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A TIMELINE OF MAJOR PARTICLE ACCELERATORS

By

Andrew Robert Steere

A THESIS

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ABSTRACT

A TIMELINE OF MAJOR PARTICLE ACCELERATORS

By

Andrew Robert Steere

Progress in particle physics and the resulting gradual unpacking of the fundamental properties of the universe has historically marched in lock-step with progress in particle accelerators. Progress in particle accelerators is measured by the acceleration of particle beams to higher energies, the utilization of new technology and application of new ideas. The first accelerators in the early 1930's utilized direct voltage to accelerate ions to energies of a few hundred keV, resulting in the first induced nuclear disintegrations in 1932. Voltage breakdown limited these first accelerators to less than 1 MeV, and new ideas were needed to push past the 1 MeV barrier. The concept of resonant acceleration provided this impetus in the 1940's by the application of RF electric fields oscillating in resonance with the particles passing through a series of accelerating gaps. This led from the linear accelerator to the cyclotron, where another seemingly impassable energy barrier was reached at approximately 25 MeV.

Then came the principle of phase stability, which allowed the invention of the synchrocyclotron and synchrotron, and the energy barrier was pushed back to 2 GeV by the early 1950's. In the 1950's came alternating gradient focusing, allowing a dramatic reduction in magnet size in large accelerators, and the barrier moved again to 400 GeV. Then came the concept of colliding beams in the 1960's, and the energy frontier moved dramatically forward. We are limited in the 21st century only by the prohibitive cost of building new accelerators, and the question of where to build them.

To Mardi, for her love.

ACKNOWLEDGEMENTS

A wise man once admonished his readers that “whoever heeds instruction is on the path to life, but one who rejects a rebuke goes astray.” I can’t even begin to speculate where I would be were it not for the gracious and wise instruction I have received from the important people in my life. I would like to thank first of all my parents, without whose patience, wisdom, and instruction I would still be stocking shelves in a grocery store. Thank you, mom, for not giving up on me.

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At MSU I am grateful most of all for the advice and counsel of my advisor, Martin Berz. Were it not for Dr. Berz’s encouragement, I would have quit at my first glimpse of the equations of motion in curvilinear coordinates. The beam physics program he pilots at MSU is first-rate, and I am grateful to have had the privilege to work with him.

Dad, you are a role model and mentor to me in every way. Thank you for your integrity and your example of a purposeful life. You are one of my greatest heroes.

Last of all, my most humble and profound thanks go to my wife. You left everything you knew in Australia seven years ago to move into the unknown with this Yank, and words fail me. Thank you.

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Introduction

In the history of particle accelerators we could, with very little error, establish our origin at the Cavendish Laboratory at Cambridge University in England, with a $t_0 = 1910$. It was here that the interest in accelerating particles had its beginnings when Ernest Rutherford fired some α -particles at a thin sheet of gold foil and was astonished to observe some of the α -particles bounce back. He was the first to realize that atoms have an incredibly small, dense mass at their center. A decade later, he achieved another first when he used α -particles of about 5 million electron volts (MeV) produced by radioactive isotopes to disintegrate nitrogen nuclei (Rutherford, "The Stability of Atoms" 389). In a speech before the Royal Society of London in 1927, Rutherford expressed publicly the desire of the scientific community to accelerate charged particles to energies greater than those of natural α -decay in order to disintegrate nuclei with higher binding energies than nitrogen (Rutherford, "Annual Address to the Royal Society" 3). He challenged the attendees to fulfill his long-time desire for 'a copious supply' of projectiles of higher energy than naturally created α and β particles. His challenge received a lot of press and attention, and several proposals were immediately raised to meet his goal. Another decade later, two men started down this path at the Cavendish, and were the first to accelerate particles using a potential difference.

1930—The First Particle Accelerator

The first accelerators to be designed and constructed relied on principles of electrostatics. If we have a time independent electric field, it can be written in terms of its potential via

$$\vec{E} = -\nabla\vec{V}$$

From this, we can show that the increase in energy a particle would experience in the presence of this electric field while traveling from point 1 to point 2 is

$$\Delta U = q \cdot \left(V\left(\vec{r}_1\right) - V\left(\vec{r}_2\right) \right)$$

The first accelerator to be intentionally conceived of as such was constructed by John D. Cockcroft and E.T.S. Walton in 1930 at the Cavendish Laboratory in Cambridge, England (Cockcroft and Walton, 619). Cockcroft and Walton were among many scientists wanting to probe deeper into the fundamental structure of matter by penetrating the nucleus. Knowing that creating and maintaining a voltage that would allow them to accelerate α -particles to energies above those of radioactively-produced α 's was currently impossible, they looked to accelerate something lighter instead—protons.

Cockcroft made estimations of the minimum energy required to penetrate a nucleus based on some calculations he found in an article circulating in the Cavendish on the new theory of wave mechanics. The author of this article, George Gamow, a young Russian employed by Niehls Bohr's Institute of Theoretical Physics in Copenhagen,

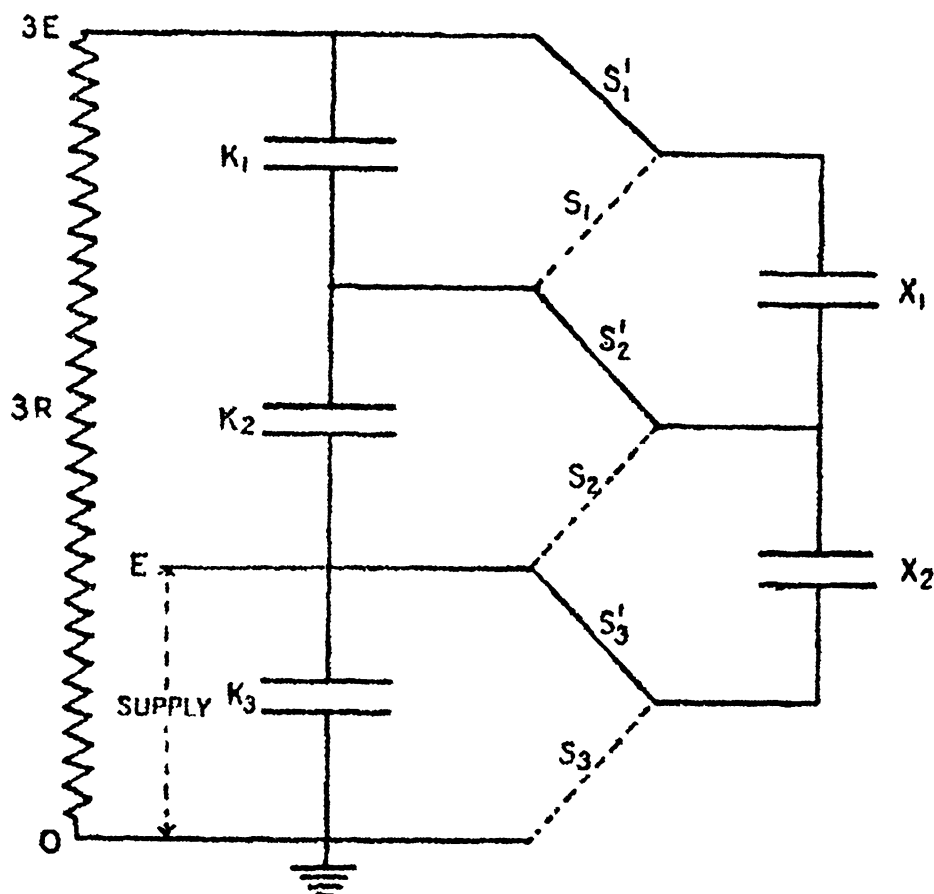


Figure 1. Cockcroft and Walton's voltage multiplier (Cockcroft and Walton, 620).

theorized that a charged particle making a head-on collision with a nucleus has a chance of penetration (tunneling) even if it does not have as much energy as would be required by pre-wave mechanics physics (Gamow, 496). Cockcroft deduced that protons would be a better agent than α 's, and that a proton with energy of 300 kilovolts (kV) would be about one-thirtieth as efficient against boron as an α from polonium would be against aluminum.

He and Walton went straight to work. They initially used a 200 kV transformer to accelerate protons through a straight discharge tube. When this yielded no results, they concluded that they needed higher potentials. They decided to build a voltage multiplier consisting of a complicated set of capacitors connected to rectifying diodes acting as

switches. They discovered that by opening and closing these switches in various sequences they could achieve a potential of 800 kV from their 200 kV transformer. In 1932 they were vindicated when they used a potential of 500 kV to accelerate protons down a vacuum tube eight feet long towards a lithium target, and found that the protons disintegrated the lithium nucleus into two α -particles (Cockcroft and Walton, 621). This result was duplicated by a Soviet research team in Kharkov a year or so later.

1931—The Ubiquitous Van de Graaff

Robert J. Van de Graaff was a Rhodes scholar at Oxford in 1928, and became interested while studying there in the need for machines that could generate and maintain high voltages. In 1930, while at Princeton doing post-doctoral work, he came up with an idea utilizing similar principles of time-independent electric fields as the Cockcroft-Walton accelerator. In a speech before the American Physical Society in 1931, he described his first model (Van de Graaff, 1919). It consisted of two hollow spherical insulated conductors, 24 inches in diameter, made of aluminum. These were mounted on glass rods 7 feet high while two insulated silk belts driven by motors transported electricity of opposite charge to either sphere. Charge was transferred to the belts by point discharge from needle points, and discharged inside the insulating spheres through similar needle points. One sphere was given a positive charge, and the other a negative charge. The spheres build up charge until spark formation occurs, and charge arcs between the spheres.

In 1931, Van de Graaff estimated he had already charged his spheres to approximately 750 kV each, for a total potential difference of about 1.5 MV (Van de Graaff, 1919).

Because Van de Graaff's idea was so simple, and because he had already produced a relatively high steady voltage, several other laboratories joined him in developing newer

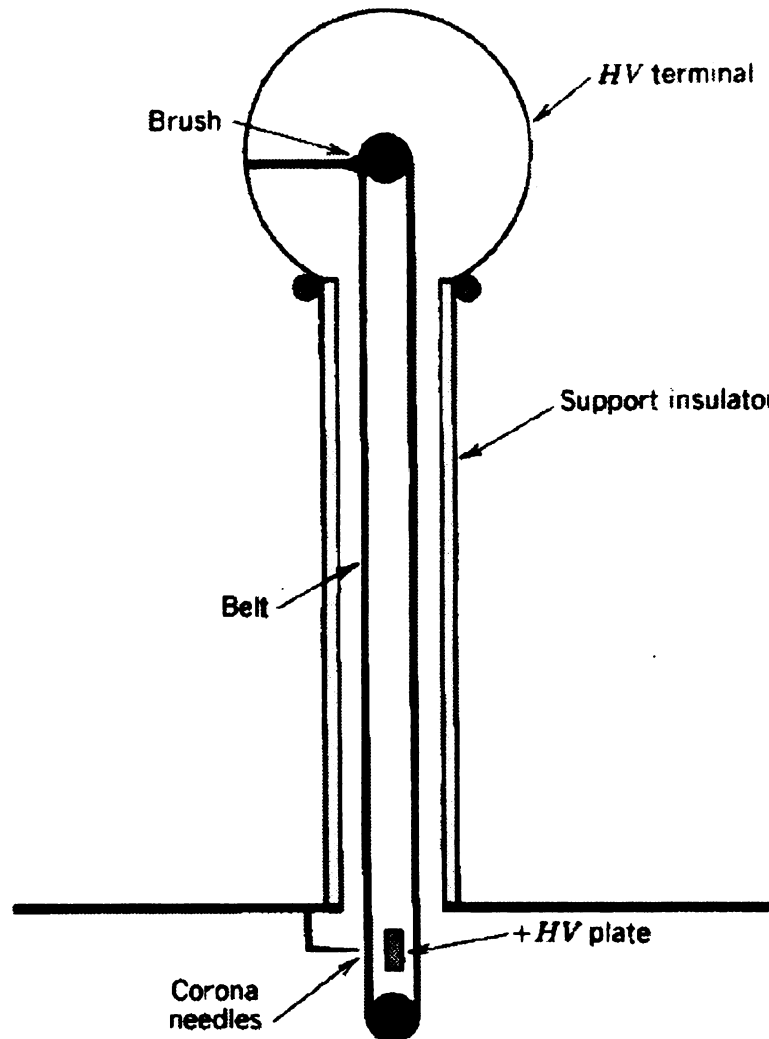


Figure 2: Principle of the original Van de Graaff generator.

and larger generators of this type, including Massachusetts Institute of Technology (Trump and Van de Graaff, 1160), the Carnegie Institute of Washington, and the University of

Wisconsin. As Van de Graaff had already experienced, there were several difficulties in maintaining a constant, high voltage—the most immediate of which was the prevention of spark formation between the spheres. Van de Graaff discovered he could reach and maintain higher voltages without sparking by increasing the size of the spheres—since if the potential is constant, an increase in sphere size will decrease the strength of the electric field. Other laboratories, such as a group at the University of Wisconsin in 1935 experimented with using inert gases at high pressures to increase the insulating effects of spheres. By 1933, the first practical Van de Graaff generator was in operation producing 0.6 MeV hydrogen ions (Tuve, Hafstad, and Dahl, 306).

