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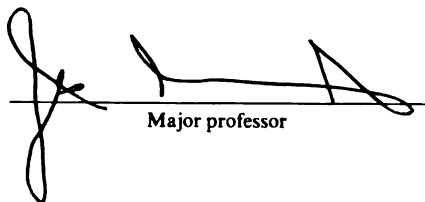
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Mark Alan Perrin

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**INVESTIGATION OF A 17.8 CM DIAMETER END FEED MICROWAVE  
CAVITY PLASMA SOURCE WITH AND WITHOUT A STATIC  
MAGNETIC FIELD**

**VOLUME I**

By

Mark Alan Perrin

**A DISSERTATION**

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## ABSTRACT

### **INVESTIGATION OF A 17.8 CM DIAMETER END FEED MICROWAVE CAVITY PLASMA SOURCE WITH AND WITHOUT A STATIC MAGNETIC FIELD**

By

Mark Alan Perrin

In the early years of the microelectronics revolution (1970's and 80's) most experimental low pressure microwave plasma sources used for etching included some form of electromagnet or permanent magnet. The purpose of the magnetic field was to sustain the plasma at lower pressures through ECR heating. However, the last decade has seen increased interest in non-magnetized, low pressure microwave plasma sources. The purpose of this dissertation is to understand some of the conditions for which static magnetic fields are a benefit or a detriment to plasma source performance. To provide this understanding the performance of a specific microwave plasma source that is able to operate both with and without a static magnetic field is investigated.

The performance of a 17.8 cm diameter, end feed, microwave cavity plasma source, with 13 cm diameter discharge was characterized with and without multipolar magnets. Conclusions were drawn about the influence of magnets at pressures between 1 and 45 mtorr. Comparisons were made between magnet and non-magnet discharges using measured: electron densities, electron temperatures, electron energy distributions, discharge wall temperatures, microwave coupling efficiencies, and ion production costs for a range of the input variables, such as, absorbed power and discharge pressure. These measurements were also compared to the global plasma model predictions.

Findings demonstrated that for a range of pressures from 10 to 45 mTorr the non-magnetized discharge had on the order of 2 times the charge density output as the magnetized source. Subsequent investigations explained this finding and indicated that the charged species were more readily lost to the discharge walls with multipolar magnets at higher pressures.

The multipolar magnetic field does have some advantages. The discharge could be maintained at less than 1 mTorr with magnetic fields present, but only down to approximately 4 mTorr without magnetic fields. Hence, a static magnetic field is required for very low pressure operation. The presence of a magnetic field also makes the source easier to ignite at both low and high pressures. Differences in electron energy distribution function (EEDF) have been observed. EEDFs appear to have a depleted high energy tail when multipolar magnets are present. The EEDF for the non-magnetic field case is consistently Maxwellian. The implications of these findings for future microwave plasma source designs are discussed.

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2002

Dedicated to my parents

ALAN D. PERRIN and LOUISE A. PERRIN

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## TABLE OF CONTENTS

|                      |      |
|----------------------|------|
| LIST OF TABLES ..... | xiii |
|----------------------|------|

|                       |     |
|-----------------------|-----|
| LIST OF FIGURES ..... | xiv |
|-----------------------|-----|

### Chapter 1 Introduction

|                                                    |   |
|----------------------------------------------------|---|
| 1.1 Introduction and Motivation for Research ..... | 2 |
| 1.2 Research Objectives .....                      | 4 |
| 1.3 Summary of this Dissertation .....             | 5 |

### Chapter 2 Literature Review: A Review of Recent Non-Magnetized Low Pressure Microwave Sources

|                                                                                 |    |
|---------------------------------------------------------------------------------|----|
| 2.1 Background: Early Non-magnetized Microwave Discharges .....                 | 7  |
| 2.2 Large Area Dielectric Slab Sources .....                                    | 11 |
| 2.2.1 A Waveguide Excited Planar Surface Wave Plasma Device. ....               | 12 |
| 2.2.2 An End-Feed-Cavity Excited Dielectric Slab Source. ....                   | 15 |
| 2.2.3 The Concentric Spread Plasma Source. ....                                 | 17 |
| 2.2.4 A Microwave Plasma Device with High-Permittivity Material<br>Window. .... | 20 |
| 2.3 Large Tube Surface Wave Plasma Source (Okamoto Cavity). ....                | 22 |
| 2.4 The Distributed Element Microwave Plasma Source. ....                       | 24 |
| 2.5 Conclusion. ....                                                            | 26 |

### Chapter 3 The Experimental System

|                                                        |    |
|--------------------------------------------------------|----|
| 3.1 Introduction .....                                 | 28 |
| 3.2 System Overview .....                              | 29 |
| 3.3 The Plasma Source .....                            | 30 |
| 3.4 The (500 W Capacity) Microwave Power Supply .....  | 33 |
| 3.5 The (1500 W Capacity) Microwave Power Supply ..... | 34 |
| 3.6 The Gas Delivery and Vacuum Systems. ....          | 35 |

Chapter 4  
The Multivariable Plasma Reactor

|                                           |    |
|-------------------------------------------|----|
| 4.1 The Input/Output Model .....          | 39 |
| 4.2 Specific Experimental Variables ..... | 41 |
| 4.3 Input Variables .....                 | 41 |
| 4.4 Internal Variables .....              | 43 |
| 4.5 Output Variables .....                | 44 |

Chapter 5  
Single Langmuir Probe Construction and Experimental Techniques

|                                                                       |    |
|-----------------------------------------------------------------------|----|
| 5.1 Introduction .....                                                | 51 |
| 5.2 The Single Langmuir Probe .....                                   | 51 |
| 5.2.1 Construction of the Single Langmuir Probe .....                 | 52 |
| 5.2.2 Theory of the SLP .....                                         | 55 |
| 5.2.3 Measurement of $d^2I/dV^2$ with a Lock-in Amplifier (LIA) ..... | 59 |
| 5.2.4 Description of the measurement circuit .....                    | 63 |
| 5.2.5 Measurement Procedure and Program Flow .....                    | 66 |
| 5.2.5 Resistive Deposition Layers and Cleaning .....                  | 69 |
| 5.2.6 Problems with variable AC and DC resistance of the SLP .....    | 70 |

Chapter 6:  
The Global Plasma Model

|                                                                                                    |     |
|----------------------------------------------------------------------------------------------------|-----|
| 6.1 Introduction .....                                                                             | 73  |
| 6.1.1 General Derivation and Assumptions of the Global Model .....                                 | 73  |
| 6.1.2 Global Model Pressure Regimes .....                                                          | 81  |
| 6.2 Particle Conservation Solutions: Density Profiles and Electron<br>Temperatures .....           | 83  |
| 6.2.1 High Pressure Discharges: The Sheathless Case .....                                          | 83  |
| 6.2.1.1 Charge Density Profile and Diffusion Length for the<br>One Dimensional Slab Geometry ..... | 85  |
| 6.2.1.2 Charge Density Profile and Diffusion Length for the<br>Cylindrical Geometry .....          | 87  |
| 6.2.1.3 Solutions to the Particle Conservation Equation .....                                      | 89  |
| 6.2.2 Adding the Sheath to the High Pressure Discharge .....                                       | 94  |
| 6.2.3 Low and Intermediate Pressure Discharges .....                                               | 99  |
| 6.2.3.1 Charge Density Profiles .....                                                              | 99  |
| 6.2.3.2 Solutions to the Particle Conservation Equation .....                                      | 104 |

|                                                                        |     |
|------------------------------------------------------------------------|-----|
| 6.3 Power Balance. ....                                                | 108 |
| 6.3.1 Energy Flux in the Plasma Discharge. ....                        | 109 |
| 6.3.2 The Electron Subgas. ....                                        | 110 |
| 6.3.3 Electron Energy Absorption Processes. ....                       | 111 |
| 6.3.2.1 Ohmic Heating. ....                                            | 112 |
| 6.3.2.2 Electron Cyclotron Resonance Heating ....                      | 114 |
| 6.3.2.3 Stochastic Heating. ....                                       | 115 |
| 6.3.4 Electron Energy Loss Processes. ....                             | 119 |
| 6.3.5 Power Balance for Nonuniform High Pressure Discharges. ....      | 125 |
| 6.3.6 Power Balance for Low and Intermediate Pressure Discharges. .... | 128 |
| 6.4 Plasma Source Performance Figures of Merit. ....                   | 130 |
| 6.4.1 General Plasma Source Efficiency. ....                           | 130 |
| 6.4.2 Ion Production Energy Cost. ....                                 | 132 |
| 6.4.3 Average Discharge Power Density. ....                            | 135 |
| 6.5 Conclusion. ....                                                   | 136 |

## Chapter 7

### Electron Temperature Measurements

|                                                                                                         |     |
|---------------------------------------------------------------------------------------------------------|-----|
| 7.1 Introduction. ....                                                                                  | 138 |
| 7.2 Global Model and Electron Distribution Functions. ....                                              | 139 |
| 7.2.1 The Global Model Calculation of Electron Temperature. ....                                        | 139 |
| 7.2.2 Electron Energy Distribution Functions. ....                                                      | 140 |
| 7.3 SLP measurements at the Base of the Discharge ( $r=0, z=0$ ). ....                                  | 144 |
| 7.3.1 EEDFs of Non-magnetized & Magnetized Discharges at<br>Several Pressures. ....                     | 144 |
| 7.3.2 Electron Temperatures vs. Discharge Pressure ....                                                 | 160 |
| 7.3.2.1 Comparison of $T_e$ between Magnetized and<br>Non-Magnetized Configurations. ....               | 160 |
| 7.3.2.2 Comparison of Measured Electron Temperatures<br>to Global Model Predictions. ....               | 160 |
| 7.3.3 Study of $T_e$ dependence on EM Excitation Intensity and<br>Mode Type. ....                       | 162 |
| 7.3.3.1 Influence of Pabs on $T_e$ for the Non-magnetized<br>$TM_{012}$ Mode. ....                      | 162 |
| 7.3.3.2 Comparison of $T_e$ between EM modes in a<br>Non-magnetized Discharge. ....                     | 163 |
| 7.3.4 Comparison of Plasma Potential, $V_p$ , between Magnetized<br>and Non-magnetized Discharges. .... | 165 |

|                                                                                                         |     |
|---------------------------------------------------------------------------------------------------------|-----|
| 7.4 Variation of EEDF with distance into discharge (z). . . . .                                         | 168 |
| 7.4.1 EEDF and $T_e$ vs. Distance into the Chamber for the<br>Non-magnetized Discharge. . . . .         | 169 |
| 7.4.1.1 EEDF vs. Distance into the Non-magnetized Discharge<br>Chamber. . . . .                         | 169 |
| 7.4.1.2 Electron Temperature, $T_e$ , vs. Distance up into the<br>Discharge Chamber. . . . .            | 176 |
| 7.4.1.3 Plasma Potential, $V_p$ , vs. Distance up into the Discharge<br>Chamber. . . . .                | 178 |
| 7.4.2 EEDF and $T_e$ vs. Distance into the Chamber for the Magnetized<br>Discharge. . . . .             | 180 |
| 7.4.2.1 EEDF vs. Distance into the Magnetized Discharge Chamber. .                                      | 180 |
| 7.4.2.2 Electron Temperature, $T_e$ , vs. Distance up into the<br>Magnetized Discharge Chamber. . . . . | 190 |
| 7.4.2.3 Plasma Potential, $V_p$ , vs. Distance up into the Magnetized<br>Discharge Chamber. . . . .     | 192 |
| 7.5 Summary of Findings. . . . .                                                                        | 194 |
| 7.5.1 Findings from measurements at $z=0$ (i.e. base of the discharge). . . . .                         | 194 |
| 7.5.2 Findings from measurements vs. $z$ into the discharge. . . . .                                    | 195 |

## Chapter 8

### Measured Charge Density and Ion Production Cost

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| 8.1 Introduction. . . . .                                                                  | 198 |
| 8.2 The Experimental Configuration and the Experimental Parameter Space. . . . .           | 198 |
| 8.3 Global Model Calculations; A Benchmark for Experimental Measurements. . . . .          | 201 |
| 8.3.1 The Cylindrical Discharge Model. . . . .                                             | 201 |
| 8.3.2 The Open Ended Cylindrical Discharge Model. . . . .                                  | 208 |
| 8.4 Electron Density Measurements. . . . .                                                 | 214 |
| 8.4.1 Experimental Electron Density Measurements. . . . .                                  | 214 |
| 8.4.2 Comparison of Electron Densities Between $TM_{012}$ and<br>Near Field Modes. . . . . | 223 |
| 8.4.3 Comparison of Charge Density Between Magnetized and<br>Non-magnetized Cases. . . . . | 224 |
| 8.4.4 Comparison to the Global Model. . . . .                                              | 228 |
| 8.5 Electron Density Measurements Under the Conditions of High Incident Power. . .         | 233 |
| 8.6 Radial Profiles of Charge Density and Relative Ion Saturation Current. . . . .         | 239 |
| 8.6.1 The Radial Distribution of Electron/Ion Density. . . . .                             | 240 |
| 8.6.2 Comparison Between Magnetized and Non-Magnetized<br>Configurations. . . . .          | 241 |
| 8.6.3 Comparison Between $TM_{012}$ and Near Field Modes. . . . .                          | 245 |
| 8.7 Axial Variation of $I_j$ Measurements. . . . .                                         | 246 |
| 8.7.1 Observations from Axial $I_j$ measurements. . . . .                                  | 247 |
| 8.8 Skin Depth of The Plasma. . . . .                                                      | 256 |

|                                                                                           |     |
|-------------------------------------------------------------------------------------------|-----|
| 8.9 Visual Images of the Plasma Discharge. . . . .                                        | 260 |
| 8.10 Ion Production Cost. . . . .                                                         | 264 |
| 8.10.1 Experimental Measurement of Ion Production Cost. . . . .                           | 265 |
| 8.10.2 Comparison of Measured Ion Production Cost vs.<br>Global Model Prediction. . . . . | 266 |
| 8.11 Summary of Findings. . . . .                                                         | 268 |
| 8.11.1 Findings from Charge Density Measurements at ( $r=0$ , $z=0$ ). . . . .            | 268 |
| 8.11.2 Findings from Radial and Axial Charge Density Measurements. . . . .                | 269 |

## Chapter 9

### Measured Quartz Wall Temperatures

|                                                                 |     |
|-----------------------------------------------------------------|-----|
| 9.1 Introduction. . . . .                                       | 273 |
| 9.2 Experimental Equipment and Setup. . . . .                   | 274 |
| 9.3 Experimental Quartz Wall Temperature Measurements. . . . .  | 276 |
| 9.3.1 Quartz Wall Temperature vs. Time. . . . .                 | 276 |
| 9.3.2 Quartz Wall Temperature vs. Power. . . . .                | 278 |
| 9.3.3 Quartz Wall Temperature vs. Pressure. . . . .             | 278 |
| 9.4 Analysis of the Temperature Measurements. . . . .           | 282 |
| 9.4.1 Estimation of the Radiated Power. . . . .                 | 282 |
| 9.4.2 Estimation of the Wall Temperatures. . . . .              | 288 |
| 9.5 Observations from the Wall Temperature Experiments. . . . . | 291 |

## Chapter 10

### Summary and Conclusions

|                                                                                           |     |
|-------------------------------------------------------------------------------------------|-----|
| 10.1 Summary of Findings and Physical Explanations. . . . .                               | 299 |
| 10.1.1 Discharge Stability and Sustainability. . . . .                                    | 299 |
| 10.1.2 Measurements of EEDF, $T_e$ and $V_p$ . . . . .                                    | 301 |
| 10.1.3 Measurements of Charge Density and Charge Density Profile. . . . .                 | 303 |
| 10.1.4 Plasma Skin Depth and Regions of Microwave Heating. . . . .                        | 305 |
| 10.1.5 Quartz Wall Temperatures. . . . .                                                  | 306 |
| 10.1.6 Measured Ion Production Cost. . . . .                                              | 308 |
| 10.1.7 Global Model Predictions. . . . .                                                  | 309 |
| 10.1.8 General Comparison Between the Magnetized and Nonmagnetized<br>Discharges. . . . . | 310 |
| 10.1.9 Electron Loss Processes for the Magnetized Discharge. . . . .                      | 312 |
| 10.2 General Discussion of Collisionless Heating and Hot Electrons. . . . .               | 313 |
| 10.3 Future Follow-on Research and Possible New Plasma Source Designs. . . . .            | 317 |
| 10.3.1 The Search for High Energy Electrons. . . . .                                      | 317 |
| 10.3.2 New Plasma Source Designs . . . . .                                                | 318 |

## APPENDICES

|                                                                                           |     |
|-------------------------------------------------------------------------------------------|-----|
| Appendix A                                                                                |     |
| <u>Cylindrical Cavity: Stored Energy, Power Lost and Cavity Q Calculations</u> . . . . .  | 323 |
| Appendix B                                                                                |     |
| <u>Variations on the Design of the Microwave Cavity Plasma Source.</u> . . . . .          | 339 |
| Appendix C                                                                                |     |
| <u>Close-up Photographs Of The Magnetic Field Cusps At Different Pressures.</u> . . . . . | 341 |
| Appendix D                                                                                |     |
| <u>Cavity Tuning Height for the Magnetized and Non-Magnetized Cases.</u> . . . . .        | 344 |
| Appendix E                                                                                |     |
| <u>The Transmission Line Model.</u> . . . . .                                             | 351 |
| Appendix F                                                                                |     |
| <u>Electric Field Probe Measurements.</u> . . . . .                                       | 358 |
| Appendix G                                                                                |     |
| <u>Absorbed Power Curves For The Non-Magnetized Discharge.</u> . . . . .                  | 369 |
| Appendix H                                                                                |     |
| <u>Adding 3 Different Size Plates To The End Of The Coupling Antenna.</u> . . . . .       | 394 |
| REFERENCES. . . . .                                                                       | 405 |

## LIST OF TABLES

|             |                                                                                                                                                                  |     |
|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Table 4.1 - | Input Variables of the Experimental System . . . . .                                                                                                             | 48  |
| Table 4.2 - | Internal Variables of the Experimental System . . . . .                                                                                                          | 49  |
| Table 4.3 - | Output Variables of the Experimental System . . . . .                                                                                                            | 49  |
| Table 6.1 - | Effective diffusion length, $d_{eff}$ , for various discharge geometries. . . . .                                                                                | 106 |
| Table 8.1 - | Significance of collisions in the sheath. . . . .                                                                                                                | 215 |
| Table 8.2 - | Calculation of Estimated Charge Density and Skin Depth<br>for a range of pressures and an absorbed power of 280W . . . . .                                       | 257 |
| Table 9.1 - | Power Delivered to the Quartz Wall. . . . .                                                                                                                      | 288 |
| Table A.1 - | First Five Roots of the First Derivative of the Bessel Functions<br>of Order $J'_0$ to $J'_5$ . Used for choosing $x'_{nm}$ in the TE mode<br>equations. . . . . | 325 |
| Table A.2 - | First Five Roots of the of the Bessel Functions of Order $J_0$ to $J_5$ .<br>Used for choosing $x_{nm}$ in the TM mode equations. . . . .                        | 325 |



## LIST OF FIGURES

|               |                                                                                                                           |    |
|---------------|---------------------------------------------------------------------------------------------------------------------------|----|
| Figure 2.1 -  | Several Early Nonmagnetized Microwave Plasma Discharges. . . . .                                                          | 8  |
| Figure 2.2 -  | Basic Elements of a Large Area Dielectric Slab Source. . . . .                                                            | 11 |
| Figure 2.3 -  | Two surface-wave eigenmodes as seen from the bottom of<br>the process chamber . . . . .                                   | 12 |
| Figure 2.4 -  | The Planar Surface Wave Plasma Device [Gha-96]. . . . .                                                                   | 13 |
| Figure 2.5 -  | An End-Feed-Cavity Excited Dielectric Slab Source [Odr-98] . . . . .                                                      | 16 |
| Figure 2.6 -  | The Concentric Spread Plasma Source. . . . .                                                                              | 18 |
| Figure 2.7 -  | A modified version of the concentric spread plasma source using<br>a resonant cavity and a ring of slot antennas. . . . . | 19 |
| Figure 2.8 -  | The High-Permittivity Window Plasma Device. . . . .                                                                       | 21 |
| Figure 2.10 - | The Large Tube Surface Wave Source (Okamoto Cavity) [Oka-96] . . .                                                        | 23 |
| Figure 2.11 - | The Distributed Element Microwave Plasma Source. . . . .                                                                  | 25 |
| Figure 3.1 -  | Block Diagram of The Experimental System . . . . .                                                                        | 29 |
| Figure 3.2 -  | Diagram of the Microwave Plasma System and Diagnostic<br>Probes. . . . .                                                  | 31 |
| Figure 3.3a - | 500W Microwave Delivery System . . . . .                                                                                  | 33 |
| Figure 3.3b - | 1500W Microwave Delivery System . . . . .                                                                                 | 34 |
| Figure 3.4 -  | Gas Delivery and Vacuum System . . . . .                                                                                  | 35 |
| Figure 3.5 -  | Experimental System . . . . .                                                                                             | 37 |
| Figure 4.1 -  | The Input/Output Model. . . . .                                                                                           | 39 |

|              |                                                                                                                                                                                                                                                                                                                                                           |    |
|--------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4.2 - | Block diagram showing the categorization of the specific variables. ....                                                                                                                                                                                                                                                                                  | 42 |
| Figure 4.3 - | Reactor with and without ECR magnet array. ....                                                                                                                                                                                                                                                                                                           | 43 |
| Figure 5.1 - | Single Langmuir Probe and Positioning Apparatus. ....                                                                                                                                                                                                                                                                                                     | 53 |
| Figure 5.2 - | (a) Typical current vs. voltage curve for a planar single Langmuir probe, (b) the potential $F$ vs. distance $z$ away from the surface of a planar probe when $V_0$ is large negative, (c) when $V_0$ equals the floating potential, $V_f$ (d) $V_0$ equals the plasma potential, $V_p$ , (e) $V_0$ is greater than $V_p$ (Note: $DV = V_p - V_0$ ) ..... | 55 |
| Figure 5.3 - | Planar Approximation for an SLP where the sheath thickness is much less than the radius of the probe. Electrons without the required $z$ -component of kinetic energy are repelled from the negatively biased probe. ....                                                                                                                                 | 57 |
| Figure 5.4 - | This figure illustrates graphically how the small AC signal applied to the probe at operating point $V_0$ can give rise to higher harmonics that are proportional to the curvature of the IV curve .....                                                                                                                                                  | 62 |
| Figure 5.5 - | Diagram of SLP measurement circuit .....                                                                                                                                                                                                                                                                                                                  | 63 |
| Figure 5.6 - | Schematic diagram of the relay circuit and corresponding parallel port pins for an IBM comparable PC .....                                                                                                                                                                                                                                                | 65 |
| Figure 5.7 - | Determination of $I_s$ from a measured SLP IV curve .....                                                                                                                                                                                                                                                                                                 | 68 |
| Figure 5.8 - | Simplified schematic of the SLP measurement circuit .....                                                                                                                                                                                                                                                                                                 | 71 |
| Figure 6.1 - | Parallel Plane Discharge. ....                                                                                                                                                                                                                                                                                                                            | 86 |
| Figure 6.2 - | The density variation vs. $x$ . ....                                                                                                                                                                                                                                                                                                                      | 86 |
| Figure 6.3 - | Cylindrical Discharge Chamber. ....                                                                                                                                                                                                                                                                                                                       | 88 |
| Figure 6.4 - | Density variation in the radial dimension $r$ for the cylindrical discharge .....                                                                                                                                                                                                                                                                         | 88 |
| Figure 6.5 - | Figure 6.5 - Electron Temperature vs. neutral gas density, $n_g$ , times diffusion length, $L$ , for a plasma discharge in the high-pressure regime .....                                                                                                                                                                                                 | 92 |
| Figure 6.6 - | Electron temperature vs. $p_g$ and neutral gas temperature $T_g$ for a specific discharge geometry and discharge gas. ....                                                                                                                                                                                                                                | 93 |

|               |                                                                                                                                                                                                                          |     |
|---------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 6.7 -  | Functions $n(x)$ , $G(x)$ , and $u(x)$ for a parallel plate geometry with the sheathless model. ....                                                                                                                     | 95  |
| Figure 6.8 -  | Sheathless (dashed curves) and sheathed (solid curves) models for $n(x)$ and $u(x)$ at the sheath edge .....                                                                                                             | 96  |
| Figure 6.9 -  | Approximate charge density profile for the low or intermediate pressure regime, with parallel plate separated by distance $l$ .....                                                                                      | 103 |
| Figure 6.10 - | Electron Temperature vs. neutral gas density, $n_g$ , times effective diffusion length, $d_{eff}$ for a plasma discharge in the intermediate pressure regime .....                                                       | 107 |
| Figure 6.11 - | Trajectory for an electron gaining energy in an ECR zone. ....                                                                                                                                                           | 115 |
| Figure 6.12 - | Stochastic Energy Transfer Mechanisms. ....                                                                                                                                                                              | 117 |
| Figure 6.13 - | Generic Plasma Discharge Chamber. ....                                                                                                                                                                                   | 120 |
| Figure 6.14 - | Typical Plasma Source Discharge Geometry .....                                                                                                                                                                           | 133 |
| Figure 7.1 -  | Global model prediction of electron temperature vs. discharge pressure for a 6.5 cm radius, 10.25 cm height argon discharge with a neutral gas temperature of 600K. ....                                                 | 141 |
| Figure 7.2 -  | Both Maxwellian and Druyvesteyn energy distribution functions plotted for an effective temperature of $T_e = 3$ eV. (a) Linear and (b) Logarithmic plots are shown for both distributions. ....                          | 143 |
| Figure 7.3a - | EEDF in argon at 1 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 5.21$ eV, $V_p = 22.71$ V, $L_s = 13.675$ cm ..... | 146 |
| Figure 7.3b - | EEDF in argon at 1 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 5.21$ eV, $V_p = 22.71$ V, $L_s = 13.675$ cm ..... | 147 |
| Figure 7.4a - | EEDF in argon at 4 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.96$ eV, $V_p = 22.27$ V, $L_s = 13.95$ cm. ....         | 148 |

|                                                                                                                                                                                                                                       |     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 7.5a - EEDF in argon at 4 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.42$ eV, $V_p = 14.46$ V, $L_s = 15.75$ cm. .... | 148 |
| Figure 7.4b - EEDF in argon at 4 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.96$ eV, $V_p = 22.27$ V, $L_s = 13.95$ cm. ....        | 149 |
| Figure 7.5b - EEDF in argon at 4 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.42$ eV, $V_p = 14.46$ V, $L_s = 15.75$ cm. .... | 149 |
| Figure 7.6a - EEDF in argon at 5 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.50$ eV, $V_p = 20.17$ V, $L_s = 14.1$ cm. ....         | 150 |
| Figure 7.7a - EEDF in argon at 5 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.32$ eV, $V_p = 14.41$ V, $L_s = 15.85$ cm. .... | 150 |
| Figure 7.6b - EEDF in argon at 5 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.50$ eV, $V_p = 20.17$ V, $L_s = 14.1$ cm. ....         | 151 |
| Figure 7.7b - EEDF in argon at 5 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.32$ eV, $V_p = 14.41$ V, $L_s = 15.85$ cm. .... | 151 |
| Figure 7.8a - EEDF in argon at 7 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.17$ eV, $V_p = 17.20$ V, $L_s = 15.10$ cm. ....        | 152 |
| Figure 7.9a - EEDF in argon at 7 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.17$ eV, $V_p = 13.57$ V, $L_s = 15.9$ cm. ....  | 152 |

|                                                                                                                                                                                                                                          |     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 7.8b - EEDF in argon at 7 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.17$ eV, $V_p = 17.20$ V, $L_s = 15.10$ cm. ....           | 153 |
| Figure 7.9b - EEDF in argon at 7 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 3.17$ eV, $V_p = 13.57$ V, $L_s = 15.9$ cm. ....     | 153 |
| Figure 7.10a - EEDF in argon at 10 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.87$ eV, $V_p = 14.89$ V, $L_s = 15.85$ cm. ....         | 154 |
| Figure 7.11a - EEDF in argon at 10 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.95$ eV, $V_p = 12.54$ V, $L_s = 16.2$ cm. ....   | 154 |
| Figure 7.10b - EEDF in argon at 10 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.87$ eV, $V_p = 14.89$ V, $L_s = 15.85$ cm. ....         | 155 |
| Figure 7.11b - EEDF in argon at 10 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.95$ eV, $V_p = 12.54$ V, $L_s = 16.2$ cm. ....   | 155 |
| Figure 7.12a - EEDF in argon at 15 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.48$ eV, $V_p = 13.54$ V, $L_s = 16.2$ cm. ....          | 156 |
| Figure 7.13a - EEDF in argon at 15 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.71$ eV, $V_p = 12.53$ V, $L_s = 16.575$ cm. .... | 156 |
| Figure 7.12b - EEDF in argon at 15 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.48$ eV, $V_p = 13.54$ V, $L_s = 16.2$ cm. ....          | 157 |

|                                                                                                                                                                                                                                                     |     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 7.13b - EEDF in argon at 15 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.71$ eV, $V_p = 12.53$ V, $L_s = 16.575$ cm. ....            | 157 |
| Figure 7.14a - EEDF in argon at 45 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 1.92$ eV, $V_p = 10.08$ V, $L_s = 19.1$ cm. ....                     | 158 |
| Figure 7.15a - EEDF in argon at 45 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.08$ eV, $V_p = 11.26$ V, $L_s = 20$ cm. ....                | 158 |
| Figure 7.14b - EEDF in argon at 45 mTorr, measured at $r=0$ , $z=0$ in the discharge, with no magnets present. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 1.92$ eV, $V_p = 10.08$ V, $L_s = 19.1$ cm. ....                     | 159 |
| Figure 7.15b - EEDF in argon at 45 mTorr with multipolar magnets present, measured at $r=0$ , $z=0$ in the discharge. Discharge parameters are: $P_{abs} = 280$ W, TM012 mode, $T_e = 2.08$ eV, $V_p = 11.26$ V, $L_s = 20$ cm. ....                | 159 |
| Figure 7.16 - Single Langmuir probe measured electron temperatures vs. discharge pressure. Magnetized and non-magnetized configuration are compared. ....                                                                                           | 161 |
| Figure 7.17 - Single Langmuir probe measured electron temperatures vs. discharge pressure in a non-magnetized discharge. Several absorbed power levels are shown. Data for both the TM012 and the near field mode are included. ....                | 164 |
| Figure 7.18 - Plasma potential vs. discharge pressure for non-magnetized and magnetized discharges in the TM012 mode with 280 W absorbed power. The solid curve is the global model prediction of plasma potential assuming a Maxwellian EEDF. .... | 166 |
| Figure 7.19 - Linear plots of EEDF for a 7 mTorr, non-magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                               | 170 |
| Figure 7.20 - Log plots of EEDF for a 7 mTorr, non-magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                  | 171 |

|                                                                                                                                                                                                                                                                                                                                                                                 |     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 7.21 - Linear plots of EEDF for a 10 mTorr, non-magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. . . . .                                                                                                                                                                       | 172 |
| Figure 7.22 - Log plots of EEDF for a 10 mTorr, non-magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. . . . .                                                                                                                                                                          | 173 |
| Figure 7.23 - Linear plots of EEDF for a 25 mTorr, non-magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. . . . .                                                                                                                                                                       | 174 |
| Figure 7.24 - Log plots of EEDF for a 25 mTorr, non-magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. . . . .                                                                                                                                                                          | 175 |
| Figure 7.25 - Single Langmuir probe measured electron temperatures vs. discharge pressure for several vertical positions, $z$ in a non-magnetized discharge. The solid curve represents the intermediate regime global model prediction assuming a Maxwellian electron distribution function. For all points shown absorbed power was 280W and the EM mode was TM012. . . . .   | 177 |
| Figure 7.26 - Single Langmuir probe measured electron temperatures vs. vertical position $z$ for three discharge pressures in a non-magnetized discharge. For all points shown absorbed power was 280W and the EM mode was TM012.. . . .                                                                                                                                        | 177 |
| Figure 7.27 - Single Langmuir probe measured plasma potential $V_p$ vs. discharge pressure for several vertical positions, $z$ , in a non-magnetized discharge. The solid curve represents the intermediate regime global model prediction calculated using a Maxwellian distribution function. For all points shown absorbed power was 280W and the EM mode was TM012. . . . . | 179 |
| Figure 7.28 - Single Langmuir probe measured plasma potential $V_p$ vs. vertical position $z$ for several discharge pressures in a non-magnetized discharge. For all points shown absorbed power was 280W and the EM mode was TM012. . . . .                                                                                                                                    | 179 |
| Figure 7.29 - Linear plots of EEDF for a 1.84 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. . . . .                                                                                                                                                                         | 182 |

|               |                                                                                                                                                                                                                                                                                                                                                                |     |
|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 7.30 - | Log plots of EEDF for a 1.84 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                                                                                                                                            | 183 |
| Figure 7.31 - | Linear plots of EEDF for a 4 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                                                                                                                                            | 184 |
| Figure 7.32 - | Log plots of EEDF for a 4 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                                                                                                                                               | 185 |
| Figure 7.33 - | Linear plots of EEDF for a 7 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                                                                                                                                            | 186 |
| Figure 7.34 - | Log plots of EEDF for a 7 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                                                                                                                                               | 187 |
| Figure 7.35 - | Linear plots of EEDF for a 10 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                                                                                                                                           | 188 |
| Figure 7.36 - | Log plots of EEDF for a 10 mTorr, magnetized discharge, 280 W absorbed power, in the TM012 EM mode, with the probe positioned at: a) $z=0$ cm, b) $z=2$ cm, and c) $z=4$ cm. ....                                                                                                                                                                              | 189 |
| Figure 7.37 - | Single Langmuir probe measured electron temperatures vs. discharge pressure for several vertical positions, $z$ in a magnetized discharge. The solid curve represents the intermediate regime global model prediction calculated assuming a Maxwellian distribution function. For all points shown absorbed power was 280W and the EM mode was TM012.. ....    | 191 |
| Figure 7.38 - | Single Langmuir probe measured electron temperatures vs. vertical position $z$ for several discharge pressures in a magnetized discharge. For all points shown absorbed power was 280W and the EM mode was TM012.. ....                                                                                                                                        | 191 |
| Figure 7.39 - | Single Langmuir probe measured plasma potential $V_p$ vs. discharge pressure for several vertical positions, $z$ , in a magnetized discharge. The solid curve represents the intermediate regime global model prediction calculated assuming a Maxwellian distribution function. For all points shown absorbed power was 280W and the EM mode was TM012.. .... | 193 |



|               |                                                                                                                                                                                                                                                                                                                                                                |     |
|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 7.40 - | Single Langmuir probe measured plasma potential $V_p$ vs. vertical position $z$ for several discharge pressures in a magnetized discharge. For all points shown absorbed power was 280W and the EM mode was TM012..                                                                                                                                            | 193 |
| Figure 8.1 -  | Experimental parameter space vs. power absorbed, $P_{abs}$ , and discharge pressure, $p$ ..                                                                                                                                                                                                                                                                    | 200 |
| Figure 8.2 -  | Global model prediction of electron temperature in an argon discharge vs. pressure for a 6.5 cm radius, 10.25 cm height discharge with a neutral gas temperature of 600K..                                                                                                                                                                                     | 203 |
| Figure 8.3 -  | Global model calculated charge density vs. power absorbed, $P_{abs}$ , and discharge pressure, $p$ , (in mTorr)..                                                                                                                                                                                                                                              | 204 |
| Figure 8.4 -  | 3D plot of global model calculated charge density vs. absorbed power and discharge pressure (in mTorr)..                                                                                                                                                                                                                                                       | 205 |
| Figure 8.5 -  | Closed Ended and Open Ended discharge models. In the closed ended model the end wall is formed by an extraction grid or a wafer..                                                                                                                                                                                                                              | 206 |
| Figure 8.6    | Global model calculated ion production cost vs. discharge pressure..                                                                                                                                                                                                                                                                                           | 207 |
| Figure 8.7 -  | Finite difference grid for the 10.25 cm tall discharge dome and 55 cm tall process chamber. Grid points are 1 cm apart..                                                                                                                                                                                                                                       | 211 |
| Figure 8.8 -  | Surface plot of the relative charge density in a 2D cross section of a high pressure discharge with both discharge dome and process chamber shown. This is the result of a finite difference simulation of the diffusion equation. The generation term is 1 in the discharge dome and 0 in the process chamber. The discharge is assumed to be phi-symmetric.. | 212 |
| Figure 8.9 -  | Side view of a logarithmic surface plot for relative charge density in both the discharge dome and process chamber..                                                                                                                                                                                                                                           | 213 |
| Figure 8.10 - | Charge density measured at $r=0$ and $z=0$ vs. Absorbed Power at six different discharge pressure levels for the TM012 Mode with no magnets present. Solid lines are experimental data. Gray dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line)..                                                       | 217 |

|                                                                                                                                                                                                                                                                                                                                                                                                    |     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 8.11 - Charge density measured at $r=0$ and $z=0$ vs. absorbed power at six different discharge pressure levels for the Near Field mode with no magnets present. Solid lines are experimental data. Gray dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line). . . . .                                                                 | 218 |
| Figure 8.12a - Charge density measured at $r=0$ and $z=0$ vs. absorbed power at 7 different discharge pressure levels (point at 280 W is at 1 mTorr) for the TM012 Mode, with multipolar magnetic field. Solid lines are experimental data. Gray dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line). . . . .                                | 219 |
| Figure 8.12b - Expanded view of Figure 8.12a. Charge density measured at $r=0$ and $z=0$ vs. absorbed power at 7 different discharge pressure levels (point at 280 W is at 1 mTorr) for the TM012 Mode, with multipolar magnetic field. Solid lines are experimental data. Gray dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line). . . . . | 220 |
| Figure 8.13a - Charge density measured at $r=0$ and $z=0$ vs. absorbed power at six different discharge pressure levels for the Near Field Mode with multipolar magnetic field. Solid lines are experimental data. Gray dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line). . . . .                                                         | 221 |
| Figure 8.13b - Expanded view of Figure 8.13a. Charge density measured at $r=0$ and $z=0$ vs. absorbed power at six different discharge pressure levels for the Near Field Mode with multipolar magnetic field. Solid lines are experimental data. Gray dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line). . . . .                          | 222 |
| Figure 8.14 - Comparison of Charge Density vs. Absorbed Power between TM012 and Near Field Modes for the Non-Magnetized discharge. Solid black lines are TM012 data. Gray dashed lines are Near Field Mode data. Six different discharge pressure levels are compared. . . . .                                                                                                                     | 225 |
| Figure 8.15a - Comparison of Charge Density vs. Absorbed Power between TM012 and Near Field Modes for the Magnetized discharge. Solid black lines are TM012 data. Gray dashed lines are Near Field Mode data. Six different discharge pressure levels are compared. . . . .                                                                                                                        | 226 |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                               |     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 8.15b - Expanded view of Figure 8.15a. Comparison of Charge Density vs. Absorbed Power between TM012 and Near Field Modes for the Magnetized discharge. Solid black lines are TM012 data. Gray dashed lines are Near Field Mode data. Six different discharge pressure levels are compared . . . . .                                                                                                                                                   | 227 |
| Figure 8.16 - Comparison of Charge Density vs. Absorbed Power between Magnetized and Non-Magnetized Discharges in the TM012 Mode. Solid black lines are Non-magnetized data. Gray dashed lines are Magnetized data. Six different discharge pressure levels are compared. . . . .                                                                                                                                                                             | 229 |
| Figure 8.17 - Comparison of Charge Density vs. Absorbed Power between Magnetized and Non-Magnetized discharges in the Near Field Mode. Solid black lines are Non-Magnetized data. Gray dashed lines are Magnetized data. Six different discharge pressure levels are compared. . . . .                                                                                                                                                                        | 230 |
| Figure 8.18 - Experimental parameter space vs. power absorbed and discharge pressure. . . . .                                                                                                                                                                                                                                                                                                                                                                 | 234 |
| Figure 8.19 - Charge density measured at $r=0$ and $z=0$ vs. absorbed power at five different discharge pressure levels for the Near Field mode with no magnets present. The 1500W capacity microwave source was used in this data set. Solid lines are least squares fit to the experimental data for each pressure. Dashed lines are global model prediction where the upper dashed line is for 45 mtorr and the lower dashed line is for 4 mTorr . . . . . | 236 |
| Figure 8.20 - Charge density measured at $r=0$ and $z=0$ vs. absorbed power at six different discharge pressure levels for the Near Field mode with magnets present. The 1500W capacity microwave source was used in this data set. Solid lines are least squares fit to the experimental data for each pressure. Dashed lines are global model prediction where the upper dashed line is for 45 mtorr and the lower dashed line is for 4 mTorr . . . . .     | 237 |
| Figure 8.21 - Charge density measured at $r=0$ and $z=0$ vs. absorbed power at six different discharge pressure levels for the Near Field mode with magnets present. This graph is an expanded view of Figure 8.25. . . . .                                                                                                                                                                                                                                   | 238 |

|                                                                                                                                                                                                                                                                                                                                                                                                                 |     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 8.22 - Radial profiles of SLP measured charge density at 45 mTorr. Density profiles of both magnetized and non-magnetized for TM012 and near field modes are displayed. Dashed lines are a parabolic fit through two points: the measured center density point and the global model predicted edge density at $r=6.5$ cm. Note: y-axis data range is 0 to $1.4 \times 10^{12} \text{ cm}^{-3}$ . . . . . | 242 |
| Figure 8.23 - Radial profiles of SLP measured charge density at 15 mTorr. Density profiles of both magnetized and non-magnetized for TM012 and near field modes are displayed. Dashed lines are a parabolic fit through two points: the measured center density point and the global model predicted edge density at $r=6.5$ cm. Note: y-axis data range is 0 to $8 \times 10^{12} \text{ cm}^{-3}$ . . . . .   | 243 |
| Figure 8.24 - Radial profiles of SLP measured charge density at 7 mTorr. Density profiles of both magnetized and non-magnetized for TM012 and near field modes are displayed. Dashed lines are a parabolic fit through two points: the measured center density point and the global model predicted edge density at $r=6.5$ cm. Note: y-axis data range is 0 to $4 \times 10^{12} \text{ cm}^{-3}$ . . . . .    | 244 |
| Figure 8.25 - Ion saturation current vs. axial position into the discharge at 45 mTorr. $z=0$ cm is the discharge chamber opening and $z=10.25$ cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between $z=4.5$ cm and $z=7$ cm as shown in the figure. . . . .                                                                   | 250 |
| Figure 8.26 - Ion saturation current vs. axial position into the discharge at 25 mTorr. $z=0$ cm is the discharge chamber opening and $z=10.25$ cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between $z=4.5$ cm and $z=7$ cm as shown in the figure. . . . .                                                                   | 251 |
| Figure 8.27 - Ion saturation current vs. axial position into the discharge at 15 mTorr. $z=0$ cm is the discharge chamber opening and $z=10.25$ cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between $z=4.5$ cm and $z=7$ cm as shown in the figure. . . . .                                                                   | 252 |
| Figure 8.28 - Ion saturation current vs. axial position into the discharge at 10 mTorr. $z=0$ cm is the discharge chamber opening and $z=10.25$ cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between $z=4.5$ cm and $z=7$ cm as shown in the figure. . . . .                                                                   | 253 |

|                                                                                                                                                                                                                                                                                                                                                    |     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 8.29 - Ion saturation current vs. axial position into the discharge at 7 mTorr. $z=0$ cm is the discharge chamber opening and $z=10.25$ cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between $z=4.5$ cm and $z=7$ cm as shown in the figure. . . . .       | 254 |
| Figure 8.30 - Ion saturation current vs. axial position into the discharge at 4 mTorr. $z=0$ cm is the discharge chamber opening and $z=10.25$ cm is inside top of the quartz discharge chamber. For the magnetized the position of the multipolar magnet array occupies the space between $z=4.5$ cm and $z=7$ cm as shown in the figure. . . . . | 255 |
| Figure 8.31 - Collisionless skin depth vs. plasma charge density for 2.45 GHz incident microwave radiation. . . . .                                                                                                                                                                                                                                | 258 |
| Figure 8.32 - Estimated charge density near the top of the quartz dome and calculated skin depth vs. discharge for the magnetized and non-magnetized discharges. The absorbed power was 280 W. Note: this curve is specific to absorbed power level, i.e. higher or lower power levels will change charge density and skin depth . . . . .         | 259 |
| Figure 8.33 - Photographs of the plasma discharge seen looking up into the discharge from the process chamber. The discharge absorbed power was 280 W. The electromagnetic mode was the TM012 mode. . . . .                                                                                                                                        | 262 |
| Figure 8.34 - Photographs of the plasma discharge seen looking through the chamber side window. The discharge absorbed power was 280 W. The electromagnetic mode was the TM012 mode . . . . .                                                                                                                                                      | 263 |
| Figure 8.35 - Diagram illustrating the concept of Ion Production Cost. . . . .                                                                                                                                                                                                                                                                     | 264 |
| Figure 8.36 - Ion Production Cost calculated from the gradient of charge density measured by an SLP at (0,0,0) and (0,0,1). Dashed line is the global model prediction . . . . .                                                                                                                                                                   | 267 |
| Figure 9.1a - OS36-2 Optical Thermocouple with digital readout. Measurement positions #1 and #2 are shown. . . . .                                                                                                                                                                                                                                 | 275 |
| Figure 9.1b - Arrows depict compressed air flow as it escapes from the air cooling holes near the base of the quartz dome. The air flows between the quartz and the aluminum magnet holder until it escapes into the cavity . . . . .                                                                                                              | 275 |

|              |                                                                                                                                                                                                                                                                                                                                                                                           |     |
|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 9.2 - | Measurement of the quartz discharge dome temperature vs. time after the microwave power was turned off. The compressed air cooling remained on for the whole 5 minute period of measurement. Discharge pressure was 45 mTorr and initial discharge power absorbed was 320 Watts. The near field microwave cavity mode was used. Room temperature was 22°C . . . . .                       | 277 |
| Figure 9.3 - | Optically measured surface temperatures of the (non-magnetized) quartz discharge dome vs. discharge absorbed power. The near field microwave cavity mode was used. Several discharge pressures are shown. Temperatures taken from the side of the discharge dome (Measurement Position #1) are shown with temperatures taken from the top of the dome (Measurement Position #2) . . . . . | 280 |
| Figure 9.4 - | Comparison of quartz dome surface temperatures in the magnetized and non-magnetized discharges vs. discharge pressure at an absorbed power of 280 Watts. The near field microwave cavity mode was used. All temperature measurements were taken from the side wall of the discharge (Measurement Position #1). . . . .                                                                    | 281 |
| Figure 9.5 - | Total energy loss per electron/ion pair lost from the plasma vs. electron temperature. Also shown are the individual loss components due to: excitation, collision, ionization, ion sheath losses ( $5.2T_e$ ), and electron kinetic losses ( $2T_e$ ). Note $\Sigma_c$ (the sum of excitation, collision, and ionization) is also shown . . . . .                                        | 286 |
| Figure 9.6 - | This plot shows the fraction of power lost to the discharge wall vs. electron temperature. The complementary plot of excitation losses vs. electron temperature is also shown. The total power deposited into the discharge walls can be calculated by multiplying the power loss fraction for the walls by the discharge absorbed power, $P_{abs}$ . . . . .                             | 287 |
| Figure 9.7 - | Calculated external quartz wall temperature, $T_w$ , as a function of power flux to the walls of the discharge. In the inset equation $P_{wall}$ is a function of quartz wall temperature. The terms of this equation are described in the text of this section . . . . .                                                                                                                 | 292 |
| Figure 9.8 - | Comparison of experimentally measured (magnetized and non-magnetized) vs. theoretically calculated quartz dome surface temperatures vs. discharge pressure at an absorbed power of 280 Watts. All temperature measurements were taken from the side wall of the discharge (Measurement Position #1). . . . .                                                                              | 293 |

|               |                                                                                                                                                                                                                                                                                                      |     |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 9.9 -  | Calculation of the predicted quartz wall temperature vs. discharge absorbed power for several discharge pressures. ....                                                                                                                                                                              | 294 |
| Figure 10.1 - | Single Langmuir probes for measurement of EEDF: a) vertically (axially) oriented probe tip, and b) horizontally oriented probe tip. ....                                                                                                                                                             | 318 |
| Figure 10.2 - | New plasma source designs: a) permanent magnets are placed in on the top side of the sliding short to create an axial magnetic field, b) a plate is placed at the end of the probe antenna for enhanced stochastic heating at the top of the discharge (the 8 multipolar magnets are optional). .... | 320 |
| Figure A.1 -  | A Cylindrical Cavity with radius $a$ and length $L_s$ . ....                                                                                                                                                                                                                                         | 323 |
| Figure B.1 -  | Eleven MPDR Configurations Ordered by Discharge Size. ....                                                                                                                                                                                                                                           | 340 |
| Figure C.1 -  | Close-up Photographs of the magnetic cusps for 7, 15, and 45 mTorr. ....                                                                                                                                                                                                                             | 342 |
| Figure D.1 -  | Cavity Tuning Height, $L_s$ , vs. Discharge Absorbed Power, $P_{abs}$ , for the non-magnetized $TM_{012}$ mode. ....                                                                                                                                                                                 | 345 |
| Figure D.2 -  | Cavity Tuning Height, $L_s$ , vs. Discharge Absorbed Power, $P_{abs}$ , for the magnetized and non-magnetized $TM_{012}$ mode at 4 mTorr. ....                                                                                                                                                       | 347 |
| Figure D.3 -  | Cavity Tuning Height, $L_s$ , vs. Discharge Absorbed Power, $P_{abs}$ , for the magnetized and non-magnetized $TM_{012}$ mode at 7 mTorr. ....                                                                                                                                                       | 347 |
| Figure D.4 -  | Cavity Tuning Height, $L_s$ , vs. Discharge Absorbed Power, $P_{abs}$ , for the magnetized and non-magnetized $TM_{012}$ mode at 10 mTorr. ....                                                                                                                                                      | 348 |
| Figure D.5 -  | Cavity Tuning Height, $L_s$ , vs. Discharge Absorbed Power, $P_{abs}$ , for the magnetized and non-magnetized $TM_{012}$ mode at 15 mTorr. ....                                                                                                                                                      | 348 |
| Figure D.6 -  | Cavity Tuning Height, $L_s$ , vs. Discharge Absorbed Power, $P_{abs}$ , for the magnetized and non-magnetized $TM_{012}$ mode at 25 mTorr. ....                                                                                                                                                      | 349 |
| Figure D.7 -  | Cavity Tuning Height, $L_s$ , vs. Discharge Absorbed Power, $P_{abs}$ , for the magnetized and non-magnetized $TM_{012}$ mode at 45 mTorr. ....                                                                                                                                                      | 349 |
| Figure E.1 -  | Transmission Line Equivalent Model of the MPDR13. ....                                                                                                                                                                                                                                               | 352 |
| Figure E.2 -  | The input impedance of transmission line section III. ....                                                                                                                                                                                                                                           | 353 |

|                     |                                                                                                                                                                                                                                                                                                                                                                      |     |
|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure E.3 -        | Example Standing Wave Voltage Envelope for a multiple section transmission line. ....                                                                                                                                                                                                                                                                                | 355 |
| Figure E.4 -        | Inclusion of higher order modes in the transmission line model. ....                                                                                                                                                                                                                                                                                                 | 356 |
| Figure F.1 -        | Diagram of the Electric Field Probe and Microwave Cavity. ....                                                                                                                                                                                                                                                                                                       | 360 |
| Figure F.2 -        | Microwave Circuit for E-field Probe Calibration: (1) Micro-coax E-probe, (2) Empty Cavity, (3) hp 432A power meter, (4) hp 478A thermistor sensor. Note: input power is ~100 mW so no additional attenuators are used at the measurement ports of the directional couplers. ....                                                                                     | 362 |
| <b>Figure F.3 -</b> | Electric Field vs. Vertical Hole Position for the (a) Non-Magnetized and (b) Magnetized Source at 7 mTorr and $P_{abs} = 330W$ . Diamonds indicate field sampled at $45^\circ$ line and squares indicate field sampled at $90^\circ$ line. Dashed line marks top of belljar. Dotted line marks end of coupling probe. Solid line marks sliding short position. ....  | 365 |
| <b>Figure F.4 -</b> | Electric Field vs. Vertical Hole Position for the (a) Non-Magnetized and (b) Magnetized Source at 15 mTorr and $P_{abs} = 330W$ . Diamonds indicate field sampled at $45^\circ$ line and squares indicate field sampled at $90^\circ$ line. Dashed line marks top of belljar. Dotted line marks end of coupling probe. Solid line marks sliding short position. .... | 366 |
| <b>Figure F.5 -</b> | Electric Field vs. Vertical Hole Position for the (a) Non-Magnetized and (b) Magnetized Source at 45 mTorr and $P_{abs} = 330W$ . Diamonds indicate field sampled at $45^\circ$ line and squares indicate field sampled at $90^\circ$ line. Dashed line marks top of belljar. Dotted line marks end of coupling probe. Solid line marks sliding short position. .... | 367 |
| <b>Figure G.1 -</b> | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 4mTorr, $P_{inc} = 330W$ , and $L_p = 3.5cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . ....                                                                                                                       | 371 |
| <b>Figure G.2 -</b> | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 4mTorr, $P_{inc} = 330W$ , and $L_p = 3.25 cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . ....                                                                                                                     | 371 |



|                      |                                                                                                                                                                                                                                             |     |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure G.3 -</b>  | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 4mTorr, $P_{inc} = 330W$ , and $L_p = 3.0$ cm. Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ .   | 372 |
| <b>Figure G.4 -</b>  | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 4mTorr, $P_{inc} = 330W$ , and $L_p = 2.75$ cm. Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ .  | 372 |
| <b>Figure G.5 -</b>  | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 4mTorr, $P_{inc} = 330W$ , and $L_p = 2.5cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ .   | 373 |
| <b>Figure G.6 -</b>  | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 10mTorr, $P_{inc} = 130W$ , and $L_p = 3.5cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ .  | 374 |
| <b>Figure G.7 -</b>  | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 10mTorr, $P_{inc} = 130W$ , and $L_p = 3.25cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . | 374 |
| <b>Figure G.8 -</b>  | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 10mTorr, $P_{inc} = 130W$ , and $L_p = 3.0$ cm. Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ .  | 375 |
| <b>Figure G.9 -</b>  | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 10mTorr, $P_{inc} = 130W$ , and $L_p = 2.75cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . | 375 |
| <b>Figure G.10 -</b> | Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 10mTorr, $P_{inc} = 130W$ , and $L_p = 2.5cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ .  | 376 |

- Figure G.11 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 377
- Figure G.12 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 377
- Figure G.13 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.0\text{ cm}$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 378
- Figure G.14 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 378
- Figure G.15 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 379
- Figure G.16 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 380
- Figure G.17 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 380
- Figure G.18 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 381

- Figure G.19 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 381
- Figure G.20 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 382
- Figure G.21 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 383
- Figure G.22 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 383
- Figure G.23 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 384
- Figure G.24 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 384
- Figure G.25 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 385
- Figure G.26 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 386

- Figure G.27** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 386
- Figure G.28** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 387
- Figure G.29** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 387
- Figure G.30** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 388
- Figure G.31** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 4.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 389
- Figure G.32** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 389
- Figure G.33** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 390
- Figure G.34** - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 390

|                                                                                                                                                                                                                                                                                                                     |     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure G.35</b> - Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 25mTorr, $P_{inc} = 330W$ , and $L_p = 2.75cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . .                                            | 391 |
| <b>Figure G.36</b> - Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 25mTorr, $P_{inc} = 330W$ , and $L_p = 2.5cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . .                                             | 391 |
| <b>Figure G.37</b> - Absorbed Power Curve for the <u>Non-Magnetized</u> Plasma Discharge at 25mTorr, $P_{inc} = 330W$ , and $L_p = 2.0cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . .                                             | 392 |
| <b>Figure H.1</b> - Diagram showing the MPDR 13 with a 9 cm coupling plate attached to the end of the coupling probe. . . . .                                                                                                                                                                                       | 395 |
| <b>Figure H.2</b> - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with <u>3cm Coupling Plate</u> at 45mTorr, $P_{inc} = 330W$ , and <u><math>L_p = 3.0cm</math></u> . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . .    | 398 |
| <b>Figure H.3</b> - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with <u>6cm Coupling Plate</u> at 45mTorr, $P_{inc} = 330W$ , and $L_p = 3.0cm$ . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . .                      | 399 |
| <b>Figure H.4</b> - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with <u>6cm Coupling Plate</u> at 45mTorr, $P_{inc} = 330W$ , and <u><math>L_p = 6.85cm</math></u> . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . .   | 399 |
| <b>Figure H.5</b> - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with <u>6cm Coupling Plate</u> at 7 mTorr, $P_{inc} = 330W$ , and <u><math>L_p = 6.875 cm</math></u> . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . . | 400 |
| <b>Figure H.6</b> - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with <u>9cm Coupling Plate</u> at 45mTorr, $P_{inc} = 330W$ , and <u><math>L_p = 3.0cm</math></u> . Triangles represent points taken while increasing $L_s$ and squares represent points taken while decreasing $L_s$ . . . . .    | 401 |

- Figure H.7 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 9cm Coupling Plate at 45mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.875\text{ cm}$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 401
- Figure H.8 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 9cm Coupling Plate at 15 mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.875\text{ cm}$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 402
- Figure H.9 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 9cm Coupling Plate at 7 mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.875\text{ cm}$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ . . . . . 402
- Figure H.10** - Radial Charge Density Profiles for several coupling probe configurations and modes. Data for the standard probe, 9cm disk, 6 cm disk, and 3 cm disk are shown. All profiles were taken at an absorbed power of 330W and a pressure of 15 mTorr. . . . . 403
- Figure H.11** - Radial Charge Density Profiles for several coupling probe configurations and modes. Data for the standard probe, 9cm disk, 6 cm disk, and 3 cm disk are shown. All profiles were taken at an absorbed power of 330W and a pressure of 45 mTorr. . . . . 403

## Chapter 1

### Introduction

**1 . 1 Introduction and Motivation for Research**

**1 . 2 Research Objectives**

**1 . 3 Summary of this Dissertation**

# Chapter 1

## Introduction

### **1.1 Introduction and Motivation for Research:**

Low pressure microwave plasma sources have a great variety of applications. They can be used in several semiconductor fabrication processes: 1) anisotropic submicron etching [Tep-94], 2) thin film deposition [Mus-86], 3) ion implantation, and 4) III-V and II-VI crystal growth [Abe-93,Mac-95]. They have also served as sources of ions for high energy physics experiments [Sri-94] and experimental spacecraft propulsion [Whi-86]. Small diameter (5 cm) sources can be used in MBE applications [Str-91] while large diameter (32.5+ cm) sources can provide large processing areas needed for 300 mm diameter wafers or flat panel displays.

From the mid 1970's to the mid 1990's the most common method of generating low pressure plasma (~10 mTorr or less) with microwave excitation was through electron cyclotron resonance (ECR), which requires a strong impressed static magnetic field [Pop-94]. At the same time, in the 1970's and 1980's other researchers demonstrated that under some special conditions it was possible to sustain a discharge at low pressures without a static magnetic field. At MSU Asmussen, Fredericks, Root, Dahimene, and more recently Mak all noted that microwave cavity discharges could be sustained at much lower pressures (although with more sensitive tuning requirements) than was thought possible with



ohmic plasma heating alone [Asm-89, Fre-71, Roo-85, Dah-87, Mak-97]. Before the mid 1990's it was widely believed that ECR was necessary to sustain microwave plasmas at low pressure since no other collisionless heating mechanisms had been clearly demonstrated. Lack of understanding of low pressure heating mechanisms and lack of a compelling industrial application led most researchers away from the development of low pressure, non-magnetized, microwave sources.

However, recent investigations [Oka-96] and a notable review paper by Popov [Pop-94] have indicated that other heating mechanisms, such as plasma resonance and stochastic heating, may play a significant role in microwave plasma heating at low pressures. In addition, the need for plasma sources with increasingly larger processing areas has, in the last five years, generated interest in and spurred the development of many new large area, non-magnetized, low pressure microwave plasma sources [Sug-98]. These recent developments have raised a set of questions relevant to plasma source development and understanding plasma source behavior. Some of these questions are:

What influence does ECR magnetic field configuration have on microwave discharge behavior and performance? Under what conditions do static magnetic fields and/or ECR volumes increase or decrease plasma source performance? Are static magnetic fields not beneficial at some discharge pressures?

More specific questions regarding the 17.78 diameter cavity source investigated in this dissertation can be asked:

What is the performance of this microwave plasma source under various controllable input conditions, such as input power, discharge pressure, and flow rate, as well as static magnetic field configuration? What then are the best operating conditions for a given application?

How does the performance of this source compare to the predictions of charge density and ion production efficiency made by global plasma models?

## 1.2 Research Objectives:

The objective of this research was to answer the questions presented above by measuring the experimental performance of a 17.78 diameter cavity microwave plasma source (with 13 cm diameter discharge) both with and without the application of a multipolar static magnetic field. Comparisons were made between the performance of these two configurations and to the global plasma model. In particular, the experimental objectives of this investigation were to:

- 1) Measure the plasma source output variables ( $Y_2$ : charge density, electron temperature, impressed electric field, etc.) and performance variables ( $Y_1$ : ion production cost, microwave coupling efficiency, and discharge output uniformity) vs. a predetermined variable space ( $U_1$ : input power, discharge pressure, flow rate, etc.).
- 2) Make comparisons between the performance of the two different configurations: (1) with a multipolar static magnetic field and (2) without an applied static magnetic field. Develop physical explanations for any significant differences in performance between these configurations.
- 3) Compare the source measured output and performance variables to the predictions from the global plasma model. Calculate charge densities, electron temperatures and ion production costs from the global model and compare with the measured data. Note any differences between theory and experiment and explore these differences.

These objectives are part of a larger objective as clearly stated by Dr. T. Grotjohn to “advance the understanding of the electromagnetic coupling and heating processes in physically bounded, ECR and non-ECR, overdense microwave discharges operating at conditions of interest for plasma-assisted materials processing” [Gro-00].

### 1.3 Summary of this Dissertation:

The three main parts of this dissertation are: 1) a review of the literature (*Chapter 2*), 2) a description of the equipment and theoretical background (*Chapters 3-6*), and 3) a discussion of the results of the research conducted in this investigation (*Chapters 7-10*).

Chapter 2 reviews the literature on recent non-magnetized microwave plasma sources and briefly analyses the physical principles of their operation. Chapter 3 is a description of the experimental system used in this investigation. In Chapter 4 the basic input output model is presented with a description of the system variables. Chapter 5 is a detailed discussion of the single Langmuir probe technique used in this investigation. In Chapter 6 the global plasma model is explained in detail and related to important observable plasma parameters. Chapter 7 presents single Langmuir probe measured electron energy distribution functions, electron temperatures, and plasma potentials for both magnetized and non magnetized sources for several power and pressure levels. Similarly, Chapter 8 presents the single Langmuir probe measured charge densities vs. power and pressure and vs. radial and axial location. Photographs of the plasma are also given in Chapter 8. Chapter 9 discusses the measurement of discharge wall temperature with an optical thermocouple, and an accompanying power balance model is used to explain the results. Chapter 10 is a detailed discussion of all the findings of this research and the corresponding physical explanations. Follow on research is also discussed in the final section of Chapter 10.

## Chapter 2

### Literature Review:

#### Large Area Non-Magnetized Microwave Plasma Sources

##### 2.1 Background: Early Nonmagnetized Microwave Plasma Discharges

##### 2.2 Large Area Dielectric Slab Sources

###### 2.2.1 A Waveguide Excited Planar Surface Wave Plasma Device

###### 2.2.2 An End-Feed-Cavity Excited Dielectric Slab Source

###### 2.2.3 The Concentric Spread Plasma Source

###### 2.2.4 A Microwave Plasma Device with High-Permittivity Material Window

##### 2.3 The Large Tube Surface Wave Plasma Source (Okamoto Cavity)

##### 2.4 The Distributed Element Microwave Plasma Source

##### 2.5 Conclusion

## Chapter 2

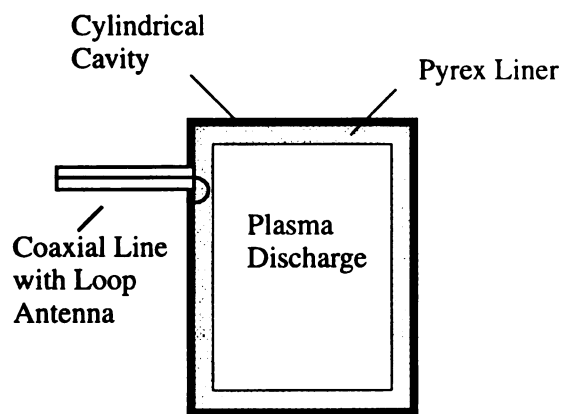
### Literature Review:

#### Large Area Non-Magnetized Microwave Plasma Sources

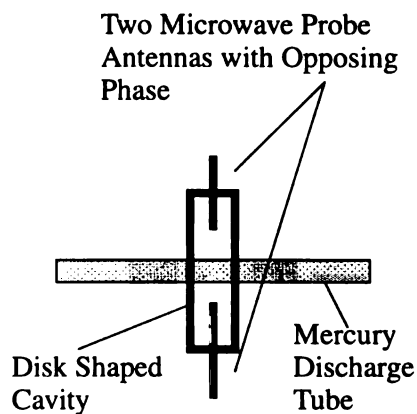
##### **2.1 Background: Early Nonmagnetized Microwave Plasma Discharges**

Nonmagnetized low pressure microwave sources are not new. They have been around in some incarnation since researchers started exciting plasmas with microwaves [Bro-52, Agd-62, Hal-69, Lep-71, Fre-71b, Asm-74, Moi-79]. However, since the heating mechanisms that allow microwave discharges to operate at low pressures were not well known or understood, most research from the mid 1970's to the early 1990's centered on electron cyclotron resonance discharges for low pressure (less than ~50 mTorr) plasma production. Excitation of plasmas without magnetic fields was thought to be impossible or unreliable since the electron neutral collision frequency was so low ( $\sim 1 \times 10^7$  1/s) at pressures near or below 10 mTorr and this meant that ohmic heating in the discharge would be very limited.

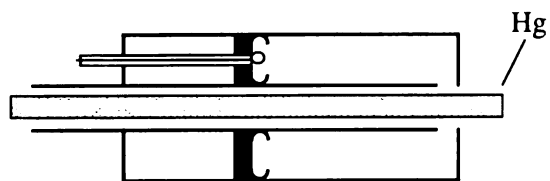
Some early nonmagnetized microwave plasma sources to be described are shown in Figure 2.1. Halverson and Hatch [Hal-69] investigated a loop excited cylindrical cavity where the plasma was allowed to fill the entire discharge cavity. The inside of the cavity was lined with a Pyrex vacuum liner.



Halverson and Hatch, 1969

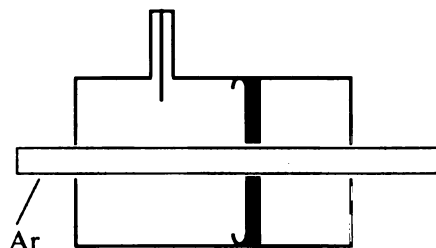


Leprince, et. al., 1971



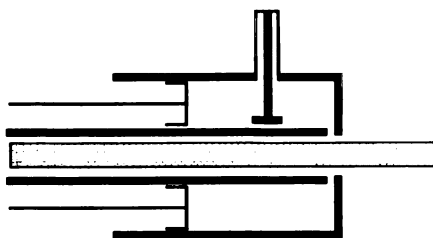
Reentrant Coaxial Cavity with  
Sliding Short and Loop Antenna

Fredericks and Asmussen, 1971



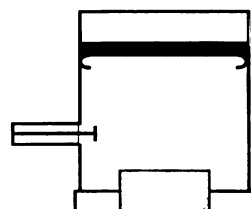
Cylindrical Cavity with  
Sliding Short and Probe Antenna

Asmussen et. al. , 1974



Coaxial Surface Wave Launching  
Source with Capacitive Probe Coupler

Moisan, et. al., 1979



Cylindrical Cavity with  
Plasma Discharge at Bottom

Root and Asmussen, 1982

Figure 2.1 - Several Early Nonmagnetized Microwave Plasma Discharges

Leprince, Matthieussent, and Allis[Lep-71] investigated a small disk shaped cavity that excited a mercury discharge. The cavity was excited below fundamental resonant frequency with two probe antennas that were 180 degrees out of phase with each other, producing a dipolar excitation field.

Fredericks and Asmussen [Fre-71, Fre-71b] investigated a coaxial short-gap (or reentrant) cavity with a sliding short and coupling loop antenna at one end for internally tuning the cavity. This discharge consisted of a mercury discharge tube that could also be sustained with a DC current (useful for low power microwave resonance studies). Electromagnetic modes excited in this cavity were primarily the coaxial half-wavelength eigenmodes.

Asmussen et. al. [Asm-74] also investigated a cylindrical cavity source terminated at one end with a sliding short. Power was delivered to this source through an adjustable probe antenna at the side of the cavity. Several transverse electric (TE) and transverse magnetic (TM) eigenmodes could be excited in the plasma loaded cavity. A quartz tube flowing argon (or other gasses) passed axially through the center of the cavity. This source was able to operate at powers of 100 to 500 Watts with pressures ranging from several Torr down to ~10 mTorr. At the time, this low pressure operation (~10 mTorr) raised questions among the researchers (Asmussen et. al.) about how the discharge could be ohmically (collisionally) sustained with such high electron mean free path and low electron-neutral collision frequency.

Another source with similar electromagnetic features to the reentrant cavity investigated by Fredericks and Asmussen was introduced by Moisan, et. al. [Moi-79] and extensively developed in the following years. This source had an adjustable length coaxial

cavity with a capacitively coupled probe antenna at the side. The main feature of this source is its ability to launch plasma surface waves along the discharge tube with the small gap at one end of the coaxial cavity.

Root and Asmussen [Roo-82, Roo-85] developed a microwave plasma source consisting of a cylindrical cavity with the plasma discharge excited at the bottom of the cavity. Several electromagnetic eigenmodes including TE and TM modes could be excited in this cavity source. Many types of discharge gasses could be used including molecular reactive gasses. This apparatus was initially designed as an ion beam source, but later was developed extensively for materials processing.

Most of the above plasma discharges were designed mainly for scientific studies of the behavior of plasma discharges in microwave excited systems. However, the last discharge geometry [Roo-82, Roo-85] was well suited for plasma processing applications such as for materials and semiconductor wafer processing. Similarly, the plasma sources discussed in the next sections of this literature review are designed primarily for large area semiconductor wafer processing.



## 2.2 Large Area Dielectric Slab Sources

Several large area dielectric slab sources have been investigated by a large number of researchers over the last seven years. All of these microwave source designs have a common feature: a large dielectric slab or window where surface-waves are launched and spread out over the volume of the slab (or form a resonance in the slab) and deliver power to the plasma on the lower face of the slab (See Figure 2.2). The main differences between these sources are the way the surface waves are launched using different microwave applicators.

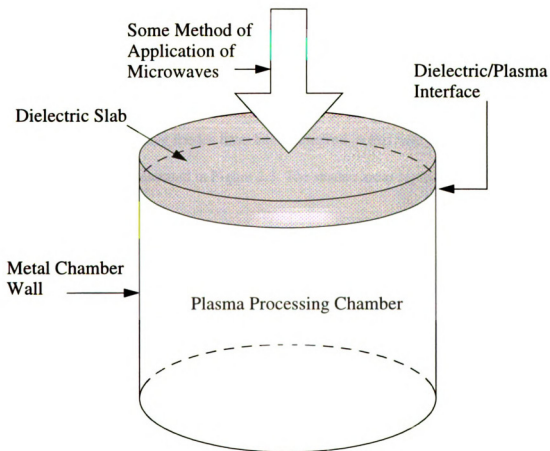


Figure 2.2: Basic elements of a Large Area Dielectric Slab Source

### 2.2.1 A Waveguide Excited Planar Surface Wave Plasma Device

The first of these surface-wave sources to appear was the “Planar Surface Wave Plasma Device” investigated extensively by I. Ghanashev, M. Nagatsu, and H. Sugai [Nag-96, Gha-97, Sug-98, Nag-98, Gha-99]. This source consisted of a square waveguide propagating the fundamental  $TE_{01}$  mode placed on top of a large disk like dielectric slab (240 mm diameter). Two angled slot antennas were cut from the waveguide to provide a method of coupling between the waveguide and the dielectric slab. Microwaves enter the waveguide from the left, as shown in Figure 2.4. A movable short is placed on the right side (as shown in Figure 2.4) in order to tune the microwave coupling to the slot antennas. Not shown in the figure is a microwave generator that is isolated from the source by a waveguide circulator as is common for microwave plasma systems. All power reflected from the source passes through the circulator and into a dummy load (also not shown).

Several surface wave modes have been observed in this source. Two examples of the modes excited are illustrated in Figure 2.3. The shaded areas represent localized

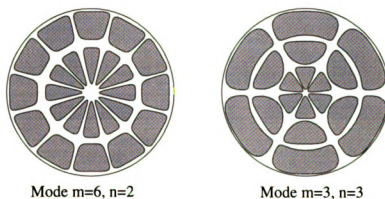


Figure 2.3 - Two surface-wave eigenmodes as seen from the bottom of the process chamber

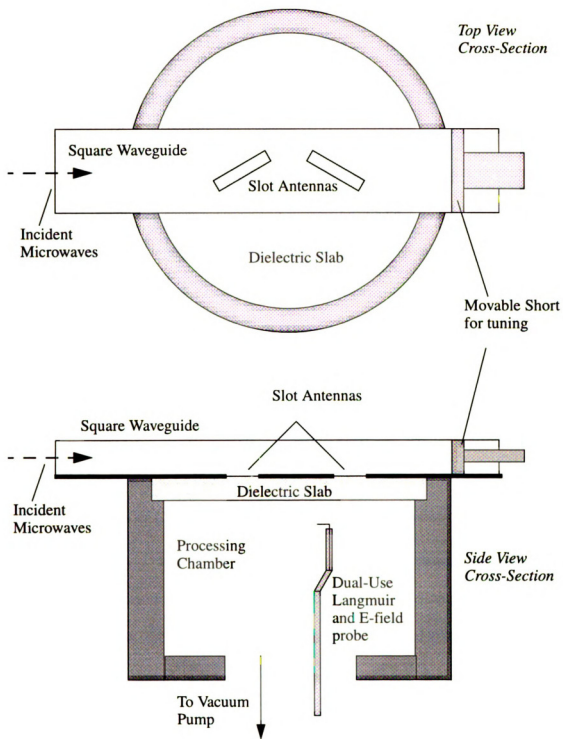


Figure 2.4 - The Planar Surface Wave Plasma Device [Gha-96]

regions of plasma excitation as they would be seen looking up at the dielectric slab from the bottom of the process chamber.

Nagatsu, et. al. used this plasma source to study plasma resonances near the plasma/dielectric boundary. In their apparatus they used a single Langmuir probe that also could be used as a small coaxial probe antenna (see Figure 2.4) to measure electric fields inside the plasma discharge [Nag-96, Gha-99]. They found a local peak in electric field strength near the location where the plasma density equals the critical density (i.e. where  $\epsilon=0$ ). This local peak in electric field strength was seen to move closer to the dielectric slab when the overall charge density was higher and move away from the slab interface when the overall charge density was lower [Gha-99] (overall charge density could be varied by increasing or decreasing absorbed power). These findings have implications for the study of collisionless heating discussed later in this dissertation (Chapter 6, and Chapter 10).

This discharge can be operated at 2.45 GHz with a power of 1-2 kW and pressures of ~10 mTorr argon or CF<sub>4</sub>. Charge densities measured in this power and pressure range were approximately  $1 \times 10^{11} \text{ cm}^{-3}$ . Note: this value of charge density is similar to the charge densities measured at 10 mTorr for the microwave source discussed in this dissertation. This source has been used in plasma etching. When operated at lower pressure of 0.3 to 1 Torr the charge density output is on the order of  $2 \times 10^{12} \text{ cm}^{-3}$  for argon.

### 2.2.2 An End-Feed-Cavity Excited Dielectric Slab Source

Another surface wave source was developed by Odobinda, Kudela, and Kando [Odr-98, Kud-01] that utilized an end feed microwave cavity as the microwave applicator. The cylindrical cavity (similar to the cavity design discussed in Chapter 3 of this dissertation) had an internal diameter of 11 cm. It also was tuned with the adjustment of a movable short and adjustable probe antenna at the top of the cavity structure. At the bottom of the cavity structure was an annular slot antenna that was bounded by the inner wall of the cavity. Microwaves from the cavity passed through this annular slot antenna into a 35 cm diameter quartz disk which is bounded on the top by a metal plate and on the bottom by the plasma discharge. Power was delivered to the plasma through the propagation of surface waves along this quartz disk. The quartz disk formed the entire top of the discharge/process chamber which had a diameter of 31.2 cm and a height of 35 cm.

The annular slot antenna preferentially excites modes in the dielectric/plasma system that are azimuthally symmetric. This is beneficial since it creates more uniform plasmas for wafer processing.

This source operates with the standard 2.45 GHz microwave frequency. Power delivered to the source is from 1 to 2 kW at pressures from 5 to 200 mTorr. At 5 mTorr and absorbed power of 1400W the measured charge density was  $6.6 \times 10^{11} \text{ cm}^{-3}$ . If higher pressures of 200 mTorr are used the charge densities can be as high as  $5.5 \times 10^{12} \text{ cm}^{-3}$  for 1 kW of absorbed power. Electron temperatures were also measured in this discharge at 5 mTorr and found to be near 2 eV.

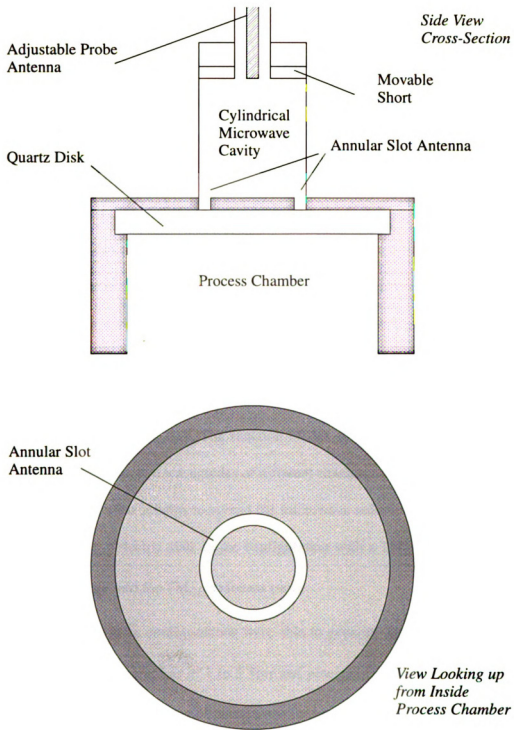


Figure 2.5 - An End-Feed-Cavity Excited Dielectric Slab Source [Odr-98]

### 2.2.3 The Concentric Spread Plasma Source

Following the theme of an azimuthally symmetric applicator another source has been developed by Watanabe, Masahiro, Sumiya, and Kawasaki that applies a coaxial applicator directly to the dielectric slab (See Figure 2.6). This coaxially excited concept was also explored by these researchers in a modified design (See Figure 2.7) that included a cavity resonator and ring of angled slot antennas over the dielectric slab.

Both source designs investigated by Watanabe, et. al. were powered by a 2.45 GHz magnetron that operated at powers up to 1.2 kW. The magnetron was isolated from reflected power by a waveguide circulator and dummy load. A waveguide to coaxial converter was used to deliver power to the coaxial input at the top of the microwave applicator. A small impedance transforming structure is introduced at the interface between the coaxial line and the dielectric slab. The function of this structure is similar to a quarter wave transformer between two waveguides of different characteristic impedance. From the electric field point of view it helps to spread the microwave radiation and launch the surface wave across the dielectric slab. In the configuration with a  $TM_{011}$  resonant cavity it helps to couple energy into the  $TM_{011}$  resonant mode.

Both plasma source configurations were able to generate densities from  $3.8 \times 10^{11}$  to  $5 \times 10^{11} \text{ cm}^{-3}$  in  $O_2$  at pressures of 1 to 5 Torr and powers of approximately 1 kW. It is interesting to note that a bright ring of plasma was formed under the dielectric slab for the coaxial applicator. This ring of plasma was seen to increase in diameter with increasing power. It was also seen to decrease in diameter with increasing pressure. Watanabe, et. al have speculated that this ring plasma is a self guided microwave structure.

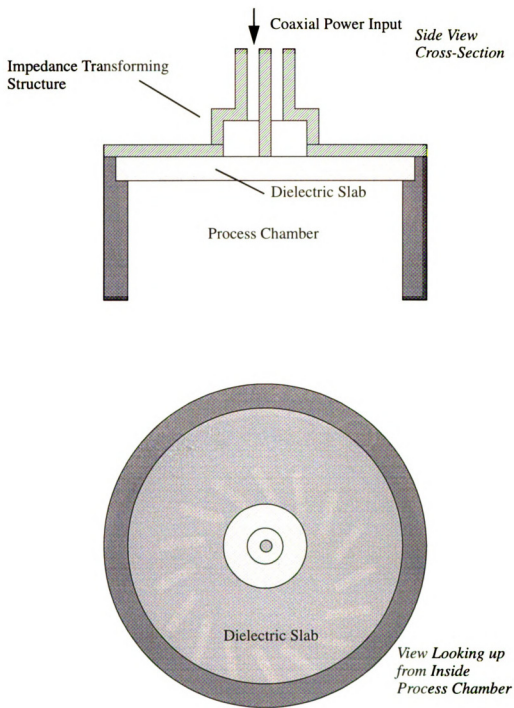


Figure 2.6 - The Concentric Spread Plasma Source



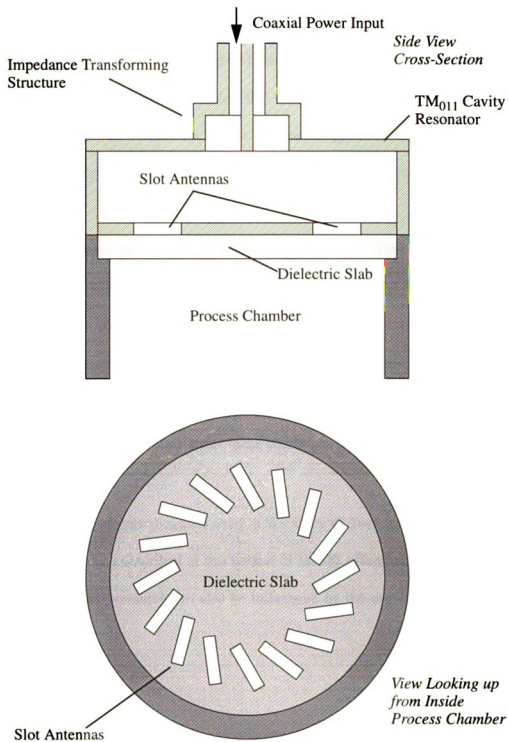


Figure 2.7 - A modified version of the concentric spread plasma source using a resonant cavity and a ring of slot antennas

## 2.2.4 A Microwave Plasma Device with High-Permittivity Material Window

Research by Furukawa, et. al. [Fur-98] has demonstrated that the dielectric constant of the material chosen for the dielectric slab can be used to enhance plasma charge density. This research was carried out with a microwave applicator that consisted of a TE<sub>10</sub> to TM<sub>01</sub> rectangular to circular mode converter and a section of tapered circular waveguide structure.

Experiments were performed at microwave power levels from 100 to 1000W in argon at a pressure of 1 Torr. Furukawa, et. al found that output charge density was significantly effected by the choice of dielectric material. For a 7 mm thick quartz plate charge densities for an absorbed power of 1000W and pressure of 1 Torr were  $\sim 1 \times 10^{12} \text{ cm}^{-3}$ . For the same conditions a quartz plate with thickness of 13 mm delivered a charge density of  $3.5 \times 10^{12} \text{ cm}^{-3}$ . For an alumina plate under these conditions a charge density of  $8.5 \times 10^{12} \text{ cm}^{-3}$  is obtained.

Although the discharge pressures used in this study (1 Torr) are much higher than those of the other sources described in this review (5 to 100 mTorr) it is very likely that charge density at lower pressures can also be influenced by the use of a high dielectric constant window.

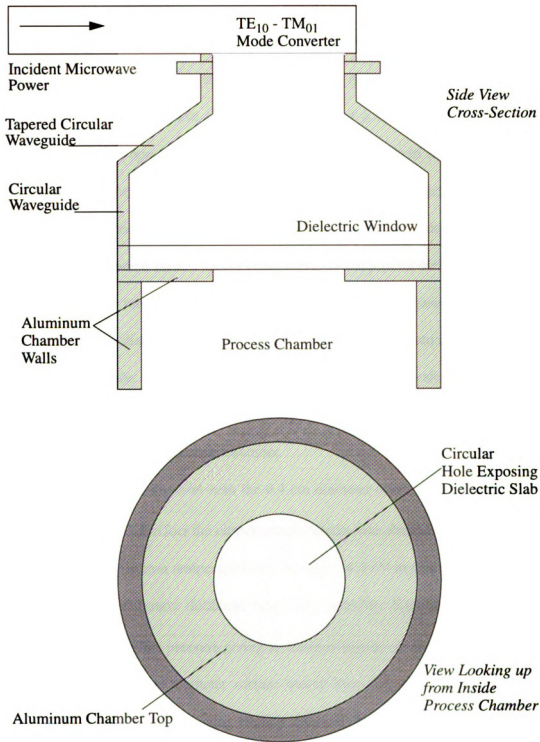


Figure 2.8 - The High-Permittivity Window Plasma Device

### 2.3 Large Tube Surface Wave Plasma Source (Okamoto Cavity)

A plasma source with a gap launched surface wave tube was developed by Okamoto [Oka-96]. This source was excited by 2.45 GHz microwaves through a standard waveguide input. The microwave applicator consisted of a rectangular resonant cavity with a tapered circular opening cut through the narrow dimension of the rectangular cavity. The tapering of the cavity near the circular opening (through which a quartz plasma discharge tube is placed) provides ideal conditions for the high intensity fringing electric field structures that launch surface waves along a cylindrical plasma dielectric interface.

The discharge tube first used in this design was 6.4 cm in diameter and was later increased to 16 cm in diameter with a correspondingly larger Okamoto cavity by Kaneko, et. al. [Kan-98] in order to provide a larger area plasma for large wafer processing. The process gas flows into both discharges at the top of the quartz tube and continues down through the quartz tube to the process chamber.

In Okamoto's investigation with the 6.4 cm diameter source at an input power of 500W and pressure of 3.3 mTorr the output charge density was about  $1 \times 10^{11} \text{ cm}^{-3}$ .

Okamoto also found electron temperatures in the range of 3 eV in this discharge. For the larger (16cm diameter) quartz discharge tube investigated by Kaneko, et. al. the input power was 700W at 4 mTorr pressure giving an electron density of near  $1.5 \times 10^{11} \text{ cm}^{-3}$ .

Several similar large diameter surface waved launched plasma tubes have been investigated by other researchers using slightly different means of launching the surface wave along the tube. Notable among these are M. Moisan, et. al.[Moi-95] and J. Engemann, et. al. and others [Wu-99, Bec-97]

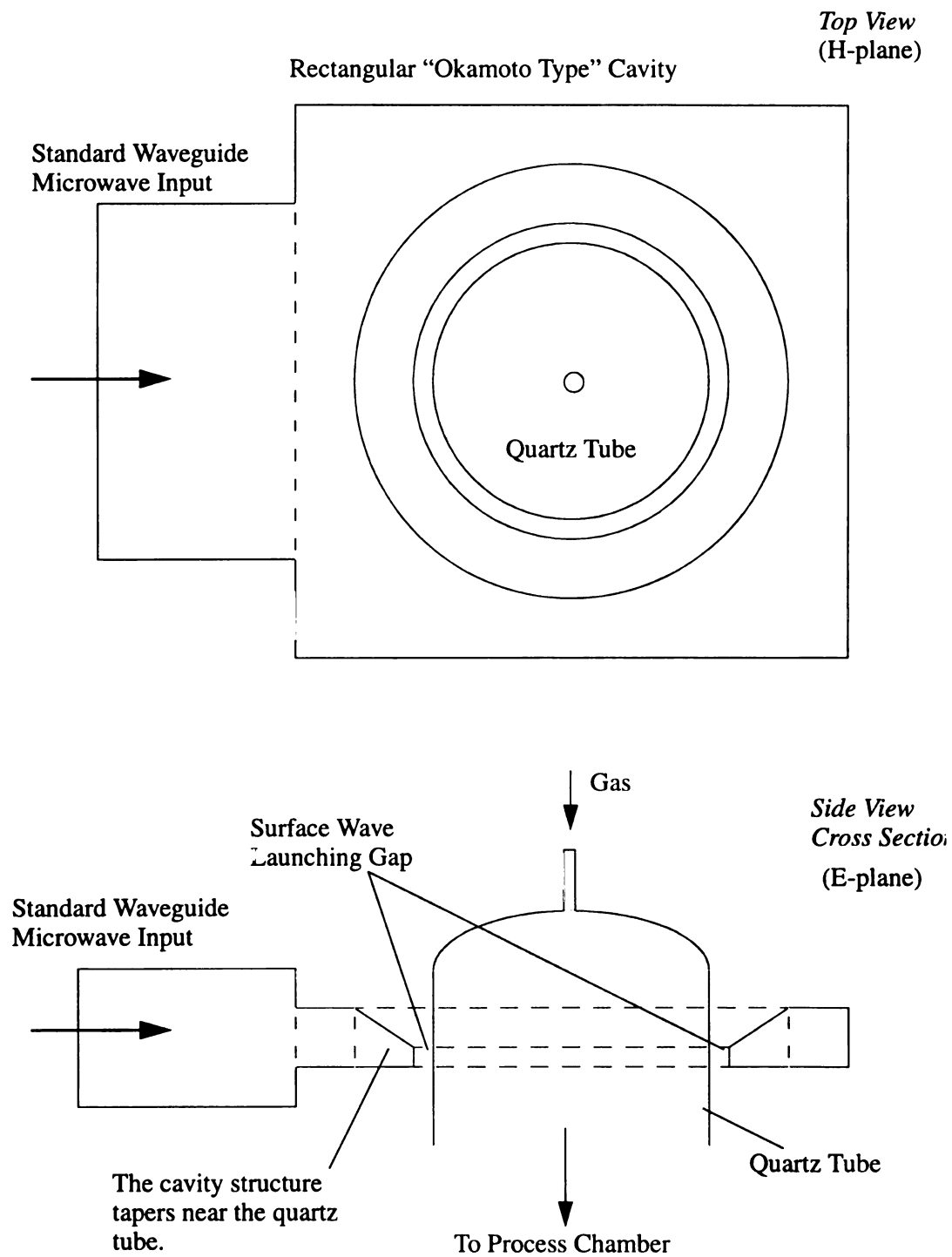


Figure 2.10 - The Large Tube Surface Wave Source (Okamoto Cavity) [Oka-96]

## 2.4 The Distributed Element Microwave Plasma Source

The next nonmagnetized microwave source is somewhat of a departure from the previous sources described in this review. It has a rectangular geometry instead of a circular. It is also based on damping any kind of standing wave that may exist in the structure, with matched loads at all waveguide termination points. In fact this source does not use any matching device such as a triple stub tuner external to the applicator. The other sources in this review have some kind of resonant structure that requires tuning either internally or externally.

This “distributed element microwave plasma source” as it is known, was investigated by Guo and Ohl [Guo-98, Ohl-98]. The microwave applicator consisted of two R22 rectangular waveguides assembled in a T-shape configuration (as shown in Figure 2.11). The incident 2.45 GHz microwave power was delivered to the upper waveguide which propagated the  $TE_{01}$  mode. This microwave power was then coupled selectively into the lower waveguide with an array of tunable coupling elements distributed along the length of the interface of the two waveguides. Ideally the coupling antennas can be adjusted such that microwave power is delivered evenly (or optimally) across the length of the rectangular quartz window and generating a uniformly distributed plasma discharge. Several of these sources are intended to be assembled side by side to create a very large square area of uniform plasma discharge for large area processing.

The microwave power applied to this plasma source was 0.1 to 1 kW at pressures from 10 mTorr to 700 mTorr. For low pressure conditions charge densities on the order of  $1 \times 10^{11} \text{ cm}^{-3}$  have been reported.

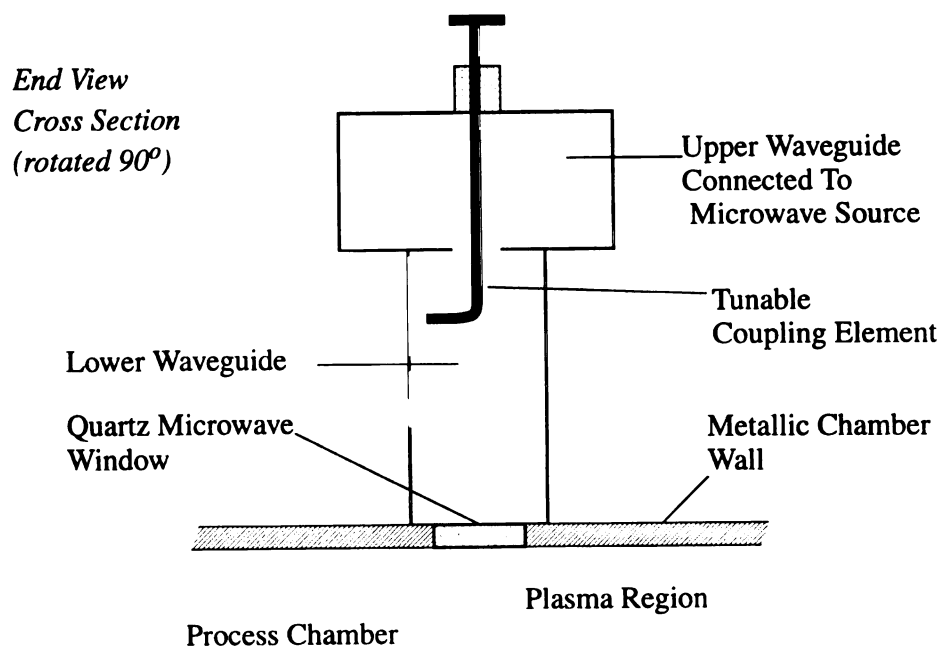
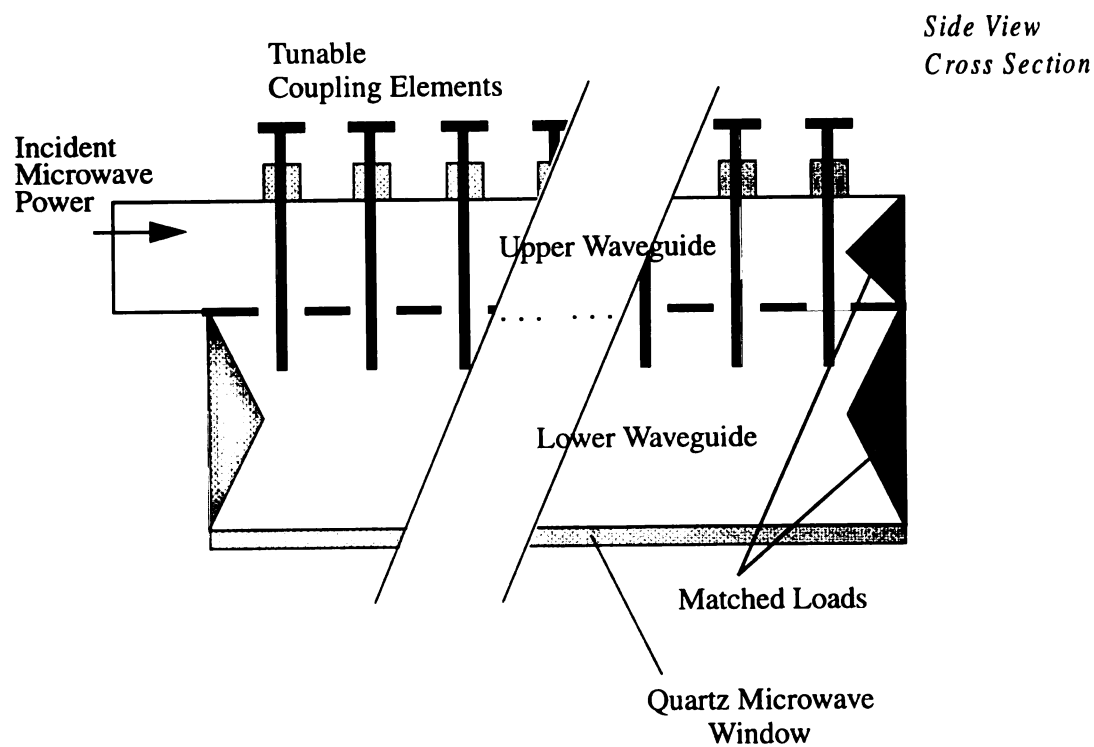


Figure 2.11 - The Distributed Element Microwave Plasma Source

## **2.5 Conclusion**

Several nonmagnetized microwave plasma sources were described in the above review. All of the large area sources were based upon either standing surface waves (sections 2.2.1-2.2.4) or traveling surface waves (sections 2.3-2.4). The dielectric medium for propagating these surface waves was either a large dielectric slab at the top of the process chamber or a quartz discharge tube.



## Chapter 3

### The Experimental System

#### 3.1 Introduction

#### 3.2 System Overview

#### 3.3 The Plasma Source

#### 3.4 The (500 W Capacity) Microwave Power Supply

#### 3.5 The (1500 W Capacity) Microwave Power Supply

#### 3.6 The Gas Delivery and Vacuum Systems

## Chapter 3

### The Experimental System

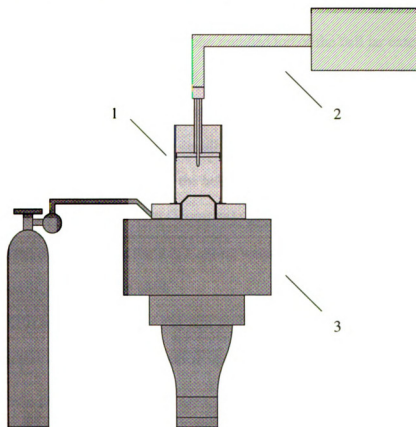
#### **3.1 Introduction:**

The microwave plasma reactor described in this chapter is the latest version of a microwave reactor with a quartz enclosed plasma disk discharge first introduced in the early 1980's by Root and Asmussen [Roo-85]. It is the result of many years of design innovations contributed by Asmussen and several co-researchers [Dah-87,Hop-90,Sze-93,Mak-97]. An account of the historical development of this plasma source design can be found in several sources [Sze-93,Mak-97]. The version of this microwave plasma reactor, described in this chapter, was designed and constructed by P. Mak and the details of this design are also described in his Ph.D. Dissertation [Mak-97]. The research described in this dissertation continues research initiated by P. Mak to characterize this source's performance and develop a physical understanding of its operation.

The objective of this chapter is to give an overview of the major components of the experimental system and then describe each of those components in detail. Note: when the variables of the experimental system are encountered their variable classification is listed in boldface. These boldface variables representing input  $U$ , internal  $X$  and output  $Y$ , variables are described in detail in chapter 4.

### 3.2 System Overview:

The experimental system consists of three main subsystems: 1) the plasma reactor [where the microwave energy is focused into the plasma discharge], 2) the microwave power delivery system, and 3) the vacuum and process gas delivery system. These subsystems are depicted in Figure 3.1. Note: two different microwave power delivery systems were used, one with a 500 W capacity and another with a 1500 W capacity. Each of these subsystems are described in sections 3.3, 3.4, 3.5, and 3.6.



- 1) Microwave Plasma Reactor
- 2) Microwave Power Delivery System
- 3) Gas Delivery and Vacuum System

Figure 3.1 - Block Diagram of The Experimental System

### 3.3 The Plasma Source:

The plasma generating apparatus, shown in Fig. 3.2, consists of a 17.78 cm diameter ( $U_2$ : cavity radius  $R_A = 8.89$  cm) aluminum cavity applicator (1) with a sliding short (2) ( $U_1$ : cavity height  $L_s$ ) and an adjustable probe antenna (3) ( $U_1$ : probe length  $L_p$ ) allowing internal cavity tuning. Finger stock (4) is used to provide electrical contact between the sliding short and the cavity walls and also is used to provide electrical contact at the base of the cavity. The argon discharge is generated in the volume of a 13 cm inner diameter ( $U_2$ : discharge radius  $R = 6.5$  cm), 10.25 cm tall ( $U_2$ : discharge height  $l = 10.25$  cm), quartz bell jar (6). Note that only 3.3 cm of the rounded top of the bell jar extends into the volume of the cavity. The bell jar is cooled by compressed air through eight air cooling holes (7) equally spaced around the bottom of the bell jar. Argon enters the chamber through 8 (1/64" diameter) pin holes (9) equally spaced around the circumference of the stainless steel base plate at the bottom of the bell jar.

ECR magnets (11) ( $U_2$ :Magnet Geometry) can be placed in the apparatus near the center plane of the discharge, See Fig 3.2. Cooling water circulates through a channel (12) around the magnets when they are used.

Single (16) and Double (17) Langmuir probes are positioned inside the discharge to measure electron densities ( $Y_2:n_e$ ) and temperatures ( $Y_2:T_e$ ). A microcoaxial electric field measurement probe (18) is inserted into the many E-field measurement holes (5) in the wall of the aluminum cavity wall. The power sampled by the E-field probe is measured by a microwave thermistor/power meter (19). From this sampled power the electric field normal to the cavity wall ( $X:|E_r|$ ) can be calculated from a calibration constant.

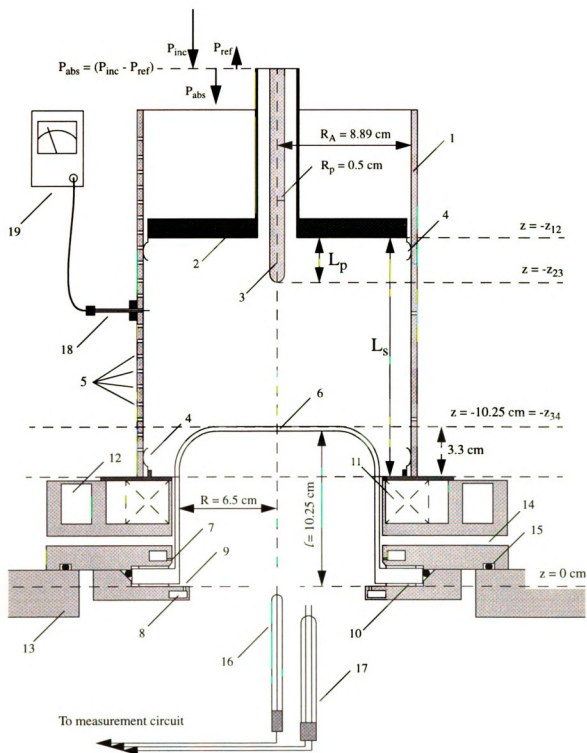


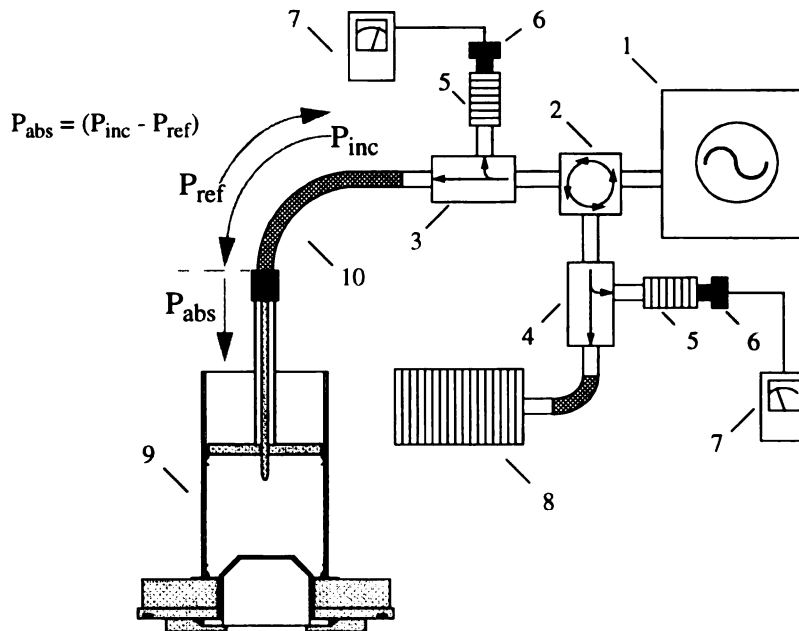
Fig. 3.2: Diagram of the Microwave Plasma System and Diagnostic Probes

- |                              |                              |
|------------------------------|------------------------------|
| 1) Aluminum Cavity Wall      | 11) ECR Magnet Location      |
| 2) Brass Sliding Short       | (when magnets are present)   |
| 3) Aluminum Excitation Probe | 12) Water Cooling Channel    |
| 4) Finger Stock              | 13) Vacuum Chamber Top Plate |
| 5) E-Field Measurement Holes | 14) Laser Access Port        |
| 6) Quartz Discharge Chamber  | 15) Rubber O-ring            |
| 7) Air Cooling Hole          | 16) Single Langmuir Probe    |
| 8) Discharge Gas Channel     | 17) Double Langmuir Probe    |
| 9) Discharge Gas Outlet Hole | 18) E-Field Probe            |
| 10) Teflon Spacer            | 19) Microwave Power Meter    |

Fig. 3.2 - Continued - (Number Key)

### 3.4 The (500 Watt Capacity) Microwave System:

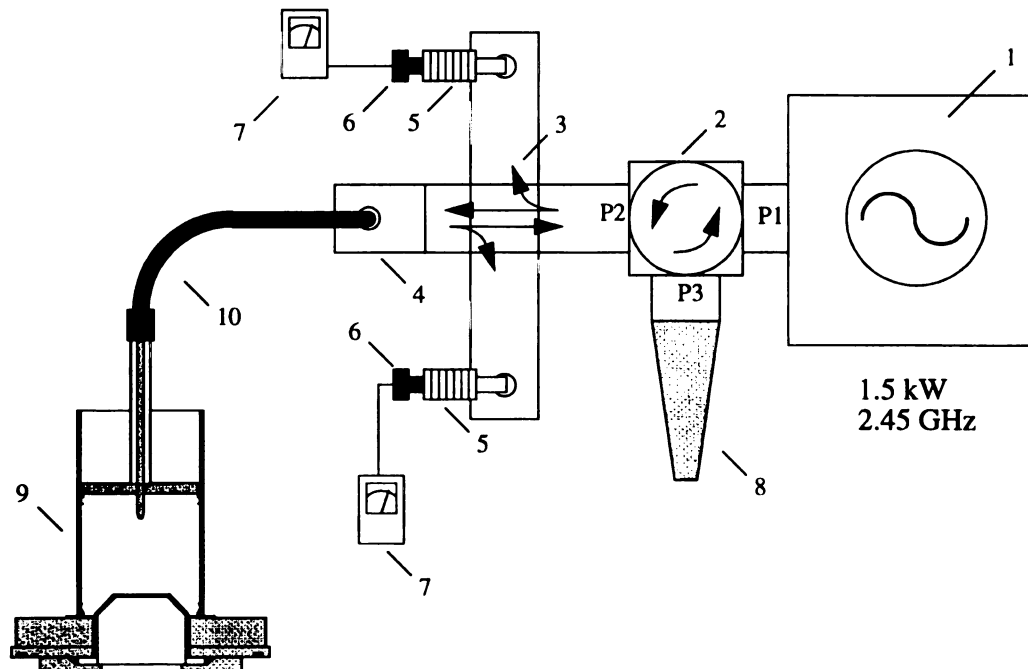
The 2.45 GHz ( $U_1:f$ ) microwave power is generated by a 500 W rated magnetron power supply (1) from MicroNow, Inc. (See Fig. 3.3a). A three port circulator (2) is used to isolate the power supply from the microwave circuit. Two directional couplers are used: one with a 30 dB sampling port to measure incident power (3) ( $U_1:P_{inc}$ ), and another with a 20 dB sampling port to measure reflected power (4) ( $X:P_{ref}$ ). A 20 dB attenuator (5) is connected to each sampling port bringing the attenuation to a total of 50 dB for incident power and 40 dB for reflected. The output of each attenuator is connected to a Hewlett Packard 478A themistor sensor (6) and an HP432A power meter (7). Reflected power is dissipated in a 500 W rated matched load (8). Power is delivered to the microwave cavity (9) through a 700 W rated coaxial cable (10) with a measured 0.7 dB attenuation. All microwave conduits have characteristic impedance of  $50\ \Omega$  and all connectors are n-type.



**Figure 3.3a - 500W Microwave Delivery System:** (1) 2.45 GHz power supply, (2) circulator, (3) forward power directional coupler, (4) reflected power directional coupler, (5) 20 dB attenuator, (6) thermistor power sensor, (7) power meter, (8) matched load, (9) microwave cavity, (10) coaxial cable.

### 3.5 The (1500 Watt Capacity) Microwave System:

The 2.45 GHz ( $U_1:f$ ) microwave power is generated by a 1500 W rated magnetron power supply (1) from Cheung, Inc. (See Fig. 3.3b). The power output port from this source is a standard rectangular waveguide. P1 (Port 1) of a waveguide circulator (2) is connected at this power output. A 1000W rated, water cooled, dummy load (8) is connected to P3 of the circulator. A cross waveguide dual directional coupler (3) with 40 dB of attenuation was connected to P2 of the circulator. A 20dB attenuator (5) is added at each of the forward and reflected sensing outputs for a total of 60dB of attenuation. A thermistor power sensor (6) and power meter (7) is attached to each of the attenuated outputs. A waveguide to coax converter (4) was used to connect to a 900W rated coaxial cable (10) in order to deliver power to the microwave cavity (9).

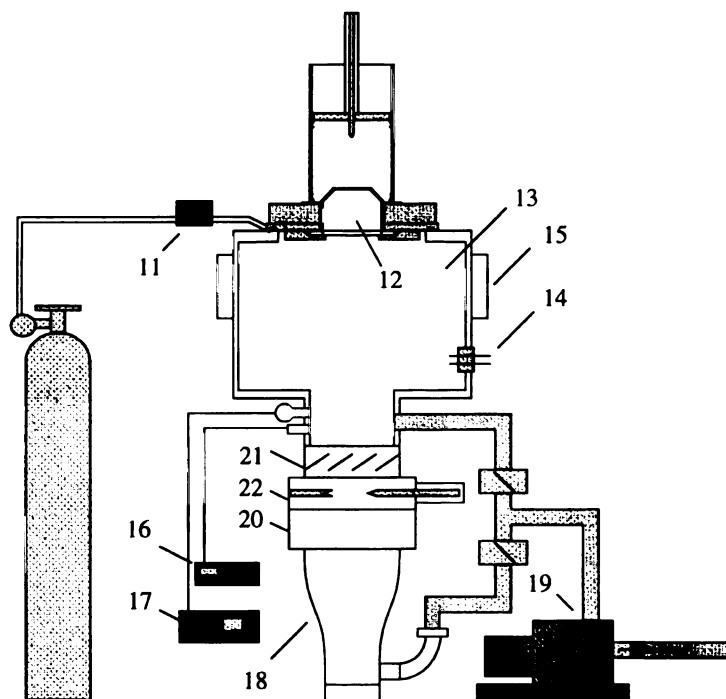


**Figure 3.3b - 1500W Microwave Delivery System:** (1) 2.45 GHz power supply, (2) 3 port circulator, (3) crossed waveguide directional coupler, (4) waveguide to coax converter, (5) 20 dB attenuator, (6) thermistor power sensor, (7) power meter, (8) water cooled dummy load, (9) microwave cavity, (10) coaxial cable.



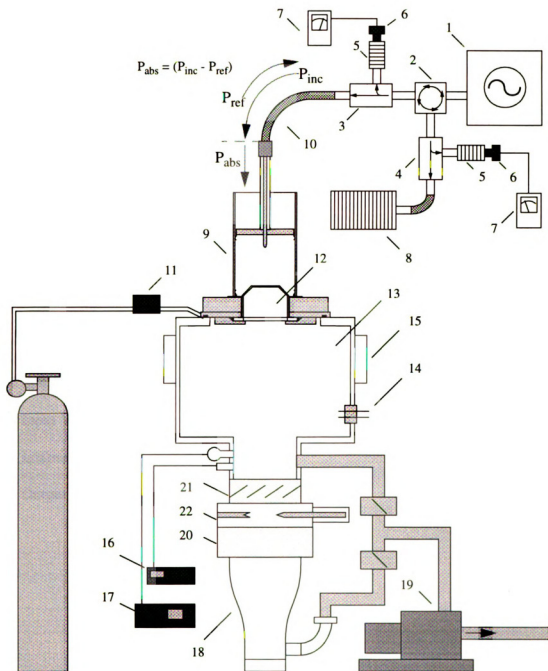
### 3.6 The Gas Delivery and Vacuum System:

Argon gas ( $U_1$ :Gas Type) of 99.999% purity flows ( $U_1$ : $f_t$ ) through a 50 sccm max. flow (or a 400 sccm max. flow) MKS digital flow controller (11) into the discharge chamber (12). The discharge chamber sits on top of a 285 liter stainless steel vacuum chamber (13), with electrical feed-through (14) and 5 windows (15) for viewing the plasma. Pressures ( $U_1$ : $p$ ) in the chamber are measured by: an MKS (1 mTorr rated) baratron gauge (16) which measures pressures from 0.1 mtorr to 100 mtorr, and an ion gauge (17) which measures pressures from  $10^{-7}$  to  $10^{-3}$  Torr.



