accelerators

U. S. ATOMIC ENERGY COMMISSION / Division of Technical Information

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OF A SERIES ON
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UNITED STATES
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Nuclear energy
is playing a vital role
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In the years ahead
it will affect increasingly
all the peoples of the earth.
It is essential
that all Americans
gain an understanding
of this vital force if
they are to discharge thoughtfully
their responsibilities as citizens
and if they are to realize fully
the myriad benefits
that nuclear energy
offers them.

The United States
Atomic Energy Commission
provides this booklet
to help you achieve
such understanding.

Edward J. Brunenkant
Director
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accelerators

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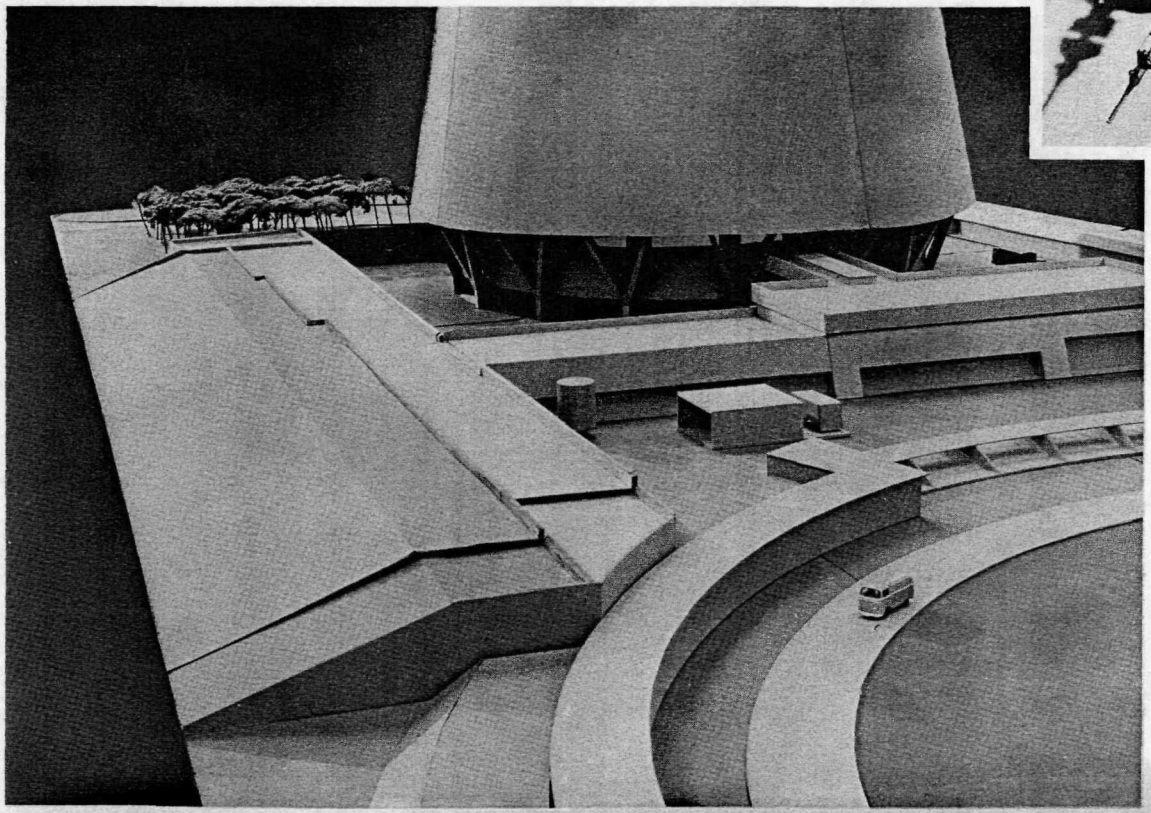
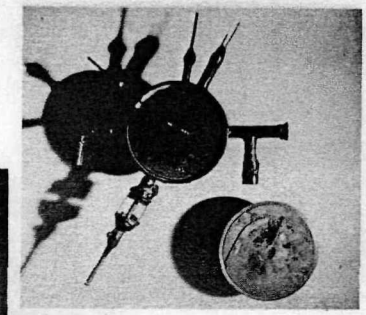




accelerators

By William J. Kernan

MAN'S MOST COMPLEX INSTRUMENTS

At Stanford University a 2-mile electron linear accelerator (see cover) has been put into operation. The United States Atomic Energy Commission has begun construction on a proton accelerator near Batavia, Illinois, which will be about 4 miles in circumference.

A description of these machines almost staggers the imagination.

The Stanford accelerator propels subatomic particles to .9999999997 the speed of light. It cost $114,000,000, and it requires 1200 persons and $20,000,000 a year to operate it.

The National Accelerator Laboratory near Batavia will require 5 years or more to build. It will occupy a 6800-acre site (40% larger than Kennedy International Airport in New York). It will use about 2000 gallons of cooling water a minute. It will attract scientists from around the world and will have a permanent staff of 1650. It will cost about $250,000,000.

How did these machines, the largest and most complex ever built by man, originate? What are they used for?

It is the purpose of this booklet to answer those questions.

A table containing information on U. S. accelerators with energy greater than 200 Mev is on page 50.

A model of the central building complex of the National Accelerator Laboratory. The long low building in the left foreground will house a linear accelerator, or Linac, which will serve as part of the 200 billion electron volt proton accelerator. The Linac will give the protons a boost in energy that will take them to 200 million electron volts, or one-thousandth of their ultimate energy in the accelerator system. The insert is the vacuum chamber of the first cyclotron to accelerate ions developed by the late Ernest O. Lawrence at the University of California in 1930. The $4^1/_2$-inch brass chamber was hooked to an oscillator and placed between the poles of a magnet. The whole apparatus operated on house current.

EARLY EXPERIMENTS WITH RADIOACTIVITY

One usually thinks of atomic energy as a very recent development, yet some of the discoveries that paved the way for modern physics were made as long ago as the 1890s. For example, the German scientist, Wilhelm Roentgen, discovered X rays in 1895 and Henri Becquerel, a French physicist, discovered radioactivity in a sample of pitchblende in 1896.

The importance of these new discoveries was recognized almost immediately, and talented, dedicated scientists began to search for additional radioactive substances and to study the radiation emitted by them Their interest was aroused because there was nothing in older physical theories that explained the energy involved in radioactivity. Two of the scientists who became interested were Pierre and Marie S. Curie of France. They managed to separate radium from pitchblende. This gave them a fairly intense source of radioactivity.

In the process of studying radioactive materials, scientists discovered that there were at least three different forms of radiation emanating from them. They were named alpha, beta, and gamma rays after the first three letters in the Greek alphabet. All the rays were found to be capable of darkening photographic plates inside a closed film holder. They differed, however, in their abilities to penetrate matter. Alpha rays could be stopped by the addition of a very small amount of shielding material. A greater thickness of shielding was required to stop beta rays. There did not appear to be any thickness of shielding that would screen out all the gamma rays.

In experiments performed in 1899 it was shown that alpha and beta rays, but not gamma rays, were deflected from a straight course when subjected to magnetic forces. This proved that alpha and beta rays were electrically charged particles. Alphas were subsequently found to be positively charged and betas to be negatively charged. The beta particles were finally identified as electrons.

In 1909, Ernest Rutherford and other scientists working in Great Britain showed that alpha particles were doubly charged nuclei of helium atoms, that is, helium atoms

minus two electrons. They made this discovery by collecting alpha particles from the decay of radon gas in a vacuum chamber and then sending an electrical discharge through them. What they observed was the optical spectrum characteristic of helium.

Between 1908 and 1913 Rutherford and his associates carried out a classically beautiful series of experiments on the scattering of alpha particles by thin foils. Their experimental results could be explained only by assuming that most of the volume occupied by each atom in the foil was "empty" and that almost all the mass of the atom was concentrated in a much smaller region called the nucleus. In 1908 Rutherford received the Nobel Prize in Chemistry.

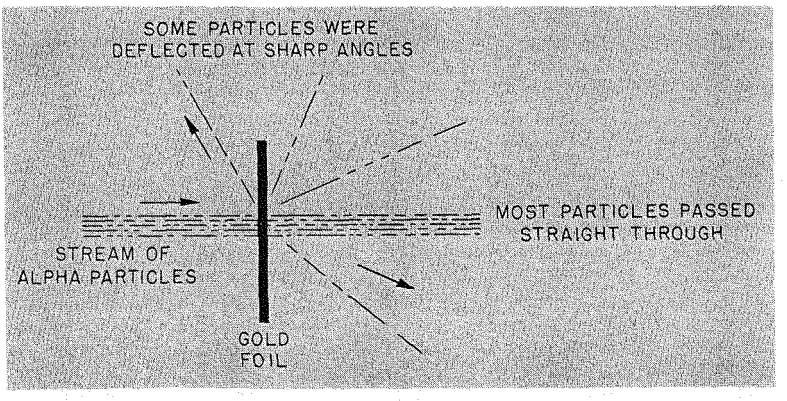


Figure 1 *In 1908 Ernest Rutherford bombarded a gold foil sheet, 2000 atoms (or one fifty-thousandth of an inch) thick with heavy positively charged alpha particles. A very few bounced back while most of them passed through and were recorded on a photographic plate. From this experiment he concluded that atoms were mostly space, but, since some particles were deflected at sharp angles, the atom must contain a small, dense positively charged core, the nucleus.*

The early study of radioactivity led to the conclusion that the emission of alpha and beta particles was associated with a chemical change in a radioactive atom. On the basis of the scattering experiments, the radioactive transformations could be attributed to spontaneous changes of an atomic nucleus.

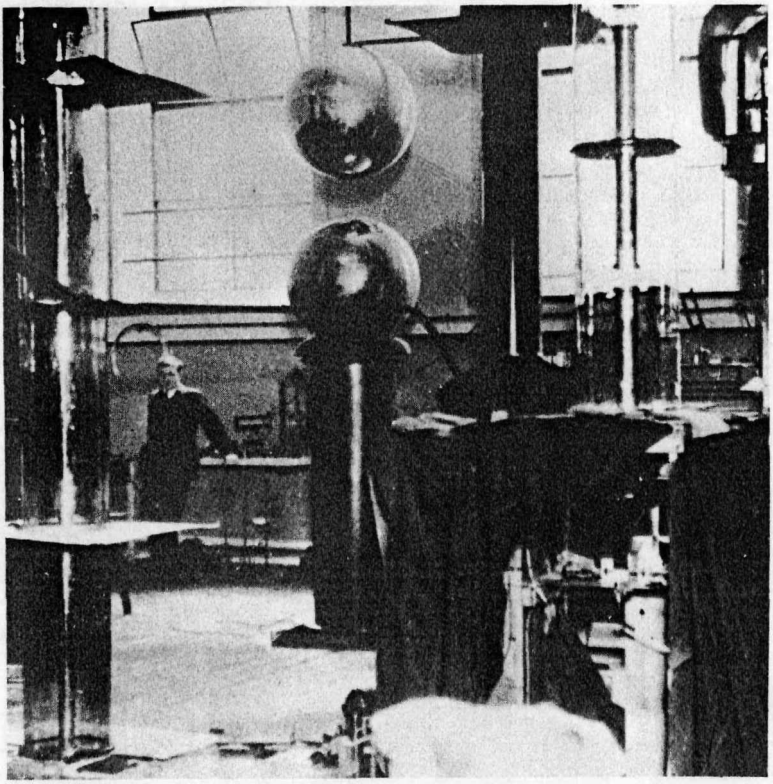


Figure 2 *Rutherford's laboratory at Cambridge University in the 1930s.*

In 1912 cosmic rays were discovered. These are ionizing particles that impinge upon the earth's surface from high in the atmosphere. "Primary" cosmic rays are those that come into the atmosphere from outer space. They interact with gas molecules in the atmosphere to produce other particles called "secondary" cosmic rays. What finally reaches the earth's surface is a mixture of the primary and secondary rays.*

*For more information on historic discoveries and their significance in atomic energy, see *Our Atomic World;* for detailed explanations of cosmic rays, see *Space Radiation*. Both are companion booklets in this series.

The First Accelerators

In the early 1900s, radioactive particles could be obtained only from materials found in nature. The studies that physicists wanted to perform even then required both higher intensities and higher energies than were obtainable from the natural sources. The ability to vary energy and intensity to suit a particular experiment was also desirable. In addition, there was a need to know precisely the composition of the beam of particles, where the beam was hitting the target, and the spread in energy at the target. In other words, what was needed was control, which is the essence of the experimental method.

In the 1930s, scientists began to build machines with which the needed degree of control could be achieved. These machines were called accelerators.

The source of particles for the first accelerators was the simplest atomic element, hydrogen. Hydrogen atoms are composed of a *proton*—a heavy core for the atom, with positive electrical charge—and a much lighter particle, the *electron* with a negative electrical charge. Since opposite electrical charges attract, there is a force holding these two particles together in a normally stable configuration, somewhat analogous to the moon in its stable orbit around the earth. If hydrogen gas and a few extra electrons are introduced into a chamber where there is a positive electrical charge on one side of the chamber and a negative electrical charge on the other side, the result will be collisions between electrons, protons, and atoms that knock apart many of the atoms. When this happens we say that the hydrogen gas has been ionized. The free protons produced by such ionization are used as the particles to be accelerated.

These free protons are now introduced into another chamber where again there is an electrical force on them. This force *accelerates* the protons. That is, it increases their velocity (because acceleration is defined as *time rate of change of velocity*). Since the kinetic energy (the energy of motion) of a particle is given (at least for velocities much less than the speed of light) by

$$K = \frac{1}{2} MV^2$$

where K = the kinetic energy
M = the mass of the particle and
V = the velocity

the acceleration of the proton by this electrical force also increases the *energy* of the proton.

The amount of acceleration is determined by the potential difference measured in volts in this electrical field. The energy imparted to the particles is measured in units called *electron volts.* Thus, if a proton is accelerated across a gap by means of a 10,000 volt, or 10 kilovolt (kv), potential difference, it is said to have gained 10,000 electron volts (10 kev) of energy after traversing the gap.

Ten kv was a potential easily achieved, but scientists wanted to accelerate particles to many times this energy. One way to accomplish this, shown in Figure 3, was to apply 10 kv potential to each of many gaps and have the particle traverse these gaps one after another, gaining 10 kev in energy for each gap traversed. Alternatively, a voltage many times larger than 10 kv might be applied to a single gap. One way to do this is to charge a group of condensers in *parallel* and then connect them in *series.* This is shown in Figure 4. In order to charge the condensers all switches are set to position A. After the condensers are charged to the full voltage V, the switches are all set to position B; if there are N condensers, they now provide an accelerating voltage across the gap of NV.

The latter method was the one used in Rutherford's laboratory in 1932 by John D. Cockcroft and Ernest T. S. Walton to build a machine (named after them) that accelerated protons to 700 kev. On this machine they performed the first nuclear experiments with particles from an accelerator.* (See Figures 2 and 5.)

The dream of the ancient alchemists had been to change one element into another, a process known as transmutation. In one of the experiments on this accelerator, Cock-

*Cockcroft and Walton were awarded the Nobel Prize in Physics in 1951.

