PARTICLE ACCELERATORS

F.T. COLE

Fermi National Accelerator Laboratory

and

M. TIGNER

Cornell University

I Definition and Introduction
II Types of Accelerators
III Particle Motion
IV Accelerators of the Future
V Bibliography

GLOSSARY

1. Particle Accelerator - a machine built to increase the kinetic energy of a beam of atomic particles.
2. Electron-Volt (eV) - a unit used to describe the energy of particles in an accelerator.
3. High-Voltage Accelerator - a particle accelerator in which each particle passes once through a high potential. The main types of high-voltage accelerators are Cockcroft-Walton accelerators, Van de Graaf generators, and Marx generators.
4. Induction Accelerator - a particle accelerator in which particles are accelerated by electric fields that are generated from a changing magnetic field by Faraday's law of induction.

5. Cyclic Accelerator - a particle accelerator in which each particle passes many times through a small potential difference to be accelerated to high energy.
6. Linear Accelerator - a cyclic accelerator in which acceleration takes place along a straight line as particles pass sequentially through repeated accelerating units in synchronism with an electromagnetic wave.
7. Circular Accelerator - a cyclic accelerator in which particles are bent by magnetic fields around closed paths, passing many times through the same accelerating system.
8. Cyclotron - a circular accelerator in which protons or heavy ions spiral outward from the center as they are accelerated by a radiofrequency voltage.
9. Microtron - a circular accelerator in which electrons move in circles that are all tangent at one point where a radiofrequency voltage accelerates them.
10. Betatron - a circular induction accelerator for electrons. The magnetic guide field rises during acceleration to keep particles on a circle of constant radius.
11. Synchrotron - a circular accelerator in which particles are kept in a circle of constant radius by a magnetic guide field that rises in time as they are accelerated by a radiofrequency voltage.
12. Focusing System - A system for maintaining divergent particles in a beam close to the ideal orbit during the course of acceleration and storage.
13. Strong-Focusing System - a system of alternating focusing and defocusing lens which produce a strong net focusing effect.
14. Fixed Target - a target fixed in location that the beam strikes after acceleration to produce physical changes of interest.

15. Colliding Beams - a system in which the fixed target is replaced by a second beam of accelerated particles moving in the opposite direction. The collisions of moving particles produce very high energy phenomena.

16. Storage Ring - a ring like a synchrotron with magnetic field fixed in time so that one or more beams of particles can circulate continuously to produce colliding beams.

I. Definition and Introduction

A. Definition

A Particle Accelerator is a machine built by human beings for the purpose of increasing the kinetic energy of atomic particles. These particles can be electrons, protons, or heavier ions. They are always electrically charged. The particles are accelerated by electromagnetic forces and they all move in the same direction. They form a beam, somewhat like the beam of a flashlight.

Particles are accelerated in order to be used in scientific research, in medicine, or in industry. After the particles are accelerated to the desired energy, the beam is steered to strike a target. Particles are accelerated to cause physical changes that occur in the target. These changes and the study of them are the desired objective of a particle accelerator.

B. Units

The final energy of the accelerated particles is the most important parameter of a particle accelerator. The particles have charge equal to the electron charge e or a multiple of it and they are accelerated by potentials measured in volts (V), so a natural unit of energy is the electron-volt (eV), the energy acquired by one electron charge in passing through a potential difference of one volt.

The electron-volt is a very small unit of energy (1 eV = 1.6×10^{-19} Joules) more directly applicable to energy levels in atoms than to accelerators. There are therefore multiples of the electron-volt that are used to describe accelerators. For example,

1 keV = 10^3 eV
1 MeV = 10^6 eV = 10^3 keV
1 GeV = 10^9 eV = 10^3 MeV
1 TeV = 10^{12} eV = 10^3 GeV

The energies of particles accelerators now being operated range from a few hundred keV to 1 TeV. The sizes of particle accelerators range from small devices that fit on a table to devices stretching over several miles. One of the largest, the Fermi National Accelerator Laboratory near Chicago, is shown in an aerial view in Fig. 1.

A second important parameter used to described an accelerator is its intensity, usually the number of particles accelerated per second.

C. Uses of Accelerators

1. Science

Particle accelerators are essential tools of high-energy or elementary-particle physics, as it is also called. They are used to accelerate particles to very high energy so that the particles can probe the innermost structure of matter and the forces that govern its behavior. In the interaction between a projectile particle and the target particle it strikes, new kinds of particles can be produced that provide clues to the nature of matter. These particles are usually short-lived and decay radioactively in a time much less than a microsecond. Such reactions were produced copiously in the first moments of the "big bang" (q.v.) from which our universe is believed to have evolved, but are now produced only infrequently in nature by cosmic rays (q.v.).

Systematic study of these particles and their interactions requires controlled, copious production using accelerators.

Several different kinds of things can happen when a beam particle strikes a particle in the target:

(i) the beam particle can be scattered. The distribution of scattered particles that is observed is used to determine the size and shape of the scatterer, as Rutherford did in the classic experiments that demonstrated the existence of the atomic nucleus.

(ii) the target nuclei or atoms can be changed into a different state by the collision. The nucleus can be excited to a higher energy level and the radiation observed when it drops back to its ground state. In other cases, the target nucleus can be broken up into small fragments, or the beam particle can be fused into the target nucleus. The product nuclei are then observed.

(iii) New kinds of particles can be created in the collision. For example, positrons, antiprotions, mesons and hyperons can be created and their properties observed. In some cases, the particles created are formed into a beam and this secondary beam is used for experiments.

When an accelerated particle strikes a stationary particle in a target, a large fraction of the energy so laboriously put into the particle goes to move all the products forward in the direction of motion of the beam, because momentum is conserved in all collisions. Thus a 400-GeV proton accelerator has available only approximately 27 GeV for making new particles. When the proton energy is increased to 1000 GeV, the available

energy increases to only 43 GeV.

A way to make all the energy useful is to utilize a second accelerated beam as a target. If the two beams are moving in opposite directions, the total momentum of the system is zero and none of either beam's energy need be used in moving products downstream. This colliding-beams method is a more economical method of creating new, higher-energy interactions and new particles, as depicted schematically in Fig. 2.

The collision rate in colliding beams is much lower than in a fixed target, because the particle density is much less than in a solid target and there are therefore many fewer particles to interact with in a beam. This difficulty can be partially overcome by storing two circulating beams of particles in a storage ring. There they pass many times through one another to increase the effective collision rate.

In all these kinds of experiments, a physical change is produced by the beam particles, which are used as a probe to induce these changes. Higher energies are needed to probe to smaller distances within the atomic nucleus, and there has been a constant drive toward higher energy. The highest energies now used for physics experiments are approaching 1 TeV in fixed-target research and 2 beams each of 1 TeV energy in colliding-beam research. At this time, a collider with beams up 20 TeV each is being designed. These accelerators are very large in size. They are also very complex. Large accelerators are among the most complex devices built by human beings and large numbers of people are needed to operate them. As an example, the accelerator and tunnel of Fermilab are shown in Fig. 3.

An analogy can be made between a light source-microscope combination and an accelerator-detector combination. In a microscope, light passes

through a target under study and scatters from it. The transmitted or scattered light is gathered by the microscope and directed to the eye or to a photographic film where an image is focused that can be analysed. In an accelerator-detector combination, a target is illuminated by the beam from the accelerator. Scattered or transmitted particles or new particles created in the high-energy interaction are then registered in a detector for analysis. The detector can be a simple photographic film or a complex electronic device containing tens of thousands of individual elements and weighing hundreds of tons. The fineness of detail that can be studied with the microscope depends upon the wavelength of the light used; the shorter the wavelength the finer the detail. Similarly, with illumination by accelerated particles; the higher the energy or the shorter the deBroglie wavelength, the smaller the scale of matter that can be studied.

The analogy is not complete, because the transmitted or scattered light in a microscope makes only small changes in the object under study and the purpose is to study the unchanged object. In an accelerator, major changes can be made in the target. For example, new particles can be produced and studied.

Another scientific application of accelerator that has wide use is in production of synchrotron radiation in the form of intense ultraviolet light or X-rays. This intense source has opened up many new areas of atomic physics, biology and chemistry for study.

2. Medicine

Smaller accelerators are used in both the two great arms of medicine, diagnosis and treatment. Their use is very much like that of the familiar X-ray machines. In fact, an X-ray machine is a particle accelerator. In

it, electrons are accelerated and made to strike a target to produce X-rays. These X-rays are used to examine tissue, bones, and organs inside the body as an aid in diagnosis. In CAT scanning, computers are used to reconstruct images.

X-rays are also used in treatment to kill cancer tumors by irradiating them. Here higher-energy electrons are used to produce more penetrating X-rays. The highest energies are approximately 0.5 to 10 MeV. In addition, accelerators of heavier particles are used to produce protons, neutrons, or heavy ions for use in cancer therapy. In many cases, these heavier particles offer a better method of radiation therapy than electrons or X-rays, because heavy particles deposit their energy over a much smaller depth of tissue than electrons or X-rays and the energy deposition can be much better confined to the tumor site. Heavy particles of energies 10 MeV to several GeV are used in this therapy.

Particle accelerators are also used in medicine to produce radioactive isotopes, which are then used to trace the movement of chemicals through the human system as an aid in diagnosis.

3. Industry

The uses of accelerators in industry have some similarity to the uses in medicine. The particle energies are usually low, hundreds of kilovolts to 10 MeV in most cases. A major industrial use is in diagnosis and testing. Pressure vessels, boilers, and other large metal castings are routinely X-rayed to search for internal flaws and cracks, which would lower the strength of the casting. Particle energies of 20 MeV or more are often used for greater penetration of thick castings.

Particle accelerators are also used in materials treatment. Precise

concentrations of impurity ions are implanted in metal surfaces for solid-state electronics (semiconductor) manufacture. Particle beams are used to etch microchips in the production of integrated circuits.

Many manufactured objects are sterilized by accelerators. Such sterilization is the preferred method for bandages and surgical instruments, because it damages them less than heat sterilization. The accelerator energies used for sterilization are low enough that no radioactivity is induced in the object being sterilized.

Materials are also changed chemically by accelerator radiation. A notable application is in the polymerization of plastics. Transparent shrink wrapping is treated by accelerators to prodcue the desired shrinkability with the application of heat.

Development is being carried out to test the applicability of accelerators to controlled fusion nuclear reactions to produce energy. In the systems envisaged, beam of high-energy particles would be used to bombard a very small deuterium-tritium pellet and heat it by implosion to the point at which energy-producing deuterium-tritium reactions would take place. A very large system would be needed to produce energy economically and the development is expected to require many years of work.

Food preservation by accelerator radiation is also being carried out, mostly on a trial basis at this time, but with some large-scale application by the military services.

A recent accelerator application is to the destruction of harmful bacteria in sewage by accelerator beams, in order that the treated sewage can then be used as fertilizer.

Some military uses have been suggested, but none have as yet been put

into actual practice.

D. Types of Accelerators

Accelerators can be divided into two classes, those in which acceleration is carried out by use of a high dc voltage and those in which acceleration is carried out by a lower voltage through which particles pass many times, which are called cyclic accelerators

High-voltage accelerators charge a terminal to high voltage with respect to ground. In some high-voltage accelerators, such as the Cockcroft-Walton set and Marx generator, a voltage-multiplying circuit is used and charge is carried to the terminal electronically. In others, such as the Van de Graaf accelerator, known also as the electrostatic generator, charge is carried mechanically to the terminal by a moving belt system. The Van de Graaf can be expanded to the Tandem Van de Graaf, in which negative ions are accelerated to high voltage, then stripped of electons so that they become positive ions and are accelerated back to ground, thus receiving twice the kinetic energy corresponding to the terminal potential. An electrostatic generator installation is shown in Fig. 4.

High-voltage accelerators are limited in peak energy by practical problems of holding high voltage against sparking or discharges to ground. Cockroft-Walton and Marx generators can reach approximately 1 MV. Van de Graaf generators have reached 25 MV and tandems have accelerated particles to 50 MeV.

Cyclic accelerators always have accelerating fields that vary in time. The particle's motion is synchronized with this variation. (If the fields were constant, they would be high-voltage accelerators, with the energy limitations of that class.) In linear accelerators, each particle passes once through a sequence of accelerating structures. In circular accelerators, a magnetic field is used to bend the particles around a closed path to pass repeatedly through the

same accelerating structure.

Linear accelerators for electrons or others particles moving at speeds close to the speed of light make use of a traveling electromagnetic wave in a special waveguide. Electrons ride the crest of the wave like a surfer on an ocean wave. The largest electron linear accelerator is the 50 GeV Stanford accelerator, which is two miles long. It is shown in Fig. 5.

For particles moving much slower than the speed of light, a different structure is needed because the wave velocity cannot be slowed down enough for the particles to keep in step. In this cae, drift tubes are used to shield particles from decelerating fields. The largest proton linear accelerator is the 800-MeV accelerator at Los Alamos National Laboratory.

The cyclotron was the first circular accelerator. Particles are injected at the center of a circle and spiral outward in the constant magnetic field as they gain energy. Accleration takes place as the particles cross the gap between two D-shaped drift tubes. The particles must stay in step with the radiofrequency accelerating voltage. For higher energy, this synchronism cannot be maintained and the accelerating voltage is frequency modulated in the synchrocyclotron. More recent cyclotrons utilize azimuthally varying fields (AVF) to maintain synchronism. A modern cyclotron is shown in Fig. 6. Cyclotrons have been built to operate up to 800 to 900 MeV. For electrons, the cyclotron is not a useful device. Instead, the microtron, in which particles travel longer paths as they gain energy, is appropriate.

The circular accelerator that is used to go beyond 1 GeV is the synchrotron, in which the magnetic field increases in time to keep particles circulating at a constant radius. The frequency of the accelerating voltage is varied to maintain synchronism with the particles as they are accelerated. The largest synchrotron,

which utilizes superconducting magnets, is the Tevatron at Fermilab; it accelerates protons to almost 1000 GeV. It is the lower ring of magnets in Fig. 3.

Storage rings ar similar to synchrotrons, but the magnetic field is held constant so that particles can continue to circulate. Storage rings with particles circulating in both direction are utilized for colliding-beam experiments.

Particles can be accelerated by the electric fields induced by changing magnetic fields (Faraday's Law) and there are smaller accelerators, the linear induction accelerator and the circular betatron, which uses this principle to accelerate electrons to energies of the order of 100 MeV.

Although it is possible in principle to build a synchrotron for an arbitrarily high energy, it eventually becomes impossible economically. There are accelerator scientists looking beyond to new ways of accelerating particles, perhaps using the intense electromagnetic fields possible in lasers or in plasmas for acceleration and guidance of particles. This work is still in the research phase, with many interesting ideas and configurations of these collective accelerators.

E. Physical Principles

Particle accelerators operate according to well-established laws of nature, the laws of electromagnetic fields and the laws of electrodynamics governing the motion of charged particles in these fields. Research and development of accelerators is an active field of science, but it is a field that utilizes known laws of nature rather than seeking new laws. Accelerators are tools used in seeking new laws.

A charged particle moving in an electric field experiences a force in the

direction of the field (or the opposite direction if it is a negative charge) and is accelerated in that direction, as shown in the upper part of Fig. 7. Thus its velocity and its kinetic energy will increase. The force $F = qE$, where q is the particles charge and E the electric field. If q is measured in coulombs and E in volts per meter, F is given in newtons.

This is the basic mechanism of operation of a particle accelerator. The electric field can be either constant in time, in which case particles are accelerated continuously and come out in a steady stream, or varying in time, in which case particles are accelerated only when the electric field is in the right direction, and come out in bunches.

A charged particle in a static magnetic field experiences a force in the direction perpendicular to the plane formed by two vectors, the magnetic-field vector and the particle's velocity vector, as shown in the lower part of Fig. 7. A particle moving in the direction of the magnetic field experiences no mmagnetic force. Because the force on a particle in a static magnetic field is perpendicular to its velocity, no work is done on the particle and its energy does not change. The energy increase in a circular accelerator comes from the accelerating system, not from the magnetic field.

The force on a particle moving at velocity v perpendicular to a magnetic field B is

$$F = q\ v\ B \qquad (1.1)$$

If B is measured in Tesla ($T = 10^4$ gauss) and v in meters per second, the force F is in newtons. When the magnetic field provides the centripetal force that bends the particle in a circle of radius ρ then

$$\frac{mv^2}{\rho} = q\ v\ B$$

and there is a relation between the momentum p and the product of radius and field

$$p = mv = q\ \rho\ B \qquad (1.2)$$

Thus as the momentum of a particle is increased during acceleration, either the radius of curvature must increase, as in cyclotron, or the magnetic field must incrase, as in a synchrotron. This relation $p = q\rho\beta$ is very basic for circular accelerators. It holds for slow and fast particles, including effects of special relativity (q.v.). For practical calculations, if B is in Tesla, ρ in meters and p in MeV/c,

$$p = 300\ B\rho \qquad (1.3)$$

There is a sense in which magnetic fields can increae the energy of particles. The linear induction accelerator and betatron discussed above make use of a magnetic field changing in time to induce an electric field that increases the energy of the prticles.

In circular accelerators, the paths of particles during the course of acceleration are very long, sometimes many thousands of kilometers. A particle injected at an angle with respect to the ideal path will stray farther and farther during this long distance and will leave the confines of the magnetic field and be lost, unless some means is provided to focus the particles back toward the ideal path. This focusing is accomplished by building in carefully designed gradients (variations in space) of the magnetic field. Focusing is one of the most important elements of accelerator design.

We emphasize here the difference between a particle accelerator and a nuclear reactor. In the accelerator, the particles are focused and form a beam, all moving in the same direction with the same energy, whereas in a reactor, the particles are heated and move with the random directions and wide energy distribution of a hot gas. In addition, the reactor accelerates particles by nuclear forces, whereas the accelerator makes use of electromagnetic forces. These electromagnetic forces cease when the electric power supplied to the accelerator is interrupted. Thus the radiation from an accelerator stops, except for small residual effects, when the accelerator is turned off.

F. HISTORY

During the 19th century, physicists experimented with Crookes tubes, evacuated glass sytems containing internal electrodes. A current of electrons will flow when a large enough voltage is applied between these electrodes. J.J. Thomson used a Crookes tube in his discovery of the electron in 1890. Roentgen discovered X-rays using a Crookes tube in 1896. The X-ray tube was later made into a practical device for use in medicine by Coolidge.

Rutherford spurred the development of particle accelerators for use in nuclear-physics research in a famous lecture in 1920. He pointed out the need for higher-energy particles for the further development of understanding of the atomic nucleus. During the next decade, both high-voltage and cyclic accelerators were invented. Many different methods of producing high voltage were demonstrated, but there was always great difficulty in providing an accelerating tube that would not spark at high voltage. Cockcroft and Walton, in Rutherford's Cavendish Laboratory, developed a successful accelerating tube. They used an existing voltage-multiplying circuit and built a 300-keV proton accelerator, which they used in 1932 to do the first nuclear-physics experiment

with accelerated particles

Ising was the first to conceive (in 1925) a cyclic accelerator, a drift-tube linear accelerator. Wideroe expanded the idea and built a working accelerator in 1928. It accelerated mercury ions to twice the impressed radiofrequency voltage.

Perhaps the most important consequence of Wideroe's work was to stimulate Lawrence to conceive the cyclotron. Lawrence and Livingston built the first operating cyclotron in 1932 and a succession of cyclotrons was built in Lawrence's laboratory through the 1930's.

Lawrence's cyclotrons and electrostatic generators, which had been conceived and demonstrated by Van de Graaf in 1931, were used for nuclear-physics research throughout the 1930's. Both were limited to energies of 15 MeV or less and reaching energies beyond this limit was a major topic of research in the 1930's. Beams conceived the traveling-wave linear accelerator and demonstrated it, but radiofrequency power sources were not adequate at that time to build useful accelerators. Thomas proposed the AVF cyclotron in 1938, but his work was not understood until much later. Kerst built the first successful betatron in 1941 and built a second 20-MeV machine before World War II intervened. This model was built in large quantities for use in X-ray testing of large castings, particularly for the armor of military tanks.

The next great step in energy began in 1944 and 1945 when Veksler in the USSR and McMillan in the US independently conceived the principle of phase stability, permitting frequency modulation of the accelerating voltage in a cyclotron to overcome effects of relativity and making the synchrotron possible. In 1946, the first synchrocyclotron was operated and a number of 300-MeV electron synchrotrons came into operation in the next few years. The research done with

these accelerators was important in learning the properties of the pi meson.

World War II radar work had stimulated the development of high-frequency power sources and these were used in linear accelerators. Travelling-wave electron linear accelerators, at frequencies of approximately 3 GHz, were extensively developed by Hansen, Ginzton, Panofsky and their collaborators, leading over many years to the 50-GeV Stanford Linear Center. Alvarez extended the concept of the drift-tube accelerator for heavier particles and built the first of many drift-tube accelerators used in physics and chemistry research and as injectors for synchrotrons.

Work also began in the late 1940's to build proton synchrotrons. The first proton synchrotron, the 3-GeV Cosmotron at Brookhaven, N.Y., came into operation in 1952 and the 6-GeV Bevatron at Berkeley, California, came into operation in 1954. An interesting precursor, a 1-GeV proton synchrotron, conceived in 1943 independently of the principle of phase stability, was built in Birmingham, UK, but shortages of money slowed its construction and it did not operate until after the Cosmotron. The proton synchrotrons were used for research in heavier mesons, the "strange" particles that had been observed in cosmic-ray experiments, and in antiprotons.

Speculative discussions aimed toward increasing the highest accelerator energy led to the conception of the strong-focusing principle by Courant, Livingston, and Snyder in 1952. It was later found that Christofilos had developed the principle independently in 1950. Strong or alternating-gradient focusing keeps the oscillations of particles about the ideal orbit much smaller and makes possible much more compact, more economical magnets.

The discovery of strong focusing led to an explosion of ideas, knowledge, and techniques in particle accelerators. In 1953, Kitigaki and White

independently conceived the separated-function strong focusing synchrotron, which makes possible higher guide fields and more economical designs. In 1958, Collins conceived the long straight section, which makes possible economical configurations with space for injection, acceleration, extraction and detection equipment. As well as making it possible to go to higher energy with proton synchrotrons, the strong-focusing principle gave impetus to new thinking in many other directions. Linear accelerators were greatly improved in performance by the addition of strong focusing along the orbit, first conceived by Blewett. The AVF principle was rediscovered by a number of people, among them Kolomensky, Ohkawa, Snyder, and Symon. It was extended to spiral-sector focusing by Kerst in 1954. Kerst then proposed that successively accelerated beams could be "stacked" in circulating orbits in a fixed-field alternating gradient (FFAG) accelerator, a variant of the AVF configuration. The intense stacked beam can then be used in colliding-beam experiments. The concept of colliding beams had been known for many years (it was patented in 1943 by Wideroe), but beam stacking is essential to achieve useful rates of collisions. Shortly afterward, a number of people (Newton, Lichtenberg and Ross and, independently, O'Neill) proposed the conecpt of a storage ring separate from the accelerating device. The storage ring is a much-better colliding-beam system than the FFAG accelerator because it is less costly and because it makes it possible to provide much more free space for detectors.

