards lower energy as the pressure increases, although this IEDF shift (with changing pressure) is not as obvious as it was for Figures 5.8 and 5.9 (which showed the input power variation of IEDFs). As was mentioned in Chapter Four, this shift of the IEDFs towards lower energies for increasing pressure is probably due to the fact that as the pressure falls, the diffusion of charged species to the chamber walls increases, and therefore, higher electron temperatures are needed to sustain the plasma. And these high electron temperatures at the lower pressures, lead to higher plasma potentials, with a corresponding increase in the ion energy as the ions diffuse towards the grounded, shielded Faraday cup through the sheath potential set up on the surface membrane of the cup. This plasma potential variation with pressure has been reported earlier for 2.45 GHz excitation of the 610 (see for example Figure 4.16, Chapter Four). Figure 5.13 clearly shows an increase in the average ion energy with decreasing pressure for both frequencies of operation. Note that the 915 MHz ion energies are about twice those of the 2.45 GHz plasma, the same variation seen in Figure 5.10 where the variation of average energies is plotted versus input power.

Similar energy data - that is, a decreasing ion energy with increasing pressure and an increasing ion energy with input power have also been observed in other larger microwave discharges [Hop-91]. The ion energies in larger discharges, however, vary much more slowly with power and pressure, than they do in the more compact MPDR 610.

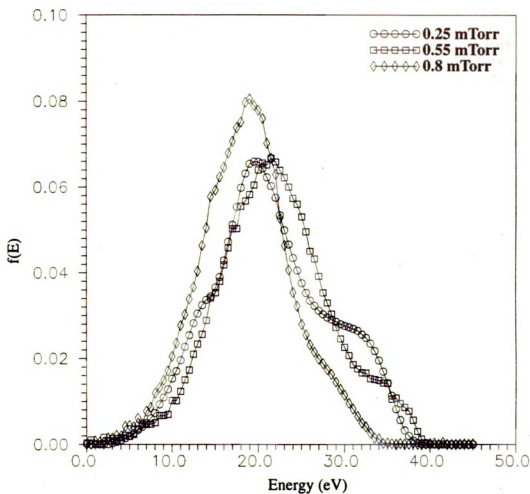


Figure 5.11 Ion energy distribution function variation with discharge pressure at 2.45 GHz

Data are taken with the ion energy analyzer 3 cm downstream for a 150 W argon discharge at various pressure levels.

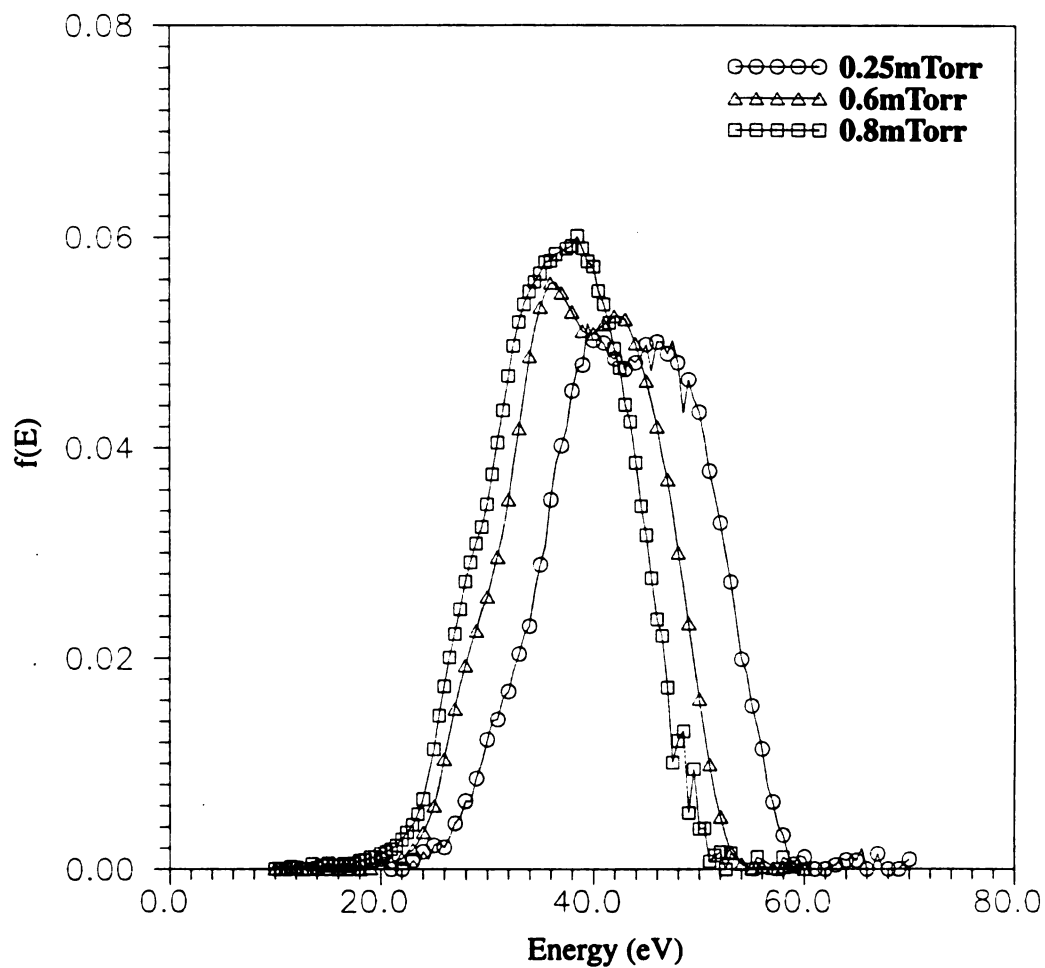


Figure 5.12 Ion energy distribution function variation with discharge pressure at 915 MHz

Data are taken with the ion energy analyzer 3 cm downstream for a 150 W argon discharge at various pressure levels.

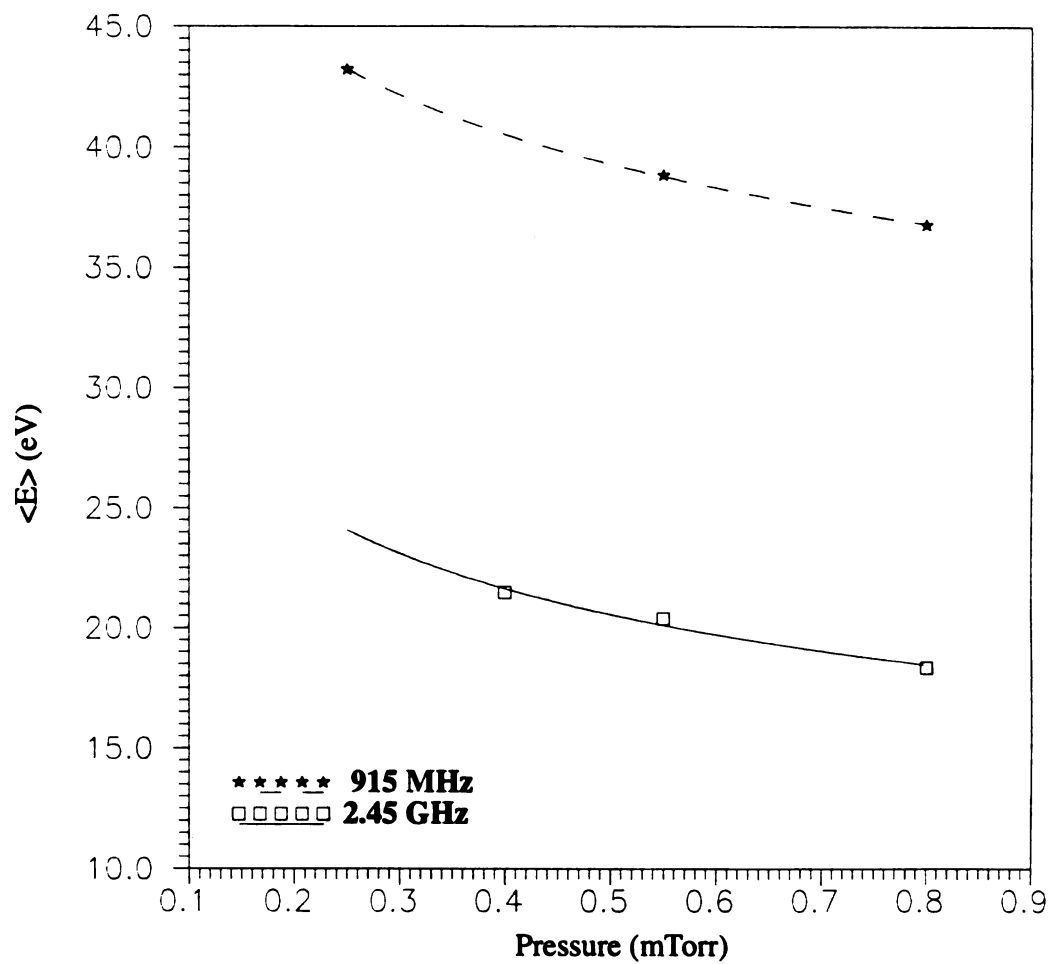


Figure 5.13 Average ion energy variation with discharge pressure for the two frequencies

Data are taken with the ion energy analyzer placed 3 cm downstream for a 150 W argon discharge.

5.5 Concluding Remarks

It is seen in this chapter that the performance of the MPDR 610 has many common features when excited at either of the two frequencies - 2.45 GHz and 915 MHz. At both frequencies, the plasma source readily produces argon charge densities of high 10^{10} cm^{-3} to low 10^{11} cm^{-3} at moderate input power levels of 100 - 200 W for sub-mTorr discharge pressures. When measured with the IEA placed 3 cm downstream from the discharge generation region, ions impinging on the analyzer have mostly narrow and peaked distribution functions, typically with less than 20 eV full width at half maximum (FWHM) at either frequency of operation. The IEDFs and average ion energies are, for both cases, relatively narrow and controllable by using power, pressure and substrate bias variations. Also, the average ion energy in both cases increases with increasing power, while it decreases with increasing pressure. Another common feature of the 610's operation in argon gas at either frequency is the hysteresis loop observed in the ion density variation with pressure at any input power level - an effect that leads to two ion densities for the same operating pressure.

There are, however, some differences also. A 915 MHz discharge displays higher electron temperatures than the discharge at 2.45 GHz, specially at higher pressures (0.5 mTorr - 0.9 mTorr). The reason for this difference in electron temperature variation (and specially the lack of the drop in electron temperatures with increasing pressures at 915 MHz as observed for a 2.45 GHz discharge) is not precisely known. However, it is speculated to be related to the different location of the ECR zones within the discharge for the two frequencies, which might produce different charged particle diffusion characteristics out of

the discharge generation region. The source therefore has different diffusion processes within and out of the discharge at the two frequencies of operation, that might produce the different electron temperatures. It is speculated that when using molecular gases, the differences in electron temperatures between the discharge at the two frequencies of operation may translate into different atomic radical production efficiencies. An analysis of radical flux density using a quartz crystal microbalance (as was done for the Oxford Applied Research radical gun, see Section 2.2.8, Chapter Two) would be able to confirm this hypothesis.

Another difference is observed when measuring the average ion energies, which are higher for a 915 MHz discharge, compared to those at 2.45 GHz (45 eV compared to 22 eV, for example). This too is directly related directly to the higher electron energies, and thereby the higher plasma potential of the 915 MHz excited discharge. Also, close to the discharge creation region, the radial profile of the ion density of a 915 MHz plasma indicates a hollow beam effect - this is not seen in the 2.45 GHz discharge. This hollow beam at 915 MHz does smooth out, however as distance downstream increases and the diffusion processes are controlled by the larger vacuum processing chamber.

Ion production efficiency is another figure of merit that may be used to characterize the plasma. It is measured in watts/beam amps, or eV/ion (both of which are identical units), and defines the efficiency of the plasma source, and the costs in terms of the power supplied to create the ions. Based on the available data of ion density, saturation current density and electron temperatures, it is estimated that the ion production costs in the MPDR 610 for both frequencies is high, about 1500 - 2000 eV/ion, as compared to the ion

production costs of larger ion sources [Sze-93b].

Another important conclusion from this study is the absolute lack of evidence for the “frequency squared scaling” effect that is well publicized in the multiply charged ECR ion source community. According to that law, the ion density at 915 MHz should have decreased as the square of the ratio of the two frequencies (i.e. densities of a 915 MHz excited discharge should be approximately eight times less than those at 2.45 GHz excitation). The data in this chapter indicates little variation in the ion density when the frequency of operation is changed from 2.45 GHz to 915 MHz. Two reasons may be attributed to the lack of the frequency squared scaling effect. First, the results presented here might indicate a complete breakdown of the theoretical developments that led to the frequency squared scaling law, at least in the realm of ECR plasma sources used in industrial applications. As will become clear later in this dissertation (in Chapter Eight) when multiply charged ion sources are discussed, the operating conditions of the two types of sources (i.e. low charge state ion/plasma sources for industrial applications, and the multiply charged ion sources for accelerator injection and atomic physics), are radically different, even though both may be ECR sources. While the frequency squared scaling law will again come under close scrutiny (even for multiply charged ECRIS - in Chapter Ten of this dissertation), data presented in this chapter clearly provide no indication that this law is valid for the ECR plasma sources used in industrial applications.

The second, and more important reason that may be attributed to this lack of evidence for the beleaguered frequency squared scaling law highlights the discussion of Chapter One, where power absorption into ECR plasma sources

was discussed (see Sections 1.2.1 and 1.2.2). It was mentioned there, that while a plasma source like the MPDR 610 may be technically called an "ECR source," the method of power transfer to the discharge is significantly more complicated than the "pure ECR," as the phenomenon is commonly understood. It may be that within the plasma sources used in industrial applications in general (and for the MPDR 610 in particular) which usually generate weakly to moderately ionized plasmas, the presence of energy transfer techniques other than ECR alone (like stochastic heating, or second harmonic resonance, etc.), repudiates the frequency squared scaling law from taking effect, and that this law might be valid only for plasma sources where pure ECR heating does occur (as may be the case for multiply charged ECRIS where ECR conditions - like extremely low operating pressure - are more likely to be met).

There is a lot of work that is needed to complete this particular sub-study of multiple frequency excitation of the MPDR 610, and some of this is mentioned now. As mentioned above, atomic/radical flux density measurement on molecular gases may indicate a difference in the radical production costs, and the difference in the electron temperatures at the two frequencies of operation. Also, optical emission spectroscopy might be used to understand the individual plasma constituents, specially the relative increase or decrease in the atomic species concentration at the two frequencies. It has already been shown in Chapter Four that many conclusions drawn for an argon discharge do not apply to diatomic gases, specifically nitrogen. This lack of correlating conclusions in the two discharge gases when operated at 2.45 GHz must be tested at 915 MHz also. Techniques like laser induced fluorescence may be used to compare the neutral gas temperatures at both frequencies of excitation, providing data on the

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energies of atomic species. Finally, a more accurate electron energy measurement needs to be done using the single Langmuir probe technique detailed in Chapter Three. This would provide definite results of the variation of electron temperatures and plasma potentials for the two frequencies of operation.

Errata: An error in Reference Sri-93a needs to be mentioned. Figure 5 of this reference has an incorrect caption and associated description. The data that are plotted in this figure were actually taken 5 cm downstream, and at 0.7 mTorr argon pressure (and not at 3 cm downstream at 0.55 mTorr pressure, as is mentioned in the article). Any inconvenience due this error is regretted.

Chapter 6

Evaluation: 610- α and the Electric Fields of the MPDR 610

6.1 Introduction

6.2 Description of Experimental Configuration

6.2.1 Description of the 610- α

6.2.2 Description of the Micro-coaxial Probes

6.3 Operational Performance - Plasma Loaded Measurements

6.4 Operational Performance - Empty Cavity Measurements

6.5 Operational Performance - Wall losses, Plasma Loaded Q and Coupling Efficiency Estimates

6.6 Summary of Results

6.7 Concluding Remarks

Errata

Chapter 6

Evaluation: 610-a and the Electric Fields of the MPDR 610

6.1 Introduction

The previous two chapters have been devoted to the description, and evaluation of the operational performance of the MPDR 610. A variety of experiments that were conducted on the plasma source have been detailed. The results of Chapters Four and Five present output performance characteristics such as the magnitude and spatial variation of ion density, ion and electron energy distribution functions and saturation current density versus the external input parameters such as microwave power, discharge pressure/flow, gas type, microwave frequency, etc.

Power is transported to the plasma source through a $50\ \Omega$ flexible cable that terminates in a loop antenna attached to the sliding short of the microwave cavity. The performance evaluation of the 610 cannot be complete without understanding the method of electromagnetic energy transfer from the loop microwave antenna, to the plasma load. In the last few chapters, it has been implicitly assumed that due to the unique coaxial design of the source, a

transverse electromagnetic (TEM) field is generated within the body of the 610. Energy is then transferred to the plasma load through a standing wave pattern set up between the sliding short and the terminus of the center conductor. Accurate measurements of the electric fields need to be made however, to validate and correlate the theoretical assumptions about the EM field to the actual fields that are set up within the source. A knowledge of how the electric field varies with pressure/flow, power, and gas type is invaluable for validating numerical models (that are currently being developed) and can lead to better understanding, and further optimization of this plasma source.

This chapter evaluates the impressed electric fields within the 610 by making direct measurements of the spatial variation and intensity of the fields. The data presented here are limited to the measurement of the electric fields within the plasma source. The relationship between these fields and the output - ion, electron, and radical species concentrations and energies - is not covered in this chapter. However, by comparing data from Chapters Four and Five with similar experimental input parameters as those used in this study, the relationships between the output species characteristics (from the previous two chapters) and these electromagnetic fields may be understood. This chapter is based on a presentation at the ICOPS-94 [Sri-94a], and which was subsequently published in a refereed journal [Sri-95a].

The format of this chapter is as follows. As will be seen, a new ion source similar to the MPDR 610 had to be built for these experiments. Due to the similarities between the new source, known hereafter as the 610-*a* (the adapted 610) and the original MPDR 610, data taken here may be used to infer vital knowledge about the 610. The experimental configuration used in this sub-

study is first described in detail, along with the necessity of designing and building the new ion source. The design of the 610-*a* is then detailed, using several computer aided design (AUTOCAD™) and assembly drawings. Three different kinds of micro-coaxial probes were used to measure the electric fields, and these are described. Data are taken here in accordance to the principles detailed in Chapter Three (Section 3.5), and the theory is briefly recapped here, along with some necessary details specific to the 610-*a* not mentioned in Chapter Three.

The measured electric field data (both the field patterns, and the exact, calibrated field strength) of a plasma loaded cavity as the gas flow/pressure, input power and gas type vary, are presented. Note that all data are taken at 2.45 GHz excitation frequency. Most data are taken with argon as the working gas, however some data on nitrogen is also presented. In Chapter Four it was noticed that the performance of the 610 differs significantly with nitrogen as the discharge gas, as compared to its argon performance. Data presented here will also highlight the fact that differences exist in the electric field patterns for the performance of the plasma source when the operating gas is nitrogen, as compared to argon.

Electric field data with no plasma ignited in the 610-*a* are presented next. These data, known as empty cavity measurements are taken at very low input powers (several mW), with the 610-*a* on a test bench. These measurements allow for a calculation of the empty cavity quality factor (Q_p). However, a more important reason to conduct these experiments was to try to understand the unique electric field patterns in the evanescent circular waveguide section and the plasma discharge section (enclosed by the permanent magnets) of the 610-*a*,

and by inference the 610. As will be seen later, this could only be done with no plasma in the 610-*a*. The results of these experiments help establish crucial conclusions about the performance of the 610.

Knowledge of the exact (calibrated) electric field strength within the plasma source may be used to arrive at several important analytical results. These include the following calculations: the power lost to the walls in the coaxial section of the ion source, the plasma loaded quality factor (Q_l), the total energy stored in the cavity, and finally the power coupling efficiency of the coaxial microwave applicator. This coupling efficiency is calculated two different ways. Comparing the two efficiency calculations then allows for an estimation of the exact amount of power lost to the walls, as well as to the loop antenna. This information may then be used to establish an equivalent microwave circuit with lumped circuit elements for the 610-*a*, and by inference for the MPDR 610. The equivalent circuit is discussed in a later section of this chapter. The chapter ends with some conclusions, and comments on further studying the 610-*a* to gain more insight into the performance of the MPDR 610.

6.2 Description of the Experimental Configuration

The electric fields that are set up inside an ion source can be calculated from a calibrated power measurement performed by inserting micro-coaxial probes into the conducting body of the source, as reported earlier [see Chapter Three, and Reference Hop-90b in particular]. Figures 4.3 and 4.4 (Chapter Four) show the configuration of the MPDR 610 as it is mounted on the vacuum processing vessel of the Yorktown T. Since the MPDR 610 is designed to

penetrate deep inside the vacuum chamber and generate a plasma close to the substrate, it is not possible to insert the probes directly into the body of the 610 itself. A modified source had to be used to conduct these experiments. This adapted plasma source, known as the 610-*a* was designed specifically for this sub-study, and is now described in detail.

6.2.1 Description of the 610-*a*

The 610-*a* is shown schematically in Figure 6.1 (not to scale) in its assembled form. Note that the inside of the source has a coaxial section of length l and, the circular waveguide section of length d just before the beginning of the quartz plasma tube. The thick brass wall of the 610-*a* is shown with the probe insertion holes (not all are shown) and the micro-coaxial probe (both holes and the probe are drawn larger than actual size), with its fixed collar. Figures 6.2 through 6.6 detail the CAD drawings (with exact dimensions in inches) of the individual parts, and these details are briefly discussed now.

The 610-*a* consists of an outer shell (shown in Figure 6.2) made of unleaded Naval brass with a wall thickness of 0.55 inches (about 1.4 cm). (Unleaded Naval brass is the proper choice where joints are to be soldered.) Small holes of 2.26 mm diameter for inserting the micro-coaxial electric field probes are drilled through the wall structure evenly at 45° angles (eight holes in each circumferential set), with 30 such sets spaced 0.25 inches (0.635 cm) apart. These holes constitute the micro-coaxial probe insertion points in the wall of the source. The thick outer wall prevents the micro-coaxial probes from bending, or warping inside the source while data are being collected. Another

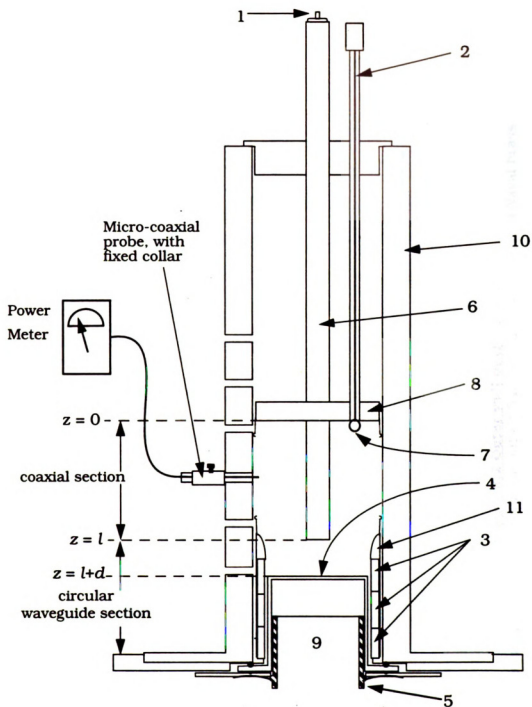


Figure 6.1 Cross section of the MPDR 610-a (not to scale).

- | | | |
|----------------------------------|--------------------------|----------------------|
| 1. Cooling air feed | 4. Quartz plasma chamber | 8. Sliding short |
| 2. Rigid coaxial cable | 5. Quartz chimney | 9. Discharge region |
| 3. Ring shaped permanent magnets | 6. Center conductor | 10. Outer brass wall |
| | 7. Loop antenna | 11. Magnet holder |

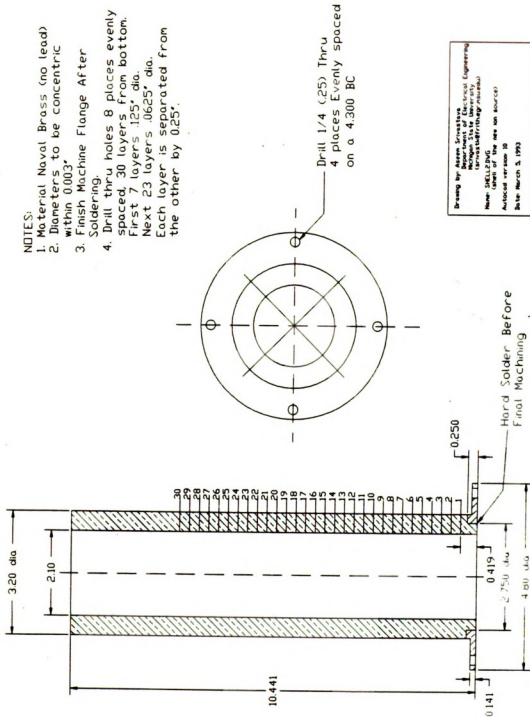
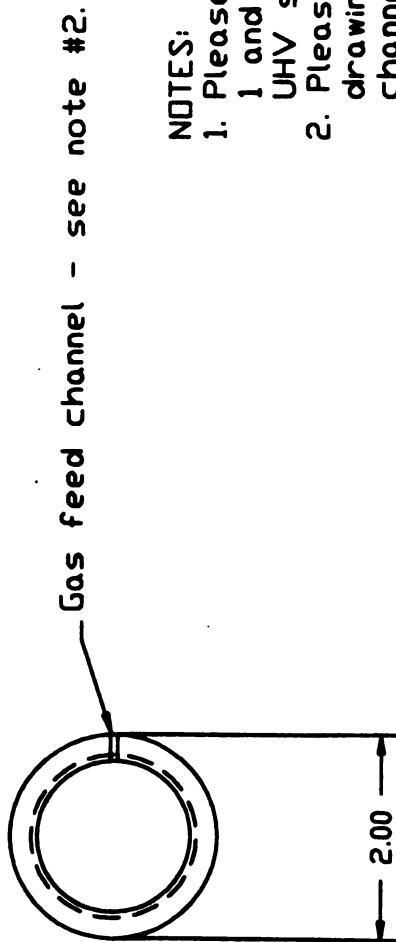


Figure 6.2 Outer wall of the 610-a

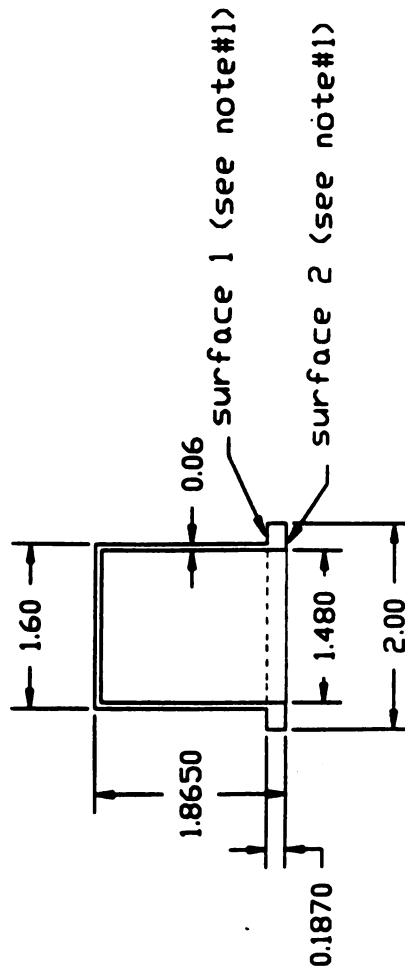
Note the thickness of the wall, about 0.55 inches. The wall, made of Naval brass (lead free) is thick to prevent warping, or bending of the micro-coaxial probe when it is inserted to measure the electric field.

QUARTZ PLASMA CUP



NOTES:

1. Please make surfaces 1 and 2 compatible with UHV seal.
2. Please refer to WAVEMAT drawing #031432 for the channel dimensions, and all tolerances.



Drawing by: Asoen Srivastava
 Department of Electrical Engineering
 Michigan State University
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 (517) 353-5866

Name: QUARTZ2.BUG
 (Quartz plasma cup for the new ion source)

Autocad Version: 18
 Date: March 18, 1993

Figure 6.3(a) Quartz plasma chamber

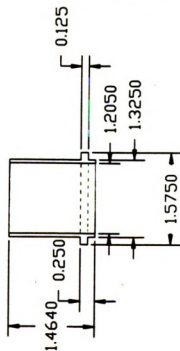
All dimensions of the plasma chamber and the chimney for the 610-a are maintained the same as those of the original MPDR 610.

QUARTZ GAS FEED CHIMNEY



NOTES:

1. Please refer to WAVEMAT drawing #031465 for all tolerances.



Drawn by Aspen Engineering
Department of Electrical Engineering
Michigan State University
(crivastu@enginr.msu.edu)
(517) 353-5066

Name: CHARTZ DVG
(quartz gas feed chimney for the new ion source)

Autocad version: 10

Date: March 18, 1993

Figure 6.3 (b) Quartz chimney of the 610-g

All dimensions of the plasma chamber and the chimney for the 610- α are maintained the same as those of the original MPDR 610. The chimney circulates the working gas all around the plasma chamber.

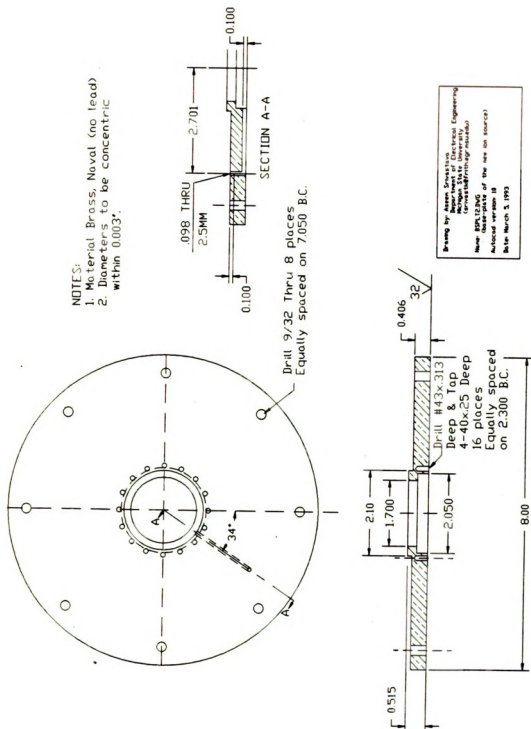


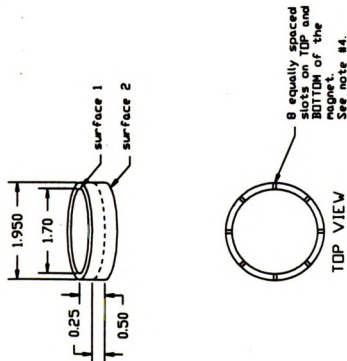
Figure 6.4 Base plate for the 610-a

Note the channel in the base plate through which a narrow tube connects an external VCR fitting to the gas feed into the quartz chamber of the 610-a.

option, as was done for the MPDR 5 described in Chapter Seven, would have been to use a thinner wall for the source construction, but with thick bands of brass wrapped around the source where the probe insertion holes are located. These bands would then prevent the warping or bending of the probes as they are inserted into the source.

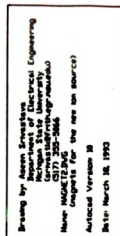
The internal dimensions of the 610-*a* are maintained exactly the same as those of the original MPDR 610 such that maximum correlation of data between the two sources could be made. Indeed, the center conductor/sliding short assembly shown in Figure 6.1 (and also in Figure 4.6) may be removed from the original 610, and used interchangeably between the two sources. Also, the dimensions of the quartz plasma chamber, the quartz chimney and the magnets for the 610-*a* are the same as those for the MDPR 610. The quartz plasma chamber, shown in Figure 6.3(a) is sealed to the base plate, shown in Figure 6.4 using a VitonTM O-ring and a HelicoflexTM spring seal (similar to that used to seal the 610). A small plate is used to clamp the seals and the quartz tube to the base plate. This base plate also has a small channel for the gas line (see Section A-A in Figure 6.4). A VCR fitting is soldered on the outside of the base plate and working gas is fed through this small tube into the quartz plasma chamber. An optional quartz chimney, (shown in Figure 6.3(b)) may be used to direct the gas to the top of the plasma chamber, where the plasma ignition takes place.

The 610 has three axially magnetized ring shaped rare earth permanent magnets, as shown in Figure 4.2(a). A set of magnets with the exact same dimensions was also used for the 610-*a*. In order to probe the impressed electric fields in the magnet (or plasma loaded) region of the 610, the magnets for the 610-*a* were modified. Figure 6.5 shows that the modifications were minor - all



NOTES:

1. Ring shaped magnet like the one for the WAVEMAT MPDR-610 ion source.
2. Axially magnetized - see WAVEMAT order for minimum pole face field strength.
3. Drill 8 thru holes 1/16 inch dia. equally spaced around the dashed line (in the center of the magnet).
4. Make 8 slots 1/16 inch dia. equally spaced on top AND bottom of the magnet (surfaces 1 and 2).

**Figure 6.5 Magnets for the 610-q**

Note the 0.0625 inch diameter holes drilled in the center plane of the magnets, and also the grooves on the top and bottom. When aligned together, this gave seven sets of holes for the probes to be inserted into the magnet section of the 610-q.

dimensions (inner and outer diameter, and height) remained the same as for the magnets of the original 610, but eight 0.0625 inch (0.156 cm) diameter holes were drilled through the center plane of each magnet, with slots of similar diameter at the top and bottom of the rings. When aligned properly seven sets of holes in the magnet assembly were available (with eight holes located 45° apart in each set) in which the micro-coaxial probe could be inserted to measure the power of the radial component of the impressed electric field in the discharge region of the 610-*a*. It must be mentioned that the addition of holes and slots on the magnets did not change the pole face strength, and is therefore expected that the magnetic fields within the discharge of the 610-*a* are the same as those in the original 610 (with its normal magnets).

The two parts of the magnet holder are shown in Figure 6.6(a) and (b), and the assembly is shown in Figure 6.6(c). This holder, used for the magnet assembly of the commercial MPDR 610 ion sources was bought from Wavemat, Inc. (Figures 6.6(a) through 6.6(c) are courtesy of Wavemat, Inc. of Plymouth Michigan.) The aluminum holder also has 0.125 inch diameter holes drilled in the appropriate locations (seven sets with eight holes each, 45° apart) such that they are aligned with the seven sets of eight 0.0625 inch diameter holes of the magnets. Note that larger holes in the magnet holder help in physically aligning the smaller magnet holes to those on the holder when the assembly is being put together.

A word of caution about assembling the three magnets. As shown in Figure 4.2(a), the configuration of the magnets for the MPDR 610, and therefore for the 610-*a* is such that the three rings naturally repel (i.e. the South poles of two rings face each other). Care must be exercised when putting the magnets

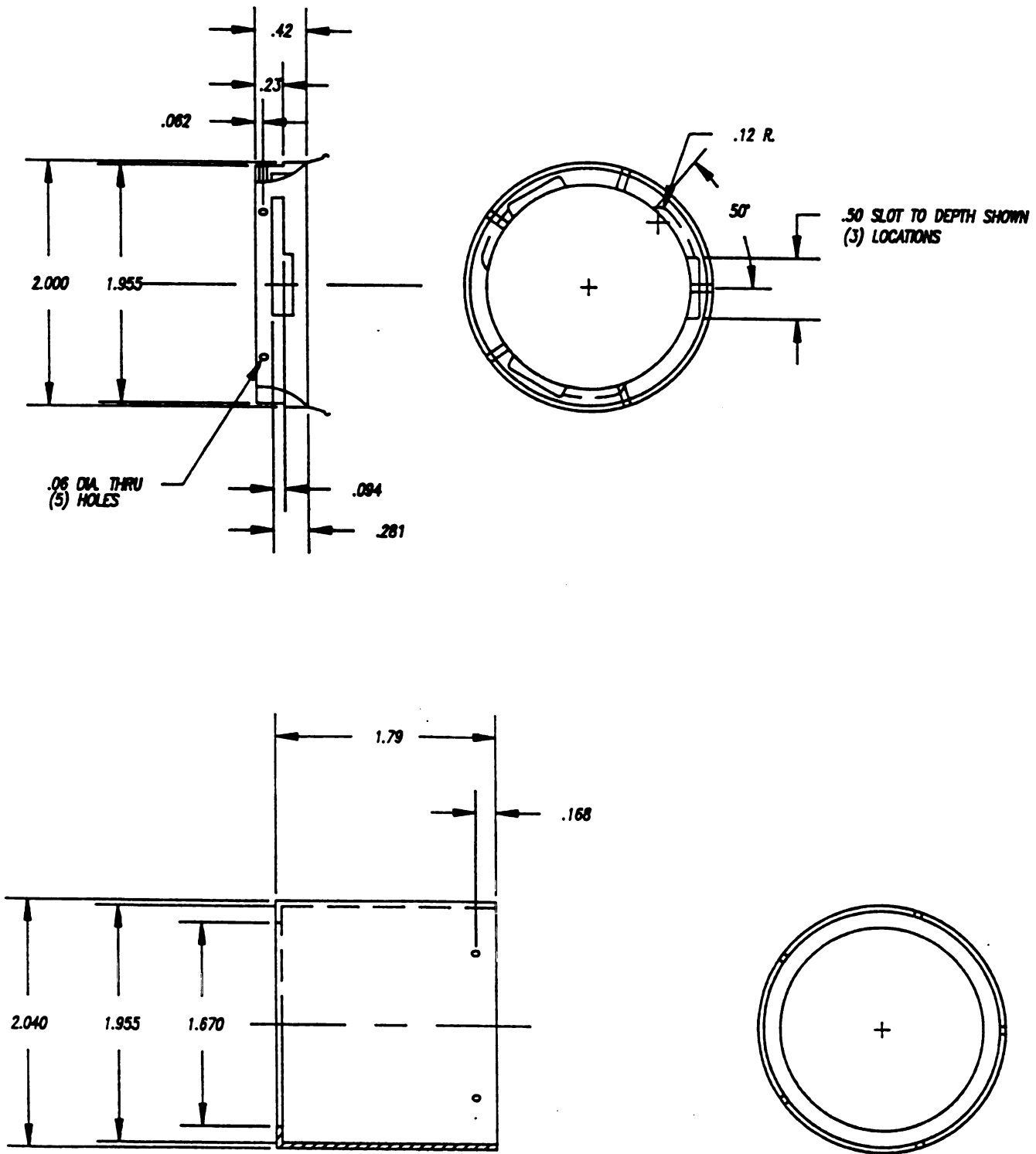


Figure 6.6(a) and (b) The two magnet holder sections for the 610-a

This aluminum magnet and stainless steel magnet holder assembly was bought from Wavemat Inc. and is the same as that used for the MPDR 610 sources. The outer aluminum shell also had holes drilled (0.125 inch diameter) that aligned with the magnets inside, and the brass outer wall of the 610-a outside.

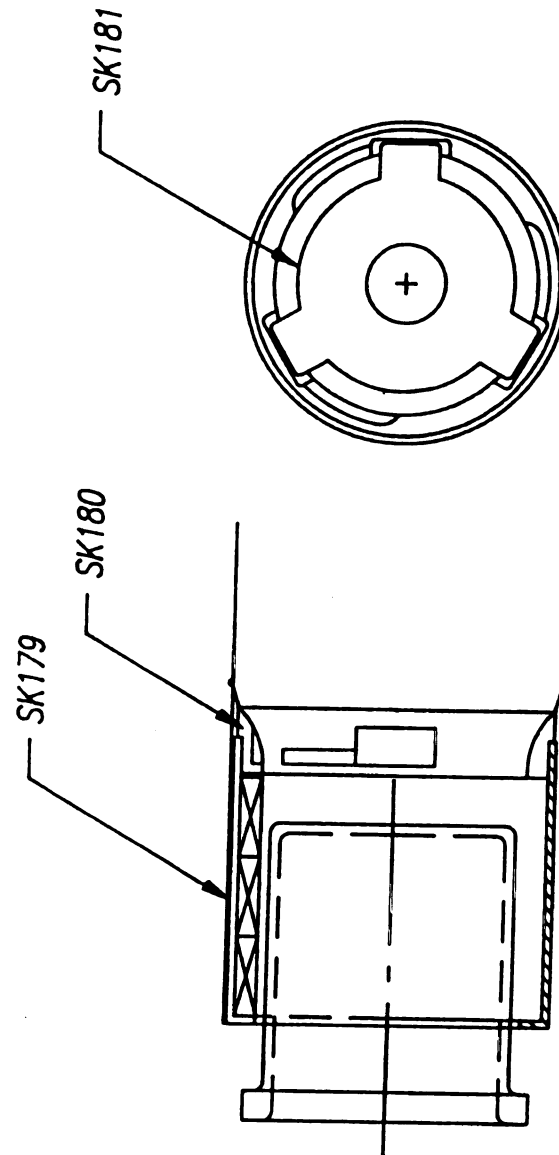


Figure 6.6(c) The assembled magnet holder for the 610-a

The two sections of Figure 6.6(a) and (b) are attached using set screws. This figure shows the position of the magnets, the holder assembly, and the quartz discharge chamber

together, not only so that all the holes and slots on the magnets align, but also because the slightest lapse can cause the magnets to flip over and smash into each other (or into some other magnetic material). This may also be hazardous to health since the magnets could act as fast projectiles when being attracted towards other magnetic materials. Due to the thin dimensions (0.125 inches thickness, 0.5 inch high), and also because of the probe insertion holes drilled in the rare earth SmCo material, the magnets are exceedingly fragile. Indeed, such an accident did occur when the magnets were being put together, leading to destruction of two of the three rings. The broken magnets had to be reordered that led to several weeks loss of valuable time

Figure 6.7 shows the two ion sources (610, and the 610-*a*) as they are mounted on the vacuum chamber of the Yorktown T. As can be seen, the main difference between the two sources is that the 610-*a* sits outside of the vacuum chamber and the vacuum seal is formed near the plasma discharge region (as is the case for all other MPDR sources), while the discharge of the 610 is generated deep inside the vacuum, far away from its 4.5 inch Conflat flange vacuum seal. This keeps the entire body of the 610-*a* outside of the vacuum, and allows for electromagnetic field pattern measurements to be performed on the source through the small holes drilled in the outer wall. Regular VitonTM O-rings are used to make the vacuum seal between the 610-*a* and the vacuum chamber. These seals are capable of achieving base pressures up to the mid 10^{-8} Torr range. As in Chapters Four and Five, the input gas flow rate and the chamber pressure are related due to the absence of a variable conductance valve on the vacuum system. Thus experiments described here are defined in terms of the stack pressure alone. The corresponding gas flow rates for the pressures

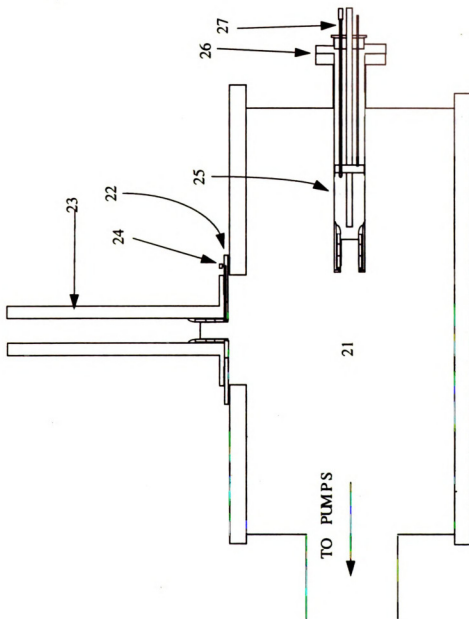


Figure 6.7 The MPDR 610 and 610-a on the vacuum chamber.

Note the location of the vacuum seals for the two sources. (21) Vacuum chamber, (22) Vacuum seal of the 610-a, (23) the 610-a, (24) gas feed of the 610-a, (25) the MPDR 610, (26) vacuum seal of the 610, and (27) the center conductor and sliding short assembly common to both sources.

indicated in the forthcoming sections may be looked up in the previous two chapters.

6.2.2 Description of the Micro-coaxial Probes

As stated earlier, measurements of the electric fields are conducted using a set of semi-rigid micro-coaxial probes. The outer diameter of the probes is 2.25 mm, and the inner conductor diameter is 0.6 mm. The details of using such micro-coaxial probes (also known as the E-field probes) have been described earlier [Hop-90b, Hop-91, Asm-87, Rog-82], and also detailed in Chapter Three (section 3.5). For the sake of completion, a brief recapitulation is presented here. The E-field probe is inserted such that the outer conductor is flush with the inner wall of the plasma source, and there is good electrical contact between the outer conductor and the source wall - i.e. the probe does not move, bend or warp inside the hole. The inner conductor of the probe penetrates slightly deeper into the source body. This creates a monopole over a semi-infinite plane effect, where the inner conductor acts as a receiving antenna, and measures the normal (radial) component of the impressed electric field. This type of coaxial probe is identified as the "penetrating probe" in this dissertation (see Figure 3.13, Chapter Three).

To maintain the sensitivity of the measurement, the inner conductor of the probe must be inserted sufficiently deep into the source. Yet, the deeper the probe penetrates into the source, the more the impressed electric fields are perturbed. To minimize this perturbation while maintaining the sensitivity of the measurement, the inner conductor of the probe was inserted only 30/1000 of an

inch into the ion source body. A fixed collar, as shown in Figure 6.1 was used on the outer conductor of the probe so that at each insertion hole, the probe was inserted into the source body to exactly the same depth (also see Figure 3.15, Chapter Three). This maintained the relativity of the power measurement at every hole with respect to other measuring positions.

Note that in the magnet region of the ion source, the E-field probe has to be inserted deeper into the source, since the magnets, which are in good electrical contact with the outer wall of the source, effectively increase the wall thickness. Hence probes with two different lengths had to be used - one for the coaxial section of the source (outer wall only), and one for the magnet (or the discharge loaded) section of the source (outer wall plus the magnet/magnet holder). Care was taken when constructing the probes, that for each type of probe, the insertion of the inner conductor is exactly 30/1000 of an inch, while the outer conductor of the probe is still flush with the inner wall of the source (in the coaxial section), or the magnet (in the discharge loaded section).

Another type of probe, with its inner and outer conductor both flush with the inner wall of the ion source was used to calibrate the data [Hop-90b, Hop-91, Bur-85]. The micro-coaxial probe power measurement (P_{pr}) made with this "flush" probe is related to the absolute magnitude of the radial electric field (E_r) by the equation [Bur-85]:

$$E_r = \left(\epsilon_0 K_r \pi c^2 \omega \right)^{-1/2} \sqrt{\frac{2P_{pr}}{R_0}} \quad (6.1)$$

where c is 0.3 cm - the radius of the inner conductor of the micro-coaxial probe, ω is the frequency of operation ($2\pi \times 2.45$ GHz), ϵ_0 is the permittivity of free

space, K_r is a dimensionless area multiplier and equals 3.846 from Ref. B-1 for a flush probe, and R_0 is the 50 Ω characteristic impedance of the coaxial probe. Figure 3.13 (Chapter Three) shows the details of the two types of probes that were used to measure, and calibrate the electric fields. As with any other experiment mentioned in this dissertation, each data acquisition session with the micro-coaxial probe was conducted several times to minimize random errors and ensure repeatability. Note that the accuracy of this measurement depends heavily on the use of the constant K_r whose value is taken from literature to be 3.846, and this may be a source of error while calibrating the measurement of the electric fields. The validity of using this value of the constant is currently being tested by comparing the electric field data that is taken on another MPDR source using this constant, with the electric field data calculated by another method. Initial evidence may indicated that the actual value of the electric fields may be less than those calibrated using this K_r value [Mak-95].

6.3 Operational Performance - Plasma Loaded Measurements

In general, the input microwave power (at 2.45 GHz) coupled into the source is given by $P_t = P_i - P_r$ where P_i is the incident power, P_r is the reflected power. P_t is therefore the net input power absorbed by the plasma source. However, the walls of the plasma source are not perfectly conducting, and so not all input power is actually absorbed by the plasma discharge. The net input power may therefore be further divided between the power delivered to the conducting walls P_w , and power delivered to the plasma load P_l . The exact division of the input power between the walls and the plasma load depends on

the relative losses to the plasma, and the losses on the conducting walls. All electric field data points presented in this chapter were taken with the source optimally matched to minimum reflected power. Under all operating conditions for both the MPDR 610 and the 610-*a* discussed in this chapter, the reflected power is less than 5% of the incident power when the source is optimally tuned, and so P_t can usually be approximated by P_i .

Figure 6.8 shows a typical measured electric field curve, versus the cavity length for a discharge loaded 610-*a*. The argon gas discharge, at a pressure of 1.0 mTorr with about 130 W input power was matched to the external transmission line by adjusting the lengths l to be 8.25 cm, and d to be 2.5 cm. (See Figure 6.1, or Figure 4.6 of Chapter Four for the definitions of the two lengths l and d .) The abscissa on the experimental data plot corresponds to the probe insertion holes on the wall of the 610-*a*, each point being 0.25 inches apart, while the ordinate of the data plot is the absolute (calibrated) electric field strength in kV/m. This absolute field is calculated using Eqn. 6.1 after the relative power measurements that are taken with the "penetrating" probe are calibrated with the "flush" probe.

As can be seen, experimental data are taken for holes 12 - 20, and 24 - 30. Because of interference from the finger stock of the sliding short, data could not be taken for holes below number 12. Similarly, the data between hole numbers 20 through 24 is unavailable, due to interference from the finger stock of the magnet holder. Note however, that based on the measured data for holes 12 through 20, a dashed curve is plotted for holes 9 through 12 which then extrapolates the measured data to the expected experimental standing (sine function) wave electromagnetic field that starts from the sliding short surface

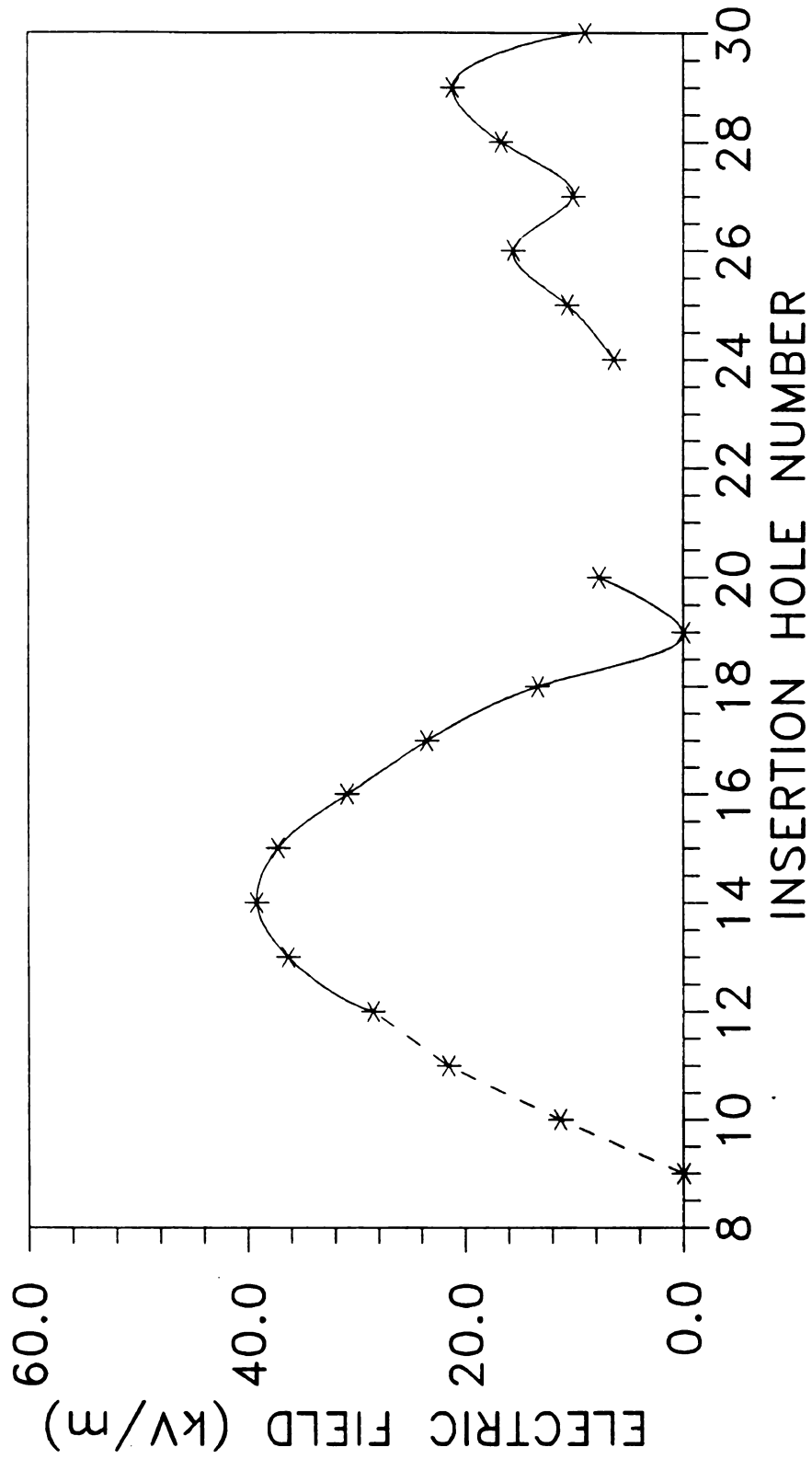


Figure 6.8 Typical measured radial electric field curve versus length of the 610-a.