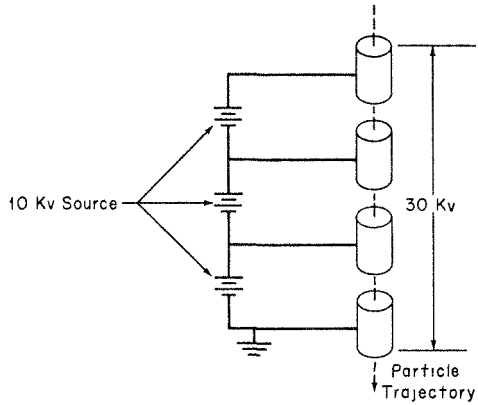


Figure 3 *Accelerating particles by applying equal voltage to many gaps.*

croft and Walton achieved the transmutation of lithium. The reaction was as follows:

$$^{1}_{1}\mathrm{H} + ^{7}_{3}\mathrm{Li} \rightarrow ^{8}_{4}\mathrm{Be} \rightarrow ^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He}$$

That is, the nucleus of a lithium-7 atom, denoted $^{7}_{3}\mathrm{Li}$, when bombarded with protons ($^{1}_{1}\mathrm{H}$) formed an excited beryllium-8 nucleus ($^{8}_{4}\mathrm{Be}$), which subsequently disintegrated into two helium nuclei ($^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He}$). The study of threshold energies and energy releases in reactions of this type started to bring scientists real understanding of the structure and forces inside atomic nuclei.

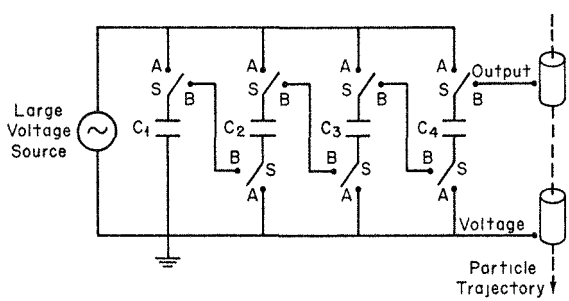


Figure 4 *Diagram for circuit to charge capacitors (C_1 to C_4) in parallel and discharge in series When all switches, S, are in position A, the voltage source will charge the capacitors in parallel When all switches, S, are in position B, the capacitors will be connected in series across the output voltage terminals.*

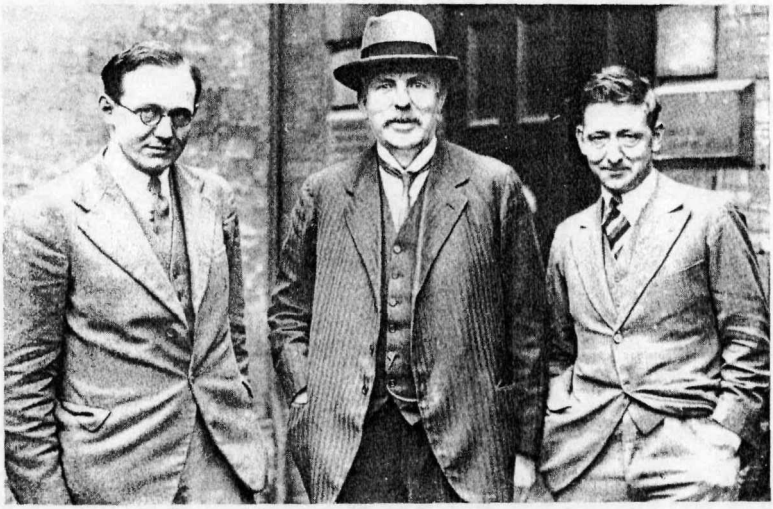


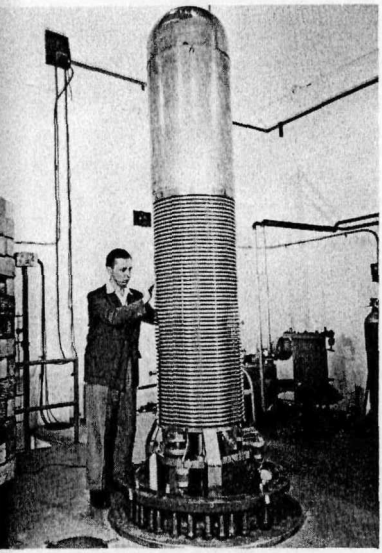
Figure 5 *Inventors of one of the first accelerators, Dr. Ernest T. S. Walton, left, and Dr. John D. Cockcroft, right, with Lord Rutherford, pioneer nuclear scientist, at Cambridge University in the early 1930s.*

In 1931 Robert Van de Graaff proposed and subsequently constructed in the United States a machine of a different type. In Van de Graaff's first workable model a silk belt $2^1/_2$ inches wide was carried by two pulleys, one at ground potential and powered by an electric motor, and the second inside a polished metal sphere 24 inches in diameter. The sphere was supported by glass insulating rings. Electric charge from a row of needle points held at a positive potential of about 10 kv was sprayed as corona current (an electrical discharge in air) onto the belt surface just after it left the grounded pulley. Before the belt reached the second pulley another row of needle points picked up the charge and conducted it to the metal sphere. This process could be continued until a very high potential was developed in the sphere.

Once the sphere of a Van de Graaff machine is charged to its maximum voltage, the protons or other particles to be accelerated are ejected from an ion source in the high-voltage terminal into the accelerating tube. They are accelerated by the potential difference between the sphere and the grounded end of the tube.

Many machines have since been built following the general principles of this first Van de Graaff model. There are two factors that can limit the maximum potential of the sphere in a Van de Graaff device. One is the leakage current across the insulators, and through the air (or other gas) surrounding the sphere, and the other is gaseous breakdown. The leakage limit is reached when the leakage current, which increases with the voltage, becomes equal to the current carried up by the belt. The breakdown limit is reached if a spark in the gas discharges the sphere.

The limitations on Van de Graaff machines are for the most part practical engineering problems; for instance, how to make better insulators, or how to raise the voltage at which sparking occurs. The machines have been improved over the years by placing the sphere and accelerating tube in high pressure gas atmospheres (to minimize leakage current and increase sparking voltage) and by other changes.



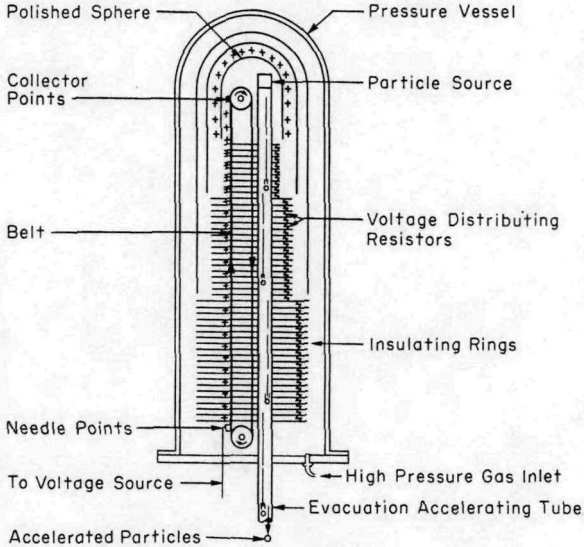


Figure 6 *A Van de Graaff electrostatic generator. A belt of an insulating material run at high speed over pulleys conveys electric charge from a voltage source upward to the sphere. Positive particles are injected at this high-voltage end and are accelerated downward. On the left is a 2-Mev Van de Graaff generator. The pressure vessel that usually covers the entire assembly has been removed, and the insulating rings are visible.*

By placing Van de Graaff accelerators in series, it is possible to achieve much higher particle energies. For example, in a two-stage tandem, negative ions are injected at ground potential into the accelerator system and accelerated to a positive high-voltage terminal where they are stripped of their negative charge and then accelerated back to ground by the same terminal voltage. This has made it possible to use a terminal voltage of about 9 million volts and obtain protons of 18 million electron volts (18 Mev). Still higher energy systems are under construction and one three-stage machine is being planned for about 36-Mev protons.

In present-day research, the Van de Graaff generator serves two purposes. One is as a source of particles for research in low-energy nuclear physics; the second is to inject particles into much larger accelerators.

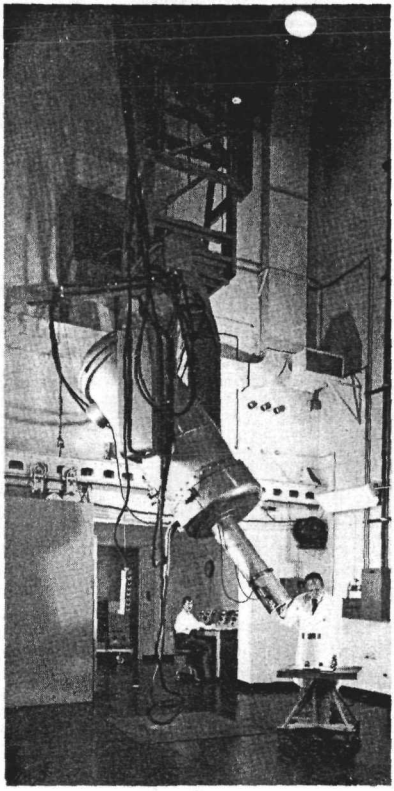


Figure 7 *Two million electron volt Van de Graaff generator at the University of California's Lawrence Radiation Laboratory.*

DEVELOPMENT OF THE CYCLOTRON

The attempt to reach higher energies than were available with the devices of these early days led Ernest O. Lawrence* of the University of California to propose the first cyclotron. The idea was simple. Instead of trying to accelerate the particles in one stage, it was proposed that many small accelerations be used so that their sum would be what was desired. Other proposed systems employed this same method. The unique aspect of the cyclotron proposal was that a magnet was to be used to bend the particles into a circular path, in order to keep the dimensions of the system small.

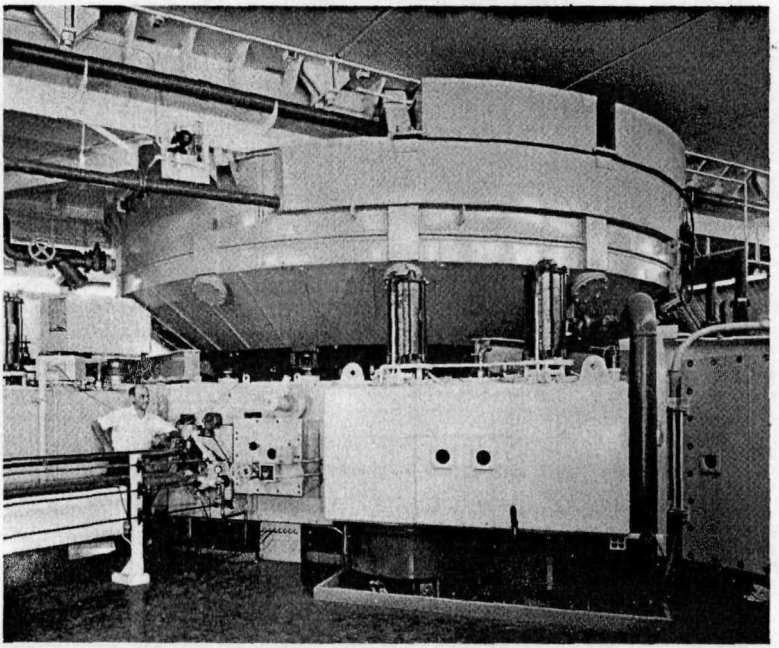


Figure 8 *The 184-inch cyclotron at the Lawrence Radiation Laboratory. It was completed in 1946 with an energy for deuterons of 200 Mev, making it the first atom smasher in the Mev energy range. It was also the first machine with which mesons, a class of elementary particles, were produced and identified.*

*Lawrence received the Nobel Prize in Physics in 1939.

Now, if a charged particle of mass m and charge q moves in a uniform magnetic field, where the magnetic field strength is H, with a velocity v, which is perpendicular to H, it will describe a circular trajectory whose radius R is given by the expression:

$$R = \frac{mv}{qH} \tag{1}$$

The critical fact that underlies the operation of the cyclotrons is this: As the energy of the particles is increased, the particles travel in ever-widening orbits, but these ever-widening orbits *are all traversed in the same time.*

To see this fact clearly, we take the circumference of a circle of radius R where R is given by equation (1).

$$2\pi R = \frac{2\pi mv}{qH} \tag{2}$$

Now a particle of velocity v will travel this distance in time T. So we get:

$$vT = \frac{2\pi mv}{qH} \tag{3a}$$

and solving for T:

$$T = \frac{2\pi m}{qH} \tag{3b}$$

We can see that the time for one orbit is therefore independent of the velocity and the radius and depends only on the mass, charge, and magnetic field. Therefore, the particles in a cyclotron complete an orbit of any radius in the same time as one of any other radius.

In constructing a cyclotron, a hollow box electrode is introduced between the poles of a magnet and is split in half to form two sections that look like the letter D, and are hence referred to as "dees".

By maintaining a high-frequency alternating voltage between the dees, an alternating electric field is established in the gap that separates them. This high-frequency alternating voltage is supplied by an external voltage source

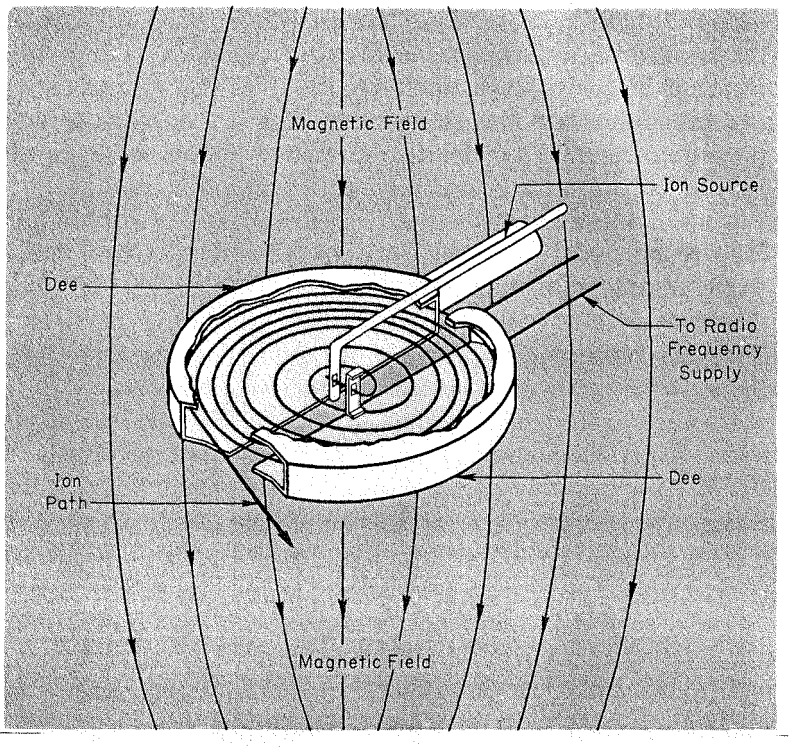


Figure 9 *Basic plan of the cyclotron. Particles injected at the center are bent into circular paths by traveling in a vertical magnetic field. A rapidly alternating horizontal electric field applied between hollow electrodes (dees) accelerates the particles each time they complete a half circle. The particles are extracted and aimed at an external target. The dees are enclosed in a vacuum so that air molecules will not obstruct the motion of the particles.*

usually called a radio frequency voltage supply. The term radio frequency (RF) is used because, for typical cyclotron-design, the frequency, given by 1/T, is in the usual frequency band of radio use. Protons or other charged particles are ejected at low energy from an ion source in the center of the cyclotron. The protons travel in a curved orbit until they reach the separation between the dees. As a proton approaches the slit, it finds a positive electric potential on the dee it is in and a negative potential on the opposite dee, and it is therefore accelerated across the slit.

