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# The Brookhaven Alternating Gradient Synchrotron

## Construction of a massive nuclear research machine requires ideas, men, and methods from many fields.

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A noteworthy characteristic of the evolution of physical science is the increasing degree of effort required to push back the frontiers of knowledge. A few centuries ago important fundamentals were elucidated by individuals, often working alone, and dealing with phenomena of man's order of size—say, a meter. Atomic nuclei are roughly $10^{14}$ times smaller, and galaxies are $10^{21}$ times larger. Modern particle accelerators and astronomical telescopes for studying phenomena at these extreme scales require years of planning, millions of dollars, hundreds of man-years, and elaborate ancillary experimental equipment. The resources required exceed the capacity of individuals or even of universities to provide—a far cry from the work of Galileo, Faraday, and Hertz. The new proton accelerator under construction at the Brookhaven National Laboratory is an outstanding example of the immense effort required for modern research at the very small size scale of nuclear phenomena.

### Brookhaven National Laboratory

The Brookhaven National Laboratory was created after World War II, on the site of the Army's old Camp Upton, by Associated Universities, Incorporated, an organization established by Columbia, Cornell, Harvard, Johns Hopkins, Massachusetts Institute of Technology, Pennsylvania, Princeton, Rochester, and Yale for the pursuit of large research projects. Brookhaven National Laboratory is operated by Associated Universities, Incorporated, for the U.S. Atomic Energy Commission for research in physics, chemistry, biology, medicine, and related fields. The laboratory lies about 70 miles east of New York City, just over halfway out toward the eastern tip of Long Island. Here was built the world's first multibillion-volt accelerator, the cosmotron, completed in 1952, which is capable of producing 3-Bev protons. Cosmotron research has already contributed greatly to man's knowledge of elementary particles and high-energy physics.

### Alternating Gradient Synchrotron

The construction of a still larger accelerator for production of proton energies approaching ten times those of the cosmotron is now under way at Brookhaven. This accelerator will be the world's largest when it is completed in 1960.

The use of the new alternating gradient "strong focusing" principle (*1*) permits the construction of such a high-energy machine with relatively much less magnet steel than would be needed with the older "weak focusing" designs. Thus, the Brookhaven alternating gradient synchrotron, or AGS, will require about 4000 tons of steel to produce protons of over 25-Bev energy, while the largest existing machines (the synchrophasotron in the U.S.S.R. and the bevatron in California) have used, respectively, 36,000 and 10,000 tons for the production of 10- and 6.2-Bev protons. The cosmotron has about 2000 tons of magnet steel.

The Brookhaven AGS is somewhat larger than the similar alternating gradient synchrotron being built simultaneously near Geneva, Switzerland, by the 12-nation European Organization for Nuclear Research (CERN) and scheduled for completion shortly before our synchrotron. A project to construct a 50-Bev alternating gradient machine has recently been announced in the U.S.S.R.

An over-all plan of the Brookhaven AGS complex is shown in Fig. 1 (north is toward the top of Fig. 1), while Fig. 2 is an aerial view, looking southward, of the state of construction in May 1957. The size of the synchrotron ring may be compared with that of the large flat-roofed building (at the upper right of the AGS ring in Fig. 2) which houses the cosmotron, and with the Brookhaven research reactor (pile) at the upper left; a diffusion basin for AGS magnet cooling water is shown at the lower left.

Figure 3 shows the magnet tunnel during construction. The opening is about 18 feet square, and the ring is ½ mile in circumference. The inward projections in the upper part of the tunnel support the rails of two 20-ton traveling cranes that span the tunnel for handling the magnets and other equipment. The tunnel is now covered with earth, for radiation shielding and to aid the air-conditioning system in keeping the interior temperature constant to ± 2°F.

### Injection

The operation of the alternating gradient synchrotron may be described by following the protons from source to target in Fig. 1.

Protons are the nuclei of the most common isotope of hydrogen. Hydrogen gas is supplied to a cold cathode dis-

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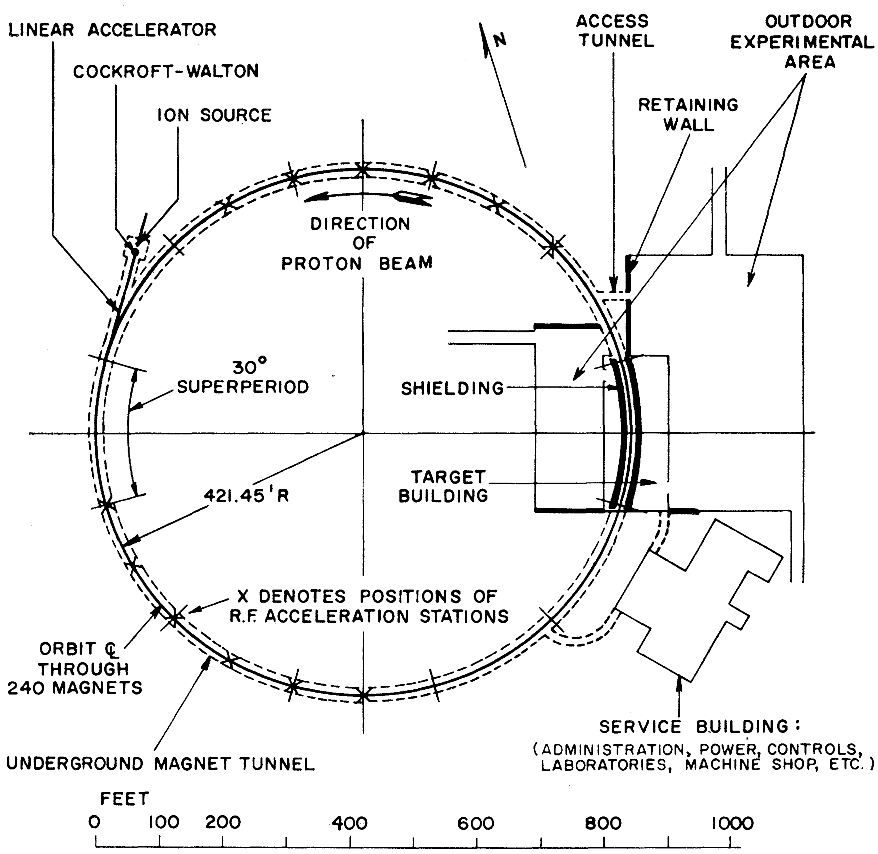


Fig. 1. Plan of the Brookhaven alternating gradient synchrotron.

charge at a pressure of about 1/20,000 of an atmosphere in the ion source shown at the upper left of Fig. 1. Protons from the ionized gas in the discharge pass through a small orifice 1 or 2 millimeters in diameter in the cathode, whereupon they are accelerated through 750 kilovolts by a Cockcroft-Walton generator.