Data is taken for a 1.0 mTorr argon plasma at 130 W input power. Dashed line indicates extrapolated data for positions 9-12.

plane located at hole number 9.

Several salient features of the data stand out. For about 130 W input power, the radial electric field strength can reach up to several tens of kV/m. If, as shown in Figure 6.8, using the $40 \times 10^3 \sin(kz)$ functional dependence, the experimental data is extrapolated back from hole number 12, the electric field does indeed reduce to zero as expected, at hole number 9 - which is the location of the sliding short. From position 9, the electric field increases to a maximum at hole 14, and again decreases to almost zero at hole 19 indicating the presence of a typical standing wave pattern. Taking the distance between the local maximum and the local minimum on the data plot, the experimentally measured wavelength is calculated to be about 12.7 cm within the coaxial section of the source. The discrepancy in the experimentally determined wavelength and the theoretical TEM mode wavelength at 2.45 GHz of 12.24 cm is probably due to the limitation in taking the data at discrete intervals - i.e. every 0.25 inch. The discrepancy may also be enhanced by the slight shifts in the local minimum of the field pattern caused by the fringing evanescent fields from the terminus of the center conductor.

Despite this minor limitation, the measurements confirm that a standing wave is set up in the coaxial section of the source. Based on this, it is expected that a local maximum be set up at the termination of the coaxial section of the 610 (or the 610- α), which is at the end of the center conductor at hole number 22. This will be corroborated later in Figure 6.12, when data taken without interference from the magnet holder's finger stock are presented. The distance l in Figure 6.1, from the end of the sliding short (position 9) to the end of the center conductor (position 22) can now be expressed in terms of the TEM mode

wavelength. The length l is equal to about 0.67λ . Note that this is neither 0.5λ , nor 0.75λ , but somewhere in the middle.

Boundary conditions at the terminus of the center conductor dictate that evanescent electromagnetic modes be set up in positions 22 through 30, in the circular waveguide and the plasma loaded sections of the microwave applicator. This is because the diameter of this part of the source is less than that required for the lowest cutoff propagating mode at 2.45 GHz (TE_{11}). However, as can be seen in Figure 6.8, there is clearly some evidence of a non-decaying electric field in the plasma loaded section of the source, and there may be some low intensity standing waves being set up in, or on the surface of the discharge that have a radial component (the micro-coaxial probes can only measure radially directed electric fields). It is difficult to represent the exact analytical shape of the field in this region without a more thorough theoretical solution. However, the measured data do indicate that the electric field strength at the inner walls of the magnets is diminished - about half, to one third the field strength in the coaxial section of the source.

Figure 6.9 shows the variation of the absolute radial electric field versus the plasma cavity length for several argon discharge pressures at a fixed input power of 130 W. As had been reported earlier in Chapter Four of this dissertation, the MPDR 610 has two distinct modes of operation: the low density mode at low pressures, and the high density mode at higher pressure. There is a discontinuous jump in ion density and brightness of the plasma between the two modes (see Figure 4.8, Chapter Four). In Figure 6.9, two pressures (1.5 mTorr, and 1 mTorr) correspond to the high density mode, and two pressures (0.7 mTorr and 0.2 mTorr) correspond to the low density mode. In the low density

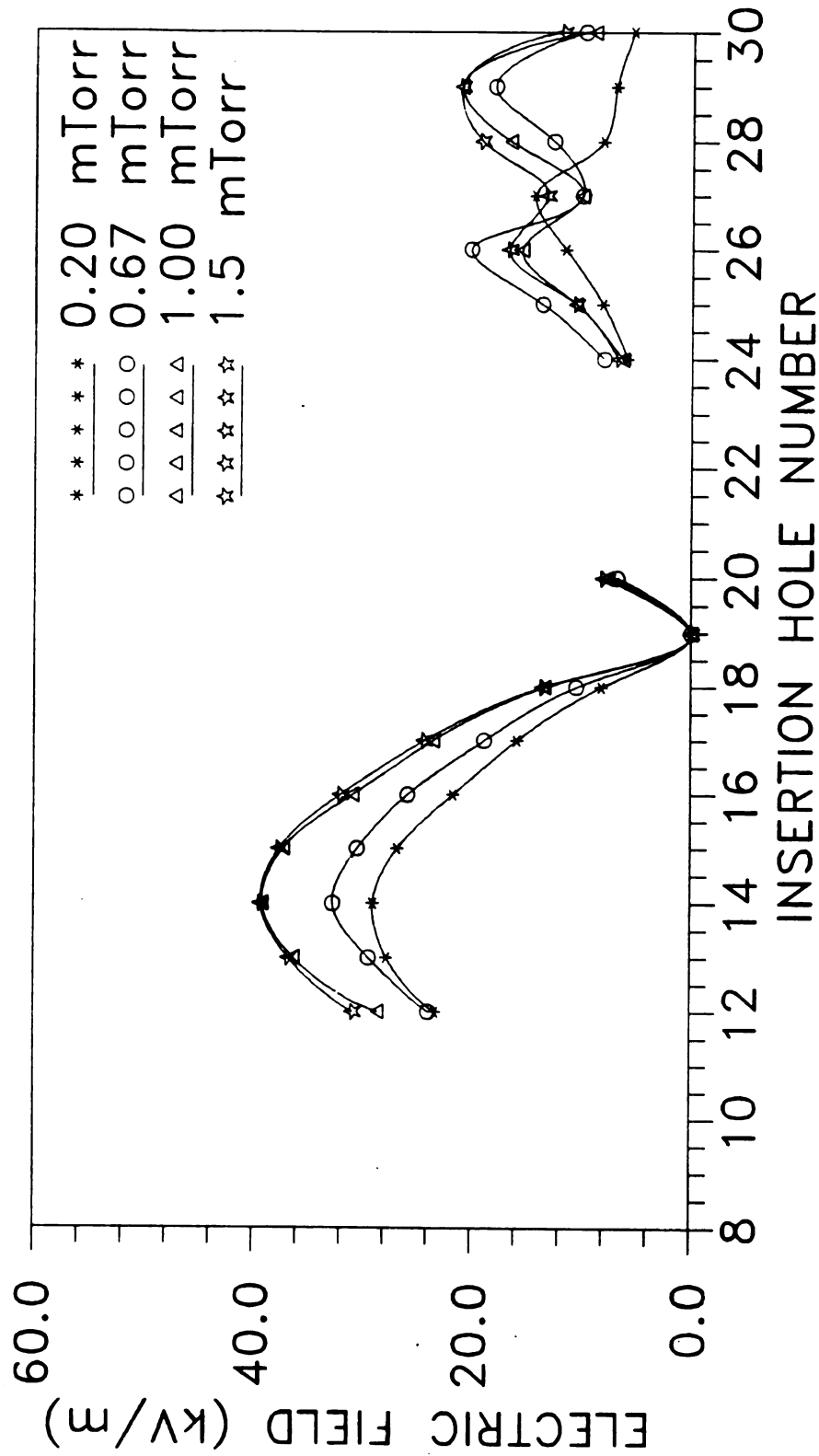


Figure 6.9 Electric field versus cavity length showing argon pressure dependence.

Data taken at 1.5, 1.0, 0.67 and 0.2 mTorr argon pressure, at 130 W input power.

mode the peak electric field strength is approximately 30 kV/m, while the peak field strength for the high density mode is 40 kV/m. Data are taken for argon gas, with a net input power of 130 W and optimized tuning for each case. Cavity tuning for the two modes is essentially the same, with minor adjustments necessary on the length of the center conductor (about 1 mm).

When the source jumps between the two modes of an argon discharge, both the ion density output of the source and electric field strength within the source body increase and decrease together. Once the ion source is in either the low density, or high density mode, the electric field varies only slightly over the respective experimental range of pressures shown in Figure 6.9. However in both modes the electric field strength decreases with decreasing pressure. Since the loaded quality factor of the cavity is directly proportional to the electric field strength, a lower field strength in the low density mode seems to indicate that the loaded quality factor has decreased in this mode. Hence, the power coupling to the plasma seems to actually get better at the low density mode - there is more collisionless damping at lower pressure. This field strength variation is very slight between 1.0 mTorr and 1.5 mTorr, but there is a 4 kV/m decrease between 0.67 mTorr and 0.2 mTorr. Figure 6.10 shows the input power dependence of the electric field for a 1.0 mTorr argon plasma. As expected, the absolute field strength increases with power. In both Figures 6.9 and 6.10, there is once again, evidence of a non decaying field in the discharge (magnet) region of the source.

Figure 6.11 displays the pressure dependance of the plasma source operating in nitrogen gas with a constant input power of 130 W. Some difference in the measurements of electric fields between discharges of the two gas types

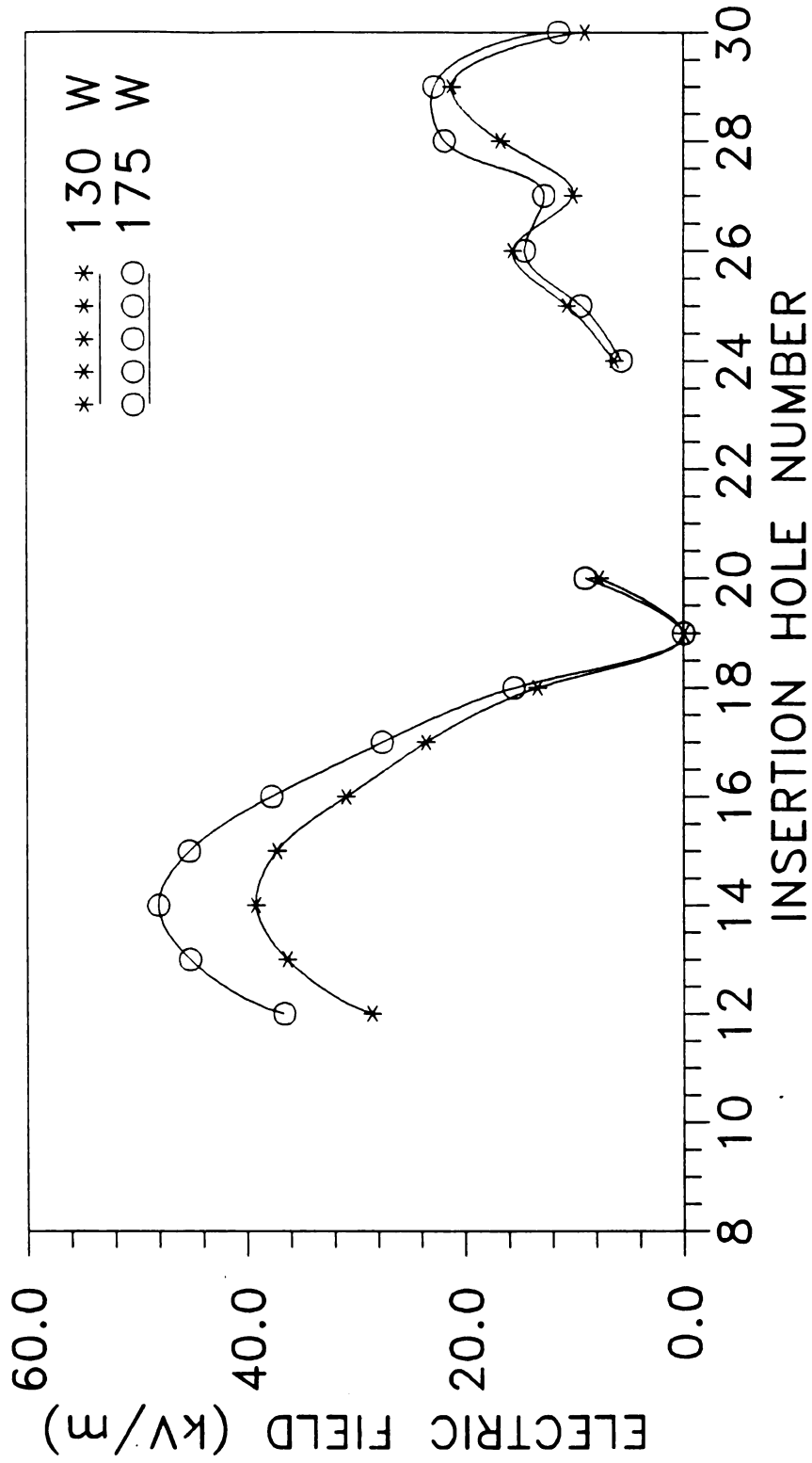


Figure 6.10 Electric field versus cavity length showing argon power dependence.

Data taken for 175 and 130 W input power, for a 1.0 mTorr argon discharge.

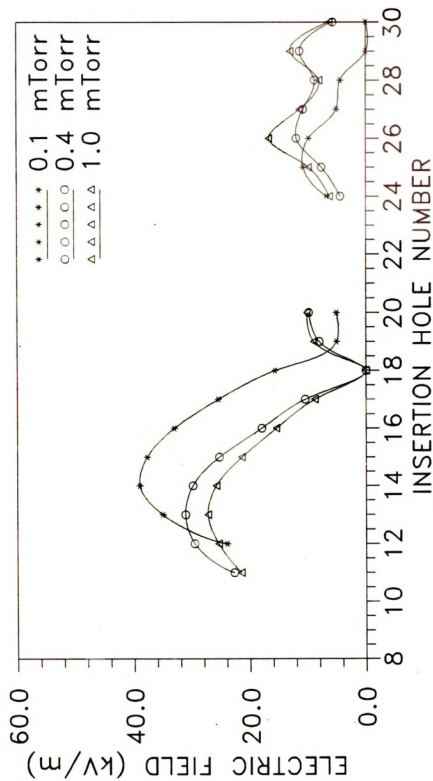


Figure 6.11 Electric field versus cavity length showing nitrogen pressure dependence.

Data taken at 0.1, 0.4 and 1.0 mTorr; for 130 W input power. Note that the zero of the electric field is at a position different from that of the argon plasma.

were observed. In contrast to an argon discharge, the 610-*a* had to be retuned to match the nitrogen plasma load impedance as discharge pressure was varied. In particular, for 0.4 mTorr and 1.0 mTorr, the sliding short and the center conductor were shifted together approximately 0.7 cm further away from the positions that were necessary for matching an argon plasma, and so the length d is about 3.2 cm. However, since both the center conductor and the sliding short had to shift together, the length l remained approximately constant a 0.67λ , - the same length required to sustain an argon discharge. The pressure dependence of the electric field is opposite that observed in argon - the electric field increases with decreasing pressure. Despite these differences, the spatial variation and absolute magnitude of the electric fields within the source body for a nitrogen discharge are similar to that for argon. Finally, the standing wave in the coaxial section, and a non-decaying field in the circular waveguide region are once again clearly visible.

6.4 Operational Performance - Empty Cavity Measurements

For empty cavity measurements on the MPDR 610 and the 610-*a*, the sources were excited at low power (a few mW) using a sweep oscillator set at 2.45 GHz while placed at atmospheric conditions on a test bench. The power absorption versus frequency curve was displayed on an oscilloscope, and the 610, or the 610-*a* then tuned to its typical plasma loaded position. From the power absorption curve, the empty cavity quality factor (Q) of the MPDR 610 and the microwave generator equipment was determined using the following formula:

$$Q = \frac{f_0}{\Delta f}, \quad (6.2)$$

where, Δf is the half maximum width of the Q curve when the resonant frequency is matched to the external microwave circuit, and f_0 is the resonant frequency (approximately 2.45 GHz). For the case of critically coupled cavity (minimum reflected power, and maximum power transfer to the load), the empty cavity Q_E of the 610 is twice the measured Q , and was determined to be about 1800. This high unloaded cavity quality factor indicates that the coupling loop and the cavity walls have low losses. Such a low loss cavity also provides the benefit of simple discharge ignition at low (sub-mTorr) vacuum pressures. The high electric fields required for gas breakdown at sub-mTorr pressures are readily achieved inside the cavity with low incident powers because of this high unloaded (empty cavity) quality factor.

In order to improve the understanding of the high power plasma loaded behavior several low power (10 mW to 12 mW), empty cavity experiments were also performed on the 610-a. The sweep oscillator was adjusted to 2.45 GHz continuous wave operation and approximately 10 - 12 mW of incident power was applied to the source. The positions l and d were adjusted for a matched resonance, and using the same micro-coaxial probes from the plasma loaded experiments above, the electric field strength versus position was measured for several cavity configurations: (1) empty cavity with the magnets in place (i.e. this is the high power cavity configuration, but without the plasma load), (2) empty cavity with the magnets removed and (3) empty cavity with the inner surface of the magnets covered with a layer of thin conducting tape (the reason for choosing these configurations will become apparent shortly). Due to the minimal

power being applied to the 610- α , the electric field patterns measured by the probes in these experiments were actually amplified numerical voltage signals that had to be normalized to the plasma loaded cavity measurements for comparison.

In Figure 6.12 the measured electric fields for two of these cavity configurations are displayed, and compared with an example plasma loaded data set for argon gas. This data set for argon gas in Figure 6.12 displays the actual measured data (plasma loaded cavity), while the low power measured field strengths were amplified and are displayed with the two low power curves normalized to 40 kV/m maximum. It is observed that all three curves have a similar standing wave shape versus axial position in the coaxial $0 < z < l$ section. So the plasma source, for an argon discharge, needs little adjustment from the empty cavity sliding short and center conductor positions to match power for the operating conditions at 130 W input. For the empty cavity measurements, the lengths l and d remain the same as for the plasma loaded cavity - at 0.67λ and 2.5 cm respectively.

However, the curves differ in the circular waveguide region $z > l$. When the magnets are removed it is possible to make micro-coaxial probe measurements in positions 20 through 24 because there is no more magnet holder finger stock to interfere with the measurements. As expected, this "empty cavity - no magnets" curve in Figure 6.12 has a local maximum approximately at position 22 where the center conductor terminates. Beyond this position, for holes 23 through 30, the electric field decays. This spatial field variation is expected for the evanescent (cutoff) electromagnetic fields set up in the circular waveguide section of the source. When the magnets and the magnet holder assembly are

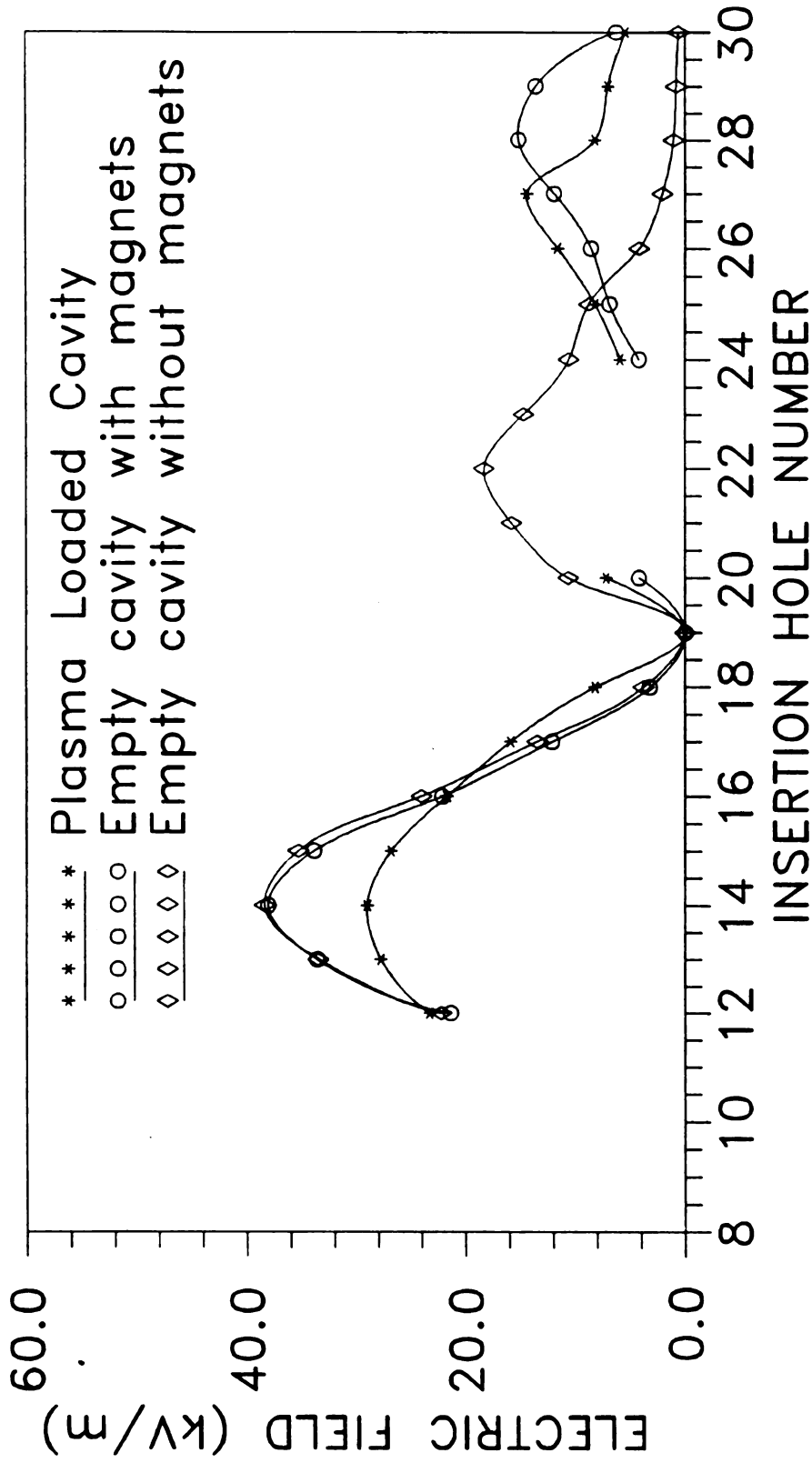
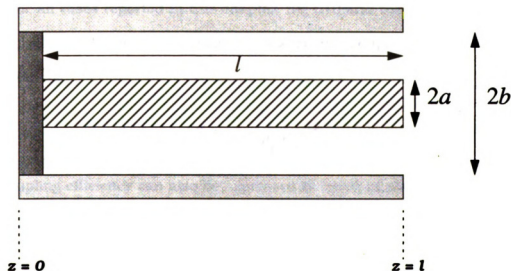


Figure 6.12 Empty cavity measurements on the 610-a
 Plasma loaded cavity data (argon plasma, 0.2 mTorr pressure, 130 W input power) compared to empty cavity with magnets, and empty cavity without magnets data.

reinserted into the source, the field exhibits a non decaying behavior for positions 25 through 30 which is similar in shape to the fields measured when the cavity is loaded by a discharge. Note that with the magnets in place, the field can not be measured in holes 20 through 24, for both the empty cavity and the discharge loaded cavity cases. These empty cavity data, specially the "empty cavity - no magnets" curve, suggest that the rare earth permanent magnets, which are made of Samarium-Cobalt - a material with a higher surface resistivity than brass or stainless steel (the material of which the 610-*a* and the 610 are made of, respectively) may actually help the electromagnetic field penetration into the discharge region by creating a localized standing wave in this region of the MPDR 610, where EM theory allows the existence of evanescent modes only.

To test this hypothesis further, the magnets were coated with conductive copper tape having a conductive adhesive, with small openings left for probe insertion. This allowed the entire length of the 610-*a* from the end of the center conductor (position 22) to the bottom (position 30) to be an excellent electrical conductor. Again measurements were made with about 10 - 12 mW of power from the sweep oscillator, and the amplified voltage signal was normalized, as before. It was observed that the electric field in the coaxial part of the source matched exactly with the plasma loaded cavity. In the magnet region however, when the magnets were covered with the conductive tape, the fields decayed exponentially exactly as in the case of the "empty cavity - no magnets." Clearly, the lossy material of the magnets helps in some way to produce the non-decaying fields that are observed in the discharge region (holes 24 through 30) as seen in Figures 6.8 through 6.12.



$$2a = 1.2 \text{ cm}$$

$$2b = 5.3 \text{ cm}$$

$$l = 8.25 \text{ cm}$$

Figure 6.13 Topology of the coaxial section of the 610-a

This figure shows where the exact calculations of the wall losses, and the loaded quality factor of the 610-a are conducted. Here, l is the length of the center conductor of the 610.

6.5 Operational Performance - Wall Losses, Plasma Loaded Q , and Coupling Efficiency Estimates

The microwave power absorbed by the conducting walls, P_w , and the coupling efficiency of the microwave power into the plasma source may now be estimated from the measured spatial electric field strengths. In general, the plasma loaded coupling efficiency is given by [Asm-87]:

$$Eff = \left(\left(\frac{P_l}{P_i} \right) \times 100 \right) = \left(1 - \frac{P_w}{P_i} \right) \times 100. \quad (6.3)$$

Since for all cases reported in this chapter, the 610 and the 610- α are tuned to an optimal match (minimum reflected power), the coupling efficiency can be expressed as:

$$Eff = \left(1 - \frac{P_w}{P_t} \right) \times 100. \quad (6.4)$$

The coupling efficiency can also be expressed in terms of plasma loaded quality factor, Q_L and empty cavity quality factor, Q_E , [Mak-92], i.e.

$$Eff = \left[1 - \frac{Q_L}{Q_E} \right] \times 100. \quad (6.5)$$

By substituting the measured electric field from the experimental measurements of Section 6.3, the power loss to the walls in the coaxial section of the resonant cavity of the 610- α , and by inference, the MPDR 610 can be approximately calculated. Figures 6.1 and 6.13 (previous page) shows the exact $z = 0$ to $z = l$ region for which this calculation is made. For a TEM mode, the transverse electromagnetic fields are:

$$\vec{E} = -\hat{r} \frac{V_0}{\ln(b/a)} \frac{1}{r} \exp[j(\omega t - kz)] \quad \text{and} \quad (6.6)$$

$$\vec{H} = -\hat{\phi} \frac{V_0}{Z_{TEM} \ln(b/a)} \frac{1}{r} \exp[j(\omega t - kz)] \quad (6.7)$$

When standing waves are generated, these equations simplify to:

$$H_{\phi} = \frac{V_0}{Z_{TEM} \ln(b/a)} \frac{1}{r} \cos(kz) \exp(j\omega t) \quad \text{and} \quad (6.8)$$

$$E_r = \frac{V_0}{\ln(b/a)} \frac{1}{r} \sin(kz) \exp(j\omega t) \quad (6.9)$$

where, $Z_{TEM} = \frac{\eta}{\sqrt{\epsilon_r}} = \eta = 377\Omega$ and $k = 2\pi/\lambda = 51.33 \text{ m}^{-1}$ for 2.45 GHz.

Then, using perturbation theory [Har-61], power lost to the walls is given by:

$$P_W = \frac{1}{2} \Re \int_S |H_{\phi}|^2 ds \quad (6.10)$$

where the surface resistivity of brass $\Re = 5.11 \times 10^{-7} \sqrt{f} \Omega$ for a given frequency of operation f (in Hertz), and S is the interior conducting surface of the plasma source. Then, the power loss to the walls in the coaxial section of the source may be written as:

$$\begin{aligned}
P_{CW} = \frac{1}{2} \Re \left(\int_0^l \int_0^{2\pi} |H_\phi|^2 \Big|_{r=a} r (d\phi) dz \right) + \frac{1}{2} \Re \left(\int_0^l \int_0^{2\pi} |H_\phi|^2 \Big|_{r=b} r (d\phi) dz \right) + \\
\frac{1}{2} \Re \left(\int_a^b \int_0^{2\pi} |H_\phi|^2 \Big|_{z=0} r (d\phi) dr \right) \quad (6.11)
\end{aligned}$$

Substituting Eqn. 6.8 into Eqn. 6.11 and integrating with respect to ϕ leads to the following equation:

$$P_{CW} = \frac{1}{2} \Re \frac{2\pi V_0^2}{Z_{TEM}^2 (\ln(b/a))} \left(\left(\frac{1}{a} + \frac{1}{b} \right) \int_0^l (\cos kz)^2 dz + \int_a^b \frac{1}{r} dr \right), \quad (6.12)$$

Now, the electric field strength at some given power and pressure for an argon plasma is known. Hence, the constant V_0 can be calculated by substituting the electric field strength into Eqn. 6.9, evaluated at a maximum of the field pattern, where the measurement is most sensitive. For example, at $z = 3.175$ cm (130 W, 1 mTorr argon plasma), $E_r = 40$ kV/m. Substituting $a = 0.6$ cm, $r = b = 2.65$ cm, and $\Re = 5.11 \times 10^{-7} \sqrt{2.45 \times 10^9} = 0.0253 \, \Omega$, Eqns. 6.9 and 6.12 lead to $V_0 = 1575$ V, and $P_{CW} = 6.0$ W.

When the source is operating at the low density mode (0.2 mTorr curve on Figure 6.9), the maximum electric field is 30 kV resulting in $V_0 = 1181$ V. Then, the power loss to the walls, P_{CW} is about 3.5 W. In either mode of operation, the electric fields for the circular waveguide section ($z > l$) are half, to one third the field strength in the coaxial section of the source. Also, the surface area for $z > l$

region is about half the coaxial section. Hence the power lost to the walls in the circular waveguide section of the source is at most 15% of the power lost in the coaxial section of the source, and so total wall losses (in the coaxial section, plus the circular waveguide section of the 610-*a* and the MPDR 610) are $1.15P_{CW}$, or 7 W and 4 W for the two modes of operation, respectively. In either case, less than 6% of the net input power is lost to the walls of the cavity and the coupling efficiency for the source, by letting $P_W = P_{CW}$ in Eqn. 6.4, is then seen to be approximately 94%.

Having measured the electric field in the coaxial section of the plasma source, the discharge loaded quality factor (Q_L) can also be estimated by the following equation:

$$Q_L = \omega_0 W / P_t, \quad (6.13)$$

where ω_0 is the frequency of excitation ($2\pi \times 2.45$ GHz),

W is the total energy stored in the cavity, and

P_t is the time average power lost, or absorbed in the applicator/plasma system.

As mentioned earlier, Figure 6.13 shows the exact topology, and dimensions for which the loaded quality factor calculations are conducted.

For a typical argon discharge, the input power, or P_t , is about 130 W. Also, the total energy stored in the cavity is given by:

$$W = \frac{\epsilon_0}{2} \int_V |E|^2 dV, \quad (6.14)$$

where V is the internal volume of the plasma source, including the discharge region. The electric field Eqn. 6.9, and the cavity dimensions used for the power

loss calculation above can also be utilized for this calculation. Then, the stored energy for $z = 0$ to $z = l$ region is:

$$W = \frac{\epsilon_0}{2} \left(\int_a^b \int_0^{2\pi} \int_0^l |E_r|^2 r dz d\phi dr \right). \quad (6.15)$$

Substituting Eqn. 6.9 into Eqn. 6.15, this leads to the following derivation:

$$W = \frac{\epsilon_0 V_0^2}{2 (\ln(b/a))} \int_a^b \int_0^{2\pi} \int_0^l \frac{(\sin(kz))^2}{r^2} r dr d\phi dz \quad (6.16)$$

$$\Rightarrow W = \frac{\epsilon_0 V_0^2}{2 (\ln(b/a))} 2\pi \int_a^b \frac{1}{r} dr \int_0^l (\sin(kz))^2 dz \quad (6.17)$$

$$W = \frac{\epsilon_0 V_0^2}{2 (\ln(b/a))} 2\pi \left[\frac{l}{2} - \frac{\sin(2kl)}{4k} \right] \quad (6.18)$$

Here, $V_0 = 1575.6$ V, $\epsilon_0 = 8.85 \times 10^{-12}$ F/m, $b = 2.65 \times 10^{-2}$ m, $a = 0.6 \times 10^{-2}$ m, $l = 8.25 \times 10^{-2}$ m and $k = 2\pi/\lambda = 51.33$ m⁻¹. After substitutions, it is observed that $W = 1.76 \times 10^{-6}$ Joules, and $Q_L = 200$. If the energy storage in the circular waveguide region ($z > l$) is to be included in the efficiency calculations, the total energy stored in the plasma source (coaxial region plus the circular waveguide section) may be estimated to increase by at most 15%, resulting in $Q_L = 230$. As

mentioned before, the empty cavity quality factor Q_E is 1800. Using this value of Q_E , Eqn. 6.5 and $Q_L = 230$, the coupling efficiency is calculated to be about 87%, i.e. of the net input power being injected into the source (incident minus reflected), about 87% is coupled directly into the plasma.

While both methods of calculating coupling efficiency involve approximations, the first method does not include the power losses in the loop antenna. Thus the coupling efficiency of 94% calculated by this method is expected to be slightly high. The second method of efficiency calculation does take the losses in the loop antenna into account. Also, both methods account for the energy stored in the circular waveguide region. Thus the 7% difference between the two coupling efficiency calculations must be related to the power loss in the loop antenna. With 130 W input power, this amounts to approximately 9 W of power lost to the coupling loop.

6.6 Summary of Results

These experimental measurements can now be used to establish an equivalent microwave circuit for the MPDR 610, using lumped circuit elements. Such a circuit is shown in Figure 6.14. The source consists of four interconnected components: (1) a coupling loop, (2) a resonant coaxial waveguide of length l , (3) a circular waveguide of length d excited with evanescent fields and (4) the ECR plasma loaded waveguide section. Each of these components is represented as either a special transmission line, or lumped circuit element. This circuit is similar to the equivalent circuit developed for other loop coupled coaxially excited microwave discharges [Fre-71a, Fre-

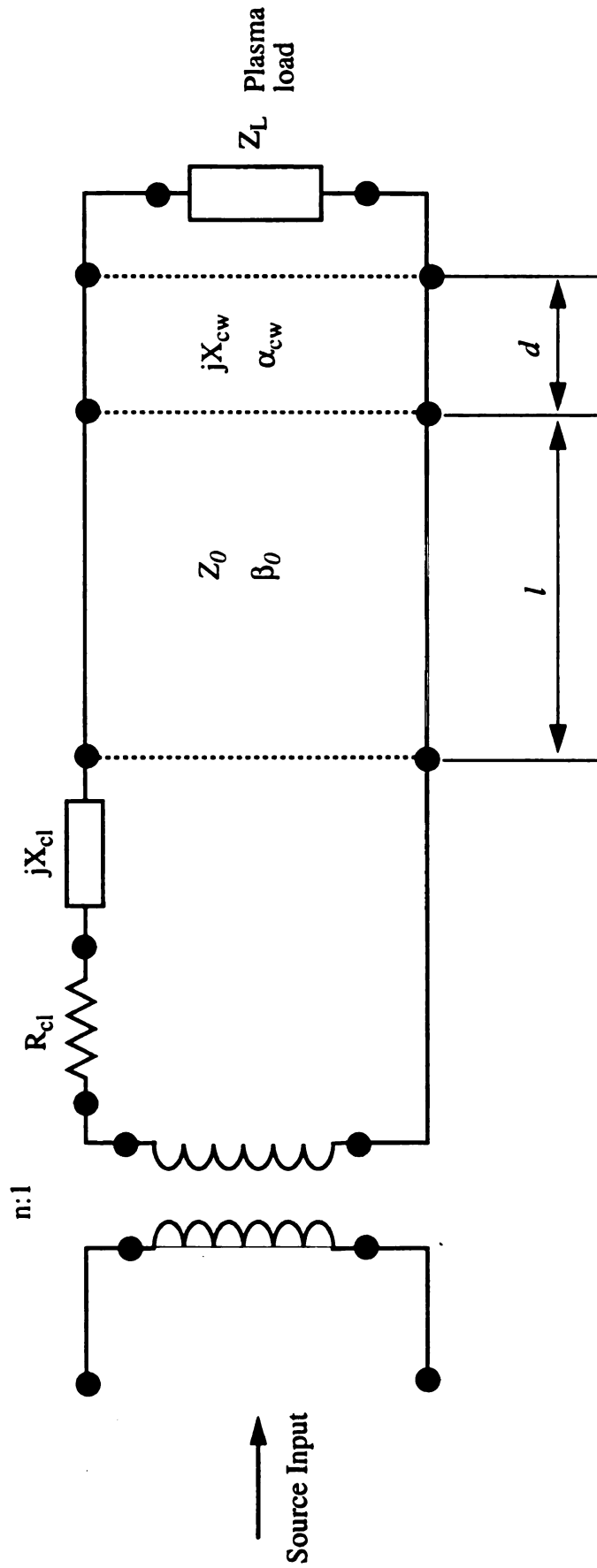


Figure 6.14 Equivalent circuit for the ECR microwave plasma source.
 $R_{cl} + jX_{cl}$ is the coupling loop impedance, Z_0 and β_0 are characteristic impedance and propagation constant for the coaxial section of the source (length l), jX_{cw} and α_{cw} are characteristic impedance and decay constant for the circular waveguide section of the source (length d), and Z_L is the plasma load impedance.

71b]. The major difference between this ECR plasma source, and those in References Fre-71a and Fre-71b is that for this source, the plasma almost fills the entire waveguide section, and an adjustable impedance matching circular waveguide (evanescent fields only) section has also been added.

The coupling loop is represented as a lumped resistance and reactance of an ideal transformer with an $n:1$ turns ratio. In contrast to some of the other internally tuned cavity applicators where the coupling circuit is adjustable [Roo-85, Whi-87], here the loop is fixed with the correct orientation and size. Initial trial models of the 610 had a movable loop to aid in tuning the source, but production models of the 610 are built with a fixed loop position and orientation. This reduces the degrees of freedom (number of adjustments) for tuning, but it is obvious that two adjustments - the sliding short and the center conductor positions - are sufficient for the cavity to be matched reasonably well over a range of experimental gas type, pressure and power inputs, typically with less than 5% reflected power. Note that this also simplifies greatly the load impedance matching. In the equivalent circuit of Figure 6.14 the loop is therefore represented as a fixed impedance and a fixed ideal transformer.

The coaxial and circular waveguide sections of the source are represented as transmission lines, each with its own propagation constant and characteristic impedance. Note that in the coaxial section a TEM propagating mode is set up, and so the transmission line circuit has a real characteristic impedance Z_0 and a free space propagation constant $\beta_0 = \omega/c$ (c is the speed of light), while the circular waveguide section has a capacitive wave impedance $\pm jX$ and an imaginary propagation constant $\pm j\alpha_{cw}$ which produces fields in this region that decay as $\exp(\pm \alpha_{cw}z)$. Because the fields of the TEM mode have rotational

symmetry, it is expected that only the azimuthally symmetric TM_{0m} fields are excited in the circular waveguide. Since these TM_{0m} modes are all below cutoff, and TM_{nm} modes are typically capacitive, they have more energy stored in the electric field than in the magnetic field. (As a corollary, TE_{nm} modes are typically inductive with the evanescent TE_{nm} fields concentrating power in magnetic fields.) Therefore, the wave impedance in the circular waveguide region is capacitive. While the circular waveguide section of the source is represented through Figure 6.14 as a simple reactance and propagation constant, it is understood that more than one evanescent TM_{0m} mode may contribute to the total field in this region. Thus in the circular waveguide section, the fields are not produced by just one single decaying mode, but are the sum of several evanescent modes.

Finally the plasma is represented as a simple lumped impedance which is the input impedance presented to the source by the plasma at the $z = l + d$ plane. Since the discharge region consists of a circular plasma loaded waveguide, this section could also be represented as a special transmission line. However for simplicity the discharge is represented here as a simple impedance at $z = l + d$ which varies as the experimental conditions (input power, gas flow/pressure, gas type, etc.) change.

Referring to the circuit in Figure 6.14, some of the details of the operational performance of the ECR plasma source are illuminated. It is known that the resistance and reactance of the plasma load impedance will vary as input power, pressure and gas type are changed. Thus the lengths d and l are the impedance matching adjustments required to match the impedance of the transmission line to that of the discharge. Note that in the experiments reported

here the length l varies only slightly - this predicts an almost constant load impedance at the plane $z = l$ looking back toward the microwave oscillator. Thus, as the plasma impedance varies, the length of the circular waveguide section, d is adjusted to yield the best match conditions at the source input. The role of the circular waveguide section therefore, is that of a variable impedance transformer section required for matching the impedance of the coaxial section of the source to the discharge impedance.

6.7 Concluding Remarks

These experiments have verified and clarified the internal electromagnetic field behavior of this compact ECR source. The experimental data presented here, together with the evaluation characteristics detailed in Chapters Four and Five should provide valuable experimental information for numerical modelers. However, additional experimental work is necessary to understand and better define the relationships between the measured impressed electromagnetic fields, and the densities and energies of the various output charged and radical species. In particular, additional experiments in an argon discharge that investigate the electromagnetic fields as the source switches between the two discharge modes (which are shown clearly in Chapter Four, Figure 4.8) are needed.

Note that this type of non-linear behavior, as well as other phenomena such as the presence of hysteresis loops in density versus pressure or input power, has been observed in microwave discharges for many years [Fre-71a, Fre-71b, Asm-74], and have recently been shown to exist in plasma processing

discharges as well [Ayd-93, Asm-94]. The cause of this non-linear behavior is most likely due to several phenomena such as electromagnetic mode switching, plasma-circuit instabilities, etc. and each must be understood in order to design improved and more optimal microwave plasma sources.

Errata: Before this chapter concludes, some errors in Reference Sri-95a need to be mentioned. Eqns. 9 and 13 have been incorrectly printed in the journal. The limits on Eqn. 9 (page 1033 of the journal) have not been correctly printed. The first integral goes from 0 to 2π , while the second integral goes from 0 to l . This typographical error is repeated twice in Eqn. 9. Also, the triple integral of Eqn. 13 (page 1034 of the journal) has an incorrect differential volume. This volume under the integral sign should have been printed as: $r \, dz \, d\phi \, dr$, and not $r^2 \, dz \, d\phi \, dr$. The calculations of the stored energy using Eqn. 13 have been done with the correct differential volume, and the results discussed in the paper are the correct calculations.

7.1

7.2

7.3

7.4

Chapter 7

Evaluation: The MPDR 5 - a Multipolar ECR Plasma Source

7.1 Introduction

7.2 Description of the Source - MPDR 5

7.2.1 Source Design

7.2.2 Microwave Cavity Design Considerations

7.3 Operational Performance of the MPDR 5

7.3.1 Previous Characterization of the MPDR 5 - a Synopsis

7.3.2 Further Characterization of the MPDR 5

7.4 Concluding Remarks

Chapter 7

Evaluation: The MPDR 5 - a Multipolar ECR plasma source

7.1 Introduction

The past several chapters have been devoted to the description, and performance evaluation of the MPDR 610 - a compact, coaxial ECR plasma source. This evaluation has been conducted both by direct measurements on the 610 (as in Chapters Four and Five), and also indirectly, with the aid of the 610-*a* (as described in Chapter Six, where results of the 610-*a* are used to characterize properties of the 610). Valuable information has been obtained about the output characteristics of the 610, and the dependence on input parameters (like pressure/flow, power, gas type, etc.) as the latter are varied within the ranges defined in Chapters Four through Six.

Focus now shifts briefly to another compact, multipolar plasma source which was studied during this research - the MPDR 5. The MPDR of course, stands for "microwave plasma disk reactor," while the "5" at the end denotes the 5 cm diameter of the discharge. This source was designed and developed at the Plasma Science Laboratories of the Department of Electrical Engineering (EE) at

Michigan State University (MSU) by Mahoney and Asmussen and was introduced at the ICIS-89 conference in Berkeley, USA [Mah-89b]. Since then, it has been the subject of several studies at MSU. The interest in this small source continues today, as modified versions of the MPDR 5 are being evaluated at several other universities where plasma research is conducted, including ongoing studies at MSU like the one presented in this chapter. This sustained interest implies not only the importance of compact plasma sources, but also reiterates the fact that despite several years of effort, much still needs to be learned about this type of plasma/ion beam source.

This chapter continues the work of Mahoney and Sze on the MPDR 5, both of whom partially based their M.S. thesis [Mah-89a] and Ph.D. dissertation [Sze-93a] respectively on this source. Some sections of the work described here were presented at the ICIS-93 in Beijing, China [Sri-93b], with subsequent publication in the proceedings [Sri-94b] of the conference. The chapter begins with a detailed description of the MPDR 5, and the minor modifications to the Yorktown T that were necessary to mount this source on the vacuum system. The unique multipolar design of the magnets is also described. The resonant microwave cavity parameters (like the diameter, height, etc.) are critically dependent on the electromagnetic mode which is to be excited in the ion source, and these dimensions are therefore important factors in the overall design of the ion source. The structure of the MPDR 5, designed around its operation at a specific electromagnetic mode is then discussed.

While ion density, ion energies and ion beam extraction data have already been discussed in earlier publications by Mahoney and Sze [Mah-89b, Mah-90, Sze-93b], further data on electric field pattern, ion and electron energy

distribution functions (EEDF, IEDF) are presented in this chapter. Some of this data initially appeared in Sze's dissertation, but were co-published after presentation at ICIS-93 in Beijing, China [Sri-93b, Sri-94b]. This published data are presented here in a section that briefly recapitulates some of the results obtained prior to the work for this dissertation. New data acquired for this sub-study are then presented in a later section. As will be seen, the electric field pattern measurements confirmed the single EM mode at which the source was designed to operate. The EEDFs indicate that electron energy distribution for the MPDR 5 is closer in shape to the Druyvesteyn function than to the Maxwellian (as is commonly assumed), while the IEDFs reveal a possibility of the production in this source, of doubly charged ions.

The chapter ends with some concluding remarks that summarize the data that were presented in earlier sections, while also proposing several new experiments that need to be undertaken for continued study of the salient features of the MPDR 5.

7.2 Description of the Source - the MPDR 5

While the MPDR 5 was designed and built by Mahoney and has been described in detail earlier, specifically in his MS thesis [Mah-89a] a description of the source is presented in the following sub-section. The discussion on the overall design of the source is followed by a brief digression into the electromagnetic considerations that determined the exact dimensions, and other design criteria of the resonant microwave cavity structure that comprises this small source.

7.2.1 Source Design

Figure 7.1 shows a schematic of the MPDR 5 (not to scale), while Figure 7.2 (not to scale) shows the MPDR 5 mounted on the processing chamber of the Yorktown T. (As for the 610, and 610-*a* experiments, there is no variable conductance valve on the vacuum system, and so the gas flow determines the discharge pressure.) Unlike the 610, the MPDR 5 is an “external” source, where the microwave cavity structure is outside the vacuum system. The design of the 610-*a* was in fact based to some extent on the MPDR 5. The plasma is formed near the vacuum seal between the MPDR 5 and the vacuum (or processing) chamber, as in the case of the 610-*a*.

The MPDR 5 consists of a cylindrical microwave cavity structure (4) made of brass with an 8.9 cm inner diameter. The cavity is bounded on the top by a position adjustable sliding short (1). Finger stock connected to the sliding short keep it in good electrical contact with the conducting cavity walls. The discharge is confined by a quartz cup (6), with a 4.9 cm inner diameter, and 2.8 cm height. A silicone O-ring between the stainless steel base plate (7), and the quartz cup, and a larger VitonTM O-ring between the base plate and the top plate of the vacuum processing chamber form the two vacuum seals, allowing minimum base pressures in the low 10^{-7} Torr range. The Yorktown T therefore did not require much modification for operating the MPDR 5. Only a new top plate with a hole in the center had to be built (see Figure 7.2). This plate was made of 1.5 inch thick aluminum with a polished vacuum finish where the vacuum chamber O-rings were to be fitted. The plasma generated in the quartz cup of the MPDR 5 diffused out of the source through this hole in the aluminum top plate and into

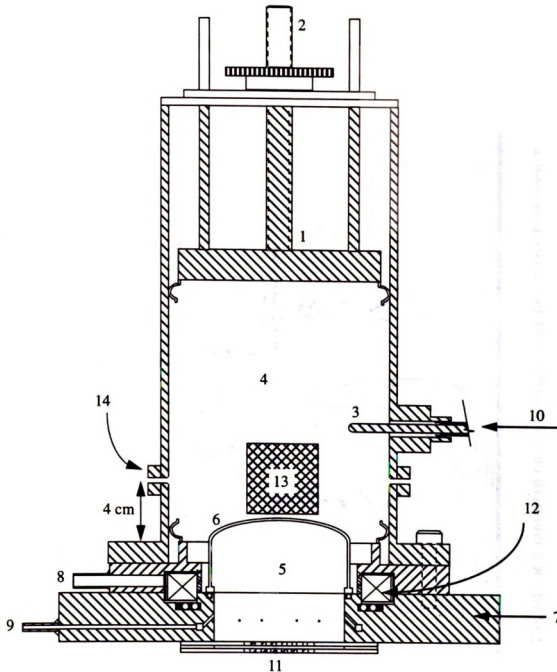


Figure 7.1 The MPDR 5

- | | |
|-------------------------------|---|
| 1. Sliding Short | 8. Air/water cooling |
| 2. Short moving gear assembly | 9. Discharge gas feed |
| 3. Movable antenna (or probe) | 10. Microwave feed from power supply |
| 4. Microwave cavity | 11. Extraction grids (not used in this paper) |
| 5. Discharge creation region | 12. Permanent magnets |
| 6. Quartz cup | 13. Screened window |
| 7. Stainless Steel base plate | 14. Micro-coaxial probe holes (circumferential) |

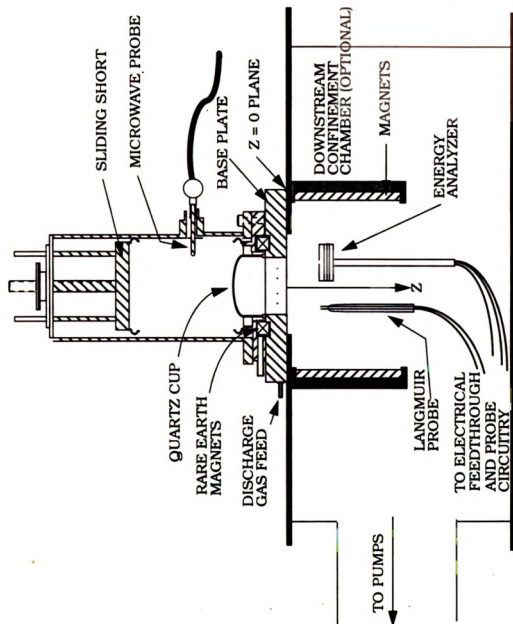


Figure 7.2 The MPDR 5 mounted on the vacuum chamber of the Yorktown T
 Note that the downstream magnetic confinement chamber shown in this figure is not present for all experimental results taken for this sub-study.

the vacuum chamber. As mentioned above, the MPDR 5 was vacuum sealed to this new top plate using a Viton O-ring. As in other MPDR sources, the resonant microwave cavity itself, therefore is at atmospheric pressure, while the quartz dome (or cup) confines the plasma to the low pressure discharge region. With the base plate of the source (7) being 2 cm high and having a 4.8 cm diameter orifice through which the plasma diffuses out, the total discharge volume is about 90 cm^3 . Extraction grids can be attached to the bottom of this base plate for high voltage ion beam extraction.

Microwave energy is transported from the 2.45 GHz power supply using a flexible coaxial cable (as shown in Figure 4.5(b), Chapter Four), and into the MPDR 5 through a length adjustable antenna (3). The length of this antenna, and the height of the resonant cavity are critical parameters in tuning the source by reducing the reflected power, and thereby maximizing the absorption of incident power into the discharge. Techniques of plasma ignition and sustenance through minimizing the reflected power by adjusting these two degrees of freedom will be discussed in a later section.