Experimental confirmation of these ideas did not lag far behind. The first strong-focusing electron synchrotron was operated by Wilson and his collaborators in 1954, followed by several other electron synchrotrons. The FFAG principle and beam stacking were demonstrated by Kerst and his collaborators in the 1950's. Travelling-wave electron linear accelerators reached the 1-GeV energy range in

this same era and a series of important experiments on electron proton scattering was done that elucidated the structure of the proton. The first electron storage rings were built and operated in the early 1960's. Two large proton synchrotrons of 28 and 33-GeV energy were built by CERN, a new international laboratory in Europe and by the Brookhaven Laboratory. These became the foundation of major advances in high-energy particle physics, with discovery of many new particles and the beginning a conceptual ordering among them and understanding of them. The electron synchrotrons and the Stanford linear accelerator, which reached 20 GeV in 1966, added to this understanding.

In the later 1960's, the first major proton storage ring, the ISR, was built at CERN. It stored proton beams of 28 GeV each, equivalent to a fixed-target accelerator of over 1500 GeV energy.

The second generation of strong-focusing synchrotons also began to be built in the later 1960's. These incorporated the more-efficient separated-function magnet system and long straight sections. A proton synchrotron that reached 400 GeV was completed at the new Fermilab in Illinois in 1972. A similar synchrotron was later built at CERN. These workhorses incorporated new beam-sharing methods and each could provide beam simultaneously to several targets and a dozen major experiments. An important feature that has made this multiple use possible is the very high degree of precision in beam handling and manipulation. The data from these and ISR experiments led to the development of Quantum Chromodynamics and Electroweak Theory, large advances in our understanding of the basic building blocks of nature.

Important experimental evidence also came from the second generation of electron storage rings, now always with positrons as the second beam, the first of which reached 3 GeV in each beam at Stanford in 1972. Electron-positron

storage rings have now reached 23 GeV per beam. As in the case of proton synchrotrons, electron-positron storage rings have been developed to a high art. Radiofrequency systems to replace the energy lost in synchrotron radiaion are a major factor in the design and cost of electron storage rings, but at the same time the synchrotron radiation can make the beam very small in size, making precise manipulations possible and increasing the colliding-beam interaction rate. In fact, synchrotron radiation has become a valuable experimental tool in its own right for use in atomic-physics and materials-science research and a number of single-beam electron storage rings have been built for this purpose.

The two large proton synchrotrons were developed further in quite different directions. At Fermilab, superconducting magnets underwent long, arduous development and a superconducting magnet ring was built and installed in the tunnel of the 400-GeV accelerator. It reached 800 GeV in 1983. The CERN synchrotron was converted to a proton-antiproton storage ring by the addition of a small ring to accumulate antiprotons, making use of the new technique of beam cooling invented by van der Meer. Colliding-beam experiments have been carried out there, culminating in the discovery of the W and Z particles in 1983. Thes particles have rest energies close to 100 GeV and cannot be produced even by a 1-TeV fixed-target proton accelerator.

The spectacular successes of these accelerators and storage rings have led to a number of new initatives. An electron-positron ring (LEP) to reach initially energies of 50 GeV in each beam, with 100 GeV per beam as the ultimate goal, is being built at CERN. An electron-proton ring (HERA) is being built in Germany. A 3-TeV proton synchrotron, convertible to a proton-antiproton storage ring, is being built in the USSR. A single-pass colliding-beam system, SLC, is bing built at Stanford. Here the two beams collide only once in a linear system,

not a circulating configuraion. It is believed that a useable event rate will be achieved by very small beam sizes (thus increasing the density) and very high repetition rates. Design work is in progress in the US on a proton-proton collider, SSC, with 20 TeV in each beam. Research work has been carried out for many years on methods of collective acceleration, with the goal of achieving much larger accelerating fields. The historical development of the energy of particle accelerators, with a look to the future, is plotted in Fig. 8.. One can see from the chart that the development of each new type of accelerator gave an energy increase. Each accelerator type is eventually replaced by another.

II. TYPES OF ACCELERATORS

A. High-Voltage Accelerators

In a high-voltage accelerator, a terminal or electrode is charged to high voltage and particles are accelerated from it to ground potential. If the terminal is charged to a voltage +V, a singly charged positive ion will gain energy eV in the accelerator. Thus the terminal is at potential V with respect to ground and the maximum possible voltage is limited by problems of holding voltage. Above some voltage, the terminal will spark to ground. The voltage is also limited by less-dramatic corona discharge. With ample space to ground and scrupulous attention to detail in design, terminals have been built that hold 25 MV.

The simplest way to produce high-voltage is with an ac electrical step-up transformer system. X-ray machines produce voltages up to 1 MV by this method. Beam is only accelerated on half the ac cycle and varies in energy throughout the pulse.

In order to avoid scattering of beam particles by residual gas, there must

be an accelerating tube that is evacuated to low pressure. The voltage drop must be distributed somewhat uniformly aong this tube to avoid sparking. For voltages above approximately 1 MV, the accelerating tube is almost always insulated outside the vacuum by a pressurized gas of high dielectric strength, often sulfur hexafluoride.

To produce a dc voltage, electric charge is brought to the terminal to produce high voltage. Charge may be brought electronically by voltage-multiplying circuits or mechanically by moving devices.

1. Voltage-multiplying devices

The first successful high-voltage accelerator, the Cockcroft-Walton accelerator, made use of a voltage-doubling circuit, the Greinacher circuit, shown in Fig. 9. Two rectifiers act on opposite sides of the ac sine wave to charge a capacitance to twice the voltage. The principle can be extended to many stages. Cockcroft and Walton used the Greinacher circuit and developed the first accelerating tube. They accelerated protons to 300 keV and in 1932 demonstrated the first nuclear reaction with artifically accelerated particles, bombarding lithium with protons to produce two alpha particles (helium nuclei). Modern Cockcroft-Walton generators are available commercially up to voltages of approximately 1 MV. Special pressurized systems have been built to 3 MV. Cockcroft-Walton generators are widely used as the first stage of higher-energy accelerator systems because they produce beams with very good energy regulation.

The Marx generator is similar in principle. The rectifier system is external to the capacitor stack. In essence, the capacitors are charged in parallel, then discharged in series through spark gaps. Marx generators were originally used in the 1920's to produce surges of high voltage to test

electrical generating and transmitting equipment. They are used in modern accelerator work to produce very intense (1,000 to 10,000 A) short (10 to 50 nsec) pulses of 1 to 10 MeV particles. The particle energy is very poorly regulated during the pulse.

2. Charge-carrying devices

The most prominent of the accelerators in which charge is carried mechanically to the terminal is the electrostatic generator or Van de Graaf accelerator. In this device, depicted schematically in Fig. 10, charge is carried by a moving belt to the high-voltage terminal. In most modern accelerators, the belt is made of a series of insulated metal links, looking a little like a bicycle chain. Van de Graaf accelerators played an important role in the development of knowledge in nuclear physics during the 1930's and are still in used in that field. They are now frequently also used in industrial applications.

An electrostatic generator has produced a terminal voltage of 25 MV. It is possible to double the effective voltage by accelerating negative ions (ions with extra electrons) from ground to a high positive voltage, then stripping electrons off by passing the beam through a metal foil and accelerating the positive ions back to grund potential. This tandem Van de Graaf produces higher energy, but with lower intensity because the process of stripping cannot be made perfectly efficient. The dc beam current in a single electrostatic generator can be as large as 10 to 20 μA, but the dc beam current in a tandem is of the order of 1 μA.

B. Cyclic Accelerators

There are two kinds of accelerators in which a low voltage is used repeatedly to produce high-energy particles: linear accelerators, in which each particle passes once through a sequence of accelerating structures, and circular accelerators, in which each particle traverses a closed path (not necessarily exactly a circle) and passes repeatedly through the same accelerating structure. A magnetic field is used to bend the particles around the closed path. In a cyclic accelerator, the accelerating forces must vary with time, in contast with the dc forces in high-voltage accelerators. If the forces did not vary with time, they could not be used over and over again to produce high energy.

1. Linear accelerators

In the linear accelerator, or linac, the particles being accelerated follow paths that are straight to a very close approximation. These particles are accelerated in the desired direction by the action of electric fields, as we saw in Fig. 7. In the transverse directions, the particles are confined or focused into a beam by the action of lenses employing static electric or magnetic fields, or in some cases by time-varying harmonic fields, as in the radiofrequency quadrupole (RFQ) focusing system.

In the accelerators of today, the electric field that provides the accelerating force is shaped by conductors or dielectric media near the beam. The kinetic-energy increase of the beam particles as they pass through the accelerator is gained at the expense of energy stored in the accelerating electric field. Because of the conservative nature of the static electric field, the high-voltage dc accelerators of sec. IIA, the most elementary form of linac, are limited in maximum particle kinetic

energy gain by the maximum constant electric potential that can be supported by an array of conductors. In practical cases this is a few million volts (MV). If the accelerating electric field is time varying, continuous acceleration can be achieved and there is no physical limit to the maximum particle kinetic energy that can be achieved. In the time-varying field linac, a substantial fraction of the accelerating field energy is contained in an accelerating wave.* Particles traveling with the crest of the wave gain energy from it much as a surfer gains energy from a travelling water wave near a beach. The accelerating force will be proportional to the strength of the electric field along the axis of the accelerator. That is, $F = qE$. The travelling accelerating wave field will vary with time t and with distance z along the accelerator as

$$E = E_o \cos[\omega(t - \frac{z}{v_w}) + \phi_i]$$

where ω is the frequency of the wave, v_w is the phase velocity of the wave and ϕ_s is a constant that measures the initial value of the wave strength at the beginning of acceleration i.e. $t = 0$, $z = 0$.

*A large part of good accelerator design lies in configuring the field shaping conductors or dielectrics to maximize the fraction of the total field energy in the accelerating wave component of the field.

If the particles being accelerated have a velocity v_p along the accelerator axis their position is given by

$$z = v_p \cdot t \qquad (2.2)$$

As a consequence, if the linac is designed so that $v_w = v_p$, the particles are accelerated by a constant force in the z direction

$$F = qE_o\cos\phi_i$$

As a consequence of the wave nature of the acceleration, only particles near the wave crests i.e. $\phi_i = 0, 2\pi, 4\pi$...receive useful acceleration. Thus the beams from linacs employing time-varying fields are bunched, the separation of the bunches being $\lambda \cdot v_\omega/c$, where λ is the free space wave length of the accelerating harmonic field. As the particles are accelerated, their velocity increases according to the relation

$$\frac{v_p}{cy} = 1-\left[\frac{1}{1+\frac{T}{M_oc^2}}\right]^2$$

where T is the kinetic energy of the particle being accelerated and m_oc^2 is its rest energy, c being the velocity of light. For kinetic energies much less than the rest energy $T << M_oc^2$, this expression simplifies to

$$\frac{v_p}{c} \sim \frac{2T}{M_oc^2}$$

the classical relation between velocity and kinetic energy. For T much greater than the rest energy, $T >> M_oc^2$,

$$\frac{v_p}{c} - 1$$

Preaccelerators for linacs are often high-voltage dc or pulsed-dc accelerators, operating at from a few hundred kilovolts (kV) to a few MV. Protons and heavier ions have rest energies (masses) of one to many giga electron volts (GeV) so that they emerge from the preaccelerator still with velocities only a small fraction of c. Electrons have a mass of 511 keV so that even a preaccelerator of only 80 keV boosts their velocity to 0.5 c. The arrangements needed for efficient generation of accelerating waves depend markedly on the desired wave velocity and the designs of linacs for proton or heavier ions and for electrons differ markedly.

a. Proton and Heavier Ion Linacs

The travelling-wave system does not work for prticle speeds very much less than c, because the wave cannot be efficiently slowed down enough to match the particle speed. If the wave velocity is greater than the particle velocity, the wave passes by each particle. As it passes, a particle will experience decelerating forces during the negative-field portion of the sinusoidal variation of the wave. Instead of a travelling wave, a standing wave is used and conducting drift tubes are placed around the particle trajectories in the regions of negative fields in order to shield particles from these fields. These drift tubes are shown schematically in Fig. 11. Acceleration then takes place in the gaps between drift tubes and the particles drift through the tubes unaffected by negative fields. In most standing-wave linear accelerators, the drift tubes contain focusing devices to contain the transverse motion, a subject we shall discuss below.

Drift-tube linear accelerators are used for acceleration of protons or heavy ions. They are capable of producing high intensities of accelerated beam.

The presence of drift tubes strongly affects the choice of frequency in a standing-wave linac. The accelerating frequency cannot be so high that the drift tubes are too small to contain focusing elements. Proton linear accelerators usually utilize frequencies of approximately 200 MHz. Heavy-ion linear accelerators, which inject at even lower speed, often have frequencies in the 60 to 80 MHz range.

The linac cavities that form the outer envelope of the accelerator and contain the electromagnetic field are built in sections for convenience in manufacture. A 200-MeV proton linac is approximately 500 ft long. The pulse length is short enough that the average rf power is only a few kW. The separate amplifiers for each cavity are synchronized by a master oscillator. Peak currents of 200 mA of 200-MeV protons are achieved in injectors for proton synchrotrons. Linear accelerators with longer pulse length are built for applications in which very high intensity is desired. For higher energy, a standing-wave linac can be used to inject into a travelling-wave linac when the particle speed is comparable to the speed of light.

The copper lining and drift-tubes of a standing-wave linac can be replaced by superconducting metals such as a niobium or lead and the entire system cooled down to superconducting temperature (2 to 4 K). A superconducting heavy-ion linac, ATLAS, is in operation. The use of superconductivity is economically justifiable for long-pulse or continuous (CW) linacs.

Particles can also be accelerated by the electric fields induced by

time-varying magnetic fields according to Faraday's Law. In a linear induction accelerator, magnetic fields are pulsed sequentially in synchronism with particle motion through the accelerator. Linear induction accelerators are particularly useful for producing short (10-50 nsec) pulses of very high peak intensity (1000 A) at energies of 10 to 50 MeV.

b. The Electron Linac

In this kind of linac, the wave velocity is made constant at just less than the velocity of light in free-space over almost the entire length. An efficient conductor arrangement that supports the needed longitudinal electromagnetic accelerating wave is shown in the photograph view in Fig. 12. This waveguide is a cylindrical pipe periodically loaded with diaphragms spaced between one fourth and one half of the free space wavelength of the driving harmonic field. The wave velocity is controlled by the diameter of the pipe, about equal to the wave length, while the rate at which power flows down the waveguide is controlled by the size of the hole in the diaphragm. The operating wave length of such linacs is set by the simultaneous need for efficient acceleration and for efficient generation of the microwave power carried by the accelerating wave. Operating wave lengths between 30 cm and 3 cm have been used, with 10 cm being the most common today.

Rather tight tolerances must be maintained in construction of the waveguides. At 10 cm operating wavelength, tolerances of about 0.02 mm must be held. At shorter wavelengths, the tolerances are correspondingly smaller. Maintenance of the correct wave velocity also requires regulation of the waveguide temperature to a fraction of a degree.

With proper synchronization by a master oscillator, a large number of

units such as those of Fig. 12 can be strung together end to end to produce as high a beam energy as needed. Copper accelerating waveguides available today can maintain effective accelerating fields of 15 to 20 MV per meter of length, for a power expenditure of 3 to 5.4 MW per meter of accelerating waveguide. Thus the output energy of the 3000-m Stanford Linear Accelerator will be about 50 GeV with each of its 240 power amplifiers pulsing at 50 MW.

While magnetron tubes are sometimes used as power sources for linacs of a few MeV output energy, klystron amplifiers are the usual choice at microwave frequencies. Today, accelerator klystrons capable of 50 megawatts (MW) peak power with pulse lengths of a few microseconds are being made. Tubes capable of up to 1 gigawatt (GW) for a fraction of a μsec are being contemplated.

As with proton or heavy-ion linacs, it is possible to replace the normal copper conductor with a superconductor, such as niobium or lead, operating at liquid helium temperatures (2-4.5 K). The amount of microwave power needed to establish the accelerating fields is then reduced by a factor of 10^5 to 10^6. This benefit is somewhat offset by the need to provide powerful refrigerators to maintain the linac at close to absolute zero temperature. The technology has proven difficult, but is beginning to come into limited use for accelerators requiring continuous operation, as contrasted with the short-pulse operaton mode of conventional linacs.

2. Circular Accelerators

Like linear accelerators, circular accelerators utilize time-varying fields to accelerate particles. In addition, there must be magnetic fields to bend particles around a closed path that returns them to the accelerating structure. The configuration of the accelerating structures and magnetic

fields can take many different forms in different circular accelerators.

a. The cyclotron

The earliest circular accelerator was the cyclotron, invented by Lawrence and first operated by Lawrence and Livingston in 1932. In the cyclotron, particles are injected at the center of the cyclotron and spiral outward as they are accelerated. A uniform, time-independent magnetic field provides the bending to make these spirals. The drift tubes in a cyclotron are in the form of hollow boxes called "dees", after their shape. Acceleration takes place as a particle crosses the gap between dees. Figure 13 is a sketch of cyclotron orbits through the dees.

A particle of higher energy moves faster along the orbit, but has a longer distance to go between gap crossings. The frequency of gap crossings, and therefore accelerations, is constant in the cyclotron and it produces a steady stream of bunches of accelerated particles. Quantitatively, from Eq. (1.2) $mv = e\rho B$, but $v = \omega\rho$, so that $m\omega = eB$, and ω is independent of the radius ρ and the energy.

According to the laws of motion when a particle's velocity approaches the velocity of light, i.e. special relativity, the mass of a particle increases as its energy is increased. As a consequence, for the same increase in energy, the velocity of a particle of higher energy does not increase as much. The gap-crossing frequency therefore decreases and particles fall out of step. This effect makes a noticeable difference at 15 MeV for protons, which limits the peak energy of the Lawrence cyclotron. Several systems to circumvent this problem have been invented. One of these is the synchrocyclotron, in

which the frequency of the accelerating voltage is reduced to keep in step with a group of bunches of particles as they are accelerated. The synchrocyclotron produces bursts of a series of bunches of accelerated particles. Synchrocyclotrons have been built to produce protons of 750 MeV energy. They have been largely superseded by azimuthally varying field (AVF) cyclotrons, which are also called sector-focused cyclotrons. Here the magnetic field varies periodically around the azimuth of the cyclotron in such a way as to keep the frequency of gap crossings constant. Like cyclotrons, AVF cyclotrons produce a steady stream of bunches. The intensity possible is much larger than in a synchrocyclotron and there are many being used for science research.

b. The microtron

The relativistic effects that limit cyclotrons set in at much lower energies for electrons and a different configuration, the microtron, is appropriate. In the simplest microtron, electron orbits are a series of circles tangent at the position of the accelerating cavity. The periods of revolution on each of these circles differ by an integral number of periods of the accelerating voltage and the electron bunches therefore stay in phase with the accelerating voltage. These simple orbits are sketched in Fig. 14. Microtrons can also be built in the shape of racetracks and have been used to accelerate electrons to energies of more than 100 MeV.

c. The synchrotron

Energies greater than 1 GeV require a different configuration, the synchroton. The magetic guide fields in all the circular accelerators

discussed above are constant in time. In the synchrotron, the magnetic field is increased in time as the particles energy is increased by a radiofrequency accelerating voltage. A graph of a synchrotron cycle is shown in Fig. 15. The radius of the particle orbit is held constant. Synchrotron magnetic fields need to extend over a relatively small aperture, rather than over the entire circle, as in constant-field configurations. The synchrotron is therefore a far more economical design for energies in the GeV range. The largest synchrotron, four miles (six kilometers) in circumference, accelerates protons to an energy close to 1 TeV. It was shown in Fig. 3.

Electron synchrotons, although they share the principle and magnetic-field configuration with proton synchrotrons, have a separate feature. Charged particles radiate electromagnetic waves when they are accelerated, as they are in following a curved path. In accelerators, this is called synchrotron radiation. For light particles like electrons, the energy radiated away is large enough that it must be replaced if the electrons are not to spiral inward and strike the walls. The energy loss per revolution ΔT by an electron of kinetic energy T following a circle of radius ρ is

$$\Delta T = \frac{88.5T^4}{\rho} ,$$

where ΔT is in keV if T is in GeV and ρ is in meters. Thus the energy lost in the form of synchrotron radiation increases very rapidly as T is increased. The accelerating system must make up this energy loss,

as well as provide voltage for acceleration. Radiofrequency systems to carry out these functions become so large that electron synchrotrons become uneconomical compared with linear accelerators at very high energies.

d. The storage ring

Storage rings are very similar in general configuration to synchrotrons. The magnetic guide fields are constant in time and a beam of particles circulates continuously. In some designs, two storage rings are intertwined with one another and beams of particles circulate in opposite directions, colliding at the intersection points. The intersection point can be clearly seen in the photograph of the CERN Intersecting Storage Rings in Fig. 16. In other designs, beams of particles and antiparticles (electrons and positrons or protons and antiprotons) circulate in opposite directions on the same path in the same magnetic field, often with small auxiliary fields to keep them from colliding except at the designated collision points. Like electron synchrotrons, electron storage rings are limited in energy by synchrotron radiation. Present-day technology utilizing superconducting microwave cavities could be used in a storage ring of a few hundred GeV.

e. The betatron

As with linear accelerators, it is possible to accelerate particles by induction in a circular configuration. Circular induction accelerators are called betatrons. They are used to accelerate electrons; many betatrons are used to provide 20-30 MeV electrons for medical or industrial work. The largest betatron produced 300-MeV electrons.

III. PARTICLE MOTION

The motion of particles in an accelerator is one of the most important aspects of accelerator science. The importance of particle dynamics arises in part from the fact that in many kinds of accelerator particles travel very large distances in the course of acceleration or storage, sometimes many millions of miles or kilometers. Stability against small perturbations and errors is vital if the particles are to stay in the accelerator for such distances.

In addition, in most accelerators it is desirable to accelerate as high an intensity of particles as possible. At high intensity, the mutual electromagnetic forces among the charged particles, space charge, can be important, disturbing the stability that each particle would have by itself.
To produce a stable beam in an accelerator, particles will execute only small oscillations about the ideal path during acceleration. These oscillations will occur in both of the two directions transverse to the ideal path and in the longitudinal direction along that path. Although there can be situations in which the transverse and longitudinal motions are coupled, in most accelerator configurations the coupling is very small and the two kinds of motion can be discussed separately, as we shall do.

A. Transverse Motion

1. Betatron Oscillations

Transverse oscillations are called betatron oscillations because Kerst and Serber gave the first clear discussion of them in connection with Kerst's development of the first successful betatron. The equations of motion of transverse oscillations had in fact already been given by Walton and in a form more useful for cyclotrons by Thomas.

The over-all objective is to make the transverse motion dynamically stable, so that particles injected in the vicinity of the ideal orbit will remain in that vicinity. In some short accelerating systems, this can be achieved by focusing the beam at the particle source but in longer accelerators, restoring forces along the orbit are required in order to achieve this stability. These restoring forces are supplied by external electric and magnetic fields.

We can neglect the effects of the acceleration process for the discussion of transverse motion. We also neglect here the space-charge forces between particles and thus discuss the motion of a single particle in an external field that is constant in time. This field is not necessarily constant in space and these variations with distance are important to focusing.