The 750-kev protons are then accelerated to 50 million electron volts (Mev) in the linear accelerator, or "linac." In the linac, the protons pass through 124 drift tubes of varying length and diameter placed along the axis of a copper-lined tank about 1 meter in diameter and 110 feet long. Figure 4 shows an experimental model of a tank section with three drift tubes. The tank is both a vacuum enclosure and a cavity resonator which will be driven at 200 megacycles per second so that adjacent drift tubes will oscillate in opposite phase electrically.

The protons are "bunched" in the beam like beads on a string, and the spacing of bunches increases with velocity through the linac. Each bunch experiences a forward or accelerating electric field in the gap between drift tubes. While the bunch is passing at constant velocity through the axial hole within the drift tube, the cavity oscillation reverses the electrical polarity of the tubes so that the bunch is again subjected to an accelerating field by the time it reaches the next gap. By proper choice of the voltages, tube lengths, and spacings, bunches are accelerated simultaneously at alternate gaps all along the linac. The peak gap voltages vary from 116 kilovolts at the beginning to 890 kilovolts at the end, and the cavity requires 3 megawatts of power at 200 megacycles per second during the acceleration. The oval shaping of the drift tubes, as shown in Fig. 4, materially reduces the energy required to excite the electromagnetic oscillations within the cavity to given gap voltages and permits higher voltages to be used without electrical breakdown.

Figure 5 shows the junction of the linac and main ring tunnels. The ion source and Cockcroft-Walton set will be housed in the enclosure which can be seen in the distance at the left. The linac tank will be supported on the line of pedestals in front of this enclosure, and the beam will be injected at 50.8 Mev into the ring near the point from which the picture was taken.

The beam will be conducted from the linac into the main synchrotron ring through an elaborate injection system of debunching, deflecting, focusing, and monitoring gear mounted on the four floor-level pile caps shown in the left foreground of Fig. 5. At injection into the ring, the beam will be about 1.7 inches in diameter and will comprise several milliamperes of protons with a total angular spread of 5 milliradians (diverging horizontally and converging vertically) and an energy spread of about 0.1 percent.

## Ring Acceleration

In the linac each proton passes each accelerating gap only once. By deflection into circular orbits the protons may be made to pass many times through each acceleration station around the ring. The magnet arrangements for producing the circular orbits are discussed below.

There will be 12 radio-frequency acceleration stations around the ring at the points marked *X* in Fig. 1. Each station consists of a double tunable radio-frequency cavity (as shown in Fig. 6) which will impose accelerating electric forces on the proton bunches at each passage by means of a pair of accelerating gaps about four feet apart in the vacuum chamber wall; the gaps are made vacuum-tight with ceramic insulators. At each passage, each station (two gaps) will accelerate the protons by 8000 volts —that is, the protons will gain about 96 kev from the 12 stations for each transit around the ring.

On this basis, the protons must go around the ring 260,000 times, or 130,000 miles, to gain 25 Bev in energy.

As the energy increases, the velocity of the protons will increase rapidly at first and then more slowly as the protons approach the velocity of light.

Due to the velocity increase, the transit time of each proton bunch around the ring will decrease. Therefore, the frequency at the accelerating stations must be increased so that the protons will arrive at the gaps in the right phase to experience a forward or accelerating impulse. The cavities will be tuned to resonate at the right frequency by adjusting the permeability of the ferrite rings with which the cavities are loaded. The magnetic permeability of a ferrite is a function of the degree of constant magnetization which may be simultaneously impressed on it by a direct current. By the ingenious double-cavity arrangement shown in Fig. 6, the direct-current saturating bias may be superimposed on the alternating radio-frequency currents in the cavity walls.

The cavities will be operated on the 12th harmonic of the revolution frequency, and there will be 12 equally spaced bunches of protons circulating around the ring during acceleration. Since the protons are accelerated from less than one-third of the velocity of light to within a fraction of a tenth of one percent of light velocity, the frequency of the accelerating cavities will increase, in proportion, from 1.40 to 4.46 megacycles per second. To keep them in step, the power amplifiers for the 12 double cavities will be driven either in phase or 180 degrees out of phase from a common driving source. The exact frequency and phase of the driving source will be governed by the revolution frequency and radial position of the proton bunches, as sensed electrically by suitably placed "pickup electrodes" within the vacuum chamber.

## Target and Experimental Areas

Two methods of conducting experiments with the accelerated protons are contemplated.

At first, target substances will be suddenly inserted into the beam in the vacuum chamber to intercept the circulating procession of protons, thus producing the reactions to be studied by means of the radiations emitted. Ultimately it is planned to deflect the beam of high-energy protons out of the vacuum chamber, as has been done very successfully with the 3-Bev protons produced by the cosmotron. Ejection greatly enhances the usefulness of the machine because many separate experiments may be simultaneously set up along the path of the beam and the direct beam may be used by each as needed. The large earth dike visible below the cosmotron building in Fig. 2 had to be constructed as a backstop for the ejected beam.

The target building and experimental areas are shown at the right in Fig. 1. With targets in the vacuum chamber, positive product particles would tend to be deflected to the west (left) in the fringing field of the magnets; negative particles, to the east. When the beam is ejected, it will pass east of north through the target building and out across the larger of the two outdoor experimental areas.

The target building, visible at the left of the ring in Fig. 2, is 100 feet wide by 252 feet long and 40 feet high. A 40-ton traveling crane spans its width, and 14,000 tons of heavy concrete shielding cover the ring within the target building, as is shown in cross section in Fig. 7, to intercept most of the intense radiations. Channels can be built through the shield-