**Figure 3.4 - Gas Delivery and Vacuum System:** (11) mass flow controller, (12) discharge chamber, (13) vacuum chamber, (14) electrical feed through, (15) window, (16) baratron pressure gauge, (17) ion pressure gauge, (18) diffusion pump, (19) mechanical pump, (20) cold trap, (21) automated throttle valve pressure controller, (22) high vacuum gate valve.

The vacuum chamber is evacuated by a, 1250 l/s, water cooled diffusion pump (18) charged with inert Santovac 5 diffusion pump oil. The diffusion pump is backed by a, 11 l/s, 2033C Alcatel mechanical pump (19). Above the diffusion pump is a freon cooled cold trap (20). The chamber pressure is controlled by: an MKS-651C pressure controller with throttle valve (21) and a manual high vacuum gate valve (22). Base pressures measured by the ion gauge are below  $10^{-6}$  Torr.



**Figure 3.5 - Experimental System:** (1) 2.45 GHz power supply, (2) circulator, (3) forward power directional coupler, (4) reflected power directional coupler, (5) 20 dB attenuator, (6) thermistor power sensor, (7) power meter, (8) matched load, (9) microwave cavity, (10) coaxial cable, (11) mass flow controller, (12) discharge chamber, (13) vacuum chamber, (14) electrical feed through, (15) window, (16) baratron pressure gauge, (17) ion pressure gauge, (18) diffusion pump, (19) mechanical pump, (20) cold trap, (21) automated throttle valve pressure controller, (22) high vacuum gate valve.

## Chapter 4

### The Multivariable Plasma Reactor

#### 4.1 The Input/Output Model

#### 4.2 Specific Experimental Variables

#### 4.3 Input Variables

#### 4.4 Internal Variables

#### 4.5 Output Variables

## Chapter 4

### The Multivariable Plasma Reactor

#### 4.1 The Input/Output Model:

Given a system under investigation, such as a microwave plasma reactor, it is customary and useful to formulate a model where the system's input vectors, knowable internal variables or states, and output vectors are defined and categorized. Such a model provides a framework for logical investigation of the input-output behavior and unknown internal workings of the system. Figure 4.1 depicts this input/output model where the vector  $U$  represents the collection of all input variables,  $X$  represents the collection of all internal variables, and  $Y$  represents the collection of all output variables. Each vector  $U$ ,  $X$ , or  $Y$  can be subdivided into coherent categories of subvectors. For example, the input

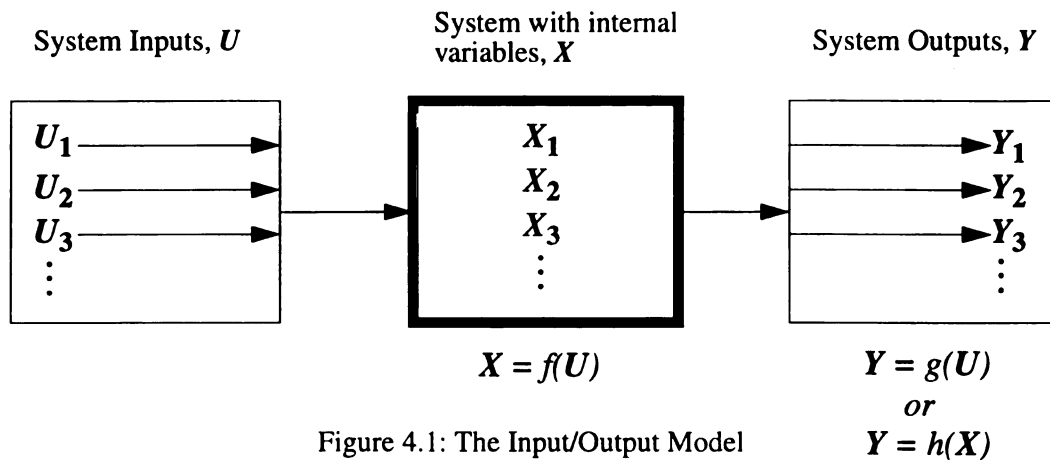


Figure 4.1: The Input/Output Model

vector  $U$  can be subdivided into subvectors  $U_1$ ,  $U_2$ , and  $U_3$ , etc., each representing a categorized collection of individual inputs. Examples of individual inputs are incident microwave power, gas flow rate, or chamber pressure. The nonlinear functional relationships between the input, internal, and output variables are shown in Figure 4.1. The internal variable vector  $X$  is a function of the system inputs  $U$ , i.e.  $X = f(U)$ . The output variable vector can be represented as either a function of the input variable vector  $U$ , i.e.  $Y = g(U)$ , or a function of the internal variable vector  $X$ , i.e.  $Y = h(X)$ . The microwave plasma reactor consists of a nonlinear discharge which is a complex function of many experimental variables. Hence, the functions  $f(U)$ ,  $g(U)$ , and  $h(X)$  are complex non-linear functions dependent on many experimental variables. A comprehensive theory that describes the relationships between these variables does not yet exist, and particularly for microwave plasma reactors, the experimental relationships between  $U$ ,  $X$ , and  $Y$  are poorly understood. However, knowledge of these complex relationships is essential for improved reactor design and, ultimately, reactor control. In order to understand the behavior of a plasma reactor, not only must the relationships between the input variables and the output variables be understood, but relationships must also be established between the reactor internal variables and both the input and output variables. Investigating these input-output relationships and developing a theory that describes them is the objective of the research presented in this dissertation.

## 4.2 Specific Experimental Variables:

In the following sections the categorization, description or definition of the specific input, internal and output variables is described. Figure 4.2 depicts these specific variables in a block diagram format illustrating their relationships. Tables 4.1, 4.2, 4.3 list the specific input, internal, and output variables, respectively.

## 4.3 Input Variables:

The input variables  $U$  are defined as those that can be independently controlled by a reactor operator or designer. These input variables are divided into two input subvectors (i.e.  $U=[U_1, U_2]$ ) where  $U_1$  represents the *controllable input variables* and  $U_2$  represents the *reactor geometry variables*. Examples of controllable input variables are operating pressure,  $p$ , gas flow rate,  $f_p$ , and incident power,  $P_{inc}$ . Examples of reactor geometry variables are cavity applicator radius,  $R_A$ , and magnet geometry. A full listing of the specific input variables and their classification is given in Table 4.1. The input variables that remain constant are indicated in Table 4.1 by the side heading “Fixed” and those that are varied are labeled “Varied” with a range of values is given.

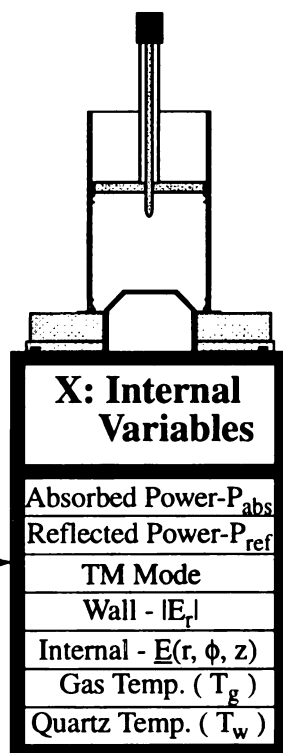
Most of the input variables listed in Table 4.1 have been explained in Chapter 3, however a few need more explanation. The aluminum applicator surface resistivity is important in the calculation of the microwave power lost to the walls. The dielectric and thermal properties of the quartz discharge chamber play an important role in electromagnetic coupling to the plasma and determining the temperature distribution of the quartz walls. The variable coupling configuration is given to emphasize that other methods of coupling into a microwave cavity applicator can be used, such as: with an

## U<sub>2</sub>: Reactor Geometry Variables

|                                    |
|------------------------------------|
| Cavity Applicator Radius ( $R_A$ ) |
| Excitation Probe Radius ( $R_p$ )  |
| Discharge Chamber Radius ( $R$ )   |
| Discharge Chamber Height ( $l$ )   |
| Applicator Material                |
| Discharge Chamber Material         |
| Coupling Configuration             |
| Magnet Configuration               |

## U<sub>1</sub>: Macroscopic Controllable Input Variables

|                              |
|------------------------------|
| Excitation frequency ( $f$ ) |
| Gas Type                     |
| Pressure ( $p$ )             |
| Gas Flow Rate ( $f_t$ )      |
| Incident Power ( $P_{inc}$ ) |
| Cavity Height ( $L_s$ )      |
| Probe Length ( $L_p$ )       |



## Y<sub>1</sub>: Reactor Figures of Merit

|                                                |
|------------------------------------------------|
| Ion Production Cost ( $\eta_{ion}$ )           |
| Microwave Coupling Efficiency ( $Eff_{coup}$ ) |
| $n_e$ Uniformity                               |

## Y<sub>2</sub>: Process Output Variables

|                                                          |
|----------------------------------------------------------|
| Charge Density $n_e(r, \phi, z)$                         |
| Electron Energy Distribution Function $EEDF(r, \phi, z)$ |
| Electron Temperature $T_e(r, \phi, z)$                   |
| Plasma Potential $V_p(r, \phi, z)$                       |

Figure 4.2: Block diagram showing the categorization of the specific variables



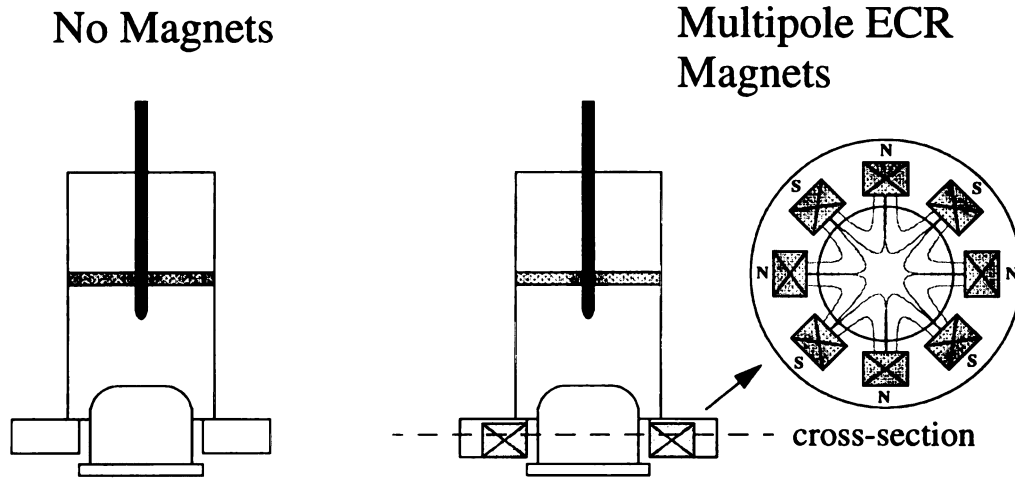


Figure 4.3: Reactor with and without ECR magnet array

excitation probe at the side of the cavity, or an excitation loop at the end of the cavity. In this investigation the two states of the variable magnet configuration are 1) the system without permanent magnets present, and 2) the system with magnets present. The magnet configurations are shown in Figure 4.3.

#### 4.4 Internal Variables:

The internal variable vector ( $X$ ) contains important internal plasma reactor quantities such as absorbed power, internal cavity electric field strength, and neutral gas temperature. A complete set of the internal variables is listed in Table 4.2.

Absorbed and reflected power ( $X: P_{\text{abs}}, P_{\text{ref}}$ ) are considered internal variables because they are strongly dependent on:  $P_{\text{inc}}$ ,  $L_s$ ,  $L_p$  and pressure  $p$ , as well as the other input variables. With the plasma present in the discharge chamber one of three resonant

electromagnetic modes can be tuned as  $L_s$  and  $L_p$  are varied. These modes correspond approximately to cavity lengths ( $L_s$ ) of  $1/2$ ,  $1$ , and  $3/2$  of the  $TM_{01}$  mode wavelength (14.4 cm at 2.45 GHz), and are therefore called the  $\lambda_g/2$  ( $TM_{011}$ ),  $\lambda_g$  ( $TM_{012}$ ), and  $3\lambda_g/2$  ( $TM_{013}$ ) modes. Any of these modes can generally be selected by varying  $L_s$  and  $L_p$  for a given set of input variables such as  $P_{abs}$  and  $p$ , and are therefore considered internal variables. The electric fields measured normal to the walls of the cavity applicator, as well as those inside the plasma discharge are considered internal variables because they are dependent on  $P_{inc}$  and tuning ( $L_s$ ,  $L_p$ ) as well as the electromagnetic properties of the discharge. The spectrum and intensity of light radiated from the various species in the plasma discharge is an important measurable internal variable and is measured using optical emission spectroscopy (OES). Two other important and related internal variables are neutral gas temperature  $T_g$  and discharge wall temperature  $T_w$ . The neutral gas temperature can be measured using OES. The temperature of the quartz discharge wall  $T_w$  can be measured using either a small thermocouple device or an optical pyrometer.

#### 4.5 Output Variables:

The output variable vector ( $Y$ ) includes all the parameters related to the desired source performance and processing capability. It's subvectors (i.e.  $Y=[Y_1, Y_2]$ ) are:  $Y_1$  the *reactor figures of merit* and  $Y_2$  the *process output variables*. Examples of reactor figures of merit are performance variables such as ion production cost or microwave coupling efficiency. Examples of process output variables are directly measurable quantities important to wafer processing such as charge density or electron temperature. The output

variables are listed in Table 4.3.

The first reactor figure of merit, ion production cost ( $Y_1:\eta_{ion}$ ), is defined as the total cost in electron volts to produce one ion useful for processing. The ion production cost can be measured by taking the ratio of the total absorbed microwave power divided by the total ion current that can be extracted from the open end of the plasma discharge chamber. It has units of W/A. The units W/A are numerically equivalent to the units eV/Ion. An expression for ion production cost,  $\eta_{ion}$ , is given by:

$$\eta_{ion} = \frac{P_{abs}}{\int_A J_s ds} \quad \text{Eq. 4.1}$$

where  $A$  is the area of the opening at one end of the discharge chamber, and  $J_s$  is the ion current density passing through the discharge chamber opening.

The uniformity of the ion density (or ion flux) out of the plasma source is an important figure of merit  $Y_1$ , because it characterizes the ability to process (i.e. etch) a wafer uniformly over its entire surface area. A uniformity factor can be defined as the standard deviation of sampled charge densities divided by the average charge density over a cross sectional processing area. The expression used to calculate the uniformity factor is:

$$\text{Uniformity} = 100\% \times \frac{1}{n_{ave}} \sqrt{\frac{1}{k} \sum_{i=1}^k (n_i - n_{ave})^2} \quad \text{Eq. 4.2}$$

where  $n_{ave}$  is the average charge density of all the samples taken,  $n_i$  is the density for an individual sample, and  $k$  is the number of samples.

The microwave coupling efficiency is another important figure of merit  $Y_1$ . As illustrated in Fig. 3.3a the power absorbed ( $P_{abs}$ ) by the MPDR13 is equal

to:  $P_{abs} = P_{inc} - P_{ref}$ , where  $P_{inc}$  is the microwave power incident to the plasma source, and  $P_{ref}$  is the power reflected from the plasma source. However, since the aluminum walls and coupling probe have a finite conductivity the power loss in these applicator structures must be considered. The power absorbed exclusively in the plasma discharge ( $P_a$ ) is then equal to:  $P_a = P_{abs} - P_w$ , where  $P_w$  is the amount of power absorbed in the applicator wall and coupling probe. The microwave coupling efficiency is then defined as the percentage of incident power,  $P_{inc}$ , actually dissipated in the plasma discharge:

$$\text{Coupling Efficiency} = 100\% \times \frac{P_a}{P_{inc}} = 100\% \times \left(1 - \frac{P_{lost}}{P_{inc}}\right) \quad \text{Eq. 4.3}$$

where  $P_{lost}$  is the power lost in the applicator plus the reflected power; i.e.  $P_{lost} = P_w + P_{ref}$ . The major task in calculating the coupling efficiency is in calculating  $P_w$ . This can be accomplished by measuring the electric fields at the walls of the applicator  $|E_{normal}|$  while the plasma is present in the system. If the electromagnetic mode excited is close to an ideal (empty cavity) mode the tangential magnetic field can be determined from  $|E_{normal}|$  with the modal field equations. The power lost in the walls of the cavity can then be given from the following formula:

$$P_w = \frac{1}{2} \mathcal{R} \int_s |H_t|^2 ds \quad \text{Eq. 4.4}$$

where  $s$  is the entire inside metal surface of the applicator including the coupling probe,  $H_t$  is the tangential magnetic field intensity on the inside surface, and  $\mathcal{R}$  is the surface resistivity of the metal surfaces. When the electric field pattern for the excited mode in the plasma loaded cavity is significantly different from the corresponding mode in an empty

cavity the plasma loaded electric field structure and wall losses may best be estimated/ calculated with the aid of a finite difference time domain (FDTD) simulation of the electromagnetic cavity and plasma. Recent simulations [Gro-00] indicate that wall losses are on the order of 1% or less of the total power absorbed by the discharge.

The process output variables  $Y_2$  are plasma density  $n_0$ , electron energy distribution function (EEDF), electron temperature  $T_e$ , and plasma potential  $V_p$ . The plasma density and electron temperatures can be measured using single or double Langmuir probes and are discussed in Chapter 5. The electron energy distribution function and the plasma potential can be measured only using a single Langmuir probe.

**Table 4.1: Input Variables of the Experimental System**

| Input Variables (U)                         |        | Variable Description                                                                            | Range                                                                                                                         |
|---------------------------------------------|--------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Macroscopic Controllable Variables<br>$U_1$ | Fixed  | Excitation Frequency ( $f$ )                                                                    | 2.45 GHz                                                                                                                      |
|                                             |        | Gas Type                                                                                        | Argon (99.999%)                                                                                                               |
|                                             | Varied | Chamber Pressure ( $p$ )                                                                        | 1 - 60 mTorr                                                                                                                  |
|                                             |        | Gas Flow Rate ( $f_t$ )                                                                         | 1 - 400 sccm                                                                                                                  |
|                                             |        | Incident Microwave Power ( $P_{inc}$ )                                                          | 100 - 600 W                                                                                                                   |
|                                             |        | Cavity Height ( $L_s$ )                                                                         | 9 - 25 cm                                                                                                                     |
|                                             |        | Excitation Probe Length ( $L_p$ )                                                               | 0 - 5.0 cm                                                                                                                    |
| Reactor Geometry Variables<br>$U_2$         | Fixed  | Cavity Applicator Radius ( $R_A$ )                                                              | 8.89 cm                                                                                                                       |
|                                             |        | Excitation Probe Radius ( $R_p$ )                                                               | 0.5 cm                                                                                                                        |
|                                             |        | Discharge Chamber Radius ( $R$ )                                                                | 6.5 cm                                                                                                                        |
|                                             |        | Discharge Chamber Height ( $l$ )                                                                | 10.25 cm                                                                                                                      |
|                                             |        | Applicator Material and Surface Resistivity                                                     | Aluminum<br>$\mathcal{R}_s = 0.0161 \Omega$                                                                                   |
|                                             |        | Discharge Chamber Material<br>Rel. Dielectric Constant<br>Thermal Conductivity<br>Specific Heat | Quartz:<br>$\epsilon_r = 4.0$<br>$k = 1.05 \text{ J/(s}\cdot\text{m}^*\text{°C)}$<br>$c = 837.4 \text{ J/(kg}\cdot\text{°C)}$ |
|                                             |        | Coupling Configuration<br>(End or Side Feed, Probe or Loop)                                     | End Feed Probe                                                                                                                |
|                                             | Varied | Magnet Configuration<br>(No Magnets, 8 pole Multicusp,<br>or Electromagnet Coil)                | No Magnet,<br>Multicusp,<br>and Coil                                                                                          |

**Table 4.2: Internal Variables of the Experimental System**

| Internal Variables (X)  | Variable Description                                                                          | Range                                    |
|-------------------------|-----------------------------------------------------------------------------------------------|------------------------------------------|
| Internal Variables<br>X | Absorbed Power ( $P_{abs}$ )<br>(Absorbed by Applicator and Load)                             | 10 - 100% of $P_{inc}$                   |
|                         | Reflected Power ( $P_{ref}$ )                                                                 | 0 - 90% of $P_{inc}$                     |
|                         | Resonant TM Mode                                                                              | $\lambda_g/2, \lambda_g, (3/2)\lambda_g$ |
|                         | Internal Cavity Electric Fields ( $E_r$ )<br>(Measured at the Walls)                          | 0 - 10 kV/m                              |
|                         | Electric Fields Internal to Discharge<br>and Spatial Distribution $\underline{E}(r, \phi, z)$ | (To be measured)                         |
|                         | Neutral Gas Temperature ( $T_g$ )                                                             | 500 - 700 K                              |
|                         | Discharge Wall Temp. ( $T_w$ )                                                                | (To be measured)                         |
|                         | Spectrum and Intensity of<br>Radiated Light vs. (r, $\phi$ , z)                               | —                                        |

**Table 4.3: Output Variables of the Experimental System**

| Output Variables (Y)                                 | Variable Description                                                             | Range                               |
|------------------------------------------------------|----------------------------------------------------------------------------------|-------------------------------------|
| Reactor<br>Figures<br>of Merit<br><br>Y <sub>1</sub> | Ion Production Cost<br>or eV/Ion Efficiency ( $\eta_{ion}$ )                     | 150 - 500 eV/Ion                    |
|                                                      | Uniformity of $n_e$ at the Output                                                | 6 - 7.8 %                           |
|                                                      | Microwave Coupling Efficiency,<br>( $Eff_{coup}$ )                               | ~ 98%                               |
| Process<br>Output<br>Variables<br><br>Y <sub>2</sub> | Electron, Ion Density ( $n_e, n_i$ )<br>and Spatial Distribution (r, $\phi$ , z) | $10^{11} - 10^{12} \text{ cm}^{-3}$ |
|                                                      | Electron Energy Distribution<br>Function ( EEDF ) vs. (r, $\phi$ , z)            | —                                   |
|                                                      | Electron Temperature ( $T_e$ )<br>and Spatial Distribution (r, $\phi$ , z)       | 2 - 4 eV                            |
|                                                      | Plasma Potential ( $V_p$ )<br>and Spatial Distribution (r, $\phi$ , z)           | 12 - 19 V                           |

## Chapter 5

### Single Langmuir Probe Construction and Experimental Techniques

#### 5.1 Introduction

#### 5.2 The Single Langmuir Probe

##### 5.2.1 Construction of the Single Langmuir Probe

##### 5.2.2 Theory of the SLP

##### 5.2.3 Measurement of $d^2I/dV^2$ with a Lock-in Amplifier (LIA)

##### 5.2.4 Description of the measurement circuit

##### 5.2.5 Measurement Procedure and Program Flow

##### 5.2.5 Resistive Deposition Layers and Cleaning

##### 5.2.6 Problems with variable AC and DC resistance of the SLP



## Chapter 5

### Single Langmuir Probe Construction and Experimental Techniques

#### **5.1 Introduction:**

This chapter describes in detail the construction and experimental techniques used with a Single Langmuir Probe. It provides the background for the experimental data presented in Chapters 7 and 8, as well as, a guide for any similar experiments to be performed in the future. Descriptions of other experimental techniques such as measurement of dome temperature and electric field are described in the later chapters or appendices in which these measurements are discussed.

#### **5.2 The Single Langmuir Probe:**

The single Langmuir probe (SLP) has been a fundamental tool for plasma diagnostics since it was employed by Langmuir in the early 1920's. Langmuir and Mott-Smith published a detailed study in 1924 [Lan-24]. By varying the voltage of its electrode placed in a plasma the single Langmuir probe is able to measure the electron energy distribution function (EEDF),  $g_e(\mathcal{E})$  [Dru-30]. From the EEDF the average electron energy,  $E_{ave}$ , and electron temperature,  $T_e$ , can be calculated. The SLP can also measure ion saturation current,  $I_s$ . If the collection area of the probe,  $A$ , is known the charge density,  $n_i$ , can be calcu-

lated using  $I_s$  and  $T_e$ . Since the probe is biased with respect to the grounded metal chamber wall the plasma potential,  $V_p$ , can be determined. Finally, the ion production cost,  $\eta_{ion}$ , can be determined if a profile of  $I_s$  is obtained at the opening of the discharge.

### **5.2.1 Construction of the Single Langmuir Probe:**

The single Langmuir probe is constructed from a tungsten rod (1) enclosed in a quartz tube (2) (see Figure 5.1). Both tungsten and quartz are used because they can reliably withstand the high temperatures of the plasma environment. Tungsten rods can be obtained as a welding supply item. The tungsten rod used for this probe has a diameter of 16 mills (16/1000 inches or a radius of 0.406 mm).

Only 2 mm of the length of the tungsten rod is exposed to the plasma. This forms the collection surface (3) of the probe. Both the diameter and the exposed length of the tungsten rod were kept relatively small to reduce the large amount of current (on the order of several milliamperes) that flows through the probe circuit when it is positively biased in a dense plasma. The other (enclosed) end of the tungsten rod is silver-tin soldered (4) to 50 cm length of braided steel wire (5) that has a vacuum compatible and heat resistant woven ceramic insulation. The quartz shell nearest the plasma (2) is kept small at a diameter of 0.5 cm to reduce its perturbation of the plasma. At 14 cm below the probe tip the diameter of the quartz tubing expands to 1 cm (6) to provide increased mechanical strength. The entire quartz shell, from probe tip to base, is a total of 40 cm long to ensure that the probe positioning apparatus (7) and insulated wire leads (8) are kept far from the plasma

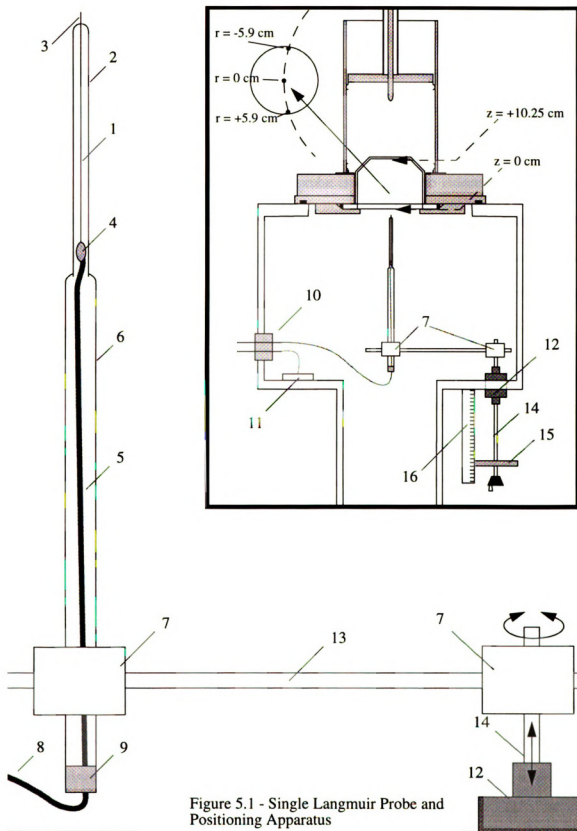


Figure 5.1 - Single Langmuir Probe and Positioning Apparatus

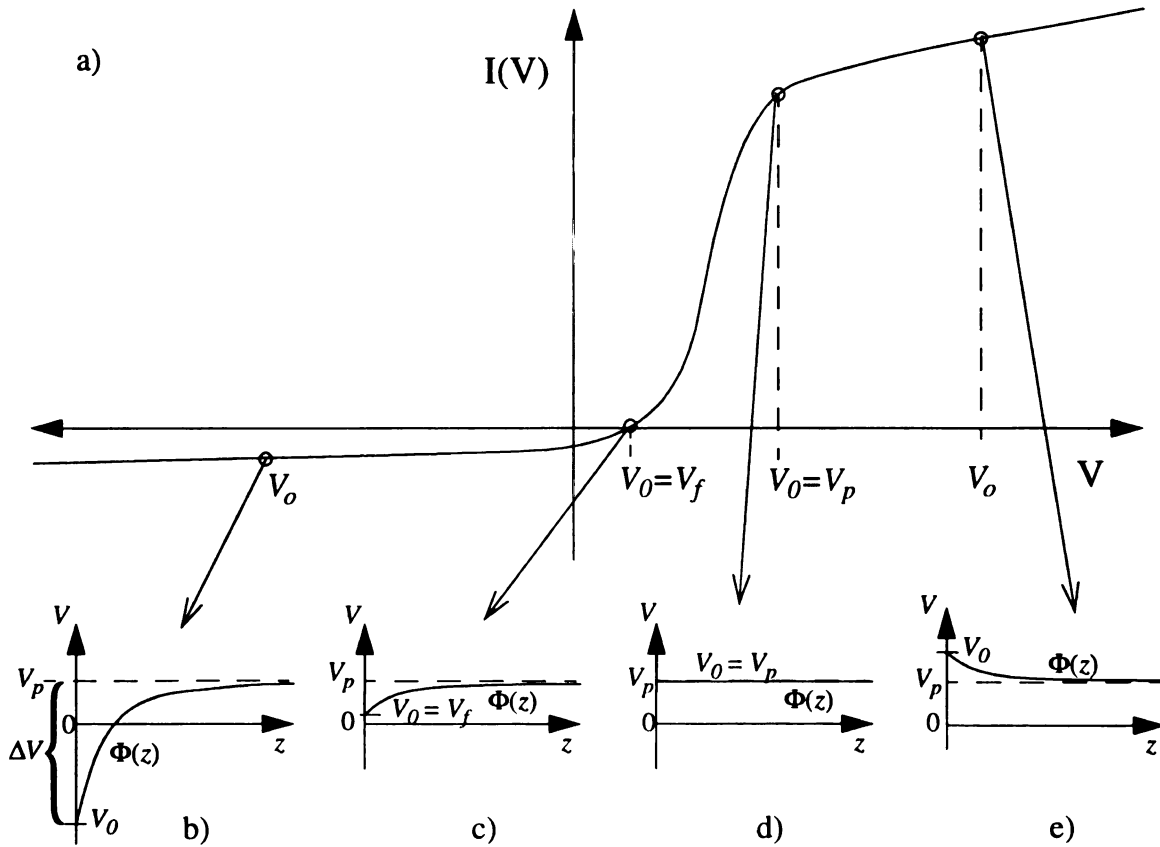
discharge and hence do not perturb the plasma or sputter unknown elements into the discharge (or onto chamber and probe surfaces). Shrink wrap is shrunk tightly around the base (9) of the quartz shell and the braided wire lead (where it exits the quartz tube) to prevent internal twisting of either the solder joint or the brittle tungsten rod. The shrink wrap is fully covered by a section of woven ceramic cloth (9) to minimize any possible sputtering of the shrink wrap polymer. The probe is connected to external measurement circuits through an electrical vacuum feed-through (10). Care was taken insure that no part of the probe's conductor or wire was exposed to plasma except the probe's collecting surface (3). A wire in good electrical contact with the chamber wall was used as the ground (11) for the probe circuit.

A special apparatus was designed to position the tip of the SLP at precise locations in the discharge. The probe tip can be positioned from  $z=0$  cm at the base of the discharge up to  $z=10.25$  cm at the top of the quartz discharge chamber. The probe can also be positioned radially from  $r=-5.9$  cm (the back of the discharge) through  $r=0$  cm to  $r=+5.9$  cm (the front of the discharge). In this way radial or axial profiles of any SLP measured parameter can be obtained. A top view of the trajectory of the probe across the discharge opening is shown in the upper left corner of the inset of Figure 5.1.

The positioning apparatus consists of a mechanical feed through (12) with two degrees of freedom: one rotational and one linear. Right-angle clamps (7) are used to secure the probe to the support bar (13) and the mechanical feed through bar (14). Accurate radial positioning is obtained with an aluminum disk (15) calibrated to indicate the radial position of the probe in cm. Accurate axial ( $z$ ) positioning is obtained by noting the position of the disk next to a vertically mounted ruler (16).

### 5.2.2 Theory of the SLP:

We can get information about the energy distribution of electrons in the plasma by varying the potential on the probe. Figure 5.2a shows a typical current vs. voltage curve for a single Langmuir probe. Note: current out of the probe is defined as positive, hence ions colliding with the probe contribute to negative current and electrons reaching the probe contribute to positive current. In Figures 5.2(b-e) the  $z$  axis represents distance away



**Figure 5.2:** (a) Typical current vs. voltage curve for a planar single Langmuir probe, (b) the potential  $\Phi$  vs. distance  $z$  away from the surface of a planar probe when  $V_0$  is large negative, (c) when  $V_0$  equals the floating potential,  $V_f$ , (d)  $V_0$  equals the plasma potential,  $V_p$ , (e)  $V_0$  is greater than  $V_p$ . (Note:  $\Delta V = V_p - V_0$ )

from the surface of a planar probe and  $\Phi(z)$  is the potential vs.  $z$ . When the probe voltage,  $V_0$ , is a large negative value only a small number of the highest energy electrons can overcome the high potential barrier of the probe (the potential barrier seen by electrons is  $\Delta V = V_p - V_0$ ), see Figure 5.2b. Since most electrons don't reach the probe, the current here is due to the positively charged ions that fall into the probe's negative potential well. As the potential,  $V_0$ , is gradually increased more electrons overcome the potential barrier,  $\Delta V$ , and increasingly cancel out the ion current. When  $V_0$  equals the floating potential,  $V_f$ , the number of electrons overcoming  $\Delta V$  (per second) exactly cancels the number of ions falling into the probe potential (per second), and hence the net probe current is zero, see Figure 5.2c. When  $V_0$  equals the plasma potential,  $V_p$ , neither electrons or ions feel any electrostatic forces from the probe, see Figure 5.2d. Since electrons are traveling many times faster than the ions the probe collects many times more electrons (per second) than ions and registers a large positive current. Finally, when  $V_0$  is significantly greater than  $V_p$  most electrons fall into the positive probe potential and most positive ions are repelled, see Figure 5.2d.

The probe tip used in this investigation is cylindrical in shape, however since plasma Debye length,  $\lambda_D$ , ( $\lambda_D$  is typically on the order of 0.04mm in this investigation) is much less than the probe radius (0.406mm) we can approximate the cylindrical probe as a planar probe with area:  $A_p \sim 2\pi rl$ .

As discussed above and illustrated in Figure 5.3, in order to reach the probe an electron in the bulk plasma must have a component of kinetic energy, normal to the probe surface, that is greater than  $\Delta V$ . Any incident electron with less than this required directed energy will be reflected back into the bulk plasma. For a given  $\Delta V$  the minimum normal

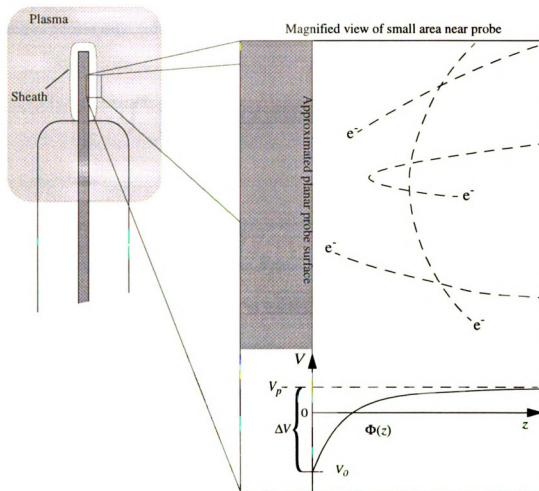


Figure 5.3: Planar Approximation for an SLP where the sheath thickness is much less than the radius of the probe. Electrons without the required  $z$ -component of kinetic energy are repelled from the negatively biased probe.

component of velocity to overcome the probe potential is:

$$v_{min} = \sqrt{\frac{2e(\Delta V)}{m_e}} \quad \text{Eq. 5.1}$$

where  $e$  is the charge on an electron and  $m_e$  is the mass of an electron. Hence, the total electron current collected by a probe with potential  $V_0$  can be expressed as:

$$I = eA \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{v_{min}}^{\infty} [v_z f_e(\mathbf{v})] dv_z dv_y dv_x \quad \text{Eq. 5.2}$$

where  $A$  is the area of the probe, and  $f_e(\mathbf{v})$  is the electron velocity distribution function. By a series of mathematical manipulations including converting to spherical coordinates, a change of variables from velocity,  $v$ , to energy,  $\mathcal{E}$ , and two differentiations, the above expression can be transformed into an expression for the electron energy distribution function,  $g_e(V)$ , in terms of  $(d^2I/dV^2)$  [Lie-94, page 176]:

$$g_e(\Delta V) = \left[ \frac{2m_e}{e^2 A \sqrt{\frac{2e(\Delta V)}{m_e}}} \right] \left( \frac{d^2 I}{dV^2} \right) \quad \text{Eq. 5.3}$$

From this expression we can make the more general statement:

$$g_e(\mathcal{E}) \propto \sqrt{V_p - V_0} \left( \frac{d^2 I}{dV^2} \right) \quad \text{Eq. 5.4}$$

where  $\mathcal{E} = \Delta V$ . This expression is useful when only the relative magnitude of  $d^2I/dV^2$  can be measured. In this case a normalized  $g_e(\mathcal{E})$  (i.e. normalized EEDF) is calculated.  $E_{ave}$



and  $T_e$  can still be determined from this normalized function.

### 5.2.3 Measurement of $d^2I/dV^2$ with a Lock-in Amplifier (LIA):

One method of determining  $d^2I/dV^2$  is to numerically differentiate the IV curve twice. However, each numerical differentiation magnifies the random fluctuations (noise) in the discretely sampled IV curve. Curve fitting and averaging techniques have been used by some investigators to solve this problem, but are not used here. Alternately, a lock-in amplifier (LIA) can determine  $d^2I/dV^2$  (referred to as  $I^{(2)}$  below) point by point without any discrete numerical differentiation of the IV curve. The LIA determines  $d^2I/dV^2$  by measuring the second harmonic current response of the probe to a small applied voltage signal. How this can be used to determine  $d^2I/dV^2$  is discussed below.

A typical current vs. voltage curve of a single Langmuir probe is shown in Figure 5.2. The current can be thought of as a function of the probe voltage  $I = I(V)$ . The Taylor series representation of this function near an applied DC voltage point  $V=V_0$  is given as:

$$I(V) = \sum_{k=0}^{\infty} \frac{[I^{(k)}(V_0)][V - V_0]^k}{k!} \quad \text{Eq. 5.5}$$

where  $I^{(k)}(V_0)$  denotes the  $k$ th derivative of  $I(V)$  where  $V=V_0$ . If a small sinusoidal signal of amplitude  $v$  is added to the argument of  $I(V)$  we have:

$$I(V) = I[V_0 + v \sin(\omega t)] \quad \text{Eq. 5.6}$$

The Taylor series can then be represented as:

$$I(V_o + v \sin(\omega t)) = \sum_{k=0}^{\infty} \frac{[I^{(k)}(V_o)][v \sin(\omega t)]^k}{k!} \quad \text{Eq. 5.7}$$

The first few terms of this series can be written as:

$$\begin{aligned} I(V) = I(V_o) + \frac{I^{(1)}(V_o)}{1} [v \sin(\omega t)] + \frac{I^{(2)}(V_o)}{2} [v^2 \sin(\omega t)^2] + \\ \frac{I^{(3)}(V_o)}{6} [v^3 \sin(\omega t)^3] + \frac{I^{(4)}(V_o)}{24} [v^4 \sin(\omega t)^4] + \dots \end{aligned} \quad \text{Eq. 5.8}$$

Substituting the trigonometric identities for  $\sin^2(x)$ ,  $\sin^3(x)$ , and  $\sin^4(x)$ , see Appendix B, into the above series we can group together the resulting terms as coefficients of the Fourier harmonic components (i.e. group all  $\cos(2\omega t)$  terms together as the second harmonic, etc.). The DC component term is given as:

$$I_{DC} = I(V_o) + \frac{v^2}{4} I^{(2)} + \frac{v^4}{64} I^{(4)} + \dots \quad \text{Eq. 5.9}$$

The first harmonic term:

$$I_{1st} = \left[ v I^{(1)} + \frac{v^3}{8} I^{(3)} + \dots \right] \sin(\omega t) \quad \text{Eq. 5.10}$$

The second harmonic term:

$$I_{2nd} = \left[ \frac{v^2}{4} I^{(2)} + \frac{v^4}{48} I^{(4)} + \dots \right] [-\cos(2\omega t)] \quad \text{Eq. 5.11}$$

where  $I$  and its derivatives (i.e.  $I^{(1)}$ ,  $I^{(2)}$ ,  $I^{(3)}$ , ...) are a function of  $V$  in all of the above equations. The terms for higher harmonics (3rd, 4th, 5th ...) can be obtained similarly. It is the non-linearity of the probe's IV curve at each DC operating point that distorts the sinusoidal current response and produces higher harmonics. The more non-linear the IV curve near the operating point the more pronounced the higher harmonics generated. The above discussion is illustrated in Figure 5.4.

We are interested in finding a signal that is proportional to  $d^2I/dV^2$  (i.e.  $I^{(2)}$ ). The DC component has an  $I^{(2)}$  term, however this small offset in DC current is difficult to measure accurately. The  $I^{(2)}$  term is dominant in the second harmonic component,  $I_{2nd}$ , and if the signal amplitude,  $v$ , is kept small the higher order terms of the second harmonic become negligible. Neglecting the higher order terms, taking the magnitude of both sides, and rearranging we obtain:

$$I^{(2)} \equiv \frac{d^2 I}{dV^2} \equiv 4 \left[ \frac{|I_{2nd}|}{v^2} \right] \quad \text{Eq. 5.12}$$

where  $I^{(2)}$  and  $I_{2nd}$  (and as discussed below, even  $v^2$ ) are functions of  $V$ . The second harmonic,  $I_{2nd}$ , curve is measured directly with the use of a lock-in amplifier. A lock-in amplifier is used because it can act as a very selective notch filter. It passes and amplifies a very narrow band around the 2nd harmonic frequency signal and blocks the signals and noise at all other frequencies. Once  $I_{2nd}$  and  $v^2$  are obtained  $d^2I/dV^2$  is then calculated using Eq. 5.12.

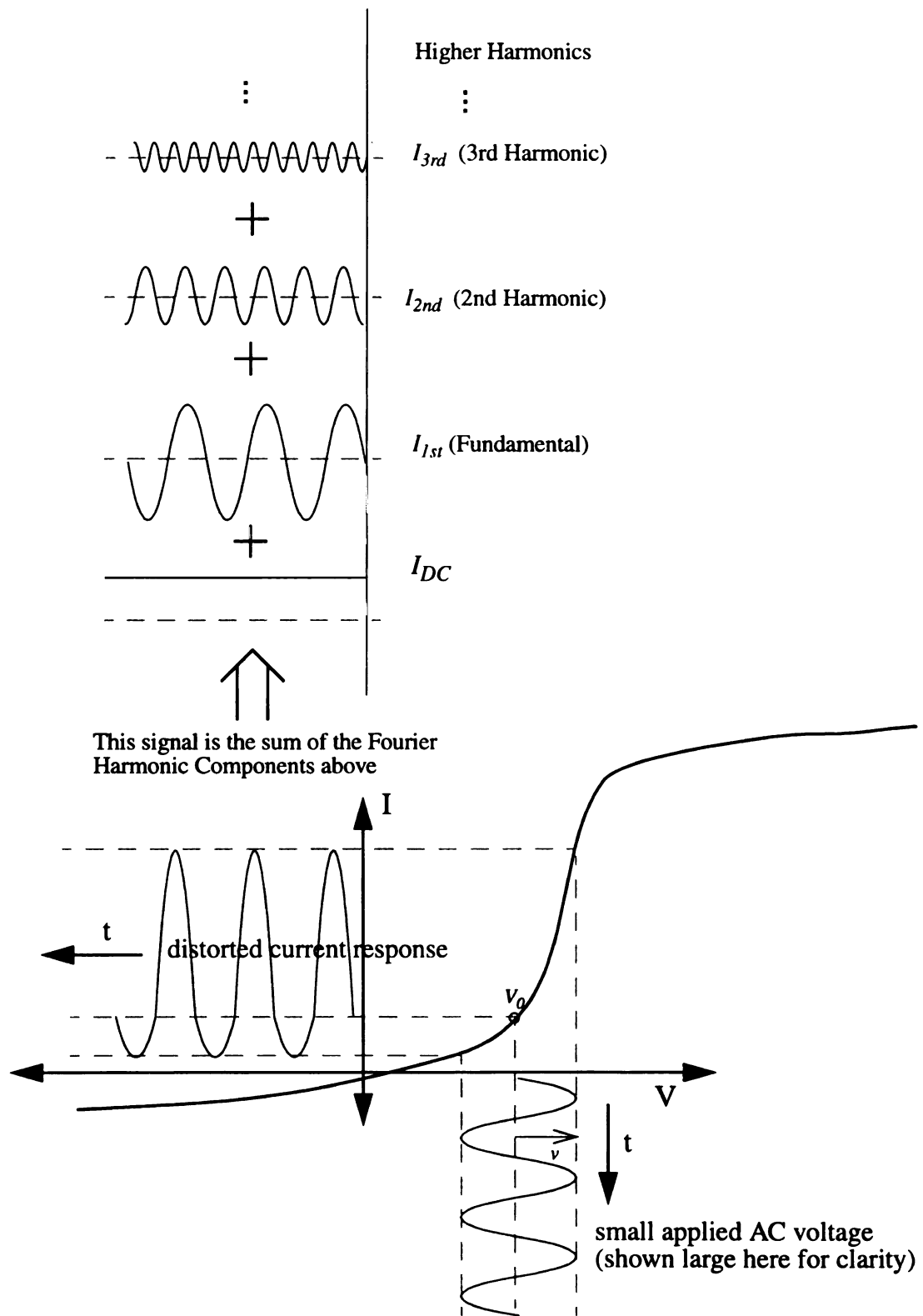


Figure 5.4: This figure illustrates graphically how the small AC signal applied to the probe at operating point  $V_0$  can give rise to higher harmonics that are proportional to the curvature of the IV curve.

### 5.2.4 Description of the measurement circuit:

The circuit used to apply both DC and AC voltage to the probe and measure its  $I$  and  $d^2I/dV^2$  response is shown in Figure 5.4. The DC voltage applied to the SLP generally begins at -20 V and is increased in 1 V intervals up to near +30 V (over a period of approximately 10 minutes). This voltage is applied by a programmable Hewlett Packard 6634A System DC power supply (1) with a range of 0 to 100V. A computer controlled

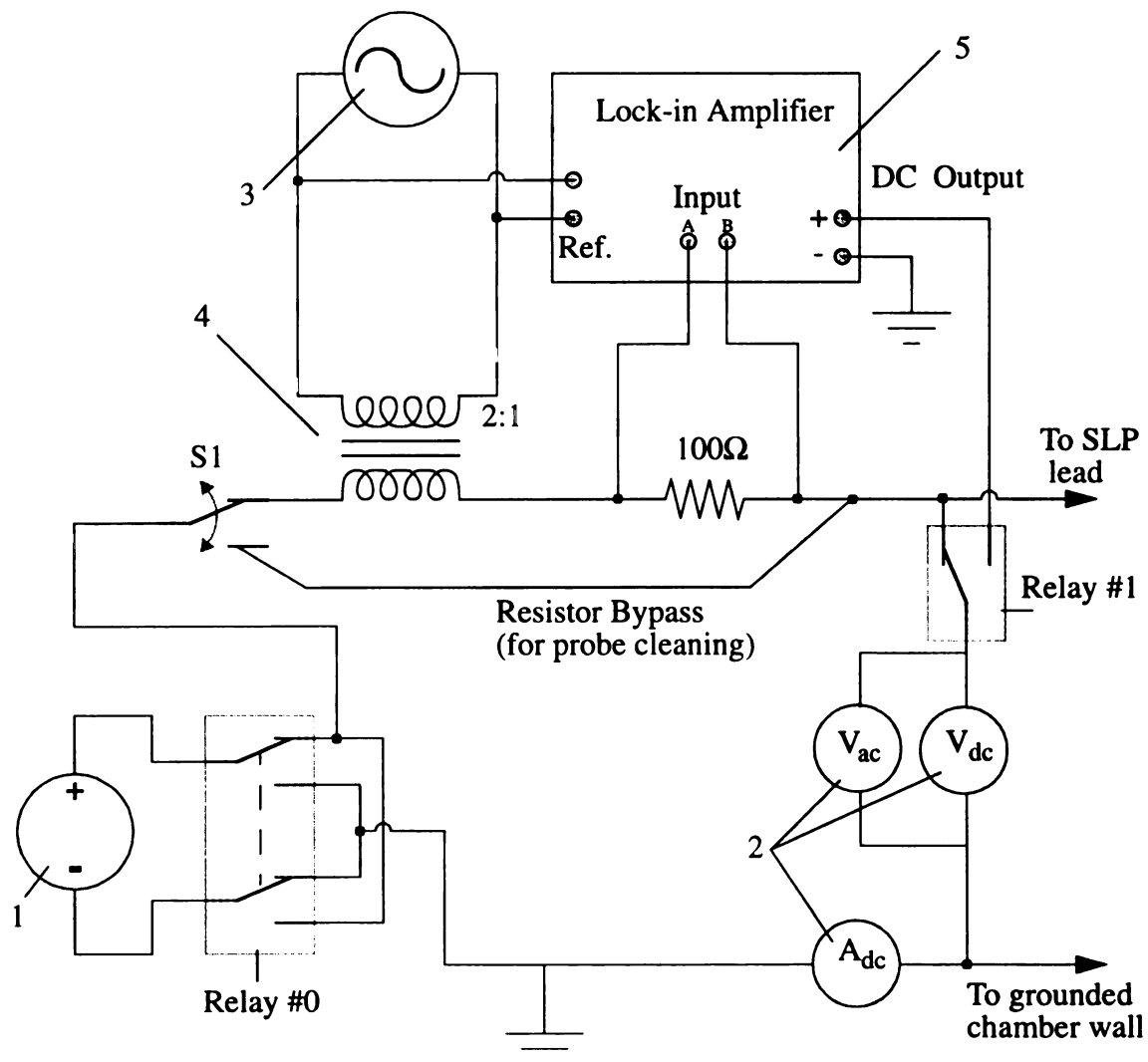


Figure 5.5: Diagram of SLP measurement circuit

relay (Relay #0) is used to switch the polarity of this DC supply output, making it's effective range: -100V to +100V. Note that the DC supply itself is floating and the circuit ground is connected to the plasma chamber wall and all voltages are measured with respect to this surface. As the DC voltage is swept through its range a Hewlett Packard 3478A digital multimeter (2) records both the current through and voltage across the SLP. This IV curve data is sequentially stored in a data file by the controlling quickbasic program (MSLP\_899.BAS).

As discussed in section 5.2.3  $d^2I/dV^2$  can be obtained by applying a small ( $< 1 V_{pp}$ ) sinusoidal signal to the SLP and then measuring the second harmonic,  $I_{2nd}$ , current response generated by the non-linear IV curve of the SLP. The small sinusoidal signal is applied to the probe circuit by a Hewlett Packard 651B Test Oscillator (3) (set to 1 kHz) through a 25 Watt capacity 2:1 step-down audio transformer(4). Small audio transformers may experience harmonic distortion when subject to high DC currents. Hence this transformer was selected because it could handle high DC currents without harmonic distortion. The second harmonic signal,  $I_{2nd}$ , is extracted from the total current response by a Princeton Applied Research Model 128A Lock-In Amplifier (5). At each incremental DC voltage applied to the probe by the DC power supply an AC voltage across the probe is measured by the hp 3478A multimeter (2). The same multimeter is then used to measure the DC output of the lock-in amplifier (LIA) (which is the relative amplitude of  $I_{2nd}$ ) by switching a computer controlled relay (Relay #1) from sensing the SLP electrode to sensing the LIA output lead. Hence,  $d^2I/dV^2$  is calculated from  $I_{2nd}$  and recorded in the data file along with the IV curve.

A manual switch (S1) is added to the circuit to facilitate the high forward bias that

is required in heat cleaning of the SLP. Since large forward bias currents through the  $100\Omega$  resistor may burn it out or overheat the windings of the transformer it is best to bypass these components when heat cleaning the probe.

As mentioned above two 12 V relays are used in this circuit and labeled: Relay #1 and Relay #2. The power that switches these relays is provided by two high power () op-

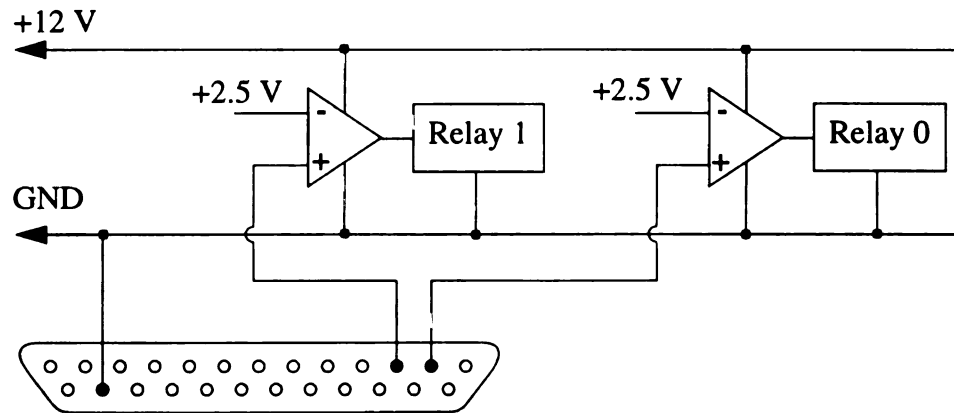


Figure 5.6: Schematic diagram of the relay circuit and corresponding parallel port pins for an IBM compatible PC

amps wired as voltage comparators, see Figure 5.6. A (0 or 5V) digital signal from one pin (bit) of the parallel port of an (IBM compatible PC, 486) computer is connected to the positive input of the () op-amp. The negative input to the op-amp is biased at 2.5 V relative to signal ground. When the parallel port pin is 0 V the output of the op-amp is 0 V, but when the parallel port pin is at 5 V the output of the op-amp goes to 12 V and the relay is switched.

The parallel port of the PC is addressed in the controlling quickbasic program at location (Hex) 3BC. Recall that ports and memory addresses are addressed differently in

the PC architecture. In this setup bit #0 of port address 3BC is used to control the polarity of the DC power supply (0 - negative bias, 1 - positive bias) and bit #1 is used to control the sensing of the multimeter (0 - SLP voltage, 1 - LIA output). The corresponding port pins are shown in Figure 5.4.

### **5.2.5 Measurement Procedure and Program Flow:**

The procedure for taking an EEDF and IV curve are as follows. First the probe is positioned at the r and z position to be studied. Then the probe is cleaned by forward or reverse biasing if necessary. The quickbasic program MSLP\_899.BAS is initiated. This program is able to communicate with the HP 6634A DC power supply and HP multimeter via an GPIB bus. The DC power supply is first set to -20V and then this voltage is incremented by a user defined interval (1 V is chosen most often). At each voltage increment several measurements are taken. The AC and DC voltage across the probe and DC current through the probe is measured. After a 10 second delay period (to let the LIA transients decay) Relay #1 is switched and the voltage across the LIA output is sampled. Twenty samples are taken and an average is calculated and stored in the sequential data file. The DC voltage supply is then incremented. When the value of  $d^2I/dV^2$  is 10% less than its running maximum value (this indicates that the plasma potential has been passed) the voltage increments stop.

A subroutine then searches the data file to find the voltage where the maximum of  $d^2I/dV^2$  occurs. This voltage is considered the best estimate of plasma potential,  $V_p$  [Run-79]. The values of an EEDF curve are then calculated using Eq. 5.X. The EEDF is then



numerically integrated and normalized such that:

$$\sum_{i=1}^{i_{max}} g(E_i) \Delta E = 1 \quad \text{Eq. 5.13}$$

where  $E_i$  is a value of electron energy,  $g(E_i)$  is the measured value of the EEDF at  $E_i$ ,  $\Delta E$  is the energy increment and  $i_{max}$  is the highest energy sample taken. The average electron energy,  $E_{ave}$ , and electron temperature,  $T_e$ , is then calculated:

$$E_{ave} = \sum_{i=1}^{i_{max}} E_i g(E_i) \Delta E = \frac{3}{2} T_e \quad \text{Eq. 5.14}$$

The normalized EEDF curve along with the corresponding  $E_{ave}$  and  $T_e$  are stored in a data file separate from the  $I$  and  $d^2I/dV^2$  data file.

The charge density can be calculated using the measured IV curve. First, the floating potential,  $V_f$ , is found (i.e. the voltage where the current collected by the probe is zero). A vertical line is drawn at this voltage (see Figure 5.7). Then a tangent line is drawn from the slope of the IV curve in the negatively biased region. A good estimate of the ion saturation current,  $I_s$ , is taken as the current value where the tangent line crosses the floating potential.

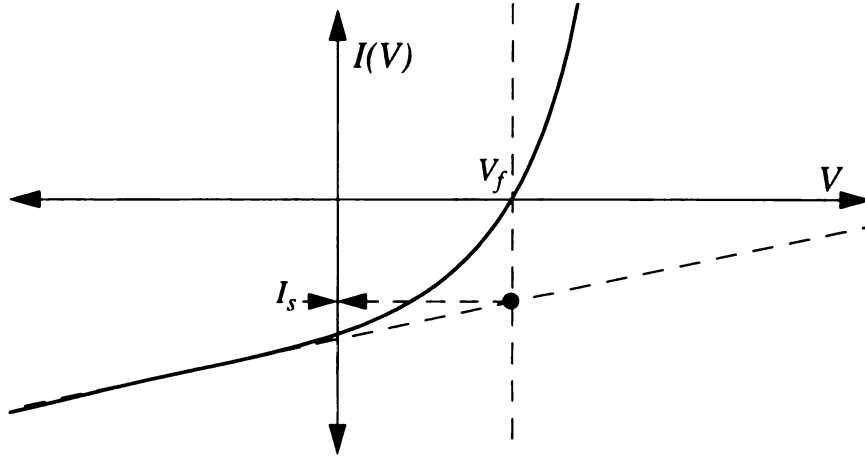


Figure 5.7: Determination of  $I_s$  from a measured SLP IV curve

Once  $I_s$  is known then a charge density,  $n_i$ , can be obtained using:

$$n_i = \frac{I_s}{(0.61)eA_p} \sqrt{\frac{M_i}{k_b T_e}} \quad \text{Eq. 5.15}$$

where  $I_s$  is the ion saturation current, the factor 0.61 is the ratio of sheath edge density to bulk plasma density,  $A_p$  is the effective area of the probe,  $M_i$  is the mass of an argon atom,  $k_b$  is Boltzmann's constant,  $e$  is the electron charge, and  $T_e$  is the SLP measured electron temperature.

Since the total collection area of the probe depends on the thickness of the sheath surrounding the probe (approximated as the Debye length,  $\lambda_D$ ) which varies with changing charge density then an iterative calculation is necessary to determine  $n_i$  more accurately.  $n_i$  is first calculated with  $A_p$  set to the physical area of the metal probe.  $\lambda_D$  is then calculated with this density and measured temperature  $T_e$ . Using  $\lambda_D$  a new effective probe area is calculated, by adding  $\lambda_D$  to the radius and length of the probe. This new area is then used to

calculate a new charge density. This procedure is iterated (using a computer program) until the charge density,  $n_i$ , converges to a constant value. Hence, the parameters  $T_e$ ,  $V_p$ ,  $I_s$  and  $n_i$  can all be calculated using a single Langmuir probe.

### **5.2.5 Resistive Deposition Layers and Cleaning:**

A significant problem encountered with single Langmuir probe measurements is the deposition of insulating material on the surface of either the tungsten probe tip or the metal walls of the chamber. The origins of this deposited material are not fully known, but some have suggested it to be a product of diffusion pump oil or a metal oxide. Good electrical contact between the plasma and probe or metal ground surfaces are essential to accurate probe measurements. Since electrical current flows through the plasma from the probe tip to the grounded metal walls of the chamber (or vice versa) any resistive layers add unwanted resistance to this circuit path. Figure 5.8 shows the effect of this resistance on the probe measurement circuit. This extra resistance causes the voltage dropped across the probe to be artificially high resulting in incorrectly high values for  $V_p$ . The added resistance also causes the EEDF to spread out over a larger voltage range and hence also results in artificially high values of  $E_{ave}$  and  $T_e$ .

Two commonly used methods of cleaning an SLP while immersed in a plasma are extreme reverse bias (ion sputter cleaning) and extreme forward bias (heat cleaning). When the probe is given a negative bias of approximately -40V ions accelerate into and sputter impurities from the surface of the probe. One disadvantage to this method is that it

can also sputter tungsten from the probe tip to any surface inside the chamber including the quartz discharge chamber.

Heat cleaning involves forward biasing the probe to approximately +40V or more. The probe tip draws large current of electrons from the plasma and will commonly begin to glow a bright orange. The heat causes the impurities to evaporate off the probe tip. If the resistive layer of the probe is too thick the current drawn will be less and heat cleaning may not be possible. In this case reverse bias can be applied or the probe can be carefully cleaned by hand with fine sandpaper.

#### **5.2.6 Problems with variable AC and DC resistance of the SLP:**

In order to measure the second derivative accurately the values  $V_0$  and  $v$  must be measured directly across the probe and ground and not just read from the settings of the AC and DC power supplies. The 100  $\Omega$  resistor necessary for LIA signal measurement creates a voltage divider situation, see Figure 5.8 (assume resistive layers have been removed). When the AC or DC resistance of the probe is large compared to the 100  $\Omega$  resistor (such as when the probe voltage is negative) most of the voltage applied by the AC or DC power supplies is dropped across the probe. However, when the AC or DC resistance is comparable or less than 100  $\Omega$  (such as when the IV curve slope is greatest) the AC or DC voltages across the probe will be noticeably less than those applied by the

power supplies. Therefore, measurement of  $V_0$  and  $v$  directly across the probe and ground

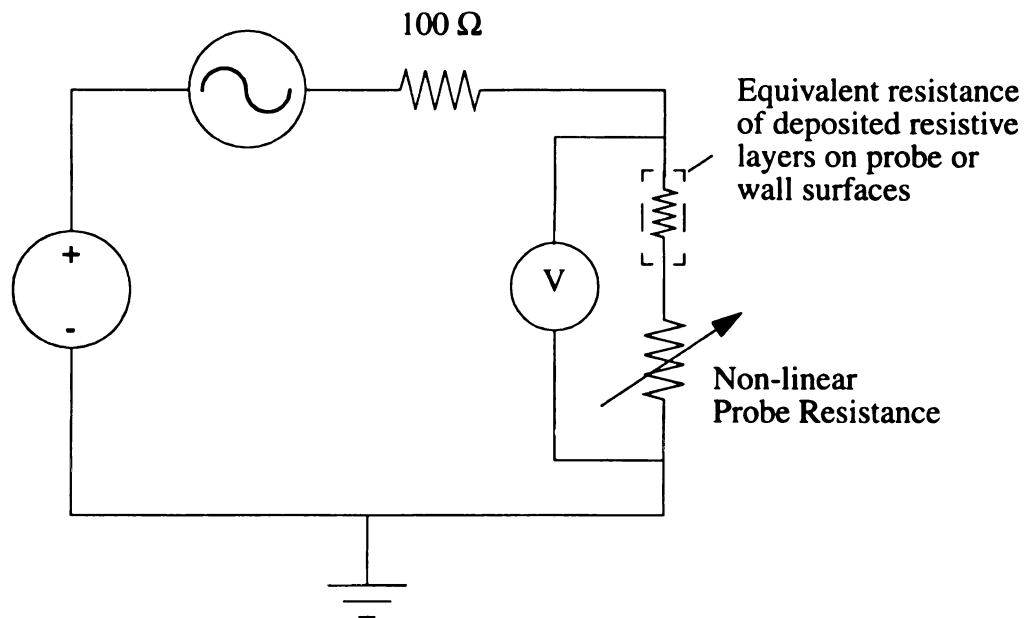


Figure 5.8: Simplified schematic of the SLP measurement circuit

is necessary for accurate measurements. The measured values of both  $V_0$  and  $v$  are used in Eq. 5.X to determine each value of  $I^{(2)}$ . Note: DC resistance is determined by the value of  $I/V$  on the IV curve, while AC resistance is determined by the slope of the IV curve at the DC operating point. Ideally a constant  $v$  signal would be applied. An improvement to the above circuit could be made if a digitally controllable AC signal generator is used. With a controllable AC source a feedback loop could be utilized to maintain a constant AC voltage amplitude at the probe.

## Chapter 6

### The Global Plasma Model

#### 6.1 Introduction

##### 6.1.1 General Derivation and Assumptions of the Global Model

##### 6.1.2 Global Model Pressure Regimes

#### 6.2 Particle Conservation Solutions: Density Profiles and Electron Temperatures

##### 6.2.1 High Pressure Discharges: The Sheathless Case

###### 6.2.1.1 Charge Density Profile and Diffusion Length for the One Dimensional Slab Geometry

###### 6.2.1.2 Charge Density Profile and Diffusion Length for the Cylindrical Geometry

###### 6.2.1.3 Solutions to the Particle Conservation Equation

##### 6.2.2 Adding the Sheath to the High Pressure Discharge

##### 6.2.3 Low and Intermediate Pressure Discharges

###### 6.2.3.1 Charge Density Profiles

###### 6.2.3.2 Solutions to the Particle Conservation Equation

#### 6.3 Power Balance

##### 6.3.1 Energy Flux in the Plasma Discharge

##### 6.3.2 The Electron Subgas

##### 6.3.3 Electron Energy Absorption Processes

###### 6.3.2.1 Ohmic Heating

###### 6.3.2.2 Electron Cyclotron Resonance Heating

###### 6.3.2.3 Stochastic Heating

##### 6.3.4 Electron Energy Loss Processes

##### 6.3.5 Power Balance for Nonuniform High Pressure Discharges

##### 6.3.6 Power Balance for Low and Intermediate Pressure Discharges

#### 6.4 Plasma Source Performance Figures of Merit

##### 6.4.1 General Plasma Source Efficiency

##### 6.4.2 Ion Production Energy Cost

##### 6.4.3 Average Discharge Power Density

#### 6.5 Conclusion

## Chapter 6

### The Global Plasma Model

#### **6.1 Introduction**

##### **6.1.1 General Derivation and Assumptions of the Global Model**

A simple plasma model based upon the steady state conservation of particles and energy was first employed by Langmuir and Tonks [Ton-29] and by Schottky [Sch-24] in the 1920's. Since then the global models have been used to describe the behavior of the positive column in DC discharges and more recently have been used by Godyak [God-86] and Lieberman, et. al. [Lie-94], in characterizing the plasma properties of RF and microwave excited plasma discharges. For the last two decades the calculation of important plasma parameters such as electron temperature and charge density using the global model has been part of the course material taught in Electrical and Computer Engineering course number ECE 989 at Michigan State University [Asm-93]. Mahoney has a detailed development, including electron temperature and charge density predictions, of the global model for both free fall and high pressure discharge pressure regimes [Mah-89].

A development of the global model from the most general principles begins with the Boltzmann Equation [Lie-94]:

$$\frac{\partial}{\partial t}f(\mathbf{r}, \mathbf{v}, t) + \mathbf{v} \cdot \vec{\nabla}_{\mathbf{r}}f(\mathbf{r}, \mathbf{v}, t) + \frac{\vec{F}}{m} \cdot \vec{\nabla}_{\mathbf{v}}f(\mathbf{r}, \mathbf{v}, t) = \left. \frac{\partial}{\partial t}f(\mathbf{r}, \mathbf{v}, t) \right|_c \quad \text{Eq. 6.1}$$

where  $f(\mathbf{r}, \mathbf{v}, t)$  is the particle density distribution function dependent on three space variables,  $\mathbf{r}=\langle x,y,z \rangle$ , three particle velocity variables,  $\mathbf{v}=\langle v_x, v_y, v_z \rangle$ , and time,  $t$ . The Boltzmann Equation can be thought of as a continuity equation for the flow of particles in the six dimensional phase space  $(x,y,z,v_x,v_y,v_z)$ , i.e. the rate of increase in particle density,  $f(\mathbf{r}, \mathbf{v}, t)$ , in a (six dimensional) differential volume must be accounted for by the influx of particles into that volume.

The term  $\frac{\partial}{\partial t}f(\mathbf{r}, \mathbf{v}, t)$  represents the time rate of change (increase) of particles in a differential volume of phase space at the point  $(x,y,z,v_x,v_y,v_z,t)$ . The term  $\mathbf{v} \cdot \vec{\nabla}_{\mathbf{r}}f(\mathbf{r}, \mathbf{v}, t)$  represents the flux of particles out of the differential volume by simple flow into an adjacent spatial volume at velocity  $\mathbf{v}$ . The term  $\frac{\vec{F}}{m} \cdot \vec{\nabla}_{\mathbf{v}}f(\mathbf{r}, \mathbf{v}, t)$  represents the flux of particles out of the differential volume by acceleration into an adjacent velocity volume. The acceleration  $(\vec{F}/m)$  is produced by an external force, such as an electric field. The right hand side of the equation  $\left. \frac{\partial}{\partial t}f(\mathbf{r}, \mathbf{v}, t) \right|_c$  represents the flux of particles into or out of the differential volume due to collisions that instantly change the velocity of a particle.

The Boltzmann Equation is used to yield moment equations in the more useful mac-



roscopic terms of density, average velocity, and pressure. Multiplying the Boltzmann Equation by either  $v^0$ ,  $mv^1$ , or  $\frac{1}{2}mv^2$  and integrating over velocity space we can determine the moment equations for conservation of mass, momentum, or energy for each individual particle species,  $\alpha$ . The conservation equations for mass, momentum, and energy are given below:

Mass (Particle) Conservation:

$$\frac{\partial n_\alpha}{\partial t} + \vec{\nabla} \cdot (n_\alpha \vec{u}_\alpha) = G_\alpha - L_\alpha \quad \text{Eq. 6.2}$$

where  $n_\alpha$  is the particle density at point  $(x,y,z)$ ,  $\vec{u}_\alpha$  is the particle average velocity at point  $(x,y,z)$ ,  $\frac{\partial n_\alpha}{\partial t}$  is the rate of change of charge density at a point  $(x,y,z)$ ,  $\vec{\nabla} \cdot (n_\alpha \vec{u}_\alpha)$  is the flux density of species out of a differential volume surrounding point  $(x,y,z)$ ,  $G_\alpha$  is the rate of particle generation (through ionization) in that infinitesimal volume, and  $L_\alpha$  is the rate of particle annihilation (through recombination or attachment) in that volume.

Momentum Conservation:

$$n_\alpha m_\alpha \frac{\partial \vec{u}_\alpha}{\partial t} + n_\alpha m_\alpha (\vec{u}_\alpha \cdot \vec{\nabla}) \vec{u}_\alpha = n_\alpha \vec{F} - (\vec{\nabla} \cdot \vec{\bar{p}}_\alpha) + \vec{F}_c \Big|_{coll} \quad \text{Eq. 6.3}$$

where  $\vec{F}$  is an external force (such as an electric field acting on the electron gas), and  $\vec{\bar{p}}_\alpha$  is the tensor gas pressure. Taken as a whole the left hand side of the above equation can be

written as the “total” or “convective” derivative of the average momentum density,

$n_\alpha m_\alpha \frac{D\hat{n}_\alpha}{Dt}$ , and expresses the time rate of change of the average momentum in a collec-

tive particle gas element moving in a frame of reference with velocity  $\hat{n}_\alpha$ . Taking each

part of the total derivative separately  $n_\alpha m_\alpha \frac{\partial \hat{n}_\alpha}{\partial t}$  represents the acceleration of the particle

gas over time at a specific point in space, and  $n_\alpha m_\alpha (\hat{n}_\alpha \cdot \bar{\nabla}) \hat{n}_\alpha$  represents the steady state

change in particle gas velocity over a spatial volume. On the right hand side of equation

6.3  $n_\alpha \vec{F}$  is the external force term,  $-(\bar{\nabla} \cdot \vec{p}_\alpha)$  is the force density due to the pressure and

viscus shear forces on the gas, and  $\vec{F}_c|_{coll}$  represents the “damping” or “friction” force

term due to collisions with other particles.

#### Energy Conservation:

$$\frac{3}{2} \frac{\partial p_\alpha}{\partial t} + \left[ \nabla \cdot \frac{3}{2} (p_\alpha \hat{n}_\alpha) \right] + (\vec{p}_\alpha \cdot \bar{\nabla}) \cdot \hat{n}_\alpha + (\bar{\nabla} \cdot \hat{q}) = \langle P \rangle_{cl\alpha} + \langle P \rangle_{cg\alpha} + \langle P \rangle_{s\alpha}$$

Eq. 6.4

where  $\frac{3}{2} p_\alpha$  is the energy density (i.e. from the ideal gas law  $\frac{3}{2} p_\alpha = n_\alpha \left[ \frac{3}{2} k T_\alpha \right]$ ). The

first term  $\frac{3}{2} \frac{\partial p_\alpha}{\partial t}$  represents the change in energy density at a specific point over time,

$\nabla \cdot \frac{3}{2} (p_\alpha \hat{n}_\alpha)$  represents the flux of energy density out of an infinitesimal volume due to

particle diffusion,  $(\vec{\bar{p}}_\alpha \cdot \vec{\nabla}) \cdot \vec{n}_\alpha$  is the change of energy density due to expansion or compression of the particle gas, and  $\vec{q}$  is the heat flow vector with  $\vec{\nabla} \cdot \vec{q}$  representing heat flow out of the infinitesimal volume. The term  $\langle P \rangle_{cl\alpha}$  represents the power density losses due to collisions with other particle species, specifically it includes losses due to elastic and inelastic collisions (this term is described in more detail in section 6.3.4). The term  $\langle P \rangle_{cg\alpha}$  represents collisional gains such as “ohmic” heating (this term is described in more detail in section 6.2.3.1). The final term  $\langle P \rangle_{s\alpha}$  represents the power density due to any collisionless heating processes such as cyclotron resonance or stochastic heating (this term is described in more detail in sections 6.2.3.2 and 6.2.3.3). Both  $\langle P \rangle_{cg\alpha}$  and  $\langle P \rangle_{s\alpha}$  are proportional to the square of the amplitude of the forcing electric field, i.e.

$$\propto |E|^2.$$

The three equations above represent the generic particle conservation equations.

More specifically for an electron gas these equations become:

#### Electron Conservation

$$\frac{\partial n_e}{\partial t} + \vec{\nabla} \cdot (n_e \vec{u}_e) = G_e - L_e \quad \text{Eq. 6.5}$$

#### Electron Momentum Conservation

$$n_e m_e \frac{\partial \vec{u}_e}{\partial t} + n_e m_e (\vec{u}_e \cdot \vec{\nabla}) \vec{u}_e = n_e \vec{F} - (\vec{\nabla} \cdot \vec{P}_e) + \vec{F}_c|_{coll} \quad \text{Eq. 6.6}$$

#### Electron Gas Energy Conservation

$$\frac{3}{2} \frac{\partial p_e}{\partial t} + \left[ \vec{\nabla} \cdot \frac{3}{2} (p_e \vec{u}_e) \right] + (\vec{P}_e \cdot \vec{\nabla}) \cdot \vec{u}_e + (\vec{\nabla} \cdot \vec{q}) = \langle P \rangle_{cle} + \langle P \rangle_{cge} + \langle P \rangle_{se} \quad \text{Eq. 6.7}$$

A similar set of equations govern the ion and neutral gas distributions where the e subscripts are replaced by *i* and *g* for the ion and neutral gases respectively.

A very useful set of equations can be obtained using the following simplifying assumptions:

- 1) Steady state discharge: all derivatives with respect to time are zero
- 2) The electron temperature is assumed to be a constant with respect to position
- 3) The electron gas can be described by a Maxwellian electron energy distribution function with a temperature  $T_e$

4) Viscous shear forces are assumed to be zero, hence  $\bar{\nabla} \cdot \vec{\bar{p}}_e$  reduces to  $\bar{\nabla} p_e$  and

the electron pressure becomes a scalar

6) No expansion or compression of the gasses:  $\left(\vec{\bar{p}}_e \cdot \vec{\nabla}\right) \cdot \vec{u}_e = 0$

7) No volume loss processes, i.e. electron-ion recombination or electron attachment are zero, i.e.  $L_e = 0$

8) Plasma consists only of electrons, singly charged positive ions, and neutrals

9) One step ionization

10) Weakly ionized,  $n_g \gg (n_e \text{ or } n_i)$

Using these assumptions and utilizing the electron gas equations for conservation of particles, i.e. eq. 6.3, and conservation of energy, i.e. eq. 6.4, we obtain two fundamental equations that describe the behavior of the electron gas in a plasma. These are described in more detail below.

1) Particle conservation: the number of electrons lost to diffusion in a differential plasma volume equals the number of electrons generated in that volume:

$$\nabla \cdot (n_e \vec{u}_e) = \nu_{iz} n_e \quad \text{Eq. 6.8}$$

where  $n_e$  is the particle density,  $\vec{u}_e$  is the average particle velocity and  $\nu_{iz}$  is the particle creation frequency (ionization frequency). Integrating over the total volume of the discharge and using the divergence theorem, the electron flux out of the total sur-



### 6.1.2 Global Model Pressure Regimes

A further set of assumptions can be made based on the behavior of the ion gas for different discharge pressure regimes. There are three global model pressure diffusion regimes:

- 1) Low pressure, also called the Langmuir or Free Fall regime
- 2) Intermediate pressure
- 3) High pressure, also called the Schottky regime

In all three regimes (under the condition that  $T_e \gg T_i$ ) the motion of the electron gas is assumed to be ruled by Boltzmann dynamics (and essentially Maxwellian in distribution). Hence, electron thermal velocities are much greater in magnitude than electron drift velocities. The main difference for each of the pressure regimes is in the dynamics of the ion gas.

In the low pressure regime the ions are considered essentially collisionless. Here the ion mean free path,  $\lambda_i$ , is larger than the discharge size, i.e. in the cylindrical discharge  $\lambda_i \geq (R, L)$ , where  $R$  is the radius and  $L$  is the length of the cylindrical discharge chamber. Hence, ion velocity is determined by free fall dynamics. [Lie-94, Ton-29]

In the intermediate pressure regime the ion mean free path is on the order of or less than the discharge dimensions. Since ion-neutral collisions are more frequent the ion velocity in the ambipolar electric field is mobility limited, but is still much greater than the ion thermal velocity. The condition  $(R, L) \geq \lambda_i \geq \left(\frac{T_i}{T_e}\right)(R, L)$  applies at intermediate pressures for a cylindrical discharge; where  $T_e$  and  $T_i$  are the electron and ion temperatures,

respectively. [Lie-94, God-86]

In the high pressure regime, frequent collisions with neutral atoms limit the motion of ions to the point that the ion drift velocity is on the order of the ion thermal velocity. Motion of the ions approach a Boltzmann dynamic, although ion mobilities and diffusion

constants are much lower than those for electrons. The condition  $\lambda_i \leq \left(\frac{T_i}{T_e}\right)(R, L)$

applies in this pressure regime for a cylindrical discharge. [Lie-94, Sch-24]



## 6.2 Particle Conservation Solutions: Density Profiles and Electron Temperatures

The particle conservation equation can be solved for the high pressure and intermediate discharge pressure regimes yielding both discharge density variation and electron temperature. The high pressure sheathless discharge is described first, since the solutions for density distribution are analytical.

### 6.2.1 High Pressure Discharges: The Sheathless Case

In the high pressure (Schottky) diffusion regime both electrons and ions obey Boltzmann dynamics, however the mobility and diffusion constants for electrons remain much greater than for ions. Note that electron and ion flux density must be equivalent,  $\vec{\Gamma}_e = \vec{\Gamma}_i$ , and electron and ion charge density are approximately equivalent,  $n_e \approx n_i$ , (Note: a small excess of ion density must exist, increasing from discharge center to walls, as a source for the ambipolar E-Field) everywhere in the discharge volume (except the sheath). In effect, electron and ion gasses are linked together with an electrostatic tether. The ions create a drag on electron motion, and reciprocally the electrons “pull” the ions along increasing their rate of movement [Asm-93]. The effective diffusion constant,  $D_a$ , is given by: [Che-79]

$$D_a = \frac{(D_e\mu_i + D_i\mu_e)}{\mu_i + \mu_e} \quad \text{Eq. 6.12}$$

where  $D_e$  and  $D_i$  are the electron and ion diffusion constants, respectively, and  $\mu_e$  and  $\mu_i$  are the electron and ion mobilities, respectively. The ambipolar diffusion constant,  $D_a$ , applies to both electrons and ions in the high pressure discharge, and has a value between  $D_e$  and  $D_i$ . The ambipolar diffusion constant is used in Fick's Law:

$$\vec{\Gamma}_e = -D_a \nabla n_e \quad \text{Eq. 6.13}$$

where  $\vec{\Gamma}_e$  is the electron flux density and  $\nabla n_e$  is the gradient of electron density. Fick's Law can be substituted into the electron continuity equation (from particle conservation):

$$\nabla \cdot \vec{\Gamma}_e = n_e \nu_{iz} \quad \text{Eq. 6.14}$$

giving:

$$-D_a \nabla^2 n_e = n_e \nu_{iz} \quad \text{Eq. 6.15}$$

where  $\nu_{iz}$  is the electron neutral ionization frequency. Rearranging we obtain the steady state equation for the electron density:

$$\nabla^2 n_{\begin{Bmatrix} e \\ i \end{Bmatrix}} + \left( \frac{\nu_{iz}}{D_a} \right) n_{\begin{Bmatrix} e \\ i \end{Bmatrix}} = 0 \quad \text{Eq. 6.16}$$

Since  $n_e \cong n_i$  everywhere Eq. 6.16 can be used to solve for the charge density profile of either electrons or ions in a high pressure discharge.

Charge density profiles for the slab and cylindrical geometries are derived in the sections below.

### 6.2.1.1 Charge Density Profile and Diffusion Length for the One Dimensional Slab Geometry

Consider an infinite parallel plane discharge with walls located at  $x=L/2$  and  $-L/2$  as shown in Figure 6.1 The diffusion equation (Eq. 6.14) in one dimension ( $x$ ) is written:

$$\frac{\partial^2 n_e}{\partial x^2} + \left( \frac{v_{iz}}{D_a} \right) n_e = 0 \quad \text{Eq. 6.17}$$

Applying the boundary condition that  $n_i = 0$  at  $x = \pm \frac{L}{2}$  we can determine an analytical function for the density variation vs.  $x$ . This function is plotted in Figure 6.2:

$$n_e = n_0 \cos \beta x \quad \text{where} \quad \beta = \frac{\pi}{L} \quad \text{Eq. 6.18}$$

The separation equation then can be written

$$(\beta)^2 - \left( \frac{v_{iz}}{D_a} \right) = 0 \quad \text{Eq. 6.19}$$

Hence:

$$\beta = \left( \frac{v_{iz}}{D_a} \right)^{\frac{1}{2}} = \frac{\pi}{L} = \frac{1}{\Lambda} \quad \text{where } \Lambda \text{ is the diffusion length.} \quad \text{Eq. 6.20}$$

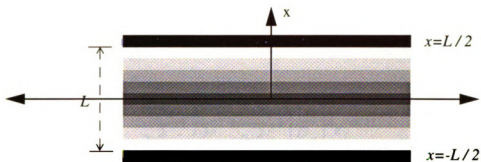


Figure 6.1: Parallel Plane Discharge

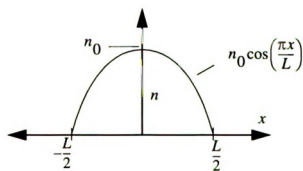


Figure 6.2: The density variation vs.  $x$

### 6.2.1.2 Charge Density Profile and Diffusion Length for the Cylindrical Geometry

Now consider cylindrical discharge with end walls located at  $z=L/2$  and  $-L/2$  and radius  $R$  as shown in Figure 6.3. Casting the diffusion equation in cylindrical coordinates we have:

$$\frac{\partial^2 n_e}{\partial r^2} + \frac{1}{r} \frac{\partial n_e}{\partial r} + \frac{\partial^2 n_e}{\partial z^2} + \left( \frac{v_{iz}}{D_a} \right) n_e = 0 \quad \text{Eq. 6.21}$$

Solving with the boundary conditions of  $n_e = n_i = 0$  at the walls yields:

$$n_e = n_0 \cos\left(\frac{\pi z}{L}\right) J_0\left(\frac{2.405}{R} r\right) \quad \text{Eq. 6.22}$$

The density variation in the  $r$  direction is shown in Figure 6.4. The density variation along the  $z$  axis is similar to the variation shown in Figure 6.2 with  $x$  replaced by  $z$ .

Also from Eq. 6.14 we arrive at the separation equation:

$$\frac{v_{iz}}{D_a} = \frac{1}{\Lambda^2} = \left( \frac{2.405}{R} \right)^2 + \left( \frac{\pi}{L} \right)^2 \quad \text{Eq. 6.23}$$

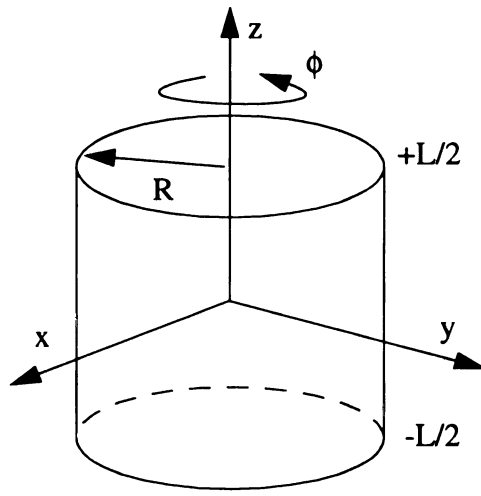


Figure 6.3: Cylindrical Discharge Chamber

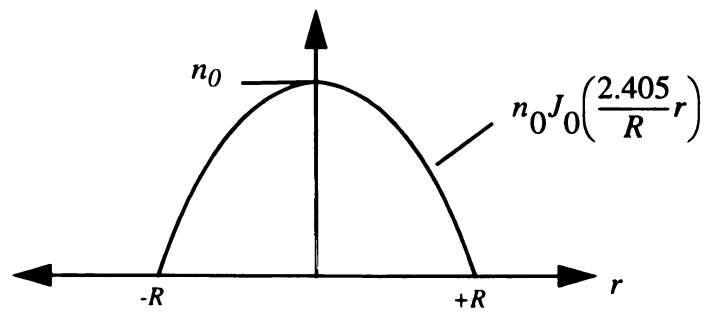


Figure 6.4: Density variation in the radial dimension  $r$  for the cylindrical discharge

### 6.1.2.3 Solutions to the Particle Conservation Equation

Returning to the particle continuity equation:

$$\nabla \cdot \vec{\Gamma}_e = v_{iz} n_e \quad \text{Eq. 6.24}$$

and once again integrating over the volume of the discharge and applying the divergence theorem we arrive at:

$$\oint_A \vec{\Gamma}_e \cdot d\vec{S} = \int_V (v_{iz} n_e) dV \quad \text{Eq. 6.25}$$

The electron density distribution and electron flux density for the parallel plate discharge are:  $n_e(x) = n_0 \cos(\beta x)$  and  $\vec{\Gamma}_e(x) = (\hat{x}) D_a \beta n_0 \sin \beta x$ . Substituting for  $n_e$  we have:

$$\int \vec{\Gamma}_e \left( \frac{L}{2} \right) \cdot (\hat{x}) dy dz + \int \vec{\Gamma}_e \left( -\frac{L}{2} \right) \cdot (-\hat{x}) dy dz = \int_{V_L} (v_{iz} n_0 \cos \beta x) dV_L \quad \text{Eq. 6.26}$$

For a parallel plate discharge this reduces to:

$$2 D_a \beta n_0 = 2 v_{iz} \frac{1}{\beta} n_0 \quad \text{Eq. 6.27}$$

Then, rearranging we obtain:

$$\beta^2 = \frac{v_{iz}}{D_a} = \left( \frac{\pi}{L} \right)^2 = \frac{1}{\Lambda^2} \quad \text{Eq. 6.28}$$

The particle balance equation applied to the slab geometry yields the separation equation for the slab geometry.

A similar result holds for the cylindrical geometry.

$$\int_0^R \int_0^{2\pi} \int_0^l [v_{iz} n_e(r, z)] r dr d\theta dz = 2u_B \int_0^R \int_0^{2\pi} \Gamma_{iz}(r) r dr d\theta + u_B \int_0^{2\pi} \int_0^l \Gamma_{ir}(z) R d\theta dz \quad \text{Eq. 6.29}$$

Volume Ionization                      Ion Flux to End Walls                      Ion Flux to the Side Wall

where  $R$  and  $l$  are the dimensions of the discharge,  $v_{iz}$  is the electron neutral collision frequency for an individual electron, and  $n_e(r, z)$  is the electron density at a point  $(r, z)$ . and  $\Gamma_{iz}(r)$  and  $\Gamma_{ir}(z)$  are ion flux densities at the end walls and side wall, respectively, they are defined as:

$$\Gamma_{iz}(r) = -D_a \frac{\partial n_e}{\partial z} \quad \text{Eq. 6.30}$$

and

$$\Gamma_{ir}(z) = -D_a \frac{\partial n_e}{\partial r} \quad \text{Eq. 6.31}$$

They can be evaluated using:

$$n_e(r, z) = n_0 J_0 \left( \frac{x_{01}}{R} r \right) \cos \left( \frac{\pi z}{l} \right) \quad \text{Eq. 6.32}$$

yielding the separation equation for the cylindrical geometry.

$$\frac{v_{iz}}{D_a} = \frac{1}{\Lambda^2} = \left( \frac{2.405}{R} \right)^2 + \left( \frac{\pi}{l} \right)^2 \quad \text{Eq. 6.33}$$

In general for any discharge

$$\frac{v_{iz}}{D_a} = \frac{1}{\Lambda^2} \quad \text{Eq. 6.34}$$

where  $\Lambda$  is the diffusion length and  $D_a \equiv (eT_e)/(Mn_g K_{mi})$ . The ion-neutral collision rate constant,  $K_{mi}$ , is approximately  $4.2 \cdot 10^{-16} (\text{m}^3/\text{s})$  for typical ion energies of  $\sim 0.05 \text{ eV}$ .



Since  $v_{iz} = n_g K_{iz}$  and substituting for  $D_a$  in Eq. 6.34 we have

$$\Lambda^2 n_g K_{iz} = \frac{e T_e}{M n_g K_{mi}} \quad \text{Eq. 6.35}$$

using the definition of the Bohm velocity we can substitute

$$\Lambda^2 n_g^2 = \frac{u_B^2}{K_{iz} K_{mi}} \quad \text{Eq. 6.36}$$

where  $u_B$  and  $K_{iz}$  are functions of  $T_e$  and  $K_{mi}$  is a constant. Now taking the square root we have this significant result:

$$\Lambda n_g = \frac{u_B}{\sqrt{K_{iz} K_{mi}}} \quad \text{Eq. 6.37}$$

where the formula for the electron neutral collision rate constant is [Lie-94]:

$$K_{iz} = \sigma_0 \left( \frac{8eT_e}{\pi m_e} \right)^{\frac{1}{2}} \left( 1 + \frac{2T_e}{E_{iz}} \right) \exp \left( -\frac{E_{iz}}{T_e} \right) \quad \text{Eq. 6.38}$$

here  $E_{iz}$  is the ionization potential for the specific gas.

Note that the right hand side of equation 6.37 is only a function of electron temperature,  $T_e$ , while the left hand side is a function of gas density and discharge geometry. Using equation 6.37 and equation 6.38 electron temperature can be plotted vs.  $\Lambda$  and  $n_g$  (see Figure 6.5). Note also that electron temperature does not depend upon input power.

Using the ideal gas law:  $p_g = n_g K T_g$ ; where  $T_g$  is the neutral gas temperature,

Equation 6.37 becomes:

$$C p_g \Lambda = \frac{u_B}{\sqrt{K_{iz}}} \quad \text{Eq. 6.39}$$

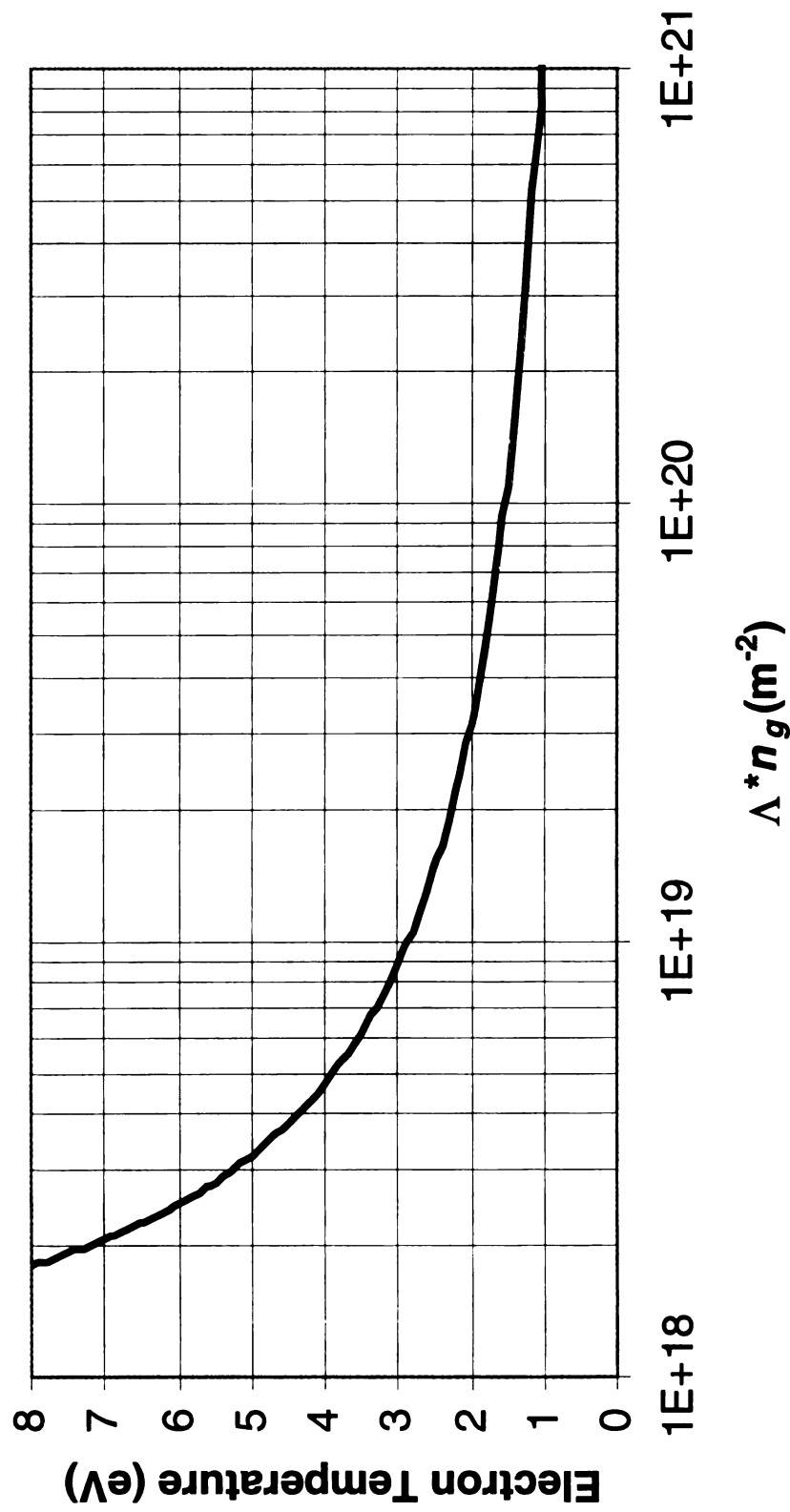


Figure 6.5 – Electron Temperature vs. neutral gas density,  $n_g$ , times diffusion length,  $\Lambda$ , for a plasma discharge in the high pressure regime

where  $C$  is the gas constant given by  $\sqrt{K_{mi}/(kT_g)}$ . Equation 6.39 is often referred to as the “C-P-Lambda” curve. Given the gas constant,  $C$ , the operating gas pressure,  $p_g$ , and geometry,  $\Lambda$ , the discharge electron temperature can then be determined.

We could also plot electron temperature as a function of pressure alone for a specific discharge geometry and discharge gas.

$$p_g = \frac{u_B}{C\Lambda\sqrt{K_{iz}}} = \frac{u_B\sqrt{kT_g}}{\Lambda\sqrt{K_{mi}K_{iz}}} \quad \text{Eq. 6.40}$$

however in this case we need to be mindful that this curve will change with changing neutral gas temperature as depicted in Figure 6.6.

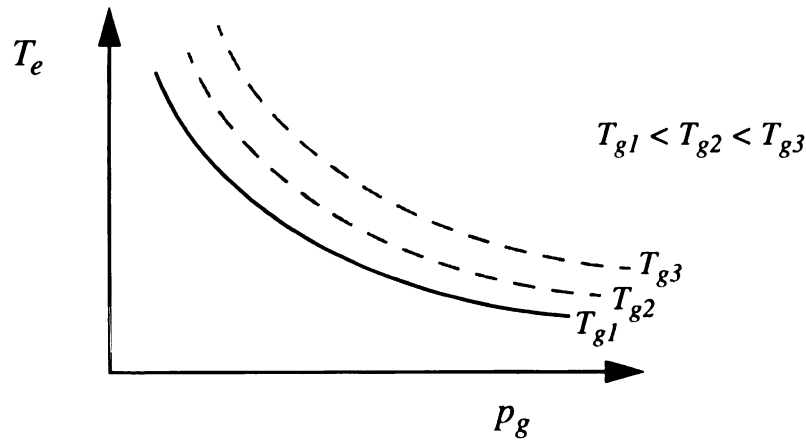


Figure 6.6: Electron temperature vs.  $p_g$  and neutral gas temperature  $T_g$  for a specific discharge geometry and discharge gas

## 6.2.2 Adding the Sheath to the High Pressure Discharge

The developments in sections 6.2.1.1 and 6.2.1.2 do not describe the sheath that exists adjacent to the discharge walls. In addition the boundary condition  $n_i = n_e = 0$  at the walls is not self consistent, as will be explained below. From Section 6.2.1.1, in the parallel plate geometry the charge density as a function of position,  $n(x)$ , is given by:  $n(x) = n_0 \cos \beta x$ ; where  $n_0$  is the center charge density,  $\beta = \pi/L$  and  $L$  is the separation between the plates. From the density function,  $n(x)$ , and Fick's Law we can determine an expression for particle flux:

$$\Gamma = -(D_a) \frac{\partial}{\partial x} n(x) = D_a n_0 \beta \sin \beta x \quad \text{Eq. 6.41}$$

where  $D_a$  is the ambipolar diffusion constant. Thus, the flux of charged particles arriving at the walls (at  $x = L/2$ ) is given by  $D_a n_0 \frac{\pi}{L}$ . Since  $u = \frac{\Gamma}{n}$  we can write an expression for  $u(x)$ , the ion or electron velocity, vs. position  $x$ .

$$u(x) = \frac{D_a n_0 \beta \sin \beta x}{n_0 \cos \beta x} \quad \text{Eq. 6.42}$$

However, if we evaluate this expression at the wall where  $x = L/2$  then:

$$u(x) \Big|_{x = \frac{L}{2}} = D_a \left( \frac{\pi}{L} \right) \tan \left( \frac{\pi L}{2L} \right) \rightarrow \infty \quad \text{Eq. 6.43}$$

Thus, in this mathematical model, in order to maintain the boundary condition  $n_i = n_e = 0$  the electron and ion velocities at the walls must approach infinity. This condition can not

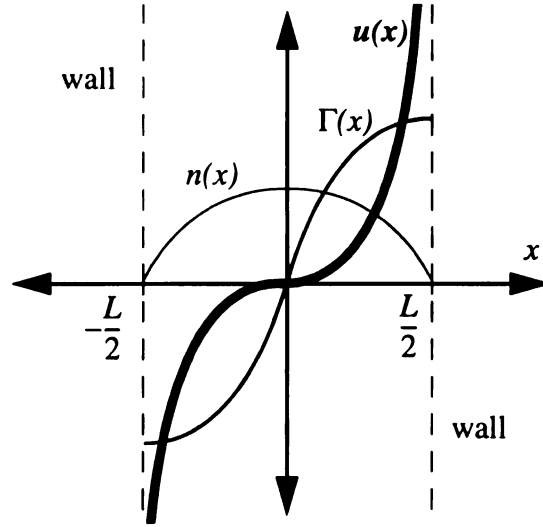


Figure 6.7: Functions  $n(x)$ ,  $\Gamma(x)$ , and  $u(x)$  for a parallel plate geometry with the sheathless model

be satisfied physically. Even though the above relations for  $n(x)$ ,  $u(x)$  and  $\Gamma(x)$  (Shown in Figure 6.7) are a very accurate approximation of the physical system near the center of the discharge this model breaks down near the plasma edge.

The nonuniform sheathless plasma model must be modified to include the sheath. Clearly, of the functions  $n(x)$ ,  $u(x)$  and  $\Gamma(x)$ , it is  $u(x)$  that must be modified near the plasma boundary to allow for finite velocity. In order to maintain the relation  $\Gamma(x) = u(x)n(x)$  either  $n(x)$  or  $\Gamma(x)$  must also be modified. Since  $\Gamma(x)$  at the boundary is determined by steady state particle balance, it is  $n(x)$  that must be modified near the wall.

We assume that the sheathless solutions:  $n(x)$ ,  $u(x)$  and  $\Gamma(x)$  adequately describe the discharge everywhere except in a thin region of thickness  $s$  next to the wall. It is assumed that  $s \ll L/2$ . The boundary of this region in the parallel plate geometry would

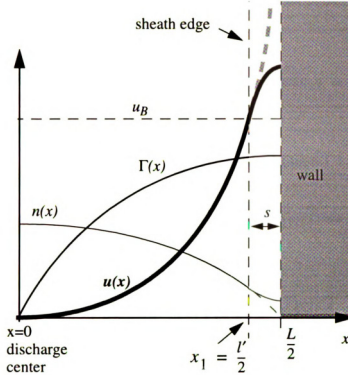


Figure 6.8: Sheathless (dashed curves) and sheathed (solid curves) models for  $n(x)$  and  $u(x)$  at the sheath edge

be  $x_1 = \frac{L}{2} - s = \frac{l'}{2}$  near the right side wall as shown in Figure 6.8 and

$x_2 = -\frac{L}{2} + s = \frac{l''}{2} = -\frac{l'}{2}$  near the left side wall (not shown in Figure 6.8). To modify the

sheathless model it is assumed that  $u(x_1) = u_B$ ; where  $u_B$  is the Bohm velocity:

$$u_B = \sqrt{\frac{k_b T_e}{M}} \quad \text{Eq. 6.44}$$

where  $k_b$  is the Boltzmann constant,  $T_e$  is the electron temperature in Kelvin, and  $M$  is the mass of the ion.

If the discharge electron temperature and  $\beta$  are known then the sheath thickness,  $s$ , can be determined from:

$$u_B = D_a \beta \tan \frac{\beta l'}{2} \quad \text{or} \quad \frac{l'}{2} = \frac{1}{\beta} \operatorname{atan} \left( \frac{u_B}{D_a \beta} \right) \quad \text{where } s = \frac{L-l'}{2} \quad \text{Eq. 6.45}$$

where  $\beta$  is defined in section 6.1.2.1 and  $D_a$  is defined in section 6.1.2.3. The charge density at the sheath edge then follows from:  $n_s = n_0 \cos \frac{\beta l'}{2}$ . This leads to an expression of the ratio of sheath to center density in the planar geometry

$$\frac{n_s}{n_0} = \cos \left( \frac{\beta l'}{2} \right) = \cos \left( \operatorname{atan} \left( \frac{u_B}{D_a \beta} \right) \right) = \left[ 1 + \left( \frac{u_B}{D_a \beta} \right)^2 \right]^{-1/2} = h_l \quad \text{Eq. 6.46}$$

where  $h_l$  is a dimensionless constant that relates sheath edge density,  $n_s$ , to the center discharge density,  $n_0$ . Note that this model provides values for  $n(x)$  and  $u(x)$  at the sheath edge, but not within the sheath. A similar development can be made for the sheath in the cylindrical geometry to obtain  $h_R$  which relates  $n_s$  to  $n_0$  in the cylindrical geometry.

Now we can derive the basic “CPA” equation for the nonuniform discharge with a sheath. Consider the parallel slab geometry as derived at the beginning of section 6.1.2.3. This problem is independent of  $y$  and  $z$ . Again we start with the continuity equation:

$$\nabla \cdot \vec{\Gamma}_e = v_{iz} n_e \quad \text{Eq. 6.47}$$

and once again integrating over the volume of the discharge and applying the divergence theorem we arrive at:

$$\oint_A \vec{\Gamma}_e \cdot d\vec{S} = \int_V (v_{iz} n_e) dV \quad \text{Eq. 6.48}$$

Given the electron density distribution and electron flux density for the parallel plate discharge and substituting for  $n_e$  we have:

$$\int_{\text{Top}} \vec{\Gamma}_e \Big|_{\left(\frac{L}{2} - s\right)} \cdot (\hat{x}) dy dz + \int_{\text{Bottom}} \vec{\Gamma}_e \Big|_{\left(-\frac{L}{2} + s\right)} \cdot (-\hat{x}) dy dz = \int_{(V_L - V_S)} (v_{iz} n_0 \cos \beta x) dV_L$$

$\nwarrow = \frac{l'}{2}$ 
 $\nwarrow = -\frac{l'}{2}$

Eq. 6.49

We choose a volume and surface that only includes the bulk plasma region - we do not include the sheath in the volume integral. Since the problem is independent of  $y$  and  $z$  we can cancel from both sides and integrate over a unit length for each. The result is:

$$D_a \beta n_0 \sin\left(\beta \frac{l'}{2}\right) + (-1) D_a \beta n_0 \sin\left(\beta \frac{-l'}{2}\right) = 2 \int_0^{l'} v_{iz} n_0 \cos \beta x dx$$

Eq. 6.50

evaluating and simplifying we get:

$$2 D_a \beta n_0 \sin\left(\beta \frac{l'}{2}\right) = 2 \frac{v_{iz}}{\beta} n_0 \sin\left(\beta \frac{l'}{2}\right) \quad \text{Eq. 6.51}$$

cancelling the common terms we arrive at:

$$\beta^2 = \frac{v_{iz}}{D_a} \quad \text{Eq. 6.52}$$



which is the same as the characteristic equation for the sheathless discharge. Hence, the same “CPL” curve applies to both the sheathless discharge and the discharge with sheath included.

### 6.2.3 Low and Intermediate Pressure Discharges

#### 6.2.3.1 Charge Density Profiles

In the case of a high pressure plasma ion motion is dominated by frequent collisions with the neutral gas. Hence the ion thermal velocity,  $v_{thi}$ , is much greater than the ion drift velocity,  $\vec{u}_i$ . Under these conditions the ion neutral collision frequency,  $\nu_{mi}$ , is a function of ion temperature,  $T_i$ , and independent of  $\vec{u}_i$ . At lower pressures (i.e. the intermediate pressure regime) ions undergo fewer collisions with the neutral gas and  $\lambda_i$  becomes longer. The ions then have a chance to gain more directed velocity after each collision creating the condition:  $\vec{u}_i \gg v_{thi}$ . The ion gas loses its Maxwellian-like distribution and the ion-neutral collision frequency  $\nu_{mi}$  becomes less a function of  $T_i$  and more a function of  $\vec{u}_i$  until the approximate relation,  $\nu_{mi} \approx |\vec{u}_i|/\lambda_i$ , holds [Lie-94]. This makes the ion mobility,  $\mu_i$ , a non-linear function of  $\vec{u}_i$ . Hence, the physical model that describes this regime is known as the *variable mobility* model [God-86]. In addition, the equation:

$$\vec{n}_i = \mu_i \vec{E} \quad \text{Eq. 6.53}$$

is no longer a linear relation. Consequently, the continuity equation,

$$\nabla \cdot (n\mathbf{u}_i) = n\nu_{iz} \quad \text{Eq. 6.54}$$

becomes a non-linear differential equation. To find charge density as a function of position,  $n(x)$ , for a parallel plate discharge the continuity equation can be transformed into this non-linear differential equation:

$$\left(\frac{2\lambda_i kT_e}{M\pi}\right)^{1/2} \frac{d}{dx} \left(-n \frac{dn}{dx}\right)^{1/2} = n\nu_{iz} \quad \text{Eq. 6.55}$$

where  $M$  is the ion mass and  $\nu_{iz}$  is the electron-neutral ionization frequency. The solution,  $n(x)$ , of the above equation is a lengthy analytical function of  $x$  given in references [Lie-94] and [God-86]. Essentially, the density profile is similar to the cosine profile of the high pressure discharge, however it is more uniform in the center and falls to zero steeply near the discharge edge.

In the low pressure regime (i.e. ion free fall regime) where the ions undergo very few collisions the ion velocity is determined by unimpeded acceleration through the potential drop to the walls of the discharge. If the ions begin in the bulk plasma at near zero velocity they have maximum potential energy and zero kinetic energy. As the ions fall through the potential drop the potential energy is converted to kinetic energy. Hence  $u_i$  can be expressed as a function of potential,  $\Phi$ , which is also a function of position,  $x$ :

$$u_i(x) = \sqrt{\frac{-2e\Phi(x)}{M}} \quad \text{Eq. 6.56}$$

where  $M$  is the ion mass,  $e$  is the electron charge and  $\Phi$  is the space charge potential at a point in the discharge. Using the Boltzmann relation the potential can be expressed in terms of charge density:

$$\Phi(x) = T_e \ln\left(\frac{n(x)}{n_0}\right) \quad \text{Eq. 6.57}$$

where  $T_e$  is the electron temperature in Volts, and  $n_0$  is the center plasma density. Substituting for potential in the equation for  $u_i$ :

$$u_i(x) = \sqrt{\frac{-2eT_e \ln\left(\frac{n(x)}{n_0}\right)}{M}} \quad \text{Eq. 6.58}$$

Now substituting into the continuity equation and simplifying for the parallel plane geometry (i.e. one dimensional problem) we arrive at another non-linear differential equation for  $n(x)$ :

$$\frac{d}{dx} \left[ n \left( \frac{-2eT_e}{M} \ln\left[\frac{n}{n_0}\right] \right)^{1/2} \right] = n \nu_{iz} \quad \text{Eq. 6.59}$$

where  $M$  is the ion mass and  $\nu_{iz}$  is the electron-neutral ionization frequency. This equation has a solution given in reference [Ton-29]. This charge density profile  $n(x)$  is similar to the previous intermediate pressure profile, i.e. it is very uniform near the center and tapers off quickly at the edges.

Both of the above charge density profiles have the same feature of being flat near the center and steep near the edges. Consequently, for some calculations it is useful to approximate the plasma density, in the intermediate and low pressure regimes, to be uni-

form with value  $n_0$  over the bulk of the discharge region (such as the calculation of the total rate of ion creation in a discharge,  $n_0 v_{iz} V_{volume}$ ). For other calculations, however, it is useful to know,  $n_s$ , the charge density at the sheath edge relative to,  $n_0$ , the bulk charge density (i.e. the calculation of ion current density to the walls,  $n_s u_B$ ). This ratio,  $n_s/n_0$ , is expressed in the form of a geometric constant  $h$ , where  $h = n_s/n_0$ . This ratio can be determined from the charge density profile  $n(x)$ . From the solutions of both the *variable mobility* and *free fall* models above Godyak [God-86] has constructed a heuristic (curve fitting) transition that provides expressions determining  $n_s/n_0$  continuously from the intermediate pressure range down to low pressures. In Godyak's development;

$$h_l = \frac{n_{sl}}{n_0} \approx 0.86 \left( 3 + \frac{L}{2\lambda_i} \right)^{-1/2} \quad (\text{for the sheath at a planar wall}) \quad \text{Eq. 6.60}$$

where  $n_{sl}$  is the planar sheath edge density,  $n_0$  is the bulk plasma density,  $L$  is the distance between planes, and  $\lambda_i$  is the ion-neutral mean free path. This relation is constructed from the solutions of the *free fall* and *variable mobility* models for a parallel plate geometry.

Also,

$$h_R = \frac{n_{sR}}{n_0} \approx 0.80 \left( 4 + \frac{R}{\lambda_i} \right)^{-1/2} \quad (\text{for the sheath at a cylindrical wall}) \quad \text{Eq. 6.61}$$

where  $R$  is the radius of the cylindrical discharge. This relation is derived from the solutions of the *free fall* and *variable mobility* models for an infinite cylindrical geometry in cylindrical coordinates. Note that at very low pressures: as  $\lambda_i \rightarrow \infty$  then  $h_l \approx 0.5$  and

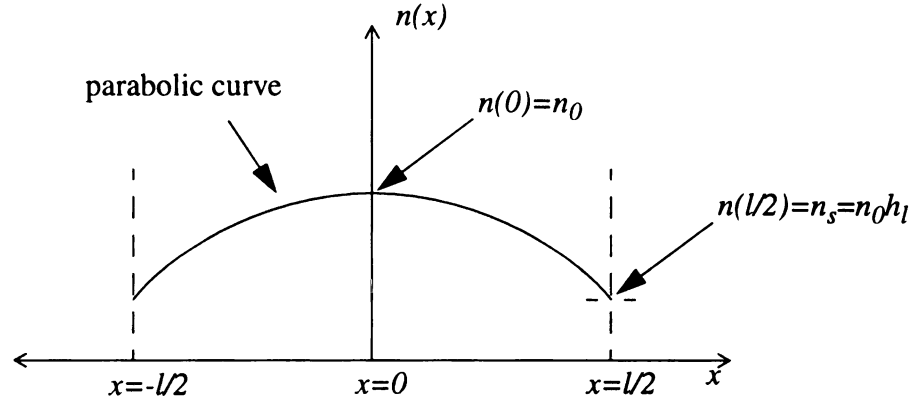


Figure 6.9: Approximate charge density profile for the low or intermediate pressure regime, with parallel plate separated by distance  $l$

$h_R \approx 0.4$ . The sheath edge density,  $n_s$ , is never more than half the bulk density,  $n_0$ , at the lowest pressures and only decreases as pressure is increased.