The magnetic field structure of the MPDR 5 is different from that of the MPDR 610, or the 610-*a*. While the latter two sources employ axially magnetized ring shaped magnets, the MPDR 5 has a radial "multipolar" field generated by eight equally spaced permanent magnets around the circular perimeter of the quartz cup. The field structure is shown clearly in Figure 7.3 (not to scale), that shows a top view of the quartz surrounded by the 16 neodymium-iron-boron magnets (with dimensions 1.3 cm X 1.3 cm X 1.0 cm) stacked two together. These magnet pairs are placed in a non-magnetizable base plate and generate the radial octapolar static magnetic field configuration for ECR and charge

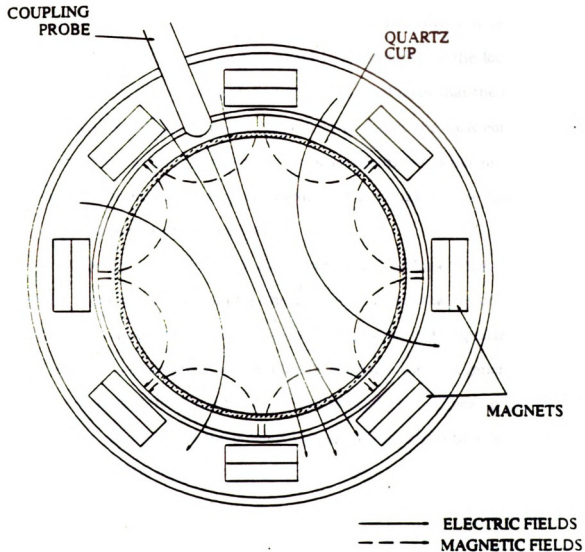


Figure 7.3 The octapolar magnetic field configuration for the MPDR 5

Note that the position of the antenna ensures that the impressed electric field is perpendicular to the static magnetic field generated by the 16 neodymium boron magnets (stacked two together). This is a condition for ECR heating.

species confinement within the quartz cup of the MPDR 5. The maximum poleface strength of these magnets is about 0.35 Tesla [Mah-89a]. The direction, and lines of force of both the static magnetic fields, and the impressed electric field (from the antenna) are also super-imposed on Figure 7.3. Note that the orientation of the impressed electric field is determined by the location of the antenna relative to the magnets, and it is positioned such that the electric field is perpendicular to the static magnetic field to satisfy the ECR condition. The magnets are covered by a brass plate that keeps them cool, while providing a flat surface for the reflection and confinement of resonant electric field standing waves within the microwave cavity.

Discharge gas is fed through a tube (9) in the base plate, and into an annular channel that distributes the gas into the plasma region (5) through eight equally spaced pin holes. Compressed air cooling of the quartz, and water cooling (8) for the base plate are required to dissipate the heat generated during the experiments. Critical location of these cooling devices allows up to 200 W of power to be absorbed into the plasma, for several hours at a time without harm to the magnets, the quartz, or the silicone O-rings.

7.2.2 Microwave Cavity Design Considerations

The theory of resonant electromagnetic cavity design is covered in several texts and references [Har-61, Ram-84], and so only a concise report is presented here to briefly explain the design of the MPDR 5. The inner diameter of the microwave cavity is 8.9 cm, as mentioned before. The excitation of microwave resonant standing waves within this cavity structure determines the dimensions

of the cavity. The MPDR 5 is designed to be a microwave cavity supporting a single resonant electromagnetic mode. This is the TE_{11} mode - the lowest propagating transverse electric (or H) mode. For a perfectly conducting cylindrical cavity with closed ends, the resonant frequency of a particular mode depends on the cavity diameter, cavity height (or length), and the appropriate root of the Bessel function solution to the partial differential equations. Conversely, for a fixed cavity radius (a), and free space frequency of operation ($f = c/\lambda$), the cavity length (L_s) for a TE_{lmn} mode may be determined by the following equation [Mah-89a]:

$$L_s = \frac{\lambda}{2n \left[1 - \left(\frac{x'_{lm} \lambda}{2\pi a} \right)^2 \right]^{1/2}} \quad (7.1)$$

where x'_{lm} are the m^{th} zeros of the l^{th} order Bessel function $J'_l(x')$. For operation at 2.45 GHz and with an 8.9 cm diameter cavity, the theoretical height for TE_{111} mode operation is calculated to be about 10.5 cm - the distance from the base plate to the sliding short. Note that the MPDR 5 is not an ideal microwave resonant cavity - there are several differences between the source and a perfect cylindrical cavity. For example, the brass cavity is not a perfect conductor and there is a quartz cup present along with the lossy discharge (after plasma ignition) or a large hole in the base plate (before plasma ignition). When combined, these differences lead to a perturbed value of the cavity length (as compared to the calculated length for an ideal cavity) under optimal operating conditions of the plasma source. This length is usually found empirically. Hence,

the total height (or length, both terms mean the same dimension L_s for the source) of the microwave cavity was made to be several centimeters more than 10 cm. This was done to provide ample buffer space for the motion of the sliding short while optimizing the resonance for ignition of the plasma, or for further tuning if the plasma load conditions were to change due to variation of external parameters (like pressure, power, etc.). Indeed, operation of the MPDR 5 with zero reflected power could be achieved at two different cavity heights and microwave antenna (or probe) lengths, as seen in Table 4-1 and Figure 4.14 of reference Mah-89a.

7.3 Operational Performance of the MPDR 5

This section describes the experimental data obtained for the MPDR 5. Since its conception, a lot of research has been conducted on this ion source, and a brief synopsis of the previous work by Mahoney and Sze is presented in Sub-section 7.3.1, specially data from Sze's dissertation that was co-published in the ICIS-93 proceedings. The supplemental data that were acquired specifically for this evaluative sub-study of the source are presented in Sub-section 7.3.2.

7.3.1 Previous Characterization of the MPDR 5 - a Synopsis

Evaluation of the MPDR 5 was conducted primarily by Mahoney as part of his MS thesis [Mah-89a]. Sections of this data were presented at the ICIS-89 at Berkeley, California [Mah-89b], and published in the conference proceedings

[Mah-90]. Further characterization of the MPDR 5 was undertaken by Sze, as part of a comparative study of several multipolar microwave ECR plasma reactors with different sizes and structural designs (most of them were MPDRs). This study was featured in Sze's Ph.D. dissertation [Sze-93a], and also published in a refereed journal [Sze-93b]. Information presented in this section is taken from references Mah-89a, Sze-93a and Sri-94b, and briefly discusses the salient features of the operational performance of the MPDR 5.

Mahoney observed that a discharge in the MPDR 5 could be easily ignited for pressures of less than 10 mTorr and with input powers less than 100 W without the need of Tesla coils, or ignition filaments. Double Langmuir probe data (taken in accordance with the methods described in Chapter Three), at 0 cm downstream indicate a high degree of ionization. For a 2 mTorr argon discharge, the ion density was $2 \times 10^{11} \text{ cm}^{-3}$, increasing to about 10^{12} cm^{-3} as pressure was raised to 40 mTorr at a constant 170 W input power. It was also noted that this small source is capable of operating over three decades of discharge pressure - from sub-mTorr pressures, and up to several tens of mTorr. At the higher pressures, processes other than ECR are probably contributing to power transfer to the discharge. Ion density increased with input power. CPA and CP α curves indicated a falling electron temperature with increasing pressure, indicative of typical ambipolar diffusion losses out of the plasma generation region.

Mahoney also conducted high voltage ion beam extraction experiments from the MPDR 5. Two flat, graphite grids were used, one attached to the source, while the other was biased negative to accelerate ions and retard electrons. At a very low flow/pressure of 3.5 sccm (5×10^{-5} Torr) argon discharge with 250 W

input power and a 1.35 kV extraction potential, the total argon ion beam current output was almost 60 mA. This beam current increased with input power, and also with the applied potential. The beam profile (as indicated by the full width at half maximum) got better with increasing extraction potential - that is, the beam became more focussed and collimated when the extraction potential was raised. Similar results were obtained for oxygen (with about 45 mA maximum beam current for a 224 W input power, 5 sccm oxygen flow, 6×10^{-5} Torr discharge with 2 kV extraction voltage), and nitrogen (35 mA maximum current for 245 W input power, 5 sccm nitrogen flow, with 1.4 kV extraction bias) discharges also.

In his evaluation of the MPDR 5, Sze concentrated mainly on the downstream and radial performance of the source output. Also, he used a multi-polar magnetic confinement chamber (see Figure 7.2) with a 20 cm inner diameter. This downstream confinement chamber improves the uniformity of the ion density radial profile diffusing out of the source [Sze-93b], and may be installed on any of the MPDRs (except the MPDR 610, which is an "internal" source). Using a double Langmuir probe, it was observed that the argon ion density decreased exponentially with downstream distance, confirming the classical ambipolar diffusion typical of reactors of this design (and also the MPDR 610, as noted in Chapters Four and Five). Radial profiles of the ion density improved in uniformity as the Langmuir probe was moved further downstream ($z > 0$, see Figure 7.2) from the discharge generation region. These downstream and radial profiles are shown in Figures 7.4, through 7.6. It must be re-iterated that Sze acquired these curves with the downstream multi-polar magnetic confinement in place, and hence the uniformity of the radial profile is

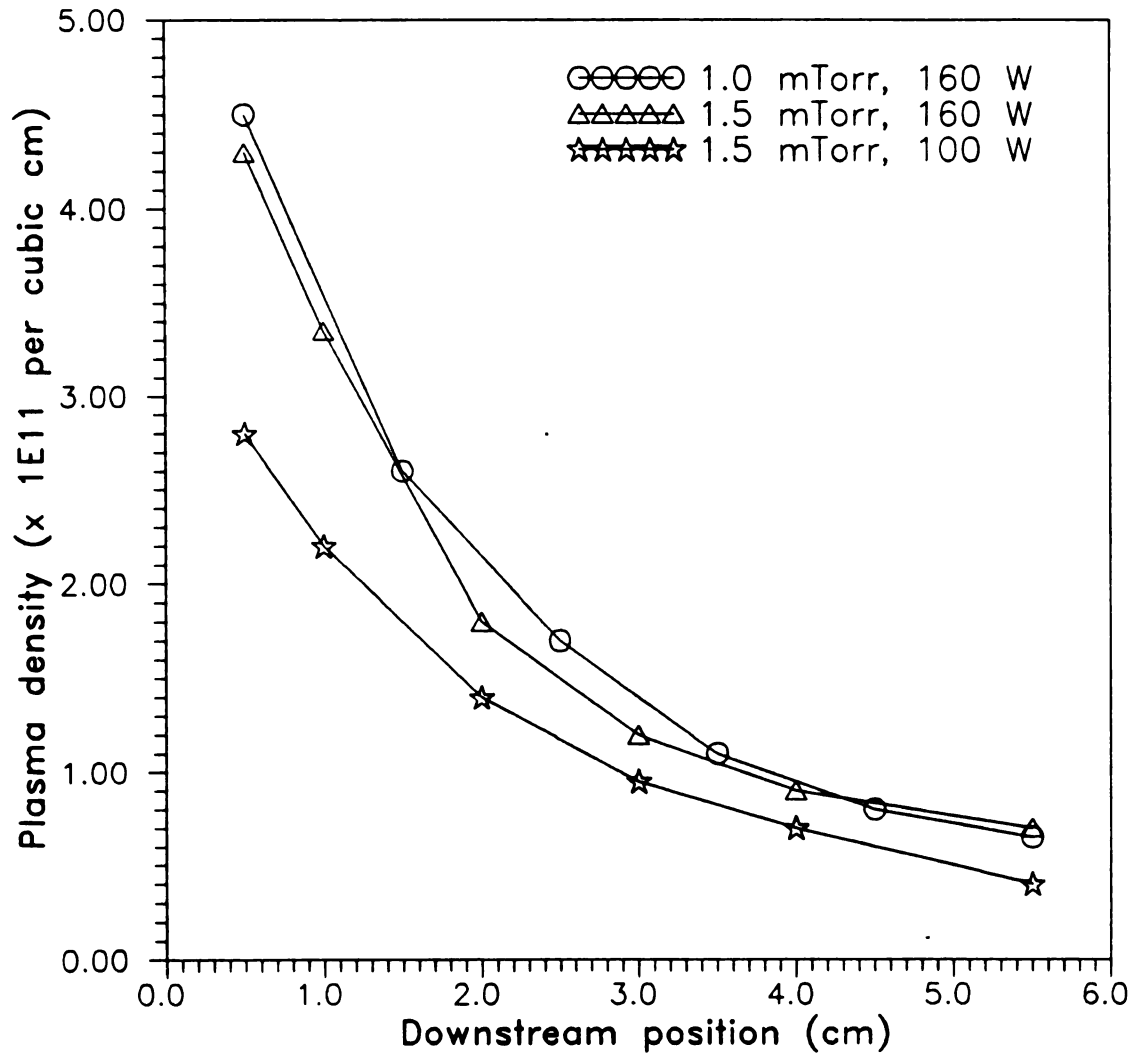


Figure 7.4 Variations in plasma density with downstream distance.
 Data are taken for an argon discharge with a double Langmuir probe centered at $r = 0$ axis, with the downstream magnetic confinement chamber in place.

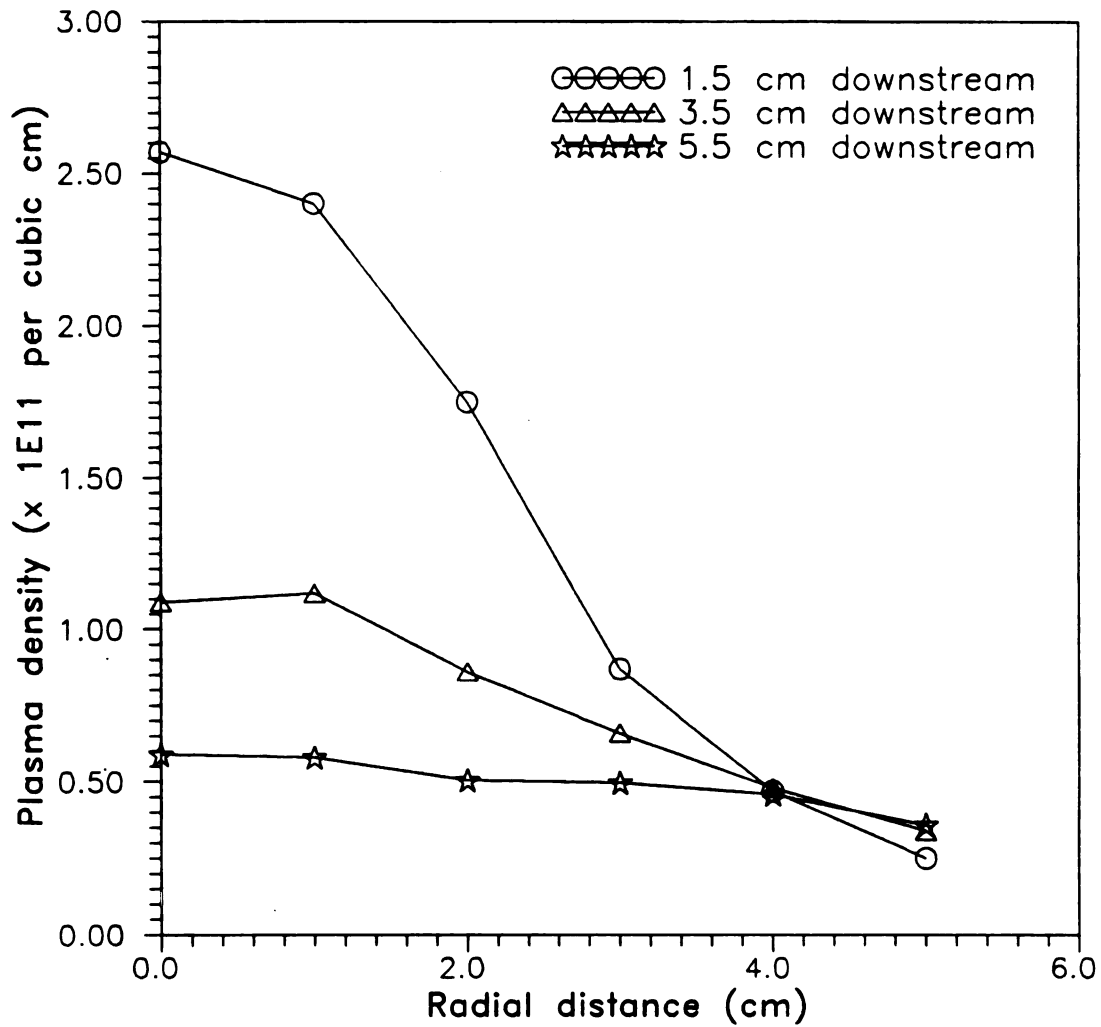


Figure 7.5 Radial distribution of plasma density at different downstream positions.

Data are taken for a 1.0 mTorr argon discharge with 160 W input power, and with the downstream magnetic confinement chamber in place.

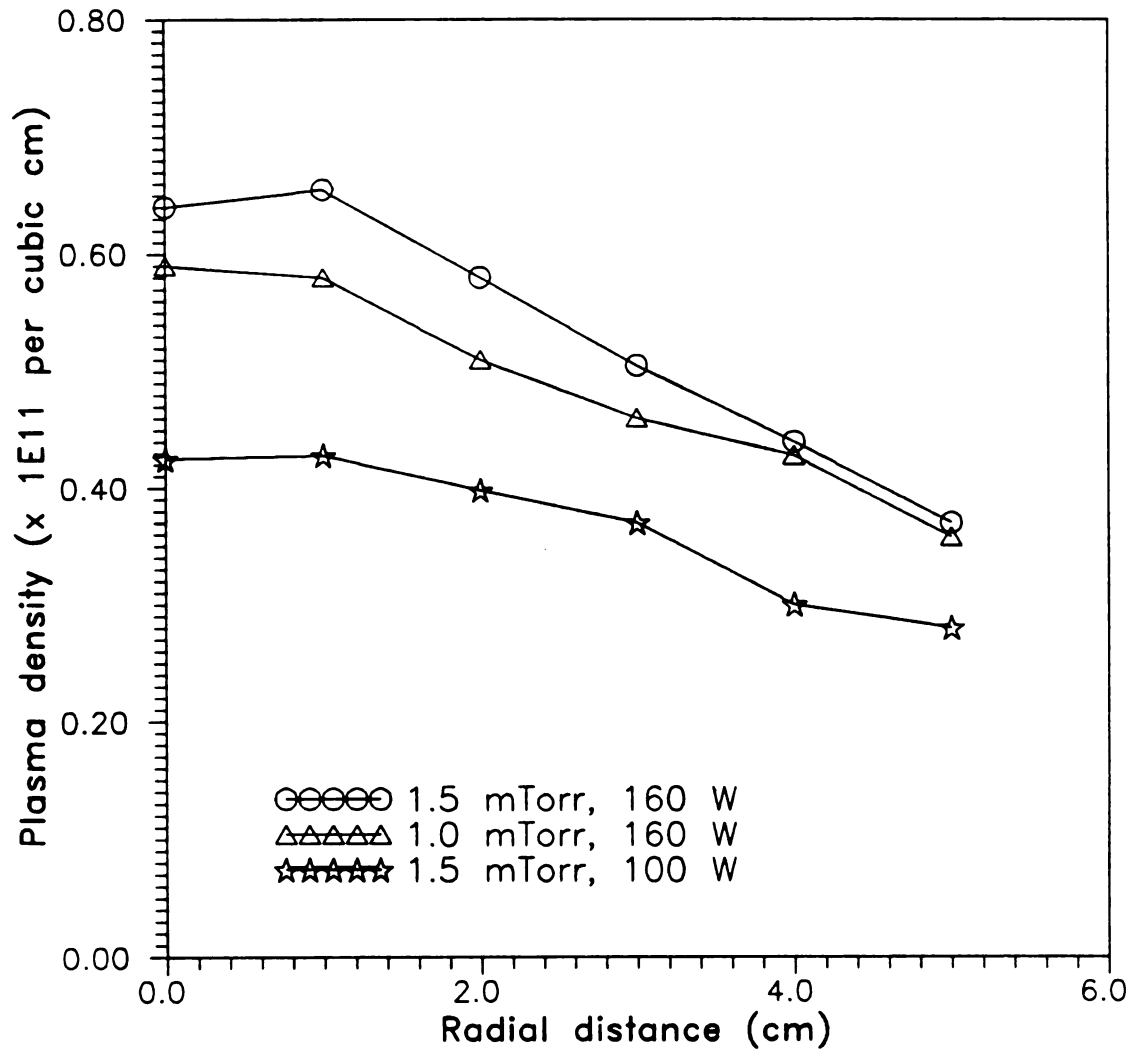


Figure 7.6 Radial distribution of plasma density at different discharge conditions.

Data are taken using a DLP 5 cm downstream for various pressure and power conditions, with the downstream magnetic confinement chamber in place.

much better than would normally be expected with magnetic field-free radial diffusion. These data were jointly presented at ICIS-93, and co-published [Sze-93a, Sri-93b] in the proceedings.

Sze also performed electron and ion energy analyses with a single Langmuir probe (SLP), and the multi-grid ion energy analyzer(IEA) respectively on the MPDR 5, again with the magnetic confinement structure in place. The EEDF measurements, confirmed in this sub-study indicated a near Druyvesteyn electron energy distribution function. This is clearly seen in Figure 7.7, that shows a typical EEDF of the MPDR 5 for a 150 W input power (almost 0 W reflected), 13 sccm (5×10^{-4} Torr) argon discharge. Once again it must be reiterated that often for simplicity theoretical developments of ECR plasma physics assume a perfect Maxwellian distribution of electron energies, and this is clearly not the case either for the MPDR 5, or for the MPDR 610. Under usual operating pressure and power conditions, the average electron energies within the MPDR 5 are about 8 - 10 eV, while the plasma potential is about 20 - 22 V. Radial and downstream variation of plasma potential, as measured by Sze, is shown in Figure 7.8, which indicates a relatively uniform plasma potential radial profile at 5 cm downstream, with a small decrease in the plasma potential as distance downstream from the generation region increases.

The ion energy analysis performed by Sze on the MPDR 5 revealed interesting results. For a 1.0 mTorr, 160 W input power argon discharge, the IEDF acquired at 2 cm downstream (with the ion energy analyzer centered at $z = 0$ location, the axis is defined in Figure 7.2) showed a typical curve with average ion energy about 29 eV. As the distance downstream increased to 3 cm, 4 cm and then to 5 cm (for $r = 0$, the central axis of the source), there developed a

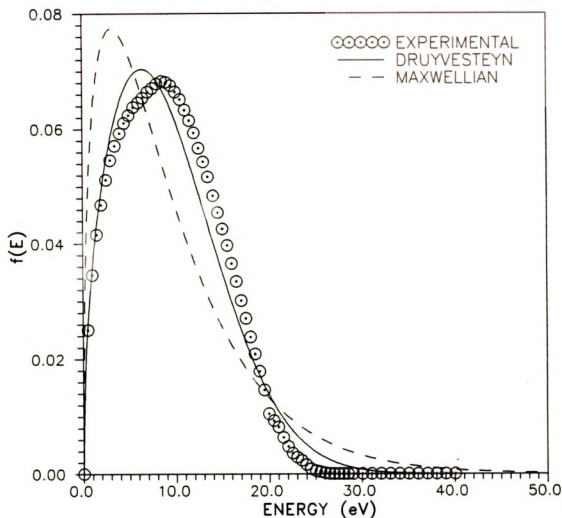


Figure 7.7 Typical EEDF for the MPDR 5.

Note the near Maxwellian distribution of electrons in the MPDR 5. Data taken for a 13 sccm (about 0.5 mTorr) argon discharge with 150 W input power, 5 cm downstream. The downstream confinement chamber is not present.

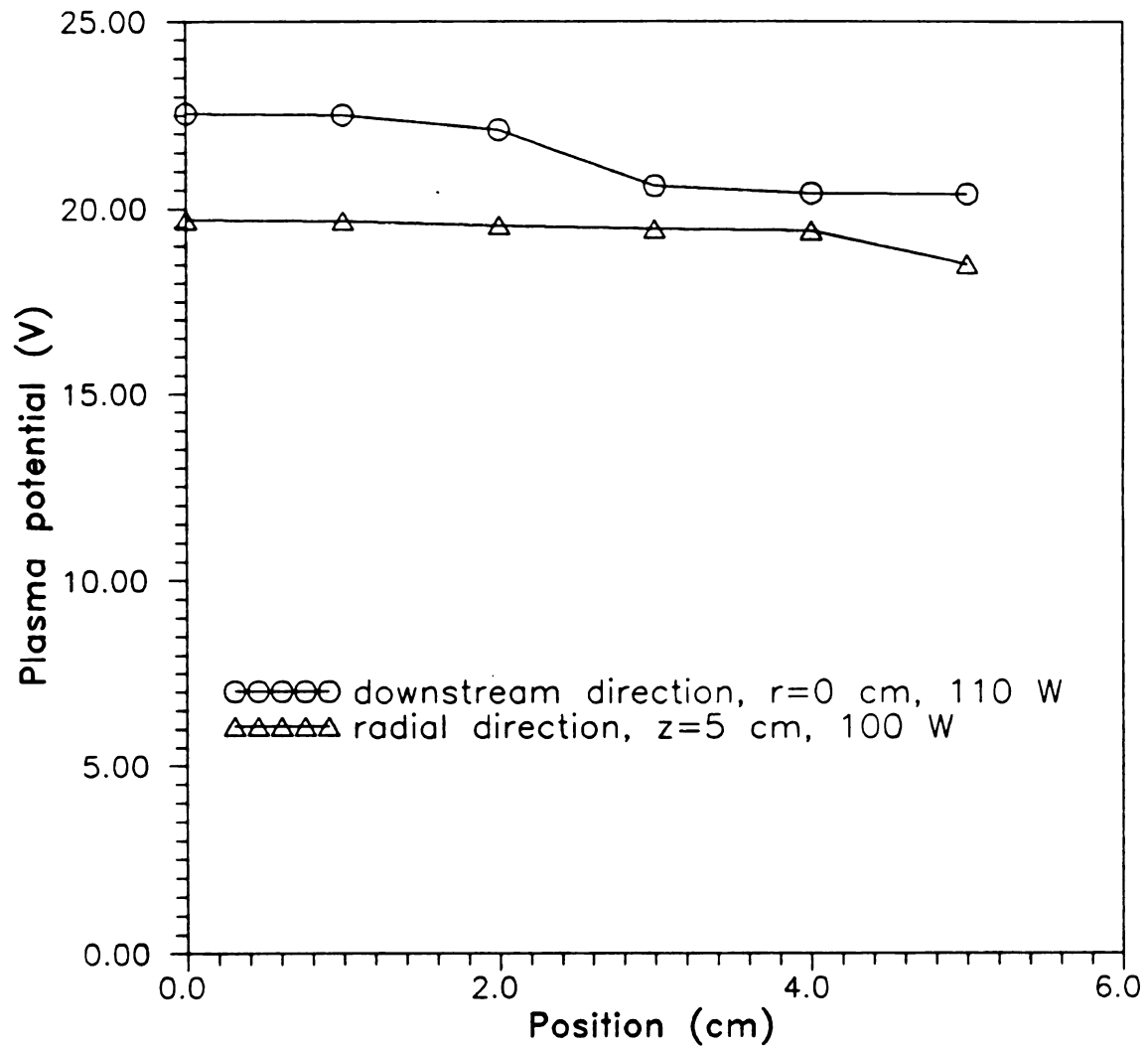
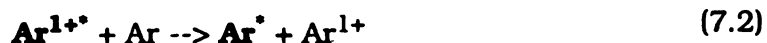


Figure 7.8 Radial and downstream variation of plasma potential.
Data taken with a single Langmuir probe (EEDFs), with the downstream magnetic confinement chamber in place.

more distinct second peak at about half the energy, even as the intensity of the 30 eV peak (known heretofore as the high energy peak) declined. A similar effect was observed for a 100 W input power 1.5 mTorr argon discharge, where a bimodal distribution developed as the distance downstream increased (for the same $r = 0$ position). This bimodal distribution was also present when the IEA position was radially varied at a constant downstream $z = 5$ cm position, for r values of 1 cm, 2 cm, 3 cm and 4 cm. This phenomenon is illustrated well through Figures 5.15 through 5.17 of reference Sze-93a.

Sze gave two possible explanations for the development of this bimodal distribution. First, it may be due to downstream ionization of the residual argon gas away from the hypothetical "discharge generation region," leading to the development of the low energy peak in the IEDFs. However, this cannot explain the resulting decline in the high energy peak. The second, and more probable reason, is that there is resonant charge exchange occurring within the downstream multi-polar magnetic confinement structure. As the 30 eV average energy ions diffuse out of the plasma generation region, they are effectively confined by the downstream magnetic field of the confinement structure, increasing the ion neutral collision frequency, and probably leading to charge exchange between the high energy ion (Ar^{1+*}) and low energy neutral atom (Ar). This results in the formation of low energy ions (Ar^{1+}), and high energy neutrals (Ar^*), with a subsequent decline in the high energy ion population. The process may be presented as an equation:



This charge exchange process has been explained in literature [Kau-87]. No other MPDR seems to exhibit this development of a low energy peak as the distance downstream increases. Indeed, further ion energy evaluation of the MPDR 5 without the downstream multi-polar magnetic confinement structure indicates other interesting phenomena as will be seen later, but there seems to be no evidence of resonant charge exchange occurring downstream of the discharge generation region, as observed by Sze.

7.3.2 Further Characterization of the MPDR 5

The primary aim of this sub-study was to confirm several performance characteristics of the MPDR 5, while at the same time to conduct further evaluation in order to develop a better understanding of the small source. Using micro-coaxial probes similar to those described in Chapter Six (and in the relevant diagnostics sections of Chapter Three), the electric field structures set up in the MPDR 5 were measured. Only relative field measurements were conducted, with no calibration to the exact field strength (as was done on the 610-a in Chapter Six). Data were taken both in the circumferential (about 4 cm above the base plate), and axial directions. Special bands of brass with small feed-through holes for the micro-coaxial probes were soldered on the body of the source so as to prevent the probes from buckling, or moving while data is being taken. As was noted in Chapter Three, this electric field measurement is extremely susceptible to give false readings if the probe positions are even minutely disturbed. Such a brass band with micro-coaxial probe holes (14) is shown in the cross-section sketch of the MPDR 5 in Figure 7.1.

Figure 7.9 shows the variation of the measured power (which is proportional to $|E|^2$), around the circumference of the MPDR 5. The circles indicate the experimentally measured power levels, while the solid line is a normalized sine squared curve. Note that the experimental data fits the theoretical sine squared dependence, confirming that a TE_{111} standing wave is generated within the MPDR 5. No data were available between 150° and 200° due to the presence of a screened observation window (13) on the cavity wall (see Figure 7.1). However, it is expected that the electric field reduces to a local minimum about 180° , closely following the theoretical curve. Also, the antenna that launches the microwaves into the cavity is azimuthally fixed at 270° - at the maximum of the second peak. The near zone fields from the antenna (evanescent modes are also set up in the cavity) may explain why the second peak in Figure 7.9 is higher than the first.

Figure 7.10, shows the vertical variation of the measured power between the sliding short and the base plate. The single peak with a maximum in the center and zero fields at both ends again confirms the generation of the TE_{111} electric field standing wave within the microwave cavity of the MPDR 5.

Additional ion energy measurements were performed on the MPDR 5 for confirmation trials of the resonant charge exchange hypothesis of Sze (Section 7.3.1). The IEDF acquisition for these experiments was conducted without the downstream multi-polar confinement chamber. Figure 7.11 displays the IEDF's variation with input microwave power at a constant argon discharge pressure of 1.2 mTorr. Data are taken with the grounded ion energy analyzer 5 cm downstream from the $z = 0$ location. The IEDFs are narrow and peaked for moderate input power levels (< 160 W). The full width at half maximum (FWHM)

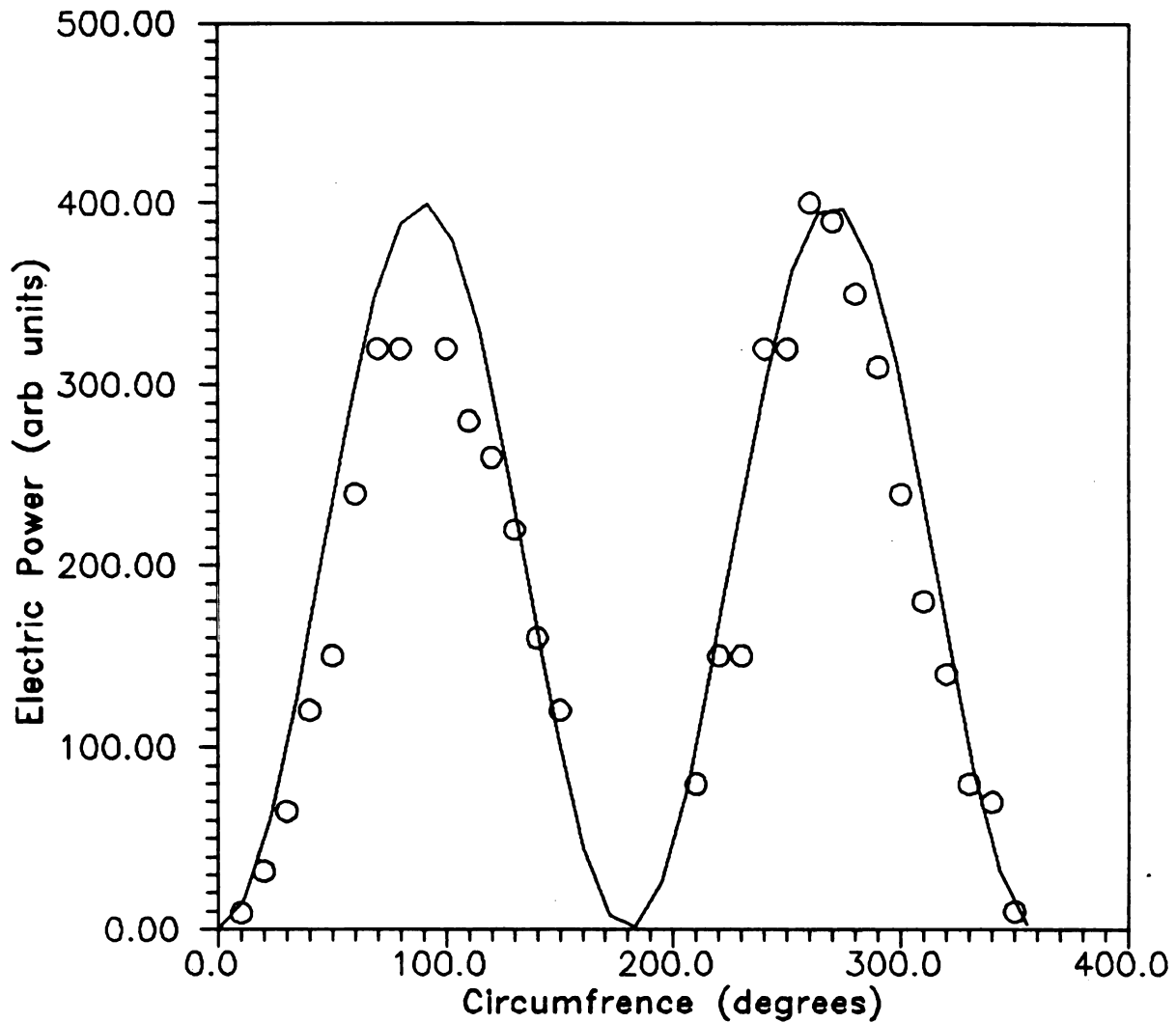


Figure 7.9 Electric field pattern measurements for the MPDR 5.

Data taken with a micro-coaxial probe. Note that the power measurements are not absolute (no calibration was conducted for these tests, as was done in Chapter Six for the 610-a). The microwave antenna is located at 270° . The second peak is therefore higher due to the evanescent near zone fields.

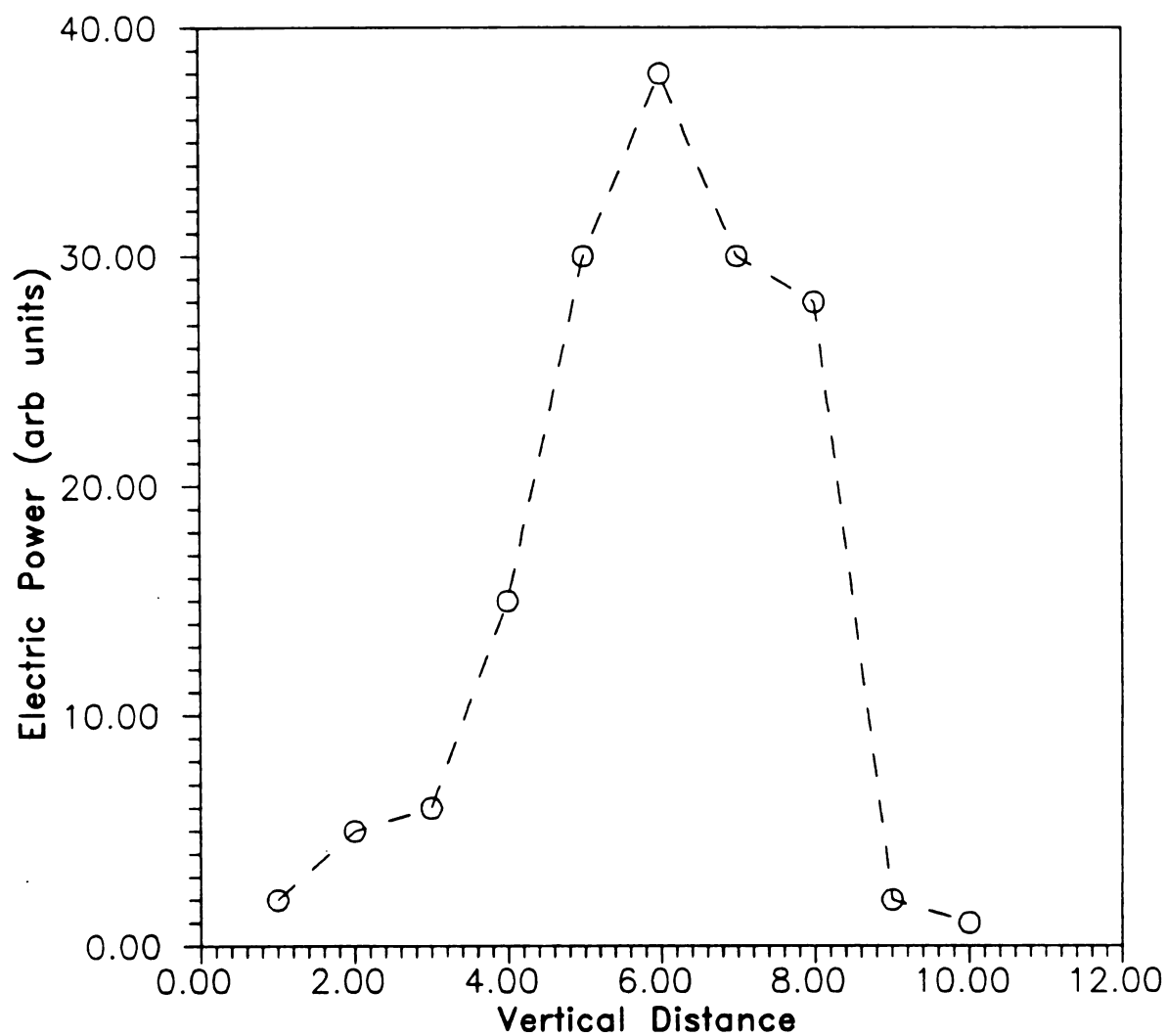


Figure 7.10 Vertical variation of the electric fields in the MPDR 5.
The vertical variation shows only one peak in the center, confirming the TE_{111} mode operation of the MPDR 5.

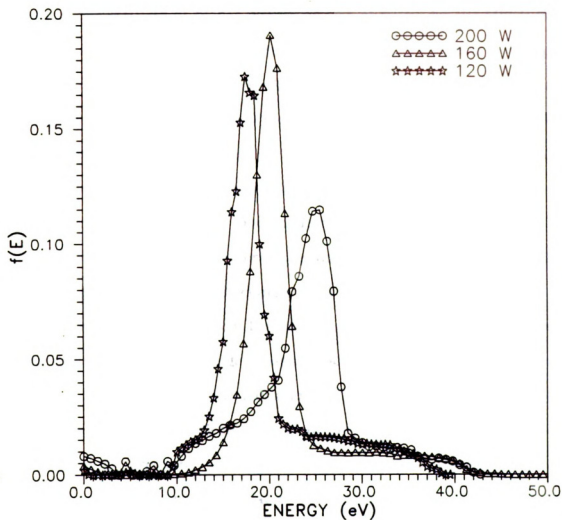


Figure 7.11 IEDF variation with power for the MPDR 5.

Data taken with the IEA 5 cm downstream for a 1.2 mTorr argon discharge, without the downstream confinement chamber. Note that there is no evidence of the low energy peak as reported by Sze.

increases with input power, going up from 4.5 eV at 120 W, to 5.5 eV at 160 W. However, the IEDF broadens significantly as the input power increases to 200 W. This broadening is not fully understood at this time, but it is speculated that it may be due to gas heating - the IEDF broadening may be due to the increased electron temperatures at higher powers as was observed for the MPDR 610 in Chapters Four and Five. It has been reported earlier that the absorbed power density of this small ECR discharge is 2-4 W/cm³ [Sze-93b]. This is because of the high surface-to-volume ratio of the discharge region. Significant ion-electron wall recombination occurs at high density and low pressure operation resulting in a higher electron temperatures, and a correspondingly higher thermal energy of the ions and neutrals in this small ECR discharge.

Figure 7.12 shows the pressure dependence for a constant 120 W absorbed power in an argon discharge. Data are taken 5 cm downstream from the discharge generation region. It is clearly seen that the IEDFs shift towards lower energies as the discharge pressure increases. As mentioned in Chapter Four (see Section 4.6.1 for the ionization-diffusion loss balance theory), these trends are related to the electron temperature and plasma potential variation with discharge pressure, whereby raising pressure decreases the electron temperature and plasma potential of the discharge. This leads to a lower potential through which the ions fall on their way to the IEA, which ultimately lowers the ion energy at higher pressures. This pressure and power dependence of the IEDFs in the MPDR 5 is consistent with measurements reported on both larger [Mak-92, Sze-93b], and smaller [Sri-92a, Sri-93a] permanent magnet ECR plasma sources.

The low pressure IEDF shown in Figure 7.12 displays considerable

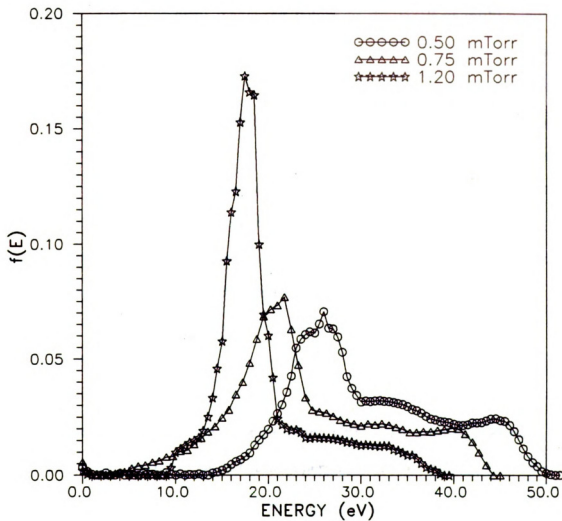


Figure 7.12 IEDF variation with discharge pressure.

Data taken with the IEA 5 cm downstream, for a 120 W input power argon discharge, and without the downstream magnetic field confinement chamber. Note the development of the secondary peak at twice the energy of the primary peak, as the discharge pressure decreases.

broadening beyond that which would be expected from ordinary gas heating. This IEDF in fact shows the development of a second peak at an energy approximately twice that of the major peak, suggesting the possibility of multiply charged ions, i.e. the production of Ar^{2+} in this source. Evidence of multiply charged ions has not been measured before in the IEDF of multi-polar ECR sources, but a recent charge state distribution of the MPDR 610 indicates about 5% Ar^{2+} production [Sri-94c, see also Chapter Eight]. The fact that this small ECR source operates with high power densities, and hence higher exciting electric fields may result in Ar^{2+} production as the discharge pressure decreases. Furthermore, the octapolar magnetic field of the source efficiently traps high energy electrons producing confinement times that are possibly long enough to allow the electrons to achieve enough energy to create multiply charged ions through successive electron impact ionization.

7.4 Concluding Remarks

From the data presented here, along with other studies that have been completed on the development and operation of the MPDR 5, some key conclusions may be drawn. It is an electrode-less, high ion/electron density, efficient microwave ECR plasma source, with predictable, and repeatable operating performance. A TE_{111} mode standing wave is set up within the microwave cavity structure that enhances power transfer from the impressed electric field to the discharge load. Most characterization has been conducted with argon as the discharge gas. Radial profiles of ion density and plasma potential are very uniform, especially in the presence of the magnetic

confinement structure.

The electron gas has a near Druyvesteyn distribution, contrary to most theoretical predictions (that assume a Maxwellian distribution), while under most operating conditions, the ion energies are narrow and peaked. Under certain conditions however (like with high input powers, or at very low pressures), the IEDF tends to spread out, in part due to gas heating (at high powers). At low pressures, this energy spread may be due in part to the possibility of the production of doubly charged ions, since electron confinement increases and collision frequencies decrease as the discharge pressure falls, leading to successive electron impact ionization. There is also some evidence of resonant charge exchange and a bi-modal ion energy distribution function in the presence of a multi-polar magnetic confinement structure, but this has not yet been confirmed.

Much work needs to be done, however, for further understanding of this small source. Can the low energy secondary IEDF peak be reproduced with the magnetic confinement in place? Without this confinement structure, can the high energy secondary IEDF peak be reproduced as pressure decreases? How does the MPDR 5 operate without its complement of octapolar magnets, i.e. is there power transfer to the working gas without ECR, and at what pressure/power conditions?

Characterization of the source with other discharge gases (like nitrogen, hydrogen, helium etc.) needs to be done as well. As was seen with the MPDR 610, nitrogen and helium operation of the source varied significantly from its operation in argon. It needs to be confirmed that this dependence on working gas is observed in the MPDR 5 also. Other diagnostic techniques like optical

emission spectroscopy (to identify other plasma species), quartz crystal microbalance (to obtain atomic flux density), and laser induced fluorescence, etc. will also contribute valuable data towards further understanding of this source.

Finally, some beam development was conducted by Mahoney. This needs to be repeated and further studied, with a better design of ion extraction optics and with proper beam characterization techniques (like emittance and brightness measurements, and charge state distribution evaluation). The ion extraction system may be constructed for a broad ion beam using multiple apertures on the grids. Conversely, a single central aperture, with a three grid accel-decel system may be designed to extract high current, high energy ion beams from the MPDR 5. More knowledge about the operational characteristics of this source will lead to further understanding of the plasma physics in small ECR sources. Possible applications of the MPDR 5 are foreseen to be as a source of ion beams, reactive atomic species, or quasi-neutral plasma for materials processing.



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**PROPERTIES OF
ELECTRON CYCLOTRON RESONANCE PLASMA SOURCES**

**By
Aseem Kumar Srivastava**

**A DISSERTATION
VOLUME II**

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Chapter 8

Application: The 610 as an Injector to the SCECR

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8.8 Operational Performance - 610 on, SCECR on

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Chapter 8

Application: The 610 as an injector to the SCECR

8.1 Introduction

Other than semiconductor processing applications, there is another very important field of science where ion sources are used - to create ion beams for injection into particle accelerators. These accelerated beams (up to 20 GeV per nucleon at the CERN supercollider in Europe) are then used in a variety of nuclear physics and particle fragmentation experiments. There are currently about 45 electron cyclotron resonance ion sources (ECRIS) for multiply charged positive ion beams in operation throughout the world, with 10 - 15 more under construction [Lyn-92]. On the campus of MSU, is the National Superconducting Cyclotron Laboratory (NSCL), where nuclear physics experiments are carried out. Prior to the mid 80s when the first ECRIS was commissioned at the NSCL, beam injection into the two cyclotrons at the NSCL (the K500 and the K1200) was done using PIG (Phillips/Penning Ionization Gauge) sources. However, PIG sources have cathodes that are immersed in the plasma. Energetic ion bombardment from the plasma leads to erosion of the cathodes and therefore,

short lifetimes for these sources. Indeed the PIG sources at the NSCL had to be replaced every few hours depending on the ion beam that was to be injected into the cyclotron (every two hours, for example when a neon beam was used [Col-95]).

As mentioned earlier, these PIG sources were subsequently supplanted by multiply charged ECR ion sources, developed at the NSCL by Dr. Timothy Antaya's research group. Beam injection from the electron cyclotron resonance ion sources (ECRIS) has several advantages over the conventional Penning sources: a much longer lifetime due to the absence of any electrodes in the plasma, so that the only consumed material in the ion source is the working gas itself. The ECR sources are also better able to reproduce the performance on a day to day basis. Finally, a wider selection of ion beams may be extracted from the ECRIS, including metallic ions since a broader spectrum of charge states is available.

Many differences exist between the use of ECR technology for multiply charged ion sources (like the ones used at the NSCL) and the way this very same technology is used in plasma sources that find industrial semiconductor applications (like the MPDR 610). This will become more apparent in the next few sections where multiply charge state ECRIS and their operating conditions are discussed. Despite this, several areas of mutual interest between the two ion source groups at MSU were identified for investigation. This chapter describes the first of several experiments conducted at the NSCL as a collaborative effort of the Antaya ion source group at the NSCL and the Asmussen group at Electrical Engineering (EE). These experiments employed the expertise and knowledge of both research groups. The results of these experiments verified and further

explained phenomena concerning intense high current multiply charged ECRIS (detailed in Chapters Eight and Ten), while at the same time allowed continued characterization of the MPDR 610 (as detailed in Chapter Nine).

The chapter begins with a brief introduction to multiply charged ECRIS. While several books discuss these sources in greater detail, an introduction is warranted to lay a foundation for the rest of this chapter (and also Chapter Ten). Also, the main differences in design and operating conditions between multiply charge state ECRIS and the ion sources from the EE group (that are similar to the ion/free radical sources which were reviewed in Chapter Two) are detailed. An excellent summary of multiply charged ECRIS of the world is provided in Reference Jon-89, where the history of the SUPERMAFIOS, MINIMAFIOS, ECREVETTE, OCTOPUS, and several other multiply charged ECRIS from around the world is discussed (see, for example Table 10.2, Reference Jon-89). Sections of this reference also discusses some of the crucial theoretical background and basic principles of multiply charged ECRIS in a concise and readable manner.

The next section in this chapter presents a simplified, black box model of a multiply charged ECRIS, followed by a description of the Superconducting ECR Ion Source (SCECR), one of three multiply charged ECRIS currently in operation at the NSCL (the others being the Room Temperature ECR ion source - RTECR, and the Compact ECR ion source - the CPECR). A majority of the collaborative experimental work (between the NSCL and the EE ion source groups) was conducted on the SCECR. Details of the experiments that were performed for this chapter are then discussed, followed by the results, which were presented at the ICIS-93 [Sri-93c], and subsequently published in the

proceedings [Sri-94c].

8.2 Multiply Charged ECRIS - a Brief Introduction

As the name suggests, multiply charged ion sources create a plasma whose constituents include ions that have lost more than one of their electrons. Multiply charged ion sources are now easily able to produce beams of fully stripped charged species ($^{14}\text{N}^{7+}$ or $^{16}\text{O}^{8+}$), to inject the oxygen or nitrogen nuclei into the cyclotrons, or these nuclei may be used directly in atomic physics experiments. ECRIS may now also be used to generate metallic ion beams through sputter ionization of metals immersed in an intense plasma.

The reason for using beams of multiply charged ions is that the acceleration of the charged species through an extraction potential is directly proportional to the charge of the ions. In theory, a doubly charged ion will be accelerated twice as much as a singly charged ion when going through the same potential difference. (Note, however that in a cyclotron the energy gained by an ion is proportional to the square of its charge.) Hence, the higher the charge on the ion, the more it can be accelerated through the cyclotrons. This is in fact, precisely the reason why industrial semiconductor applications of ECR ion sources do not desire multiply charged ions - energetic ion bombardment of the substrate may lead to prohibitively high damage rates on the surface during the microchip manufacturing or film deposition being carried out with the aid of some plasma species.