Acceleration of the proton causes it to gain energy. As this happens the particle moves outward to follow a path

with a larger radius. When the proton approaches the slit the next time,* the high-frequency alternating voltage has changed polarity (negative to positive) so that the proton is again accelerated across the slit. The proton continues to travel in widening circles at increasing speed, so that each revolution takes the same amount of time.

This process continues until the proton has been accelerated to so great an energy that its trajectory has expanded to the maximum radius of the machine. There it finds a reduced value or "bump" in the magnetic field and is ejected from the machine, aided by an auxiliary electric field furnished for this purpose by a deflecting electrode.

Protons are emitted by the ion source continuously. However, only those emitted while the accelerating voltage on the dees is in one direction will be accelerated through the full process and reach the maximum radius. This imposes a time structure on the final emerging beam. In an idealized

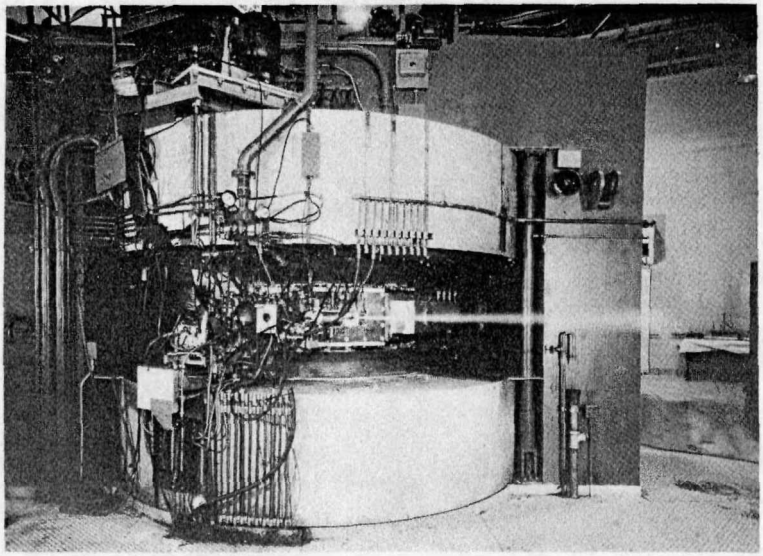


Figure 10 *A beam of deuterons emerges from the vacuum chamber of the 60-inch cyclotron at the Argonne National Laboratory in Illinois. The beam becomes visible by the excitation of air molecules along its path.*

*This time is given by T/2, where T is determined from equation 3b.

case, the beam would consist of an evenly distributed array of protons spread over a time T/2, followed by no protons arriving for a time T/2, and then another packet of protons in the next T/2 time period and so on in a continuously repetitive cycle. The actual case is not ideal, however, and the protons arrive in shorter bursts.

There is a theoretical limit to the energies that can be achieved in a fixed-frequency cyclotron like that we have just described. This limit is imposed by the relativity theory, which tells us that the *mass of a particle increases as its energy gets larger.* This effect becomes important when particles are accelerated to speeds approaching that of light.

For example, if in equation 3b, the magnetic field strength, H, remains constant, but the mass of the particle *increases*, then the time, T, for a revolution *also* increases. Therefore the particle will not reach the gap between the dees in time to receive the usual push from the alternating voltage. In fact, it may arrive so late that it actually will be decelerated instead of accelerated.

This was predicted by the theory of relativity, in which the expression for m is:

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} \tag{4}$$

where m_0 = the "rest mass", that is the mass at zero velocity,
v = the particle velocity, and
c = the velocity of light

Once the term

$$\sqrt{1 - v^2/c^2}$$

differs appreciably from 1, the proton begins to arrive late at the gap.

The meaning of equation 4, as representing the mass of a particle as a function of its velocity, was included in the theory of relativity worked out by Albert Einstein early in the twentieth century, long before any particle accelerators

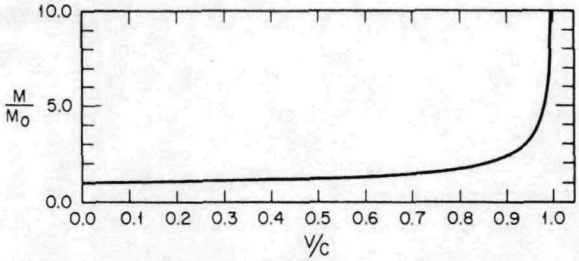


Figure 11 *The ratio of the relativistic mass of a particle to its rest mass as a function of its velocity, where the velocity is measured in units of the speed of light.*

had been built. Actually the use of accelerators to raise the particle velocity very close to the speed of light (such as within one part in ten thousand) is one of the most sensitive tests of this theory. If this prediction of the behavior of the particle mass had been wrong, accelerators would not function properly. For example, at the Alternating Gradient Synchrotron at Brookhaven National Laboratory in New York, which will be described later, protons can be accelerated to an energy such that v/c is greater than 0.999, or 99.9% of the speed of light.

These factors limited early fixed-frequency cyclotrons to proton energies of about 10 Mev. Notwithstanding this

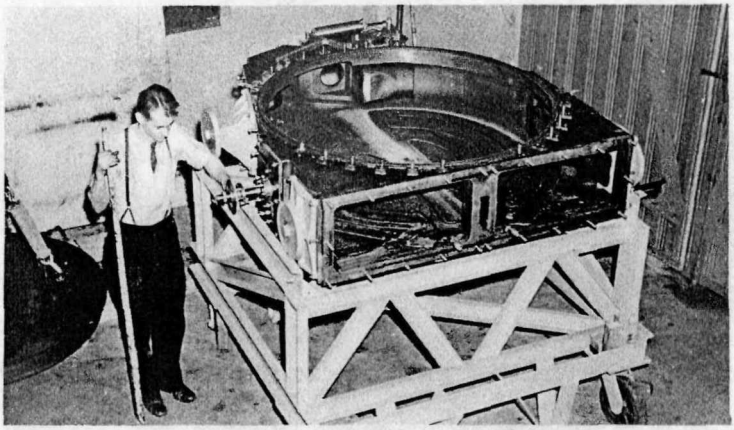


Figure 12 *Dr. Edwin M. McMillan stands next to the accelerating chamber of the cyclotron in February 1940. Later in that year, in experiments with the cyclotron, he and Philip H. Abelson discovered element 93.*

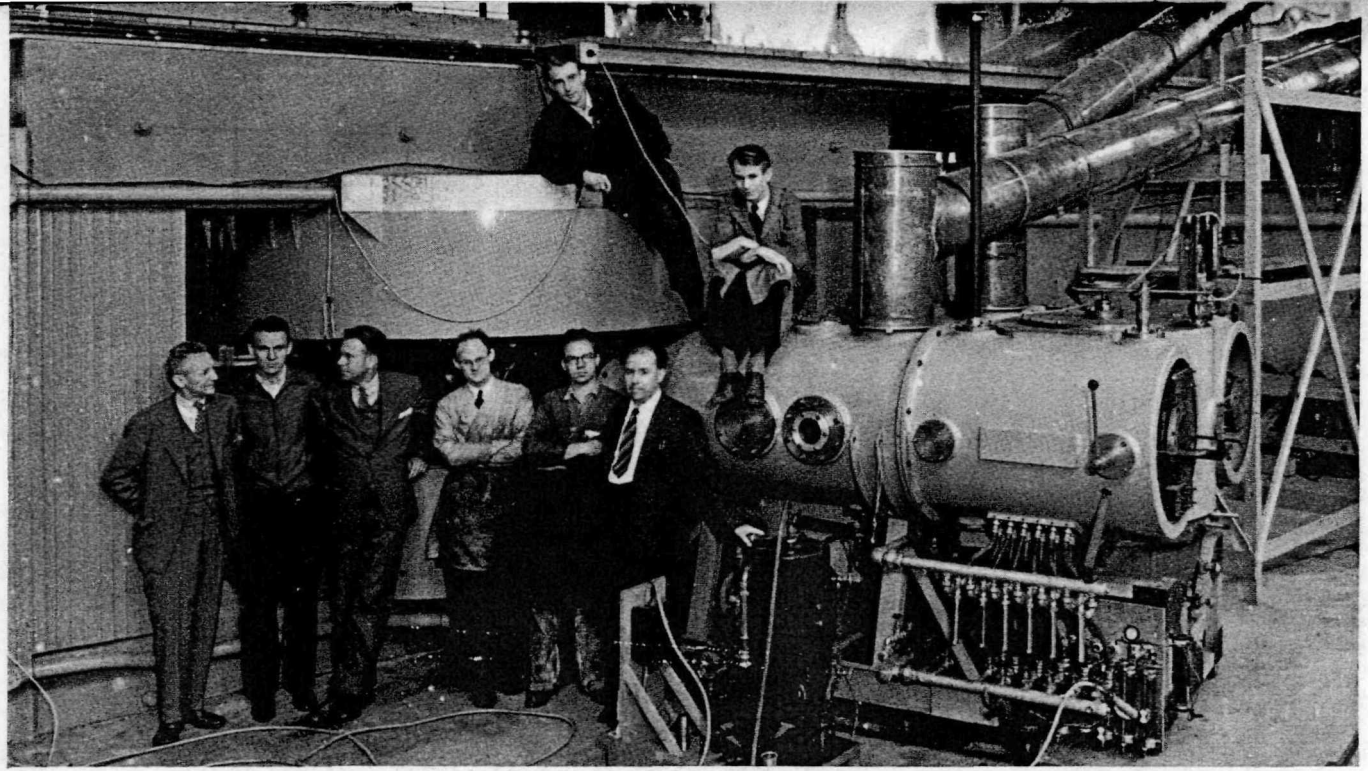


Figure 13 *The 60-inch cyclotron at the Lawrence Radiation Laboratory soon after its completion in 1939. Key figures in the development of the machine are: standing, left to right, Dr. Donald Cooksey, Dr. Dale Corson, Dr. Ernest O. Lawrence, Dr. Robert Thornton, Dr. John Backus, and Winfield W. Salisbury. Top right are Dr. Luis W. Alvarez and Dr. Edwin M. McMillan. Dr. Alvarez leans against part of the magnet and half sits on the housing for the coils; Dr. McMillan sits on one of the tanks holding the dees inside the accelerating chamber. The copper cylinders slanting down from right carry power for the accelerating system.*

fact, they were the most common source of high-energy laboratory-produced particles from 1932 to the late 1940s, and were very important in attempts to understand proton-nucleon interactions in the region below 10 Mev. (The term "nucleon" refers to either a proton or neutron.)

Cyclotrons also serve as tools in producing radioactive isotopes and elements previously unknown to scientists. This is accomplished by irradiating a target of natural materials with protons, deuterons, or alpha particles (a deuteron is a nucleus of deuterium or "heavy hydrogen" and an alpha particle is a nucleus of helium) from a cyclotron, and then studying the resulting radionuclei.

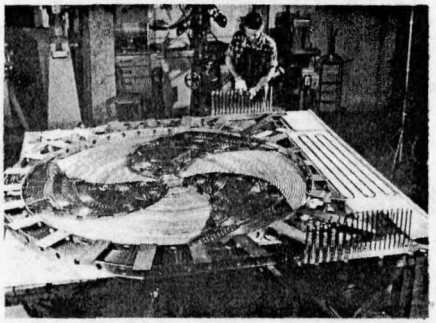


Figure 14 *One of the pole plates of the 88-inch cyclotron, which is a member of a new and sophisticated generation of cyclotrons, at the Lawrence Radiation Laboratory. One of its important functions is to produce radioisotopes that are not produced in reactors. It also allows greater precision of experiment in nuclear research in its energy range (50 to 120 Mev) and has opened up new areas of research.*

The knowledge gained in these experiments was significant in the development of the early atomic bombs. Plutonium, element 94, a fissionable material used in atomic bombs, was first obtained by bombarding uranium-238 with deuterons in the University of California cyclotron built by Lawrence.*

The cyclotrons of the classical type described here are now being replaced by a new design. It is possible to shape the magnetic field to maintain a constant period frequency even though the accelerated ions gain in mass as their velocity increases. These new machines are called isochronous cyclotrons. These facilities are very versatile research tools permitting multiparticle and variable energy operation. One recently completed machine provides protons of about 75 Mev and heavy ions of energies above 100 Mev.

*Lack of cyclotrons was one of the major factors in the failure of Germany to produce an atomic bomb during World War II.

BEATING THE RELATIVISTIC LIMIT—SYNCHROCYCLOTRONS

By the late 1930s, still higher energies were recognized as needed to extend studies of nuclear interactions. Physicists were beginning to think of more advanced machines to achieve these higher energies. The outbreak of World War II shelved these plans, as scientists became involved in the Manhattan Project, which built the first atomic bomb, and other war-related research. With the return of peace, they began to think again of higher energies.

The limiting factor with the fixed-frequency cyclotron was its inability to compensate for the slowing down of the revolution frequency of protons once they had been accelerated to near the speed of light. To overcome this, scientists hit upon the idea of developing a radio-frequency power supply in which the frequencies would *decrease with time* to match exactly the slower revolutions of the protons.

To do this, a machine was designed that operated in a pulsating manner, protons being accelerated in bursts. Unlike the fixed-frequency cyclotron, which can continuously accelerate a stream of particles,* the new machine, the synchrocyclotron, has to push one group of protons through an entire cycle, from the initial highest frequency to the final lowest one, before it can begin accelerating a new group.

The rapidity with which synchrocyclotrons can repeat whole cycles, known as the repetition rate, is naturally very important and is often stated along with maximum energy and other parameters when defining their characteristics. The rates may vary from 60 to 300 per second. The acceleration of particles in bunches necessarily reduces significantly the average beam intensity obtainable from the accelerator. However, the primary goal, a higher energy for the particles in each bunch, is achieved.

More than a dozen synchrocyclotrons that can accelerate protons to greater than 100 Mev have been built. The three

*As explained earlier, this beam is not completely continuous, but is on for a period less than T/2, then off for a period greater than T/2, repetitively, where T is the revolution time of the beam.

largest provide protons with energies of 600, 680, and 740 Mev and are located, respectively, at the CERN Nuclear Research Center near Geneva, Switzerland, at Dubna in the U.S.S.R., and at Berkeley, California.