An approximation for the density profile  $n(x)$ , appropriate for the low and intermediate pressure regimes where the  $h$  parameters above apply, was presented by Godyak. It is simply the fitting of a parabolic curve between the center density,  $n_0$ , and the sheath edge density,  $n_s$ . For planar geometries the profile is:

$$n(x) \approx \left( \frac{n_{sl} - n_0}{(l/2)^2} \right) x^2 + n_0 = n_0 \left( \frac{h_l - 1}{(l/2)^2} x^2 + 1 \right) \quad \text{Eq. 6.62}$$

where  $(l/2)$  is the position of the planar wall of the discharge. Note that when  $x=0$  then  $n(x)=n_0$  and when  $x=l/2$  then  $n(x)=n_{sl}$ . This curve is plotted in Figure 6.9. For cylindrical geometries the profile is:

$$n(x) \approx \left[ \left( \frac{n_{sR} - n_0}{(R)^2} \right) r^2 + n_0 \right] = n_0 \left( \frac{h_R - 1}{(R)^2} x^2 + 1 \right) \quad \text{Eq. 6.63}$$

where  $R$  is the position of the cylindrical wall of the discharge. The plot for this function is similar to that shown in Figure 6.9

### 6.2.3.2 Solutions to the Particle Conservation Equation

The particle balance equation that was valid at high pressure still applies in the low and intermediate pressure regimes:

$$\oint_A \vec{\Gamma}_i \cdot d\vec{S} = \int_V (v_{iz} n_i) dV \quad \text{Eq. 6.64}$$

where the left hand side is the total ion flux to the discharge walls and the right hand side is the total number of ions created in the discharge volume per second. As was mentioned in the previous section, the spatial charge density profile  $n(x)$  in the low and intermediate pressure regimes can be approximated as almost constant over the discharge. Major density variations only occur near the walls. Thus, the discharge plasma density can be approximated by the center density,  $n_0$ , over most of the discharge volume. Consequently, the right hand side of the balance equation simplifies to:

$$(v_{iz} n_0) \int_V dV = v_{iz} n_0 V \quad \text{Eq. 6.65}$$

neglecting the density variation near the sheath.

where  $V$  is the volume of the discharge. The left hand side of the particle balance equation can be developed as follows:

$$\oint_A \vec{\Gamma}_i \cdot d\vec{S} = \sum_j \int_{A_j} \vec{\Gamma}_{ij} \cdot d\vec{S} = \sum_j \Gamma_{ij} A_j = \sum_j (n_{sj} u_B) A_j = \sum_j ((n_0 h_j) u_B) A_j \quad \text{Eq. 6.66}$$

(I)                      (II)                      (III)                      (IV)                      (V)

Term (I) is the total ion flux flowing through the total outer surface of the discharge,  $A$ . This term can be thought of as term (II) the sum of the ion fluxes flowing through each outer surface,  $A_j$ , of the plasma; where the subscript  $j$  denotes an individual surface of the discharge. Assuming that the vector flux density over one surface of the plasma is a constant,  $\Gamma_{ij}$ , multiplied by the area of that surface,  $A_j$ , then one obtains term (III). The flux density for a specific surface, can be given by the ion Bohm velocity,  $u_B$ , multiplied by the sheath edge density,  $n_{sj}$ , at that surface, hence term (IV). The sheath edge density is found by multiplying the bulk charge density,  $n_0$ , by the geometric constant,  $h_j$ , for each surface, leading to term (V). Hence, the low and intermediate pressure balance equation can be written in this general form:

$$n_0 u_B \sum_i h_i A_i = v_{iz} n_0 V \quad \text{Eq. 6.67}$$

Now, using  $v_{iz} = n_g K_{iz}$ ; where  $n_g$  is the neutral gas density, and  $K_{iz}$  is the electron neutral ionization rate constant, it can then be simplified to:

$$\frac{K_{iz}(T_e)}{u_B(T_e)} = \frac{1}{n_g \left( \frac{V}{\sum_i h_i A_i} \right)} \equiv \frac{1}{n_g d_{eff}} \quad \text{Eq. 6.68}$$

where both the numerator and denominator of the left hand side are functions of electron temperature,  $T_e$ , and where we define the effective diffusion length:

$$d_{eff} \equiv \frac{V}{\sum_i h_i A_i} \quad \text{Eq. 6.69}$$

rearranging we have:

$$n_g d_{eff} = \frac{u_B(T_e)}{K_{iz}(T_e)} \quad \text{Eq. 6.70}$$

where

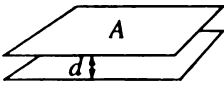
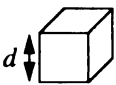
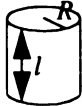
$$u_B(T_e) = \sqrt{\frac{eT_e}{M}} \quad \text{Eq. 6.71}$$

and

$$K_{iz}(T_e) = \pi \left( \frac{e}{4\pi\epsilon_0\epsilon_{iz}} \right)^2 \left( \frac{8eT_e}{\pi m_e} \right)^{1/2} \left( 1 + \frac{2T_e}{\epsilon_{iz}} \right) \exp\left( \frac{-\epsilon_{iz}}{T_e} \right) \quad \text{Eq. 6.72}$$

Evaluating  $n_g d_{eff}$  as a function of  $T_e$ , with  $M = 6.6904 \times 10^{-26}$  kg and  $\epsilon_{iz} = 15.76$  eV for argon gas, the curve plotted in Figure 6.10 is obtained. Thus, by choosing the gas, the gas pressure with appropriate diffusion theory, boundary conditions, discharge geometry and discharge dimensions; i.e.  $d_{eff}$ , the discharge electron temperature can be determined.

**Table 6.1:** Effective diffusion length,  $d_{eff}$  for various discharge geometries.

|                                                                                                 |                                                                                     |                                                                                         |
|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| <u>Parallel plate</u> with plate separation, $d$ , and plate area, $A$ .                        |  | $d_{eff} = \frac{Ad}{h_l A + h_l A} = \frac{d}{2h_l}$                                   |
| <u>Cubical</u> discharge with side length, $d$ .                                                |  | $d_{eff} = \frac{d^3}{6(h_l d^2)} = \frac{d}{6h_l}$                                     |
| <u>Cylindrical</u> discharge with radius, $R$ , and height, $l$ .                               |  | $d_{eff} = \frac{\pi R^2 l}{2(h_l \pi R^2) + h_R 2\pi R l} = \frac{Rl}{2(Rh_l + lh_R)}$ |
| <u>Spherical</u> discharge with radius, $R$ , where $h_p$ is the spherical $n_s/n_0$ parameter. |  | $d_{eff} = \frac{\frac{4}{3}\pi R^3}{h_p (4\pi R^2)} = \frac{R}{3h_p}$                  |



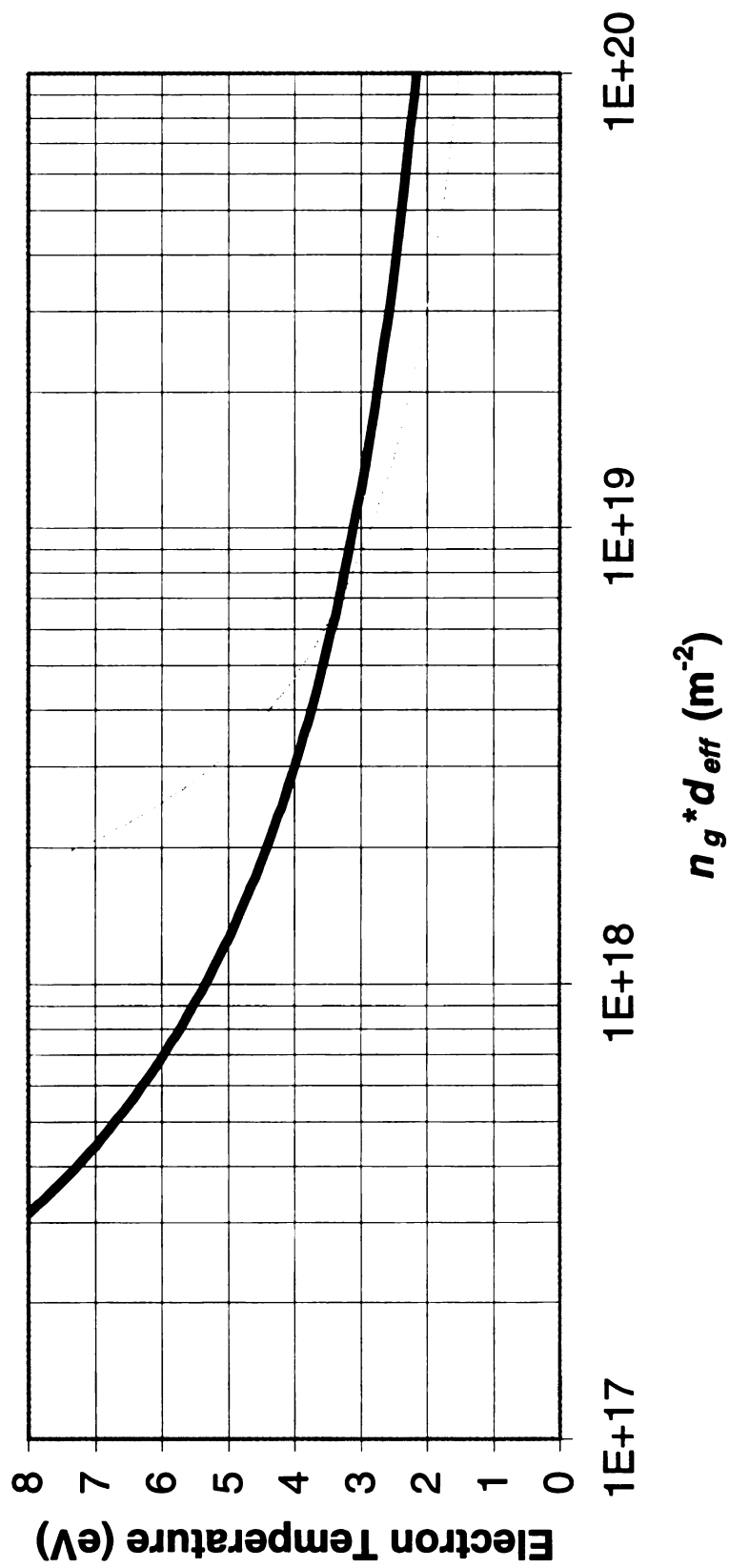


Figure 6.10 – Electron Temperature vs. neutral gas density,  $n_g$ , times effective diffusion length,  $d_{eff}$ , for a plasma discharge in the intermediate pressure regime

### 6.3 Power Balance

As was discussed in section 6.1, the simplified steady state form of the energy conservation equation equates (I) the total amount of energy flux from a differential volume of plasma per second and (II) the total energy absorbed or lost in that differential volume through collisional and non-collisional processes:.

$$\nabla \cdot \left( \frac{3}{2} p_e \mathbf{\dot{n}}_e \right) = \langle P \rangle_{cle} + \langle P \rangle_{cge} + \langle P \rangle_{se} \quad \text{Eq. 6.73}$$

(I)                      (II)

where  $p_e$  is scalar electron pressure, and  $\mathbf{\dot{n}}_e$  is the average electron velocity,  $\langle P \rangle_{cle}$  is the electron collisional loss term,  $\langle P \rangle_{cge}$  is the electron collisional gain term, and  $\langle P \rangle_{se}$  is the electron collisionless gain term. Integrating over the total volume of the discharge and using the divergence theorem we have:.

$$\oint_A \left( \left( \frac{3}{2} p_e \mathbf{\dot{n}}_e \right) \cdot d\mathbf{\hat{S}} \right) = \int_V (\langle P \rangle_{cle} + \langle P \rangle_{cge} + \langle P \rangle_{se}) dV \quad \text{Eq. 6.74}$$

(III)                      (IV)

where term (III) can be thought of as the rate of drift and diffusion energy losses at the surface of the discharge, while term (IV) can be thought of as the sum of 1) the total rate of energy gained thorough collisional (both elastic and inelastic),  $\langle P \rangle_{cge}$ , or collisionless,  $\langle P \rangle_{se}$ , processes in the plasma volume and 2) the total energy lost through collisional processes,  $\langle P \rangle_{cle}$ , in the volume. Now setting the energy loss terms on the left hand side and the energy gain terms on the right hand side we have:

$$\oint_A \left( \left( \frac{3}{2} p_e \hat{n}_e \right) \cdot d\hat{S} \right) + \int_V (\langle P \rangle_{cle}) dV = \int_V (\langle P \rangle_{cge} + \langle P \rangle_{se}) dV \quad \text{Eq. 6.75}$$

|                                                                                                                    |          |                                                                                                         |          |                                                                                                                 |
|--------------------------------------------------------------------------------------------------------------------|----------|---------------------------------------------------------------------------------------------------------|----------|-----------------------------------------------------------------------------------------------------------------|
| <p>Total electron energy<br/>flux lost through drift or<br/>diffusion through the<br/>surface of the discharge</p> | <p>+</p> | <p>Total rate of electron<br/>energy lost through<br/>collisions in the volume<br/>of the discharge</p> | <p>=</p> | <p>Total rate of electron<br/>energy gained through<br/>collisions or other energy<br/>absorption processes</p> |
|--------------------------------------------------------------------------------------------------------------------|----------|---------------------------------------------------------------------------------------------------------|----------|-----------------------------------------------------------------------------------------------------------------|

In a steady state system the total flux of energy (power) absorbed in the discharge must equal the total flux of energy (power) lost from the discharge, i.e.  $P_{lost} = P_{abs}$ .

### 6.3.1 Energy Flux in the Plasma Discharge

Electromagnetic energy can be delivered to a weakly ionized plasma in many ways, i.e. through DC current, AC current, rf coupling or microwave coupling. In all of the methods mentioned above the electromagnetic energy is primarily absorbed by the electron gas. The other components of the plasma such as neutrals, and ions absorb very little energy directly from the electromagnetic fields. Hence, effectively all the electromagnetic energy introduced into the plasma is coupled into the electron gas. (Note: in a magnetized discharge ions may absorb a large amount of energy directly from the EM field if the conditions for ion cyclotron resonance are met)

Electrons dissipate energy through elastic and inelastic collisions with the ions and neutrals, as well as, by carrying away kinetic energy through diffusion to the discharge chamber walls. Since electrons have such small mass compared to the neutrals or ions only a small amount of energy (as compared to the electron energy lost in ionizations or excita-

tions) is transferred per elastic collision from electrons to neutrals or ions. Hence, the electron gas is not in thermodynamic equilibrium with either the neutral or ion gases and  $T_e \gg T_i$ .

### 6.3.2 The Electron Subgas

Since most of the EM power is coupled into the electron gas, then in a steady-state discharge the electrical power coupled into the electron gas must equal the power lost by the electron gas. This is true for all points in the discharge. Consequently, a power balance equation can be written in terms of the absorption and losses of the electron gas:

$$\langle P \rangle_{abs}(\vec{r}) = \langle P \rangle_{loss}(\vec{r}), \quad \text{Eq. 6.76}$$

where  $\langle P \rangle_{abs}(\vec{r})$  is the time average power density absorbed by the electron gas and  $\langle P \rangle_{loss}(\vec{r})$  is the time average power density lost from the electron gas in a differential volume centered at  $\vec{r}$ .

### 6.3.3 Electron Energy Absorbing Processes

The total time averaged electromagnetic power delivered to the discharge electron gas,  $P_{abs}$ , is given by integrating the time average power absorbed density over the discharge volume,  $V_L$

$$P_{abs} = \int_{V_L} \langle P \rangle_{abs}(\vec{r}) dV \quad \text{Eq. 6.77}$$

In an experimental system  $P_{abs}$  can be measured by determining the net power absorbed by the discharge. It can also be calculated from knowledge of  $\vec{J}$  and  $\vec{E}$  within the discharge. The time averaged power absorbed per differential plasma volume from an impressed electromagnetic field is given by

$$\langle P \rangle_{abs}(\vec{r}) = \frac{1}{2} \text{Re}(\vec{J} \bullet \vec{E}^*). \quad \text{Eq. 6.78}$$

where the operator  $\text{Re}$  denotes the real part of the complex vector dot product. Hence, integrating over the plasma volume we have:

$$\int_{V_L} \langle P \rangle_{abs}(\vec{r}) dV = \int_{V_L} \frac{1}{2} \text{Re}(\vec{J} \bullet \vec{E}^*) dV = P_{abs} \quad \text{Eq. 6.79}$$

However, note that knowledge of  $\vec{J}$  and  $\vec{E}$  at all points in the plasma can be difficult to obtain experimentally.

There are several possible electromagnetic electron gas heating mechanisms. The main mechanisms important in low pressure discharges are:

- (1) Ohmic heating
- (2) Electron Cyclotron Resonance (ECR) heating
- (3) Stochastic heating

These processes are described below.

### **6.3.2.1 Ohmic Heating**

A free electron in a vacuum subjected to a spatially uniform, sinusoidally oscillating, electric field will oscillate under the influence of the field. However, in the steady state the electron will gain no time average energy since over one half cycle the electron is being accelerated by the field (gaining energy) and the other half cycle decelerated (giving energy back to the field) an equal amount. Also, an electron in a plasma will have a similar behavior if it does not undergo any collisions with other particles (assuming uniform E and zero B fields).

This collisional (also called Ohmic or Joule) heating process requires electron elastic collisions to randomize the electron motion (i.e. each electron-neutral collision causes the electron to break out of phase with the oscillating EM field) and thus to transfer electromagnetically induced electron kinetic energy into the randomized thermal energy of the electron gas. The electron neutral collision frequency is represented as  $\nu_m$ . As described above if  $\nu_m = 0$  there is no electron gas heating.

An expression for the ohmic heating in a sinusoidally time varying electromagnetic field can be derived from:

$$\langle P \rangle_{abs}(\vec{r}) = \frac{1}{2} Re(\vec{J} \bullet \vec{E}^*) \quad \text{Eq. 6.80}$$

where the current density can be expressed as:

$$\vec{J} = j\omega\epsilon_c \vec{E} \quad \text{Eq. 6.81}$$

This expression for the effective plasma dielectric constant,  $\epsilon_c$ , can be derived (from the momentum equation):

$$\epsilon_c = \epsilon_0 \left[ 1 - \frac{\omega_{pe}^2}{\omega(\omega - j\nu_m)} \right] \quad \text{Eq. 6.82}$$

where  $\omega$  is the excitation frequency, and  $\omega_{pe}$  is the plasma frequency given by:

$$\omega_{pe} = \sqrt{\frac{N_{0e}(\vec{r})e^2}{\epsilon_0 m_e}} \quad \text{Eq. 6.83}$$

where  $N_{0e}(\vec{r})$  is the non-time varying electron density as a function of position ( $\vec{r}$ ).

Thus substituting and rearranging we have,;

$$\langle P \rangle_{ohm}(\vec{r}) = \frac{N_{0e}(\vec{r})e^2}{2m_e \nu_m} \left( \frac{\nu_m^2}{\omega^2 + \nu_m^2} \right) |\vec{E}_0(\vec{r})|^2 \quad \text{Eq. 6.84}$$

where  $|\vec{E}_0(\vec{r})|$  is the magnitude of the impressed electric field as a function of position.

The above expression is the time average power density ohmically absorbed by the elec-

tron gas given the electric field strength, plasma density, and electron neutral collision frequency. Note that the most efficient heating (or the most efficient electromagnetic coupling) occurs when  $v_m = \omega$ .

### 6.3.2.2 Electron Cyclotron Resonance Heating

If a static magnetic field  $\vec{B}_0(\vec{r})$  is impressed on the discharge the electron gas can be heated by Electron Cyclotron Resonance (ECR) coupling.

Again we relate the power absorbed density to the current and E-field:

$$\langle P \rangle_{ecr}(\vec{r}) = \frac{1}{2} \text{Re}(\vec{J} \cdot \vec{E}^*) = \frac{1}{2} \text{Re}[j\omega \tilde{\epsilon}_p \cdot |E|^2] \quad \text{Eq. 6.85}$$

where here  $\tilde{\epsilon}_p$  is the tensor dielectric constant of the magnetized plasma. For the special

case when  $\vec{E}(\vec{r})$  is perpendicular to  $\vec{B}_0$  we have:

$$\langle P \rangle_{ecr}(\vec{r}) = \frac{N_{0e}(\vec{r})e^2}{2m_e v_m} \left[ \frac{v_m^2}{2} \left( \frac{1}{v_m^2 + (\omega - \omega_{ce})^2} + \frac{1}{v_m^2 + (\omega + \omega_{ce})^2} \right) \right] \left| \vec{E}_0(\vec{r}) \right|^2 \quad \text{Eq. 6.86}$$

If  $(v_m/\omega)$  is small, then the first term becomes very large when  $\omega_{ce} = \frac{eB}{m_e} = \omega$ . This

occurs within a volume in the discharge often called an ECR heating volume or ECR heating surface. If the exciting microwave (rf) frequency is 2.45 GHz then ECR occurs in the



volumes where  $B_0 = 875$  Gauss. Figure 6.11 displays the motion of a single electron accelerated by the time harmonic EM field within an ECR volume.

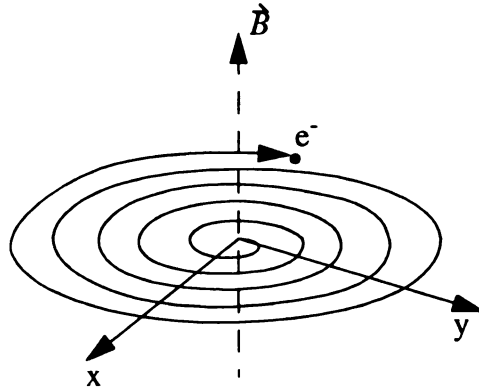


Figure 6.11: Trajectory for an electron gaining energy in an ECR zone

### 6.3.2.3 Stochastic Heating

As stated in section 6.3.2.1 an electron in a, spatially uniform, time harmonic electric field will gain no net energy from the field without collisions with neutrals or ions, since energy is gained over one half cycle and lost over the other half cycle. However, if the electric field is spatially non-uniform stochastic heating can occur when a moving electron passes through a region of locally strong E-fields gaining energy and then passes out of the local region before fully giving back that energy to the field over the next half cycle. There are many ways this can occur (see Figure 6.12), involving moving electrons and/or moving field distributions, however in all cases of Stochastic heating the electron gains some net energy on average over the electromagnetic cycle.

Capacitive stochastic heating has been described as an electron colliding with a moving potential wall [Lie-94]. On one side of the wall are low E-fields and the other side are high E-fields. An electron incident upon a sheath edge moving into the bulk plasma gains energy in the sheath fields as it is decelerated and then re-accelerated (reflected) back out into the bulk plasma. An electron incident upon a sheath edge that is moving away from the bulk plasma is decelerated and loses some kinetic energy to the sheath. Since a sheath moving into the bulk plasma interacts longer with incident electrons than a sheath moving away from the bulk plasma, there is a net (time average) energy gain for electrons.

Stochastic heating in an inductive discharge occurs when an electron passes through the high field skin depth region of the plasma near the discharge wall. If the electron is fast enough to pass through this high field region (and still be reflected by the static sheath potential at the wall) in shorter than one half cycle of the electric field it will gain net energy from the field.

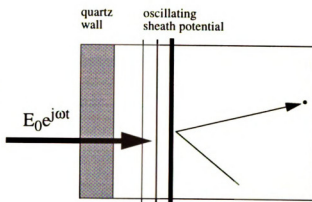
Spatially non-uniform high E-field regions occur surrounding plasma resonance zones (local areas of the plasma with charge density exactly equal to critical density, i.e. where  $\omega_{pe} = \omega$ ). Some fast electrons pass through these high field regions in time periods shorter than one half cycle, hence gaining net energy.

An expression for stochastic power delivered in the inductive case has been derived [Tur-93, Lie-94; page 557]:

$$\langle P \rangle_{stoc} = \frac{1}{4} \frac{e^2 n_s \delta}{m_e} \frac{v_{stoc}}{v_{stoc}^2 + \omega^2} |E|^2 \quad \text{Eq. 6.87}$$

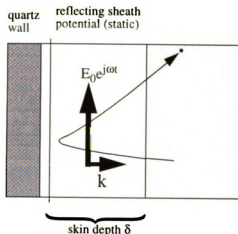
### Capacitive:

Fast electrons gain energy via collisions with an oscillating sheath potential



### Inductive:

Fast electrons traveling through the skin depth region can gain energy from the EM field. They must have high enough velocity to experience net E-field in only one direction.



### Plasma Resonance:

Fast electrons traveling through a plasma resonance zone gain net energy by traversing the resonance region in shorter time than about one half electromagnetic cycle.

plasma resonance zone, where  $\omega_{pe} \sim \omega$

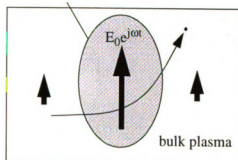


Figure 6.12: Stochastic Energy Transfer Mechanisms

where  $n_s$  is the charge density at the plasma sheath,  $\delta$  is the electromagnetic skin depth,  $\omega$  is the frequency of electromagnetic excitation,  $|E|$  is the electric field amplitude of the electromagnetic excitation, and  $\nu_{stoc}$  is an effective collision frequency. The term  $\nu_{stoc}$  is approximated for two regimes, low  $\omega$  and high  $\omega$ .

For  $\omega \ll \nu_{stoc}$ :

$$\nu_{stoc} \sim \frac{\bar{v}_e}{\delta} \quad \text{Eq. 6.88}$$

where  $\bar{v}_e$  is the average electron velocity.

For  $\omega \gg \nu_{stoc}$ :

$$\nu_{stoc} \sim \frac{(\bar{v}_e)^3}{\delta^3 \omega^2} \quad \text{Eq. 6.89}$$

This derivation is discussed in detail in Appendix C of reference [Lie-94].

### 6.3.4 Electron Energy Loss Processes

Once the electromagnetic energy is coupled into the random kinetic energy (heat) of the electron gas, as described by the processes above, the electron gas then couples energy via elastic and inelastic collision processes into the ion and neutral gases.

Using the energy conservation equation for the electron gas it can be shown that the power lost per unit volume by the electron gas is (in the Schottky discharge model):

$$\langle P \rangle_{loss}(\vec{r}) = \left[ \frac{5}{2} e T_e \left( \frac{D_a}{\Lambda} \right) + \nu_{el} \left( \frac{3m_e}{M} \right) e T_e + \nu_{iz} e V_i + \sum_j e V_{exj} \nu_{exj} \right] N_{0e}(\vec{r}) \quad \text{Eq. 6.90}$$

where  $e$  is the electron charge,  $T_e$  is the electron temperature,  $D_a$  is the ambipolar diffusion constant,  $L$  is the diffusion length,  $\nu_{el}$  is the electron neutral collision frequency,  $m_e$  is the electron mass,  $M$  is the ion mass,  $\nu_{iz}$  is the ionization frequency,  $V_i$  is the ionization potential,  $\nu_{exj}$  is the excitation frequency for excitation process  $j$ ,  $V_{exj}$  is the excitation potential, and  $N_{0e}(r)$  is the time average charge density at point  $r$ .

Also from diffusion theory:

$$\nabla \cdot \vec{\Gamma}_e = \nu_{iz} N_{0e}(\vec{r})$$

or

$$N_{0e}(\vec{r}) = \frac{\nabla \cdot \vec{\Gamma}_e}{\nu_{iz}} \quad \text{Eq. 6.91}$$

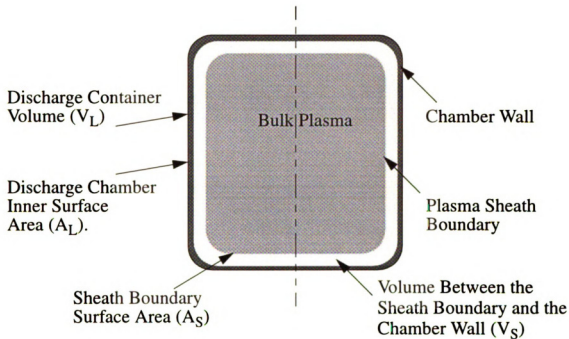


Figure 6.13: Generic Plasma Discharge Chamber

Then substituting and integrating over the entire plasma volume, i.e. integrating over the discharge volume (see Figure 6.13) minus the sheath volume yields:

$$P'_{loss} = \int_{(V_L - V_S)} [\langle P \rangle_{loss}(\vec{r})] dV \quad \text{Eq. 6.92}$$

$$P'_{loss} = \int_{(V_L - V_S)} \left[ \left( \frac{5}{2} e T_e \left( \frac{D_a}{\Lambda} \right) + v_{el} \left( \frac{3m_e}{M} \right) e T_e + v_{iz} e V_i + \sum_j e V_{exj} v_{exj} \right) \frac{\nabla \cdot \vec{\Gamma}_e}{v_{iz}} \right] dV \quad \text{Eq. 6.93}$$

where  $V_L$  is the total volume of the plasma within the containing vessel,  $V_s$  is the volume of the plasma surrounded by the sheath,  $\Gamma_e$  is the electron flux density, and  $dV$  is an infinitesimal volume element. Now, employing the divergence theorem:

$$\int_{(V_L - V_s)} (\nabla \cdot \vec{\Gamma}_e) dV_L = \oint_{A_s} \vec{\Gamma}_e \cdot \vec{dS} \quad \text{where } A_s \text{ is the surface of the sheath boundary}$$

Eq. 6.94

The electrons are diffusing through the plasma sheath surface at the rate given by:

$$e(\vec{\Gamma}_e \cdot \vec{n})|_{A_s} = eu_B n_s|_{A_s} \quad \text{Eq. 6.95}$$

where  $u_B$  = Bohm velocity,  $\vec{n}$  is the unit vector normal to the discharge/sheath surface, and  $n_s$  is the magnitude of the electron density on the plasma sheath boundary. Thus,

$$e \oint_{A_s} \vec{\Gamma}_e \cdot \vec{dA} = eu_B \oint_{A_s} n_s dS \quad \text{Eq. 6.96}$$

Since the plasma sheath thickness is usually very small, then  $A_s$  approximately equals  $A_L$  the surface area of the discharge. Thus,

$$P'_{loss} = \left[ \frac{5}{2} T_e \left( \frac{D_a}{\Lambda} \right) \frac{1}{v_{iz}} + \frac{v_{el}}{v_{iz}} \left( \frac{3m_e}{M} \right) T_e + V_i + \sum_j \frac{V_{exj} v_{exj}}{v_{iz}} \right] eu_B \oint_{A_s} n_s dS \quad \text{Eq. 6.97}$$

Note that  $\frac{D_a}{\Lambda} = v_{iz}$ ;  $V_i = \epsilon_{iz}$ ;  $V_{exj} = \epsilon_{exj}$

Then

$$P'_{loss} = \left[ \underbrace{\frac{5}{2}T_e}_{(I)} + \underbrace{\frac{K_{el}3m_e}{K_{iz}}T_e}_{(II)} + \underbrace{\epsilon_{iz}}_{(III)} + \underbrace{\sum_j \frac{\epsilon_{exj}K_{exj}}{K_{iz}}}_{(IV)} \right] eu_B \oint_{A_s} n_s dS \quad \text{Eq. 6.98}$$

where  $K_{el}$  is the electron neutral collision rate constant,  $K_{exj}$  is the excitation rate constant for excitation process  $j$ , and  $K_{iz}$  is the ionization rate constant. This equation represents the steady-state power lost by the discharge electron gas within the plasma volume. Note that terms (II) plus (III) plus (IV) represent the collisional energy,  $E_c$ , lost per electron. Term (I) represents the mean kinetic energy lost per electron-ion pair lost by diffusion.

As the ions diffuse through the sheath they are accelerated by the sheath potential  $V_s$ . This represents energy transfer to the ion gas. Thus, the total  $P_{loss}$  for the discharge becomes

$$P_{loss} = P'_{loss} + en_s u_B A V_s \quad \text{Eq. 6.99}$$

where  $V_s$  is the sheath voltage and the last term represents the power absorbed by the ion gas as it diffuses through the sheath onto the discharge chamber walls.

Alternately, following the approach of Lieberman, et. al. the discharge power balance can be expressed as

$$P_{abs} = P_{en} + P_{ew} + P_{in} \quad \text{Eq. 6.100}$$

where  $P_{abs}$  is the power absorbed by the discharge,  $P_{en}$  is the energy loss due to all electron neutral collision processes in the discharge volume,  $P_{ew}$  is the electron energy loss to



the walls, and  $P_{in}$  is the ion energy loss to the walls. These losses can be expressed in terms of the energy lost per ion-electron pair lost from the discharge [Lie-94]. That is

$$E_T = E_c + 2T_e + E_i \quad \text{Eq. 6.101}$$

where  $E_T$  is the energy lost per created ion-electron pair,  $E_c$  is the collisional energy lost per created ion-electron pair,  $2T_e$  is the mean kinetic energy lost per lost electron by diffusion to the walls, and  $E_i$  is the mean kinetic energy lost per ion lost by diffusion to the walls usually determined by the potential drop between the main discharge volume and the wall. Most of the potential drop occurs in the sheath region designated by  $V_s$ . The potential drop between the sheath edge and the center of the plasma is the Bohm energy  $T_e/2$ . Hence,  $E_i = V_s + T_e/2$ .

The collisional energy lost per electron-ion pair created [Lie-94] is given by

$$K_{iz}E_c = K_{iz}E_{iz} + K_{ex}E_{ex} + K_{el}\frac{3m}{M}T_e \quad \text{Eq. 6.102}$$

which becomes:

$$E_c = E_{iz} + \frac{K_{ex}E_{ex}}{K_{iz}} + \frac{K_{el}}{K_{iz}}\left(\frac{3m}{M}\right)T_e \quad \text{Eq. 6.103}$$

This  $E_c$  is identical to the sum of terms (2) - (4) in Eq. 6.98. This energy can be determined from knowledge of the electron temperature and the various electron collision rate constants  $K_{iz}$ ,  $K_{ex}$ , etc.

If all electron-ion pairs are lost to the walls, then  $P_{loss}$  is given as

$$P_{loss} = J_S A E_T \quad \text{Eq. 6.104}$$

where  $J_s$  is the ion current density flowing through the sheath adjacent to the walls and  $A$  is the area of the walls.

$$J_s = en_s u_B = e \Gamma_i \quad \text{Eq. 6.105}$$

where  $u_B = \sqrt{(eT_e)/M}$  = Bohm velocity and  $n_s$  is the ion density at the plasma sheath edge. Thus,

$$P_{loss} = en_s u_B A E_T = P_{abs} \quad \text{Eq. 6.106}$$

$P_{loss}$  is a function of the gas type, the electron temperature, the surface area of the discharge, and the electron (or ion) density. Often these quantities can be experimentally measured or determined theoretically. Thus in contrast to the impressed electric fields and currents expressed in Eq. 6.79 the discharge temperature, density, etc. can usually be more readily estimated.

The density at the sheath surface,  $n_s$ , often can be related to the discharge center density,  $n_0$ , by geometrical functions,  $h_i$ , i.e. in general:

$$n_s|_{S_1} = h_1|_{S_1} n_0; \quad n_s|_{S_2} = h_2|_{S_2} n_0; \quad \dots \quad n_s|_{S_n} = h_n|_{S_n} n_0 \quad \text{Eq. 6.107}$$

where  $S_1 + S_2 + \dots + S_n = S$  and  $S_1, S_2, \dots$  are subsurfaces of  $S$ . Then equation 6.106 becomes

$$P_{abs} = en_0 u_B A_{eff} E_T \quad \text{Eq. 6.108}$$

$$\text{where } A_{eff} = \sum_i^n h_i S_i$$

We will find later that this equation, which is often called the power loss load line, relates the input power to the discharge density, electron temperature and the discharge size and shape. If the discharge size and pressure are fixed, as they usually are for a specific plasma source operating at a constant pressure, it then relates the input power to the discharge density.

### 6.3.5 Power Balance for Nonuniform High Pressure Discharges

At high pressures  $\lambda_i \leq \left(\frac{T_i}{T_e}\right)(R, L)$  and the discharge density profile becomes non-uniform. There are two cases (1) the sheathless plasma case and (2) the discharge with a sheath.

We first consider the sheathless case using Eq. 6.93 yields:

$$P'_{loss} = e \left( E_c + \frac{5}{2} T_e \right) \oint_A \vec{\Gamma} \cdot d\vec{A} = P_{abs} \quad \text{Eq. 6.109}$$

where  $\vec{\Gamma}|_A$  is the charged particle flux on the walls given by Fick's Law. Solving for  $\vec{\Gamma}$  for a cylindrical discharge yields:

$$\vec{\Gamma} = -D_a \vec{\nabla} n = \hat{r} \left\{ -D_a n_0 k J_0(kr) \cos(\beta z) \right\} + \hat{z} \left\{ -D_a n_0 J_0(kr) (-\beta) \sin(\beta z) \right\} \quad \text{Eq. 6.110}$$

where  $k^2 = \left(\frac{x_{01}}{R}\right)^2$ ;  $\beta^2 = \left(\frac{\pi}{L}\right)^2$  and from the separation equation

$\frac{1}{\Lambda^2} = k^2 + \beta^2$ . Then integrating the flux density over the end walls and the side wall:

$$\Phi_{ends} = 2 \int_0^{2\pi} \int_0^R \left( \vec{\Gamma} \Big|_{z=\frac{L}{2}} \cdot \vec{z} \right) r dR d\theta = 4\pi D_a \beta n_0 \int_0^R J_0(kr) r dR \quad \text{Eq. 6.111}$$

$$\Phi_{ends} = 4\pi D_a \beta n_0 \int_0^R J_0(kr) r dR = 4\pi D_a \beta n_0 \left\{ \frac{R^2}{x_{01}} J_1(x_{01}) \right\} \quad \text{Eq. 6.112}$$

$$\Phi_{side} = \int_{-\frac{L}{2}}^{+\frac{L}{2}} \int_0^{2\pi} \left( \vec{\Gamma} \Big|_{r=R} \cdot \vec{r} \right) R d\theta dz = -2\pi k D_a n_0 J_0(x_{01}) R \int_{-\frac{L}{2}}^{+\frac{L}{2}} \cos(\beta z) dz \quad \text{Eq. 6.113}$$

$$\Phi_{side} = -2\pi k D_a n_0 J_0(x_{01}) R \int_{-\frac{L}{2}}^{+\frac{L}{2}} \cos(\beta z) dz = 4\pi k D_a n_0 \frac{J_1(x_{01})}{\beta} R \quad \text{Eq. 6.114}$$

Summing over the walls yields

$$\Phi_{Total} = \Phi_{ends} + \Phi_{side} = 4\pi n_0 D_a [J_1(x_{01})] R \left[ \frac{R\beta}{x_{01}} + \frac{k}{\beta} \right] \quad \text{Eq. 6.115}$$

The discharge power balance then becomes

$$P'_{abs} = \Phi_{total}(eE_T') = 4\pi n_0 D_a [J_1(x_{01})] \left[ \frac{R^2 \pi}{x_{01} L} + \frac{L x_{01}}{\pi} \right] (eE_T') \quad \text{Eq. 6.116}$$

where  $E_T' = E_C + \frac{5}{2}T_e$

and

$$n_0 = \frac{P'_{abs}}{4\pi D_a [J_1(x_{01})] \left[ \frac{R^2 \pi}{x_{01} L} + \frac{L x_{01}}{\pi} \right] (e E_T')} \quad \text{Eq. 6.117}$$

When the plasma model is adjusted to include a thin sheath the power delivered to the ion gas from the sheath potential must be included, i.e.

$$P_{loss} = e \left( E_c + \frac{5}{2} T_e \right) \oint_S \vec{\Gamma} \cdot d\vec{S} + e V_s \oint_S \vec{\Gamma} \cdot d\vec{S} \quad \text{Eq. 6.118}$$

$$P_{loss} = e \underbrace{(E_c + 2T_e + E_i)}_{E_T} \oint_S \vec{\Gamma} \cdot d\vec{S} \quad \text{Eq. 6.119}$$

$$P_{loss} = e E_T \oint_S \vec{\Gamma} \cdot d\vec{S} = P_{abs} \quad \text{Eq. 6.120}$$

If  $s \ll R, L$  then

$$\oint_S \vec{\Gamma} \cdot d\vec{S} = \oint_A \vec{\Gamma} \cdot d\vec{A} \quad \text{Eq. 6.121}$$

and for the cylindrical discharge

$$P_{abs} = 4\pi n_0 D_a [J_1(x_{01})] \left[ \frac{R^2 \pi}{x_{01} L} + \frac{L x_{01}}{\pi} \right] (e E_T) \quad \text{Eq. 6.122}$$

and

$$n_0 = \frac{P_{abs}}{4\pi D_a [J_1(x_{01})] \left[ \frac{R^2 \pi}{x_{01} L} + \frac{L x_{01}}{\pi} \right] (e E_T)} \quad \text{Eq. 6.123}$$

Thus the sheathless model underestimates the  $P_{abs}$  by

$$e V_s \oint_A \vec{\Gamma} \cdot \vec{dA} \quad \text{Eq. 6.124}$$

which represents the power lost as the ions fall through the sheath potential.

### 6.3.6 Power Balance for Low and Intermediate Pressure Discharges

From Eq. 6.106

$$P_{abs} = e n_s u_B A E_T \quad \text{Eq. 6.125}$$

Equations 6.60 and 6.61 relate the discharge center density to the sheath density. For a cylinder the axial sheath edge density  $n_{sl}$  is related to the center density by Equation 6.60

$$h_l = \frac{n_{sl}}{n_0} \quad \text{Eq. 6.126}$$

and the radial sheath edge density  $n_{sR}$  is related to the center density by Eq. 6.61; i.e.

$$h_R = \frac{n_{sR}}{n_0} \quad \text{Eq. 6.127}$$

The power balance equation for a cylindrical discharge can then be rewritten as

$$P_{loss} = \underbrace{(n_0 h_l) u_B (2\pi R^2) e E_T}_{\text{Power to end walls}} + \underbrace{(n_0 h_l) u_B (2\pi RL) e E_T}_{\text{Power to side wall}} = n_0 u_B A_{eff} e E_T = P_{abs}$$

Eq. 6.128

where  $A_{eff} = 2\pi R(Rh_l + Lh_R)$  and then

$$n_0 = \frac{P_{abs}}{u_B A_{eff} (e E_T)}$$

Eq. 6.129

$$d_{eff} \equiv \frac{V}{\sum_i h_i A_i} = \frac{V}{A_{eff}} \quad \text{Where } A_{eff} \equiv \sum_i h_i A_i \quad \text{Eq. 6.130}$$

## 6.4 Plasma Source Performance Figures of Merit

Plasma sources can be evaluated by comparing plasma source figures of merit and by comparing specific internal discharge variables while the different plasma sources are operating under similar input conditions. The figures of performance adopted here are (1) general plasma source efficiency (2) ion production energy costs,  $\eta$ , and the internal variables chosen are (3) average discharge absorbed power density  $\langle P \rangle_{abs}$ , and (4) plasma potential or electron temperature. It is important to note that each of these are a function of diffusion length (or a function of the discharge geometry and size), input power, and gas pressure. Thus comparisons between different plasma sources must be made under the same input power and pressure conditions. These above identified performance measures can be used to evaluate the performance differences between plasma sources, and are also used to evaluate an individual plasma source as pressure, input power, etc. are changed. Several of these figures of performance are described in detail below.

### 6.4.1 General Plasma Source Efficiency

One measure of plasma source efficiency is its ability to produce ions and electrons or other radical species. An important figure of merit that describes the ion or electron production is the number of ion/electron pairs created per Watt input. This information is included in the discharge power loss line.



For example consider a cylindrical discharge container with radius  $R$  and length  $L$ . In section 6.3.6 the expression for the power loss line was derived for this cylindrical discharge at low and intermediate pressures and was found to be:

$$P_{abs} = n_0 u_B 2\pi R (Rh_l + Lh_R) (eE_T) \quad \text{Eq. 6.131}$$

and in section 6.3.5 the corresponding expression for high pressure discharges was found to be:

$$P_{abs} = 4\pi n_0 D_a J_1(x_{01}) \left[ \frac{R^2 \pi}{x_{01} L} + \frac{L x_{01}}{\pi} \right] (eE_T) \quad \text{Eq. 6.132}$$

The  $P_{abs}/n_0$  ratio represents the slope of the plasma loss line. This slope is a measure of how efficiently the plasma source creates an ion/electron pair.

Is there an optimum operating pressure or electron temperature? Note that equations 6.131 and 6.132 are functions of  $E_T$ .  $E_T$  represents the total electron energy lost per electron/ion pair lost from the discharge.  $E_T$  is the sum of the collisional energy lost,  $E_c$ , the kinetic energy lost to the walls by the electrons,  $E_e$ , and the kinetic energy lost by the ions,  $E_i$ , as they diffuse to the walls.

$$E_T = E_c + E_e + E_i \quad \text{Eq. 6.133}$$

$$E_e = 2T_e \quad \text{Eq. 6.134}$$

$$E_i = V_s + \frac{T_e}{2} = 5.2T_e \text{ (for Argon with an insulating wall)} \quad \text{Eq. 6.135}$$

For a plot of  $E_c$ ,  $E_e$ ,  $E_i$ , and  $E_T$  vs.  $T_e$  see Figure 9.5. It is clear that the sum of the energies,  $E_T$ , has a minimum near 4 eV. Collisional losses dominate for low temperatures while the kinetic energy losses are significant for high temperature argon discharges.

Since  $u_B$  is a weak function of  $T_e$  the  $(E_T)_{\min}$  gives the most efficient electron temperature operating regime, i.e. if the discharge electron temperature lies near 4 eV then the most ion/electron pairs will be produced per input Watt.

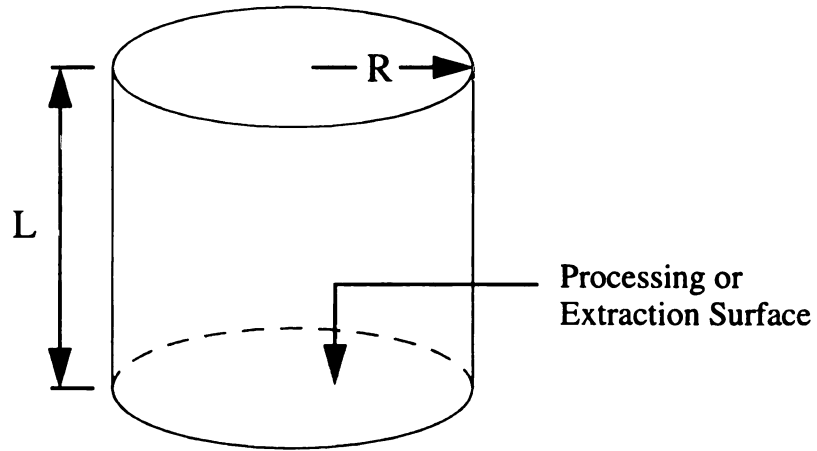
#### 6.4.2 Ion Production Energy Cost

An efficiency figure of merit that is often used to evaluate and compare the operational performance of plasma and ion sources is the ion production energy cost factor. This figure of merit was first developed by the ion source community to evaluate the performance of broad beam ion sources. This efficiency,  $\eta$ , is defined by the ratio of the total input power,  $P_{abs}$ , divided by the total ion current that can be extracted from the open end of the source. In a cylindrical discharge this “open end” usually is the circular bottom end of the discharge with an area  $\pi R^2$  (See Figure 6.14). Thus  $\eta$  is given by

$$\eta = \frac{P_{abs}}{\int J_s \cdot d\vec{S}} \quad \text{Eq. 6.136}$$

$\pi R^2$

where  $P_{abs}$  is the input power in Watts,  $J_s$  is the ion saturation current density at the source opening. The integration is carried out over the entire source output area  $\pi R^2$ . The units of  $\eta$  are either given in Watts/Ampere or electron volts/ion.



The surface area of the cylinder is  $A = 2\pi R^2 + 2\pi RL$

Figure 6.14: Typical Plasma Source Discharge Geometry

These ion energy production costs do not represent the energy cost to produce an ion since ions that diffuse to the cylinder's top wall and side walls are not included. This efficiency does represent the energy required to create an ion that diffuses out of one end of the source. These are the useful ions that are produced by the plasma source.

The global model equations can be used to derive useful ion production cost expressions. In the low and intermediate pressure regimes the ion production energy cost can be expressed as

$$\eta = \frac{en_0u_B2\pi R(Rh_l + Lh_R)(eE_T)}{n_0u_B\pi R^2h_l} \quad \text{Eq. 6.137}$$

$$\eta = 2(eE_T)\left(1 + \frac{Lh_R}{Rh_l}\right) \quad \text{Eq. 6.138}$$

In a similar fashion an expression for ion production cost can be derived for the high pressure diffusion regime.

$$\eta = \frac{4\pi n_0 D_a J_1(x_{01}) \left[ \frac{R^2 \pi}{x_{01} L} + \frac{L x_{01}}{\pi} \right] (e E_T)}{2\pi n_0 D_a J_1(x_{01}) \left[ \frac{R^2 \pi}{x_{01} L} \right]} \quad \text{Eq. 6.139}$$

$$\eta = 2(e E_T) \left[ 1 + \frac{L^2 x_{01}^2}{R^2 \pi^2} \right] \quad \text{Eq. 6.140}$$

### 6.4.3 Average Discharge Power Density

The average discharge power density is determined from

$$\langle P \rangle_{abs} = \frac{P_{abs}}{\pi R^2 L} \quad \text{Eq. 6.141}$$

This figure of performance measures the average volume power density required to achieve a certain discharge condition. Since high discharge power densities usually result in wall erosion and gas heating, it is desirable to create discharges with lower power densities.

As has already been pointed out, the  $P_{abs}$  vs.  $n_0$  describes the plasma loss line or load line. This is an important experimental curve associated with all plasma sources. It is determined by the macroscopic power gas balance of the discharge and is a function of discharge gas type, pressure and reactor size and geometry. Thus absorbed power density loss line can be determined from the experimental data simply by dividing the input power,  $P_{abs}$ , by the discharge volume. Thus, for low and intermediate pressures the power loss line or power load line can be rewritten in terms of average discharge power density as

$$\langle P \rangle_{abs} = \frac{P_{abs}}{\pi R^2 L} = \frac{n_0 u_B (e E_T)}{d_{eff}} \quad \text{Eq. 6.142}$$

This equation describes the discharge power density - loss line for an average volume.

## 6.5 Conclusion

We have seen in this chapter that the particle balance and power balance equations of the global plasma model are a special case of the full Boltzmann moment equations. The particle balance equations for both one dimensional slab geometry and three dimensional cylindrical geometry have been solved and yield both the spacial distribution of normalized charge density and the electron temperature. The power balance equations have been solved and yield the expected discharge center density,  $n_0$ . Quantitative models for both the sheathless discharge and the discharge including the sheath have been derived.

Although the global plasma model is by no means an all encompassing or exact model it provides a good basis for qualitative understanding and quantitative “ballpark” predictions for the plasma parameters (such as charge density and electron temperature) of many laboratory discharges. It provides a good benchmark comparison for most of the experimental observations in this dissertation.

## Chapter 7

### Electron Temperature Measurements

#### 7.1 Introduction

#### 7.2 Global Model and Electron Distribution Functions

##### 7.2.1 The Global Model Calculation of Electron Temperature

##### 7.2.2 Electron Energy Distribution Functions

#### 7.3 SLP measurements at the Base of the Discharge ( $r=0$ , $z=0$ )

##### 7.3.1 EEDFs of Non-magnetized & Magnetized Discharges at Several Pressures

##### 7.3.2 Electron Temperatures vs. Discharge Pressure

###### 7.3.2.1 Comparison of $T_e$ between Magnetized and Non-Magnetized Configurations

###### 7.3.2.2 Comparison of Measured Electron Temperatures to Global Model Predictions

##### 7.3.3 Study of $T_e$ dependence on EM Excitation Intensity and Mode Type

###### 7.3.3.1 Influence of $P_{abs}$ on $T_e$ for the Non-magnetized $TM_{012}$ Mode

###### 7.3.3.2 Comparison of $T_e$ between EM modes in a Non-magnetized Discharge

##### 7.3.4 Comparison of Plasma Potential, $V_p$ , between Magnetized and Non-magnetized Discharges

#### 7.4 Variation of EEDF with distance into discharge ( $z$ )

##### 7.4.1 EEDF and $T_e$ vs. Distance into the Chamber for the Non-magnetized Discharge

###### 7.4.1.1 EEDF vs. Distance into the Non-magnetized Discharge Chamber

###### 7.4.1.2 Electron Temperature, $T_e$ , vs. Distance up into the Discharge Chamber

###### 7.4.1.3 Plasma Potential, $V_p$ , vs. Distance up into the Discharge Chamber

##### 7.4.2 EEDF and $T_e$ vs. Distance into the Chamber for the Magnetized Discharge

###### 7.4.2.1 EEDF vs. Distance into the Magnetized Discharge Chamber

###### 7.4.2.2 Electron Temperature, $T_e$ , vs. Distance up into the Magnetized Discharge Chamber

###### 7.4.2.3 Plasma Potential, $V_p$ , vs. Distance up into the Magnetized Discharge Chamber

#### 7.5 Summary of Findings

##### 7.5.1 Findings from measurements at $z=0$ (i.e. base of the discharge)

##### 7.5.2 Findings from measurements vs. $z$ into the discharge

## Chapter 7

### Electron Temperature Measurements

#### 7.1 Introduction

The objective of this chapter is to experimentally measure the electron temperature,  $T_e$ , electron energy distribution function (EEDF), and plasma potential,  $V_p$  for a range of discharge conditions: pressure, absorbed power, EM mode, and presence of a permanent magnet array. These measurements are then compared whenever possible to the predictions of the global plasma model.

In these experiments a single Langmuir probe (SLP) is used to measure  $T_e$ , EEDF, and  $V_p$  (See Chapter 5). These parameters are determined as follows. First the EEDF is determined from the 2nd derivative of the SLP I-V curve using a lock-in amplifier. Next the electron temperature,  $T_e$ , is determined by numerically integrating the EEDF. Finally, the plasma potential,  $V_p$ , is taken as the potential at the maximum of the 2nd derivative I-V curve.



## 7.2 Global Model and Electron Distribution Functions

### 7.2.1 The Global Model Calculation of Electron Temperature

In order to get a theoretical reference or benchmark for the experimental data, global model calculations are made for this specific discharge. The general details of this calculation were developed in Chapter 6. The important parameters for this model are discharge dimension, gas type, and discharge pressure. We have a cylindrical discharge of 10.25 cm height and 6.5 cm radius. The gas is argon between a pressure of 4 mTorr to 45 mTorr, and a gas temperature assumed to be 600 degrees Kelvin.

The first step in this calculation is to determine the appropriate pressure regime for the discharge (i.e. low pressure, intermediate, or high pressure). This experimental discharge satisfies the criteria for the intermediate pressure regime if the following relation is satisfied [Lie-94]:

$$(R, L) \geq \lambda_i \geq \left( \frac{T_i}{T_e} \right) (R, L) \quad \text{Eq. 7.1}$$

where  $R$  is discharge radius,  $L$  is discharge length,  $\lambda_i$  is the ion-neutral mean free path,  $T_i$  is the ion temperature and  $T_e$  is the electron temperature. Since the smaller of  $R$  or  $L$  dominates the properties of the discharge we choose 6.5cm for the left hand term of Eq. 7.1. The range of  $\lambda_i$  is 1.6cm at 4 mTorr to 0.14cm at 45 mTorr. For  $T_i$  we have 0.05eV (i.e. ~600K) and for  $T_e$  we have a minimum of 2eV. This gives an approximate value of

0.16 cm to the right hand term of Eq. 7.1 Hence, the intermediate regime is valid for this discharge and pressure range.

The next step is to calculate the electron temperature using the particle balance equation for the appropriate pressure regime (see Section 6.2.2.2).

$$n_g d_{eff} = \frac{u_B(T_e)}{K_{iz}(T_e)} \quad \text{Eq. 7.2}$$

where  $n_g$  is the neutral gas density,  $d_{eff}$  is the effective diffusion length,  $u_B$  is the Bohm velocity (dependent on  $T_e$ ) and  $K_{iz}$  is the ionization rate constant (dependent on  $T_e$ ). A plot of the electron temperature vs. discharge pressure is shown in Figure 7.1. Since  $d_{eff}$  is dependent on  $n_g$  this curve was calculated iteratively, and is only valid for an argon discharge with radius 6.5 cm and height 10.25 cm. A more general curve for argon plotting  $T_e$  vs.  $n_g d_{eff}$  is presented in Chapter 6.

### 7.2.2 Electron Energy Distribution Functions

The above global model development assumes a Maxwellian energy distribution function for electron energies. However, the EEDF is not always Maxwellian. The two most common “benchmark” electron energy distribution functions, the Maxwellian and Druyvesteyn, are described and plotted below.

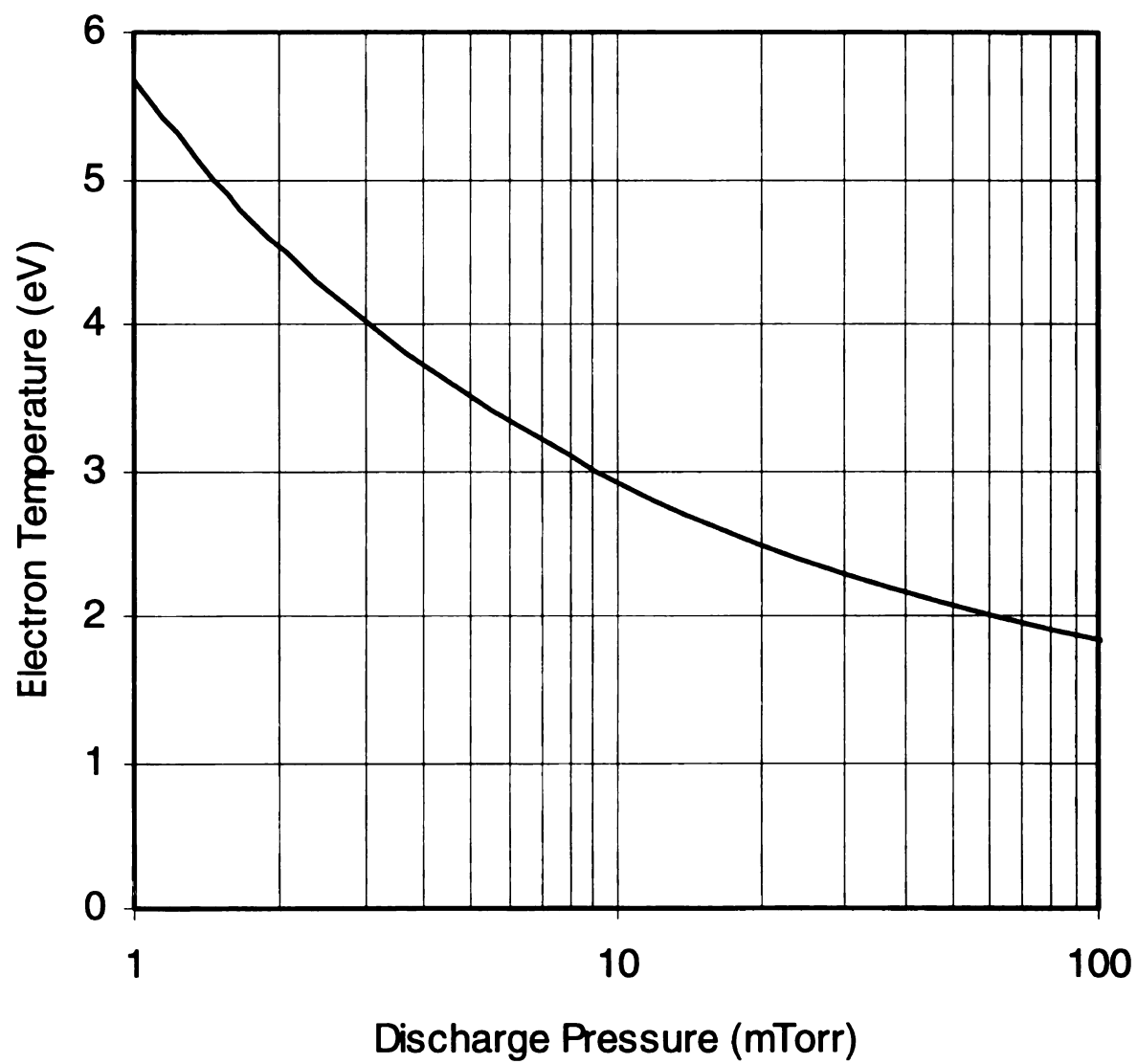


Figure 7.1: Global model prediction of electron temperature vs. discharge pressure for a 6.5 cm radius, 10.25 cm height argon discharge with a neutral gas temperature of 600K.

The Maxwellian electron energy distribution function assumes that electron-electron collisions are much more frequent than electron-neutral collisions and that collision frequency is constant vs. electron energy. The normalized Maxwellian energy distribution function is given below for an electron temperature  $T_e$  (measured in eV):

$$f(\mathcal{E}) = (2.073) \left( \frac{3}{2} T_e \right)^{-3/2} \mathcal{E}^{1/2} \exp(-\mathcal{E}/T_e) \quad \text{Eq. 7.3}$$

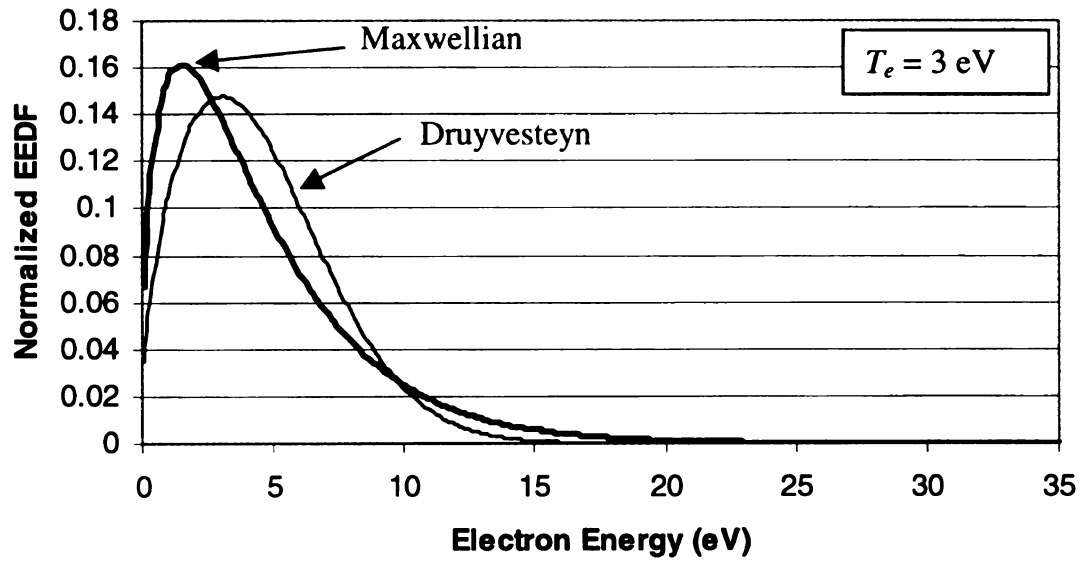
where  $\mathcal{E}$  is the electron energy in eV. This distribution function is plotted in Figure 7.2 vs. electron energy.

The Druyvesteyn distribution function assumes that electron-neutral collisions are prevalent and have a significant influence on the electron energy distribution. In this case the electron-neutral collision cross section vs. electron energy is assumed to be constant. The Druyvesteyn distribution may also be produced in a plasma when a constant, uniform electric field is present. The normalized Druyvesteyn energy distribution function is given below [Gun-01]:

$$f(\mathcal{E}) = (1.038) \left( \frac{3}{2} T_e \right)^{-3/2} \mathcal{E}^{1/2} \exp \left( -(0.5471) \frac{\mathcal{E}^2}{\left( \frac{3}{2} T_e \right)^2} \right) \quad \text{Eq. 7.4}$$

where  $T_e$  is the effective temperature of the electron distribution in eV,  $\mathcal{E}$  is the electron energy in eV. This distribution function is plotted in Figure 7.2 along with the Maxwellian distribution.

a) Linear Plot



b) Log Plot

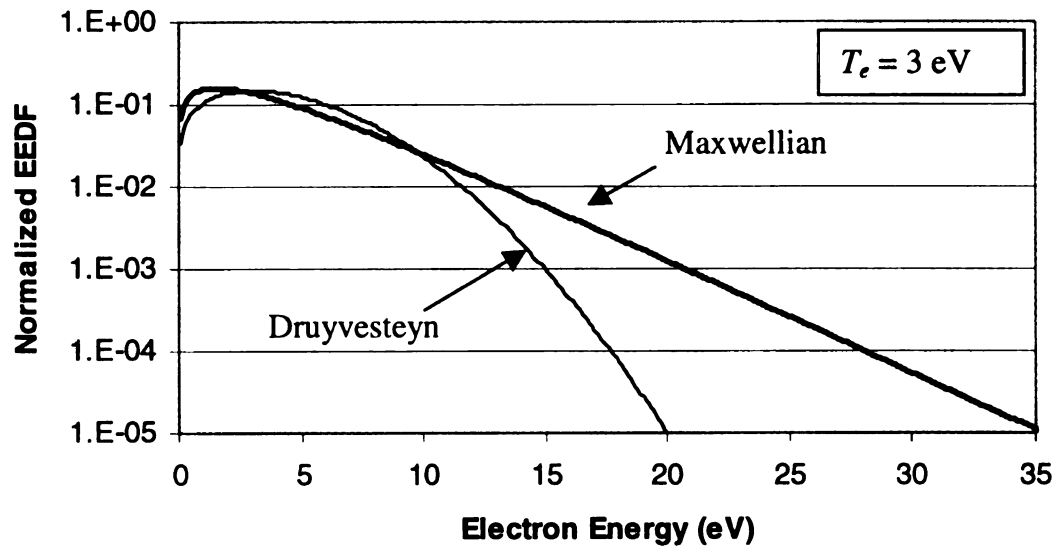


Figure 7.2: Both Maxwellian and Druyvesteyn energy distribution functions plotted for an effective temperature of  $T_e = 3$  eV. (a) Linear and (b) Logarithmic plots are shown for both distributions.

Both linear and logarithmic plots are shown in Figures 7.2a and 7.2b respectively. As will be seen later in this Chapter, the linear plot shows low electron energies (0 to 10 eV) in good detail, while the logarithmic plot is needed to show the high electron energies ( $>10$  eV) in sufficient detail to make any observations or comparisons.

### **7.3 Single Langmuir Probe Measurements at the Base of the Discharge ( $r=0$ , $z=0$ ):**

#### **7.3.1 EEDFs of Non-magnetized & Magnetized Discharges at Several Pressures**

The single Langmuir probe was positioned at the bottom center of the discharge ( $r=0, z=0$ ). Measurements were made for magnetized and non-magnetized configurations from discharge pressures of 1, 4, 5, 7, 10, 15, and 45 mTorr (Note that at 1 mTorr only a magnetized discharge could be sustained). The EEDFs of these measurements are shown in Figures 7.3 (a,b) through 7.15(a,b).

Figures 7.3-7.15 directly compare the non-magnetized and magnetized EEDFs. Note in these figures Maxwellian and Druyvesteyn curves are plotted (with the same average energy as the measured EEDF, see Section 7.2) for comparison. In these figures the Maxwellian curve is always represented as the thicker solid line and the Druyvesteyn curve is represented as the thinner solid line. The experimental EEDF data points are represented by open circles. For all measurements the argon gas flow was 29.5 sccm, the power absorbed in the discharge,  $P_{abs}$ , is 280 W, and the power reflected from the microwave cavity,  $P_{ref}$ , is 30 W. The cavity excitation probe antenna length,  $L_p$ , was held constant at 3 cm.

Since the non-magnetized discharge could not be sustained at 1 mTorr only the magnetized discharge EEDF was measured, shown in Figures 7.3a and 7.3b. The linear plot, Figure 7.3a, shows that the measured data fits a Maxwellian profile from 0 to 8 eV, but then appears to exceed the Maxwellian profile between 8 and 18 eV (note the “bump” in the distribution). The logarithmic plot, Figure 7.3b, shows that a more Druyvesteyn like or depleted high energy tail exists from 21 to 34 eV. This low pressure profile may be the result of inelastic collisions that deplete high energy electron populations and send them to lower energy levels (in this case the 8 to 18 eV range).

Figures 7.4-7.15 show that at pressures from 4 to 15 mTorr the EEDFs for the non-magnetized discharge are very Maxwellian from low to high electron energies. The EEDFs for the magnetized discharge fit Maxwellian distributions at low energies but fall between the Maxwellian and Druyvesteyn curves at high energies. Such a distribution can be said to have a depleted high energy electron tail. This depleted high energy tail raises several questions. First, is this depleted distribution maintained at increasing vertical positions in the discharge? This will be investigated and presented in section 7.4. Second, what is the physical cause of this depleted high energy tail? This will be discussed in chapter 10.

The magnetized and non-magnetized EEDFs were also measured at 45 mTorr, see Figures 7.14(a,b) and 7.15(a,b). We must note that at this pressure both EEDFs appear less than Maxwellian. However, the high energy tail of the magnetized discharge appears to be more depleted than the non-magnetized EEDF. The depleted high energy tail here for both discharges could in part be the result of increased electron neutral collisions at high pressures.

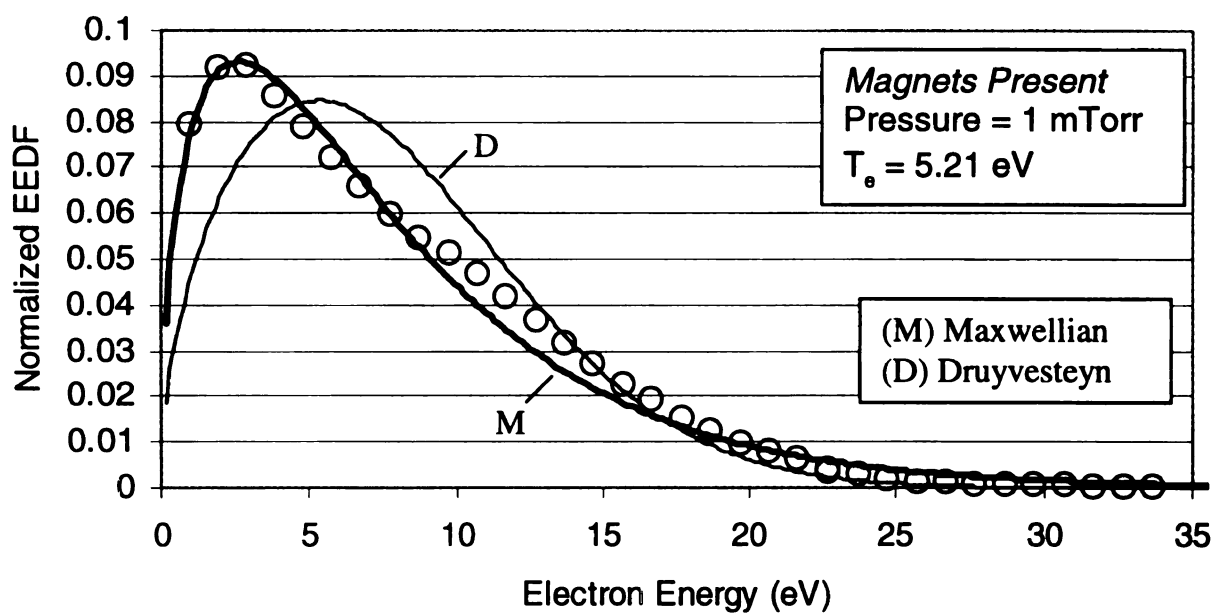


Figure 7.3a - EEDF in argon at 1 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 5.21$  eV,  $V_p = 22.71$  V,  $L_s = 13.675$  cm.



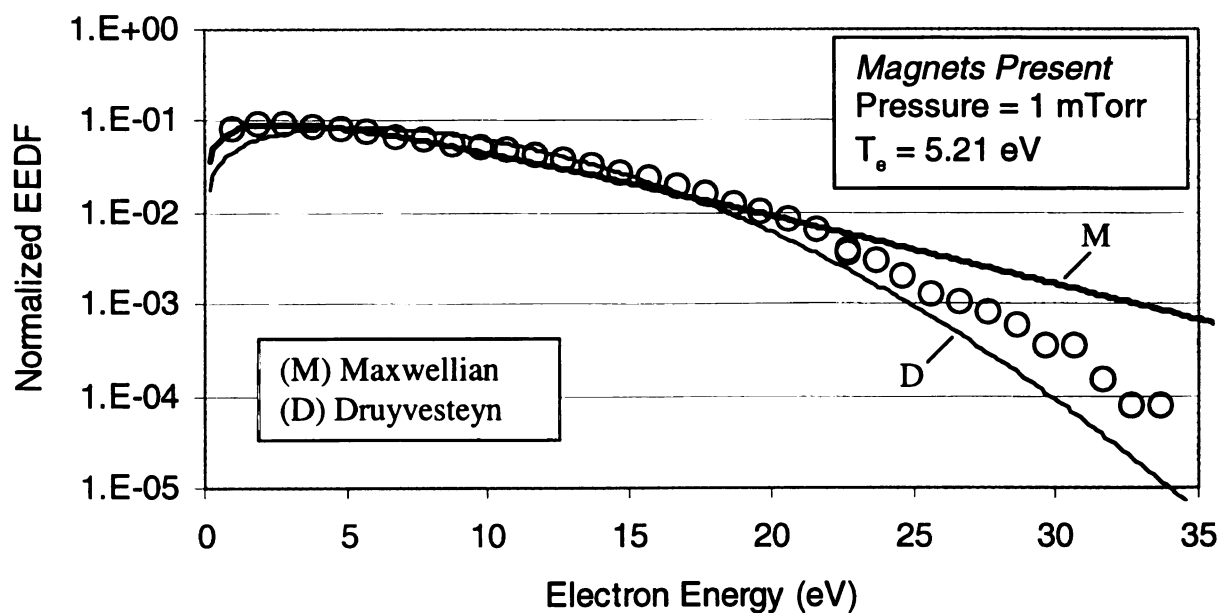


Figure 7.3b - EEDF in argon at 1 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 5.21$  eV,  $V_p = 22.71$  V,  $L_s = 13.675$  cm.

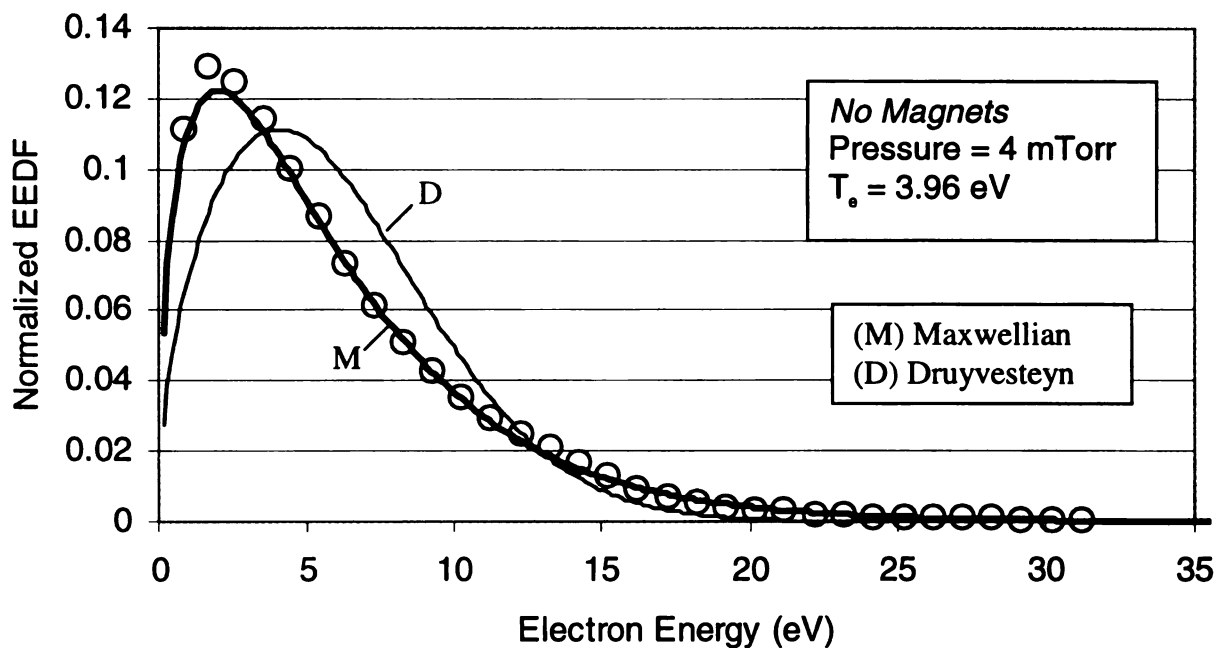


Figure 7.4a - EEDF in argon at 4 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.96$  eV,  $V_p = 22.27$  V,  $L_s = 13.95$  cm.

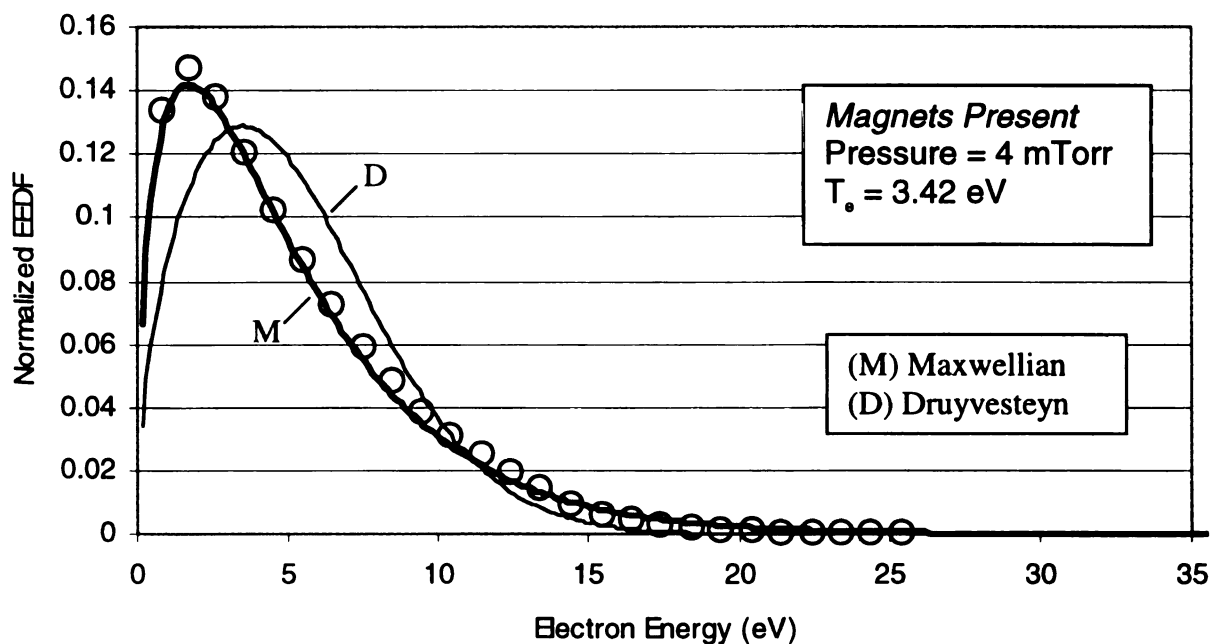


Figure 7.5a – EEDF in argon at 4 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.42$  eV,  $V_p = 14.46$  V,  $L_s = 15.75$  cm.

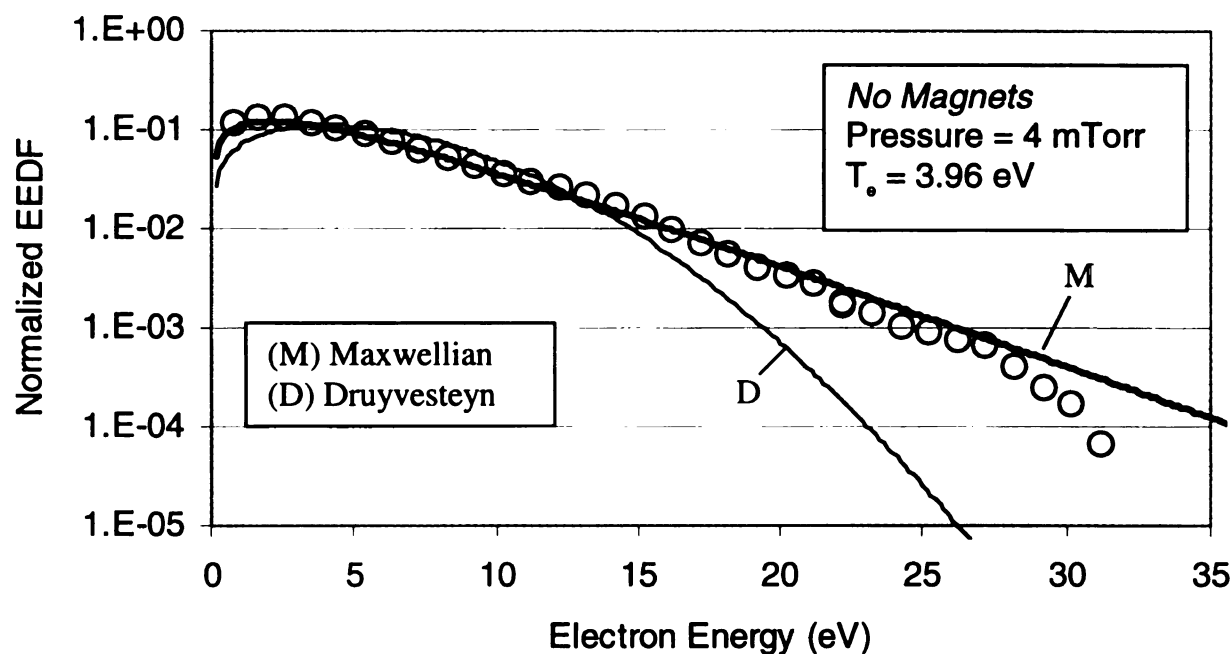


Figure 7.4b - EEDF in argon at 4 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.96$  eV,  $V_p = 22.27$  V,  $L_s = 13.95$  cm.

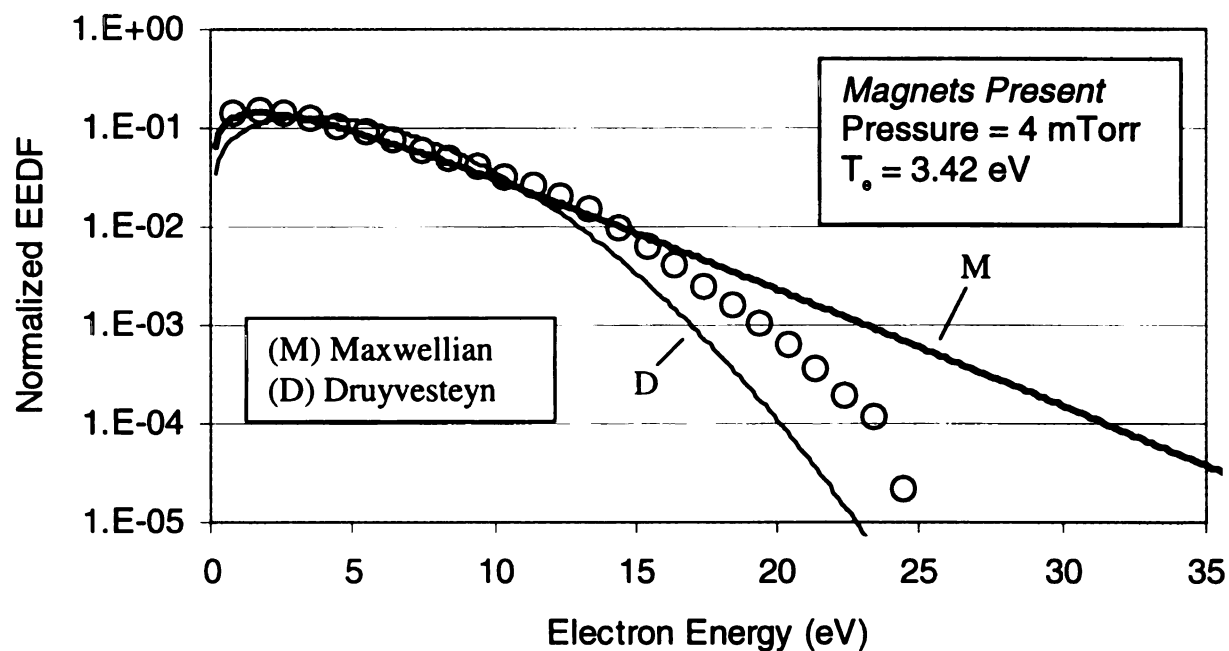


Figure 7.5b – EEDF in argon at 4 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.42$  eV,  $V_p = 14.46$  V,  $L_s = 15.75$  cm.

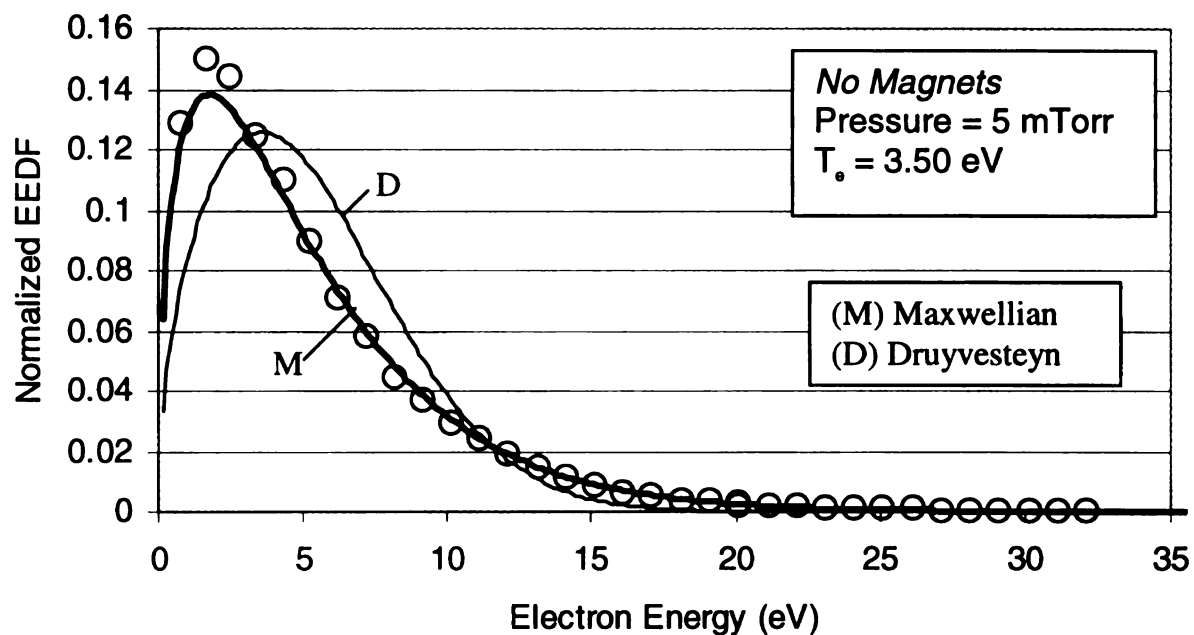


Figure 7.6a – EEDF in argon at 5 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.50$  eV,  $V_p = 20.17$  V,  $L_s = 14.1$  cm.

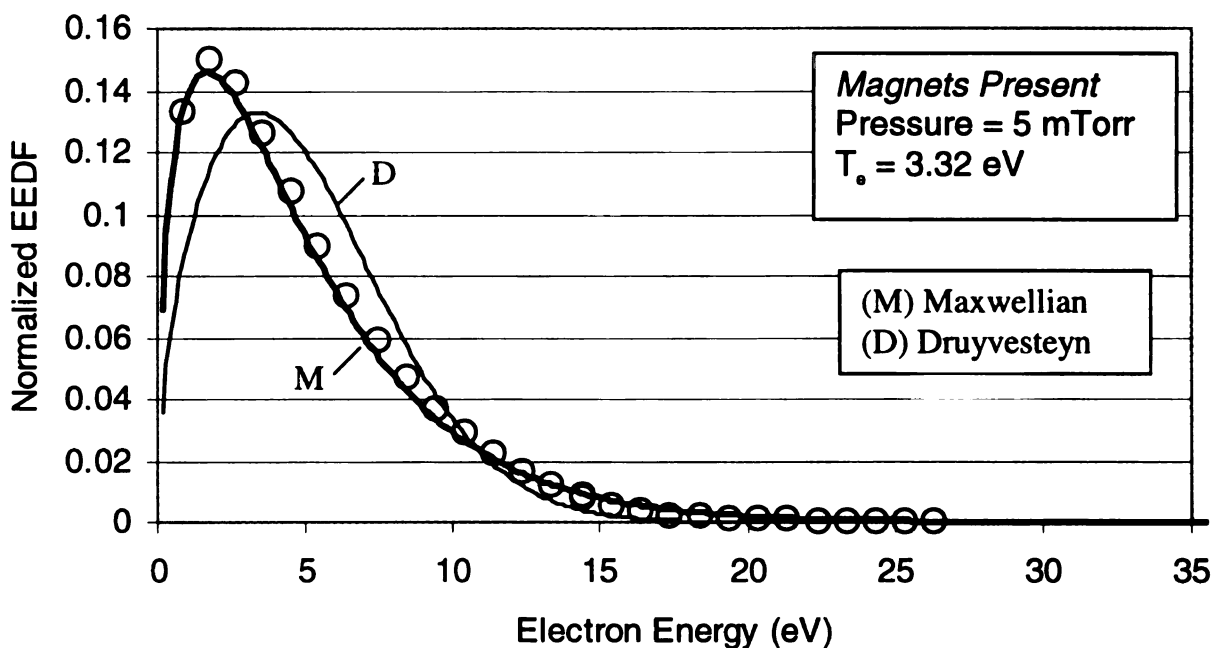


Figure 7.7a – EEDF in argon at 5 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.32$  eV,  $V_p = 14.41$  V,  $L_s = 15.85$  cm.

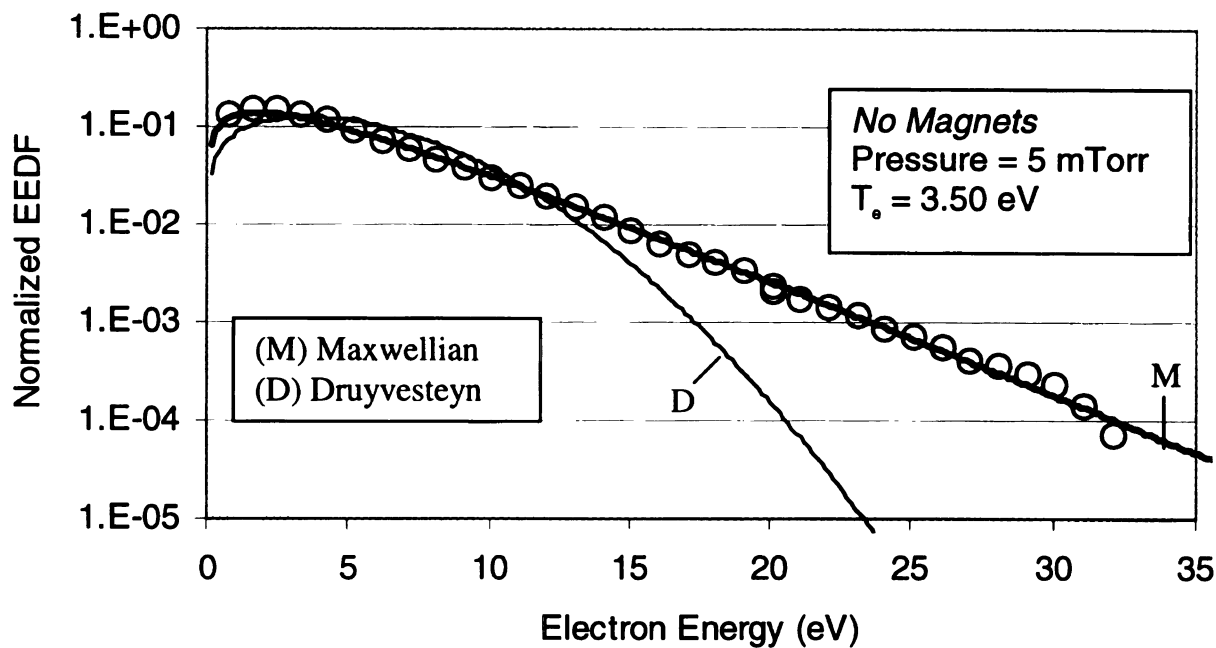


Figure 7.6b – EEDF in argon at 5 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.50$  eV,  $V_p = 20.17$  V,  $L_s = 14.1$  cm.

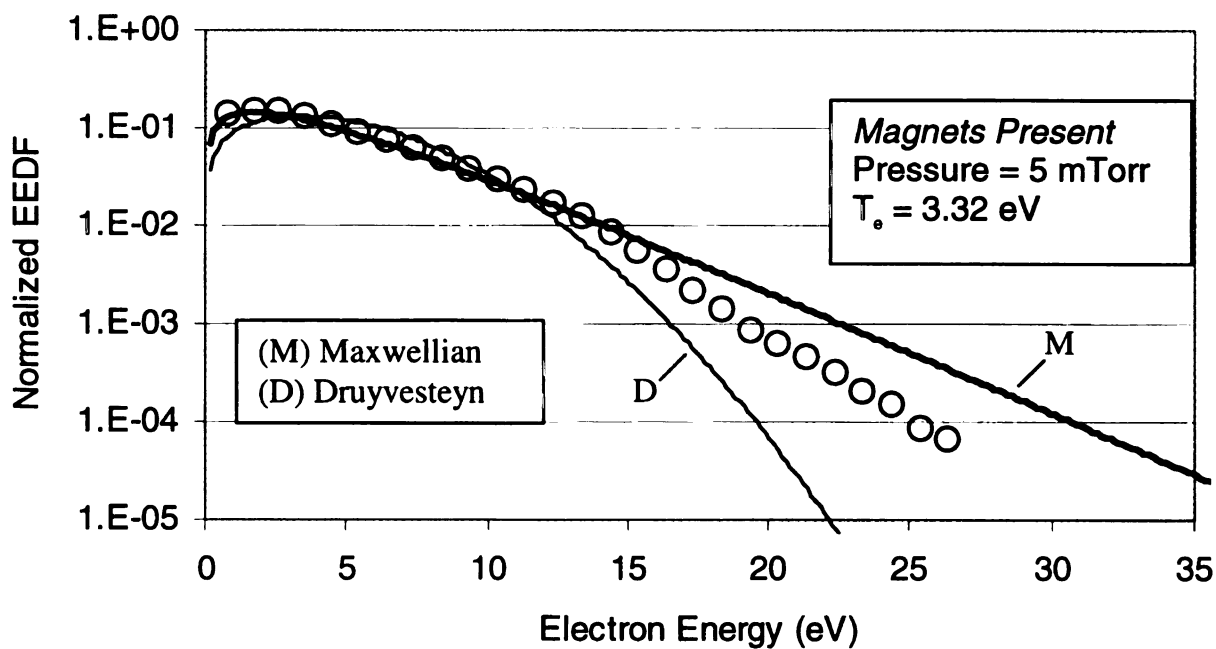


Figure 7.7b – EEDF in argon at 5 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.32$  eV,  $V_p = 14.41$  V,  $L_s = 15.85$  cm.

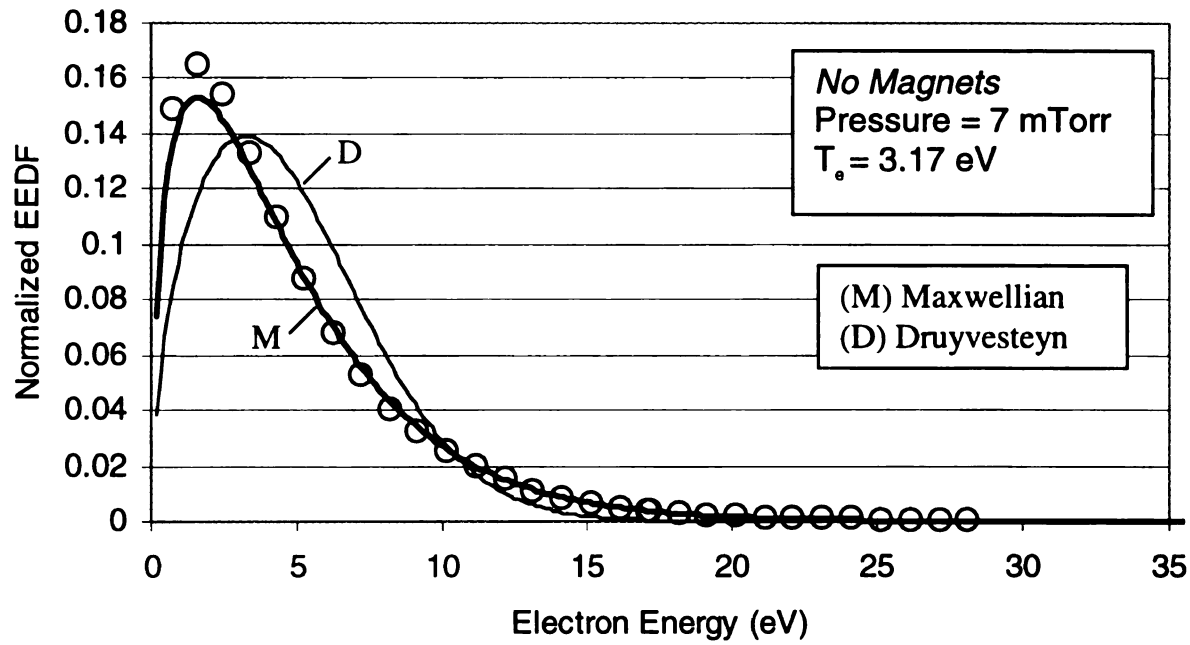


Figure 7.8a – EEDF in argon at 7 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.17$  eV,  $V_p = 17.20$  V,  $L_s = 15.10$  cm.

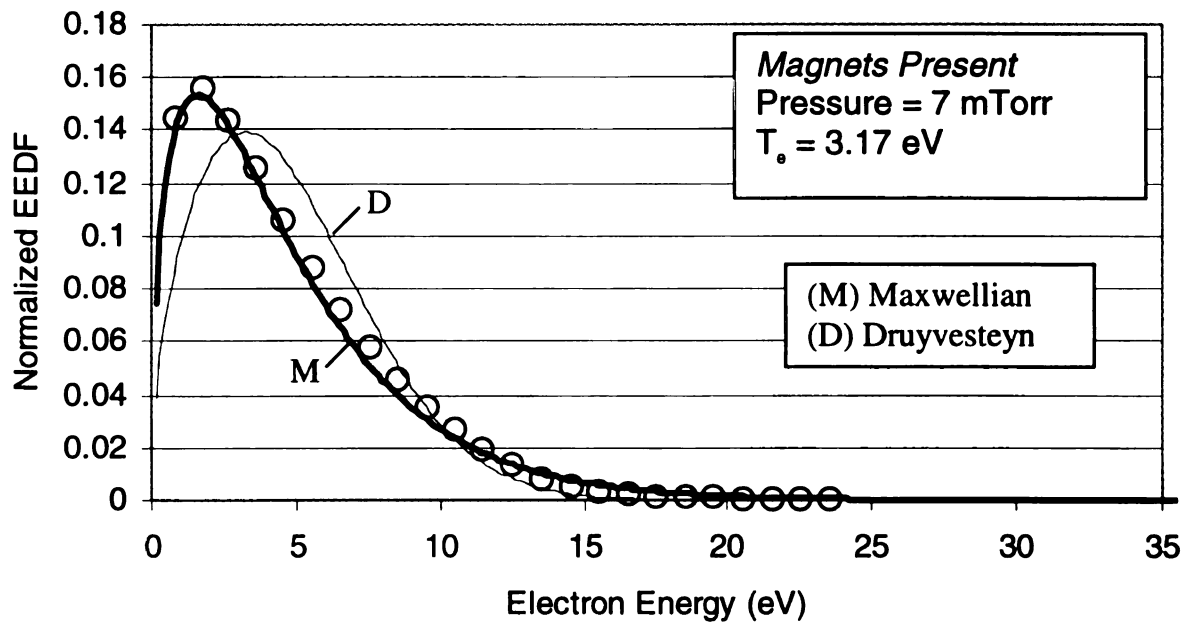


Figure 7.9a – EEDF in argon at 7 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.17$  eV,  $V_p = 13.57$  V,  $L_s = 15.9$  cm.

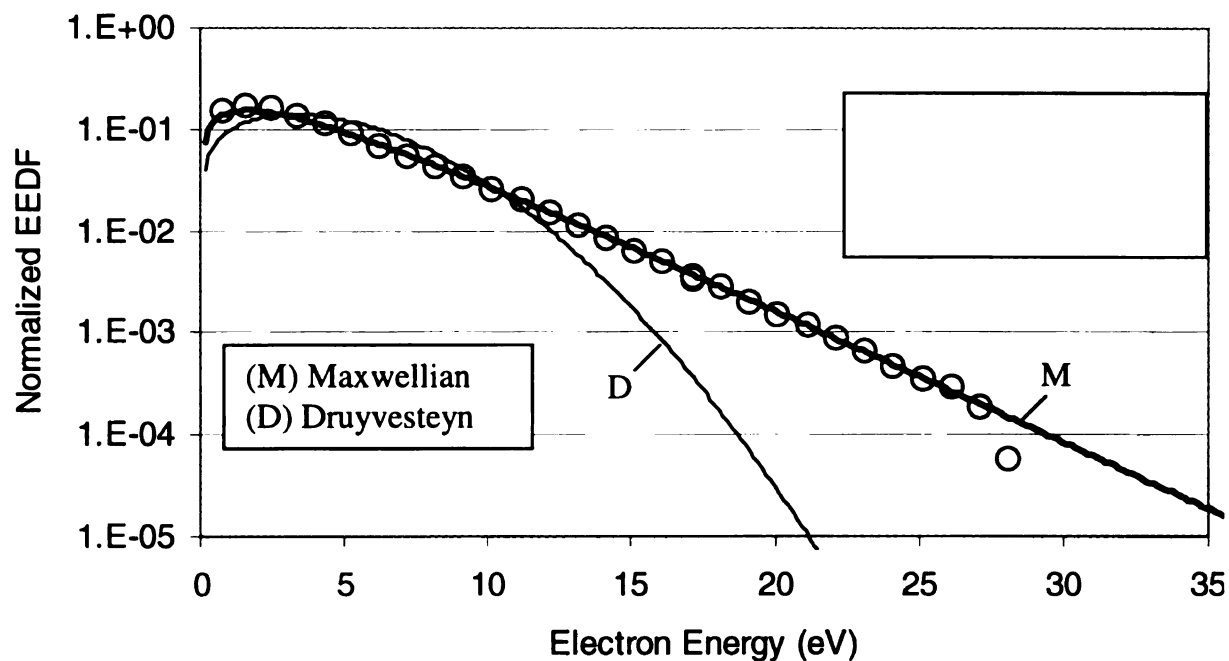


Figure 7.8b – EEDF in argon at 7 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.17$  eV,  $V_p = 17.20$  V,  $L_s = 15.10$  cm.

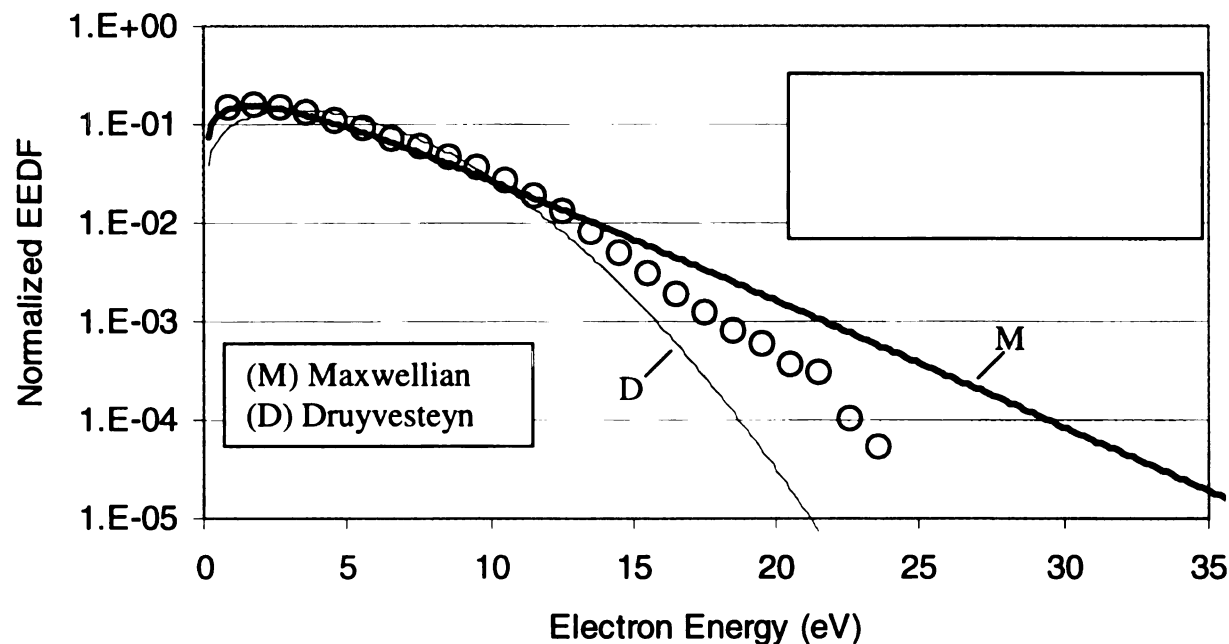


Figure 7.9b – EEDF in argon at 7 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 3.17$  eV,  $V_p = 13.57$  V,  $L_s = 15.9$  cm.

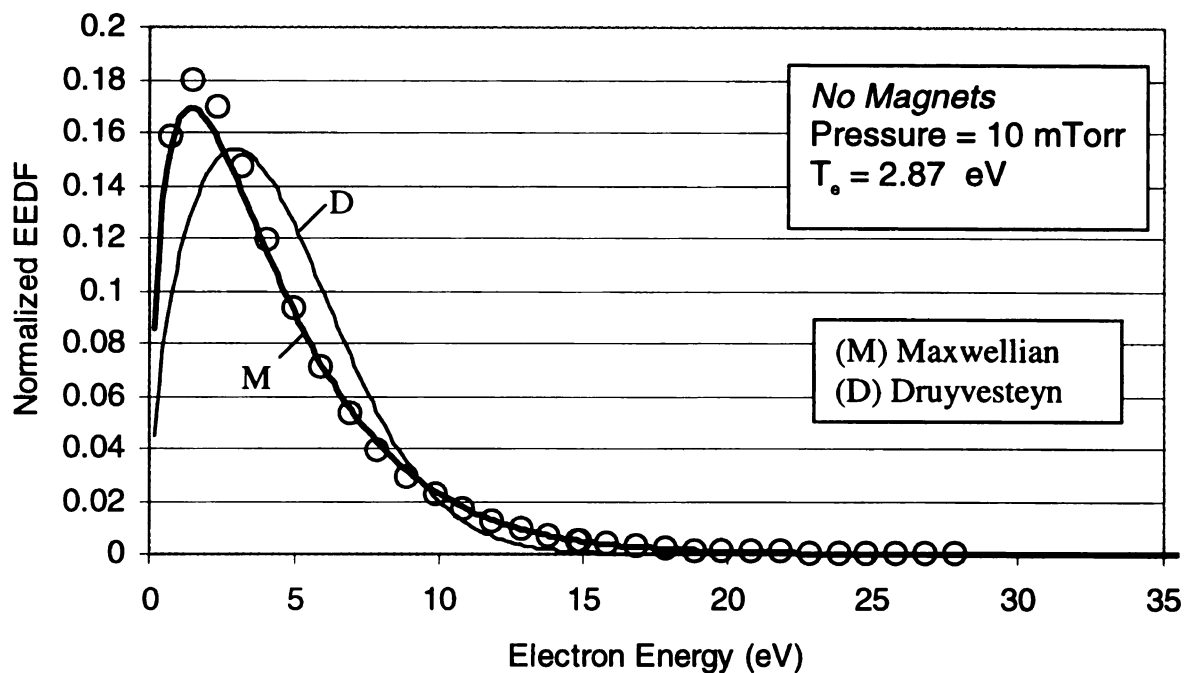


Figure 7.10a – EEDF in argon at 10 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{\text{abs}} = 280$  W,  $\text{TM}_{012}$  mode,  $T_e = 2.87$  eV,  $V_p = 14.89$  V,  $L_s = 15.85$  cm.

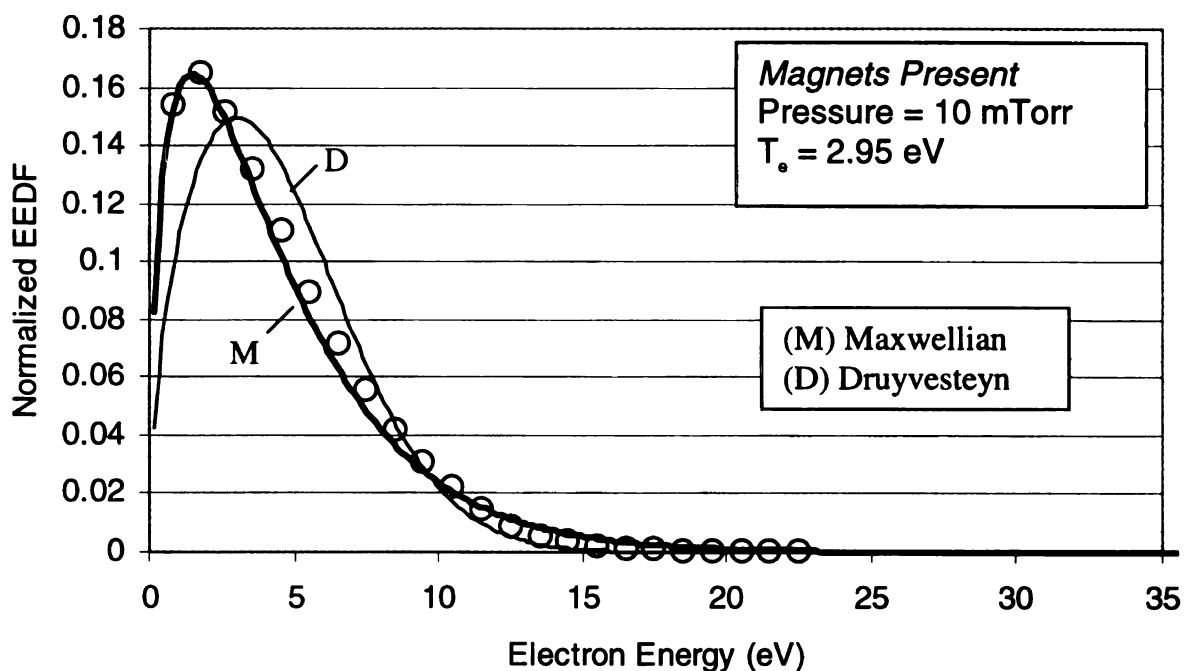


Figure 7.11a – EEDF in argon at 10 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{\text{abs}} = 280$  W,  $\text{TM}_{012}$  mode,  $T_e = 2.95$  eV,  $V_p = 12.54$  V,  $L_s = 16.2$  cm.



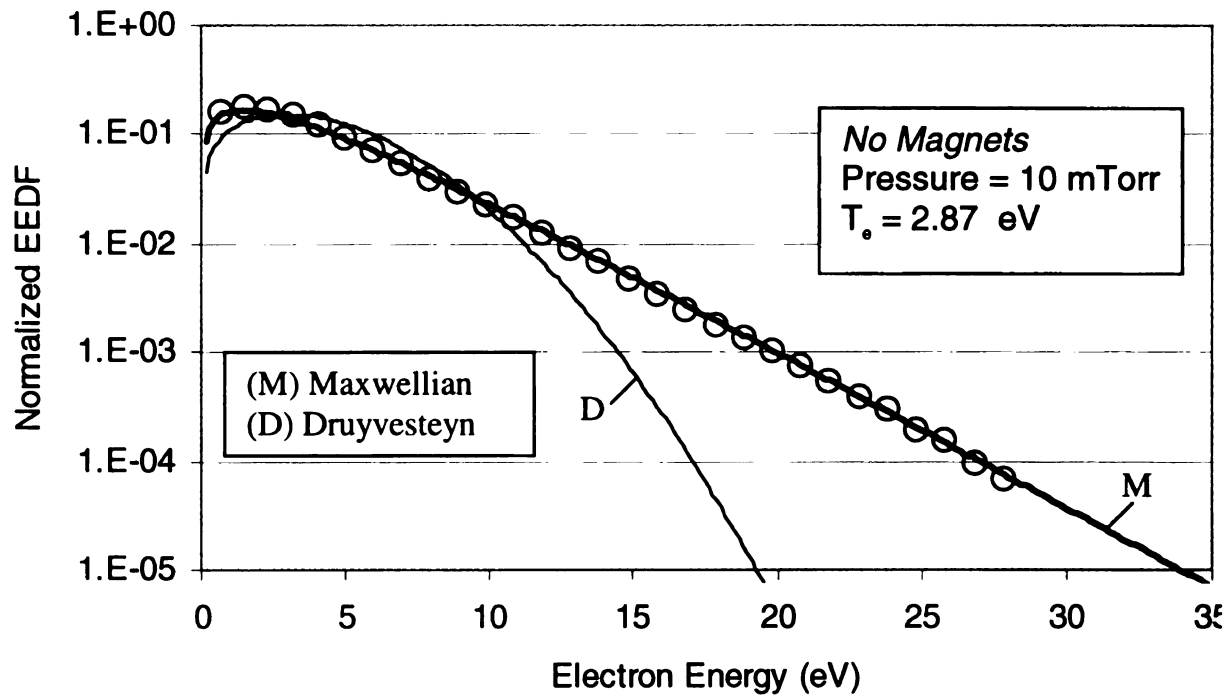


Figure 7.10b – EEDF in argon at 10 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 2.87$  eV,  $V_p = 14.89$  V,  $L_s = 15.85$  cm.