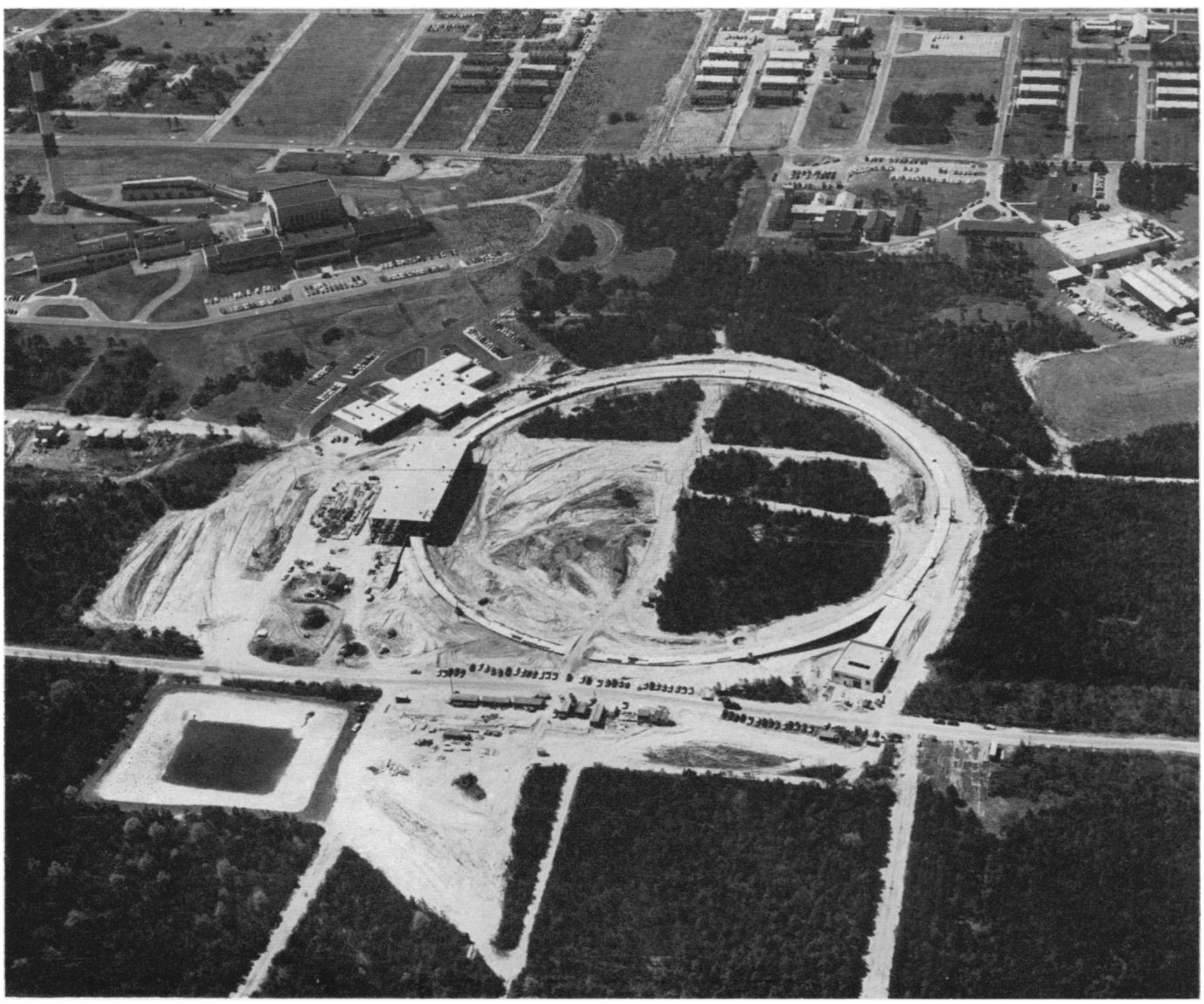

Fig. 2. Aerial view of construction of the Brookhaven alternating gradient synchrotron in May 1957, looking south. The size of the AGS may be compared with that of the cosmotron, housed under the large flat roof at upper right.

ing by rearranging small plug blocks in the median plane for selected experimental beams.

Figure 7 also shows the construction of the floor slab for supporting the shielding weight, to minimize the effect on the piles carrying the main magnet ring; sheet piling has been inserted around each set of piles in the target building to isolate the piles even more from the effects of the local shield loading.

**Magnet Ring**

In describing the acceleration of the protons from source to target, we postponed discussion of the main magnet ring. The magnets perform two functions: (i) guiding the proton beam into a circle and (ii) focusing the beam.

The deflection of the protons into a circular path is accomplished by the force exerted on a charged particle moving across a magnetic field. This phenomenon is essentially three-dimensional and awkward to describe by two-dimensional diagrams. In the alternating gradient synchrotron the magnetic field at the median plane of the orbit (for example, the plane of Fig. 1) is directed vertically downward, from the zenith toward the center of the earth. The protons from the linac shown at the left of Fig. 1 move southward (toward the bottom of the page in the figure), and, being positively charged, they will experience a force toward the east which guides them into the ring.

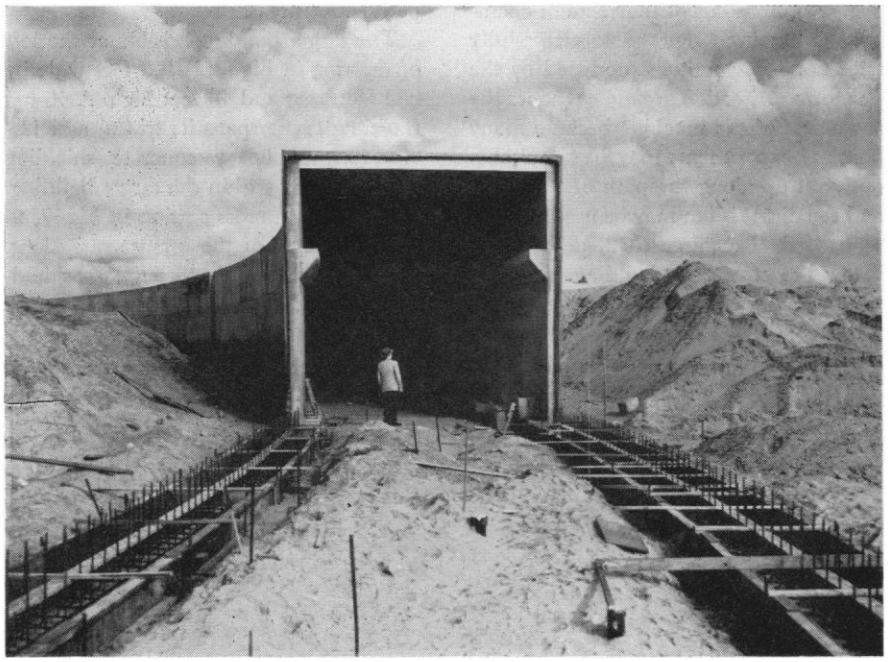

Fig. 3. Section of the Brookhaven alternating gradient synchrotron magnet tunnel during construction.