1. Circular Accelerators

Let us consider the case of the transverse magnetic field in a circular accelerator, the field that bends the particle around a closed path. Here r is the radial direction in the plane of the closed-orbit path, the median plane, and z is the dimension perpendicular to the orbit plane. The distance along the orbit is s. If the vertical magnetic field B_z varies as a function of r, that is, if it has a gradient, then there is a radial field B_r at positions off the median plane, as follows from the Maxwell equation $\nabla \times B = 0$. A particle moving in the s direction experiences a vertical force whenever it is away from the median plane. If the vertical field decreases with radius ($dB_z/dr < 0$), the force deflects the particle back toward $z = 0$ for z either positive or negative. This force is depicted in Fig. 17. On the other hand, the force of the particle is always in the direction away

from the median plane if $dB_z/dr > 0$.

Thus if the guide field decreases with radius, motion off the median plane is stable in the sense that a particle starting off the median plane will not move to ever-larger z. This vertical focusing was found experimentally in the earliest cyclotrons and understood qualitatively at that time. It was made quantitive by Kerst.

In a decreasing field, the radial force on a particle decreases with radius. But the centripetal force mv^2/r needed to keep the particle of mass m and speed v in a circle radius r decreases as 1/r. Thus, if the field decreases less rapidly than 1/r, a particle at larger radius feels a larger force focusing it back toward the ideal orbit and and the particle has horizontal or radial focusing. Kerst expressed these results in terms of the relative derivative or field index

$$n = - \frac{r}{B} \frac{\partial B_z}{\partial r} , \tag{3.1}$$

and the condition for focusing in both transverse directions is

$$0 < n < 1 . \tag{3.2}$$

In this weak focusing, horizontal and vertical focusing are complementary to one another in the sense that each decreases as the other increases and a balance must be struck in design between vertical and horizontal aperture. For example, the fields in cyclotrons decrease very little with radius, in order to keep as close as possible to isochronous motion and the vertical focusing is very weak.

Many synchrotrons were built with weak focusing and operated well. But the amplitudes of oscillations about the ideal orbit are larger in a larger accelerator (approximately proportional to the radius), reaching 10 to 20 cm in the Cosmotron (3 GeV) and Bevatron (6 GeV) proton accelerators. It would be extremely costly to make use of weak focusing in a much higher energy accelerator, when oscillation amplitudes could be as large as several meters.

Strong focusing overcomes this difficulty by using an alternating series of gradients, thus alternating-gradient focusing, to focus both horizontally and vertically. An alternating series of gradients focuses a particle in a manner similar to an alternating series of optical lenses, as we can see in Fig. 18. A ray is farther from the axis in the converging (focusing) lenses than in the diverging (defocusing) lenses and so is bent more sharply, so that the net result is focusing.

A gradient that is focusing for horizontal motion is defocusing for vertical motion, but the alternation produces focusing in both. The complementarity that limits weak focusing is avoided and the focusing can be much stronger. The gradients vary periodically around the circumference of the accelerator, with a fixed number of periods per revolution. Oscillation amplitudes in a large synchrotron are a few centimeters or less and the vacuum chambers and magnet apertures are correspondingly small.

A particle that is not injected on the ideal orbit will execute betatron oscillations about that orbit. These oscillations are usually characterized by ν, the number of complete oscillations per revolution around the accelerator. There are separate values for horizontal (ν_r) and vertical (ν_z) oscillations. In a weak-focusing accelerator, the

oscillations are sinusoidal and both ν-values are less than unity. In a strong-focusing accelerator, these oscillations are sinusoidal on the average, with periodic excursions around the average sine wave, shown in Fig. 19, and ν_r and ν_z are usually considerably larger than unity. Thus in a weak-focusing accelerator, the oscillations have the form

$$\begin{aligned} r &= r_o + A_r \cos(\nu_r s/R + \theta_r) \\ z &= A_z \cos(\nu_z s/R + \theta_z), \end{aligned} \tag{3.3}$$

where the amplitudes A_r and A_z and the phases θ_r and θ_z are determined by the initial conditions at injection.

In a strong-focusing accelerator, the oscillations have the form

$$\begin{aligned} r &= r_o + A_r\sqrt{\beta_r(s)}\cos(\phi_r(s) + \theta_r) \\ z &= A_z\sqrt{\beta_z}\cos(\phi_z(s) + \theta_z) \end{aligned} \tag{3.4}$$

$$\phi_r(s) = \int_0^s \frac{ds}{\beta_r(s)}$$

and

$$\phi_z(s) = \int_0^s \frac{ds}{\beta_z(s)}$$

The periodic functions β_r and β_s are the betatron <u>amplitude functions.</u> By Eq. (3.4) the amplitude varies periodically with $\sqrt{\beta}$. By Eq. (3.5), the phase

advances as $1/\beta$, so that β is the instantaneous wavelength of the oscillation. The amplitude function and the ν-value are related because the total phase advance per revolution is

$$\phi(2\pi R) = 2\pi\nu = \int_0^{2\pi R} \frac{ds}{\beta(s)} \tag{3.6}$$

for either r or z.

A group of particles is injected with angles and positions distributed around the ideal orbit. It is instructive to plot the motion of the group of particles in a space whose axes are position and angle at a given point s, as in Fig. 20. This is called a phase space. As the group moves around the accelerator and s varies, the envelope containing the group will vary in shape, but its area will remain constant. If instead of the angle the product of angle and total momentum is taken as a phase-space coordinate, the phase-space area remains constant during acceleration. This is an example of a general dynamical rule called Liouville's Theorem. We shall return to this theorem in the discussions of beam stacking and cooling below.

The horizontal and vertical motions are independent in an ideal accelerator and each has a separate two-dimensional phase space. In a real accelerator, nonlinear restoring forces, magnetic-field imperfections or magnet misalignments can introduce horizontal-vertical coupling and the two motions can affect each other. The phase spaces are then not independent, but the four-dimensional volume of the combined phase spaces occupied by particles remains constant.

Magnetic-field errors and magnet misalignments can also

distort the beam path by inducing forced oscillations in the beam. The central orbit then moves in a periodic forced oscillation. the closed orbit, and all particles oscillate about this closed orbit. The occupied region of phase space than moves in this forced oscillation. If the ν-value is close to an integer, the closed-orbit oscillation becomes very large and the beam can rapidly leave the accelerator. This integral resonance can be kept under control by careful construction and alignment of the magnets and by careful control of the ν-value to avoid integers.

In a strong-focusing accelerator, errors in magnetic-field gradients can make the oscillations about the closed orbit unstable if the ν value is a half-integer. In this case, the occupied region of phase space becomes elongated, even though area is still preserved, and particles reach very large oscillation amplitudes. Half-integral resonances are not as serious as integral resonances, but care must be taken in construction and alignment to avoid them.

Even in an ideal accelerator, not all particles will have exactly the same momentum. Each particle's momentum will also vary relative to the ideal momentum during longitudinal oscillations, discussed below. A particle whose momentum is different from the central momentum will undergo forced transverse oscillations about the closed orbit. These will appear in phase space as overlapping groups of particles. This phenomenon is called dispersion in analogy to optics.

To be focused toward one another, two particles on different orbits must encounter different magnetic fields, as in a gradient magnet or quadrupole, or go through different lengths of field. Different lengths can be achieved by building magnets whose edges are not perpendicular to

particle orbit as we see in Fig. 21. This edge focusing is used in AVF cyclotrons. If an edge is slanted so that the path length increases with radius, the edge is horizontally defocusing and vertically focusing.

In a radial sector AVF cyclotron, both upstream and downstream magnet edges are vertically focusing. Radial focusing is provided by the increase of guide field with radius. This system is called Thomas focusing. In a spiral-sector AVF cyclotron, one edge is vertically focusing and the other is vertically defocusing, giving alternating-edge focusing, analogous to alternating-gradient focusing.

2. Linear Accelerators

The paths of particles in high-voltage accelerators are short enough that adequate focusing for the entire accelerator can be achieved at injection. Small radiofrequency electron linear-accelerators also need no external focusing. Longer electron linear-accelerator structures are interrupted periodically for focusing magnets.

Proton linear accelerator beams need focusing, partly because the transverse and longitudinal motions are more closely coupled than those in synchrotrons and energy from the longitudinal motion can drive transverse oscillations. There is no centripetal force in a linear accelerator, so there is no analogue of weak focusing. Before strong focusing was developed, many proton linear accelerators had wire grids installed in the drift-tube bore opening to change the variation with longitudinal distance and radius of the electric field to make it focus particles rather than defocus them. But the grids intercepted many beam particles and were unsuitable for high-intensity beams, because they were heated and burned by beam.

After strong focusing was developed, quadrupole focusing magnets were built into the drift-tube interiors and linear accelerators became high-intensity accelerators. More recently, methods of shaping the radiofrequency field to produce quadrupole focusing (RFQ) have been developed and provide even higher intensities and smaller beam losses.

Beams extracted from an accelerator and secondary beams produced in a target can also be steered and focused by sequences of bending magnets and strong-focusing lenses. These beam lines are used to bring beams to the point of use in an optimally focused configuration.

3. Synchrotron Lattices

The lattice of a synchrotron is the periodic arrangement of bending and focusing magnets around the circumference. The focusing, amplitude functions, and dispersion all depend on the lattice. Two developments make it possible to vary these functions and to achieve optimal desired orbit properties.

a. Separated-function Magnets

Particles are bent around the accelerator by dipole fields that are independent of radius. They are focused to stay close to the central orbit by quadrupole fields that vary linearly with distance from the center. In the original conception of strong focusing, these two functions of bending and focusing were combined in one gradient magnet, in a combined-function lattice. A separated-function lattice carries out these two functions in separate magnets. This lattice is more efficient because the bending field is the same throughout the magnet and is not limited by the maximum field attainable at the high-field side of the magnet. The bending field in a

separated-function conventional iron dipole can easily be 1.8 to 2 T, while in a gradient magnet it is difficult to achieve more than 1.3 T without significant field distortion. The difference is even more striking in superconducting magnets, where it is more difficult to design a gradient magnet. The focusing is also more efficient in a separated-function lattice, because focusing magnets are concentrated at locations where the amplitude function β is large and defocusing magnets are concentrated at locations at locations where β is small. Combined-function and separated function magnets are shown in cross section in Fig. 22. Separated-function lattices are now almost always used in synchrotrons and storage rings.

b. Long Straight Sections

The usual lattice has straight sections, field-free spaces between magnets whose maximum length is of the order of the magnet length. For the introduction of necessary auxiliary apparatus, such as accelerating cavities, injection equipment and particle detectors for experiments in storage rings, the long straight section has proven most useful. If the normal bending arcs of the accelerator are simply interrupted by field-free regions of size necessary to emplace necessary auxiliary equipment, the natural divergence of the beam will result in excessive aperture requirements. This divergence can be avoided by use of a few separate focusing lenses (quadrupoles) to maintain the focusing properties of the lattice without significantly encumbering the needed space. Periodic arrays, or sub lattices, of concentrated lenses permit design of straight, almost field-free regions of arbitrary length.

4. Experimental Measurement of Transverse Motion

It is possible to "fly blind" and operate a particle accelerator without measurements of the beam. Indeed, early accelerators operated this way, with the only indication of beam coming from the final accelerated beam striking a target and producing X-rays or radioactivity. But an accelerator can be operated much more easily and at much higher intensity if the beam position and size are known during acceleration or storage.

The first methods of beam measurement were movable probes to stop the beam at an adjustable radius in a cyclotron. In early synchrotons, probes were replaced by flourescent screens which were observed through transparent windows. These rudimentary devices are still sometimes used in the early stages of searching for circulating beam, although nowadays the energy is high enough that flourescent screens are viewed remotely using television cameras.

The center of mass of a circulating beam can be measured continuously by detecting the electric fields of the beam bunch with pickup electrodes or the magnetic fields with pickup coils, in each case surrounding the beam. By using these methods, it is possible to measure the transverse position at given locations and the phase of the beam bunches relative to the accelerating voltage. The transverse position as a function of azimuth is just the closed orbit discussed above. The beam is seen as a tube of charge centered on the closed orbit. The closed-orbit information can be used to set currents in correction magnets to reduce its distortion and to analayze magnet misalignments. The closed-orbit and beam-phase information are used

together as input to the rf feedback systems discussed in Sec. III-B. A measured closed orbit is shown in the upper part of Fig. 23.

Another important practical aspect of particle bending and focusing is scattering by the residual gas in the accelerator. Neglecting special space-charge effects, single charged particles or low-intensity beams suffer significant scattering and diffusion in even a few feet of air at normal pressure. Accordingly, the beam must pass through an evacuated space. Usually a vacuum-tight metal or ceramic tube surrounds the beam and is evacuated by pumps. In most accelerators, a residual pressure of 10^{-8} atmospheres is acceptable. In storage rings, where the effective path length may be several billion kilometers, a substantially better vacuum, 10^{-11} to 10^{-12} atmosphere, is required.

It is also possible to measure the beam shape making use of ionization of a dilute gas by the beam or by analysis of the frequency spectrum of the beam electric field, with knowledge of the dispersion function at the location of the pickup. In places where each beam particle passes only once, grids of wires can be used in connection with ionization or a single wire can be moved rapidly through the beam. Two measurements arriving at the acceleration system at different locations can be combined to give the distribution in phase space. An example of such a measurement is shown in the lower part of Fig. 23.

B. Longitudinal Motion

1. Introduction

In dc high-voltage accelerators or in induction accelerators (betatrons), particles that are accelerated at different times experience

the same accelerating field. But in accelerators that utilize radiofrequency fields to accelerate particles (linear accelerators, microtrons, cyclotrons, and synchrotrons), particles at different times will experience different accelerating fields and will consequently have different motions.

2. Longitudinal Stability and Acceleration

How the longitudinal motion evolves will depend on how the frequency of revolution depends on particle energy. Let us illustrate this by a simple physical example. In the accompanying plot of Fig. 24, the ordinate is the accelerating voltage and the abscissa is time. Thus on this plot the accelerating voltge is a sine wave. Consider now two particles that cross the accelerating gap at the same time on one revolution. The voltage is rising as they cross. Particle 1 is in step with the accelerating voltage and crosses the gap the second time at the same phase. Particle 2 has higher energy. Let us consider two alternatives:

(i) Revolution frequencies increases with energy ($df/dE > 0$). Then the revolution period is smaller for particle 2 and it will arrive earlier, lower on the sine wave and will gain less energy than particle 1. The energy difference between the two particles will be decreased after the second pass. Similarly, a particle of lower energy would arrive later, higher on the wave, and would gain more energy, again decreasing the energy difference. Thus the energy difference across the entire group of particles will not increase and they will be accelerated together. The accelerating longitudinal motion is stable.

(ii) Revolution frequency decreases with energy ($df/dE < 0$). Now particle 2 arrives later and gains more energy than particle 1. It continues to gain more energy at every pass and the energy difference increases continuously. Thus the longitudinal motion is unstable and the group of particles will break up and not be usefully accelerated.

Luckily, there is a saving grace. There is another side to the voltage wave, where the voltge is still in the right direction to accelerate, but is falling. Now the arguments of less or more voltage are just reversed and the acceleration longitudinal motion is stable in an accelerator with $df/dE < 0$.

What affects df/dE? There are two factors: a particle with higher energy goes faster, which always increases its frequency, but in some accelerators, it goes on a different orbit between gap crossings, which in almost all cases decreases its frequency of revolution. These two factors are in opposite directions; how they balance depends on the kind of accelerator.

In linear accelerators, all particles travel the same path and there is no difference in path length, only difference in speed; thus df/dE is always positive. On the other hand, in weak-focusing synchrotrons, orbits corresponding to different energies are relatively widely separated because the guide-field variation with radius is small. Here the path-length difference always overbalances the speed difference and df/dE is always negative. The same is true in a microtron. In strong-focusing synchrotrons, the speed difference is larger than the path-length difference at

low energy in protron accelerators, so $df/dE > 0$, but the path-length difference is constant and the speed difference decreases as particle speeds approach the speed of light, so that $df/dE < 0$ at high energy. There is thus a transition energy at which df/dE is zero. At this energy, the radiofrequency accelerating voltage must be turned off, then turned back on within a few milliseconds at a different phase relative to the beam particles. Acceleration then continues on the back side of the wave. This has not been difficult in practice in proton synchrotrons. It is not necessary at all in strong-focusing electron synchrotrons because electrons move at close to the speed of light at much lower energy and the transition energy in an electron synchrotron is therefore lower than the injection energy and is never crossed.

In this discussion, cyclotrons are an anomaly. In principle, speed differences and path-length differences just balance in cyclotrons and they are always exactly at transition energy. In practice, there are small effects beyond our present discussion that give enough mariginal stability that particles are accelerated.

3. Phase Oscillations

The qualitative discussion of longitudinal stability can be made quantitative. The results of quantitative study can be described graphically in a plot like that of Fig. 25, giving angular momentum of the particle (almost the same thing as energy) against phase of a particle relative to the radiofrequency

accelerating voltage. This phase can vary between 0 and 2π (360°). If the accelerating voltage is turned off and a group of particles is simply coasting around the ring, this group is represented by a band stretching horizontally across the entire range of 2π in phase and stretching vertically across a range in angular momentum (and energy) that corresponds to the energy spread of the group.

When there is an accelerating voltage, there is a region of closed curves representing stable oscillations. These curves surround an equilibrium phase, which appears on the plot as a point at the center. A particle that starts at this phase and angular momentum will remain at it as the whole plot rises vertically during accleration. Particles that start within the stable region will move on a closed curve around the equilibrium phase, oscillating in momentum and phase. These oscillations are called phase oscillations or synchrotron oscillations. In almost all cases, the frequency of these oscillations is very much smaller than the frequency of revolution, so that many revolutions are needed to complete one circuit around the diagram. Particles of different energy have different orbits in a circular accelerator and there is a radial oscillation corresponding to the energy oscillation of phase oscillations.

The stable region is called a bucket. The edge of a bucket is called the separatrix. Particles starting beyond the separatrix will slip in phase relative to the accelerating voltage and will not be accelerated continuously.

During acceleration, the particles form a bunch within the

bucket. Even if they fill the bucket to the separatrix, they do not occupy the full 2π in phase; a bucket that accelerates occupies less than 2π, because the voltage is decelerating for half the range in phase.

It is also possible to have a stationary bucket, where the equilibrium particle crosses the accelerating gap at the moment the voltage is zero. In a stationary bucket, particles can occupy the entire 2π in phase. It is also possible to accelerate a bunch in a stationary bucket by starting it near the bottom and continuing through half a phase oscillation, where it is near the top. This is how acceleration takes place in a electron linear accelerator.

In circular accelerators, the accelerating frequency is an integral multiple of the revolution frequency. Use of a higher frequency will make it possible to use smaller accelerating cavities and power amplifiers. It may also make it possible to use radiofrequency components developed for other applications. The multiple h is the harmonic number. There are now h buckets stretched across the range of 2π in phase. Each of these buckets has the properties discussed above.

The operation of a synchrotron accelerating system can be improved considerably by a beam feedback system. Pickup electrodes of the kind described in Sec. II-B above are used to measure the phase and radius of the beam bunches. This information is fed back electronically to correct the phase and voltage of the accelerating sytem to keep the beam centered in the vacuum chamber and the beam and radiofrequency accelerating sytem in phase with each other.

External signals can be used at particular times in the cycle to move the beam either laterally or longitudinally for purposes of extraction, targeting, or stacking.

In this plot of angular momentum vs. phase, the area occupied by a group of particles remains constant during acceleration. This combination is a longitudinal phase space, analogous to the phase spaces discussed in connection with transverse motion.

Even though phase-space area is preserved, in many cases the bunch will filament into many small threads that wind around the bucket. The empty areas between filaments are carried along with bunches in acceleration and the effective area of the bunch can increase, thus "mixing in empty space." It is possible to avoid this decrease of density by turning accelerating voltages on and off very slowly or by overfilling buckets at the start, so they stay full through acceleration, while some particles are thrown away.

4. Beam Stacking

A batch of accelerated particles can be left to circulate in a storage ring. Then another batch can be injected, accelerated, and put next to the first bunch in energy. This stacking process can be repeated many times. If care is taken to avoid mixing in empty space, the total phase-space area occupied is the sum of the areas of the individual batches. The particle density in physical space can be increased greatly by beam stacking and this makes colliding beams feasible.

Synchrotron radiation in electron or positron storage rings

helps, because the emission of radiation damps motion in a properly designed ring and increases the density in phase space and the particle density in physical space, which increases the interaction rate.

C. Many-Particle Effects

1. Introduction

In almost every use of accelerators, higher intensity is desirable. But higher intensities bring with them new phenomena arising from the electromagnetic forces between particles. These forces can affect the focusing of particles and can also introduce new kinds of instabilities.

2. Effects on Focusing

The electrostatic repulsion between particles in a beam decreases the restoring forces that focus the beam. This decreases the transverse-oscillation frequency of the focusing. As more particles are added, the frequency continues to decrease until it reaches a resonance. Then additional particles will be driven to large amplitude by the resonance and lost. The beam is space-charge limited.

Two charges moving on parallel paths repel each other electrostatically, but they also form two parallel currents, which are attracted to each other by magnetic forces. The magnetic forces reduce the electrostatic repulsion and increase the space-charge limit. The repulsive force is always greater, but the magnetic force increases as the particles are speeded up, so space-charge forces are very small at high energies. Both the electrostatic and magnetic forces are modified at high energy by the presence of the conducting vacuum chamber surrounding the beam. walls.

It is possible to cancel space-charge forces by injecting charges of the

opposite sign, electrons in a positive-ion beam or positive ions in a electron beam. These attract beam particles and the combination of this charge neutralization and magnetic attraction can completely cancel space-charge effects, making it possible for the beam to "pinch" down to a thread. But this pinched beam is like the free end of a spurting water hose - it kinks and lashes around like a snake, so that it is highly unstable and not useful for accelerating particles.

3. Instabilities

The kink instability is an example of the phenomena that arise from the electromagnetic fields of the beam. These fields can be reflected back from the metal vacuum chamber to react on the beam. They can drive the beam either longitudinally or transversely. These phenomena are called coherent instabilities because all the beam particles feel the same forces and move coherently together. Because it is coherent, the motion can be detected by a beam pickup and an opposing electromagnetic force applied to electrodes inside the chamber. The bad effects of coherent instabilities can be overcome to some extent by such feedback systems. In some cases, however, the frequencies involved are too high to make feedback practical and the instabilities must be controlled by design changes.

D. Beam Cooling

We have emphasized in our discussion above the constancy of phase-space area, both longitudinal and transverse. But there are methods to reduce the phase-space area and thus to increase the density of particle beams, which is advantageous for colliding beams. These methods are called beam cooling.

In all kinds of beam cooling, there is an interaction with another physical system. The phase-space area of the total physical system is constant, but the

area of a smaller part can be decreased by transferring phsae-space area to the rest of the system.

1. Synchrotron Radiation

All charged particles radiate electromagnetic energy when accelerated. The only effects usually significant for particle accelerators occur for the lightest charged particles, electrons and positrons, although at the multi-Tev energies now being discussed, synchrotron radiation is also important for protons. As they are bent around the curved path by centripetal acceleration in a circular accelerator or storage ring, electrons and positrons emit a narrow cone of radiation, tangent to their instantaneous orbits. The radiated energy is mostly in the ultraviolet and X-ray regions. The energy radiated increases rapidly as the particle energy is increased, as we saw in Eq. (2.5). Most of the accelerator voltage in a multi-GeV electron synchrotron is needed to make up the energy radiated away.