Most multiply charged ion sources that are in use in the particle accelerator laboratories of the world are ECR ion sources [Ant-94a, Cla-83, Lyn-

92, Loi-84]. As mentioned earlier, some ECRIS are also used directly in atomic physics experiments (like the MICROMAFIOS). All ECRIS employ the same electron cyclotron resonance theory as industrial plasma sources to couple power from the electromagnetic fields into the electron gas in the presence of a specified static magnetic field. These hot electrons then impart energy to the neutrals and ions through collisions. It is believed that an ion gets multiply charged through a process known as "successive electron impact ionization" whereby, an ion of charge i (having lost i electrons) undergoes an inelastic collision with an energetic electron and gets ionized further - to a charge of $i+1$, while losing another electron. This may be shown through the following equation, where e^* indicates an energetic electron:

$$A^i + e^* = A^{i+1} + 2e \quad (8.1)$$

While the process of energy transfer may be the same (ECR), the conditions under which multiply charged ions are generated in the ECRIS are significantly different from the singly (or at most doubly) charged substrate processing industrial ECR ion sources. Successive electron impact ionization (also known as step-wise ionization) occurs if and only if the charged species in the plasma chamber are confined long enough to undergo several elastic (non-ionizing) and inelastic (ionizing) collisions with energetic electrons. This long confinement time is achieved through the use of magnetic bottling of the charged species. As the electrons oscillate around the field lines and travel from a region of low magnetic field strength to a region of high field strength, the directed (non rotational) velocity decreases due to the force of the magnetic

fields. If the ratio of the lowest to highest magnetic field strength (known as the magnetic mirror ratio) is large enough, the electron will come to a full halt, and start moving back to the region of low field strength, gaining energy as it goes through the ECR regions (assuming the ECR zones lie somewhere within the magnetic bottle). The electron is then said to be "confined" by the magnetic bottle. Due to this confinement, the electron temperatures in multiply charged ECRIS are usually very high - typically from 1 keV to 10 keV (compared with the several eV of average electron energy in the ion sources used in industrial applications, like the MPDR sources in EE).

All multiply charged ion sources employ magnetic confinement (both radial and axial) to prevent loss of charged species before successive ionization has occurred. Hence the design of these confining magnetic fields is critical to the performance of the ECRIS, and several computer codes exist (like POISSON and PANDIRA, or TOSCA) to accurately construct the requisite magnetic field topology. These confinement magnets also provide the closed "ECR zones" in certain parts of the plasma chamber (within the magnetic bottle), which allows the ECR power transfer mechanism to take place as the electrons oscillate about the static magnetic field lines. The magnetic field simulating computer codes may also be used to critically locate these ECR zones for optimal electron cyclotron resonance heating (ECRH) and source performance.

Since the electrons are selectively heated in an ECRIS, the ion gas temperature (and hence the random energy of the ions) remains relatively low - probably less than 1 eV [Jon-89]. This is a major ramification of ECRH because most of the beam broadening, energy spread and the corresponding high emittances of the ion beam is caused by high random energy of the ion gas

(some broadening may also be linked to space charge, and charge exchange effects). In an ECRIS, the ion gas is relatively cold, which reduces the energy spread, and enhances ion beam transportability. The emittance of the ion beams extracted from an ECRIS is therefore dominated by the properties of the beam extraction and transport systems, and not by the effects of random ion energy.

Another major factor in creating multiply charged species is the pressure at which the ion source operates. For multiply charge state ion sources, an interesting trade off is encountered while considering the discharge pressure. ECRIS for multiply charged ions normally operate at pressures about 10^{-6} Torr or less - two to three decades lower than their plasma processing cousins used in industrial applications. At such pressures, to a first approximation, ion density (and hence the high charge state ions) produced by the ion source is directly proportional to the neutral density (more neutrals equals more ions that can be formed), which is in itself defined by the discharge pressure. So increasing pressure should increase ion density. However, a high discharge pressure also means more ion-neutral collisions leading to scattering and a loss of confinement of the ions, and also phenomena like charge exchange. These phenomena retard the successive (or stepwise) electron impact ionization and hence at higher pressures, the production of high charge states is also depressed.

Therefore, a compromise in the operating conditions is usually necessary, where the neutral density in the plasma is high enough to generate the required amount of charged species, but the discharge pressure is low enough to allow long ion lifetimes, that in turn allow successive ionization. This optimal operating pressure in an ECRIS is generally reached through empirical means.

As will be seen in a later section, this difference of operating pressure was a major obstacle in the experiments detailed in this chapter.

When heavier gases like neon, or krypton are used to produce multiply charged ions, a process known as "super gas mixing" may be used to enhance ion confinement and generation of multiply charged species [Ant-92]. As a rule, no amount of magnetic confinement can keep the high energy electrons from breaking away from the field lines and leaving the confined plasma. When energetic electrons break out of the magnetic confinement and are lost to the walls, the ions in the plasma must follow these lost electrons to maintain quasi-neutrality in the plasma. If the electron loss was not complemented by a similar ionic loss, the plasma potential would continuously increase with time and increasing electric fields would be set up inside the plasma.

To contain this loss of heavy ions (and thereby increasing the ion lifetimes), a "ballast gas" with a much lower atomic weight is injected into the plasma and ionized. The lighter ballast gas ions then follow the break away energetic electrons and allow the heavier main gas ions to remain confined inside the plasma to undergo multiple ionization. In effect, this technique "cools" the heavy ions. The plasma potential in the source is reduced, and usually varies between 10 to 40 V (positive) in a multiply charged state ECRIS like the AECS at Lawrence Berkeley Laboratory [Xie-93]. For example, oxygen may be used as the ballast gas for the krypton ion beam in the SCECR. The results are shown in the sample charge state distribution of Figure 3.15, Chapter Three, which shows the individual ion peaks of the krypton/oxygen plasma. Because of the lighter oxygen ions, the krypton ions had sufficiently long lifetimes in the SCECR so as to allow the production of high charge states.

A final crucial difference between the two sets of ion sources is the theory of "frequency squared scaling" that has been used till now for designing multiply charged state ECRIS. This will be covered more thoroughly in Chapter Ten, but a synopsis is presented here in the context of discussing these ECRIS. According to this rather simplified theory (which employs many assumptions), the plasma may be modelled as a high pass filter. Subsequent derivations from this simplified model imply that the ion density produced in an ECRIS is directly proportional to the square of the frequency of excitation [Jon-89]. Hence, there has been (and continues to date) a steady migration in the development of multiply charged state ECRIS to higher frequencies, and most such sources now operate at frequencies ranging from 6 GHz to 18 GHz, while some operate at even higher frequencies. In comparison, almost all ion sources that are used in industry utilize the commonly available frequency of 2.45 GHz. (Some operate at even lower frequencies - radio frequencies - but none go higher than a few GHz.) While discussing the frequency squared scaling in Chapter Ten, it will also be noted that while this law has been successful in producing higher densities (and higher charged states) in ECRIS, other criteria are equally important for producing high intensities of multiply charged ion beams. This was postulated as far back as 1984 [Jon-84].

8.3 Multiply Charged ECRIS - a Black Box Model

A simplified picture of an ECRIS for multiply charged ion beams now emerges, and is depicted in Figure 8.1. Made of copper or brass, it usually consists of two stages: the first stage which is thought to pre-ionize the working

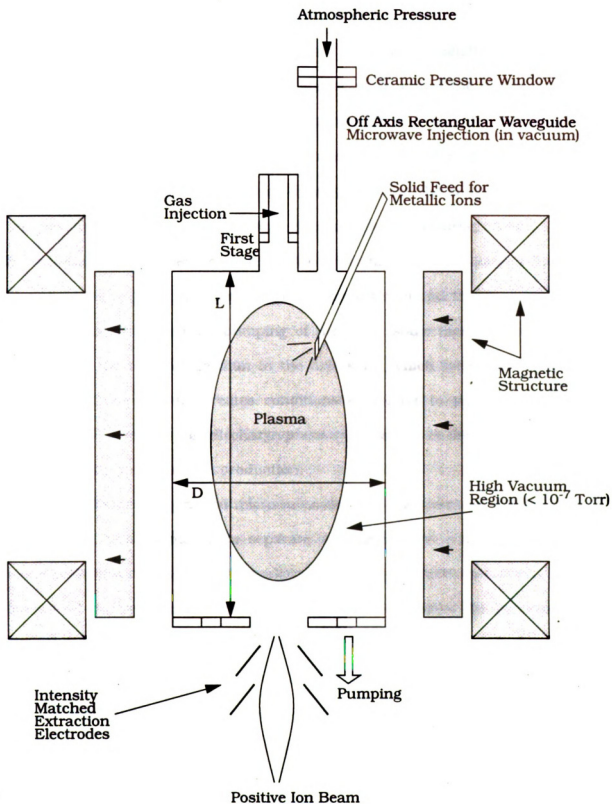


Figure 8.1 Schematic of a typical ECRIS for multiply charged ions.
Note the aggressive magnetic confinement of the plasma in the main stage.

gas and inject the low density, low charge state plasma into the main stage, where - under the right discharge pressure, power and magnetic confinement conditions - successive electron impact ionization generates the highly charged ions. The main reason for a dual stage source, however was thought to be to satisfy the trade off that was discussed earlier in Section 8.2 - how to keep the pressure high enough to increase ion density, while at the same time keeping the pressure low enough for successive electron impact ionization. This is solved by maintaining a higher pressure in the first stage that pre-ionizes the gas (thereby satisfying the Paschen law for gas breakdown) and thereby increasing the ion density. Differential pumping of the main stage then allows a lower pressure in the main stage than in the first stage which increases the mean lifetime of the ions (and creates conditions conducive to successive impact ionization). The main stage discharge pressure is kept at or below 10^{-6} Torr for optimal multiply charged ion production.

Both stages may be fed microwaves through one generator (typically via waveguides), or they may have separate waveguides that transport the TE_{10} mode (lowest waveguide cutoff mode) to the plasma. Both stages may even operate at different microwave frequencies. Note that since the frequency of operation for the multiply charge state ECRIS ranges from about 6 GHz to 35 GHz, the high power klystron (or gyrotron) based microwave transmitters are extremely expensive to purchase and maintain, compared to the plasma sources used in industrial applications which are usually operated using the abundantly available (and cheaper) 2.45 GHz magnetrons. At the base of the source is the extraction apparatus, from where specially designed multiple electrodes extract the ion beam. Note that ALL ions which diffuse to the base are extracted, and

the separation of different charge states (like $^{14}\text{N}^{7+}$ from $^{14}\text{N}^{6+}$, for example) takes place later as the beam is deflected through a dipole magnet downstream from the extraction electrodes. Hence there is the "injection end" and the "extraction end" of the ECRIS.

The magnetic field structure surrounding the main stage is a crucial design parameter and about one third of the financial resources in building a new ECRIS may be devoted for the design and development of magnets alone. The magnets may be permanent and/or electric coils that may be at room temperature, or there may be cryogenically cooled superconducting coils. A special magnetic field topology known as the "minimum B configuration" is generally used for multiply charged state ECRIS, where the field strength is minimum in the center of the source and increases in every direction. This magnetic field configuration provides confinement of charged species in both the axial and radial directions, and also produces the field strength necessary for ECR at the operating frequency of the ion source. Generally axial confinement is produced from magnetic field generated by a series of solenoid coils surrounding the plasma chamber. The ratio of maximum to minimum field is known as the mirror ratio. For optimal axial confinement, the mirror ratio at the injection end of the ECRIS (close to the first stage) is higher than the ratio at the extraction end of the source. Radial confinement is produced by a multi-polar field (like a hexapole, or octapole field). Finally, the minimum B configuration also stabilizes the plasma boundary from magneto-hydro-dynamic (MHD) instabilities [Jon-89, Jon-84].

As simple as this picture looks (specially in Figure 8.1), the multiply charged ECRIS is a complicated system. It incorporates several different

technologies like electromagnetics, cryogenics, surface science (electron emitting surfaces work well for the plasma chamber - as will be seen later), vacuum science, and the theories of extracting and transporting ion beams. The complexity and sophistication of such an ECRIS is now further clarified with the description of the SCECR, which has been demonstrated as having some of the world's best operation performance characteristics today [Ant-94a, Ant-89] for generating high intensities of multiply charged ions.

8.4 The Superconducting ECR Ion Source (SCECR)

Figure 8.2 is a schematic of the SCECR at the NSCL. Commissioned in 1989, it is a variable frequency, fully superconducting, hexapole stabilized tandem mirror ion source with a collisional pre-ionizing injector and a multimode microwave cavity as the main stage. An explanation of the above statement follows. The SCECR has a full compliment of five liquid helium cooled, superconducting coils containing copper stabilized niobium titanium conductors (with formvar insulation), stacked three (at the injection end) and two (at the extraction end), that provide the axial confinement. These coils are theoretically able to generate field strengths to satisfy ECR and confinement conditions for frequencies as low as 2.45 GHz and up to 35 GHz. The source has a hexapole for radial confinement, which is also superconducting and resides inside the bore of the tandem mirror. It provides the radial confinement for the charged species, thereby generating the radial component of the minimum B configuration. The design of the SCECR is very robust, with separate systems acting independently of each other. For example, the cryogenic vacuum system operates independent

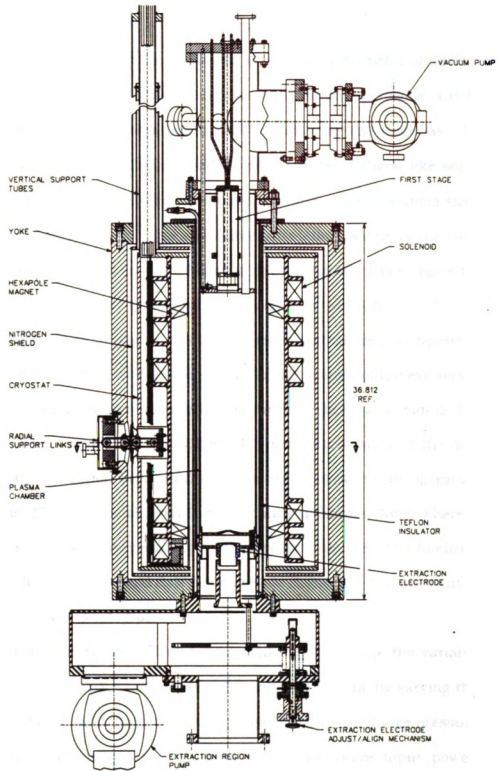


Figure 8.2 Schematic of the SCECR.

Note the 5 solenoid coils and the hexapole coils within the bore. All magnets are superconducting. The system is set up for 6.4 GHz frequency injection into the main stage.

of the plasma vacuum system.

The length of the main stage is 50 cm, and it has a diameter of 14 cm, which creates a standard circular waveguide multimode microwave cavity structure. Some multiply charge state ECRIS may be as large as the SUPERMAFIOS with a 100 cm length and 35 cm diameter. Others, like some Japanese sources at RIKEN are relatively smaller - ECRIS come in various sizes [Jon-89]. A three electrode Pierce-type accel-decel extraction system at the base of the SCECR provides the necessary voltages at appropriate electrode angles for ion beam extraction. The first electrode is connected to the SCECR and so is maintained at high potential (up to 30 kV). The second electrode may be either grounded, or at a negative potential - hence the "accel" section of the extraction apparatus. The final electrode is generally grounded, thereby providing the "decel" section of the apparatus. The spherical "quasi-Pierce" angle of the first electrode, and the separation between the electrodes is critical to the operation of the apparatus. (This will be covered in more detail in Chapter Nine, where a similar system is designed for extracting beams directly from the 610.) In effect, two electrostatic lenses are created that focus and accelerate the ion beam out of the SCECR and into the beam pipe.

The SCECR is therefore a fixed volume ion source (unlike the variable volume MPDRs like the 610) where tuning of the source is done by varying the flux of species from the first stage, the gas type (gas mixing), discharge pressure (flow rate of the working gas) in the main stage, microwave input power, extraction voltages and by adjusting the various magnetic fields (hence the necessity of having electromagnetic coils). As mentioned earlier, all of this tuning ultimately controls the plasma potential inside the source that equalizes the ion

and electron losses to the walls [Xie-93].

As noted above, the SCECR is a two stage source. Working gas is fed through the first stage, and microwaves (at 6.4 GHz) are injected into the main stage through a waveguide terminating at the baffle plate that separates the main stage from the first stage. The microwaves migrate down into the main stage, and at the same time up into the first stage where, by design, the falling edge of the axial magnetic field (from the injection end mirror field) creates an ECR zone. The high pressure (compared to the main stage) in the first stage is thought to generate a cold, collisional low charge state plasma which then diffuses freely into the main stage because of a density and pressure gradient. In fact, a bias disk raised to a potential relative to the source may be attached to the egress of the first stage to "extract" the collisional plasma (or a certain charged species) from the first stage more efficiently. The very low pressures ($\sim 10^{-6}$ Torr, or lower), ECR heated electrons (up to 10 keV) and the minimum B magnetic field confinement in the main stage, and gas mixing all provide the conditions necessary for successive impact ionization.

A typical SCECR charge state distribution was shown in Chapter Three (Figure 3.15), where a krypton beam was being extracted with oxygen used as a ballast gas. More exotic species, for example $^{238}\text{U}^{40+}$ have also been successfully produced in the SCECR. While the necessity of the first stage for the optimal performance of the SCECR has been proven beyond doubt (removing the first stage depresses the performance of high charge states from the source), the exact role played by the first stage was ambiguous. What specific species of the cold, collisional, low charge state plasma generated by the first stage were actually required by the main stage for optimal performance? A unique

opportunity to study this arose through the collaboration with the EE ion source research group, and the following sections of this chapter detail the experiments and the results, starting with the description of the hardware.

8.5 Experimental Hardware Description

The design, operation and performance characteristics of the MPDR 610 have been thoroughly detailed in Chapters Four through Six. At 2.45 GHz operation, the source is able to successfully produce ion densities of about 10^{11} cm^{-3} , with narrow controllable ion energy distributions, and near Maxwellian (or more specifically, near-Druyvesteyn) electron energy distribution functions. Typical average ion energies are about 20 to 40 eV, while typical average electron energies range from 3 to 8 eV. The 610, therefore, is a highly intense and very bright plasma source that can be raised to a potential, and from which electrons or ions may be selectively extracted. Indeed, Chapter Nine is a discussion on the beam extraction and characterization from the 610. Or a neutral plasma may flow freely out of the source if the extraction potential is reduced to zero.

The premise behind the experiments of this chapter was to mount the 610 on the SCECR in a manner such that the 610 would act as the first stage of the SCECR. If the 610 was electrically isolated from the SCECR, this would allow either positive, neutral or negative injection from the 610 into the main stage of the SCECR, depending on the potential on the 610 with respect to the SCECR. Theoretically it would then be possible to compare the operation of the SCECR as various species are injected from the 610 into its main stage, and determine exactly which species (ions, electrons, or neutral plasma) from the first stage

results in the best operational performance of the SCECR.

To this effect, the "hybrid source" was designed. Shown in Figure 8.3, the 610+SCECR source was designed to retain as much of the SCECR hardware as possible. The first stage of the SCECR was replaced by the 610, which itself was mounted on a small alumina isolation platform. This allowed the 610 to be electrically floating with respect to the SCECR and thereby to be biased at positive, negative, or neutral potential relative to the SCECR. However, the diameter of the 610 (5.8 cm) is larger than that of the original first stage of the SCECR (about 4.5 cm). Due to this, and the 4.5 inch Conflat flanges of the 610 and the alumina isolation platform, two minor changes in the waveguide feeding the microwaves (at 6.4 GHz) into the main stage had to be made. These are discussed below, and shown in Figure 8.3. This figure, showing the new "first stage" and the two minor modifications, may be compared to the original first stage of the SCECR shown in Figure 8.2.

First, the full height 6.4 GHz waveguide (WR 137) had to be replaced by a half height waveguide inside the first stage since there was no room on the top 8 inch Conflat flange to place the appropriate connectors for both the 610 and the full height waveguide. Note that since the TE_{10} mode is being transported in these waveguides, the exact height of the waveguide is irrelevant (as long as it is not so small that the power density at the edges becomes prohibitively high). This transition from the full height 6.4 GHz waveguide to the half height waveguide was done using a brass quarter wave transformer, which is detailed in Figure 8.4. The full height waveguide outer dimensions are - 1.5 inches by 0.75 inches (3.81 cm by 1.90 cm), while the half height waveguide dimensions are - 1.5 inches by 0.44 inches (3.81 cm by 1.12 cm). The wall thickness of both

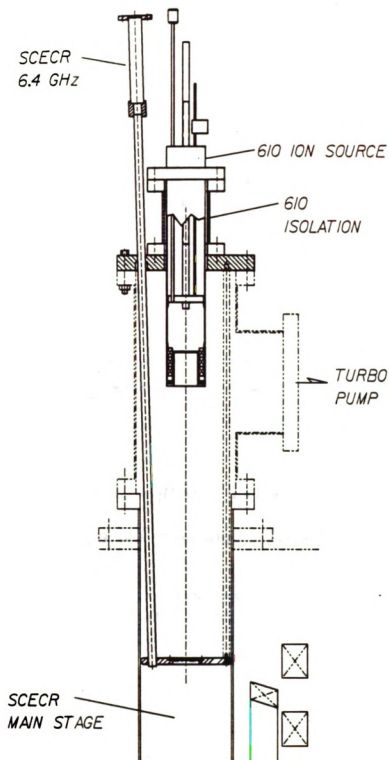
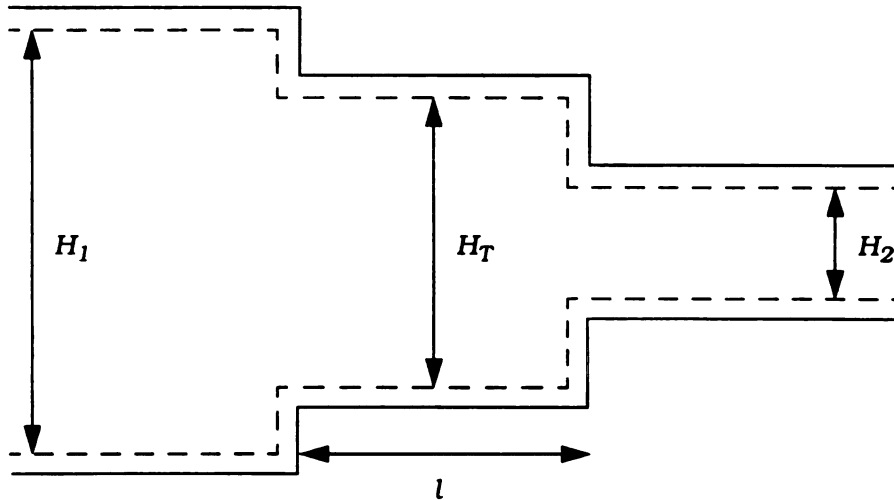


Figure 8.3 Schematic of the SCECR+610 "Hybrid Source".

Note that the 610 is about 30 cm from the SCECR main stage. Also, the SCECR is powered by a 6.4 GHz waveguide, while the 610 has a coaxial connector for 2.45 GHz microwave power.



$$H_T = \sqrt{H_1 H_2} = 1.11 \text{ cm}$$

Here, H_1 is 1.58 cm, while H_2 is 0.8 cm

$$l = \lambda_g / 4 = \frac{\lambda}{\sqrt{1 - (\lambda / (2a))^2}} = 1.613 \text{ cm}$$

Figure 8.4 Schematic of the quarter wave transformer.

This transformer was used to connect the regular height WR 137 waveguide to its half height counterpart (both for 6.4 GHz transmission). Note that for all calculations, the inside dimensions were used. a is the width of the waveguide, and λ is the free space wavelength at 6.4 GHz (4.68 cm).

waveguides is 1/16 of an inch (0.16 cm). A similar transformer will be used in Chapter Ten for a 2.45 GHz waveguide, and so its design is detailed now.

The theory of quarter wave transformers may be found in several texts [Rag-48, Ram-65, Riz-88], and so only the specifics of the design of this transformer are presented here. Essentially, quarter wave transformers are used to match a resistive load to an input transmission line, or to match two transmission lines with different characteristic impedances so as to minimize reflection of power from an unmatched joint, thereby maximizing the power transfer from one line to the other. If the impedance of one transmission line is Z_1 and that of the other line is Z_2 , then the quarter wave transformer impedance Z_T is given by [Ram-65]:

$$Z_T = \sqrt{Z_1 Z_2} \quad (8.2)$$

For waveguide matching where only the narrow dimensions of the two sections differ (as in the case here), the calculation of the quarter-wavelength transformer becomes much simpler since the characteristic impedance is proportional to the narrow dimension (height) only. Thus, the above equation simplifies to the following [Rag-48]:

$$H_T = \sqrt{H_1 H_2} \quad (8.3)$$

where H_T is the height of the transformer and H_1 , and H_2 are the heights of the two waveguide sections (see Figure 8.4).

The length l of the transformer is also an important parameter and is given in terms of the guided wavelength λ_g of the quarter-wave transformer by the following equations:

$$l = \lambda_g / 4 \text{ where} \quad (8.4)$$

$$\lambda_g = \frac{\lambda}{\sqrt{1 - (\lambda / (2a))^2}} \quad (8.5)$$

Here, λ is the wavelength in free space at 6.4 GHz (4.6875 cm), and a is the width of the waveguide.

When all the numbers are substituted into the above equations (using the inner dimensions of the two waveguides - WR 137 and the half height 6.4 GHz waveguide), the quarter wave transformer dimensions are calculated to be:

$$H_T = 1.11 \text{ cm (0.44 inches)}$$

$$\lambda_g = 6.322 \text{ cm (2.489 inches)}$$

$$l = \lambda_g / 4 = 1.58 \text{ cm (0.623 inches)}$$

If the corners of the transformer are filleted by a radius for ease of machining, then the length of the transformer increases slightly [see for elucidation, Reference Bra-71, Eqn. 3]:

$$l = 1.613 \text{ cm (0.635 inches)} \text{ for an } 1/8 \text{ inch fillet on each corner.}$$

The second change that was made in the microwave delivery system was

that the half height waveguide had to be tilted slightly, to clear the 4.5 inch Conflat flange of the 610. Both these changes are minor, and while there may be some power loss in the quarter wave transformer due to reflections, it is expected that there is no significant disruption in the power transfer from the 6.4 GHz transmitters to the plasma in the SCECR. This was confirmed by the experimental results where the SCECR was easily able to ignite and sustain a plasma at 6.4 GHz using the quarter wave transformer without much reflected power, or heating of the waveguide. Note that the waveguide transition from full height to half height may also be accomplished using a gently tapering transformer, which is, in effect an infinite number of smaller transitions. In theory, the smaller the transition steps, the lesser the power loss (due to reflections), and therefore, having many small steps in the transition is probably better for power transfer than having one large step. However, as a first order trial, the single step quarter wave transformer was used, and this worked well for the forthcoming experiments here, and also later in Chapter Ten.

It was necessary in these experiments to bias the 610 up to 1 kV relative to the SCECR. In order to maintain the 2.45 GHz microwave power supply and the power meters (that read the incident and reflected powers to the 610 - see Figure 4.5(b) for the microwave circuit) at ground potential, an isolation joint was designed. Shown in Figure 8.5 (not to scale), the isolation joint consisted of a 1/4 inch thick teflon plate sandwiched between the two waveguide to coaxial cable adapters at one end of the bi-directional crossguide coupler. This waveguide bi-directional coupler was used instead of the regular (more compact) coaxial directional coupler precisely so that such a DC isolation joint can be made. The two waveguide-coaxial adapters of the isolation joint that sandwich

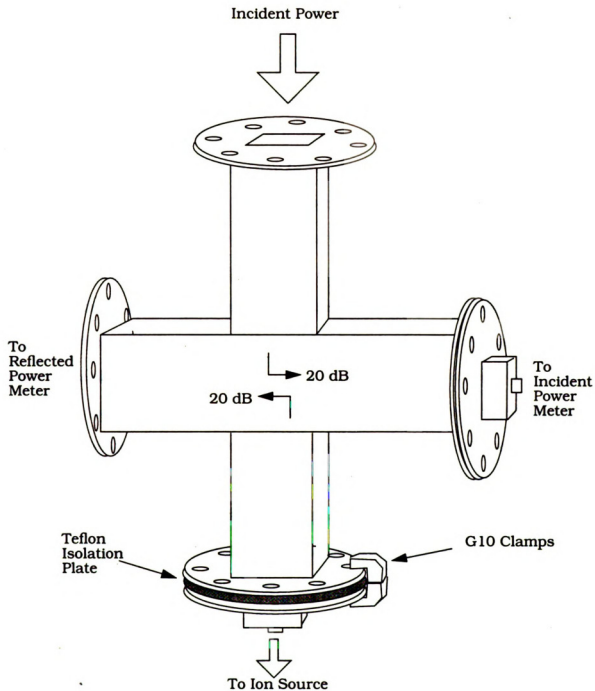


Figure 8.5 The high voltage isolation joint on the waveguide bidirectional coupler.

Only the waveguide-coaxial cable adapter, and the coaxial cable shown here were at high voltage. All other ports were isolated and at ground potential.

the teflon plate are clamped together using four G-10 clamps (G-10 is a machinable, isolating dielectric). In this manner, only the coaxial cable to the 610, the gas line to the 610 (assuming it is a metal line - a teflon line with polyflow fittings would work also), and the 610 itself are at high potential. The crossguide bi-directional coupler, the power meters, the attenuators and the 2.45 GHz microwave power supply are all at ground potential. This not only protects the microwave apparatus from being subjected to high potential and its fluctuations, it also dispels any need for special isolation cages to safely house the microwave apparatus if it is to be raised to a high potential. The 2.45 GHz power supply may now be plugged into the standard power outlets, without the need for isolation amplifiers, and may be handled as usual, with the flexibility of changing, or completely shutting off power levels even when the 610 is biased at some potential.

Note that with the placing of the teflon plate between the two waveguide-coaxial cable adapters to create the DC isolation, an effective teflon filled "waveguide" has been created with the two adapters acting as the two semi-infinite planes of this "waveguide." Hence there will be some microwave power loss through this pseudo-waveguide. Using an electric field probe, it was seen that at normal operating conditions (about 100 W input to the 610), this power loss at the isolation joint was less than 10 mW/cm^2 near the joint, decreasing rapidly as the distance from the joint increased. (This power loss may be reduced somewhat by sticking conductive aluminum tape on the G-10 clamps. Care must be taken that the tape does not short out the two waveguide to coaxial cable adapters.) At about 5 cm from the joint, the microwave power was negligible - it is a near zone field with no health risks beyond 5 - 10 cm of the

isolation joint, and also has no effect on the performance of the 610. As an aside, this DC isolation joint could be redesigned using radial waveguide theory such that the diameter of the isolating flanges is just right for minimum radiation.

8.6 Operation of the Hybrid Source

The operation of the hybrid source (610+SCECR) is now described. It was mentioned in the introduction that the SCECR typically operates at pressures of 10^{-6} Torr or less, while the 610's normal operating pressures are about 10^{-4} to 10^{-3} Torr. This difference in the optimal pressure conditions implies that in order for the 610 to operate under its optimal conditions (about mTorr pressure), the SCECR would be unable to produce highly charged species due to the collisional nature of the plasma at those pressures. As a corollary, the 610 cannot operate well at the SCECR's optimal operating pressures. To rectify this, a small boron nitride baffle plate with a 1.0 cm diameter hole in the center was attached to the outlet of the 610 to throttle its output and create a pressure differential between the 610's plasma generation region and the rest of the first stage. This allowed a slightly higher pressure inside the 610's quartz tube, while the first stage differential pumping, and then the regular pumps of the SCECR kept the pressure in the main stage low enough for long ion confinement times. Even with the baffle plate attached to the 610, it is expected that the compact ECR ion source was operating at a pressure of less than 10^{-4} Torr, and therefore in its "low density mode," since the pressure differential on either side of the BN baffle plate cannot be three decades high. Note that this pressure differential is

determined by the gas type, the aperture size, the gas flow rate and the rate at which the ions are extracted from the source.

Throttling the output of the 610 however, reduced the net current density exiting the compact source. A 0.5 cm diameter BN baffle plate was also tried, but this smaller aperture severely reduced the 610 output, while still being unable to provide the differential pressures necessary for the 610 to be in its "high density mode" at the optimal SCECR pressure conditions. The 1.0 cm BN baffle was therefore used in these experiments, noting that neither the 610, nor the SCECR were operating at their respective optimal pressures. The 610 still performed well, with less than 10% reflected power, although due to the low pressure and low density plasma being generated inside the quartz, the electron temperatures were probably very high. This was reflected in the heat conducted into the plasma source body, which got much warmer than it would under the 610's normal "high density mode" operation. A variation of the MPDR 610 designed for ion extraction at low pressures must therefore have a better cooling system for the quartz and the magnets than the current source.

The plasma from the 610 streamed out of the throttled output plane and diffused down to the main stage through the large copper baffle plate. Note that since the solenoid fields of the SCECR are increasing as the plasma diffuses towards the main stage, it is expected that the charged species experience a small focussing effect through the baffle plate that isolates the main stage from the "first stage". This baffle plate also has a 1.0 cm hole through which the plasma is injected into the main stage. There might also be some plasma reflection back towards the 610 due to the mirror field.

8.7 Operational Performance - 610 On, SCECR Off

As mentioned above, the 610 was operated successfully at 2.45 GHz frequency, while microwaves at 6.4 GHz were fed to the main stage of the SCECR. The first experiments, however were conducted with just the 610 on. The SCECR microwave supply was switched off, so that the output of the 610 was the only beam being extracted from the base of the SCECR. To extract this beam, the SCECR magnets (solenoids and hexapole coils) were switched on. For this experiment, the alumina isolation platform (that electrically isolates the 610 from the SCECR) was not used and the 610 was mounted directly on the SCECR so that it could be biased at the same potential as the main stage. When the following results are presented, the currents of individual solenoid coils (five) from top to bottom, and the hexapole will be written in parentheses. For example, the six currents (in amperes) for a set of experiments may be written as: (8.7, 8.7, 8.7, 7.4, 7.2, 49.2 A), where the first five numbers denote the solenoid coil currents (three at the injection end and two at the extraction end), and the sixth denotes the hexapole current.

With the SCECR off, the MPDR 610 was switched on. The chamber pressure in the injector stage was about 3.5×10^{-5} Torr of argon, and the input power at 2.45 GHz was about 150 W (less than 5 W reflected). The 610+SCECR was raised to 10 kV, and the SCECR magnets were then switched on (8.7, 8.7, 8.7, 7.4, 7.2, 49.2 A). A charge state distribution of the 610 beam injection was taken (in accordance with the acquisition techniques of Chapter Three), and this is shown in Figure 8.6. Note that the numbers C1 to C6 in the column on the right hand side of the plot represent the magnet currents as listed above. At an

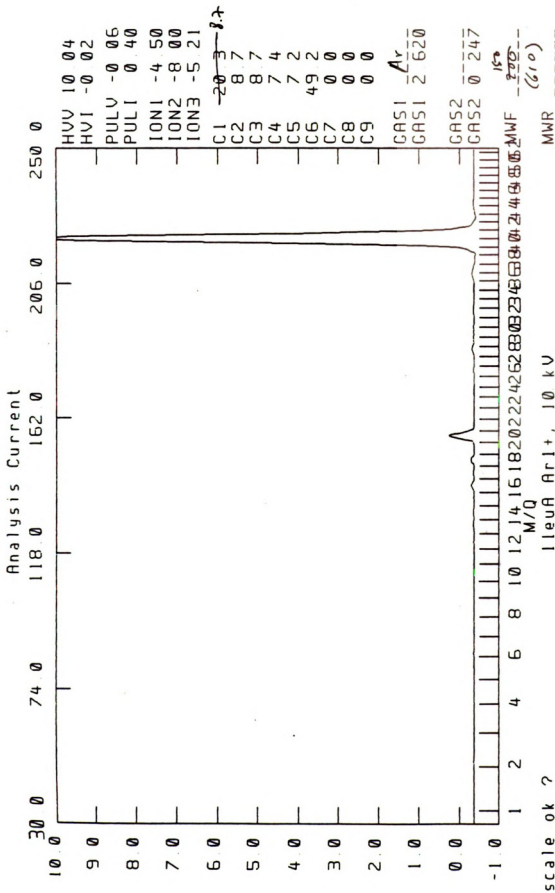


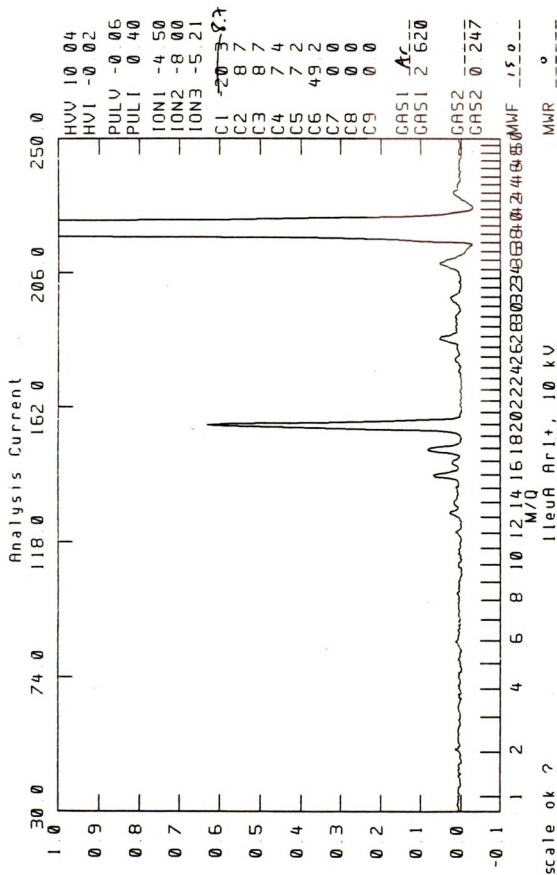
Figure 8.6 CSD of 610 on, SCECR off.

Data taken at 150 W 2.45 GHz power to the 610, 3.5×10^{-5} Torr argon pressure and 10 kV bias on the SCECR+610. The Ar^{1+} current is measured to be about 11.7 μA .

extraction potential of 10 kV, the Ar^{1+} current is 11.7 μA . The same CSD is shown in more detail in Figure 8.7, and now the doubly and possibly triply charged argon ion beams are clearly visible, as are other peaks, like the N_2^{1+} , H_2O , O_2^{1+} and a very minor carbon peak at M/Q of 12. Note that since the SCECR is not on, there is no plasma in the main stage (other than that streaming from the 610), and so the nitrogen, water and oxygen have not yet outgassed from the main stage, as indicated by the very small peaks. The Ar^{2+} generation in the 610 is measured to be about 0.65 μA , as compared to 11.7 μA of the Ar^{1+} generation. Hence the 610, biased at 10 kV, produces about 95% of Ar^{1+} , and about 5% Ar^{2+} with trace amounts of Ar^{3+} . It is therefore confirmed that the 610 is a high intensity low charge state ion source.

For the next study, the gas flow, chamber pressure and all SCECR magnets are maintained at the same levels while the effect on the beam current of raising microwave input power to the 610 is studied. At 100 W input power, the Ar^{1+} current is 8.8 μA , at 150 W the current is 9.4 μA and at 175 W the Ar^{1+} current is 9.7 μA . Data are taken with a 5 kV bias on the 610+SCECR. The intensity of the ion current from the 610, therefore, goes up slightly with increasing microwave input power. Note the similarity with Figure 4.8 (Chapter Four) where the ion density of the 610 at any pressure increases with increasing input microwave power.

Using the wire scan method mentioned in Chapter Three (Section 3.6.3), the emittance of the 610 beam was taken. The pressure in the first stage was about 2.6×10^{-5} Torr, and data were taken with 100 W input power to the 610 at 5 kV 610+SCECR bias. The emittance measurement apparatus was placed about 2 meters away from the 90° bending magnet (see Figure 3.14, Chapter



Three). The Ar^{1+} current was about $8.8 \mu\text{A}$. Figures 8.8 and 8.9 display two such emittance measurements. The shape of the ellipses indicate a divergent beam (third quadrant to first quadrant - see Figure 3.5 of Reference Kel-89), with an emittance of about 86 mm-mrad with 70% coverage and about 135 mm-mrad with 90% coverage of the data by the ellipses. This is relatively high, probably due to space charge effects, high random energy of the ions from the 610 and also due to the extraction apparatus that is optimized for SCECR operations and not for a beam from the 610.

At a constant 610 input power (100 W), the Ar^{1+} current extracted (at 5 kV bias) from the SCECR was measured as the chamber pressure was varied. The SCECR was still switched off, but its magnets were on as before (8.7, 8.7, 8.7, 7.3, 7.3, 50 A). The result is seen in Figure 8.10, where the pressure in the chamber is increased from 1.5×10^{-5} Torr to 2.75×10^{-4} Torr. The data indicates that at very low pressures (less than 2×10^{-5} Torr), the Ar^{1+} current is very low, but it rises steadily to reach a local maximum at about 3×10^{-5} Torr. As the pressure increases further, the current drops slightly, reaching another local maximum about 1×10^{-4} Torr, falling again slightly as additional argon flows through the 610. At about 2.1×10^{-4} Torr, the 610 suddenly jumps to its high density mode, and the current being extracted from the SCECR also goes up sharply.

When this jump occurs, the 610 displays a sudden increase in reflected power, and has to be retuned after the high voltage bias on the 610 is shut off. A remote controlled stepper motor may be attached to the tuning mechanism of the 610 so that any re-tuning may be performed without shutting off the high voltage. Beyond this pressure, the beam current is seen to drop again. This may

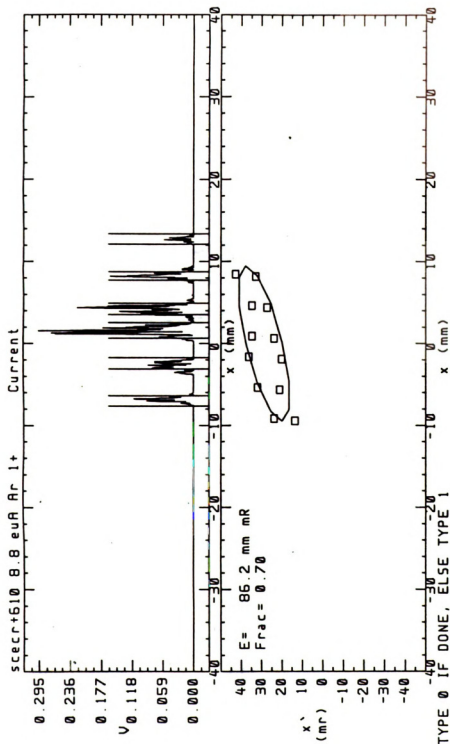


Figure 8.8 Emittance plot of the 610 (SCECR off).

Emittance taken at 100 W input power to the 610, 2.6×10^{-5} Torr argon pressure, and 5 kV SCECR+610 bias, and 70% coverage by the ellipse. The Ar^{1+} current is maximized to about $8.8 \mu A$.

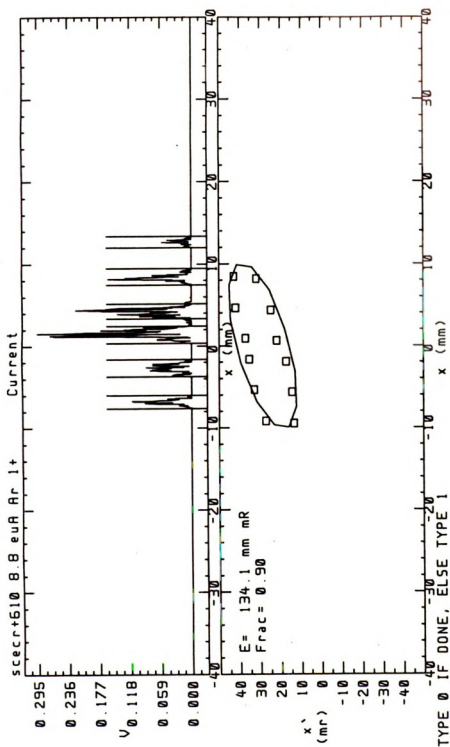


Figure 8.9 Emittance plot of the 610 (SCECR off).

Emittance taken at 100 W input power to the 610, 2.6×10^{-5} Torr argon pressure, and 5 kV SCECR+610 bias, and 90% coverage by the ellipse. The Ar^{1+} current is maximized to about $8.8 \mu\text{A}$.

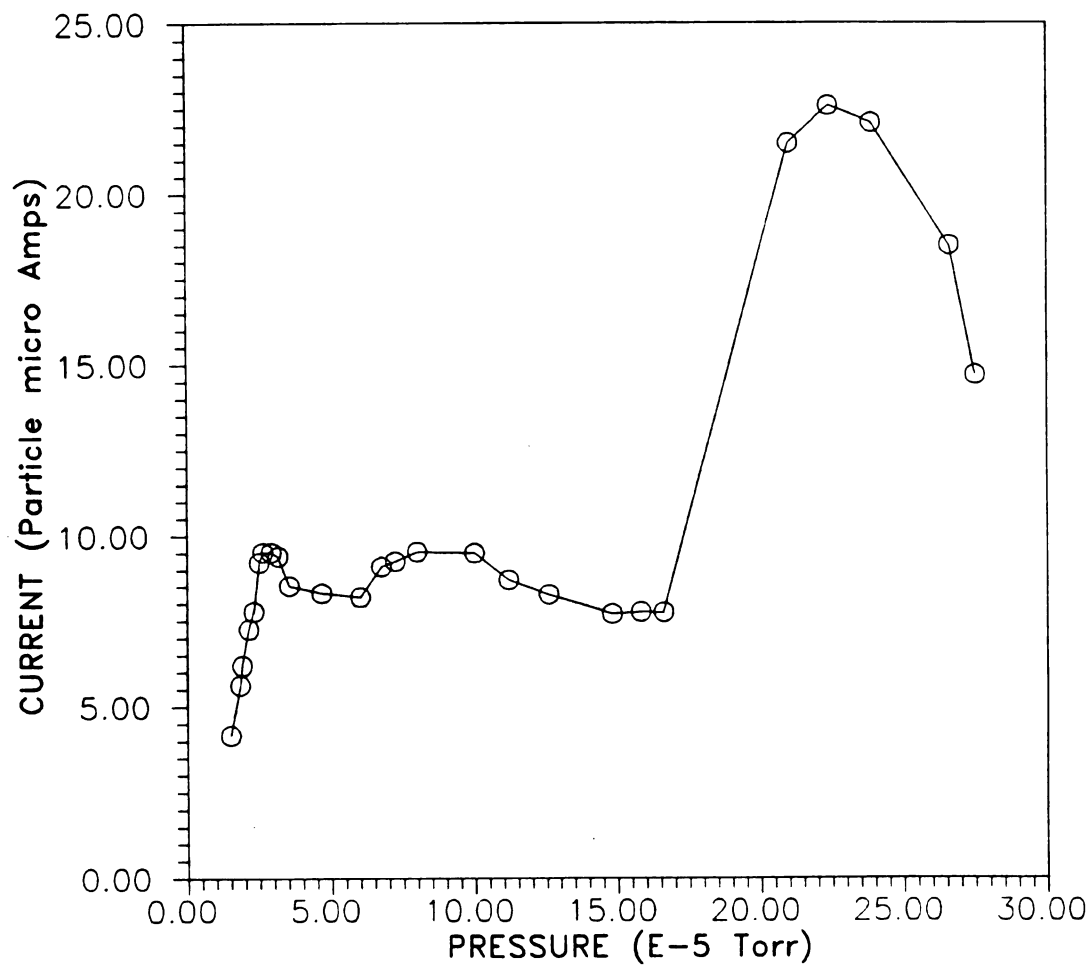


Figure 8.10 Ar^{1+} current versus pressure in the injection stage.
 Data are taken at 100 W input power to the 610 (SCECR is off) as the argon pressure is varied by adjusting the flow rate. Note the jump in current values at about 0.2 mTorr as the 610 changes modes.

be because the beam exiting the 610 is not well focussed into the 1 cm hole of the large copper baffle plate. In the "high density mode" of the 610, the total current was probably increasing with pressure. However, due to lack of any focussing (other than the weak magnetic focussing due to the rising mirror field at the injection end of the SCECR), the "beam" from the 610 spreads out such that only part of it may be transmitted through the hole in the baffle plate. The beam current therefore drops, although the total current intensity out of the 610 was probably higher as pressure rose beyond 0.25 mTorr.

This exercise of measuring the Ar^{1+} current with pressure provided several important results. It confirms that below the pressure of about 2×10^{-4} Torr in the first stage, the 610 operates in its low density mode. If the 610 is operated at a higher pressure in its high density mode, the SCECR cannot generate multiply charged ions because of high collision rates and the corresponding low confinement times of the ions. Hence even with its 1 cm BN baffle plate, the 610 must be operated in its low density mode. At the lower pressures, there is a local current maxima, and further experiments with the SCECR switched on were conducted with the first stage pressure at or around this maxima, with the understanding that the 610 is operating in its low density mode. These experiments are now described.

8.8 Operational Performance - 610 On, SCECR On

The operation of the 610 as an injector to the SCECR is now described. Oxygen was chosen as the working gas. Before these experiments were conducted (SCECR on, 610 on), however, a crucial and significant development

occurred in the performance of the SCECR - the "High-B mode" of operating the SCECR was confirmed by Antaya and Gammino [Ant-94a, Ant-93a, Ant-94b] and presented at the 1993 International Conference on Ion Sources in Beijing, China in 1993. It was originally proposed as an alternate theoretical analysis of the minimum-B magnetic confinement of charged particles by Ciavola and Gammino at the 1991 International Conference on Ion Sources in Bensheim, Germany [Cia-92]. While the details of this development, and its impact on the theoretical and mechanical design of ECRIS are discussed in the appropriate references, and utilized in Chapter Ten, the gist is now presented.

The operation of the SCECR at 6.4 GHz with a standard axial field topology and having a magnetic mirror ratio of about 2 (based on the operating conditions of the RTECR) places the SCECR's performance well amongst the better designed ECRIS for multiply charged ions. However, it was observed by Antaya and Gammino that if the mirror ratio was raised to above 7 at the injection end, and about 3 to 4 at the extraction end by sharply raising the currents of the three outermost coils and dropping the currents of the two inner coils to zero, the extra confinement provided by this enhanced bottling dramatically shifted the charge state distribution of the SCECR to higher states once the neutral density pressure was optimized for the particular confinement configuration. In its High-B mode, the production of high charge states from the SCECR at 6.4 GHz is comparable to all ECRIS, even those operating at higher frequencies (14.4 GHz, or even 18 GHz).

For the following experiments (610 on, SCECR on), a similar High-B mode field topology was adopted. The typical currents in the coils therefore are: 38, 13, 0, 0, 22.5 A in the solenoids, and 50 A on the hexapole. At 5 kV 610+SCECR

bias with 100 W 2.45 GHz input power to the 610, there was an immediate change in the charge state distribution. The Ar^{2+} current remained relatively constant at 0.22 μA , but the Ar^{1+} current dropped from 8.8 μA to 6.15 μA . So with higher confinement, the ratio of Ar^{1+} to Ar^{2+} has already changed (from times 40 to times 28). As will be seen later, this ratio actually reverses (with the Ar^{2+} current being higher than the Ar^{1+} current) as the hybrid source is further tuned. This tuning was done with the SCECR set up at 10 kV high voltage, while the relative DC bias on the electrically isolated 610 (the alumina isolation platform was utilized in these experiments) was varied from negative 1 kV, to zero, and then to positive 1 kV.

Before any experiments were conducted, the 6.4 GHz power to the SCECR was switched on (with the 610 off) and an oxygen plasma sustained for several hours to burn off all remaining argon and hydrocarbons from the source and gas lines. Once this "conditioning" of the SCECR was completed, the SCECR was switched off and the 610 was switched on with 125 W at 2.45 GHz. The pressure in the injection stage of the hybrid source was about 6.8×10^{-6} Torr, while the pressure in the main stage was about 2.8×10^{-7} Torr. Once the 610 was tuned to its best performance (with about 10% reflected power), the SCECR was switched on with about 300 W at 6.4 GHz. The magnets of the SCECR were then ramped up (38, 13, 0, 0, 22, 70 A), and the high voltage bias on the SCECR brought up to 10 kV. Note that the injection stage pressure is much lower than that required for optimal 610 operation, which was probably in its low density mode. All gas flow into the hybrid source was through the gas line of the 610 with no independent feed to the main stage, and the collisional, low charge state plasma ignited in the 610 then diffused out of the small source and followed the

magnetic flux lines into the main stage of the SCECR.