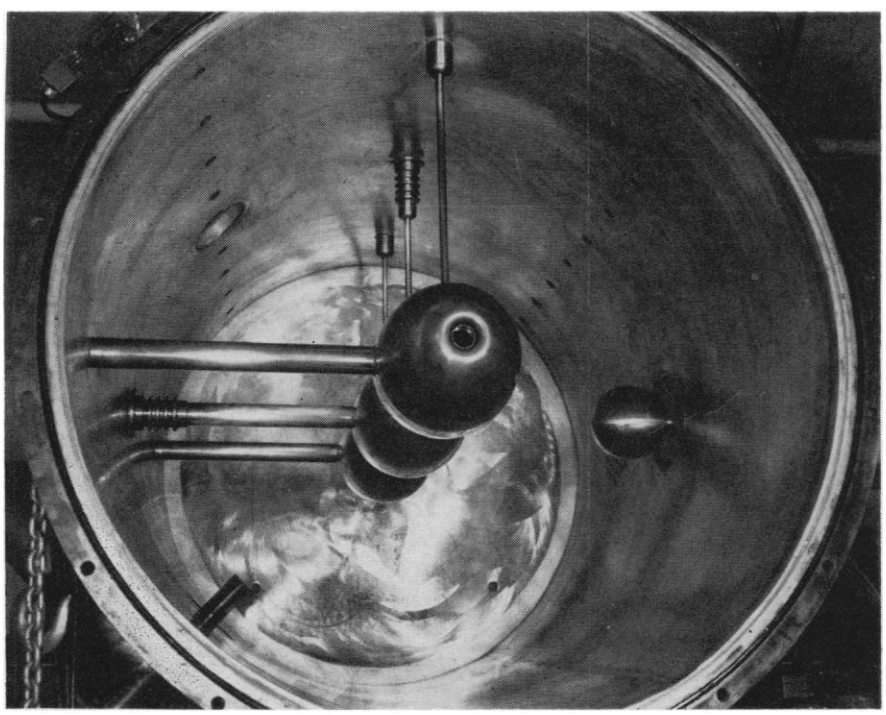

Fig. 4. Experimental section of linear accelerator tank with three drift tubes. The protons will pass through the axial hole in the drift tubes.

As the direction of the horizontal velocity $v$ of the charge $e$ changes, the direction of the deflecting force $F = Bev$ also changes so that $F$ is always at right angles to both $v$ and the vertical magnetic field $B$. Note that this deflecting force does not change the speed or kinetic energy of a particle; it only changes the direction of its velocity.

Each of the 240 magnets around the AGS ring will deflect the protons by about 1.5 degrees, or 360 degrees in all, to complete the (nearly) circular path. The reference circle is 842.90 feet in diameter. The physical length of the magnets occupies about two-thirds of the circumference, the rest being available as straight sections between magnets for other equipment, such as acceleration stations and vacuum pumps, and equipment for injection, targeting, ejection, and so on.

A typical magnet cross section is shown in Fig. 8, which is a photograph of one of the laminations of which the magnet cores are being assembled. In "open" magnets, the gap shown at the left flares away from the "back leg" at the right. There are also "closed" magnets in which the gap has an identical contour but flares toward the back leg.

The careful pole shaping is required for the focusing function of the magnetic fields, to be discussed below.

A nearly elliptical vacuum chamber, just over 6½ by 3 inches inside, will be centered in the gap between the magnet poles on the "aperture center line," which lies 5.25 inches from the open side of the poles, where their vertical separation is 3.500 inches. A pressure of $10^{-6}$ millimeters will be maintained in the whole vacuum chamber by 48 titanium getter-ion pumps distributed around the ring to prevent undue loss of protons by collision with residual air molecules. The chamber is made of nonmagnetic Inconel X, 0.078 inches thick, which offers relatively high electrical resistivity against eddy currents.

## Magnets

Figure 9 shows an assembled magnet of the "closed" type with the magnetizing coils in place. Each of the four coil sections or "pancakes" consists of eight turns of extruded rectangular copper, 1 and 19/32 inches wide and $\frac{7}{8}$ inch high, with a $\frac{3}{8}$-inch-diameter cooling water hole in the center and about 0.001 ohms resistance per pancake.

The closed magnet shown is 90 inches long and consists of about 2800 laminations of 0.031-inch steel plus 1-inch end plates. It is held together by the eight longitudinal straps, which were welded to the outer periphery while the laminations were compressed by a force of 80 tons. The core shown weighs 15 tons; the copper, 3200 pounds. The laminations are insulated from one another by a varnish to inhibit eddy currents. About 98 percent of the core volume is steel. This excellent lamination factor shows that the steel produced for the AGS magnets is unusually flat.

The 96 "closed" magnets are all of the 90-inch length shown in Fig. 7. There will be two lengths of "open" magnets; 48 will be 90 inches long and 96 will be 75 inches long, giving a total of 240 magnets in the three classes: *A*, "long open"; *B*, "short open"; and *C*, "long closed."

The flaring magnet gap illustrated in Fig. 6 is essential to the alternating-gradient strong-focusing system. Exceptionally stringent mechanical tolerances and magnetic uniformity are required to hold the protons within the 3-by-$6\frac{1}{2}$-inch vacuum chamber while they travel more than 100,000 miles! The roughly hyperbolic pole contour is being held to $\pm 0.002$ inch of the prescribed form by punching the 633,000 laminations with a very accurate carbide die. The blanks are reversed right to left by pairs before punching to compensate for residual variations in thickness from side to side; after punching, every 20 laminations are turned over, top to bottom, in stacking the magnets in order to keep the gap contour symmetrical about the median plane through the gap. The latter inverts the shearing direction in the punch and gives rise to the attractive striped appearance of the core in Fig. 9. The tolerances on straightness of lamination stacking, placement on the ring, and so on, are all of the order of $\pm 0.010$ inch.

The magnets will be placed by pairs on 120 large steel girders, some of which are visible on the right in Fig. 5. The ends of the girders are supported on piles. Each pile cap, as seen in Fig. 5, is mechanically separated from the tunnel floor and covers four 10-inch H-section steel bearing piles driven about 50 feet into the sand and gravel of Long Island, which extends hundreds of feet down and has been undisturbed for thousands of years. There are 120 sets of four piles each, and this foundation for the ring is considered to be exceptionally advantageous in view of the stability problems faced by synchrotrons constructed elsewhere. Sand acts as an effective damper for earth tremors and eliminates dangers of faults occurring in local substrata, with the accompanying physical shift of adjacent regions.