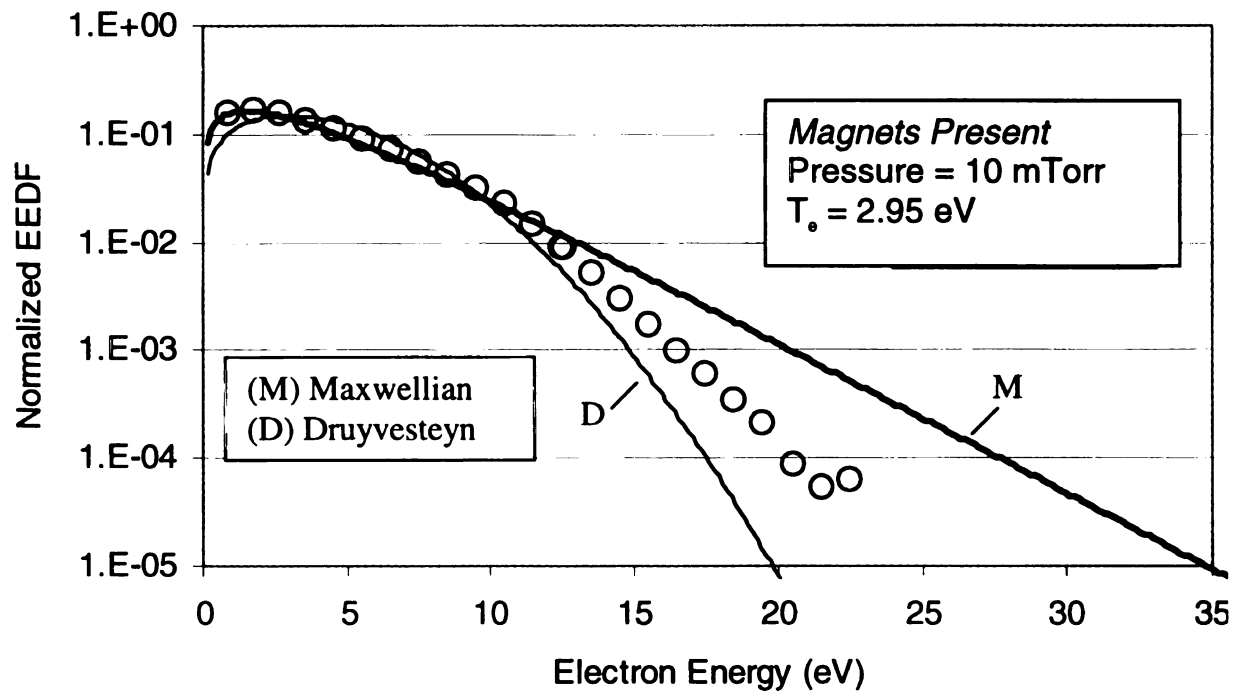


Figure 7.11b – EEDF in argon at 10 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 2.95$  eV,  $V_p = 12.54$  V,  $L_s = 16.2$  cm.

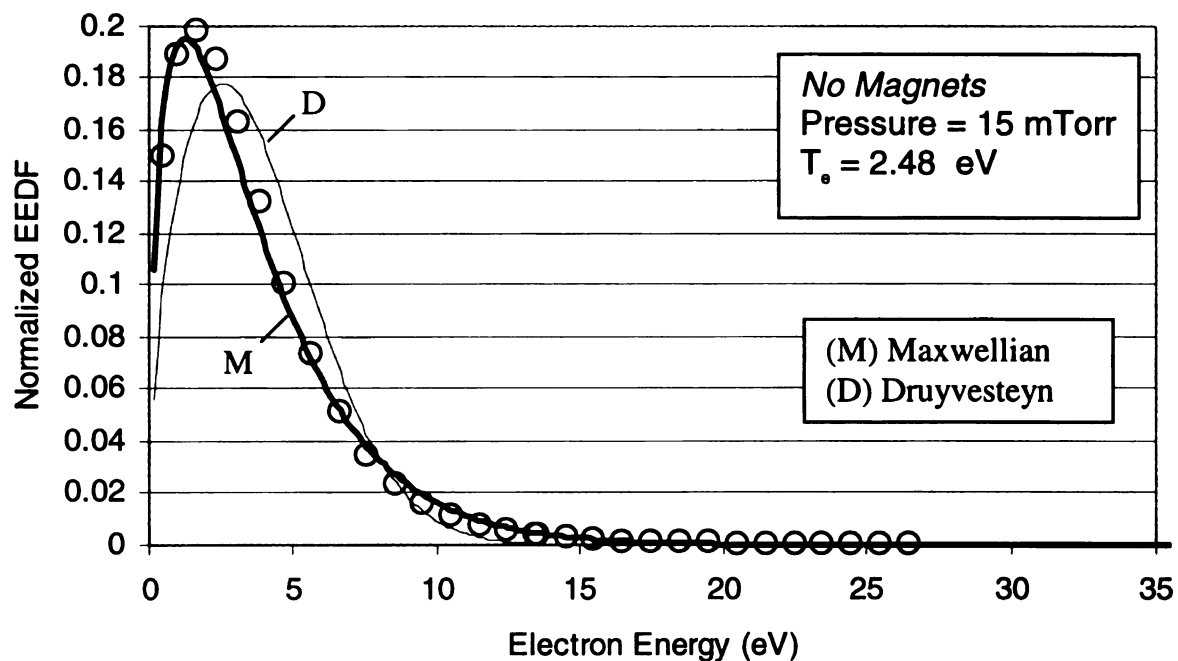


Figure 7.12a – EEDF in argon at 15 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 2.48$  eV,  $V_p = 13.54$  V,  $L_s = 16.2$  cm.

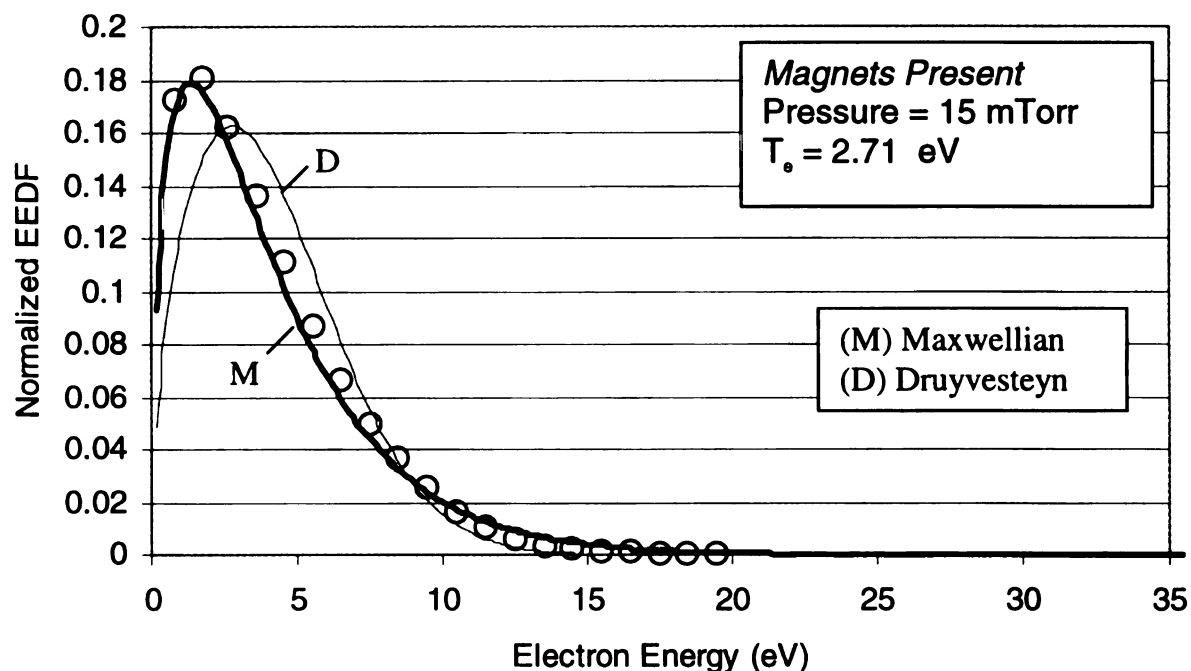


Figure 7.13a – EEDF in argon at 15 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 2.71$  eV,  $V_p = 12.53$  V,  $L_s = 16.575$  cm.

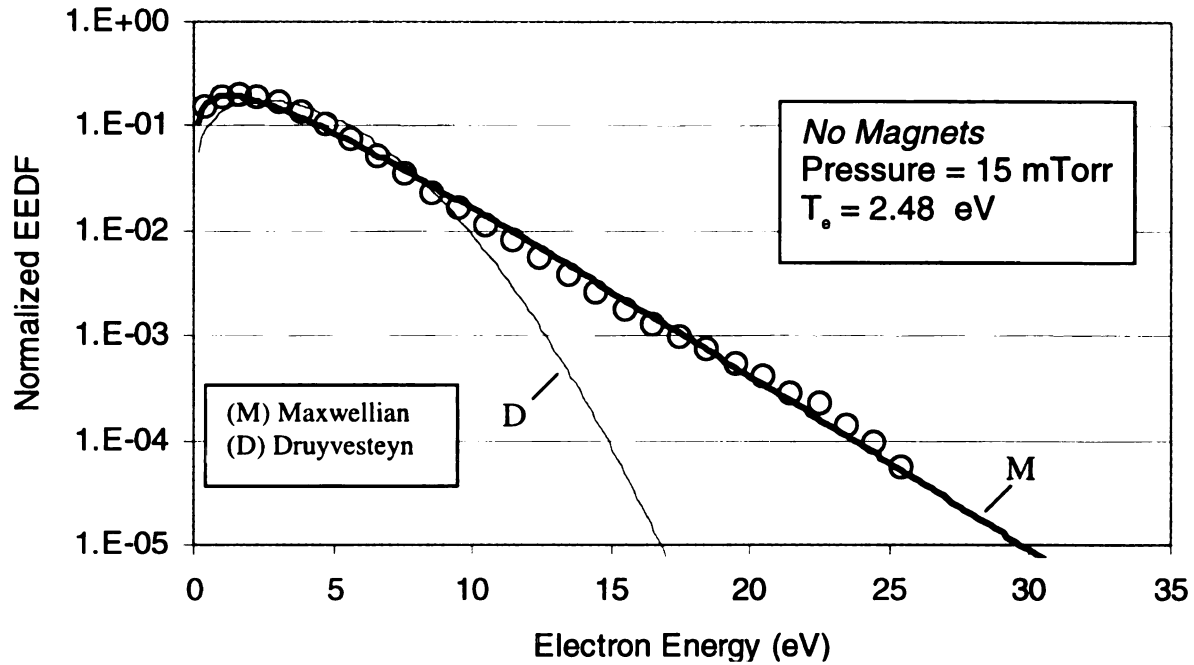


Figure 7.12b – EEDF in argon at 15 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 2.48$  eV,  $V_p = 13.54$  V,  $L_s = 16.2$  cm.

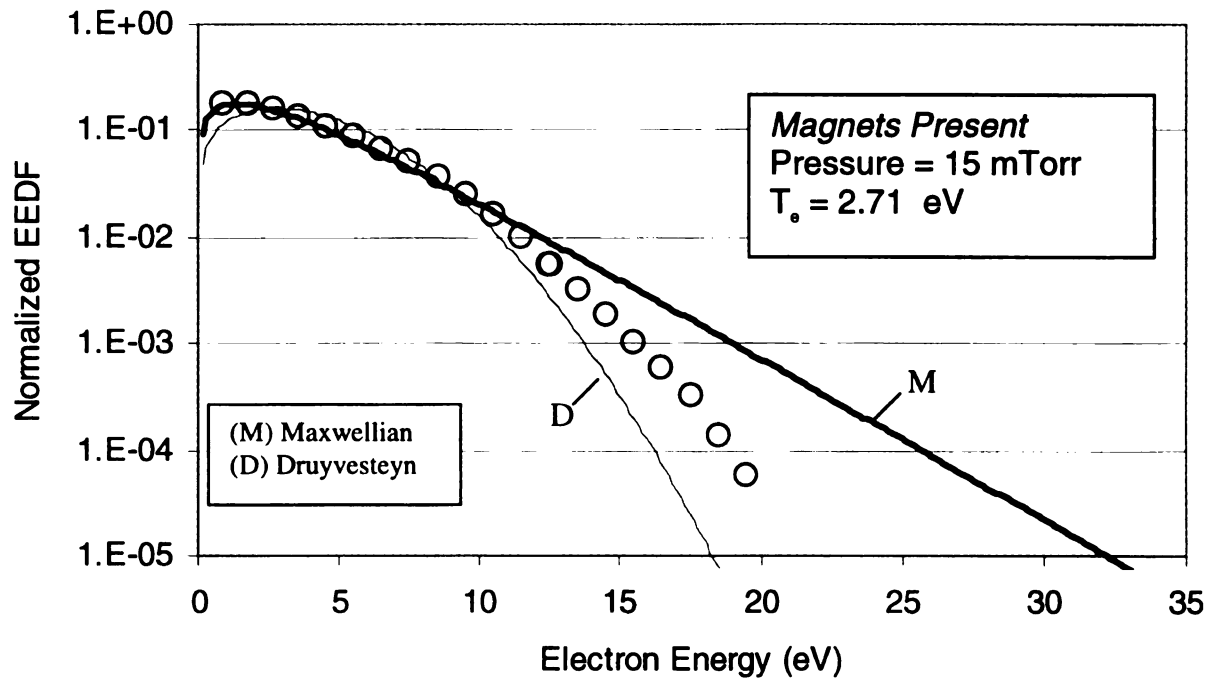


Figure 7.13b – EEDF in argon at 15 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 2.71$  eV,  $V_p = 12.53$  V,  $L_s = 16.575$  cm.

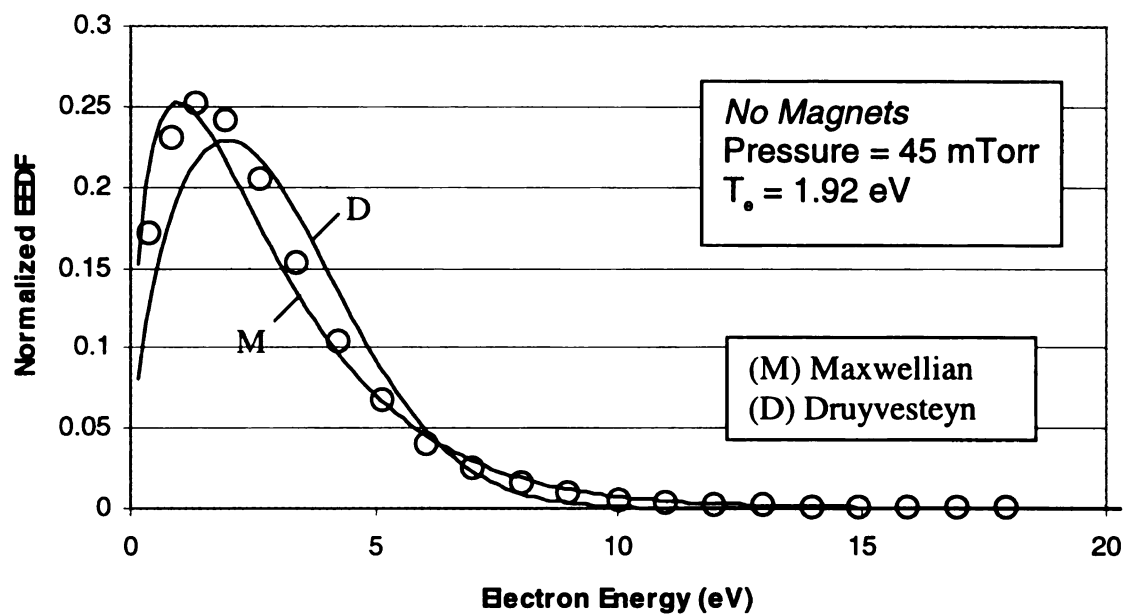


Figure 7.14a – EEDF in argon at 45 mTorr , measured at  $r=0, z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 1.92$  eV,  $V_p = 10.08$  V,  $L_s = 19.1$  cm.

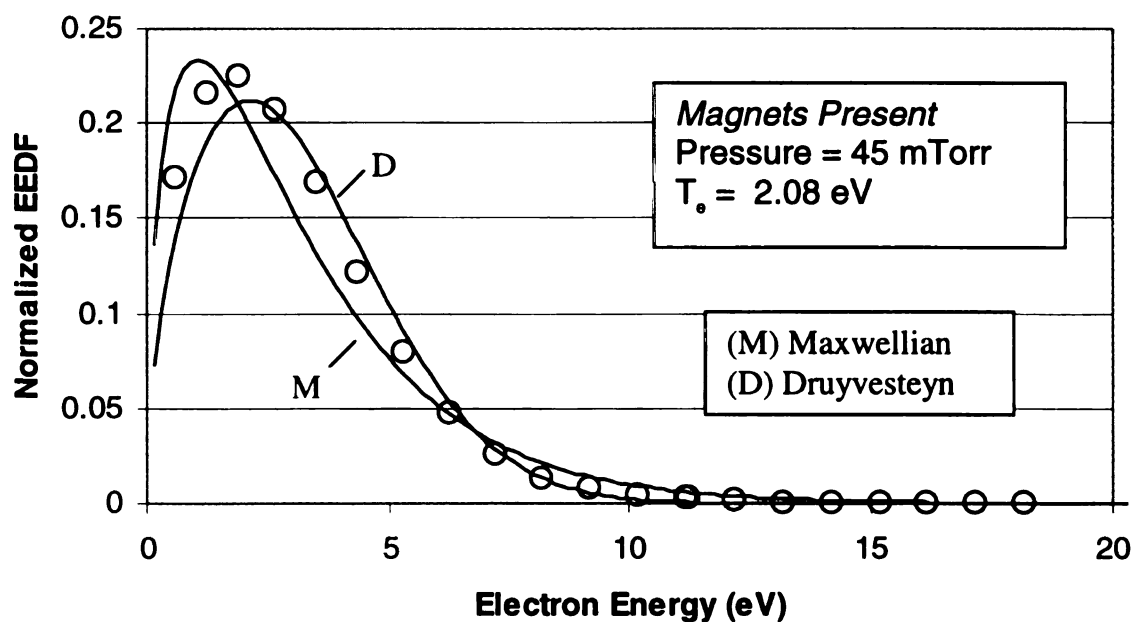


Figure 7.15a – EEDF in argon at 45 mTorr with multipolar magnets present, measured at  $r=0, z=0$  in the discharge. Discharge parameters are:  $P_{abs} = 280$  W,  $TM_{012}$  mode,  $T_e = 2.08$  eV,  $V_p = 11.26$  V,  $L_s = 20$  cm.

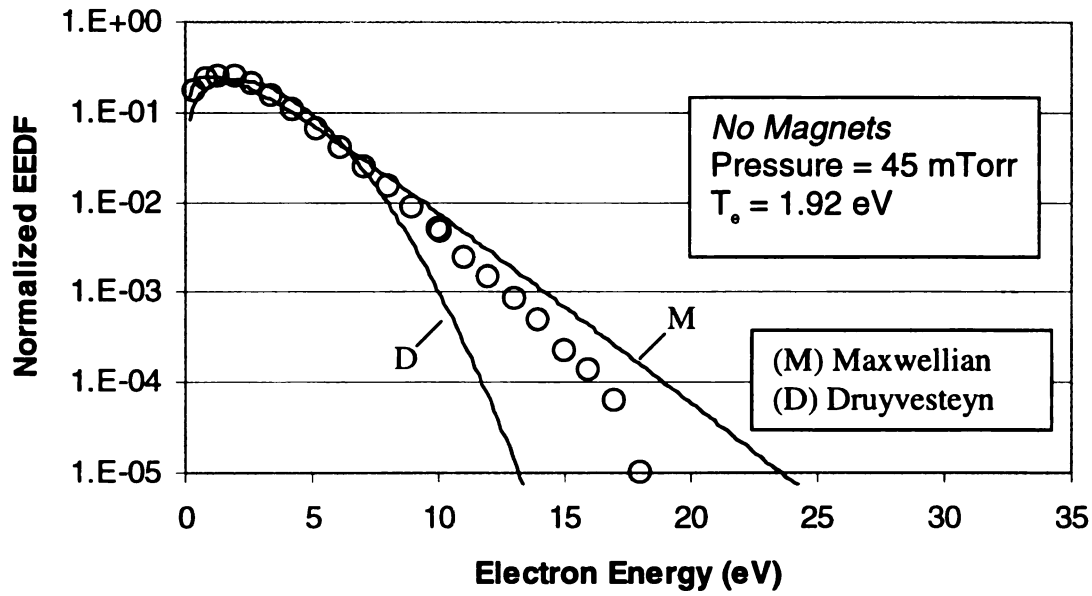


Figure 7.14b – EEDF in argon at 45 mTorr , measured at  $r=0$ ,  $z=0$  in the discharge, with no magnets present. Discharge parameters are:  $P_{\text{abs}} = 280$  W,  $\text{TM}_{012}$  mode,  $T_e = 1.92$  eV,  $V_p = 10.08$  V,  $L_s = 19.1$  cm.

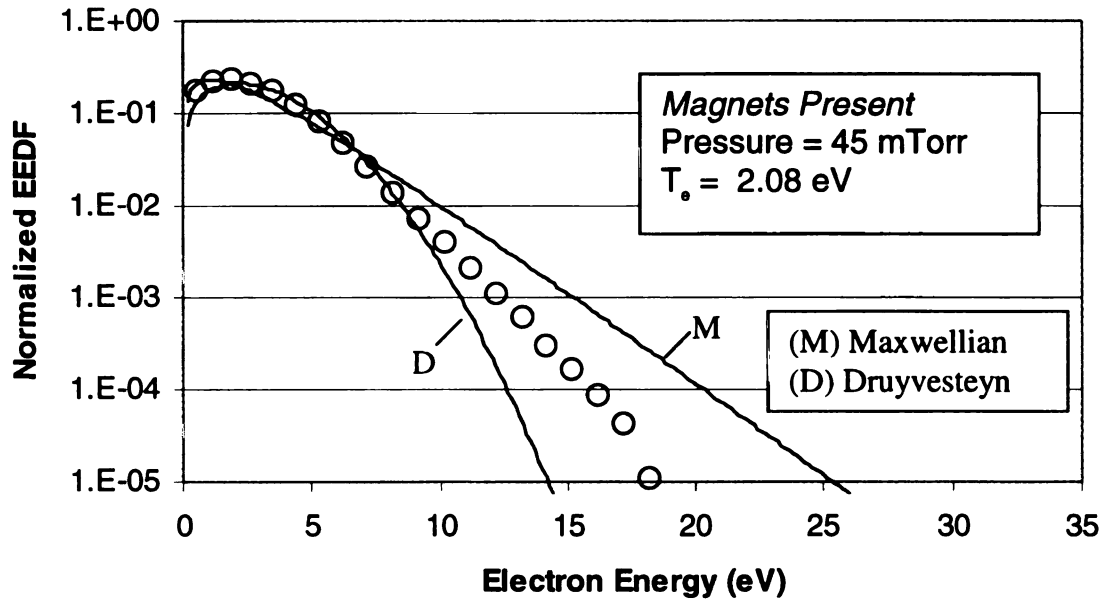


Figure 7.15b – EEDF in argon at 45 mTorr with multipolar magnets present, measured at  $r=0$ ,  $z=0$  in the discharge. Discharge parameters are:  $P_{\text{abs}} = 280$  W,  $\text{TM}_{012}$  mode,  $T_e = 2.08$  eV,  $V_p = 11.26$  V,  $L_s = 20$  cm.

### 7.3.2 Electron Temperatures vs. Discharge Pressure

#### 7.3.2.1 Comparison of $T_e$ between Magnetized and Non-Magnetized Configurations:

Figure 7.16 plots SLP measured electron temperatures vs. pressure and compares the magnetized vs. non-magnetized plasma with all points being taken in the TM<sub>012</sub> mode and at 280 W absorbed power.

The experimental  $T_e$  points for both Magnetized and Non-Magnetized configurations in Figure 7.16 both decrease with increasing discharge pressure. Also, no differences in  $T_e$  larger than 0.5 eV are observed between magnetized and non-magnetized configurations. Thus, we could argue that the electron temperatures between magnetized and non-magnetized are not significantly different within experimental error. However, we should note that the non-magnetized discharge has slightly higher  $T_e$  than the magnetized discharge at 4 and 5 mTorr and lower than magnetized at 7, 10, and 15 mTorr. Note, once again, that only the magnetized discharge could be sustained for  $T_e$  measurement at 1 mTorr.

#### 7.3.2.2 Comparison of Measured Electron Temperatures to the Global Model Predictions:

For all SLP data presented in section 7.3.1 the tungsten tip of the probe was placed at the bottom center of the discharge, i.e. at  $r = 0$  and  $z = 0$ , as shown in Figures 3.2 and 5.1. The discharge geometries and pressures for the experiments presented here

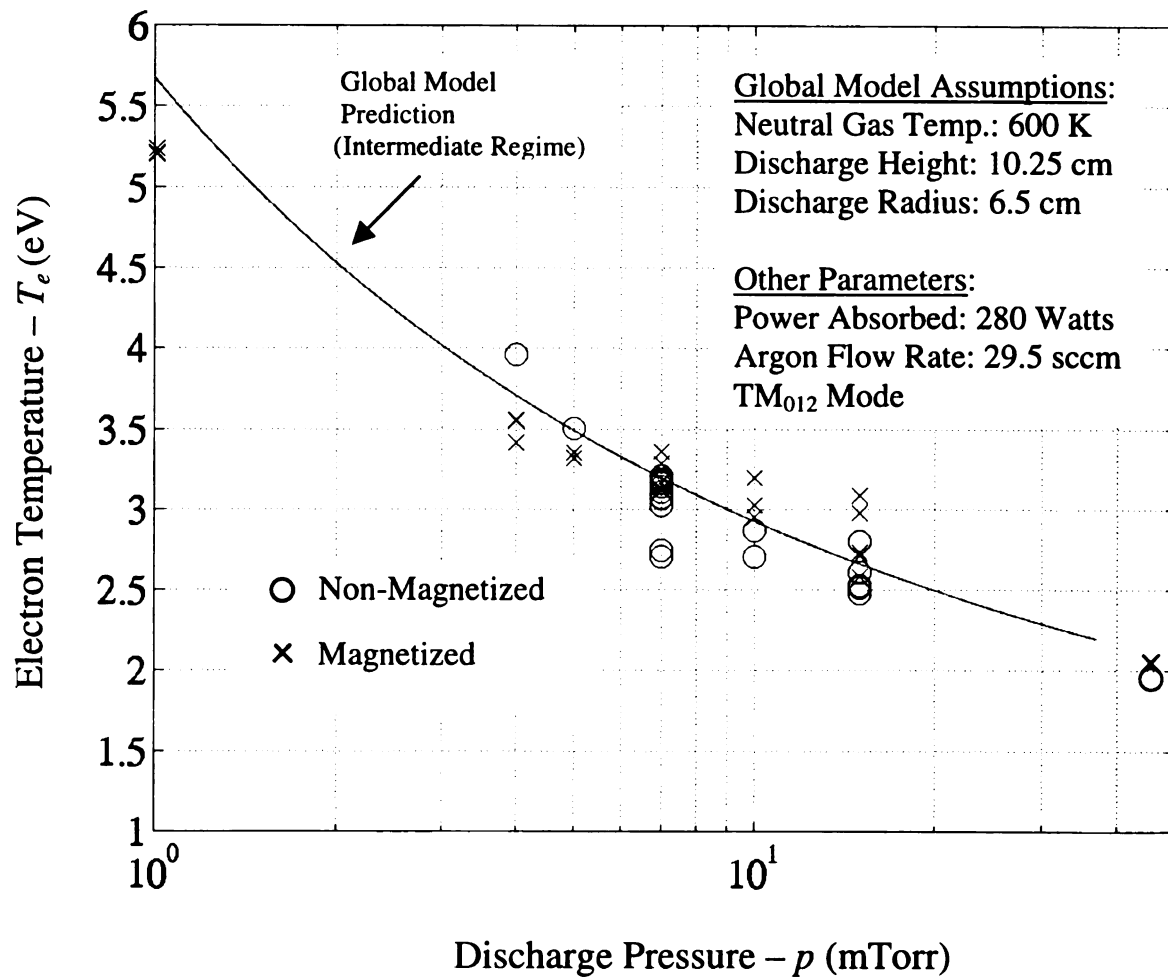


Figure 7.16 - Single Langmuir probe measured electron temperatures vs. discharge pressure. Magnetized and non-magnetized configurations are compared.

are best described by the intermediate pressure global model. For this discharge the intermediate pressure regime falls between the pressure range of 1 to 42 mTorr. The solid curve plotted in Figure 7.16 represents the intermediate pressure regime global model prediction.

Note that the global model is a good approximation or “benchmark” to plasma behavior and should not be taken as a quantitatively exact predictive model. Nevertheless, the experimentally measured electron temperatures plotted in both Figures 7.16 and 7.17 fit quantitatively well and experimental data falls within a range of  $\pm 0.5$  eV from the electron temperatures predicted by the intermediate pressure global model. The experimental data fits within this range for the range of different absorbed power and EM mode conditions displayed in Figure 7.16 and for the different magnetic field configurations displayed in Figure 7.17.

### **7.3.3 Study of $T_e$ Dependence on EM Excitation Intensity or Mode Type**

#### **7.3.3.1 Influence of $P_{abs}$ on $T_e$ for the Non-Magnetized $TM_{012}$ Mode:**

All points in Figure 7.17 were taken in a non-magnetized discharge at various absorbed power levels and in both the  $TM_{012}$  and near field modes.

The measured electron temperatures for several different absorbed power,  $P_{abs}$ , levels are displayed in Figure 7.17 for the non-magnetized  $TM_{012}$  mode. The value of  $P_{abs}$  does not appear to have a strong influence on  $T_e$ . However, a weak dependence is observed where the electron temperature increases slightly as  $P_{abs}$  increases. Note that the



collection of 280-300 W and 330 W data points fall generally in the upper half of the data set (above the global model intermediate regime curve) and the collection of 130 W and 230 W data points fall generally in the lower half of the data set.

For  $P_{abs}$  power levels measured (between 160-320 W) an average increase of 0.3-0.4 eV/100W is observed in  $T_e$  vs.  $P_{abs}$ . A similar  $T_e$  vs.  $P_{abs}$  dependence was observed by Mak in the magnetized, end-feed, MPDR 13 discharge [Mak-97; pp.261-265]. Similarly, for the side feed configuration of the MPDR 13 at 1 mTorr, Mak found a similar 0.3-0.4 eV/100W increase in  $T_e$  vs.  $P_{abs}$  over a  $P_{abs}$  range of 250-800W.

### **7.3.3.2 Comparison of $T_e$ between EM modes in a Non-Magnetized Discharge:**

A direct experimental comparison of electron temperature between the  $TM_{012}$  mode and the near field mode was made. In this comparison the electron temperature was first measured for the  $TM_{012}$  mode at 280 W and then the experimental system was immediately tuned to the near field mode and the electron temperature measured. Next the system was again tuned to the  $TM_{012}$  mode for a second  $T_e$  measurement and then back to the near field mode for a second measurement there. This was done at an absorbed power of 280 W and at a pressure of 7 mtorr in a non-magnetized discharge. The same procedure was also carried out at 15 mTorr. The electron temperatures measured for the different modes differed by less than 0.1 eV. This was true for both pressures. These experiments indicate that electron temperature is not influenced by changing from the  $TM_{012}$  mode to the near field mode in the non-magnetized discharge.

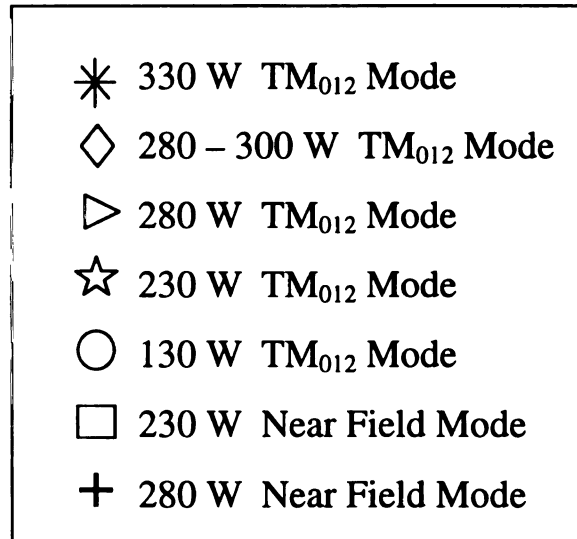
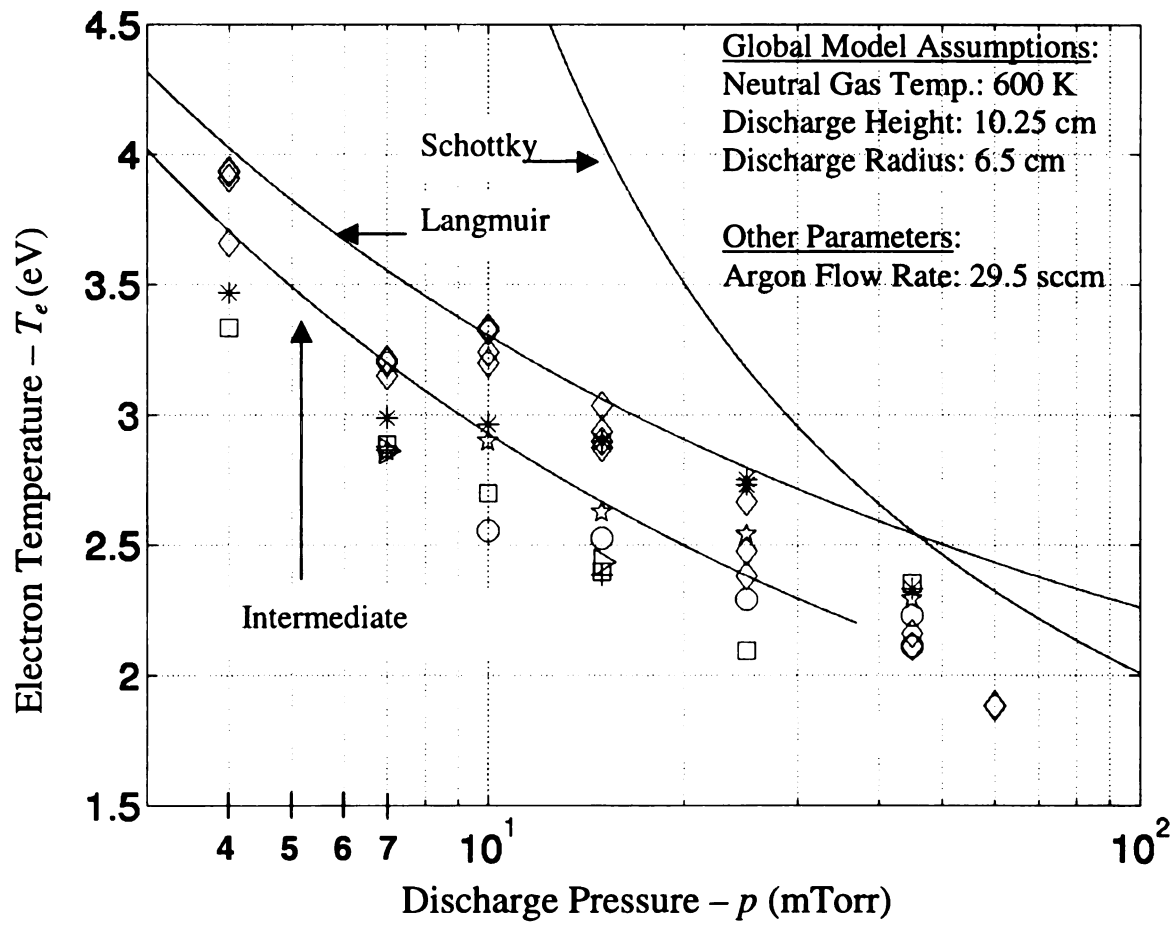


Figure 7.17 - Single Langmuir probe measured electron temperatures vs. discharge pressure in a non-magnetized discharge. Several absorbed power levels are shown. Data for both the  $TM_{012}$  and the near field mode are included.

Note, all modes excited with the end feed excitation are phi symmetric, and TE modes are not effectively excited.

A. Khan [Kha-00] has found that in the MPDR 7 (a 7 cm diameter discharge with multipole static magnetic field and 10 cm cavity) SLP  $T_e$  measurements show clear differences in  $T_e$  for the different EM modes excited. Under equivalent discharge input parameters of pressure, flow rate and absorbed power the "TM-like" modes show both higher  $T_e$ 's and charge densities than the "TE-like" modes. Direct comparisons of  $T_e$  for the end feed (TM mode) and side feed (TE mode) modes in the 13cm diameter discharge have not been made.

#### **7.3.4 Comparison of Plasma Potential, $V_p$ , between Magnetized and Non-magnetized Discharges**

The SLP measured plasma potentials ( $V_p$ ) are plotted in Figure 7.18 vs. pressure for the Magnetized and Non-magnetized cases. The solid line in Figure 7.18 represents the global model solution for  $V_p$  vs. pressure. To obtain this curve the global model curve for  $T_e$  vs. pressure was calculated (see Figure 7.1) then the following equation was used to obtain  $V_p$  vs. pressure (Lie-94):

$$V_p = \frac{T_e}{2} + \frac{T_e}{2} \ln\left(\frac{M}{2\pi m_e}\right) \quad \text{Eq. 7.5}$$

where  $V_p$  is the plasma potential,  $T_e$  is the global model predicted electron temperature,  $M$  is the mass of a neutral or ion, and  $m_e$  is the mass of an electron.

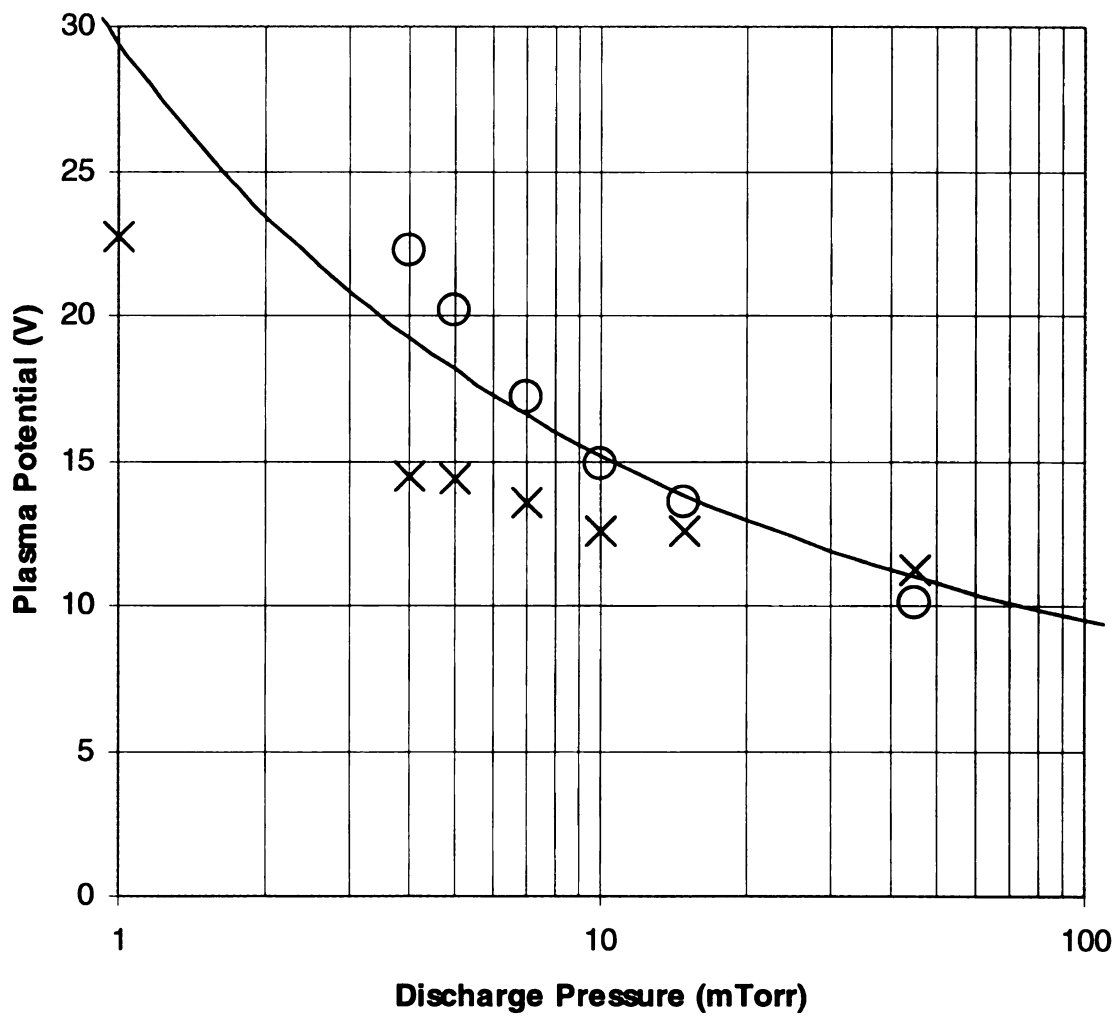


Figure 7.18 – Plasma potential vs. discharge pressure for non-magnetized and magnetized discharges in the  $TM_{012}$  mode with 280 W absorbed power. The solid curve is the global model prediction of plasma potential assuming a Maxwellian EEDF.

The SLP measured values in Figure 7.18 were taken while the plasma source was in the  $TM_{012}$  mode and with 280W of absorbed power. For the unmagnetized discharge the plasma potentials calculated using measured  $T_e$ 's fall close to the global model predicted curve, while for the magnetized discharge the directly measured plasma potentials fall 3 to 5 Volts below the predicted curve. The Non-magnetized plasma potentials are close to global model predictions and calculated values in the 10-15 mTorr pressure range but rise 1-2 Volts above the predicted values in the 4-7 mTorr range.

Both magnetized and non-magnetized plasma potentials decrease with pressure as predicted qualitatively by the global model. As pressure is increased the directly measured plasma potentials both decrease and converge to similar values. At 4 mTorr the non-magnetized discharge has a measured  $V_p$  that is 8 Volts higher than the magnetized discharge. At 15 mTorr the non-magnetized  $V_p$  is only approximately 1 Volt higher than the magnetized discharge.

#### 7.4 Variation of EEDF with distance into discharge (z)

In the previous section we observed that the EEDF was Maxwellian for a non-magnetized discharge and had a depleted energy tail for a magnetized discharge. These measurements were done at location  $r=0$ ,  $z=0$  at the base of the discharge. This raises another question, do these EEDFs remain the same as we move the probe up into the discharge in either the non-magnetized or magnetized discharges? The following set of experiments answers this question. All of the following experiments were performed in the  $TM_{012}$  cavity mode with an absorbed power of 280W, reflected power of 30W, and a microwave coupling probe length of  $L_p = 3$  cm. The single Langmuir probe was positioned at the radial center of the discharge ( $r=0$ ), and three possible  $z$  positions (up from the base of the discharge)  $z=0$  cm,  $z=2$  cm, and  $z=4$  cm.

#### **7.4.1 EEDF and $T_e$ vs. Distance into the Chamber for the Non-magnetized Discharge**

##### **7.4.1.1 EEDF vs. Distance into the Non-magnetized Discharge Chamber**

Figure 7.19(a,b,c) shows the linear plots of EEDFs measured at  $z=0$  cm,  $z = 2$  cm, and  $z = 4$  cm in the non-magnetized discharge at 7 mTorr. All of these measured EEDFs appear to correlate well with the Maxwellian distribution. Figure 7.20(a,b,c) shows the same data that was plotted in Figure 7.19(a,b,c) plotted on a logarithmic scale. All of the logarithmically plotted EEDFs fit well with a Maxwellian distribution at high energies. At 7 mTorr in the non-magnetized discharge the EEDF appears to be very Maxwellian from  $z=0$  cm to  $z=4$  cm into the discharge.

Increasing the pressure to 10 mTorr Figures 7.21(a,b,c) and 7.22(a,b,c) also show a very Maxwellian distribution from  $z=0$  cm to  $z=4$  cm.

However, at 25 mTorr the EEDF appears to be very Druyvesteyn in nature in the linear plots of Figure 7.23(a,b,c). With the logarithmic plots in Figure 7.24(a,b,c) appearing to follow a slightly depleted Maxwellian distribution at high energies, becoming less depleted as distance into the discharge increases.

The conclusion can be drawn from the above plots that the EEDF does not change significantly vs.  $z$ -distance up into the discharge for 7 and 10 mTorr, but changes slightly vs. increasing  $z$ -distance into a non-maxwellian distribution at 25 mTorr.

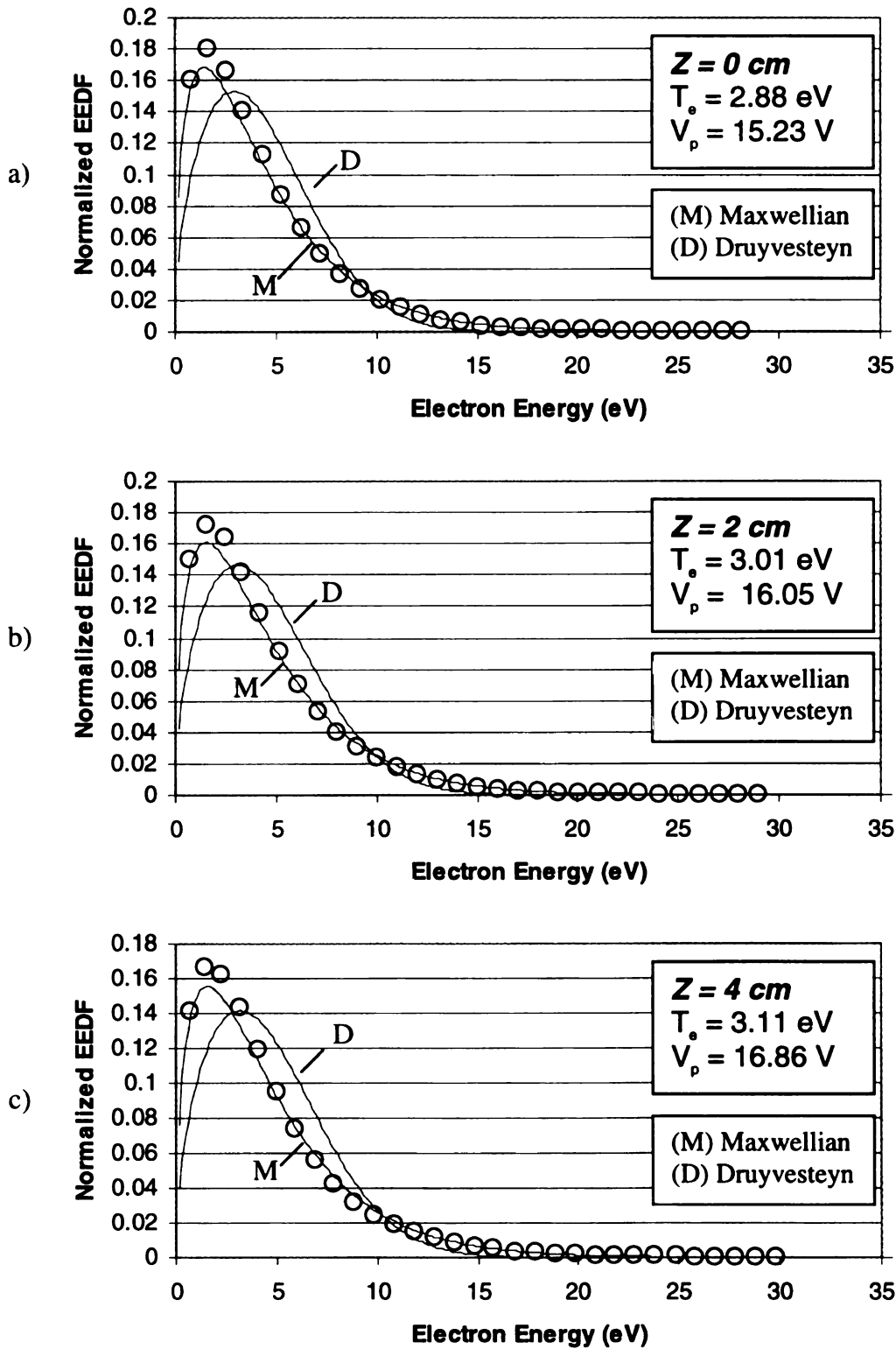


Figure 7.19 - Linear plots of EEDF for a 7 mTorr, non-magnetized discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0 \text{ cm}$ , b)  $z=2 \text{ cm}$ , and c)  $z=4 \text{ cm}$ .



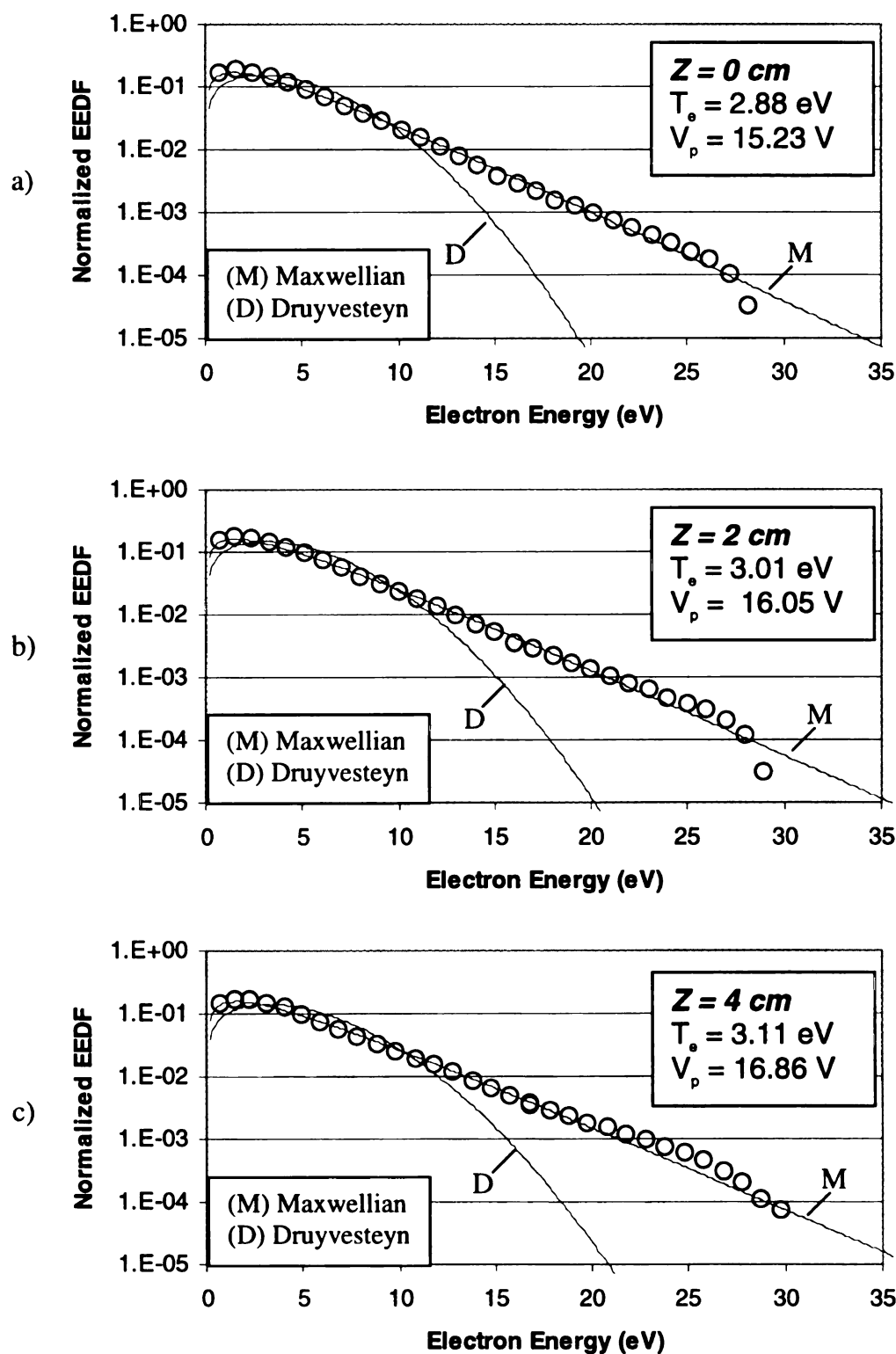


Figure 7.20 - Log plots of EEDF for a **7 mTorr, non-magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0 \text{ cm}$ , b)  $z=2 \text{ cm}$ , and c)  $z=4 \text{ cm}$ .

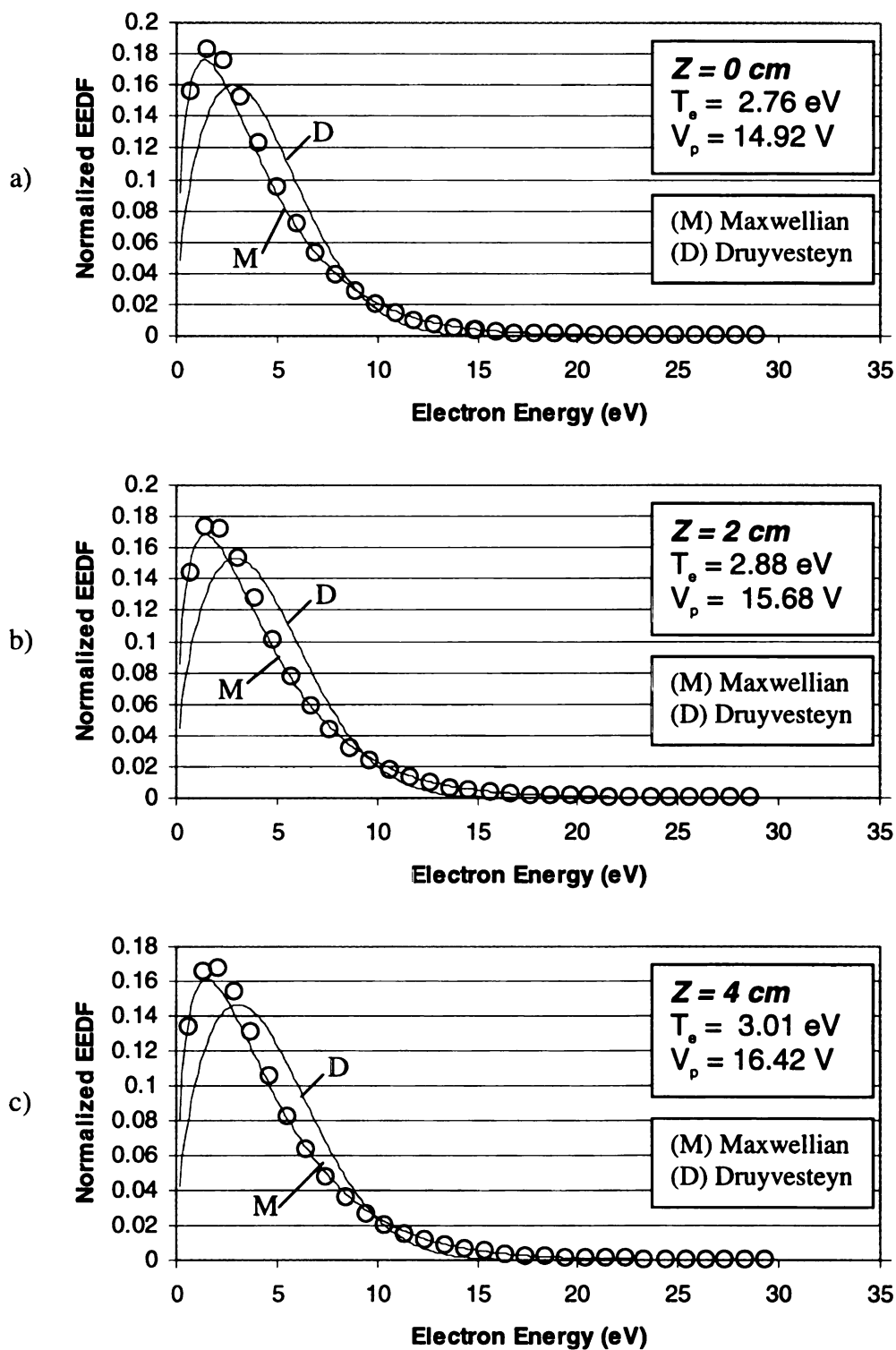


Figure 7.21 - Linear plots of EEDF for a **10 mTorr, non-magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

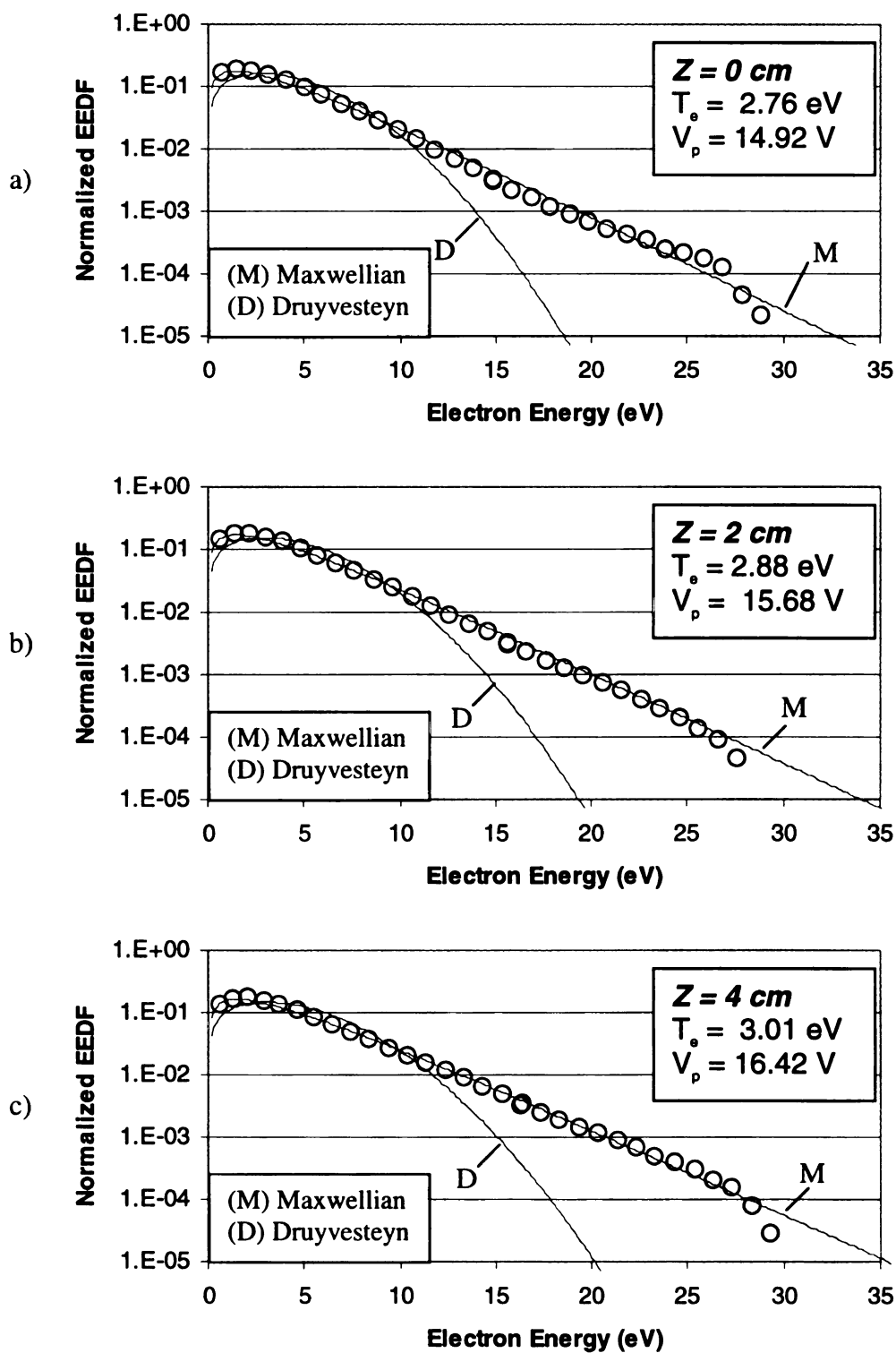


Figure 7.22 - Log plots of EEDF for a **10 mTorr, non-magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

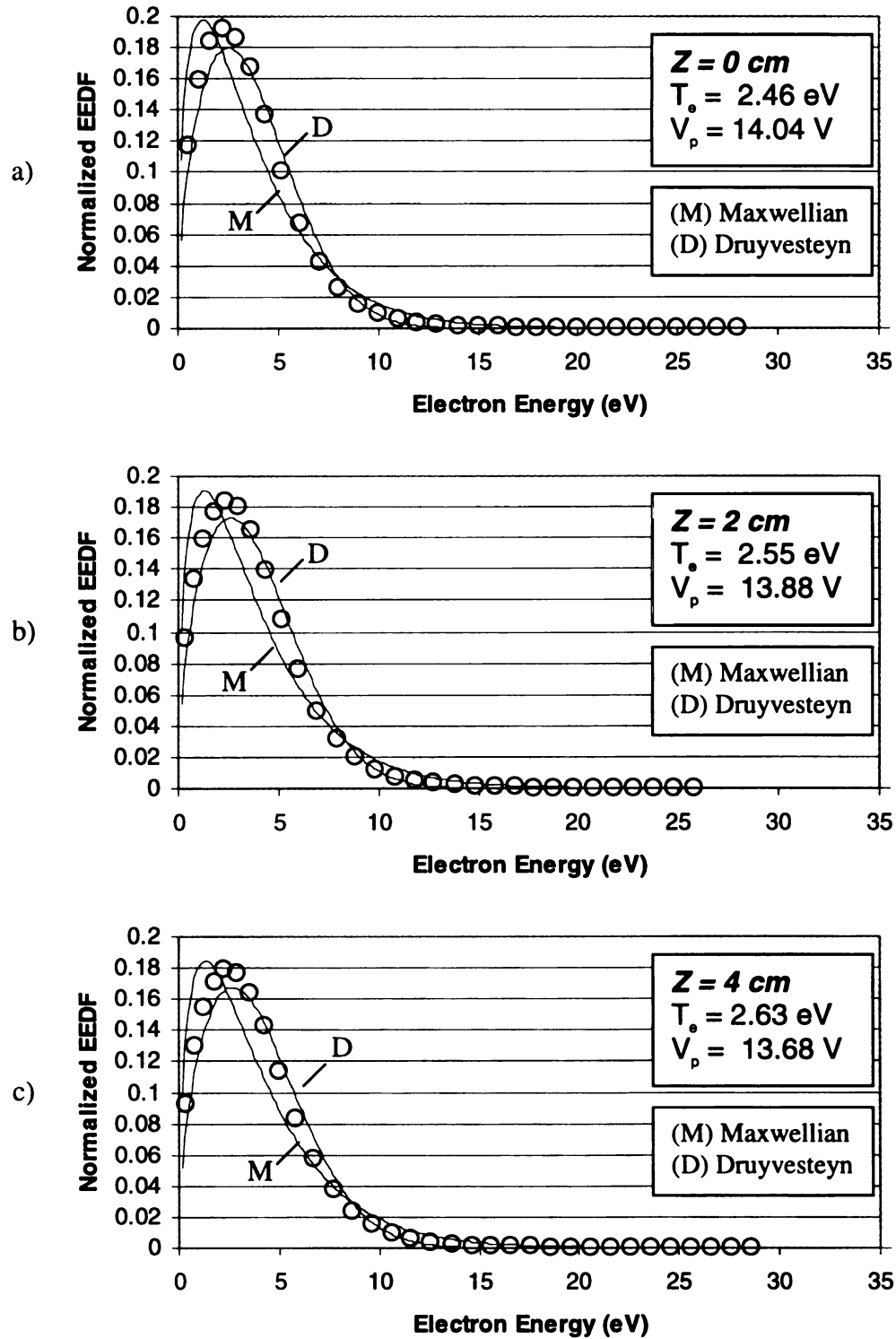


Figure 7.23 - Linear plots of EEDF for a **25 mTorr, non-magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

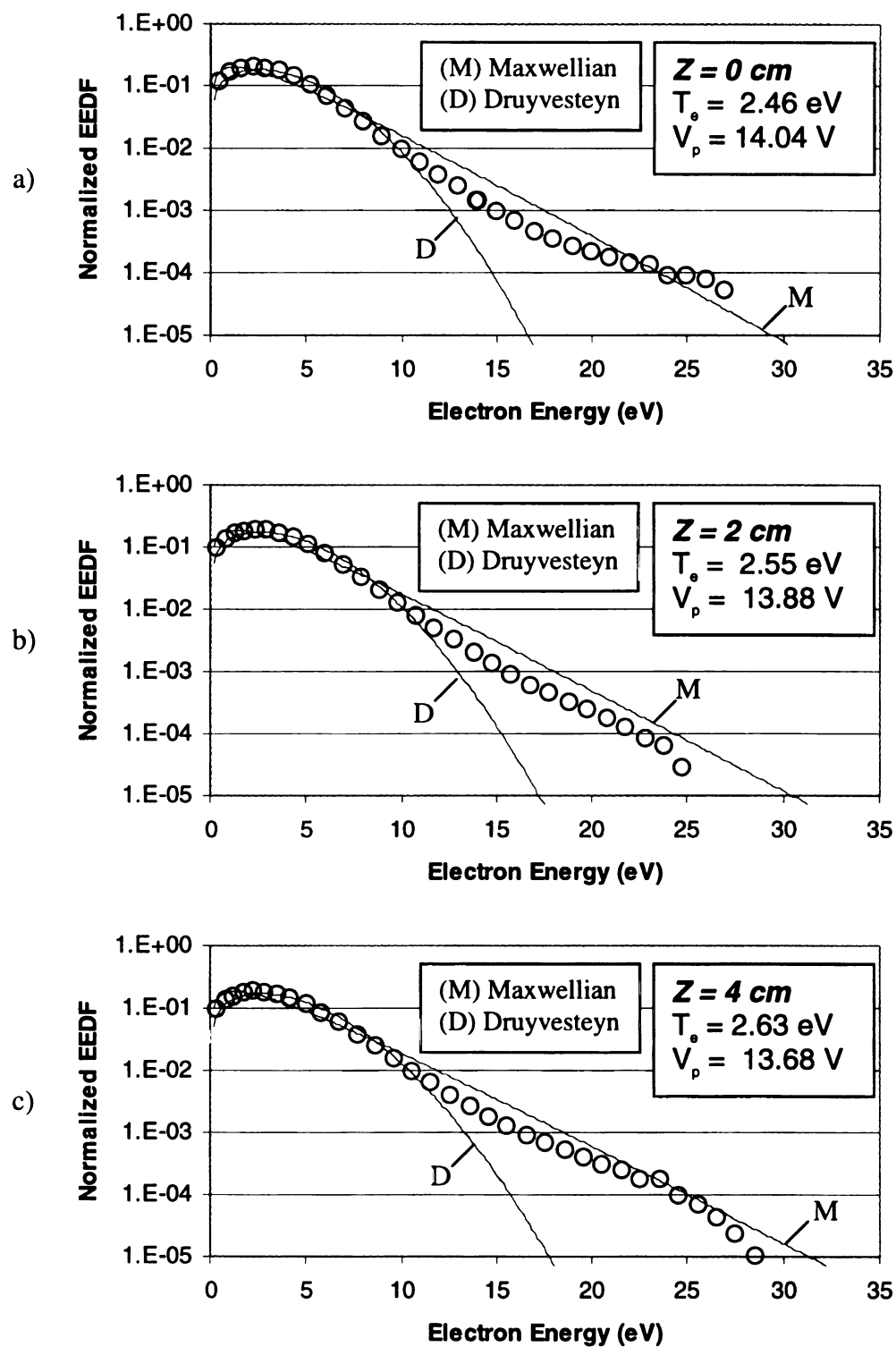


Figure 7.24 - Log plots of EEDF for a **25 mTorr, non-magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0 \text{ cm}$ , b)  $z=2 \text{ cm}$ , and c)  $z=4 \text{ cm}$ .

#### 7.4.1.2 Electron Temperature, $T_e$ , vs. Distance up into the Discharge Chamber

Plotting the electron temperatures,  $T_e$ , vs. discharge pressure, see Figure 7.25, we find that the temperatures fall close to the global model prediction. It is also clear that electron temperature increases with distance up into the discharge chamber for 7 and 10 mTorr, see both Figures 7.25 and 7.26. Figure 7.26 plots the electron temperature vs. height into the discharge for three pressures. This plot shows that at 7 and 10 mTorr the electron temperature increases 0.4 eV from  $z=0$  cm to  $z=6$  cm. At 25 mTorr the electron temperature reaches a peak at 4 cm and then begins to decrease at  $z=6$  cm. Note, measurements were not made higher than 6 cm into the discharge because of concerns with overheating of the Langmuir probe.

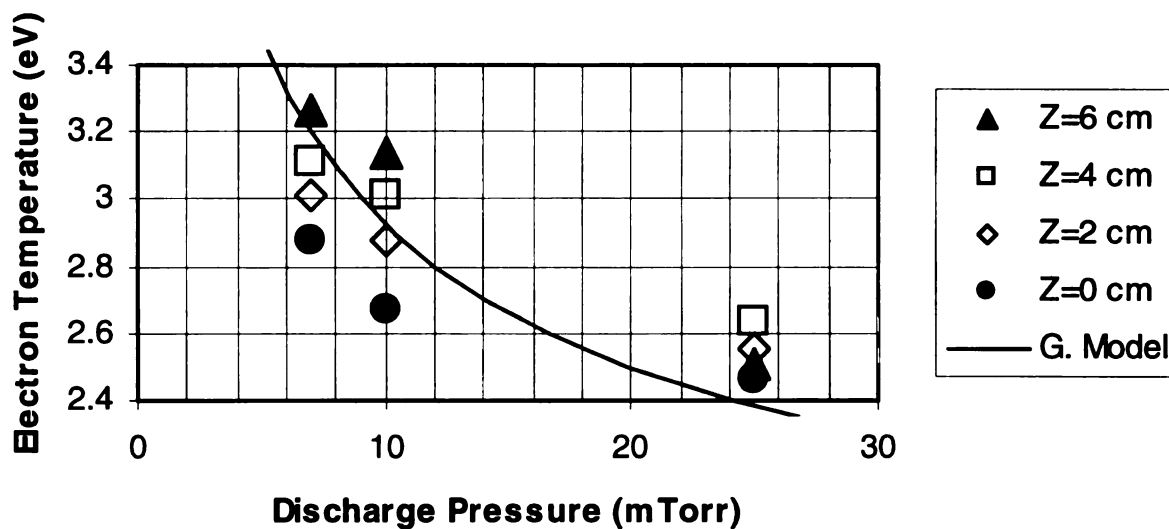


Figure 7.25 - Single Langmuir probe measured electron temperatures vs. discharge pressure for several vertical positions,  $z$  in a non-magnetized discharge. The solid curve represents the intermediate regime global model prediction assuming a Maxwellian electron distribution function. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

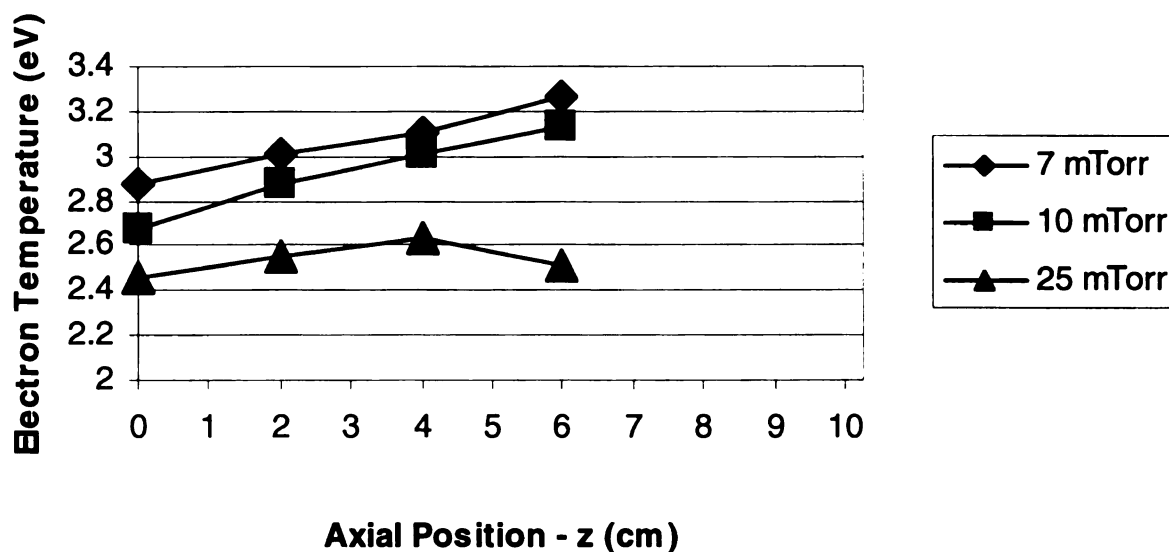


Figure 7.26 - Single Langmuir probe measured electron temperatures vs. vertical position  $z$  for three discharge pressures in a non-magnetized discharge. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

#### 7.4.1.3 Plasma Potential, $V_p$ , vs. Distance up into the Discharge Chamber

Observing the plasma potentials, in Figure 7.27, we see that they fall near the global model prediction. As with the electron temperature in Figures 7.25 and 7.26 the plasma potentials increase with distance up into the discharge for 7 and 10 mTorr at a rate of about 0.5 V/cm. Both start at a  $V_p=15$  V at  $z=0$  cm and increase to  $V_p = 18.5$ V for 7 mTorr and  $V_p=17$  V for 10 mTorr. However, Figure 7.28 also demonstrates that at 25 mTorr the plasma potential monotonically decreases from  $V_p=14$  V at  $z=0$  cm to about  $V_p=12.5$  V at  $z=6$  cm.



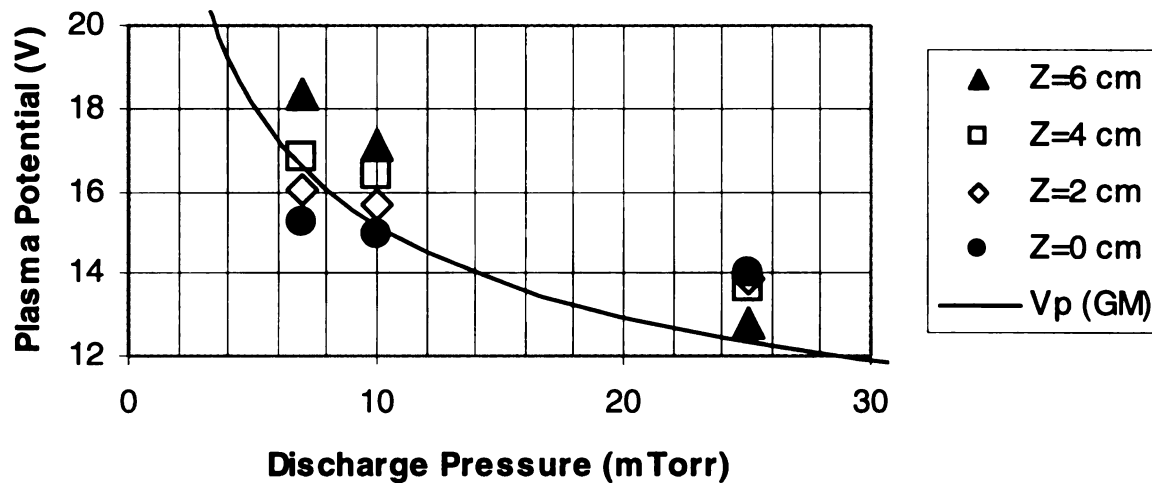


Figure 7.27 - Single Langmuir probe measured plasma potential  $V_p$  vs. discharge pressure for several vertical positions,  $z$ , in a non-magnetized discharge. The solid curve represents the intermediate regime global model prediction calculated using a Maxwellian distribution function. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

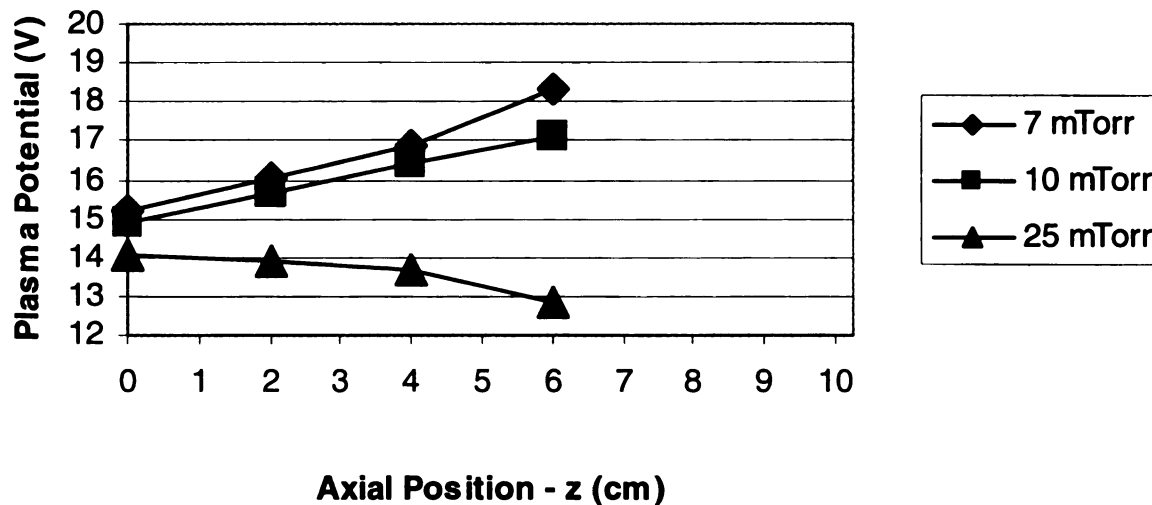


Figure 7.28 - Single Langmuir probe measured plasma potential  $V_p$  vs. vertical position  $z$  for several discharge pressures in a non-magnetized discharge. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

## 7.4.2 EEDF and $T_e$ vs. Distance into the Chamber for the Magnetized Discharge

### 7.4.2.1 EEDF vs. Distance into the Magnetized Discharge Chamber

For the magnetized discharge Figure 7.29(a,b,c) shows the linear plots of EEDFs measured at  $z=0$  cm,  $z = 2$  cm, and  $z = 4$  cm at a pressure of 1.84 mTorr. All of these measured EEDFs appear to correlate well with the Maxwellian distribution in the 0 to 10 eV range. Figure 7.20(a,b,c) shows the same data plotted on a logarithmic scale. Figure 7.20a shows a definite depleted high energy tail (strongly Druyvesteyn) for the discharge at  $z=0$  (as was seen in Figure 7.3b). However, the distribution becomes more Maxwellian in nature for Figures 7.20b and 7.20c for  $z=2$  cm and  $z=4$  cm. In effect, the depleted high energy tail disappears higher up into the discharge.

At 4 mTorr Figure 7.31(a,b,c) shows that at low energies the magnetized distribution function appears very Maxwellian. At high energies the log plots in Figure 7.32(a,b,c) show similar behavior as seen at 1.84 mTorr, i.e. that the distribution function is depleted for high energies at  $z=0$  cm and progressively more Maxwellian for  $z=2$  cm and  $z=4$  cm.

Increasing the pressure to 7 mTorr the behavior of the distribution is similar to that at 1.84 and 4 mTorr. Figure 7.33(a,b,c) shows Maxwellian behavior, while Figure 7.34(a,b,c) shows a depleted high energy tail that becomes less depleted and more Maxwellian with increasing distance up into the discharge. Figures 7.35(a,b,c) and 7.36(a,b,c) also show the same behavior at a pressure of 10 mTorr.

Hence, for the magnetized discharge we can conclude that a depleted high energy tail exists at the base of the discharge, i.e.  $z=0$  cm. However, this depleted high energy tail disappears with distance up into the discharge.

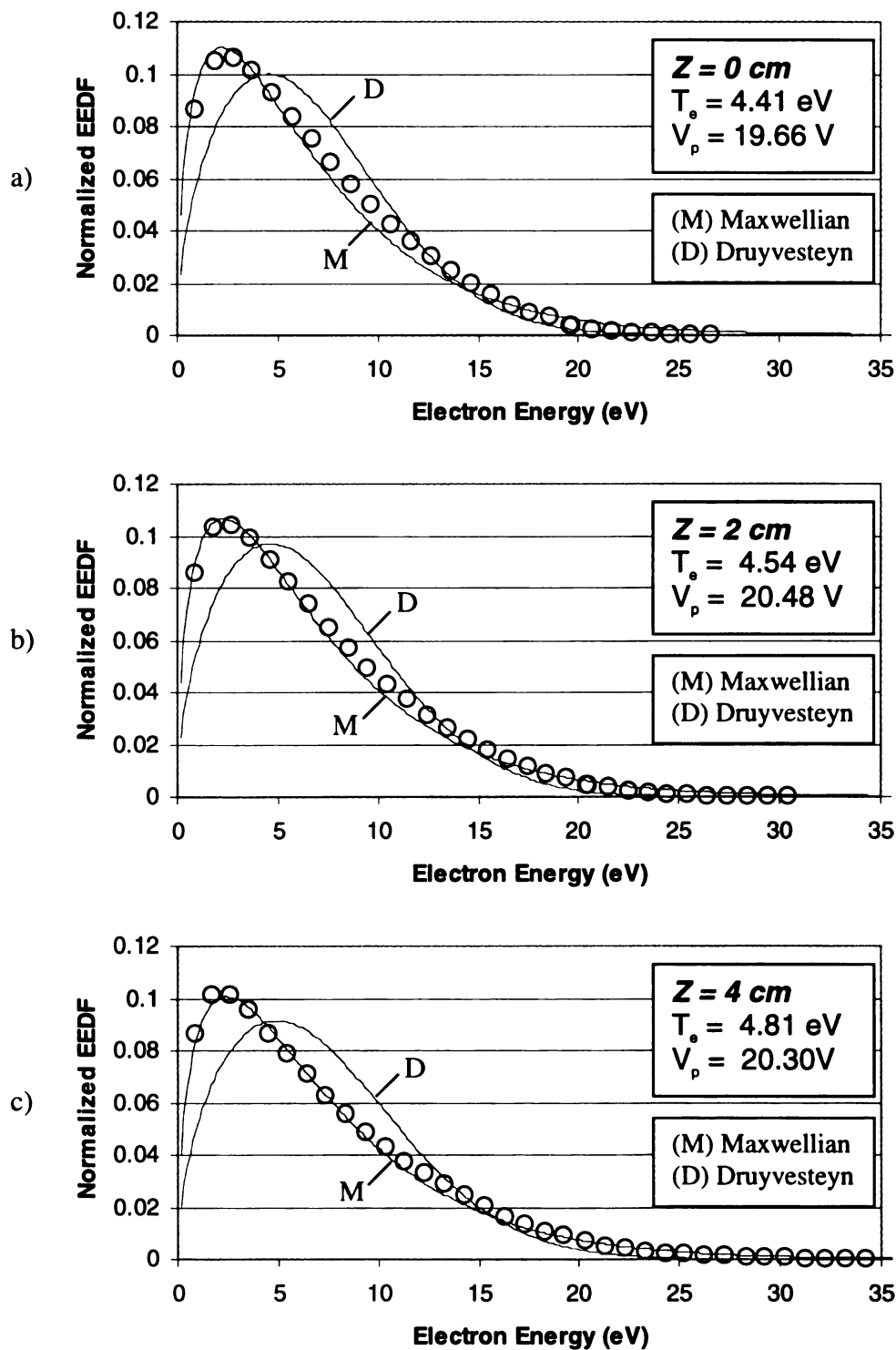


Figure 7.29 - Linear plots of EEDF for a **1.84 mTorr, magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

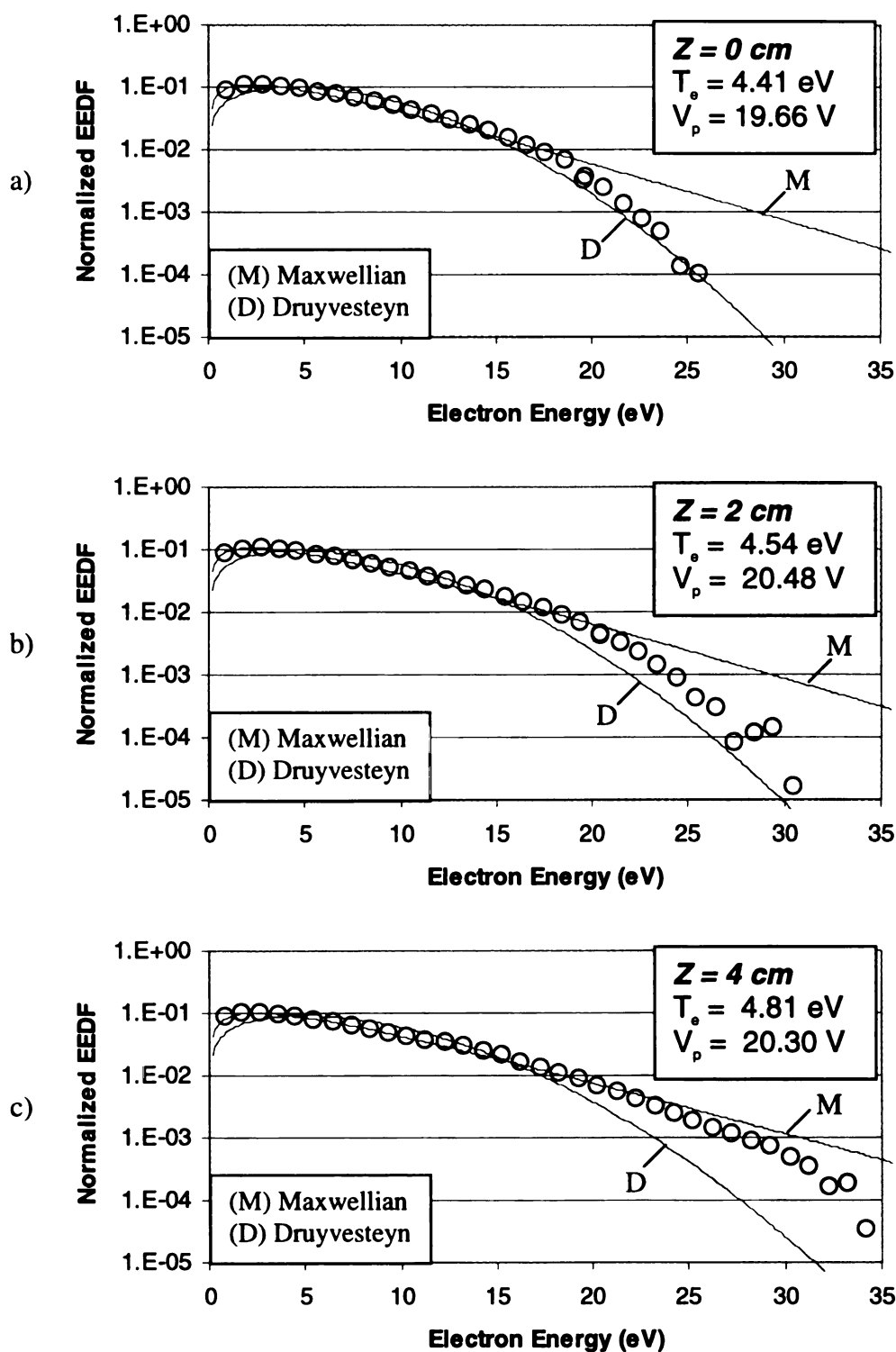


Figure 7.30 - Log plots of EEDF for a **1.84 mTorr, magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

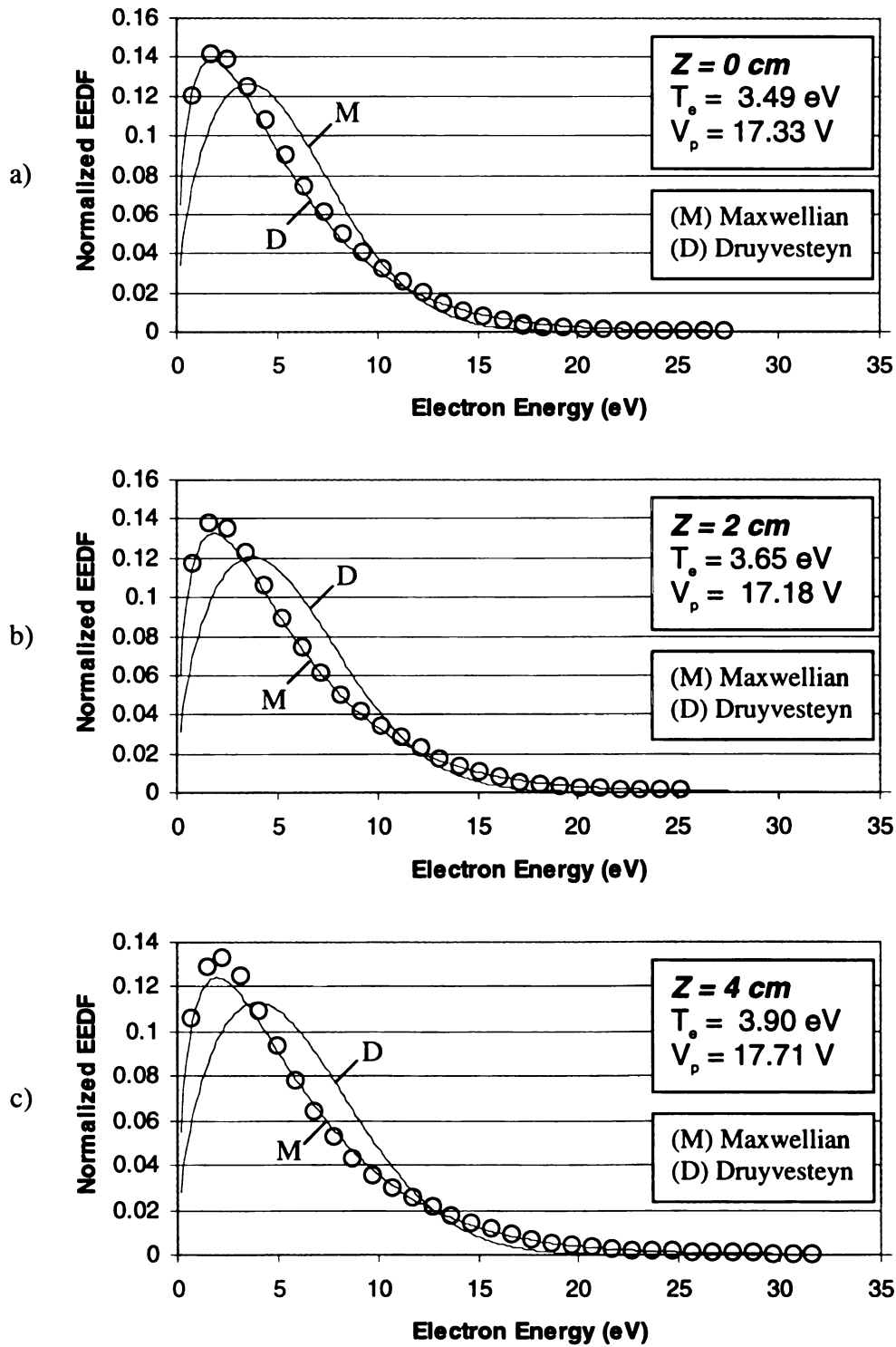


Figure 7.31 - Linear plots of EEDF for a **4 mTorr, magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

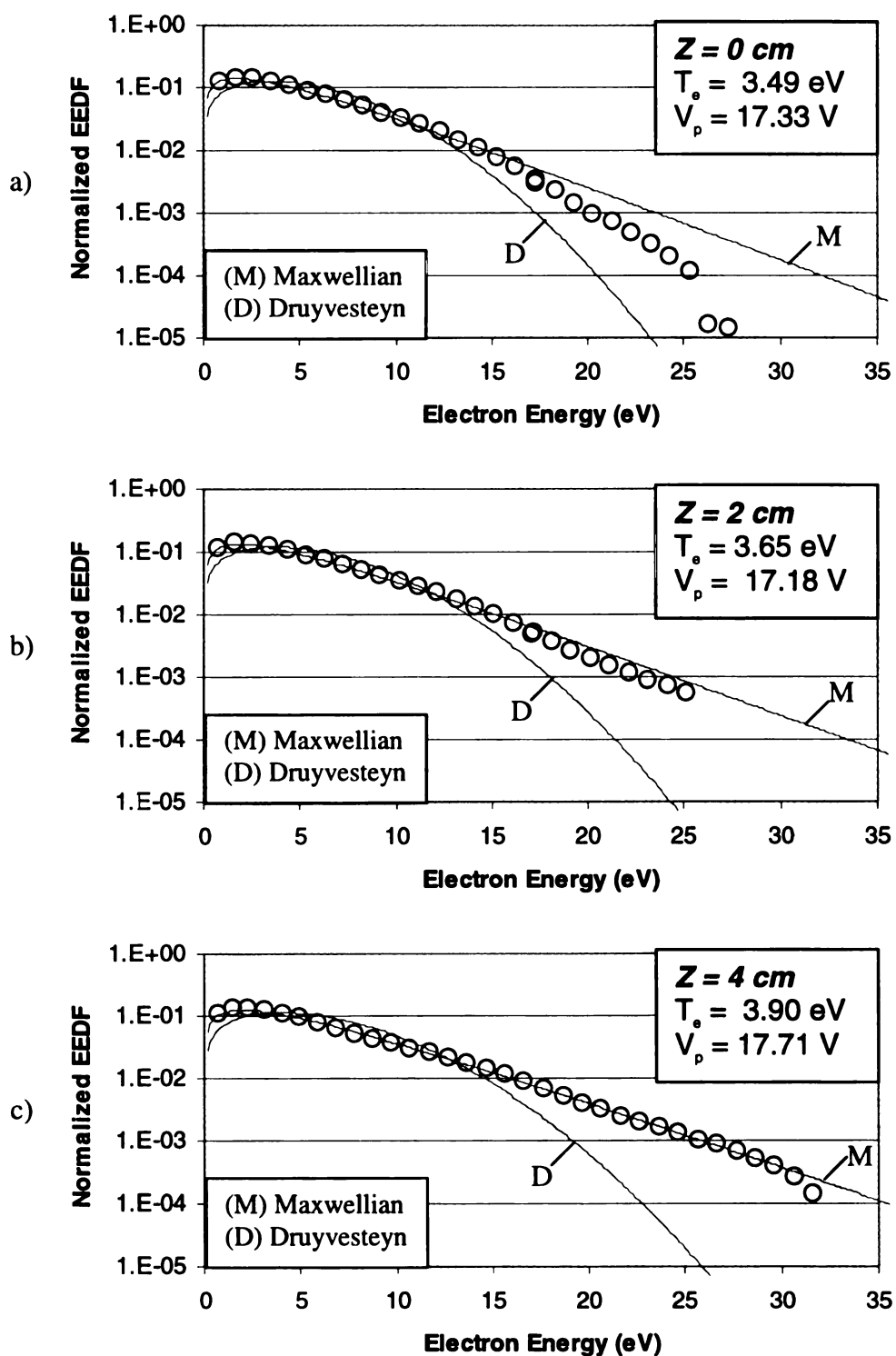


Figure 7.32 - Log plots of EEDF for a **4 mTorr, magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0 \text{ cm}$ , b)  $z=2 \text{ cm}$ , and c)  $z=4 \text{ cm}$ .

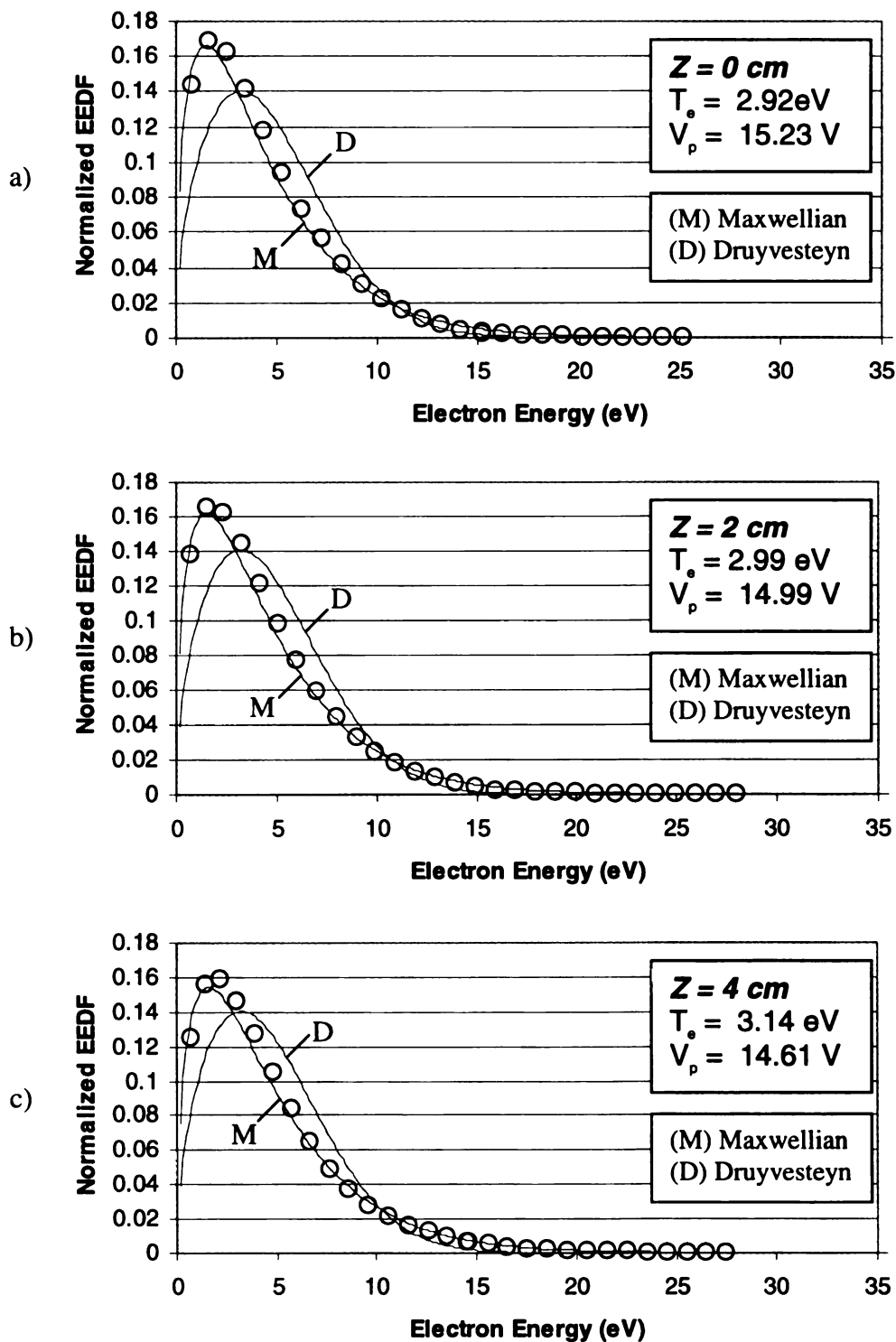


Figure 7.33 - Linear plots of EEDF for a **7 mTorr, magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.



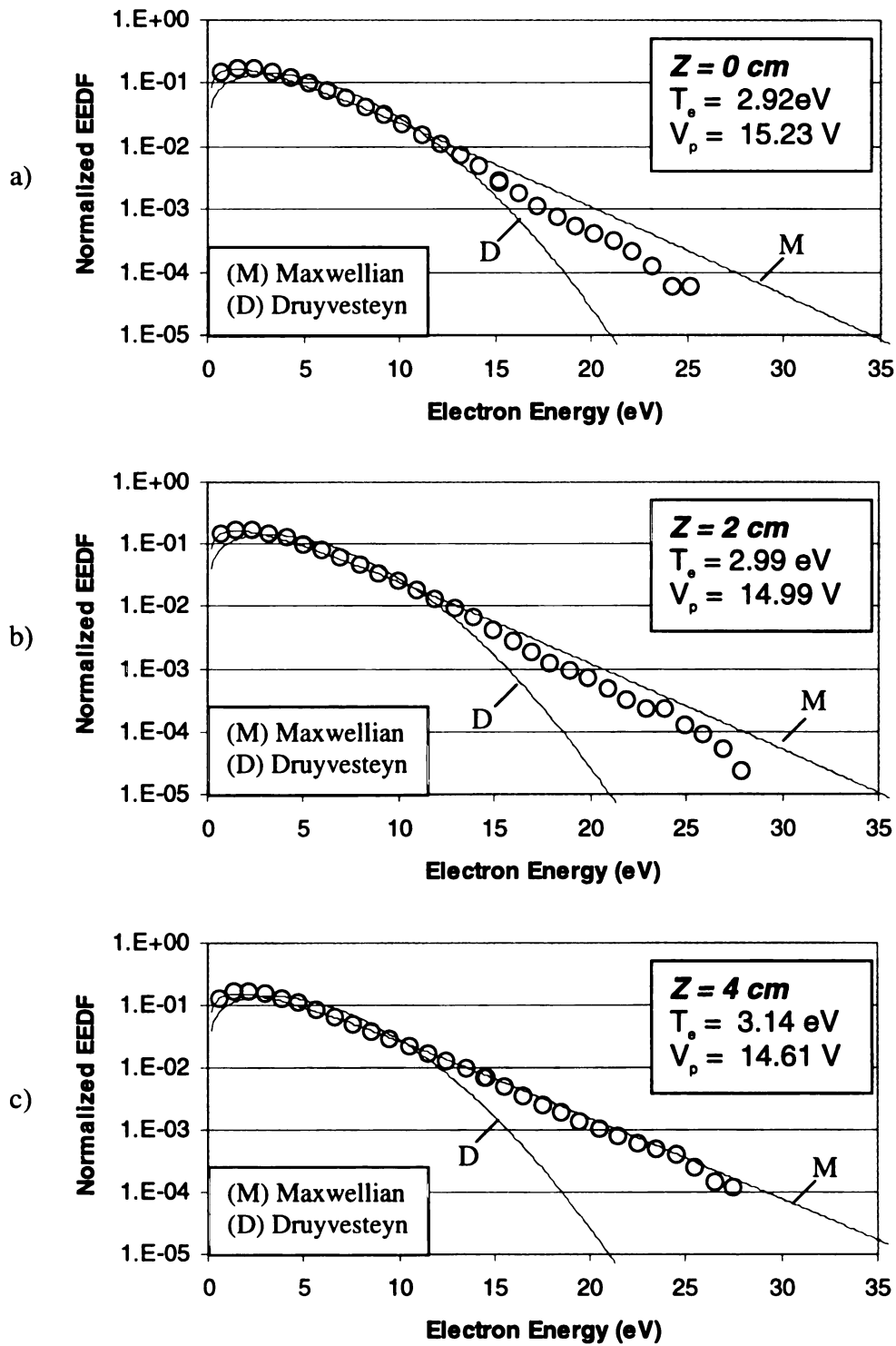


Figure 7.34 - Log plots of EEDF for a 7 mTorr, magnetized discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

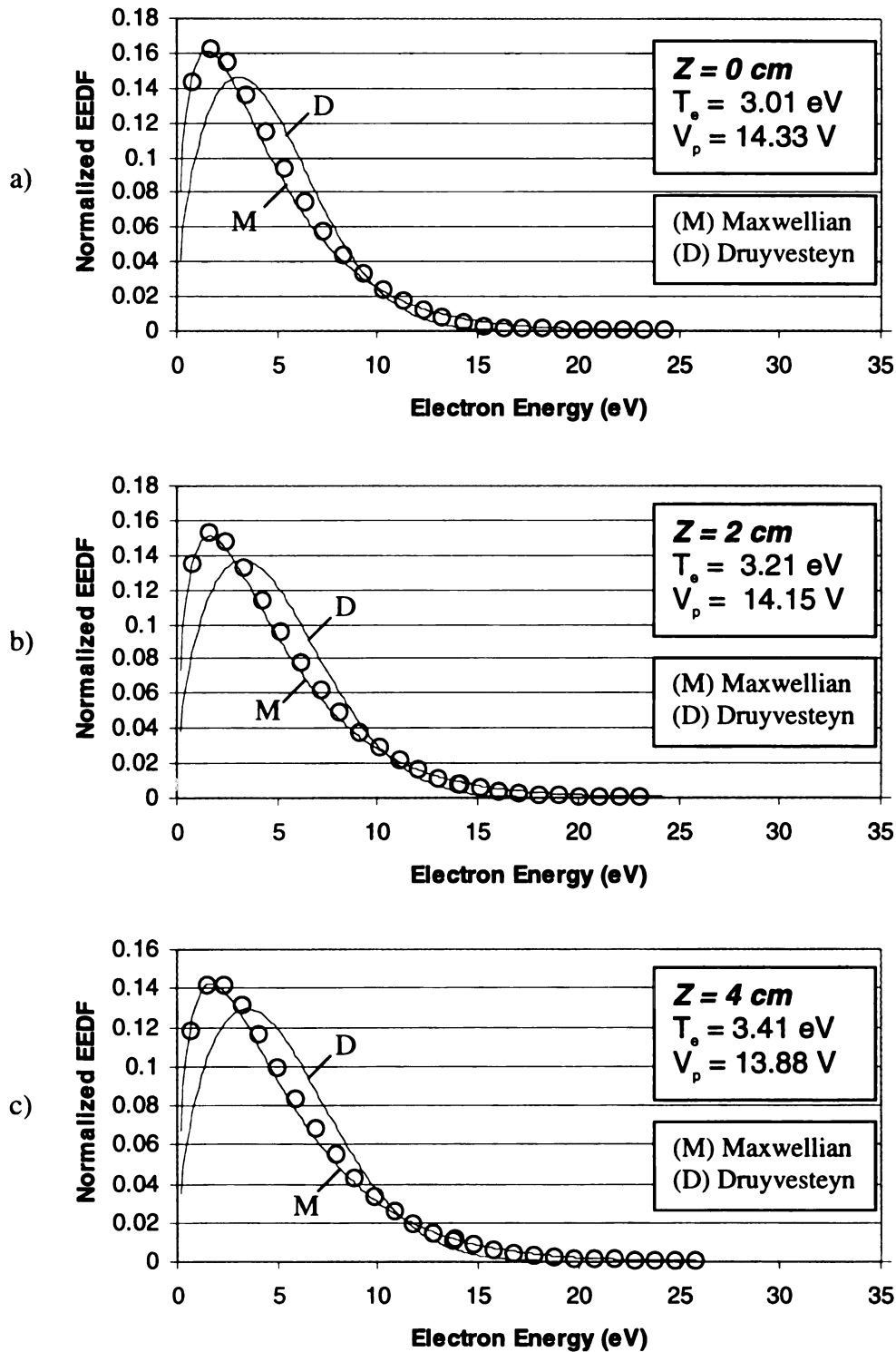


Figure 7.35 - Linear plots of EEDF for a 10 mTorr, magnetized discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0$  cm, b)  $z=2$  cm, and c)  $z=4$  cm.

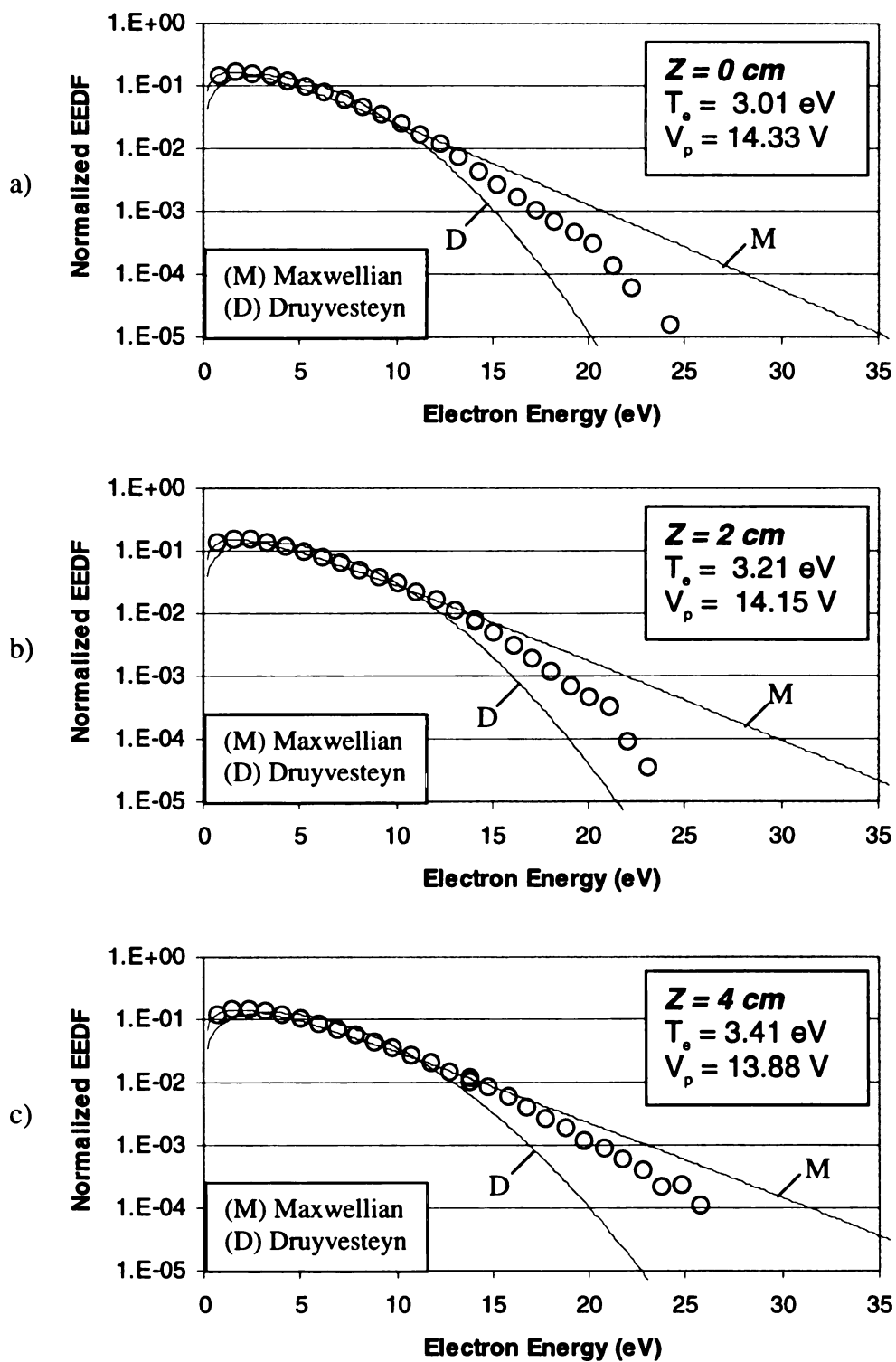


Figure 7.36 - Log plots of EEDF for a **10 mTorr, magnetized** discharge, 280 W absorbed power, in the  $TM_{012}$  EM mode, with the probe positioned at: a)  $z=0 \text{ cm}$ , b)  $z=2 \text{ cm}$ , and c)  $z=4 \text{ cm}$ .

#### 7.4.2.2 Electron Temperature, $T_e$ , vs. Distance up into the Magnetized Discharge Chamber

The electron temperatures,  $T_e$ , vs. discharge pressure (see Figure 7.35) fall close to the global model prediction. As in the non-magnetized discharge the electron temperatures increase with distance up into the discharge chamber for all pressures measured in the magnetized discharge (see figure 7.38). The electron temperatures increase on the order of 0.5 eV from  $z=0$  cm to  $z=4$  cm. Note, measurements were not made higher than 4 cm into the magnetized discharge because of concerns with overheating of the Langmuir probe.