Results of the relative bias on the 610 with respect to the SCECR are tabulated on Table 1 below, and graphically depicted in Figure 8.11. Note that these currents (in particle micro-amperes) are the highest values chosen from several different tunes of the hybrid source. This is done to indicate that these high currents may indeed be generated from the source, but the source has to be effectively optimized for each charge state.

Table 1: Particle currents of oxygen charge states in the hybrid source.

Oxygen Charge State	+1 kV bias on 610 (eμA)	O bias on 610 (eμA)	-1 kV bias on 610 (eμA)
1+	251.0	253.3	113.0
2+	107.0	190.8	223.5
3+	37.30	105.0	182.0
4+	15.20	46.3	126.0
5+	2.90	18.8	58.25
6+	0.50	4.70	23.5
7+	0.013	0.22	1.55

The data for the above table are taken using a Faraday cup in the SCECR beam line under the following conditions: 610 on (125 W input at 2.45 GHz), SCECR on (300 W input at 6.4 GHz) with positive 1 kV, negative 1 kV and zero bias on the 610 with respect to the SCECR.

Charge state distributions for the three conditions (positive, neutral and negative bias on 610 with respect to the SCECR) are shown in Figures 8.12 through 8.14. The table, and Figure 8.11 denote the total electrical current of

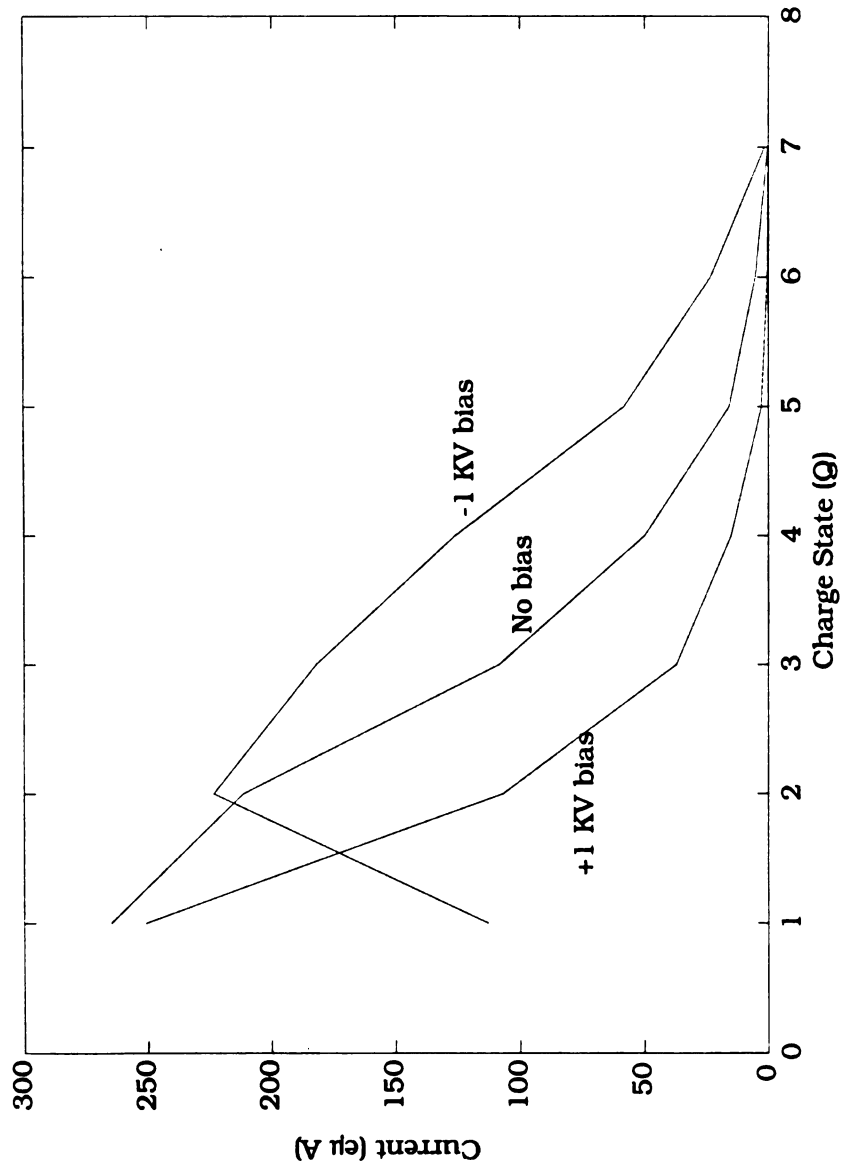


Figure 8.11 Current versus charge states (610 on, SCECR on) for various 610 biases with respect to the SCECR.

Data is taken at various 610 biases (relative to the SCECR) with a 6.8×10^{-6} Torr oxygen pressure in the injection stage. The SCECR is in its "High-B" mode.

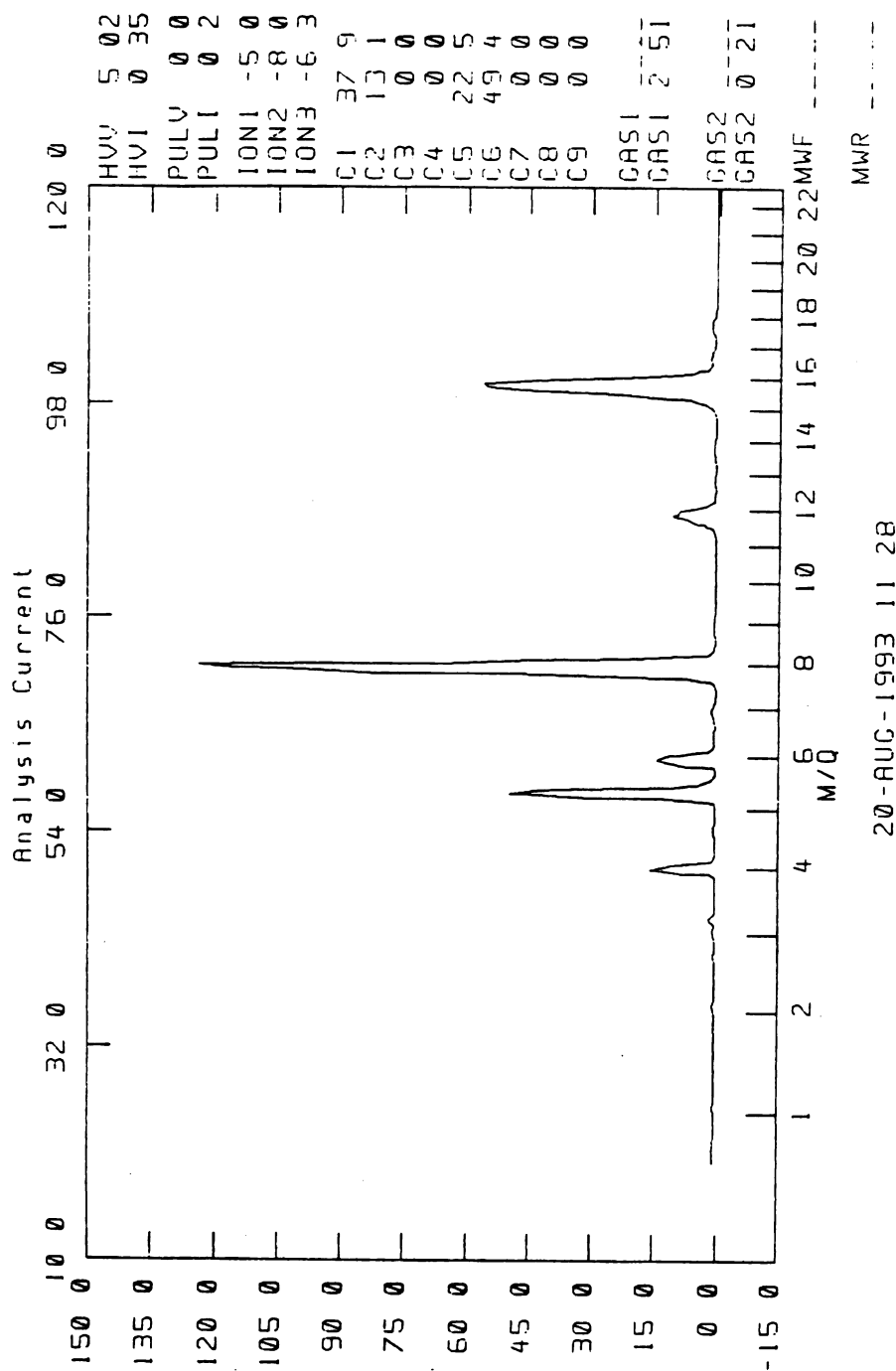


Figure 8.12 CSD. 610 on SCECR on +1 kV relative bias on 610.
 Data taken with 125 W 2.45 GHz input power to 610, 300 W 6.4 GHz power incident on SCECR, 6.8×10^{-6} Torr oxygen pressure in injection stage. The 610 is biased +1 kV relative to the SCECR (which is at 10 kV bias).

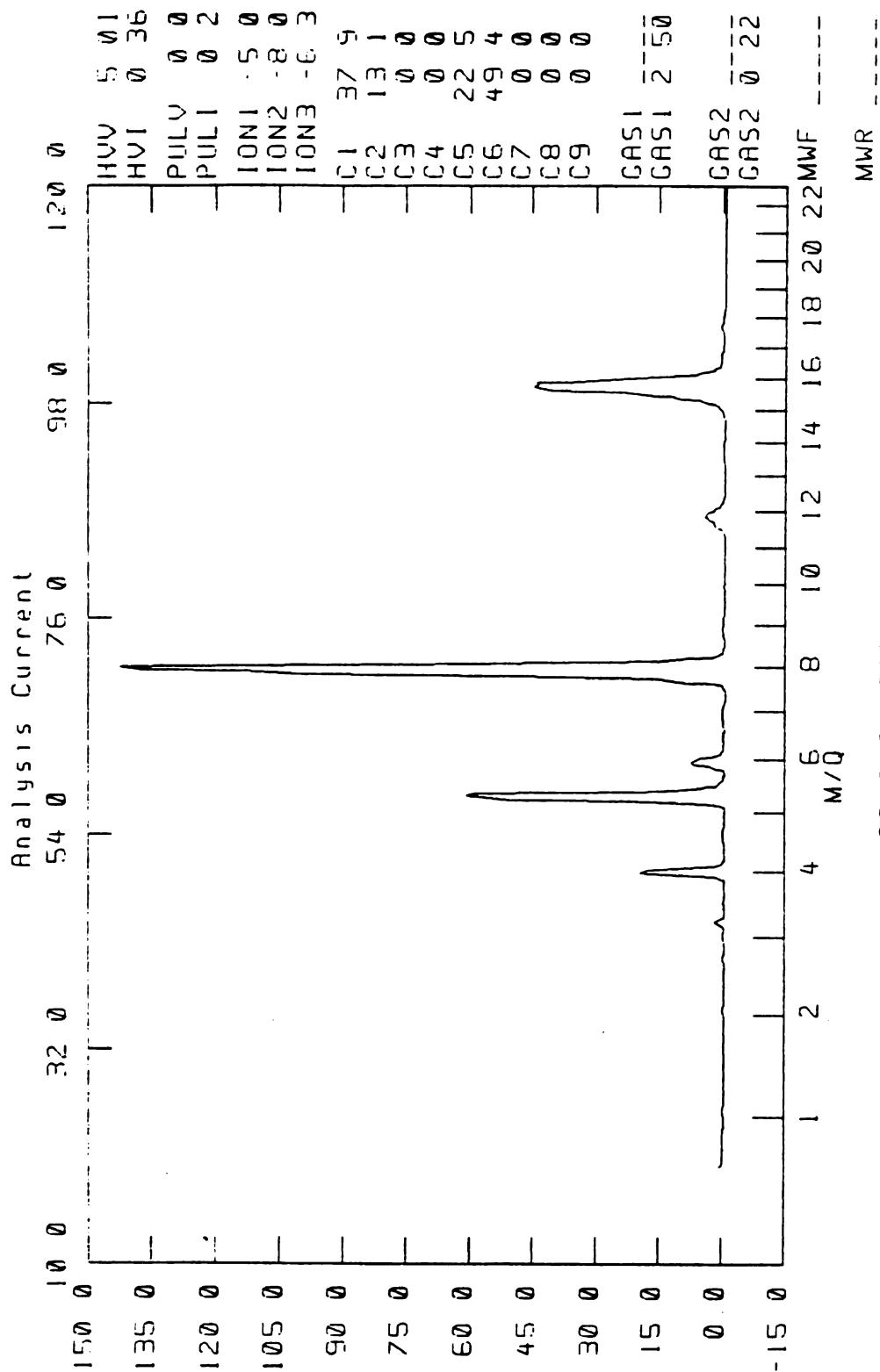


Figure 8.13 CSD, 610 on SCECR on, 0 relative bias on 610.

Data taken with 125 W 2.45 GHz input power to 610, 300 W 6.4 GHz power incident on SCECR, 6.8×10^{-6} Torr oxygen pressure in injection stage. The 610 is floating relative to the SCECR (which is at 10 kV bias).

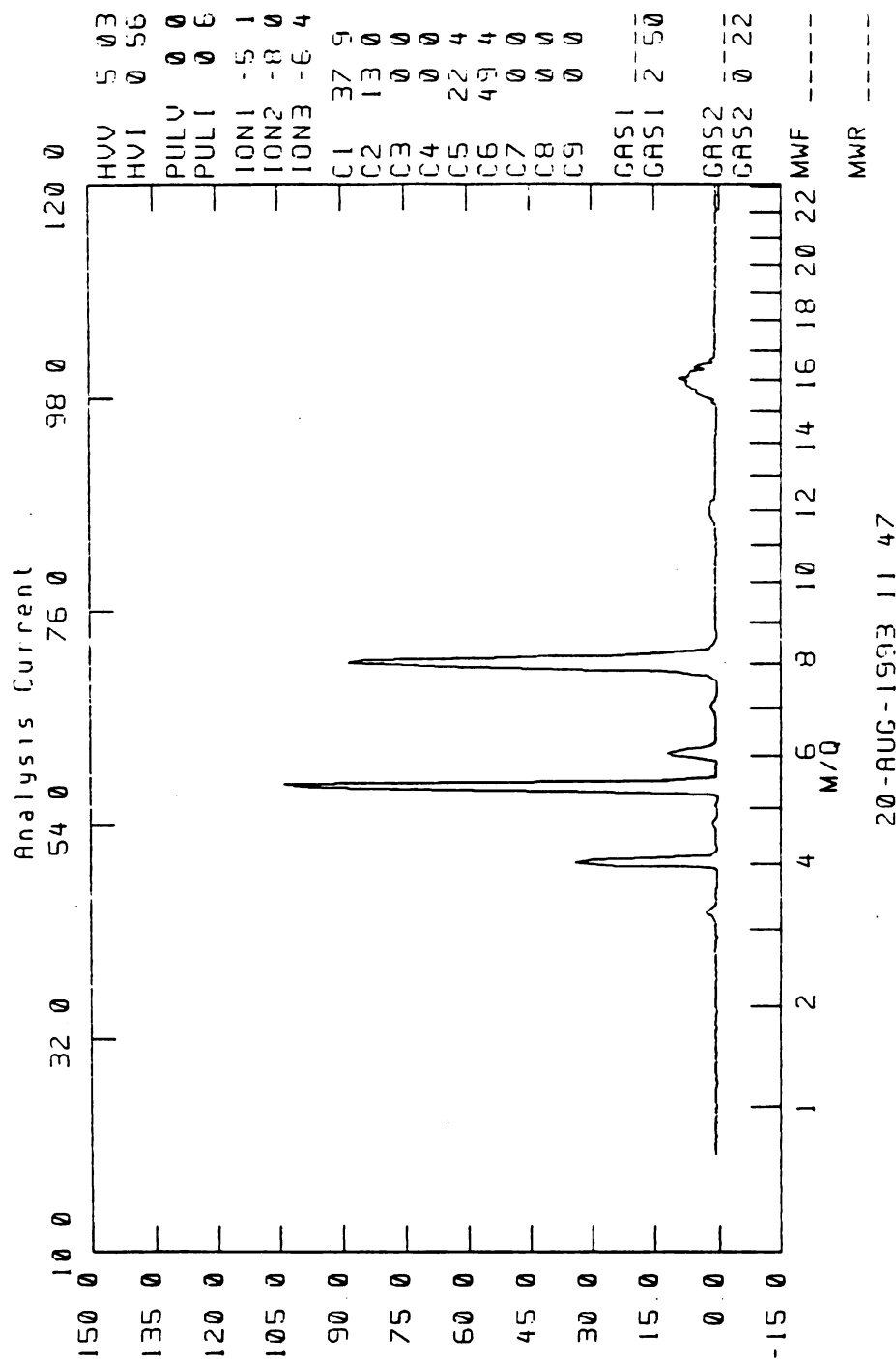


Figure 8.14 CSD, 610 on SCECR on, - 1 kV relative bias on 610.

Data taken with 125 W 2.45 GHz input power to 610, 300 W 6.4 GHz power incident on SCECR, 6.8×10^{-6} Torr oxygen pressure in injection stage. The 610 is biased - 1 kV relative to the SCECR (which is at 10 kV bias).

each oxygen charge state extracted from the SCECR. When the 610 is biased at +1 kV relative to the SCECR, the net potential seen by the plasma diffusing out of the 610 is 11 kV, enhancing positive (ion) injection into the main stage of the SCECR. Similarly, when the 610 is biased -1 kV relative to the SCECR, the net potential seen by the plasma from the 610 is 9 kV, enhancing negative (electron) injection into the main stage of the SCECR. Neutral plasma injection into the main stage occurs when the 610 is floating with respect to the SCECR.

It is seen in Figure 8.11 that even at main stage pressures that are higher than the optimal SCECR performance conditions, the hybrid source is able to produce up to O_2^{7+} ions. For both positive and neutral injection into the main stage, the particle current drops as the mass to charge ratio (or the charge state, as shown in Figure 8.11) increases, with a peak current on the O_2^{1+} state. However, with negative injection, the entire charge state shifts towards higher ionized species, and the peak current is now seen to be on the O_2^{2+} ion. Production of the O_2^{1+} ions is depressed, while that of all other higher charge states goes up, with respect to positive and neutral injection from the 610. This is also seen graphically on the CSDs of Figures 8.12 through 8.14 where the peaks of multiply charged ions are enhanced with a negative bias on the 610.

8.9 Summary of Results

It has been shown that a high pressure plasma source (the 610) can be coupled to a low pressure ECRIS for multiply charged species (the SCECR). Note that the pressures at which the hybrid source (SCECR with the 610 as an injector) were too high for optimal high charge state production from the SCECR,

while the pressures were too low for the 610 to be in its high density mode. Hence the performance of both the 610 and the SCECR were below their respective individual operational performance (specially if the SCECR is operated with the regular first stage in its High-B mode). Despite this, the hybrid source may have helped in answering an old question: the ECRIS plasmas require low energy electrons from the first stage. As was mentioned earlier, even in the presence of strong magnetic fields of the minimum B configuration, some percentage of the high energy electrons are able to escape and are lost to the walls. The low energy electrons from the first stage compensate for these lost electrons and help in maintaining the quasi-neutrality in the main stage, thereby increasing the ion confinement times. Without these low energy electrons the ions would also be lost to maintain the quasi-neutral status of the plasma. Similar conclusions have been drawn in work at other laboratories also [Lyn-91, Mel-91], but heretofore no complete positive-negative-neutral injection study could have been attempted.

The first stage at the Lawrence Berkeley Laboratory (the AECS) has in fact been replaced by a LaB_6 electron gun with an enhanced production of multiply charged states [Xie-93]. Another technique to increase flow of cold electrons into the plasma is by coating the plasma chamber walls with a material like SiO_2 which has a high secondary electron emission coefficient. This is done by "Silane conditioning" the source - a process routinely employed at the NSCL, where a silane (SiH_4) and oxygen plasma is generated and sustained in the main stage for several days. The process deposits a layer of SiO_2 on the chamber walls and enhances electron emission when the plasma species bombard the walls. Alumina coating, or aluminum liners on the walls that have been oxidized also

emit secondary electrons. The operation of the multiply charged state ECRIS is seen to improve by these techniques.

8.10 Concluding Remarks

The results of this study are very promising. Future research involves a stronger coupling between the 610 and SCECR to operate both at their respective optimal pressures. A proper beam extraction (using Pierce type accel-decel electrodes like those used later in Chapter Nine) from the 610 that may be injected directly into the main stage could also enhance the results of this study. Also, in the current design, the 610 is almost 30 cm from the baffle plate that separates the main stage from the injection stage. Better results may be achieved if a longer "610 like" source is designed such that the injected plasma is close to the main stage. Finally, once optimal pressure and position variables are satisfied for the 610 injection into the main stage, techniques like silane conditioning, gas mixing or aluminum liners in the main stage may be used to improve the performance of the high charge states from the SCECR and further study the effects of the first stage.

Chapter 9

Evaluation: Beam Extraction from the MPDR 610

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Chapter 9

Evaluation: Beam extraction from the MPDR 610

9.1 Introduction

There are over 50 commercial models of the MPDR 610 that have been sold by Wavemat Inc. of Plymouth, Michigan to research laboratories throughout North America, and also in Europe. Most of the applications to date for the 610 have been limited to semi-conductor processing, and no commercial application yet has demanded an ion beam to be extracted from the 610. Hence the evaluation of the beam characteristics of the MPDR 610 has been largely neglected up to now (except for the crude “beam” that was extracted from the 610 during the “610+SCECR hybrid source” experiments detailed in Chapter Eight). Whether this plasma/free radical source may also find applications as an ion beam source will now be investigated.

The beam development aspects of the MPDR 610 were evaluated as part of the on-going characterization and application study of this source at the National Superconducting Cyclotron Laboratory (NSCL). Experiments were conducted through which an ion beam was successfully extracted from the 610.

This involved rigorous application of beam optics, and other technological know-how of the NSCL personnel - key among them being Dr. T. Antaya, Mr. K. Harrison, Mr. D. Cole and the support of Dr. A. Zeller. As with Chapter Eight, in an example of true collaborative research, experiments detailed in this chapter provided valuable data for both the Electrical Engineering (EE) and NSCL ion source research groups. Several conclusions regarding beam extraction from an ion source have been drawn from these tests, including the so called "meniscus effect," which defines the exact shape of the plasma meniscus as the extraction high voltage changes. While the theoretical development of beam extraction, and the formation of the meniscus has been known for several decades, for the first time this effect was observed and photographed in an actual ion beam, and may now be used to corroborate, or refute the theory.

The chapter begins with an introduction to beam extraction from a generic ion beam source. Some different types of ion beams that may be extracted are discussed, along with the relevant nomenclature. Several strata of beam extraction experiments were conducted on the 610, and each is extensively discussed, including the design and development of a special three electrode extraction system for the MPDR 610. Results of these tests in terms of the charge state distributions and emittance measurements are presented. Finally, the concluding remarks review the above experiments. It is noted in the conclusion that despite the research conducted on ion beam extraction from the 610 for this chapter, a lot of work still needs to be done. Therefore, several future experiments are proposed to completely characterize the beam development from the MPDR 610. Some interesting applications are also discussed.

9.2 Ion Beams - a Brief Introduction

By definition, a beam is a flow of charged particles with lateral boundaries [For-88]. It may be composed of primarily positive particles (ions), negative particles (electrons, or negative ions), or neutral particles (like atomic or radical species - as in the case of the Oxford radical beam source discussed in Section 2.2.8, Chapter Two). The most important types of beams are those of positive ions, in terms of applications - these include ion propulsion (electrothermal propulsion, or magneto-hydro-dynamic thrusters), energetic sputtering and/or ion implantation on substrate surface, and positive ion beam injection into accelerators. Neutral beams are typically used for injection into magnetic fusion devices. It is the injection of positive ions into the cyclotron that involves the ion source research group at the NSCL, while the sputtering and ion implantation techniques require ion beams in the semiconductor industry (and hence the Electrical Engineering ion beam source research). Study of beam development therefore enhances the knowledge base of both ion source research groups.

Several books delve into the fundamentals of ion beam technology, mostly discussing beams in context of the above applications, or focussing on specific topics related to beam development. Forrester's book [For-88] for example, encompasses the generation, acceleration and propagation of ion beams (including a comprehensive coverage of numerical simulation of beam transport), while Valyi [Val-77] and Brown [Bro-89] both have good coverage of ion beam sources and beam extraction. In particular, the chapters by Brown, Jongen and Lyneis, Sakudo, Ishikawa, Donnets, and several others in Reference Bro-89 are very enlightening on the development of the various types of ion

sources currently in use. So, while the general study of ion beam sources and beam technology is best left to these books and related publications, it is the purpose of this section to discuss information relevant only to beam development from the MPDR 610.

A plasma source like the MPDR 610 may easily be converted to an ion beam source by attaching an extraction system at the outlet of the source. Based on the design of this extraction system, there are two types of beams that can be extracted from an ion source. The electrodes may have several small apertures spaced evenly across the area. Such a multi-aperture grid system was used to extract beams from the MPDR 5 by Mahoney [Mah-89a]. This extraction setup normally produces tiny beamlets that interact with each other and generate a relatively uniform broad beam. Such "broad beam sources" - like the Kaufman source [Kau-87] are heavily used in the semiconductor industry where uniformity over large substrate areas (6 to 8 inch diameter wafers, for example) is essential.

However, several problems are encountered while using such an extraction system. If the generation, or diffusion of the plasma out of the source is radially non uniform (like for the MPDR 610 - see Figure 4.12, Chapter Four) the multi-aperture grid may have to be designed for the changing ion density across the radius of the grid. This may be tackled by gradually increasing the diameter of the apertures as the radial distance increases, as was done by Sohl et al. (see Figure 5.22, Reference For-88), but such a grid design is rather complex. Moreover, if two or more grids are used to extract these broad beams (as is normally the case), the construction and alignment of high transparency grids can also lead to problems. As will be seen later, the Child-Langmuir law

about the extracted current versus applied bias dictates that to increase the current from the source for a fixed extraction potential, the separation between the grids must be decreased. With high transparency grids in use, this may lead to loss of alignment, stress fractures, arcing and an ultimate decrease in the lifetime of the extraction apparatus.

An optimal extraction system was devised by Pierce [Pie-40, Pie-54], and is appropriately known as the Pierce geometry - specifics about this geometry will be discussed in a later section. A final problem with multi-aperture extraction system is that it is impossible to achieve a Pierce type geometry, as will become evident in detailed discussions later. (In actuality Pierce geometry is impossible to achieve even with a single centralized aperture, and so a "quasi-Pierce" system is often used.) However, despite all the problems with multiple aperture electrodes (some of which are mentioned above), extraction systems with such grids are very much in use, specially for low energy (≤ 1 kV) broad beam production for semiconductor processing, and for electrothermal thrusters where uniformity over large diameters is vital.

The other type of extraction system uses a single aperture in the center of the electrode. Such a system produces one beam from the highest density area of the discharge generation region (as before, see Figure 4.12 from Chapter Four). While the beam produced by a single aperture system is not "broad beam," it can be extracted at very high voltages (up to 30 kV) with good collimation for travelling long distances with magnetic or electrostatic refocussing at appropriate positions. Such an extraction system is very prevalent for multiply charge state ECR ion sources from which highly collimated beams are needed for injection into particle accelerators. As will be seen in the

upcoming sections, it was this type of extraction system that was designed for the MPDR 610.

9.2.1 Space Charge Effects

A very common term used in ion beam development is "space charge," and its effect on the beam characteristics. By definition [For-88], space charge is the "phenomenon associated with the flow of charged particles in sufficient numbers that their density substantially changes the potential in the region through which they flow." A typical ion beam is rich in positive charge species (or negative charge if it is a negative ion or electron beam). As a result, there is substantial coulomb repulsion between the ions, specially if the ion density is high. This repelling force spreads out the beam leading to high emittance and therefore high transport losses.

As the extraction potential is initially raised above zero, the beam current increases linearly (when plotted on a log-log scale). However, beyond a certain bias potential, there is a saturation of the beam current, with no further increase (or a mild increase with a much lower slope) for raising the bias voltage. At low potentials when the I-V characteristics are in the linear region, the beam is said to be space charge limited, while at high voltage (during saturation) the beam is ion density limited. This is because at low extraction bias, there is sufficient ion density being produced by the source to provide for the beam at that potential, but the amount of current extracted is limited by the electrostatic interactions (space charge) between the ions at that potential. However, beyond the linear region, the ion density produced by the source is being optimally

depleted, and any further increase in voltage does not produce a similar increase in the ion current. In this saturation region of the I-V characteristics, the beam is said to be ion density limited.

A unique way to alleviate space charge effects and increase the focussing of ion beams is by using a "neutralizer." This is done, for example in the Kaufman broad beam ion sources [Kau-87], where a source of secondary electrons is placed at the outlet of the extraction grids. This tends to increase the negative species in the beam, whereby negating some of the coulomb interactions between the ions. Space charge neutralization is also discussed in other books [Hol-89] if further references are needed. Note that there is no danger of a drop in the ion density in the beam due to electron-ion recombination, which is a three body process, and typically occurs on the walls of the discharge confinement chamber. Also, volumetric recombination, either in the discharge generation region, or in the ion beam itself can occur only at relatively high pressures (several Torr) where the neutral density is high enough to provide the third body (neutral atom or molecule) for the process to occur. Therefore the depletion of ion density due to volumetric recombination is too rare a process at the operating pressures of most ECRIS (and of the ion beams that are extracted from them) to factor into this effort to neutralize space charge through supplemental electron injection.

9.3 Beam Extraction from the MPDR 610 - Initial Trials

The earliest, and rather crude "beam" from the 610 was extracted during the experiments in Chapter Eight when the 610 was mounted in place of the

regular first stage of the SCECR (see Figure 8.2 showing the “hybrid 610+SCECR” source, Chapter Eight). Biasing the 610 relative to the SCECR (which itself was at potentials up to 10 kV) generated a mostly positive, or mostly negative beam from the 610 that was injected into the main stage of the SCECR producing interesting results in the performance of the multiply charge state source (see Figure 8.10 and Table 8.1, Chapter Eight). While visual confirmation of this “beam” formation from the 610 was not possible due to its location on top of the SCECR, the changing beam current with applied extraction potential, and the magnetic field topology of the SCECR solenoid coils at the position where the 610 was mounted, indicate that a beam (of mostly negative, or mostly positive particles depending on the bias) was being extracted from the 610 and injected into the main stage of the SCECR.

A problem with the 610 has been the excessive amount of current that is produced by the source, specially when it is operated in its “high density mode.” If this current is too high, biasing the 610 to any high voltage would produce significant drain current at even low potentials (less than 100 V). The beam extraction would then be limited by the maximum current capacity of the DC biasing power supply. This problem will resurface several times in the forthcoming sections. Note that in the experiments of Chapter Eight where the 610 was used to inject a “beam” into the main stage of the SCECR, there was a plate with 1 cm diameter hole that was placed on the outlet of the 610. This thin (0.125 inch thickness) stainless steel or BN plate throttles the amount of current allowed to exit the plasma source. The plate also acted as a baffle for differential pressure, allowing slightly higher pressure inside the 610's discharge confinement quartz chamber as compared to the pressure in what was the

"vacuum box" of the SCECR first stage. While the current output of the source is severely restricted, the small baffle plate allowed the "high pressure" 610 (operating in the range of 10^{-5} Torr, in its low density mode) to act as the first stage for the main stage of the SCECR that normally operates at much lower pressures (in the range of 10^{-7} Torr). Note that this pressure differential created by the BN/stainless steel plate is not expected to be much due to the large 1 cm diameter hole, but is necessary during these experiments, because the 610 was operated at some of the lowest pressures ever for the experiments of Chapter Eight - in the 10^{-5} Torr range.

However, this "beam development" of Chapter Eight was rather crude, especially in light of the fact that this beam had to travel approximately 30 cm from the small baffle plate of the 610 to the entrance of the SCECR main stage without the benefit of much focussing other than the rising edge of the first mirror maximum of the axial confinement magnetic field. It is expected that most of the beam was lost during this transport. This will become evident soon when the ion beam current from Chapter Eight is compared to the current produced in the studies of this chapter - beam current production is about four to six times higher with a properly focussed beam.

Better beam development from the source was therefore necessary, not only to study the characteristics of ion beams that can be extracted from the 610, but also to provide a basis for future injection from a "610 like" source into the main stage of a multiply charged state ion source, and for several other applications of such an ion beam source that will be discussed during the concluding remarks of this chapter.

9.4 Further Beam Development - the MPDR 610 on the Beam Line of the SCECR

The next step in the MPDR 610 beam development and evaluation was conducted at a time when the K1200 cyclotron, and the SCECR were both down for maintenance. This left the beam line from the SCECR to the cyclotron free to be used for this experiment. The object box (along with the object slit) and the first diagnostic Faraday cup (called SFC1) immediately below the SCECR extraction apparatus were removed, and the 610 was mounted on an appropriate 8" to 4.5" Conflat reducing flange. Fortuitously, the outlet of the 610 was visible through the 8" viewing window on the side, through which video and still photographs could be taken. This set up is shown in Figure 9.1 (not to scale). Note that the 610 is mounted on its DC insulator. To extract a beam, a copper baffle plate with a 2 cm diameter hole in the center similar to the one used between the first and main stages of the SCECR was placed 1.8 cm below the 610. As before, the output of the 610 was throttled by a stainless steel plate with a 1.5 cm diameter hole in the center to allow a pressure differential. A somewhat crude two electrode extraction system was thereby set up, in which the 610 could be biased positively relative to the larger copper baffle plate (that was connected to the beam pipe - at ground potential) and an ion beam may be extracted from the source. Note also that this is similar to maintaining the source at ground while the copper baffle plate is biased to a negative (ion accelerating) potential.

As is shown in Figure 9.1, the ion beam traverses the vertical length of the beam pipe, and would then be bent through 90° by the solenoid, into the

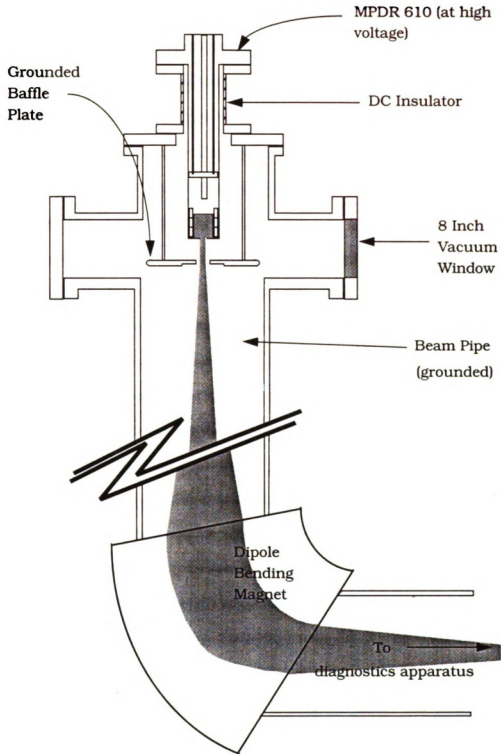


Figure 9.1 Initial beam extraction from the 610 (overleaf)

The 610 is mounted on the SCECR beam line to the K1200 cyclotron. Note that the ion source is electrically isolated from the grounded beam line, and can therefore be raised to high voltages.

horizontal section of the beam pipe. At an appropriate distance from the solenoid (where the image slit is located) is another Faraday cup (called SFC2), and emittance measurement apparatus (wire scanning method, as detailed in Chapter Three). This 90° bending is necessary to magnetically mass separate the different ion species in the beam, and to obtain the charge state distribution of the beam that would indicate the amount of current and relative concentration of each ion species constituting the beam.

On the circumference of the 610, from where the plasma streams out, are a series of 20 “10-24” bolts (or threaded rods) that tighten the HelicoflexTM vacuum seal in place around the quartz (or alumina) plasma chamber. These bolts are clearly seen in the photographs of the 610 (see Figures 9.6(a) - 9.6(f) later in the chapter). There was a concern that these bolts would be too close to the large, grounded copper baffle plate and cause shorting or arcing between the electrodes, or redistribute the equi-potential surfaces such that beam extraction is not optimal, specially at high potentials and with high beam currents. However, a series of electrostatic simulations using the “PANDIRA” code showed that with respect to the equi-potential surfaces set up between the 610 and the copper baffle plate, there is no difference between the two cases wherein one simulation was done with the 610 bolts intact, and the other simulation was conducted with bolts filed away. The results of these simulations are shown in Figure 9.2 where the assembly has been exaggerated in size, but maintains the relative dimensions of each part. It is seen that there is little, or no difference in the equipotential surfaces in the beam extraction region between the two cases, and there is no necessity to file away, or remove, the bolts. The step in the plasma electrode was simulated so as to prevent arcing between the 610 bolts

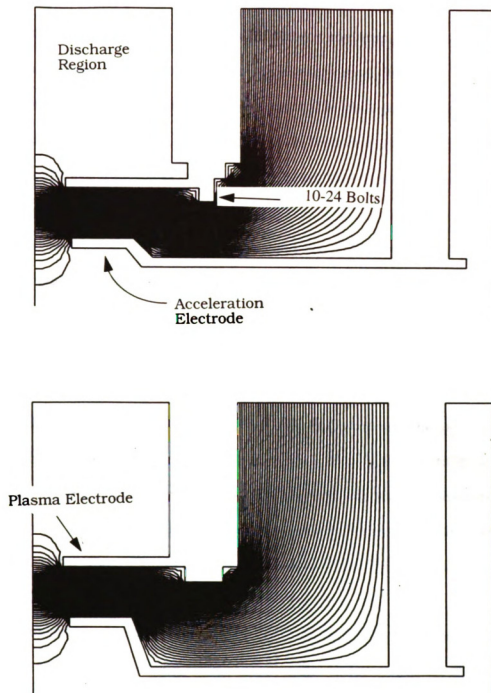


Figure 9.2 PANDIRA simulations for electric fields on the 610.

These simulations were done to confirm that the bolts sticking out of the bottom of the 610 would not interfere with the electric fields being set up between the 610 and the grounded copper baffle plate. The top simulation has the bolts, while the bottom simulation they have been filed away. Note that there is no difference in the electric field configuration since the electrode gap is the same.

and the grounded baffle plate. However, further simulation (not shown here) indicated that there could be no arcing even without the step, and in the final design, no such step was incorporated. As a precaution however, a small annular ring of Teflon was attached to the copper baffle plate just below the 10-24 bolts of the 610. Note that the equipotential contours between the two electrodes would have a focussing effect on the beam that is emerging from the throttled outlet of the 610.

9.5 Operational Performance of the Two Electrode Extraction Apparatus on the MPDR 610

The 8 inch quartz vacuum window shown in Figure 9.1 could be used effectively as a viewing port to visually "see" the beam. Since the operating pressure of the MPDR 610 is relatively higher than that of the SCECR, it is possible to visualize the streaming plasma from the 610 and the ion beam as it develops when the bias potential is raised. A series of still photographs and video film were taken for the different bias potentials on the 610 relative to the grounded baffle plate to capture this beam development.

The operating pressure of the 610 in this configuration was maintained about 3×10^{-5} Torr (argon), with about 100 W incident power. As in Chapter Eight, the 2.45 GHz microwave power supply, the power meters etc. were maintained at ground potential by using the DC isolation joint on the cross guide bi-directional coupler (see Figure 8.4, Chapter Eight). Also as before, a coaxial cable was used to transport the microwave energy to the 610. With another set of power meters and directional couplers placed at the source end of

the coaxial cable, the net power being injected into the plasma source could be measured (at no DC bias on the 610). By comparing the power levels at both ends of the cable, this measurement would indicate the power loss in the cable. At low power levels (less than 100 W), there was almost no power loss in the cable. However, as the incident power increased to 150 W, and then to 200 W, the power being injected into the 610 was 145 W and 190 W respectively. So at higher power levels, there is some loss in the microwave transport system, but not enough to cause alarm. This loss is taken into account when the net input power is reported for the experiments.

The first beam extraction from the MPDR 610 was not successful. A HYPOTRONICSTM high voltage tester was used to bias the 610. Its power output is limited, and the 610 produced too much current even in its low density mode for any reasonable bias potential applied on the source. (The rated power of a biasing power supply is a combination of the net drain current and the bias potential, and is a constant specification of a DC power supply. If there is too much current, the bias potential is limited by this power rating of the supply.) A solution was found to this problem by using a "jumper" from the high voltage line of the SCECR (which was down for maintenance) to the 610. The SCECR power supply is rated for 30 kV and 5 mA maximum current. During the ongoing tests, power supplies of the CPECR and the RTECR, which are also rated at similar levels were brought into use to bias the 610 (whichever multiply charge state ECRIS was not in use for beam injection into the cyclotron at the time), and provided sufficient power levels (potential and current) for the 610 experiments.

Once the high voltage supply problem was solved, a beam could easily be

extracted from the 610. At 5 kV bias, the total beam current was 2 mA, and the beam had perfect definition as it exited out of the source. A charge state distribution of the beam was taken, and is shown in Figure 9.3. It shows about 40 μA of Ar^{1+} production, and an order of magnitude less Ar^{2+} , a similar ratio as was seen with the 610 mounted on top of the SCECR (Chapter Eight) where the 2+ ion current constituted 5%, while the 1+ current was about 95% of the argon ion current density. Note that the total current production is higher in this case, since the 610 is directly feeding the beam pipe with a better extraction and focussing system, where as in Chapter Eight, the ion source was located much farther from the extraction electrodes - about 30 cm from the main stage of the SCECR, and therefore had a much larger distance to traverse before being detected by the Faraday cup.

For the experiments above, the operating pressure of the 610 is in the low 10^{-5} Torr range, and despite its stainless steel baffle plate with a 1.5 cm diameter hole that should create a pressure differential between the discharge generation region and the vacuum chamber outside the 610, the plasma source is still operating in its "low density mode." This was evidenced by the excess heat generated in the 610, and conducted out through the compressed air cooling. As before, the source could not be used in its high density mode (at higher pressure - about 10^{-4} Torr and higher) because the current production of the 610 in this mode is normally too high, and again limited the application of the extraction voltage due to the limited power rating of the supply. Even the SCECR or other ECRIS high voltage power supplies could not provide enough power to run the 610 in its high density mode.

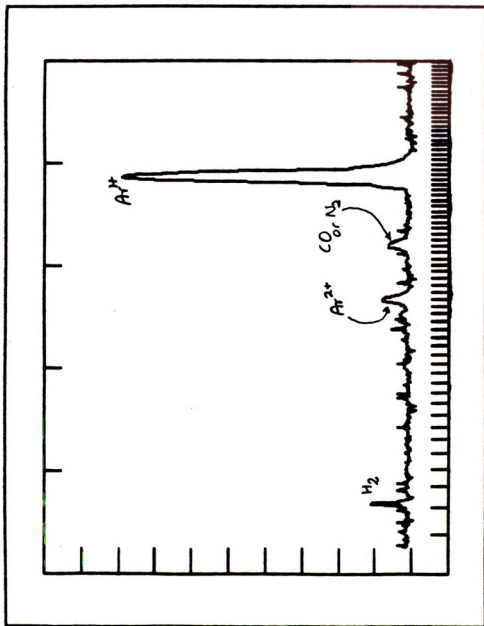


Figure 9.3 CSD of the MPDR 610

Data is taken at 100 W 2.45 GHz power to the 610, 3.0×10^{-5} Torr argon pressure and 5 kV bias on the 610 relative to the grounded second electrode. The Ar^{1+} current is measured to be about $40 \mu\text{A}$.

9.5.1 Emittance Measurements for the Two Electrode System

Several sets of emittance measurements were taken with the 610 in this configuration, in accordance with the wire scanning techniques explained in Chapter Three. At 5 kV bias for a 100 W input discharge of 3×10^{-5} Torr argon, the net drain current was about 2 mA. The Ar^{1+} peaked with about 38 μA with an emittance anywhere between 350π mm-mRad to over 550π mm-mRad depending on the focussing of the beam. The Ar^{2+} peaked at about 4.5 μA with an emittance of about 100π mm-mRad. This data was compiled with a 0.7 fitting fraction using 100% of the beam current. For both charge states, the emittance is seen to be very high. This may be because of the excess Ar^{1+} current being produced by the 610, even in its low density mode, as was confirmed with the next set of experiments that were conducted at a higher bias potential. Also, several data sets indicated overlapping peaks, or other types of optical aberrations on the beam.

The discharge pressure for the next set of experiments was then raised to about 7×10^{-5} Torr. The bias potential was also raised to about 7.5 kV, producing 4.62 mA of drain current. Note that this comes close to exceeding the SCECR HV current rating, (the power supply is rated at 5 mA maximum) and indeed, the bias potential on the 610 relative to the grounded copper baffle plate could not be raised beyond this level.

Several emittance measurements were taken for this setting of the 610 ion beam source also. Once again the emittance, calculated with a 0.7 fitting fraction is seen to be high, ranging from about 550π mm-mRad, to almost 680π mm-mRad for the Ar^{1+} . The current for this peak fluctuated between 55 mA to

71 mA, depending on the focussing magnet. All emittance plots for the Ar^{1+} charge state, one of which is shown in Figure 9.4 (data taken for a 100 W, 7×10^{-5} Torr argon discharge with an extraction potential of 7.5 kV), stretched from the third quadrant to the first quadrant, meaning that the beam was roughly defocussing, as discussed by Keller [Kel-89]. Note that there are 12 peaks in the emittance plot shown in Figure 9.4 - an indication of the large amount of current being extracted from the 610.

These emittance numbers are very high - good emittances are normally below or about 100π mm-mRad. This means that the Ar^{1+} beam is not well collimated. There may be several reasons for the high emittance. First, the potential at which the beam is being extracted (7.5 kV) may not be high enough for the amount of current being produced. Second, the beam optics in terms of the placement of the 90° bending (analysis) magnet and the imaging system beyond this magnet are specialized for extraction from the SCECR, where initial focussing of the beam from the multiply charge state ECRIS is on the object slit, beyond which the beam de-focuses and bends through the analysis magnet into the image slit. The beam outlet of the MPDR 610 is not precisely at the object slit of the SCECR, and so the optics may not be right for beam extraction from the 610. There might be some space charge de-focussing of the beam also. And finally, the apertures in the extraction system has a 1.5 cm diameter which is large for typical beam extraction, and may indeed be contributing to the large emittance of the beam. Discussions with Gammino [Gam-94] indicate that by reducing the aperture to several mm, the emittance may be reduced to less than 10π mm-mRad.

Since the current in the $2+$ beam was much lower (a maximum of about

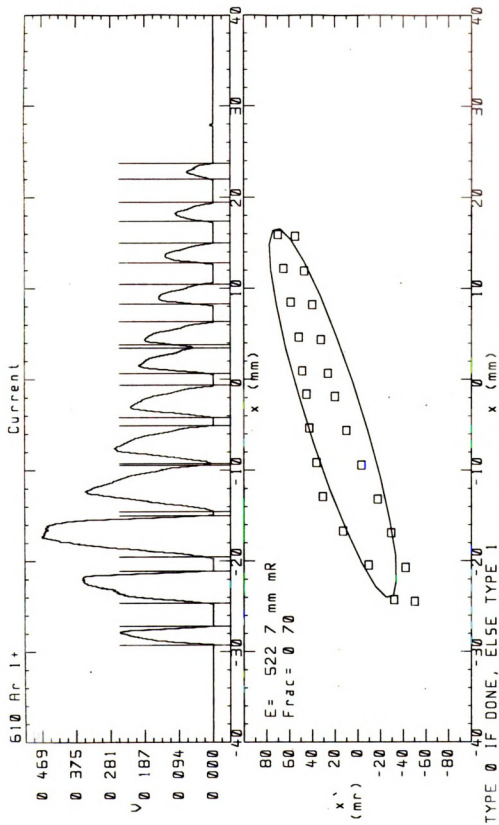


Figure 9.4 Typical emittance diagram of the 610.

The wire scanner method was used to obtain the relative Ar^{1+} currents of each beamlet, and the emittance calculated from this information. Data were taken at an argon discharge pressure of 7×10^{-5} Torr with approximately 100 W input power. The Ar^{1+} current at 7.5 kV bias was about 70 μA , with a total drain current about 4.62 mA.

5.38 mA), the emittance of the Ar^{2+} beam was also better - about 100π mm-mRad. Also, the emittance contours for the $2+$ extend from the second to the fourth quadrant, indicating a somewhat converging beam.

The next modification to be made was the following: the stainless steel baffle plate on the egress of the 610 with a 1.5 cm diameter hole was replaced by a similar thickness (0.125 inch) stainless steel plate with a 1.0 cm diameter hole. This was done so as to further restrict the plasma flow out of the 610, thereby throttling the total current output even more, which would allow the bias potential to be raised further before the total current production by the 610 and the applied bias saturates to the power rating of the DC supply. Also, with a 1.5 cm diameter hole, the emittance plots had indicated a high peak for the Ar^{1+} that was being magnetically bent with great aberrations. By reducing the total current produced in the $1+$ beam, these aberrations would be removed, thereby increasing the transportability of the beam.

9.5.2 Beam Current Measurements for the Two Electrode System

With the new 1.0 cm diameter stainless steel baffle plate installed on the 610, the drain current did indeed drop, to about half its value compared to the larger 1.5 cm diameter hole plate. At 7.5 kV DC bias on the 610, the total current was about 2 mA for a 100 W input, 7×10^{-5} Torr argon discharge. The extraction bias could now be raised up to 10 kV without the drain current increasing beyond the maximum 5 mA off the bias power supply. The variation of the total drain current with the applied extraction bias with a 1.0 cm aperture is shown in Table 1:

High Voltage (kV)	Drain Current (mA)
0.5	0.975
1.0	1.1
2.0	1.193
3.0	1.296
4.0	1.38
5.0	1.583
6.0	1.843
7.0	2.062
8.0	2.21
9.0	2.33
10.0	2.4

Table 1: Variation of drain current versus applied bias on the MPDR 610

This data is plotted in Figure 9.5, which suggests that there seems to be a monotonous increase in beam current as the extraction voltage on the 610 increases, with no evidence of the more characteristic linear increase followed by saturation (as might be seen on the log-log scale). As mentioned earlier, the beam current in the linear region is limited by space charge effects, while the current in the saturation region is limited by the ion density being produced by the source. Figure 9.5 seems to indicate that at least up to 10 kV, there is no saturation region for the ion beam produced by the MPDR 610. The beam current is not limited by the ion density, and therefore the source is producing an ion density higher than the beam's requirements. Hence, a further increase

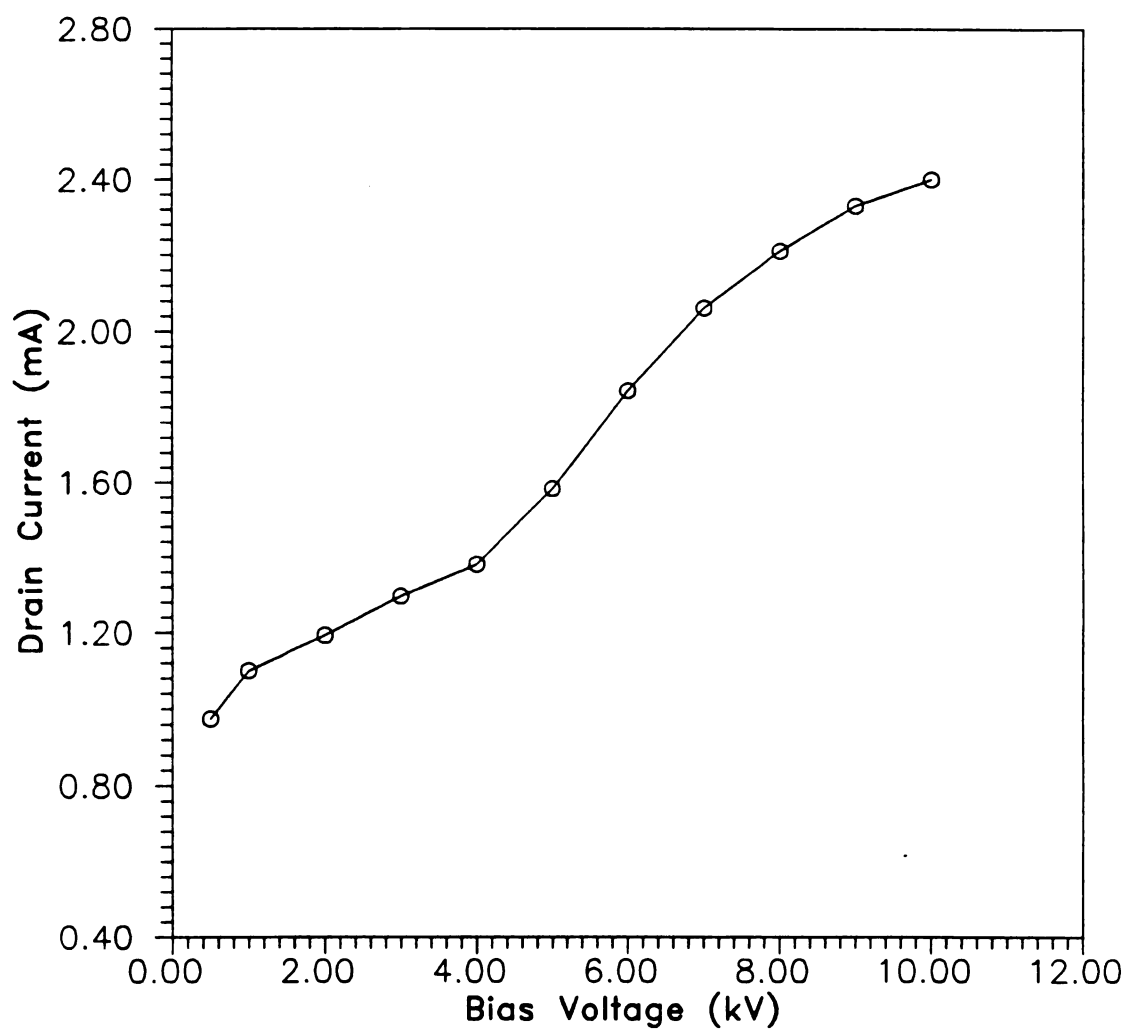


Figure 9.5 Variation of beam current with extraction bias

Data are taken at 100 W 2.45 GHz power to the 610, 7.0×10^{-5} Torr argon pressure, with the ion source mounted on the object box of the SCECR beam pipe. Note the almost linear increase in current with the applied extraction bias.

in the bias voltage may could to a higher beam current. However, this hypothesis was not tested, and the maximum bias applied to the 610 was maintained at 10 kV. The reason for this is that the focussing effect of 10 kV bias on the 610 was already very pronounced, as will be seen in the photographs of the following section, and further increase in the bias potential would over-focus the beam even more.