## Magnet Power Supply

As the energy of the protons increases during acceleration, their momentum, $p$, also increases. To hold the orbits to the over-all ring curvature set by the vacuum chamber, the deflecting magnetic fields $B$ must increase in proportion to $p$. A 100-fold increase in $B$ is required in a

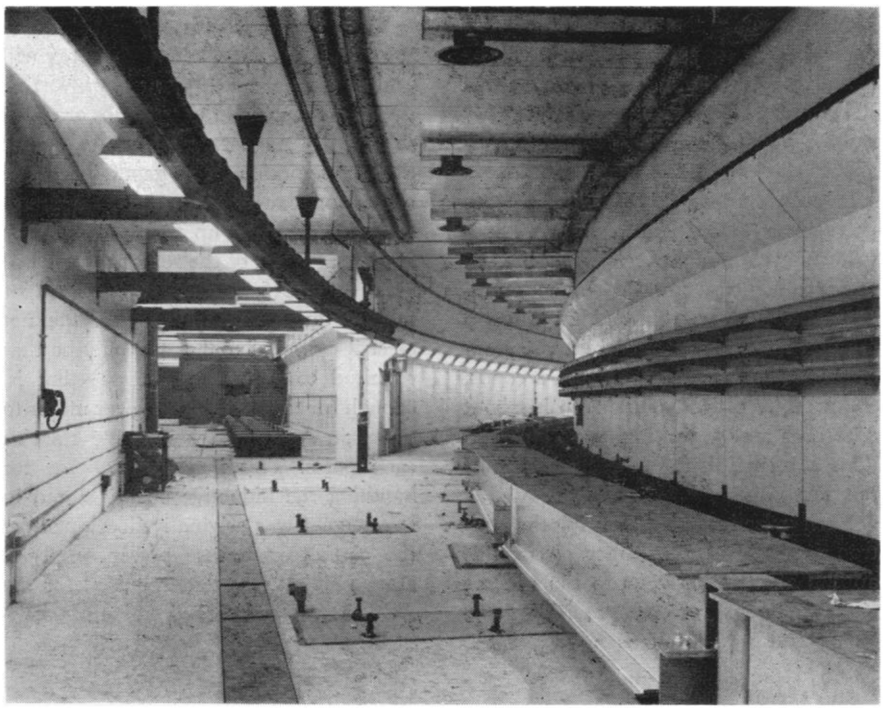

Fig. 5. Junction of linear accelerator and main ring.

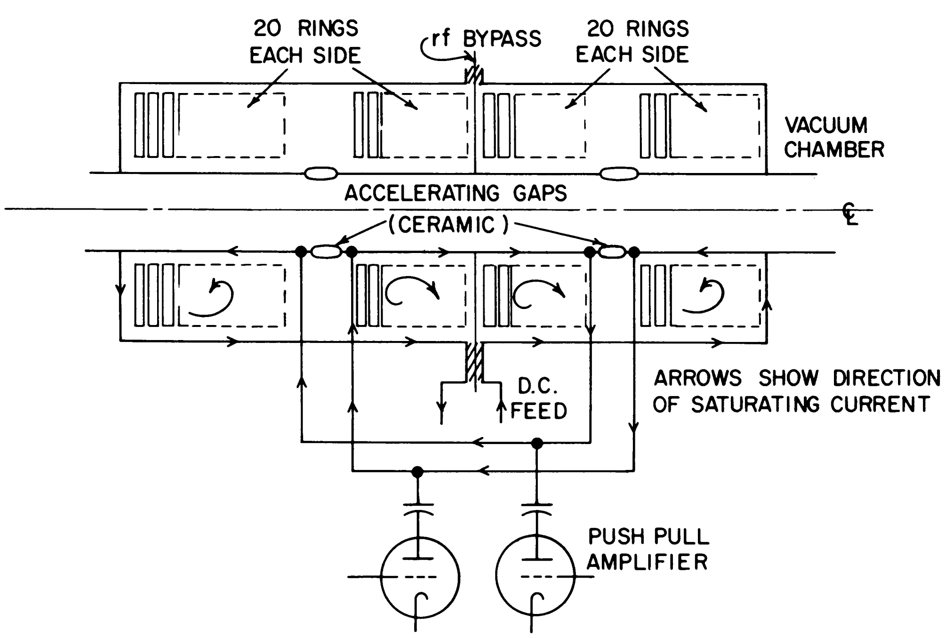


Fig. 6. Cross section of radio-frequency cavity at each acceleration station.

little over a second following injection at $B = 120$ gauss.

The magnets are energized by passing electric currents through the coils shown in Fig. 9. To make the field rise uniformly around the ring, the magnet coils are connected in series so that the same current will flow in all magnets. Actually there will be two such series circuits, each containing two of the four pancakes on each magnet. The currents flow in opposite directions around the ring in the two series circuits in order to avoid undesirable magnetic effects of a single turn around such a large ring. Further, a pulse-shaping saturating inductor will be included, and the two series circuits will be connected in parallel across the power supply, which consists of an ignitron-rectified, 12-phase, 36,000 kilovolt-ampere generator, a 47-ton flywheel, and a 5500-horsepower motor driven from 13,800-volt, 60-cycle mains.

For top-energy protons the accelerating pulse will be repeated 20 times a minute; it consists of a current rise from 0 to 6500 amperes in about $1\frac{1}{4}$ seconds, followed by a decrease to zero in about a second and a waiting period of less than a second before the beginning of the next pulse.

Each pulse is started by firing the ignitron rectifiers in the proper phase; this applies about 5000 volts to the magnet circuit. The magnet current will begin to rise against the inductance and resistance of the magnet circuits. As the current rises through 45 amperes the protons are injected from the linac, and ring acceleration begins and continues until the magnet current reaches about 145 times the injection value.

At top current, about 14 million joules of energy will be stored in the magnetic field of the magnets, and over 10 million watts will be being turned into heat in the resistance of the magnet coils. The heat will be carried away by cooling water flowing in the axial $\frac{3}{8}$-inch hole in the coil copper.

To bring the magnet current down to zero again, the magnetic-field energy will be drawn off into the flywheel by inverting the phase at which the ignitrons are fired so that the magnet current flows *against* the electromotive forces generated in the alternator, causing it to act as a motor and thus speeding up the flywheel. The rotational speed of the rotating parts will vary from 815 to 875 revolutions per minute during the pulse, and the net electric-power demand will only be that required to supply the losses—that is, enough for the 5500-horsepower motor to maintain full speed before the start of each pulse. This ingenious scheme for handling the inductive energy stored in the magnet was originally developed for the cosmotron, whose power supply is almost as large as that required for the AGS, and it has proved eminently satisfactory.