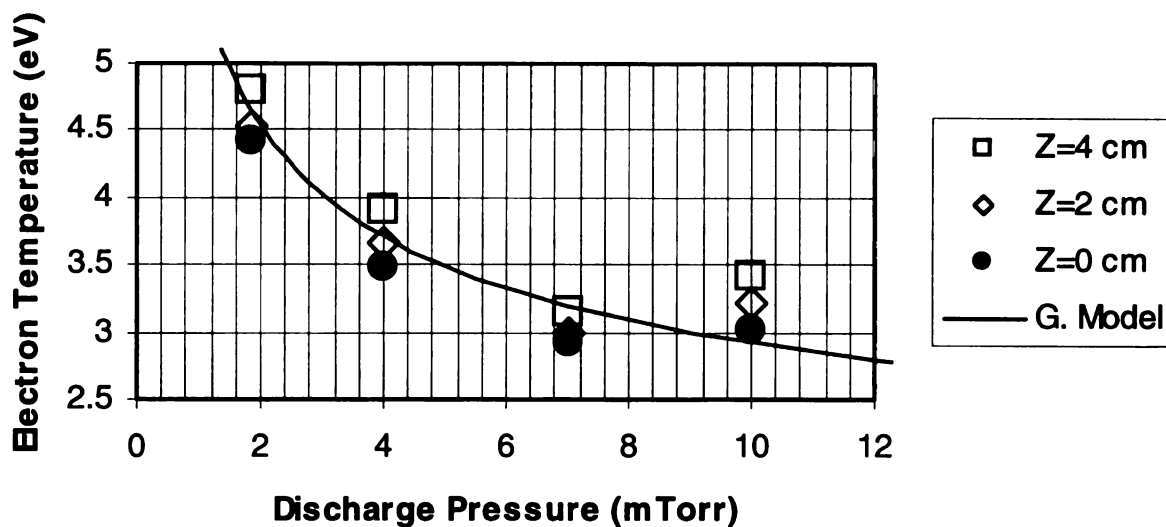


Figure 7.37 - Single Langmuir probe measured electron temperatures vs. discharge pressure for several vertical positions,  $z$  in a magnetized discharge. The solid curve represents the intermediate regime global model prediction calculated assuming a Maxwellian distribution function. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

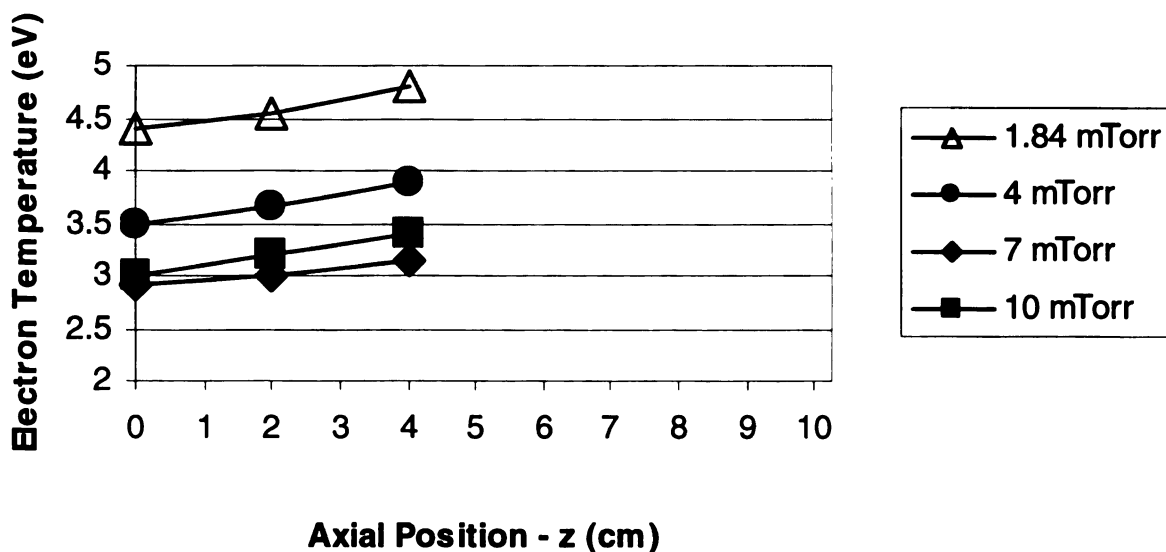


Figure 7.38 - Single Langmuir probe measured electron temperatures vs. vertical position  $z$  for several discharge pressures in a magnetized discharge. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

### **7.4.2.3 Plasma Potential, $V_p$ , vs. Distance up into the Magnetized Discharge Chamber**

Observing the magnetized plasma potentials, in Figure 7.39, we see that they fall slightly below the global model prediction (which here assumes a Maxwellian distribution). Figure 7.40 shows that at none of the pressures measured does the plasma potential consistently increase with distance up into the discharge chamber. Discharge with pressures of 1.84 and 4 mTorr show a slight increase in plasma potential with distance up into the discharge. While, discharge pressure of 7 and 10 mTorr show a slow monotonic decrease in plasma potential with distance up into the discharge.

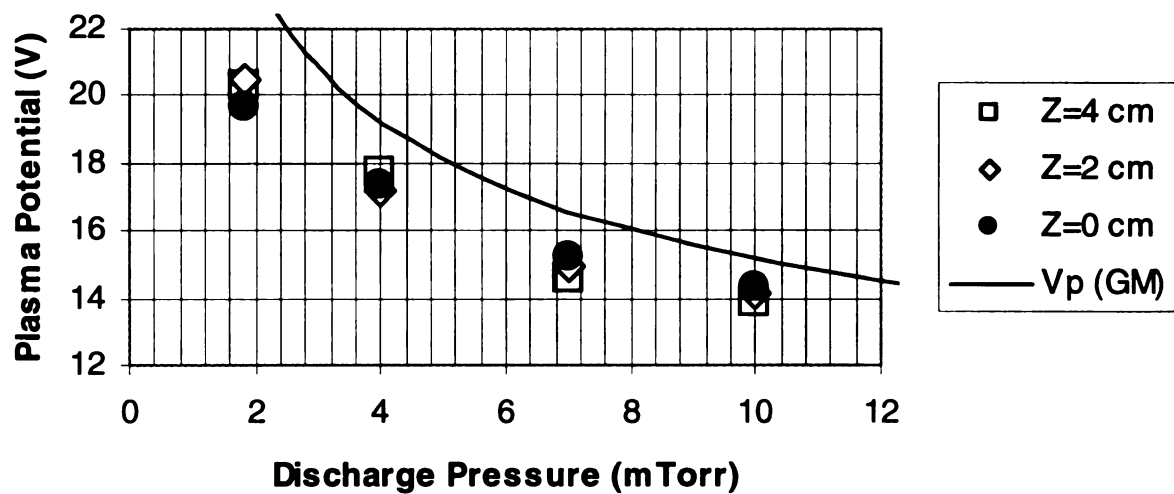


Figure 7.39 - Single Langmuir probe measured plasma potential  $V_p$  vs. discharge pressure for several vertical positions,  $z$ , in a magnetized discharge. The solid curve represents the intermediate regime global model prediction calculated assuming a Maxwellian distribution function. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

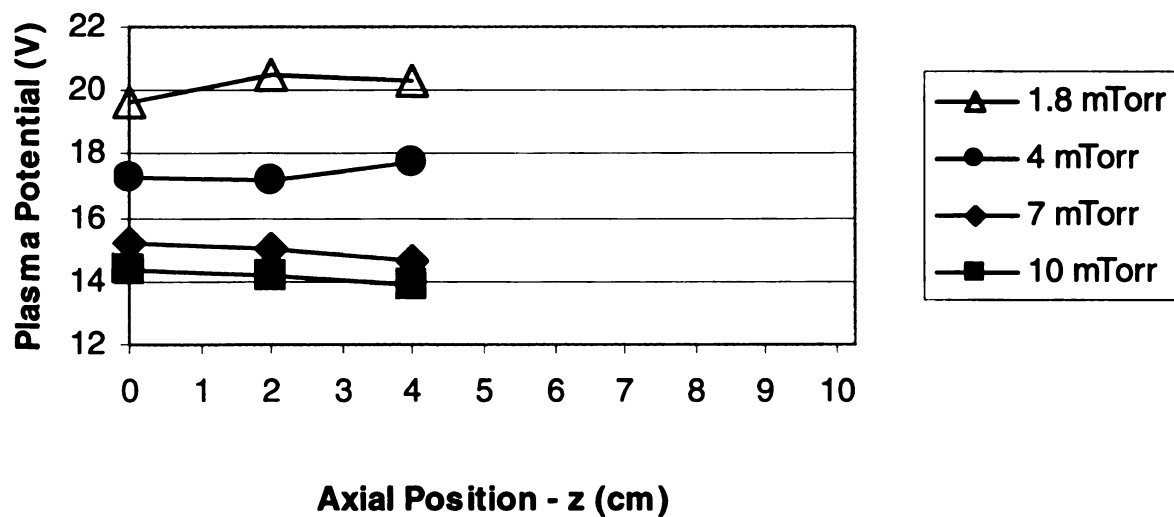


Figure 7.40 - Single Langmuir probe measured plasma potential  $V_p$  vs. vertical position  $z$  for several discharge pressures in a magnetized discharge. For all points shown absorbed power was 280W and the EM mode was  $TM_{012}$ .

## **7.5 Summary of Findings**

### **7.5.1 Findings from measurements at $z=0$ (i.e. base of the discharge)**

- 1) Measured electron temperatures at  $z=0$  for both magnetized and non-magnetized discharges fall close to the global model predicted electron temperatures.
- 2) At  $z=0$  cm EEDFs are Maxwellian for non-magnetized discharges and have a depleted high energy tail for magnetized discharges.
- 3) Plasma potentials for the non-magnetized discharge fit well with the global model prediction assuming a Maxwellian EEDF. Plasma potentials for the magnetized discharge tend to be less than the global model prediction (assuming a Maxwellian EEDF).
- 4) Careful observation shows that electron temperature increases with increasing absorbed power, on the order of 0.1 eV / 100W, at a constant discharge pressure. (Note: increasing neutral temperature and hence decreasing neutral density is the likely cause of the increase in electron temperature, see Chapter 10)



### 7.5.2 Findings from measurements vs. $z$ into the discharge

- 1) In the non-magnetized discharge the EEDFs are Maxwellian at all points measured up into the discharge from  $z=0$  cm to  $z=6$  cm.
- 2) In the magnetized discharge the EEDFs have a depleted high energy tail at  $z=0$  cm, but this tail becomes less depleted and more Maxwellian with distance  $z$  up into the discharge.
- 3) Electron temperatures increase with distance  $z$  up into the discharge for both magnetized and non-magnetized discharges at approximately 0.1 eV/cm (note that at 25 mTorr the electron temperature appears to peak at 4 cm and begin to decrease at 6 cm).
- 4) Plasma potentials for the non-magnetized discharge tend to increase with distance up into the discharge for low pressures, 7 to 10 mTorr, but tend to decrease with distance into the discharge for higher pressures, 25 mTorr.
- 5) For low pressures of 1.84 to 4 mTorr the plasma potentials for the magnetized discharge appear to increase with distance up into the discharge. For higher pressures of 7 to 10 mTorr the plasma potentials appear to decrease with distance up into the discharge.

6) The low energy portion of EEDFs (i.e.  $<10\text{eV}$ ) of all magnetized and non-magnetized, as seen in the linear EEDF plots, appear to be very Maxwellian in nature for pressures of 10 mTorr and below. However, for pressures of 25 and 45 mTorr the EEDFs tend to be more Druyvesteyn in nature.



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**INVESTIGATION OF A 17.8 CM DIAMETER END FEED MICROWAVE  
CAVITY PLASMA SOURCE WITH AND WITHOUT A STATIC  
MAGNETIC FIELD**

**VOLUME II**

By

Mark Alan Perrin

**A DISSERTATION**

Submitted to

Michigan State University

in partial fulfillment of the requirements

for the degree of

**DOCTOR OF PHILOSOPHY**

Department of Electrical and Computer Engineering

2002

## Chapter 8

### Measured Charge Density and Ion Production Cost

#### 8.1 Introduction

#### 8.2 The Experimental Configuration and the Experimental Parameter Space

#### 8.3 Global Model Calculations; A Benchmark for Experimental Measurements

##### 8.3.1 The Cylindrical Discharge Model

##### 8.3.2 The Open Ended Cylindrical Discharge Model

#### 8.4 Electron Density Measurements

##### 8.4.1 Experimental Electron Density Measurements

##### 8.4.2 Comparison of Electron Densities Between $TM_{012}$ and Near Field Modes

##### 8.4.3 Comparison of Charge Density Between Magnetized and Non-magnetized Cases

##### 8.4.4 Comparison to the Global Model

#### 8.5 Electron Density Measurements Under the Conditions of High Incident Power

#### 8.6 Radial Profiles of Charge Density and Relative Ion Saturation Current

##### 8.6.1 The Radial Distribution of Electron/Ion Density

##### 8.6.2 Comparison Between Magnetized and Non-Magnetized Configurations

##### 8.6.3 Comparison Between $TM_{012}$ and Near Field Modes

#### 8.7 Axial Variation of $I_s$ Measurements

##### 8.7.1 Observations from Axial $I_s$ measurements

#### 8.8 Electromagnetic Skin Depth

#### 8.9 Visual Images of the Plasma Discharge

#### 8.10 Ion Production Cost

##### 8.10.1 Experimental Measurement of Ion Production Cost

##### 8.10.2 Comparison of Measured Ion Production Cost vs. Global Model Prediction

#### 8.11 Summary of Findings

## Chapter 8

### Measured Charge Density and Ion Production Cost

#### **8.1 Introduction:**

The objective of this chapter is to experimentally measure the charge density output performance of this plasma source over a selected experimental parameter space (described in Section 8.2). Using this performance data several important comparisons are made by changing only one experimental variable: 1) the charge density output performances are compared with and without a multipolar magnet array, and 2) the  $TM_{012}$  and near field EM mode excitations are compared. The experimental data are also compared against benchmark predictions from the global plasma model. The most significant observations of this data are presented and wherever possible physical explanations are put forward.

#### **8.2 The Experimental Configuration and the Experimental Parameter Space:**

The equipment configuration for the following set of experiments is described in detail in Chapter 3 and is specifically shown in Figure 3.2.

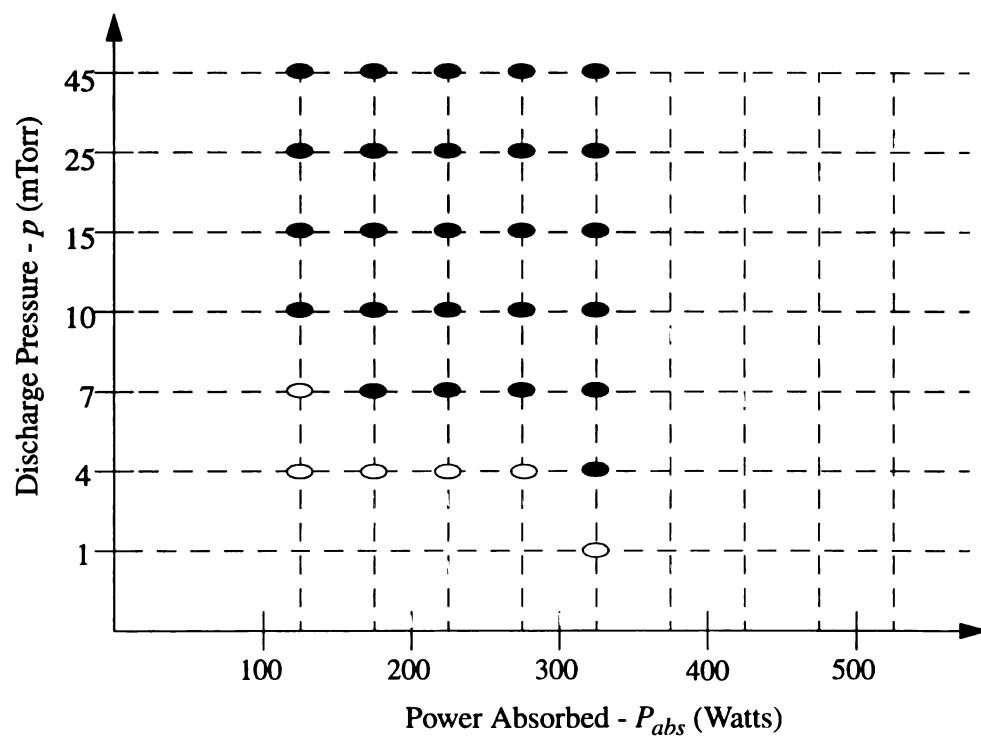
The output performance variable space ( $Y_1, Y_2$ ) of this plasma source can be thought of as a multi variable function of the input parameters ( $U_1, U_2$ ). This full parameter space is described in full detail in Chapter 4 and shown in Tables 4.1 - 4.3.



A subset of this parameter space is investigated and presented in this chapter. The subset of input parameters varied are: chamber pressure ( $p$ ), incident microwave power ( $P_{inc}$ ), cavity height ( $L_s$ ), and magnet configuration ( $U_2$ ). All of the remaining input parameters are held constant.

The subset of internal variables measured are absorbed power ( $P_{abs}$ ) and resonant mode type ( $X$ ) (i.e.  $TM_{012}$  or near field, etc.). Note that  $L_s$  is selected in each experiment to maintain a reflected power of 30 W when matching to a specific cavity mode. Also, note that since  $P_{abs}$  and resonant mode type can be selected by careful tuning of  $P_{inc}$  and  $L_s$  they may in some cases be considered input variables.

The subset of output variables measured are: charge density ( $n_e$ ), spatial variation of electron/ion density, and ion production cost ( $\eta_{ion}$ ). A graphical layout of the parameter space subset vs. pressure and absorbed power is shown in Fig. 8.1. Note, accurate measurements of charge density also require the electron temperature ( $T_e$ ) to be measured (see Equation 8.10). Electron temperatures were measured for these experiments, but are not discussed in this chapter; they are discussed along with the measured electron energy distribution function (EEDF) and plasma potential in Chapter 7.



- experimental data points where  $I_s$  and  $n_e$  ( $r = 0, z = 0$ ) are measured
- data points that are only obtainable with a magnet array present in the system

Figure 8.1: Experimental parameter space vs. power absorbed,  $P_{abs}$ , and discharge pressure,  $p$ .

## 8.3 Global Model Calculations; A Benchmark for Experimental Measurements

### 8.3.1 The Cylindrical Discharge Model

In order to get a theoretical reference or benchmark for the experimental data global model calculations are made for this specific discharge. The general details of this calculation are developed in Chapter 6. The important parameters for this model are discharge dimension, gas type, and discharge pressure. We have a cylindrical discharge of 10.25 cm height and 6.5 cm radius. The gas is argon between a pressure of 4 mTorr to 45 mTorr, and a gas temperature assumed to be 600 degrees Kelvin.

The first step in this calculation is to determine the appropriate pressure regime for the discharge (i.e. low pressure, intermediate, or high pressure). This experimental discharge satisfies the criteria for the intermediate pressure regime [Lie-94]:

$$(R, L) \geq \lambda_i \geq \left( \frac{T_i}{T_e} \right) (R, L) \quad \text{Eq. 8.1}$$

where  $R$  is discharge radius,  $L$  is discharge length,  $\lambda_i$  is the mean free path,  $T_i$  is the ion temperature and  $T_e$  is the electron temperature. Since the smaller of  $R$  or  $L$  dominates the properties of the discharge we choose 6.5cm for the left hand term of Eq. 8.1. The range of  $\lambda_i$  is 1.6cm at 4 mTorr to 0.14cm at 45 mTorr. For  $T_i$  we have 0.05eV (i.e. ~600K) and for  $T_e$  we have a minimum of 2eV. This gives an approximate value of 0.16 cm to the right hand term of Eq. 8.1

The second step is to calculate the electron temperature using the particle balance equation for the appropriate pressure regime (see Section 6.2.2.2). A plot of the electron temperature vs. discharge pressure is shown in Figure 8.2. The next step is the global model calculation of electron density from the power balance equations (see Section 6.3.6). The experimental parameter space used for the calculation here is given in Section 8.2 and depicted in Figure 8.1. The corresponding global model electron density predictions are shown in Figures 8.3 and 8.4.

The ion production cost,  $\eta_{ion}$ , for the cylindrical geometry can be derived from the global model (as described in Section 6.4.2). This "closed" cylinder geometry assumes that an ion extraction grid or silicon wafer forms the entire lower end wall boundary of the cylinder, see Figure 8.5. The energy it takes to create one electron/ion pair in the bulk plasma is given as  $\mathcal{E}_T$ . The flux,  $\Phi$ , of ions to the walls can also be calculated.

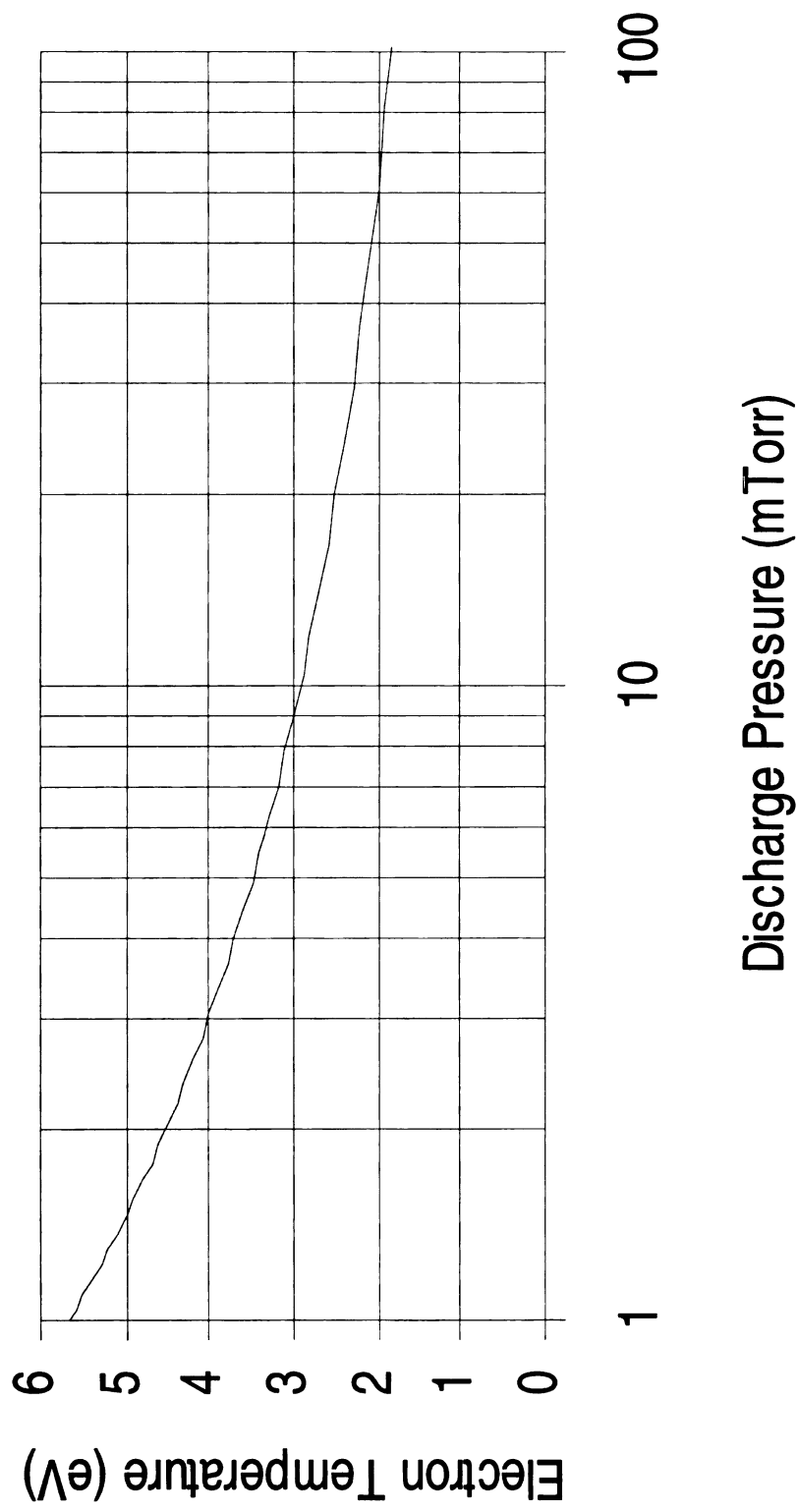


Figure 8.2 Global model prediction of electron temperature in an argon discharge vs. pressure for a 6.5 cm radius, 10.25 cm height discharge with a neutral gas temperature of 600K.

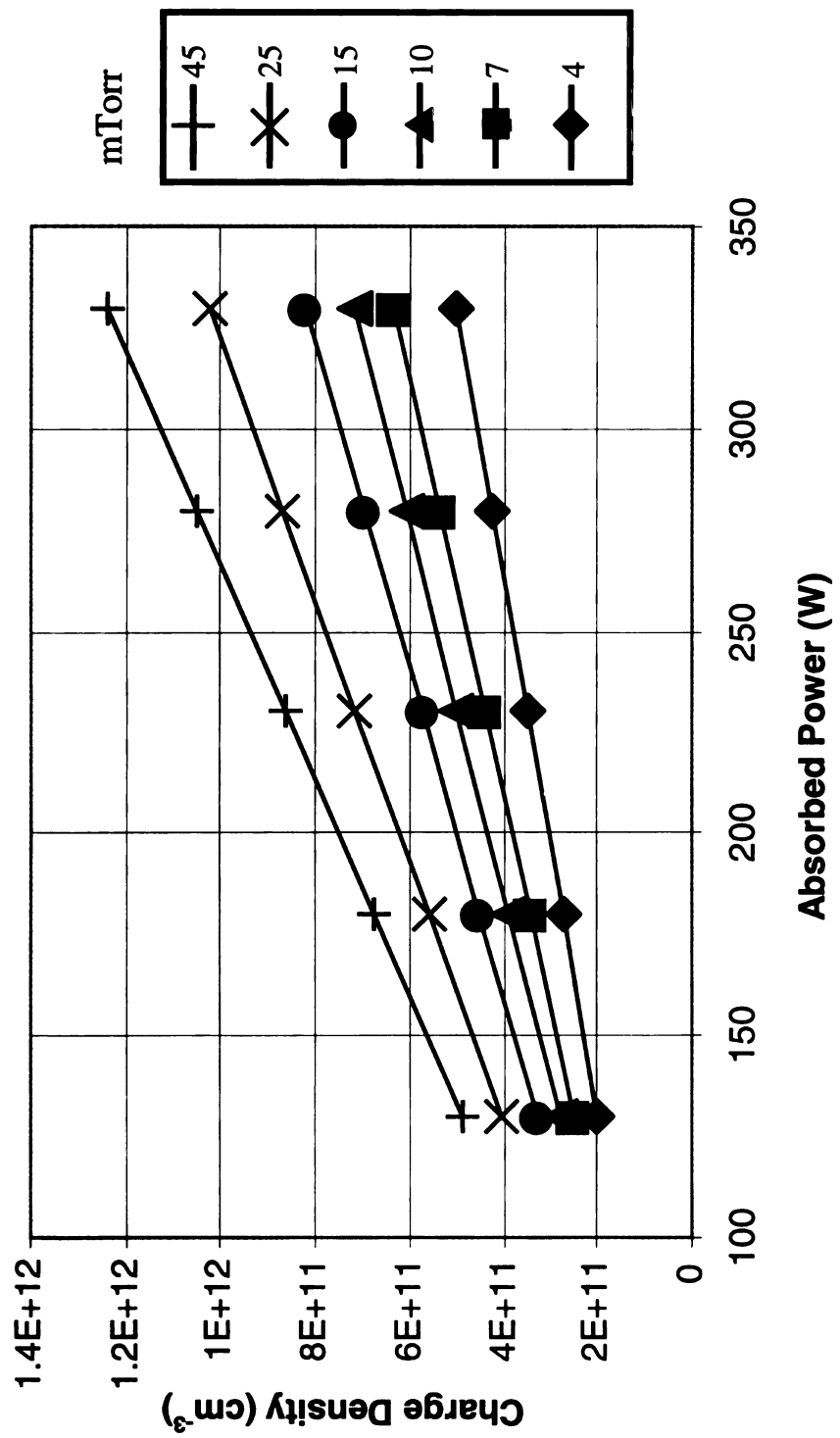


Figure 8.3: Global model calculated charge density vs. power absorbed,  $P_{\text{abs}}$ , and discharge pressure,  $p$ , (in mTorr)

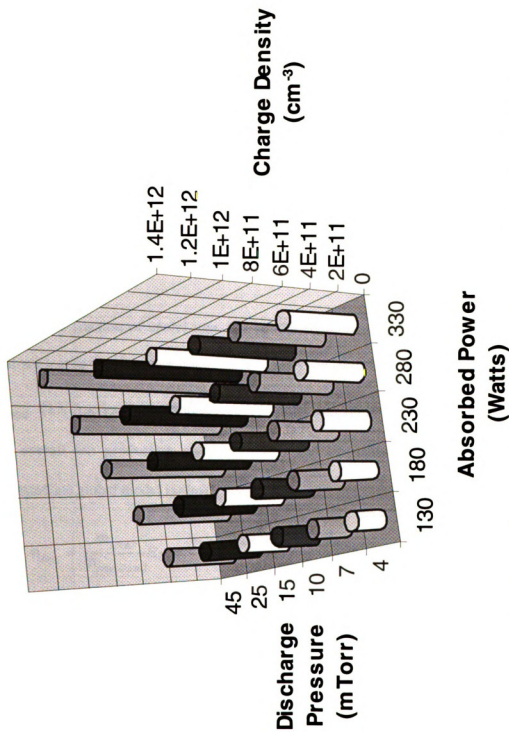


Figure 8.4: 3D plot of global model calculated charge density vs. absorbed power and discharge pressure (in mTorr)

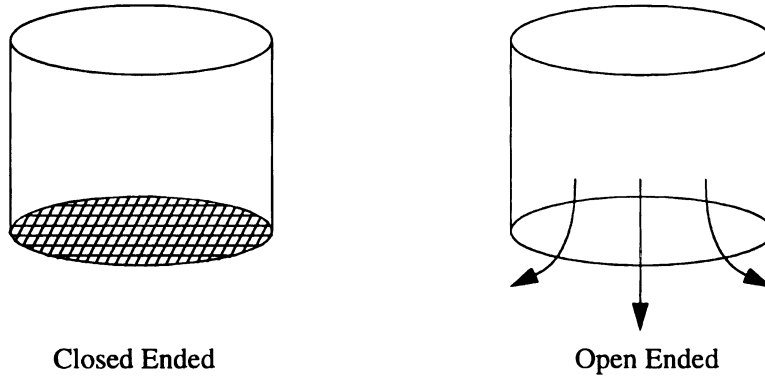


Figure 8.5: Closed Ended and Open Ended discharge models. In the closed ended model the end wall is formed by an extraction grid or a wafer.

The fraction of useful ions can be calculated by dividing the total number ions that are lost to the bottom end wall,  $\Phi_{one-end}$ , by the total number of ions lost to all walls,  $\Phi_{total}$ . This fraction is multiplied by the energy lost per ion-electron pair,  $\mathcal{E}_T$ , to obtain the overall ion production cost,  $\eta_{ion}$ . This can be defined mathematically (for the intermediate global model regime):

$$\eta_{ion} = \frac{\Phi_{total}}{\Phi_{one-end}} \mathcal{E}_T = \frac{n_0 u_B (2\pi R^2 h_l + 2\pi R l h_R)}{n_0 u_B \pi R^2 h_l} \mathcal{E}_T = 2\mathcal{E}_T \left( 1 + \frac{l h_r}{R h_l} \right) \quad \text{Eq. 8.2}$$

where  $\mathcal{E}_T$  is the energy lost per electron ion pair,  $n_0$  is the bulk charge density,  $u_B$  is the bohm velocity,  $R$  is the radius of the cylindrical discharge,  $l$  is the height of the discharge,  $h_l$  and  $h_R$  are the bulk to sheath edge density ratios for the planar and cylindrical walls (see Ch. 6, Equations 6.137 and 6.138). The ion production cost for the closed discharge geometry is plotted vs. discharge pressure in Figure 8.6.



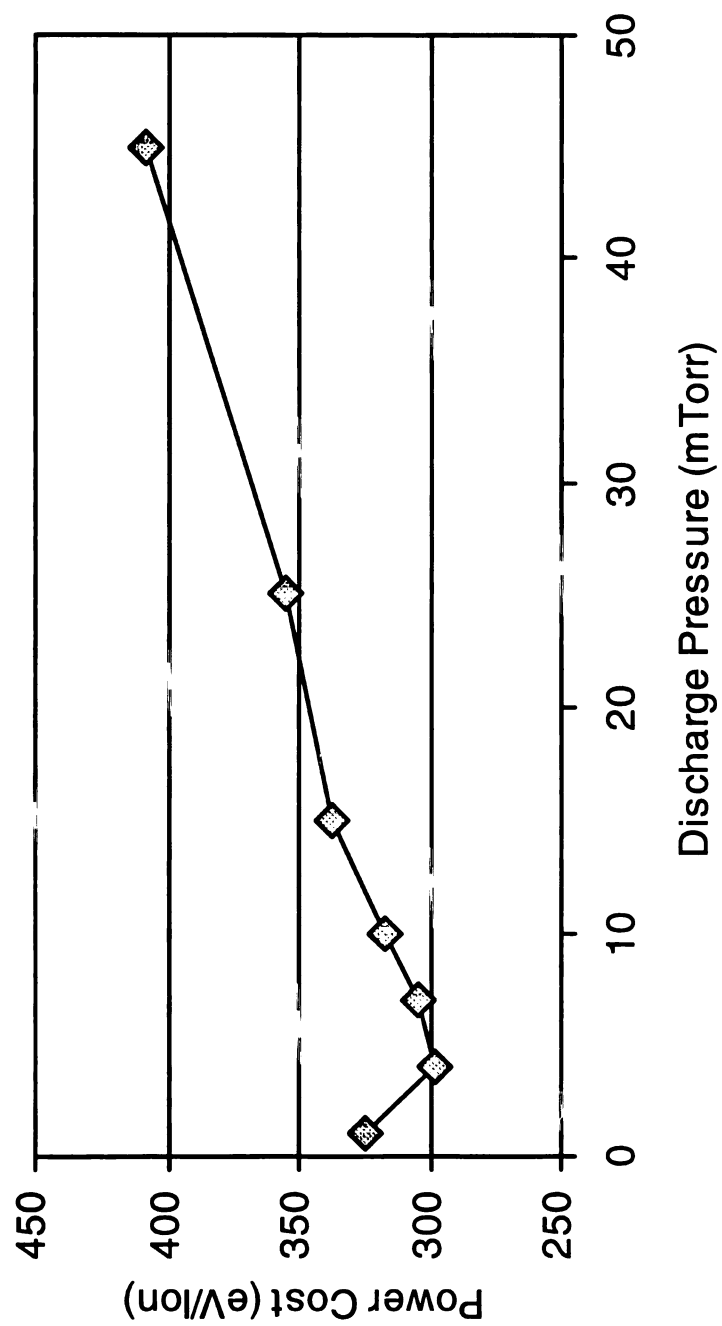


Figure 8.6 Global model ion production cost vs. discharge pressure for the closed discharge geometry.

### 8.3.2 The Open Ended Cylindrical Discharge Model

We should also consider the case when the discharge is open at the bottom end. In this case there are plasma sheaths at the side and top walls, but not at the bottom. The sheath acts to repel low energy electrons that can not climb the potential. If the sheath is absent at the bottom of the discharge more electrons may diffuse out of the discharge. This may be a significant cause of charged species loss at low discharge pressures in open ended geometries.

The physical model of an open ended discharge is more complex than for a closed discharge. Hopwood [Hop-90] presented a two chamber discharge model where the quartz dome was the upper smaller chamber opening at the bottom to the large process chamber below. The primary purpose of this model was to calculate the expected spatial distribution of discharge density in the process chamber (below the discharge opening). In this model the process chamber boundary conditions were defined as  $n_e=0$  at all walls and  $n_e=(\text{Constant})$  at the planar opening of the belljar. It was assumed there was no ionization (i.e.  $v_{iz} = 0$ ) in the process chamber.

It may be somewhat more difficult to specifically model an open ended discharge, with the goal of determining the spatial distribution of density in the discharge dome (and process chamber) especially at low pressures. An accurate calculation of ion/electron flux out of the discharge would likely require numerical modeling of the steady state diffusion processes in two dimensions ( $r,z$ ) using a finite difference grid. This spatial grid should include both discharge dome and process chamber.

For example, a two dimensional finite difference simulation using the high pressure ambipolar diffusion equation in cylindrical coordinates is shown in Figures 8.7 - 8.9. The ambipolar diffusion equation is:

$$\nabla^2 n + \frac{v_i}{D_a} n = 0 \quad \text{Eq. 8.3}$$

where  $n$  is the charge density,  $n_i$  is the ionization frequency, and  $D_a$  is the ambipolar diffusion constant. To simplify the equation we approximate the generation term as a constant [Gro-93]:

$$G \approx \frac{v_i}{D_a} n \quad \text{Eq. 8.4}$$

Then we have:

$$\nabla^2 n = -G \quad \text{Eq. 8.4}$$

In cylindrical coordinates (assuming phi symmetry) we have:

$$\nabla^2 n = \frac{1}{r} \frac{\partial n}{\partial r} + \frac{\partial^2 n}{\partial r^2} + \frac{\partial^2 n}{\partial z^2} = -G \quad \text{Eq. 8.5}$$

The above equation can be written as the following finite difference equation:

$$n_{i,j} = \frac{1}{r} \left( \frac{n_{(i+1,j)} - n_{(i-1,j)}}{2} \right) + \frac{n_{(i+1,j)} + n_{(i-1,j)} + n_{(i,j+1)} + n_{(i,j-1)}}{4} + G \quad \text{Eq. 8.6}$$

where  $i$  and  $j$  are the elements of a finite difference grid.

A finite difference model 2D (r,z) grid of the discharge and process chamber used in this dissertation is shown in Figure 8.7. A finite difference calculation of charge density setting  $G=1$  inside the discharge dome and  $G=0$  in the process chamber is shown in Figures 8.8 and 8.9. Note that this is a high pressure model so diffusion into the process chamber is much less than it would be for a lower pressure model. Figure 8.9 shows a logarithmic plot of the axial downstream density.

Unfortunately this high pressure example (i.e. for pressures  $>200$  mTorr) does not directly apply to the pressure regimes used in this investigation (4-45 mTorr). The above development and calculation should be done for each of the other pressure regimes: intermediate pressure "mobility limited" discharges (Lie-94; Sec. 5.3), and very low pressure "free fall" discharges (Lie-94; Sec. 5.3). However, the diffusion equations for these discharge pressure regimes are non-linear and require more sophisticated finite difference modeling algorithms. These lower pressure models should show greater electron diffusion into the process chamber and more accurately model the behavior of the experiments found in this dissertation.

One question in modeling the open ended discharges is how to include the contribution of ions that are created by energetic electrons outside the discharge volume. This may be a significant source of useful ion production at lower pressures where high energy electrons stream out of the discharge.

Although the open ended discharge model (when developed) would be more accurate, the simpler closed ended discharge model will be used in this thesis as an approximation to the open ended model for comparison to experimentally determined charge density and eV/Ion values.

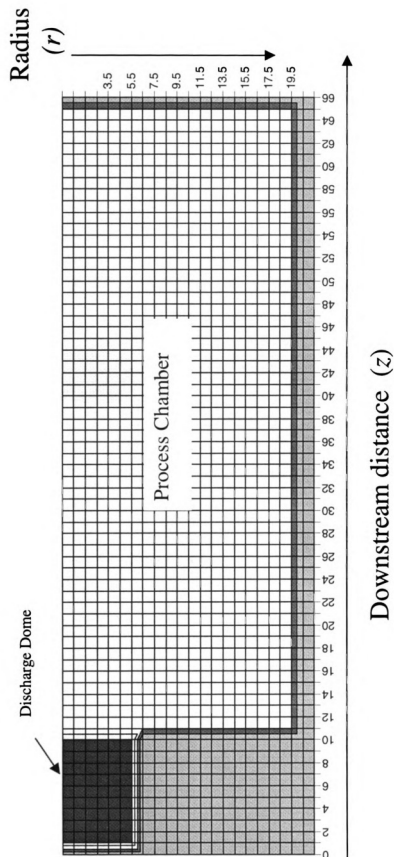


Figure 8.7: Finite difference grid for the 10.25 cm tall discharge dome and 55 cm tall process chamber. Grid points are 1 cm apart.

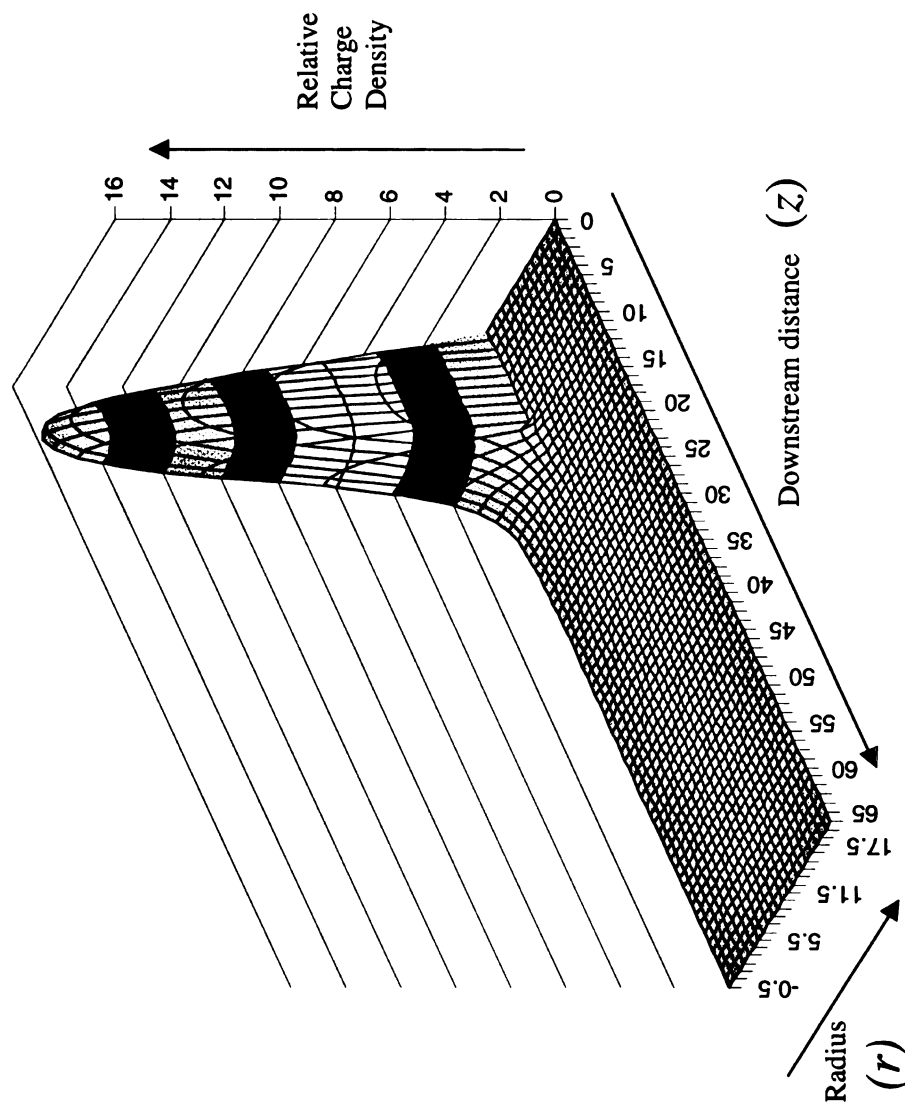


Figure 8.8: Surface plot of the relative charge density in a 2D cross section of a high pressure discharge with both discharge dome and process chamber shown. This is the result of a finite difference simulation of the diffusion equation. The generation term is 1 in the discharge dome and 0 in the process chamber. The discharge is assumed to be phi-symmetric.

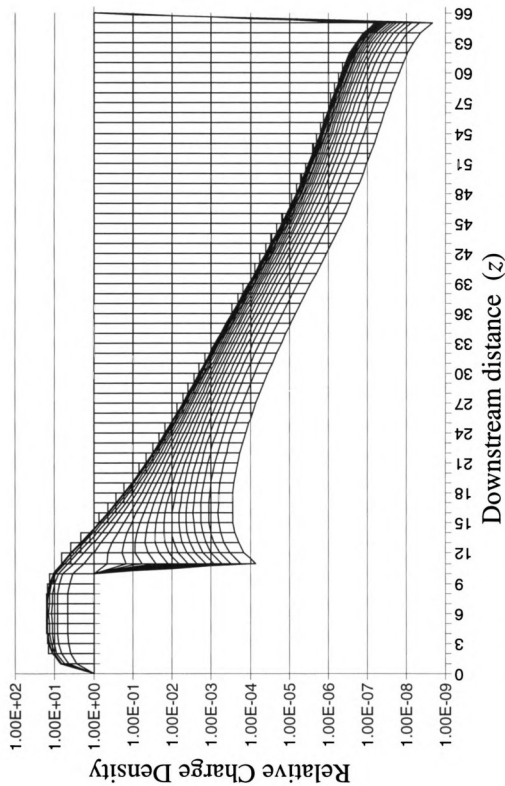


Figure 8.9: Side view of a logarithmic surface plot for relative charge density in both the discharge dome and process chamber.

## 8.4 Electron Density Measurements

### 8.4.1 Experimental Electron Density Measurements

Charge density,  $n_e$ , was measured using a single Langmuir probe placed at ( $r=0$ ,  $z=0$ ) at the bottom of the discharge chamber in the center of the discharge opening. The SLP consisted of a 2.5 mm long, 0.5 mm diameter tungsten electrode placed at  $r=0$ ,  $z=0$  at the base of the plasma discharge. The knee of the measured IV curve was used to determine the ion saturation current,  $I_s$  (Note: see Chapter 5).

The expression for  $I_s$  is given as:

$$I_s = en_s A_p u_s \quad \text{Eq. 8.7}$$

where  $e$  is the electron charge,  $n_s$  is the charge density at the probe's sheath edge,  $A_p$  is the effective area of the probe, and  $u_s$  is the ion velocity at the probe's sheath edge. The charge density at the sheath edge,  $n_s$ , can be related to the bulk charge density,  $n_0$ , with the Boltzmann relation assuming a potential of  $\Phi = T_e/2$  at the sheath edge [Lie-94; p. 160]:

$$n_s = n_e e^{\left(\frac{-\Phi}{T_e}\right)} \cong (0.61)n_e \quad \text{Eq. 8.8}$$

The ion velocity at the sheath edge,  $u_s$ , can be expressed approximately as [God-90, Lie-94; p. 171]:

$$u_s \approx \frac{u_B}{\sqrt{1 + \frac{\pi \lambda_{De}}{2 \lambda_i}}} \quad \text{Eq. 8.9}$$



where  $\lambda_{De}$  is the Debye length,  $\lambda_i$  is the ion mean free path, and  $u_B$  is the Bohm velocity.

The above equation is important when a collisional sheath is present, i.e.  $\lambda_i \sim \lambda_{De}$ . Table 8.1 illustrates the significance of collisions in the sheath at various pressures and discharge conditions observed in this experimental investigation:

| Table 8.1 - Significance of collisions in the sheath |       |                                 |       |             |                |                          |           |
|------------------------------------------------------|-------|---------------------------------|-------|-------------|----------------|--------------------------|-----------|
| Pressure                                             | $T_g$ | $n_e$                           | $T_e$ | $\lambda_i$ | $\lambda_{De}$ | $\lambda_i/\lambda_{De}$ | $u_s/u_B$ |
| 1 mTorr                                              | ~600K | $10^{11}\text{cm}^{-3}$         | 5.5eV | 6cm         | 0.0055cm       | 1091                     | 0.9993    |
| 45 mTorr                                             | ~600K | $5 \cdot 10^{11}\text{cm}^{-3}$ | 2eV   | 0.13cm      | 0.0015cm       | 86.7                     | 0.9911    |

We can conclude from Table 8.1 that under the experimental conditions presented in this thesis investigation  $\lambda_i \gg \lambda_{De}$  and collisions in the sheath do not significantly effect measurement of  $I_s$  or  $n_e$ .

For conditions where  $\lambda_i \gg \lambda_{De}$  an expression for the bulk charge density,  $n_e$ , can be derived from Eq. 8.7 and Eq. 8.8:

$$n_e = \frac{I_s}{(0.61)eA_p} \sqrt{\frac{M_i}{eT_e}} \quad \text{Eq. 8.10}$$

where  $I_s$  is the ion saturation current, the factor 0.61 is the ratio of sheath edge density to bulk plasma density,  $A_p$  is the effective area of the probe,  $M_i$  is the mass of an argon atom,  $e$  is the electron charge, and  $T_e$  is the SLP measured electron temperature in volts. Since

the total collection area of the probe depends on the thickness of the sheath surrounding the probe, which in turn varies with changing charge density, the charge density was determined by an iterative procedure (described in Section 5.1).

Electron density,  $n_e$ , measurements were taken over a range of pressures and power levels, as shown in Figure 8.1. The pressures investigated were: 1, 4, 7, 10, 15, 25, and 45 mTorr (note the discharge could not be sustained below 4 mtorr without magnets). The discharge absorbed power levels investigated were: 130, 180, 230, 280, and 330 Watts.

For each of the power, pressure parameter points the following procedure was carried out. An  $n_e$  measurement was taken first at the  $TM_{012}$  mode, then the system was tuned to the near field mode and another  $n_e$  measurement was taken, the  $n_e$  measurement was repeated at the  $TM_{012}$  mode, and then again at the near field mode. This procedure provided both a direct comparison between the density output for the two different modes, and also a confirmation of the density at each mode. The two duplicate measurements for each mode generally differed in density by less than 5%. This  $n_e$  data is plotted in Figures 8.10-8.13 for the four plasma source configurations (i.e. the  $TM_{012}$  and near field modes both with and without ECR magnets). Each plotted point represents the average of the two experimental  $n_e$  measurements for each mode. For clarity no error bars are plotted on Figures 8.10-8.13, but the experimental error for each point is estimated to be no more than 10%. For all four plots in Figures 8.10-8.13 the benchmark electron density predictions from the global model intermediate regime (see Fig. 8.3) are plotted as dashed lines.

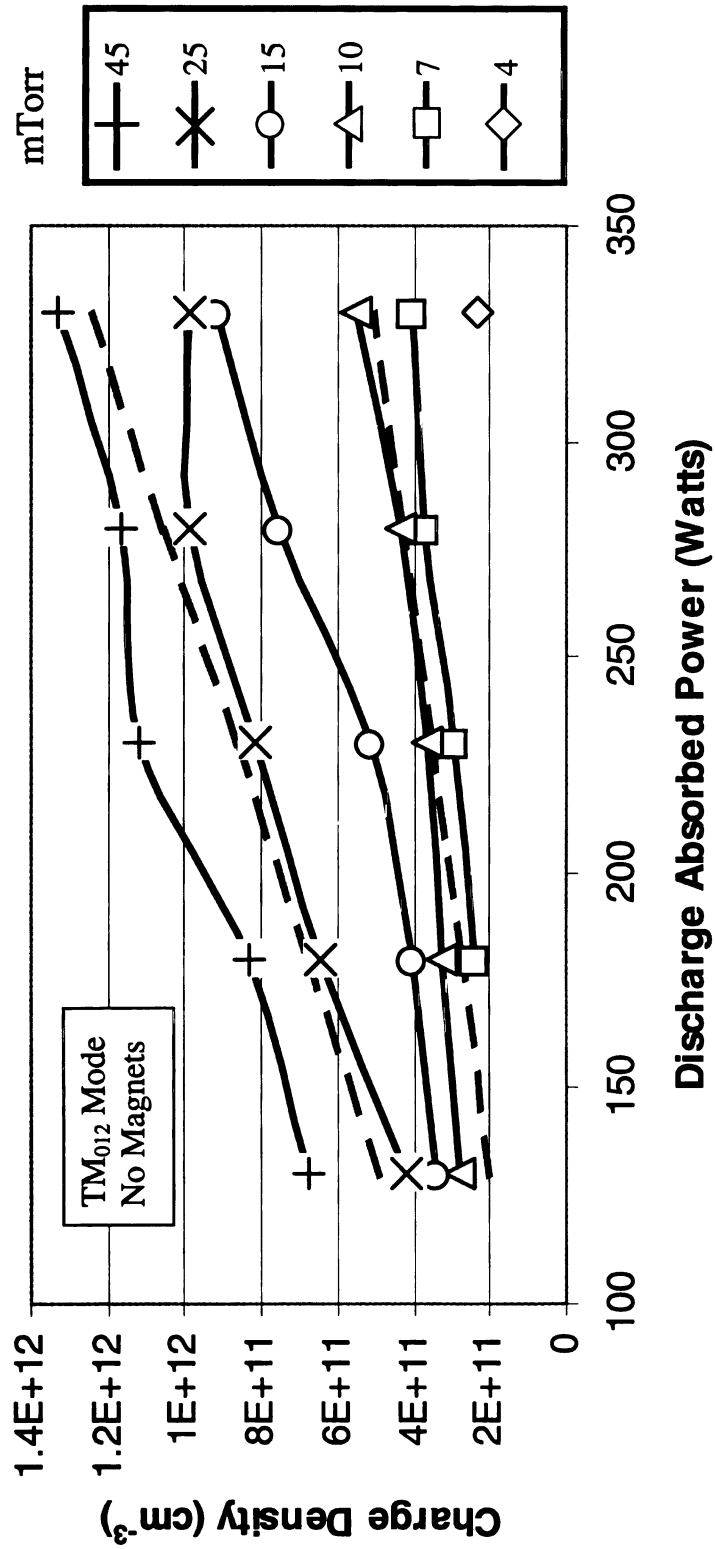


Figure 8.10 - Charge density measured at  $r=0$  and  $z=0$  vs. Absorbed Power at six different discharge pressure levels for the TM<sub>012</sub> Mode with no magnets present. Solid lines are experimental data. Red dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line).

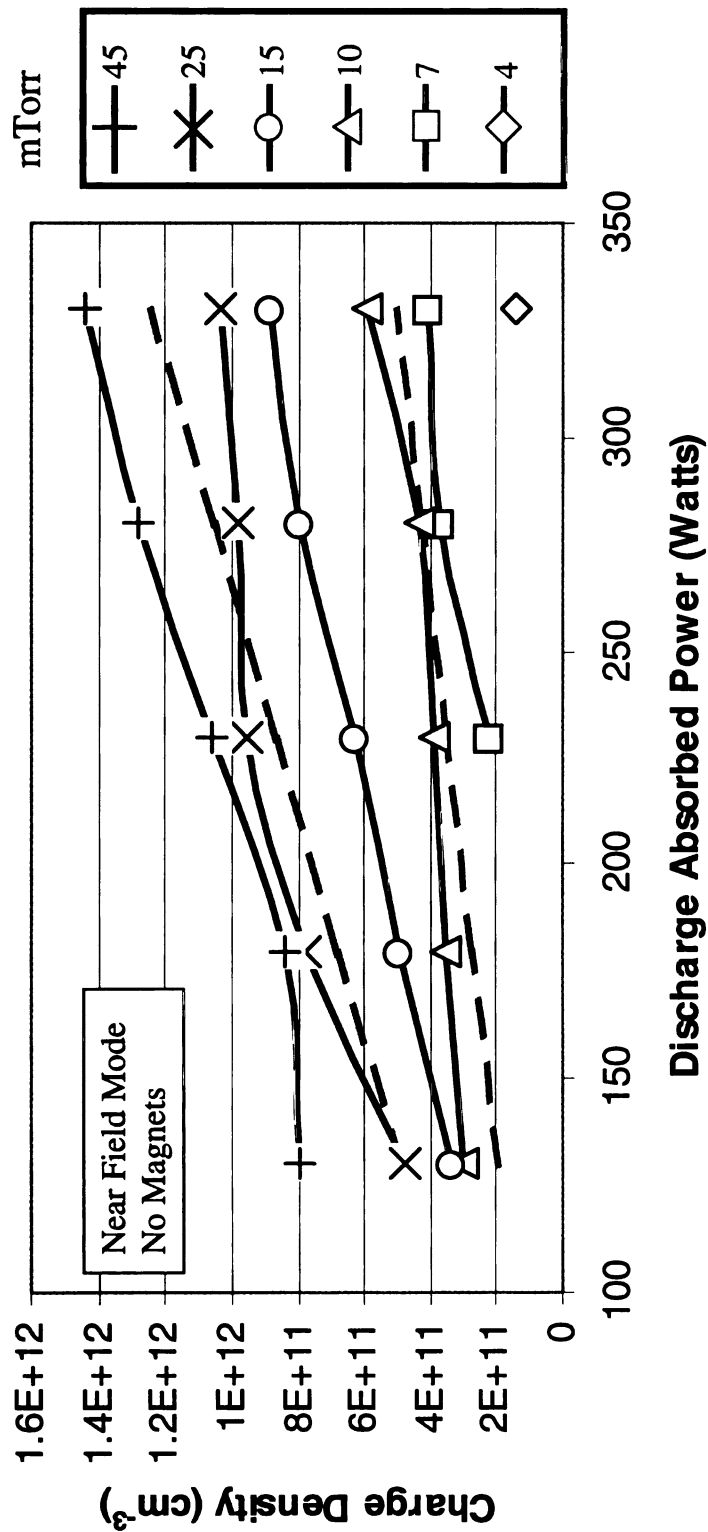


Figure 8.11 - Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at six different discharge pressure levels for the Near Field mode with no magnets present. Solid lines are experimental data. . Red dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line).

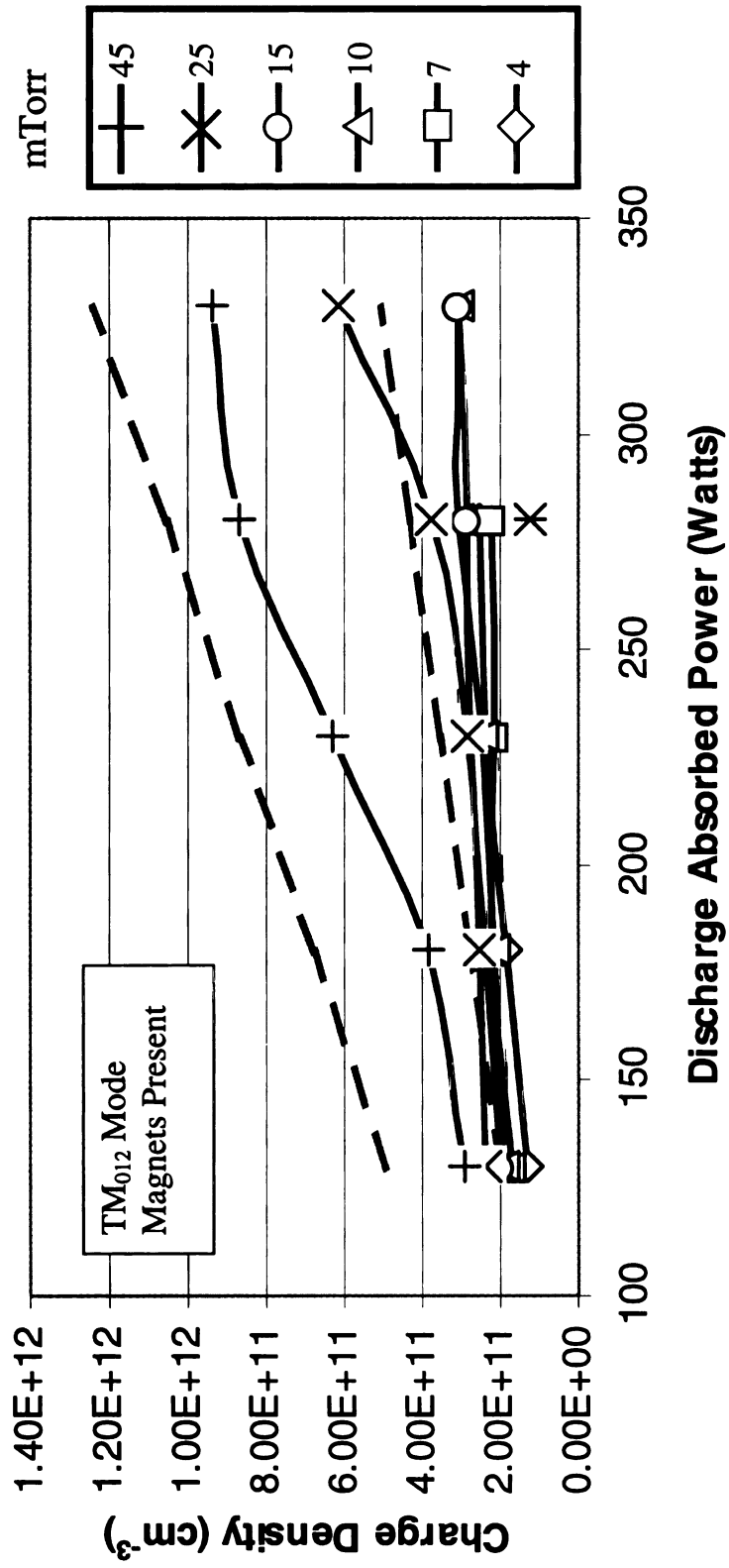


Figure 8.12a - Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at 7 different discharge pressure levels (point at 280 W is at 1 mTorr) for the TM<sub>012</sub> Mode, with multipolar magnetic field. Solid lines are experimental data. Red dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line).

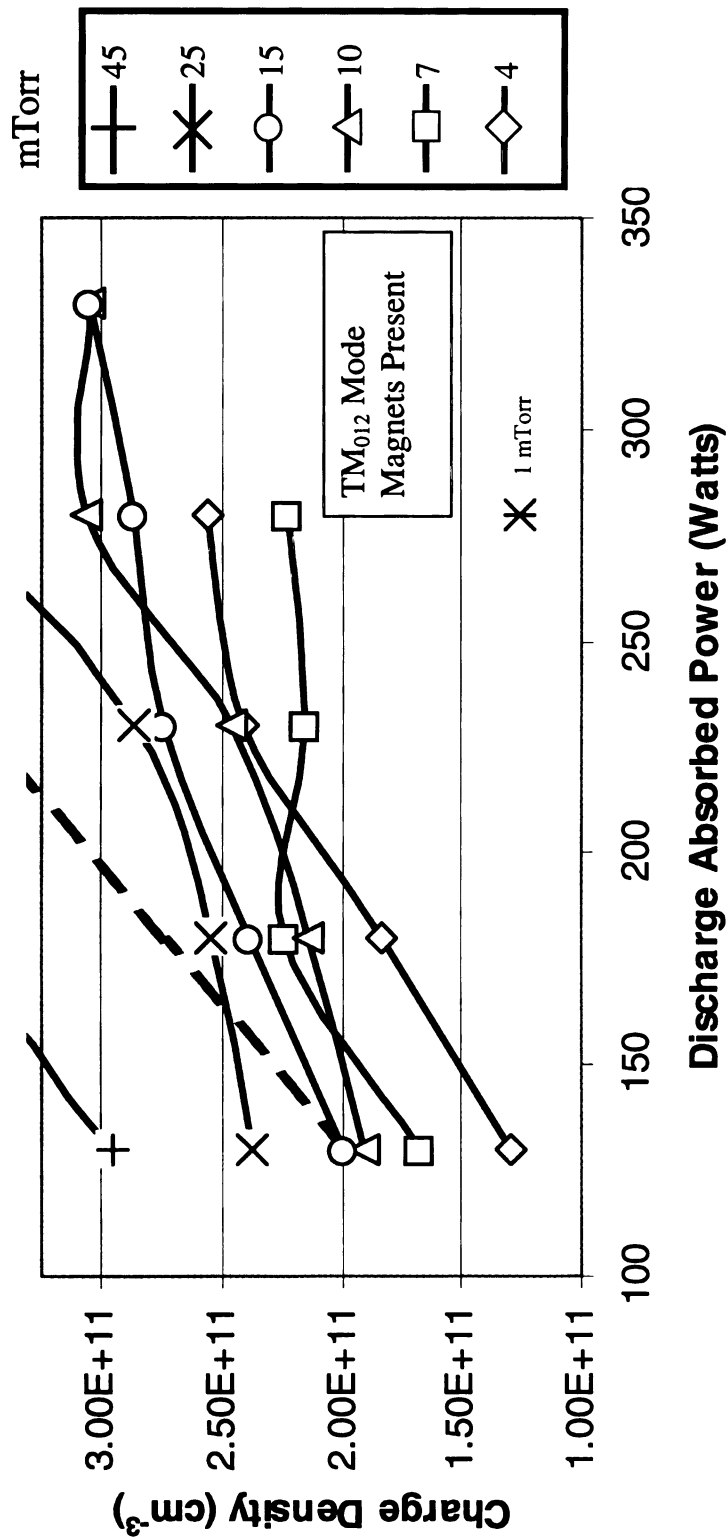


Figure 8.12b – Expanded view of Figure 8.12a. Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at 7 different discharge pressure levels (point at 280 W is at 1 mTorr) for the TM<sub>012</sub> Mode, with multipolar magnetic field. Solid lines are experimental data. Dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line).

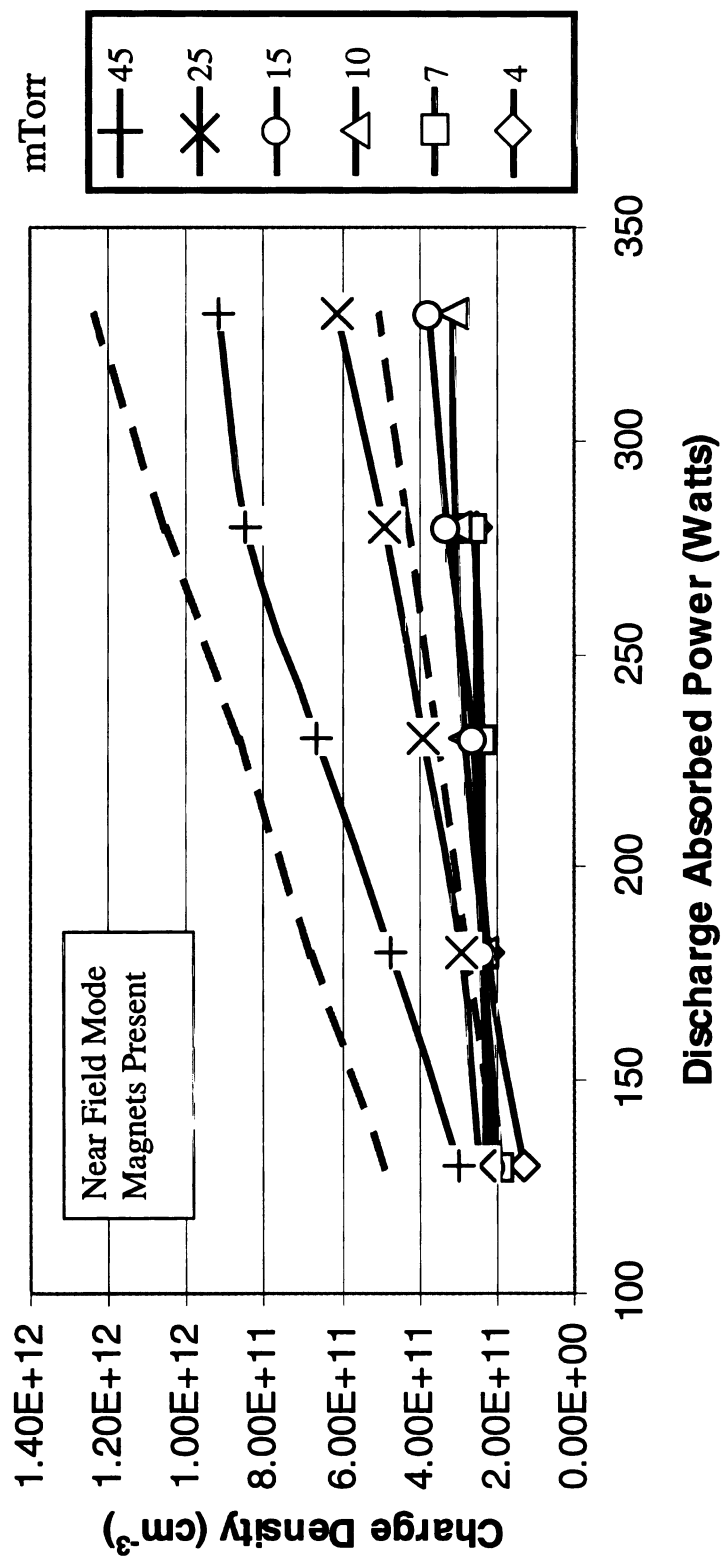


Figure 8.13a - Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at six different discharge pressure levels for the Near Field Mode with multipolar magnetic field. Solid lines are experimental data. Dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line).

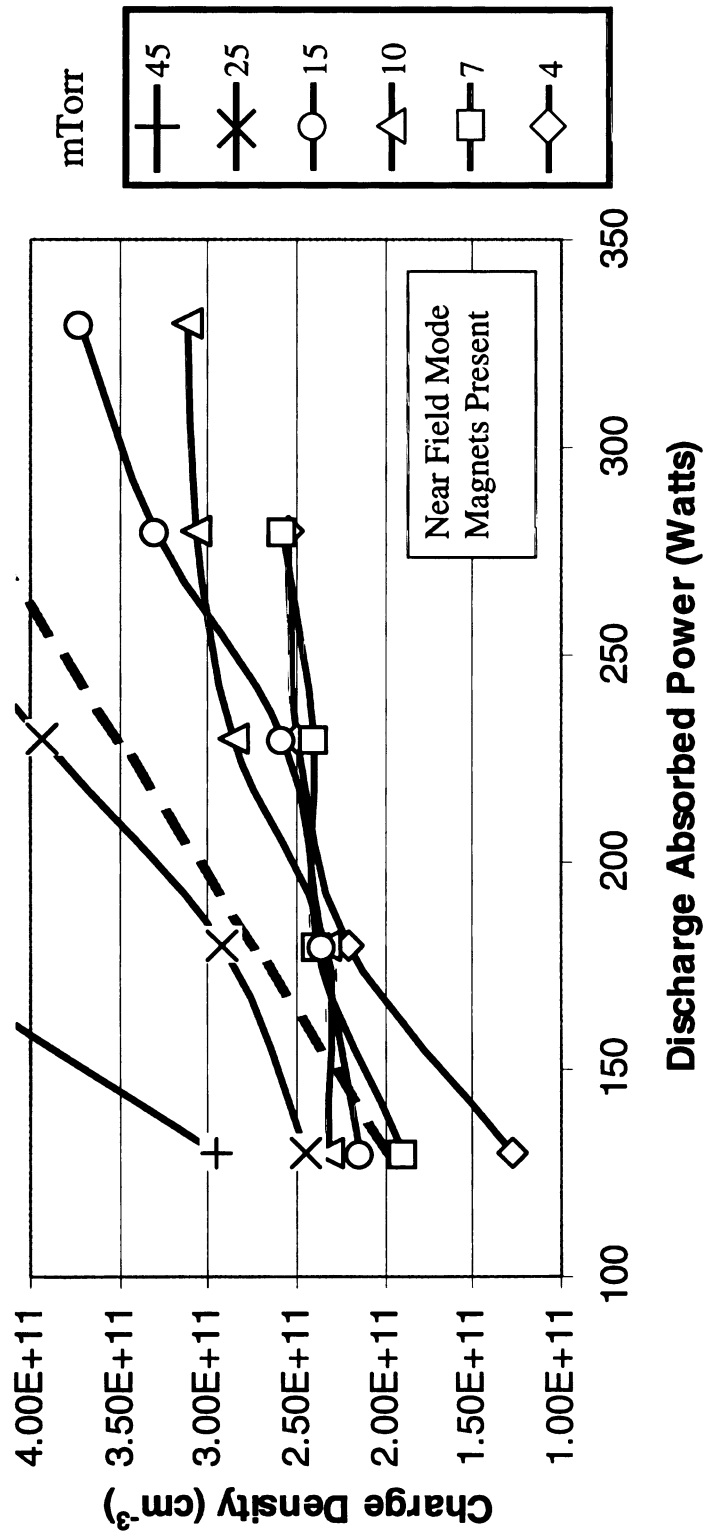


Figure 8.13b – Expanded view of Figure 8.13a. Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at six different discharge pressure levels for the Near Field Mode with multipolar magnetic field. Solid lines are experimental data. Dashed lines are global model prediction for 4 mTorr (lower dashed line) and 45 mTorr (upper dashed line).



#### 8.4.2 Comparison of Electron Densities Between TM<sub>012</sub> and Near Field Modes

In Figures 8.14 and 8.15 the density output is compared vs. electromagnetic mode excited. A comparison between the TM<sub>012</sub> and near field modes in the non-magnetized discharge provides no significantly large differences in density for pressures from 7-45 mTorr. However, at 4 mTorr in the non-magnetized discharge the TM<sub>012</sub> mode has about 1.5 times the charge density as the near field mode.

Taking a closer look, there are some differences in the 7-45 mTorr range that fall marginally within experimental error that should be mentioned. Careful observation shows that the near field mode has on average higher (by  $1 \times 10^{11} \text{ cm}^{-3}$  or approximately 10%) charge density than the TM<sub>012</sub> mode at pressures of 10 to 45 mTorr.

Even though the differences in density are small, some explanations may be forwarded. The slightly higher  $n_e$  for the near field mode in the 7-45 mTorr range may be due in part to its smaller cavity height,  $L_s$ , than the TM<sub>012</sub> mode, hence reducing by comparison the amount of EM energy that is lost to the cavity walls. However, calculation of power lost in the cavity walls indicates that the percentage of power lost there is quite small, on the order of 1% or less. Another explanation may be that the electric fields of the near mode at pressures between 7-45 mTorr range couple energy into the plasma somewhat differently than the TM<sub>012</sub> mode. This different coupling may result in fewer ions and electrons lost to the discharge walls and produce a more efficient density output.

For the magnetized case, again, there are no extremely large differences but it should be noted that for almost all cases the near field mode has consistently a few

percent higher density than the  $TM_{012}$  mode. See Figures 8.14 and 8.15. These differences for the most part fall within experimental error, but since the trend is consistent it should be noted. More noticeable differences in density occur at 25 mTorr where the near field mode is approximately  $1 \times 10^{11} \text{ cm}^{-3}$  higher for 180, 230, and 280 W of absorbed power. The explanations for the ( $\sim 10\%$ ) higher near field mode densities are similar to those given for the non-magnetized configuration, i.e. slightly lower wall losses.

### 8.4.3 Comparison of Charge Density Between Magnetized and Non-magnetized Cases

Very significant differences in charge density are observed if magnetized and non-magnetized discharges are compared. Figures 8.16 and 8.17 compare the density output of magnetized and non-magnetized discharges for the  $TM_{012}$  mode (Figure 8.16) and Near Field mode (Figure 8.17). In Figure 8.16 the  $TM_{012}$  mode non-magnetized densities are measured to be significantly higher (in some cases more than two times higher) than those produced by the  $TM_{012}$  mode with magnets included. A similar observation is made for Figure 8.17 where the near field mode is excited: the non-magnetized configuration produces much higher charge densities than the magnetized configuration. Note one exception for both modes: at 4 mTorr the magnetized configuration produces higher density than the non-magnetized configuration. In Figures 8.16 and 8.17 the non-magnetized data point at 4 mTorr is shown as a single diamond at  $P_{abs} = 330\text{W}$  (330W is the minimum power level that could sustain a plasma without

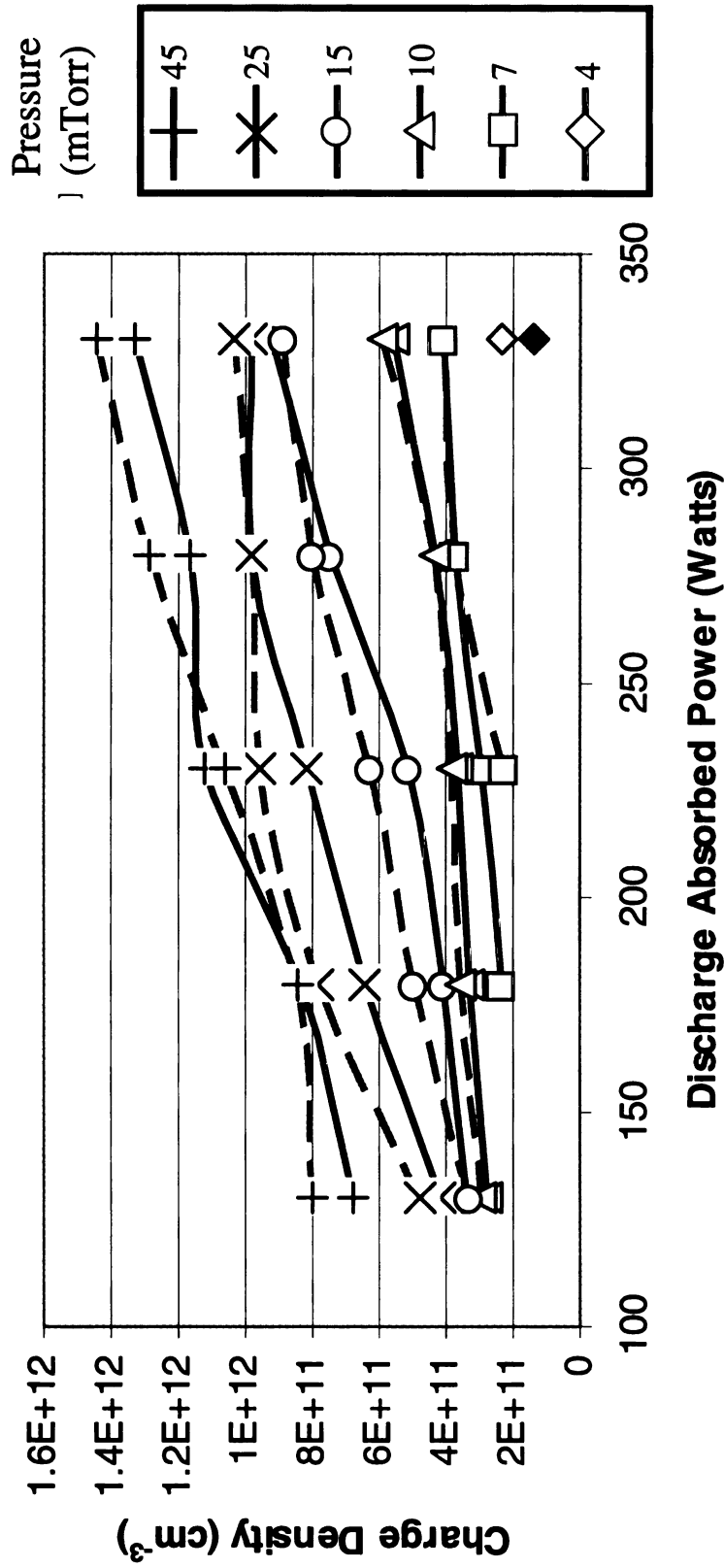


Figure 8.14 - Comparison of Charge Density vs. Absorbed Power between TM<sub>012</sub> and Near Field Modes for the Non-Magnetized discharge. Solid black lines are TM<sub>012</sub> data. Gray dashed lines are Near Field Mode data. Six different discharge pressure levels are compared.

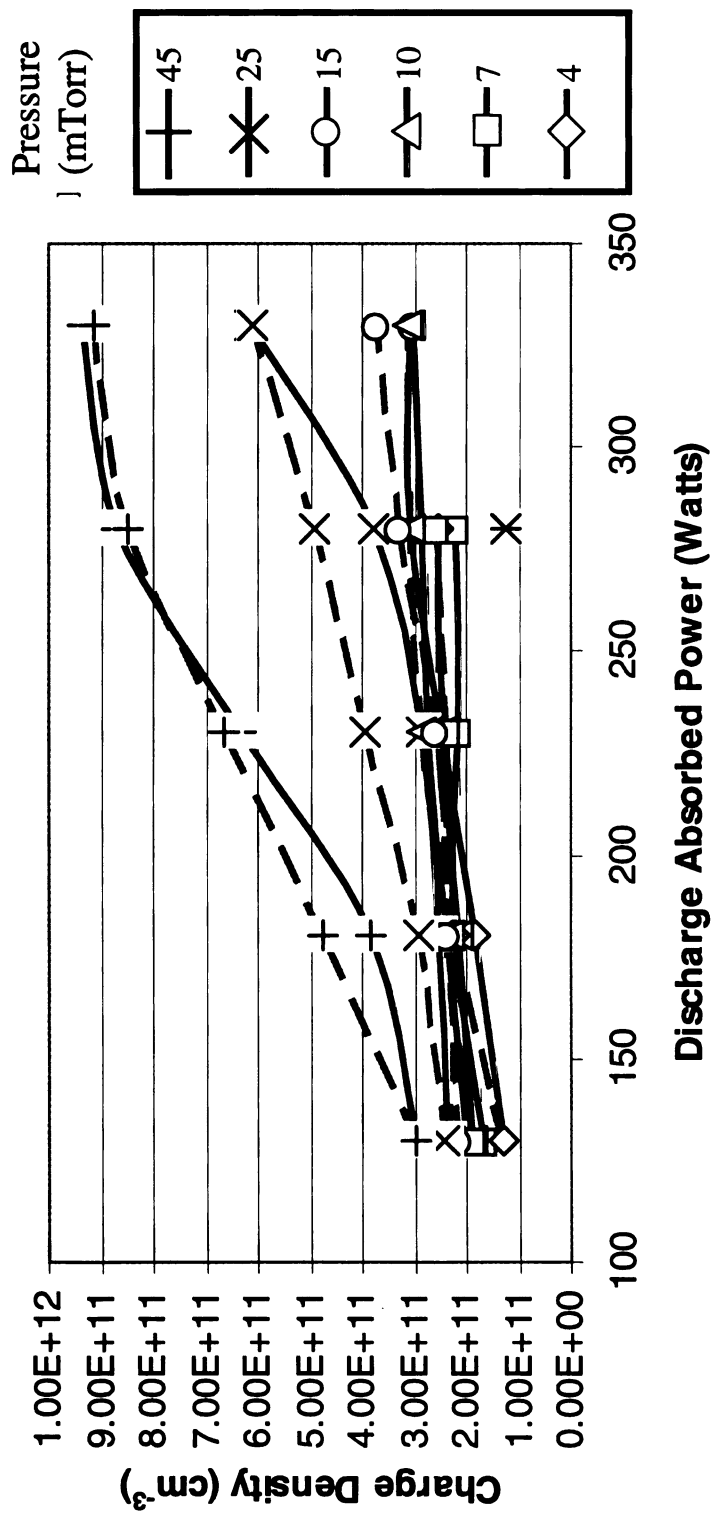


Figure 8.15a - Comparison of Charge Density vs. Absorbed Power between TM<sub>012</sub> and Near Field Modes for the Magnetized discharge. Solid black lines are TM<sub>012</sub> data. Gray dashed lines are Near Field Mode data. Six different discharge pressure levels are compared.

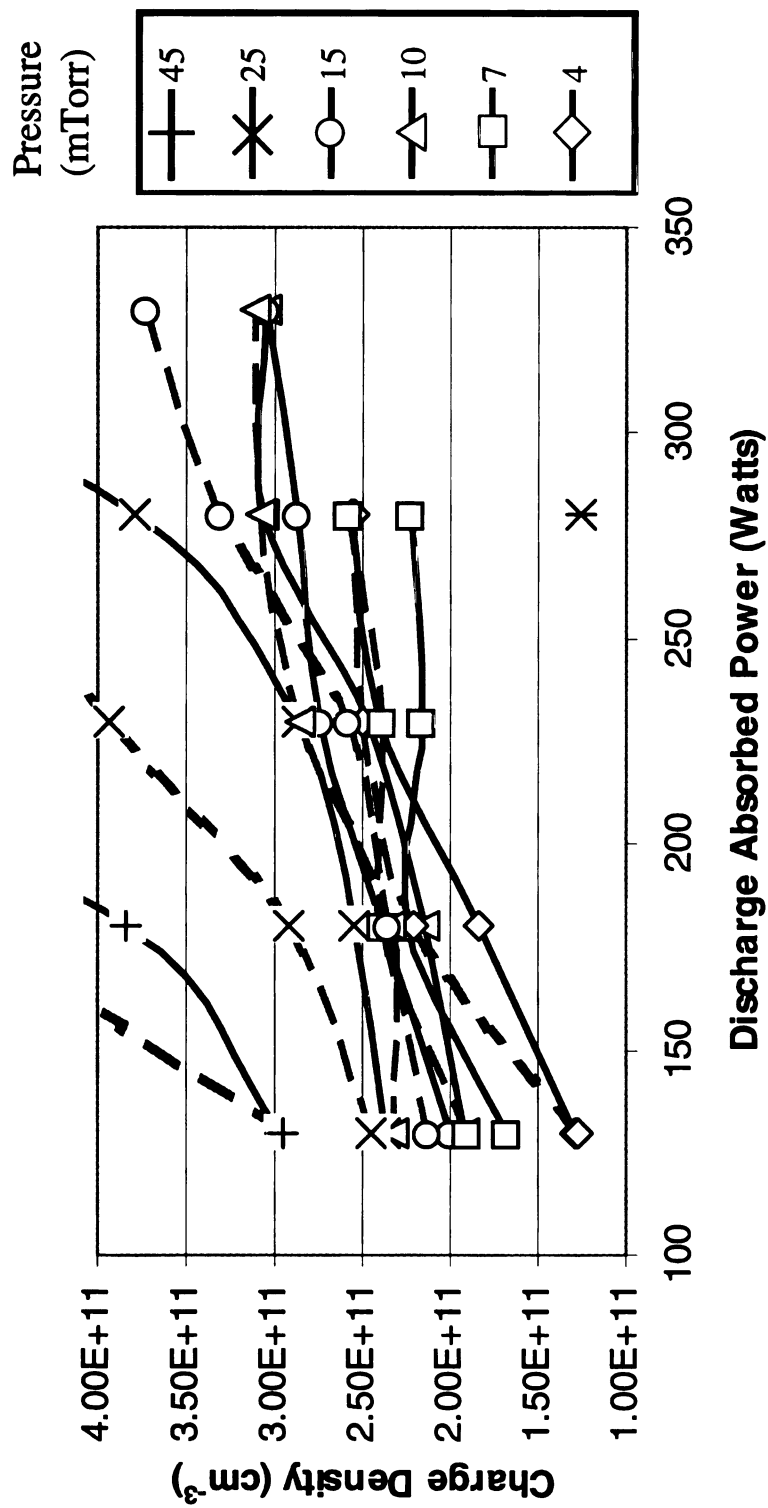


Figure 8.15b – Expanded view of Figure 8.15a. Comparison of Charge Density vs. Absorbed Power between TM<sub>012</sub> and Near Field Modes for the Magnetized discharge. Solid black lines are TM<sub>012</sub> data. Gray dashed lines are Near Field Mode data. Six different discharge pressure levels are compared.

magnets at 4 mTorr for this system geometry). The plasma can not be reliably sustained below 4 mtorr, with an incident power of 360W, without ECR magnets. The plasma can be sustained below 1 mtorr with ECR magnets included. From the above observations it can be concluded that the presence of a static magnetic field reduces output charge densities output at pressures above 10 mTorr, however it is beneficial and necessary for reliable operation at 4 mTorr and below.

The charge density in this set of experiments was measured only in one discharge location, i.e.  $r=0$ ,  $z=0$ . This left open the possibility that the differences in charge density output between magnetized and non-magnetized configurations were due more to a difference in output density profile than to differences in total output density. The best way to answer this question was to measure the charge density at several points across the diameter of the discharge opening. This set of experiments is described in section 8.6.

#### 8.4.4 Comparison to the Global Model

In comparing the magnetized and non-magnetized discharges with the global model it must be recognized that this discharge is far more complex than the discharge assumed by the global model. Thus one would not necessarily expect perfect agreement.

What we are looking for, first of all, is a general agreement in the behavior of the discharge as compared to the global model for a given change in variables such as: discharge pressure  $p$ , absorbed power  $P_{abs}$ , and reactor geometry. The behavior observed are outputs such as: electron density  $n_e$ , electron temperature  $T_e$ , and discharge efficiency.

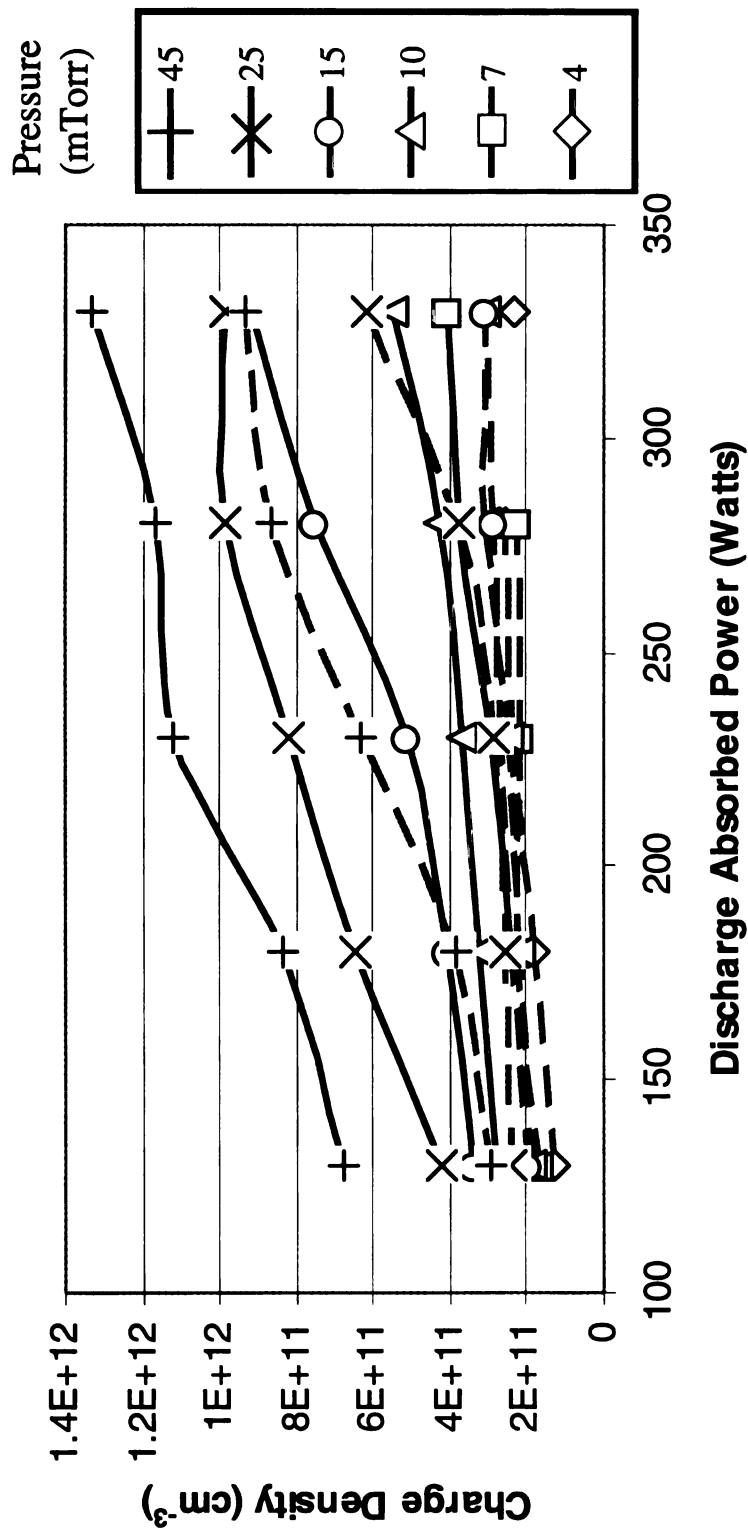


Figure 8.16 - Comparison of Charge Density vs. Absorbed Power between Magnetized and Non-Magnetized Discharges in the TM<sub>012</sub> Mode. Solid black lines are Non-magnetized data. Gray dashed lines are Magnetized data. Six different discharge pressure levels are compared.

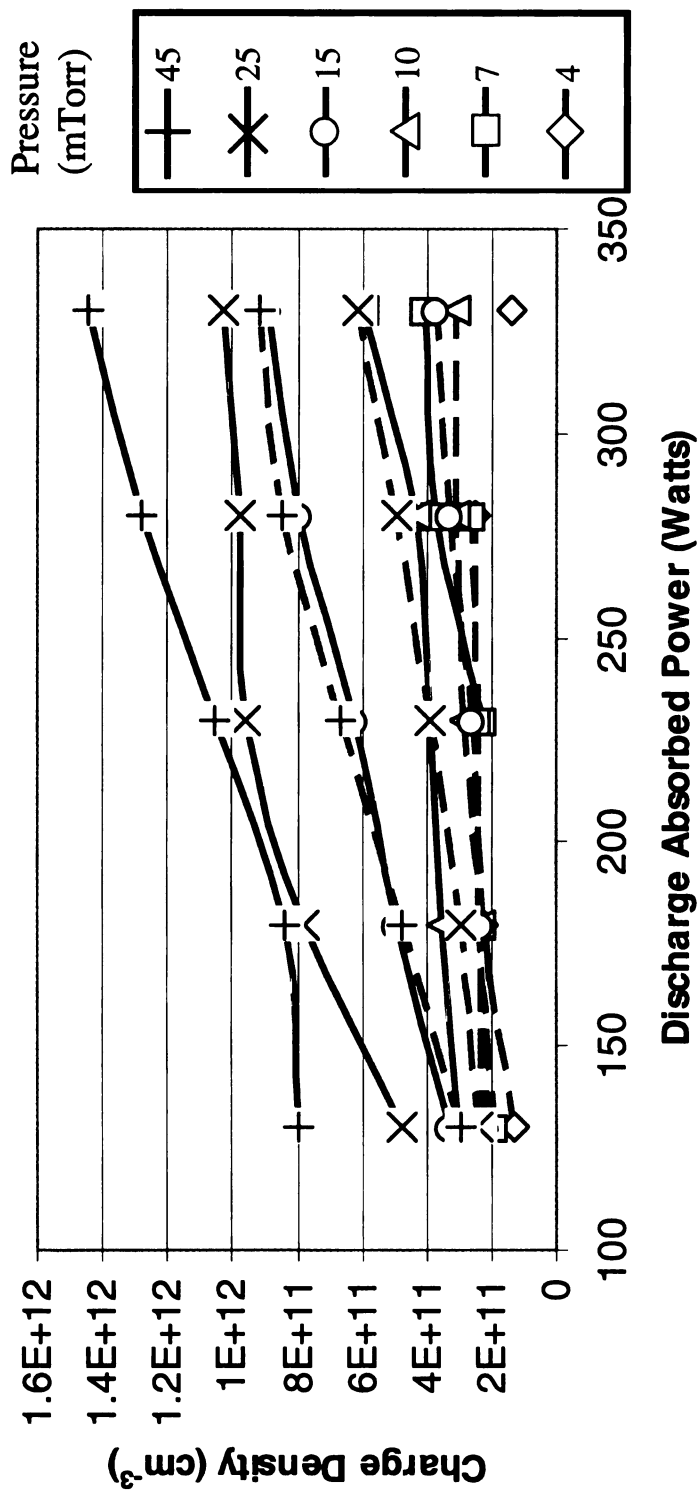


Figure 8.17 - Comparison of Charge Density vs. Absorbed Power between Magnetized and Non-Magnetized discharges in the Near Field Mode. Solid black lines are Non-Magnetized data. Gray dashed lines are Magnetized data. Six different discharge pressure levels are compared.



It is understood that microwave discharges differ considerably from point to point spatially from the global model. For example, EM energy coupling only takes place in part of the microwave discharge, the electron and gas temperatures vary spatially, there is neutral gas heating that varies as pressure and power are varied, and when magnetic fields are present the diffusion processes are much more complicated than those assumed in the global models. We are, however, still interested in knowing if the global models do provide a useful and an approximate model that can provide a first pass qualitative understanding of microwave discharge behavior. We are also interested in knowing if these models can allow quick "back of the envelope" methods of calculating and understanding microwave discharge behavior.

In Figures 8.10 and 8.11 the densities for the  $TM_{012}$  and near field modes in the non-magnetized discharge are plotted. The measured data shows a good qualitative agreement with the global model. The general "load line" behavior of the measured densities is similar to the behavior of the global model. Making a quantitative comparison we note that the experimental charge densities are somewhat higher than the global model in Figures 8.10 and 8.11 for higher pressures and somewhat lower than the global model for the lower pressure range.

Figures 8.12 and 8.13 plot the measured densities for the  $TM_{012}$  and near field modes in the magnetized discharge. Here a different qualitative behavior is observed than is predicted by the global model. The measured densities for both  $TM_{012}$  and near field modes are in all cases less and in most cases significantly less than the predictions of the global plasma model. At pressures between 25 and 4 mtorr and especially between 15 and 4 mtorr the density "load lines" fall near  $2.5 \times 10^{11} \text{ cm}^{-3}$  and within a narrow range

of density that differs by no more than plus or minus  $0.7 \cdot 10^{11} \text{ cm}^{-3}$  (The one point measured at 1 mtorr for the  $\text{TM}_{012}$  mode falls below this range at  $1.2 \cdot 10^{11} \text{ cm}^{-3}$ ). The charge density of the magnetized discharge appears to be clamped near  $2.5 \cdot 10^{11} \text{ cm}^{-3}$ , increasing with very small slope for pressures between 15 and 4 mTorr and absorbed power levels between 130 and 330 Watts. The charge density is only weakly dependent on pressure,  $p$ , or absorbed power,  $P_{abs}$ , for these ranges.

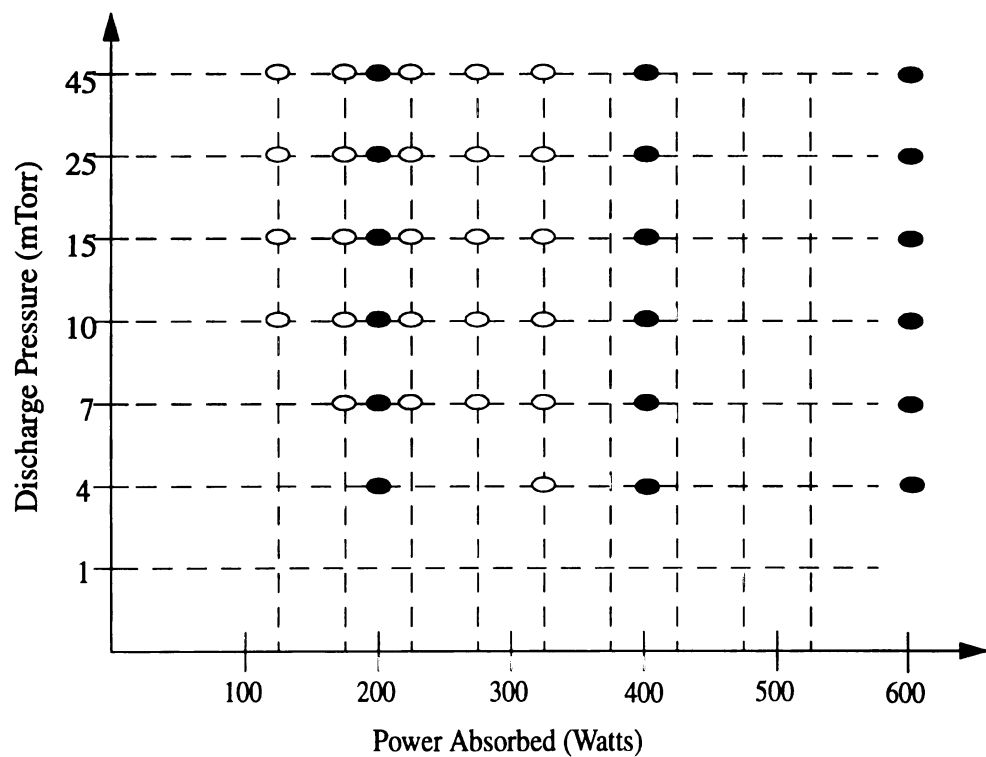
## **8.5 Electron Density Measurements Under the Conditions of High Incident Power (200W to 600W)**

A high power microwave source with maximum output of 1500 W was employed to investigate electron densities in the discharge at high incident power. The high power equipment setup is described in Section 3.5.

As shown in Figure 8.18 the range of power used in this experiment was from 200 to 600W. The range of pressures investigated was between 7 and 45 mTorr for the non-magnetized source and between 4 and 45 mTorr for the magnetized source.

In all the experiments using the 1500W capacity Cheung microwave power supply only the more stable near field mode was used. The  $TM_{012}$  mode could not be sustained for more than a few seconds due to frequency instability of the Cheung power supply. A spectrum analyzer was used to determine that this power supply had a working bandwidth of 15 MHz as well as random variations in center frequency. These random variations in center frequency were probably the cause of the inability to sustain the  $TM_{012}$  mode for greater than a few seconds. In earlier investigations P. Mak [Mak-97] also observed that the  $TM_{012}$  mode has a more narrow tuning range vs. cavity height (or frequency) and is more sensitive to detuning than the near field mode.

The non-magnetized charge density values, plotted in Figure 8.19, show distinctive "load line" behavior. This is similar to the plots at lower absorbed power levels, and is also what is predicted by the benchmark global plasma model. The dashed lines in Figure 8.19 show the global model predictions for 45 mTorr and 4 mTorr.



- parameter points where the high power (1500W) microwave source was used and where  $n_e$  and  $T_e$  ( $r = 0, z = 0$ ) was measured.
- parameter points where the 500W microwave power source was used. (This data was presented in Section 8.4)

Figure 8.18: Experimental parameter space vs. power absorbed and discharge pressure.

Magnetized charge density values, plotted in Figure 8.20, have trends similar to the low power experiments. Note the clamping of charge density near the  $2.5 \times 10^{11} \text{ cm}^{-3}$  range. Note also that the magnetized discharge density is much below that predicted by the global model. Again, the dashed lines show the global model predictions for 45 mTorr and 4 mTorr. An expanded view of the magnetized source charge density is shown in Figure 8.21. The maximum charge density reading was  $2.5 \times 10^{12} \text{ cm}^{-3}$  with an incident power of 600W at 45 mTorr.



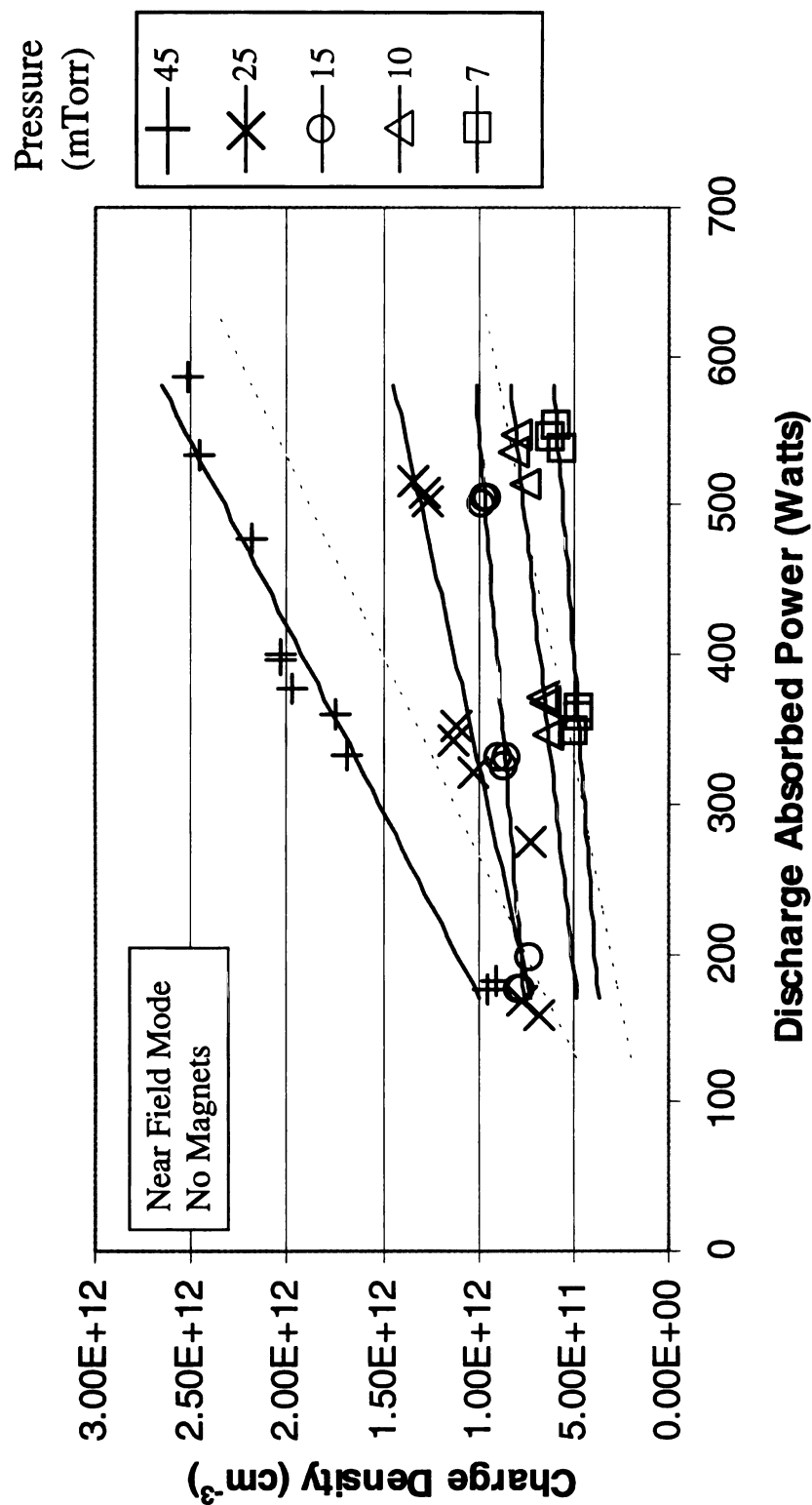


Figure 8.19: Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at five different discharge pressure levels for the Near Field mode with no magnets present. The 1500W capacity microwave source was used in this data set. Solid lines are least squares fit to the experimental data for each pressure. Dashed lines are global model prediction where the upper dashed line is for 45 mTorr and the lower dashed line is for 4 mTorr.

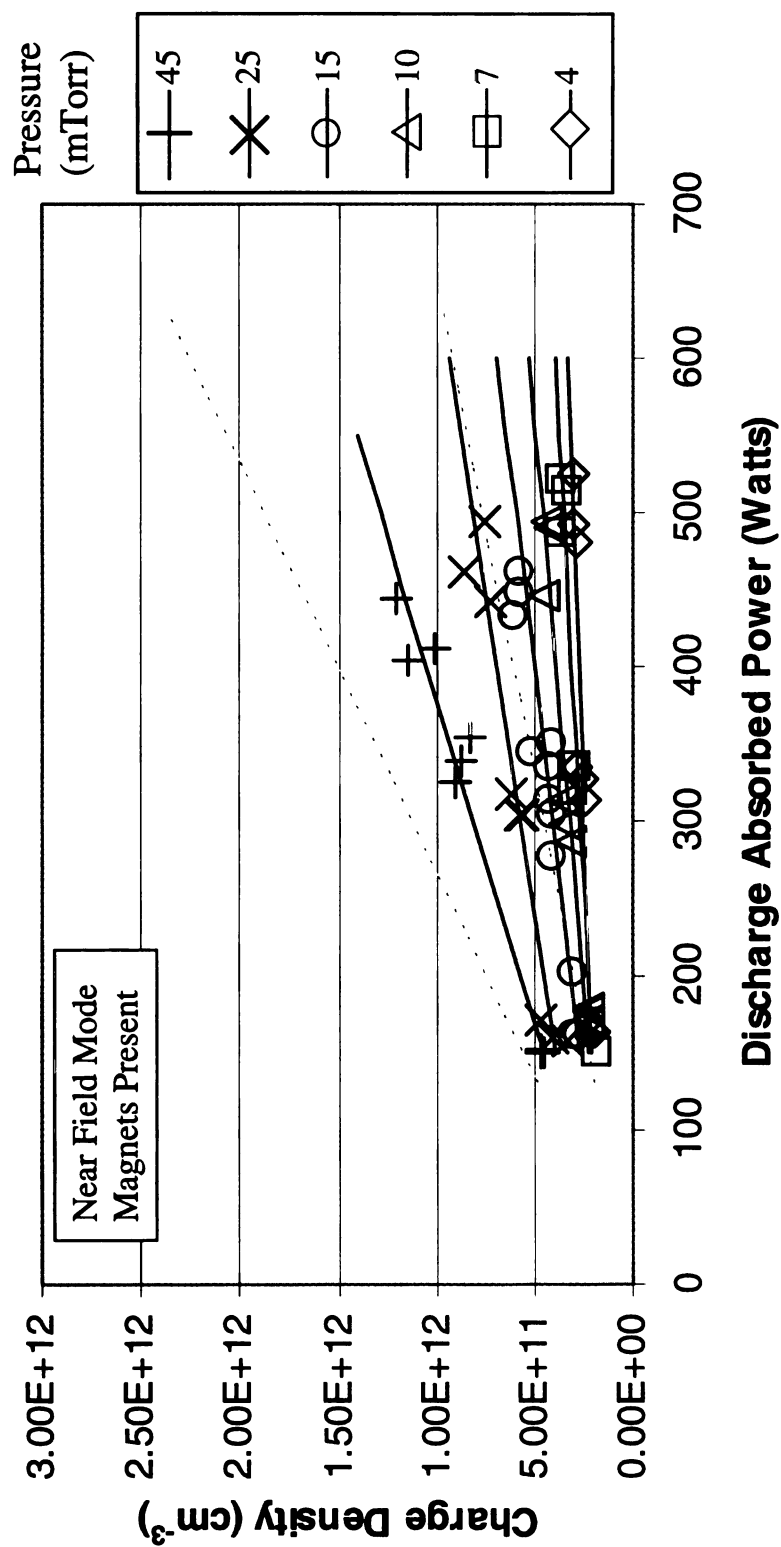


Figure 8.20: Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at six different discharge pressure levels for the Near Field mode with magnets present. The 1500W capacity microwave source was used in this data set. Solid lines are least squares fit to the experimental data for each pressure. Dashed lines are global model prediction where the upper dashed line is for 45 mtorr and the lower dashed line is for 4 mTorr.



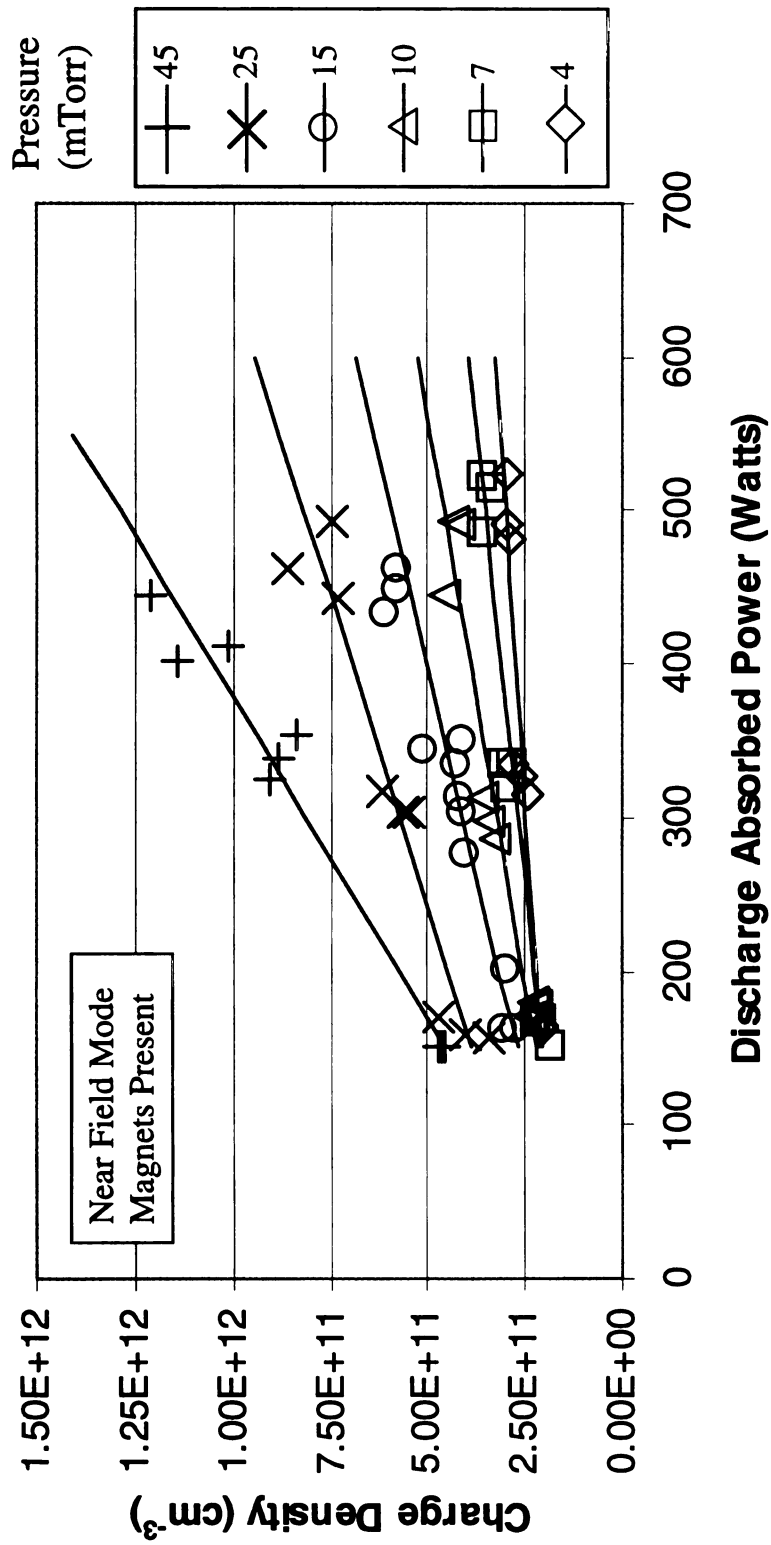


Figure 8.21: Charge density measured at  $r=0$  and  $z=0$  vs. absorbed power at six different discharge pressure levels for the Near Field mode with magnets present. This graph is an expanded view of Figure 8.20.