Synchrocyclotrons are huge machines. For example, the 450-Mev synchrocyclotron at the University of Chicago has a magnet poleface diameter of 170 inches, its magnet weighs 2073 tons, and it takes 650 kilowatts of electrical power to maintain the magnetic field at 18.6 kilogauss (gauss is a unit of magnetic field strength). The frequency of the RF system ranges from 28.6 to 11.8 megacycles per second. To design and construct machines of this size and complexity is both time-consuming and expensive.

The first synchrocyclotron was the one at Berkeley, and it began operation in 1946. Exciting experiments, not possible with lower energy machines, were quickly begun. Among the most important were those which involved creation of the pi-meson, or pion, a particle whose existence was predicted in 1935 by Hideki Yukawa,* a Japanese physicist, and was discovered in cosmic radiation in 1947. A pion has about 273 times the mass of an electron, and a lifetime of about 2×10^{-8} second (2/100,000,000 of a second). It is believed to be the basis of the forces binding the nucleus of an atom together.

By the early 1950s there were five synchrocyclotrons in the United States capable of producing pions in controlled experiments. As more experiments were performed, the details of the interaction between pions and nucleons became clearer and understanding progressed.

In addition to studying pion-nucleon interactions (which in physics are called "strong" interactions), scientists using synchrocyclotrons have studied the "weak" interactions involved in the decay of charged pi-mesons and of muons (a decay product of the pion). A theoretical concept, which for years was thought to be valid in the weak interactions, was the idea of parity. This can be thought of as the identity of any process and the "mirror image" of the process; equivalently one can say that there is no preferred direction

*Another Nobel Prize winner (1949) whose theoretical conclusions were proved by use of accelerators.

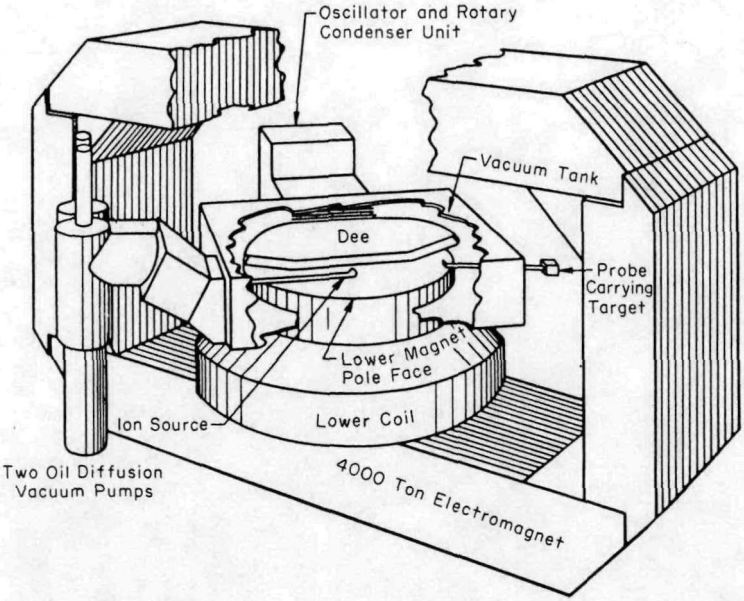
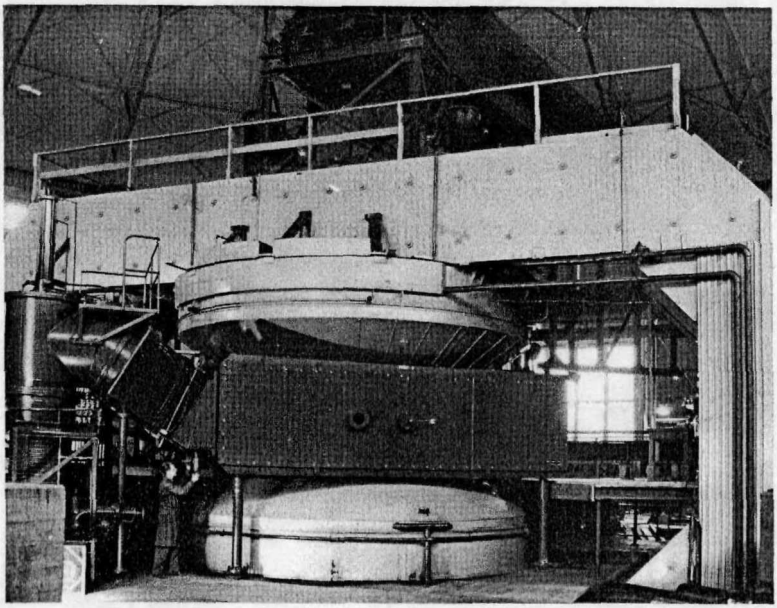


Figure 15 *The 184-inch (diameter of magnet pole faces) synchrocyclotron at the Lawrence Radiation Laboratory. In this machine many more impulses can be applied "in phase" than in a fixed frequency cyclotron, resulting in particles of greater energy.*



in space. With the synchrocyclotron, this principle, previously believed to apply in all matter, was shown to be "violated"—that is, *not* to apply in the weak interactions.

Another important experiment in weak interactions was performed at the synchrocyclotron at CERN, where the decay of a pion into an electron and a neutral particle called the neutrino was first observed. This experiment enabled physicists to differentiate among a number of possible theories or pictures of the weak interactions.

Such experiments were only the highlights of years of dedicated and fascinating work on synchrocyclotrons by hundreds of scientists.*

The Push to Bev Energies – Proton Synchrotrons

There is no theoretical limit on the energy of a synchrocyclotron. There is, however, a practical limit from the point of view of economics. As the desired energy increases, so must the radius of the magnet. As this radius increases, the magnet's area increases as the *square* of the radius and its cost may increase by a factor almost equal to the *cube* of the radius. Thus, the cost rises much too steeply for the synchrocyclotron technique to be used to reach energies in the billion electron volt (Bev) region.

Accordingly, in seeking such energies, scientists tried another technique. This was to develop machines in which the magnetic field rises *in step* with the momentum of the particles being accelerated. This keeps the particles moving in a circle of virtually constant radius rather than in the widening spirals of cyclotrons and synchrocyclotrons. The advantage is that it eliminates the entire center section of the magnet, with resultant cost savings.

Essentially, a magnet surrounds a doughnut-shaped vacuum tank, with the area of the hole of the doughnut much larger than the area covered by the magnet. After preacceleration in a Van de Graaff or a linear accelerator, the particles are injected into the vacuum tank inside the magnet. The magnetic field then rises as the particles are accelerated by successive traversals of one or more gaps

*For more information on experiments of this kind, see *Microstructure of Matter*, another booklet in this series.

across which RF fields are provided. The necessity for pre-acceleration can be understood by reference to equations 1 and 3b. The radius cannot be equal to zero. Therefore, if the velocity in equation 1 is to be zero (as in the case of zero energy, no pre-acceleration), then the magnetic-field strength, H, must be zero. If H is zero, then the period, T, in equation 2b is *infinite* and no acceleration is possible.

Proton synchrotrons operate on cycles of anywhere from .05 to 10 seconds duration, at the end of which time the high-energy beam leaves the machine and the system is returned to conditions appropriate for the injection of the next pulse, and this cycle is continuously repeated.

The size of the magnet in a proton synchrotron is determined by two factors. One is the energy desired, which determines how wide a circle the particles must traverse.

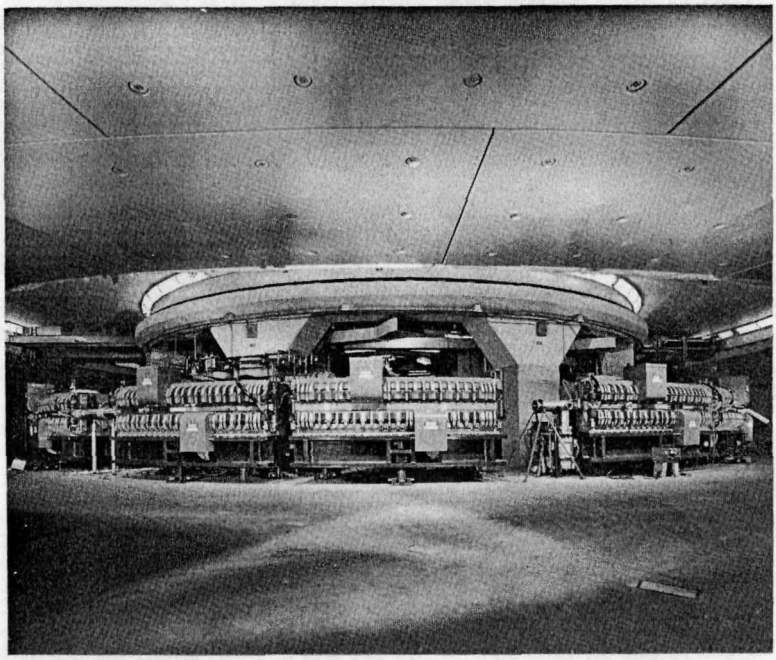


Figure 16 *Magnet ring of the Princeton–Pennsylvania 3-Bev proton synchrotron located at Princeton University's James Forrestal Research Center.*

(The strength of the magnetic field tends to be comparable from one machine to the next because of the magnetic characteristics of iron and related cost factors.) The other is the degree to which the particles are concentrated or "focused" in the magnetic field. This determines the size of the vacuum chamber. (For a more detailed discussion of focusing, see the next chapter.)

The particles being accelerated do not all follow one particular orbit around the accelerator. Instead they perform "oscillations" about such an "equilibrium orbit". With the simplest magnet design for the accelerator, the amplitudes of these oscillations are fairly large (particularly at low energies, such as at the beginning of the acceleration cycle). Such a machine is known as a "weak focusing" accelerator and its vacuum tank must be fairly large. More complicated magnet designs can be used that reduce the amplitudes of these oscillations, and therefore the size of the vacuum tank is reduced, and machines of this type are known as "strong focusing" accelerators.

The first proton synchrotron completed was the Cosmotron at Brookhaven National Laboratory. It accelerated protons to 2.3 Bev in 1952 and later to 3 Bev. This was a "weak focusing" accelerator. Other machines of this type were built in the United States, Great Britain, France, and the

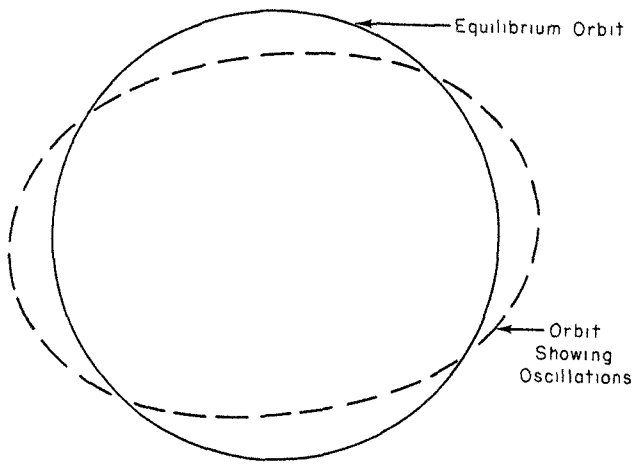


Figure 17 *Idealized schematic showing oscillations about the equilibrium orbit.*

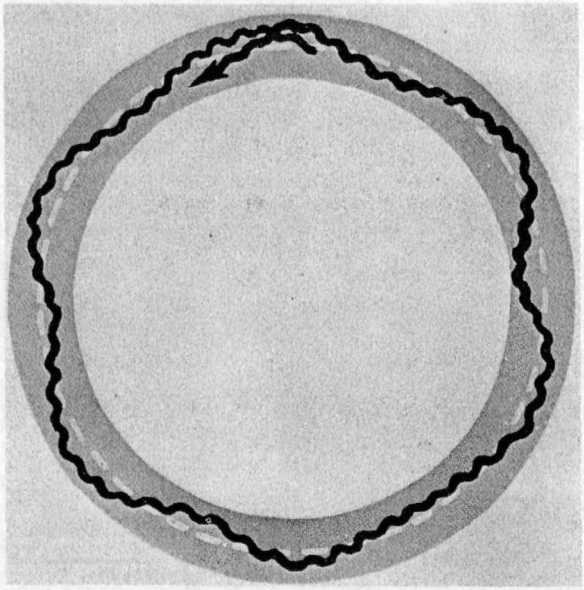
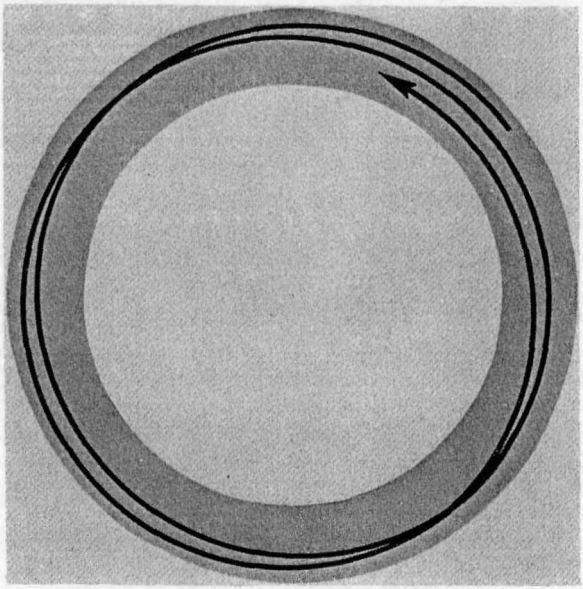


Figure 18 *Strong focusing (above) causes high frequency oscillations to occur, reducing orbit excursions and allowing the construction of synchrotrons with much smaller magnets. Weak focusing below allows large orbit excursions. The "wavelength" is comparable to the circumference of the synchrotron.*



Soviet Union. They range in energy from 1 to 12.5 Bev, the American Zero Gradient Synchrotron at Argonne National Laboratory in Illinois having the greatest energy.

Over the last decade, the contributions to high-energy physics resulting from the use of proton synchrotrons have been very impressive. One of the most impressive single experiments was the identification of the antiproton with the Bevatron (6.2 Bev) at the University of California. This identification of the antiproton convincingly established the validity of a theoretical concept dating from the 1930s, which stated that for every type of particle (such as a proton) there should be a related state in nature, the antiparticle (in this case, an antiproton). The particle and antiparticle should have some properties, such as mass and

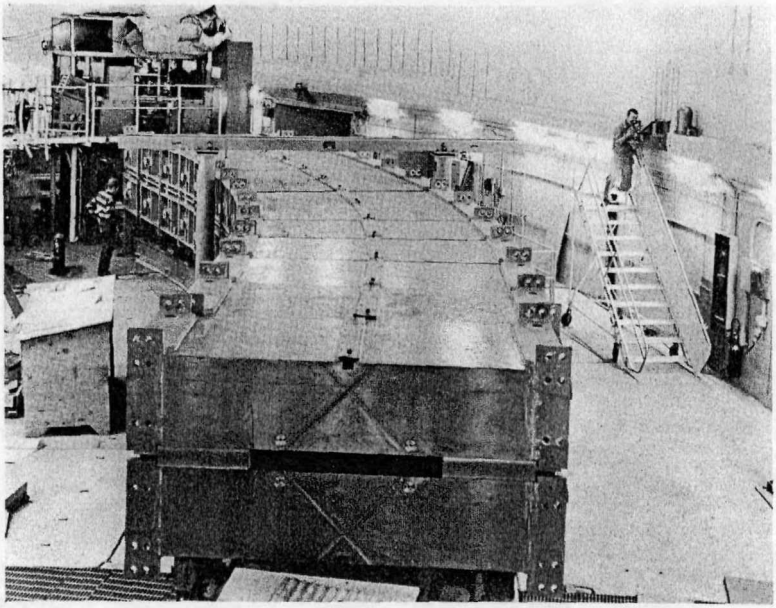


Figure 19 *The Zero Gradient Synchrotron under construction. Man at right is using an optical alignment device. The gap in the magnet is for the vacuum chamber. In the background is the radio-frequency cavity that accelerates the protons. The frequency of this cavity is varied from 4 to 14 megacycles per second as the protons pick up speed from the 20,000 volt "kick" they receive each time they traverse the cavity. The beam enters the ring from the linear accelerator through the tunnel whose opening can be seen just to the right of the radio-frequency station.*

lifetime, which are identical and some other properties, such as electrical charge, which are identical in magnitude but opposite in sign. Many other antiparticles have also been found.