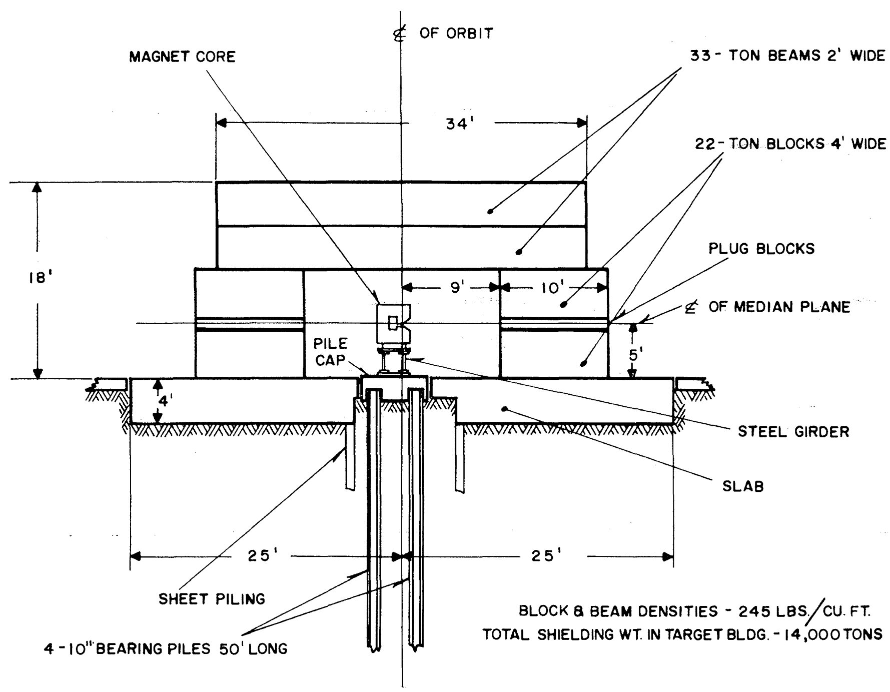


Fig. 7. Cross section of shielding and ring in the Brookhaven alternating gradient synchrotron target building.

## Focusing

The research usefulness of an accelerator depends on beam intensity as well as on the top energy achieved. It is not enough to accelerate an ideal particle; as many actual particles as possible in the vicinity of the mathematical ideal must be kept from striking the walls of the vacuum chamber and kept in phase at the accelerating gaps so that they will arrive at the target at the top energy.

We may think of an actual particle as following a path which deviates radially and vertically from the ideal, nearly circular, equilibrium orbit. Focusing forces are those which tend to deflect the particle toward the ideal orbit, and the strength of focusing forces may be described by the frequency with which they cause an actual particle to oscillate back and forth across the equilibrium orbit. In the older "weak focusing" machines, such as the cosmotron and bevatron in this country and the synchrophasotron in Russia, these "betatron oscillations" take place less than once per revolution; in the AGS there will be $8\frac{3}{4}$ betatron oscillations per revolution and in the CERN proton synchrotron, or PS, there will be $6\frac{3}{4}$. For this reason the term "strong focusing" has been applied to alternating-gradient machines.

The AGS magnets are arranged in 12 identical 30-degree superperiods of 20 magnets each, as marked in Fig. 1. The arrangement within a superperiod is shown in Fig. 10. Magnets 1 through 10, numbered in the direction of the proton beam, from right to left, are placed with their back legs outside the ring on five successive girders; magnets 11 through 20 are in the same sequence as magnets 1 through 10 but have their back legs inside the ring. There are 10-foot straight sections between magnets at each back-leg reversal; 5-foot straight sections for auxiliary equipment following magnets 3, 5, 7, 13, 15, and 17; and only 2-foot straight sections to accommodate coils, vacuum chamber junctions, and so on between the rest, as shown.

The sequences of ten magnets with back legs all on the same side of the orbit leave open access to the vacuum chamber on the other side; this greatly facilitates tangential injection and ejection of the beam and leaves paths for product particles ejected from targets suitably placed in 10-foot straight sections. These advantages are the main reason for adopting a basic plan in which the back legs are placed all on one side of the orbit for long intervals.

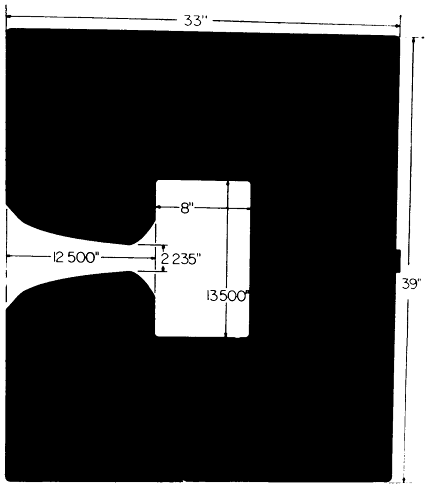


Fig. 8. An "open" magnet lamination, showing cross section of a typical AGS magnet.

The gaps of magnets labeled "+" in Fig. 10 flare toward the outside of the ring, while those labeled "–" flare toward the inside, regardless of the position of the back legs. The + and – magnets alternate in pairs, and four successive magnets constitute one alternating gradient period. Thus, the gaps of the four short magnets adjoining each 10-foot straight section flare away from their back legs; this accounts for the 96 short open magnets of class B. It can be seen that half of the magnets of each class are placed with their back legs inside the orbit, the other half with their back legs outside. By such means a maximum over-all symmetry of the guiding and focusing fields is to be attained in spite of residual random variations between and within magnet classes.