200

200

200

200

200

200

200

200

200

200

200

200

200

200

200

200

## 8.6 Radial Profiles of Charge Density and Relative Ion Saturation Current

In order to determine the radial profile of charge density,  $n_e$ , at the vertical position  $z=0$  (the discharge opening) single Langmuir probe  $n_e$  measurements were taken along a radial profile at  $z=0$ . These measurements were made for both magnetized and non-magnetized configurations. Charge density was determined using the same procedure as described in section 8.2. The single Langmuir probe was fastened to a rotating mechanical vacuum feed-through that allowed the probe to be scanned from the center to the edge ( $r=0$  cm to  $r=5.9$  cm) of the opening of the plasma discharge while maintaining a fixed height at  $z=0$  cm (at the discharge opening). This is identical to the setup described in Figure 5.1 in section 5.2.1. The radial location of the probe in the plasma was carefully correlated to corresponding position markings outside the vacuum chamber, so that the probe could be easily positioned to  $r=-5,-4,-3,-2,-1,0,1,2,3,4$ , and 5 cm from outside the chamber. Beginning at the center of the discharge, if the probe is swept toward the back wall of the chamber the positions are defined as negative: i.e. 0 to -5. If the probe is swept toward the front of the system the positions are defined as positive: i.e. 0 to 5 cm.

The absorbed power was held at 280 W for all the points in this profile experiment. The discharge pressures used were: 45 mtorr, 15 mtorr, and 7 mtorr. Both  $TM_{012}$  and near field modes are studied.

### 8.6.1 The Radial Distribution of Electron/Ion Density

Figure 8.22 shows radial profiles of charge density. These measurements were taken at 45 mTorr. Figure 8.23 shows similar measurements at 15 mTorr and likewise Figure 8.24 corresponds to measurements at 7 mTorr. Note charge density measurements were taken every 2 cm radially.

A theoretical approximation can be made for the radial charge density profile in a cylindrical plasma chamber. This approximating function is a parabolic curve with a center maximum value equal to the bulk charge density,  $n_0$ , and the value at the sheath edge  $r \sim R_A$  ( $R_A$  is the radial edge of the discharge chamber) given by  $n_0 * h_r$ , where  $h_r$  is the discharge pressure dependent global model parameter that relates bulk density to sheath edge density (see Section 6.2.2.1). The function is given as [God-86; p.99]:

$$n(r) = n_0 \left[ \frac{(h_r - 1)}{(R_A)^2} r^2 + 1 \right]. \quad \text{Eq. 8.11}$$

In Figures 8.22 - 8.24 the theoretical curves based on Equation 8.11 were plotted by fitting two points:  $n_0$  and  $h_r$ . The center density  $n_0$  was chosen to be the same as the measured center density and  $h_r$  was calculated from Equation 6.53. All experimentally measured  $n_e$  and  $I_s$  profiles across the diameter of the discharge opening have a general parabolic shape and compare well with the theoretically predicted profiles. This is true for both magnetized and non-magnetized configurations, as well as, both the TM<sub>012</sub> and near field modes. However, at 45 mTorr (Figure 8.22) the experimental profiles appear to have less curvature (i.e. are flatter and more uniform) than the predicted profile. This

flattening of these profiles may be due to the largest proportion of charge density being created in the microwave skin depth near the quartz wall regions and then diffusing into the center of the discharge.

The parabolic shape of all profiles measured clearly demonstrates that the differences in charge density observed in section 8.4 between magnetized and non-magnetized discharges are not due to local variations in density profiles, but to differences in total charge density output.

In order to calculate the total ion flux the curvature of the parabolic profile must be estimated. The value of density measured at  $r=-4$  cm or  $r=+4$  cm is approximately 70% of the center density for all of the profiles observed. This allows an approximate radial function of ion saturation current, similar to Eq. 8.11, to be determined, and hence integrated over the discharge opening to determine the total output ion flux.

### **8.6.2 Comparison Between Magnetized and Non-Magnetized Configurations**

In Figure 8.22 we can see that the non-magnetized density profile (for both modes) at 45 mtorr is approximately 1.4 times higher than the profile for the magnetized configuration. At 15 mtorr (see Figure 8.23) the non-magnetized profile is approximately 2.1 times higher than the magnetized profile and at 7 mTorr (see Figure 8.24) the non-magnetized profile is approximately 1.4 times the magnetized profile. These findings are consistent with the differences in density for magnetized and non-magnetized configurations found in Figures 8.10-8.13.



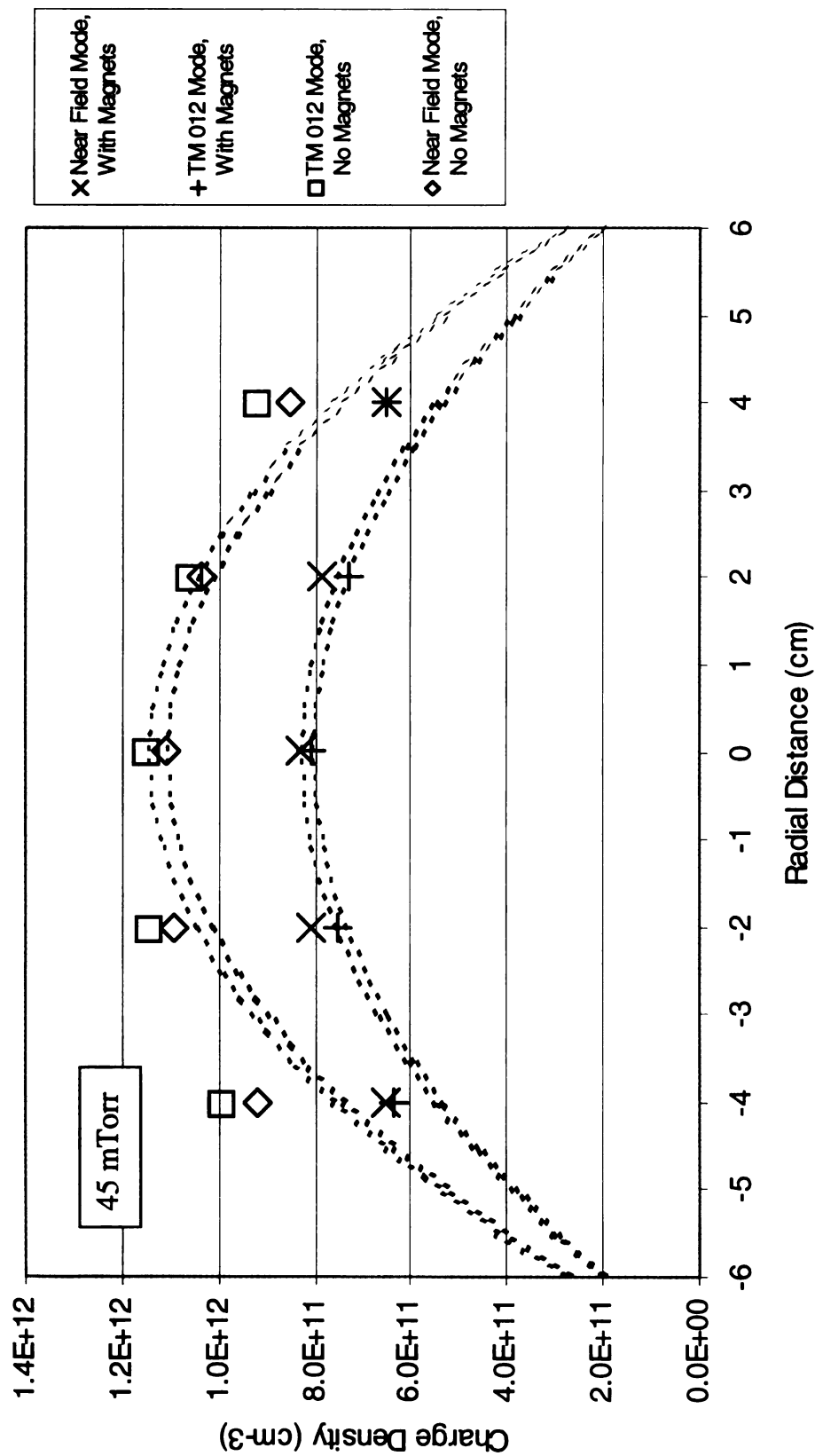


Figure 8.22 – Radial profiles of SLP measured charge density at 45 mTorr. Density profiles of both magnetized and non-magnetized for TM<sub>012</sub> and near field modes are displayed. Dashed lines are a parabolic fit through two points: the measured center density point and the global model predicted edge density at  $r=6.5$  cm. Note: y-axis data range is 0 to  $1.4 \times 10^{12} \text{ cm}^{-3}$ .





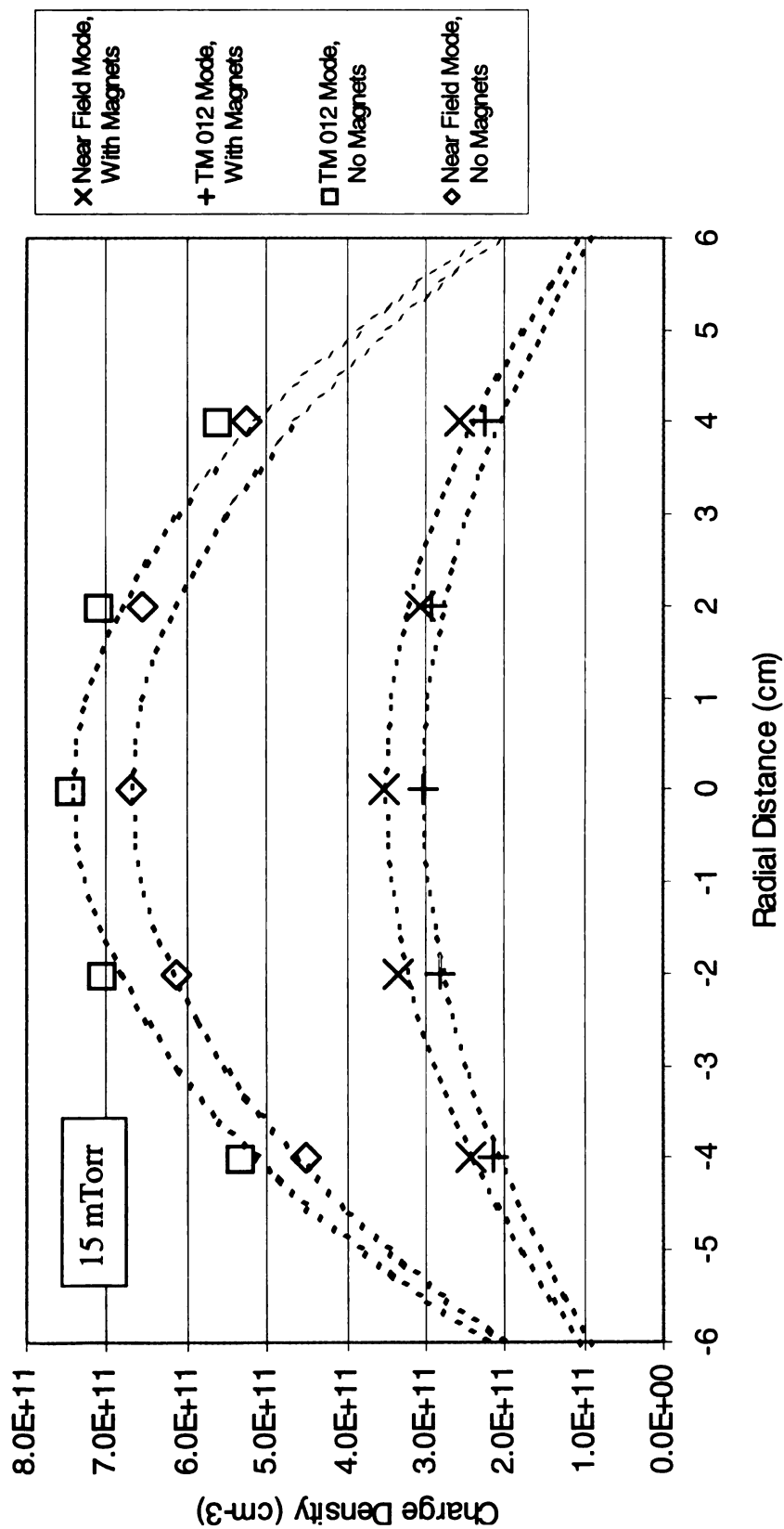


Figure 8.23 – Radial profiles of SLP measured charge density at 15 mTorr. Density profiles of both magnetized and non-magnetized for TM<sub>012</sub> and near field modes are displayed. Dashed lines are a parabolic fit through two points: the measured center density point and the global model predicted edge density at  $r=6.5$  cm. Note: y-axis data range is  $0$  to  $8 \times 10^{12} \text{ cm}^{-3}$ .

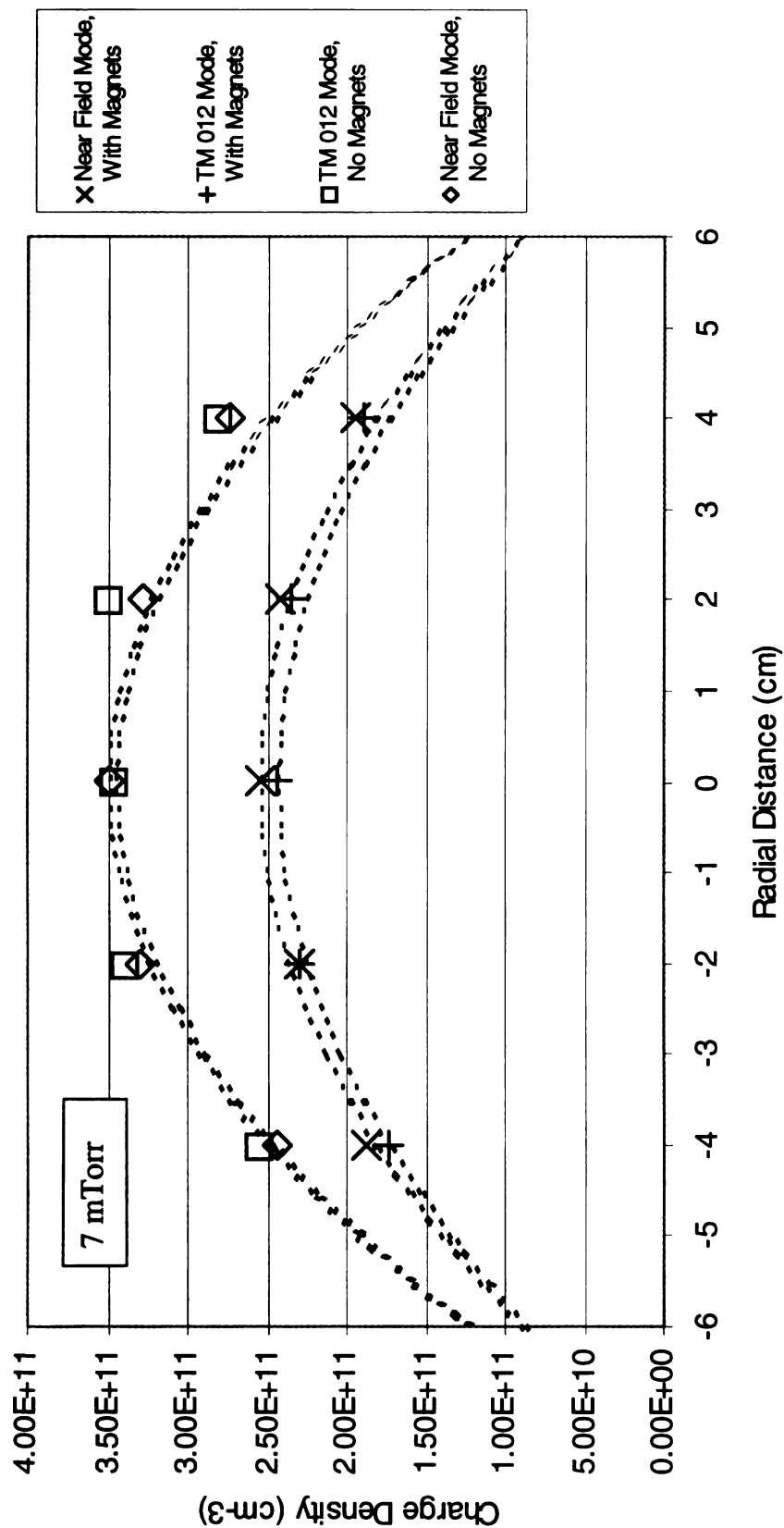


Figure 8.24 – Radial profiles of SLP measured charge density at 7 mTorr. Density profiles of both magnetized and non-magnetized for TM<sub>012</sub> and near field modes are displayed. Dashed lines are a parabolic fit through two points: the measured center density point and the global model predicted edge density at  $r=6.5$  cm. Note: y-axis data range is 0 to  $4 \times 10^{12}$  cm<sup>-3</sup>.

Measurements of charge density at  $r=0$ ,  $z=0$  from Section 8.4 show that the magnetized configuration has higher charge density than the non-magnetized case at 4 mTorr. There appears to be a transition in plasma discharge properties between 7 and 4 mTorr that make the magnetized configuration a more efficient producer of charge density than the non-magnetized configuration at pressures below  $\sim 5$  mTorr.

### **8.6.3 Comparison Between $TM_{012}$ and Near Field Modes**

No significantly large difference in density is observed between the  $TM_{012}$  mode and the near field mode for 7, 15, or 45 mTorr or regardless of magnetic configuration.

## 8.7 Axial Variation of $I_s$ Measurements

As discussed in Sections 8.4, 8.5, and 8.6 the charge density measured at the output of the discharge is lower for the magnetized discharge than for the non-magnetized discharge. To investigate this difference in more detail a measurement of the ion saturation current,  $I_s$ , at discrete points up into the discharge was required. Charge density measurements were not made inside the discharge dome since the possible extreme conditions (heat, microwave radiation, etc.) there required short sample times. Hence only  $I_s$  measurements were made, since they could be performed quickly without excessive heating of the probe.

A single Langmuir probe apparatus was fastened to a vacuum feed-through (the same feed through used in sections 8.4-8.6 and described in section 5.2.1) with linear and rotational degrees of freedom. This feed through allowed the probe to be scanned from  $z=0$  cm to  $z=10.25$  cm above the opening of the plasma discharge. Single Langmuir probe  $I_s$  measurements were taken at 1 cm intervals along the axis of the discharge (at  $r=0$ ) from  $z=0$  to  $z=9$  cm as shown in Figures 8.25-8.30. Measurements were limited to positions less than  $z=9$  cm (i.e. 1.25 cm down from the top of the quartz discharge chamber) to avoid coupling of microwave energy into the probe. These axial  $I_s$  measurements were made for both magnetized and non-magnetized configurations. The  $TM_{012}$  cavity mode was used in all of the axial  $I_s$  measurements. The absorbed power was held at 280 W for all the points in this experiment.

$I_s$  measurements were taken both moving up into the discharge and down out of the discharge. Due to heating of the probe in the discharge dome volume the  $I_s$  value was

consistently higher on the downward path by about 0.1 mA than the upward path. This increase in probe current on the downward path was likely due to increased thermionic emission of electrons from the probe tip, hence for simplicity only the upward traveling  $I_s$  measurements are shown in Figures 8.25-8.30.

### 8.7.1 Observations from Axial $I_s$ measurements

From the axial  $I_s$  measurements plotted in Figures 8.25-8.30 several observations can be made.

The first observation, which is consistent with data from sections 8.4-8.6, is that the  $I_s$  value at the opening of the discharge ( $z=0$ ) is in all cases (i.e. 45 mTorr to 7 mTorr) is less for the magnetized discharge than for the non-magnetized discharge. This indicates that the charge density is greater at the discharge opening for the non-magnetized discharges (as was shown in Sections 8.4-8.6).

The next observation is that the peak  $I_s$  location, and hence the location of peak charge density, along the  $z$  axis is different for magnetized and non-magnetized cases. The peak  $I_s$  for magnetized discharges consistently occurs near or above  $z=7$ cm which coincides with the top of the multipolar magnet array (note: the position of the magnet array is shown graphically in each figure 8.25-8.30). The peak  $I_s$  for the non-magnetized configuration is near the geometric center of the discharge chamber at  $z=5$  cm at a pressure of 45 mTorr. As pressure is decreased however the peak  $I_s$  location moves upward (i.e.  $z=5.5$  for 25 mTorr,  $z=6.5$  for 15 and 10 mTorr, and  $z=7$ cm for 7 mtorr). This may be the result of the open end of the discharge. While the discharge walls at the

top and side of the plasma reflect low energy electrons with their electrostatic sheath, electrons may diffuse out from the open end of the discharge with increasing freedom as the mean free path increases at lower pressures. It also may have something to do with where the microwave heating occurs. As the discharge pressure and charge density decrease the skin depth increases and microwave heating volumes may change. Skin depth is discussed in more detail in section 8.8.

Another observation is that the  $I_s$  value and charge density decrease moving out of the discharge away from the  $I_s$  peak. Since the peak  $I_s$  for the magnetized discharge occurs higher in the discharge than for the non-magnetized case, the  $I_s$  value decays to a much lower value for the magnetized discharge at the opening of the discharge than for the non-magnetized case. The skin depth may be smaller for the magnetized source and larger for the non-magnetized source. However, the presence of the magnetic field may allow some EM propagation into the plasma along the field lines. The electron excitation may occur at a higher or thinner layer for the magnetized discharge than for a non-magnetized discharge.

At 45 mTorr, 10 mTorr, and 7 mTorr the peak  $I_s$  value for the magnetized discharge is greater than the peak  $I_s$  value for the non-magnetized discharge, indicating a higher peak charge density up into the discharge for the magnetized case. The peak  $I_s$  values at 25 and 15 mTorr for the non-magnetized case appear to be higher in value than the magnetized cases. However, the  $I_s$  values near the top of the discharge are measured to be comparable or higher in all cases for the magnetized discharge over the non-magnetized discharge.

The above observations indicate that while similar orders of magnitude of charge density are measured in both magnetized and non-magnetized discharges the magnetic fields act to effectively confine (concentrate) this charge density and prevent it from reaching the opening of the discharge. Magnetic fields reduce diffusion out of the source, except at the low pressures.

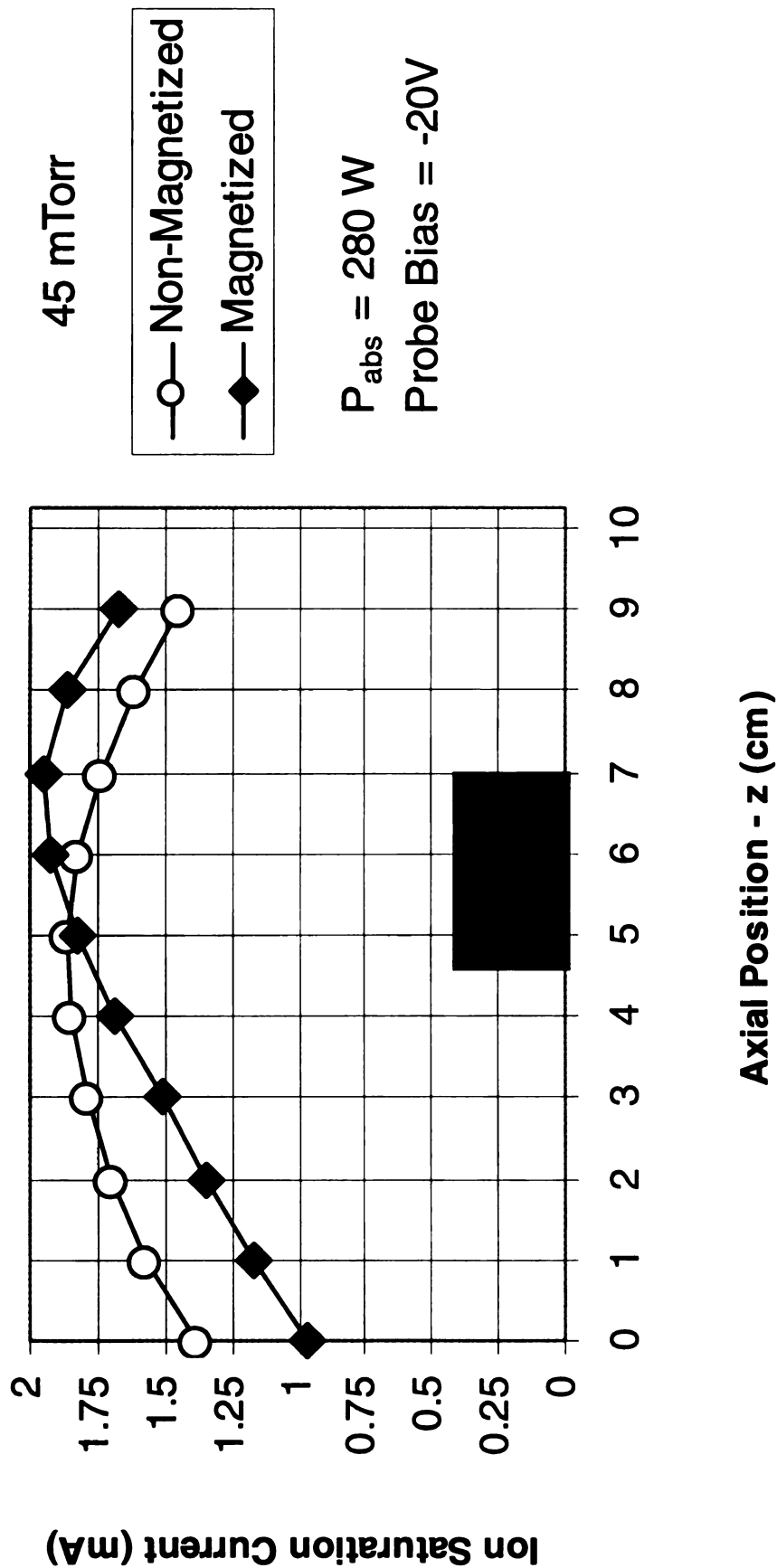


Figure 8.25 - Ion saturation current vs. axial position into the discharge at 45 mTorr.  $z=0$  cm is the discharge chamber opening and  $z=10.25$  cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between  $z=4.5$  cm and  $z=7$  cm as shown in the figure.



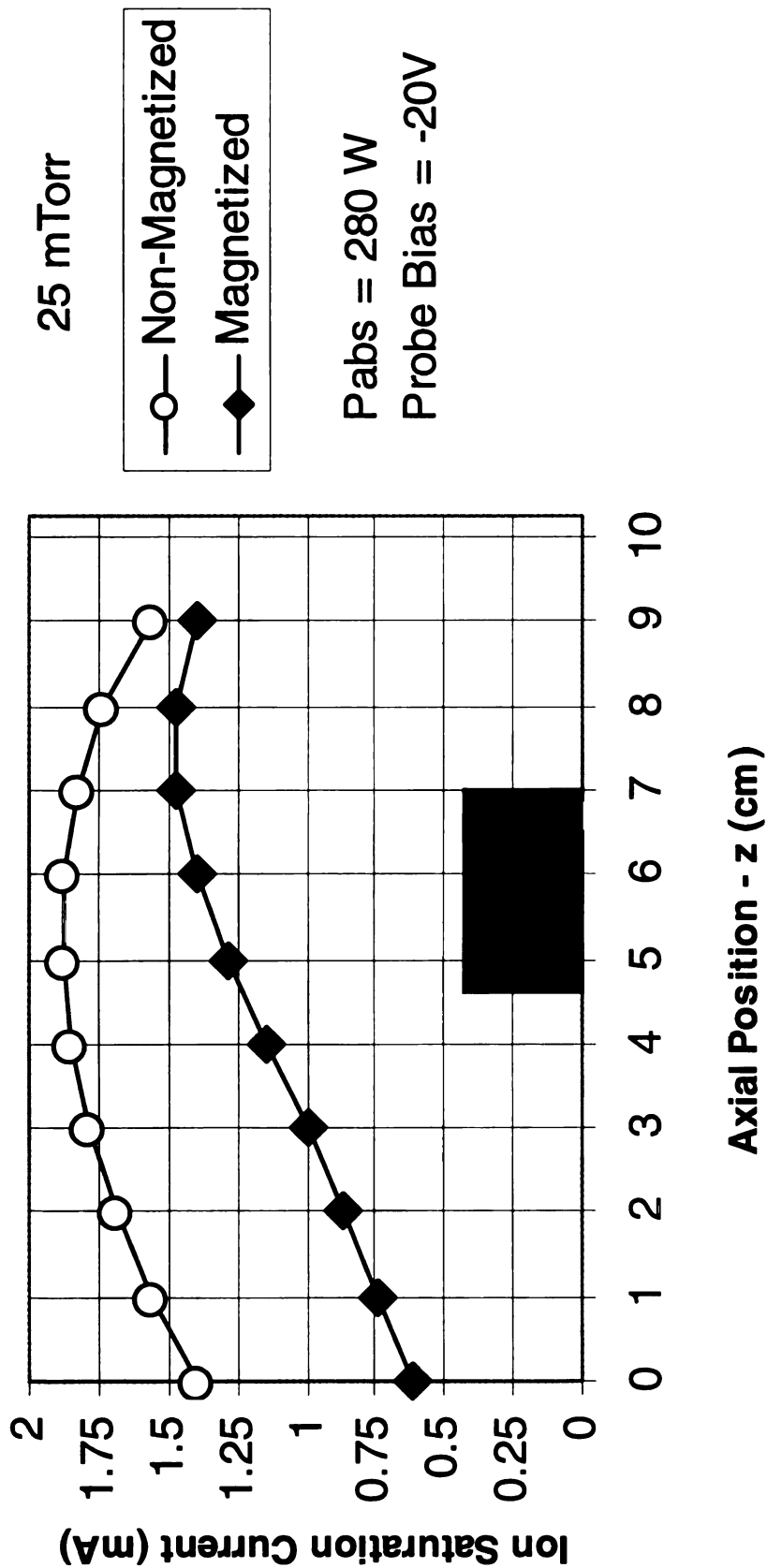


Figure 8.26 - Ion saturation current vs. axial position into the discharge at 25 mTorr.  $z=0$  cm is the discharge chamber opening and  $z=10.25$  cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between  $z=4.5$  cm and  $z=7$  cm as shown in the figure.

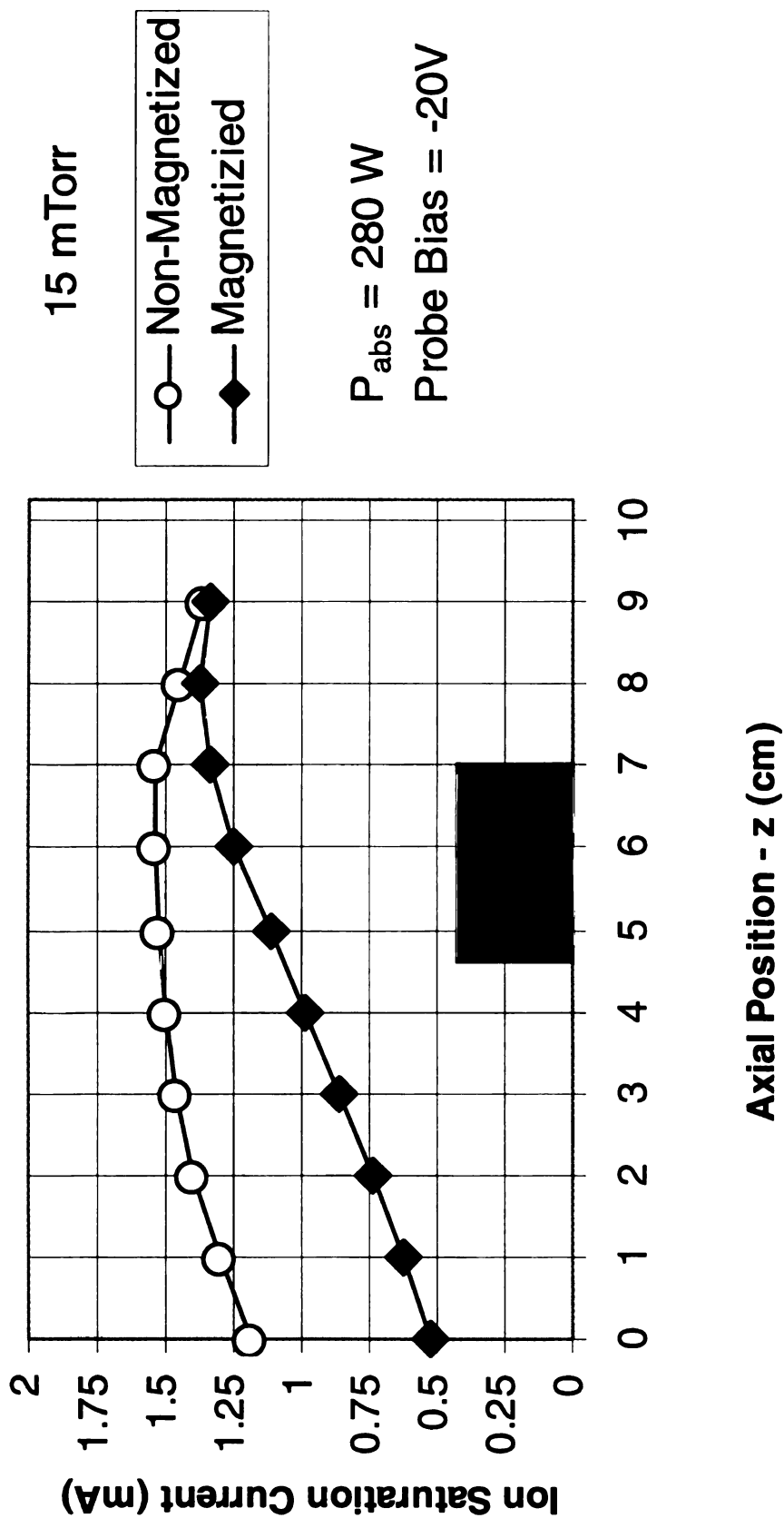


Figure 8.27 - Ion saturation current vs. axial position into the discharge at 15 mTorr.  $z=0$  cm is the discharge chamber opening and  $z=10.25$  cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between  $z=4.5$  cm and  $z=7$  cm as shown in the figure.

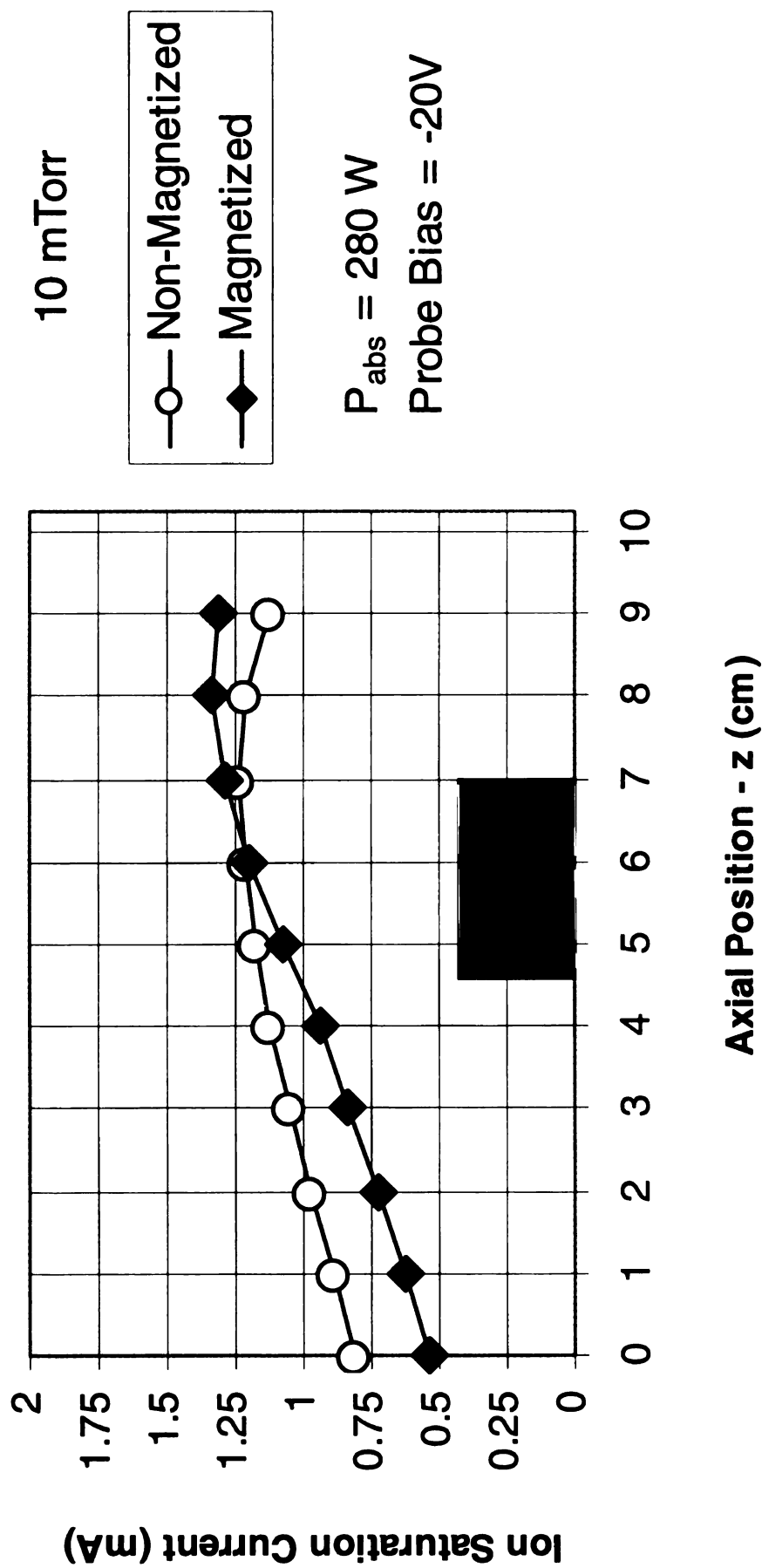


Figure 8.28 - Ion saturation current vs. axial position into the discharge at 10 mTorr.  $z=0$  cm is the discharge chamber opening and  $z=10.25$  cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between  $z=4.5$  cm and  $z=7$  cm as shown in the figure.

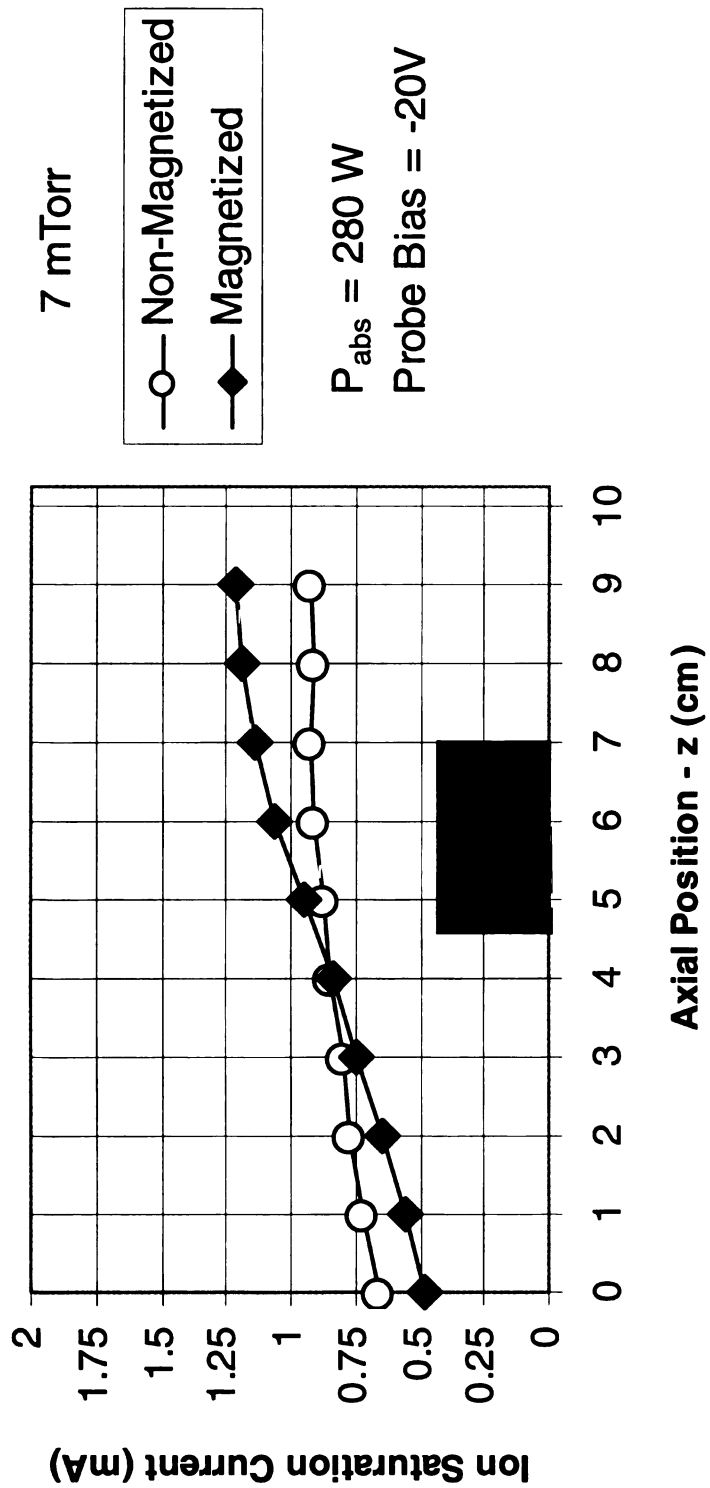


Figure 8.29 - Ion saturation current vs. axial position into the discharge at 7 mTorr.  $z=0$  cm is the discharge chamber opening and  $z=10.25$  cm is inside top of the quartz discharge chamber. For the magnetized discharge the multipolar magnet array occupies the space between  $z=4.5$  cm and  $z=7$  cm as shown in the figure.

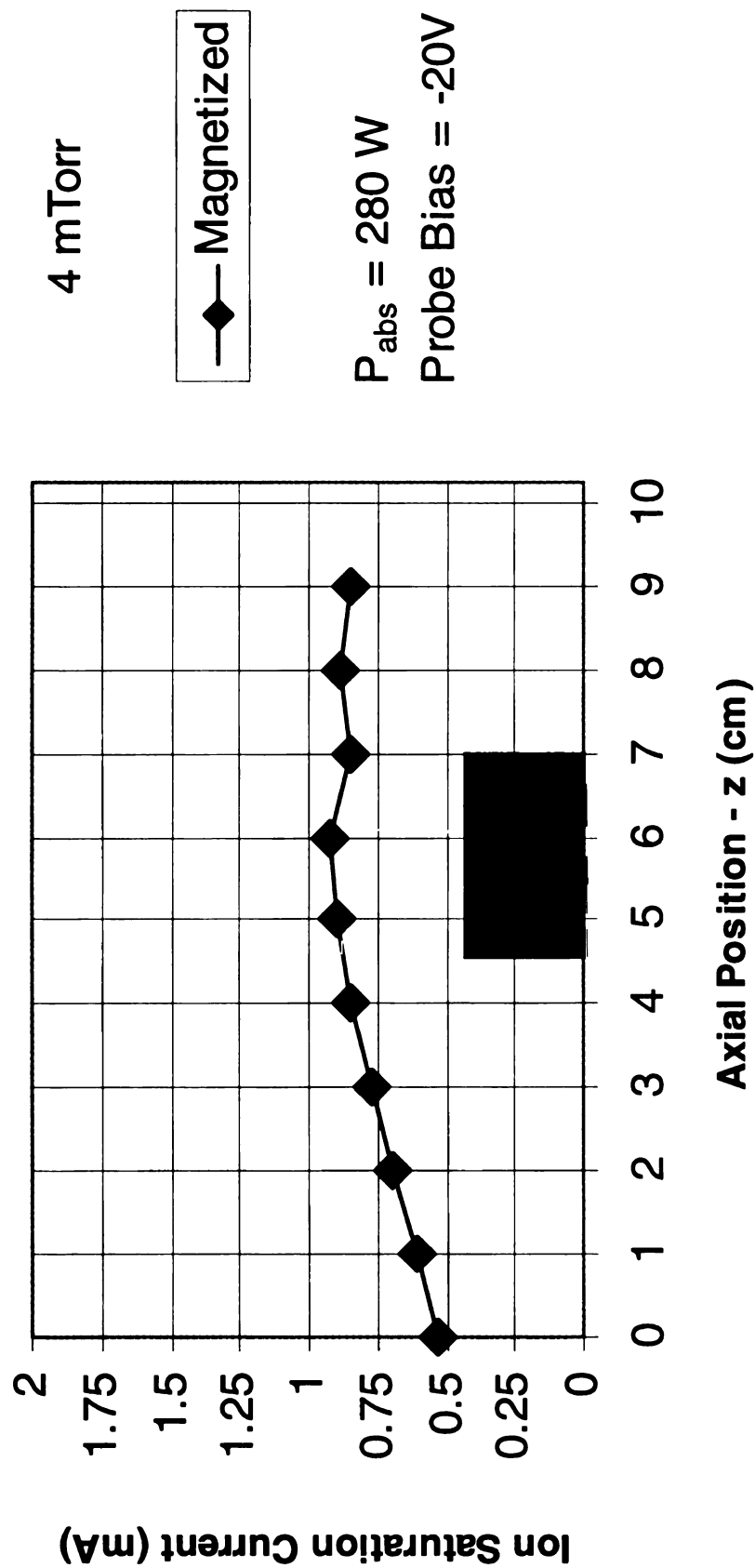


Figure 8.30 - Ion saturation current vs. axial position into the discharge at 4 mTorr.  $z=0$  cm is the discharge chamber opening and  $z=10.25$  cm is inside top of the quartz discharge chamber. For the magnetized the position of the multipolar magnet array occupies the space between  $z=4.5$  cm and  $z=7$  cm as shown in the figure.

## 8.8 Skin Depth of The Plasma

Now that we have a good estimate for charge density in the discharge near the top of the discharge dome (from section 8.7) it is possible to estimate the plasma skin depth. The skin depth,  $\delta$ , of a discharge can be calculated from the following equation [Gro-99]:

$$\frac{1}{\delta} = -\text{Imag} \left[ \frac{1}{c} \left( \omega^2 - \frac{\omega_{pe}^2}{1 + \left(\frac{\nu_m}{\omega}\right)^2} - j \frac{\omega_{pe}^2 \left(\frac{\nu_m}{\omega}\right)}{1 + \left(\frac{\nu_m}{\omega}\right)^2} \right)^{\frac{1}{2}} \right] \quad \text{Eq. 8.12}$$

where  $c$  is the speed of light,  $\omega$  is the excitation frequency,  $\omega_{pe}$  is the plasma frequency and  $\nu_m$  is the collision frequency for momentum transfer.

For discharges where the electron temperatures are between 2-4 eV a rough estimate for  $\nu_m$  can be obtained by multiplying the discharge pressure by  $10^6$  ( $\text{s}^{-1} \text{ mTorr}^{-1}$ ). For discharges of 4-45 mTorr  $\nu_m$  falls in the range of  $10^7$  to  $10^8$  ( $\text{s}^{-1}$ ). For  $2.45 \times 10^9$  Hz microwave excitation  $\omega = 1.54 \times 10^{10}$  1/s. Thus  $\omega$  is 2 orders of magnitude greater than the collision frequency (i.e.  $\omega \gg \nu_m$ ). This allows Equation 8.12 to be simplified to the collisionless skin depth equation, also provided that  $\omega_{pe} > \omega$  (i.e. the discharge density is greater than the critical density). The collisionless skin depth equation is [Gro-99]:

$$\delta = \left( \frac{m_e}{e^2 \mu_0 n} \right)^{1/2} \quad \text{Eq. 8.13}$$

where  $m_e$  is the mass of an electron,  $e$  is the electron charge,  $\mu_0$  is the permeability of free space, and  $n$  is charge density. The above equation is plotted vs. charge density in Figure 8.31.

The skin depth for the discharge described in this investigation can be calculated from Eq. 8.13 if a good estimate of charge density is known near the quartz wall. A range of discharge densities vs. discharge pressure for 280W absorbed power can be obtained from the data in section 8.4. However, this data was taken at  $z=0$  and  $r=0$ cm at the bottom of the discharge (the center of the discharge opening). The charge density near the top of the quartz dome can be estimated using the data and figures in section 8.7. It is assumed that the ion saturation current in Figures 8.25 to 8.30 is directly proportional to charge density. Given the charge density at  $z=0$  the charge density at  $z=10$  cm can be estimated as shown in Table 8.2. Estimated charge density and calculated skin depth are plotted in Figure 8.32.

**Table 8.2**

Calculation of Estimated Charge Density and Skin Depth for a range of pressures and an absorbed power of 280W.

| Discharge Pressure (mTorr) | Magnet Config. | Charge Density at $r=0, z=0$ cm (cm-3) | Estimated Density at $r=0, z=10$ cm (cm-3) | Calculated Skin Depth (cm) |
|----------------------------|----------------|----------------------------------------|--------------------------------------------|----------------------------|
| 4                          | Magnetized     | 2.6E+11                                | 3.9E+11                                    | 0.86                       |
|                            | Non-Mag.       | --                                     | --                                         | --                         |
| 7                          | Magnetized     | 2.2E+11                                | 5.3E+11                                    | 0.73                       |
|                            | Non-Mag.       | 3.8E+11                                | 4.8E+11                                    | 0.77                       |
| 10                         | Magnetized     | 3.1E+11                                | 7.7E+11                                    | 0.61                       |
|                            | Non-Mag.       | 4.3E+11                                | 5.8E+11                                    | 0.70                       |
| 15                         | Magnetized     | 2.9E+11                                | 7.2E+11                                    | 0.63                       |
|                            | Non-Mag.       | 7.5E+11                                | 7.5E+11                                    | 0.61                       |
| 25                         | Magnetized     | 3.8E+11                                | 7.9E+11                                    | 0.60                       |
|                            | Non-Mag.       | 9.9E+11                                | 9.9E+11                                    | 0.53                       |
| 45                         | Magnetized     | 8.7E+11                                | 1.1E+12                                    | 0.51                       |
|                            | Non-Mag.       | 1.2E+12                                | 1.1E+12                                    | 0.52                       |

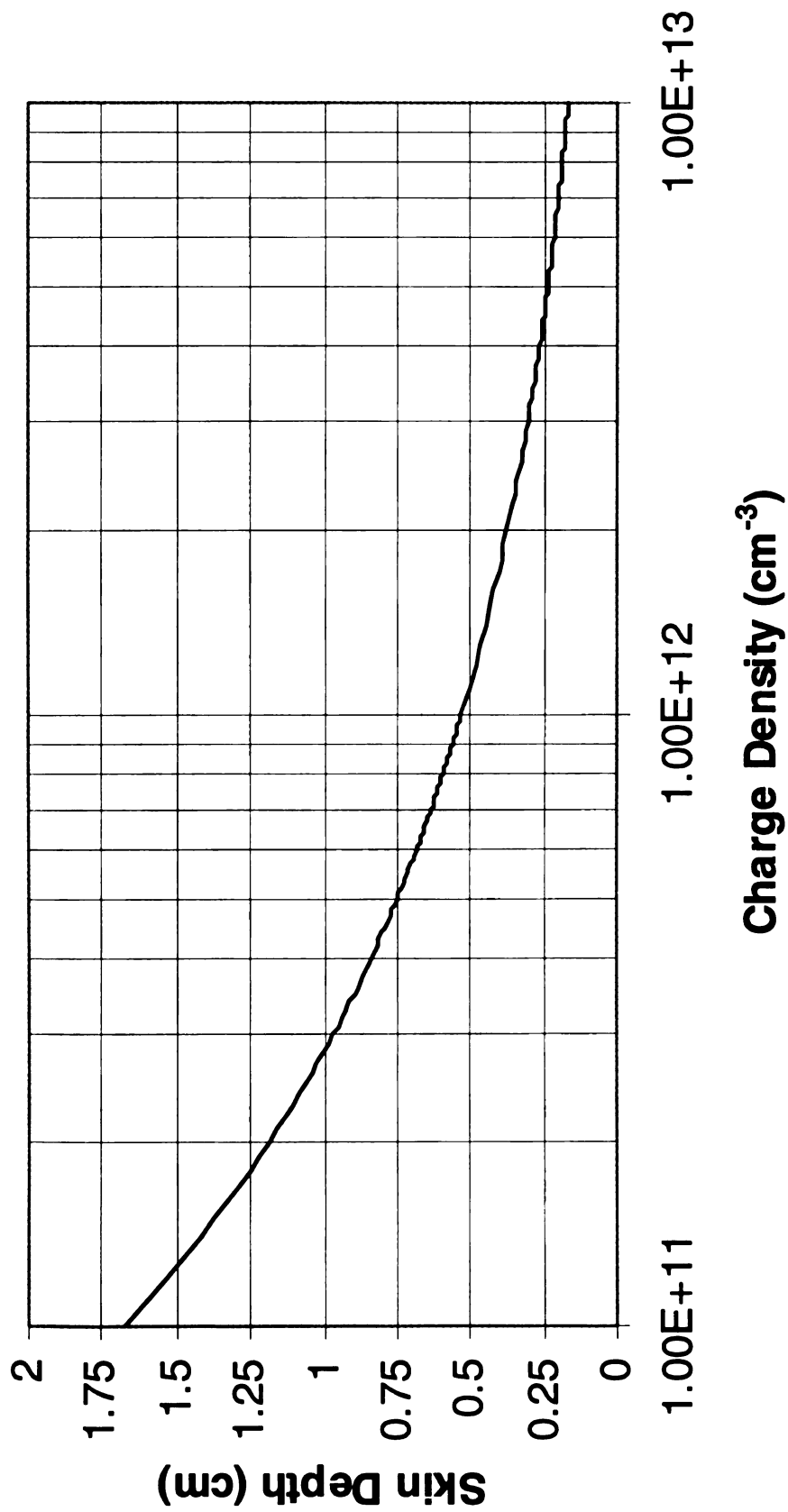


Figure 8.31: Collisionless skin depth vs. plasma charge density for 2.45 GHz incident microwave radiation.



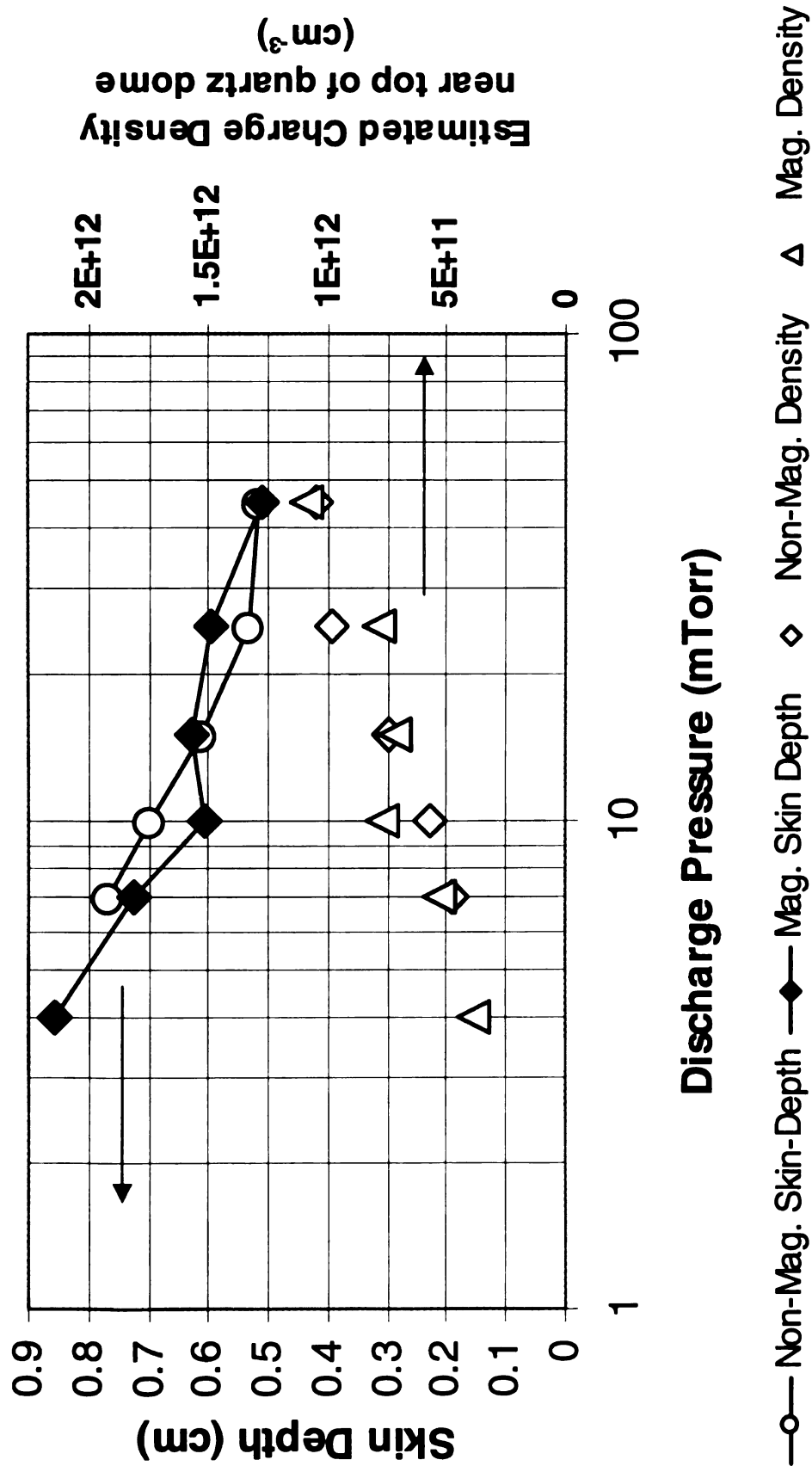


Figure 8.32 – Estimated charge density near the top of the quartz dome and calculated skin depth vs. discharge for the magnetized and non-magnetized discharges. The absorbed power was 280 W. Note: this curve is specific to absorbed power level, i.e. higher or lower power levels will change charge density and skin depth.

Note Table 8.2 and Figure 8.32 are for a specific absorbed power of 280 W. If the absorbed power is changed the charge density and skin depth will change as a result. As can be observed in Figure 8.31 the skin depth for the discharge in this investigation is typically between 0.25 cm and 1.5 cm. Recall that the discharge has a 10.25 cm height and 6.5 cm radius. The skin depth confines the microwave excitation region to within three centimeters from the quartz wall.

### **8.9 Visual Images of the Plasma Discharge**

Sections 8.4-8.7 have mapped the charge density vs. power and pressure, and spatially vs.  $r$  and  $z$ . However, valuable information can also be gained by visual inspection of the plasma discharge. Digital photographs were taken for both magnetized and non-magnetized discharges for pressures of 7, 15, and 45 mTorr. The electromagnetic mode used was the  $TM_{012}$  mode. The absorbed power was 280W. Two angles of view were photographed. The view shown in Figure 8.33 was taken looking up from the bottom of the discharge. A mirror was used so that this view could be obtained by looking through window on the side of the process chamber. The view shown in Figure 8.34 was a side view of the plasma streaming out of the discharge chamber above. This view was also photographed through a window on the side of the process chamber.

Several observations can be made from Figures 8.33 and 8.34. In figure 8.33 the color of light emitted from the plasma changes from a deep blue at 7 mTorr to a light purple at 45 mTorr. The color change is present in both magnetized and non-magnetized discharges, but appears more evident in the non-magnetized discharge. This color change

is likely due to a change in the collection of argon energy states excited as electron temperature changes with pressure. The eight lobe-like plasma structures (caused by magnetic confinement of the plasma) visible in the magnetized discharge appear to shrink toward the walls as plasma pressure is increased. The electron mean free path is large at 7 mtorr allowing electrons that are heated near the walls to diffuse into the discharge and to excite argon neutrals several centimeters into the plasma. However, at higher pressures the electron mean free path decreases (and skin depth) keeping the hot electrons more near to the microwave excitation zones. Note, the tip of the probe antenna and plate of the sliding short are visible in the background through the quartz dome.

In Figure 8.34 the opening of the plasma discharge can be seen as a bright disk at the top of each picture. At 7 mTorr in the non-magnetized discharge a blue stream of plasma is seen to be emitted from the discharge opening. This plasma stream decreases in intensity as pressure is increased for the non-magnetized discharge. This is probably due to decreasing electron mean free path at higher pressures. For the magnetized discharge a plasma stream is not very pronounced and looks similar in intensity for all pressures. Magnetic confinement likely prevents hot electrons from streaming out of the discharge at all pressures of 7, 15 and 45 mTorr. Note: the circular structure in the background is a chamber window covered with aluminum foil. A withdrawn Langmuir probe can also be seen in front of this window.

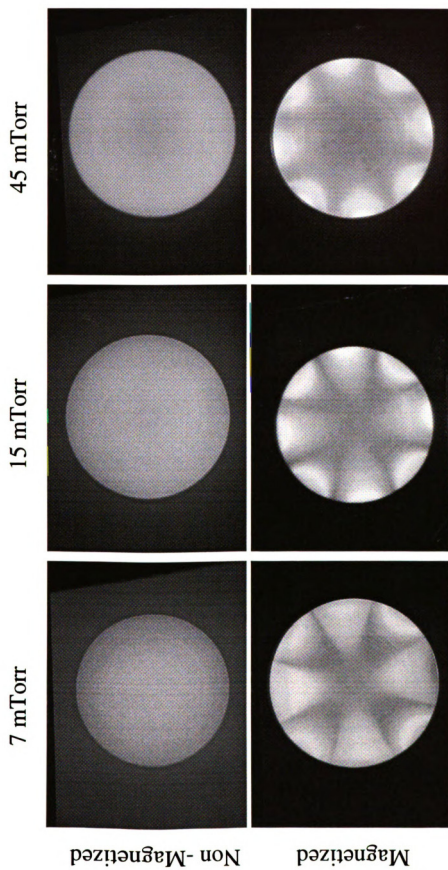


Figure 8.33 - Photographs of the plasma discharge seen looking up into the discharge from the process chamber. The discharge absorbed power was 280 W. The electromagnetic mode was the  $TM_{0,2}$  mode.

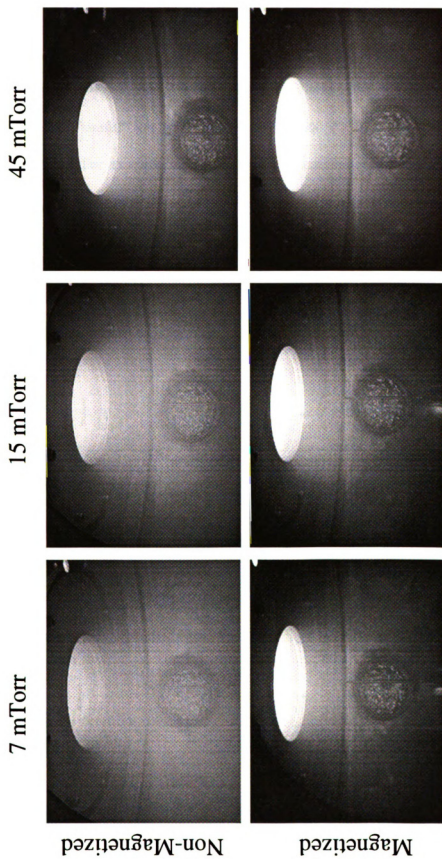


Figure 8.34 - Photographs of the plasma discharge seen looking through the chamber side window. The discharge absorbed power was 280 W. The electromagnetic mode was the  $TM_{012}$  mode.

### 8.10 Ion Production Cost - eV/Ion efficiency

The definition of ion production cost,  $\eta_{ion}$ , is the total amount of energy required to produce one “useful” ion, and is measured in units of eV/Ion (or Watts per amp of ion output current). For example, in sputter etch applications only those ions that strike the wafer are useful, all others lost to the discharge walls are, in effect, wasted. A general means of defining ion production cost for a plasma source involves defining a plasma output boundary with area  $A$ , see Figure 8.35. The net ion current that flows across this boundary is defined as the useful ion current.

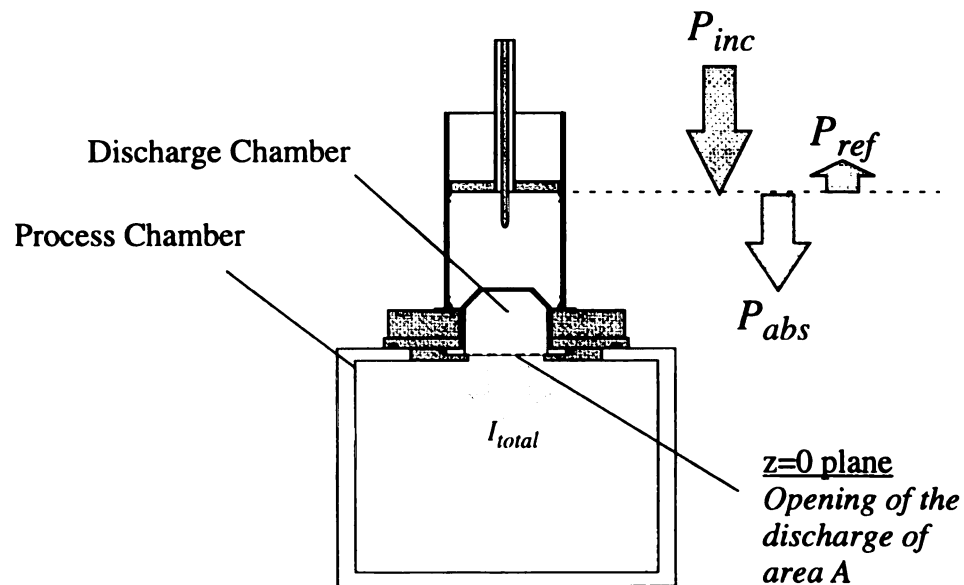


Figure 8.35: Diagram illustrating the concept of Ion Production Cost

The ion production cost can be calculated by dividing the total power absorbed in the discharge,  $P_{abs}$  ( $P_{abs} = P_{inc} - P_{ref}$ ), by the net ion current,  $I_{total}$ , streaming out of the discharge into the processing region. This is described mathematically as:

$$\eta_{ion} = \frac{P_{abs}}{I_{total}} = \frac{P_{abs}}{\int_A J dS} \quad \text{Eq. 8.14}$$

where  $A$  is the defined area of the opening of the discharge, and  $J$  is the ion current density directed out of the discharge through area  $A$ .

### 8.10.1 Experimental Measurement of Ion Production Cost

This experimental method uses the measured gradient of charge density in the axial direction to estimate ion flux. Two or more closely spaced (1cm or less) measurements of charge density are made along the central axis of the discharge using a single Langmuir probe. With these measurements the axial gradient of charge density can be estimated. Depending on the plasma pressure regime (the intermediate pressure regime for the case discussed here, also known as the variable mobility regime, see Lieberman 5.3) the gradient of density can be used to calculate ion current density in the axial direction. For the variable mobility regime the ion velocity,  $u_i$ , is given as (Eq. 5.3.5 Lieberman):

$$u_i^2 = \frac{k_b T_e}{M} \left( \frac{2}{\pi} \right) \left( \frac{\lambda_i}{n} \right) \left( \frac{\partial n}{\partial x} \right) \quad \text{Eq. 8.15}$$

where  $k_b$  is boltzmann's constant,  $T_e$  is the electron temperature in Kelvin,  $M$  is the mass of an Ion,  $\lambda_i$  is the ion mean free path,  $n$  is the local charge density which is a function of distance  $x$ .

From the above equation we can derive an expression for the magnitude of ion flux density:

$$|\Gamma_i| = u_i n = \sqrt{\frac{\lambda_i k T_e}{M} \left(\frac{2}{\pi}\right) \left(n \left|\frac{dn}{dx}\right|\right)} \quad \text{Eq. 8.16}$$

From this we can calculate the ion current density,  $J$ , integrate  $J$  over area  $A$ , and determine the approximate ion production cost.

### 8.10.2 Comparison of Measured Ion Production Cost vs. Global Model Prediction

Calculations based on the above method are plotted in Figure 8.36 and compared to the global model prediction. Values for the global model prediction are calculated from Eq. 6.131. For the non-magnetized case the measured ion production cost follows the global model prediction fairly well at higher pressures from 15 to 45 mTorr. However it becomes much larger than global model prediction at pressures of 10 and 7 mTorr. This may be due to discrepancies between the open ended discharge and closed ended discharge model predictions. An open ended model may show this eV/ion behavior.

The magnetized case shows a much higher ion production cost than both the non-magnetized case and the global model, except for the highest and lowest pressures. At



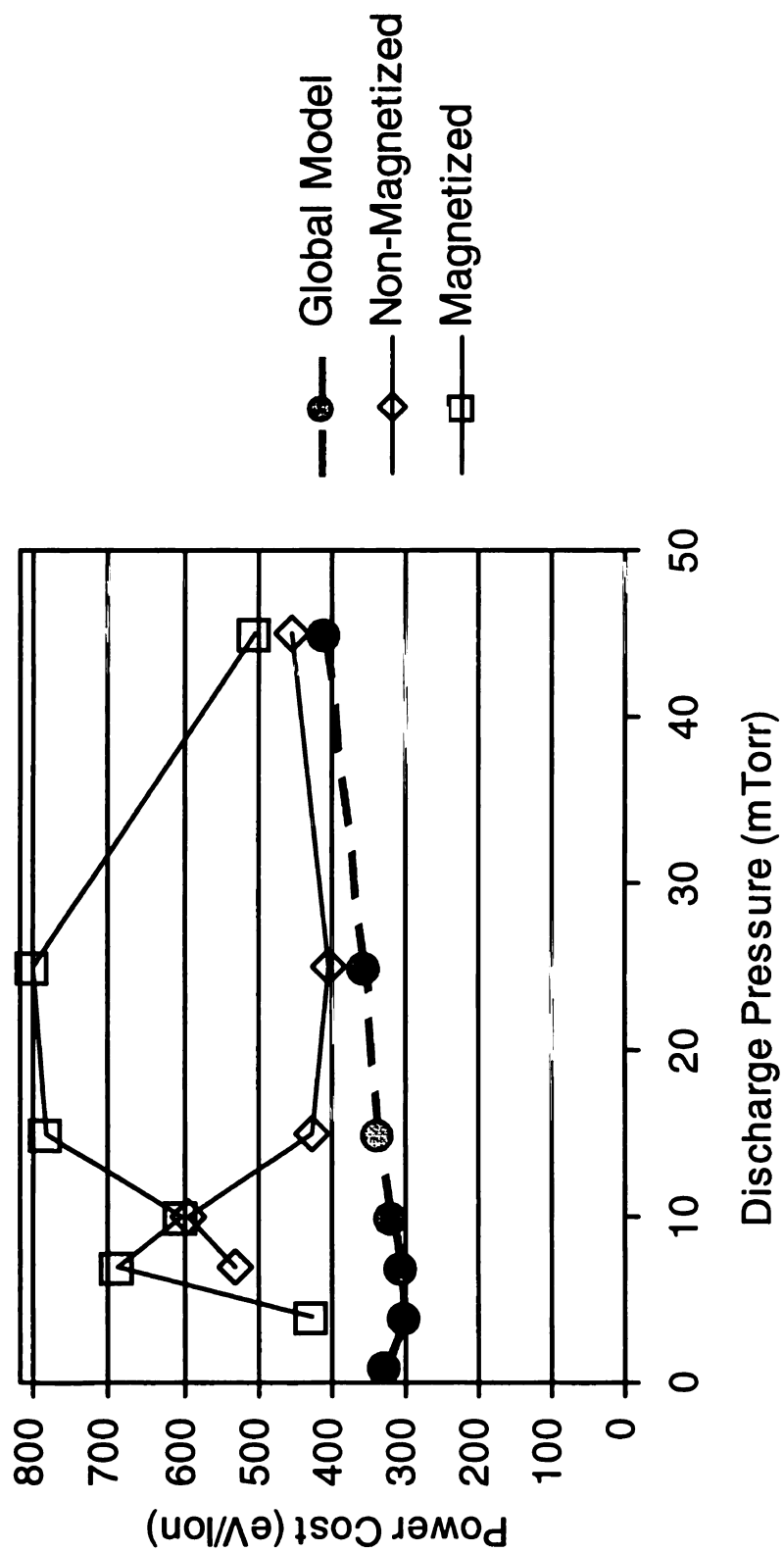


Figure 8.36 – Ion Production Cost calculated from the gradient of charge density measured by an SLP at (0,0,0) and (0,0,1). Dashed line is the global model prediction.

higher pressures this is very likely due to the magnetic field preventing the diffusion of electrons (and ions) out of the discharge, hence increasing ion production cost for useful ions. However, magnets provide a very important function in that they improve the low pressure sustain ability of the discharge (i.e. down to ~1 mTorr).

## **8.11 Summary of Findings**

### **8.11.1 Findings from charge density measurements at ( $r=0$ , $z=0$ ) (i.e. base of the discharge)**

- 1) Measured at ( $r=0\text{cm}$ ,  $z=0\text{cm}$ ) the opening of the discharge the non-magnetized configuration is observed to have higher output density than the magnetized configuration, by a factor of 1.5 to 2. This is true at all pressures measured.
- 2) The electromagnetic mode excited (i.e. the near field mode or the  $\text{TM}_{012}$  mode) does not have a significant effect on the output density. One mode does not produce more plasma output than the other.
- 3) The non-magnetized discharge output density is similar in trend and value to the charge density prediction of the global model for this set of discharge conditions. However, at lower pressures of 4 and 7 mTorr the charge density appears to be lower than global model prediction for the non-magnetized

discharge. This may be due to increased diffusion out of the discharge opening that is not considered in the closed cylinder model.

- 4) The magnetized discharge output density is consistently lower than the prediction of the global model. The charge density of the magnetized discharge appears to be clamped near  $2.5 \times 10^{11} \text{ cm}^{-3}$ , increasing with very small slope for pressures between 15 and 4 mTorr and absorbed power levels between 130 and 330 Watts. The charge density output is very likely limited by magnetic confinement of the plasma.
- 5) For higher absorbed discharge powers of 200W to 600W the discharge output density is predictably increased proportional to power. The trend is similar to the charge density trend vs. power for lower power levels. The maximum charge density reading was  $2.5 \times 10^{12} \text{ cm}^{-3}$  with an incident power of 600W at 45 mTorr. Only the near field mode was measured.

#### **8.11.2 Findings from Radial and Axial Charge Density Measurements:**

- 1) Radial charge density measurements across the  $z=0$  plane demonstrate that the plasma output profile is parabolic for both magnetized and non-magnetized discharges and for 7, 15, and 45 mTorr.

- 2) Radial measurements confirm that the non-magnetized discharge has higher charge density output at the  $z=0$ cm plane than the magnetized discharge.
- 3) Axial charge density measurements for a range of pressures demonstrate that the charge density near the top of the quartz dome is similar for both magnetized and non-magnetized discharges. However, the charge density for the magnetized discharge decays at a much faster rate than for the non-magnetized discharge. Hence, at the  $z=0$  plane the non-magnetized charge density is higher than the magnetized charge density, but at  $z=10$  cm the charge densities for both configurations are similar. This indicates that more charged species are lost to the walls for the magnetized discharge.
- 4) Estimates of the charge density near the top of the quartz dome lead to calculations of approximate skin depth of the plasma. For conditions that exist in this investigation microwave skin depths should be on the order of 0.25 cm to 1.5 cm. As a general rule we assume the microwave intensity to be effectively zero after 3 skin depths. Hence, most of the microwave energy is absorbed near the quartz walls of the discharge.
- 5) Visual images of the plasma identify a strong plasma beam out of the discharge opening at 7 mTorr in the non-magnetized configuration. This is likely due to increased electron mean free path at 7 mTorr. This beam is not seen in the

magnetized discharge likely due to magnetic confinement of the discharge electrons.

6) Measurement of ion production cost agrees with the global model calculated ion production cost for the non-magnetized discharge at pressures of 15 mTorr and above. However, the measurement diverges from prediction at lower pressures of 7 to 10 mTorr. This may be a result of the closed cylinder model not accounting for diffusion out of the discharge at lower pressures. The magnetized discharge ion production cost is much higher since much of the electrons and ions do not make it to the  $z=0$  plane and are probably lost to the walls.

## Chapter 9

### Measurement of the Quartz Dome Temperature

#### 9.1 Introduction

#### 9.2 Experimental Equipment and Setup

#### 9.3 Experimental Quartz Wall Temperature Measurements

##### 9.3.1 Quartz Wall Temperature vs. Time

##### 9.3.2 Quartz Wall Temperature vs. Power

##### 9.3.3 Quartz Wall Temperature vs. Pressure

#### 9.4 Analysis of the Temperature Measurements

##### 9.4.1 Estimation of the Radiated Power

##### 9.4.2 Estimation of the Wall Temperatures:

#### 9.5 Observations from the Wall Temperature Experiments

## Chapter 9

### Measurement of the Quartz Dome Temperature

#### **9.1 Introduction:**

The primary objectives of the experiments described in this chapter were to compare the quartz surface temperature with and without multipolar magnetic fields. This information was intended aid in understanding of the mechanisms at work in the plasma discharge with and without magnets. Additionally these experiments were expected to help characterize and qualitatively understand the behavior of quartz wall temperatures vs. discharge absorbed power and pressure.

The steady state temperature of the quartz dome was non-intrusively measured during powered operation with the aid of an optical thermocouple, described below. The quartz wall temperature was compared between magnetized and non-magnetized discharges. In addition, the non-magnetized discharge was exclusively studied vs. a large range of power (100-500W) for several discharge pressures. The quartz temperatures were then compared to a predictive model developed using the same steady state power balance principles utilized in the global plasma model. Since the neutral gas was assumed to be in thermal equilibrium with the quartz discharge wall these measurements also have implications for other discharge parameters such as neutral gas density and electron temperature.

## 9.2 Experimental Equipment and Setup:

An OS36-2 series optical thermocouple made by Omega Engineering, Inc. was used to measure the external surface temperature of the quartz discharge dome. The optical thermocouple is designed to measure the amount of radiant IR flux density emitted from an object by using a silicon photo detector. The magnitude of the signal from the photo detector is then used to determine the object's temperature. The OS36-2 is sensitive only in a band of IR radiation that does not readily pass through quartz ( $\lambda = 6\text{-}14\text{ }\mu\text{m}$ ), and hence it can be used to measure the surface temperature of quartz.

The optical thermocouple (1) had a detector area (2) with diameter of 5 mm (see Figure 9.1). The thermocouple was secured in an aluminum fixture (3) which was tightly bolted to the side of the microwave cavity (4). A 2.5 mm diameter hole (5) was drilled into the side of the cavity to allow a line of sight (6) from an area of the quartz dome to the detector. The hole was kept to a small radius to avoid microwave leakage. Note: the cylindrical hole limits the amount of radiant flux from the quartz dome that reaches the silicon detector. Hence, the temperatures measured through this hole are probably underestimated by a numerical factor and the actual temperature of the quartz dome is probably greater than the measured value. However, the relative differences between measured temperature values remain valid.

Compressed air at 40 psi was continuously blown on the quartz dome through 8 small holes (1mm diameter) in the base plate at the base of the quartz dome



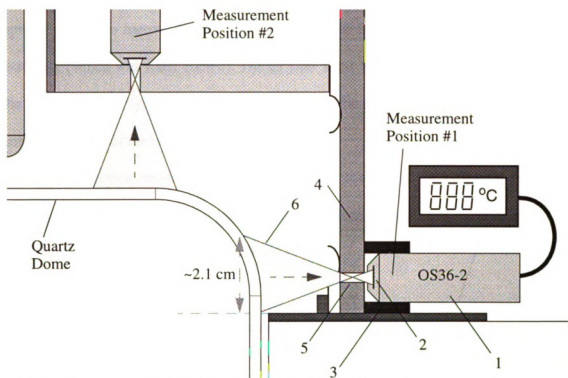


Figure 9.1a - OS36-2 Optical Thermocouple with digital readout. Measurement positions #1 and #2 are shown.

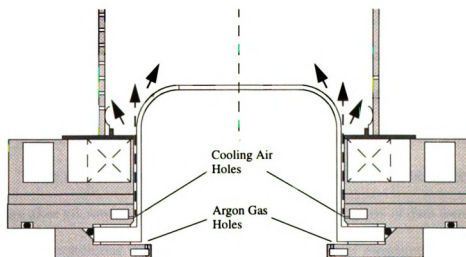


Figure 9.1b - Arrows depict compressed air flow as it escapes from the air cooling holes near the base of the quartz dome. The air flows between the quartz and the aluminum magnet holder until it escapes into the cavity.

(See Figure 9.1b). It was assumed that the air flow was from the bottom of the dome upward along the narrow gap between the dome and the aluminum wall of the magnet assembly (which was water cooled). The air flow at the top of the discharge opens up into the microwave cavity and ultimately exits through the many electric field measurement holes in the side of the cavity.

The electromagnetic mode used for all experiments was the near field mode. The Cheung microwave power supply was used. The schematic layout of the power delivery circuit is the same as shown in Figure 3.3b.

### **9.3 Experimental Quartz Wall Temperature Measurements:**

#### **9.3.1 Quartz Wall Temperature vs. Time**

Figure 9.2 shows how the quartz discharge dome cools off after microwave power is switched off. Initially the absorbed power in the discharge,  $P_{abs}$ , is 320 Watts and discharge pressure is 45 mTorr. At the moment the microwave source is turned off the quartz dome is measured to be 47°C. Compressed air remains on and the quartz dome temperature is observed to decay exponentially to room temperature (22°C) over 5 minutes.

While the above data was taken to demonstrate the transient behavior of wall temperature after microwave power was turned off the following sets of data were taken under steady state conditions. Each quartz wall temperature was measured while plasma discharge was sustained under constant conditions for several minutes to allow the temperature to reach a steady state.

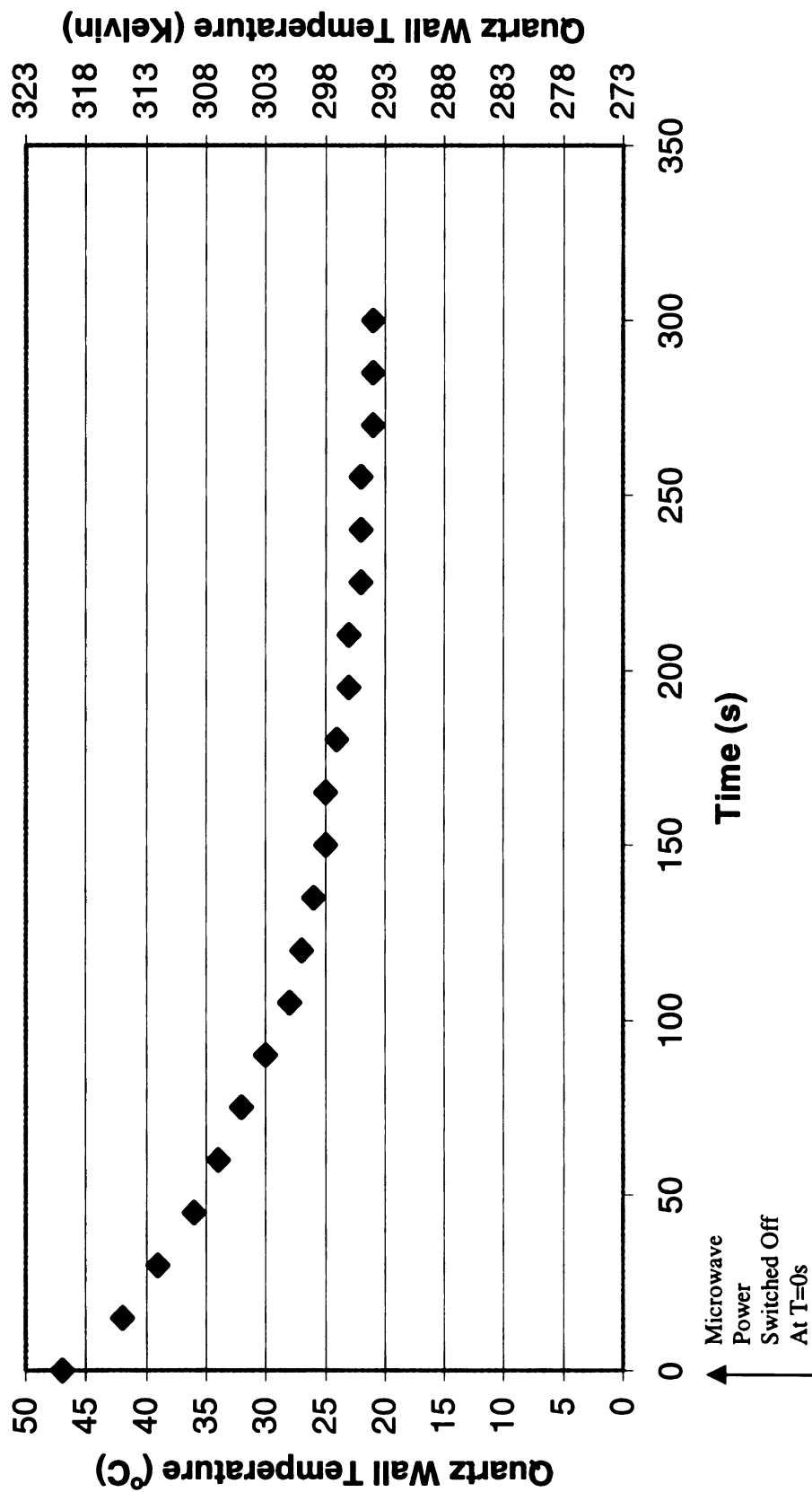


Figure 9.2 – Measurement of the quartz discharge dome temperature vs. time after the microwave power was turned off. The compressed air cooling remained on for the whole 5 minute period of measurement. Discharge pressure was 45 mTorr and initial discharge power absorbed was 320 Watts. The near field microwave cavity mode was used. Room temperature was 22°C.

### 9.3.2 Quartz Wall Temperatures vs. Power

Figure 9.3 shows the non-magnetized discharge wall temperatures vs. power absorbed by the plasma for a range of discharge pressures. As would be expected in this steady state discharge, when discharge absorbed power is increased the temperature of the outer quartz dome surface increases. This is true for all discharge pressures investigated and for both measurement positions (#1 side, #2 top). It is interesting to note that as power is increased from 180W to about 500W the wall temperature increases with a smaller slope ( $\sim 0.07$  °C/Watt) at 45 mTorr and increases by a larger slope ( $\sim 0.1$  °C/Watt) at the lower pressures of 10 mTorr and 7 mTorr.

Temperatures measured from position #2 at the top of the quartz dome show similar values to position #1 (the side) at 45 mTorr. However, at higher discharge power absorbed (510W) and lower pressures (10 mTorr) the top of the quartz dome appears to be higher in temperature than the quartz side wall. Intense capacitive heating at the top of the discharge dome at low pressures and high power levels may generate excessive heat at the top of the dome. Also, the different dynamics of cooling air flow at the top of the dome vs. the side of the dome may play a role in this temperature difference.

### 9.3.3 Quartz Wall Temperatures vs. Pressure

In Figure 9.3 it is observed that as discharge pressure is decreased the temperature of the outer quartz dome surface increases. The temperature points measured at the higher pressures, i.e. 45 and 25 mTorr, have the lowest surface temperatures. Dome temperatures

measured at 15 mtorr have intermediate values, and points measured at 10 and 7 mTorr have the highest temperatures.

The trend of quartz wall temperature vs. pressure is more clearly plotted in Figure 9.4 which compares quartz dome temperature of the magnetized discharge with the non-magnetized discharge vs. discharge pressure. For this plot the discharge power absorbed was held constant at 280W. Consistent with the previous plot (Fig. 9.3), Figure 9.4 shows a definite increase in quartz wall temperature as discharge pressure is decreased. This trend is observed for both magnetized and non-magnetized discharges. Comparison of the temperatures between magnetized and non-magnetized discharges shows that between the pressures of 7 mTorr to 45 mTorr the magnetized discharge is from 10°C to 15°C higher in temperature than the non-magnetized discharge. However, at lower pressures of 4 mTorr to 1 mTorr the temperatures for both configurations appear to converge.

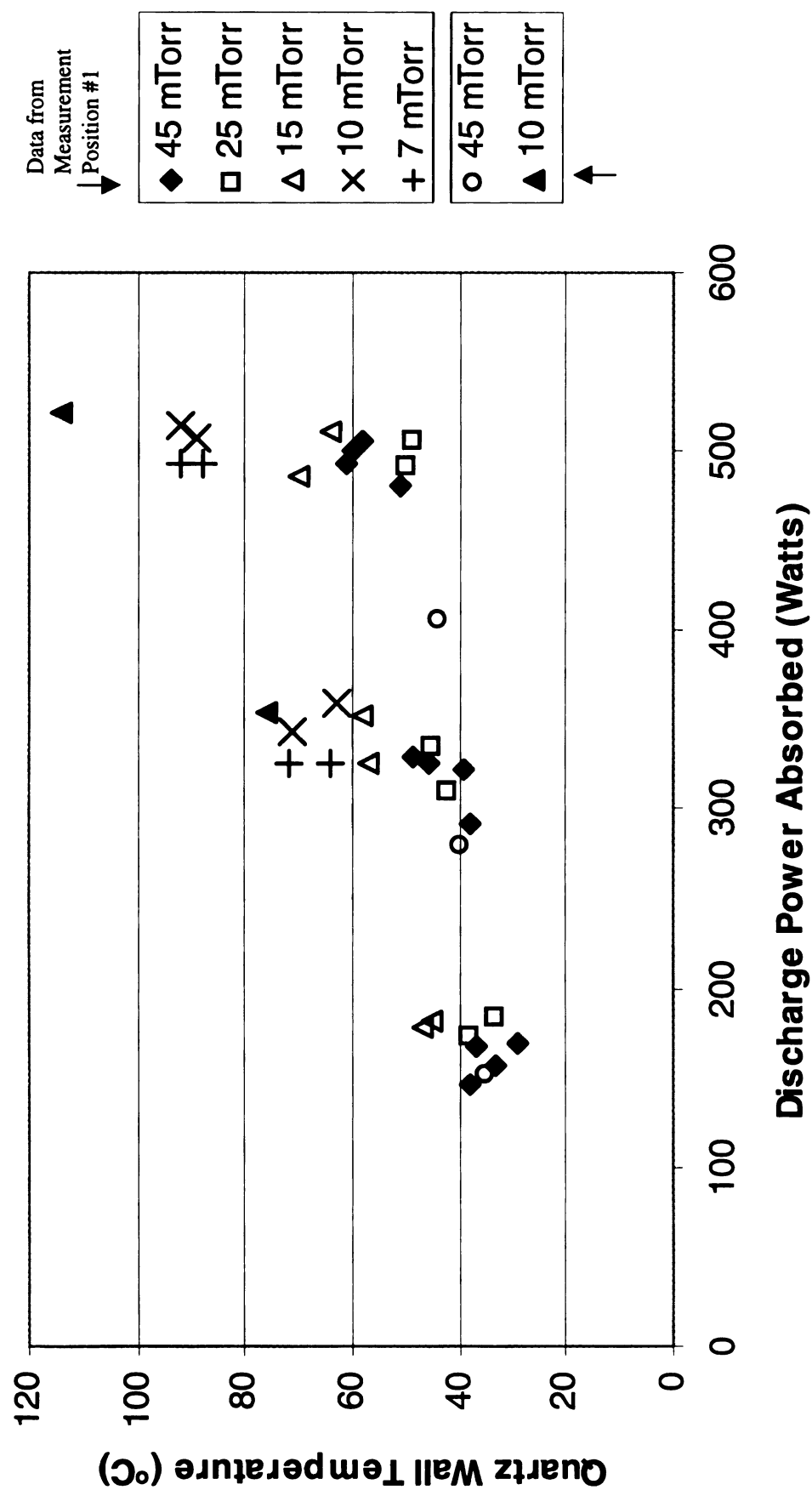


Figure 9.3 – Optically measured surface temperatures of the (non-magnetized) quartz discharge dome vs. discharge absorbed power. The near field microwave cavity mode was used. Several discharge pressures are shown. Temperatures taken from the side of the discharge dome (Measurement Position #1) are shown with temperatures taken from the top of the dome (Measurement Position #2).

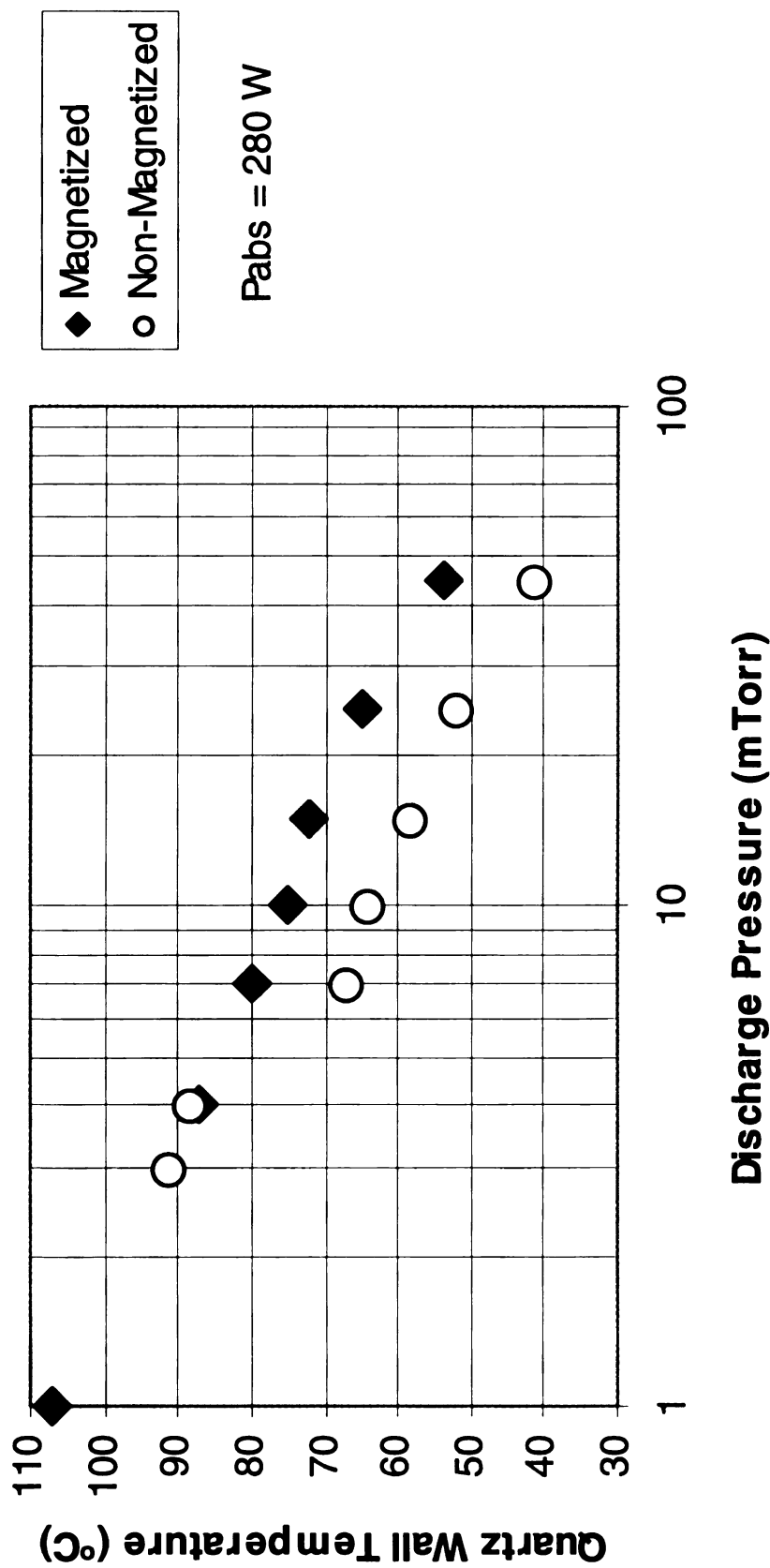


Figure 9.4 – Comparison of quartz dome surface temperatures in the magnetized and non-magnetized discharges vs. discharge pressure at an absorbed power of 280 Watts. The near field microwave cavity mode was used. All temperature measurements were taken from the side wall of the discharge (Measurement Position #1).

## 9.4 Analysis of the Temperature Measurements

### 9.4.1 Estimation of the Radiated Power

The above collection of temperature measurements can be explained using the balance of power loss mechanisms in the plasma discharge. Note: this is the same balance of power loss used in the global plasma model and is assumed to be applicable here since comparisons with earlier experimental measurements show approximate agreement.

The total energy lost per electron-ion pair created in the discharge,  $\mathcal{E}_T$ , is given as, from [Lie-94]:

$$\mathcal{E}_T = \mathcal{E}_{iz} + \underbrace{\left[ \frac{K_{ex}}{K_{iz}} \right] \mathcal{E}_{ex} + \left[ \frac{K_{el}}{K_{iz}} \right] \frac{3m}{M} T_e + 2T_e}_{\mathcal{E}_c} + \mathcal{E}_i \quad \text{Eq. 9.1}$$

where  $\mathcal{E}_{iz}$  is the ionization energy (15.76 eV for argon),  $K_{ex}$  is the effective excitation rate coefficient (a function of  $T_e$ ),  $K_{iz}$  is the electron-neutral ionization rate coefficient (a function of  $T_e$ ),  $\mathcal{E}_{ex}$  is the effective excitation energy (11.55 eV for argon),  $K_{el}$  is the electron-neutral momentum transfer collision rate constant (a function of  $T_e$ ),  $m$  is the mass of an electron,  $M$  is the mass of an argon atom,  $2T_e$  is the average kinetic energy delivered to the wall by an electron, and  $\mathcal{E}_i$  is the kinetic energy delivered to the wall by an ion accelerated through the presheath and sheath ( $5.2T_e$  for argon). The losses (per electron-ion pair) due to electron collisions with atoms (ionizations, excitations, and momentum collisions) are



commonly grouped together into one term,  $\mathcal{E}_i$ . The total energy loss per electron-ion pair,  $\mathcal{E}_T$ , and the individual energy loss mechanisms per electron-ion pair are plotted vs.  $T_e$  in Figure 9.5.

The energy lost per electron-ion pair is related to the total power absorbed in the discharge through this equation [Lie-94]:

$$P_{abs} = [en_0 u_B A_{eff}] \mathcal{E}_T \quad \text{Eq. 9.2}$$

where  $P_{abs}$  is the total power absorbed, and the bracketed terms are described in detail in chapter 6. Since  $\mathcal{E}_T$  is a sum of several components (see Eq. 9.1) we could write each of the power loss mechanisms as individual power loss components:

$$P_{iz} = [en_0 u_B A_{eff}] \mathcal{E}_{iz} \quad \text{Eq. 9.3}$$

$$P_{ex} = [en_0 u_B A_{eff}] \left[ \frac{K_{ex}}{K_{iz}} \right] \mathcal{E}_{ex} \quad \text{Eq. 9.4}$$

$$P_{el} = [en_0 u_B A_{eff}] \left[ \frac{K_{el}}{K_{iz}} \right] \frac{3m}{M} T_e \quad \text{Eq. 9.5}$$

$$P_{e-kin} = [en_0 u_B A_{eff}] 2T_e \quad \text{Eq. 9.6}$$

$$P_{i-kin} = [en_0 u_B A_{eff}] \mathcal{E}_i \quad \text{Eq. 9.7}$$

where the sum of all the above power loss components equals  $P_{abs}$ . Note  $P_{e-kin}$  and  $P_{i-kin}$

are the power delivered to the walls by the kinetic energy of the electrons and ions, respectively.

All of the power loss mechanisms will deliver power that heats the discharge walls except excitation ( $P_{ex}$ ). It is assumed that most of the electromagnetic radiation emitted by excited atoms passes through the quartz without heating it significantly. Hence, it is possible to determine the fraction of the total absorbed discharge power that is delivered to the walls of the discharge, or conversely the amount of power that is lost from the discharge due to excitation-radiation:

$$\begin{aligned} \text{Fraction of power absorbed that heats the discharge walls} &= \frac{P_{iz} + P_{el} + P_{e-kin} + P_{i-kin}}{P_{abs}} \\ &= \frac{\epsilon_{iz} + \left[ \frac{K_{el}}{K_{iz}} \right] \frac{3m}{M} T_e + 2T_e + \epsilon_i}{\epsilon_T} \end{aligned} \quad \text{Eq. 9.8}$$

$$\begin{aligned} \text{Fraction of power absorbed that is lost to excitation-radiation} &= \frac{P_{ex}}{P_{abs}} = \frac{\left[ \frac{K_{ex}}{K_{iz}} \right] \epsilon_{ex}}{\epsilon_T} \end{aligned} \quad \text{Eq. 9.9}$$

The above two equations are plotted in Figure 9.6. Note: these equations are independent of charge density. Also note: this model assumes a closed discharge system with no opening at the bottom of the quartz discharge. All energy either is delivered to the walls as heat or passes through the quartz walls as light. A more complex model would include the flux of particles and energy out of the bottom of the discharge dome.

According to Figure 9.6 as electron temperature increases the total fraction of power lost to the walls increases. For example, in a  $T_e = 2\text{ eV}$  argon plasma only 30% of the power is delivered to the discharge walls and 70% of the power is lost to excitation-radiation. However, in a  $T_e = 4\text{ eV}$  argon plasma 65% of the power is delivered to the walls and 35% is lost to excitation-radiation.

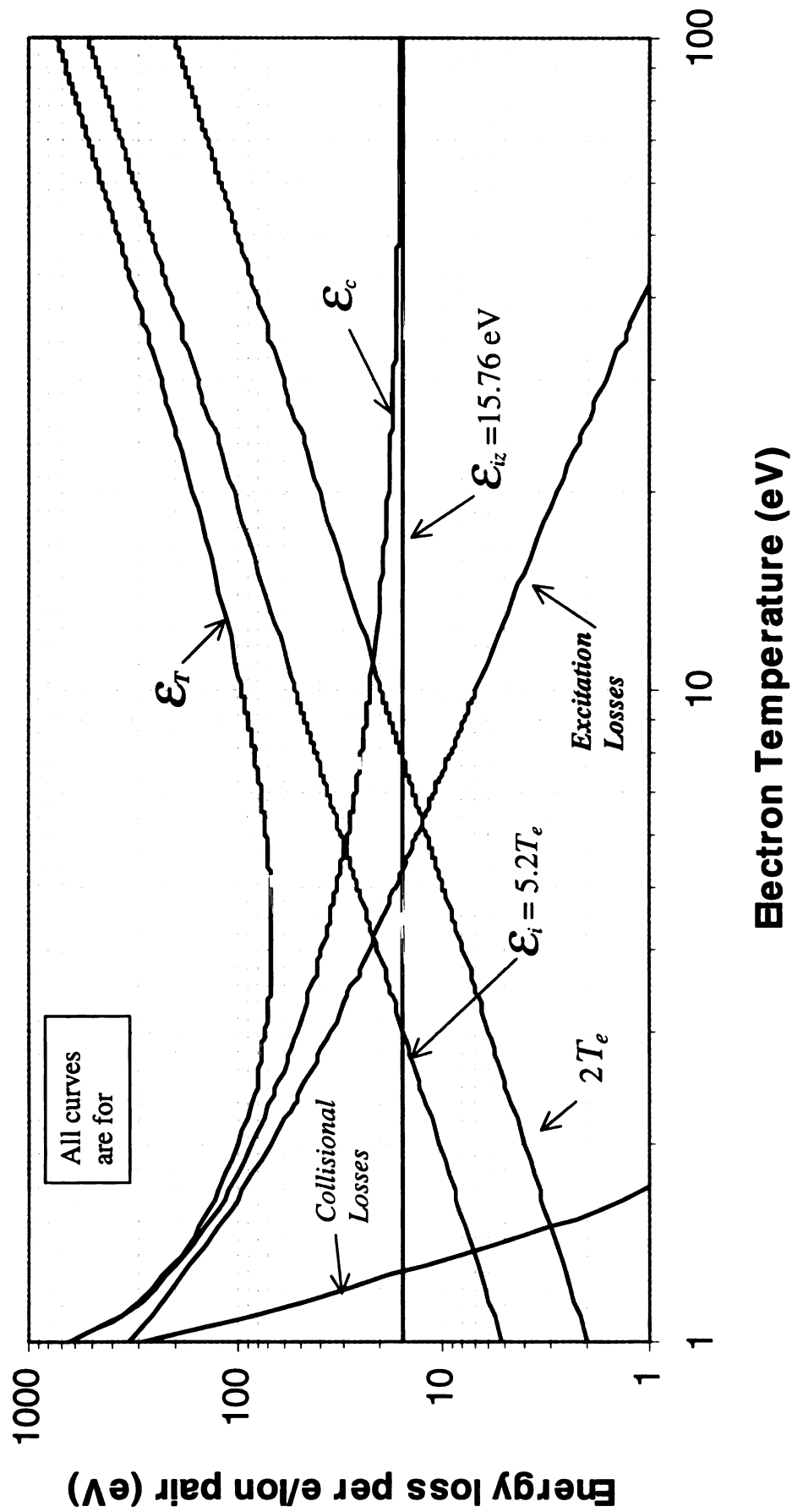


Figure 9.5 – Total energy loss per electron/ion pair lost from the plasma vs. electron temperature. Also shown are the individual loss components due to: excitation, collision, ionization, ion sheath losses ( $5.2T_e$ ), and electron kinetic losses ( $2T_e$ ). Note  $E_c$  (the sum of excitation, collision, and ionization) is also shown.

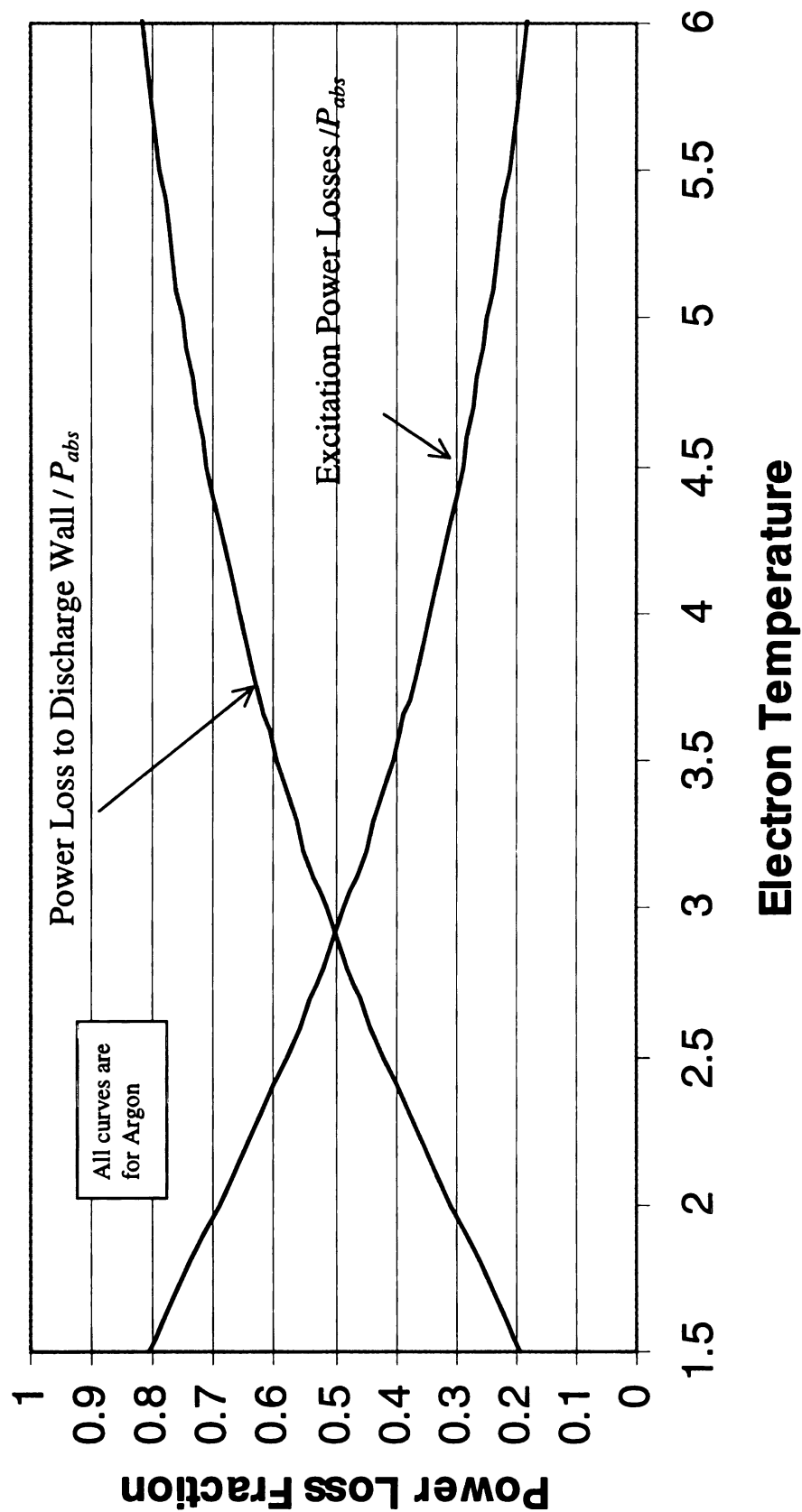


Figure 9.6 – This plot shows the fraction of power lost to the discharge wall vs. electron temperature. The complementary plot of excitation losses vs. electron temperature is also shown. The total power deposited into the discharge walls can be calculated by multiplying the power loss fraction for the walls by the discharge absorbed power,  $P_{abs}$ .

Table 9.1 shows several important parameters including the total calculated power delivered to the walls for each of the pressures studied in Figure 9.4. Note that for all data points in Figure 9.4 the total absorbed discharge power was 280W.

Table 9.1 - Power Delivered to the Quartz Wall

| Pressure<br>(mTorr) | $T_e$<br>(eV) | $P_{\text{wall-loss}}$ Frac. | $P_{\text{wall}}$<br>(Watts) |
|---------------------|---------------|------------------------------|------------------------------|
| 1                   | 5.95          | 81.3%                        | 228                          |
| 4                   | 3.79          | 63.5%                        | 178                          |
| 7                   | 3.25          | 55.9%                        | 156                          |
| 10                  | 2.98          | 51.4%                        | 144                          |
| 15                  | 2.71          | 46.6%                        | 130                          |
| 25                  | 2.42          | 40.9%                        | 114                          |
| 45                  | 2.13          | 35.2%                        | 99                           |

#### 9.4.2 Estimation of the Wall Temperatures:

A calculation can be made to estimate the expected temperature,  $T_w$ , of the outer quartz surface vs. power lost from walls of the discharge [Uya-01]. The power lost from the surface of the quartz must be from both: 1) Convection due to the forced air cooling, and 2) Radiation. Heat conduction through the quartz wall to the stainless steel base plate will be neglected as a significant heat loss mechanism since the heat conductivity of quartz is quite low. The quartz surface temperature can be determined from a power balance

equation, where the power delivered to the quartz wall by the plasma discharge,  $P_{wall}$ , must equal the power lost from the quartz surface due to convection and radiation:

$$P_{wall} = P_{convection} + P_{radiation} \quad \text{Eq. 9.10}$$

Fortunately the power lost due to convection and radiation can both be expressed in terms of,  $T_w$ , the outer quartz wall temperature. For convection, power loss from the quartz wall to the forced air is given as:

$$P_{convection} = hA(T_w - T_{air}) \quad \text{Eq. 9.11}$$

where  $h$  is the heat transfer coefficient of forced air (approximately 20 Watts/m<sup>2</sup> K),  $A$  is the total area of the outer quartz wall (approx. 0.06 m<sup>2</sup>),  $T_w$  is the outer quartz wall temperature, and  $T_{air}$  is the temperature of the cooling air (assumed to be at 20°C). For radiation power loss from the quartz wall to the external environment (at ~20°C) is:

$$P_{radiation} = \epsilon\sigma A(T_w^4 - T_{air}^4) \quad \text{Eq. 9.12}$$

where  $\epsilon$  is the effective emissivity of quartz (approx. 0.9),  $\sigma$  is the Stefan-Boltzmann constant (5.67x10<sup>-8</sup> J/s m<sup>2</sup> K<sup>4</sup>),  $A$  is the outer area of the quartz wall (~0.06m<sup>2</sup>),  $T_w$  and  $T_{air}$  (room temp. air ~293K) are the temperature of quartz wall and surrounding

environment, respectively (Note: to use this equation correctly temperatures must be entered in degrees Kelvin). We can express  $P_{wall}$  as a function of  $T_w$ :

$$P_{wall} = hA(T_w - T_{air}) + \epsilon\sigma A(T_w^4 - T_{air}^4) \quad \text{Eq. 9.13}$$

the inverse relation, i.e.  $T_w$  plotted as a function of  $P_{wall}$ , is shown in Figure 9.7.

We can then use the calculated values of  $P_{wall}$  in Table 7.5 to determine corresponding estimates for wall temperatures using Figure 9.7. These estimates for wall temperature are plotted along with measured temperature data in Figure 9.8. A plot of the calculated quartz dome temperatures vs. power and pressure is shown in Figure 9.9. Note that the calculated values in Figure 9.8 are  $\sim 40^\circ\text{C}$  higher than the measured values. This error may be a result of the closed discharge model not accounting for the energy lost by particles diffusing out of the bottom opening of the discharge. It is also possible that the experimental thermocouple temperature measurement is too low by some factor as discussed at the beginning of this chapter. Further, it is possible that the estimated heat transfer coefficient  $h$  should be greater than  $20 \text{ Watts/m}^2 \text{ K}$ . Even though the theoretically calculated values are higher than the measured temperatures, the trend for both curves appears to be very similar, and the qualitative physical mechanisms explaining the increase in wall temperature with decreasing discharge pressure are compelling.