Today's Van de Graaff generators used in particle accelerators typically sustain voltages up to 15 MV (Humphries, 26). A standard configuration is very similar to Van de Graaff's original design. The source of charge is corona discharge from a set of needles immersed in gas. The electrons are attracted to a positive electrode, and deposit on a moving belt. The belt, enclosed in an inert high pressure gas carries charge mechanically (via a belt motor) into a high-voltage terminal. The charge is transferred to the terminal via metal brushes. When a load is applied (such as a beam to be accelerated), a current controlled by the corona discharge or belt speed is used to drive it.

The beam energy of a Van de Graaff can be increased by approximately a factor of two by utilizing a tandem Van de Graaff configuration. Negative ions originating from a ground potential are sent through a first Van de Graaff generator, and pass through a foil which strips some electrons, converting some of the ions to positive ions. They are then sent through a second Van de Graaff back to ground. These and the single Van de Graaff

generators are ubiquitously used throughout world physics laboratories and educational institutions today for research and education.

1931—Rolf Wideröe: The Linac, the Betatron, and the Cyclotron

There are several difficulties with maintaining a high voltage in a small acceleration gap, chief among them the tendency for spark formation. As this became evident, several physicists proposed allowing the particles to traverse the acceleration gap repeatedly, applying a lower voltage more than once. In 1925, a young Norwegian PhD candidate in electrical engineering at the Technische Hochschule Karlsruhe in Germany was searching

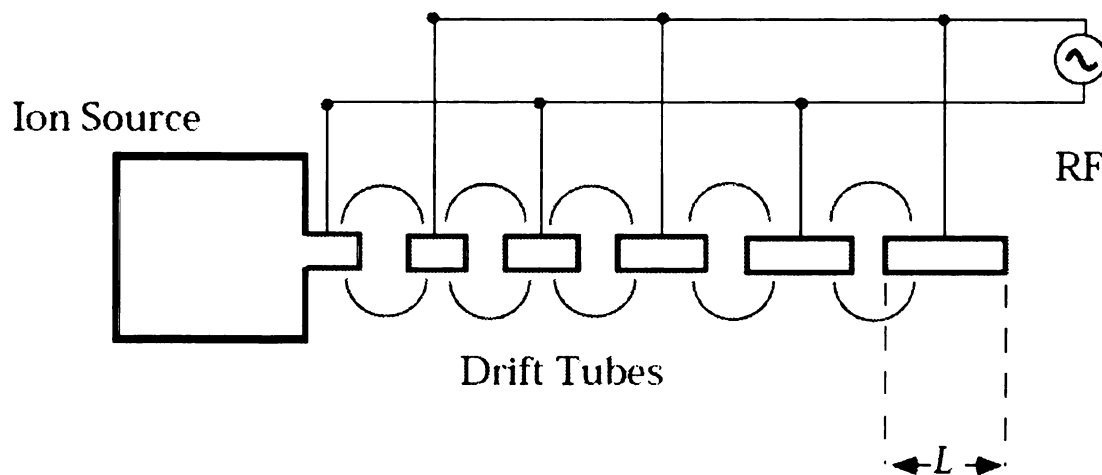


Figure 3: Basic operation of Rolf Wideröe's linac for heavy ion acceleration

for a topic for his thesis. Inspired like many other students by Ernest Rutherford's

experiments at the Cavendish, Rolf Wideröe's first idea was something he called an 'electron beam transformer' (which would later become the betatron)—and was turned down by his advisor (Voss, 78). He decided he would need to invent another new idea in order to earn his PhD, and so he looked more closely at an idea published in 1924 by a Swedish scientist, Gustav Ising, for the acceleration of heavy ions in a linear path using different voltages. Wideröe applied voltages to drift tubes of different lengths, theorizing that with both the ion source and the final beam catcher at ground potential, the voltage gain of the accelerated particles would be larger than the applied voltage.

His experiments supported his theory, and he was soon experimenting with an alternating field of potential 25 kV at 1 MHz to accelerate potassium ions to 50 kV (Yee, 7). As illustrated in Figure 3, potassium ions fell through 25 kV across the first gap when the oscillating RF potential reaching its maximum negative value on the first metal drift tube. As the ions move through the first drift tube, the potential switches to its maximum positive value, and the ions fall through another 25 kV across the second gap. The accelerated ions eventually emerged from a final grounded tube and struck a screen at a distance below the horizontal axis of the drift tubes. Wideröe was able to confirm that the ions had reached energies of 50 keV by measuring this distance. He received his PhD in 1927 (Voss, 78).

1931—An American Linac

However, it was Wideröe's influence on two American scientists that would result

in an avalanche of research and accelerator building. In 1928, he published the results of his 'new principle for the production of higher voltages' in the *Archiv für Elektrotechnik*, a German journal of electrical engineering (Heilbron and Seidel, 97). In 1929, a young English-speaking associate professor at the University of California was browsing with difficulty through this German publication, and came upon the article by Wideröe. He spoke hardly any German, but the diagrams were enough. Ernest Orlando Lawrence would later credit these diagrams for inspiring him to take a closer look at how to re-use the same fields—resulting two years later in the first cyclotron.

A graduate student working with Lawrence at Berkeley, David Sloan decided to experiment with Wideröe's linac while Lawrence commenced work on a cyclotron. Sloan experimented with linacs of ten or more tubular electrodes in series connected alternately to an RF source. By 1931, he had built a linac with a series of 21 accelerating tubes, and in May he and Lawrence succeeded in accelerating mercury ions to 1.25 MeV. Two other linacs were built at Berkeley within a few years that accelerated Hg^+ and Li^+ ions to 2.8 MeV and 1.0 MeV respectively. However, with the materials available at the time, Lawrence decided while the linacs were useful for acceleration of heavy ions, they were impractical for lighter particles such as α 's, as they would require vacuum tubes many meters long, and RF oscillators that they were not yet capable of building. At the energies they were accelerating the heavy ions to, they would not be capable of producing significant nuclear disintegrations of the sort that Cockcroft and Walton had done. Work on the linacs was abandoned for the time being, and all work at Berkeley focused on Lawrence's cyclotron.

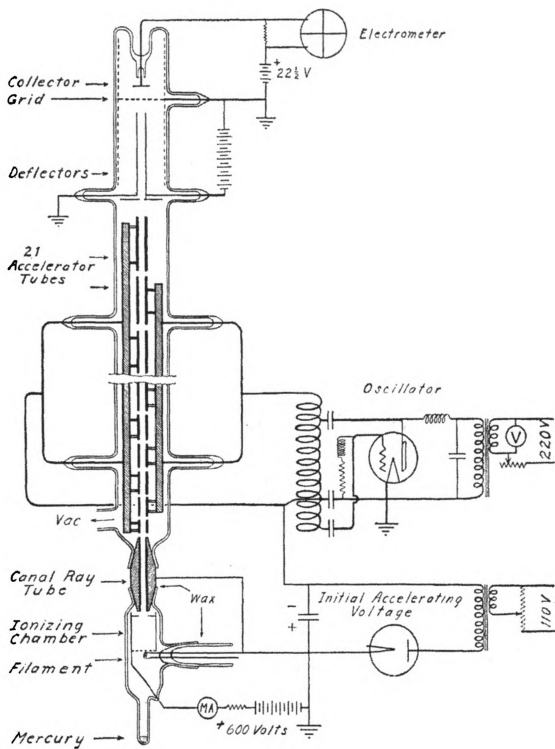


Figure 4: Sloan's linac (Lawrence and Sloan, 69).

1931—A Close Second: The First Cyclotron

While scanning the diagrams in Wideröe's published article in 1929, Lawrence immediately noted that a similar acceleration of particles might be possible by utilizing a curved path. Recalling that a particle of mass m traveling in a circular orbit of radius r will feel a centrifugal force

$$\frac{F = mv^2}{r},$$

Lawrence knew that in the presence of a magnetic field, \mathbf{B} perpendicular to the plane of motion of the particle, the particle would experience a compensating force toward the center of the circle of revolution of

$$F = qvB.$$

In order to describe stable motion for a particle traveling in such a system, we see that

$$\frac{v}{r} = \frac{qB}{m}.$$

And hence that the frequency of rotation

$$\omega = \frac{v}{r} = \frac{qB}{m}$$

of an ion of charge q and mass m in a field \mathbf{B} is independent of the radius of the orbit r .

The greater distances traveled in larger orbits are exactly compensated for by the increased velocity of the ion.

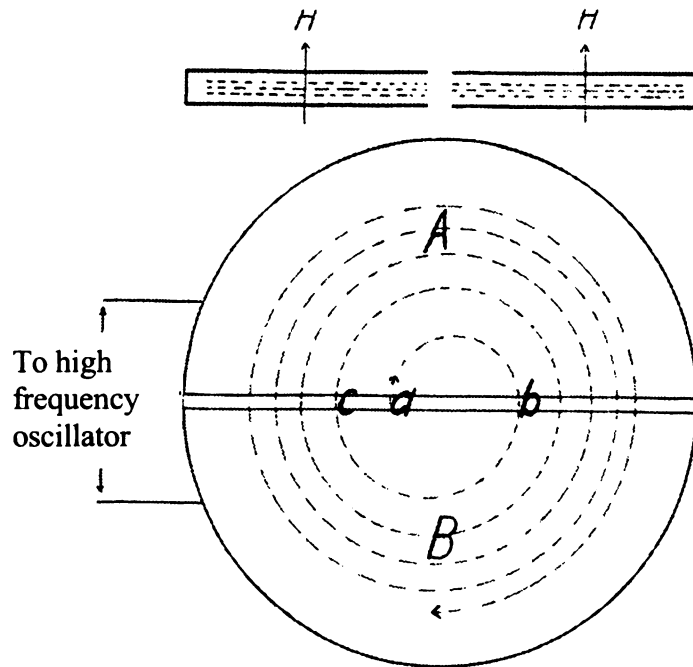


Figure 5: Schematic of Lawrence's cyclotron (Lawrence and Livingston, 23).

Lawrence took this fact, and combined it with Wideröe's idea to use fields repeatedly to accelerate particles in discrete steps (Birge, 324). After skimming the diagrams, he quickly sketched out on paper the basic schematic shown in Figure 5. **A** and **B** are hollow metal half-cylinders alternately charged to a voltage by an oscillator. Hydrogen ions enter the gap between the cylinders when the electric force from the oscillating field pulls them in the direction shown at **a**. When they enter **A** (where they are shielded from the RF field), the ions revolve in a semicircle **ab** because of the magnetic field **H**, and cross the gap at **b** just when the field has reversed and pulls them into **B**. The acceleration at **b** increases the ions' orbit radius due to the relation

$$r = \frac{mv}{qB},$$

and the ions complete a wider half-orbit and emerge at **c** to cross the gap again in step with

the RF field. The momentary radius of the orbit increases every time the ions accelerate, and they gradually spiral out under the influence of \mathbf{B} , acquiring energy every time the gap is crossed. Lawrence knew that if he could tune the oscillator to alternate with the same frequency with which the ions appear at the acceleration gap, this would be possible. Once the correct frequency was established—tuned to the mass of the ion being accelerated and the strength of the magnetic field—the alternating current would be resonant with the magnetic field. Hence, the cyclotron's original name was the magnetic-resonance accelerator. Lawrence estimated he would reach an ion energy of one million eV shortly.

With his graduate student, Stanley M. Livingston, Lawrence began work on his first resonance accelerator. Their first machine used a 13,000 G magnet with 4 inch poles, and a flat brass vacuum chamber sealed with wax, which fit between the poles. The chamber contained a single D-shaped electrode to which the RF peak potential of 1000 V and 10 MHz frequency was applied. By flooding the center of the vacuum chamber with gas at low pressure and ionizing it with electrons from a tungsten cathode, hydrogen ions were formed. The ions that reached the edge of the chamber after completing their revolutions were collected in a shielded cup, and their energies were recorded by measuring their deflection in an electric field. The highest energies recorded with this first machine were 80,000 eV in January 1931 (Lawrence and Livingston, 1970). This machine was enough to earn Livingston his PhD, but was not powerful enough to cause nuclear disintegrations.

Upon the first successful tests of this device, Lawrence immediately laid plans to build a cyclotron capable of accelerating light particle to energies high enough to penetrate nuclei. In early 1931, he was awarded a grant by the National Research Council (\$1000) to

build a larger cyclotron. This cyclotron utilized a 14 kG magnet with poles of 10 inch diameter. In August 1931, Lawrence and Livingston had achieved proton energies of 1.1 MeV, but at a higher voltage potential than they desired. They had reached a limit they could not push beyond, and Livingston thought they might have reached the point where the increase in proton mass due to relativistic effects prevented the synchronicity of radial particle motion predicted by Lawrence's early cyclotron equation. After some

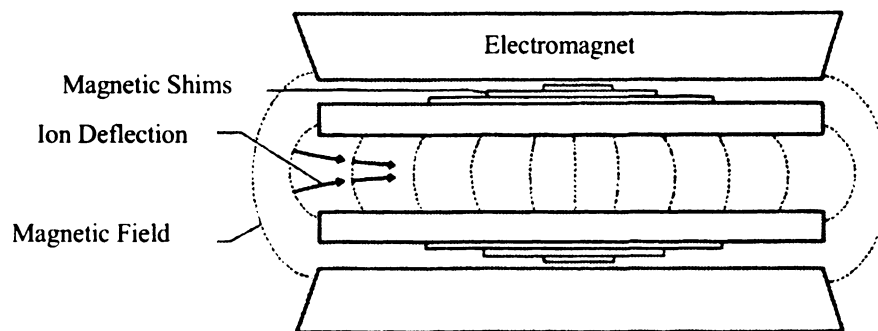


Figure 6: Effect of shims on the magnetic field (Lawrence and Livingston, 29).

experimentation, they concluded that such was not the case. Lawrence suggested placing some small iron shims in the cyclotron to 'smooth' any inhomogeneity in the magnetic field. It worked, but not for the reasons Lawrence initially imagined. Lawrence eventually realized that adding the shims had a focusing effect on charged particles traveling through the field. The shims caused a convex bulging in the magnetic field lines, helping to 'force' stray ions back toward the median plane (Lawrence and Livingston, 19). In early 1932, they achieved 1.22 MeV with a potential difference of 4000 V (Heilbron and Seidel, 100).