Two "strong focusing" proton synchrotrons have been completed and are operating. These are at Brookhaven National Laboratory (maximum energy 33 Bev) and at CERN (maximum energy 28 Bev). A third one designed for 70 Bev has been constructed in the U.S.S.R. and began operation early in 1968. These machines are capable of producing particles such as the Ω^- (omega minus) whose existence had been predicted on theoretical grounds but which had not been actually observed until 1964. This experimental observation of the Ω^- served to verify theoretical ideas that greatly simplified the physicist's conception of the ordering or interrelation of the elementary particles. At the same time, these theoretical ideas, strengthened by the confirmation that the Ω^- existed, brought speculation that if physicists pushed to still higher energies we might discover that the proton itself is not a simple system, but instead is a composite state composed of simpler particles.

In order to indicate the size of the larger synchrotrons, some figures pertaining to the AGS (Alternating Gradient Synchrotron) at Brookhaven National Laboratory are helpful. The peak energy of the protons from this machine is 33 Bev. Its circumference is about one-half mile, and it is housed in an 18-foot-square tunnel covered by earth for shielding. The shielding is necessary to protect people and sensitive experimental equipment from the radiation that is present during operation. To pre-accelerate and inject the particle beam there are a 750-kev Cockcroft-Walton generator and a 110-foot long, 50-Mev linear accelerator. The main bending and focusing magnets for the accelerator consist of 240 units, each weighing about 20 tons. About 14,000 tons of concrete shielding were used in the target building (the building where many of the experiments are set up and carried out), and over 2,000,000 linear feet of power and control cable were used in the construction of the machine.

A detailed study has been finished for the 200-Bev proton synchrotron, the design is well along toward completion,

and a site near Batavia, Illinois, has been chosen for this giant research tool.

This accelerator will be a highly sophisticated machine. Its designers will profit from experience with previous accelerators. Features already known (from the preliminary design studies carried out at the Lawrence Radiation Laboratory* of the University of California) indicate it will

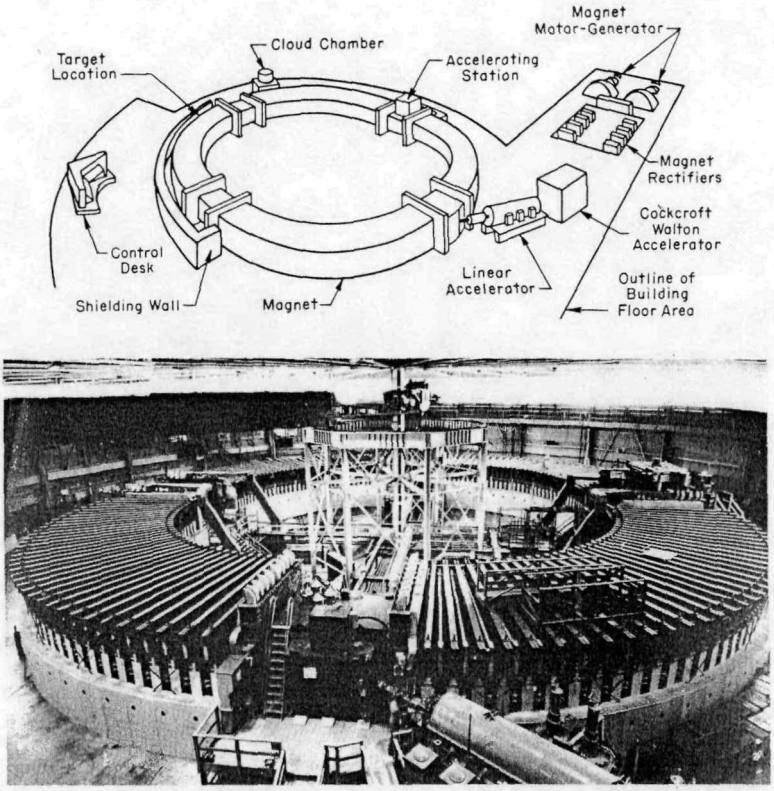


Figure 20 *The Bevatron at the Lawrence Radiation Laboratory. Protons are preaccelerated to 480-kev in a Cockcroft–Walton voltage doubler and then to 19.3 Mev in a 40-foot linear accelerator before being injected into the Bevatron. A proton travels about 394 feet per circuit and makes about 4 million revolutions in 1.8 seconds for a total distance of 300,000 miles. It ends up with a speed 99% that of light and with 6.2 Bev of energy. The photograph was taken before shielding completely enclosed the machine.*

*The laboratory was named after the late Ernest O. Lawrence.

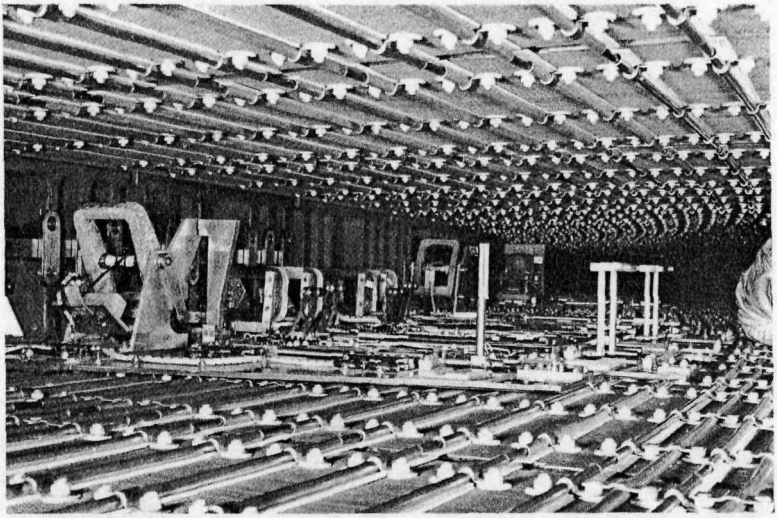


Figure 21 *Inside the vacuum chamber of the Bevatron. After protons are injected into the Bevatron and accelerated to maximum energy, a target jumps up and intercepts the beam. The beam is concentrated in an area about 6 inches wide and 2 inches high in the median plane of the magnet. Several typical targets in a raised position are on the right. The rotating coils that flip the target into position are on the left.*

be a strong focusing synchrotron, with a diameter of approximately $1\frac{1}{4}$ miles. With a designed intensity of about 5×10^{13} protons per pulse and the very high energies (up to perhaps 400 or 500 Bev, with augmented power supplies), the radiation shielding problem will be difficult. There probably will not be any facilities constructed for the use of an internal target, that is, a target inside the vacuum tank of the accelerator, that can be hit by the proton beam. Instead, the proton beam will be extracted from the accelerator and transported by a series of magnets to a target area fairly far away from the accelerator structure itself. Separate magnets will be used for focusing and bending the particle orbits. Special provisions will be made to keep the magnets properly aligned.

The European nations belonging to CERN are hard at work designing a 300-Bev proton synchrotron and very preliminary plans for even higher energy machines are being made.

ACCELERATION OF ELECTRONS

So far we have discussed the methods for obtaining high-energy protons. There are also certain types of accelerators designed to provide high-energy electrons.

The electrons accelerated in these machines are used in two ways. The first involves elastic scattering from nuclei. (In elastic scattering the sum of the momenta of the two particles, the electron and the nucleus, after the scattering is identical to the sum before scattering. The same is true of the sum of the *energies* of the particles before and after the scattering. In this sense, the scattering is like bouncing a marble off a billiard ball, and so is an elastic scattering.)

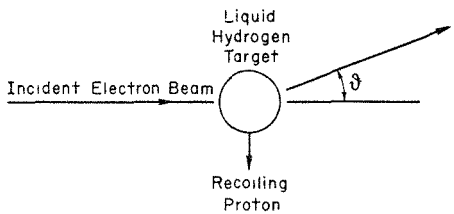


Figure 22 *An electron–proton elastic scattering experiment. Detection of an electron of the correct energy at the scattering angle ϑ shows that there was an elastic scattering.*

When an electron approaches a nucleus there is a force, the Coulomb or electrical force, between the charge of the electron and the charge of the nucleus, and this force is responsible for the scattering. The electrical charge of the nucleus is not a "point charge" but instead is "distributed" over the entire volume occupied by the nucleus. The details of how the elastic scattering occurs depend upon this charge distribution of the nucleus. The scattering process is affected in a measurable way by this nuclear charge distribution only by electrons with high energy or high momentum, however. So if high-energy electrons are scattered by nuclei and the details of the scattering process measured, the charge distribution of the nuclear target can be determined. This scattering process can also be used to study electromagnetic interactions in general.

In the second method, the electrons are made to hit a target and produce high-energy X rays, or photons, called

"bremsstrahlung", which means braking or "slowing down" radiation. An electron passing through an absorber, or radiator, gives up energy as it is slowed down by its interaction with the electrical field of the atoms of the radiator. This energy radiates in the form of photons. If the energy of the original electron beam is known, the number of photons in each energy interval of the resulting bremsstrahlung can be calculated. Then, by lowering the electron energy and repeating the experiment, the effects due only to photons in a small energy interval can be determined.

The betatron is one of the machines developed for accelerating electrons. The principle used in its acceleration mechanism was first suggested by Joseph Slepian, a mathematician working for the Westinghouse Electric Corporation, in 1922. The first accelerator of this type was constructed by Donald W. Kerst in 1940 at the University of Illinois. It achieved energies of 2.5 Mev.

In a betatron electrons are injected into a ring-shaped vacuum chamber placed between the pole pieces of a powerful electromagnet in which the magnetizing current is varied. As the magnetic field rises, the changing magnetic flux exerts a force on the circulating electrons, tangential to their

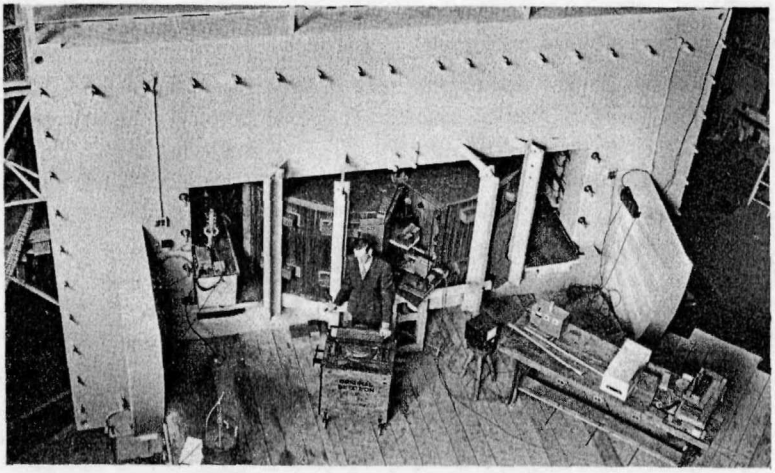


Figure 23 *University of Wisconsin Professor Donald W. Kerst, who built the first betatron, standing between his original machine (now in the Smithsonian Institution) and the University of Illinois' 300-Mev betatron, the world's largest.*

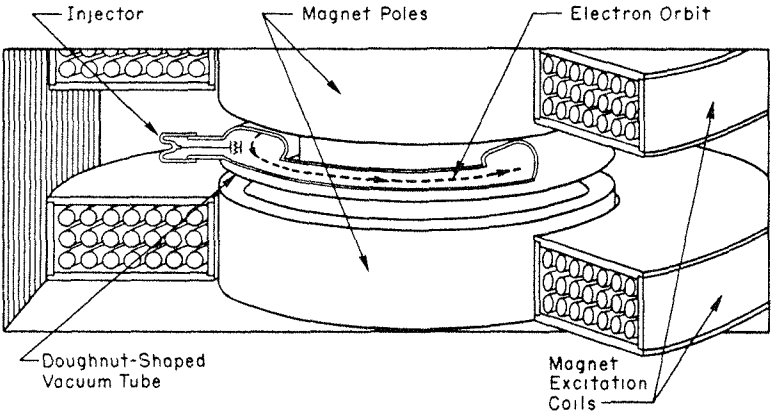


Figure 24 *Operation of a betatron. The magnet poles are energized by alternating pulsed current passing through the primary coils. Electrons from a heated filament are injected into the vacuum tube and forced into a curved path by the magnetic field. When electrons reach the desired velocity, they are displaced onto a target for the production of X rays (bremsstrahlung) or may be used for other purposes.*

motion, and therefore accelerates them in their direction of motion. The magnetic flux and the field at the desired orbit are varied together so that the electrons are kept in an equilibrium orbit corresponding to the radius of the vacuum chamber. The machine's magnetic field provides focusing effects to keep the beam from striking the walls of the chamber. At the end of the acceleration period, the beam is ejected, usually onto a target to make a secondary beam of bremsstrahlung photons. The flux is then lowered and the magnet is ready for the next acceleration cycle.

Unlike the cyclotron, the betatron magnet is designed to use alternating current. The betatron can be considered a transformer whose secondary coil has only one turn, the ring-shaped electron beam.

Betatrons have been constructed that accelerate electrons to 300 Mev. Many important and basic experiments have been carried out with these machines. One such experiment is the production of electron-positron pairs by photons. This reaction can be written as:

$$\gamma + Z \rightarrow e^{+} + e^{-} + Z$$

That is, a photon (γ) entering the strong electric field close to a nucleus Z may be converted into a positive and negative electron pair, leaving the nucleus unchanged.

An analogous reaction that has also been studied with high-energy betatrons is the photoproduction of pion pairs (the pion or pi-meson is a particle already referred to in the discussion of synchrocyclotrons), which can be written as:

$$\gamma + Z \rightarrow \pi^+ + \pi^- + Z$$

Electron Synchrotrons

The synchrotron technique can also be applied to the acceleration of electrons. The technique is much the same for protons and electrons. After a pre-acceleration, electrons are injected into a vacuum tank inside a ring magnet. The magnetic field then rises as the electrons are accelerated by successive traversals of a high voltage gap.