The quartz temperature on the internal surface of the quartz dome can be estimated from the external temperature. The equation for heat conduction is given as:

$$P_{wall} = \frac{\kappa A}{L} \Delta T \quad \text{Eq. 9.14}$$



where  $P_{wall}$  is the total heat flux through the quartz wall,  $k$  is the thermal conductivity of quartz ( $\sim 1 \text{ J/s}\cdot\text{m}\cdot\text{K}$ ),  $A$  is the total area of the discharge dome ( $\sim 0.06 \text{ m}^2$ ),  $L$  is the thickness of the quartz dome ( $0.003 \text{ m}$ ), and  $\Delta T$  is the difference between the internal surface temperature and the external surface temperature. If we assume an upper limit of  $P_{wall} = 500 \text{ W}$  the corresponding  $\Delta T$  is approximately  $25^\circ\text{C}$ , i.e. the inside surface temperature will only be  $25^\circ\text{C}$  higher than the outside surface temperature. For lower power fluxes the corresponding temperature difference will be proportionally smaller.

### 9.5 Observations from the Wall Temperature Experiments

The primary objective of this chapter was to compare the quartz surface temperature with and without multipolar magnetic fields. The experimental data shown in Figures 9.4 and 9.8 demonstrate that the quartz wall temperature is about  $10^\circ\text{C}$  to  $15^\circ\text{C}$  higher for the magnetized discharge than for the non-magnetized discharge in the pressure range of 7 to 45 mTorr. However, at pressures below 7 mTorr the temperatures for both configurations appear to converge.

The multicusp magnetic field may form an effective axial barrier for electrons that are created inside the discharge dome. This axial barrier is absent for the non-magnetized discharge. In the non-magnetized discharge more energetic species are able to escape from the bottom of the plasma, and hence direct less energy flow to the quartz wall.

Alternately, the higher wall temperatures for the magnetized discharge at pressures of 7 to 45 mTorr may be caused by enhanced radial diffusion to the walls. The

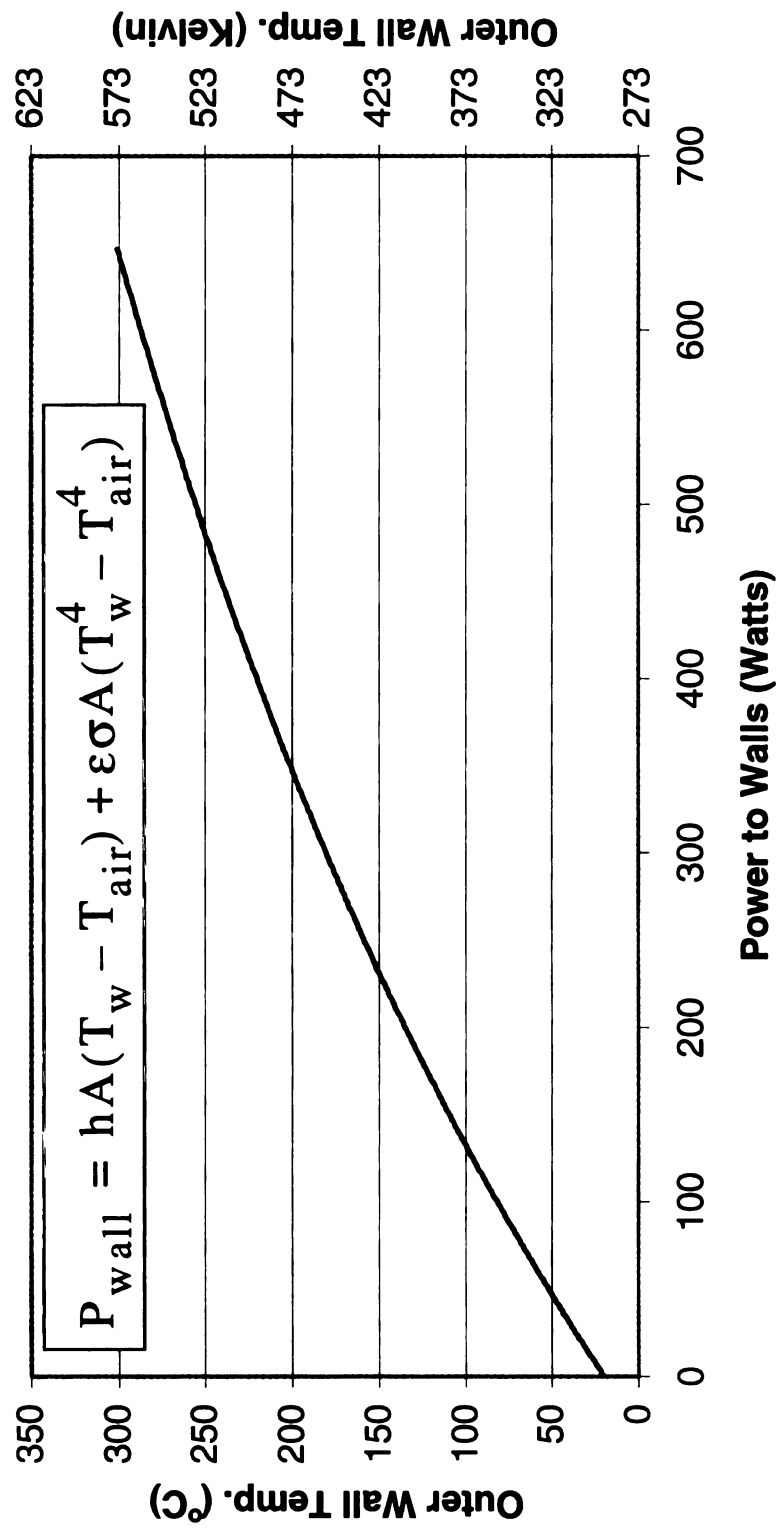


Figure 9.7 – Calculated external quartz wall temperature,  $T_w$ , as a function of power flux to the walls of the discharge. In the inset equation  $P_{wall}$  is a function of quartz wall temperature. The terms of this equation are described in the text of this section.

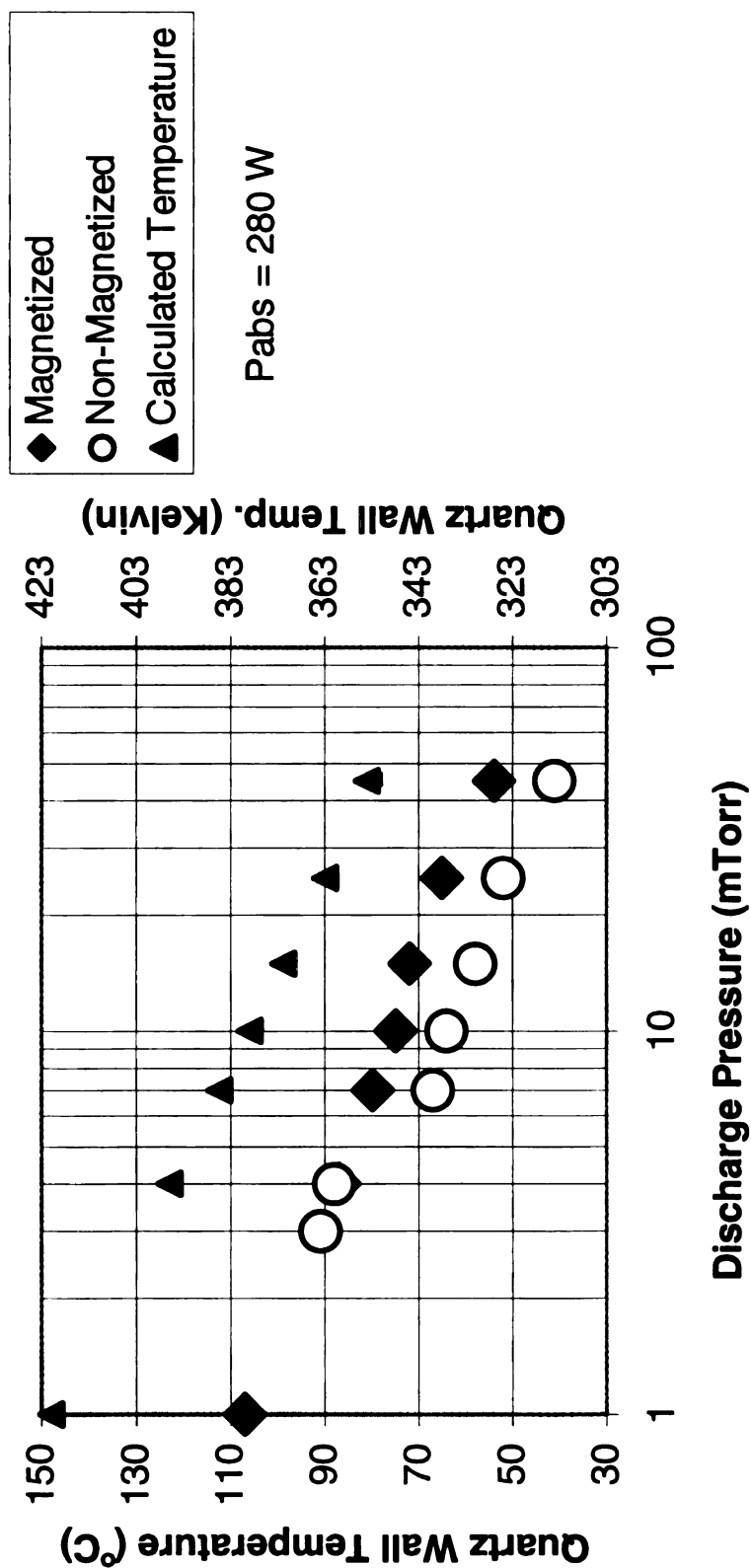


Figure 9.8 – Comparison of experimentally measured (magnetized and non-magnetized) vs. theoretically calculated quartz dome surface temperatures vs. discharge pressure at an absorbed power of 280 Watts. All temperature measurements were taken from the side wall of the discharge (Measurement Position #1).

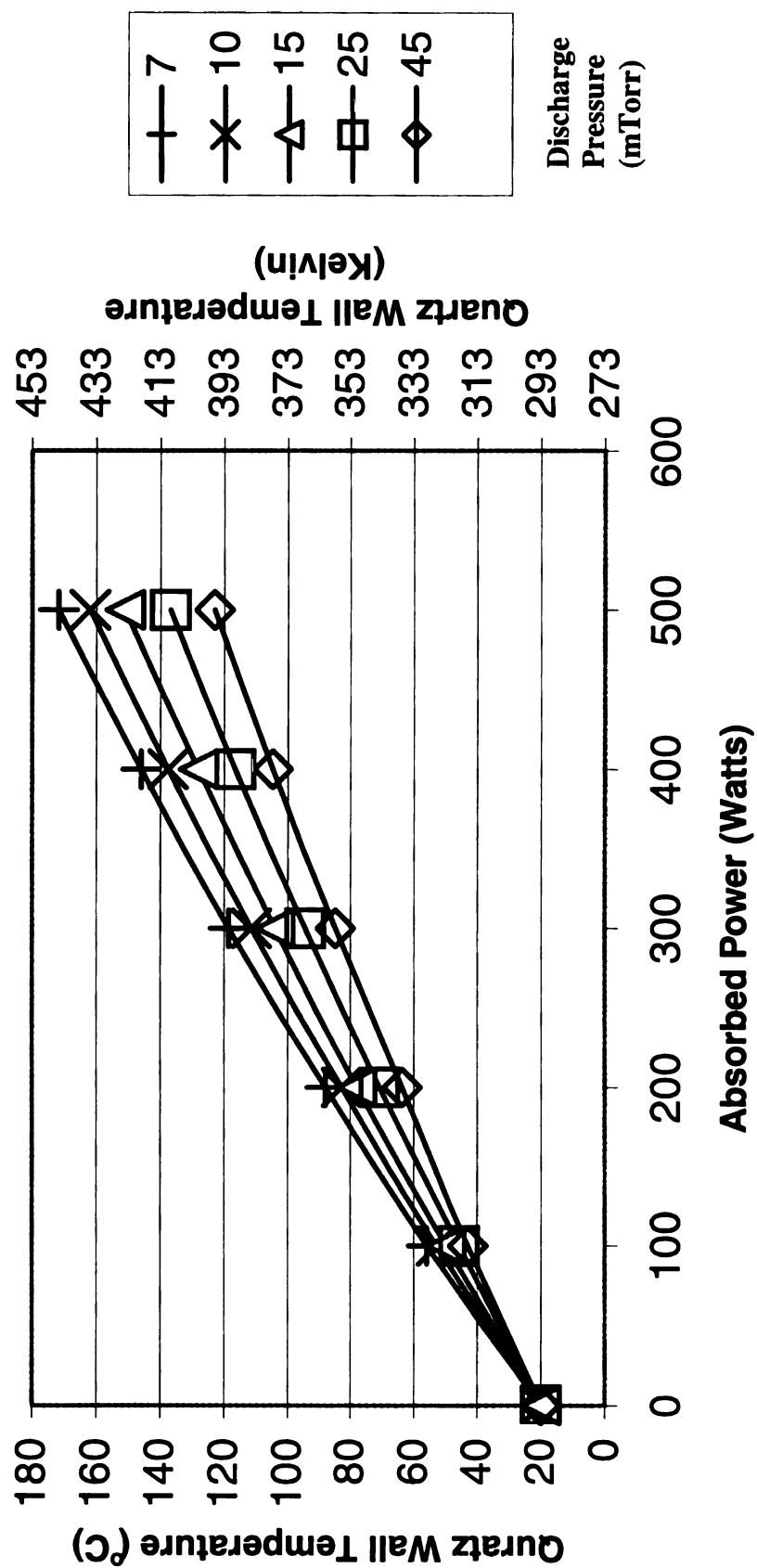


Figure 9.9 – Calculation of the predicted quartz wall temperature vs. discharge absorbed power for several discharge pressures.

multicusp magnetic fields may enhance radial diffusion when the mean free path for electron-neutral collision is small. By comparison, at lower pressures and larger electron mean free paths the electrons are better confined by the multicusp magnetic field.

Another objective of this chapter was to discover and qualitatively understand the behavior of quartz wall temperatures vs. discharge absorbed power and pressure. The basic observations from the set of data in Figures 9.3 and 9.4 are that: 1) the quartz dome temperature increases with increasing power, and 2) the quartz dome temperature increases as discharge pressure is decreased. A model was developed from the power balance assumption that provided a good qualitative explanation for the behavior of the quartz wall temperature. First, increasing the power absorbed in the plasma increases the number of electron-ion pairs that kinetically heat the wall and recombine at the wall. Second, decreasing the discharge pressure increases the electron temperature, which causes the number of ionizations to increase relative to the number of excitations.

However, as shown in Figure 9.8 the predictive model is qualitatively higher by 30°C to 40°C. This simplified predictive model assumes that the discharge is closed and surrounded on all sides by the discharge wall. In reality much of the energy flowing into the discharge could be flowing out through the open end of the quartz discharge and not just through the quartz walls. Taking into account the energy that flows out the bottom of the discharge would decrease the predicted temperatures of the model.

Also, the measured values of quartz wall temperature in this experiment could be artificially low since IR radiation was collected through a hole (See Figure 9.1a). This hole blocked some of the IR radiation from the detector. Another method of measuring the quartz wall temperature using a traditional bi-metal thermocouple measurement device

can be devised to confirm or check the validity of these optical measurements. A thin metal thermocouple probe can be inserted through a hole in the side of the cavity and touch the side of the quartz dome (i.e. one second after the microwave source has been turned off). The temperature measured should only be slightly less than the steady state quartz surface temperature before switching off the microwave supply (See Figure 9.2).

Another observation from Figure 9.3 is that under conditions of high power and low pressure the top of the discharge dome was hotter than the side. This may be caused by strong local plasma heating near the top of the discharge. Perhaps even capacitive coupling by the probe antenna. Still, it also could be the result of a lack of a direct stream of compressed air cooling at the top of the discharge (See Figure 9.1b).

Since the neutral gas is assumed to be in thermal equilibrium with the quartz discharge wall these measurements also have implications for other discharge parameters. As described in Chapter 6 the neutral gas density in a discharge has a direct effect on the electron temperature. Any parameter that changes neutral gas density will also change electron temperature.

If neutral gas pressure is held constant then a change in neutral gas temperature will cause a change in the neutral gas density. This follows from the ideal gas law:

$$p_g = n_g k_b T_g \quad \text{Eq. 9.1}$$

where  $p_g$  is the neutral gas pressure,  $n_g$  is the neutral gas density,  $k_b$  is the boltzmann constant, and  $T_g$  is the neutral gas temperature in Kelvin.

Further, as described in chapter 6, a decrease in neutral gas density in a given discharge will lead to an increase in electron temperature. Hence, anything that changes the neutral gas temperature will effect the neutral gas density and influence the electron temperature.

For example, an increase in discharge power (Figure 9.3) is shown to increase the quartz wall temperature and therefore the neutral gas temperature. This correspondingly reduces neutral gas density and increases electron temperature. Hence, in a discharge under constant pressure an increase in absorbed power should correspond to a slight but noticeable increase in electron temperature. This slight increase in electron temperature as power increases was observed in Figure 7.17 and has also been observed by others [Hop-90, Mak-97].

## Chapter 10

### Summary and Conclusions

#### 10.1 Summary of Findings and Physical Explanations:

- 10.1.1 Discharge Stability and Sustainability
- 10.1.2 Measurements of EEDF,  $T_e$  and  $V_p$
- 10.1.3 Measurements of Charge Density and Charge Density Profile
- 10.1.4 Plasma Skin Depth and Regions of Microwave Heating
- 10.1.5 Quartz Wall Temperatures and B-field Confinement
- 10.1.6 Measured Ion Production Cost
- 10.1.7 Global Model Predictions
- 10.1.8 General Comparison Between the Magnetized and Nonmagnetized Discharges
- 10.1.9 Electron Loss Processes for the Magnetized Discharge

#### 10.2 General Discussion of Collisionless Heating and Hot Electrons

#### 10.3 Future Follow-on Research and Possible New Plasma Source Designs

- 10.3.1 The Search for High Energy Electrons
- 10.3.2 New Plasma Source Designs



## Chapter 10

### Summary and Conclusions

#### **10.1 Summary of Findings and Physical Explanations**

Using the experimental data presented in this investigation a number of conclusions can be made [Asm-02]. Starting with some general comments about both the magnetized and the nonmagnetized discharges, we can make the following observations. Several possible physical explanations for these observations are discussed.

##### **10.1.1 Discharge Stability and Sustainability**

The experiments definitely demonstrate that it is possible to maintain a nonmagnetized 2.45GHz discharge in argon gas down to pressures of 4-5 mTorr and probably lower if sufficient microwave power is available. Under these conditions the discharge has a density at the  $z=0$  plane in excess of the critical density; i.e.  $1 \times 10^{11}$  to  $1 \times 10^{12} \text{ cm}^{-3}$  and the effective electron collision frequency is much less (probably about  $2 \times 10^7 \text{ 1/s}$ ) than the microwave excitation frequency (which is  $1.54 \times 10^{10} \text{ radians/sec.}$ ). Thus the nonmagnetized discharge most likely is not sustained by elastic collisional heating (ohmic heating) alone, but must be sustained by collisionless heating (stochastic heating) processes such as electromagnetic coupling to space charge waves, etc. The topic of collisionless heating will be discussed in detail in section 10.2. The experiments show that nonmagnetized dis-

charges can easily be sustained down to 5-7 mTorr in the experimental applicator with 250-400W of absorbed power. Excitation with the near field  $TM_{011}$  cavity applicator mode is slightly (5-8%) more efficient than the  $TM_{012}$  mode and is also less sensitive to tuning and excitation frequency variations. The tuning and frequency sensitivities are probably due to the fact that the short near field mode has a lower discharge loaded Q factor. It may also be related to direct capacitive coupling between the excitation probe tip and the top of the plasma discharge (since the distance of the probe from the discharge dome is on the order of a centimeter in the  $TM_{011}$  “near field” mode). This excitation method will be discussed as a possible redesigned and improved plasma source concept in section 10.3.2.

For the nonmagnetized discharge maintenance is more difficult below 5-6 mTorr. Diffusion and other losses associated with the flow of charged species to the chamber walls increases dramatically as pressure is reduced below 5 mTorr and thus the discharge requires significantly more power for maintenance. It is under these circumstances that the multipolar magnetized discharge provides superior performance.

The “multipolar ECR” microwave discharges can be continuously maintained over a large 45-0.5 mTorr (maybe even lower pressures as has been demonstrated in other investigations) pressure regime. When pressures are reduced below 5 mTorr the magnetized discharges are more efficient; i.e. at these lower pressures magnetized discharges have higher densities, and are more stable and easier to maintain than nonmagnetized discharges. It is not clear why the magnetized discharge yields better performance below 5 mTorr, but it probably has to do with the fact that the multipolar static magnetic field begins to provide improved charged species confinement (i.e. reduced diffusion of

charged species) and also improved ECR coupling as pressure is reduced. These improvements may be related to the variation of the effective electron collision frequency (and mfp) versus pressure. That is at higher pressures collisions scatter the electrons radially out of the multipolar magnetic field confinement region through the cusp throats resulting in higher diffusion rates than nonmagnetized discharges, while at low pressures with fewer collisions they are better radially confined than the nonmagnetized discharge. Computer modeling may be useful in lending more credibility to these conjectures.

### 10.1.2 Measurements of EEDF, $T_e$ and $V_p$

Single Langmuir probe measurements were made at the discharge output (i.e. the center of the  $z=0$  plane) for both magnetized and nonmagnetized discharges to measure EEDF, electron temperature, and plasma potential. Measurements of these parameters were also made versus pressure at an absorbed power of 280W.

The measurements indicated that the nonmagnetized discharge EEDF was approximately Maxwellian (i.e. Maxwellian or very close to Maxwellian) under almost all experimental conditions. Maxwellian EEDFs were measured at the  $z=0$  cross sectional plane and also up into the discharge. Slightly non-Maxwellian distributions were observed at the higher pressure regime of 25-45 mTorr. In particular for the non-magnetized discharge, the EEDF falls between a Maxwellian and Druyvesteyn distribution function at 45 mTorr.

Nonmagnetized measured electron temperatures followed closely ( $\pm 0.5$  eV) those values predicted by the global model. Electron temperatures were independent of excitation mode; i.e. independent of the near field or the  $TM_{012}$  mode. At a constant pres-

sure the measured electron temperature increased slightly (0.3-0.4 eV/100W) as the power was increased. Electron temperature increased (15% for 5-10 mTorr and 5% for 25 mTorr) as the axial distance up into the discharge increased. At the higher pressures of 7-45 mTorr the measured plasma potential versus pressure follows closely the values predicted by the global model; i.e. 10-15 eV. However at pressures below 7 mTorr the measured plasma potential is higher (17-22 eV) and increases faster as pressure is decreased than the corresponding plasma potentials predicted by the global model.

In a fashion identical to the nonmagnetized discharge SLP measurements were made at the  $z=0$  plasma source output plane for the magnetized discharge. The measurements showed that the EEDF was non-maxwellian and the distribution function consistently for all pressures displayed a distribution with a depleted (from a Maxwellian distribution) high energy tail. Over the 1-45 mTorr and 150-400W pressure and power measurement regimes the distribution function fell in between a Maxwellian and a Druyvesteyn distribution. At the higher pressures the entire distribution function became more "Druyvesteyn like." However when the SLP measurements were made axially up into the magnetized discharge the electron energy distributions become more Maxwellian as the probe was moved into the discharge. At  $Z=4$  cm into the discharge the distributions became almost Maxwellian over the entire 1.8-10 mTorr pressure measurement regime.

The measured effective electron temperatures for the magnetized discharge were within  $\pm 0.5$  eV of the values predicted by the nonmagnetized global model and were independent of whether the discharge was excited by the near field mode or the  $TM_{012}$  mode. The electron temperatures increased typically about 0.5 eV as the axial position increased from  $z=0$  to  $z=4$  cm. Depending on pressure this amounted to an 11-15%

increase in temperature from the  $Z=0$  output plane. At pressures of 15 mTorr and above the measured plasma potentials matched the predicted potentials from the nonmagnetized global model. However at pressures below 15 mTorr the measured potentials were always lower than the global model predictions with the difference between the global model and the measurements increasing as the pressure was reduced. The measured plasma potentials were similar to the nonmagnetized discharge in the 15-45 mTorr regime, but became significantly lower at lower pressures of 4-5 mTorr; i.e. 14.5eV for the magnetized discharge versus 23eV for the nonmagnetized discharge.

### **10.1.3 Measurements of Charge Density and Charge Density Profile**

Electron density measurements were taken across the opening of the discharge ( $z=0$  plane) to create radial density profiles for both magnetized and nonmagnetized discharges. These profiles were parabolic in shape for both magnetized and non-magnetized discharges.

For the nonmagnetized discharge the behavior of the measured peak, i.e. on the  $z$ -axis, densities followed the behavior versus power and pressure as predicted by the global model; i.e. for a constant absorbed power, the density increased as pressure increased, and for a constant pressure the density increased as the absorbed power increased. Measured peak densities were always above the critical density. At the  $z=0$  plane the measured peak densities varied between  $2 \times 10^{11}$  and  $3 \times 10^{12} \text{ cm}^{-3}$  as the pressure and power were varied from 125-500W and 4-45 mTorr. The higher densities are associated with the highest powers and pressures. These values tracked the density behavior versus power and pressure

predicted by the global model to within 10 to 15%. The ion saturation current density versus distance into the discharge indicated that the density increased from the  $z=0$  plane up into the discharge at  $z=6-7$  cm, by 38% at high pressures of 45 mTorr, by 56% at 10 mTorr and by 45% at the low pressure of 7 mTorr. Thus the discharge center had plasma densities in excess of  $3 \times 10^{11}$  -  $4.5 \times 10^{12} \text{ cm}^{-3}$ .

The magnetized peak discharge densities, however, were much lower than the non-magnetized output charge densities for a range of pressures from 5 to 45 mTorr. The magnetized discharge densities also fell well below the predictions of the global model at most pressures and did not follow the global model trend. At 45 mTorr the density vs. power appears to follow the increasing trend of the global model but is about  $2 \times 10^{11} \text{ cm}^{-3}$  less than global model prediction. Starting at 25 mTorr the charge densities fall well below the global model predictions. In fact, between the pressures of 4-25 mTorr and absorbed powers of 130-280W the magnetized densities are clamped near  $2.5 \times 10^{11} \text{ cm}^{-3}$ . These numbers are explained by the fact that the multipolar magnets confine the charged species and may direct much of the charged species flux to the discharge walls at higher pressures. This idea is supported by the measurements of ion saturation and plasma potential vs. distance into the discharge, and the quartz wall heating measurements and associated analysis.

These measurements indicated an increase of 100% in density from the  $z=0$  plane into the discharge core for the magnetized discharge at 45 mtorr. At pressures from 7 mTorr to 25 mTorr the increase vs.  $z$  is between 150% and 250%. Finally at the low pressure of 4mTorr the increase in charge density vs.  $z$  is more near 90%. This shows that at low pressures the charged species more readily diffuse out of the bottom of the discharge

in the magnetized case. This helps explain why the magnetized discharge performance is better by comparison to the non-magnetized discharge at lower pressures.

The axial profiles ion saturation current show that the charge densities for both magnetized and non-magnetized discharges are similar up into the discharge. Both discharges have a high density central core.

#### **10.1.4 Plasma Skin Depth and Regions of Microwave Heating**

The existence of this high density central core of the discharge indicates that the electromagnetic field in the discharge is evanescent, i.e. decaying, as it attempts to propagate into the discharge. Electromagnetic field skin depths calculated assuming the maximum and minimum measured peak densities and associated electron temperatures indicate that the skin depths range from about 0.25-1 cm for the experimental data presented here. The largest skin depth are associated with the lowest pressure discharges. Thus in all cases the electromagnetic field exists and hence performs the electron gas heating around and on the surface of the discharge. At high pressures the EM heating layer may be at most 1-1.5 cm thick while at low pressures this heating layer is about 3cm thick. Thus at low pressure in the nonmagnetized discharge the EM field is able to penetrate partially (3cm on each side and 3cm on the end of the discharge) through the cross section of the discharge. However in magnetized discharges the case may be somewhat different due to magnetic cusp electron confinement and ECR heating zones that exist near the walls. Hence the EM energy may not be spread across the cross section of the magnetized discharge in the same way as the nonmagnetized discharge.

In the nonmagnetized discharge at low pressures the EM fields then can penetrate as far as 4-5 cm axially into the quartz discharge chamber. Heating appears to be more axially uniform at the lower pressures and as pressure is decreased the EM energy may be deposited over a larger axial volume. However, there is still the question of how the electromagnetic field can heat the electron gas when ohmic heating is not effective. Recall that the effective electron neutral collision frequency is about  $1.5 \times 10^7$  at 5 mTorr and thus the ratio of collision frequency to excitation radian frequency is much less than one. This strongly suggests that some other heating process is present.

#### **10.1.5 Quartz Wall Temperatures**

Quartz wall temperature measurements indicate that the discharge neutral gas temperature is probably between 350 and 500K. It increases as pressure decreases and as global model analysis suggests this is caused by the increased energy transfer to the wall by charged particle diffusion as pressure is decreased. At a constant pressure the wall temperature increases as the absorbed power is increased. The rate of change of wall temperature versus absorbed power is greater for low pressures (0.17K/W) than for high pressures (0.7K/W). Assuming that wall temperatures are directly related to gas temperature this suggests that low pressure discharges are more sensitive to power changes and hence have larger neutral gas temperature changes than higher pressure discharges. An energy balance analysis indicates that at higher pressures a larger fraction of the absorbed power is radiated from the discharge and thus is not available for gas heating and transport to the walls.



This radiated power thus allows for a cooler neutral gas temperature at the higher pressures.

The experimental data indicates that at a constant pressure gas heating does occur as absorbed power is increased. Thus the discharge collisional mean free paths are slightly larger at higher power inputs than at lower powers. Using the global model this suggests that the electron temperature should also increase slightly as absorbed power increases. At a constant pressure a slight increase in electron temperature was observed in all experimental measurements as absorbed power was increased. Thus neutral gas heating can explain the experimentally observed slightly increased electron temperatures as the absorbed power is increased.

At pressures of 10-45mTorr the quartz wall temperatures of magnetized discharges are higher indicating that charged species are radially diffusing more rapidly to the walls, i.e. there is less radial confinement than in non-magnetized discharges. This enhanced radial diffusion then results in fewer charged species diffusing axially, thereby decreasing (increasing ion production costs) the overall efficiency of the plasma source when compared with the nonmagnetized discharge. Thus it is recommended that the multipolar magnets be removed for high pressure operation. The resulting plasma source will be more efficient, will operate with lower wall and gas temperatures and will also not be subject to wall erosion at higher power inputs.

However, if a process requires/desires low energy charged species, then the magnetized source may be the best solution for this application even in moderate to high pressure regimes. Also, in some cases (such as photoresist ashing) where molecular gases are used neutral free radicals are desired and charged particles are not wanted since they may

cause charge damage. In this case the higher pressure magnetized source has advantages over the nonmagnetized version.

#### **10.1.6 Measured Ion Production Cost**

The experimentally measured ion production costs show that the nonmagnetized discharge is a very efficient plasma source. In the 15-45mTorr pressure regime the ion production costs are approximately 410eV/ion. These values match well with predictions from the global model. At lower pressures of 10 mTorr and below the ion production costs increases dramatically to 500-700eV/ion and are well above the values of 300-350eV/ion that are predicted by the global model. At this time we do not have a good explanation for this large deviation from global model theory except that we are comparing the experimental performance with a simple cylindrical discharge geometry. We have not considered the more complex diffusion problem where the quartz discharge chamber opens into the larger external vacuum chamber. We may need a more complete numerical analysis of the diffusion process, similar to that which was carried out in Fig. 8.8 or in J. Hopwood's Thesis [Hop-90], in order to accurately predict low pressure diffusion and hence the ion production costs at low pressure. Additionally we should consider the existence of a group of "hot" electrons that are created by stochastic heating in the sheath. If high energy electrons are present they would help explain the increased (over the global model) diffusion losses to the walls of the dome and then we also need a different diffusion model for estimating the flux of charged species out of the discharge.

Since ion production cost is measured using the charge flux out of the bottom of the discharge it is clear from section 10.1.6 that the magnetized discharge will have higher ion production cost than either the nonmagnetized discharge or that predicted by the global model. The ion production cost goes from 500 eV/ion at 45 mTorr to between 600 and 800 eV/ion from 25 to 7 mTorr. It is interesting to note that the ion production cost improves dramatically at 4 mTorr to about 425 eV/ion. Figure 8.36 demonstrates once again that there is a crossover in performance for the magnetized and nonmagnetized discharges near 7 mTorr.

#### **10.1.7 Global Model Predictions**

For the nonmagnetized discharge at pressures greater than 7 mTorr the comparison between experimental measurements and the global model predictions is excellent. The global model can not only be used to make “back of the envelope” calculations for this plasma source design, but also appears to predict accurately the behavior of the electron temperature and density versus power and pressure. It does not predict the axial variation of density in the discharge. This is not surprising since the global model does not properly take into account the axial and radial variation of the input EM energy and also, as pointed out above, does not properly account for the axial diffusion out of the source into the vacuum chamber. At low pressures (4-5mTorr) the experimentally measured plasma potential and ion production costs are higher than the global model predictions for the nonmagnetized discharge. These differences may be due to the simplistic heating, diffusion and the geometric configuration considered in the global model calculations.

The electron temperatures measured with for the magnetized discharge fit reasonably well with the predictions of the global model. However, for reasons discussed above the charge density measured at the  $z=0$  plane for the magnetized discharge does not have good correlation with the global model. The plasma potentials measured for the magnetized discharge at the  $z=0$  plane are also less than predicted by the global model this is very likely due to the depleted high energy electron tail observed in the EEDF measurements.

#### **10.1.8 General Comparison Between the Magnetized and Nonmagnetized Discharges**

This experimental investigation indicates that at pressures above 6mTorr the non-magnetized discharge is superior in all aspects of performance to the magnetized discharge. Thus for moderately low pressure plasma processing applications in the pressure ranges of 8-50mTorr or above static magnetic fields are not required to efficiently operate and maintain microwave plasma processing plasma sources.

The performance at low pressure of magnetized and nonmagnetized discharges is very different. The magnetized discharge is the most efficient, i.e. the ion production costs drop from 800eV/ion at 15-25mTorr to 410eV/ion at 4 mTorr. In contrast the ion production costs for the nonmagnetized discharge increase from around 400-410eV/ion at 15-25 mTorr to 550-600 eV/ion at 7-10 mTorr. The magnetized discharge while becoming more efficient also has lower effective electron temperatures and plasma potentials and additionally it is a more stable discharge; i.e. it's easier to maintain. As the pressure is reduced the plasma potentials of the magnetized discharge are less than the global model and as the

pressure is reduced the difference becomes larger. The EEDF of the nonmagnetized discharge is Maxwellian or very close to Maxwellian over the entire experimental pressure and power regime at the source output and inside the source. However the EEDF of the magnetized discharge has a distribution that has a depleted (from Maxwellian) high energy tail at the source output for all pressures and powers. However the EEDF is Maxwellian inside the magnetic multipolar region. Given similar output densities at low pressure the nonmagnetized discharge requires more input microwave power than the magnetized discharge. As currently designed the magnetized discharge becomes the most efficient and robust source for low pressure operation.

An important question is "why are there differences?" The presence of the multipolar magnetic field, the elevated plasma potential in the nonmagnetized discharge, stochastic heating in the sheath at low pressures, and the experimental observations at low pressures of a plasma streaming out of the plasma source opening provide us clues as to what is occurring in the two discharges.

At low pressures the nonmagnetized discharge has densities above the critical density and thus the EM field is strongly evanescent and basically exists at the quartz plasma boundary. As the pressure is reduced there are more diffusion losses than predicted by the global model and hence more power is required to maintain the discharge as the pressure is reduced. At the moderate pressures of 20-45 mTorr the discharge is maintained by some combination of ohmic and stochastic sheath heating, but as the pressure is reduced to 4-5 mTorr stochastic heating becomes dominant and high energy electrons are created in the sheath adjacent to the quartz where the EM are strong. In fact the impressed EM fields

increase as the pressure is lowered to maintain the discharge because of the need for more power to maintain the discharge.

#### **10.1.9 Electron Loss Processes for the Magnetized Discharge**

The multipolar confinement behaves differently at high and low pressures. At the high pressures electron neutral collisions allow the electrons to escape radially through the throats of the magnetic cusps. These electrons, and ions that are electrostatically accelerated with them, heat the quartz walls (and have been seen to drill/burn holes in the walls under certain conditions). At lower pressures there are fewer collisions and hence confinement is improved. However  $E \times B$  and  $\text{grad}B$  drifts accelerate the plasma axially either out of the plasma source or to the top of the dome. Radial confinement is improved, and plasma source efficiency (ion production costs are lowered) is also improved. The EEDF measurements indicate that the high energy electrons are trapped by the multipolar field and they may be able to escape radially, while lower energy electrons can diffuse axially, probably by various drift processes. Thus the EEDF up in the multipolar field has more higher energy electrons than the down stream EEDF. Enhanced radial diffusion at high pressures causes hot walls and reduced source efficiency, while at low pressure the reduction in radial diffusion and increased axial diffusion improves source performance. A variation of this magnetized plasma source design that addresses the above issues is discussed in Section 10.3.2.

## 10.2 General Discussion of Collisionless Heating and Hot Electrons

Collisionless heating in cylindrical surface wave discharges has recently been explained by Aliev et. al. [Ali-92, Ali-95]. He points out that in over dense discharges adjacent to dielectric/plasma boundary there is a region where large density inhomogeneity exists as the plasma density varies from low values to the high densities in the central core of the discharge. Within this density gradient a region exists where the local plasma frequency equals the applied frequency. In this plasma resonance region then the applied electric field becomes enhanced, and can stochastically heat the electrons as they move to the wall and then are reflected by the sheath potential. This results in the formation of energetic or hot electrons which when they are reflected back into the discharge can in turn heat, ionize, and excite other species in the main core of the discharge. It is speculated that some of these hot electrons may have energies as high as 40-100eV, and if they are present at low pressure (their mfp would be large) they can cause ionization, excitation, etc. of the discharge species some distance (a number of cms) away from the plasma/wall interface. It is also useful to note that the stochastic heating process of a moving sheath as described by Lieberman [Lie-94] may play a role in heating the electron gas at low pressures.

The production of high energy electrons can explain some of the phenomenon seen in this research. As discussed above, in or adjacent to the sheath where the plasma density equals the excitation frequency, the electric field is greatly enhanced and thus provides an acceleration region for the electrons. These high energy electrons (40-100eV) then are ejected from the resonance zone near the quartz wall and move into the discharge. Some

will ionize and excite the gas in the core of the discharge while others may be absorbed at the walls if they have energies higher than the sheath potential, or if they have somewhat lower energy bounce off the sheath and return to the discharge core. Also, an important fraction of these accelerated electrons will escape through the plasma source opening at the  $z=0$  plane. If they have sufficient energy they will ionize and excite the gas in the down stream region of the vacuum chamber. As the “hot” electrons escape the discharge either by escaping to the discharge wall or out of the plasma source they will pull ions with them. This process produces an EEDF that is nonmaxwellian where the high energy tail is enhanced by the presence of hot electrons. Associated with this EEDF is an increased (from the global model Maxwellian potential) plasma potential.

Thus at low pressure in stochastically sheath/plasma resonance heated discharges one should observe the presence of excitation and probably ionization outside of the discharge. This has been seen in chapter 8, in Figure 8.34 for the nonmagnetized plasma at 7 mtorr. In this picture a broad plasma beam appears to be emitted from the discharge opening. This also occurs in A.Khan’s smaller discharges [Kha-00]. The production of hot electrons at the wall plasma interface can explain this phenomena. These pictures show that the excitation and probably ionization continue away from the EM excitation zone and this can only happen if there are some energetic electrons in this downstream region.

Additionally, the “hot” electrons that escape the discharge either to the discharge wall or through the plasma source output  $z=0$  plane will pull ions with them. As the measurements of the plasma potential indicate, see Figure 7.28, as the pressure is reduced the plasma potential increases and tips toward the output of the source indicating that as pressure is increased more and more electrons are being accelerated out of the end of the dis-



charge causing an increased and spatially varying plasma potential. This induced potential produces an electric field that pulls and accelerates the ions out of the discharge. This enhanced diffusion behavior will increase the plasma potential above that which is predicted by the global model. This has been observed in chapter 7, in Figure 7.18. It is noted that an important fraction of the input energy may be directed out of the source into the downstream chamber as accelerated electrons and ions. Recall that electrons and ions “carry with them” potential or stored energy that they later release down stream in elastic and inelastic collision processes or on the wall as heat energy when they recombine. The above discussion explains the enhanced (from the global model) plasma potential and the downstream excitation observed at low pressures in the nonmagnetized discharge.

Similar phenomena occur in the multipolar discharge except that the magnetic field allows ECR heating and reshapes the direction of the diffusing electrons. Again the discharge is over dense and as a result the EM fields are probably limited to the upper top of the discharge surface. EM heating takes place on the top surface of the discharge where the plasma density is the highest. Three heating mechanisms can be present (1) ohmic, (2) ECR, and (3) stochastic. At the higher pressures probably all three can coexist. However as the pressure is reduced the heating divides itself between ECR and stochastic. At the low pressures of 0.5-5mTorr which mechanism dominates depends of the direction and intensity of the electric field in the ECR layers and at the plasma wall density gradients. Thus heating should be mode and static magnetic field geometry dependent. In this study we held both the magnetic field geometry and EM mode fixed (there may be some differences between the near field mode and the  $TM_{012}$  mode). Certainly there is the potential for ECR heating and especially for the near field mode there is stochastic heating at the

very top of the dome where the static magnetic field is zero. There is a large applied electric field there impinging on the plasma density gradient and according to theory should create high energy electrons which would follow magnetic field lines and be caught up in bounce around in the multipolar field. Any electrons that are accelerated in the ECR layers also bounce around in the multipolar field. In both cases without collisions the high energy electrons tend to be confined by the multipolar magnetic field.

A better understanding of collisionless or stochastic heating in microwave discharges could lead to source designs that maximize this heating effect at low pressures. Maximizing plasma heating and energy absorption is key to stability and sustainability in microwave plasma sources. Improved heating creates a more lossy plasma and lowers cavity Q factor. A high cavity Q factor combined with a low loss plasma has been associated with mode jumps and hysteresis. Stability and repeatability is a primary concern of those who would implement this technology for wafer processing in the semiconductor industry. Most other factors are secondary concerns. Stability and repeatability are show stoppers! The ability to run tens of thousands of wafers with exactly the same process conditions for each wafer without system failure or gradual degradation of performance is a requirement. Optimizing stochastic heating in microwave discharges may make this more feasible for a wider range of microwave plasma source designs.

## **10. 3 Future Follow-on Research and Possible New Plasma Source Designs**

The above section has summarized the most important observations in this research and presented some theories as to the physical causes. This section proposes future work that may lead to deeper understanding of the findings of this investigation and to improved plasma source designs.

### **10.3.1 The Search for High Energy Electrons**

The experimental measurements suggest a number of important follow-on research projects. One is a search for high energy electrons. The SLP measurements were all made with the probe axis parallel to the discharge axis, and while they did show differences in EEDF between the two discharges they did not show strong direct evidence of high energy electrons that we believe are present. If there are high energy electrons present then most likely the distribution will be anisotropic. The electrons would be expected to be mostly parallel to the current orientation of the probe, and thus they would be missed in the measurement. We should take measurements with SLP oriented both parallel and perpendicular to the discharge axis and compare the ion saturation currents (See Figure 10.1). If there is a difference then it probably shows the existence of high energy electrons and this phenomena should be investigated further.

In the investigation presented in this dissertation EEDFs and electron temperature measurements were taken only along the z-axis and were not taken at periodic points along a radial path from the wall to the center of the discharge. These experiments would

be easy to complete since they only require axially oriented probes and may also lead to evidence of high energy electrons near the vertical wall of the discharge.

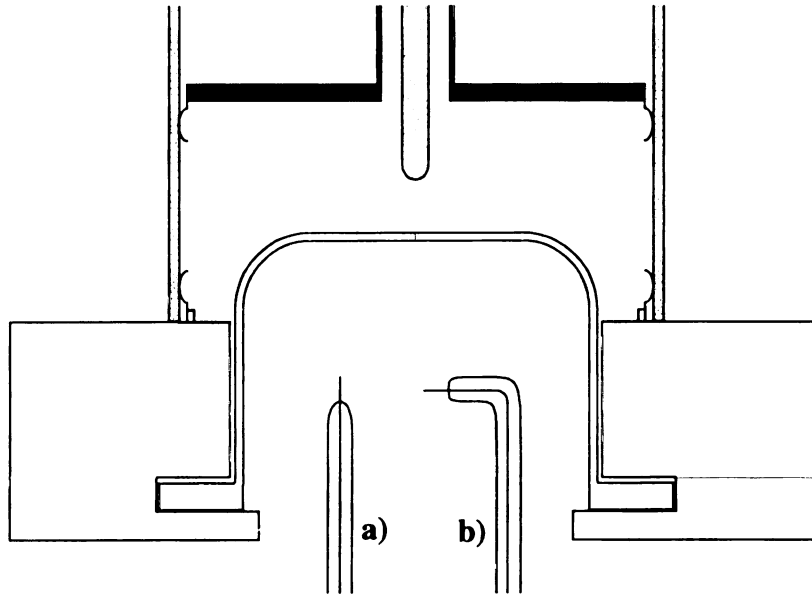


Figure 10.1 - Single Langmuir probes for measurement of EEDF:  
a) vertically (axially) oriented probe tip, and b) horizontally oriented probe tip

### 10.3.2 New Plasma Source Designs

The two plasma sources employed in this investigation (magnetized and non-magnetized) were chosen because of their availability and their present use in our laboratory. Neither source may be an optimum design for either nonmagnetized or magnetized discharges. Using what we have learned here and in other studies research should continue to develop optimum source designs.

At the lower pressures below 5-7 mTorr the multipolar magnets provide a useful role in confining the charged species and providing discharge stability. They are essential for efficient, and stable operation. Thus it is important to design optimum ECR magnetic field configurations. The experiments in this investigation show that while the multipolar configuration is useful at low pressure it may not be an optimum design. Indeed recently, the addition of a large single magnetic pole of permanent magnets to the sliding short (See Figure 10.2a) demonstrated in initial experiments improved performance in the low pressure regime. The discharge instead of being localized in the multicusp region streamed into the downstream chamber. The magnetic field pushes the charged species downstream out of the discharge zone. Certainly this and other geometries have the potential of improving plasma source performance not only at the lower pressures, but when properly designed may yield improved performance at higher pressures as well.

Another design improvement may be the placement of a metal disk at the end of the coupling probe in order to better achieve stochastic heating (See Figure 10.2b). This configuration was able to operate with three different sizes of metal disk (3 cm, 6 cm, and 9 cm diameter) with and without multipolar magnets. However, it needs to be investigated further (especially without multipolar magnets) to determine if stochastic heating is present and significantly enhances performance. Other sources that enhance stochastic heating may be designed and investigated.

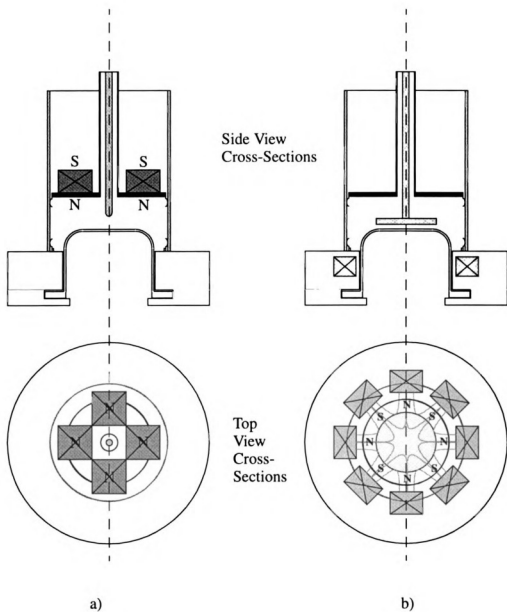


Figure 10.2 - New plasma source designs: a) permanent magnets are placed in on the top side of the sliding short to create an axial magnetic field, b) a plate is paced at the end of the probe antenna for enhanced stochastic heating at the top of the discharge (the 8 multipolar magnets are optional)

## **APPENDICES**

## Appendix A

### Cylindrical Cavity: Stored Energy, Power Lost, and Cavity Q Calculations

A.1 Field Equations for a Cylindrical Cavity

A.2 Table of the Roots of the Bessel Functions

A.3 Calculating the Energy Stored in the  $TE_{nml}$  and  $TM_{nml}$  Cylindrical Cavity Modes

A.4 Calculating the Power Lost in the  $TE_{nml}$  and  $TM_{nml}$  Cylindrical Cavity Modes

A.5 Calculating the Cavity Q Factor



## Appendix A

### Cylindrical Cavity: Stored Energy, Power Lost, and Cavity Q Calculations

#### A.1 Field Equations for a Cylindrical Cavity:

From the solution of the Helmholtz equation the phasor magnitudes for fields in a cylindrical cavity (Shown in Figure A.1) can be given [Che-93]:

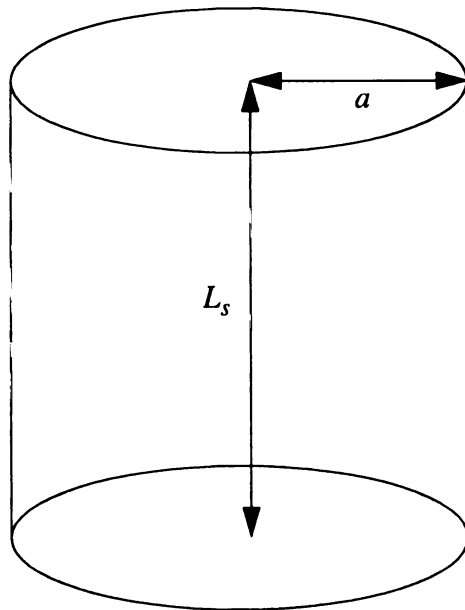


Figure A.1 - A Cylindrical Cavity with radius  $a$  and length  $L_s$ .

TE<sub>nml</sub> Field Solutions for a Cylindrical Cavity:

$$E_r = jH_0 \left[ \frac{k\eta a^2 n}{r(x'_{nm})^2} \right] J_n \left( \frac{x'_{nm}}{a} r \right) \sin(n\theta) \sin\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.1}$$

$$E_\theta = jH_0 \left[ \frac{k\eta a}{x'_{nm}} \right] J'_n \left( \frac{x'_{nm}}{a} r \right) \cos(n\theta) \sin\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.2}$$

$$H_r = H_0 \left[ \frac{\beta a}{x'_{nm}} \right] J'_n \left( \frac{x'_{nm}}{a} r \right) \cos(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.3}$$

$$H_\theta = -H_0 \left[ \frac{\beta a^2 n}{r(x'_{nm})^2} \right] J_n \left( \frac{x'_{nm}}{a} r \right) \sin(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.4}$$

$$H_z = H_0 J_n \left( \frac{x'_{nm}}{a} r \right) \cos(n\theta) \sin\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.5}$$

TM<sub>nml</sub> Field Solutions for a Cylindrical Cavity:

$$E_r = -E_0 \left[ \frac{\beta a}{x_{nm}} \right] J'_n \left( \frac{x_{nm}}{a} r \right) \cos(n\theta) \sin\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.6}$$

$$E_\theta = E_0 \left[ \frac{\beta n a^2}{x_{nm}} \right] J_n \left( \frac{x_{nm}}{a} r \right) \sin(n\theta) \sin\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.7}$$

$$E_z = E_0 J_n \left( \frac{x_{nm}}{a} r \right) \cos(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.8}$$

$$H_r = -jE_0 \left[ \frac{k a^2 n}{\eta r x_{nm}} \right] J_n \left( \frac{x_{nm}}{a} r \right) \sin(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.9}$$

$$H_\theta = -jE_0 \left[ \frac{k a}{\eta x_{nm}} \right] J'_n \left( \frac{x_{nm}}{a} r \right) \cos(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. A.10}$$

where  $H_0$  and  $E_0$  are arbitrary constants,  $(r, \theta, z)$  are the cylindrical coordinates,  $k = \frac{\omega}{c}$ ,  $\eta = \sqrt{\frac{\mu}{\epsilon}}$ , and  $\beta = \sqrt{k^2 - k_c^2}$  where  $k_c = \frac{x_{nm}}{a}$  or  $\frac{x'_{nm}}{a}$ . In the above relations  $k$  is known as the wave number,  $\omega$  is the radian frequency of the EM radiation,  $c$  is the speed of light,  $\eta$  is the intrinsic impedance of the medium filling the cavity,  $\mu$  is the permeability of the medium,  $\epsilon$  is the permittivity of the medium, and  $\beta$  is known as the phase constant. Note that  $l$  in Equations A.1-A.10, and the rest of the equations in this appendix, is an eigen number and not a length variable.

## A.2 Table of the roots of the Bessel Functions:

Table A.1 - First Five Roots of the First Derivative of the Bessel Functions of Order  $J'_0$  to  $J'_5$ . Used for choosing  $x'_{nm}$  in the TE mode equations

|          |   | <i>m</i> |         |         |         |         |         |
|----------|---|----------|---------|---------|---------|---------|---------|
|          |   | $J'_0$   | $J'_1$  | $J'_2$  | $J'_3$  | $J'_4$  | $J'_5$  |
| <i>n</i> | 1 | 3.8317   | 1.8412  | 3.0542  | 4.2012  | 5.3175  | 6.4156  |
|          | 2 | 7.0156   | 5.3314  | 6.7061  | 8.0152  | 9.2824  | 10.5199 |
|          | 3 | 10.1735  | 8.5363  | 9.9695  | 11.3459 | 12.6819 | 13.9872 |
|          | 4 | 13.3237  | 11.7060 | 13.1704 | 14.5858 | 15.9641 | 17.3128 |
|          | 5 | 16.4706  | 14.8636 | 16.3475 | 17.7887 | 19.1960 | 20.5755 |

Table A.2 - First Five Roots of the of the Bessel Functions of Order  $J_0$  to  $J_5$ . Used for choosing  $x_{nm}$  in the TM mode equations

|          |   | <i>m</i> |         |         |         |         |         |
|----------|---|----------|---------|---------|---------|---------|---------|
|          |   | $J_0$    | $J_1$   | $J_2$   | $J_3$   | $J_4$   | $J_5$   |
| <i>n</i> | 1 | 2.4048   | 3.8317  | 5.1336  | 6.3802  | 7.5883  | 8.7715  |
|          | 2 | 5.5201   | 7.0156  | 8.4172  | 9.7610  | 11.0647 | 12.3386 |
|          | 3 | 8.6537   | 10.1735 | 11.6198 | 13.0152 | 14.3725 | 15.7002 |
|          | 4 | 11.7915  | 13.3237 | 14.7960 | 16.2235 | 17.6160 | 18.9801 |
|          | 5 | 14.9309  | 16.4706 | 17.9598 | 19.4094 | 20.8269 | 22.2178 |

### A.3 Calculating the Energy Stored in the TE<sub>nm $\ell$</sub> and TM<sub>nm $\ell$</sub> Cylindrical Cavity

#### Modes

At resonance half of the time average electromagnetic energy in a cavity is stored in electric fields and half in magnetic fields. The total stored energy can be given by summing the time average electric or magnetic energy density over the volume of the cavity and multiplying by 2:

$$W = 2 \times \frac{\epsilon_0}{4} \int_V |\vec{E}(r, \theta, z)|^2 dV \quad \text{Eq. A.11}$$

or

$$W = 2 \times \frac{\mu_0}{4} \int_V |\vec{H}(r, \theta, z)|^2 dV \quad \text{Eq. A.12}$$

Where the E and H vectors are in phasor form,  $dV$  is a volume element of the cavity, and  $\epsilon_0$  is the permittivity of free space. The squared magnitude the electric field in cylindrical coordinates can be calculated as:

$$|\vec{E}(r, \theta, z)|^2 = |E_r|^2 + |E_\theta|^2 + |E_z|^2 \quad \text{Eq. A.13}$$

This gives:

$$W = \frac{\epsilon_0}{2} \int_0^{L_s} \int_0^{2\pi} \int_0^a (|E_r|^2 + |E_\theta|^2 + |E_z|^2) r dr d\theta dz \quad \text{Eq. A.14}$$

Where  $L_s$  is the height of the cavity and  $a$  is the cavity radius. Energy in the magnetic field is calculated in a similar way.

To determine the energy stored in TE modes use the electric field because  $E_z = 0$ . Only  $E_r$  and  $E_\theta$  need to be integrated. For the energy  $W$  we have:

$$W_{TE} = \frac{\epsilon_0}{2} \int_0^{L_s} \int_0^{2\pi} \int_0^a \left( |E_r|^2 + |E_\theta|^2 \right) r dr d\theta dz \quad \text{Eq. A.15}$$

Substituting for  $E_r$  and  $E_\theta$  we have:

$$W_{TE} = \frac{\epsilon_0}{2} \int_0^{L_s} \int_0^{2\pi} \int_0^a \left( \left| jH_0 \left[ \frac{k\eta a^2 n}{r(x'_{nm})^2} \right] J_n \left( \frac{x'_{nm}}{a} r \right) \sin(n\theta) \sin \left( \frac{l\pi}{L_s} z \right) \right|^2 + \right. \\ \left. \left| jH_0 \left[ \frac{k\eta a}{x'_{nm}} \right] J'_n \left( \frac{x'_{nm}}{a} r \right) \cos(n\theta) \sin \left( \frac{l\pi}{L_s} z \right) \right|^2 \right) r dr d\theta dz \quad \text{Eq. A.16}$$

Taking the magnitude, squaring, and factoring:

$$W_{TE} = H_0^2 \frac{\epsilon_0}{2} \left[ \frac{k\eta a}{x'_{nm}} \right]^2 \int_0^{L_s} \int_0^{2\pi} \int_0^a \left( \left[ \frac{an}{r(x'_{nm})} \right]^2 J_n^2 \left( \frac{x'_{nm}}{a} r \right) \sin^2(n\theta) + \right. \\ \left. J'^2 \left( \frac{x'_{nm}}{a} r \right) \cos^2(n\theta) \sin^2 \left( \frac{l\pi}{L_s} z \right) \right) r dr d\theta dz \quad \text{Eq. A.17}$$

Integrating  $\theta$  and  $z$ :

$$W_{TE} = \left[ H_0^2 \right] \frac{\epsilon_0}{2} \left[ \frac{k\eta a}{x'_{nm}} \right]^2 \left[ \frac{L_s}{2} \right] \pi \int_0^a \left( \left[ \frac{an}{r(x'_{nm})} \right]^2 J_n^2 \left( \frac{x'_{nm}}{a} r \right) + J_n'^2 \left( \frac{x'_{nm}}{a} r \right) \right) r dr$$

Eq. A.18

The integral in  $r$  can then be evaluated [Poz-90, p. 351, 711]:

$$W_{TE} = \left[ H_0^2 \right] \frac{\epsilon_0}{4} \left[ \frac{k\eta a}{x'_{nm}} \right]^2 L_s \pi \left[ \frac{a^2}{2} \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] J_n^2(x'_{nm}) \right]$$

Eq. A.19

Simplifying:

$$W_{TE} = \left[ H_0^2 \right] L_s \frac{\pi \epsilon_0}{8} \left[ \frac{k\eta}{x'_{nm}} \right]^2 a^4 \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] J_n^2(x'_{nm})$$

Eq. A.20

To determine the energy stored in TM modes it is best to use the magnetic field.

$$W_{TM} = \frac{\mu_0}{2} \int_0^{L_s} \int_0^{2\pi} \int_0^a (|H_r|^2 + |H_\theta|^2 + |H_z|^2) r dr d\theta dz$$

Eq. A.21

For TM modes  $H_z = 0$ :

$$W_{TM} = \frac{\mu_0}{2} \int_0^{L_s} \int_0^{2\pi} \int_0^a (|H_r|^2 + |H_\theta|^2) r dr d\theta dz$$

Eq. A.22

Substituting for  $H_r$  and  $H_\theta$ :

$$W_{TM} = \frac{\mu_0}{2} \int_0^{L_s} \int_0^{2\pi} \int_0^a \left( \left| -jE_0 \left[ \frac{ka^2 n}{\eta r x_{nm}^2} \right] J_n \left( \frac{x_{nm}}{a} r \right) \sin(n\theta) \cos \left( \frac{l\pi}{L_s} z \right) \right|^2 + \right. \\ \left. \left| -jE_0 \left[ \frac{ka}{\eta x_{nm}} \right] J_n' \left( \frac{x_{nm}}{a} r \right) \cos(n\theta) \cos \left( \frac{l\pi}{L_s} z \right) \right|^2 \right) r dr d\theta dz$$

Eq. A.23

Taking the magnitude, squaring, and factoring:

$$W_{TM} = \frac{\mu_0}{2} E_0^2 \left[ \frac{ka}{\eta x_{nm}} \right]^2 \int_0^{L_s} \int_0^{2\pi} \int_0^a \left( \left[ \frac{an}{rx_{nm}} \right]^2 J_n^2 \left( \frac{x_{nm}}{a} r \right) \sin^2(n\theta) \cos^2 \left( \frac{l\pi}{L_s} z \right) + \right. \\ \left. J_n'^2 \left( \frac{x_{nm}}{a} r \right) \cos^2(n\theta) \cos^2 \left( \frac{l\pi}{L_s} z \right) \right) r dr d\theta dz$$

Eq. A.24

Integrating  $\theta$  and  $z$ :

$$W_{TM} = \frac{\mu_0}{2} E_0^2 \left[ \frac{ka}{\eta x_{nm}} \right]^2 \left( \frac{\pi L_s}{2} \right) \int_0^a \left( \left[ \frac{an}{rx_{nm}} \right]^2 J_n^2 \left( \frac{x_{nm}}{a} r \right) + J_n'^2 \left( \frac{x_{nm}}{a} r \right) \right) r dr$$

Eq. A.25

Evaluating the integral [Poz-90, p. 711]:

$$W_{TM} = \frac{\mu_0}{2} E_0^2 \left[ \frac{ka}{\eta x_{nm}} \right]^2 \left( \frac{\pi L_s}{2} \right) \left[ \frac{a^2}{2} J_n'^2(x_{nm}) \right]$$

Eq. A.26

Simplifying:

$$W_{TM} = \left[ \frac{L_s \pi \mu_0 a^4}{8} \right] E_0^2 \left[ \frac{k}{\eta x_{nm}} \right]^2 J_n'^2(x_{nm}) \quad \text{Eq. A.27}$$

#### A.4 Calculating the Power Lost in the $TE_{nml}$ and $TM_{nml}$ Cylindrical Cavity Modes

Power is lost in an empty metal cavity due to current flowing in the finitely conductive walls. To calculate  $P_L$  first determine an expression for the current density in the walls from the known magnetic field pattern. Then integrate the square of the current density over all wall surfaces. This gives the total power lost.

The time average power lost per unit area is a function of current in the cavity walls. The magnitude of the current flowing in a wall at a point is directly equal to the magnitude of the magnetic field tangent to the wall at that point [Che-89]:

$$P_{average} = \frac{1}{2} R_s |J_s|^2 = \frac{1}{2} R_s |H_t|^2 \quad \text{Eq. A.28}$$

To find the total power this expression can be integrated over the inner surface of the cavity:

$$P = \frac{1}{2} R_s \oint_S |H_t|^2 dS \quad \text{Eq. A.29}$$



To find the power lost in a  $TE_{nm1}$  mode for a cylindrical cavity we need to calculate the power lost in both the cylindrical side wall and the top and bottom end walls. The side wall will have both  $H_\theta$  and  $H_z$  tangential components. The end walls will have both  $H_\theta$  and  $H_r$  components.

$$P_{side} = \frac{1}{2} R_s \int_0^{L_s} \int_0^{2\pi} \left( |H_{\theta r=a}|^2 + |H_{z r=a}|^2 \right) r d\theta dz \quad \text{Eq. A.30}$$

For the theta component of power and substituting for  $H_\theta$ :

$$P_{side} = \frac{1}{2} R_s \int_0^{L_s} \int_0^{2\pi} \left( \left| -H_0 \left[ \frac{\beta a^2 n}{r(x'_{nm})^2} \right] J_n \left( \frac{x'_{nm}}{a} r \right) \sin(n\theta) \cos \left( \frac{l\pi}{L_s} z \right) \right|^2 + \right. \\ \left. \left| H_0 J_n \left( \frac{x'_{nm}}{a} r \right) \cos(n\theta) \sin \left( \frac{l\pi}{L_s} z \right) \right|^2 \right) r d\theta dz \quad \text{Eq. A.31}$$

Taking the absolute value and squaring:

$$P_{side} = \left[ H_0^2 \right] \frac{1}{2} R_s \int_0^{L_s} \int_0^{2\pi} \left( \left[ \frac{\beta a^2 n}{r(x'_{nm})^2} \right]^2 J_n^2 \left( \frac{x'_{nm}}{a} r \right) \sin^2(n\theta) \cos^2 \left( \frac{l\pi}{L_s} z \right) + \right. \\ \left. J_n^2 \left( \frac{x'_{nm}}{a} r \right) \cos^2(n\theta) \sin^2 \left( \frac{l\pi}{L_s} z \right) \right) r d\theta dz \quad \text{Eq. A.32}$$

Integrating and simplifying (note that here  $r=a$ ):

$$P_{side} = \left[ H_0^2 \right] \frac{\pi a}{4} R_s L_s \left( \left[ \frac{\beta a n}{(x'_{nm})^2} \right]^2 + 1 \right) J_n^2(x'_{nm}) \quad \text{Eq. A.33}$$

Next calculate power lost in the end plates with  $H_r$  and  $H_\theta$ , let  $z = L_s$  top plate or  $z = 0$  bottom plate (since both are equivalent due to symmetry choose  $z=0$  and multiply by 2):

$$P_{ends} = 2 \times \frac{1}{2} R_s \int_0^{2\pi} \int_0^a \left( |H_{\theta z=0}|^2 + |H_{r z=0}|^2 \right) r dr d\theta \quad \text{Eq. A.34}$$

Substituting for  $H_\theta$  and  $H_r$  we have

$$P_{ends} = R_s \int_0^{2\pi} \int_0^a \left( \left| -H_0 \left[ \frac{\beta a^2 n}{r(x'_{nm})^2} \right] J_n \left( \frac{x'_{nm} r}{a} \right) \sin(n\theta) \cos \left( \frac{l\pi}{L_s} z \right) \right|^2 + \left| H_0 \left[ \frac{\beta a}{x'_{nm}} \right] J'_n \left( \frac{x'_{nm} r}{a} \right) \cos(n\theta) \cos \left( \frac{l\pi}{L_s} z \right) \right|^2 \right) r dr d\theta \quad \text{Eq. A.35}$$

Taking the absolute value and squaring:

$$P_{ends} = H_0^2 R_s \left[ \frac{\beta a}{x'_{nm}} \right]^2 \int_0^{2\pi} \int_0^a \left( \left[ \frac{a n}{r(x'_{nm})} \right]^2 J_n^2 \left( \frac{x'_{nm} r}{a} \right) \sin^2(n\theta) \cos^2 \left( \frac{l\pi}{L_s} z \right) + J_n'^2 \left( \frac{x'_{nm} r}{a} \right) \cos^2(n\theta) \cos^2 \left( \frac{l\pi}{L_s} z \right) \right) r dr d\theta \quad \text{Eq. A.36}$$

Integrate with respect to  $\theta$  and let  $z=0$ :

$$P_{ends} = H_0^2 R_s \left[ \frac{\beta a}{x'_{nm}} \right]^2 \pi \int_0^a \left( \left[ \frac{an}{r(x'_{nm})} \right]^2 J_n^2 \left( \frac{x'_{nm}}{a} r \right) + J_n'^2 \left( \frac{x'_{nm}}{a} r \right) \right) r dr$$

Eq. A.37

Evaluate the integral in  $r$ :

$$P_{ends} = H_0^2 R_s \left[ \frac{\beta a}{x'_{nm}} \right]^2 \pi \left[ \frac{a^2}{2} \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] J_n^2(x'_{nm}) \right]$$

Eq. A.38

Simplify:

$$P_{ends} = \frac{1}{2} H_0^2 R_s \frac{\pi \beta^2 a^4}{x_{nm}^2} \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] J_n^2(x'_{nm})$$

Eq. A.39

$$P_{total} = P_{side} + P_{ends}:$$

$$P_{total} = H_0^2 \frac{\pi a}{4} R_s L_s \left[ \left[ \frac{\beta an}{(x'_{nm})^2} \right]^2 + 1 \right] J_n^2(x'_{nm}) + \frac{1}{2} H_0^2 R_s \frac{\pi \beta^2 a^4}{(x'_{nm})^2} \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] J_n^2(x'_{nm})$$

Eq. A.40

Factoring and simplifying:

$$P_{total} = H_0^2 \frac{R_s}{2} \pi J_n^2(x'_{nm}) \left\{ \frac{a}{2} L_s \left[ \left[ \frac{\beta a n}{(x'_{nm})^2} \right]^2 + 1 \right] + \frac{\beta^2 a^4}{(x'_{nm})^2} \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] \right\}$$

Eq. A.41

To find the power lost in a  $TM_{nml}$  mode for a cylindrical cavity we need to calculate the power lost in both the cylindrical side wall and the top and bottom end walls. Since this is a TM mode the side wall has only the  $H_\theta$  tangential component. The end walls will have both  $H_\theta$  and  $H_r$  components.

For the side wall:

$$P_{side} = \frac{1}{2} R_s \int_0^{L_s} \int_0^{2\pi} |H_{\theta r=a}|^2 r d\theta dz$$

Eq. A.42

Substituting for  $H_\theta$ :

$$P_{side} = \frac{1}{2} R_s \int_0^{L_s} \int_0^{2\pi} \left| -j E_0 \left[ \frac{ka}{\eta x_{nm}} \right] J_n' \left( \frac{x_{nm}}{a} r \right) \cos(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \right|^2 r d\theta dz$$

Eq. A.43

Taking the absolute value, squaring, letting  $r=a$  and rearranging

$$P_{side} = \frac{1}{2} R_s \left[ E_0 \left[ \frac{ka}{\eta x_{nm}} \right] J_n'(x_{nm}) \right]^2 a \int_0^{L_s} \left[ \cos\left(\frac{l\pi}{L_s} z\right) \right]^2 dz \int_0^{2\pi} [\cos(n\theta)]^2 d\theta$$

Eq. A.44

Evaluating the integrals for theta and z and simplifying:

$$P_{side} = \frac{R_s \pi a L}{4} \left\{ \left[ \frac{ka}{\eta x_{nm}} \right] E_0 J_n'(x_{nm}) \right\}^2$$

Eq. A.45

The total power lost in the side wall is  $P_{side}$ .

Next calculate power lost in the end plates with  $H_r$  and  $H_\theta$ , choose  $z=0$  and multiply by 2:

$$P_{ends} = 2 \times \frac{1}{2} R_s \int_0^{2\pi} \int_0^a \left( |H_{\theta z=0}|^2 + |H_{r z=0}|^2 \right) r dr d\theta$$

Eq. A.46

Substituting for the  $H_\theta$  and  $H_r$  components:

$$P_{ends} = R_s \int_0^{2\pi} \int_0^a \left( \left| -jE_0 \left[ \frac{ka}{\eta x_{nm}} \right] J_n' \left( \frac{x_{nm}}{a} r \right) \cos(n\theta) \cos \left( \frac{l\pi}{L_s} z \right) \right|^2 + \right. \\ \left. \left| -jE_0 \left[ \frac{ka^2 n}{\eta r x_{nm}} \right] J_n \left( \frac{x_{nm}}{a} r \right) \sin(n\theta) \cos \left( \frac{l\pi}{L_s} z \right) \right|^2 \right) r dr d\theta$$

Eq. A.47

Taking the absolute value, squaring, factoring and letting  $z=0$ :

$$P_{ends} = R_s E_0^2 \left[ \frac{ka}{\eta x_{nm}} \right]^2 \int_0^{2\pi} \int_0^a \left( J_n'^2 \left( \frac{x_{nm}}{a} r \right) \cos^2(n\theta) + \right. \\ \left. \left[ \frac{an}{rx_{nm}} \right]^2 J_n^2 \left( \frac{x_{nm}}{a} r \right) \sin^2(n\theta) \right) r dr d\theta$$

Eq. A.48

Integrating with respect to  $\theta$ :

$$P_{ends} = R_s E_0^2 \left[ \frac{ka}{\eta x_{nm}} \right]^2 \pi \int_0^a \left( J_n'^2 \left( \frac{x_{nm}}{a} r \right) + \left[ \frac{an}{rx_{nm}} \right]^2 J_n^2 \left( \frac{x_{nm}}{a} r \right) \right) r dr$$

Eq. A.49

Evaluating the integral with respect to  $r$ :

$$P_{ends} = R_s E_0^2 \left[ \frac{ka}{\eta x_{nm}} \right]^2 \pi \left\{ \frac{a^2}{2} J_n'^2(x_{nm}) \right\}$$

Eq. A.50

Simplifying:

$$P_{ends} = \frac{R_s \pi a^4 E_0^2}{2} \left[ \frac{k}{\eta x_{nm}} \right]^2 \left[ J_n'^2(x_{nm}) \right]$$

Eq. A.51

The total power lost in the cavity for the  $TM_{nml}$  mode is  $P_{side} + P_{ends}$ .

$$P_{total} = P_{side} + P_{ends}$$

$$P_{total} = \frac{R_s \pi a L}{4} \left\{ \left[ \frac{ka}{\eta x_{nm}} \right] E_0 J_n'(x_{nm}) \right\}^2 + \frac{R_s \pi a^4 E_0^2}{2} \left[ \frac{k}{\eta x_{nm}} \right]^2 \left[ J_n'^2(x_{nm}) \right]$$

Eq. A.52

Simplifying:

$$P_{total} = \frac{R_s}{4} \pi a^3 E_0^2 \left[ \frac{k}{\eta x_{nm}} \right]^2 \left[ J_n'^2(x_{nm}) \right] (L_s + 2a)$$

Eq. A.53

### A.5 Calculating the Cavity Q factor:

The Q of the TE<sub>nm</sub> mode is given as:

$$Q = \frac{\omega W}{P} \quad \text{Eq. A.54}$$

$$Q = \frac{\omega \left( [H_0^2] L_s \frac{\pi \epsilon_0}{8} \left[ \frac{k\eta}{x'_{nm}} \right]^2 a^4 \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] J_n^2(x'_{nm}) \right)}{H_0^2 \frac{R_s}{2} \pi J_n^2(x'_{nm}) \left\{ \frac{a}{2} L_s \left[ \left[ \frac{\beta a n}{(x'_{nm})^2} \right]^2 + 1 \right] + \frac{\beta^2 a^4}{(x'_{nm})^2} \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] \right\}}$$

Eq. A.55

Simplifying:

$$Q = \frac{\omega \left( L_s \epsilon_0 \left[ \frac{k\eta}{x'_{nm}} \right]^2 a^3 \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] \right)}{4R_s \left\{ \frac{1}{2} L_s \left[ \left[ \frac{\beta a n}{(x'_{nm})^2} \right]^2 + 1 \right] + \frac{\beta^2 a^3}{(x'_{nm})^2} \left[ 1 - \left[ \frac{n}{(x'_{nm})} \right]^2 \right] \right\}}$$

Eq. A.56

The Q of the  $TM_{nml}$  mode is given as:

$$Q = \frac{\omega W}{P} \quad \text{Eq. A.57}$$

$$Q = \frac{\omega \left( \left[ \frac{L_s \pi \mu_0 a^4}{8} \right] E_0^2 \left[ \frac{k}{\eta x_{nm}} \right]^2 J_n'^2(x_{nm}) \right)}{\frac{R_s}{4} \pi a^3 E_0^2 \left[ \frac{k}{\eta x_{nm}} \right]^2 \left[ J_n'^2(x_{nm}) \right] (L_s + 2a)} \quad \text{Eq. A.58}$$

Simplifying:

$$Q = \frac{\omega \mu_0 a}{2R_s \left( 1 + \frac{2a}{L_s} \right)} \quad \text{Eq. A.59}$$

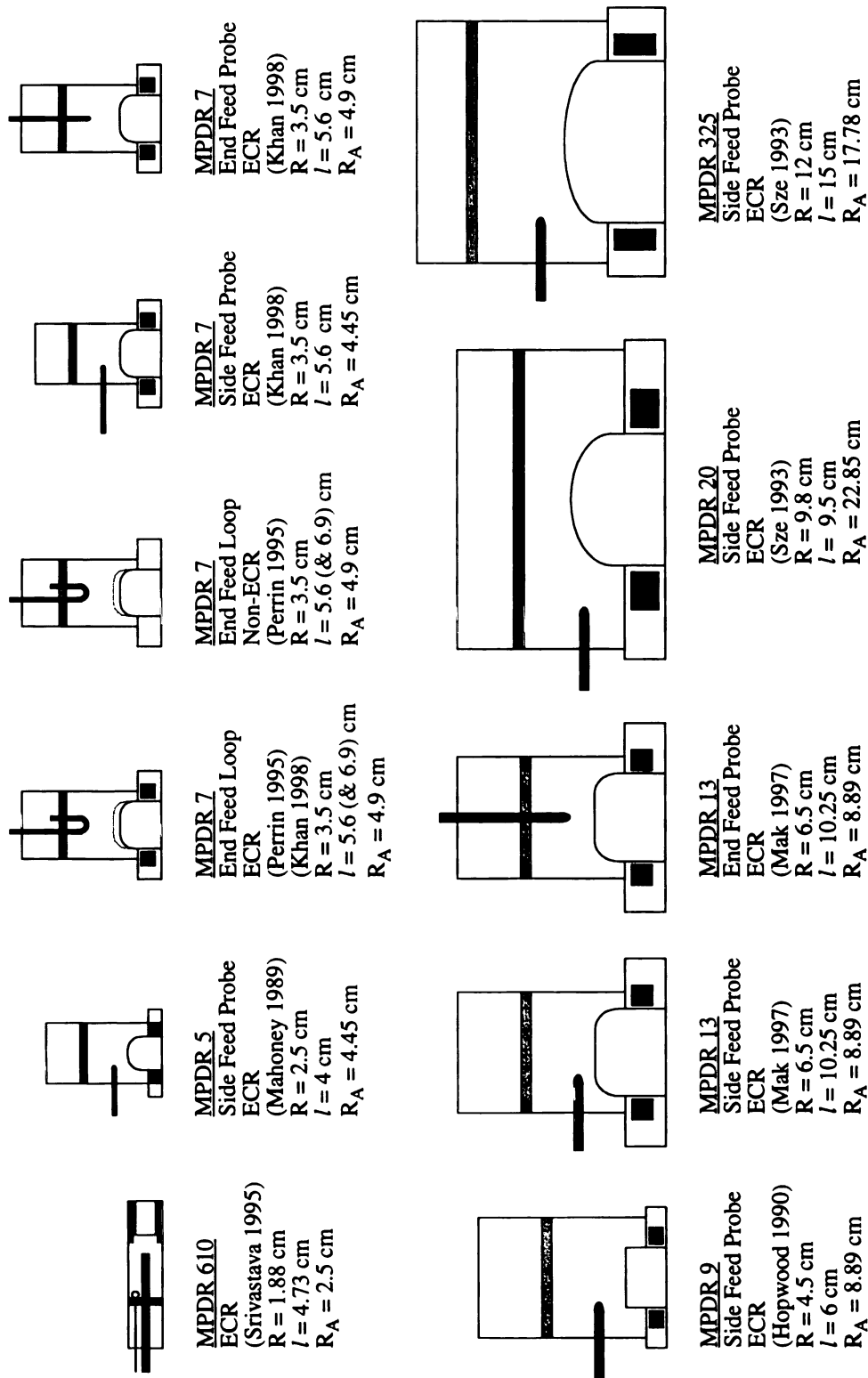


## Appendix B

### Variations on the Design of the Microwave Cavity Plasma Source

#### **B.1 Variations of the Microwave Plasma Disk Reactor:**

Eleven different configurations of the general microwave plasma disk reactor are shown in Figure B.1.



**Figure B.1: Eleven MPDR Configurations Ordered by Discharge Size**

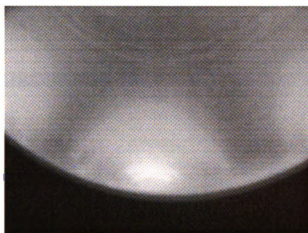
## Appendix C

### Close-up Photographs Of The Magnetic Field Cusps At Different Pressures

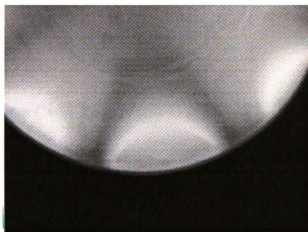
#### **C.1 Magnetic Field Cusps:**

Close-up photographs of the plasma in one of the multipolar magnetic cusps are shown in Figure C.1 for 7, 15, and 45 mTorr.

45 mTorr



15 mTorr



7 mTorr

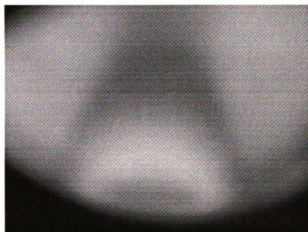


Figure C.1 - Close-up Photographs of the magnetic cusps for 7, 15, and 45 mTorr.

## Appendix D

### Cavity Tuning Height for the Magnetized and Non-Magnetized Cases

D.1 Correlation Between Cavity Tuning Height and Plasma Charge Density

D.2 Cavity Tuning Height for the Magnetized and Non-Magnetized Cases

D.3 Conclusions

## Appendix D

### Cavity Tuning Height for the Magnetized and Non-Magnetized Cases

#### **D.1 Correlation Between Cavity Tuning Height and Plasma Charge Density**

As was noted by Fredricks and Asmussen [Fre-71b], for microwave plasmas in variable length microwave cavities, a change in power input or discharge pressure will de-tune a the cavity plasma system. Cavity length retuning is then required to return the system to a similar level of absorbed power. It is widely accepted that the change in cavity tuning is caused by a change in the plasma charge density (which changes the complex impedance of the plasma load). Hence, anything that changes charge density (i.e. power input, discharge pressure, etc.) can effect the tuning and change the optimum tuning length of the cavity plasma system.

Conversely, we can also assume that a change in cavity tuning length implies a change in charge density in a cavity plasma system (neglecting any significant change in the resistive losses of the plasma). However, since the microwave radiation only penetrates on the order of a few skin depths into the plasma (i n plasmas with greater than critical density), we can only infer a change in density for this skin depth region of the plasma discharge. In this investigation it is clear that tuning length, for the  $TM_{012}$  mode in the non-magnetized discharge, increases with increasing power absorbed and discharge pressure. This is shown in Figure D.1.

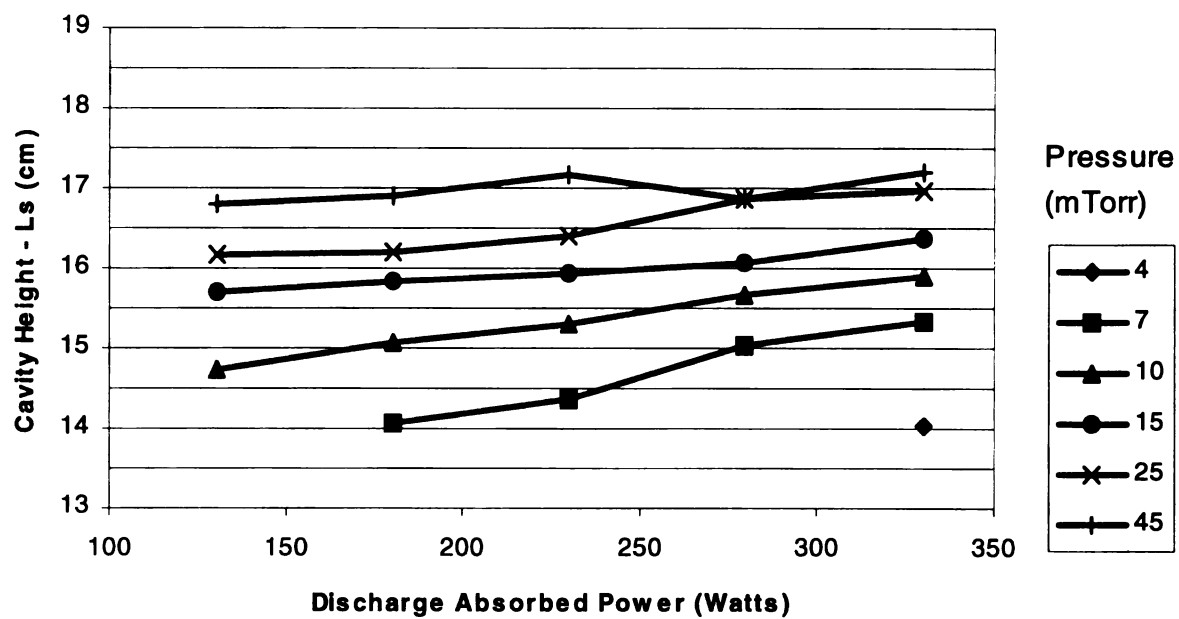


Figure D.1 - Cavity Tuning Height,  $L_s$ , vs. Discharge Absorbed Power,  $P_{abs}$ , for the non-magnetized  $TM_{012}$  mode.

## **D.2 Cavity Tuning Height for the Magnetized and Non-Magnetized Cases**

If we compare the matched positions of the magnetized and non-magnetized ( $TM_{012}$  mode) discharges we find that the magnetized discharge has a greater tuning length than the non-magnetized discharge for equivalent power and pressure. Figures D.2-D.7 plot the matched positions vs. absorbed power for six different pressure levels. Not only are the magnetized tuning lengths greater than the non-magnetized tuning lengths, the difference is more significant at lower discharge pressure levels.

## **D.3 Conclusions**

There is strong reason to conclude that the charge density in the skin depth region of the magnetized discharge is greater than the charge density in the skin depth region of the non-magnetized discharge. In chapter 8 it was shown using Langmuir probe measurements that the charge density up into the discharge for the magnetized discharge was similar if not greater than the charge density up into the non-magnetized discharge. However, the charge density for the magnetized discharge decreased more rapidly with distance down out of the discharge (along  $z$ ) than the non-magnetized discharge. This can be explained by the hypothesis that much of the charge density in the magnetic discharge is well confined up near the top of the discharge by the magnetic fields and lost to the discharge walls before it can diffuse out the opening of the discharge. By contrast the non-magnetized discharge plasma can diffuse more freely and distribute itself more uniformly throughout the discharge region.



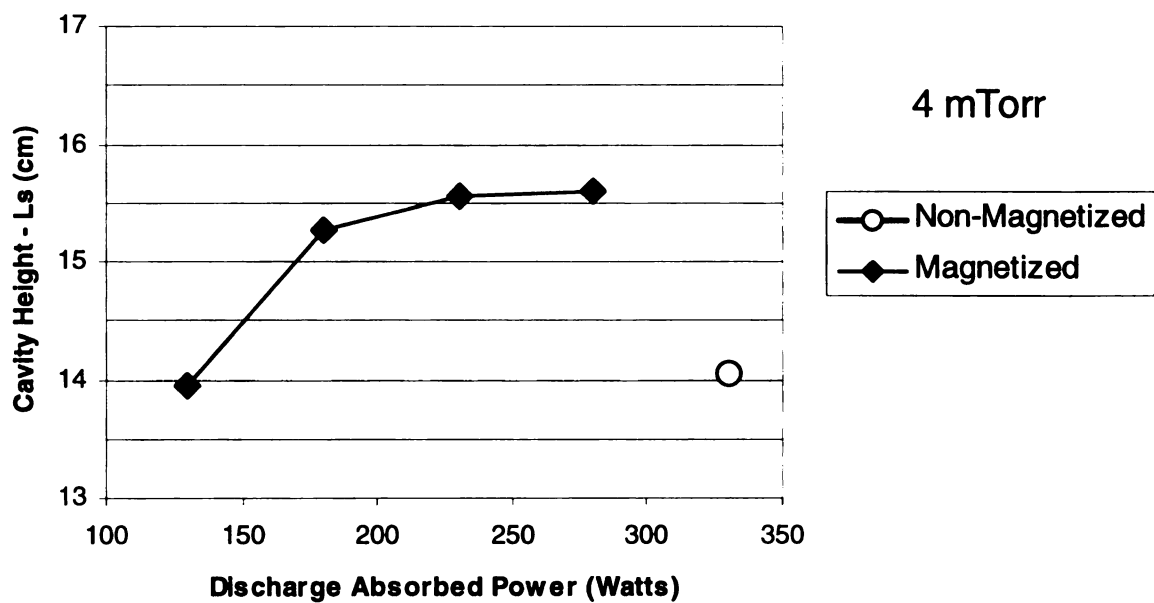


Figure D.2 - Cavity Tuning Height,  $L_s$ , vs. Discharge Absorbed Power,  $P_{abs}$ , for the magnetized and non-magnetized  $TM_{012}$  mode at 4 mTorr.

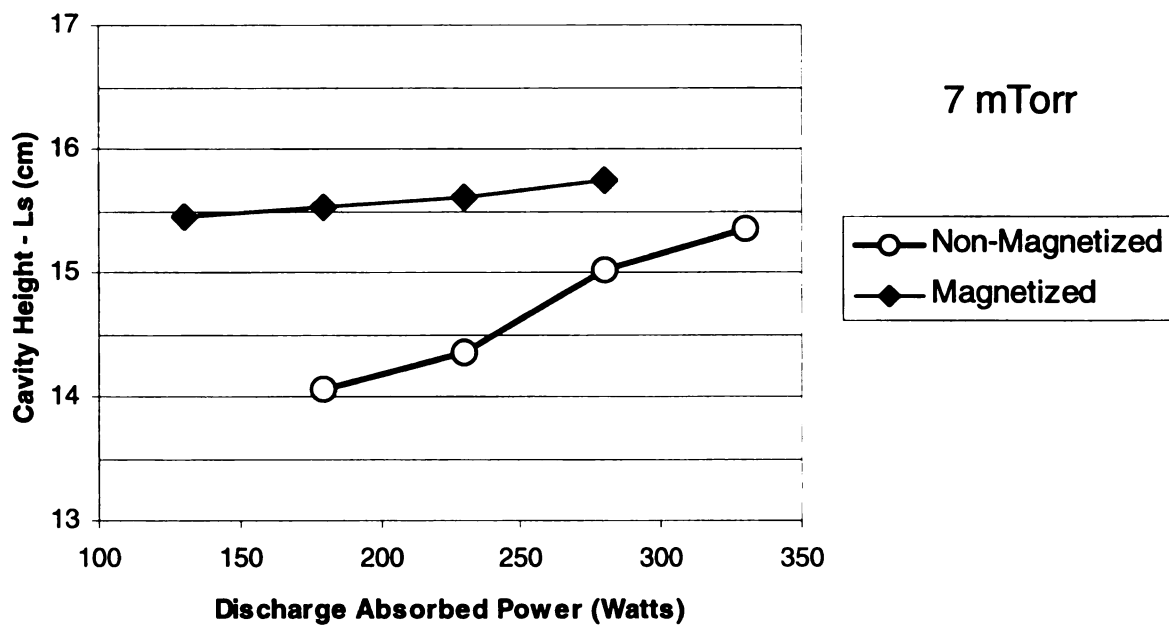


Figure D.3 - Cavity Tuning Height,  $L_s$ , vs. Discharge Absorbed Power,  $P_{abs}$ , for the magnetized and non-magnetized  $TM_{012}$  mode at 7 mTorr.

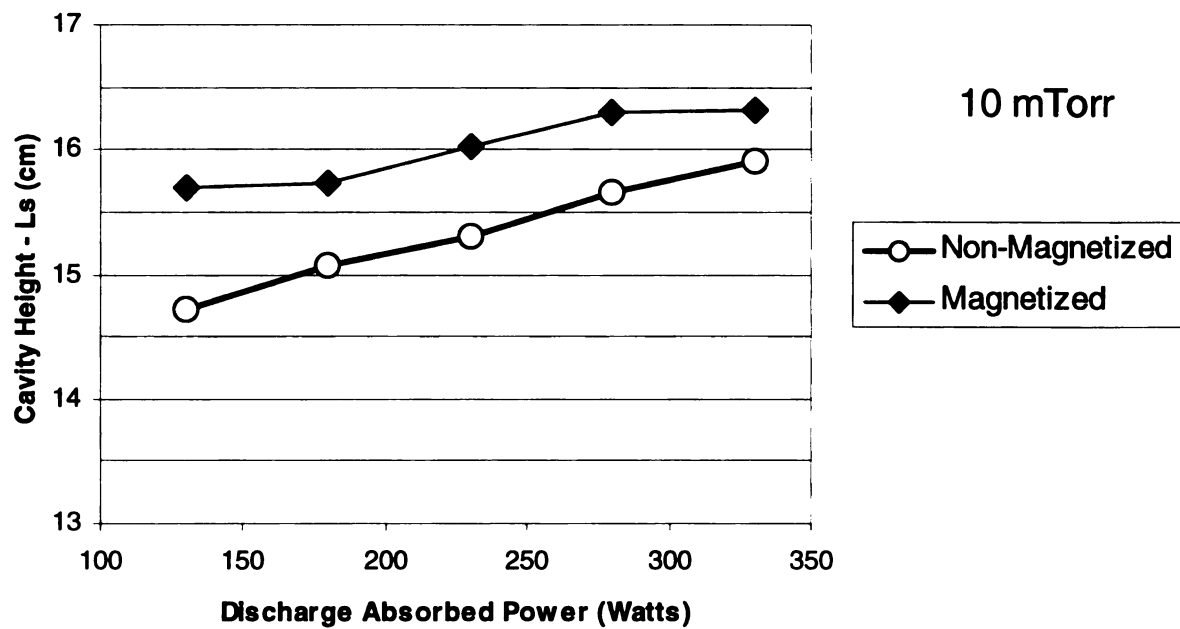


Figure D.4 - Cavity Tuning Height,  $L_s$ , vs. Discharge Absorbed Power,  $P_{abs}$ , for the magnetized and non-magnetized  $TM_{012}$  mode at 10 mTorr.

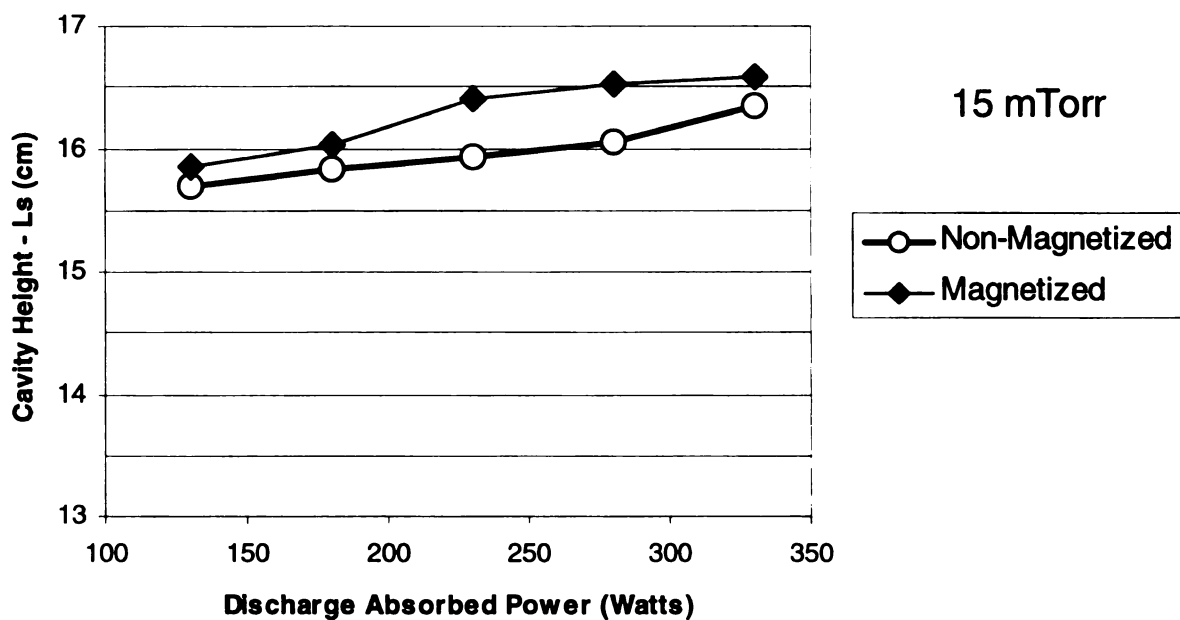


Figure D.5 - Cavity Tuning Height,  $L_s$ , vs. Discharge Absorbed Power,  $P_{abs}$ , for the magnetized and non-magnetized  $TM_{012}$  mode at 15 mTorr.

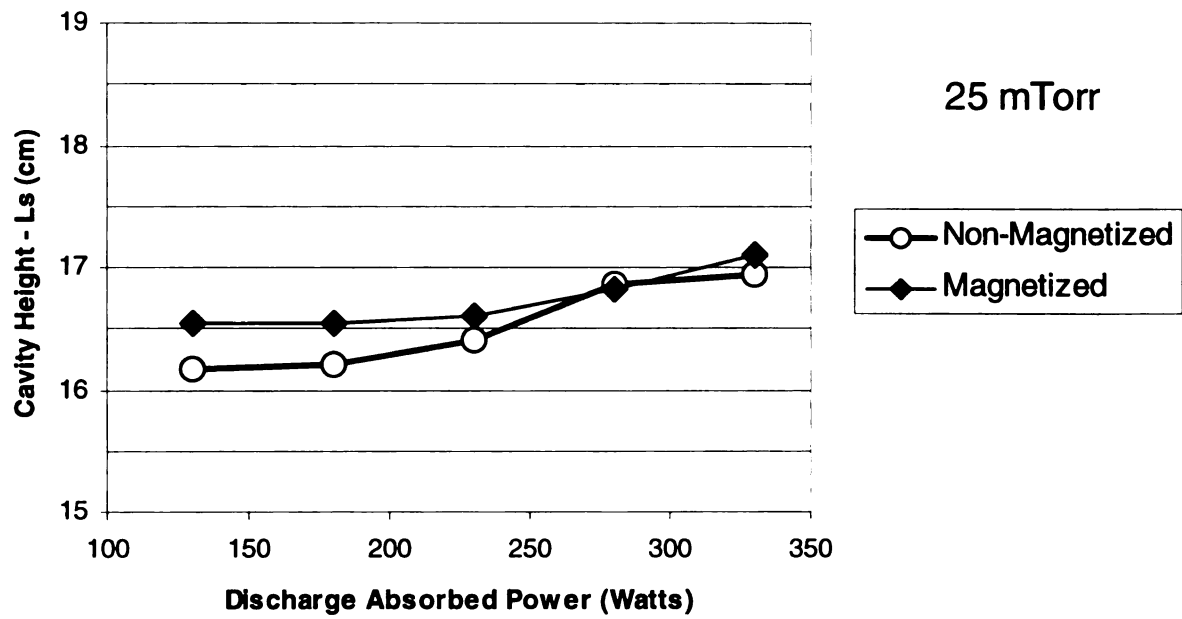


Figure D.6 - Cavity Tuning Height,  $L_s$ , vs. Discharge Absorbed Power,  $P_{abs}$ , for the magnetized and non-magnetized  $TM_{012}$  mode at 25 mTorr.

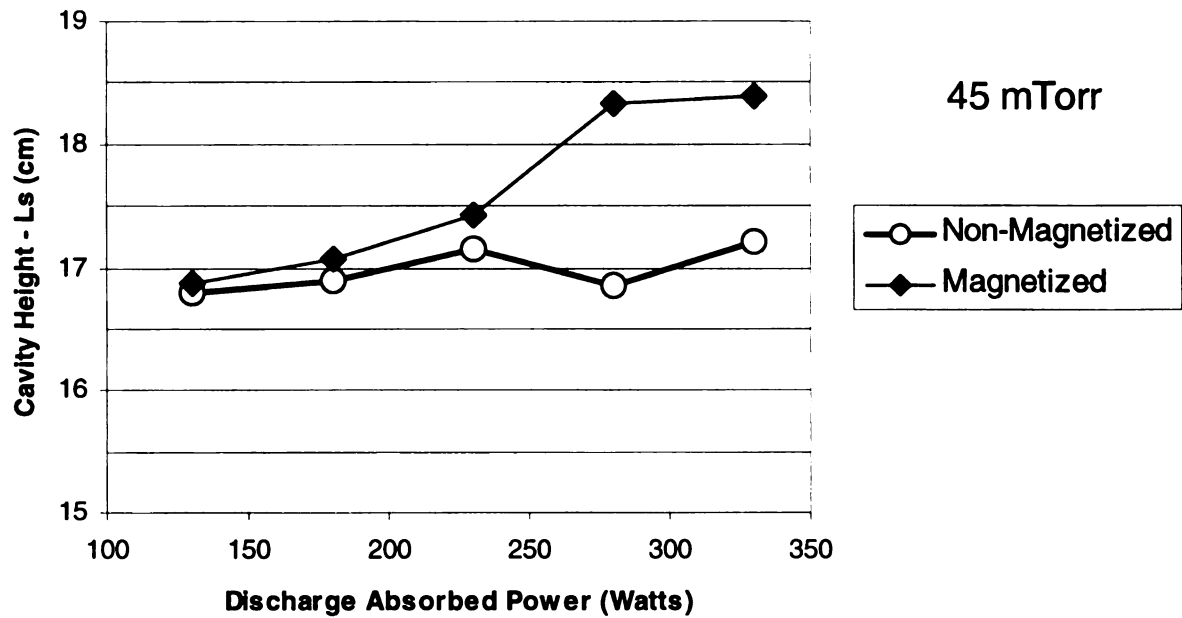


Figure D.7 - Cavity Tuning Height,  $L_s$ , vs. Discharge Absorbed Power,  $P_{abs}$ , for the magnetized and non-magnetized  $TM_{012}$  mode at 45 mTorr.

## Appendix E

### The Transmission Line Model

## Appendix E

### The Transmission Line Model

#### **E.1 The Transmission Line Model:**

Investigations of the matching characteristics and impressed electric field patterns of both small cavity excited microwave plasma sources by Perrin [Per-96] and Khan [Kha-00] and larger sources by Mak [Mak-97] have led to the development of a simplified model for the description of the cavity applicator. This simplified model has two merits: 1) it provides an intellectual bridge to understanding the complicated matching behavior of these plasma sources, and 2) it can aid in source optimization and design.

The model is best applied to reactors where the cavity is excited by a loop or probe at the top of the applicator (the so-called: “end feed” or “end excited” configuration). The end feed reactor can easily be subdivided in to several sections (I,II,III...) that can be approximated as transmission line sections with a characteristic impedance ( $Z_{I,II,III...}$ ) and propagation constant ( $\beta_{I,II,III...}$ ). The MPDR13 can be divided into three transmission line sections with the plasma discharge represented as a lumped complex load impedance ( $Z_p$ ), as shown in Fig. E.1.

In Fig. E.1 transmission line section I is the  $50\ \Omega$  coaxial input to the MPDR 13; it begins at the matched generator and ends at  $z=z_1$ . Transmission line section II is the coaxial section created by the probe extension into the cavity applicator; it begins at  $z=z_1$  and

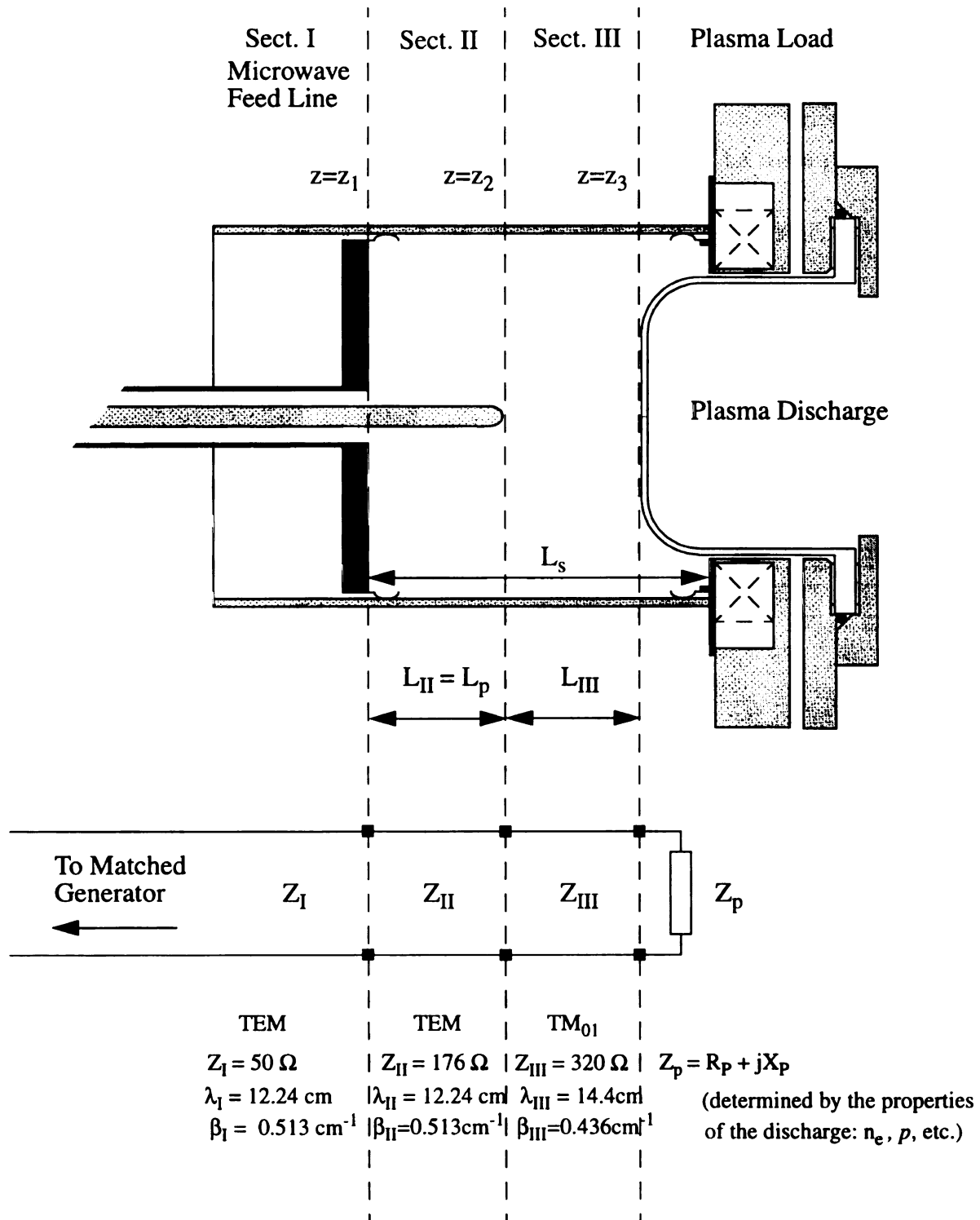


Figure E.1: Transmission Line Equivalent Model of the MPDR13

ends at  $z=z_2$ . As a first order approximation the wave propagation in transmission line section II is assumed to be only TEM with wave impedance  $176 \Omega$  and the higher order modes in this section are neglected. Transmission line section III is the empty waveguide section of the cavity, between  $z=z_2$  and the plasma load at  $z=z_3$ . The wave propagation in this section is considered  $TM_{01}$  with a wave impedance of  $320 \Omega$ . Finally, in this model the plasma discharge is represented as a lumped complex load the impedance, the value of which is determined by the properties of the discharge.

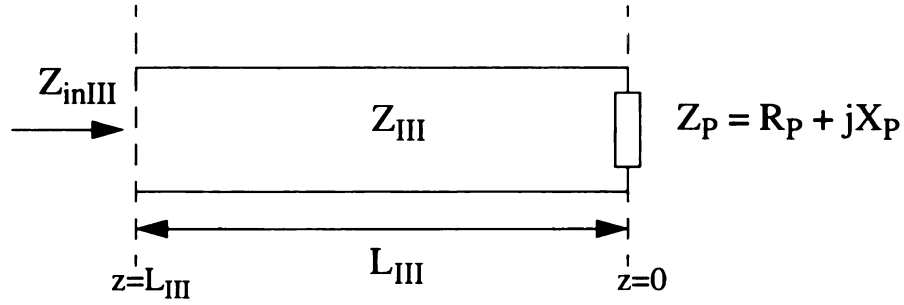


Figure E.2: The input impedance of transmission line section III.

This transmission line equivalent model can be used to model the microwave matching behavior of the MPDR 13. For example considering transmission line section III (Fig. E.2) the input impedance can be given (assuming lossless transmission lines) by the following equation:

$$Z_{inIII} = Z_{III} \frac{Z_P + jZ_{III} \tan(\beta_{III} L_{III})}{Z_{III} + jZ_P \tan(\beta_{III} L_{III})} \quad \text{Eq. E.1}$$

where  $Z_{inIII}$  is the input impedance,  $Z_{III}$  is the characteristic impedance of section III,  $Z_P$  is

the load impedance of the plasma, and  $\beta_{III}$  and  $L_{III}$  are the propagation constant and line length for section III, respectively. Once the complex input impedance transmission line section III is found the input impedance of the MPDR 13, or  $Z_{inII}$ , can be found using the corresponding equation:.

$$Z_{in(MPDR13)} = Z_{inII} = Z_{II} \frac{Z_{inIII} + jZ_{II} \tan(\beta_{II} L_{II})}{Z_{II} + jZ_{inIII} \tan(\beta_{II} L_{II})} \quad \text{Eq. E.2}$$

Using equations E.1 and E.2 the input impedance for the whole multiple transmission line system can be found for a range of  $L_{II}$  and  $L_{III}$  values.

For a given matching condition where  $L_{II}$  and  $L_{III}$  are given the standing wave voltage envelope for each of the transmission line sections can be determined. For example in transmission line section III a load reflection coefficient can be found with the following relation:

$$\Gamma_P = \frac{Z_P - Z_{III}}{Z_P + Z_{III}} = |\Gamma_P| e^{j\theta_P} \quad \text{Eq. E.3}$$

where  $\Gamma_P$  is the complex reflection coefficient for the plasma load, and  $\theta_P$  is the phase of the complex reflection coefficient. This can be used in the following equation to determine the standing wave voltage envelope vs. the length coordinate  $z$  along the transmission line:

$$|V(z)| = |V_{FIII}| \sqrt{1 + |\Gamma_P|^2 + 2|\Gamma_P| \cos(2\beta_{III}z + \theta_P)} \quad ; \quad (z \leq L_2) \quad \text{Eq. E.4}$$



where  $|V(z)|$  is the magnitude of the sinusoidal voltage at a specific point  $z$ ,  $|V_{FIII}|$  is the voltage magnitude of the total forward wave (moving toward the load) in transmission line section III. The same equation can be used to find the voltage envelope in the other transmission line sections. For example, in transmission line section II the load impedance would be  $Z_{inIII}$ ,  $\beta=\beta_{II}$ ,  $\Gamma=\Gamma_{ZinIII}$ , and Eq. E.4 would be used accordingly. The forward wave voltage amplitude  $|V_F|$  is found for each section by matching the voltages at the interface between two sections. This process begins at the first interface (I:II) where the amplitude of the forward wave from the matched generator is known or set to unity. For an arbitrary  $L_{II}$ ,  $L_{III}$ , and  $Z_P$ , an example voltage waveform is sketched in figure E.3. In this example the system is matched but has some small amount of reflected power.

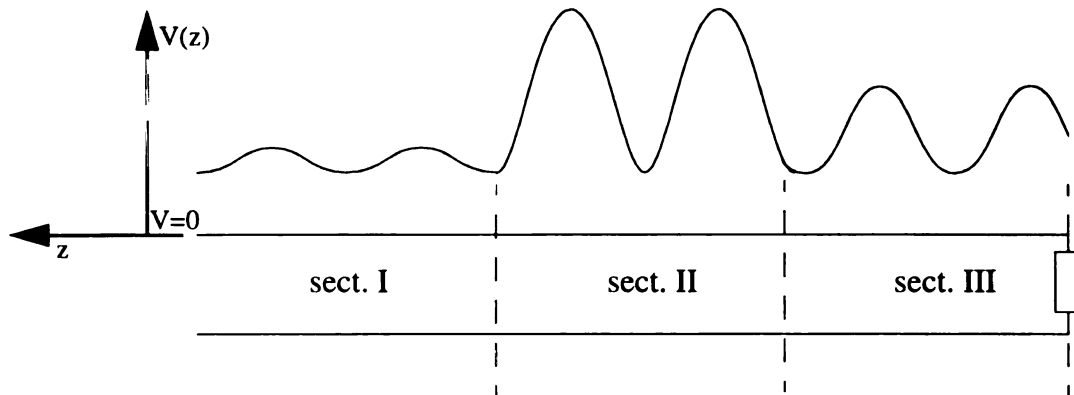


Figure E.3: Example Standing Wave Voltage Envelope for a multiple section transmission line.