The cyclotron showed promise as the best means to accelerate particles with relatively low potentials, but experimentally had yet to prove itself useful as a tool for

nucleus disintegration. Cockcroft and Walton had just published the results of their successful ion acceleration and nucleus disintegration at the Cavendish, and Lawrence was determined to equal their success. He enlisted the efforts of some researchers from Yale University to install a target inside the vacuum chamber and a thin-foil window outside the targets to record and count the particle products of disintegration (Livingston, M. Stanley, 16). A few months later, disintegrations of Li nuclei and other target atoms were observed, and the results were published in September 1932 (Lawrence, Livingston, and White).

1932-1940—The Decade of the Cyclotron

More advances in cyclotron development came quickly. By 1933, Lawrence and Livingston had acquired the iron core for a large new electromagnet from an obsolete radio transmitter donated by the Federal Telegraph Company. They machined the pole faces to a diameter of 27.5 inches, and constructed a vacuum chamber similar to their earlier cyclotrons, but with two D-shaped electrodes. By the time the machine had been completed and was operating in 1933, deuterium ions became available for acceleration for the first time, provided from heavy-water samples supplied by the Chemistry Department at Berkeley.

By 1934, the cyclotron was producing 5 MeV deuterium ions. In 1936, the magnet faces of this cyclotron were enlarged to 37 inches, and a new chamber was built. This cyclotron quickly produced deuterium ions of 8 MeV. The next step for Lawrence and his

team was a 60 inch cyclotron, dubbed the ‘Crocker cyclotron’. This was completed in 1939, and ultimately produced 20 MeV deuterons (Lawrence *et al.*, 124). The Crocker cyclotron was used as a template for many other research institution’s cyclotrons.

Over the next few years, Lawrence and his associates added a significant number of improvements to their original cyclotron design that would be adopted by cyclotron developers at other research laboratories. A sampling of these improvements includes those made to the ion source. The intent was to increase the number of electrons emitted by the tungsten wire, and hence to increase the number of ionized hydrogen (or deuterium) ions. First, the wires were surrounded by water cooling jackets—allowing a higher rate of electron output without overheating the tungsten (Livingston, “The Attainment of High Vacua in Large Metal Chambers” 214). Next, Lawrence proposed to either increase the voltage on the wires or increase the size of the wires in order to increase the electrons produced. Increasing the voltage on the wires resulted in the release of electrons of higher energy, which have a smaller probability of ionizing the hydrogen atoms. Deciding to focus on the wire size, Livingston slightly increased the vertical distance between the two D’s in the 37 inch cyclotron model. This allowed him to increase the size of the tungsten wires, and by 1938 the Berkeley’s cyclotron had raised their output current from 25 μA to about 100 μA (Livingston, Holloway, and Baker, 63).

This increase in tungsten wire size caused two dilemmas requiring solution: First, the larger wires required a larger magnet pole gap, and hence greater power applied to the electromagnet to maintain the same magnetic field. Second, the larger wires had a proportionally larger area of ionization of the hydrogen or deuterium gas, which resulted in

a larger probability that the ions produced would be off-focus. It was not until Livingston had moved on to Cornell University and was working on a new cyclotron in 1938 that this problem was solved by use of a 'capillary ion source'. Livingston and his team enclosed the tungsten wire in a double-ended cone, and the gas to be ionized filled this chamber at a pressure roughly 100 times greater than pressure of the vacuum chamber (nominally at $1\text{E-}04$ mm Hg). A small hole in the center of this chamber allowed the ions to leave the chamber and enter the D's. Through trial and error, they settled on a hole size of $1/8$ inch, and were able to increase the beam current from $5\text{ }\mu\text{A}$ to $70\text{ }\mu\text{A}$ through this improvement alone (Livingston, Holloway, and Baker, 64).

Once the breakthrough in cyclotron construction had been achieved at Berkeley in 1932 with Lawrence and Livingston's four inch model, cyclotrons were researched and constructed all over the world; often by researchers who were Berkeley graduates. By 1960, over a hundred cyclotrons had been built in laboratories around the world. (Livingston, M. Stanley, 18). Across the pond, two cyclotrons were completed in England within a year of each other: one at the Cavendish in 1938, and another at the University of Liverpool in 1939 (Hinokawa, 23). Cockcroft had been in close communication with Lawrence during the development of the Berkeley cyclotrons, and was particularly intrigued by Lawrence's desire to produce radioactive sodium, aluminum, and phosphorous isotopes for medical use. The medical community desired a more stable replacement for the radium currently being used for medical research, and Lawrence had predicted that this community might be a good source of considerable financial support for the building of new cyclotrons. The Cavendish cyclotron eventually produced 10 MeV deuterons.

Cyclotrons were also completed at Cornell University, MIT, and the University of Michigan by 1940 (Livingston, M. Stanley, 17).

1940—The Betatron

The next development in particle accelerator history will return us to Rolf Wideröe. You will recall that in 1922, Wideröe attempted to make the topic of his PhD thesis an accelerator he called the ‘electron beam transformer’. He was turned down, and moved on to work instead with RF acceleration, and inspire the cyclotron and Linac. However, in the same 1928 paper that inspired Lawrence to build his cyclotron, he also wrote down what is called the ‘betatron principle’, which is used below.

Let ρ be the radius of a beam pipe in a basic betatron. By Ampere’s law, if the total magnetic flux enclosed by the beam pipe circumference is ramped up by a time-varying magnetic flux, an electric field, E , will be induced along the beam axis by

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d}{dt} \Phi,$$

where $\Phi = \int_A \vec{B} \cdot d\vec{s}$ is the flux of the magnetic field through the surface. Because we are dealing with circular orbits of radius ρ , using a magnet of rotational symmetry, we can simplify the equation to

$$E = -\frac{1}{2\pi\rho} \frac{d}{dt} \Phi = \frac{1}{2\pi\rho} \pi\rho^2 \frac{d}{dt} B = -\frac{\rho}{2} \frac{d}{dt} B.$$

Using Newton's law, we obtain for the final particle momentum

$$\frac{d}{dt}(mv) = -qE = \frac{q\rho}{2} \frac{d}{dt} B \Rightarrow mv = \frac{1}{2} q\rho \bar{B}.$$

Because the motion is perpendicular to the magnetic field, we have

$$\frac{mv^2}{\rho} = qvB(\rho) \Rightarrow mv = q\rho B(\rho),$$

where we find that according to Wideröe's betatron principle of 1928, the relationship between the field $B(\rho)$ at the orbit ρ and the average field is

$$B(\rho) = \frac{1}{2} \bar{B}.$$

This is the principle of the betatron, where both bending and acceleration of the particle (usually electrons) come from a magnetic field increasing with time. The increase matches the increase in particle energy, so that the orbit radius is kept nearly constant, and the induced electric field provides acceleration of the particles.

In the 1930s, some interest developed in an accelerator that could accelerate electrons in order to produce X-rays for hospital and research use. In 1940, D.W. Kerst built the first successful Betatron at the University of Illinois, which produced electrons of 2.3 MeV and had an X-ray output equivalent to that from 1 gram of radium (Kerst, 841). Kerst then took a year off at the University of Illinois and worked with General Electric engineers to build a 20 MeV betatron in 1942. He returned to Illinois and built an 80 MeV betatron, and then in

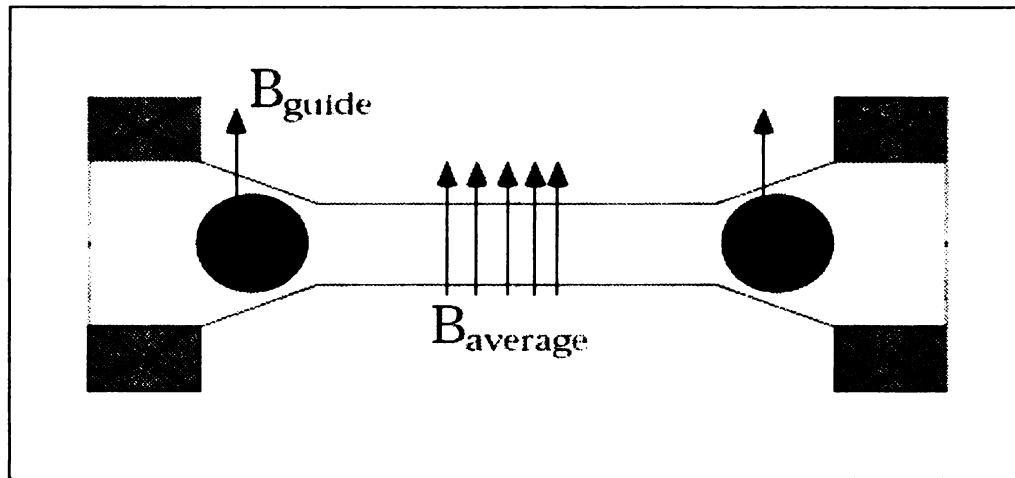


Figure 7: Schematic layout of a betatron.

1950 oversaw completion of a betatron that produced 300 MeV electrons, which holds the record for the highest energy electrons produced (Kerst *et al.*, 297). By the time this betatron was in operation, the electron synchrotron had arrived on the scene and began to displace the betatron as an accelerator of high energy electrons. Betatrons were built all over the world, largely for the purpose of accelerating electrons, although a few were designed for protons. Wideröe resumed his work on betatrons in 1942, and eventually went to work for the Brown-Boveri Corporation in Zurich, Switzerland designing betatrons for medical purposes. Wideröe achieved another first when he conceived of another idea while working on a betatron: that of colliding high-energy beams in storage rings instead of bombarding stationary targets. He received a patent for this concept in 1943 (Voss, 79).

1945—New Ideas: Synchronous Acceleration Leads to the Microtron

Prior to 1945, accelerators were all limited in maximum theoretical energy. Electrostatic generators such as the Cockcroft-Walton and the Van de Graaff were restricted by the limitations imposed by high electric fields that could lead to insulation breakdown. The cyclotron was limited by the increase in relativistic mass of protons and deuterons at energies above about 25 MeV—the increase of relativistic mass above these energies detunes the particles from synchronicity and prevents further acceleration. The betatron, while having reached energies of 300 MeV by 1950, is limited by the rapid increase in energy loss due to radiation by the orbiting electrons. The energy loss, U_0 , of electrons of nominal energy E in a ring of diameter ρ is proportional to E^4 / ρ .

In 1945, a new principle was discovered and published in both the USSR and U.S. nearly simultaneously. Desiring to use the same RF cavities repetitively in order to minimize their expensive cost, two scientists looked to establish a relationship between the synchronicity of the orbiting particles and the time-dependent RF electric fields. If we take the energy gain per turn as equal to the rest mass of the electron, we note that the cyclotron frequency at the $(n-1)$ st turn is

$$\omega_{n-1} = \frac{qB}{nm_0}.$$

Thus, if the RF frequency ω_{rf} is an integral multiple of the particle's revolution frequency, the particle acceleration will be synchronized. This principle of phase stability was published nearly simultaneously: by V. Veksler in the USSR in early 1945 (Veksler, 153),

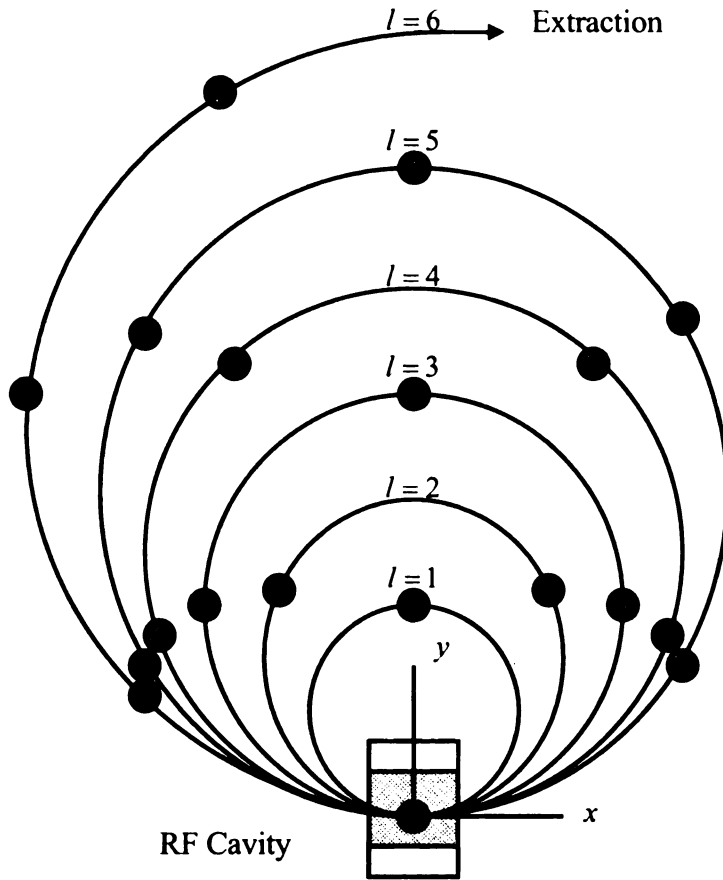


Figure 8: Basic principle of a microtron.

and also by E.M. McMillan at the University of California in late 1945 (McMillan, 143).