This synchrotron radiation decreases both longitudinal and transverse particle oscillations about the equilibrium orbit. Longitudinal or energy oscillations are reduced because particles with energy exceeding the equilibrium value will radiate at a greater rate than equilibrum particles and thereby be damped toward the equilibrium energy. Particles with energy less than the equilibrium value radiate at a smaller rate than equilibrium particles and are restored toward the equilibrium energy by the accelerating system. Transverse oscillations are damped because the synchrotron radiation is emitted along the direction of motion, reducing both longitudinal and transverse momentum components. The accelerating system restores only the longitudinal momentum component.

Neither longitudinal nor transverse oscillations are reduced all the way to zero because the sudden random emission of the photons that make up the synchrotron radiation itself excites small longitudinal and transverse oscillations. The equilibrium beam size, typically about a millimeter, results from the balance between the average damping effect and this stochastic quantum excitation.

In synchrotron radiation, the phase-space area of the beam is decreased, while the phase-space area of the electromagnetic field is increased by the additon of the radiated photons.

2. Electron Cooling

A gas of protons or heavy ions and a gas of electrons will interact with one another by Rutherford scattering. If the proton gas has more thermal energy, it will give this energy to the electrons through the scattering, thus decreasing the phase-space area of the proton gas while increasing that of the electron gas.

This exchange will also occur in a frame of reference in which both gases are moving together in the same direction, that is, if they are proton and electron beams. This electron cooling can reduce both the longitudinal and transverse enegy spreads of the beam. Electron cooling is done in practice by arranging an electron beam to move at the same speed as the proton beam through a straight section of a ring. At the same speed, the electron beam has much less momentum and is easily bent in and out of the proton beam at the ends of the straight section. The proton beam is repeatedly cooled by multiple traversals of the straight section as it circulates.

Electron cooling is more effective at lower energy, although

higher-energy cooling has been discussed. It can be made much more effective by the addition of an external longitudinal magnetic field.

3. Stochastic Cooling

Decrease of the amplitude of a coherent oscillation by means of electronic feedback was discussed above in Sec. III B. The root mean square amplitude of a beam can also be reduced by a feedback system. This is stochastic cooling. The basic plan of stochastic cooling is a beam pickup that measures the average position of the beam, an amplifier system, and a kicker that transmits the amplified signal to the beam.

Consider a ring full of N circulating particles and break the circulating beam up into N parcels, so that each parcel around the ring contains only one particle. If the electronic system has enough frequency bandwidth to respond to this small a parcel, it can give a signal to the kicker to correct each individual particle. Thus particles give up their phase-space area to the electronic system.

If, as in practice, the electronic system has smaller bandwidth, each parcel has more than one particle. Each of the other particles in a parcel gives electronic noise interfering with a given particle's correction signal and the system corrects more slowly. Eventually, as more particles are added, the noise masks the signal completely and cooling ceases.

Stochastic cooling has been used as the basis for a spectactularly successful effort to cool antiproton beams and to use them in a colliding-beam system with counter-circulating particles. Important new results in physics have been achieved with this system.

IV. Accelerators of the Future

As discussed in the historical section of the introduction, remarkable improvements in accelerator capabiliites have been achieved. In applications to science, medicine and industry, these improvements have increased maximum energy capabilities by a factor of more than 10 million in fifty years, increased beam current capacity by an even larger factor, increased the variety of atomic particles that can be accelerated and lowered the cost of particle acceleration dramatically. These improvements have been brought about by a combination of means: new acceleration methods have been devised and technological improvements to existing methods have continually come about.

Developments in accelerators for basic scientific research have emphasized energy increase at lowered cost per unit beam energy. Improvements in accelerators for medicine have focused on increasing the variety of particles that can be accelerated, the precision of control over the beams and the compactness and cost effectiveness of the devices. Industrial applications have continuously broadened through reduction in accelerator costs, increases in beam current and variety of accelerated particle and through miniaturation and increased portability.

Even though accelerators have become very sophisticated, the rate of improvement has remained steady. While this progress has occurred across the whole range of accelerator applications, the most dramatic developments have usually occurred in accelerators to be used for basic science. It is the expected developments in this area that are emphasized here. We may classify these developments as improvements to existing accelerator types and as new and improved accelerator methods.

A. Improvements to Existing Research Accelerator Types

Developments of existing methods come through deepening understanding of the physics of the method and through application of new and improved materials and techniques both in the design and in the manufacture of the accelerator. One can foresee significant improvements to both circular accelerators and microwave linacs.

1. Circular Accelerators

Basic particle physics research with colliding proton beams up to 100 TeV or more per beam can probably be carried out with circular accelerators based on the synchrotron principle. Continuing improvement in our understanding of nonlinear particle dynamics and of collective effects, in dense beams will permit use of smaller and therefore more economical magnet and beam-channel cross sections while accelerating denser beams. Superconducting materials that are available now could be used to construct a 20-TeV proton storage ring of 90 km circumference, having a peak magnetic field of 6 Tesla. Materials now under study in the laboratory may make possible accelerator magnets that operate at up to 15 Tesla. With such magnets, an accelerator of 100 TeV with 190 km circumference would be possible. Expected improvements in cryogenic technology and electronic controls will make it possible to operate such an accelerator with a few people and at power demands about the same as those of present research accelerator complexes.

Circular accelerators producing synchrotron radiation for basic physical, biological and chemical research will also be markedly improved through basic understanding of the physics of these accelerators and of the mechanisms of coherent radiation production. The next generation of such machines is likely to be about 1 km in circumference and be outfitted with

special devices called wigglers and undulators for enhancing the emitted radiation for particular research purposes. The wavelength of the radiation will be adjustable and concentrated in a narrow band and its intensity will be increased, permitting a broader range of use.

B. Microwave Linacs

Because of the intense synchrotron radiation emitted by electrons confined in circular accelerators, basic particle physics reserach with electrons at energies much above 100 GeV will probably have to be carried out with colliding beams produced by linacs. One can foresee the possibility of extending current microwave linac technology up to perhaps 1 Tev per beam. Such a collider might employ two 10-km linacs. Required for economic viability will be improved understanding of beam collective effects permitting acceleration of denser beams, as well as accelerating waveguides capable of better energy transfer to the beam while supporting effective accelerating fields of about 100 MV per meter. Such gradients have been produced in the laboratory. An additional ingredient must be microwave power sources capable of several hundred megawatts peak pulse power with high efficiency. A microwave generator based on a relativistic electron beam formed by photemission from a pulsed laser-irradiated photo cathode, the lasertron, gives some initial promise of meeting these goals. Other generators under development may also turn out to be useful. Although less far along in development, the superconducting microwave linac may play a future role in research applications requiring long pulses or continuous beams. Such machines for low-energy nuclear physics research are now in operation and an intermediate-energy machine is under construction.

New and Improved Acceleration Methods

Although circular accelerators for special purposes are likely to be used for many years to come, the dissipative synchrotron radiation to which all charged particles following curved orbits are subject will limit the viability of any type of circular accelerator at some energy. One may thus expect a growing emphasis on linear accelerators. In all such devices the particles being accelerated gain their energy at the expense of an electromagnetic wave of some type. To be useful, the wave must travel at a velocity very close to that of the particle and have a signficiant electric field component in the desired direction of motion of the particle. Different existing or potential accelerator types are distinguished by how the accelerating electromagnetic wave is created and how its velocity is controlled. In principle, these necessary conditions for acceleration can be arranged in free space near far from any material body, in a space near a specially designed array of conductors or dielectories, or in some material medium.

In free space, only plane electromagnetic waves exist. In these waves electric and magnetic fields are transverse to the wave velocity. A single-frequency plane wave is incapable of continuous acceleration of a charged particle. If two waves of different frequencies are used, however, continuous acceleration can be achieved, one wave serves to give the particle a slightly sinuous orbit so that its velocity has a component parallel to the accelerating field of the second wave. This is the inverse free electron laser. Because the orbit is slightly curved, it also is limited in its maximum energy capability by synchrotron radiation. Although no such accelerator has yet been operated, it is estimated that electron

energies of up to 300 GeV might be achieved. As currently conceived, it would not be a useful accelerator for protons or heavier particles.

Various arrangements of conductors have been devised to support longitudinal electromagnetic waves at wave velocities close to of light. The classical microwave linac is one such. By operating such a device at shorter wavelengths, it is believed that higher accelerating fields might be supported. At wavelengths of 1 cm or less, a free electron laser (q.v.) might be used as the source of the driving electromagnetic wave and is believed to have the potential for high conversion efficiency. The low-energy, high-current beam of the laser might be parallel and close to the low-current, high-energy beam being accelerated, thereby minimizing coupling losses. This idea has been called the two-beam accelerator. A free electron laser of almost 100 MW peak power at 1 cm has been operated. The maximum accelerating field capability of all accelerators using conductor arrays to control the wave type and velocity is limited by damage to the conducting material. A possible way to avoid this fundamental limit is to use a different array for each pulse so that damage is not relevant. The possibility of forming a suitable periodic array of liquid droplets made conducting by creating a plasma on their surfaces has been suggested. To take advantage of the enormous peak power available from lasers as an electromagnetic wave source, the droplets would be of microscopic size. No such accelerator has been constructed and may practical details remain to be worked out. Accelerating fields of several hundred MV/m might be possible.

The accelerators discussed above are driven by harmonic power sources. A wide frequency band conductor-controlled accelerator, the wake field transformer accelerator, has been proposed. Similar in some respects to the

two-beam accelerator, it employs as energy source a high-current, low-energy beam consisting of a series of rings propagating along their axis of syummetry at essentially the velocity of light. The energy carried by this rings is deposited as a pulse of energy near the periphery of a conducting cylinder. This pulse of energy propagates toward the center of the cylinder being compressed thereby. The resulting high fields at the center are then used to accelerate the low-current, high-energy beam. Acceleration fields of as much as 200 MV/m are expected. Prototypes are under construction.

In a medium such as a gas, plasma or charged-particle beam, electromagnetic waves propagate more slowly than in free space. One of this fact can be used to achieve continuous acceleration in a variety of ways. One of the most interesting is the beat-wave accelerator. In this device, two superposed laser beams of slightly different frequency travel coaxially or almost coaxially with and just ahead of the particle beam to be accelerated. If the difference of the two laser frequencies is just equal to the plasma frequency, the laser pulses resonantly organizes the plasma into dense clumps with ratified spaces between, like beads as a string along the path of the laser pulses. The electric fields resulting from these charge separations are calculated to be enormous, as much as several GV/m. The existence of beat waves has been established experimentally as has their ability to accelerate particles. Suitable lasers and plasma parameters needed to engender the enormous fields predicted have not yet been achieved.

Improvements in accelerator development will result from all of these studies. Which, if any, of these approaches will provide the frontline accelerators of the future remains to be seen.

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The Physics of Particle Accelerators, (review article) J.D. Lawson and M. Tigner in Annual Review of Nuclear and Particle Science, Vol. 34, p. 99, Annual Reviews, Inc. Palo Alto, CA. 1984.

Particle Accelerators, (article) Robert R. Wilson, Scientific American, Vol. 242, January 1980, p. 26.

Illustrations

Figure 1 The world's highest energy accelerator, the Fermi National Accelerator Laboratory, from the air. The accelerator is in an underground tunnel (shown in Fig. 3); a road and a cooling-water pond outline the tunnel on the surface. The accelerated beam is extracted for use in experiments in the areas stretching toward the top left of the photograph. (Photo courtesy Fermilab).

Figure 2 Schematic diagram of fixed-target and colliding-beam experimental methods.

Figure 3 The Fermilab accelerator tunnel. The upper ring of magnets is the Main Ring, completed in 1972, that accelerates protons to 400 GeV. It is now used to inject 150-GeV protons into the lower ring, the superconducting 1-TeV Tevatron. Above the rings are cooling-water lines, bus tubes for magnet current, and trays for signal wires from diagnostic equipment. The worker is riding an electric golf cart, the preferred means of getting around the 6.3-km tunnel. (Photo courtesy Fermilab).

Figure 4 Column of 14-MeV Tandem Pelletron Electrostatic Generator. In operation, it is enclosed in a steel tank 5.5 m in diameter and 22 m tall containing sulfur hexafluoride gas at a pressure of 7 atmospheres. (Photo courtesy National Electrostatics Corp.).

Figure 5 The tunnel of the Stanford linear accelerator. The accelerator waveguide is the white horizontal tube at the man's eye level. It sits on a strong girder system for alignment and stability. Radio frequency power is fed to the waveguide from klystrn amplifiers in separate buildings through the rectangular tubes. The white tubes supply cooling water (Photo courtesy SLAC).

Figure 6 The superconducting AVF cyclotron at Michigan State University. The magnet coils are in a cryostat by which the scientist is standing. Radiofrequency power is brought in through the tubes at the top. (Photo courtesy Michigan State University).

Figure 7 Electric and magnetic forces.

Figure 8 Historical development of accelerator energy.

Figure 9 Schematic diagram of a voltage-multiplying circuit.

Figure 10 Schematic diagram of an electrostatic generator or Van de Graaf accelerator.

Figure 11 Schematic diagram of a standing-wave drift-tube linear accelerator.

Figure 12 Cutaway view of a travelling-wave waveguide. The radiofrequency wavelength used is approximately 10 cm. The beam enters from the upper left and passes through the small hole. Radiofrequency power is brought in at the upper right and the wave travels with the beam. (Photo courtesy SLAC.)

Figure 13 Schematic diagram of cyclotron orbits.

Figure 14 Schematic diagram of microtron orbits.

Figure 15. Operation cycle of a synchrotron.

Figure 16. The CERN Intersecting Storage Rings. The large blocks are qradient magnets. The intersection of the two vacuum chambers can be clearly seen. (Photo courtesy CERN.)

Figure 17 Radial field and resulting vertical force in a gradient magnet.

Figure 18 Focusing of rays in a series of lenses.

Figure 19 A particle oscillation in an alternating-gradient structure (T:focussing, -:defocusing).

Figure 20 Transverse phase space. The shaded area is a group of particles. This ellipse will oscillate as the group goes around the accelerator.

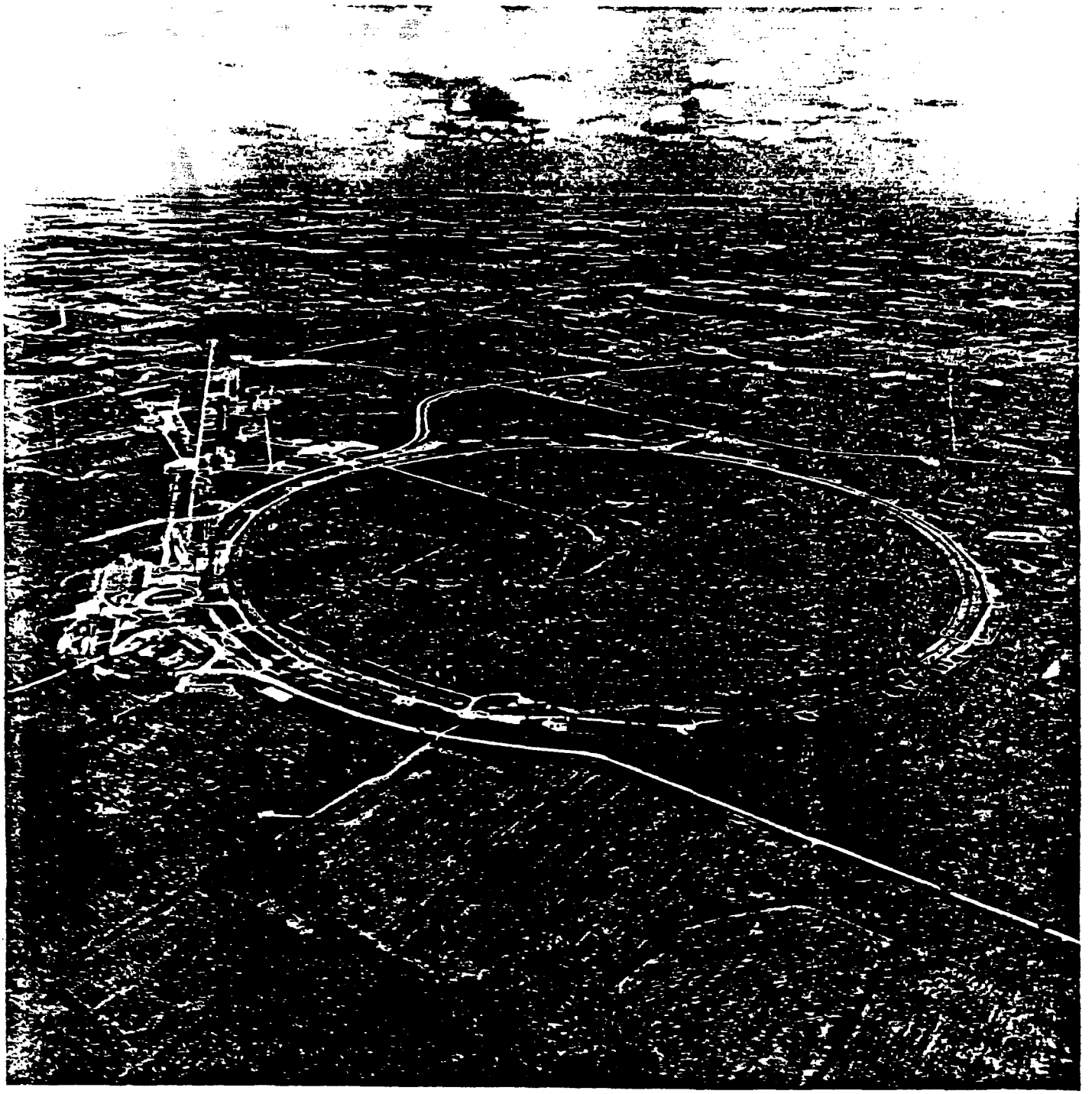
Figure 21 Gradient and edge focusing.

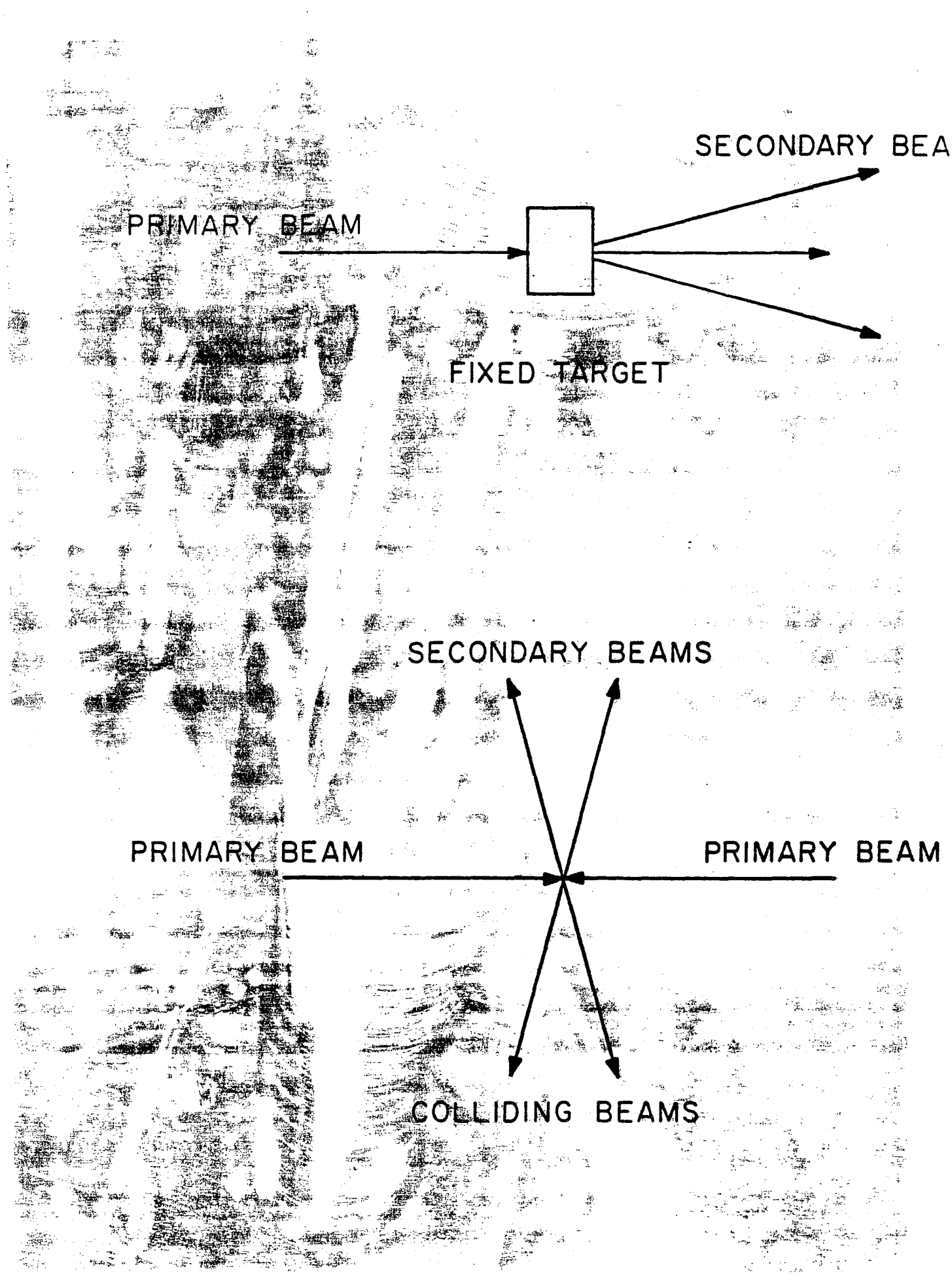
Figure 22 Alternating gradient synchrotron magnet cross sections.
a. Gradient (combined-function) magnet
b. Dipole (bending) magnet.
c. Quadrupole (focusing) magnet.
d. Superconducting dipole magnet.
e. Superconducting quadrupole magnet.