This model is an approximation of the multiple waveguide sections in the MPDR 13. A more accurate model can be created by including higher order propagating and evanescent modes in each section of the transmission line model. For example we could

include two modes in section II of the MPDR, as shown in Fig E.4. The interface at each section then has a multiport input/output relationship (matrices J1 or J2),

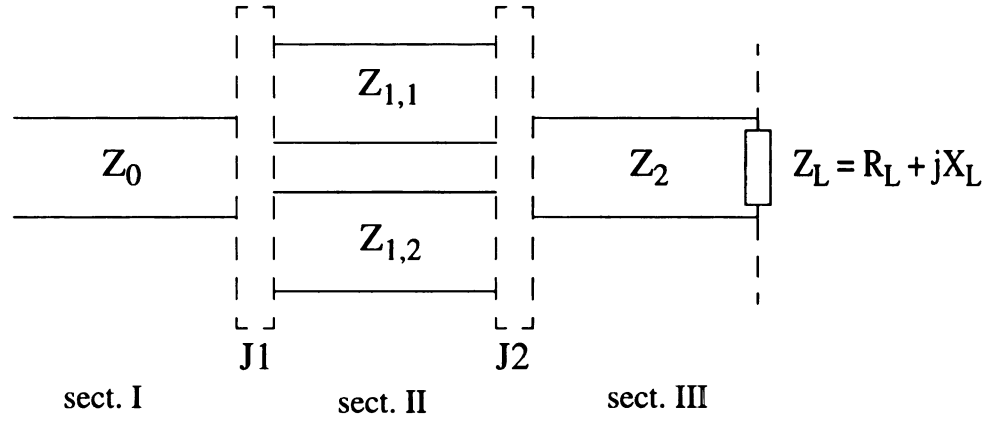


Figure E.4: Inclusion of higher order modes in the transmission line model.

where the complex voltage amplitudes of the waves output from this interface can be given in terms of the input voltage amplitudes and matrix elements by the following relationship.

$$\begin{matrix} & \text{Matrix J1} \\ \begin{bmatrix} V_{0\text{out}} \\ V_{1\text{out}} \\ V_{2\text{out}} \end{bmatrix} & = & \begin{bmatrix} G_{00} & G_{01} & G_{02} \\ G_{10} & G_{11} & G_{12} \\ G_{20} & G_{21} & G_{22} \end{bmatrix} & \begin{bmatrix} V_{0\text{in}} \\ V_{1\text{in}} \\ V_{2\text{in}} \end{bmatrix} \end{matrix} \quad \text{Eq. E.5}$$

The major task in developing this multi-mode model would be the determination of each of the matrix elements given the geometry and modes excited for each transmission line section.

## Appendix F

### Electric Field Probe Measurements

#### F.1 Electric Field Measurements

#### F.2 The E-field Probe, E-field Sampling Ports, and Measurement Circuit

#### F.3 Theory of Measurement and Calibration Procedure

#### F.4 Experimental Measurements of E-Field for the MPDR13

##### F.4.1 E-fields for the Non-Magnetized $TM_{012}$ Mode

##### F.4.2 E-Fields for the Magnetized $TM_{012}$ Mode

##### F.4.3 Comparisons Between Magnetized and Non-Magnetized Cases

## Appendix F

### Electric Field Probe Measurements

#### **F.1 Electric Field Measurements**

Measurement of the electromagnetic field present inside a resonant cavity system can provide a large amount of important information. In an ideal cavity, measurement of the time harmonic electric field pattern at the wall of the cavity can be used to identify or verify the resonant mode excited. The most common modes excited in the cavity used in this investigation are the  $TM_{011}$ ,  $TM_{012}$ , and  $TM_{013}$  resonant modes. In a plasma loaded cavity the measured E-field pattern, although certainly modified by the presence of the plasma, can be compared to similar ideal cavity mode patterns. The perturbations to these ideal modes caused by the plasma discharge or excitation probe can be studied. Determination of the electric field strength, and hence magnetic field strength and induced wall current, at the finitely conducting metal walls allows calculation of total power lost to the walls of the cavity.

The method of measuring the electric field here measures the radial component of electric field at the walls of the cavity. This is accomplished by using small coaxial probes inserted into 2.2 mm holes through the wall of the cavity.

## F.2 The E-field Probe, E-field Sampling Ports, and Measurement Circuit

The time varying electric field ( $\vec{E}$ ) normal to the inner wall of the cavity applicator (radial direction) can be measured using small coaxial probes, see Figure F.1 [Hop-90, Mak-97]. The E-field probe is constructed from a ~5 cm length of semirigid 50 $\Omega$  microcoaxial cable (1) (from Pasternack, Inc.) with outer conductor diameter of 0.086" (2.18 mm) and center conductor diameter of 0.4 mm. At one end of the probe a 2 mm length of the copper outer conductor is carefully removed (by applying a sharp knife while turning the probe on a lathe). This reveals a 2 mm section of center conductor that forms a small dipole antenna (2) when inserted into the E-field sampling holes (3) in the wall of the cavity. At the other end of the cable an SMA connector is soldered (4). When placed in an E-field sampling hole the outer conductor of the probe fits snugly, has good electrical contact, and is flush with the inside wall of the cavity. To insure repeatable penetration depth a curved stop block (5) is welded to outer conductor of the probe. The stop block conforms to the curvature of the cavity, permanently sets penetration depth, prevents azimuthal probe rotation, and insures that the center conductor is normal to the internal cavity wall.

Several 2.2 mm diameter holes are drilled into the walls of the cavity to serve as E-field sampling ports. Figure F.1 shows the spatial configuration of holes in the wall of the cavity. Two vertical lines of holes, one at 45° and another at 90°, allow the measurement of the axial (z) variation of E-field. Holes in these vertical lines are spaced 1 cm apart. Two horizontal rings of holes allow the measurement of the circumferential ( $\phi$ ) variation of E-field. One ring of holes is placed at 3.8 cm from the bottom of the cavity, which

(1) semirigid microcoaxial cable,  
 (2) 2mm center conductor antenna,  
 (3) E-field sampling holes in cavity wall,  
 (4) SMA connector, (5) welded  
 stop block, (6) Hewlett Packard 432A  
 microwave power meter, (7) Hewlett  
 Packard 478A thermistor sensor.

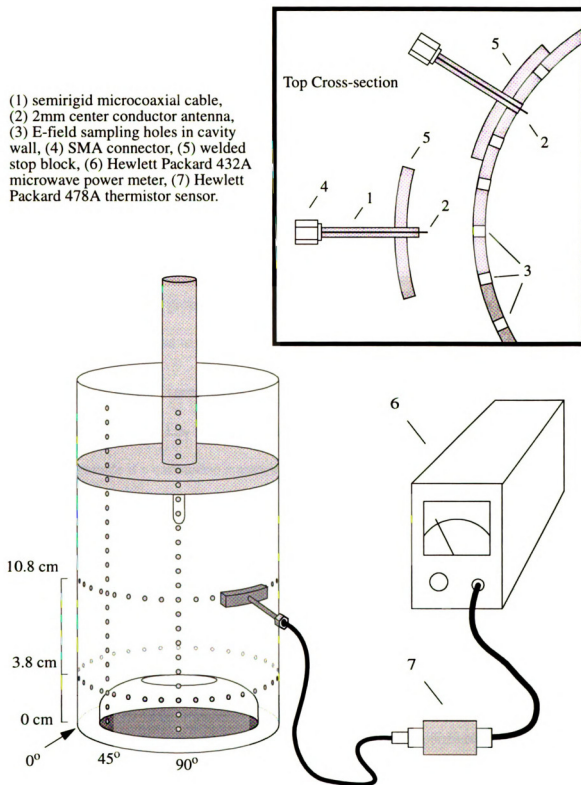


Figure F.1 - Diagram of the Electric Field Probe and Microwave Cavity.

makes it 0.5 cm above the quartz discharge chamber, and extends 360° around the cavity. There are 36 holes in this ring each placed 10° apart. Another half-ring of 19 holes is placed at 10.8 cm and extends 180° around the cavity. The power sampled by each probe is measured by a Hewlett Packard 432A power meter (6) with an Hewlett Packard 478A thermistor sensor (7).

### F.3 Theory of Measurement and Calibration Procedure

When an E-field probe is inserted into a sampling hole it samples a small amount of power,  $P_s$ , proportional to the square of the  $r$ -component of the E-field,  $E_r$ , at that hole location; i.e.  $P_s \propto |E_r|^2$  (note that  $E_z$  and  $E_\phi$  are essentially zero at the wall). Hence, the sampled power measured by the HP microwave power meter can be used to determine the E-field magnitude if a calibration constant is known:

$$|E_r| = (C_{\phi, z}) \sqrt{P_s} \quad \text{Eq. F.1}$$

where  $C_{\phi, z}$  represents the calibration constant at a sampling hole located at angle  $\phi$  and height  $z$  on the cavity wall. A calibration constant is necessary for each hole, because the thickness of the walls may vary slightly from location to location (changing the penetration depth of the probe).

To calibrate the probe a brass end plate is placed at the bottom of the cavity forming a standard empty cylindrical cavity, see Figure F.2. The cavity is carefully tuned to the  $\text{TM}_{012}$  mode such that no reflected power is observed (i.e. critically coupled). The E-field

probe is then inserted into a specific wall location (e.g.  $z = 2.5$  cm,  $\phi = 90^\circ$ ) and the power sampled by the probe is measured. (Note: the brass plate raises the inner base of the cavity by 0.5 inches, this must be taken into account in the calibration) Since the cavity is critically coupled all the power incident to the cavity is dissipated in the cavity walls and other structures such as finger stocks and coupling probe. It is estimated that 1/4 to 1/2 of the input power is lost in the coupling probe[Mak-97]. For the purposes of this investigation it is assumed that 1/4 of the incident power is lost to the coupling probe. The power lost in the walls can then be given as:  $P_w = (3/4)*P_{tot}$ ; where  $P_w$  is the power lost to the walls and  $P_{tot}$  is the total power delivered to the cavity.

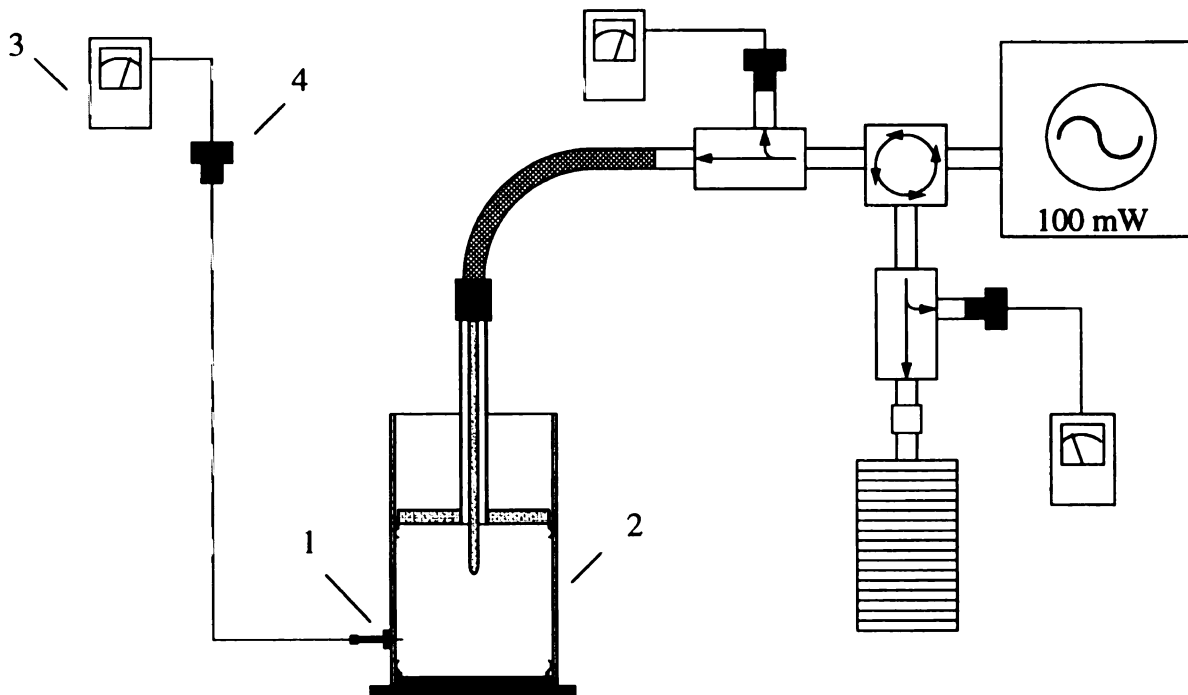


Figure F.2 - Microwave Circuit for E-field Probe Calibration: (1) Micro-coax E-probe, (2) Empty Cavity, (3) hp 432A power meter, (4) hp 478A thermistor sensor. Note: input power is ~100 mW so no additional attenuators are used at the measurement ports of the directional couplers.





Next, the equations for time harmonic magnetic field for a TM mode in a cylindrical cavity are used (see Appendix A).

$$H_r = -jE_0 \left[ \frac{ka^2 n}{\eta r x_{nm}^2} \right] J_n \left( \frac{x_{nm}}{a} r \right) \sin(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. F.2}$$

$$H_\theta = -jE_0 \left[ \frac{ka}{\eta x_{nm}} \right] J_n' \left( \frac{x_{nm}}{a} r \right) \cos(n\theta) \cos\left(\frac{l\pi}{L_s} z\right) \quad \text{Eq. F.3}$$

The power lost in the walls,  $P_w$ , can be used to establish  $E_0$  and hence the electric field magnitude using:

$$P_w = \frac{1}{2} R \int_S |H_t|^2 dS \quad \text{Eq. F.4}$$

where  $P_w$  is the power lost in the cavity walls,  $R$  is the wall surface resistivity,  $S$  represents the inner surface of the empty cavity, and  $H_t$  is the magnetic field tangential to the cavity walls. Once  $E_0$  is determined the strength of the electric field at that location, and hence the coupling constant,  $C_{\phi,z}$ , can be calculated.

## F.4 Experimental Measurements of E-Field for the MPDR13

### F.4.1 E-fields for the Non-Magnetized TM<sub>012</sub> Mode

Figures F.3a, F.4a, and F.5a show the electric field measurements vs. vertical sampling hole position for the TM<sub>012</sub> mode in the non-magnetized configuration. The vertical positions of: the top of the quartz dome, the end of the electromagnetic coupling probe, and the plane of the sliding short, are shown in these figures. There are two

curves: one taken at the vertical set of holes 45 degrees around the circumference from the 0 degree reference position (shown as open diamonds), and another taken at 90 degrees from the reference (shown as open squares). For all 3 pressures these curves have two maxima, the maxima closer to the plasma being less than the maxima closer to the coupling probe. As pressure in the discharge increases the values of the electric field maxima decrease.

#### **F.4.2 E-Fields for the Magnetized $TM_{012}$ Mode**

Figures F.3b, F.4b, and F.5b plot the electric field measurements vs. vertical sampling hole location for the  $TM_{012}$  mode in the magnetized configuration. These curves are similar in shape to the non-magnetized E-Field plots. However, the E-field values for the magnetized case do not decrease as pressure increases from 7 mTorr to 15 mTorr, the fields remain basically the same magnitude. Only when the pressure is increased from 15 to 45 mTorr in the magnetized case do the E-fields do decrease.

#### **F.4.3 Comparisons Between Magnetized and Non-Magnetized Cases**

It is observed that for 7 and 15 mtorr the E-fields are generally higher for the magnetized configuration than for the non-magnetized configuration. The E-fields for both configurations are comparable in magnitude at 45 mtorr. Note that the short height for the magnetized case is approximately 1 cm higher for all comparisons (as discussed in Appendix D) so the E-field patterns vs. vertical hole position do not align exactly.

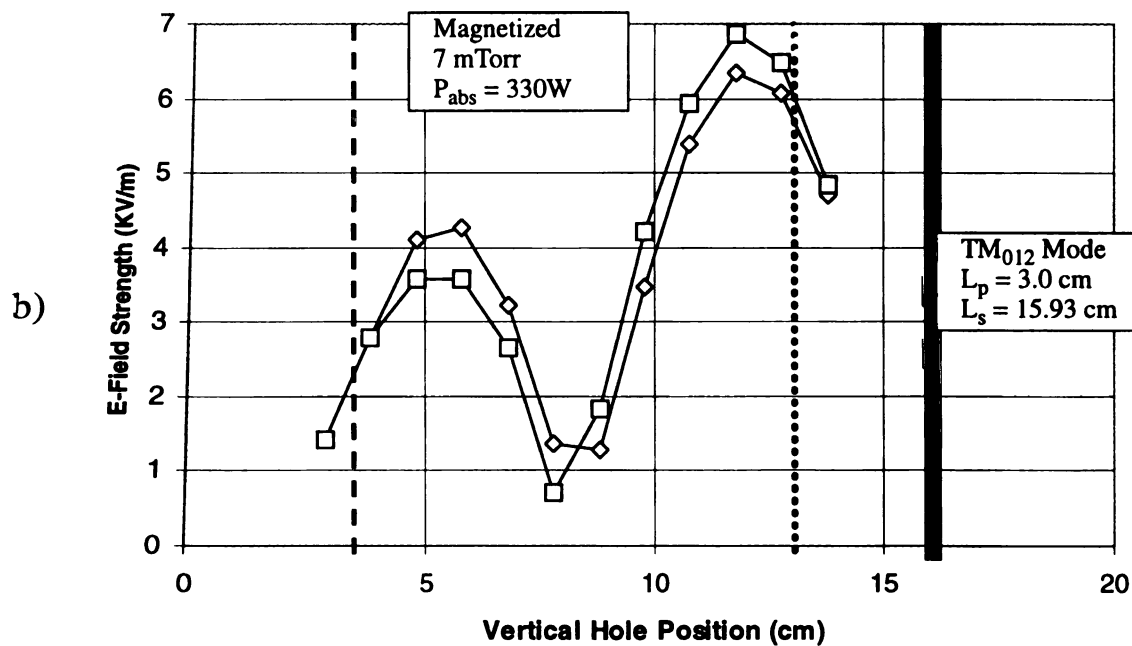
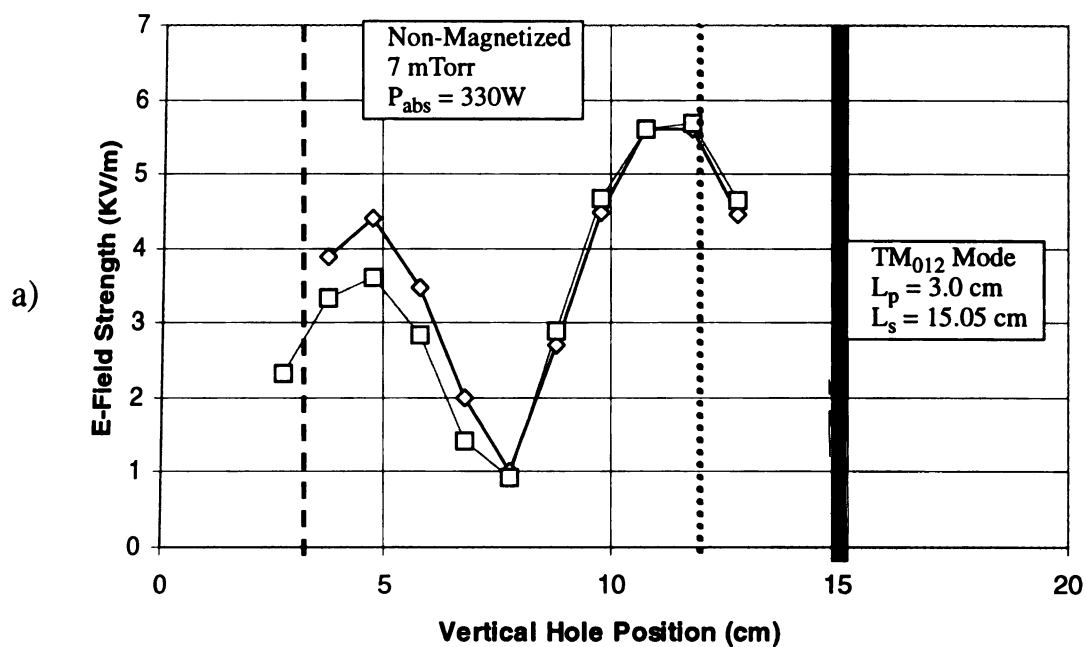
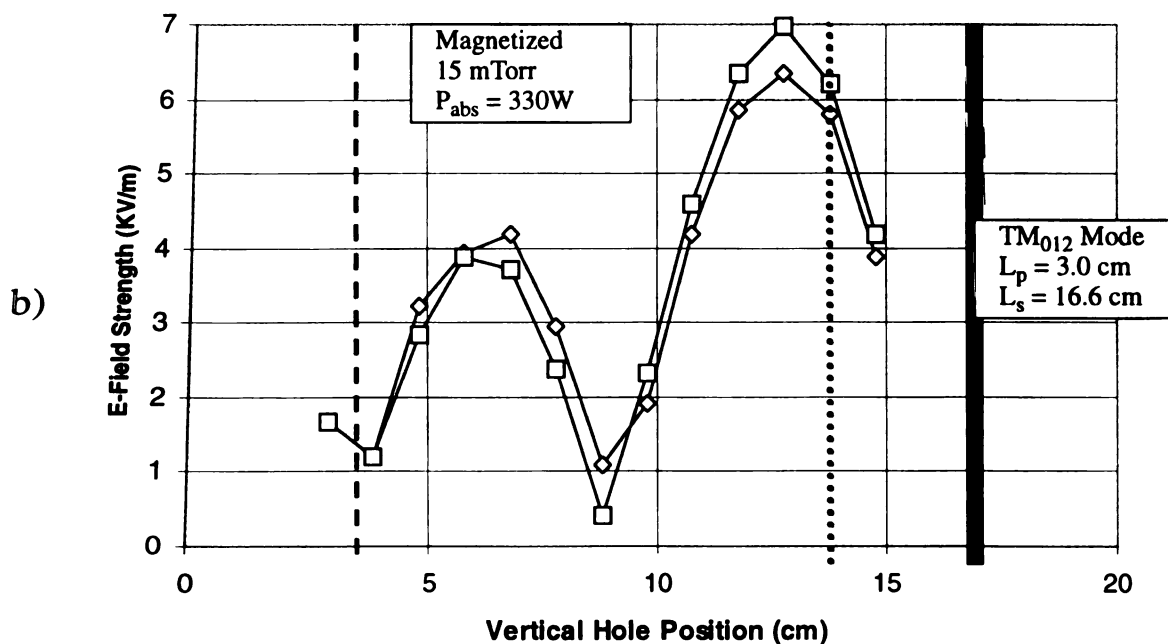
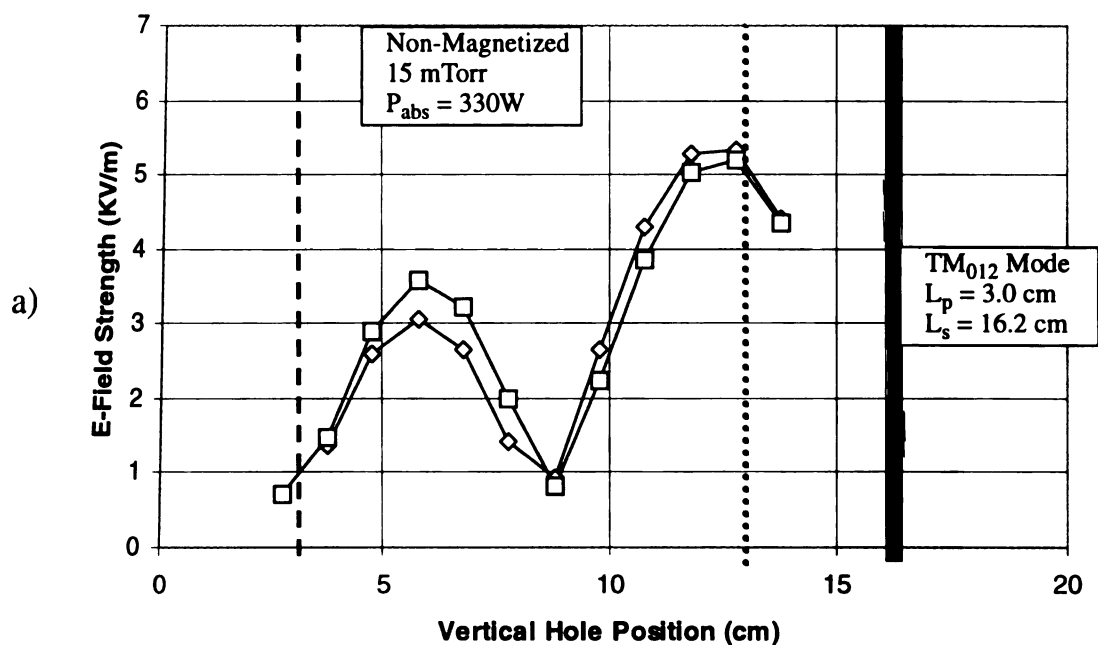


Figure F.3 - Electric Field vs. Vertical Hole Position for the (a) Non-Magnetized and (b) Magnetized Source at 7 mTorr and  $P_{abs} = 330W$ . Diamonds indicate field sampled at 45° line and squares indicate field sampled at 90° line. Dashed line marks top of belljar. Dotted line marks end of coupling probe. Solid line marks sliding short position.



**Figure F.4 - Electric Field vs. Vertical Hole Position for the (a) Non-Magnetized and (b) Magnetized Source at 15 mTorr and  $P_{abs} = 330W$ . Diamonds indicate field sampled at 45° line and squares indicate field sampled at 90° line. Dashed line marks top of belljar. Dotted line marks end of coupling probe. Solid line marks sliding short position.**

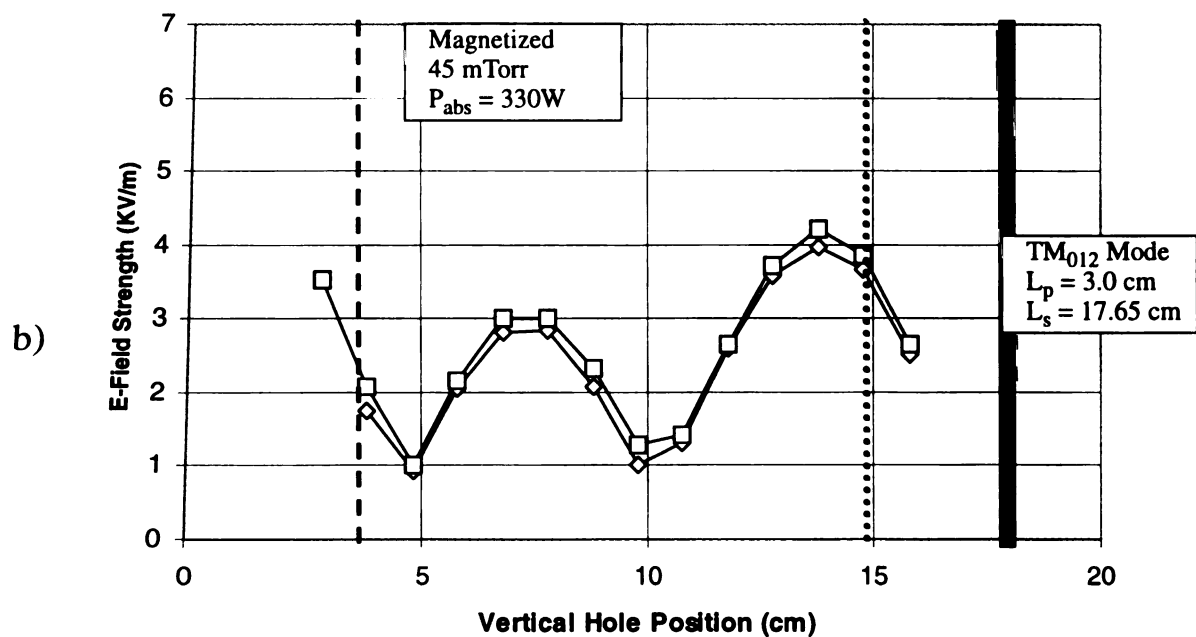
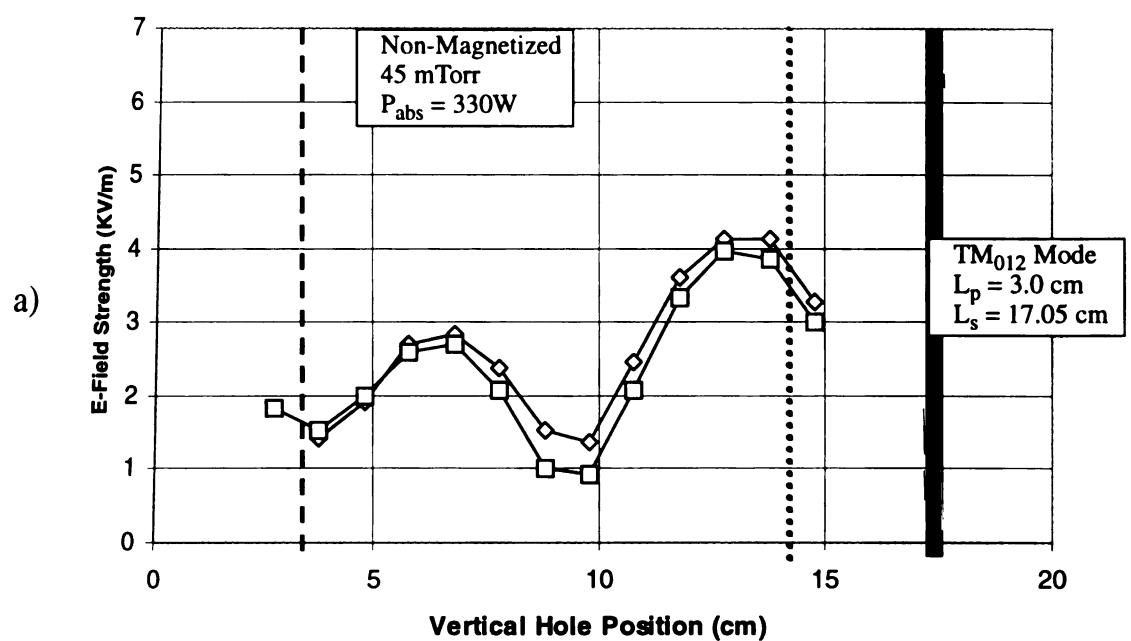


Figure F.5 - Electric Field vs. Vertical Hole Position for the (a) Non-Magnetized and (b) Magnetized Source at 45 mTorr and  $P_{abs} = 330W$ . Diamonds indicate field sampled at 45° line and squares indicate field sampled at 90° line. Dashed line marks top of belljar. Dotted line marks end of coupling probe. Solid line marks sliding short position.

## Appendix G

### Absorbed Power Curves For The Non-Magnetized Discharge

#### G.1 Summary of Absorbed Power Plots

## Appendix G

### Absorbed Power Curves For The Non-Magnetized Discharge

#### **G.1 Summary of Absorbed Power Plots**

This appendix documents several studies of absorbed power vs. cavity height for a range of coupling probe lengths for the non-magnetized MPDR13 microwave plasma cavity. In all, seven studies were done using a range of pressures and incident powers. These seven studies are:

- 1) 4mTorr @ 330W, shown in Figures G.1-G.5
- 2) 10mTorr @ 130W, shown in Figures G.6-G.10
- 3) 10mTorr @ 230W, shown in Figures G.11-G.15
- 4) 10mTorr @ 330W, shown in Figures G.16-G.20
- 5) 25mTorr @ 130W, shown in Figures G.21-G.25
- 6) 25mTorr @ 230W, shown in Figures G.26-G.30
- 7) 25mTorr @ 330W, shown in Figures G.31-G.37

These studies were performed by first setting the pressure and power level in the discharge and then sweeping the sliding short upward (increasing  $L_s$ ) and recording the absorbed power as the short is moved. Then when the highest  $L_s$  point is reached the sliding short is then swept downward (decreasing  $L_s$ ). On all the plots in this appendix the



absorbed power points recorded while increasing  $L_s$  are indicated by upward pointing triangles, and points recorded while decreasing  $L_s$  are indicated by squares. In all the plots in this appendix the absorbed power peaks of 3 resonant modes are seen. The highest mode (near the  $L_s=22$  cm range) is determined to be a  $TM_{013}$  mode. The next mode (in the  $L_s=14$  cm range) is the  $TM_{012}$  mode. Finally the lowest mode (near  $L_s=7$  cm) is thought to be either the  $TM_{011}$  mode or a combination of the  $TM_{011}$  with a strong capacitive coupling component between the probe antenna and the plasma discharge.

Absorbed power curves are useful for several reasons. First, they serve as an excellent guide or map for tuning the plasma source under various conditions of power and pressure. They can provide target  $L_s$  and  $L_p$  values to new users of the microwave plasma source who want to “dial up” a specific cavity mode. These maps point out parameter spaces where the plasma cavity system has very stable and repeatable operation. However, they can also be used to point out where the plasma cavity system is unstable, very sensitive to input variations, has hysteresis regions, or where it can not be sustained. Also, absorbed power curves can provide a starting point for developing an automated control system or “expert-system” that can auto-tune the cavity under a set of input conditions. Finally, absorbed power curves can be used to determine plasma load impedance and study the mutual interaction of the plasma and resonant cavity.

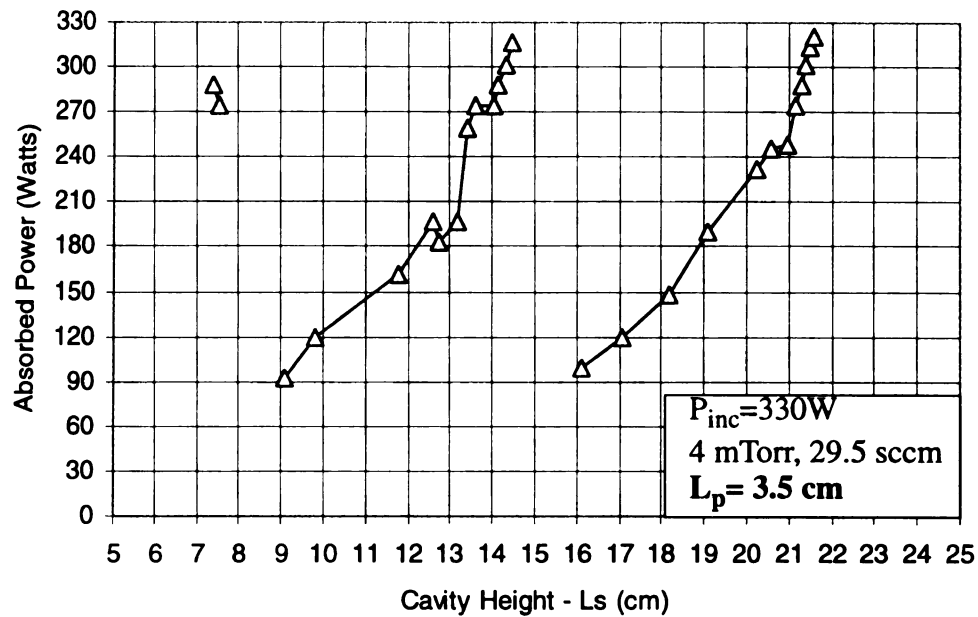


Figure G.1 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 4mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

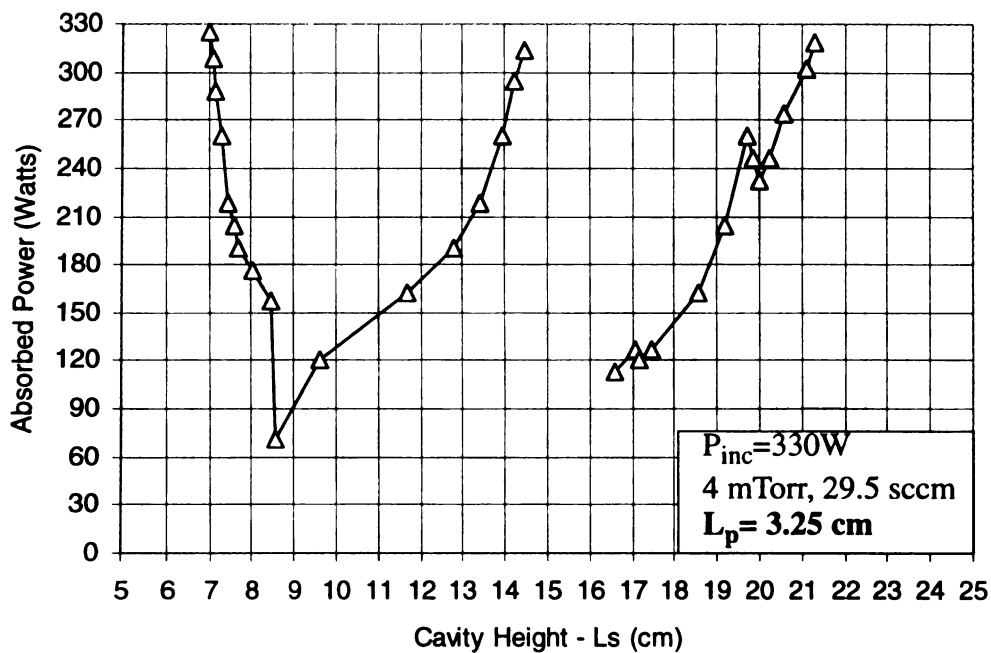


Figure G.2 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 4mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.25$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

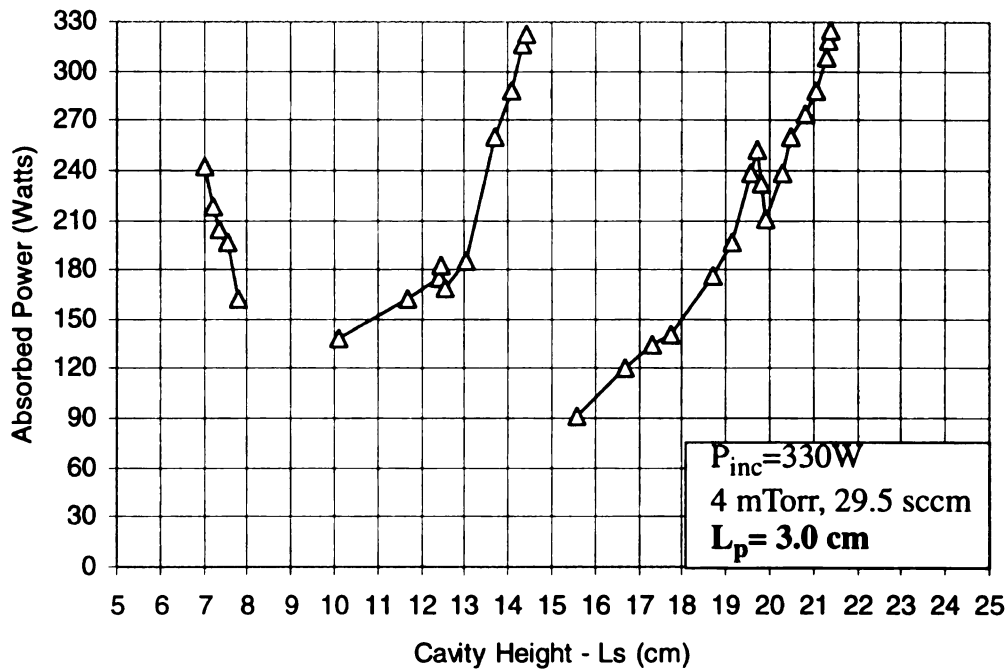


Figure G.3 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 4mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

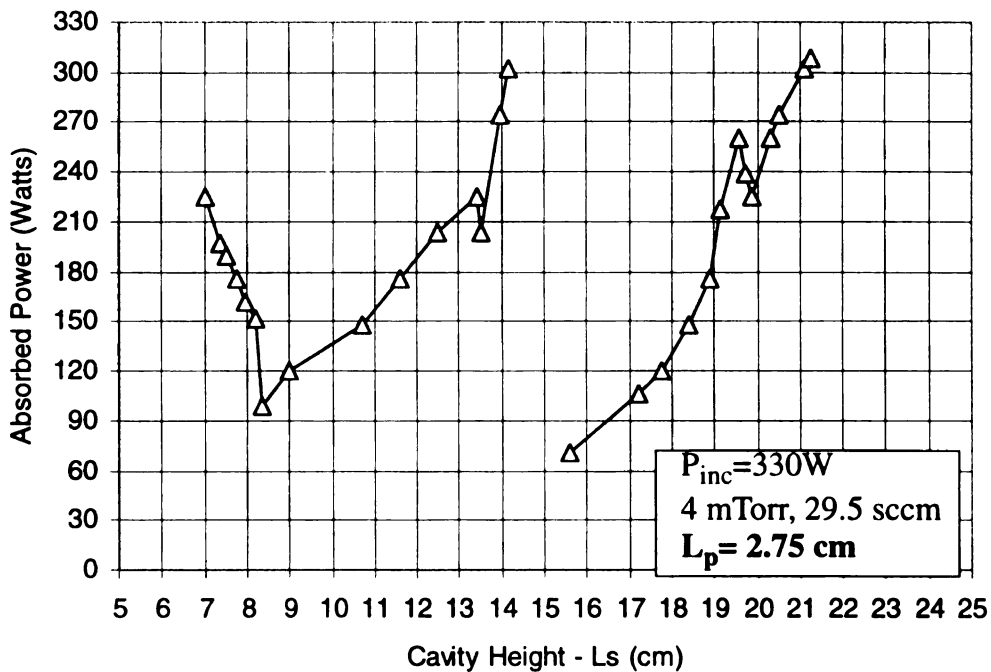


Figure G.4 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 4mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.75$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

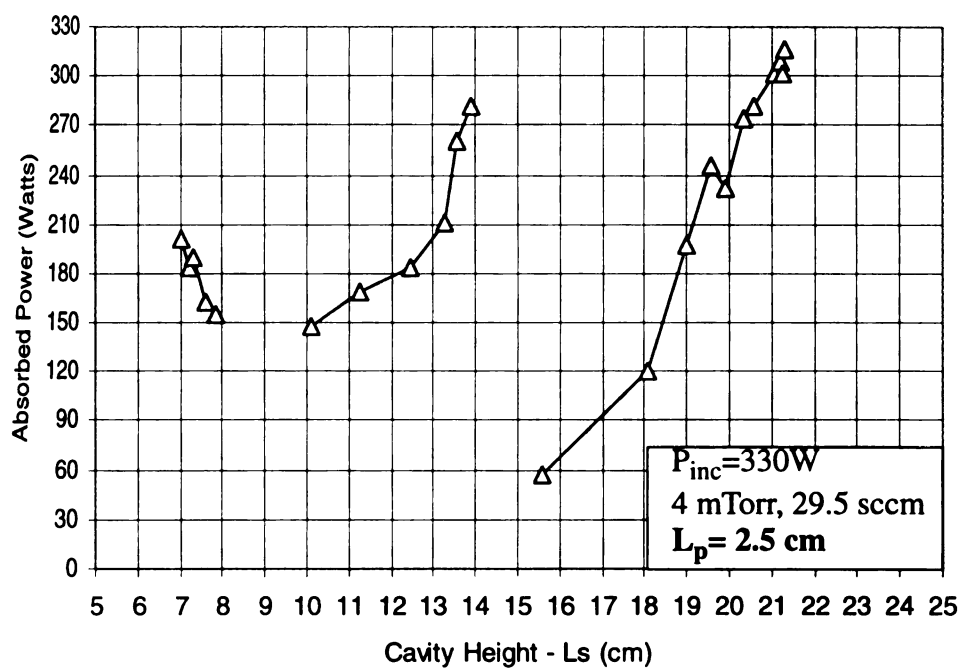


Figure G.5 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 4mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

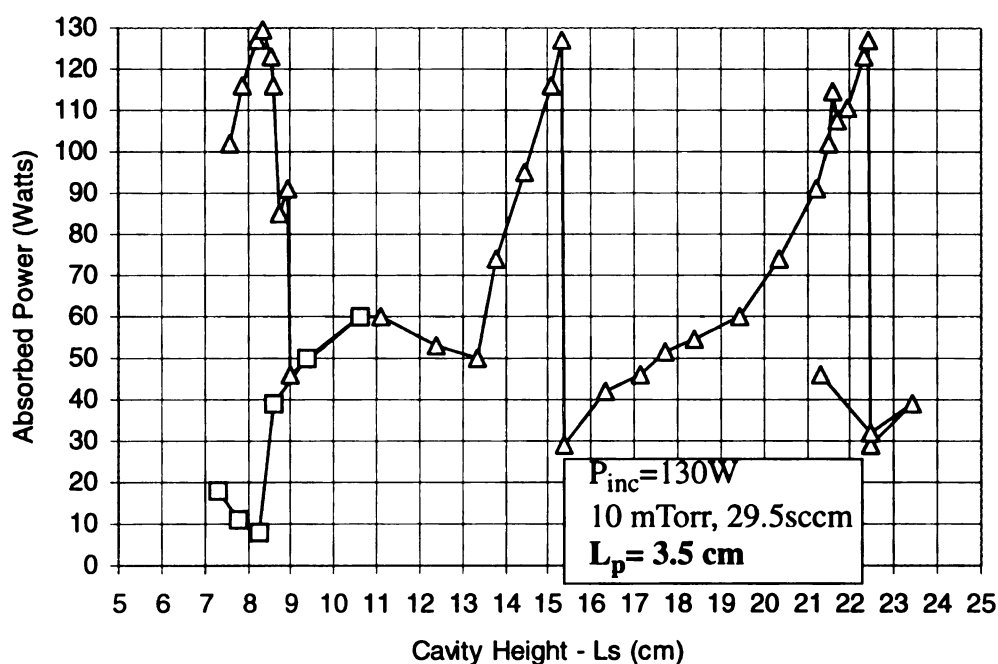


Figure G.6 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

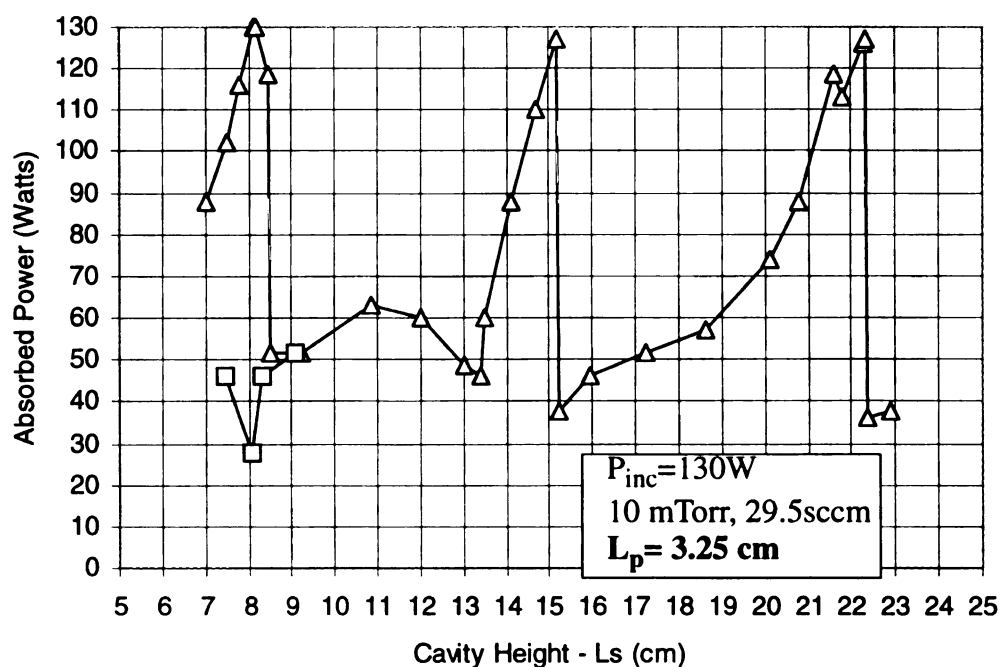


Figure G.7 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

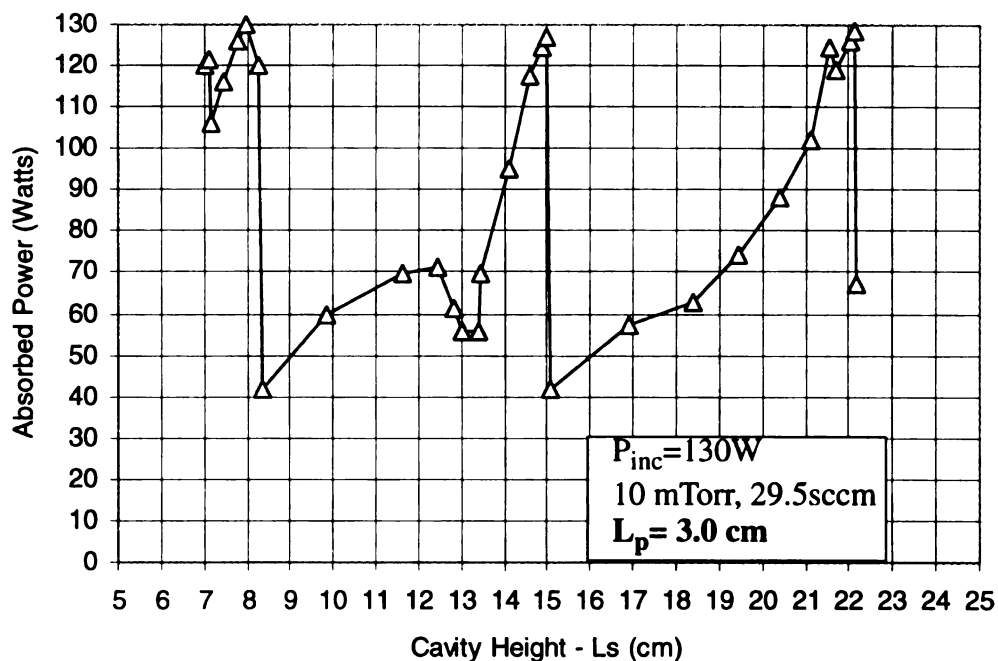


Figure G.8 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.0$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

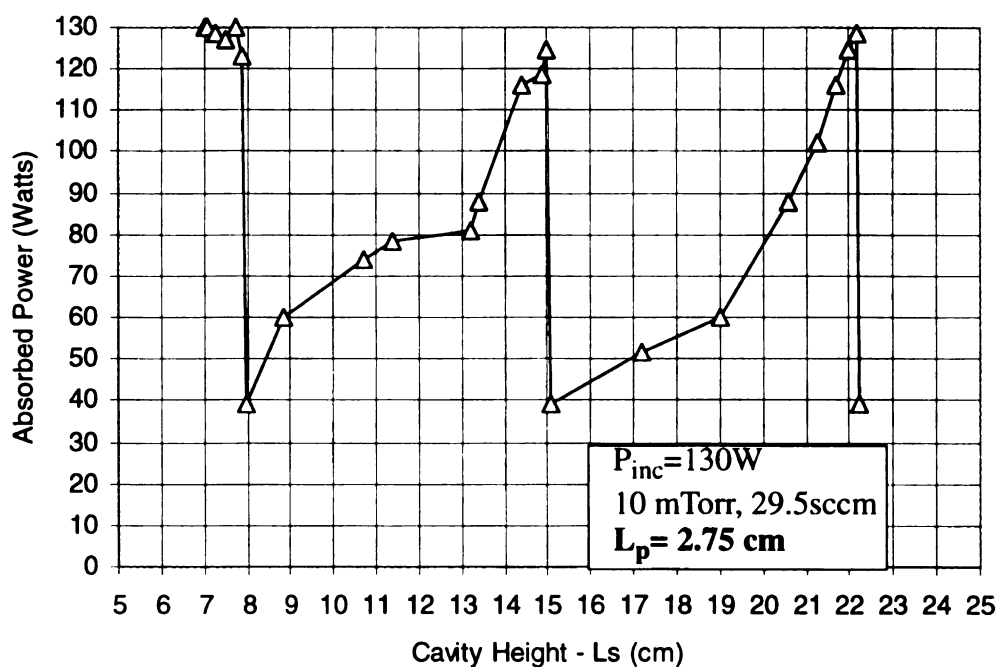


Figure G.9 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 130W$ , and  $L_p = 2.75$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

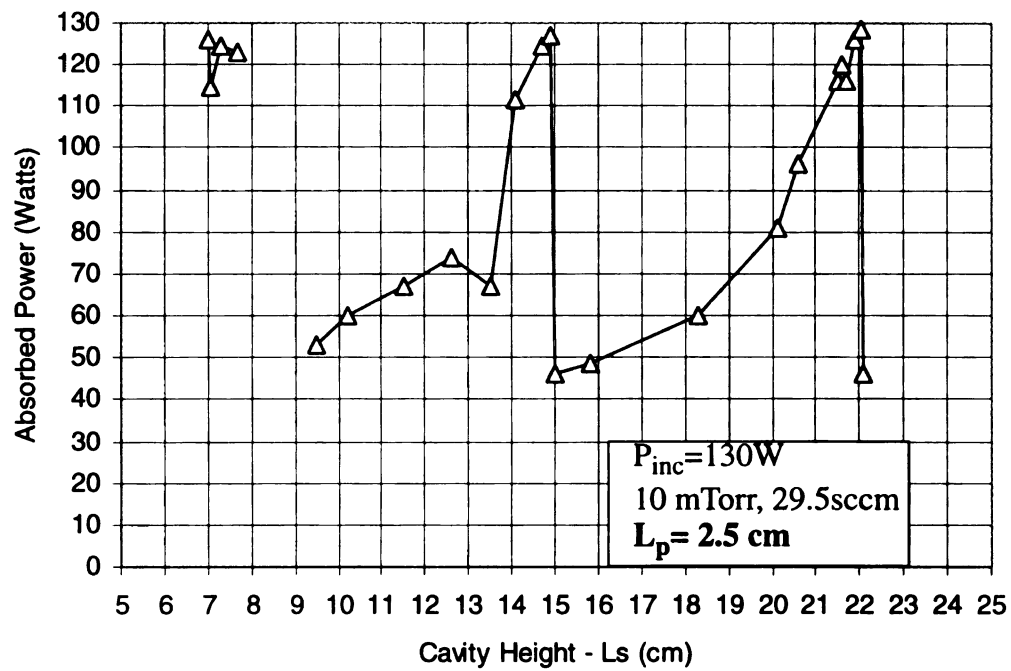


Figure G.10 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 130W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

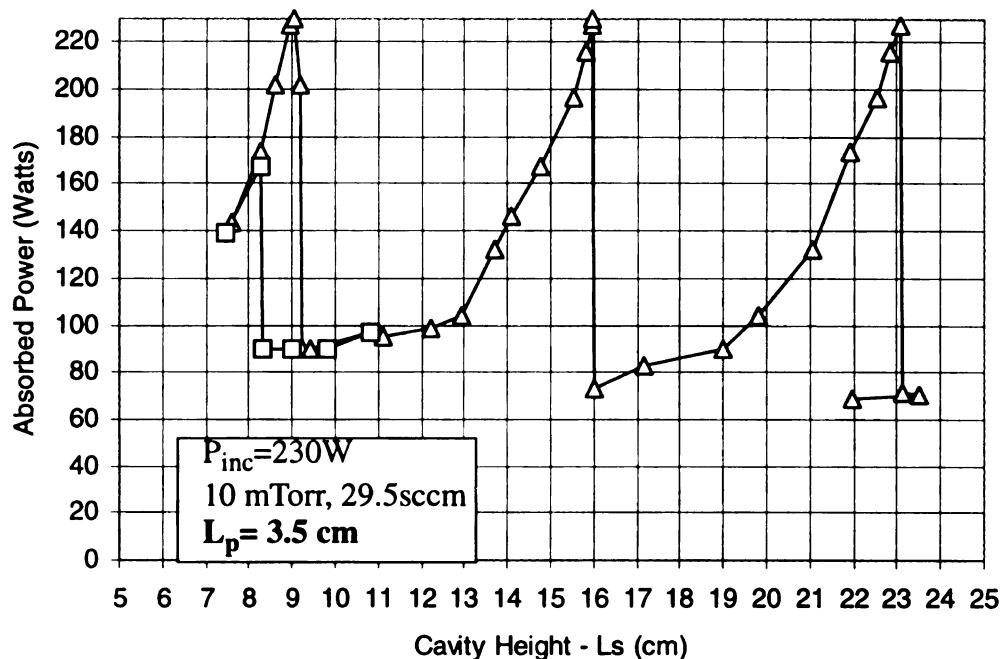


Figure G.11 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

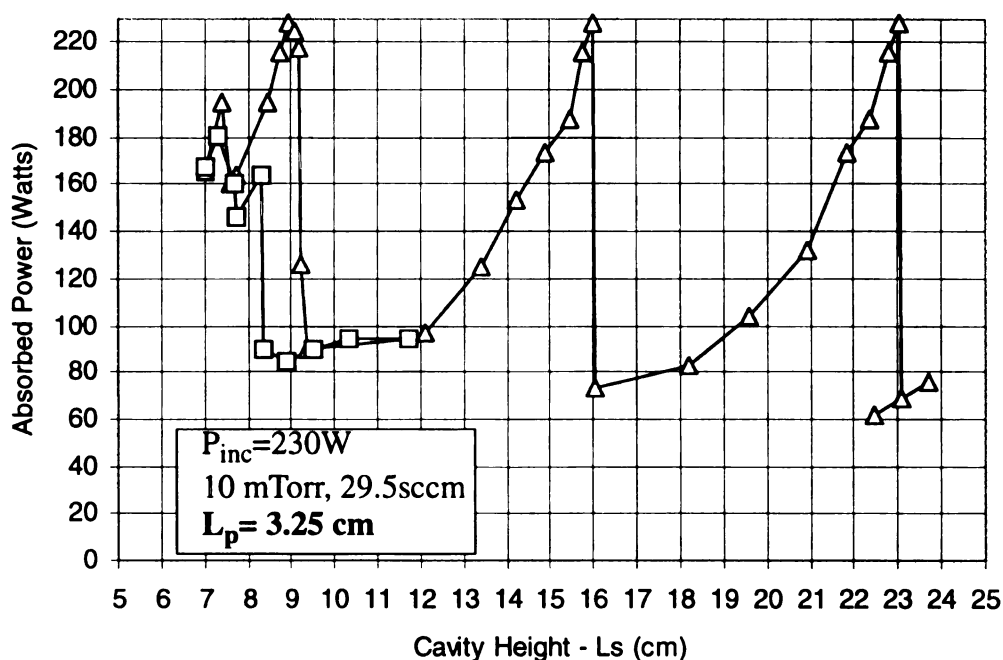


Figure G.12 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .



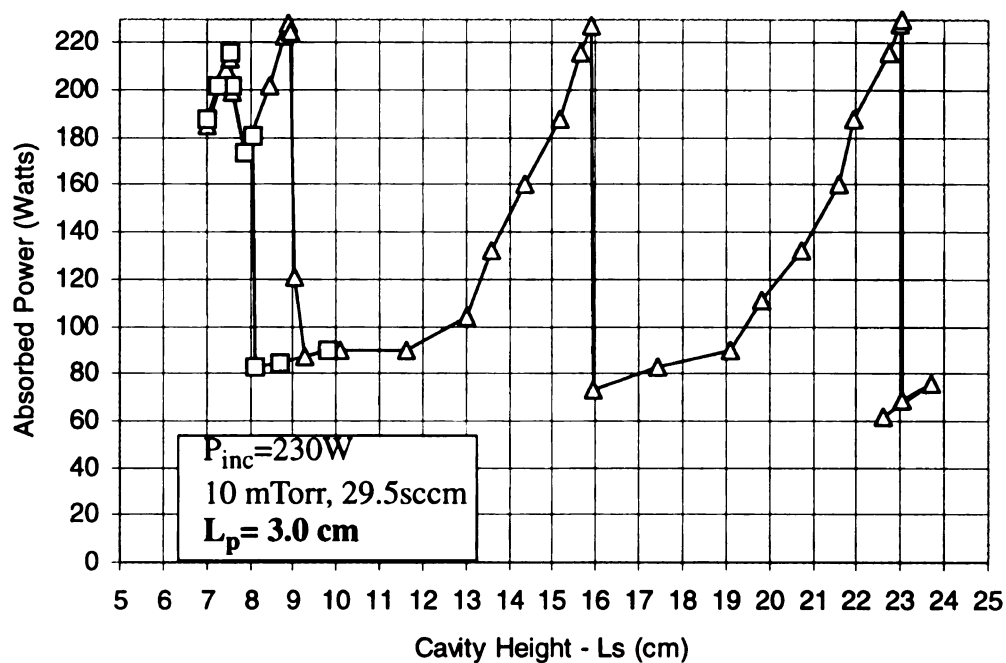


Figure G.13 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.0$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

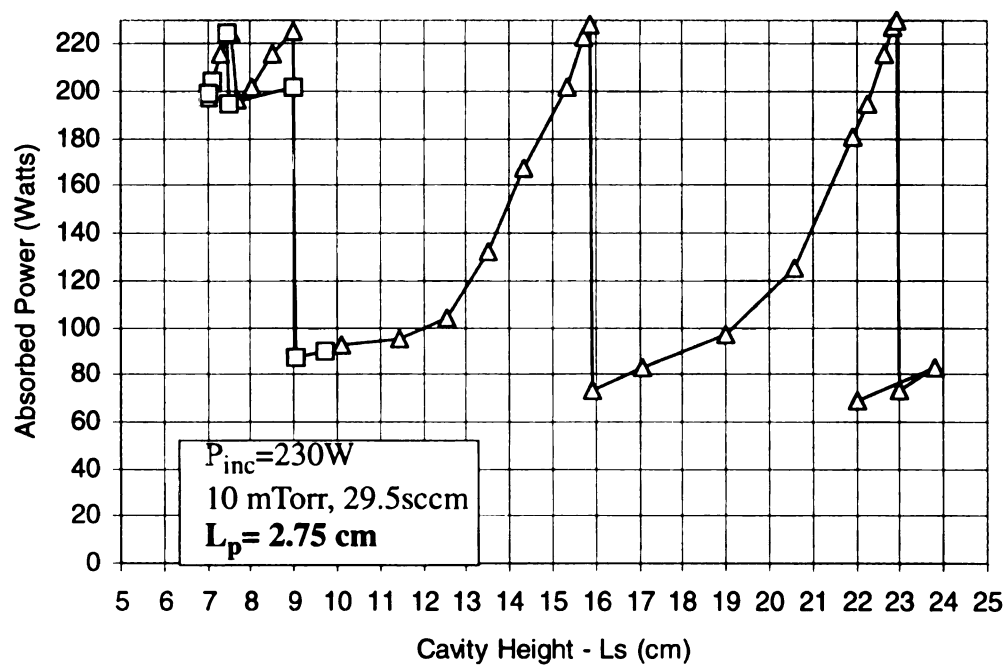


Figure G.14 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.75$ cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

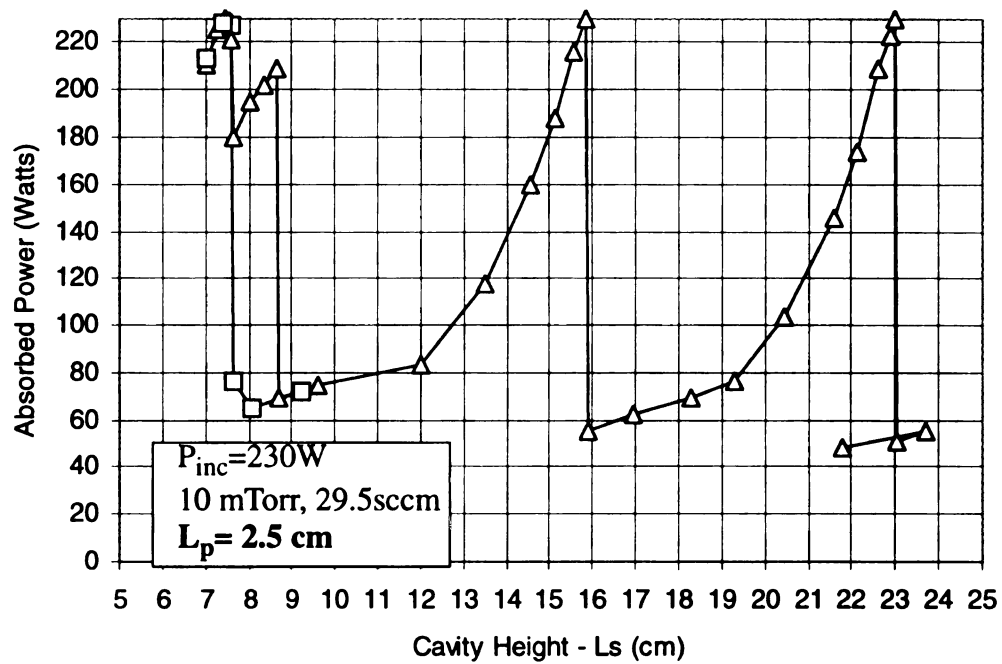


Figure G.15 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

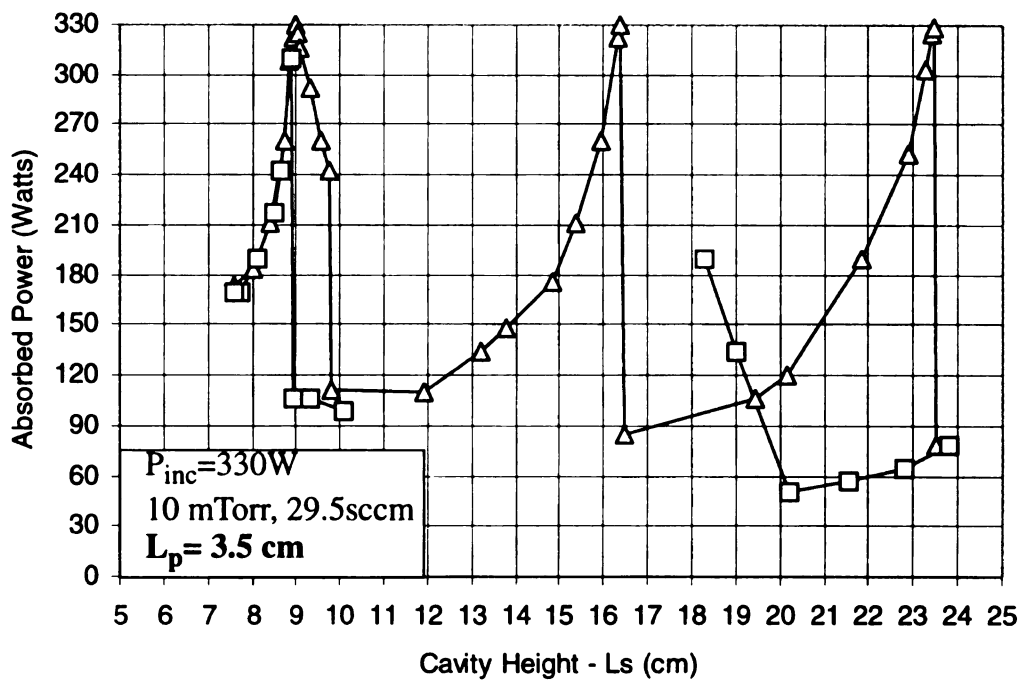


Figure G.16 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

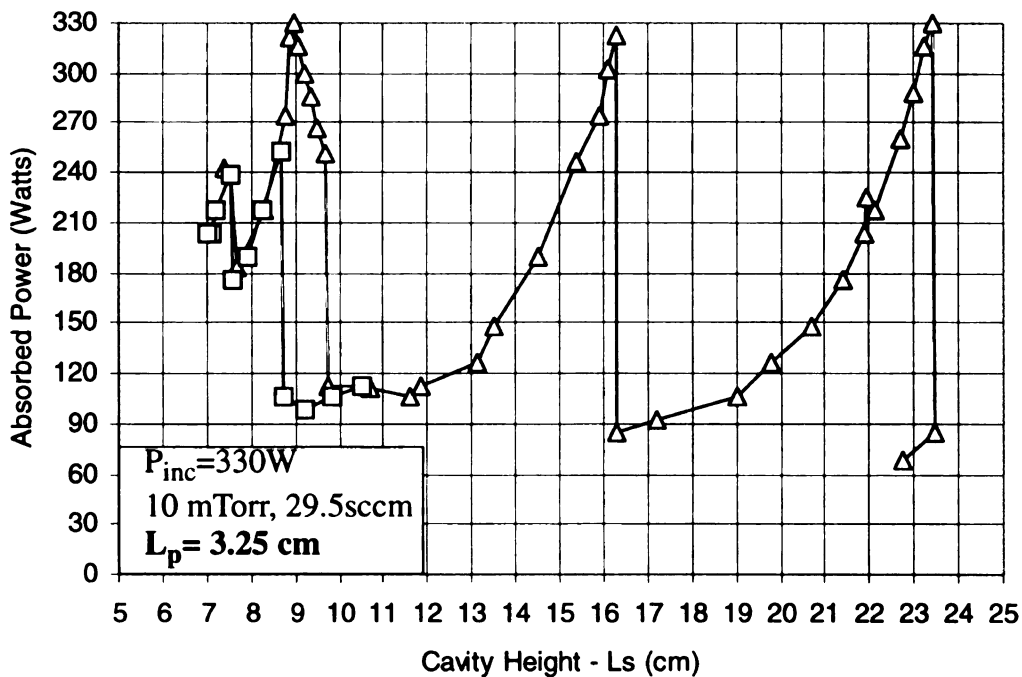


Figure G.17 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

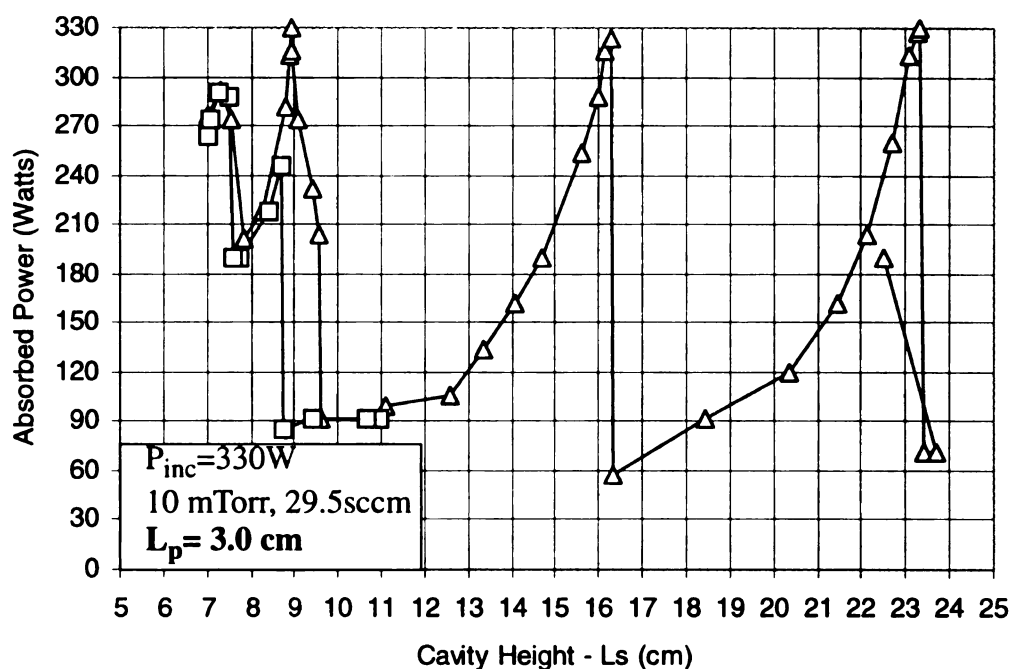


Figure G.18 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

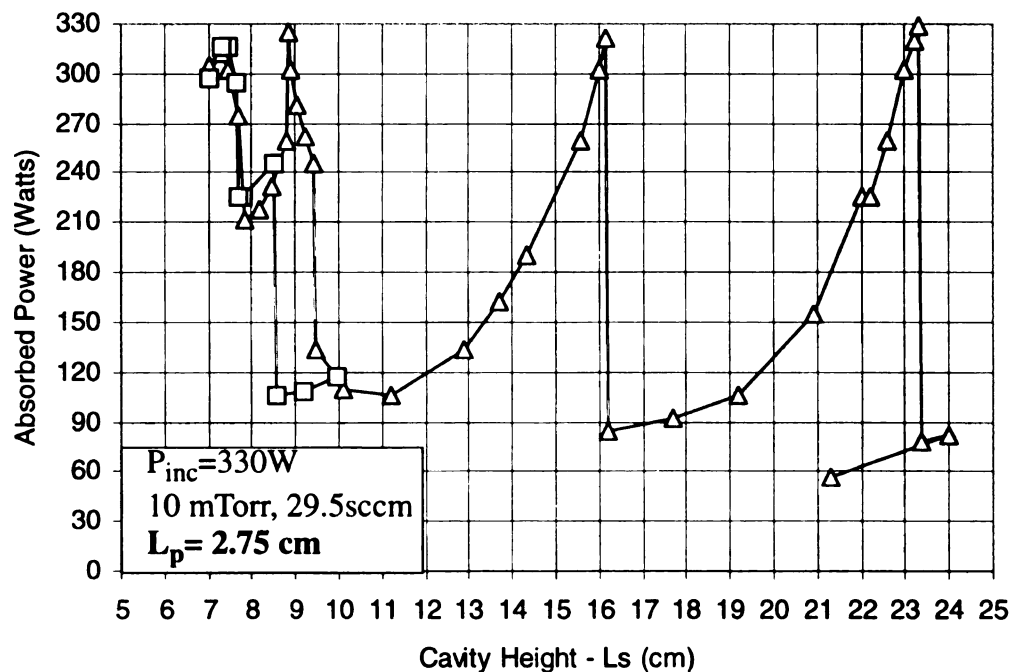


Figure G.19 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

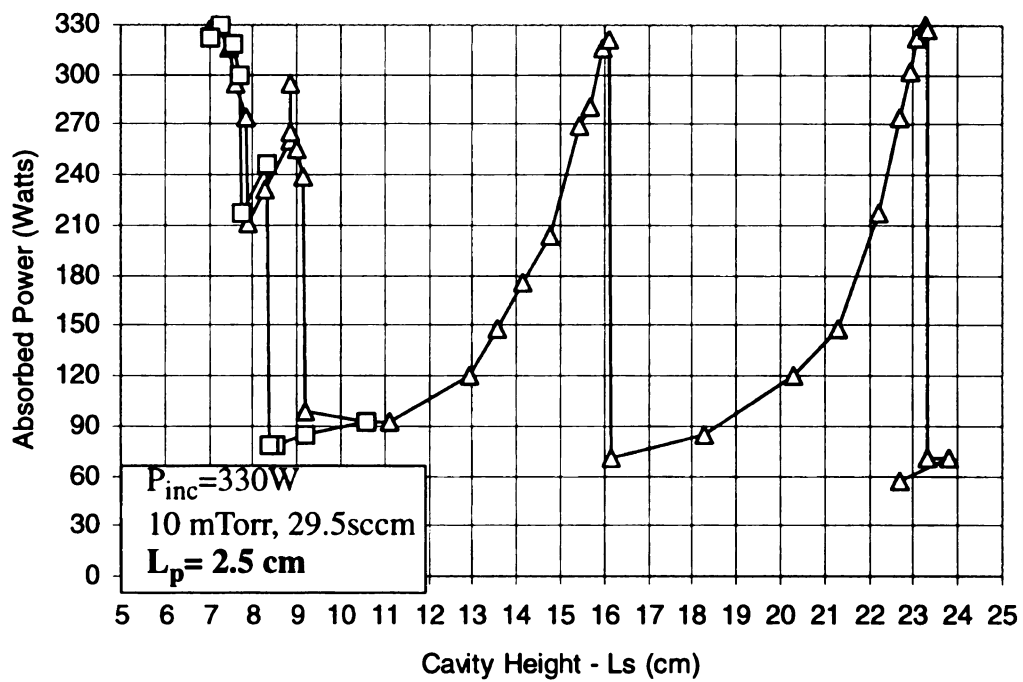


Figure G.20 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 10mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

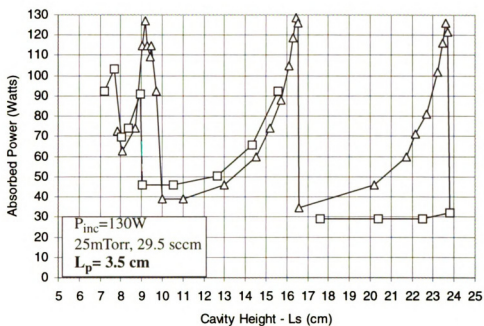


Figure G.21 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.5$ cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

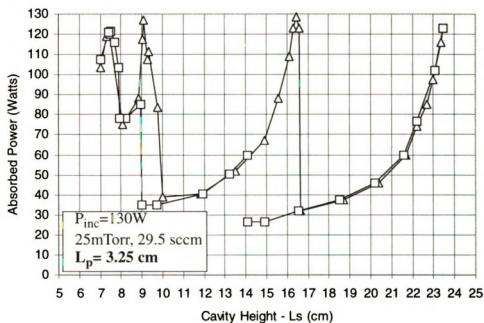


Figure G.22 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.25$ cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

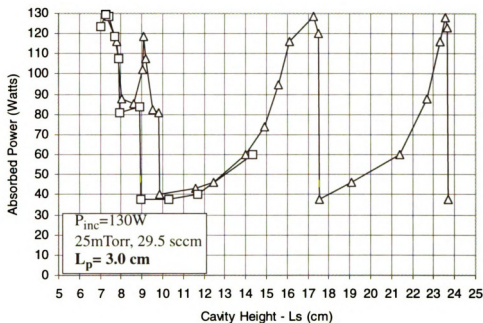


Figure G.23 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

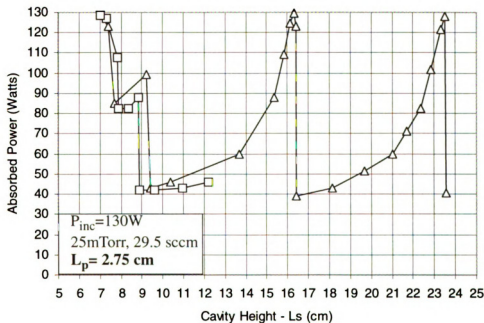


Figure G.24 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

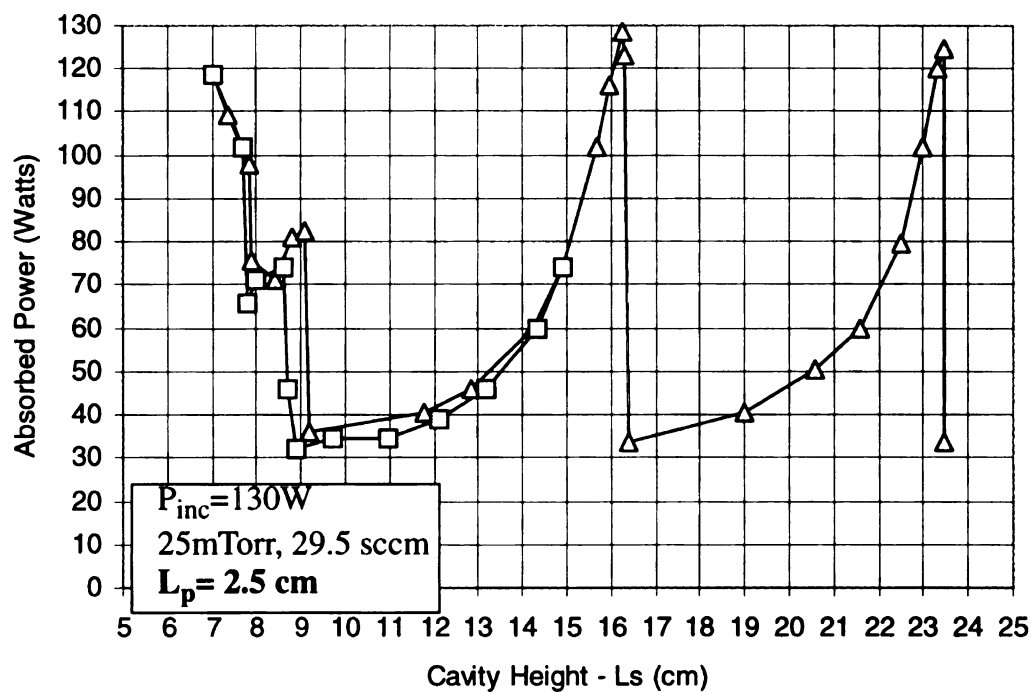


Figure G.25 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 130W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .



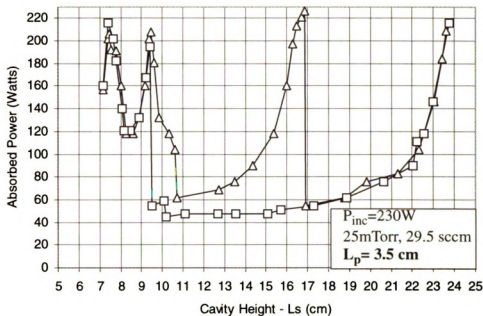


Figure G.26 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.5$ cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

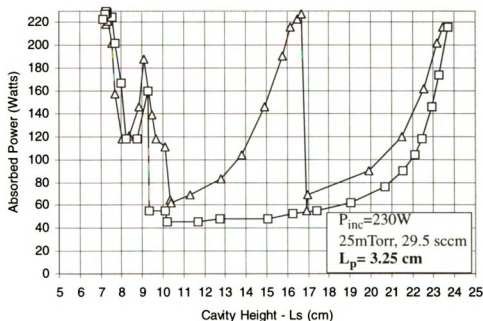


Figure G.27 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.25$ cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

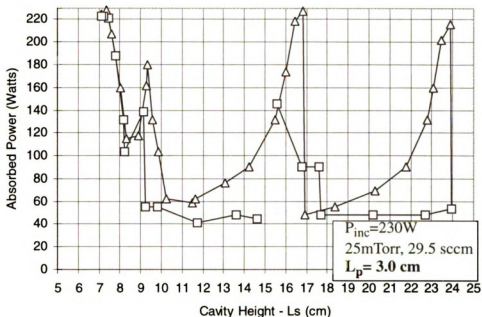


Figure G.28 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

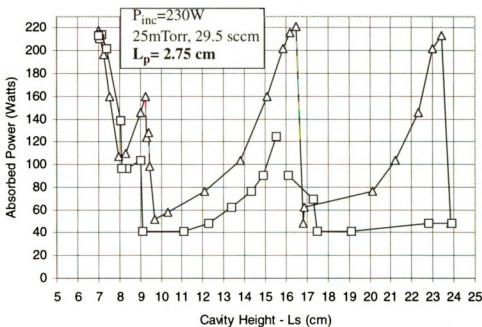


Figure G.29 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

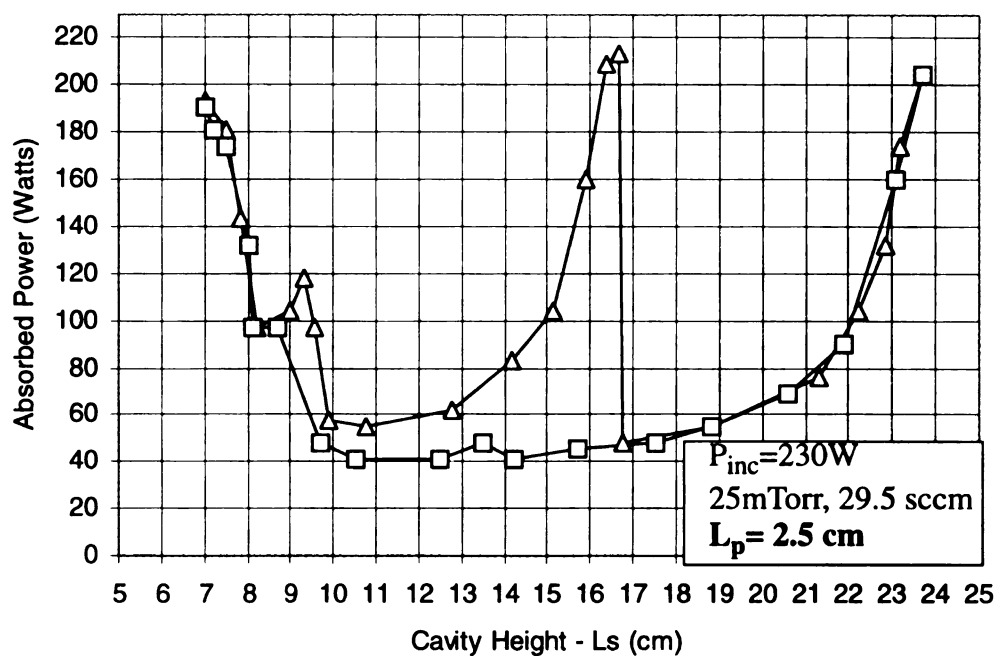


Figure G.30 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 230W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

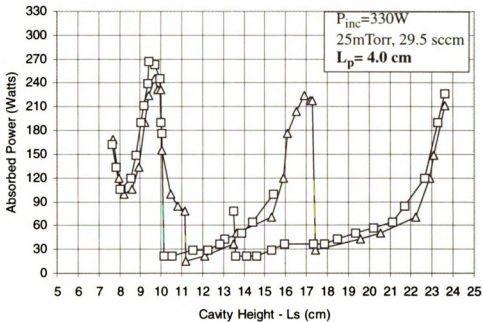


Figure G.31 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 4.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

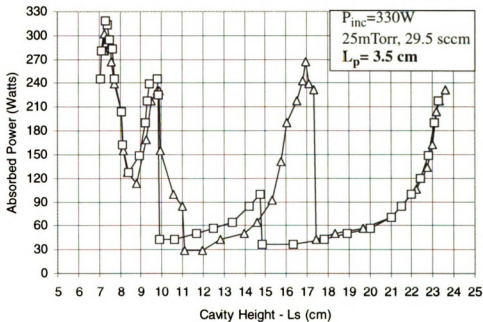


Figure G.32 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

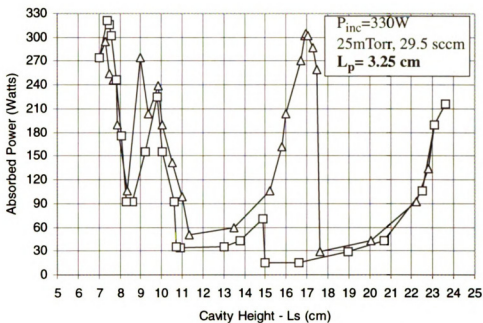


Figure G.33 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.25cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

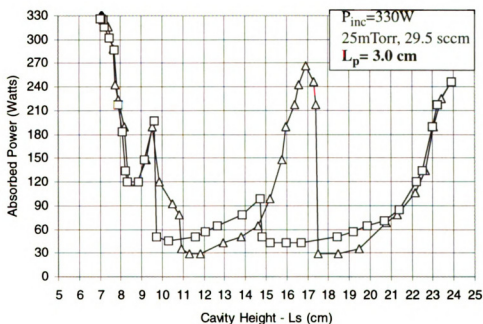


Figure G.34 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

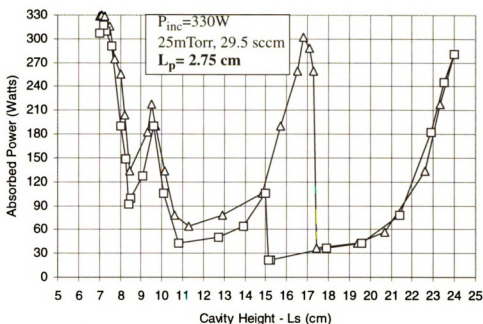


Figure G.35 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.75cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

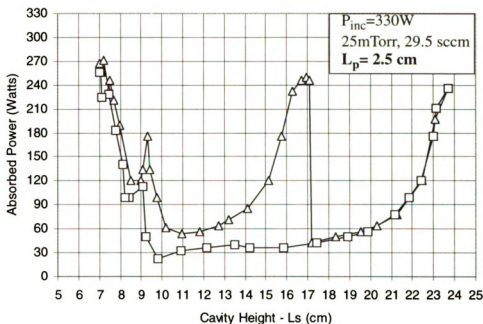


Figure G.36 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.5cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

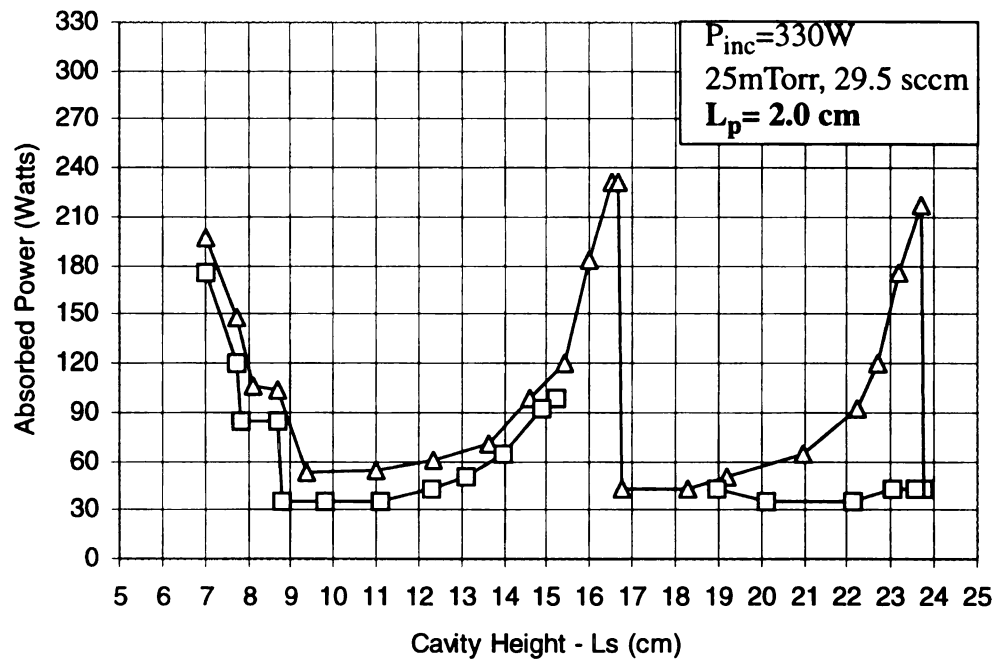


Figure G.37 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge at 25mTorr,  $P_{inc} = 330W$ , and  $L_p = 2.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

## Appendix H

### Adding 3 Different Size Plates To The End Of The Coupling Antenna

#### H.1 Background

#### H.2 Ignition Of The MPDR 13 Discharge With Coupling Disks:

#### H.3 Absorbed Power Curves

H.3.1 Coupling Disk of 3 cm Diameter at 45 mTorr

H.3.2 Coupling Disk of 6 cm Diameter at 7 and 45 mTorr

H.3.3 Coupling Disk of 9 cm Diameter at 7, 15 and 45 mTorr

#### H.4 Charge Density Profiles



## Appendix H

### Adding 3 Different Size Plates To The End Of The Coupling Antenna

#### **H.1 Background:**

In the standard configuration of the MPDR13 with a rounded coupling probe three electromagnetic modes can be tuned using  $L_s$  and  $L_p$ . Two of these modes are identified as similar to the  $TM_{012}$  and  $TM_{013}$  empty cavity modes, while the other mode, in which the coupling probe is very close to the discharge (called the near field mode in this dissertation), is considered a hybrid of the  $TM_{011}$  mode with a strong capacitive coupling between the probe tip and the discharge. This near field mode has been shown to be a very stable tuning position.

The presence of the near field mode raises an important question: can the performance of this mode be enhanced by changing the structure of the end of the coupling antenna? To answer this question a coupling probe was designed that could be fitted with three different aluminum coupling disks (see Figure H.1) of diameter: 3 cm, 6 cm and 9 cm, as well as, the standard rounded probe end. Another important question is: if the coupling probe is significantly modified can the discharge still be ignited and/or sustained?

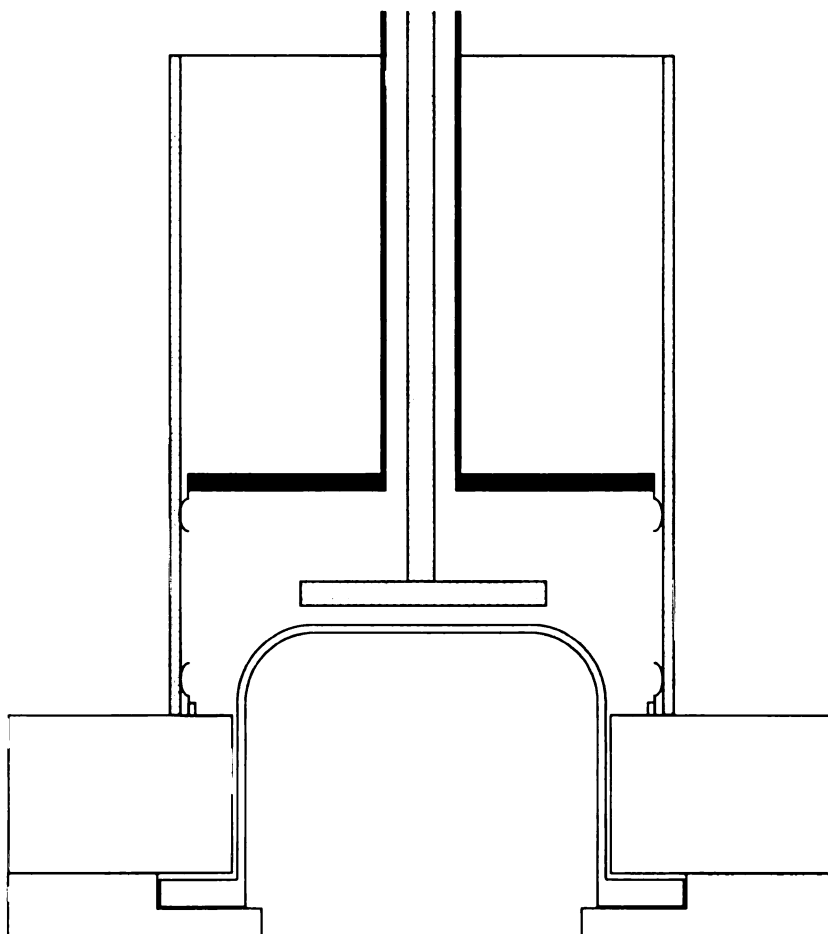


Figure H.1 - Diagram showing the MPDR 13 with a 9 cm coupling plate attached to the end of the coupling probe.

## H.2 Ignition Of The MPDR 13 Discharge With Coupling Disks:

No difficulty was found igniting the discharge for any of the three disk sizes. The procedure was to: 1) tune the cavity to a cavity height of approximately  $L_s = 9.1$  cm and a probe depth of approximately  $L_p = 3.4$  cm, 2) increase pressure to approximately 100 mTorr or more, 3) apply 330 W of incident microwave power, and 4) when discharge ignites reduce pressure to desired level and minimize reflected power by tuning the cavity.

### **H.3 Absorbed Power Curves**

In order to determine the existence and tuning locations of any electromagnetic modes produced by the new coupling disks the absorbed power was recorded vs. cavity height. These absorbed power curves give a general map of the modes that can be accessed for a given set of pressure, power and  $L_p$  conditions. These absorbed power curves were taken in the non-magnetized discharge and are described in the following sections.

#### **H.3.1 Coupling Disk of 3 cm Diameter at 45 mTorr**

Figure H.2 shows a typical absorbed power curve for the 3 cm disk for probe lengths between 2 cm and 4 cm. It was very difficult to match the cavity and reflected power was typically greater than 40%. Unfortunately, a probe length of greater than 4 cm was not attempted for the 3 cm diameter disk. It may be possible to improve reflected power by going to longer probe lengths such as  $L_s=6.875$  cm, as is the case for the 6 cm and 9 cm probes discussed below.

#### **H.3.2 Coupling Disk of 6 cm Diameter at 7 and 45 mTorr**

Figure H.3 shows the absorbed power curve for the 6 cm disk configuration at 45 mTorr and a probe length of 3.0 cm. The best absorbed power was about 200W out of 330 W incident. However, if the probe is tuned to a length of 6.85 cm for the same power and

pressure a much better absorbed power curve is obtained with 3 well matched points, shown in Figure H.4.

If pressure is lowered down to 7 mTorr the 6 cm diameter disk probe antenna produces the absorbed power curve shown in Figure H.5.

### **H.3.3 Coupling Disk of 9 cm Diameter at 7, 15 and 45 mTorr**

At a probe length of 3.0 cm and 45 mTorr the 9cm disk antenna does not provide for good matching, as shown in Figure H.6. The matching performance is much improved for a probe length of 6.875 cm, shown in Figure H.7.

At 15 mTorr and an  $L_p=6.875$  cm the 9cm disk antenna has the absorbed power curve with fairly good matching, shown in Figure H.8. The matching ability of the 9 cm disk antenna is still fairly good at 7 mTorr and an  $L_p=6.875$  cm as shown in figure H.9

## **H.4 Charge Density Profiles**

Charge density profiles were measured for all three disk antennas in the non-magnetized discharge. The method of measuring the charge density profile is the same as used in Chapter 8 of this Dissertation. The profiles for 45 mTorr and 15 mTorr are shown in Figures H.10 and H.11, respectively. All 3 disk antennas (3cm, 6 cm, and 9cm), as well as, the standard probe antenna are compared in Figures H.10 and H.11. No significant differences in charge density are observed between the 3 disks and standard probe. However, the coupling disk were not investigated with the magnetized discharge.

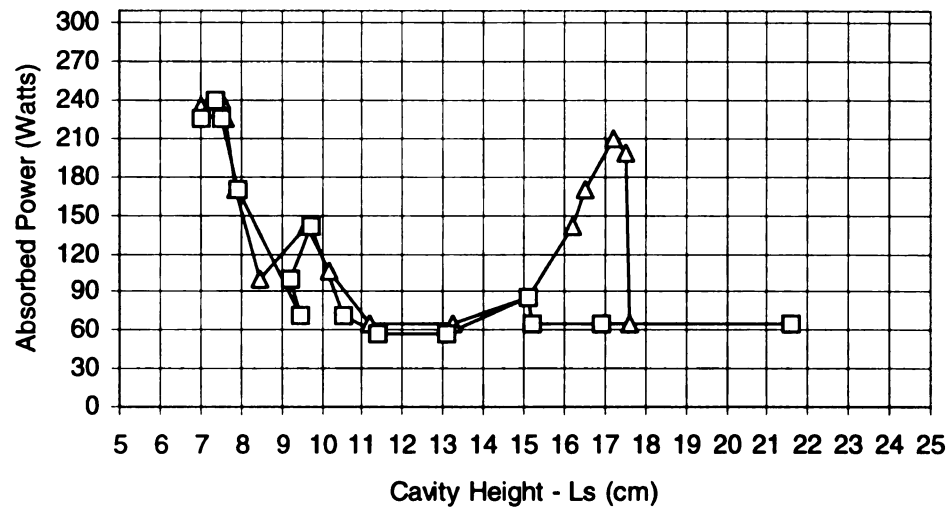


Figure H.2 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 3cm Coupling Plate at 45mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

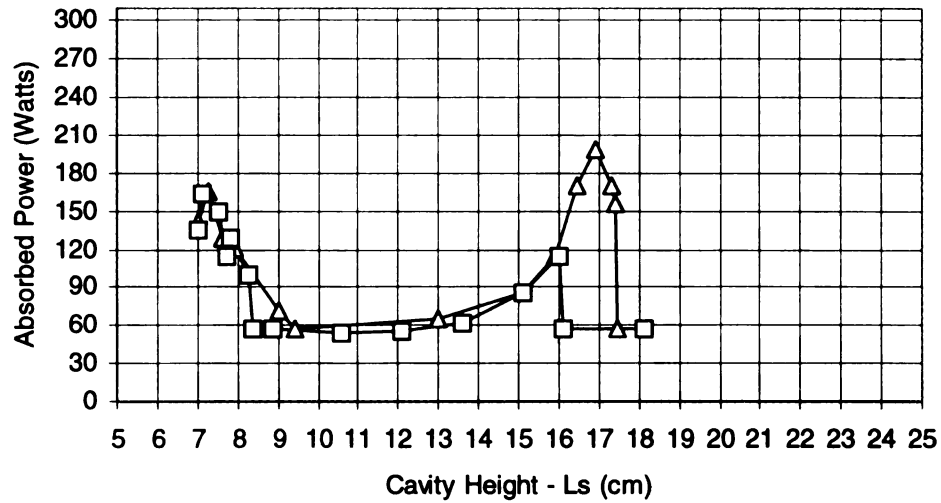


Figure H.3 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 6cm Coupling Plate at 45mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

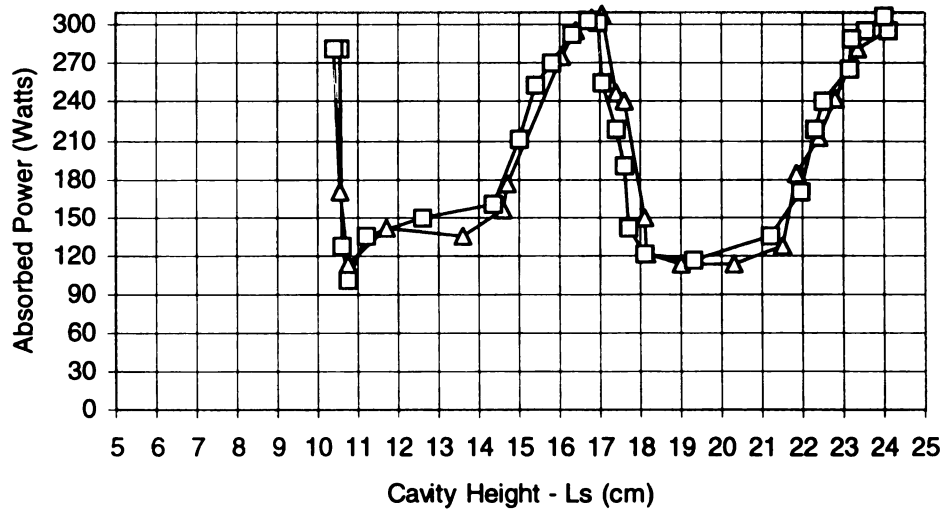


Figure H.4 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 6cm Coupling Plate at 45mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.85cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

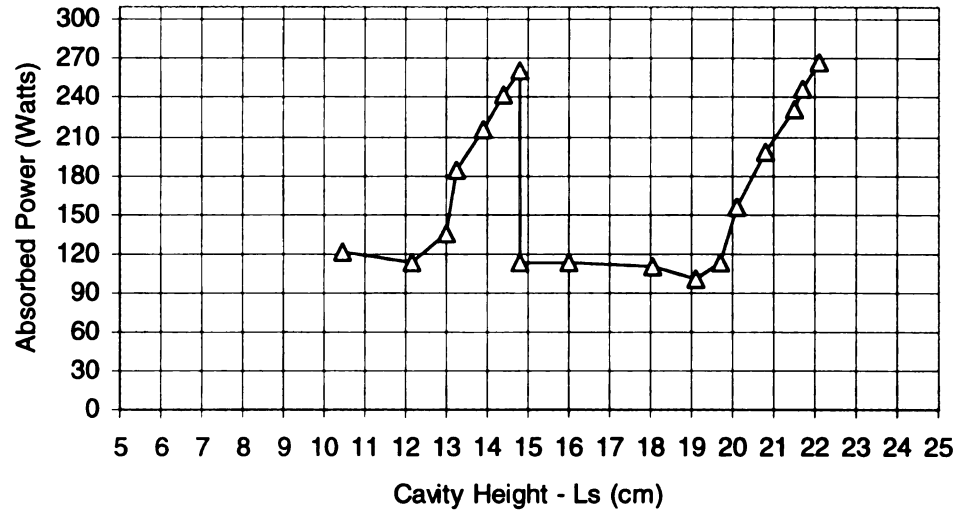


Figure H.5 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 6cm Coupling Plate at 7 mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.875$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

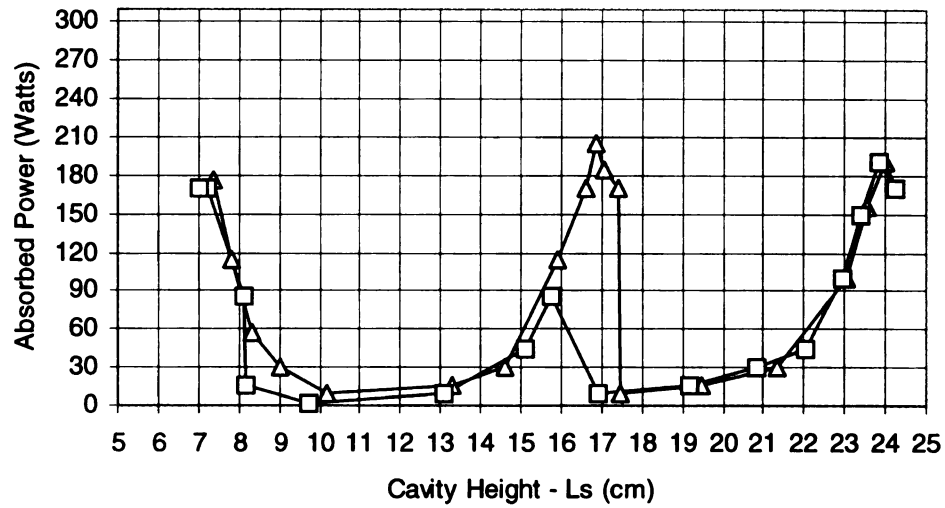


Figure H.6 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 9cm Coupling Plate at 45mTorr,  $P_{inc} = 330W$ , and  $L_p = 3.0cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

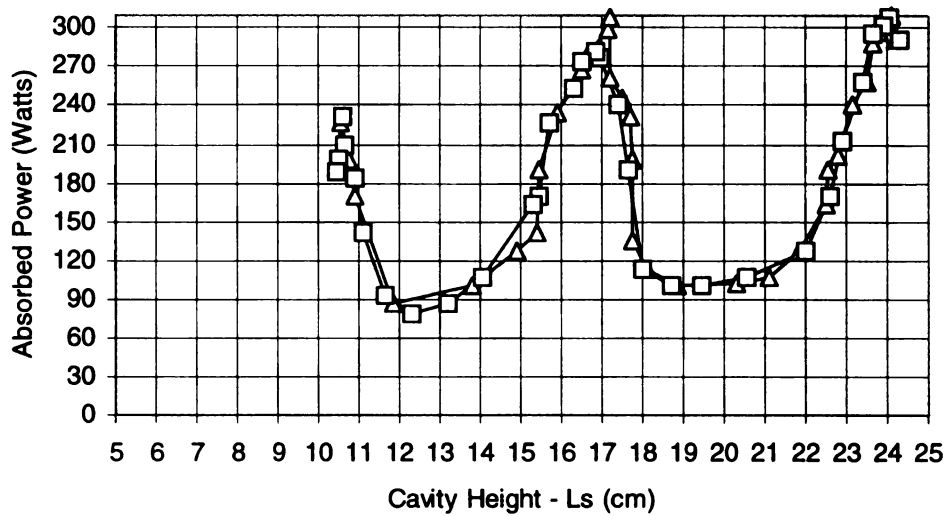


Figure H.7 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 9cm Coupling Plate at 45mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.875 cm$ . Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .



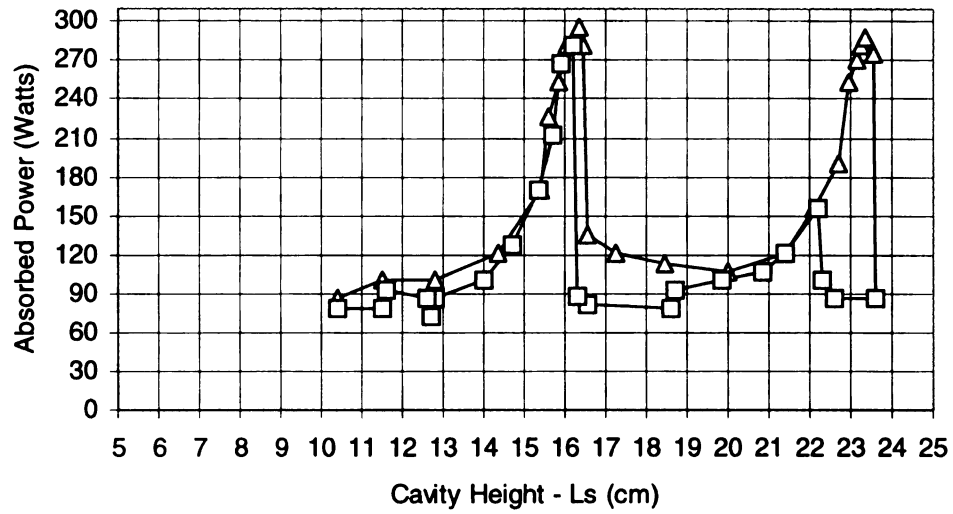


Figure H.8 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 9cm Coupling Plate at 15 mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.875$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

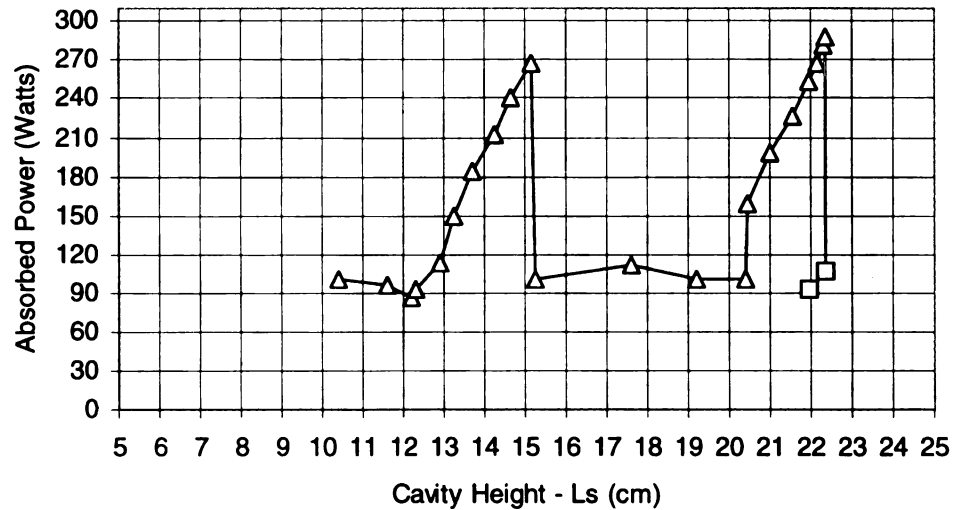


Figure H.9 - Absorbed Power Curve for the Non-Magnetized Plasma Discharge with 9cm Coupling Plate at 7 mTorr,  $P_{inc} = 330W$ , and  $L_p = 6.875$  cm. Triangles represent points taken while increasing  $L_s$  and squares represent points taken while decreasing  $L_s$ .

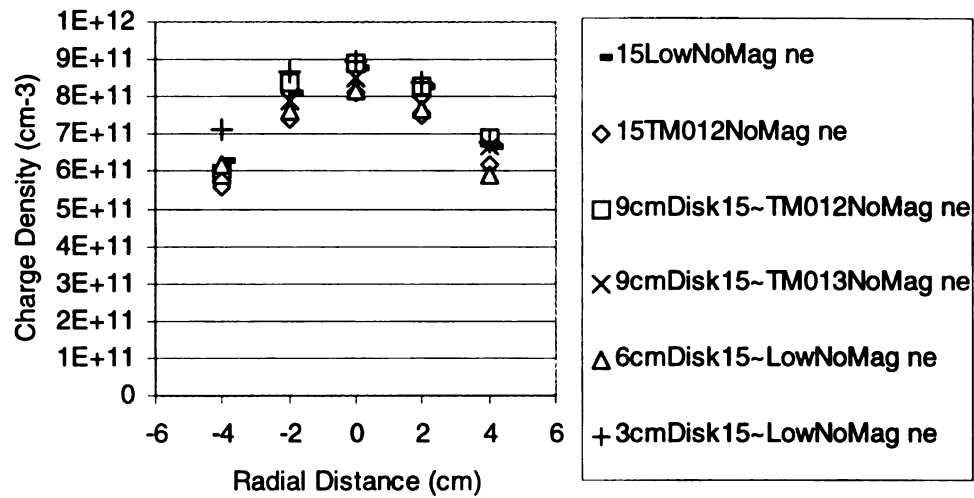


Figure H.10 - Radial Charge Density Profiles for several coupling probe configurations and modes. Data for the standard probe, 9cm disk, 6 cm disk, and 3 cm disk are shown. All profiles were taken at an absorbed power of 330W and a pressure of 15 mTorr.

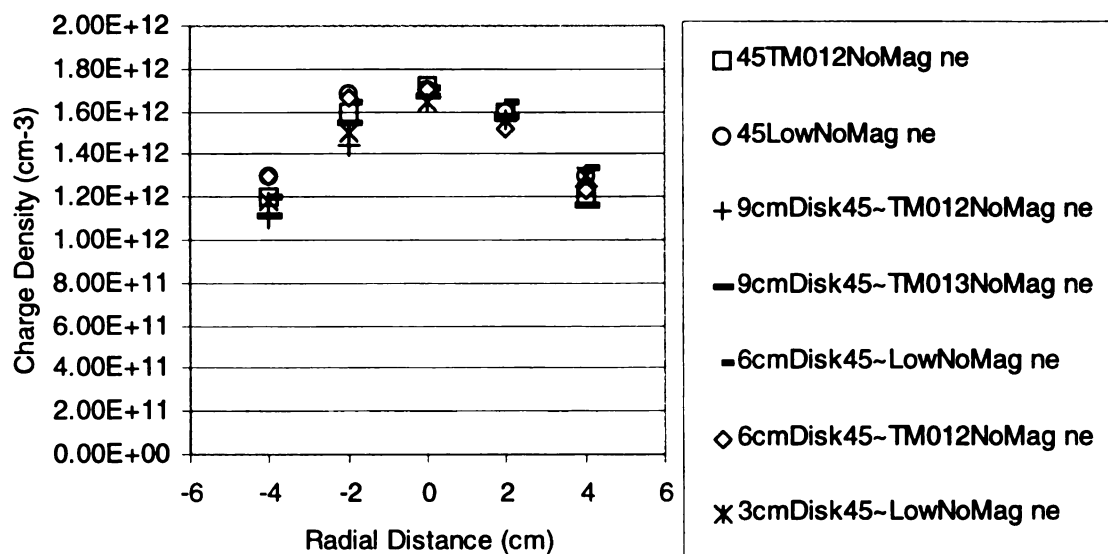


Figure H.11 - Radial Charge Density Profiles for several coupling probe configurations and modes. Data for the standard probe, 9cm disk, 6 cm disk, and 3 cm disk are shown. All profiles were taken at an absorbed power of 330W and a pressure of 45 mTorr.

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