The principle behind a microtron is similar to that of a cyclotron, but it is designed to accelerate electrons vice positive ions. The electrons pass through a circular orbit, each of which are all tangent to one another within the RF cavity. Each successive orbit is longer than the one proceeding it such that

$$\omega = \frac{qB}{\gamma m_0},$$

where the frequencies of revolution follow the sequence

$$\omega = \omega_0, \frac{\omega_0}{2}, \frac{\omega_0}{3}, \frac{\omega_0}{4}, \dots$$

Here, clearly the factor γ must follow the sequence $\gamma = \gamma_0, 2\gamma_0, 3\gamma_0, 4\gamma_0, \dots$, requiring that $\Delta\gamma = 1$ per turn. Several test microtrons were built after both of these 1945 papers.

The two largest operating microtrons today include the 855 MeV three-stage MAMI microtron at Mainz, Germany (Herrmann *et al.*, 2915), and the 175 MeV microtron at Moscow State University (Vasil'ev, Gromov, and Solodukhov, 417).

1947—More Synchronicity: The Electron Synchrotron

Once McMillan and Veksler had discovered phase stability in 1945, physicists began immediately to look to synchronizing particles in a well-defined orbit using RF electric fields and magnetic fields. The first of these to come on-line was the electron synchrotron. Because we are constrained by the energy limitation imposed by the restriction

$$B\rho = \chi_m = \frac{p}{q},$$

where χ_m is the magnetic rigidity, and p/q the relativistic momentum, we faced with the choice to either increase the magnetic field or the deflection radius, ρ . The concept of a synchrotron is to synchronize a magnetic field with the energy or momentum of the accelerating particle in order to maintain a constant orbit. Particle acceleration takes place at one or more gaps around the orbit, where an RF electric field is applied with a frequency

equal to the frequency of the orbiting electrons. The orbital frequency is essentially constant for electrons of velocity approaching the speed of light. As the electron energy and momentum increases, the magnetic field ramps up to maintain a constant orbital radius. McMillan noted that the oscillatory nature of electrons crossing the RF gap slightly out of phase or energy was analogous to the 'hunting' of the armature of a synchronous electric motor, and chose the word 'synchrotron' to describe this machine (McMillan, 143).

McMillan was the first to begin construction on an electron synchrotron, at the University of California, and it came into operation in January 1949. Before his machine could be completed, however, in 1946 F. Goward and D. Barnes in England were the first to make a synchrotron work, by modifying an old betatron (Goward and Barnes, 413). The next electron synchrotron to be completed was in 1947 by the group at the General Electric Research Laboratory (GERL) that had met with great success in developing the betatron (Elder *et al.*, 810). It was at their 70 MeV synchrotron that synchrotron radiation was first observed. The next decade saw a surge in electron synchrotron construction as scientists returned home from WWII and utilized the new skills, technology, and experience they had gleaned from their wartime assignments. In areas such as radar, electronics, and nuclear physics many new technical innovations and devices were developed during the war, and these were utilized by scientists eager to return to research (Livingston, M. Stanley, 43). Livingston also notes that perhaps the most significant benefit that scientists gleaned from WWII was their increased national prestige, which allowed quick and generous financial support for research from their governments (43).

At approximately the same time McMillan started work on his accelerator at the

University of California, scientists started construction on electron synchrotrons at Massachusetts Institute of Technology, The University of Michigan, Purdue University, and Cornell University. The scientists at the GEL followed up their 70 MeV synchrotron with a 300 MeV synchrotron that used a magnetic field generated by electrical coils without an iron core. A 140 MeV synchrotron was built in Oxford, England (Axon, H.J. *et al.*, 1988). In 1954, a 350 MeV electron synchrotron was completed at the University of Glasgow which incorporated all of the improvements of preceding synchrotrons from the last 8 years (Hogg, 1979). By this time, the capability of proton synchrotrons to reach much higher energies than electron synchrotrons had been demonstrated, and research focus shifted to the acceleration of protons.

1947—The Synchrocyclotron

In 1937, H.A. Bethe and M.E. Rose at Cornell University published their observation of the relativistic limitation of cyclotrons. They noted that at energies higher than those that had been attained at the time (about 25 MeV), the relativistic change in mass of the ions accelerated either removed the ions' from resonance with the magnetic field or caused de-focusing and a subsequent decrease in beam intensity (Bethe and Rose, 1937). Thus it was that when McMillan and Veksler published their discovery of phase stability, cyclotron researchers noted immediately that it could be applied in cyclotrons to achieve higher energies than were previously thought possible. Application of McMillan

and Veksler's discovery of phase stability was applied to a cyclotron even before it was used in development of the electron synchrotron.

If the applied RF frequency could be reduced in frequency cyclically, matching the ions' decreasing revolution frequency as their mass increases, potentially higher ion energies could be reached before they fell out of resonance. In late 1945, researchers at Berkeley tested phase stability on a cyclotron for the first time using their 'old' 37 inch cyclotron magnet. They anticipated converting their 184 inch 'Crocker' cyclotron to a cyclotron utilizing this new principle, and needed some hard data to justify doing so. So, like all good engineers, they improvised.

They simulated the expected relativistic mass change in the 184 inch machine by using an exaggerated radial decrease in the magnetic field of the 37 inch magnet. They forced a decrease in orbital frequency by decreasing the magnetic field in the 37 inch further below the field at the center—by tapering the magnet pole faces radially—for a total of 13 percent decrease in the magnetic field. They used a rotating capacitor in the RF circuit to modulate the frequency, and were astonished at the results: very low 'dee' voltages were required as compared with normal cyclotron operations to accelerate the deuterons to the same energies as had been previously achieved (Richardson *et al.*, 699).

The conversion of the 184 inch cyclotron to a 'synchrocyclotron' was now justified. By early 1947, this machine was churning out 190 MeV deuterons, and 380 MeV He^{2+} ions (Brobeck *et al.*, 449). The success of this new synchrocyclotron led to immediate commencement of several others, and within a few years, machines had been constructed at Rochester, Harvard, Columbia, Chicago, Carnegie Institute of Technology, Amsterdam,

Harwell, Montreal (McGill), Uppsala, Liverpool, Geneva, and the USSR (Russia) (Livingston, M. Stanley, p. 50). Synchrocyclotrons today can accelerate protons to 1 GeV . Today, two synchrocyclotrons are in operation, one at CERN and the other at LBNL (Yee, 11).

1952—Even Higher Energies: The Proton Synchrotron

Electrons approach the speed of light at relatively low energies, and correspondingly have a nearly constant revolution frequency as their energy increases. Protons do not approach the speed of light until relatively high energies, in the GeV range. Therefore, their velocity, and hence revolution frequency increase throughout the entire acceleration period. In order to utilize the phase stability principle for a proton accelerator, the frequency of the applied RF field must increase to synchronize with the increasing revolution frequency. This increase in RF frequency is over a large spectrum, from a small value where the protons are injected to a very large value at the final acceleration gap. The rate of change of frequency must also be synchronized with the rate of change of the magnetic field. These requirements for phase stability in a proton synchrotron introduced significant engineering challenges in the design of the RF accelerating modules, and in the design of an oscillator that could handle high frequencies. Consequently, acceleration of protons in a synchrotron was not successfully performed until 1952, five years after the first electron synchrotron was in operation.

One major hurdle to be overcome was magnet design and construction. Higher energies in accelerators utilizing magnets with solid iron cores mean bigger magnets. Scientists at the University of Birmingham in England were the first to propose a proton synchrotron. They were aiming for energies of 1.0 GeV, and noted in their published design study that the bulk of the cost would be spent on a new type of magnet—ring-shaped, with a pulsed magnetic field. They began construction in 1947, and began operations at 1.0 GeV in 1953 (Oliphant, Gooden, and Hyde, 667). Meanwhile, scientists at Brookhaven and Berkeley simultaneously began work on their own proton synchrotrons. The Brookhaven ‘cosmotron’ was finished in 1952, and reached its full energy of 3.0 GeV in 1954. The Berkeley ‘bevatron’ was finished in 1954, and brought to full energy of 6.2 GeV in 1955 (Livingston, M. Stanley, 53).

The Brookhaven cosmotron was so named because the scientists were aiming for energies similar to those of the radiation bombarding the outer regions of earth’s atmosphere. Designers of this proton synchrotron recognized that magnets with a solid iron core would be prohibitively expensive, and decided to experiment with C-shaped ring magnets to produce a magnetic field over an annular region containing the vacuum chamber in which the beam would travel. The protons to be accelerated were injected by an electrostatic generator that accelerated them first to 3 MeV before injection. The magnetic field was modulated from high to low intensity at an average increase of 14 kilogauss/second, and guided the particles in a circular orbit of constant radius. The protons experienced an electric field at a single gap in the orbit, which varied with time to match the increasing angular velocity of the protons as they accelerated. The RF electric field supplied a potential across the acceleration gap of about 2400 volts at injection,

dropping to 1400 volts at the 3.0 GeV design energy. In order to keep a constant orbit radius, the tolerance allowed for the frequency of the RF oscillator was on the order of 0.3 percent (Livingston *et al.*, 7-10).

The cosmotron was the first accelerator in history to reach the GeV range of energy, and was also the first synchrotron to provide a beam of protons for experimentation outside the accelerator itself. It operated for fourteen years, and was finally dismantled in 1969.

Three other proton synchrotrons were built shortly thereafter, and relied on the design and experience of the cosmotron: the 3.0 GeV 'Saturne' in France, the 3.0 GeV 'PPA' at Princeton, and the 7 GeV 'Nimrod' at the Rutherford Laboratory in England. Proton synchrotron energies continued to increase, with a 10 GeV 'synchrophasotron' being completed in Dubna, USSR (Russia) in 1957, and a 12.5 GeV 'zero gradient synchrotron' (ZGS) at Argonne National Laboratory in 1962. The ZGS, unlike other proton synchrotrons, used bending magnets with uniform magnetic fields. Focusing in the axial direction was provided by shaping of the end faces of the magnetic sectors (Livingston, M. Stanley, 53). Other proton synchrotrons provided axial focusing with non-uniform magnetic fields, which decrease slightly with increasing radius to force particles back to the desired equilibrium orbit.

1952—A Strong Leap Ahead: Focusing the Beam

It was in this area of guide-field magnet strength in synchrotrons that the next major

advance in the science of particle accelerators would take place. Until 1952, the only technology used for focusing in the transverse plane was known as weak, or constant-gradient focusing. In weak focusing, the magnetic guide field decreases very slightly with increasing radius, and has a constant gradient around the beam pipe circumference. This gradient had a very small tolerance, and set a limit on the size of the accelerator. The beam aperture was necessarily very large, and correspondingly the magnets became very large and expensive. The energies achieved by particle accelerators had increased at nearly an exponential rate since 1930, and the highest energy baton had been held in turn by the voltage multiplier, the cyclotron, the betatron, the synchrotron, the synchrocyclotron, and the proton synchrotron. The theoretical limit, based on magnet size and cost was believed in the early 1950's to be around 10 GeV.

Such limits appear meant to be broken. In 1952, three scientists at Brookhaven National Laboratory proposed a new type of transverse focusing, which they called strong, or alternating-gradient (AG) focusing (Courant, Livingston, and Snyder, 1950). Their new focusing technique relied on a gradient magnetic field stronger on one side than the other by tilting the pole faces of the magnet. By shaping the pole faces such that a cross section had the shape of a hyperbola, they were able to achieve a uniform gradient across the magnetic aperture. Depending on the size of the gradient, particles passing through such a field will either converge (focused) or diverge (defocused). By utilizing a combination of focusing, defocusing, and field-free magnetic sectors, they discovered a way to force the beam to converge more closely.

A rough analogy from geometrical optics is appropriate here. The combined focal

length F of a pair of thin lenses of focal lengths f_1 and f_2 separated by a distance d is given by

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}.$$

If the lenses have equal and opposite focal lengths

$$f_1 = -f_2,$$

Then the combined focal length

$$F = \frac{f^2}{d}$$

will always be positive. F will remain positive over a large range of values when f_1 and f_2 are not equal, but are merely of opposite sign. Thus, within limits, a sequence of lenses of alternating focal lengths will always focus (Bryant, 4).