One difference between proton synchrotrons and electron synchrotrons has to do with the number of particle traversals that is desirable for the machine design. A charged particle that is being accelerated radiates energy. Since a circular machine such as a synchrotron requires a circular trajectory or orbit for the particle, and this means that the velocity is changing direction as well as magnitude, it follows that a particle in a synchrotron loses energy by radiation. This energy loss can be considered as proportional to the square of the particle velocity; it must be compensated for by putting more energy into the accelerator. The relativistic kinetic energy of a particle (its kinetic energy at speeds approaching the speed of light) is given by the equation

$$E = \left(\frac{m_0}{\sqrt{1 - v^2/c^2}} - m_0 \right) c^2$$

where m_0 = the "rest mass" of the particle,
v = its velocity
and c = the speed of light

For a large E the last term can be neglected, or

$$E \sim \frac{m_0 c^2}{\sqrt{1 - v^2/c^2}}$$

for $E \gg m_0 c^2$.

The rest mass of a proton is over 1800 times that of an electron, however, so if we are to talk of electrons and protons of the same *energy*, the velocity of the electron must be much greater than that of a proton with the equivalent energy. But this in turn makes the radiation problem in a circular orbit much more serious in the case of the electron, and means that the design should try to minimize the number of traversals of the accelerator that an electron must make in being accelerated to full energy.

Many of the early electron synchrotrons achieved initial acceleration of the electrons up to 5 to 10 Mev by betatron acceleration. Only after this point was reached was the RF voltage applied and operation as a synchrotron begun. More recent machines use a Van de Graaff or linear accelerator to inject high-energy electrons into the synchrotron.

Large electron synchrotrons in the 1- to 2-Bev energy range are located in the United States at the California Institute of Technology and at Cornell University. In this same general energy range in other parts of the world there are operating electron synchrotrons in Lund, Sweden; Frascati, Italy; Tokyo, Japan; Orsay, France; Bonn, Germany; and Tomsk, USSR. In recent years a group of higher energy electron synchrotrons have been built. In the United States, these are at Harvard University (6 Bev) and at Cornell University (10 Bev). Both are completed and are operational. A 6-Bev German accelerator at Hamburg, and another at approximately the same energy at Yerevan in the Soviet Union are operational as well as one at Daresbury in Great Britain.

Before discussing electron accelerators of even higher energies, it should be noted that new accelerators need not always involve higher energies. Many designs for new accelerators, particularly electron accelerators, are under

study where the energy is quite low—a few hundred Mev or less. The purpose of these machines will be to achieve more beam intensity for more accurate and detailed experiments on interesting processes at the low and medium energies.

These high intensity accelerators, whether proton or electron machines, have a common feature; they are designed to produce a secondary beam and it is this secondary beam that will be used for most experiments. In the discussion of the acceleration of electrons we mentioned the photon beam resulting from bremsstrahlung. It is obvious that the process of using such a wide energy beam and doing subtractions to get the effects of photons of a single energy necessarily limits the accuracy with which the experiments can be done.

The process of bremsstrahlung can be represented as

$$e^- + z \rightarrow z + e^- + \gamma$$

in which z represents a nucleus. If electrons of a certain energy are detected at a particular angle in the laboratory, then, since energy and momentum must remain equal before and after scattering, the direction *and energy* of the γ or photon will be known. If a target is placed at that angle and the γ induced reactions are detected only if they occur at the same time with an electron of the correct energy then the reaction involves only one photon energy. The accuracy can be improved enormously because no subtractions are necessary. But of course, to have an appreciable counting rate when using only the photon of one energy, the incident electron intensity must be very high.

FOCUSING IN ACCELERATORS—THE NEED AND THE METHOD

Why must a particle beam in a synchrotron or other accelerator be focused? If we simply inject the particles and then let them traverse the circular path in the magnetic field, shouldn't they hit the target at the end of this acceleration cycle?

These questions are easily answered by referring to the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. During the acceleration cycle the protons in this 33-Bev machine traverse the one-half mile circumference ring about 300,000 times, traveling about 150,000 miles. (This takes about 1 second.) At the end of this journey they must hit a target about one-tenth of an inch high. There is just no way that the incident beam can be aimed well enough to do this. Even if it could be, small variations in the magnetic field of one magnet, perhaps due to a slight difference in the iron at that spot, would throw the beam far out of position after so many passes through this "bump" in the field. It is obvious that some method of "trapping" particles that wander away from the equilibrium orbit, and of forcing them to return, must be devised. The need for focusing is clear.

If the magnetic field strength of an accelerator varies with distance from the equilibrium orbit, this variation, called a "gradient", exerts a force on the particle. The force on an off-axis particle due to such a gradient can drive the particle back towards the equilibrium orbit.

If the force is made larger, the amplitudes of the oscillations about the equilibrium orbit become smaller, but usually the *number* of oscillations then gets larger. This is the difference between "strong focusing" and "weak focusing" in more detail.

Besides building high-energy accelerators with complicated magnetic field gradients, research institutions also have designed low-energy accelerators with still more complicated magnet designs. With these, beam orbits are expected that will make possible greatly refined low-energy accelerators.

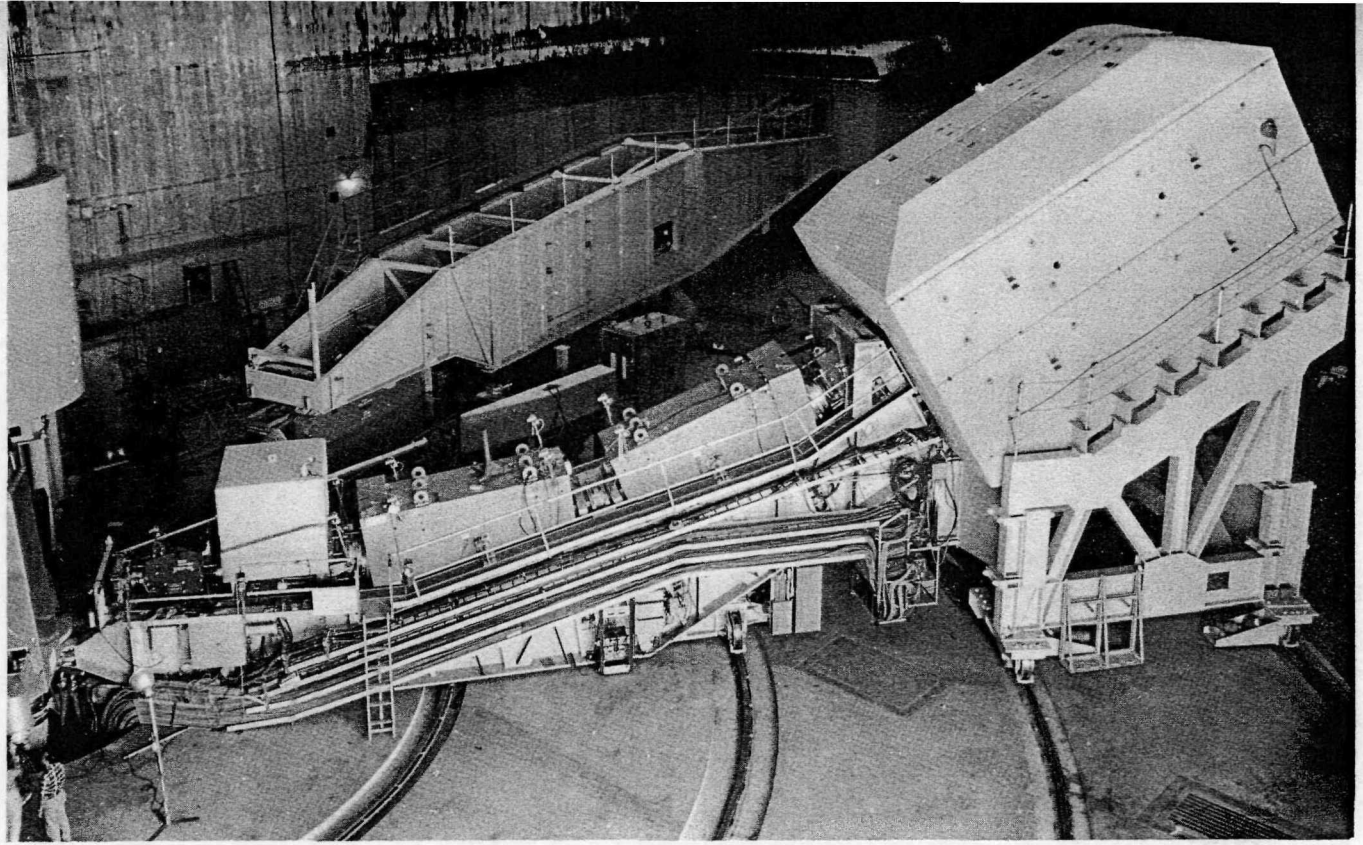


Figure 25 *Giant magnetic spectrometers at Stanford Linear Accelerator Center (SLAC) in Stanford, California. Electron beam strikes target nuclei at left. Emerging particles are separated and analyzed by powerful magnets in spectrometers. Note size of men at far left.*

LINEAR ACCELERATORS

Linear accelerators, while conceptually simple (the idea dates from 1924), were the latest machine types to be developed because of rather difficult engineering problems.

In its simplest form a linear accelerator consists of a series of electrodes. Alternate electrodes are connected electrically to each other, and holes bored through them permit the passage of an ion beam.

The electric field created by the electrodes exerts a force on the charged particles and accelerates them. The force on a particle can be expressed mathematically as the "time rate of change of momentum" or

$$F = \frac{m(t_2)\ V(t_2) - m(t_1)\ V(t_1)}{t_2 - t_1} = \frac{\Delta mv}{\Delta t}$$

where $m(t_2)$ and $V(t_2)$ mean the mass and velocity respectively, evaluated at time t_2. (The symbol Δ means "change in".) If the velocities are small compared to the velocity of light, that is, if the problem is *non-relativistic*, then the mass is a constant and this equation becomes

$$F = m\frac{\Delta v}{\Delta t}$$

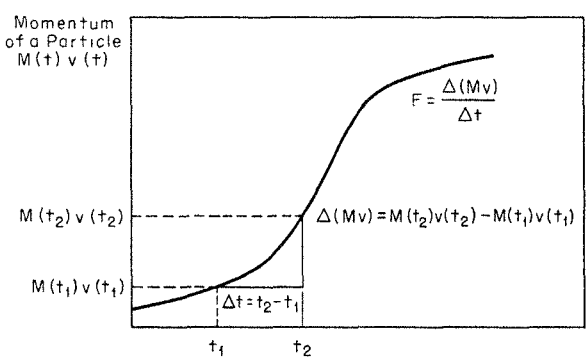


Figure 26 *If a particle's momentum changes with time, then the average force for a time interval Δt can be calculated as shown. If the time interval is made very small, then the force can be considered as applied at one instant of time and its value would be shown by the slope of the momentum-versus-time curve at that instant in time.*

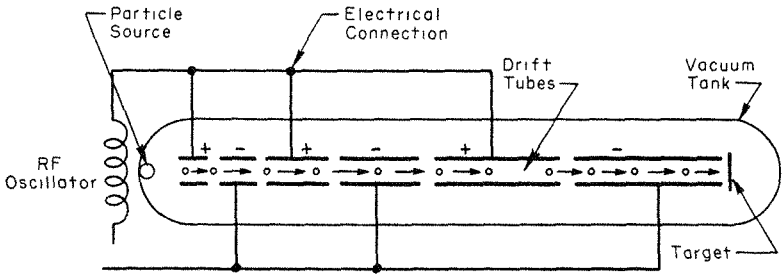


Figure 27 *A linear accelerator. The separation between accelerating gaps, which is the distance traversed by the particles during one half cycle of the applied electric field, becomes greater as the velocity of the particle increases. At any instant adjacent electrodes carry opposite electric potentials. These are reversed each half cycle.*

In this case, the force is proportional to the change in velocity per unit time. This implies that the velocity of the particle is increasing, so if the electrodes were to be spaced evenly, the particle would travel through the successive spaces in shorter and shorter times until finally it would fall out of phase with the RF accelerating voltage. The machine can be designed, however, so that the electrodes increase successively in length and the *distance* a particle traverses between accelerating gaps increases constantly; the *time* of traversal between gaps is identical.

In the relativistic region, where the velocity of the particles is near that of light, an increase in energy is *not* accompanied by a significant change in velocity. This brings up a major difference between designing linear accelerators for protons or heavier particles and designing linear accelerators for electrons. For accelerating electrons the design problems are considerably simplified. Because of their much lighter mass, electrons can be injected into the accelerator at relativistic velocities. This means they are *already* in the region where their velocity does not change appreciably during the acceleration process, and the design can use both a fixed-frequency RF power supply and constant electrode lengths. For protons, on the other hand, the accelerator must start with non-relativistic conditions and then make a transition to accommodate relativistic conditions. This is a quite complicated problem.

There are newer and more elegant methods of assuring synchronization of the electromagnetic accelerating voltage and the particle beam, but a description of them is beyond the scope of this book. The methods grew out of technological advances made in microwaves and radar during World War II.

Linear accelerators have a number of significant advantages. Chief among them is the ease with which particles may be introduced at one end and extracted at the other.

At Stanford University a 1-Bev linear electron accelerator was completed in 1951. This accelerator has been used for many significant experiments, among which are the electron elastic scattering experiments from nuclei carried out by Dr. Robert Hofstadter, Professor of Physics at Stanford University, and his co-workers. In a series of experiments over a period of years, the charge distribution on the nuclei were measured for many elements. These measurements determine the relationship of charge distribution to the number of nucleons in the nucleus and give a fairly good idea of the size of various nuclei.

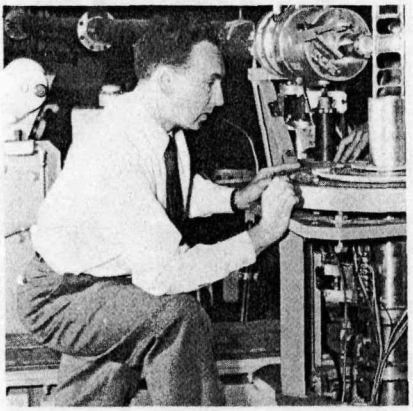


Figure 28 *Dr. Robert Hofstadter is shown here with the Stanford University Mark III linear accelerator.*

As the precision of the experiments was improved, the Stanford research group succeeded in measuring the charge distribution of the proton, one component of the nucleus. In recognition of the importance of this series of experiments, Professor Hofstadter was awarded the Nobel Prize in Physics in 1961.