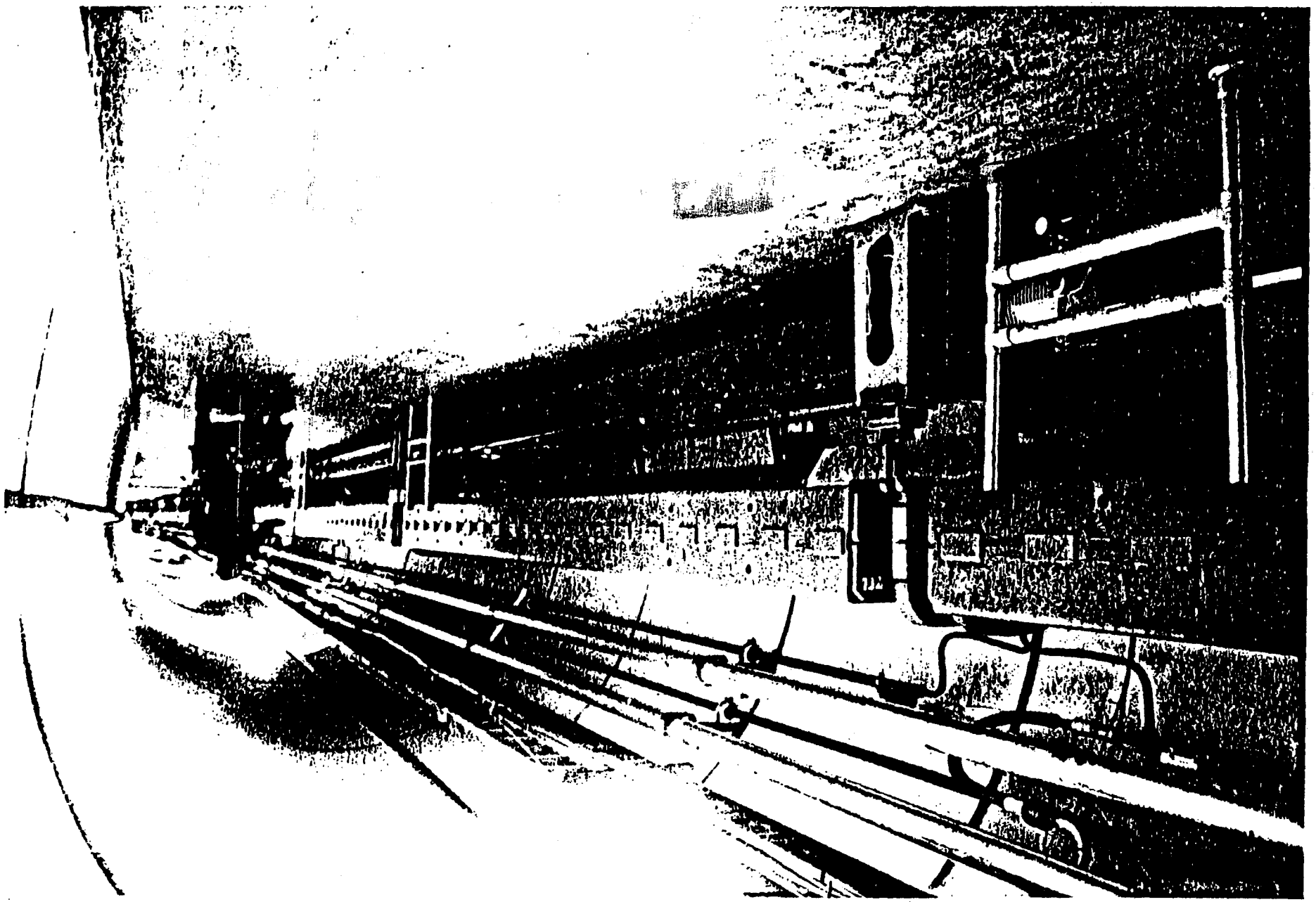
Figure 23 Measured orbit properties
a. Closed-orbit displacement around a circular accelerator.
b. Emittances. The horizontal axis of the three-dimensional plot is displacement; the diagonal axis is angle. The vertical is beam intensity. At the lower right is the distribution in angle. At the upper left is a phase-space plot of the contour containing a stated fraction of the beam. At the upper right is a plot of the fraction of beam contained within the emittance of the horizontal axis. (Photos courtesy Fermilab.)

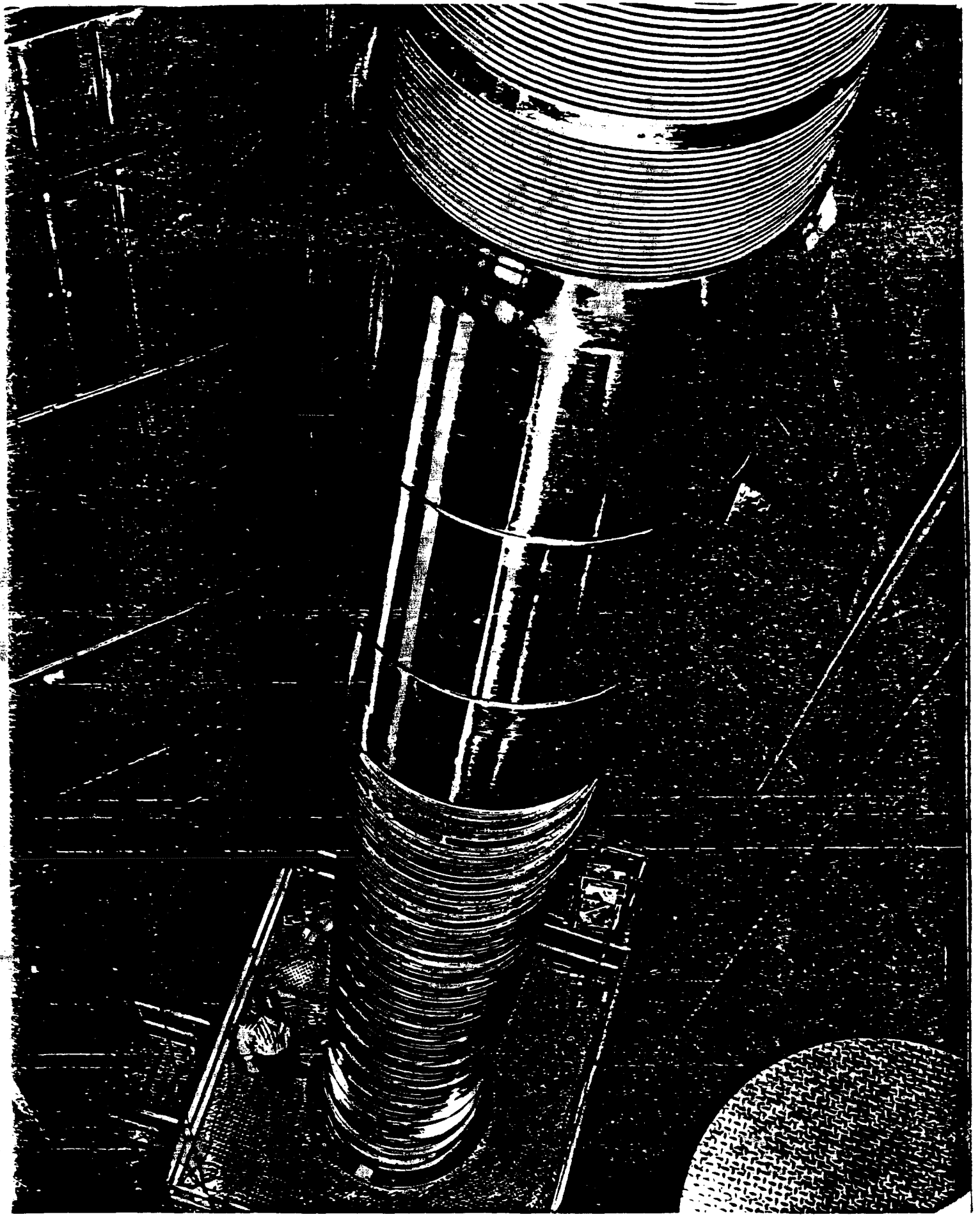
Figure 24 Particles riding on a voltage wave during acceleration (See text).

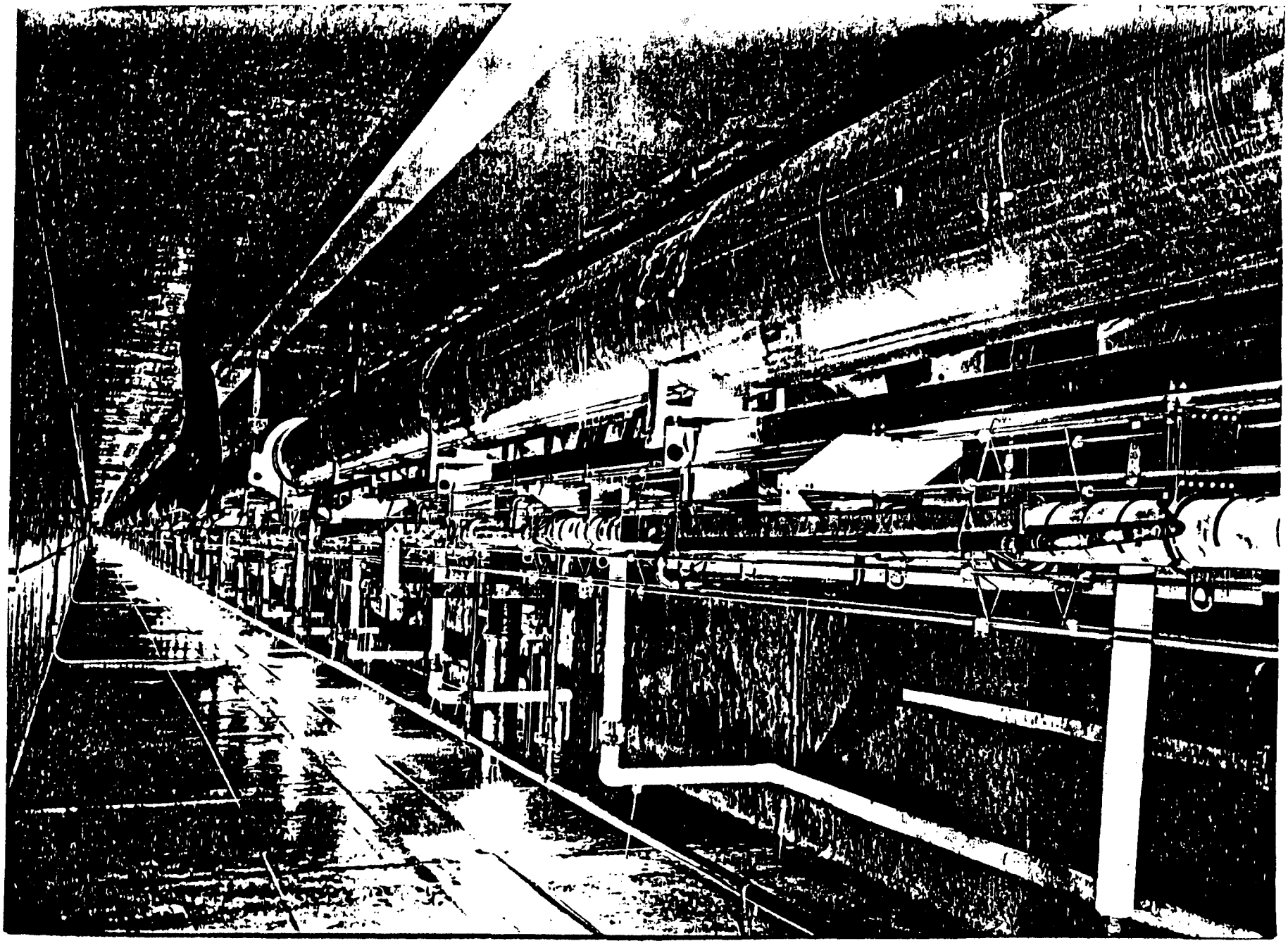
Figure 25 An accelerating bucket. Particles in the shaded area will move on closed curves as the bucket moves up in energy during acceleration. Particles outside the bucket will slip in phase and be lost.