The alternating-gradient focusing principle is roughly similar. A basic property of magnetic fields is that a region that is focusing in one transverse plane will be defocusing in the other transverse plane. A magnetic field that is convergent in the vertical direction will be divergent in the horizontal direction. Courant, Livingston and Snyder found that a sequence of focusing, defocusing, and field-free sectors will had a net focusing effect in *both* transverse planes over a large range of gradients, magnetic sector lengths, and field strengths. When used in a circular orbit, they discovered that the frequency of the particle oscillations about the central orbit was higher, and the wavelengths were shorter than in the previous constant-gradient (weak) focusing magnets. The amplitude of particle oscillations

about the central orbit was thus correspondingly smaller, and the magnets and the synchrotron vacuum chambers could be made smaller—a savings in cost and accelerator size (Livingston, M. Stanley, 61). Magnet apertures would soon be as small as 1 or 2 inches in diameter in the new AG synchrotron to be built at Brookhaven, as opposed to the apertures within the cosmotron, which ranged from 8 to 24 inches (Adams, 305). To illustrate the impact of AG focusing on the future of accelerator design and construction, consider the vacuum chamber. Without AG focusing, it was estimated that to reach energies a factor of ten higher than the cosmotron, the Brookhaven scientists would need a vacuum chamber several yards wide and a few feet high. They would have needed 100 times the amount of steel, and it would have weighed over 200,000 tons (Courant, Livingston, and Snyder, 1191). The savings in magnet weight are also well illustrated by comparing the weight of the weak-focusing 9 GeV Dubna synchrotron magnet (36,000 tons) with that of the entire CPS synchrotron (3000 tons) (Adams, 14). It can be stated without hyperbole that the principle of AG focusing completely changed the basic design for magnets used in synchrotrons, and made economically feasible the building of synchrotrons of much higher energies.

1953—Synchrotrons Become Stronger

This new development in magnet engineering had a nearly instantaneous effect. At the time that the Brookhaven team published their research into strong focusing, a visiting

team of scientists from CERN happened to be at Brookhaven for a presentation on the Cosmotron. Immediately impressed with the potential of this new focusing technique, they worked with the Brookhaven team on a new design study for an AG proton synchrotron. This collaboration went beyond the research stages, and in 1955 both laboratories began constructing similar AG synchrotrons, and sharing all of their research and lessons learned. The design studies had suggested that energies 10 times that of the cosmotron could be reached, and five times that of the bevatron, which was still under construction. In 1959, the CERN Proton Synchrotron (CPS) was brought online, eventually reaching 28 GeV (Adams, 305).

It is useful to briefly examine the CERN CPS here. In the CPS, protons were generated by ionizing hydrogen gas, and accelerated to 500 keV in a Cockcroft-Walton generator. The proton beam was then injected into a three-stage linac, which further accelerated the particles to 50 MeV. The beam was then injected into the synchrotron, where the magnetic field of the synchrotron magnets was about 140 G at injection. With a decrease in magnetic aperture also came the tricky decrease in allowable tolerances: the alignment tolerances in the vertical and horizontal planes were less than 1 mm. 16 RF cavities around the 628 m circumference of the accelerator accelerated the protons to 28 GeV, while the magnetic field of the 100 magnets rose to 14 kG in 1 s. The field then fell to zero in 1 s, and the cycle repeated every 3 s. The beams of protons were directed to a stationary target, and the resulting secondary beams were observed. The proton beam in the CPS consisted of 20 bunches at .9993c, with a transverse beam diameter of 6 mm, and energy spread of ± 15 MeV at 28 GeV (Adams, 321-322).

Shortly thereafter, in 1960, the Brookhaven Alternating-Gradient Synchrotron (AGS) began operations at 33 GeV. In the Brookhaven AGS, protons were injected into the synchrotron in a nearly identical setup to the CPS. Protons were initially accelerated by a Cockcroft-Walton generator to 750 keV and injected into a 110-foot long linac. In the linac the protons reached 50 MeV, and were injected into the synchrotron. The AGS utilized 240 magnets, and exceeded its design energy when it reached 33 GeV. It held the record for accelerator energy until 1968, and would eventually earn its researchers 3 Nobel prizes in physics for the discovery of the J/psi particle in 1976, the first example of CP violation in 1980, and in 1988 for the 1962 discovery of the muon-neutrino (Press Releases: The 1976, 1980, and 1988 Nobel Prize in Physics). The AGS has undergone multiple upgrades since its initial construction. In 1972, a 537-foot 200 MeV linac was added as a major upgrade. It includes an ion source, a radiofrequency quadrupole (RFQ) pre-injector, and nine RF cavities. The AGS continued to increase in beam energy through multiple upgrades, and today serves as the injector for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven.

While these two AG synchrotrons would go on to get most of the attention, the first AG synchrotron was actually finished in late 1953, by R.R. Wilson at Cornell University. Construction had already begun on the Cornell synchrotron before the Brookhaven scientists had published their AG focusing study. Their magnets were intended to be of the uniform-gradient type, (weak-focusing), and when they heard of the Brookhaven developments, they rapidly designed and ordered new alternating gradient pole faces for their magnets. This machine would ultimately operate at 1 GeV (McDaniel, 1039). The same Cornell group went on to build a 10 GeV electron synchrotron using AG focusing in

1967 (Akerlof, 1482).

1946-1954—The Linac Grows Up: An Electron and Proton Linac

To move to the next major development in particle accelerators, we must once again turn to our old friend, Rolf Wideröe. As we have already discussed, Wideröe used the idea proposed by Swedish scientist G. Ising to build the first linac. His research propelled Lawrence into developing the cyclotron. David Sloan, also at Berkeley, had abandoned work on his linac once it became apparent that they could not achieve frequencies of the oscillating electric fields high enough to achieve resonance in ions of experimentally useful size. At the time, the amplifiers available for generation of the RF fields were only capable of relatively low energies, on the order of 30 MHz. At frequencies these low, only heavy ions could reach resonance, and at energies too low to produce significant nuclear disintegrations.

The advances in radar and radio technology during World War II made linac re-development possible. Ultra-high frequencies were now possible, and Berkeley once again headed the pack to build a working linac. In 1946, Luis W. Alvarez and W. K. H. Panofsky built the first proton linac capable of reaching experimentally meaningful energies. Operating at 32 MeV, it consisted of a long cylindrical cavity with 46 drift tubes of increasing length along its axis. The drift tubes were essentially cylinders with rounded ends, increasing in length and decreasing in outer diameter. Because a linac uses an oscillating electric field (instead of the static field of the Cockcroft-Walton or Van de

Graaff), the phase relationship between sequential RF cavities must be perfectly matched to allow the particles being accelerated to only see the correct half of the RF field. This is accomplished by choosing drift tube lengths such that the residence time of the particles is equal to one half of the RF period. This can be shown with the length L_i of the i th tube satisfying

$$L_i \approx \frac{1}{2} v_i T_{rf},$$

Where T_{rf} is the RF period.

Protons were injected into the Alvarez linac at 4 MeV from a Van de Graaff generator, and accelerated to 32 MeV. The design of the Alvarez proton linac has become the starting point of nearly every proton linac since then, and today proton linacs of essentially the same design are used as injectors for many proton and heavy-ion synchrotrons around the world.

Electron linacs largely stem from the research of W. W. Hansen at Stanford University, which began in the 1930's. But why build an electron linac when the proton linac works perfectly well? The reader will recall that accelerating structures such as the proton synchrotron were already operating in the GeV range at this point, and there looked to be no theoretical limit yet on the energies that could be reached with larger and larger machines. Thus it was that the designers of proton linacs in the 1940's believed that the high energy research would be carried out by other, larger accelerators. This was not so with the acceleration of electrons. Synchrotron radiation becomes much more significant for electrons in a circular orbit at a given energy than for the much more massive protons.

For protons, the energy loss due to synchrotron radiation can be made up for by increasing the energy added at each accelerating gap. For electrons, however, the energy loss is much greater and the replacement of energy quickly becomes impractical above energies of 10 GeV (Dupen, 36). Thus it was that Hansen turned his attention to developing an electron accelerator without any circular orbits—the electron linac.

The accelerating structures for electron linacs are very different from those of proton linacs. Because electrons approach the speed of light at much lower energies than protons, the beam apertures may be smaller in an electron linac, and the resonant frequencies higher (due to the higher velocities being reached more quickly). Hansen was initially interested in finding a source of high-voltage electrons for use in x-ray production, but put linac research on hold in the 1930's when it became apparent that useful x-ray energies could not be obtained with the technology available at the time—specifically, RF sources with high enough power and frequency had not been developed. Hansen's initial ideas centered on the possibility of using a single cavity resonator for single-stage acceleration of electrons, but he quickly realized that he couldn't produce the power needed for such an accelerator. It wasn't until after the war, in 1947, that his team picked up linac research again with some promising new technology from the British developed during the war—the magnetron used to supply power to large radars. They built a small, 12-foot electron linac (the Stanford Mark I) which produced 6 MeV electrons (Chodorow, 131).

Further research indicated that a more promising power source capable of high frequencies was the klystron, developed by Hansen in 1939. Hansen and the other scientists at Stanford realized that if they were to build a machine capable of carrying out

research on the same scale as the recently developed betatron (by Kerst, in 1938), they would need much higher power sources than the 1 MW magnetron used in the Mark I. They resolved to build a 1.0 GeV electron linac.

In 1949, they developed and tested a klystron RF amplifier capable of more than 20 MW, and tested it on a new 14 foot linac dubbed the Mark II (Post and Shiren, 205). This linac consisted of a 14 foot cylindrical wave guide with seven two-foot subsections. Each section was constructed of 1.8-inch brass tubing periodically 'loaded' with brass irises with a diameter of 3.263 inches, and a central hole diameter of 0.872 inches. The RF electric field was powered by the klystron in pulses of 2 μ sec. The Mark II ended up producing electrons of 35 MeV in its testing phase, before being replaced by the Mark III (Post and Shiren, 206). The construction of the 1.0 GeV linac was completed in 1952, and it reached 630 MeV by 1954. It utilized 21 klystron RF amplifiers, each delivering between 10-20 MW of power in 2 μ sec pulses. The amplifiers each provided power to 21 separate 10 foot sections containing a cylindrical wave guide, similar in construct to the Mark II wave guide. Stanford's experience with the Mark I, II, and III would soon culminate in the groundbreaking of a new electron linac that is in operation today, and would eventually earn its researchers 3 Nobel prizes.

1966—Stanford Gets Serious About the Linac: SLAC

The resounding success of the Mark III linac at Stanford led its researchers to

immediately plan for a new electron linac capable of multi-GeV. It was no simple task to procure funding for a linac that was estimated to cost \$114M to build, and Stanford researchers wrote proposals and lobbied for its construction from 1957-1961. After congressional hearings on the funding, President Eisenhower announced in a speech in May 1959,

“I am recommending that the Congress of the Federal Government finance the construction, as a national facility, of a large, new, electron linear accelerator. Physicists consider the project—which has been sponsored by Stanford University—to be of vital importance. Because of the cost, such a project must become a Federal responsibility (Dupen, 57)”.

Ground was broken on the Stanford Linear Accelerator Center (SLAC) in July 1962. Design plans called for a 2 mile long linac, buried 25 feet underground for the purposes of radiation shielding. Unlike the previous linacs, the researchers calculated it would be prohibitively expensive to shield the linac in a concrete bunker, and decided instead cover the beamline with 25 feet of compacted fill to lower any radiation doses from activated components and ionizing radiation (Dupen, 60).

The basic design of the SLAC in 1962 (“Stage I”) consisted of 240 modules of 40 feet in length. Each module had RF power applied to it by a high-power klystron amplifier, producing short pulses of up to 24 MW at 2.856 GHz. The beam was contained in a 4-inch diameter tube consisting of over 80,000 copper cylinders interspersed with over 80,000 copper disks (Dupen, 86). Injection was designed to occur from a tungsten electron gun, where electrons would emerge at 80 keV and be sent to a prebuncher. The prebuncher

would perform an initial ‘rough’ bunching of the electrons, and send the electrons on to the final buncher after which they would emerge at 30 MeV and enter the linac.

Degaussing coils were used along the 2-mile long facility to compensate for electron irregularities due to the earth’s magnetic field and fields generated by the various mechanical and electrical sources. Each sector of the linac was surrounded by a set of vertical and horizontal coils with a small degaussing current to compensate for beam deviations. At the end of each sector was also located a 10 foot drift containing a focusing lens, a set of steering magnets, and monitors to provide information on any horizontal and vertical displacement of the passing electron beam (Dupen, 100).

Once the beam exited the linac beamline, it entered a 1000-foot long ‘beam switchyard’. Inside the switchyard, electromagnets steer the beam into the desired experimental area inside one of two target buildings—End Station A and End Station B. Due to the radiation produced by curving the electron beam, the switchyard is further shielded by 40 feet of earth and concrete. The SLAC was completed in December 1956, and reached a beam energy of 18.4 GeV in June of 1966. Research at SLAC from 1966 to 1972 consisted solely of fixed-target experiments with the electron beam. In 1990, three SLAC researchers were awarded the Nobel Prize in Physics for their work during this period that led to the discovery of quarks.

The SLAC beamline has undergone numerous upgrades since initial operation. In 1972, a collider ring of 80 meters diameter was added in which counter-rotating beams of electrons and positrons were circulated. Called the Stanford Positron Electron Accelerating Ring (SPEAR), it yielded a number of noteworthy contributions to scientific discovery. In

1974, the J/psi particle was discovered by Burton Richter, for which he received the 1976 Nobel Prize in Physics. In 1976, Martin Perl discovered the tau lepton, and shared the 1995 Nobel Prize in Physics for its discovery. SPEAR circulated electrons and positrons at beam energies up to 4 GeV. Dipole magnets steered the particles injected from the SLAC around the ring, and energy lost by synchrotron radiation was restored as they passed through an RF accelerating cavity. In 1973, SPEAR researchers realized that the huge amounts of synchrotron radiation released by the beams might be put to good use in experiments, and the Stanford Synchrotron Radiation Laboratory (SSRL) was created. Originally, research at the SSRL was a useful by-product of the SPEAR work, but eventually the SPEAR ring became fully dedicated to SSRL research. Today, the SSRL is actively providing a research platform for chemists, biologists, medical doctors, and physicists.