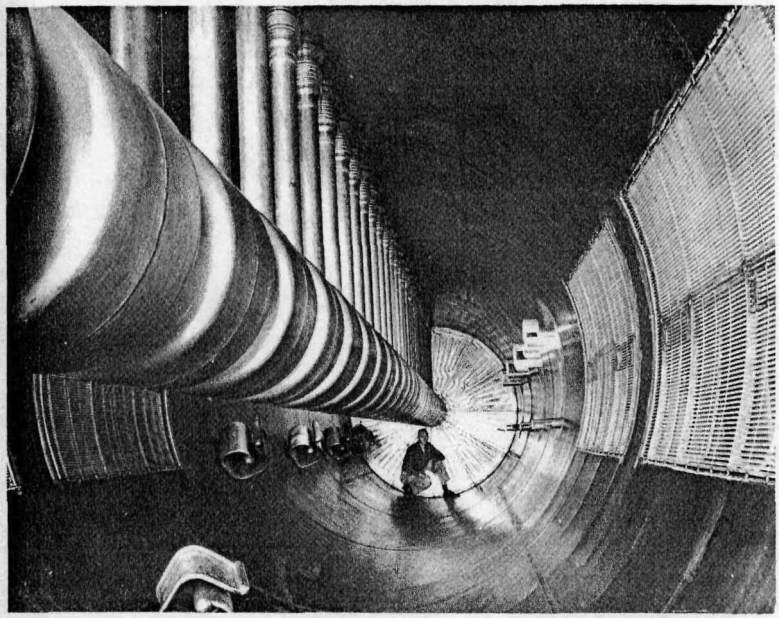


Figure 29 *Interior of the heavy ion linear accelerator (HILAC) at the Lawrence Radiation Laboratory. The photograph looks in the direction of acceleration in the main accelerating chamber with alignment of drift tubes on the left. The pattern on the end plate is formed by cooling apparatus.*

This type of experiment and many others on the electromagnetic interactions can be used to probe even deeper and determine still smaller dimensions.

For the production of electrons having energies markedly higher than 10 Bev the linear accelerator seems the most practical device since it does not produce the troublesome radiation loss associated with electron acceleration in a circular electron synchrotron.

In 1957, Stanford University physicists proposed the construction of a 2-mile electron linear accelerator to achieve a beam of 20-Bev electrons. (In contrast, the 1-Bev accelerator was 300 feet long.) Funds for the project were approved by Congress in 1961 and the accelerator began operation in 1966. A complete description of this machine would be too technical and too long to include here, but some of the unique problems encountered in its construction and their ingenious solutions can be described.

The electron beam must traverse the entire 2-mile length through an accelerating aperture only three-quarters of an inch in diameter. The desired alignment tolerances are such that the beam tube should not vary more than 1 millimeter from a straight line in the 2-mile length. In addition, once the tube is aligned to this specification, it must be maintained at this tolerance without lengthy "down times" for realignment. Earth compression and settling with time had to be considered and the situation also was somewhat complicated by the campus location, in an earthquake-active area. The problem was solved by locating the beam tube sections in a fixed position on a large vacuum pipe that houses a delicate remotely monitored optical system. A technician can carry out the entire alignment measurement procedure without ever entering the radiation areas or requiring that the accelerator be shut down.

Figure 30 *Interior of the 2-mile long klystron tube gallery at the Stanford Linear Accelerator Center is large enough so that employees find it convenient to bicycle from one end to another.*

Another serious problem was that the inside diameter of the accelerator tube had to be held constant, to 50-millionths of an inch. Special fabrication techniques were developed to construct these tubes.

In recent years heavy-ion linear accelerators have come into use as research tools. These machines are designed to accelerate ions of such elements as carbon, nitrogen, oxygen, and neon. Heavy-ion linear accelerators have been constructed at the University of California and at Yale University.

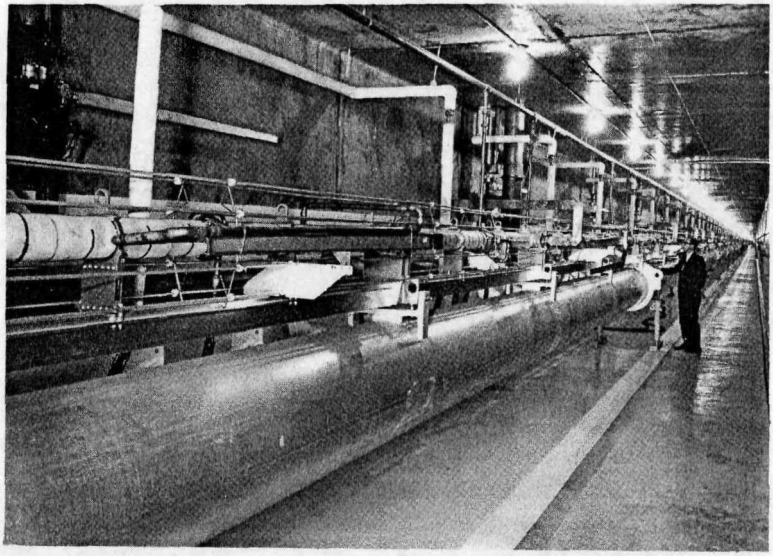


Figure 31 *Subterranean view of Stanford accelerator housing. Alignment optics (laser systems) are housed in the large tube, which also acts as support for the smaller accelerator tube above it. Target patterns dropped into the large tube at selected points produce an interference pattern at the far end of the tube. Precise alignment of the tube is achieved by aiming the laser at the center dot of the pattern. Then the section that is out of line is physically moved until the dot appears in the proper place at the other end of the tube.*

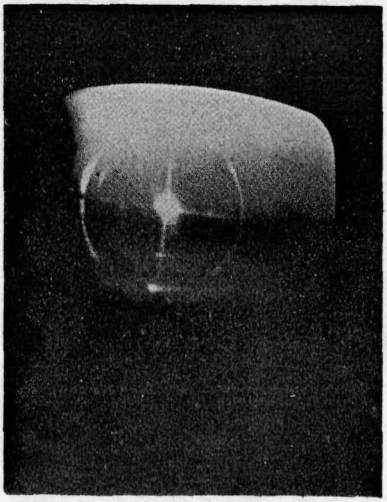


Figure 32 *Laser beam spot as observed at the end of the accelerator.*

FITTING MACHINES TO RESEARCH NEEDS

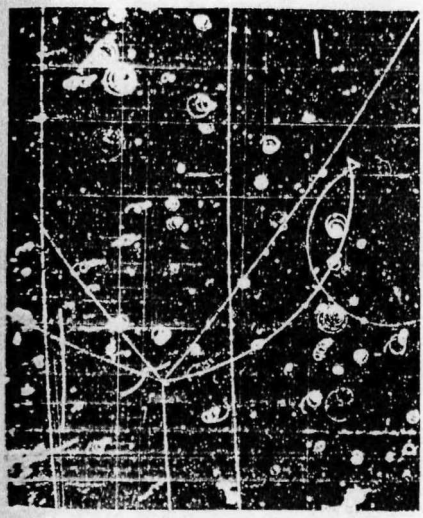
Over the years several types of accelerators have been constructed. Each has been designed either to solve a unique set of problems or to attack well-known problems in a unique fashion. Each machine had to be justified on two grounds: (1) the importance of the problems it was to attack, and (2) the probability of success.

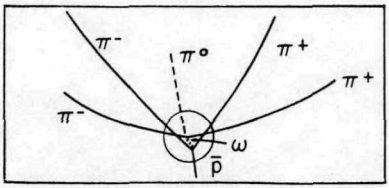
When the Bevatron at the Lawrence Radiation Laboratory was being designed, one of the questions being asked by physicists was: "Do the antiproton and antineutron exist?" (Each particle is thought to have an antiparticle; an antiparticle is a "mate" or "mirror image" of the particle; that is, some of their properties such as mass are identical, but other properties such as electrical charge are exactly opposite. For a more detailed explanation see a companion book, *Microstructure of Matter*, in this series.) The antiproton and antineutron had been thought to exist on theoretical grounds, and theoretical predictions of many of their properties could be made, but they had never been observed. Scientists, however, could calculate the minimum energy for proton beam needed to produce them, if they did exist. The Bevatron was designed for an energy of 6.2 Bev, comfortably above the calculated threshold to create antiprotons and antineutrons. The machine worked beautifully; the antiproton and the antineutron *were* found and their properties and interactions have now been studied in detail. Of course, the Bevatron also was used for many other important and unanticipated experiments, since it opened up a whole new range of particle energies, but the point here is that it performed exactly as specified.

The 33-Bev AGS machine at Brookhaven National Laboratory also worked immediately, for all its complexity, when it was first turned on. Within a few months it was able to accelerate up to 300,000 million protons per pulse. With all the factors that could have caused trouble, this was a tremendous technological feat, of which the designers and builders can justifiably be proud.

In the years since the construction of the first accelerators, the energies obtainable with these machines have increased by a factor of 47,000.

Accelerators have contributed many new and exciting insights into the structure of matter. All the questions have not been answered; in fact, many of the questions probably have not yet been formulated. Therefore one can feel confident that particle accelerators will continue to be important aids to the understanding of nature.





Vertex magnified about 5 X 10^{12} times

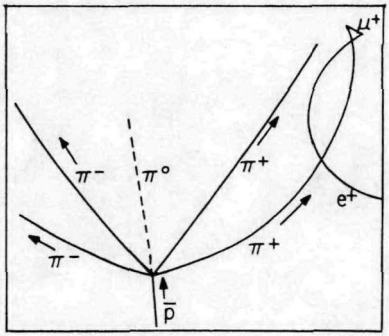


Figure 33 *Bubble chamber photo, left, led to the late 1961 discovery of a new elementary particle of matter, the omega meson (ω^0), at the Lawrence Radiation Laboratory in Berkeley, California. The omega particle, which had been predicted for several years on theoretical grounds, was found only after some 30,000 photographs, made in the 72-inch bubble chamber, had been analyzed. In 90 photos, analysis showed that the presence of omega was essentially to explain the observable phenomena. The difficulty arose from fact that the particle has an extremely short lifetime—about 10 thousand billion billionths (4×10^{-23}) of a second—and since it has no electrical charge it does not make a track of its own on the photographs. The University of California scientists, therefore, had to infer the omega's existence from the visible tracks of other particles. Lower drawing is a replica of the photograph and shows how the annihilation of an antiproton ($\bar{p}$) results in four charged pi-mesons, or pions (π), and a neutral pion. The upper drawing indicates the annihilation vertex, magnified more than a billion times (10^{12}), and shows that actually, the antiproton ($\bar{p}$), when colliding with a proton, produces an omega meson (ω^0) and two charged pions (π^- and π^+). In turn, the omega rapidly decays into a neutral pion (π^0) and two more charged pions (π^- and π^+).*

THE FUTURE

Only a few years ago it was possible to draw up a list of about 30 subatomic particles that were regarded as "fundamental", that is, they could not be explained as simple composites of one another. However, in recent years another 60 or 70 subatomic objects have been observed during experiments using the higher energy and higher intensity beams available from new accelerators. To call all these objects "fundamental particles" seemed to give a very complicated picture of nature, so physicists have searched diligently for simplifying principles. One suggestion—to use a symmetry approach—was brought forward independently by several different scientists. In this approach, many particles are grouped together to form a "class" of particles. By following this lead, scientists have been able to make many predictions that could be checked experimentally, using accelerators. The agreement of the experiments with the theoretical predictions has been very encouraging. Further speculation stemming from this root theory has been that there may exist an even more fundamental group of particles, not yet observed, from which the presently known particles are constructed. The search for this new group of particles and continuation of the studies of presently known "classes" of particles will require accelerators with even higher intensities and higher energies.

To accomplish this, practically all existing accelerators will be modified to incorporate major changes so that their intensities can be increased by factors of 10 to 100. Additionally, a new generation of accelerators is in the design stage. Some of these designs are for rather conventional accelerators, but others may make use of new features such as superconducting magnets and radio-frequency cavities. As in the past, accelerator design is making use of the very newest techniques and taking advantage of new engineering and fabrication processes.

One example is the possible use of superconducting magnets. A superconducting magnet will produce very high magnetic fields of about 100,000 gauss strength compared with a maximum of about 20,000 gauss for conventional iron yoke magnets, at a very low power cost. This will allow

lower power costs, permit smaller dimensions so that less land will be needed, and reduce construction for tunnels, shielding, and other factors associated with the size of conventional accelerators. Construction of superconducting magnets this large will entail some problems. The initial cost of the magnets is high and there must be provision to cool them to very low temperatures, in the range of a few degrees Kelvin (0 degrees Kelvin is −273 degrees Centigrade).* All these are basically engineering problems and the accelerator design staffs are devoting a considerable effort to trying to solve them so that they can build bigger machines more economically. This new generation of accelerators will have energies in the range 200 to 1000 Bev and intensities in the range 10^{12} to 10^{14} particles per second.

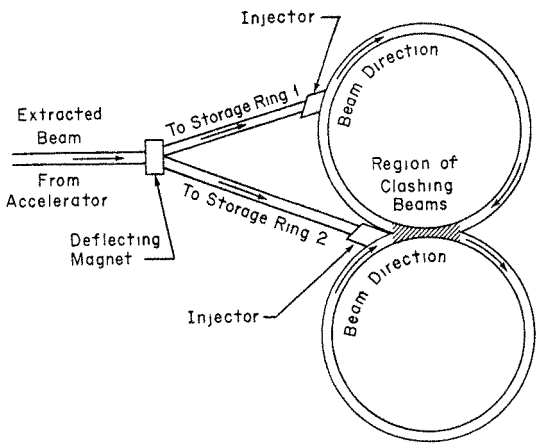


Figure 34 *Main elements of a two-storage-ring area for clashing beam experiments*

Another innovation, which has been started at CERN and at Stanford, is the addition of storage rings to proton and electron accelerators. In storage rings the output beam of the accelerator is injected in opposite directions into two rings, which closely resemble conventional circular accelerators. At a section that is common to both rings, the two

*For more about superconducting magnets, see *Cryogenics, The Uncommon Cold,* a companion booklet in this series.

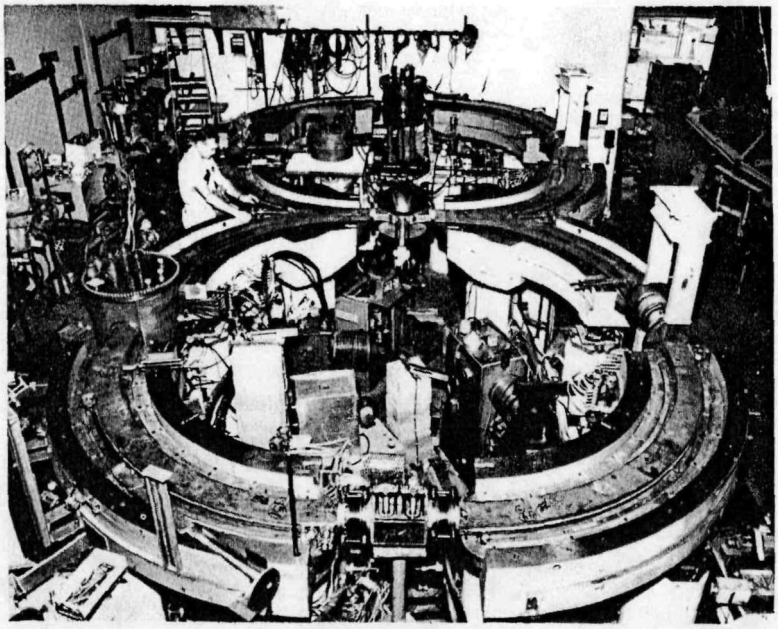


Figure 35 *Storage rings, for a joint Princeton–Stanford colliding beam experiment for electron–electron scattering are shown here under construction.*

beams collide; the total energy available in the center mass of the colliding particles is the sum of the energies of the two colliding particles. (By contrast, the total energy available with a conventional beam striking a stationary target is proportional to the square root of the energy of the accelerated beam.) Storage rings attached to a 30-Bev proton accelerator would have energies of collision (60 Bev), equivalent to that of a conventional accelerator of 1800 Bev.