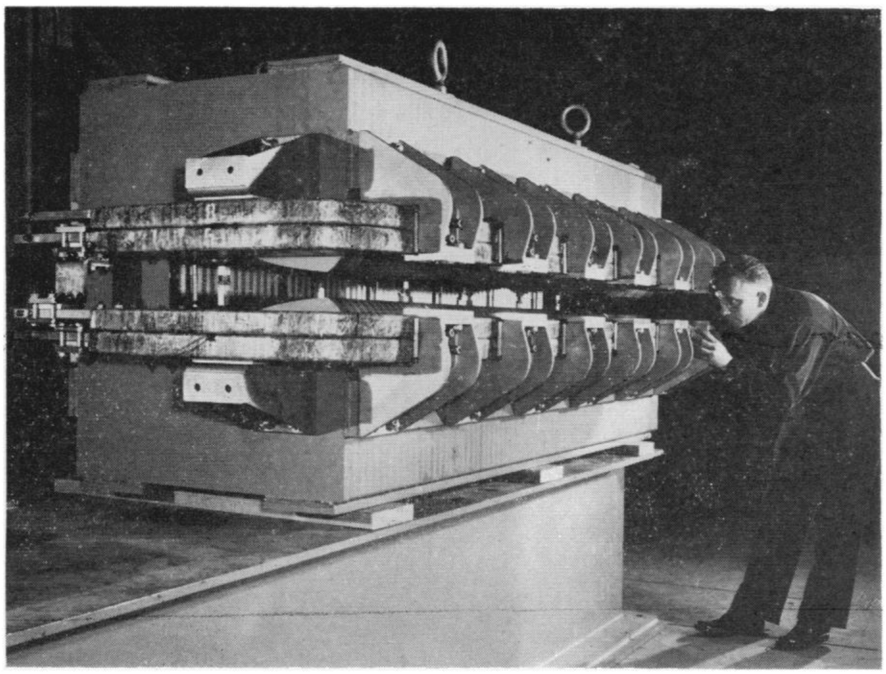

Fig. 9. An assembled "closed" magnet with coils in place.

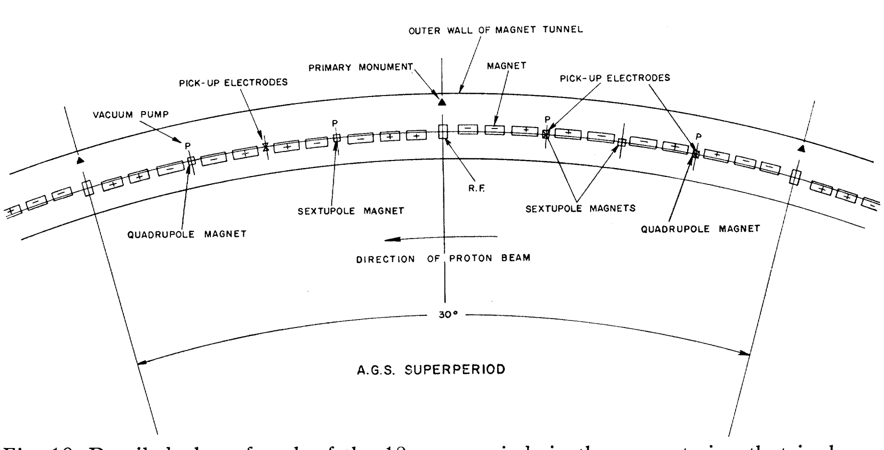


Fig. 10. Detailed plan of each of the 12 superperiods in the magnet ring that is shown schematically in Fig. 1.

Within the flaring gap of each magnet the strength of the vertical component of magnetic field decreases toward the open side of the gap; this means that particles are deflected less strongly (that there is a larger radius of curvature of path) in the wide than in the narrow side of the gap. With large magnetic field gradients, a + magnet tends to defocus the beam in the horizontal direction; the converse is true for a – magnet.

The essence of the alternating gradient discovery (*1*) is that a regular succession of focusing and defocusing elements can produce a strong net focusing action. The phenomenon is not easy to explain in elementary terms. Both focusing and defocusing elements exert stronger forces the farther away the particle is from the equilibrium orbit. It turns out that, in focusing sections, the particles are, on the long average, farther from the equilibrium orbit than in defocusing sections. Therefore a net focusing action results.

The nature of a quasi-static magnetic (or electric) field in free space is such that the "curl" of the field is zero—that is, if the vertical upward component of the field increases as the reference point moves horizontally to the right, then the horizontal component to the right will increase just as fast as the reference point moves vertically upward. A consequence of this fact is that a + magnet, which defocuses the beam in the horizontal direction, will focus the beam in the vertical direction, and conversely. Thus + magnets in Fig. 10 focus in the vertical direction and – magnets defocus in the vertical direction. Alternating-gradient focusing is provided in both the horizontal and vertical directions, and when the same amount of strong + and – focusing is provided around the ring, the net alternating-gradient focusing forces will be about the same in both the horizontal and vertical directions—that is, there will be nearly the same number (8¾) of betatron oscillations in one revolution both vertically and horizontally.

In a linear accelerator the electric fields that accelerate the particles longitudinally in the gaps between drift tubes also tend to defocus the beam laterally. Hence, in the AGS linac, magnetic alternating-gradient lateral focusing will be provided by placing quadrupole magnets within the drift tubes (*2*).

So far we have really considered only particles of a given energy and their lateral deviations from the equilibrium orbit for the corresponding momentum.

Synchrotrons would not work at all unless a kind of longitudinal focusing could also be provided, tending to hold particles of different energies in bunches which pass the accelerating gaps in synchronism with the applied radio frequency and within a required phase interval of the radio frequency (*3*). Our word *synchrotron* and the Russian *synchrophasotron* arise from this fundamental requirement for effective acceleration.

Particles of somewhat different energies within a bunch will have correspondingly different momenta and speeds. The different momenta will have different equilibrium orbits, and the time required for one transit around the ring will depend on both the circumference of the equilibrium orbit and the speed. The facts of relativity determine this transit time.

When the mean proton kinetic energy in a bunch is below about 7.2 Bev, protons whose energy is somewhat larger than the mean will tend to arrive sooner than the mean at the accelerating gaps because their transit time around the ring is smaller. If the radio frequency current is phased so that the accelerating potential across the gap is rising at each passage of the bunch, then higher energy particles, arriving early, will collect a smaller energy increment from the gap than lower energy particles arriving later. The resulting tendency to equalize the particle energies in the bunch finally causes the particles in the bunch to oscillate in energy and phase, and the frequency of this oscillation is a measure of the "bunching" forces.

Above 7.2 Bev the particle speeds are already more than 99 percent of the speed of light and therefore cannot increase much more. Protons having more than the mean energy in a bunch now tend to take longer to go around the ring because their equilibrium orbit is longer than the mean for the bunch. Thus, they arrive later at accelerating gaps, and acceleration must be phased on the falling side of the radio frequency if they are to receive smaller energy increments than the mean particle.

Therefore, to preserve synchronous stability for the bunches, the phase of the accelerating radio frequency current must be changed from the rising to the falling side rather abruptly as the "transition energy," about 7.2 Bev, is passed. Elaborate experiments with an "electron analog" machine at Brookhaven have shown that this phase shift can be accomplished with very little loss of beam.