The next upgrade to the SLAC beamline began in 1983. Desiring to achieve energies in the vicinity of 50 GeV, researchers at SLAC began construction on a linear collider. Finished in 1989, and called the Stanford Linear Collider (SLC), it was intended for two purposes: (1) to be a test platform for a larger, more powerful linear collider (the 'Next Linear Collider', or NLC), and (2) to provide collisions of beams at energies high enough to produce the Z boson in sufficient quantities for useful research. The SLC consisted of upgrades to the SLAC beamline to allow for production of 50 GeV beams of both electrons and positrons, and two curving extensions of bending magnets added to the end of the SLAC to transport the colliding beams to the collision point. Two storage rings were added near the start of the SLAC to 'damp', or re-bunch the electrons and positrons

once they reached 10 MeV.

Linacs are in operation today in many major research laboratories around the world. Proton linacs currently in operation include the 200 MeV linacs at Brookhaven and Fermilab, and the 50 MeV linacs at KEK (Japan) and CERN (Lee, 8). Major electron linacs include the 500 MeV linac at MIT (Bates), the 50 GeV SLAC linac, and the 8 GeV KEK-B linac.

1960—The Storage Ring Collider

The next major step in accelerator development is the development of the storage ring, and the subsequent move of research away from fixed targets to the colliding of beams. The total reaction energy (as a fraction of the initial beam energy) that can be obtained from having a particle smash into a stationary target is much less than the reaction energy available when two beams collide at an interaction point. The earliest recorded writing on what this might mean for particle accelerators was by one Rolf Wideröe in 1943. Wideröe explained in a letter to a Eduardo Amaldi that the idea came to him when he realized that in the non-relativistic case (for example, two automobiles colliding) two particles of equal energy which collide could dissipate four times as much energy as one particle of the same energy colliding with a particle of similar mass at rest (Amaldi, 16). It is a simple matter to apply these fundamentals of the conservation of energy and momentum to the case of colliding beams (if we limit our interest to non-relativistic

energies), and note that two beams of equal energy will have twice the energy of a single beam colliding with a fixed target, but will cause four times the reaction energy. In May 1953, Wideröe obtained a patent for his idea for proton-proton collisions, proton-deuteron collisions, and electron-proton collisions (Richter, 2). Wideröe's idea was purely conceptual in nature. Because he was working in industry at the time and had very little contact with the research community, nothing came of his idea.

It would fall to another well-known name in the history of particle accelerators to publish the idea and get the wheels rolling. In 1956, D.W. Kerst *et al.* published a paper on attaining higher reaction energies by colliding beams of particles (Kerst *et al.*, 590). Kerst realized that in the relativistic case of beam energies, the reaction energy advantage of colliding beams over a fixed-target was much greater than the factor of four in Wideröe's non-relativistic example. Kerst and his colleagues estimated that colliding two 21.6 GeV AG synchrotron proton beams would have a reaction energy equivalent to that of a single 1000 GeV AG synchrotron with a fixed target (Kerst *et al.*, 590). At the CERN Accelerator Conference later that year, G.K. O'Neill of Princeton University complemented Kerst's presentation on colliding beams with his introduction of the idea of a storage ring for accelerators (CERN, 36).

O'Neill proposed to add two storage rings to any proton synchrotron. The protons would be accelerated inside the synchrotron, and then transferred into the storage rings where they would collide in a common straight section. He estimated that the storage rings would add little to the cost of the accelerator, as the accelerated beams would require a smaller beam pipe in a storage ring once they were accelerated, and the bending magnets

could correspondingly have a much smaller cross-section. O'Neill noted, 'If storage rings could be added to the 25 GeV machines now being built at Brookhaven and Geneva, these machines would have equivalent energy of 1340 GeV or 1.3 TeV" (CERN, 36). It is important here to note that a storage ring is not a 'proper' accelerator—it does not accelerate the particles, but rather provides a machine in which particles previously accelerated by another type of accelerator (a synchrotron, for example) can orbit in storage until it is desirable to extract them for an experiment.

It would only be a matter of a few years before these ideas were turned into plans, and the plans resulted in actual machines being constructed. In 1958, the Office of Naval Research (ONR) provided an \$800,000 grant to a group of four scientists at what was then called Stanford High Energy Physics Laboratory (HEPL). These scientists planned to add two electron storage rings to the existing 700-MeV Mark III electron linac at HEPL. This addition, dubbed 'CBX', would consist of two storage rings of 12 meter circumference, with a common straight section for colliding beam experiments (Barber, W.C. *et al.*, II.2). It would be weak focusing. At the same time, scientists at the Budker's Institute for Nuclear Physics in Novosibirsk began work on a pair of storage rings to collide electrons of 140 MeV, known as VEP-1 (Rees, 4).

The research that went into designing and building the CBX storage rings was groundbreaking on numerous fronts. One example is their addition of electrostatic fields to 'clear' any ions that happened to get trapped in the orbiting electron beams. The designers built these fields into the rings believing they might be needed, and they found that they were very important after the first beams were circulated. Another example is their

addition of correctors to reduce the changes in betatron frequency with energy inside the stored beam. This allowed the betatron motion, or chromaticity, to be reduced to zero. As one of the major design considerations in a storage ring is maintaining the orbiting particles contained in a tight space over large numbers of turns, this reduction in chromatic effects turned out to be a vital part of all future storage rings (Richter, 5).

The early start of the researchers at Stanford encouraged other research laboratories to begin thinking seriously about building storage ring colliders. The CBX storage rings were not completed and operational until 1962, and in the meantime an Italian research team would beat out Stanford as the first to build an electron storage ring. In 1960, a team of researchers led by Bruno Touschek built an electron-positron (e^+e^-) storage ring dubbed AdA (Anelli di Accumulazione) at Frascati, Italy. Like the CBX, it was also weak focusing. It was the first electron (and positron) storage ring, but had a very limited research value due to its small size. It consisted of a toroidal vacuum chamber of 1 meter diameter. Electrons and positrons were injected by physically placing the toroid in front of a beam of gammas. An internal fixed target produced the electron and positrons which were trapped in the vacuum chamber (Bryant, 15). As one might imagine, the machine had a very low efficiency of injection, circulating beam current, and luminosity. In 1961, the AdA was moved to the linac at the Laboratoire de l'Accelérateur Lineaire (LAL) in Orsay, France, and became the first e^+e^- collider (Lee, 13).

It is interesting to note here that these first three storage rings were weak focusing, and did not make use of the newly available theory of strong focusing. It is worth noting here that the research community's desire to develop this new colliding storage ring

concept quickly led them to not ‘push the envelope’ of accelerator technology in their first efforts, but to just get these first few machines started to see if there was anything to the concept. Researchers knew that they would encounter as-yet unheard of design challenges, and wanted to minimize the number of new design variables they would face (Rees, 5).

During these first few years of storage ring construction, many other storage rings were added on to existing electron accelerators for the purposes of colliding beams. A few of these follow. The ADONE (for ‘big AdA’) storage ring at Frascati, completed in 1967 would eventually collide 3 GeV e^+e^- beams with a record luminosity of $6 \times 10^{29} \text{ cm}^{-2}\text{sec}^{-1}$, and a tune shift of 0.06 (Rees, 7). The Cambridge Electron Accelerator (CEA) in Cambridge, Massachusetts actually turned their synchrotron into a storage ring. They designed a ‘bypass’ that switched the orbiting beams of low energy into a section of the synchrotron on a parallel path to the synchrotron itself. It was incredibly complex. Operational by 1973, it would eventually collide e^+e^- beams of 2.5 GeV each (Richter, 10).

1969—CERN Enters the Collider Age

As mentioned previously, the first studies into the possibilities of storage ring colliders were aimed at proton colliders. There were many things as yet not understood, however, about design issues such as injection, stacking, and the effects of non-linear resonances, and so the first colliders to be built were electron colliders (Richter, 12). It was in Europe that the first proton-proton beam collisions would take place. In 1969, physicists

at CERN had studied the idea of building two intersecting storage rings that could be fed by the existing 28 GeV proton synchrotron (CERN-PS). Construction took place on the new Intersecting Storage Rings (ISR) between 1966 and 1971 (Johnsen, 620).

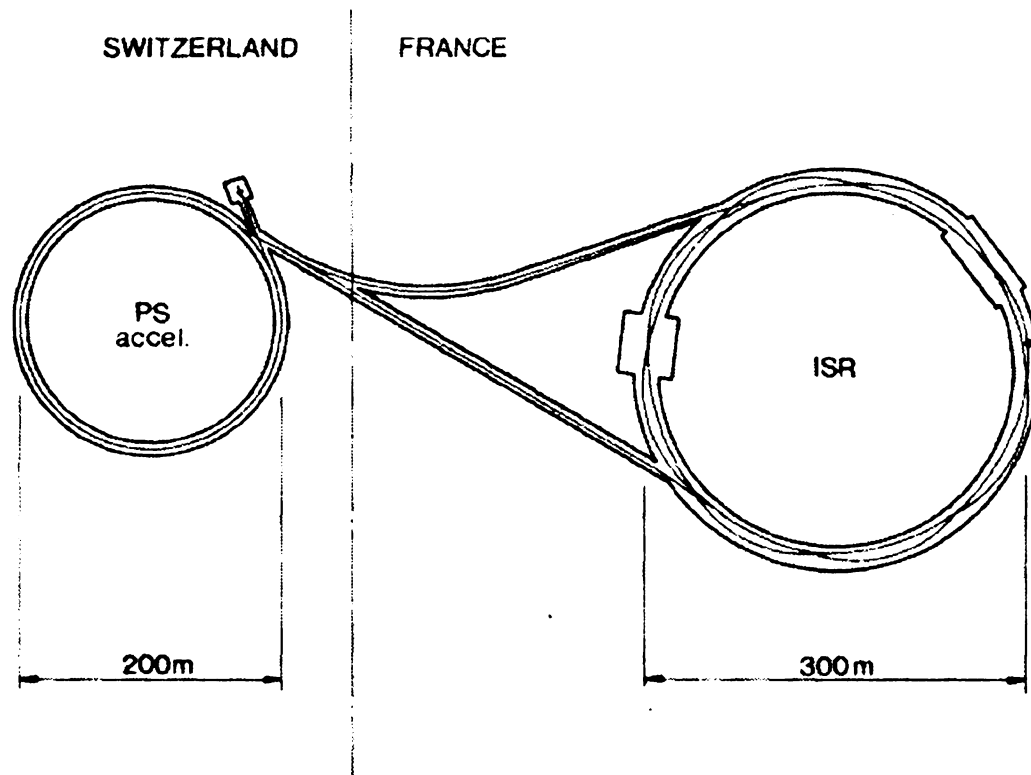


Figure 9: Layout of the ISR (Johnsen, K., 620).

They consisted of two concentric rings of magnets, 300 m in diameter. Located in an underground tunnel 200 m away from the 28 GeV proton synchrotron, the injected protons traveled in opposite directions. The two rings are not perfectly circular, and are interwoven with 8 intersection regions where the beams can be brought to collide. The ISR design aimed for a luminosity of $4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, with each of the two orbiting beams containing approximately 4×10^{14} protons, which is the equivalent of about 20 A circulating current

(Johnsen, 620). To achieve this, it was necessary to stack multiple successive pulses from the CERN-PS next to each other.

To accomplish this, an RF system was designed to move successive pulses from their initial injection orbit to an orbit closer to the vacuum chamber wall. For instance, the RF system accelerates the injected protons just enough to move them from their injection orbit to an orbit closer to the outside of the vacuum chamber. When this acceleration has been accomplished, the injection orbit is clear to receive another injection pulse, which in turn is accelerated and moved to an orbit a fraction of a millimeter from where the last pulse was left. Johnsen notes that this 'stacking' could be repeated 400 times in each ring, with the end result being a stacked beam about 70 mm wide, with a momentum spread of 2% across the beam. The protons were able to then continue their orbit for as long as 36 hours while collision experiments take place before new injection was necessary (620).

Experiments at the ISR took place at all eight of the intersection regions until 1984, when it was shut down. Beam energies for collision were standardized at 11.5, 15, 22, and 26 GeV. Injected beams were also capable of acceleration inside the ISR, and experiments were run with beam energies of 31.4 GeV (Johnsen, 625).

1970—Germany Joins the Collider Age

In the 1960's, the Deutsches Elektronen-Synchrotron (DESY) laboratory in Hamburg, Germany was conducting experiments with their 6-GeV electron synchrotron.

As they looked to the future of the DESY synchrotron, there were two camps: one for increasing the energy of the synchrotron and conducting experiments with the higher energies, and the other looked to the promising new idea of the collider, and wished to build an e^+e^- collider. They were at an impasse. After spending some time with the SLAC scientists involved with the building of Stanford's CBX storage rings, the collider camp was able to successfully lobby for the funds needed to build what became DORIS (Doppel-Ring Speicher), a 3-GeV two ring e^+e^- collider. The double-ring configuration of DORIS led to beam instabilities that hampered the performance of experiments, but led to a much greater understanding of these types of beam instabilities in future colliders (Richter, 11).