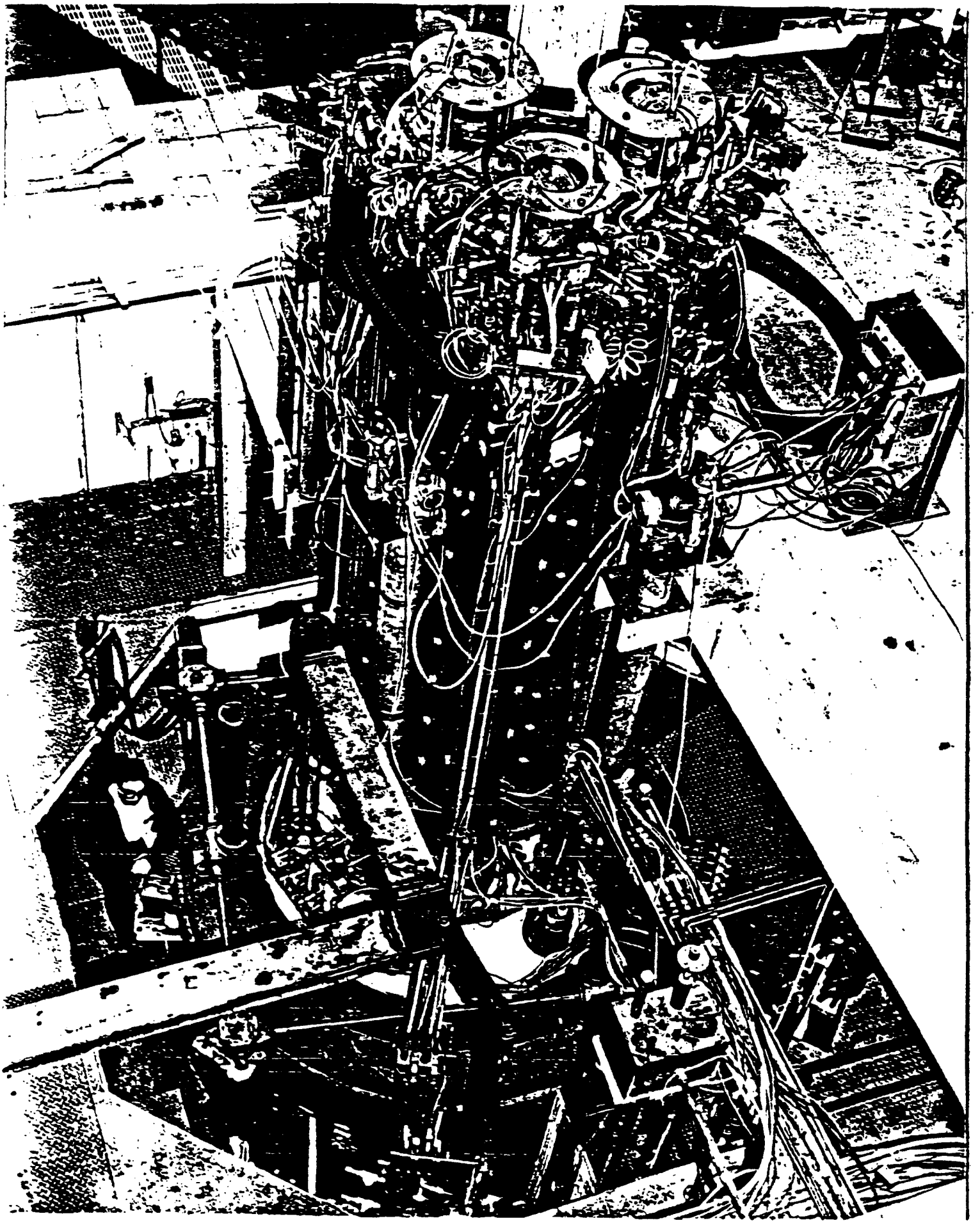


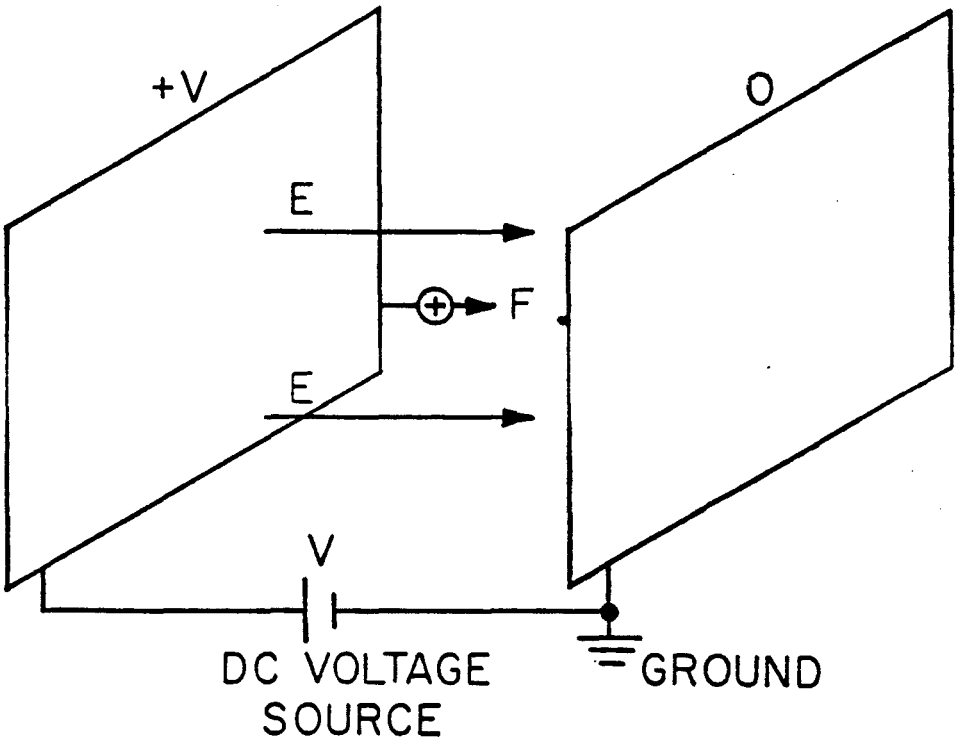

SECONDARY BEAMS
PRIMARY BEAM
FIXED TARGET
SECONDARY BEAMS
PRIMARY BEAM
PRIMARY BEAM
COLLIDING BEAMS



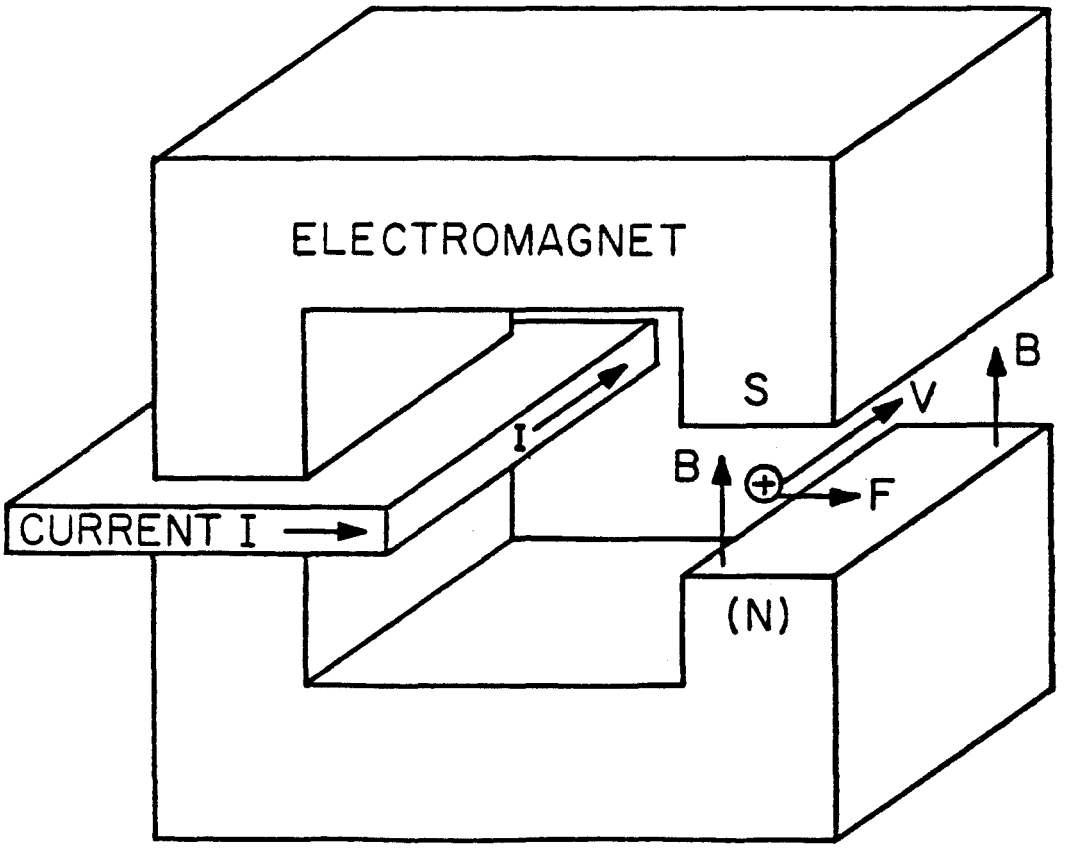




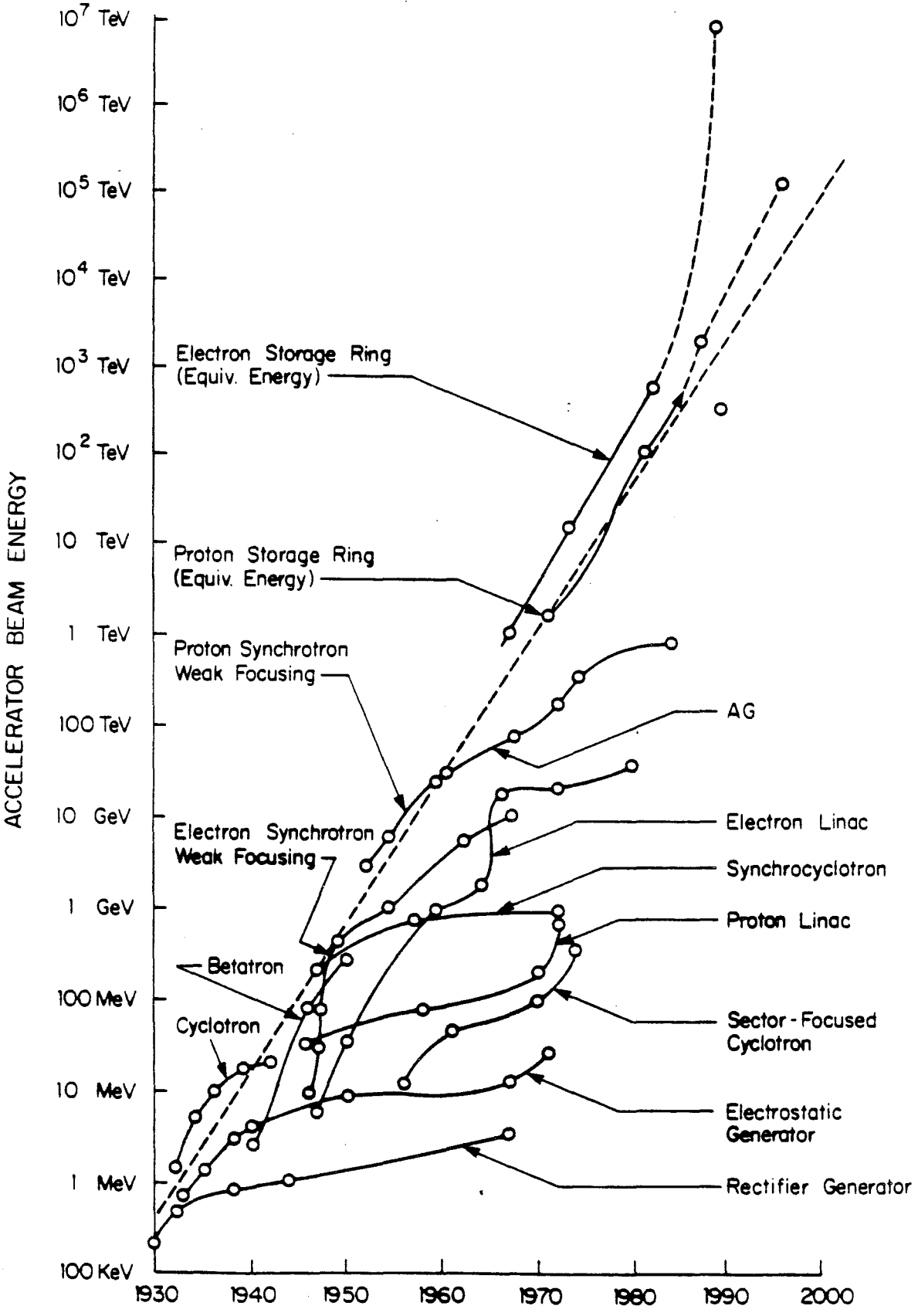


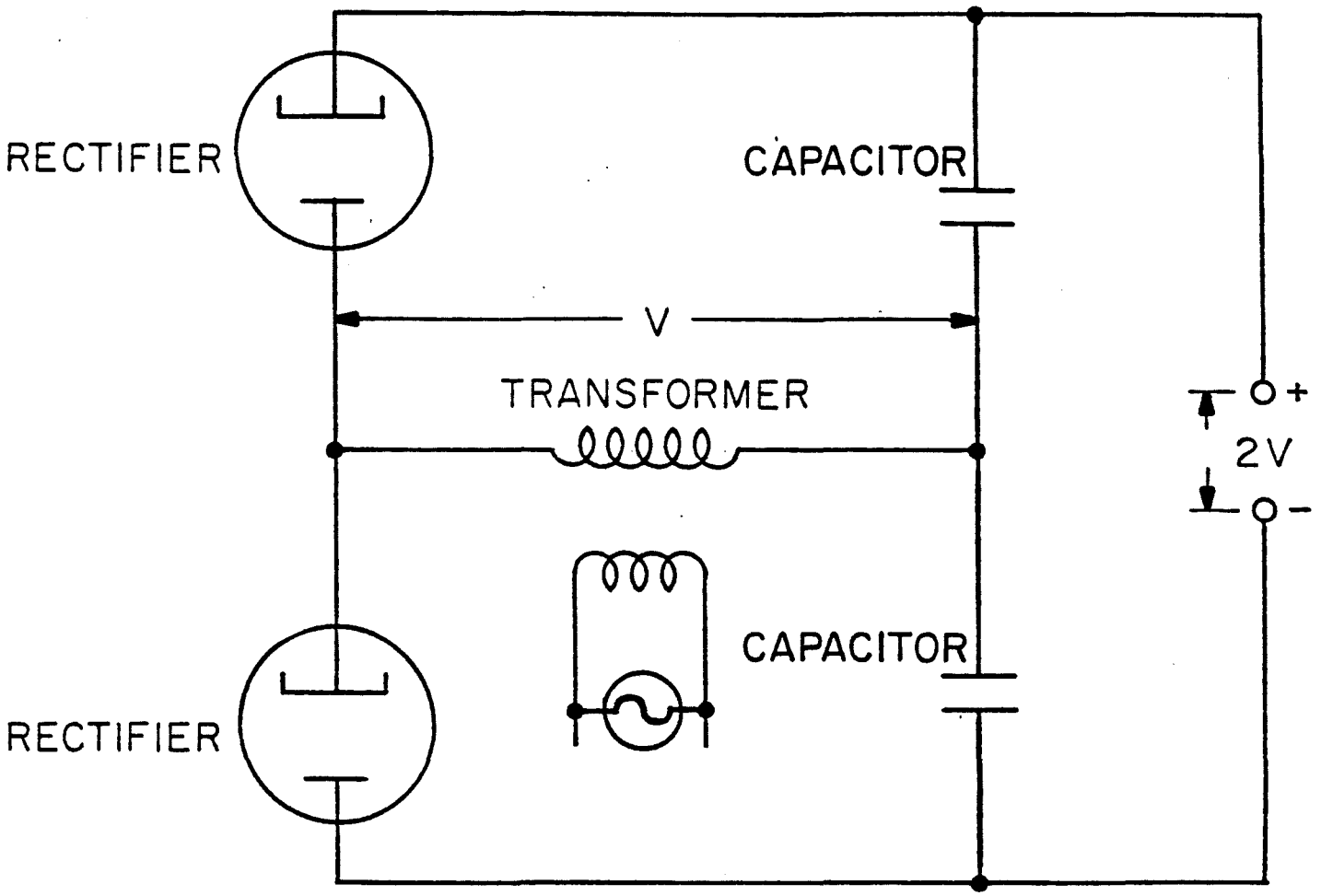


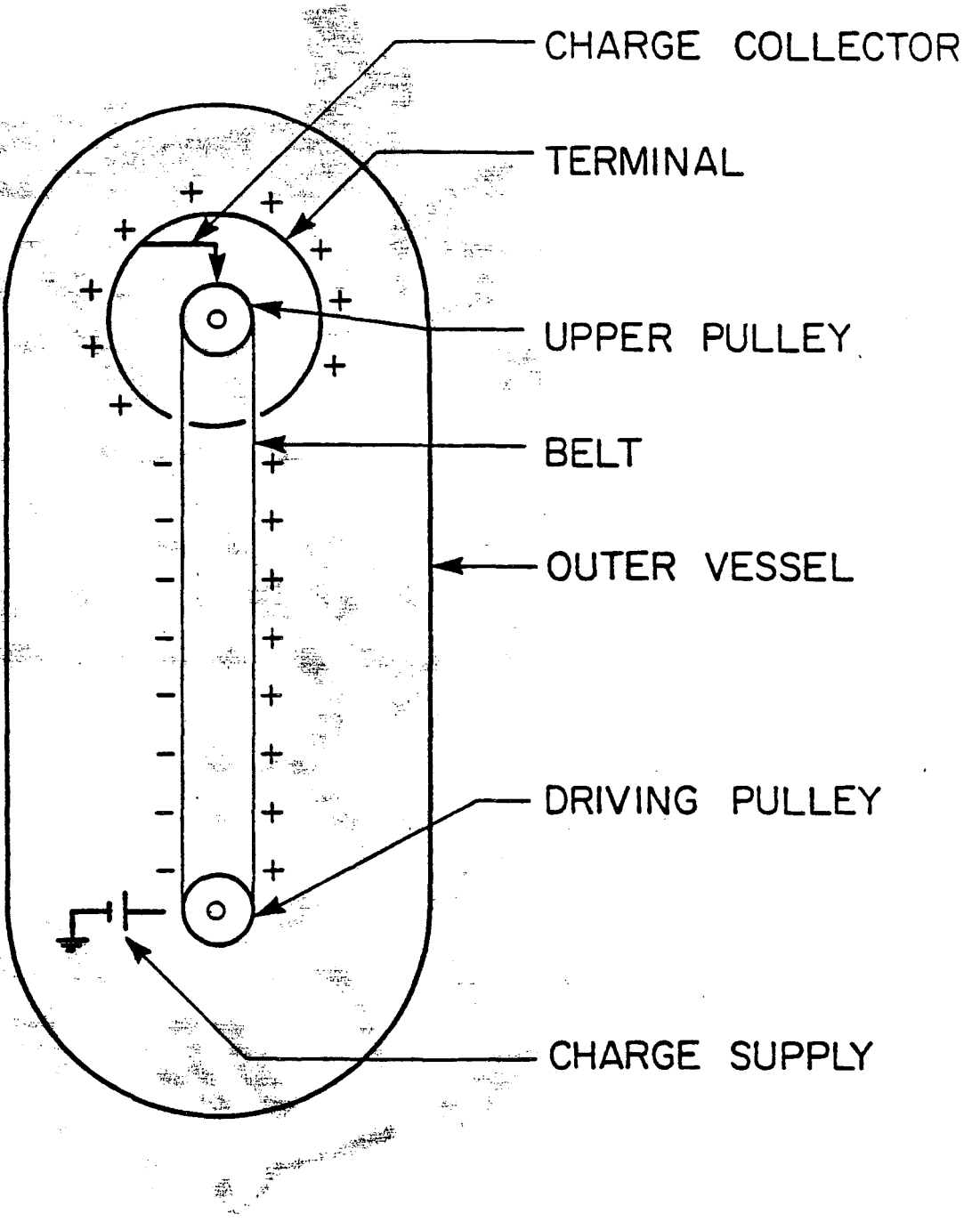
(a) ELECTRIC FIELD and FORCE

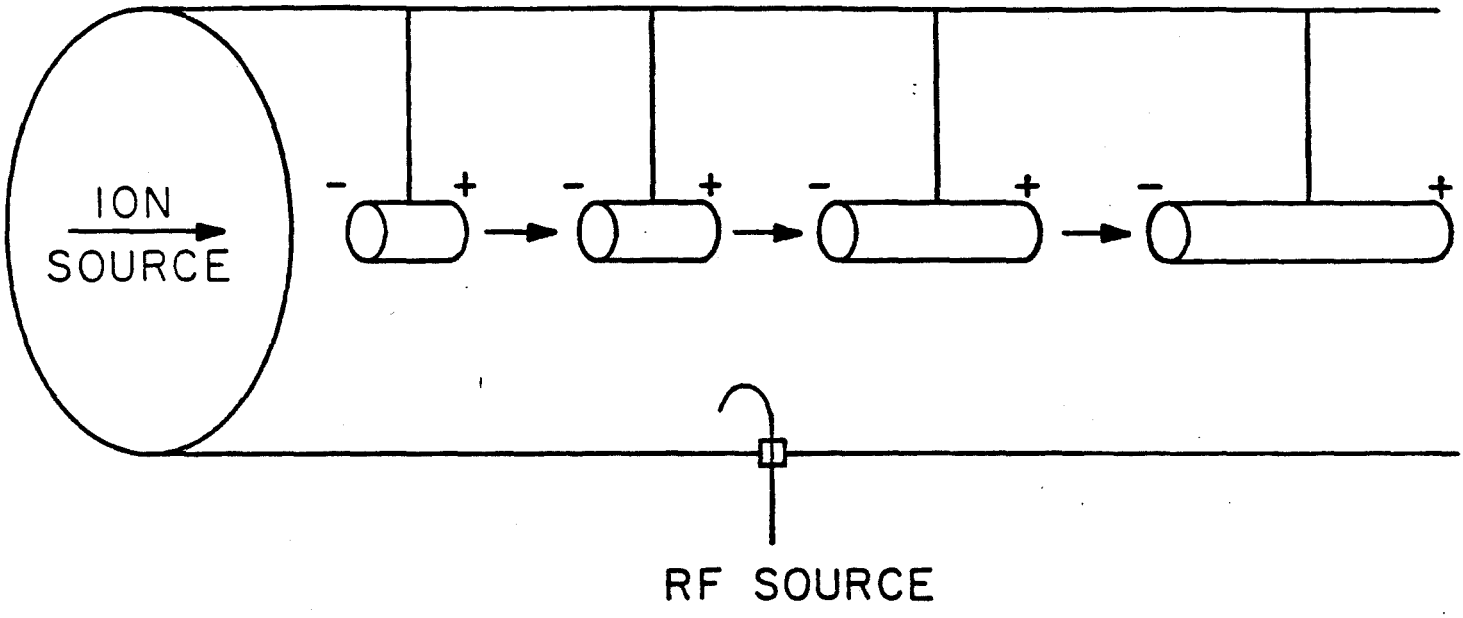


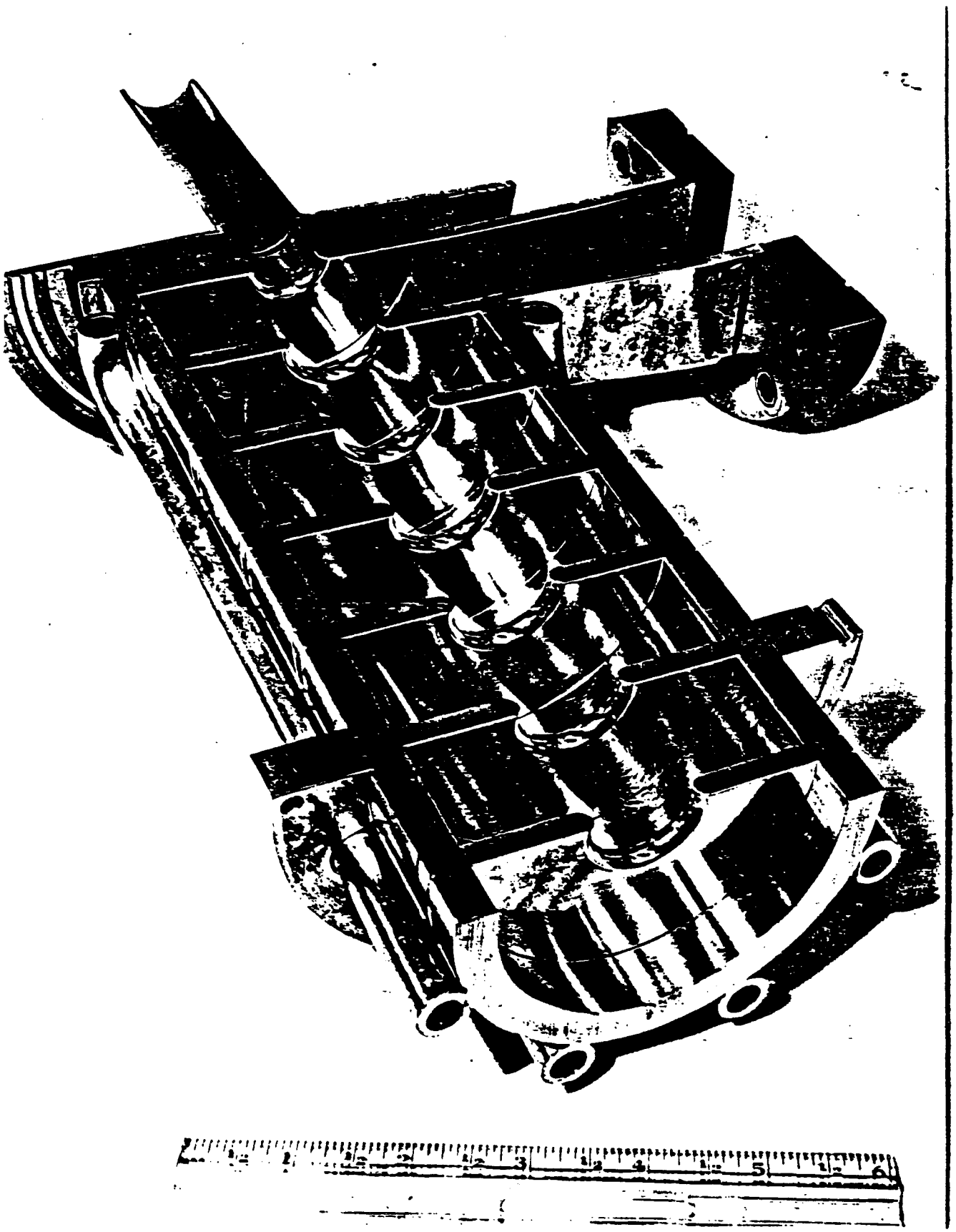
(b) MAGNETIC FIELD and FORCE

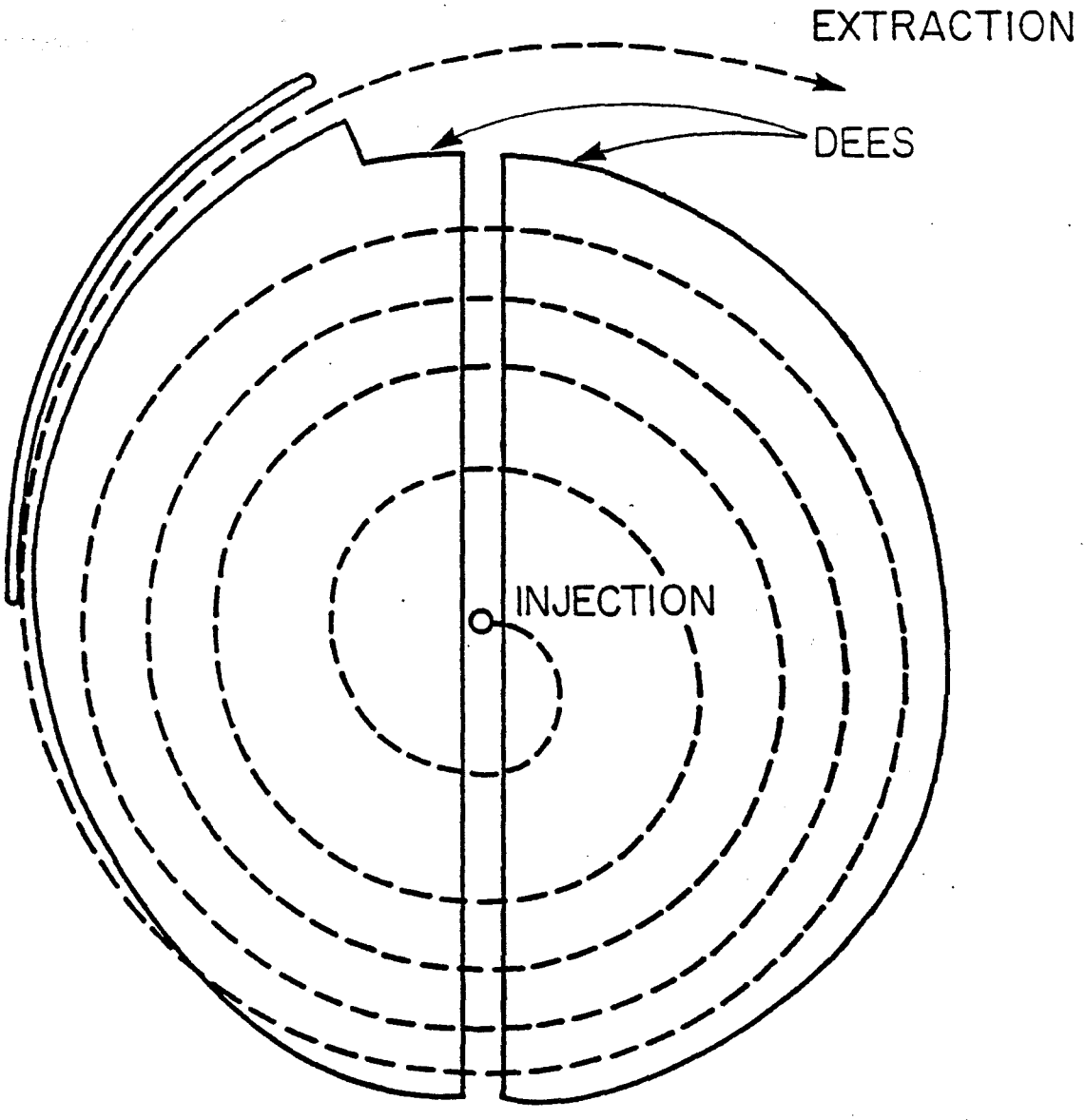

ACCELERATOR BEAM ENERGY
10^7 TeV
10^6 TeV
10^5 TeV
10^4 TeV
10^3 TeV
10^2 TeV
10 TeV
1 TeV
100 TeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 KeV
1930
1940
1950
1960
1970
1980
1990
2000
Electron Storage Ring (Equiv. Energy)
Proton Storage Ring (Equiv. Energy)
Proton Synchrotron Weak Focusing
Electron Synchrotron Weak Focusing
Betatron
Cyclotron
AG
Electron Linac
Synchrocyclotron
Proton Linac
Sector-Focused Cyclotron
Electrostatic Generator
Rectifier Generator