9.5.3 Photographic Confirmation of the “Meniscus Effect”

As mentioned earlier, due to the relatively high pressure operation of the 610 (10^{-5} to 10^{-4} Torr), the plasma and ion beam extracted from the source are visible both to the naked eye and on photographic emulsion. An interesting series of still photographs and video film were shot through the 8 inch vacuum window (see Figure 9.1) on KodakTM 400 DX film with a 28 mm PentaxTM MX camera. The exposures ranged from 3 to 5 seconds with f2.8 aperture setting. The photos were taken by Antaya [Ant-94c] and Srivastava, and were presented as a late entry poster session at ICOPS-94 [Sri-94d] in Santa Fe, New Mexico, USA. These photos show the effect of increasing bias voltage on the ion source (relative to a grounded electrode) and the development of the ion beam from the 610. The photos are shown in the following series - Figure 9.6(a) through Figure 9.6(l) on the next six pages. These photos are taken with a 0.0 kV, 0.25 kV, 0.5 kV, 0.75 kV, 1.0 kV, 2.0 kV, 3.0 kV, 4.0 kV, 5.0 kV, 6.0 kV, 8.0 kV and 10.0 kV bias on the 610 relative to the grounded copper baffle plate (see Figure 9.1). As mentioned earlier, this copper plate acts as the second electrode and is hereafter referred as electrode two or as the accelerating electrode, to avoid confusion

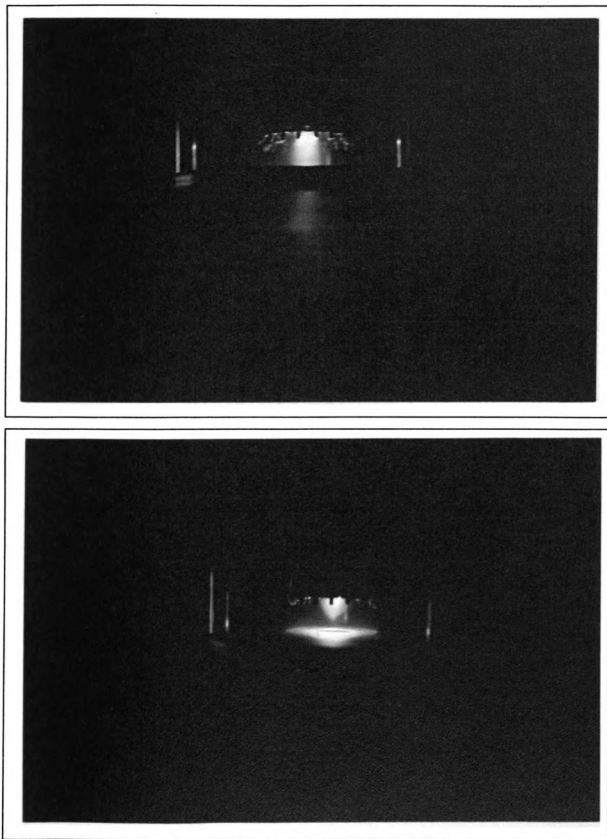


Figure 9.6 (a) Top at 0.0 kV and (b) Bottom at 0.25 kV bias

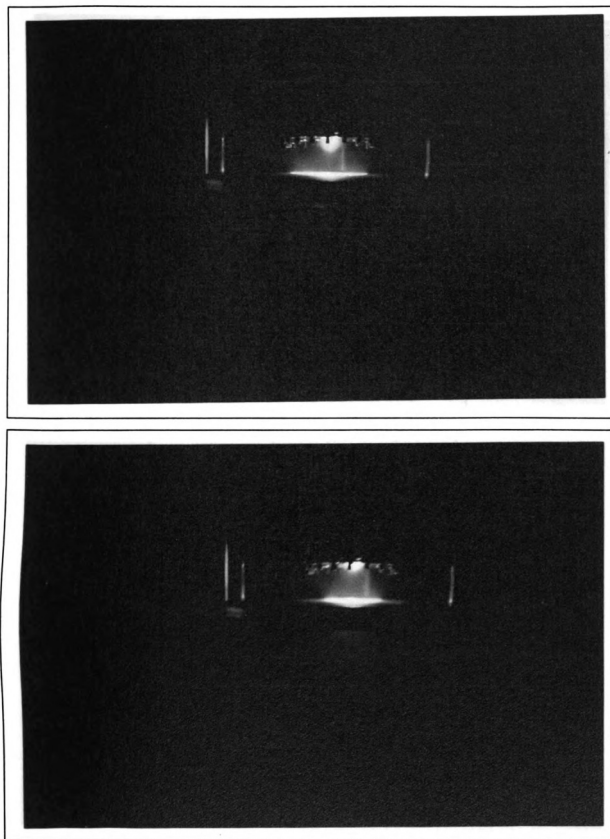


Figure 9.6 (c) Top at 0.5 kV and (d) Bottom at 0.75 kV bias

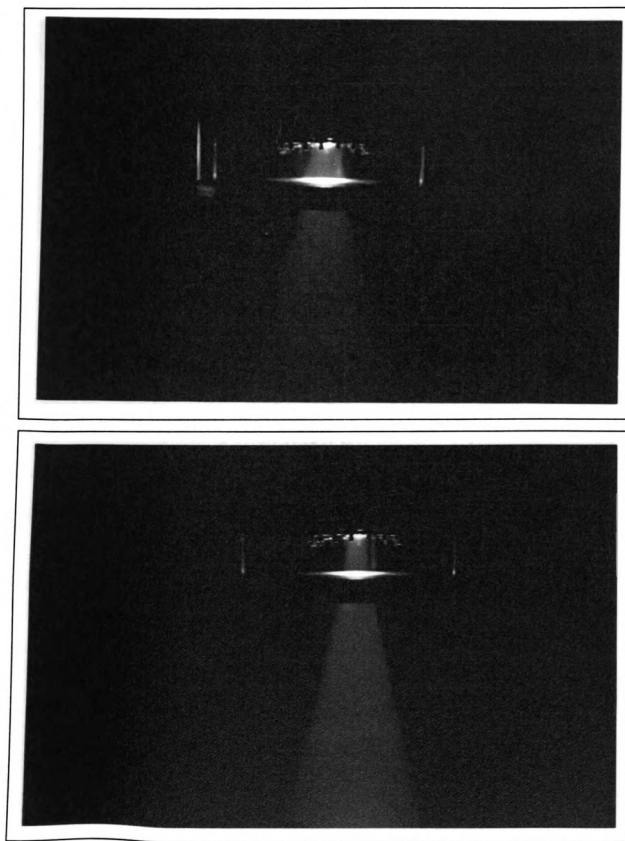


Figure 9.6 (e) Top at 1.0 kV and (f) Bottom at 2.0 kV bias

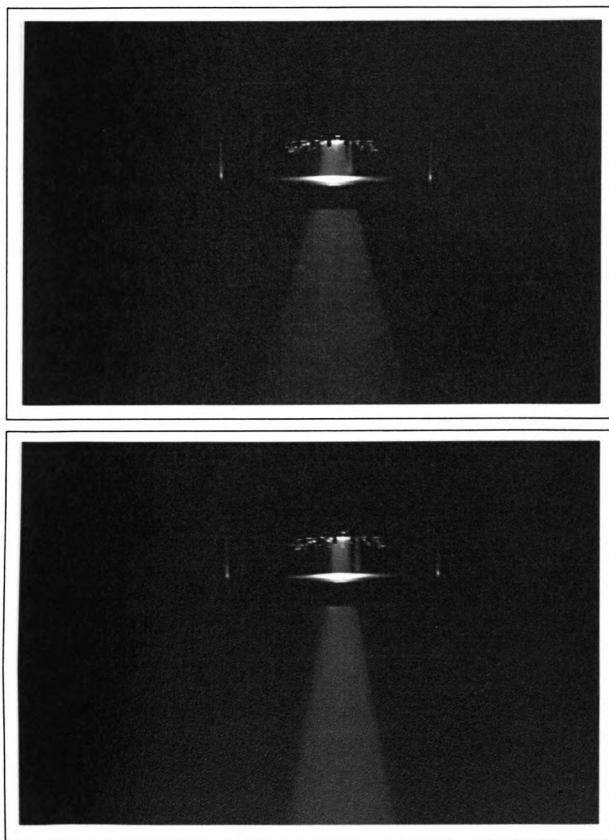


Figure 9.6 (g) Top at 3.0 kV and (h) Bottom at 4.0 kV bias

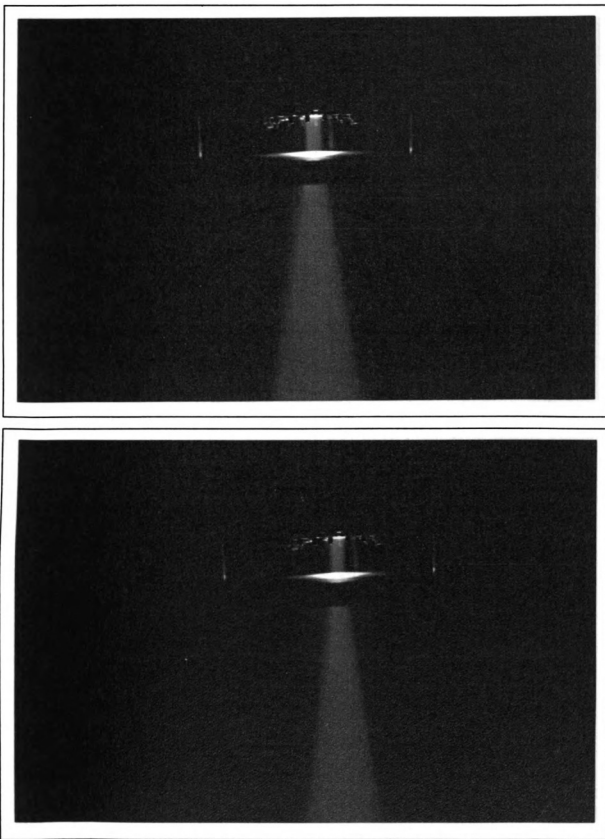


Figure 9.6 (i) Top at 5.0 kV and (j) Bottom at 6.0 kV bias

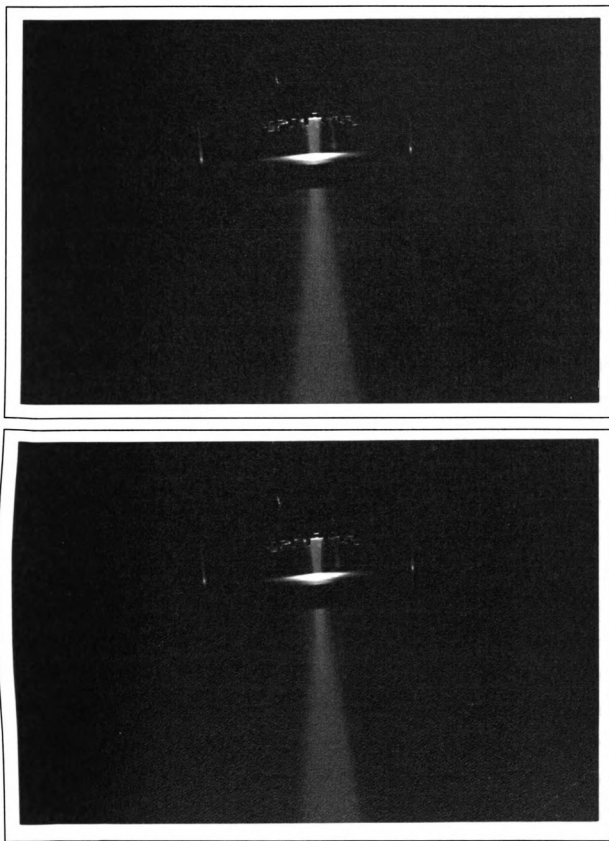


Figure 9.6 (k) Top at 8.0 kV and (l) Bottom at 10.0 kV bias

between it and the thin stainless steel baffle on the 610 (which is referred as electrode one, or the plasma electrode). Although the pictures are mostly dark, the outlet of the 610 is clearly bathed in the purple-white haze of the streaming plasma, or the deep blue definition of the ion beam. The “10-24” bolt rods that were eluded in Section 9.4 are also visible, as is second electrode of the extraction system. A discussion of these photographs, and also the “meniscus effect” follows.

At zero potential on the 610 (Figure 9.6(a)), the neutral plasma diffuses freely out of the 1.0 cm diameter hole in the stainless steel plate that is fixed on the outlet of the 610. This neutral plasma, seen as a bright white light in the photographs, hits the copper baffle plate that cuts the amount of plasma exiting to the other side (below electrode two). When the voltage on the 610 is raised to 0.25 kV (Figure 9.6(b)), the neutral plasma clearly forms a convex, tear drop shaped meniscus that has pulled away from the second electrode. At 0.5 kV (Figure 9.6(c)) and 0.75 kV (Figure 9.6(d)), the neutral plasma further recedes away from the second electrode, and a faint deep blue glow of the ion beam becomes visible below the second electrode.

It was visually confirmed that at 1.0 kV bias on the 610 (Figure 9.6(e)) relative to the second electrode, the meniscus has completely withdrawn into the ion source. This is important, and will be discussed later. The blue glow of the ion beam below the second electrode is clearly visible at 1.0 kV. However, the beam at this stage is still diverging from the first electrode, and being “chopped” as it exits out of the second electrode. At 2.0 kV (Figure 9.6(f)) and beyond, the bright white/purple haze of the neutral plasma is completely gone, replaced by the lesser, but more defined blue glow of the ion beam. Also at 2.0 kV and

beyond, despite being two dimensional the photographs clearly show the formation and definition of the ion beam on both sides of the second electrode. As the potential is raised to 3 kV (Figure 9.6(g)), and then to 4 kV (Figure 9.6(h)), the focussing effect of high voltage is now visible, and the diameter of the beam between the plasma and the accelerating electrodes decreases, which indicates a focussing beam. Note that below the second electrode the beam is still spreading out (de-focussing).

As bias potential on the 610 is further raised, another prominent voltage is reached. At 4.0 kV, the beam emerging from the 1 cm diameter hole in the first electrode is perfectly parallel, and is completely enclosed by the 1 cm diameter hole of the second electrode. There is no divergence of the beam from the 610 up to the second electrode. On both sides of the second electrode, the beam is now very sharply defined. The voltage is then increased to 5 kV (Figure 9.6(j)), and the beam from the 610 now begins to focus sharply into the second electrode. This "over focussing" is clearly visible at 8 kV (Figure 9.6(k)), and at 10 kV bias on the 610 (Figure 9.6(l)) relative to the grounded second electrode. Note that beneath this electrode, the beam still de-focuses since no other electric or magnetic focussing is available downstream from the two electrode extraction system. Also, the beam diameter at any fixed position below the second electrode decreases with increasing extraction potential, indicating a stronger over-focussing into the second electrode as the extraction potential is increased. This initial over-focussing is in part responsible for increasing the directed velocity of the ions, that travel further downstream before space charge effects begin to de-focus the beam.

9.5.4 Discussion of the Meniscus Effect

The concept of the plasma meniscus has been discussed in almost every book, chapter, or monograph on ion beam development, in connection with the details of the extraction apparatus. Some good examples of these discussions are the chapter on positive ion extraction and acceleration in Forrester's book [For-88], and Septier's monograph [Sep-80]. In particular, see Figure 5.1 in Forrester's book (page 100), or Figure 5 from the chapter by C. Lejeune in Septier's book [Lej-80]. Keller also provides a good description of the meniscus (see Figure 3.1 in his chapter from the book edited by Brown), which he defines as the "ion emitting surface" [Kel-89]. And finally, there are a lot of computer codes that numerically solve the equations governing the two dimensional or three dimensional beam extraction, as is evident from references Kel-89, and Spa-89 (both from the same book). These simulation codes not only predict the beam formation for specific bias potentials on the electrodes, they may also be used to optimally configure the extraction electrode system itself. Ray tracing codes like PARMILA, or BEAM3D for example, have been heavily used by ion beam developers to optimize the extraction systems and subsequent beam transport.

In all such discussions, the theoretical development is well detailed. However, there is no formal experimental confirmation of the meniscus effect - the recession of the neutral plasma boundary away from the accelerating electrode as the negative extraction bias on the electrode (or a corresponding positive bias on the ion beam source for a grounded second electrode) is raised. This is evidenced by the sketches that accompany the discussions in the above

mentioned books - there has been no visual or photographic confirmation of the meniscus effect to date. For the first time, the formation of the meniscus, and its variation with changing extraction potential have been visually observed and photographed, as is evident from the series of photographs in Figure 9.6. The photographs clearly corroborate several points of the theory regarding ion extraction and also bring to light certain discrepancies in the current theory. These issues are now summarized here.

At zero potential, the neutral plasma streams out and the plasma potential, or the "self bias" of the source (which may be several tens of volts at the very low pressures where the 610 is operating) defines the formation of the "beam" and the meniscus. As positive extraction potential is applied to the ion source (or conversely, a negative potential on the acceleration electrode), the beam begins to focus, while the neutral plasma confined by the meniscus begins to draw away from the increasingly "negative" second electrode. At an appropriate potential, the meniscus has completely retracted inside the plasma electrode, at which point or soon thereafter the beam is perfectly parallel. Compare Figure 5.1(a) from Forrester's book [For-88], or Figure 3.1(b) from Reference Kel-89 with Figure 9.5(h) of this chapter. If the extraction potential is raised further, the plasma surface recedes further into the source, forming a concave shape that over focuses the beam, as is seen in Figure 5.1(c) from Reference For-88, or in Figure 3.1(c) in Reference Kel-89, and also in Figure 9.6(l) in this chapter.

According to Forrester (Reference For-88, page 99), the shape of the plasma meniscus (at any applied bias) "is determined by the requirement that the solution of the unipolar space charge problem to the right of the plasma

boundary match the near zero field at that surface considering the current density of slow ions delivered by the plasma.” In other words, the electrostatic boundary conditions have to be satisfied on both sides of the plasma surface (the meniscus). Note that the electric fields within the neutral plasma must be zero, or near zero - so near the surface of the plasma (the meniscus), the electric field set up by the unipolar space charge of the ion beam, and the field due to the applied extraction bias have to add up with the individual fields due to the escaping ions in a manner so as to equal the zero (or near zero) fields within the neutral plasma.

Another, simpler explanation of the receding meniscus (with applied bias) is now presented, although there is ongoing discussion about its validity. It has been shown that the meniscus separates the quasi-neutral (field free) plasma from the positive ion beam, and the meniscus recedes away from the accelerating electrode as the positive bias on the ion source increases (or conversely, as the relatively negative potential on the second electrode increases). This “negative potential” on the second electrode accelerates ions, while limiting electron flow to the electron population that has sufficient energy to cross the potential barrier set up by the bias on the electrode. Since the meniscus is receding away from the accelerating electrode, the plasma boundary (the meniscus) must be the penetration limit of the high energy electrons as they encounter the equi-potential surfaces set up by the applied bias. In other words, the plasma boundary is defined by the high energy electrons, which therefore confine the quasi-neutral plasma from the electric fields set up between the electrodes and also the space charge fields of the ion beam. It can then be predicted that as the extraction potential increases, the equi-potential surfaces

must force the meniscus to recede away from the accelerating electrode as the high energy electrons face a higher potential "hill" to climb - exactly what is observed in Figure 9.6, and described by sketches in the books mentioned in the beginning of this section.

The theory proposed above (that the high energy electrons form the boundary of the quasi-neutral plasma) leads to a very interesting contradiction. At 1.0 kV, the meniscus has completely retracted inside the source and is neither concave, nor convex. This can occur only if the meniscus is flat. In such a situation, the equipotential surfaces between the ion source (or electrode one) and the accelerating electrode (number two) are evenly spaced. This means that at 1.0 kV, no high energy electrons produced within the ion source can exit the source due to the high ion extraction potential (that also acts as a repelling potential for the electrons), and therefore the highest energy electrons produced by the source must be at least 1.0 keV. According to direct measurements of the electron energy distribution function for the 610 in Chapters Four and Five, it seems unlikely that the source is capable of producing electrons of such high energy - results of single Langmuir probe data indicate that the typical electron energies within the 610 are at most tens of eV.

It must be noted however, that the Langmuir probe data reported in Chapters Four and Five were taken at relatively higher pressures (10^{-4} Torr, as compared to the operating pressures of 10^{-5} Torr in this chapter), and several centimeters downstream of the plasma generation region. It has been stated earlier that decreasing pressure raises the electron temperature, and the confining (or throttling) effect of the stainless steel baffle plate (electrode one), might itself provide secondary electrons to the discharge. Both conditions may

allow higher electron energies to be produced within the ion source. Despite these conditions, the probability of 1 keV electrons populating the high energy tail of the near-Maxwellian electron energy distribution function of the MPDR 610 seems remote, at best.

9.6 Further Beam Development - the Pierce type "Accel-Decel" Extraction System for the MPDR 610

The next step in the beam characterization of the 610 involved several modifications, not only in the extraction apparatus, but also in the location of the 610 at the NSCL for further testing. To recapitulate, the experiments detailed in Sections 9.4 and 9.5 were carried out with the 610 mounted in place of the object box (in the beam pipe) of the SCECR while the multiply charge state ECRIS, and the K1200 cyclotron were down for maintenance. The beams were extracted with a rather crude two electrode system consisting of a thin throttling baffle/electrode on the outlet of the 610 and a larger copper baffle plate mounted about 1.8 cm below the ion source. Both "electrodes" had a 1 cm diameter hole in the center for beam egress. The 610 was raised to positive potentials (as high as 10 kV) while the accelerating electrode (the copper baffle) was maintained at ground potential. This setup produced good results, specially providing pictorial representations, and fundamental insights into the meniscus effect discussed in the previous section. But with both the K1200 cyclotron and the SCECR scheduled to come back on line, another way to continue studying the beam characteristics of the 610 had to be found.

9.6.1 The Test Stand

The first step involved setting up an autonomous vacuum system on which the 610 could be mounted. Known as the "test stand," parts of this simple vacuum system were salvaged from a defunct experiment. It is shown in Figure 9.7 (not to scale) and consists essentially of two large 8 inch Conflat™ "Tee" shaped structures, each with four knife edge flanges. These were connected together through a small section of beam pipe. The 610 was mounted on the top "Tee" (with its alumina DC isolation joint) which had an 8 inch vacuum window on one side, and a darkened 8 inch blank off on the opposite end. Since the outlet of the 610 was critically located at the same level as the window, visual observation and still (or video) photographic documentation of the beam would be possible, as was done for experiments described in Section 9.5 (610 mounted on the object box). The connecting center beam pipe had a thermocouple tube and an ionization gauge tube. The bottom "Tee" had a sectored Faraday cup with a rotary feed through that could also be used as a beam stop. The other horizontal 8 inch flange on the bottom "Tee" was connected to a turbo molecular pump, which was backed by a roughing pump. On the bottom blank off of this second "Tee" was placed an emittance camera with Kapton film - a crude way of measuring the emittance of the beam using the "pepper pot method" as detailed in Chapter Three. All of this hardware was mounted on a very sturdy steel framed table (not shown in Figure 9.7).

Since the test stand was remotely located, the sectored Faraday cup was never used to measure the current in each jaw of the cup due to lack of computer cables that would be long enough to run from the Faraday cup to the

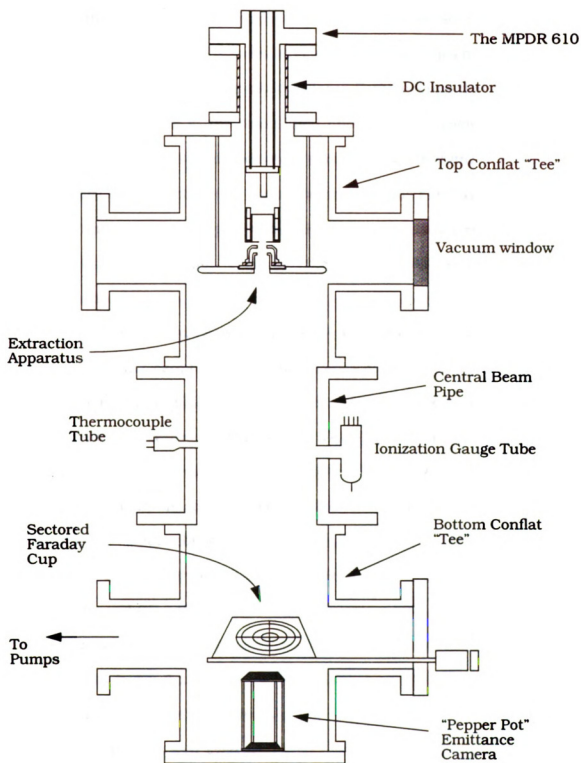


Figure 9.7 The test stand for autonomous beam characterization of the 610
 Note that the sturdy table connected to the central beam pipe on which the microwave apparatus etc. were set up is not shown.

NSCL computer that normally controls some parts of the ion source operations. (This computer is located in basement level, near the beam lines from the ECRIS to the two cyclotrons, close to the other sectored Faraday cups that are used to align the extracted beam in the beam line.) Kapton burns below the sectored Faraday cup (in the test stand) indicate a uniform, and diverging beam by the time it reaches the Kapton film. As mentioned earlier, this Faraday cup could be rotated in, and out of place just above the Kapton camera (see Figure 9.7), thereby acting as a beam stop for the film burns during emittance measurements.

The necessary microwave apparatus - including the 2.45 GHz power supply, and all other peripheral electronics were located on the mounting table. As before, the power supply, incident and reflected power meters, etc. were all at ground potential since the previously used DC isolation joint was once again utilized on the crossguide bi-directional coupler. Only the 610, and the coaxial cable used to transmit microwaves were at high voltage at the time of electrode biasing. A long coaxial cable of adequate rating was used to transport the high voltage signal from either of the three ECRIS at the cyclotron - the SCECR, RTECR or the CPECR - which ever was not in use at the time. The grounded outer conductor of this DC high voltage cable was disconnected at one end to prevent ground loops. A stand alone argon bottle provided the gas feed to the 610 through a manually controlled sapphire leak valve. Due to this manual adjustment on the gas feed system, it could not be determined what the flow rates were for the experiments, and only the ionization gauge pressure readings in the center beam pipe are reported.

9.6.2 The New Extraction System

The crude two grid extraction system used in the experiments of Sections 9.4 and 9.5 was completely over-hauled for the forthcoming tests. A new "spherical quasi-Pierce three electrode accel-decel" extraction apparatus was designed and installed on the 610. The advantages of this system, and its design are now described in more detail.

When a beam is extracted from the ion source, typically there is some amount of downstream ionization due to collisions between energetic ions and the neutral gas that also flows out of the plasma source. One of the disadvantages of the two electrode system is that electrons from this beam plasma (or secondary electrons emitted when the beam strikes the second electrode) are accelerated towards the plasma source, which is at a positive potential relative to the second electrode. These downstream electrons can attain significant potential energy, depending on the bias voltage of the extraction system, and can cause damage to the ion source. In a three electrode system, the first electrode is connected to the source (or biased at the same potential). The second electrode is generally biased negative, while the third electrode is grounded. This creates a potential well between the second and third electrodes that traps the energetic downstream beam electrons from backing up into the source and damaging it.

This potential well also provides a repository for electrons that neutralize the space charge effects in the beam and prevent "beam stalling" - a phenomenon that occurs when the space charge potential rises beyond a level such that the beam cannot be transported any further. Without space charge

neutralization from these electrons the potential of the beam (due to space charge) effects can rapidly increase up to the potential of the first (plasma) electrode. At this point the beam and the plasma are at the same potential, negating any extraction bias. Any further increase in the beam potential actually leads to reflection of ions towards the ion source [For-88] and the beam is then said to have stalled.

There is another, more important reason for using three electrodes for extraction. For the tests using two electrodes in Sections 9.4 and 9.5, the ion source (or more specifically, the plasma electrode) was raised up to positive 10 kV bias with the accelerating electrode grounded. This produced a well collimated beam of high energy (approximately 10 keV) ions. However, in some instances the ion beam of such high energy may be detrimental to the process - but at a lower potential the focussing effect of the accelerating potential is lost. Now if three electrodes are used, the ion source (and the plasma electrode) can be biased at, say 5 kV, the second (accelerating) electrode can be biased at negative 5 kV, while the third (decelerating) electrode is grounded. The ions are first accelerated to 10 kV of energy while traversing from the plasma electrode to the accelerating electrode and the beam is well focused. However, travelling between the second and third electrode, the ions are decelerated by 5 keV. Hence the name of this electrode geometry - "accel-decel." This leaves the ions with a net 5 keV of directed velocity, but the focusing generated by the extraction system remains intact. Photographic evidence of this phenomenon will be seen later when the results of this phase of experimentation are discussed in the forthcoming sections.

It was Pierce who first tackled the problem of designing the appropriate

electrode geometry for optimal extraction [Pie-40, Pie-54]. The details may be found in many references, Forrester's book in particular [For-88]. It is important to mention here that Pierce used a model of two parallel plates confining a plasma to reduce the space charge problem such that the equipotential surfaces between the two electrodes generate a smooth focussing effect on the ions travelling from one plate to another. Several assumptions (like the ions starting from the plasma surface at rest, and that the electrodes must be infinitely thin) were used to derive the results. Keller mentions many of them in his discussion of Pierce geometry [Kel-89]. Because of these assumptions, and other practical concerns, the precise Pierce configuration with its stated benefits is difficult if not impossible to achieve. However, modified electrode configurations based on his theory, known as the "quasi-Pierce" geometry have been found useful for generating parallel flow of ions for many types of beams, including long slit shaped beams, and for cylindrically converging beams. Quasi-Pierce electrodes have therefore been extensively used by ion source designers for developing intensity matched extraction apparatus.

According to the Pierce geometry, the first (plasma) electrode must make an angle of 67.5° with the axis of propagation of the ion flow, while the second electrode is spherical in shape. This configuration, along with the equipotential surfaces that are set up by it are shown in Figures 5.6 and 5.7 in Chapter Five of Forrester's book [For-88]. The design of the new extraction system for the 610 was based on the quasi-Pierce geometry with the appropriate angle of the plasma electrode but with non-spherical second and third electrodes. (Actually two types of plasma electrodes were used. A flat plasma electrode was used to compare beam formation with that in Sections 9.4 and 9.5. For most

experiments however, the other plasma electrode with the appropriate angle was used.) The electrode assembly is shown as a composite in Figure 9.8(a), which shows a cross sectional sketch (not to scale). All electrodes are made of stainless steel, and the details are discussed below using Figures 9.8(b) through Figure 9.8(g). Note that these detail figures are not to scale.

Cross sections of the two designs of the first electrode (known as the plasma electrode) are shown in Figure 9.8(b) and 9.8(c), while the top view is seen in Figure 9.8(d). With the tapered edges, both electrodes are designed to fit snugly into the outlet of the 610 (as seen in Figure 9.8(a)), and therefore also throttle the excess current output of the source. Note that there is good electrical contact between the plasma electrode and the ion source. Both plasma electrodes have a 1.0 cm diameter hole in the center. The first design (Figure 9.8(b)) is a flat electrode similar to the 0.125 inch thickness stainless steel baffle plate. This was used primarily to compare the results of this three grid system with the results of the two flat electrodes of Sections 9.4 and 9.5. The second type of the plasma electrode that was used in these experiments (Figure 9.8(c)) has the typical 67.5° Pierce angle.

Cross section of the second electrode (also known as the accelerating electrode) is detailed in Figure 9.8(e). It has a 1.27 cm diameter hole in the center. An electrical cable connected to a vacuum feedthrough is used for independently biasing this electrode. For a given radius of the hole on the first (plasma) electrode - in this case 0.5 cm, the distance between the plasma and accelerating electrodes is critical, and is determined by the Child-Langmuir law that equates the maximum current density that can be produced by the ion for a specific bias voltage. It is given by the following equation [Kel-89]:

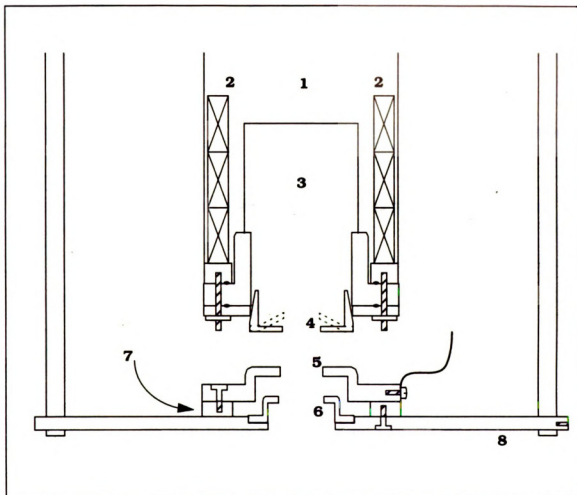


Figure 9.8 (a) Composite of the three grid accel-decel extraction system.

- | | |
|-----------------------------------|--------------------------------------|
| 1. The MPDR 610 | 5. Acceleration electrode (negative) |
| 2. Magnets of the 610 | 6. Decelerating electrode (grounded) |
| 3. Discharge region | 7. Maycor insulator |
| 4. Plasma electrode (up to 10 kV) | 8. Grounded plate |

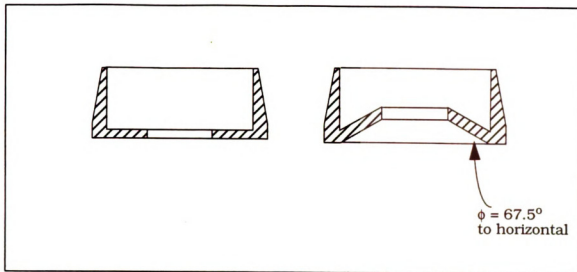


Figure 9.8 (b) and (c) side view of the two types of plasma electrodes.

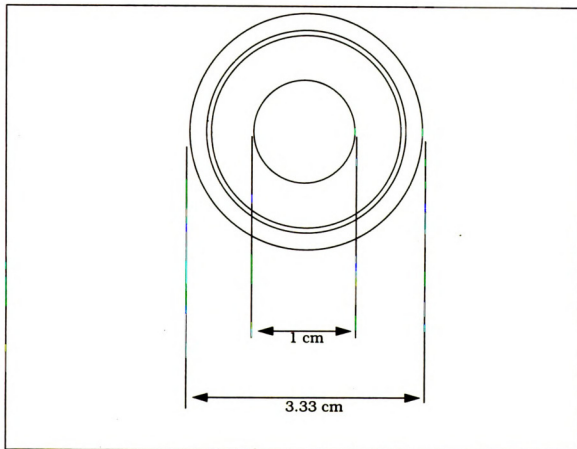


Figure 9.8 (d) Top view of the plasma electrode.

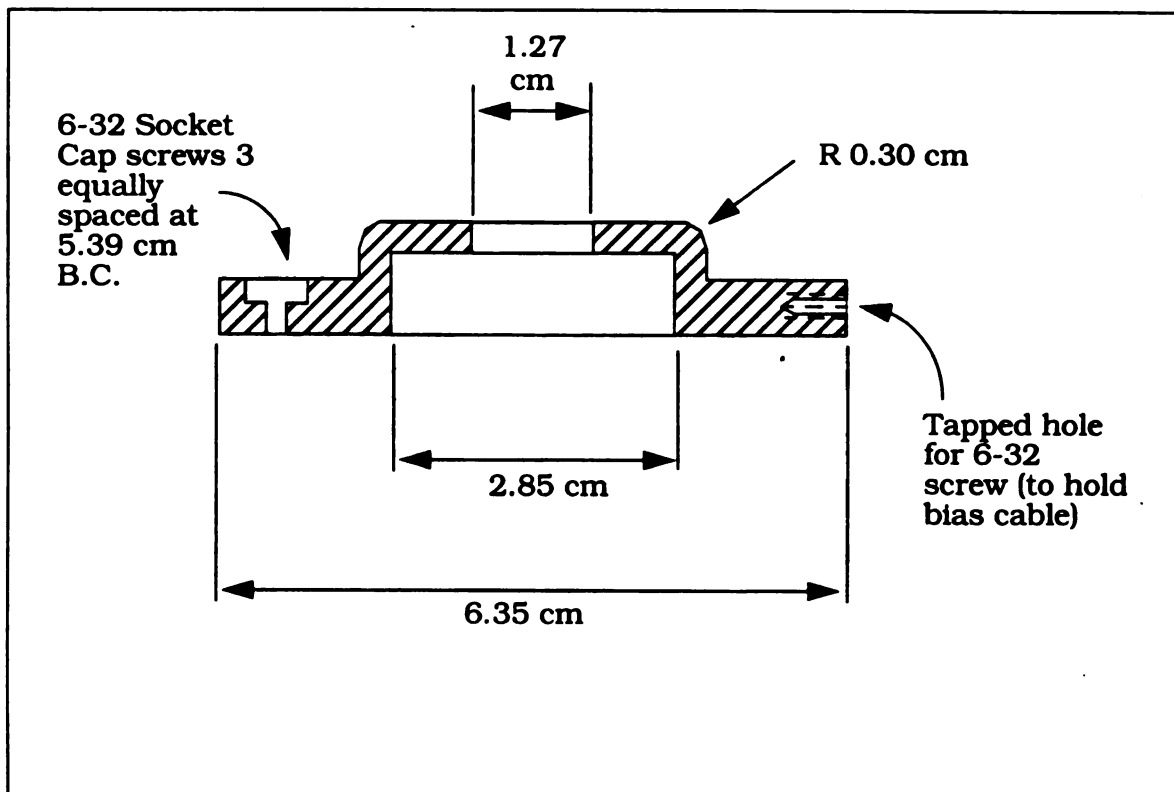


Figure 9.8 (e) Side view of the acceleration electrode.

Note the 6-32 tapped hole on the side for the bias cable. Since this electrode is attached to the Maycor ring, it can be independently biased relative to all other electrodes.

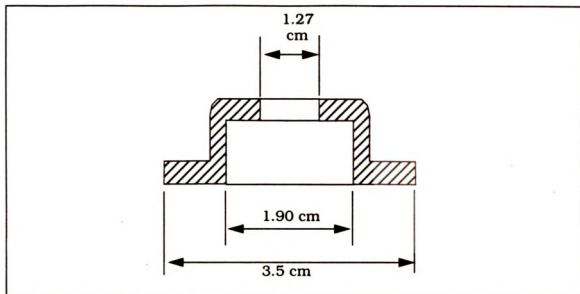


Figure 9.8 (f) Decelerating electrode (normally grounded).

This electrode sits snugly on top of the large stainless steel baffle plate.

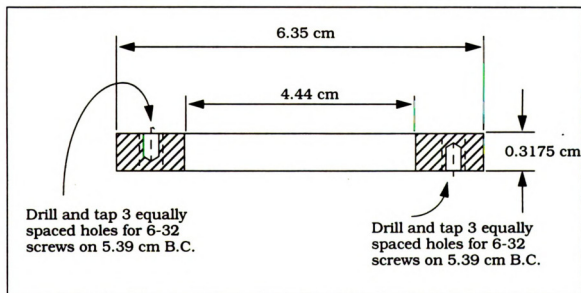


Figure 9.8 (g) The Maycor ring that isolates the acceleration electrode from the deceleration electrode.

$$J = 1.723 \sqrt{\frac{Z}{A}} \frac{V^{3/2}}{d^2} \quad (9.1)$$

Here J (in mA/cm²) is the current density being produced by the ion source. If the total current is I (in mA) and r (in cm) is the radius of the hole in the plasma electrode,

$$J = \frac{I}{\pi r^2} \quad (9.2)$$

Also, Z is the charge state of the ion beam. Since argon was used as the discharge gas and previous experiments have shown that about 95% of the ions created by the 610 are Ar¹⁺, Z is taken to be +1 for this calculation. A is the relative atomic mass of the ions, and is equal to 40 for argon. V (in kV) is the applied acceleration voltage, and finally, d (in cm) is the gap between the plasma electrode and the acceleration electrode. Now, for a specific amount of current (assumed 50 mA) at a specific bias voltage (assumed 30 kV), the distance d can be solved from Eqn. 9.1 above. Therefore,

$$\frac{50}{\pi (0.5)^2} = 1.723 \sqrt{\frac{1}{40}} \frac{(30)^{3/2}}{d^2} \quad (9.3)$$

From this calculation, d is equal to 0.837 cm. The third (decelerating) electrode is shown in Figure 9.8(f) and rests on a large baffle plate. This stainless steel baffle plate is not used to create a pressure differential (as the copper baffle plate was used when the 610 was mounted on the SCECR), it is connected to the beam pipe via set screws on to three struts, and acts as a convenient ground,

and receptacle for holding the decelerating electrode, which is therefore always grounded. Note that the accelerating electrode is isolated from the baffle plate by a maycor insulator ring, shown in Figure 9.8(g). (Maycor is a machinable insulator. While it is relatively firm, bolting the electrodes to the Maycor ring must be done with care - too much torque on the cap screws would wear out the threads on the insulator.) This allows independent biasing of the accelerating electrode with respect to the plasma electrode and the grounded decelerating electrode.

The MPDR 610, with its plasma electrode is mounted on its DC isolation joint (as in Figure 9.1), and this is then mounted on the 8 inch conflat flange. The three struts are then secured to the bottom of the 8 inch knife edge flange. The decelerating electrode is then fitted snugly into the baffle plate, the maycor ring is secured to the plate, and the accelerating electrode is screwed on to the maycor ring. Then the distance d between the accelerating and plasma electrodes is adjusted by precisely positioning the whole extraction assembly on the mounting struts.

9.7 Operational Performance of the Improved Three Electrode Extraction System

As in the case of tests done for the two electrode extraction system, the initial experiments on the test stand failed because of the prohibitively high argon discharge pressure. Once again the 610 could not be operated at 0.5 mTorr - in its "high density mode" due to the excessive drain current being produced by the source. Moreover, a minor bias application of less than a few

hundred Volts produced a "Penning type" discharge between the source and the extraction apparatus. This is because at a relatively high neutral argon pressure between the first two electrodes, the electric fields set up between the plasma and accelerating electrodes were high enough to break down the gas, and generate a DC glow discharge. This shorted out the two electrodes, thereby creating such high ion currents (up to 4 mA at a mere 100 V applied bias) as to make any beam extraction impossible. For the continuation of these experiments, the operating pressure therefore had to be reduced and once again, the 610 was optimized for its "low density" mode.

With the 610 in its low density mode, beam extraction was initially conducted with the accelerating and decelerating electrodes both grounded, while the 610 and the plasma electrode were biased to the accelerating potential. Several sets of pictures were taken for this configuration, as before - however, no emittance or charge state distribution data were taken due to the lack of appropriate equipment on the test stand. With the optimized Pierce geometry, the focussing properties of the extraction system were enhanced, as will be seen in the following discussion. While the beam current production is similar in magnitude to the two electrode geometry, the optimally positioned three electrode system manages to extract a more collimated beam than the two electrode system.

As was mentioned earlier, the major advantage of using the three electrode system was that the focussing effect of the system is enhanced for an ion beam that must maintain a low directed velocity. This is clearly seen from the photographs of Figure 9.9(a) and (b) that produce ion beams with similar collimation. However, the electrode bias configurations for the two beams are

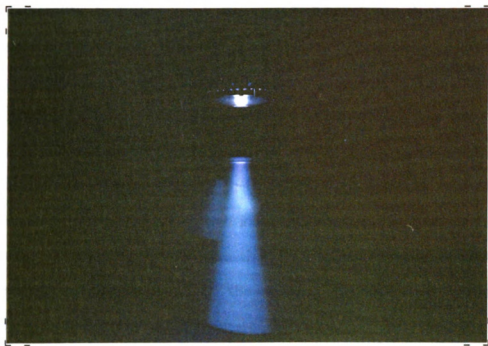


Figure 9.9(a) Plasma electrode at 6 kV, accel-decel electrodes grounded



**Figure 9.9(b) Plasma electrode at 3 kV, accel electrode at -3 kV,
decel electrode grounded**

Note that both methods have same focussing, but the beam in Figure 9.9(b) has half the energy of the beam of Figure 9.9(a).

very different. The first photograph (Figure 9.9(a)) is taken with the 610 - and the plasma electrode - at 6 kV, while the accelerating and decelerating electrodes are both grounded. The net energy of the ion beams is therefore about 6 kV (assuming zero, or near zero initial ion energy). The second photograph (Figure 9.9(b)) is taken with the plasma electrode at 3 kV, the accelerating electrode at negative 3 kV, and the decelerating electrode at ground potential. The ions are initially raised up to 6 kV and are well focussed, but then lose 3 kV as they are decelerated by the third electrode. Note that while the net energy gain is about 3 kV in this case (as compared to 6 kV), the focussing effect of this configuration is the same as from the 6 kV beam of Figure 9.9(a).

Also, with a negative bias on the accelerating electrode the potential well for containing neutralizing electrons may have been formed that would capture some electrons created by the beam, thereby lessening the space charge effect in the beam to some extent. Hence, the three electrode system provides a degree of flexibility in the collimation and the net directed velocity of ions. This is not possible in the two electrode extraction system. There might be applications of ion beams where a beam with low directed velocity ions needs precise initial focussing, and this three electrode assembly may be of considerable use. However, as a point of interest, the ECRIS at the NSCL (the SCECR, for example) use this three electrode assembly, with the accelerating and decelerating electrodes both grounded. This may be due to the fact that the purpose of the SCECR type sources is to generate ion beams with maximum energy and focussing, and hence the flexibility afforded by the three electrode system may not be absolutely necessary.

The focussing effects of the three electrode system are clearly visible when

the 10.0 kV biased photograph of the initial set (Figure 9.6(l) taken for the two electrode extraction experiments) is compared to the two photos in Figure 9.10(a) and (b). The photo in Figure 9.10(a) shows the three electrode system with the 610 biased at 10.0 kV (and the accel-decel electrodes grounded), while Figure 9.10(b) shows the beam at the same potential for a two electrode system with the separation between the electrodes down to about 0.84 cm. Note that the electrode separation in Figure 9.6(l) set is about 2 cm, while this gap is about 0.84 cm for the photographs in Figure 9.10. Clearly the focussing of the beam in Figure 9.6(l) is less defined than for the beams shown in Figure 9.10. Also, note that for the same electrode separation, the three electrode system gives better beam definition than the two electrode extraction in Figure 9.10, which is another benefit of using the accel-decel electrode system, even if the second and third electrodes are both biased to ground.

9.8 Concluding Remarks

This chapter has been devoted to extraction and characterization of ion beams from the MPDR 610. As may be discerned, this plasma source can be easily adapted such that high intensity beams may be extracted from it. Indeed, the 610 produces so much current that its output has to be throttled in order to maintain the biasing capabilities from conventional DC high voltage power supplies (30 kV, 5 mA limited, for example). Due to this excessive current production, the beam extraction never really reaches saturation, and grows monotonously with applied bias, since there is always sufficient ion density within the plasma source to satisfy the requirements of the extraction potential

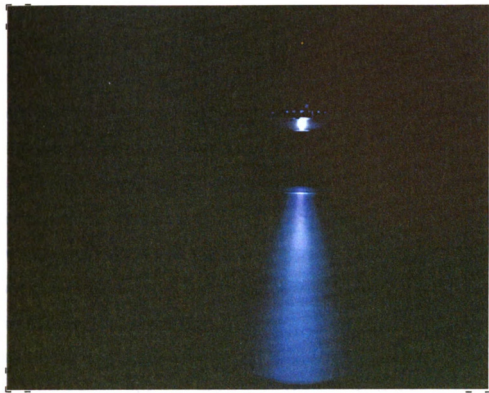


Figure 9.10(a) 3 electrode system at 10.0 kV, 0.84 cm separation.



Figure 9.10(b) 2 electrode system, 10.0 kV, 0.84 cm separation.

3 electrode system of Figure 9.10(a) gives better beam definition than the 2 electrode system (Figure 9.6(l) and Figure 9.10(b)), even for the same electrode gap.

(that is, the ion beam is space charge limited in all cases).

Also, due to the high currents being extracted the emittance of the argon beam tends to be relatively high - about 100π mm-mRad to 600π mm-mRad depending on the argon charge state (+2, or +1 respectively). Neutralizing the beam by injecting electrons immediately outside the extraction apparatus may reduce the space charge effects in the beam, thereby focussing the beam further, and reducing the overall emittance. This may have been accomplished to some extent by using the three electrode extraction system where the accelerating electrode is biased negative. This would generate the potential well to contain the neutralizing electrons and prevent them from back streaming into the plasma source, as was mentioned earlier in the theory of Section 9.6.2.

Initial experiments were conducted with a crude two electrode extraction system. This led to valuable information on the "meniscus effect" - the recession of the neutral plasma boundary within the ion beam source (and away from the accelerating electrode) as the extraction potential is raised. It is proposed that this recession is due to a potential "hill" encountered by the electrons from the quasi-neutral plasma because of the electric fields set up between the plasma electrode and the accelerating electrode. The high energy electrons from the plasma must "climb" over the potential hill to reach the second electrode, and as the hill becomes steeper (with increased acceleration bias), the neutral plasma surface is repelled farther by the accelerating electrode. In other words, the high energy electrons in the quasi-neutral plasma dictate the location of the meniscus with respect to the extraction electrodes.

The next step in the extraction experiments was to design and develop an optimized three electrode extraction apparatus for the 610 with appropriate

Pierce geometry and electrode gaps. When the new extraction system was tested on the 610, it was seen to provide better focussing of the beam (perhaps due to the neutralizing electrons in the potential well of the second and third electrodes), while also allowing flexibility on the ion beam's directed velocity for the required beam collimation.