The next step for the DESY lab would prove to be a groundbreaking one. In the fall of 1978, work was completed on PETRA (Positron Electron Tandem Ring Accelerator), then the world's highest-energy e^+e^- collider at 22 GeV (Richter, 11). The main ring had a circumference of 2300 meters, with 8 straight sections. Two of the sections were RF accelerating cavities, and the other six used for experimental areas. Acceleration and injection of electrons was via a linac, after which they were injected into the original DESY synchrotron, and further accelerated to 6 GeV before they were injected into the PETRA ring. Positrons were accelerated first in a linac, then injected via DESY into DORIS, where they were accelerated to 2.2 GeV and stored as bunches. The bunches were then transferred back to DESY for acceleration to 6 GeV, and then injected into PETRA. In 1979, DORIS was taken out of the positron injection loop, and a positron injection accumulator (PIA) was constructed in its place to store and compress bunches received from the positron linac (Duinker, 325).

PETRA would eventually reach 37 GeV, and operate successfully as a collider until 1986, when it was rebuilt as an injection ring for HERA in 1988 (PETRA II). In 1995, it began to divide its time between acting as a pre-injector for HERA, and acting as a synchrotron radiation facility (PETRA III).

The world had several e^+e^- colliders before the first e^-p collider. The idea for an electron-proton collider was first proposed by C. Pellegrini at an accelerator conference in 1971 (Pellegrini, 1039). Four proposals immediately followed from SLAC, KEK, the Rutherford Laboratory, and Frascati. Two were never built, and the other two built electron-positron colliders instead when it became apparent that the superconducting magnets necessary for the proton ring would require huge amounts of funding and experience with superconductors they did not have.

It was DESY's moment. The first electron-proton collider was built at DESY, using the existing DESY, DORIS, and PETRA accelerators to act as injectors for the new collider. Commenced in 1984, and completed in 1990, HERA (Hadron Electron Ring Accelerator) consisted of two separate storage rings built on top of each other, with a circumference of 6.3 km. The rings were built in tunnels drilled between 10 and 25 meters under ground, of six meters in diameter. The tunnels were dug under existing neighborhoods and businesses around the DESY site at Hamburg using a drill dubbed HERAKLES. This civil engineering feat was the first use of this method of tunnel drilling for a particle accelerator, and it set the stage for future collider tunnels to be built under pre-existing residential and commercial areas.

The proton ring was built with 650 superconducting dipole and quadrupole bending

magnets, which require cooling by a cryogenic helium cooling system to keep them at a nominal temperature of -269 C. The construction and use of superconducting magnets on such an enormous scale was a first in a particle accelerator, and DESY's use of superconducting technology would provide a model for future accelerators. HERA operates today by accelerating protons to 820 GeV and electrons to 30 GeV.

1981—The First Proton-Antiproton Colliders: CERN and FNAL

The first published discussion of the idea of a proton-antiproton ($p\bar{p}$) collider was in a talk by G.I. Budker (of the Institute of Nuclear Physics at Novosibirsk, Russia) at a 1966 Saclay storage ring conference (Budker). In it he included an outline of the ring design and a short description of a damping technique that could be used to allow the accumulation of a large quantity of antiprotons in a phase space small enough to provide a luminosity sufficient for experiments. A major hurdle to be overcome in a $p\bar{p}$ collider is the need for a damping mechanism to decrease the velocity spread of the proton (antiproton) beam. Budker proposed a method to perform this 'cooling' of the beam via a process that would eventually be called 'electron cooling' (Richter, 13). His idea was to co-stream a beam of electrons of small transverse and longitudinal velocity spread with a proton beam of much larger velocity spread. The electrons would exchange momentum with the protons via coulomb interaction, and thus 'cool' the proton beam—just like a heat

exchanger. For a number of reasons, the collider under construction at Novosibirsk never became a $p\bar{p}$ collider, and instead was converted to an e^+e^- collider (VEPP IV), and this method of electron cooling never took off. Because antiprotons (or protons) are almost 2000 times heavier than a positron (or electron), it was a unique challenge to collect and store them in a circulating beam.

The next step towards a $p\bar{p}$ collider was the invention in 1968 by Simon van der Meer at CERN of another method of beam cooling—stochastic cooling. Called stochastic cooling because of the stochastic nature of beams, in short it uses an active electronic feedback system to sense density fluctuations in the beam and damp them out (van der Meer). This had a greater potential advantage over electron cooling, as the rate of stochastic cooling is independent of energy, while the rate of electron cooling decreased as the 5th power of beam energy (Richter, 13).

On June 17, 1976 the new proton synchrotron at CERN, the SPS (Super Proton Synchrotron), was completed and reached its design energy of 400 GeV (100 GeV more than its design energy). Fermilab's (FNAL's) Main Ring, also a proton synchrotron, had reached 500 GeV (300 GeV more than its design energy) only a month before (Richter, 14). Enter Dr. Carlo Rubbia, an Italian physicist, who decided he was just the sort of man to discover the as-yet-undiscovered W and Z particles that would validate the Standard Model of particle physics. He decided he needed a $p\bar{p}$ collider in order to do so. Both FNAL and CERN were looking at the possibility of upgrading their existing synchrotrons to accelerate and collide protons and antiprotons, but FNAL was not enthusiastic about any sudden upgrade plans, as they were in the design phase of a new collider (what would

eventually become the Tevatron), and in the middle of upgrading the existing Main Ring.

Dr. Rubbia proposed to CERN an outlandish idea: convert the existing, and already successful SPS fixed-target accelerator into a $p\bar{p}$ collider. CERN decided to give it a go, and in 1981, the SPS (renamed the $S\bar{p}\bar{p}S$) collider provided its first collisions (Wilson, T.) It was there, two years later, that Rubbia's team discovered the elusive W and Z particles, for which he shared the 1984 Nobel Prize in Physics with Simon van der Meer. The $S\bar{p}\bar{p}S$ collider operated until 1989 when it was modified to also serve as an injector for CERN's new e^+e^- collider (LEP).

1981—CERN Gets Into the Electron-Positron Business

In 1979, CERN performed a study for an electron-positron collider of approximately 30 km in circumference, and an energy of 70 GeV per beam (Myers, 1). It was intended that when the technology for superconducting RF cavities became available, the beam energies could be increased to 100 GeV apiece. Work commenced on 1983 on what would be the largest civil-engineering project in Europe for years. The Main Ring tunnel was dug over this time, with a circumference of 26.7 km. Overall, 1.4 million m^3 of earth and rock were excavated for the new Large Electron-Positron collider (LEP)—from the Main Ring tunnel, as well as four huge experimental caverns, 18 pits, and 3 km of secondary tunnels. Through the use of a geodesic network established between the hills surrounding the site, and base lines established by a laser interferometer (a Terrameter), the

tunnel circumference was dug with a deviation of less than 1 cm in 26.67 km (Myers, 3).

On September 20, 1989, the first beams at LEP were injected, stored, and collided. It is worth noting the basic setup of LEP here—approximately three quarters of the 26.7 km circumference is made of ‘standard cells’, which are composed of magnets in the following order: a defocusing quadrupole, a vertical orbit corrector, a group of six bending dipoles, a focusing sextupole, a focusing quadrupole, a horizontal orbit corrector, another group of six bending dipoles, and a defocusing sextupole. Each standard cell is 79.11 m in length (Myers, 3). The electrons and positrons are bent in a circular trajectory via each standard cell’s groups of dipoles, which have a low field of about 0.1 T in order to increase the bending radius and correspondingly decrease the level of synchrotron radiation. The quads act as magnetic lenses and allow the beam to be contained within the vacuum chamber. Because the quads are of alternating polarity, they provide strong (AGS) focusing for the beam. The sextupoles reduce the chromaticity of the beam by producing a quadratic field (in transverse displacement) that compensates the dependence of the focusing strength on beam energy.

The LEP storage ring is preceded by four accelerators, each of which accelerates the electrons and positrons generated by their source: an electron gun and positron converter (Myers, 8). Two linacs start off the process necessary to ‘fill’ the LEP collider: one of 200 MeV and the other of 600 MeV, followed by a 600 MeV Electron-Positron Accumulator (EPA). The EPA then injects the e^+e^- beams into the CERN Proton Synchrotron (PS), which further accelerates them to 3.5 GeV, and injects into the SPS, which fills the LEP with beams of 20 GeV. An interesting engineering feat at CERN was

the modification of the SPS to accept electrons and positrons from the PS, while still operating as a proton synchrotron. Collisions between electrons and positrons take place at four equidistant interaction points where the experiments are housed.

It is worth a pause here to discuss the upgrade of the LEP to producing beams of 100 GeV each. As part of the original design study in the late 1970's, designers had anticipated the availability of superconducting RF cavities after the LEP began operation, and planned for their future insertion. The advantages of using superconducting magnets (near zero energy loss due to the vanishing electrical resistance of coils) are not the same as using superconducting RF cavities in place of normal RF accelerating cavities. Although the heat load in the cavities is several orders of magnitude smaller than in traditional copper cavities, heat losses still place another load on the refrigeration system necessary for maintaining the superconducting cavities at the low temperatures required for superconductivity (2 K in the LEP). Schmüser, in his article on RF superconductivity notes that a good rule of thumb is 1 W of heat deposited at 2 K requires approximately 1 kW additional power from the cryogenic plant (2). In spite of this heat load on the cryogenic plant, the overall electrical efficiency of converting electric power to beam power is a factor of 2 higher for a superconducting RF cavity than for a normal one (2).

Superconducting RF cavities also have a lower resonant frequency than normal RF cavities. Because the transverse wake fields generated by the bunches traveling through the cavities increase with the square of the frequency, another advantage of using superconducting RF cavities is the smaller wake fields and hence increased beam emittance and luminosity (Schmüser, 2). The LEP was upgraded with superconducting RF cavities in

1997, and was able to produce beams at 102 GeV each shortly after. Other accelerators around the world began to look seriously at superconductivity about the same time: CEBAF (a CW electron-recirculating linac) at JLAB was able to increase its beam energy from 4.0 to 5.5 GeV after a conversion to superconducting RF cavities, ATLAS (a heavy-ion accelerator) at Argonne, Cornell's CESR (e^+e^- collider) and several others have also converted and seen an increase in beam power.

LEP was shut down in November 2000, after a very successful lifespan, and underwent modifications to become the newest CERN collider: the LHC.

1983—Illinois Builds a Big Collider: The Tevatron

To examine the start of the accelerator that currently wears the mantle of the world's most powerful collider, we must go back in time to Carlos Rubbia's desire to build a $p\bar{p}$ collider capable of W and Z particle production. At the time, FNAL was in the middle of completing an upgrade to their successful Main Ring, their 500 GeV proton synchrotron. The director of FNAL at the time, Leon Lederman (credited with discovery of the bottom quark in 1977) decided to complete the upgrade to the Main Ring before starting on a new $p\bar{p}$ collider, a decision by which he knowingly passed the torch to CERN for development of the first $p\bar{p}$ collider. He believed that experiments conducted with a higher-energy $p\bar{p}$ collider planned by FNAL after completion of the Main Ring upgrade would be of greater utility than abandoning their current plans (Tollestrup, 3).

The Tevatron was constructed in the same tunnel as the Main Ring, an efficient engineering practice that CERN would follow with their future construction of the Large Hadron Collider (LHC) in the existing LEP tunnel. The Tevatron was designed to operate in two modes: as a $p\bar{p}$ collider, and to also accelerate proton beams for fixed-target experiments. In February of 1987, the Tevatron had its first $p\bar{p}$ collider physics run at its design energy: collisions of $p\bar{p}$ beams of 900 GeV. The resulting center of mass collision energy of 1.8 TeV made the Tevatron the highest energy particle accelerator in the world, a title it bears today and will keep until the commissioning of the LHC at CERN in 2007.

Protons and antiprotons to be injected into the Tevatron are born in different areas. The new Main Injector, commissioned in 1999 is a $p\bar{p}$ injector for the Tevatron itself, but also feeds an antiproton source with 120 GeV protons sent in bunches of 5×10^{12} protons every 2.4 sec. The antiproton source consists of an external nickel target followed by a lithium lens operating at 760 T/m, and a Debuncher and Accumulator where the antiprotons are collected, stored, and stochastically cooled. When the stacking lattice of the Accumulator reaches around $100\text{-}150 \times 10^{10}$ antiprotons, they are extracted and injected into the Main Injector at 8.9 GeV. The Main Injector then accelerates them to 150 GeV via its 53 MHz RF cavities and sends them to the Tevatron (Mishra, 3).

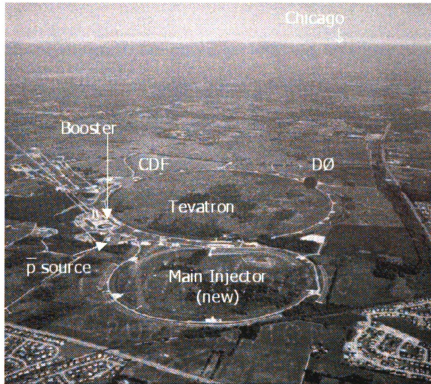


Figure 10: Aerial view of Fermilab's accelerator complex (<http://www-d0.fnal.gov/Run2Physics/displays/presentations/>).