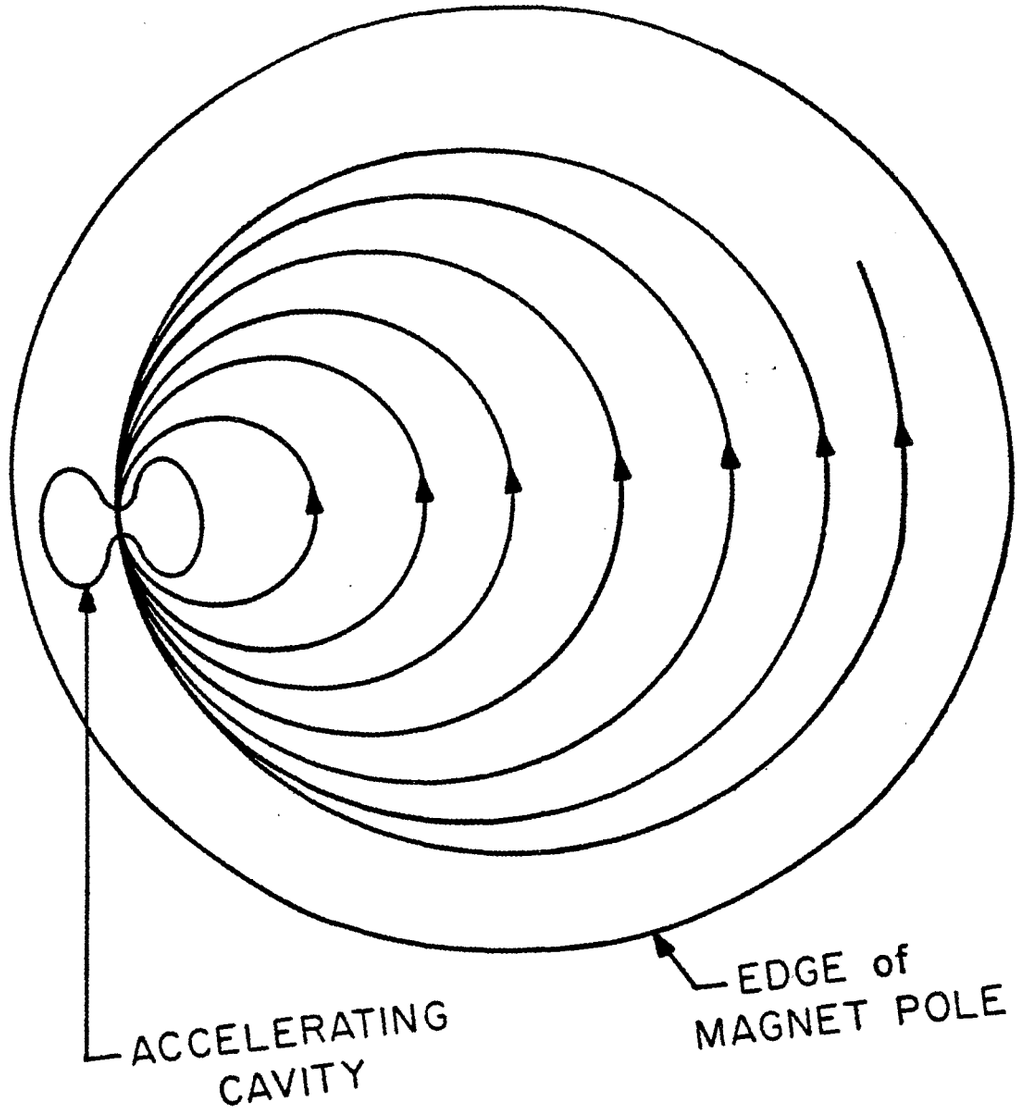

RECTIFIER
CAPACITOR
V
TRANSFORMER
+
2V
-
CAPACITOR
RECTIFIER

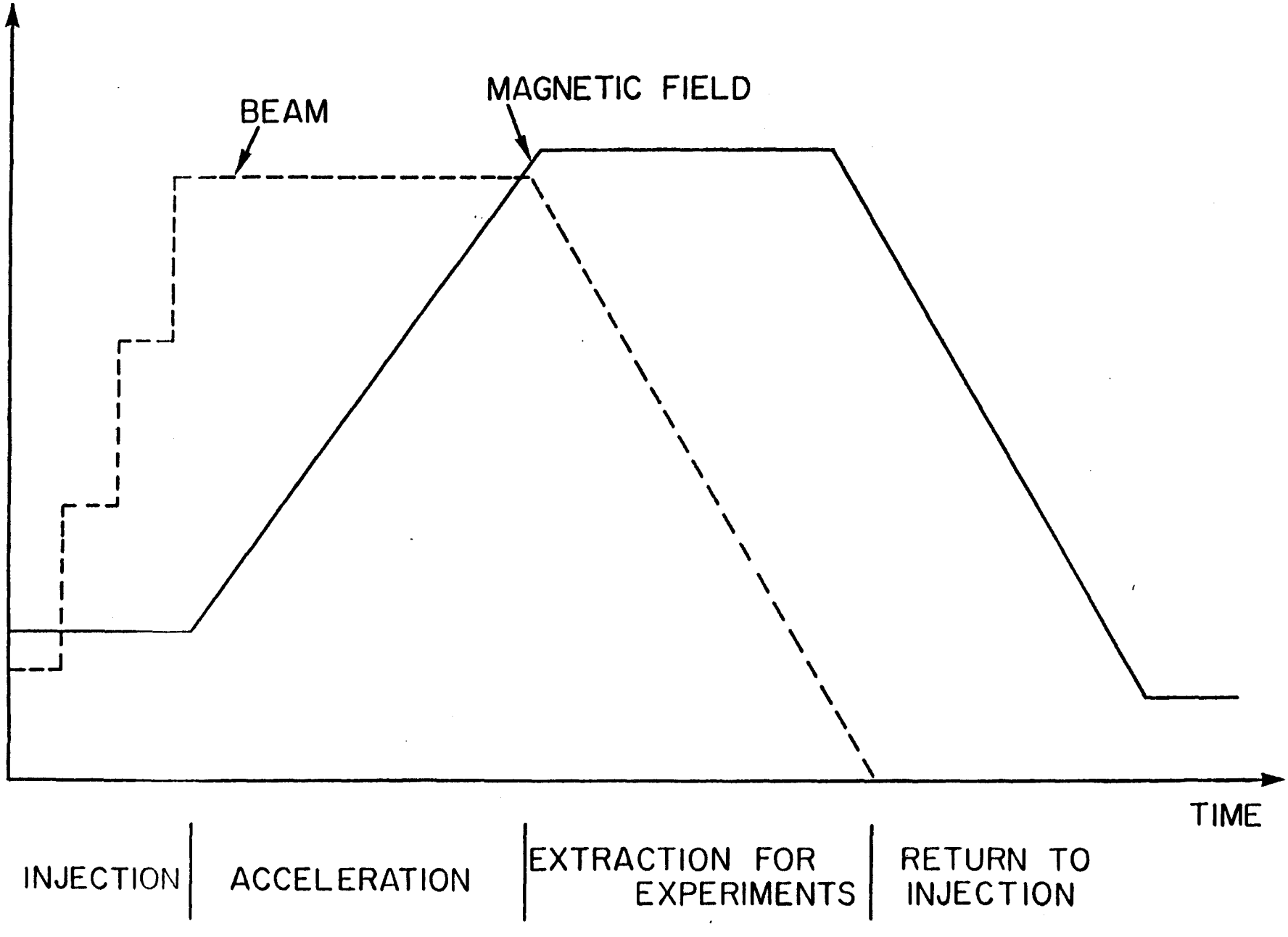

CHARGE COLLECTOR
TERMINAL
UPPER PULLEY
BELT
OUTER VESSEL
DRIVING PULLEY
CHARGE SUPPLY

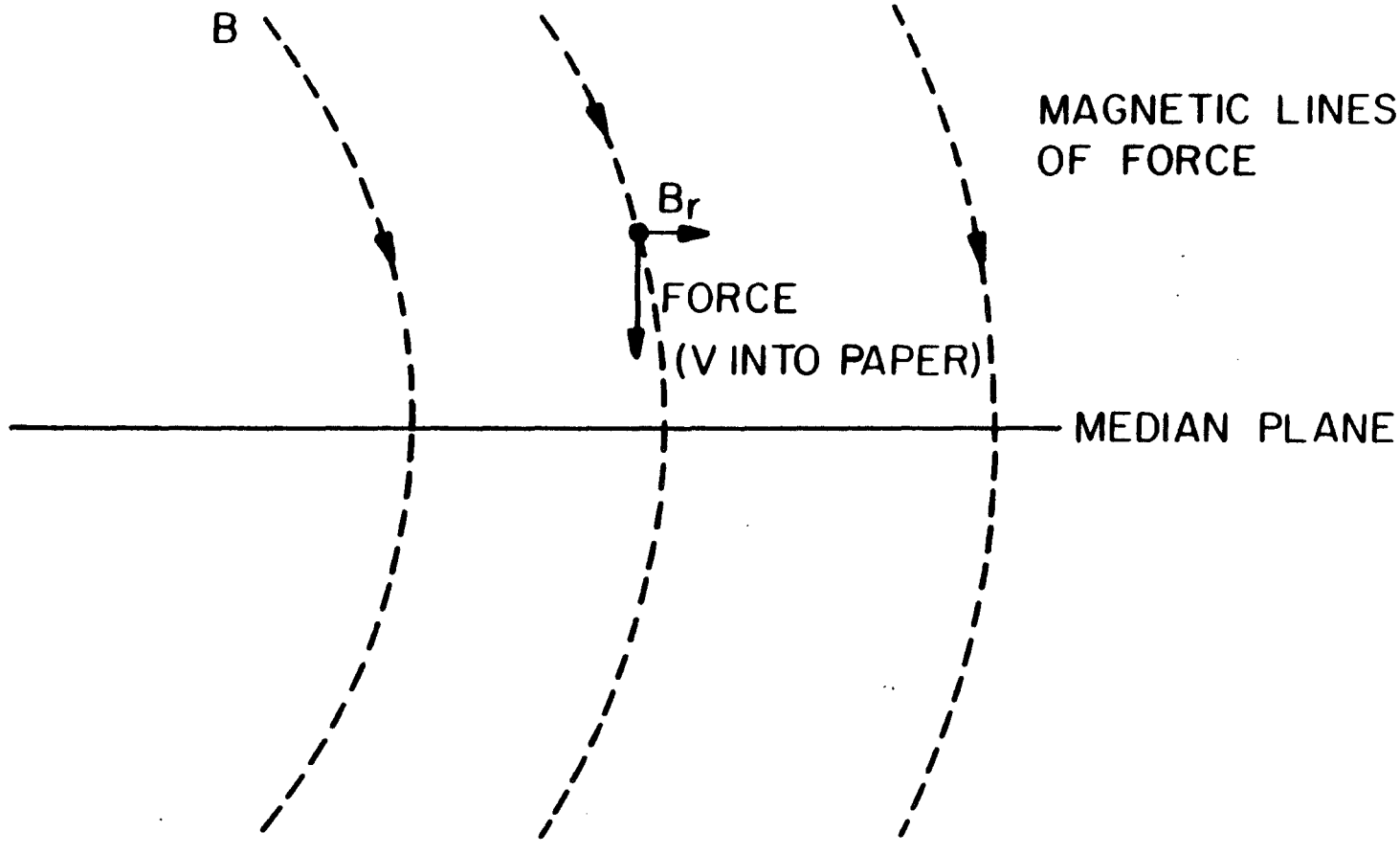

ION
SOURCE
-
+
-
+
-
+
-
+
RF SOURCE

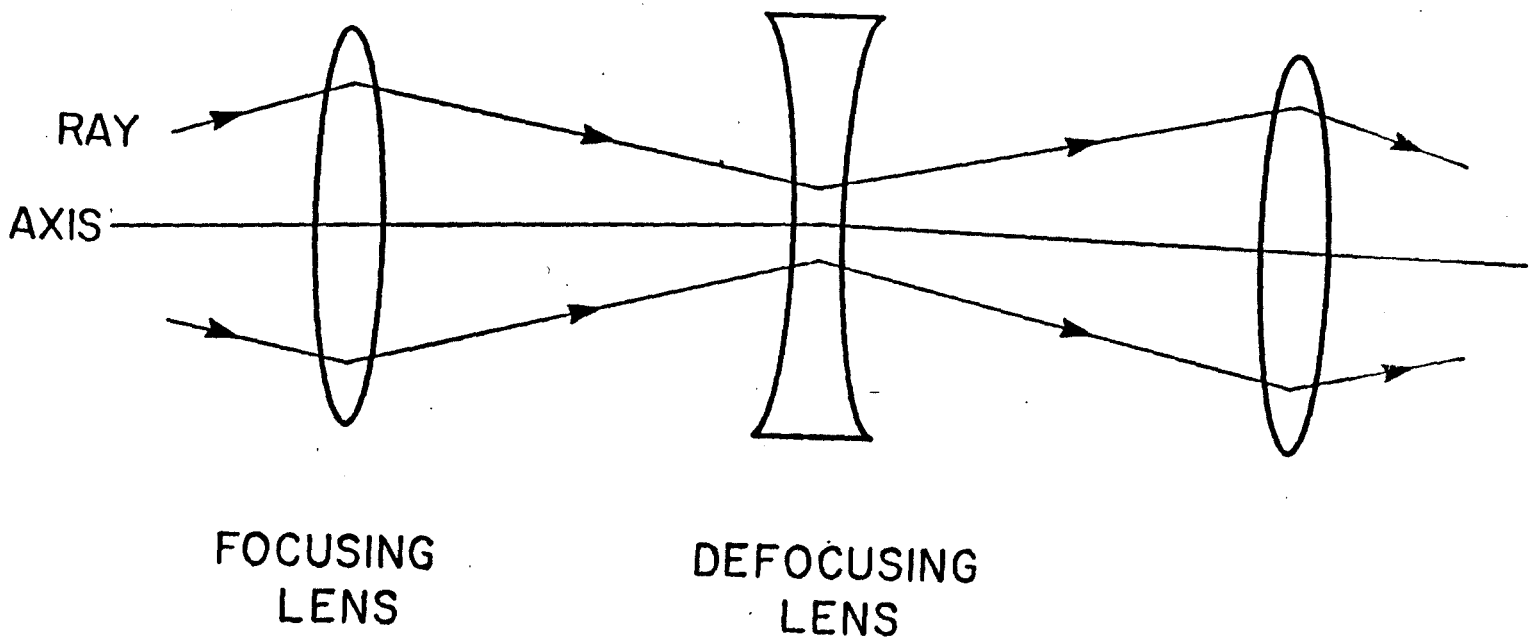


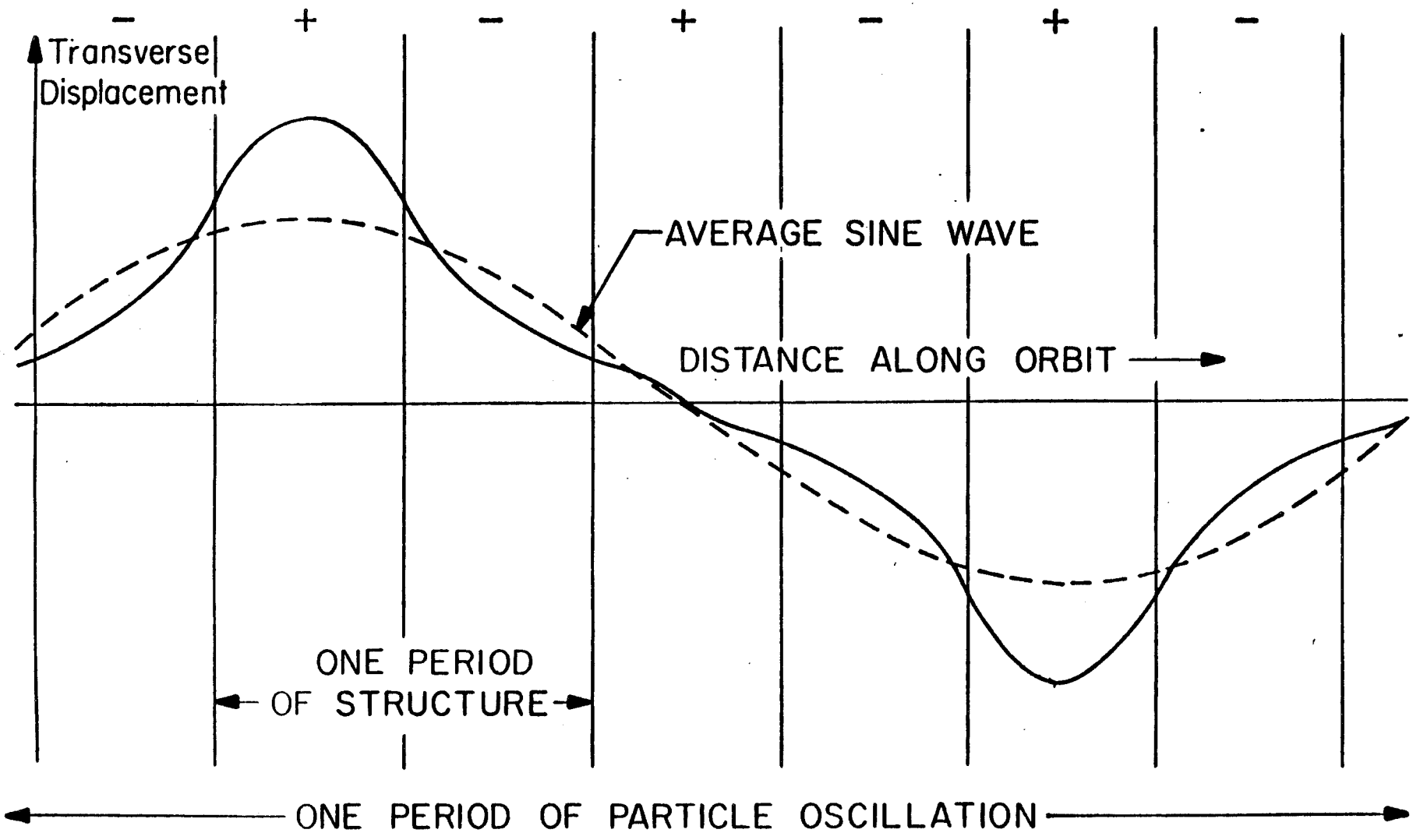

EXTRACTION
DEES
INJECTION

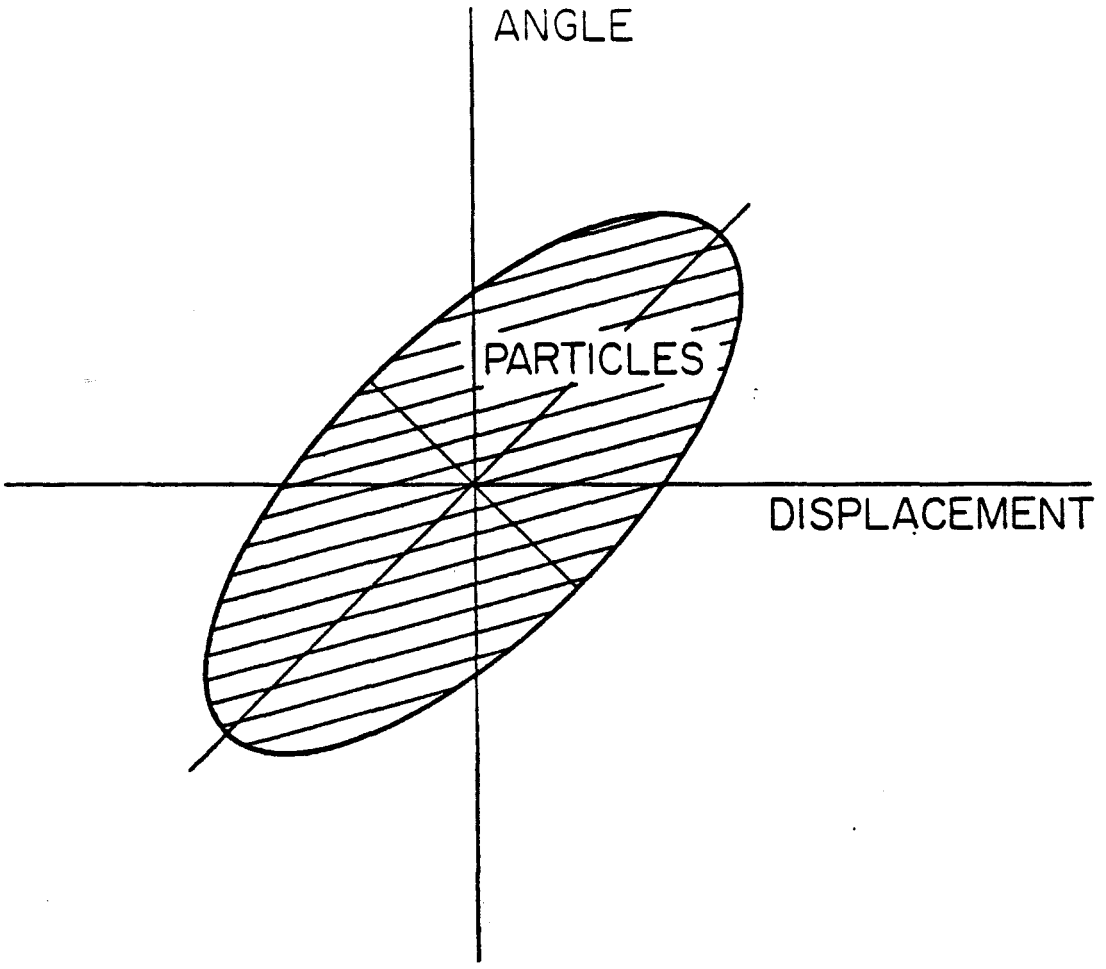

ACCELERATING
CAVITY
EDGE of
MAGNET POLE

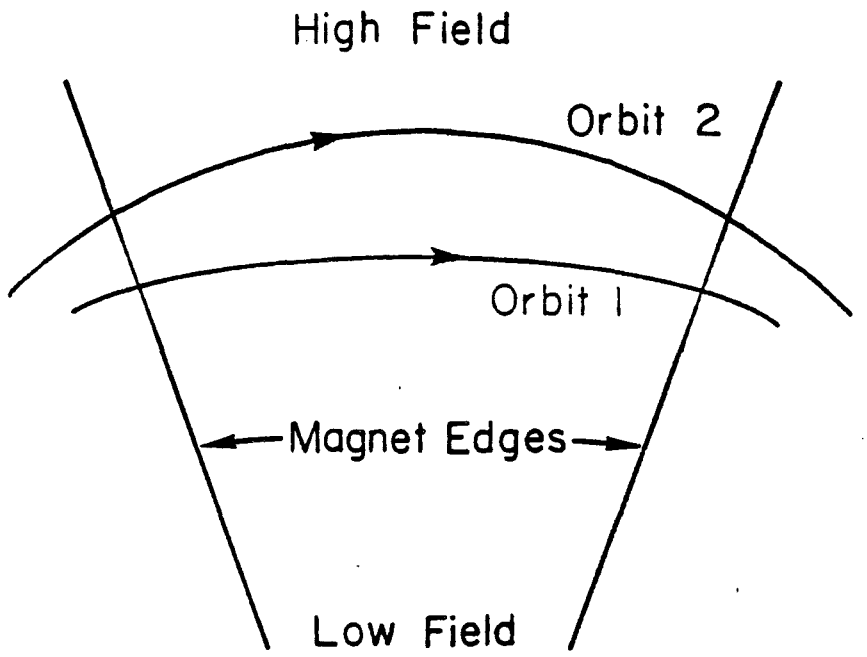

BEAM
MAGNETIC FIELD
TIME
INJECTION
ACCELERATION
EXTRACTION FOR EXPERIMENTS
RETURN TO INJECTION


B
MAGNETIC LINES
OF FORCE
B_r
FORCE
(V INTO PAPER)
MEDIAN PLANE

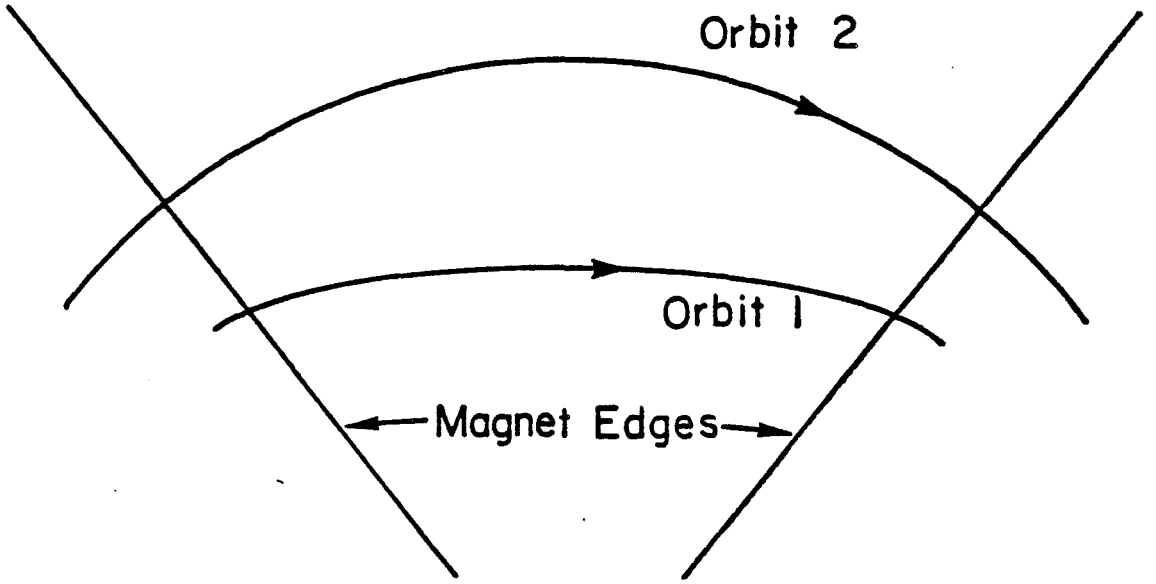

RAY
AXIS
FOCUSING LENS
DEFOCUSING LENS


− + − + − + −
Transverse Displacement
AVERAGE SINE WAVE
DISTANCE ALONG ORBIT
ONE PERIOD OF STRUCTURE
ONE PERIOD OF PARTICLE OSCILLATION