Beam analysis from the 610 has only begun with this chapter. A lot of work still needs to be accomplished to further understand these beam characteristics. Emittance, and charge state distributions of the beam that is extracted from the three electrode system need to be measured and studied. Despite a flirtation with the Kapton film camera (the pepper pot method of measuring emittance), this is best conducted with the 610 placed on the object box of the SCECR beam line (as for the experiments in Sections 9.4 and 9.5) and by using the wire scanning method. Also, some way to couple the very high currents from the 610 operating in its optimized high density mode (so as to generate a beam of even higher intensity) needs to be found. No existing power supply can handle the several tens of mA that are produced by the un-throttled 610 in its high density mode. Finally, beam development (extraction and characterization) for other gases needs to be conducted also. There is significant interest in oxygen beams for ion implantation. Finally, beams from gases like helium, nitrogen, hydrogen need to be studied.

Another interesting aspect of the beam characterization is to properly explain the meniscus effect. A physical model for the meniscus recession with increasing bias has been proposed. This needs to be corroborated by using available ray tracing programs (like BEAM3D) or other numerical computer codes to accurately predict the recession rate taking into account all the

necessary plasma and beam extraction parameters. Another approach to the problem may be to use the photographs of Figure 9.6(a to l), digitally enhance the scanned images so that the exact shape of the meniscus and its position relative to the electrodes at every potential is measurable. Along with input from PANDIRA on the equi-potential surfaces set up between the electrodes and the plasma meniscus (that may be assumed to be a conducting surface for this test), an analytical model may be constructed.

There may be some evidence of the meniscus retraction into the 610 being dependent on the gap between the plasma electrode and the accelerating electrode. As this gap is increased, it was noticed that the meniscus retracts into the source at a lower potential. This seems to be counter intuitive if the relevant equipotential surfaces that are set up between the two electrodes are taken into account, and this effect of electrode separation on the meniscus must be tested further.

Some initial applications of the 610 as an ion beam source have already surfaced. A proposed study involves using the 610 beam (mostly Ar^{1+} ions) in conjunction with an iris placed downstream (that can control the beam emittance) for studying and rectifying beam optics for experimental setups where extended distances must be traversed by high energy beams. Such beam pipes carrying packets of high energy multiply charged ions exist in all particle accelerator facilities. With the 610 and iris packaged into a small diagnostic configuration that can be retro-fitted to any part of the existing beam pipe with ease, the transport capabilities of the beam pipe may be determined without the necessity of a beam from the particle accelerator.

There is also some interest in developing a 610-like source (or the 610

beam source itself) to generate moderate quantities (10 to 20 μA) of alpha particles (He^{2+}) at the cyclotron laboratory in the Texas A&M university (TAMU) [May-95] while the main multiply charge state ECRIS at the facility is undergoing upgrades. Based upon the argon ion beams that were extracted from the 610 in this chapter, its performance with helium gas (at the EE laboratories) vis-a-vis argon, and the ionization potential for He^{2+} (about 55 eV), this modest requirement of the TAMU facility should be within reach of the 610 beam source. This can easily be confirmed by mounting the 610 on the SCECR beam line (as for Sections 9.4 and 9.5) and running a helium plasma. Useful diagnostic data like charge state distribution and emittance measurements for a helium beam may also be acquired at that time. A similar request for feasibility study of using the 610 for injection as a target ion source has also emerged from the cyclotron laboratory at the Istituto Nazionale di Fisica Nucleare, on the campus of the National University of the South, Catania, Sicily [Gam-94].

The study of the 610 ion beam source is, therefore by no means complete. In light of interest for a compact ion beam source, this important factor in the characterization of the MPDR 610 needs to be addressed in the near future.

Chapter 10

Evaluation: The 2.45 GHz excitation of the SCECR

10.1 Introduction

10.2 Theoretical Background of ECRIS Design

10.2.1 The Frequency Squared Scaling Law

10.2.2 The SCECR, and its "High-B" Mode of Operation

10.3 The 2.45 GHz Operation of the SCECR

10.3.1 Experimental Hardware Description

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10.6 Concluding Remarks

Chapter 10

Evaluation: The 2.45 GHz excitation of the SCECR

10.1 Introduction

The focus of this dissertation now shifts, to some interesting experiments that were conducted over a period of a few days on the Superconducting ECR ion source (SCECR) at the National Superconducting Cyclotron Laboratory (NSCL). Conception of this particular set of experiments arose out of a deep sense of doubt over current reigning theoretical reasoning that has shaped the design and development of ECR ion sources (ECRIS) in the last several decades [Ant-94c], and from an important development - the High-B mode of operation of the SCECR (explained in Chapter Eight, and later in Section 10.2.2 of this chapter also). Success of the experiments detailed in this chapter has led to a significant breakthrough in the field of ion source design, and also to a better understanding of the inner workings of ECRIS, especially those used for the generation of multiply charged ions like the SCECR. These experiments have also generated data for a presentation at the 6th International Conference on Ion Sources to be held in Whistler, Canada from September 10 to 17, and the

subsequent publication [Sri-95b] in the proceedings [Sri-95]. Finally, the results have led to the filing of a US patent [Ant-95], and with interest from industry, specifically from ion implantation machine designers, and also from cyclotron laboratories, there exist possibilities for licenced production from this patent issue. More importantly, it is a testament to the genuine curiosity of the researchers involved, and another stellar example of the collaborative research between the Electrical Engineering (EE) and the NSCL ion/plasma source research groups.

This penultimate chapter begins with a brief introduction of some of the theoretical developments upon which the design effort of ECRIS around the world has depended for the past decade or so. That this theory is based on several assumptions which are not necessarily valid for most (low charge state, or high charge state producing) ion sources in use today, and may therefore be inherently unsatisfactory in its conclusions, will emerge from this discussion. Solid evidence substantiating this claim will be presented in the form of developmental work conducted on the "High-B" mode of the SCECR (unrelated, to this chapter, but with a profound impact on experiments conducted here). While most of the information presented in this chapter is new, some overlap, specially regarding the description - and modification - of the hardware for the SCECR with the discussions of Chapter Eight (which also dealt with modifying the SCECR for injection of plasma species from the 610 to the main stage) is inevitable. For the sake of completion, certain descriptive details regarding the SCECR will also be recapitulated here.

Details of experiments conducted in this chapter will then be discussed, starting with the description of some new SCECR hardware that was used

during these tests. The results of argon and oxygen beam extraction from the SCECR operating at 2.45 GHz are then presented, along with comparison with data from several other higher frequency multiply charge state ECRIS in use today. As mentioned earlier, these tests lasted less than one week due to the other commitments of the SCECR (primarily for beam injection into the cyclotron), so the results discussed here are preliminary, but extremely promising. Finally, the concluding remarks recapitulate these results, and discuss the necessity of further experiments to develop the ideas broached in this chapter.

10.2 Theoretical Background of ECRIS Design

There are about 45 ECRIS in operation for the production of multiply charged positive ion beams in the world [Lyn-92, Ant-94b], with about 10 - 15 more under construction. At present an ECRIS is the leading device for the production of high charge state positive ion beams world wide. With its electrodeless (and therefore long lifetime) nature, efficient power coupling into the plasma through selective ECR heating of electrons, and good confinement of charged species, the ECR ion sources of today provide several advantages over other types of sources that had been used earlier (like the Penning ion gauge) for the production of multiply charged ions. Most of the ECRIS are used for injection into accelerators, while some are used, or being built for atomic physics experiments, and there is a new but important effort to apply them to the field of material processing. Chapter Eight discussed ECRIS for multiply charged ion production in detail (see for example Sections 8.2, 8.3 and 8.4 of Chapter Eight).

What follows in the next few sub-sections is a detailed description of the “frequency squared scaling law” which has played a prominent role in the design and development of ECRIS. Next, the SCECR and its “High-B” mode are briefly described (more details may be found in Chapter Eight and in the relevant references), that ultimately leads into the experiments of this sub-study.

10.2.1 The Frequency Squared Scaling Law

The principles of ECR heating (ECRH) have been detailed several times during the course of this dissertation. One of the important issues involving plasma sciences is the propagation of electromagnetic (EM) waves through the plasma (or on top of it - as surface waves). Once the plasma is ignited and is in a steady state, it may be modelled as a high pass filter for the transmission (or lack thereof) of EM waves. In other words, waves with a frequency higher than a specific “critical” frequency - known as the plasma frequency (ω_p) will be transmitted through the plasma, while the waves with frequency lower than ω_p will be attenuated in the plasma. For an infinite, homogeneous, non-magnetic, cold (collision-less) plasma - note these assumptions - the plasma frequency may be derived through the dispersion relation of wave propagation. This derivation is detailed in several good texts [Bit-86], and also in journal publications - in particular see Reference Ant-93a regarding this “classical” approach. As a function of ion density (n_e) in the plasma, ω_p may be written as:

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m}} \quad (10.1)$$

Here, e and m are the electronic charge and mass respectively, and ϵ_0 is the vacuum dielectric constant. For ease of calculations, this equation may be reduced to:

$$f_p = 8.91 \times 10^3 \sqrt{n_e} \quad (10.2)$$

where f_p is in Hz (and equal to $\omega_p/2\pi$) and n_e is in cm^{-3} . This equation defines the so called "critical density." If the frequency of excitation is equal to f_p i.e. the plasma frequency, Eqn. 10.2 indicates that the ionization in the ion source is limited to a maximum value by this frequency. That this "maximum density" is routinely exceeded, especially by the ion sources used in the EE labs leads to two possible conclusions. It may be that phenomena other than ECRH are sustaining the plasma in sources similar to the MPDRs in the EE labs (a legitimate possibility, considering the power transfer techniques discussed in Chapter One - see Section 1.2, and subsections 1.2.1 and 1.2.2 of Chapter One). The other possibility is that the Eqns. 10.1 and 10.2 are incomplete, or too simplistic in their conclusions. The assumptions, or simplifications that are used to reach these conclusions (some of which are mentioned earlier in this section) are necessary to obtain closed form analytical solutions to the rather complex problem of wave propagation in a plasma. Using these assumptions, the problem is indeed simplified, however the validity of the conclusions may have to be reconsidered.

Despite the fact that most of the simplifications used in the critical frequency/density derivation above are not valid for most ECRIS today, the design and development efforts of most multiply charged state ion sources for

the last decade or so have been based on this simple scaling law - double the frequency of excitation, and theoretically the ion density should quadruple. This is the "frequency squared scaling law," and will be the center of several discussions during the course of this chapter. The dependence of source design on this law was amplified after the results of the Grenoble 16.6 GHz ECRIS were presented at the Berkeley ECR Workshop in 1984 [Gel-84] ("better results at a higher frequency" must mean that the law is correct). Several other source designers and authors, including Jongen and Lyneis [Jon-89] also come to the same conclusion - that increasing frequency is a simple way to increase ion density.

A valid question that may be asked is this: a multiply charged state ion source produces high charge states, and not necessarily high density, so what is the importance of raising the frequency in the production of high charge states? Antaya and Gammino explain in Reference Ant-94b the importance of obtaining higher ion densities in a multiply charged state ion source. The production of multiply charged ions occurs through successive electron impact ionization when species confinement time is high enough, and as is shown in Reference Ant-94b, an increase in ion density (if discharge pressure is maintained in the 10^{-6} to 10^{-7} Torr range), leads to an increased probability of high charge state production. Hence the necessity for ion source designers to raise ion densities within the ion source.

Based on the frequency squared scaling law, many high frequency sources have been built for the production of high charge state ions and they do indeed have high performance, such as exhibited by: the 14 Ghz ECRIS at Julich [Beu-89], the AECR at Lawrence Berkeley Laboratory (LBL) [Lyn-91, Xie-

93], the ECR4 at Ganil [Sor-91], the 18 GHz Minimaños of Grenoble [Bar-92], the 6.4 ECRIS at Texas A and M University [May-93] and the three ECRIS at the NSCL [Ant-93b] operating at 6.4 GHz. Some of these sources have also been operated at lower frequencies (≤ 6 GHz), albeit with significantly reduced performance. There are also intense singly charged high density sources like the Chalk River ECRIS [Tay-92], and the MPDR 610 - the latter has been the focus of the past several chapters in this dissertation.

10.2.2 The SCECR, and its “High-B” Mode of Operation

The Superconducting ECR ion source was first introduced in this dissertation in Chapter Eight, and its cross-section is shown in Figure 8.2, Chapter Eight. It is a fully superconducting hexapole stabilized tandem mirror ion source with a multimode microwave cavity. Multiply charged ions are generated inside the source by aggressively confining the charged species, which leads to successive electron impact ionization. This confinement of charged species is done by using several sets of superconducting magnets. Axial confinement is provided by five coils stacked three (at the injection stage) and two (at the extraction stage) that allows fine adjustments to the magnetic mirror geometry. The hexapole (also superconducting) provides radial confinement and together with the solenoid coils, creates the “minimum-B” configuration within the plasma vessel of the SCECR. With other outstanding properties (such as a very strong magnetic field capability, a simplified axial plasma configuration, an off axis rectangular waveguide microwave launch mechanism, and with a reduced coaxial ion injection stage) the SCECR presently represents the state of

the art for multiply charged ion production in an ECRIS [Ant-94b].

Another feature of the SCECR is that it is a variable frequency source - it was designed so that the superconducting magnets may be ramped up for operation from 5 GHz to 35 GHz - the typical range of multiply charge state ECRIS. However, due to an assembly flaw with the current leads to the hexapole, this range is severely limited, and the highest magnetic field strength for ECR and electron confinement is restricted to operation at or below 10 GHz. A proposal currently being studied at the NSCL is the design and assembly of a new hexapole for the SCECR so as to avail the use of the entire range of frequencies for which the source was originally designed to operate.

The normal magnetic field configuration for axial confinement (using the solenoids) of charged species in an ion source like the SCECR is generated by mirror ratios ($B_{\max}/B_{\min}$) of typically 2 to 3, and radial confinement (by the hexapole) with a wall-to-center ratio of about 1 to 2. It was proposed by Ciavola and Gammino at the Bensheim ICIS in 1991 [Cia-92], and later confirmed by Antaya and Gammino [Ant-93a, Ant-94b] at the Beijing ICIS in 1993, that by increasing these mirror ratios to about 7 at the injection stage (compared to the normal 3), and 4 at the extraction stage (compared to the normal 2), with a comparable increase in the hexapole ratio (about 3, up from the normal 1.7), the SCECR could be optimized at 6.4 GHz operation to match, or exceed the high charge state production of all existing ECRIS, including the several that operate at higher frequencies (14.4 GHz and higher). This magnetic field configuration, with enhanced radial and axial mirror ratios is known as the "High-B" mode of operation. This high magnetic field configuration may be represented by the following equations:

$$\begin{aligned}
B_{inj}/B_{min} &\geq 7 \\
B_{ext}/B_{min} &\geq 4 \\
B_r/B_{min} &\geq 2.5
\end{aligned}
\tag{10.3}$$

where B_{inj} is the maximum magnetic field at the injection stage, B_{ext} is the maximum magnetic field strength at the extraction section of the SCECR, B_{min} is the minimum magnetic field anywhere, and B_r is the maximum radial magnetic field generated by the hexapole at the wall of the source.

With conflicting reports on the frequency dependence of ECRIS specially in light of the good High-B mode operation of the SCECR at 6.4 GHz, the question arises whether the frequency of operation has any impact on the performance of ECRIS. As an interesting aside, consider the operation of the MPDR 610 at the two frequencies of excitation - 2.45 GHz and 915 MHz, which was detailed in Chapter Five. It was observed in that chapter, that the ion density at both frequencies of operation was relatively unchanged (same order of magnitude, with similar power and pressure dependence). However, the electron temperatures, and the corresponding ion energies at 915 MHz were double those at 2.45 GHz. Note that while power coupling in the 610 may not be strictly ECR (as discussed in Chapter One), and so the frequency squared scaling laws that apply only to ECR heating may not apply, the results of Chapter Five (specially the ion density data at the two frequencies of operation) do call into question the theoretical analysis of the dependence of electron density on the frequency of operation as per Eqns. 10.1 and 10.2.

Reverting back to multiply charge state ion sources, the high performance results of the SCECR in it's High-B mode lead to another string of questions, as

were asked by Antaya and Gammino [Ant-94b]. Could the performance of the SCECR High-B mode be explained on the basis of current theoretical framework? Could the SCECR High-B mode be extended to higher frequencies, leading perhaps to even better source operation? What, if any is the effect of the frequency squared scaling law? And finally, did the frequency of operation play any role in the increasing ion density with higher frequencies, as observed by ion source researchers in several countries?

Antaya and Gammino do indeed explain the enhanced production of high charge states from the SCECR in its High-B mode with a conclusion that confinement of charged species (that is achieved through the higher mirror ratios) is the important factor in generating highly charged ions if other conditions like discharge pressure, gas mixing, etc. are tuned to optimal values. In particular, they reduce this enhanced high charge state production in the high field confinement to a simple " $\log(B_{max})$ " dependence of the average charge state being produced by the ion source. An obvious empirical method to test their hypotheses is to raise the frequency of operation of the SCECR, optimize the magnetic field geometry and other external parameters (pressure, power, etc.), and observe the operation of the SCECR in the High-B mode of that frequency of operation. There is a 14.4 GHz microwave generator at the NSCL. However, as mentioned earlier, the superconducting hexapole of the SCECR is unable at this stage to ramp up to generate magnetic field strength for 14.4 GHz operation of the SCECR, even with the normal (not High-B) magnetic configuration. Testing the theory, with the SCECR operation at 14.4 GHz was therefore not possible, and since few if any ECRIS anywhere in the world have the geometry or the flexibility in magnetic field configuration of the SCECR, it

seemed that unless the hexapole of the SCECR was redesigned with proper power leads, empirical proof (or lack thereof) of the frequency squared scaling law was to remain elusive.

10.3 The 2.45 GHz Operation of the SCECR

Rather interestingly, the ratio of 14.4 GHz to 6.4 GHz is 2.25, and the ratio of 6.4 GHz to 2.45 GHz is a close 2.61. So if the appropriate hardware could be designed, the 2.45 GHz microwave generator used for experiments on the MPDR 610 (both at the NSCL and at the EE labs) could also be used to launch microwaves into the SCECR. Instead of going UP in frequency and trying to attain higher performance, the magnetic fields of the SCECR could be scaled DOWN, and the ion source could be operated at a LOWER frequency.

If the frequency squared scaling law was to be valid, the 2.45 GHz excitation of the SCECR should not produce high charge state ions. As mentioned earlier, several high charge state ECRIS (using the “normal” magnetic mirror ratios) had been operated at lower frequencies (at Ganil, Oak Ridge National Laboratory and at Berkeley, for example) generally with poor results, which was squarely attributed to “lower frequency equals lower performance” argument. See, for example, Meyer’s comments on the 2.45 GHz performance of the Oak Ridge National Laboratory ECR ion source [Mey-85], where he blames the poor performance of the ECRIS at 2.45 GHz on the inability of the microwaves to penetrate the plasma at that frequency. Results of another effort, this time from Giessen, Germany to produce multiply charged species at 2.45 GHz have also been presented [Lie-92] at conferences, with similarly poor

results.

If, however, the experiments detailed in this chapter on the 2.45 GHz excitation of the SCECR in its High-B mode were to be successful, comparison of the results of operating the SCECR at 2.45 GHz (in the High-B mode for 2.45 GHz), vis-a-vis the High-B operation of the SCECR at 6.4 GHz (and also as compared to the performance of other high frequency high charge state ECRIS) could provide clues to not only the hypotheses presented by Antaya and Gammino in Reference Ant-94b, but also to the validity, or lack thereof of the frequency squared scaling law.

10.3.1 Experimental Hardware Description

To this effect, the SCECR was modified so that it is possible to launch microwaves at 2.45 GHz instead of the usual 6.4 GHz. Several "orders" of experimental designs of the new first stage were considered during the initial feasibility study, each order of design to be studied as time and necessity permitted. For the "zeroth order" (and most basic) design, every component on this new first stage that could be kept the same as the original first stage, was retained. With minimum modifications, the operation of the source could be aptly compared with that of the original source, and the differences then attributed not to the modifications to the first stage, but to the decreased operational frequency of the SCECR. Other "orders" of design included a coaxial end feed similar to that of the MPDR 610, impedance matching variable length antennae, and if possible, a side feed antenna as on the MPDR 5. This last option may be better studied on the room temperature source (RTECR) at the

NSCL, which has readily available radial ports since it does not need a cumbersome cryogenic system (that the SCECR requires for cooling the magnets to superconducting temperatures).

The fundamental premise was to inject microwave energy at 2.45 GHz into the SCECR in any way possible, and to generate a plasma at that frequency within the source, the next step being extraction of the various ions, and analyzing the outcome. A fortuitous "zeroth order" design that would provide the excellent preliminary results discussed below, and lack of development time on the SCECR (all experiments discussed here were performed in a span of four days), prevented testing of further designs to inject 2.45 GHz microwave into the SCECR. These designs therefore still remain to be studied at a later date. The description of this "zeroth order" modification to the SCECR, and more specifically to the first stage of the SCECR is now discussed.

The 8 inch Conflat flange on top of the SCECR is very crowded. There are feedthroughs for the two discharge gases (when super gas mixing techniques are used), water cooling for the first stage, the electrical feedthrough for the bias disc (which is actually a modification from a feedthrough for the 14.4 GHz waveguide), and for the microwave waveguide for the 6.4 GHz operation. The simplest, and possibly the best comparative method of 2.45 GHz microwave injection would be to replace the 6.4 GHz waveguide with a 2.45 GHz waveguide, keeping all other hardware the same as before. (More specifically, this would involve building a new first stage with the 2.45 GHz waveguide.) However with all the other gas, water and electrical feedthroughs on the top flange, it is impossible to fit a regular 2.45 GHz waveguide, whose cross-section outer dimensions are 7.6 cm by 3.8 cm. So based upon past experience (Chapter

Eight) the new first stage was designed with a half height 2.45 GHz waveguide feedthrough. This new first stage, retaining all aspects of the original first stage including the off-axis rectangular waveguide feed, is shown in Figure 10.1, and its design is discussed below.

As mentioned in Chapter Eight, the lowest order transverse electric mode that transports power through the rectangular waveguide (whose dimensions cut off all other transverse electric modes) is the TE_{10} mode, and this mode is not affected if the height of the waveguide is reduced. (Note, however, that if this height is made too small, the power density through the waveguide could increase to the point at which the metal might begin to warp, leading to power loss and related hardware failure. Additionally, there may be gas breakdown within the waveguide itself due to the high electric fields.) So the new first stage was constructed with the half height 2.45 GHz waveguide (WR284, with outer dimensions 7.6 cm by 2.1 cm) injecting microwaves into the main stage of the SCECR. Note that the WR284 is not exactly “half height” of the standard 2.45 GHz waveguide, but it was readily available commercially, with a height less than the regular waveguide, and it fit on the top flange with all other hardware (including the bias disc), which was kept similar to the original first stage.

Based upon the work of Chapter Eight, a full height to half height transition was designed and built. The theory of quarter wave transformers is given in Chapter Eight (see in particular Section 8.5, and Figure 8.4, Chapter Eight), and will not be repeated here. The quarter wave transformer used in this chapter is shown in Figure 10.2. A 0.125 inch (0.32 cm) thick Teflon plate sandwiched between the quarter wave transformer and the 8 inch Conflat flange provided the microwave transparent vacuum window (see Figure 10.1). Indium

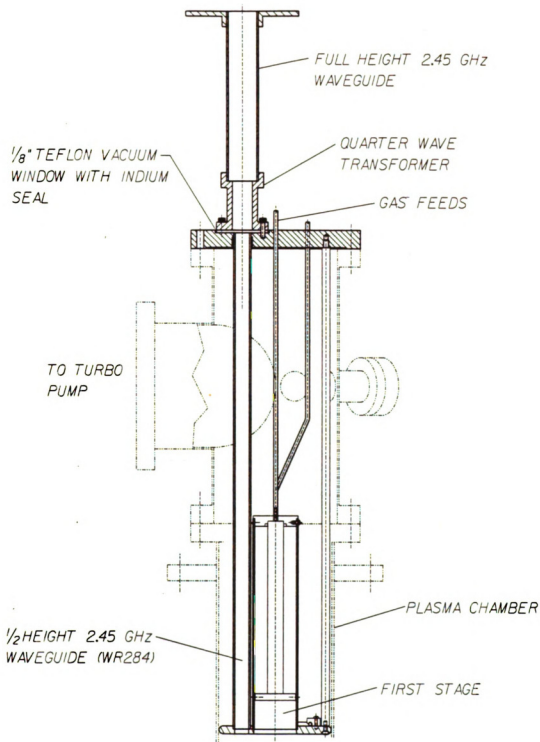


Figure 10.1 The modified first stage of the SCECR for 2.45 GHz operation

Note that compared to the original first stage, only the waveguide dimensions have changed. Also, the quarter wave transformer is bolted on top of the 8 inch flange, thereby creating the vacuum break using the 0.125 inch thick Teflon plate.

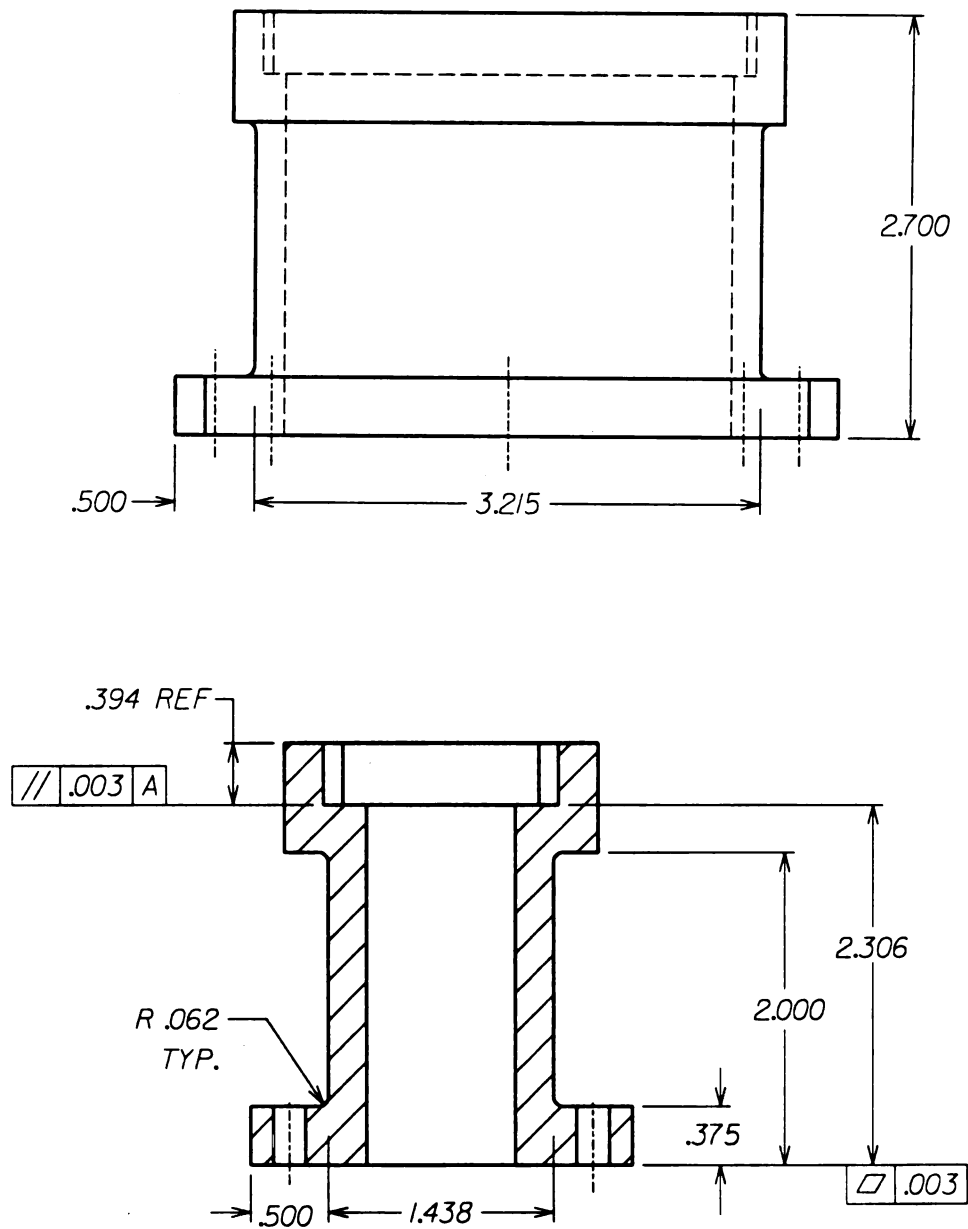


Figure 10.2 Front view (top) and side view (bottom) of the 2.45 GHz quarter wave transformer

This quarter wave transformer is based on theory discussed in Section 8.5 of Chapter Eight, and differs from the transformer used in that chapter (for 6.4 GHz operation) only in dimensions (given above in inches).

seals were used on both sides of the Teflon plate, and this vacuum break held successfully down to 10^{-7} Torr base pressure without the indium creeping into the waveguide. For regular 6.4 GHz operation, a specially designed commercially available (and expensive) mica or quartz vacuum break is used. Note that unlike the quarter wave transformer used in Chapter Eight (for the 6.4 GHz operation that is attached to the 6.4 GHz waveguide away from the 8 inch conflat), the transformer used here actually bolts on to the top 8 inch flange (as shown in Figure 10.1), using it and the half height waveguide below it as part of the step transition. As a matter of peripheral interest mentioned initially in Chapter Eight, it still remains to be seen whether a step transition, while easier to design and machine, has better - or worse - transmission of power compared to tapered waveguide transitions.

Above this quarter wave single step transformer is about 18 cm of the standard full height 2.45 GHz waveguide. A coaxial cable-to-waveguide adapter is secured on top of this, with a type N connector. Microwave power at 2.45 GHz is transported to this adapter (through the waveguide, and ultimately to the discharge) using the same coaxial cable as used for the MPDR 610. All the microwave apparatus is set up exactly as for the 610 high voltage beam extraction experiments - only the coaxial cable and part of the waveguide bi-directional coupler are raised to the SCECR high voltage. Use of the DC isolation joint on the cross-guide coupler (see Figure 8.5, Chapter Eight) allows the microwave power supply, the power meters and the circulator to be at ground potential. As before, this isolation joint is the main reason for using the cumbersome cross-guide bi-directional coupler (instead of the more compact coaxial couplers used for the 610 when no high voltage needs to be applied).

Note that the DC isolation is created by a Teflon plate sandwiched between two coaxial cable-to-waveguide adapters on the SCECR end of the bi-directional coupler and clamped down using G-10. As was mentioned in Chapter Eight there is some microwave leakage out of this joint, and so care must be taken when working near the equipment once the microwave power supply is operational. However, this microwave leakage is a near zone field, and attenuates to negligible levels within a few centimeters from the isolation joint, posing no health risks.

All operational parameters of the SCECR (like gas feed, discharge pressure, magnetic field intensities, etc.) are controlled remotely through Fermi stations, and other control software. For the 6.4 GHz operation, the microwave power supply is also remotely controlled. However for 2.45 GHz operation, the power supply had to be manually controlled. It is therefore fortuitous that the microwave power supply is at ground potential, allowing for safe switching of the microwave power levels even when the SCECR is at high voltage.

10.4 Operational Performance of the SCECR at 2.45 GHz

Operational performance of the SCECR at 2.45 GHz is now presented. Since these experiments lasted only a few days (a matter of hours if conditioning and outgassing times are subtracted), the results are presented on a chronological, day by day basis.

The High-B magnet configuration (given collectively in Eqn. 10.3) of the SCECR at 6.4 GHz was directly scaled down for the 2.45 GHz operation of the source. That is, the five coils and the hexapole currents were multiplied by 0.4,

which is the ratio of 6.4 to 2.45, such that the following magnet current configuration was reached:

Table 1: High-B Magnet current scaling for the 2.45 GHz operation of the SCECR

Magnet	6.4 GHz	2.45 GHz
SFST1I	37.4	15
SFST2I	13.66	5.5
SFST3I	1.1	0.44
SEXT1I	0	0
SEXT2I	21.4	8.6
SHEXI	75	30

In the table above, the first column represents the three first stage coils (SFST1I, SFST2I and SFST3I), the two extraction magnets (SEXT1I and SEXT2I), and the hexapole (SHEXI). The two other columns are the currents (in Amperes) carried by these coils (such that the SCECR is its High-B mode) for the operating frequency of 6.4 GHz, and also the scaled down currents for 2.45 GHz. The “normal” 2.45 GHz magnetic field configuration (scaled from the “normal” 6.4 GHz magnetic fields) is compared to the High-B magnetic field configuration in Figure 10.3. Note the higher mirror ratios for the High-B mode that maintain the axial confinement of charged species. In this chapter, several times from now data on the currents carried by these magnets will be presented. The order in which these currents are presented will be the same throughout, that is: SFST1,

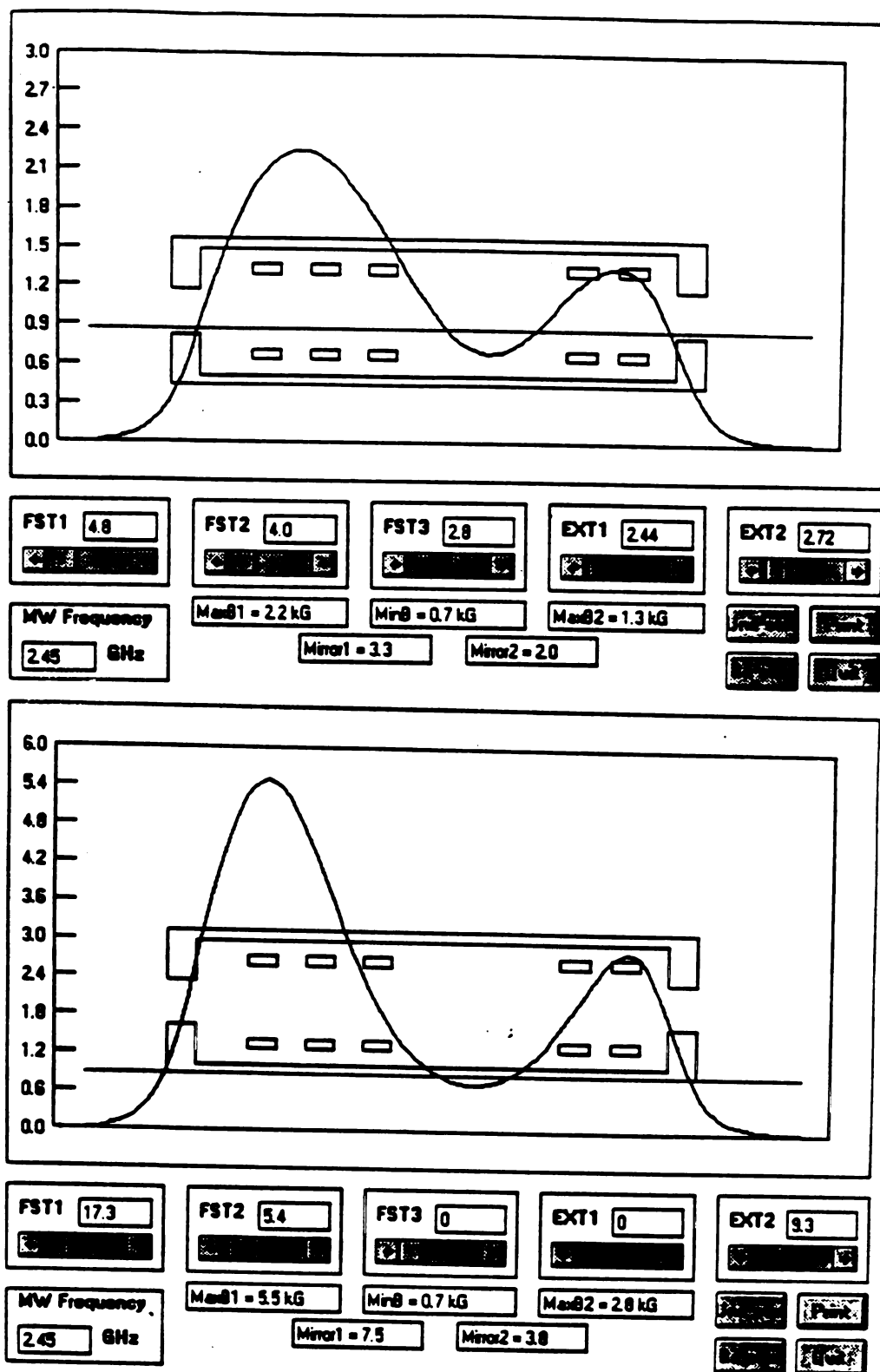


Figure 10.3 Comparison of the "normal" magnetic field (top), to the "High-B" field (bottom) at 2.45 GHz for the SCECR

Note the high mirror ratios at both ends of the SCECR that maintain axial confinement of charged particles. Also, the mirror ratio at the injection end (from the first stage) is higher than that at the extraction end.

SFST2, SFST3, SEXT1, SEXT2, SHEX.

High voltage tests were conducted on the SCECR by increasing its extraction bias to 10 kV and beyond. All the high voltage joints (like the Teflon break in the first stage) operated satisfactorily, and all the parts that would reach high voltage were caged off from inadvertent contact.

Once the vacuum seals between the new first stage and the main stage (especially the Teflon microwave window with indium seal between the quarter wave transformer and the 8 inch top flange) were satisfactorily established with base pressures of about 10^{-7} Torr, the microwave power source and support circuitry were assembled. As is standard with the SCECR operation, low power (about 30 W input, with less than 1 W reflected) was injected into the SCECR without any gas feed, and a plasma was formed in the source of residual gases. This is expected to help outgassing of condensed moisture and other hydrocarbons. Some near zone microwave leakage was observed from the DC isolation joint on the bi-directional coupler, and also from the coaxial cable to waveguide adapter above the regular 2.45 GHz waveguide. The former leak is inevitable, while the latter was fixed by tightening the adapter joint. In this configuration (30 W input, and less than 1 W reflected) the SCECR was allowed to outgas for some time.

10.4.1 Operational Performance - OXYGEN

After overnight conditioning, oxygen was leaked into the SCECR through the sapphire gas valve. At 60 W input, and with 15 W reflected, the first oxygen plasma at 2.45 GHz was ignited and easily sustained in the SCECR. At this

point, the pressure in the first stage was about 3×10^{-7} Torr, while the extraction region pressure was about 3.6×10^{-7} Torr. Preliminary results of this "new" source were already seen to "be better than the compact ECR ion source (CPECR at the NSCL)" [Ant-94c]. The first oxygen charge state distribution (CSD) of the SCECR operating at 2.45 GHz is seen in Figure 10.4, where the following should be noted: A high H^+ peak at $Q/M = 1$, and high peaks of H_2O , CO and other carbon charge states which indicate that the hydrocarbons have yet to outgas completely. More importantly, note the presence of several charge states of oxygen - O_2^+ , O^+ , O^{2+} , O^{3+} , O^{4+} and a minuscule amount of O^{5+} . The SCECR at 2.45 GHz is indeed a multiply charged state producer.

As the magnetic fields were tuned from their initial starting positions (given in Table 1) and the hydrocarbons burned off, the high charge states of oxygen became more prominent. At the end of the day's experiments, the O^{5+} current had risen to about 20 eμA. The SCECR was left to condition overnight at the low power and gas flow levels.

The following day, hydrocarbon peaks were lower and as a result of further outgassing, the operating pressure was lower also. This may be compensated for by addition of oxygen, or better, with some helium that would act as the ballast for "super gas mixing." As explained in Section 8.2 of Chapter Eight, this is a technique that enhances the production of high charge states by compensating the loss of energetic break-away electrons from the minimum-B magnetic field configuration with the lighter ions of the ballast gas (helium), thereby allowing longer confinement (and hence further ionization) of the heavier working gas - in this case oxygen.

Once helium was added to the plasma, the magnets were again tuned to

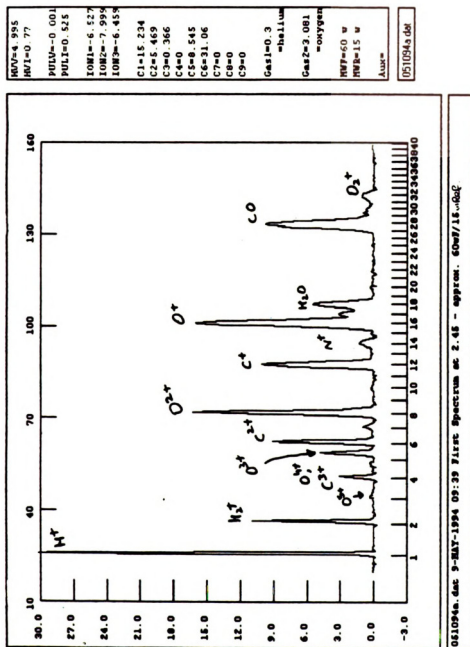


Figure 10.4. The first oxygen CSD from the 2.45 GHz SCECR
 The SCECR does indeed produce multiply charge states of oxygen, and corresponds to column (a) of Table 2 in this chapter. The data on the right indicates the coil currents (in amperes) at which this CSD was taken.

optimize the production of O^{5+} , and it was observed that the current for this charge state did indeed increase. The effects of tuning the SCECR (with magnet currents, and gas flow that controls the pressures) are significant, and are shown in Table 2 of oxygen charge state current production (in particle micro-amperes - μA) from the 2.45 GHz excitation of the SCECR. Different tunings correspond to minute changes in the solenoid and hexapole currents, discharge pressure (controlled through flow rates of the two gases), and extraction bias. Normally, the SCECR is "tuned" to a specific charge state, in this case to O^{5+} , and the result is seen in Table 2 where the 5+ current increases from column (a) - the first tune, to column (d), the final tune.

Table 2: Tuning effects on oxygen production from the 2.45 GHz SCECR

Oxygen charge state	(a)	(b)	(c)	(d)	RTECR at 6.4 GHz
7+	2	3.5	4.1	4.2	5.1
6+	36	46	58	56	52
5+	43	62	76	82	61
4+	-	-	260	290	87
3+	37	55	56	57	
2+	28	34	32	30	
1+	29	33	30	22	

Here, the second to sixth columns represent the currents (in μA) of individual charge states of oxygen at various tunes. Note that the current for the 4+ charge

state is ambiguous, being a combination of O^{4+} , He^{2+} and C^{3+} each of which has a Q/M ratio of 4. (The real O^{4+} current may only be found graphically, by extrapolating the 3+ and 5+ current levels to the expected 4+ current.) The currents of column (a) are the first results of the 2.45 GHz SCECR oxygen plasma, as plotted in the CSD of Figure 10.4. From columns (a) to (d in Table 2), the progression of further tuning and gas mixing is seen, whereby there is a gradual decrease in the low charge state production, while the high charge states increase. Data are taken with about 75 W input, 25 W reflected, and with pressure levels of 1.2×10^{-7} Torr in the first stage, and 2.4×10^{-7} Torr in the extraction stage.

As a comparison, the last column in the previous table is the oxygen production from the 6.4 GHz Room Temperature ECR ion source (RTECR) at the NSCL after over one year of optimization and tuning. Note that within two days, the SCECR at 2.45 GHz operation matches or exceeds the high charge state production from the RTECR.

A multiply charge state producing ion source may be tuned for enhancing the production of any one charge state. The above data on the SCECR are taken with the source tuned to the 5+ state, and the gradual increase in its current production, from 62, to 76 to 82 μA is evident. The final oxygen/helium charge state distribution is shown in Figure 10.5, and the comparative increase of high charge state currents (relative to the CSD of Figure 10.3) is obvious. The data on the right side of the CSD indicates the magnetic coil current settings, that at final tune are set (in Amperes) to 17.6, 5.4, 0, 0, 9, 40.7 (the SFST1, SFST2, SFST3, SEXT1, SEXT2 and SHEX magnets respectively). Compare these currents to the initial settings of the coils (15.23, 5.4, 0.36, 0, 8.5, 31.0

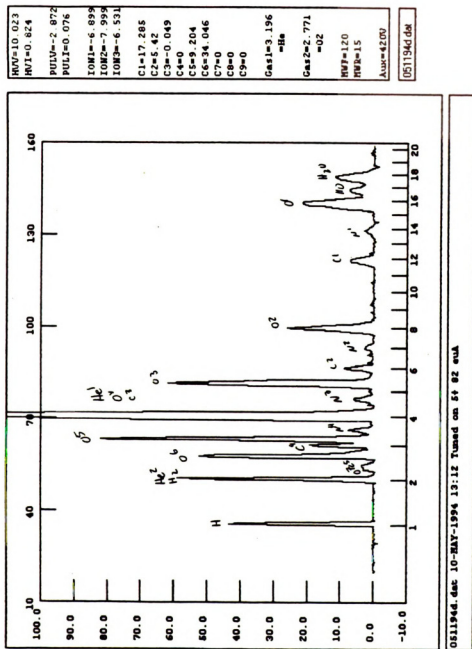


Figure 10.5 The final oxygen/helium CSD from the 2.45 GHz SCECR

This data corresponds to column (d) of Table 2 in this chapter. When compared to the CSD of Figure 10.4, the high charge states are seen to be enhanced, while the low charge states are depressed, as expected from a multiply charge state ECRIS.

Amperes) that were directly scaled down from the 6.4 GHz High-B fields. This change in coil current indicates active tuning and a dynamic response for enhancing the production of the 5+ charge state. Note that the coil currents will be different if the SCECR is tuned to optimize any other charge state.

10.4.2 Operational Performance - ARGON

Once the preliminary oxygen results were obtained, the helium valve was closed, and the gas then changed to argon, with oxygen now acting as the ballast. As may be seen from Figure 10.6, the initial charge state distribution immediately showed multiply ionized argon ions, corresponding to column (a) of Table 3 (on page 470). These data were taken with 100 W 2.45 GHz input power, about 20 W reflected. The first stage pressure was 1.43×10^{-7} Torr, while it was 3.77×10^{-7} Torr in the extraction region of the SCECR. Note that the microwave circulator being used limits the sum of the reflected and incident power to about 150 W, and therefore higher power tests could not be done using this setup. Once again, it is confirmed that the SCECR can produce multiply charged ions at 2.45 GHz operational frequency. At 10 kV extraction bias, the total drain current was about 0.40 mA. The magnet currents were as follows: 17.26, 5.40, 0, 0, 9.23, 34.45 Amperes. Within a few hours of operation and tuning, the Ar^{9+} ion beam was producing a current of about 44 e μ A. The SCECR was then left to condition in argon overnight.

By the next morning, further outgassing had resulted in lowering the pressure further, with the first stage at 1.18×10^{-7} Torr, and the extraction region pressure being 2.9×10^{-7} Torr. Several other CSDs were taken as the

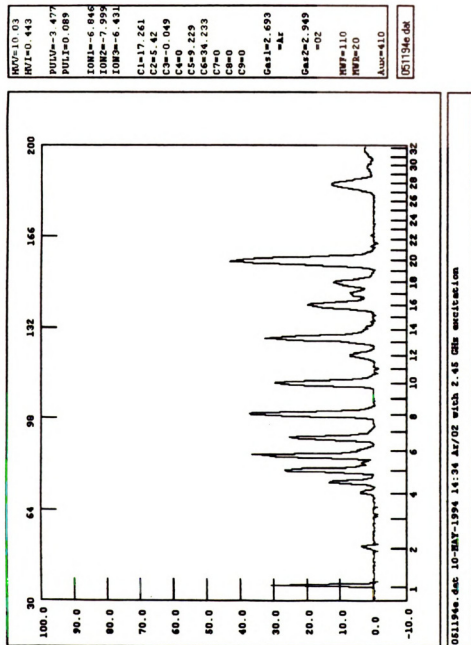


Figure 10.6 The first argon/oxygen CSD from the 2.45 GHz SCECR
 The SCECR also produce multiply charge states of argon, and corresponds to column (a) of Table 3 in this chapter. The data on the right indicates the coil currents (in amperes) at which this CSD was taken. Note that oxygen is the ballast.

SCECR was tuned to Ar^{8+} , which ultimately produced over 40 μA current, while the Ar^{11+} produced about 3.2 μA of current. Figure 10.7 shows the final argon/oxygen CSD corresponding to column (d) of Table 3 which shows the progression in argon charge state production as the SCECR is tuned over a period of less about 24 hours.

Table 3: Tuning effects on argon production from the 2.45 GHz SCECR

Argon charge state	(a)	(b)	(c)	(d)
13+	-	-	-	0.3
12+	-	-	-	-
11+	-	1	4	4.2
10+	3	18	15	22
9+	12	20.5	20	23
8+	27	42	34	36
7+	36.5	36	23	22
6+	25	30	16	15
5+	37	65	44	-
4+	30	21	10.5	10
3+	33	20	11	9
2+	42	24	14	11.5

The first column is the specific charge state of argon, while the other four columns are the currents (in μA) as the SCECR is tuned to the production of Ar^{8+} . Once again the low charge states (2+ and 3+) are depressed as the tuning

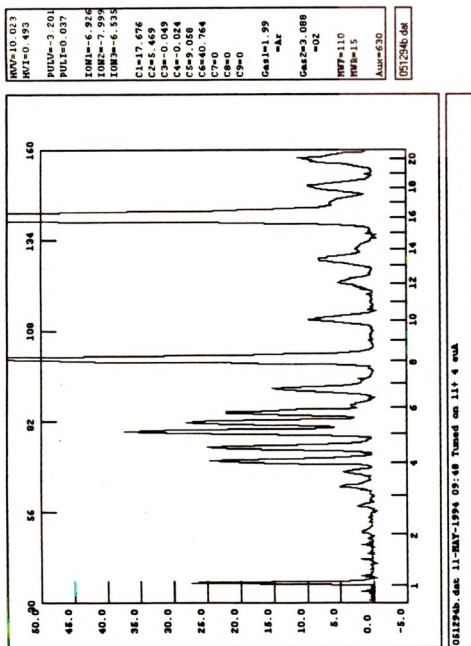


Figure 10.7 The final argon/oxygen CSD from the 2.45 GHz SCECR

This data corresponds to column (d) of Table3 in this chapter. When compared to the CSD of Figure 10.6, the high charge states are seen to be enhanced, while the low charge states are depressed, as expected from a multiply charge state ECRIS.

for high charge states gets better. Note that the 10+ charge state of argon (Q/M of 4) is a combination of Ar^{10+} and O^{4+} since oxygen is acting as the ballast gas in this experiment. The Ar^{10+} only current for the data corresponding to the fourth CSD (data column (d)) is about 10 μA , where this number is extrapolated graphically from the 9+ and 11+ current values. In Figure 10.7 once again, the final magnetic coil currents shown on the right hand side are seen to be different from the initial coil settings of Figure 10.6. Just like for the oxygen data, this indicates a dynamic tuning to optimize the production of a specific argon charge state.

At this juncture, loss of the focussing solenoid on the SCECR extraction system effectively shut down these experiments, since fixing the magnet power supply would have taken longer than the allotted time on the SCECR for these experiments. So while the design and development of new hardware for the first stage took several weeks to accomplish, the actual experiments lasted only three to four days. However, significant data were taken in these last few days that lead to some interesting conclusions, with positive future implications, which are discussed in the next two sections.