Another variant of the storage ring idea is to store particles of opposite charge in the same ring, providing for electron-positron and proton-antiproton collisions in several straight sections around the circumference.

This quest for understanding the basic fiber of our universe will continue to attract bold and imaginative minds for decades to come. It offers a challenge both in the research accomplished with accelerators and in the sophistication of the accelerators themselves.

National Accelerator Laboratory

This laboratory, described on pages 1 and 27, will be the home of the world's most powerful proton accelerator. Its components are:

The *accelerator* in which protons are speeded up to full energy and then extracted and transported to targets.

The *experimental areas* for experiments with the primary beam of protons or with secondary beams of other particles produced when the protons strike targets.

The *support facilities* (laboratories, shops, and offices) for the preparation of experiments and the analysis of their results, as well as maintenance and development of the accelerator, theoretical research, and the housekeeping functions of the laboratory.

The Linac building, shown facing page 1, will house the first two of four separate accelerators, each of which will come into play sequentially as protons are accelerated from rest to an energy of 200 billion electron volts.

The four accelerators will play the following roles:

(1) In a pre-accelerator, which provides the first stage of acceleration, hydrogen atoms are stripped of their electrons in an electrical discharge. The remaining positively charged protons, which had formed the nuclei of the hydrogen atoms, are accelerated by a 750 kilovolt electric field, and gain an energy of 750 thousand electron volts (kev).

(2) Protons are then accelerated from 750 kev to an energy of 200 Mev in the linear accelerator, or Linac, which is approximately 500 feet long.

(3) At 200 Mev, the protons are injected into a booster accelerator, which carries them to an energy of 10 Bev. The booster is a rapid-cycling synchrotron approximately 500 feet in diameter.

(4) At 10 Bev, the protons are injected into the main accelerator, which is a synchrotron with a diameter of 1.24 miles and accelerated in this final stage to full energy. Initially this energy will be 200 Bev, but more power supplies can be added later to increase the accelerator's peak energy to 400 or possibly 500 Bev. After reaching maximum energy, the protons then are extracted and transported to experimental areas.

U. S. ACCELERATORS WITH ENERGY GREATER THAN 200 MEV
(As of Jan. 1, 1968)

Location	Common name[a]
OPERATING	
Lawrence Radiation Lab., Berkeley, Calif.	184-inch Synchrocyclotron
University of Rochester, New York	130-inch Synchrocyclotron
Columbia University, New York City	Synchrocyclotron
University of Chicago, Illinois	170-inch Synchrocyclotron
Carnegie Inst. of Tech., Pittsburgh, Pa.	142-inch Synchrocyclotron
Lawrence Radiation Lab., Berkeley, Calif.	Bevatron
Brookhaven National Lab., Upton, N. Y.	AGS
Calif. Institute of Tech., Pasadena	Cal Tech Synchrotron
Cornell University, Ithaca, New York	Cornell Synchrotron
Harvard University, Cambridge, Mass.	CEA
University of Illinois, Urbana	Illinois 300-Mev Betatron
Stanford University, Palo Alto, Calif.	Mark III Electron Linac
Princeton University, New Jersey	PPA
Argonne National Laboratory, Argonne, Ill.	ZGS
Cornell University, Ithaca, N. Y.	Cornell 10-Bev Synchrotron
Stanford University, Palo Alto, Calif.	SLAC
Space Radiation Effects Laboratory, Newport News, Va.	Synchrocyclotron
UNDER CONSTRUCTION	
National Accelerator Laboratory, Batavia, Ill.	200-Bev
Massachusetts Institute of Technology, Cambridge, Mass.	Electron Linac

[a] AGS — Alternating Gradient Synchrotron
CEA — Cambridge Electron Accelerator
PPA — Princeton-Pennsylvania Accelerator
ZGS — Zero Gradient Synchrotron
SLAC — Stanford Linear Accelerator Center

Type[b]	Energy (Mev)	Particles accelerated	Year of start-up	Financial support
FMC	740	Proton	1946	AEC
	460	Deuteron		
	910	Alpha		
	1140	Helium 3		
FMC	240	Proton	1948	AEC
FMC	400	Proton	1950	NSF
FMC	450	Proton	1951	NSF
FMC	440	Proton	1952	AEC
PS	6200	Proton	1953	AEC
PS ag	33,000	Proton	1960	AEC
ES	1500	Electron	1953	AEC
ES ag	2200	Electron	1953	NSF
ES ag	6000	Electron	1962	AEC
Betatron	300	Electron	1950	NSF
Linac	1100	Electron	1950	ONR
PS	3000	Proton	1963	AEC
PS	12,700	Proton	1963	AEC
ES ag	10,000	Electron	1967	NSF
Linac	20,000	Electron	1966	AEC
FMC	600	Proton	1965	NASA
PS	200,000	Proton	1974	AEC
Linac	400	Electron	1969	AEC

[b]Key to abbreviations:
ES — electron synchrotron
FMC — frequency modulated cyclotron
Linac — linear accelerator
PS — proton synchrotron
ag — alternating gradient magnetic field
ONR — Office of Naval Research
NSF — National Science Foundation
NASA — National Aeronautics and Space Administration

At the ground-breaking ceremony for this laboratory, Dr. Glenn T. Seaborg, Chairman, U. S. Atomic Energy Commission, said, "Symbolically, we could say that the spade that breaks ground on this site today begins our deepest penetration yet into the mysteries of the physical forces that comprise our universe." This quest for understanding the basic fiber of our universe will continue to attract bold and imaginative minds for decades to come. It offers a challenge both in the research accomplished with accelerators and in the sophistication of the accelerators themselves.

SUGGESTED REFERENCES

Books

Popular Level

Particles and Accelerators, Robert Gouiran, translated by W. F. G. Crozier, McGraw-Hill Book Company, New York 10036, 1967, 254 pp., $4.95 (hardback); $2.45 (paperback).

Accelerators, Robert R. Wilson and Raphael Littauer, Doubleday and Company, Inc., New York 10017, 1960, 196 pp., $2.50 (out of print but available through libraries); $1.45 (paperback).

Technical Level

Great Experiments in Physics, Morris H. Shamos (Ed.), Holt, Rinehart and Winston, Inc., New York 10017, 1959, 370 pp., $7.95 (hardback); $5.95 (paperback). Contains several chapters relevant to this booklet.

Principles of Cyclic Particle Accelerators, John J. Livingood, D. Van Nostrand Company, Inc., Princeton, New Jersey 08540, 1961, 392 pp., $10.75. For the advanced student.

Accelerators of Charged Particles, B. S. Ratner, translated by L. A. Penn, Pergamon Press, Inc., Long Island City, New York 11101, 1964, 120 pp., $3.50.

The Development of High-Energy Accelerators, M. Stanley Livingston (Ed.), Dover Publications, Inc., New York 10014, 1966, 317 pp., $2.50.

High-Energy Accelerators, M. Stanley Livingston, John Wiley and Sons, Inc., New York 10016, 1954, 157 pp., $4.95.

Articles

CERN: The Strong Focus is on the 300-Bev Machine, John Walsh, *Science,* 155: 544 (February 3, 1967).

Particle Storage Rings, Gerard K. O'Neill, *Scientific American,* 215: 107 (November 1966).

Electrons Accelerated to the 10- to 20-Gev Range, W. K. H. Panofsky and others, *Science,* 152: 1353 (June 3, 1966).

Polarized Accelerator Targets, Gilbert Shapiro, *Scientific American,* 215: 68 (July 1966).

The Streamer Chamber, David E. Yount, *Scientific American,* 217: 38 (October 1967).

Europe's Giant Atom Smasher, *Business Week,* 66 (July 8, 1967).

Linear Accelerators for Protons: New developments, Darragh E. Nagle, *Science,* 157: 145 (July 14, 1967).

Two-mile Electron Accelerator, Edward L. Ginzton and William Kirk, *Scientific American,* 205: 49 (November 1961).

High-Energy Scattering, Vernon D. Barger and David B. Cline, *Scientific American,* 217: 77 (December 1967).

Motion Pictures

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C. 20545, and from other AEC film libraries.

Atom Smashers, 18 minutes, color, 1967. Produced by the Handel Film Corporation with the cooperation of the AEC. Explains purposes, principles, and methods of particle accelerators.

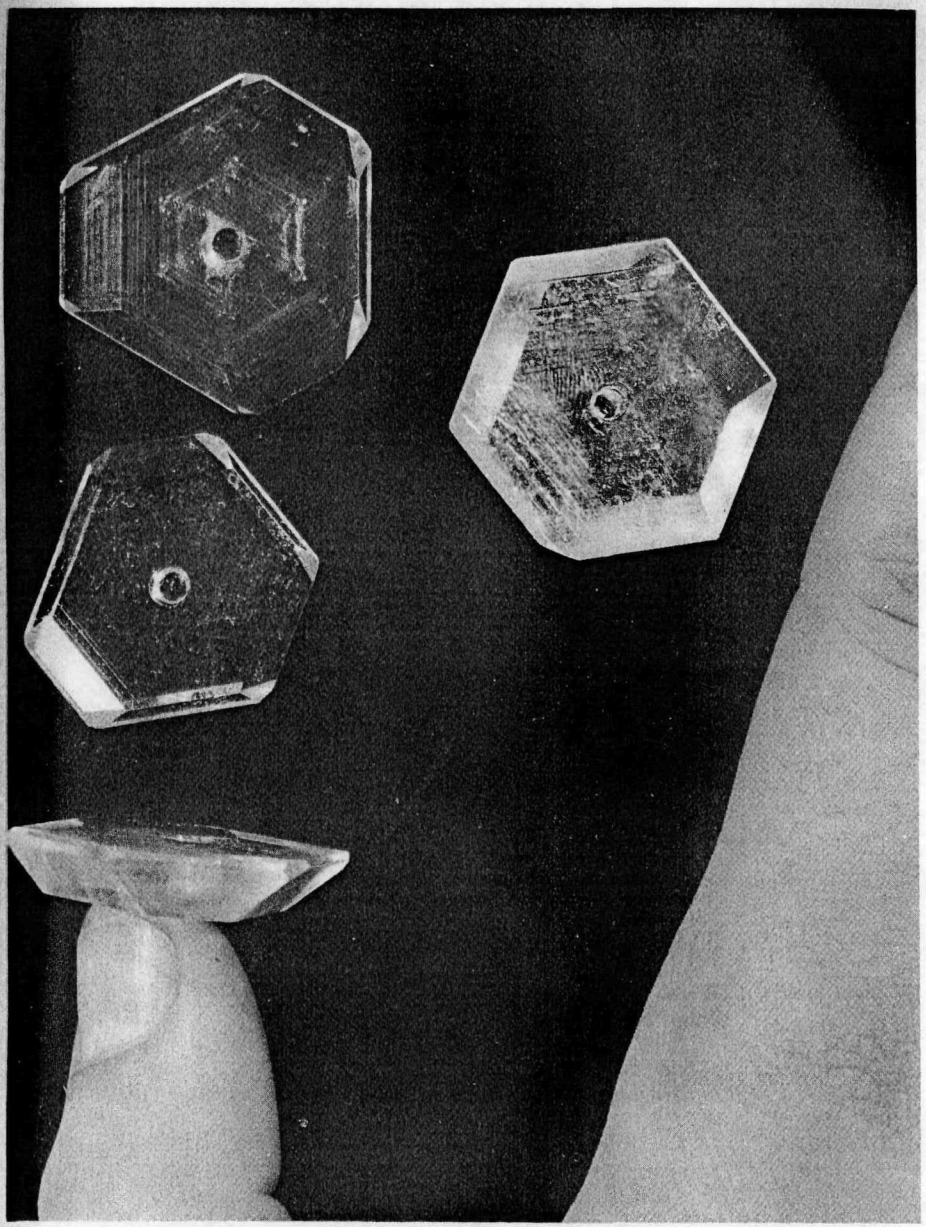
Of Man and Matter, 29 minutes, color, 1963. Produced by AEC's Brookhaven National Laboratory. Describes the design, development, and operation of the alternating gradient synchrotron (AGS) at Brookhaven National Laboratory.

The Worlds Within, 29 minutes, color, 1963. Produced by Stanford University. This nontechnical film describes the design, construction, and use of SLAC, the Stanford Linear Accelerator.

Searching for the Ultimate, 29 minutes, black and white, 1962. Produced by Ross-McElroy Productions for the National Educational Television and Radio Center under a grant from AEC's Argonne National Laboratory. Atomic structure, one of the most basic forms of nuclear research, permits the scientist to discover the nature of the universe through the use of particle accelerators. This film explains how accelerators operate and shows one of the world's largest accelerators being constructed.

High Energy Radiations for Mankind, 16 minutes, color, 1958. Produced by Public Relations Office, High Voltage Engineering Corporation, Burlington, Massachusetts. This semi-technical film describes the principles, assembly, and uses of the Van de Graaff particle accelerator to produce intense stable, controlled beams of all basic radiation for basic and applied research, industrial processing, chemistry, metallurgy, and biology and medicine.

The High Energy People, 5¼ minutes, color, 1963. Produced by AEC's Argonne National Laboratory. Offers a brief description of the problems and tools of high-energy physics, illustrated by some of the work being done with the Zero Gradient Synchrotron.



These targets used in polarized proton experiments at the Lawrence Radiation Laboratory are large single crystals of lanthanum–magnesium double nitrate. The hole in the center of each crystal is not caused by the accelerator beam; it is an imprint of the small pedestal on which the crystals were grown.

THE COVER

An aerial view of the 2-mile electron accelerator at the Stanford Linear Accelerator Center at Stanford University in California, and the experimental buildings and other facilities required for the scientists, engineers, and other workers who study the fundamental nature of matter. This and other huge machines that enable man to investigate the tiniest particles of our universe are the subject matter of this booklet.

THE AUTHOR

WILLIAM J. KERNAN is professor of physics at Iowa State University and a senior physicist at the Ames Laboratory of the United States Atomic Energy Commission. He is the author or co-author of about 15 published articles in scientific journals, such as the *Physical Review* and *Physical Review Letters*. These articles have been based on Dr. Kernan's research in high-energy physics. He has also worked as a consultant on the preliminary plans for the 200-Bev proton synchrotron at Weston, Illinois, and is presently on the Board of Trustees of Universities Research Association, which is the AEC contractor for the construction and operation of this National Accelerator Laboratory.

In addition to teaching college and graduate school physics courses, he has taught special courses for high school physics teachers. The questions asked about accelerators, both in undergraduate courses and in the course for teachers, showed the need for descriptions of some of the complex devices employed in nuclear research, and generated his interest in writing this booklet for a general audience.

Dr. Kernan received his bachelor's degree from Loyola College, Baltimore, Maryland, and his doctorate from the University of Chicago.

PHOTO CREDITS

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Whole Body Counters
Your Body and Radiation

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