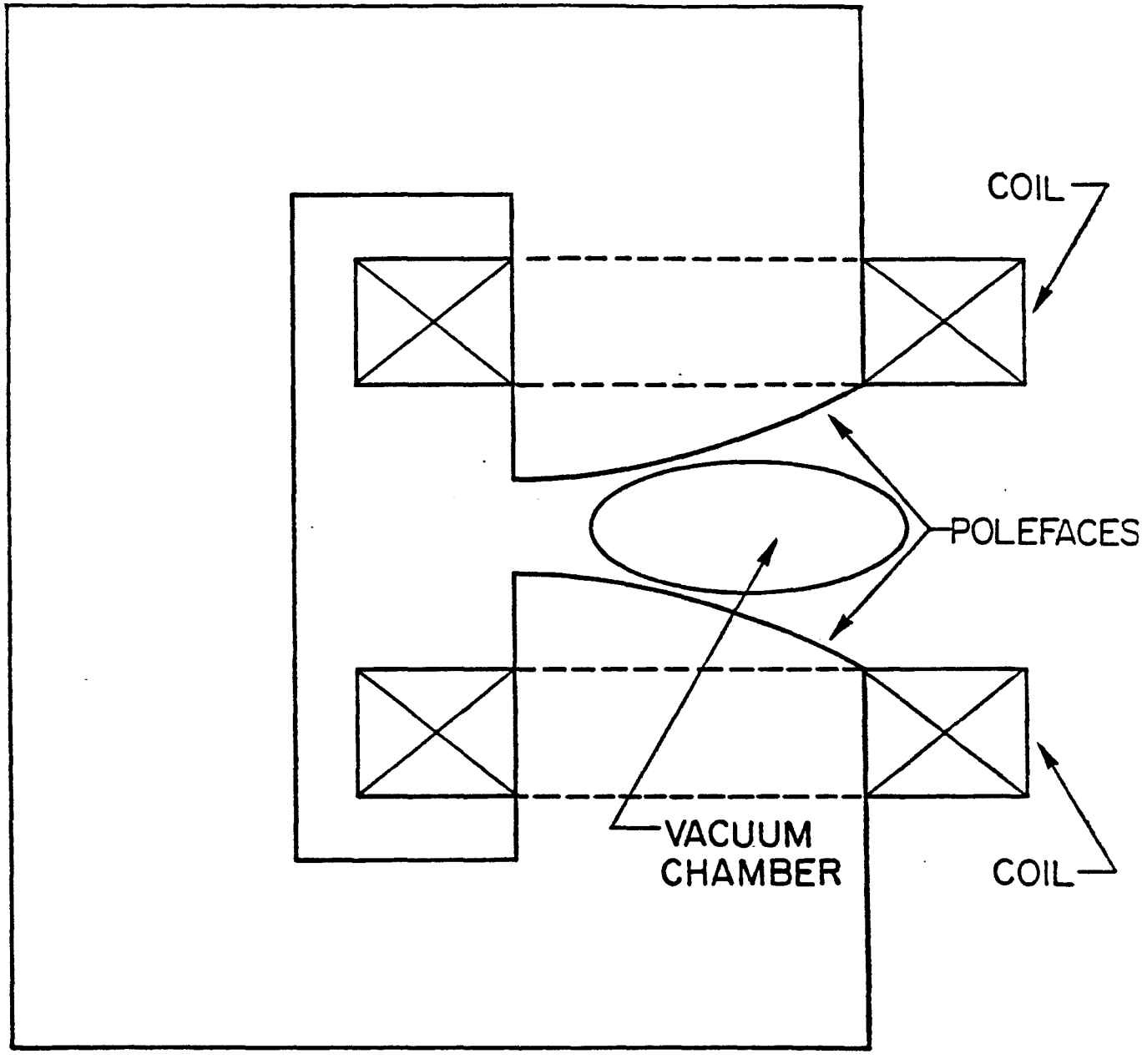

ANGLE
PARTICLES
DISPLACEMENT



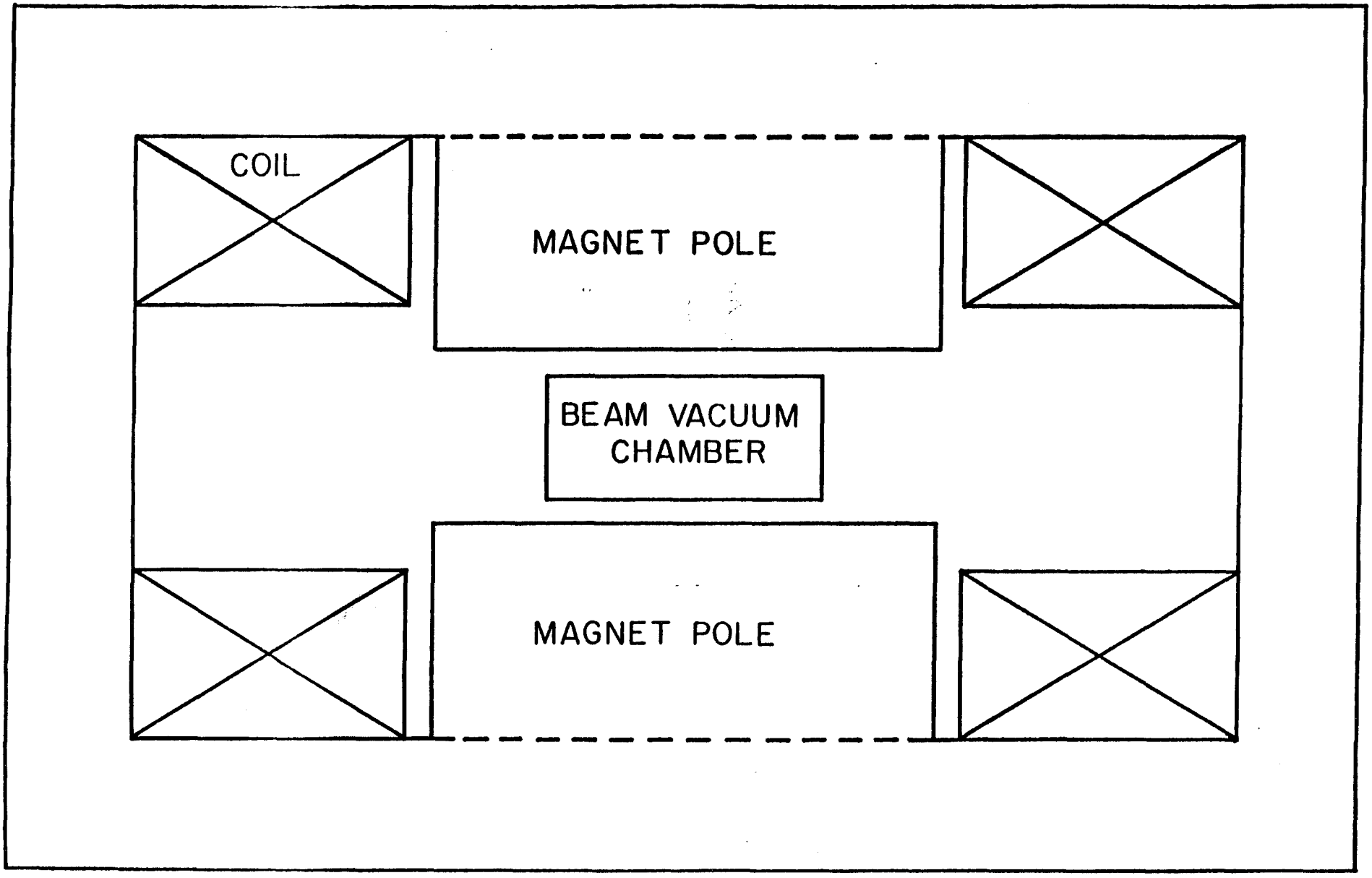
(a) Gradient Focusing



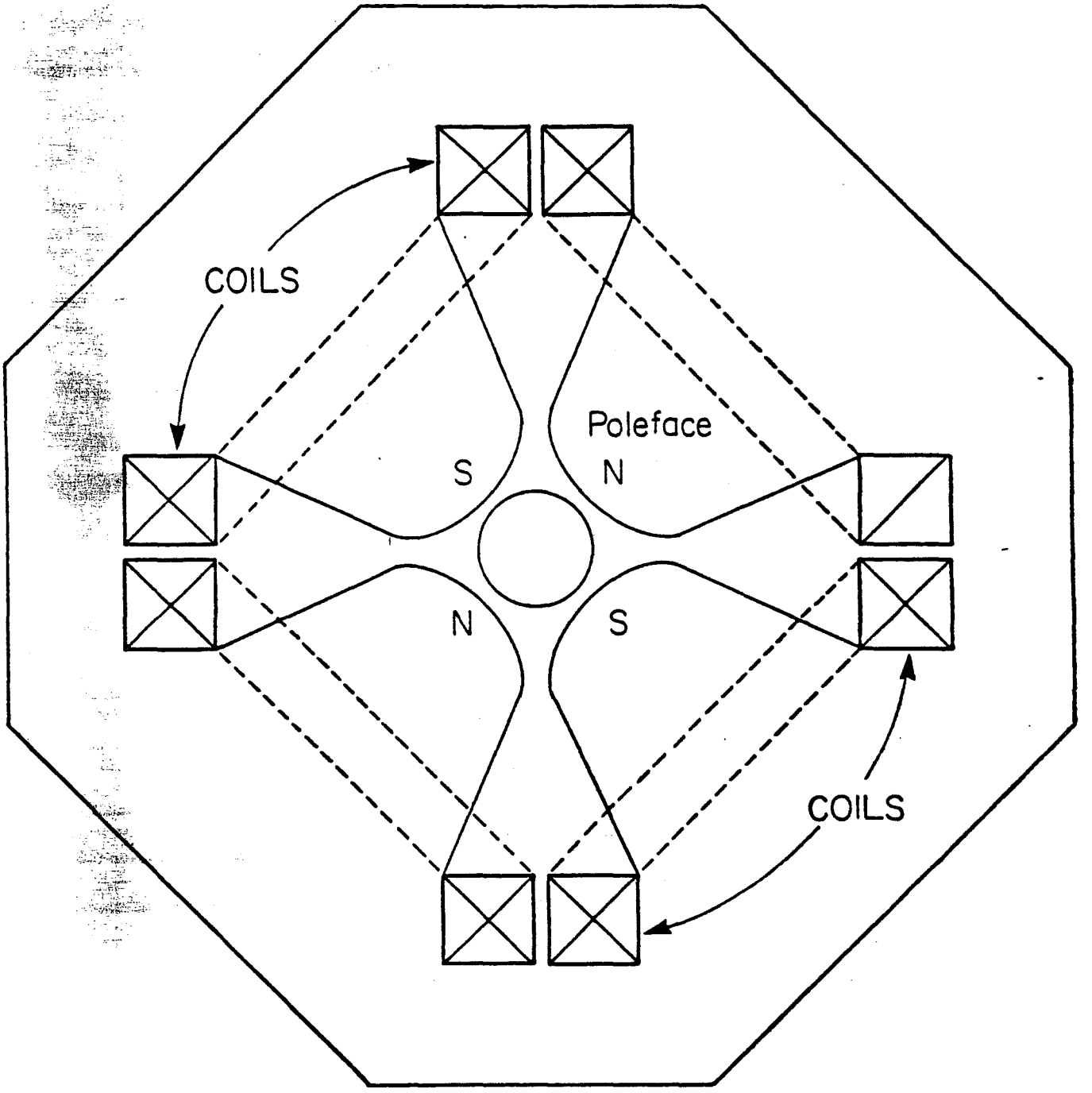
(b) Edge Focusing

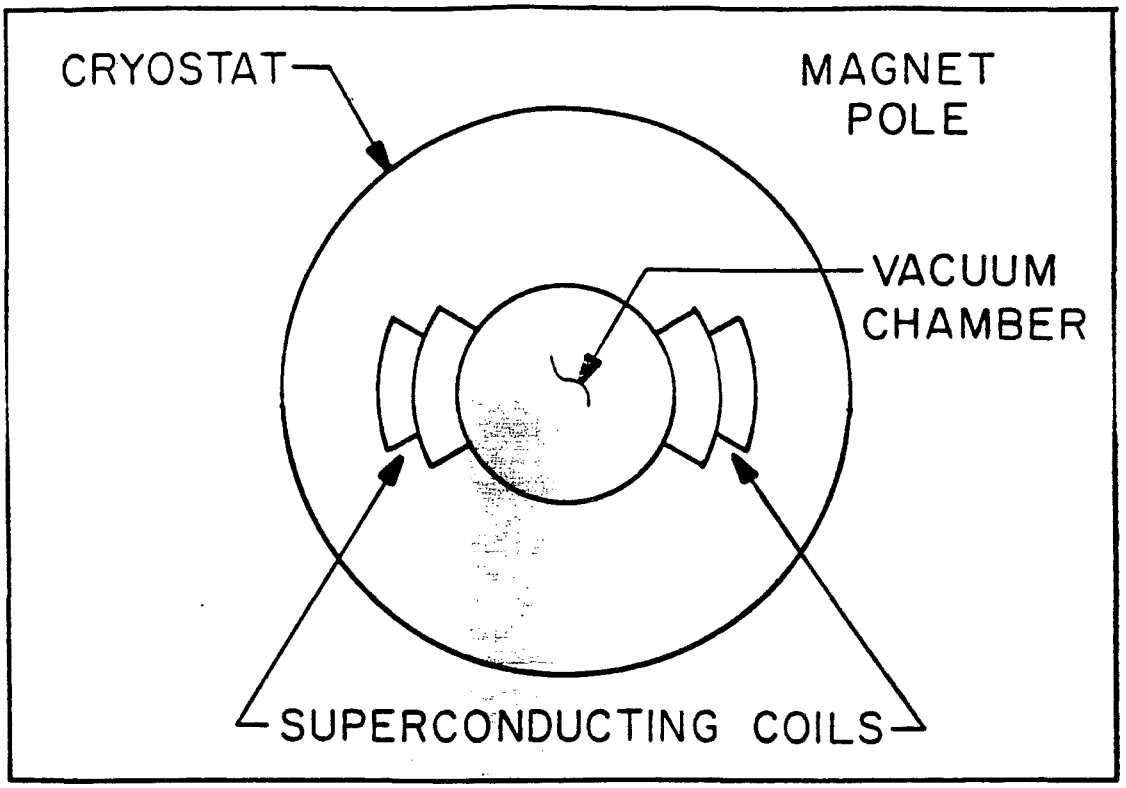


GRADIENT MAGNET

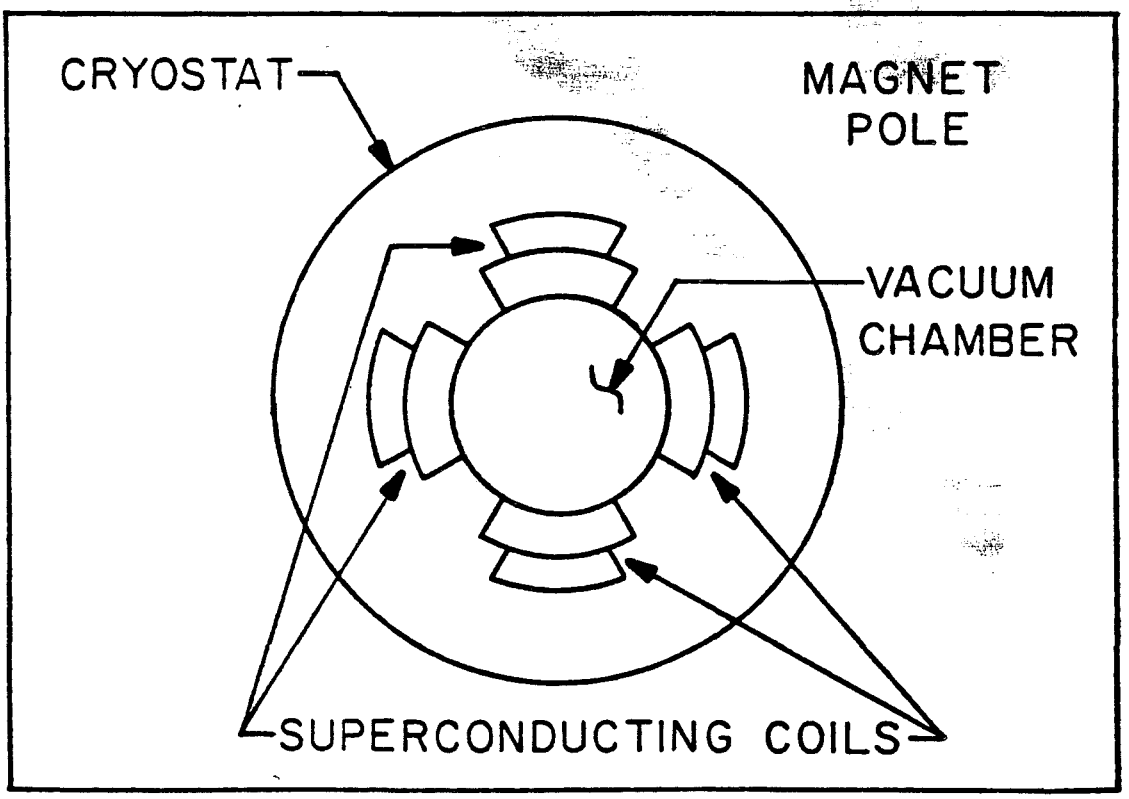


DIPOLE MAGNET CROSS SECTION

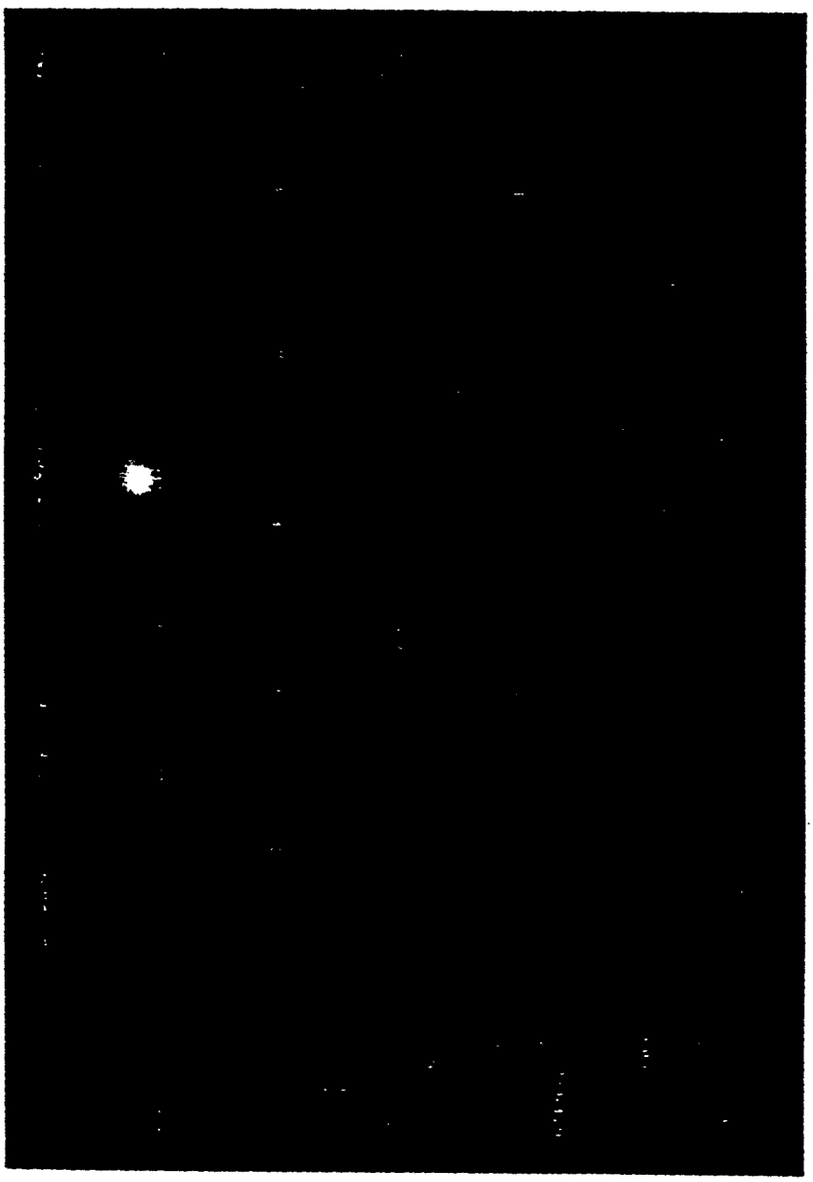

COILS
Poleface
S
N
N
S
COILS

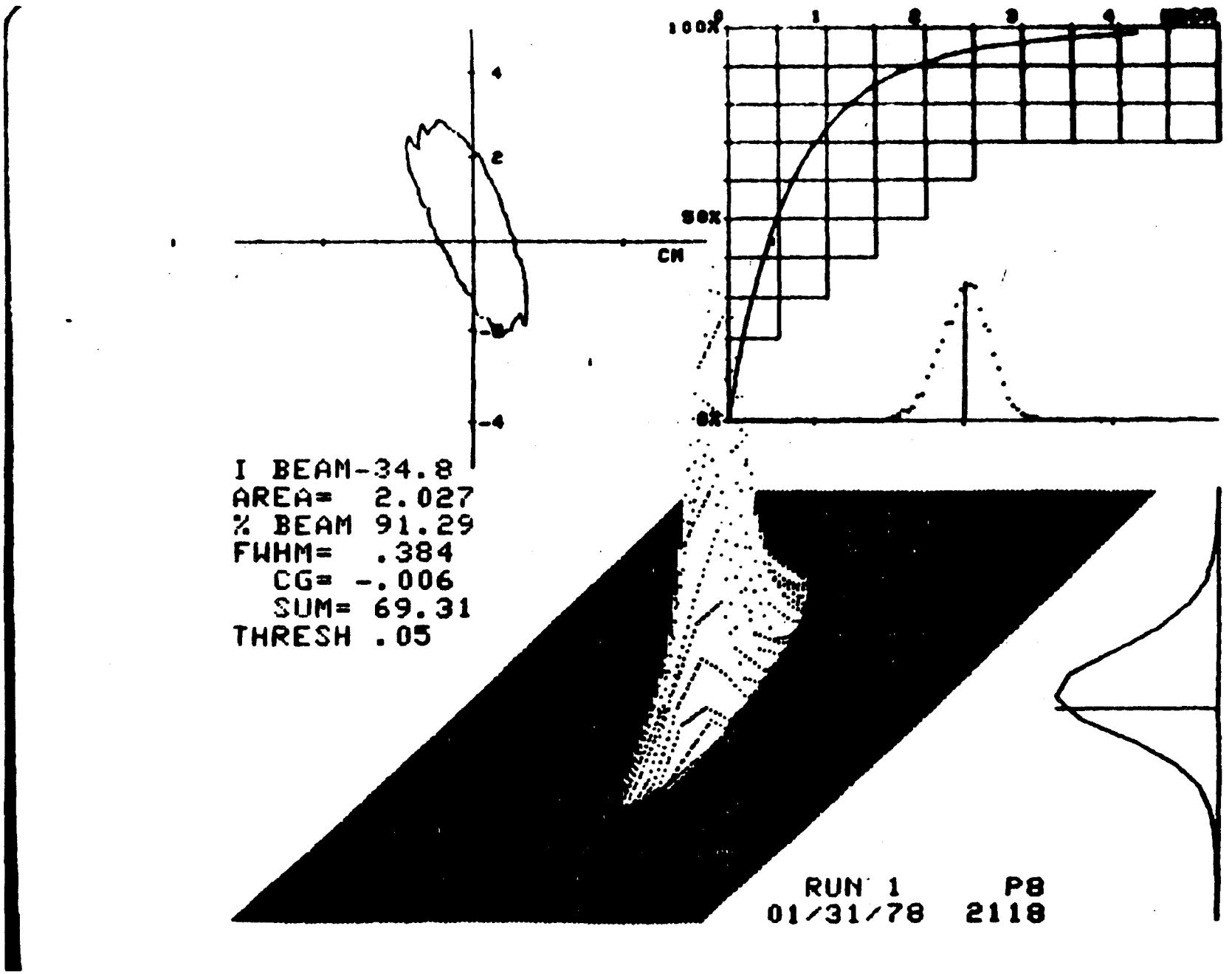


SUPERCONDUCTING DIPOLE



SUPERCONDUCTING QUADRUPOLE




4
2
-2
-4
CM
100%
50%
0%
1
2
3
4
I BEAM-34.8
AREA= 2.027
% BEAM 91.29
FWHM= .384
CG= -.006
SUM= 69.31
THRESH .05
RUN 1 P8
01/31/78 2118

VOLTAGE
TIME
ELECTRON TRAP
S, I
S
I
ONE FIELD OSCILLATION

ANGULAR MOMENTUM
PHASE
π
-π