10.5 Discussion of Results

Figures 10.8 and 10.9 compare the current production (in particle micro-Amperes) of the SCECR at 2.45 GHz with that of four other ECRIS that operate at higher frequencies. These are the 10 GHz Minimaxios [Bou-86], the Berkeley ECR ion source at 6.4 GHz [Lyn-87], the Oakridge National Laboratory (ORNL) ECRIS operating at 10.6 GHz [Mey-86], and the 6.4 GHz NSCL room

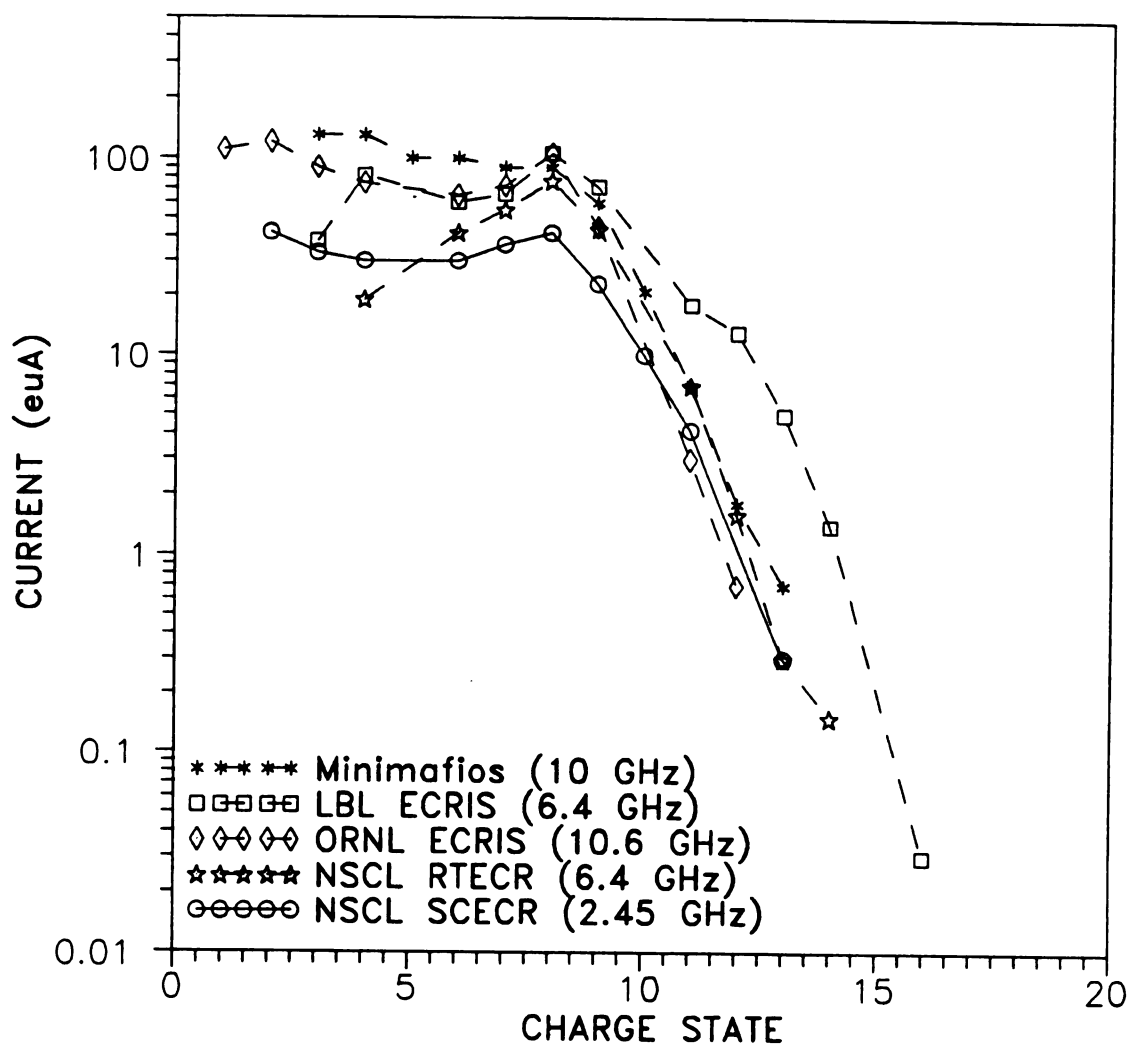


Figure 10.8 Comparison of current production (in eUA) of five ECRIS - argon
 The 2.45 GHz SCECR current production of argon charge states is compared to that of four other multiply charged ions producing ECRIS. Note that the 2.45 GHz operation of SCECR produces currents of the same order of magnitude, despite the lack of time for optimization of these experiments.

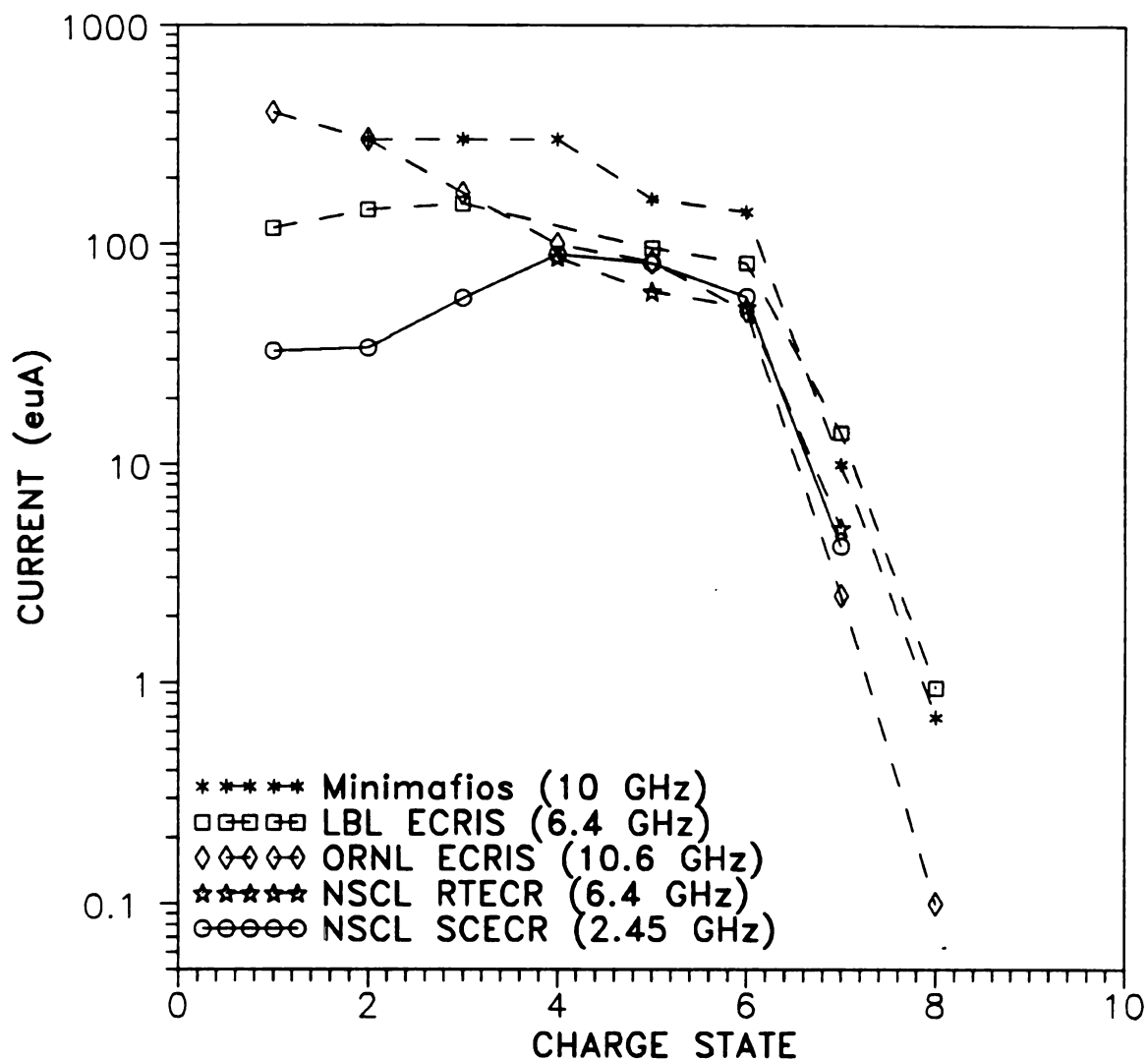
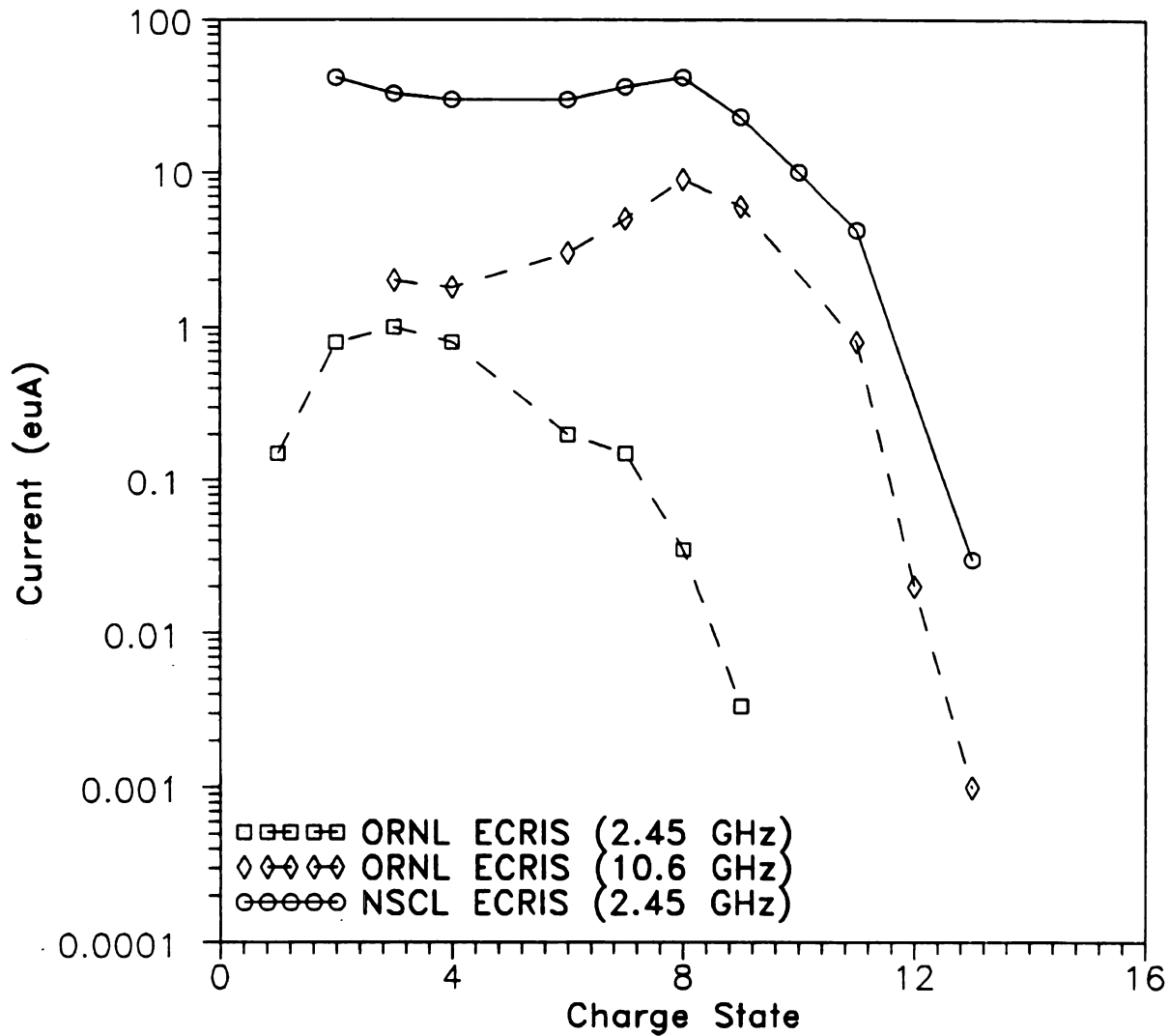


Figure 10.9 Comparison of currents (in eUA) of five ECRIS - oxygen

The 2.45 GHz SCECR current production of oxygen charge states is compared to that of four other multiply charged ions producing ECRIS. Note that the 2.45 GHz operation of SCECR produces currents of the same order of magnitude, despite the lack of time for optimization of these experiments.

temperature source RTECR [Ant-87]. Figure 10.8 compares the argon currents, while Figure 10.9 shows the oxygen currents. The object of these two figures is not for the 2.45 GHz SCECR performance to compete with that of the other sources, since the results of the SCECR operating at 2.45 GHz are preliminary and based on only four days of optimization, while the other sources have several years of tuning and optimization among them. More importantly, the 2.45 GHz performance of the SCECR is significantly lower than the High-B 6.4 GHz operational performance of the SCECR. However, Figures 10.8 and 10.9 demonstrate that 2.45 GHz is a very viable frequency for generating multiply charged ions - both figures clearly show that at this lower frequency, the SCECR has the same order of magnitude high charge state production as other higher frequency sources.

Figure 10.10 compares the 2.45 GHz performance of the SCECR with that of the ORNL ion source for an argon plasma, which was also studied for the production of high charge states at 2.45 GHz [Mey-85]. Both results (2.45 GHz and 10.6 GHz) for the ORNL ECRIS were simultaneously published in one paper, and the implication was thereby made that 2.45 GHz results were poor, therefore frequency squared scaling law had been validated. The lower frequency operation of the ORNL source is dramatically lower than its 10.6 GHz - which was then considered "proof" of the frequency squared scaling law. However, Figure 10.10 shows that the 2.45 GHz High-B mode SCECR results are better than the 10.6 GHz ORNL ECRIS results. More importantly, the shape of the curves for both the 10.6 GHz ORNL source, and the 2.45 GHz High-B SCECR are similar - indicating similar atomic physics interactions occurring in both the sources, and leading to similar order of magnitude production of high charge



**Figure 10.10 Comparison of the ORNL source at 2.45 GHz and 10.6 GHz.
with the SCECR at 2.45 GHz**

The SCECR 2.45 GHz operation clearly out performs the 2.45 GHz ORNL source operation. Note in particular the exact shape of the 10.6 GHz ORNL source data and the shape of the 2.45 GHz SCECR data.

states. Note that further optimization of the ORNL ECRIS led to somewhat higher currents, as evident from the ORNL data in Figure 10.8 (taken for this figure from Reference Mey-86).

There are some very real pay-offs to the experiments detailed in this chapter. These are discussed in the next two sub-sections, where some "problems" with conventional ECRIS are discussed, relative to the new ECRIS devised in this chapter - the modified SCECR operating in its High-B mode with 2.45 GHz excitation frequency. Interest in this new ECRIS is rising, both from academic and industrial laboratories.

10.5.1 Problems with Conventional ECRIS for Multiply Charged Ions

As mentioned in the introduction to this chapter, the "old method" of ECRIS design and development relies on the frequency squared scaling law to obtain intense multiply charged ion beams. Therefore, a typical ECRIS requires over \$200 000 capital costs, of which about a third is for microwave generation apparatus, a third for magnet design and construction, and the remaining for the mechanical structure design and construction [Ant-94c, Ant-95]. Specifically, the 6.4 GHz klystrons that power the high frequency microwave supplies are about \$60 000, and the 18 GHz klystron power supplies may cost up to \$1 000 000. These high frequency ion sources can also be very bulky due to the space requirements for high magnetic fields and klystron amplifiers. Beyond 20 GHz, the power available from the klystrons significantly decreases and even more expensive gyrotrons must be used for microwave power.

Note also that the magnetic field required for ECR heating is directly

proportional to the frequency of operation, so as this frequency is raised for higher density (based on the frequency squared scaling), the magnetic field strength for ECRH must also be raised. For example, the field strength required at 2.45 GHz is 875 Gauss, but jumps up to about 2300 Gauss for 6.4 GHz. Hence higher power coils are necessary to obtain the desired magnetic fields, or superconducting technology is utilized, leading to costs and maintenance of cryogenic systems.

There are some low frequency, low cost ion sources that produce "intense 1+ ion beams" (like the Chalk River ion source). These plasma sources produce about 0.1 mA to 1.0 mA of total extracted current, with 2+ ion current being much less than the 1+ current. The 3+ ion current is virtually zero. Many of these 1+ sources are arc discharges, based on electrodes protruding into the plasma. Hence they are sensitive to sputtering or chemical erosion that leads to reduced lifetime, and limits generation of some ion species.

10.5.2 Benefits of this "New Source"

The new type ion source developed in this chapter is a simple 2.45 GHz ECR ion source that produces significant currents of multiply charged ions without several costs associated with the higher frequency ECRIS. It is a low cost source, using an abundantly available 2.45 GHz magnetron based microwave supply (that may be obtained for as low as \$10 000 compared to the dollar figures quoted in Section 10.5.1). Compared to existing sources in the low frequency regimes, the currents of multiply charged ions generated in the SCECR discussed in this chapter are orders of magnitude higher in intensity.

There are no electrodes in the plasma, thereby no arcing or sputtering wears the source away. Other than lower intensities of current production (which may be increased by further testing and optimization), there is no difference between the performance of the SCECR at 2.45 GHz, from its performance at 6.4 GHz. Hence there should be no limitation on species generation - all ion species may be produced, including metallic ions through plasma assisted sputter feed.

Another obvious advantage of operating the SCECR at a lower frequency is the lower magnetic field requirements for both ECRH and confinement that not only reduce the power costs for the magnetic coils (room temperature, or superconducting), but may indeed be generated by permanent magnets, thereby eliminating completely the cost of magnet maintenance.

From a logistical point of view, the compact power supply for the 2.45 GHz magnetron is much easier to move, or place on a high voltage platform along with the source (as is done for the Argonne National Laboratory ECRIS) than the giant transmitters that generate the 10 GHz or higher fields. Also, there are potential cost savings from lower utilities, space requirements, air handling capacity, cooling, etc. for the low frequency magnetron based power supplies.

Several markets can potentially benefit from an ECRIS based on the 2.45 GHz excitation of the SCECR in its High-B mode. Since this new ECRIS would be small in size (compared to the klystron powered sources), with lower power consumption (tens to a hundred watts compared to the kilowatt range of power used in current ECR sources), and with minimal control apparatus due to its simple turn key design, the source may be sited at several locations where conventional multiply charged ion sources are prohibited because of their sizes. Examples of such sites are the terminal of a pre-accelerator, or a tandem

accelerator, at research and academic laboratories, or for medical accelerators (like the Harper Hospital medical cyclotron designed and maintained by the NSCL).

Due to the above mentioned advantages (small size, long lifetime, high current production, etc.), this potentially new ECRIS may find application in industrial ion implanters also. Typically these implanters have an ion source that produces low charge states (say 1+). The 1+ ions are then accelerated by biasing the extraction electrodes. However, the energy imparted to an ion is directly proportional to its charge state. So a 5+ ion would absorb five times the energy of a 1+ ion when travelling through the same potential difference. If the 5+ current produced by this new 2.45 GHz ion source is the same as the intensity of the 1+ conventional source currently being used, this leads to two possible situations. If $I_{\text{new}}(5+) \sim I_{\text{old}}(1+)$, where $I_{\text{new}}(x+)$ is the intensity of x+ ions (x is equal to 1, or 5 in the above "gedanken-experiment"), then,

$$E_{\text{new}} = 5 \times E_{\text{old}} \text{ for the same accelerating potential,}$$

where E_{new} is the energy imparted to the 5+ ions extracted from the new 2.45 GHz ion source, and E_{old} is the energy of the 1+ ions extracted from conventional ion sources in implanters for the same bias potential. As a corollary,

$$V_{\text{new}} = V_{\text{old}}/5,$$

that is, the voltage required to accelerate the 5+ ions from the new 2.45 GHz ion source to the same energy as the 1+ ions from conventional ion sources in

implanters is five times less.

It is clear from the above thought experiment that ion implanters may be made simpler and more efficient with the use of a new 2.45 GHz ion source similar to the one designed and tested in this chapter.

10.6 Concluding Remarks

A proof of principles test has been successfully conducted on the development of a new electron cyclotron resonance ion source for multiply charged ions, with no known technological show stoppers. This new source operates at a lower frequency of 2.45 GHz unlike other high charge state ion sources in the world that generally operate in the frequency range starting about 6 GHz, and up to 35 GHz. At this “microwave oven” frequency of 2.45 GHz, magnetrons are cheap and abundantly available, unlike the klystron and gyrotron based microwave supplies that may be several orders of magnitudes higher in price. Also due to this lower frequency of operation, the requirements on magnetic field strength for cyclotronic heating of electrons is reduced, leading to lesser costs for magnets design and development.

The design of such a source was followed up with several test runs at the NSCL, and while complete optimization studies have not been conducted, the operating parameters (gas flow, pressure, input power, etc.) for the generation of multiply charged ions have been identified and further optimization is considered straightforward. Results indicate that an ion source operating at 2.45 GHz is able to generate multiply charged ions as long as the appropriate magnetic configuration - through the High-B mode in this case is able to keep

the confinement time of charges species high enough for successive electron impact ionization to occur. While other trials on the operation of multiply charge state ECRIS at 2.45 GHz have been reported [Mey-85, Lie-92], this is the first time that the experiments have generated such high intensity of multiply charged ions. It has therefore been conclusively shown that contrary to "conventional wisdom," high charge states can indeed be produced at a lower frequency of excitation.

This "conventional wisdom" about frequency squared scaling to increase ion density (and hence increase high charge state production) from an ECR ion source has also been weakened. While the development of the High-B mode (Eqn. 10.3) for the 6.4 GHz operation of the SCECR was crucial to questioning the validity of this "law," results from this sub-study (2.45 GHz excitation of the SCECR) clearly indicate a need to re-evaluate the dependence on theoretical conclusions that are founded on excessively simplifying the problem to obtain closed form solutions - as in the case of the frequency squared scaling law.

Research detailed in this chapter has led to the filing of a US and international patent for such an ion source [Ant-95]. Under this patent, the following coverage is included:

(1.) A microwave injection system, inclusive of any technique of microwave energy transport and transmission into the vacuum vessel (like rectangular waveguides, coaxial cables, adjustable antennae, etc.) for all frequencies less than or equal to 5 GHz, and in particular for the prototype at 2.45 GHz.

(2.) For the prototype, an off-axis rectangular waveguide injection was used to transmit microwave energy at 2.45 GHz into the vacuum plasma vessel.

This waveguide system appears to be frequency scalable and is unique to this prototype. It has a vacuum window (made of specially constructed mica film, or of teflon, both of which are transparent to microwaves) such that part of the rectangular waveguide is under vacuum. To accommodate the waveguide at a lower frequency (the dimensions of the waveguide increase with decreasing frequency), a half height transformer, or a tapered transition may be used to reduce the height of the waveguide so that it fits on to the vacuum vessel.

(3.) An extraction system (generally with multiple electrodes biased to specific voltages) arranged so as to balance the space charge radial electric field. This produces a matched ion beam extraction system.

This patent, jointly filed by Antaya and Srivastava with Michigan State University is currently under review by the Office of Intellectual Property of MSU, with active participation of Babcock and Wilcox, an industrial partner in the patenting and possible licensing of this new source. As mentioned in the previous section, several branches of research may potentially benefit from this invention, and there is interest from several such quarters to continue research that has been merely started in this chapter.

Results presented here are preliminary. Further evaluation needs to be conducted on several fronts. More tests on oxygen and argon are needed with time to tune the source - specially with emphasis on increasing the high charge state production. While the 2.45 GHz High-B mode operation of the SCECR is able to produce high charge states, the intensities are much lower than the High-B mode operation of the SCECR at 6.4 GHz. This discrepancy needs to be explained, by something other than frequency squared scaling. An increase in confinement time to attain these high charge states may be reached either by

increasing magnetic confinement by raising the mirror ratios further, and/or by reducing the discharge pressure further. More aggressive gas mixing could also be tried to enhance high charge state production.

Further, emittance measurements need to be conducted on the extracted beams from the SCECR at 2.45 GHz. This would give an idea about the transportability, and space charge effects of such a beam, which are crucial for the ultimate acceptance of such an ion source into the entrenched environments of current ECRIS research.

An interesting recent development at the Lawrence Berkeley National Laboratory has been the use of dual frequencies (10 GHz and 14.4 GHz) for the operation of the AECR there [Xie-95]. A similar dual frequency test for the SCECR (2.45 GHz and 6.4 GHz) may be tried at the NSCL also.

Finally, other gases that are commonly used in ECRIS, like krypton, xenon, etc. also need to be tested in this new source at 2.45 GHz. Judging from the ease of operation with oxygen and argon, it is expected that high charge state production from such gases will not pose any problems. Production of metallic ions (through sputtering, or solid feed) that are also in demand at the accelerator facilities and need to be tested.

Chapter 11

Epilogue to a Dissertation

11.1 Introduction

11.2 Synopsis of the Results

11.3 Proposals for Future Research

Chapter 11

Epilogue to a dissertation

11.1 Introduction

In the past seven chapters, research spanning five years of experiments on electron cyclotron resonance ion sources (ECRIS) has been discussed. This research was conducted at two separate locations - the Electrical Engineering (EE) Plasma Sciences laboratory, and the National Superconducting Cyclotron Laboratory (NSCL), both at Michigan State University (MSU). Four different ion sources were studied - the MPDR 610, the 610- α , and the MPDR 5 - at the EE laboratory (operating at 2.45 GHz and 915 MHz), and the 6.4 GHz Superconducting ECR ion source called SCECR at the NSCL. Another two variations of the sources mentioned above - the hybrid 610+SCECR (operating at 2.45 GHz and 6.4 GHz respectively), and the SCECR operating at 2.45 GHz were studied. Also at the NSCL, research on the MPDR 610 (also referred through this dissertation as the 610) was conducted as a stand alone ion beam source.

The objective of this chapter is to bring an appropriate closure to this dissertation. The salient features of the sub-studies that constitute the chapters

are briefly reviewed in Section 11.2, along with the conclusions that were reached in that sub-study. Future experiments that might enhance the results of each chapter were proposed at the end of each chapter, and are reviewed in Section 11.3. It is expected that along with the introduction in Chapter One, this retrospective look at the results and proposed future experiments will provide a gist of this dissertation.

11.2 Synopsis of the Results

This dissertation is mainly experimental, although some theoretical analyses are presented to enhance the understanding of the experimental results. This theoretical formulation begins in Chapter One (Section 1.2) with a discussion of the phenomenon of power transfer (from the impressed electric fields to the plasma) through electron cyclotron resonance (ECR). This ECR technology is the underlying commonality between the various ion/plasma sources studied in this dissertation. While all the four main sources (and their variations) studied in this dissertation depend to some extent on ECR for coupling microwave power to the plasma, it became apparent from discussions of Section 1.2.2 that "pure" ECR may occur only under strictly limited discharge pressure and input power conditions. Most of the sources that were studied in this research (specially the EE sources) operate beyond these limits - at higher pressures, for example. Also, the output performance of these sources do not necessarily follow the predictions of ECR theory. Hence other power transfer techniques (like secondary harmonic resonance, stochastic heating, etc.) might be partially sustaining the plasma, and several such techniques are briefly

discussed in Section 1.2.2.

A black box model of a microwave ECR ion source was then presented in Section 1.3 detailing all the input parameters (like gas pressure, input power, etc.) and the expected output (ions, electrons, neutral gas, radical atomic species, meta-stable species, etc.). This was discussion important so as to lay a foundation for Chapter Two, that reviews 10 "compact" plasma/free radical sources. For this literature survey, a compact source was defined by its outer diameter being about 10 cm or less. While not exhaustive, this survey brought into focus some of the unique designs of plasma/ion/ion beam sources that are in operation today. Most of the sources discussed in Chapter Two are excited with microwave power (about 1 GHz up to 100 GHz), while some may operate at lower radio frequencies (specifically at 13.56 MHz). All sources described in this chapter are used as a source of neutral plasma, reactive radical species, ions, or ion beams - and all are used in the processing of substrates for the semiconductor industry. A significant omission from the discussion of these "compact" sources are those that are used to produce multiply charged heavy ions for injection into particle accelerators.

A prominent discussion of figures of merit that are used to characterize plasma sources is presented in Section 2.4. Different researchers evaluate their sources differently, using techniques that may often be wrong, or at the very least incomplete or inaccurately reported. It is imperative that a standardized method of source evaluation be formulated so as to make comparative studies like the one in Chapter Two more appropriate in terms of the measured data. With a variety of compact plasma sources that are available for commercial or research applications, it is important for the researchers to make a choice of the

source based on a comparative scientific evaluation.

Several such methods of evaluation were utilized to characterize the sources studied in this dissertation - Langmuir probes, multi-grid energy analyzers and micro-coaxial probes, for example. Since several different sources were studied using similar techniques, it was deemed appropriate to localize the discussion of all the characterization principles, and this is done in Chapter Three. Along with the exact methodologies for each technique, a theoretical background and limitations of the each method are also discussed. It was observed during the data acquisition for ion/electron energy distribution functions that the method was lengthy, labor intensive, and prone to human error. A radical new method of data acquisition for the electron and ion energy distributions based on numerical analysis of the data is proposed in Section 3.4 that does away with cumbersome peripheral circuitry (like a lock-in-amplifier) and completely automates the lengthy process of taking an electron/ion energy distribution function. While still prone to some errors, this method eliminates the human factor in these errors that normally creeps into the original method of energy analysis. This new method was never used to obtain the results presented in this dissertation. However, a feasibility study indicated that there are no technological show stoppers in incorporating this method into the battery of characterization principles currently in use to evaluate the EE sources.

The reason for limiting the literature review to compact plasma/ion/ion beam sources was that the plasma/ion source that has been the primary focus of studies in the past seven chapters is the MPDR 610 (microwave plasma disc reactor). This is a compact, ECR plasma/ion beam source that was designed and developed at the EE Plasma Science laboratories. The 610 has a coaxial

structure with a tunable resonant cavity that supports a propagating transverse electromagnetic (TEM) mode in the coaxial section. This allows the source to be smaller in diameter than the minimum that is required for transmitting the lowest order transverse electric or magnetic mode (the TE_{11}) mode. The source also has a variable length evanescent circular waveguide section whose length is varied to dynamically match the impedance of the coaxial structure with that of the plasma load. The MPDR 610 is commercially available through Wavemat, Inc. of Plymouth, Michigan. The source is described in detail in Chapter Four, along with the "Yorktown T" - the vacuum station on which a majority of the characterization of the EE sources was conducted.

The operational performance of the 610 in argon gas indicates that the source is capable of producing high ion densities (10^{11} cm^{-3}) at sub-mTorr pressures and with low input power (less than 200 W). Several unique features of the source are discussed in Chapter Four - like the two modes of operation: depending on external parameters, specifically input power and argon discharge pressure, the 610 may operate at a low density (10^9 to low 10^{10} cm^{-3}) mode if the discharge pressure is low, or at a high density (high 10^{10} to 10^{11} cm^{-3}) mode when the discharge pressure is raised. Evidence of hysteresis is observed as the source jumps abruptly between modes when the discharge pressure is varied. Indeed at certain pressures, the source may operate at any of the two modes depending on the initial pressure and input power conditions. The average electron temperature, measured a few cm downstream may be as high as 70,000 K in the low density mode; this temperature reduces to about 40,000 K for the high density mode in accordance with the inverse variance of electron temperature with discharge pressure. Downstream and radial density

distribution indicate typical ambipolar diffusion of charged species out of the source.

Most of the theoretical development of ECR, and other low pressure plasma analysis normally assumes that the electron energy distribution function (EEDF) is Maxwellian. It is seen from direct single Langmuir probe measurement of the argon EEDFs in Chapter Four that the EEDFs resemble the Druyvesteyn function more closely than the Maxwellian. That the EEDFs are non-Maxwellian is also evident from the double Langmuir probe I-V characteristics where the probe current continues to increase beyond a "saturation point" albeit with a smaller slope (in a perfectly Maxwellian system, the current should not increase beyond saturation for any further increase in potential). The ion energies have a narrow and peaked energy distribution also with average energies ranging from 20 eV to about 50 eV depending on the pressure and input power conditions, and may easily be controlled using pressure, power or substrate bias.

Theoretical calculations of electron temperature, ion density, etc. based on diffusion theory were conducted for a typical argon discharge in the 610. These calculated results matched well with the experimental data when these data (taken several cm downstream) were extrapolated into the discharge generation region. Such calculations may indeed be used as a guide for designing such ECR sources.

When the operating gas is changed to nitrogen, helium or oxygen, these discharges produce results that vary significantly from argon. For example, no other gas undergoes the discontinuous mode jump that is seen in argon. Also, argon exhibits a decrease in electron temperature and plasma potential with

increasing discharge pressure, in accordance with the diffusion of charged particles out of the source. However, for a nitrogen discharge, the electron temperature and plasma potential rise with increasing pressure. It is therefore clear that extrapolation of the operational performance of argon in the 610 to any other gas, specially to a diatomic gas may be inaccurate.

While the gas flow/pressure, gas type, input power were all varied in Chapter Four and the output of the 610 then studied, the frequency of operation for all experiments was maintained at a constant 2.45 GHz. As mentioned earlier, the TEM (or coaxial) nature of the source allows its diameter to be below cutoff for 2.45 GHz frequency of operation. This coaxial structure also allows the source to be operated at any microwave frequency, as long as the length of the center conductor may be adjusted to approximately $1/4\lambda$, or $3/4\lambda$ (where λ is the wavelength of the electromagnetic field at the frequency of operation). In Chapter Five, this frequency was reduced to 915 MHz, and the results of operating the 610 at this frequency were then compared with the results at 2.45 GHz. It was observed that argon ion density for both frequencies was the same order of magnitude (about 10^{10} to 10^{11} cm⁻³), and the discontinuous mode jump for an argon discharge is also exhibited at 915 MHz.

However, electron and ion energy distribution comparisons indicate several differences between the operation at the two frequencies. The average electron temperature at 915 MHz is relatively higher (about 10 to 12 eV) as compared to argon for the same pressure and input power conditions. Similarly, the average ion energies at 915 MHz, while still narrow and peaked, are also about twice those at 2.45 GHz. The variation of IEDFs with discharge pressure and input power is the same at both frequencies (that is, argon IEDFs shift

towards higher energies as input power is increased for the same pressure, or as discharge pressure decreases at the same power level). This suggests a difference in behavior between this compact source and other, larger MPDR sources - IEDFs do not vary as strongly with input power for the larger MPDRs, as they do for the 610.

The operation of an ECRIS may essentially be divided into three sections - the input variables (like power, gas type and discharge pressure, etc.), the output parameters (like ion density, electron temperatures, etc.), while in between these two known variables, are some internal parameters of the ion source that form the link between them. One such parameter is the structure of electromagnetic fields that are set up within the source. It is known that microwave power is transmitted at 2.45 GHz (or 915 MHz) through the cables and into the source, which then ignites the plasma whose output can be measured. However, it was only speculated that a TEM standing wave is set up in the coaxial section of the 610. This speculation may be put to rest by direct measurement of the calibrated electric fields (and the E-field patterns) using micro-coaxial probes inserted into small holes drilled in the wall of the source as described in Chapter Three. However, since the 610 is designed to be inserted up to half a meter inside a vacuum chamber, this electric field measurement on the MPDR 610 would be impossible.

A new source was designed and built to carry out this study, and this is detailed in Chapter Six. Known as the 610-*a*, the adapted 610 generates a plasma near the top of the vacuum chamber, leaving the body of the source out of vacuum for the micro-coaxial probe measurements. As much of the 610 design as possible was incorporated into the 610-*a*, so as to make possible the

inference of results from the 610-a to the 610. Indeed, the center conductor and sliding short assembly of the 610 was used interchangeably with the two sources.

Field pattern measurements on the 610-a confirm the presence of TEM standing waves in the coaxial section of the 610. The electric fields have strengths of up to 40 kV/m at the maximum of the standing wave. Several interesting features of the 610 also emerged. The discharge was expected to be sustained through evanescent waves in (and beyond) the impedance matching circular waveguide (that has a diameter less than cutoff for 2.45 GHz TE_{11} waveguide transmission mode). However, the presence of permanent magnets that are made of imperfectly conducting materials (samarium-cobalt) may contribute in the sustenance of this discharge by generating smaller standing waves in the discharge region of the source.

Precise field strength measurements for an argon discharge at the two modes of operation (high density and low density modes) were conducted. Experimental data shows that the electric field strength decreases with decreasing discharge pressure, indicating that loaded quality factor (proportional to the field strength) is also decreasing as pressure falls. This in turn means that the power coupling efficiency into the discharge is actually improving with decreasing pressure.

The calibration of the power measurements using micro-coaxial probes to the exact electric field strength relied upon a constant K_p , whose value was obtained from literature. It has recently been shown on another ECR source that by using the given K_p , the calibrated fields may be lower than the actual field strength on the inner wall of the source. This is currently being verified further

on a larger MPDR type source.

Plasma loaded and empty cavity measurements of the quality factor were performed, and were used to calculate the overall efficiency of the plasma source. Also, calibrated electric field measurements were used to calculate the amount of power loss to the walls of the coaxial section, and by approximating the power loss to the magnetic loop and in the circular waveguide section of the source, the net power lost during transport was calculated. Using this power loss information (and with the known amount of input power) another efficiency calculation may be done. These calculations imply that about 7% of the input power is lost to the magnetic coupling loop, and an additional 6% of the power is lost to the conducting walls of the source (included in these walls is the coaxial section and the evanescent circular waveguide sections). Hence, about 87% of the input power is transferred to the discharge. From this data, a simplified circuit model of the 610 emerged, and is discussed in Chapter Six, where lumped circuit elements represent the various sections of the source (like the coaxial section, the circular waveguide, etc.).

Once the preliminary evaluation studies were done on the 610, focus shifted briefly to another compact ECR source from the EE laboratories - the MPDR 5. This resonant cavity structure was designed and developed at MSU to resonate only at the TE_{111} mode standing waves. Electric field pattern experiments on the MPDR 5 using the micro-coaxial probes confirmed this TE_{111} electromagnetic mode that is set up in the microwave cavity structure. Some studies had already been conducted on evaluating its performance, including parts of an M.S. thesis and a Ph.D. dissertation. Several experiments had yet to be performed, however, and so this sub-study was undertaken. Prior

studies had indicated that the MPDR 5 was also capable of producing high density of ions (10^{11} cm^{-3}) at low pressures (mTorr range) for moderate input power (less than 200 W). The source has relatively uniform radial ion density distribution, in part due to the downstream multi-polar magnetic confinement chamber that was used to increase uniformity over large areas.

Also, previous ion energy analysis had indicated that while the IEDFs were narrow when the ion energy analyzer (IEA) was close to the discharge generation region, there was evidence of a low energy peak as the IEA moved downstream. This secondary peak became more prominent as the analyzer moved further away from the discharge generation region. This set of data had also been taken with the downstream magnetic confinement chamber, and it was speculated that the low energy secondary peak was due to charge exchange whereby an energetic ion may exchange its charge with a low energy neutral, creating high energy neutrals and a population of low energy ions.

Recent experiments on the MPDR 5 conducted for Chapter Seven did not use the downstream magnetic confinement chamber. Under these conditions, there was no evidence of a low energy peak as had been observed earlier, leading to a possibility that the low energy peak might have been an anomaly, or an effect of the downstream confinement chamber. However, some evidence of the formation of Ar^{2+} ions from this source has been found. As the argon discharge pressure decreased, there was a shift of the IEDFs towards higher energies, as expected because the electron temperature and plasma potential also increased at lower discharge pressure. However, as the pressure was lowered, a secondary peak at approximately twice the energy was observed. It is speculated that since the collision frequency decreases at lower pressures and the mean ion lifetime

increases, there might be sufficient ion confinement times to generate the 2+ species. It is known through experiments on the 610 (in Chapter Seven) that MPDRs are capable of producing 2+ ions. It seems that this is true for the MPDR 5 also, specially at low pressures.

As mentioned in the introduction of this chapter, there are ECR ion sources at the NSCL and several experiments of mutual benefit were identified by the two ion source research groups (EE and NSCL). Focus now shifts to these collaborative experiments. Chapter Eight describes one such test.

The ion sources at the NSCL are multiply charged sources producing highly charged ions for injection into either of the two particle accelerators. Such ECRIS are very different from the MPDRs at the EE laboratory. A brief introduction to multiply charged ECRIS is presented in Section 8.2, followed by a black box model of such a source. The Superconducting ECR Ion Source (SCECR) at the NSCL is then described in detail. It is a two stage source, with a collisional first stage, and a low operating pressure (about 10^{-7} Torr) main stage. The source is excited at 6.4 GHz. Multiply charged ions are generated in the main stage partly because of effective magnetic confinement of the charged species through the use of axial and radial confinement magnets, all of which are fully superconducting. While the importance of the first stage was known (removing it depressed the performance of the SCECR), the exact charged species that the first stage provided to the main stage was not well understood. The experiments of Chapter Eight incorporated the 610 as a replacement first stage, mounted on the SCECR, but DC isolated from it. By biasing the 610 relative to the SCECR, and observing the production of multiply charged ions, the precise charged species injected from the 610 into the main stage was

controlled, and its relationship to the better performance of the SCECR is now better understood.

Data indicates that the optimal high charge state production from the SCECR is obtained with negative bias on the 610 relative to the SCECR. This injects electrons from the collisional argon plasma of the 610 into the main stage of the SCECR - the main stage therefore desires low energy electrons from the first stage. This injection of cold electrons into the main stage of the source decreases the plasma potential, thereby enhancing ion lifetimes, and successive electron impact ionization that ultimately leads to production of multiply charged states.

During these experiments, the first stage pressure was too low for optimal performance of the 610 (10^{-5} Torr range), while the main stage pressure was too high for optimal performance of the SCECR (10^{-6} Torr range). Despite these inequities, however, the results of this study were clear. Other researchers had shown earlier that the multiple charge state production from ECRIS is enhanced by electron injection (in particular the AECS at Lawrence Berkeley Laboratory, where the first stage has been replaced by an electron gun). However, to date no conclusive study had been conducted that would allow for injection of positive, negative, or neutral particle injection from the first stage into the main stage (with positive, negative or floating bias on the first stage - the 610 in this case - respectively) using the same experimental apparatus.

With the 610 mounted on top of the SCECR, a crude "beam" of ions, or electrons (depending on the relative bias of the 610) could be extracted. With the SCECR off, the "beam" from the 610 was analyzed - the 610 produces about 95% Ar^{1+} , 5% Ar^{2+} and trace amounts of Ar^{3+} . Further beam extraction and

characterization from the 610 was also conducted, and this is detailed in Chapter Nine. Initial trials were conducted at a time when the SCECR and the K1200 cyclotron were down for maintenance, which freed up the beam line from the SCECR to the cyclotron for the 610 beam experiments. The 610 (with a throttling 1.5 cm diameter baffle plate) was mounted on the object box just below the SCECR extraction apparatus (that had been removed prior to these experiments), and a beam of argon plasma was extracted (with up to 10 kV bias), bent 90° by an analysis magnet (that also acts as a mass separator), and the current collected using a Faraday cup at the image box of the SCECR. Since the 610 in this sub-study is much closer to the collection apparatus, the beam currents were much higher than those observed in Chapter Eight.

The 95:5 ratio of 1+ to 2+ argon ions was confirmed in this stronger beam. Emittance measurements using the wire scanner method indicated a very high emittance (several hundred π mm-mRad), probably due to the large (1.5 cm diameter) extraction hole in the 610 baffle plate that acted as a plasma electrode, and also because the beam optics were precisely tuned to beam extraction from the SCECR, and not from the 610.

A series of still and video images of the beam extraction from the 610 were taken, and the photographs are presented in Chapter Nine. The still photographs dramatically show (for the first time, it is believed) the so called "meniscus effect" - the recession of the neutral plasma away from the accelerating electrode and into the plasma source as the bias potential is raised. This meniscus effect is discussed in Chapter Nine, whereby it was proposed that the meniscus is the neutral plasma boundary formed by high energy electrons. This, however leads to an interesting anomaly - according to this explanation,

the beam photographs indicate that the 610 produces electrons of up to 1 keV. Direct measurements of the electron energy done in Chapters Four and Five indicate that the average energy of electrons in the 610 is not much higher than 10 eV. Even though the beam extraction was conducted at lower pressures (where the electron temperatures are higher), the production of 1 keV electrons in the high energy tail of the distribution function by the 610 is improbable.

Beam development from the 610 continued after the SCECR and the K1200 came back on line. A stand alone vacuum station - the "test stand" was built for the continuing experiments. Also, the extraction apparatus was completely overhauled. Up to now, beam extraction was rather crude, with a plasma electrode (that also throttled the output of the 610) and a grounded baffle plate that acted as the accelerating electrode. The 610 was DC isolated, and hence positive bias on the source relative to the baffle plate allowed ion extraction and acceleration. For experiments on the test stand, a new intensity matched "quasi-Pierce" three electrode accel-decel configuration was designed and used, in which there were three electrode (the plasma, acceleration and deceleration electrodes). Beam definition out of the three electrode system was confirmed to be better than the two electrode system. Also, photographic evidence shows that the improved three electrode system allows for better control over the focussing of the beam, while maintaining a certain flexibility in the directed velocity (acceleration potential) of the beam.

In Chapter Ten, the focus of research shifted away from the 610 for the final time, and directly to the SCECR. The design of multiply charged ECRIS through the past two decades has been dominated in part by the so called "frequency squared scaling law." This law implies that the ion density generated

in an ECR ion source is directly proportional to the square of the frequency of operation. Hence, raising the frequency from 6.4 GHz, to 10 GHz, to 14 GHz and beyond had been the unwritten rule of source designers to enhance ion density (and thereby increase the production of high charge states). However in the "High-B" mode of operation of the SCECR at 6.4 GHz, the high charge state results were seen to be comparable to those from all other higher frequency (10 - 18 GHz) ECRIS in the world. This new mode uses a more aggressive confinement structure (with higher mirror ratios), and once the SCECR is optimally tuned, the production of high charge states is seen to be enhanced.

The best method of testing the "frequency squared scaling" would have been to raise the mirror ratios for operation at, say 14 GHz (magnetic confinement requirements, like the ECR requirements, scale with the frequency of operation). The SCECR could then be excited at 14.4 GHz, and the viability of both the High-B mode and the scaling law above could be tested. However, even though the SCECR is a variable frequency source with an operating frequency range from 6 GHz to 35 GHz, problems with the current leads of the hexapole severely restrict this range, and operation at 14.4 GHz even with normal (not High-B) mirrors is not possible.

Since the ratio of 6.4 to 14.4 is close to the ratio of 2.45 to 6.4, it was proposed that the frequency of operation be brought DOWN, and the SCECR be operated with the 2.45 GHz generator that was used for the 610 experiments at the NSCL. The hardware for injecting 2.45 GHz microwaves was relatively trivial to design and build. The results of these experiments were, however, far from trivial. Once the High-B mode was scaled down for operation at 2.45 GHz, it was observed that during the four days of testing, the SCECR at 2.45 GHz matched

the production of argon and oxygen ion currents from several higher frequency multiply charged ECRIS - the SCECR at 2.45 GHz is indeed capable of producing high charge state ions.

It has therefore been confirmed that 2.45 GHz is a viable frequency for the production of high charge states, a fact that had been overlooked to date due to the "frequency squared scaling" law. Since magnetron based 2.45 GHz power supplies are much more abundant and cheap (compared to the klystron and gyrotron based sources for higher frequencies), the overall cost of an aptly designed multiply charged ECRIS may be reduced. Also, at this frequency, the magnetic field requirements for both ECR and confinement are lowered, leading to lower power consumption on the current coils, and might even be eliminated if the appropriate field configuration is possible with permanent magnets. Finally, the logistical savings at 2.45 GHz in terms of space, utilities requirements, air handling capacity, water cooling, etc. may also be important factors. Overall, this feasibility study reduced the effectiveness of the scaling law. With interest from industry (specially from ion implantation machine designers), there is currently an ongoing patent procedure for the hardware involved in the 2.45 GHz excitation of the SCECR through the Office of Intellectual Property at MSU.

11.3 Proposals for Future Research

Of the eleven chapters that constitute this dissertation, seven are based on experimental work performed on four main ECR ion sources (and two variants of these sources). Each of the seven chapters has a section on

"concluding remarks," that summarizes the results of that sub-study, and also presents proposals for future research to further complete that sub-study. As was done for the results of each chapter in Section 11.2, it is the purpose of this section to concisely present some possible future experiments.

The EE ion sources (the MPDR 610, the 610- α and the MPDR 5) can all benefit from an enhanced battery of experimental techniques. In particular, future researchers must go beyond using Langmuir probes, energy analyzers and micro-coaxial probes. While these techniques provide important data, there are other characterization methods geared towards gathering information that the above mentioned techniques do not provide. For example, quartz crystal microbalance (QCM) analysis would provide information on the flux of radical oxygen (O), or radical hydrogen (H) species, both of which are important for semiconductor applications. In particular, the operation of the 610 at 915 MHz versus 2.45 GHz needs to be explained further. It is expected that the differences in the operation of the ion source at the two frequencies may generate different concentrations of these radical species.

Perhaps the simplest method of identifying the species in a plasma is through optical emission spectroscopy (OES). Using the spectra obtained with the help of an optical fiber and a spectrometer, the peaks may be identified using commonly available tables of spectroscopic data. An enhanced method would use Fabry-Perot interferometry in conjunction with OES to further increase the resolution of a particular peak, and could be used to calculate the full width at half maximum (FWHM) of the peak. This data may be used to provide information on the temperature of neutral particles that are normally difficult to characterize since they lack charge and cannot be manipulated using bias

potentials.

Laser induced fluorescence (LIF) may be used to study the meta-stable states within the plasma discharge. This is, unfortunately an extremely complicated and time consuming technique, and during the course of this dissertation, attempts were made to perform LIF on the 610 without much success. However, the neutral species' signal strength (as compared to the noise) from the 610 was probably not high enough, and time was a constraining factor when these experiments were attempted.

One of the conclusions of Chapter Four was that argon data may not be used to extrapolate information regarding other gases like nitrogen, hydrogen, or oxygen. There are fundamental differences between the performance of the 610 in argon, and for the other diatomic gases. It is very important that the more useful gases (like nitrogen) be studied separately so as to provide a base of data for the end users of the 610. For example, a nitrogen or oxygen plasma at 915 MHz needs to be characterized to see how the source operation differs for nitrogen with its performance at 2.45 GHz.

To complete the sub-study of Chapter Five (the 915 MHz operation of the 610), single Langmuir probe data for argon needs to be taken where electron energy measurements have been reported using double Langmuir probes. DLPs are normally not as accurate when predicting electron temperatures as SLPs are, since the latter directly measure electron energy distribution functions, and calculate the average energy based on the EEDF. The DLPs on the other hand sample only the high energy tail of the EEDF, and assuming a Maxwellian distribution (an assumption that is not always valid), provide data on the average electron energies.

Also in Chapter Four, it was observed that the 610 has two modes of operation - the high density (at high pressure) mode and the low density (at low pressure) mode. This discontinuous jump has been observed in other larger ECR sources also, and more work needs to be done to understand this further. Why, for example is there no evidence of this mode jump for diatomic gases?

Preliminary beam extraction has been conducted on both the MPDR 5 and the MPDR 610. While the MPDR 5 extraction apparatus consisted of multi-aperture graphite grids, the extraction from the 610 used a single centralized aperture on both the electrodes. Even the more advanced three electrode "quasi-Pierce" system for the 610 used a single aperture (1.0 cm diameter). A specialized single aperture extraction system for the MPDR 5 needs to be designed and studied. For the 610, emittance and charge state distribution data for the two electrode system were taken, but not for the three electrode apparatus - this needs to be done. Also, there is some interest in using the 610 as an ion beam source producing alpha particles (He^{2+}) and other high energy physics applications, if its emittance may be reduced from its current high levels. This feasibility needs to be studied.

While studying the meniscus effects of the beam development from the MPDR 610, certain anomalies were encountered - like the possibility of creating 1 keV electrons in the 610, or the dependence of the meniscus effect on the separation between the plasma and acceleration electrodes. These need to be studied further.

When the 610 was mounted on the SCECR for the "610+SCECR" hybrid source experiments, good preliminary results were obtained. However, several problems were targeted for future research. The output of the 610 was about 30

cm from the baffle plate that separates the normal first stage of the SCECR from the main stage - this distance needs to be shortened to ensure a higher degree of coupling between the two sources. The issue of too high a pressure for the main stage, but too low a pressure for the 610 needs to be resolved, perhaps by better differential pumping. Also, a more precise beam extraction apparatus - like the three electrode system used in Chapter Nine - should be used to aggressively inject positive, negative or neutral beam into the main stage of the SCECR.

Finally, the preliminary results of Chapter Ten (the 2.45 GHz excitation of the SCECR) need to be studied further. Operation at 2.45 GHz with gases other than oxygen and argon - like krypton, xenon etc. that are normally used for cyclotron injection need to be studied. Recent developments on the AECS at the Lawrence Berkeley National Laboratory utilize multiple frequency excitation of the AECS with interesting results. This may be attempted on the SCECR with 2.45 GHz and 6.4 GHz injection. Gas mixing, silane conditioning, aluminum liners, and other techniques like solid feed or sputtering of metallic ions commonly used for the SCECR need to be studied to ensure that 2.45 GHz is indeed a viable frequency for operating a multiply charge state ECRIS.

Despite all the work presented in Chapters Four through Ten, and all research that was conducted on the ECR ion sources prior to this effort, experimental work is never quite finished. There is always more to learn in any particular field of study, and just as surely, there will always be eager researchers to follow in the footsteps. It is expected that Section 11.2 would provide a rich field of ideas for starting researchers to exploit, thereby ensuring continued growth of knowledge on ECR ion sources.

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