The proton source begins with a Cockcroft-Walton accelerator where hydrogen ions are accelerated to 750 keV. They then enter the Linac, where they are further accelerated to 400 MeV, and passed through a stripping carbon foil. The resulting proton beam is injected into the Booster synchrotron, where it is accelerated to 8.9 GeV in 33 msec and organized into smaller bunches for injection into the Main Injector via a transfer line built with permanent magnets. The Main Injector alternately accelerates protons and antiprotons to 150 GeV for injection directly into the Tevatron, and also sends the aforementioned 120 GeV proton beam to the antiproton production target (Mishra, 1).

The Tevatron accelerator is a synchrotron utilizing both superconducting RF cavities and warm iron superconducting magnets. Of 2 km diameter, it utilizes dipoles of

4.5 T field strength to circulate protons and antiprotons in the same beam pipe. When operated in colliding mode, collisions occur between beams at the center of two particle detectors: The CDF (Collider Detector Facility at Fermilab) and the D0. The utility of waiting to build the Tevatron was realized in 1995, when the top quark, the last remaining of the six quarks predicted by the Standard Model, was discovered by scientists at both detector experiments (Fermilab News Release, March 2, 1995). The magnet cells in the Tevatron consists of a standard FODO (focusing-drift-defocusing-drift) cell sequence, and utilize superconducting quadrupoles and dipole magnets with NbTi coils (Theilacker, 139).

The superconducting technology and cryogenic plant used in the Tevatron is worth mentioning briefly. The Tevatron was the first major accelerator to make use of superconducting technology in both its RF accelerating cavities and magnet technology, and has reaped the benefits of increased beam energies at a lower input power because of it. The cryogenic plant required to maintain the low 4 K temperature required by the superconductors became the world's largest helium refrigeration system after its installation. It is a hybrid system consisting of a central helium liquefier and 24 satellite refrigerators of 1 kW capacity, each of which cools two 125 m long sequences of magnets.

1993—Everything is Bigger in Texas-The SSC

In 1985, the soon-to-be-built Superconducting Super Collider (SSC) was the talk of the scientific world, and was capturing headlines in newspapers and magazines around the

country. Estimated to cost over six billion dollars, it would have an annual operating budget of \$200 million. Where to build it was a decision made by the U.S. Department of Energy (DOE) after intensive lobbying and political maneuvering by over 100 separate locations who eagerly desired it to be built in their area (Begley, 82). Eventually settling on a site of rolling prairie and hills in Ellis County, Texas, construction on the proton-proton collider with a circumference of 87 kilometers began in January 1991. On October 21, 1993, the House-Senate conference committee with oversight on the SSC decided to take the \$640 million requested by the DOE to continue work for another year and make it a final payment on the project, rather than a yearly installment on the now \$11 billion machine (Roush, 532). With no other advance warning than the decision of the conference committee, the SSC was canceled.

The SSC was designed to be a proton-proton collider accelerating 2 proton beams to 20 TeV each, with a design luminosity of $1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. Injection into the SSC was to have begun in the 110 m Linac, where they would have been accelerated to 0.6 GeV. Three booster synchrotrons were to follow the Linac: the Low Energy Booster (11.1 GeV), Medium Energy Booster (180-200 GeV), and High Energy Booster (2.0 TeV), with planned circumferences of 500 m, 4 km, and 11 km respectively. The collider would consist of magnet half-cells of five dipoles and one quadrupole, all superconducting magnets. Both the dipoles and quadrupoles were to have operating fields of 6.6 T with gradients of 206 T/m. The superconductors were NbTi filament, and would have been maintained at 4.35 K by the SSC's cryogenic plant—which, if constructed, would have been the world's largest refrigeration plant. Overall, each of the two SSC rings was

designed to have 4,230 dipoles, and 832 quadrupoles—for a total of 10,124 superconducting magnets (Grinstein).

The SSC was built to look for particle physics phenomena that could only be observed in collisions at energies higher than current accelerators were capable of achieving. Scientists hoped to find evidence for the Higgs boson, supersymmetric partners of standard particles, technicolor resonances, new gauge bosons and a host of other new discoveries. It was not to be, at least with the SSC. This thesis is not the arena for such an discussion, but the failure of the SSC project is at least partly explained by the budget deficits of the 1990's, and budget-cutting mentality of the U.S. Congress at the time (Roush, 532).

2000—Heavy Ion Colliders: RHIC and the LHC

In 2000, two physicists at CERN evaluated the results of 15 years of experimentation with the fixed-target heavy ion (lead) beams of the SPS (Jacob and Heinz, February 2000 CERN Announcement) They concluded that as a result of their ground-breaking experiments (which were the highest-energy collisions of heavy ions to date), a 'multitude' of separate observations had given results they could not explain by anything other than a new state of matter predicted by the relatively new theory of quantum chromodynamics (QCD). In brief, QCD predicts the existence of a form of matter at extremely high energy densities, consisting of a volume of quarks, antiquarks, and gluons.

Known as the quark-gluon plasma (QGP), it is of temperatures and densities much higher than anything in the current universe, and believed to have existed only in the few microseconds after the Big Bang. Jacob and Heinz noted that they couldn't break any new ground at the energies they were limited to with the SPS, but were confident that more conclusive evidence for the QGP would be found with the new heavy colliders planned at Brookhaven and CERN (February 2000 CERN Announcement).

Enter Brookhaven's Relativistic Heavy Ion Collider (RHIC). Commissioned in 2000, RHIC was designed to accelerate and collide heavy ions, with the capability of colliding lighter ions all the way down to protons. Acceleration of heavy ions such as gold presents a unique design challenge in the design of beam focusing. For example, the Coulomb repulsion between beam particles (known as intrabeam scattering) is proportional to Z^4 / A^2 , and hence much stronger for gold ions than for protons. The beam size will correspondingly increase after a few hours' worth of circulation to large transverse and longitudinal dimensions. To accommodate for this, the RHIC utilizes stronger focusing than a typical proton collider, with short half-cells each composed of a single dipole and quadrupole.

The RHIC collider consists of two identical, nearly circular rings separated by 90 cm, in a tunnel 3.8 km in circumference. Collisions exist at six interaction regions placed at equidistant points around the circumference, where the beams are focused down to a small spot size and collided. Each ring has three inner and three outer arcs, all of which are joined by one of the six interaction regions. The arcs each have 11 FODO cells, with each half-cell containing a dipole, quadrupole, sextupole, and other correction elements

(Harrison, Peggs, and Roser, 426).

For gold-gold collisions, 56 bunches of 10^9 stripped gold ions are injected into the RHIC at an energy of 10 GeV/u by the previously-described Alternating Gradient Synchrotron (AGS). They are then accelerated to approximately 100 GeV/u per beam, and counter-circulate in their respective rings until they are brought to a collision point near one of the four current particle detectors: STAR (Solenoid Tracker at RHIC), PHENIX (Pioneering High Energy Nuclear Interaction eXperiment), PHOBOS, and BRAHMS (Broad Range Hadron Magnetic Spectrometer). Because of the relatively small physical size of the RHIC tunnel and the high energies desired for heavy ions, magnets capable of high magnetic fields were essential. To fulfill this design criteria, the RHIC uses superconducting magnets for both type of magnets used in its rings: (1) the magnets used in the arc regions (which are of 8 cm aperture), and (2) the few magnets with variable aperture used near the interaction regions. The magnets require an enormous cryogenic plant to maintain them at 4 K.

RHIC was successful from its first two runs with gold ions, achieving its design luminosity of $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ immediately (Harrison, Peggs, and Roser, 467). The increase in longitudinal phase space with time as the ions circulate in the storage ring has been as expected due to intrabeam scattering; however the transverse phase space has been growing faster than expected, resulting in modestly shorter lifetimes of design luminosity. Plans are already in the works for an upgrade to RHIC II, which Brookhaven hopes will further combat the effects of intrabeam scattering on luminosity by installing a 50 MeV electron cooling system (Harrison, Peggs, and Roser, 469).

CERN's new heavy-ion accelerator is not far behind. The Large Hadron Collider (LHC) is scheduled to be commissioned in the spring of 2007 and available for use by 2008. A brief history: in 1982, a feasibility study began at CERN to investigate the efficacy of utilizing the existing LEP tunnel for a new proton-proton or heavy ion collider. CERN eventually decided on a collider capable of colliding both, and in 1994 the LHC project was formally approved by the CERN Council (Brianti, 350). The LHC will be supplied with protons and lead ions from the existing CERN Linac, PS (and PS Booster), and SPS, which all underwent significant upgrades in order to meet the new energy requirements of injection to the LHC: an increase in Linac current, new RF systems in the PS and PS Booster, and the installation of a new extraction channel in the SPS. The LHC consists of 8 arc sections and 8 straight sections, with 8 insertions used for the 4 particle detectors, support systems, and RF accelerating cavities. Each arc consists of 23 identical cells each containing six dipoles and two quadrupoles. Small sextupole, octupole, and decapole magnets are installed in each cell to provide corrections to beam instabilities (LHC Study Group, 155).

Because there was not room in the LEP tunnel for two separate sets of magnets (one per counter-rotating beam), the LHC utilizes beam pipes installed in the same magnets—twin-aperture superconducting magnets. The magnets will have fields of 8.33 T, and will be cooled by a cryogenic plant providing superfluid helium at 1.9 K (Brianti, 357)

The LHC will receive injected protons at 450 GeV, and accelerate them to a design energy of 7 TeV per beam at a nominal luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Lead ions will be injected at 0.4 GeV, and be accelerated to a design energy of 5.7 TeV/u per beam at a

nominal luminosity of $1 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ (Schutz, S904).

2005—What Will They Build Next?

Many new particle accelerators are on the drawing board and awaiting either funding approval or various technologies to advance before construction is possible. One such accelerator, awaiting funding and final design and testing of new technologies is the International Linear Collider (ILC); a proposed e^+e^- collider. Development of this collider is an international collaboration, and is actively supported by CERN and DESY in Europe, Brookhaven, Argonne, Fermilab, JLab, and SLAC in the U.S., and KEK in Japan. The location for construction of the ILC has not yet been determined, and it is planned to operate at energies of 0.5 TeV at inception, for later upgrade to 1.0 TeV.

Several test facilities around the world are currently working on technologies for this new collider. The Next Linear Collider Test Center at SLAC is an X-band test facility working on issues related to acceleration of beams at extremely high gradients and high RF frequencies. The ATF at KEK is a prototype damping ring designed to test low emittance flat beams for higher luminosities. The Tesla Test Facility at DESY has focused specifically on technology and physics issues involved in using superconducting technology in a linac (Chao, 10). Both SLAC and KEK have a similar approach to the construction of the ILC—room-temperature accelerating RF cavities driven by klystrons at extremely high frequencies. The DESY and CERN approach differs with its reliance on

superconducting RF cavities, and use of dedicated electron ‘drive’ beams in accelerating cavities. Designs for the ILC are in the final stages of planning, and proposals wait only on funding and location determination (Shapero, *et al.*, 90)

Another accelerator waiting in the wings for new physics and technology development is a muon collider. A muon collider could produce, accelerate, and collide muons at 0.5 to 4.0 TeV. A muon collider is expected to carry out similar research to an electron collider. The acceleration of muons instead of electrons is advantageous because of their mass—with a mass 200 times that of an electron, the effects of synchrotron radiation are much less than that of a circular electron accelerator, allowing operations at much higher energies. The downside of muons is their instability—once they are produced, they decay within a few thousandths of a second. Acceleration and collision would have to occur very quickly (Shapero, *et al.*, 90).

A look at the ‘Livingston plot’ in Figure 11 shows the progress that has been made in accelerator energies in the last century. This type of plot is called a Livingston chart after M. Stanley Livingston, the aforementioned accelerator physicist who first drew up such a chart in the 1960’s. A quick glance shows that since the 1930’s, the energies achieved by particle accelerators have grown exponentially with time, with an increase by a factor of ten every seven years. These increases were always due to new ideas, and the development and use of new technologies. As we look to the future, one thing is certain: as we continue to make use of new technologies and ideas, new particle accelerators will continue to increase in energy and to unpack the fundamental properties of the universe.

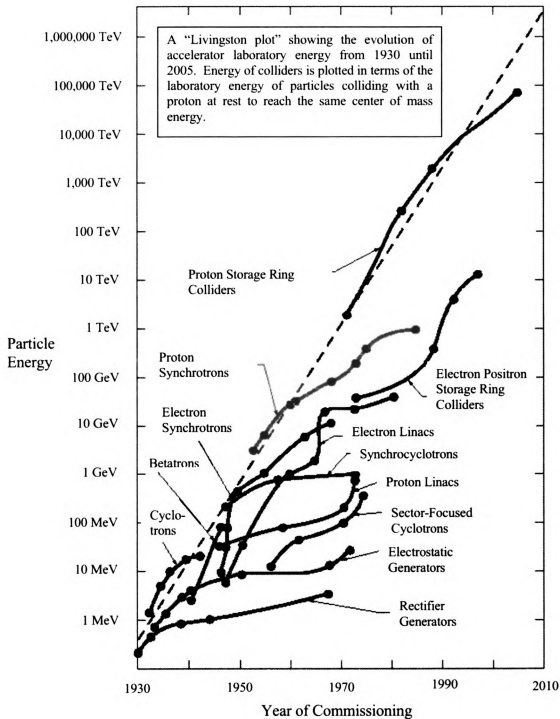


Figure 11: A Livingston plot (Chao *et al.*, 6).

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