The "breathing" of the equilibrium orbits with changes of particle energy relative to the mean energy in the bunches constitutes a "synchrotron" oscillation which is superimposed on the betatron oscillation discussed above. The synchrotron oscillations broaden the beam in the horizontal direction only, and this is the main reason why the vacuum chamber is made wider than it is high.

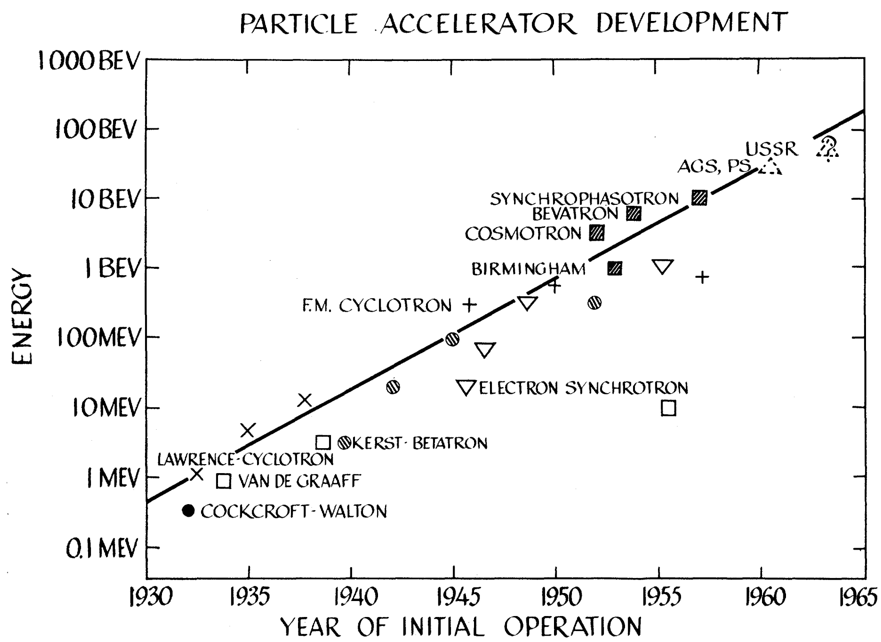


Fig. 11. Increase in particle energies achieved by accelerators during the last few decades.

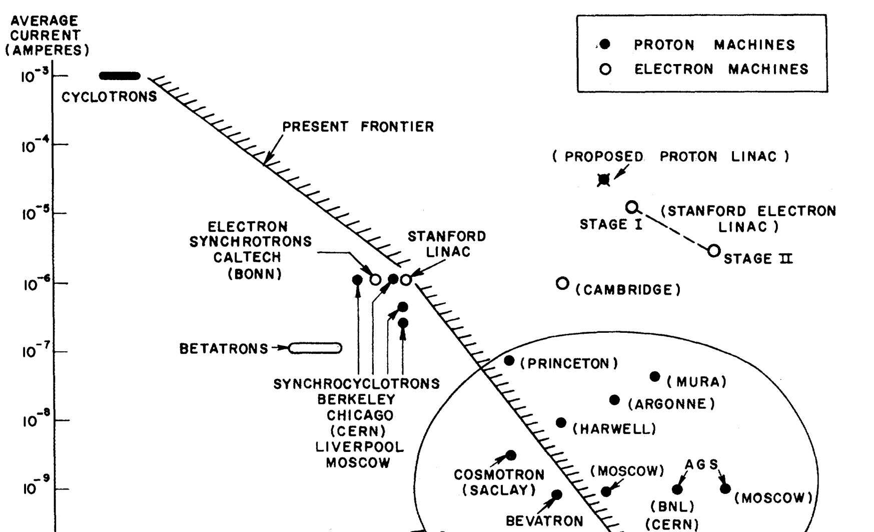


Fig. 12. Trend toward lower intensities with increase of accelerator energies.

## Magnet Steel

A maximum number of protons are to be held within the 3-by-6½-inch vacuum chamber while they travel 150,000 miles or so. To insure that the various deflecting and focusing conditions shall be fulfilled uniformly all around the ring and at all times during the acceleration, the magnets must be magnetically as well as mechanically accurate.

An electrical grade M-36 steel was chosen, containing about 1.80 percent of silicon and 0.03 percent of carbon. Before the current is turned on for a pulse, the remanent field at the aperture center line is about 15 gauss, due to the magnetization remaining in the steel core from the previous pulse. The value of this remanent field depends mainly on the coercive force of the steel, which averages around 0.77 oersted. As the pulse current rises, the injection-field value of 120 gauss should be reached simultaneously in all magnets. The increase above remanence depends mainly on the gap size and shape, but it depends partly on the low-field permeability of the steel, which averages about 740 at 100 gauss.

During the main part of the cycle, up to 10,000 gauss and more, the fields depend almost completely on the gap geometry, because the permeability of the steel is very high. By 11 or 12 kilogauss, the saturation of the steel becomes noticeable, especially since the flux density in the pole tips near the closed part of the gap can exceed $B$ at the aperture center line by 50 percent or more. The onset of saturation distorts the field distribution, especially toward the closed side of the gap, and thus sets an upper limit to the proton energy that can be attained. An average permeability approaching 140 at 18,000 gauss is attained by the AGS steel.

The stringent AGS demands for magnetic uniformity around the ring and at all times during the rising pulse cannot easily be met by commercially produced steel, even with the special care used with the 4000 tons of AGS steel. Two related problems are involved: (i) coercive force and low-field permeability show standard deviations of from 10 to 15 percent from the mean, and (ii) both properties show an "aging" deterioration of 60 percent or more, as determined by accelerated aging tests in which samples are subjected to a temperature of 150°C for 5 days. It is assumed that it will take many years for the same aging to take place at room temperature. Fortunately the high-field properties show no appreciable aging.

The first line of defense against these large variations in the steel has been to shuffle or interleave the steel for each of the three magnet classes according to a careful plan so that the steel from a given billet and rolling-mill coil will appear in all magnets of a given class at the same relative position and for about the same number of laminations. This shuffling reduces the residual variations between magnets to the order of 0.1 percent, even at injection, and will minimize them throughout the aging process, extending over several decades.

In addition to these measures to insure uniformity, a number of provisions have been made for final trimming of the orbits in the machine. Figure 10 shows the position of pickup electrodes and quadrupole and sextupole magnets in each superperiod, as well as the primary survey monuments. At each pickup electrode location, both the horizontal and vertical positions of the beam can be monitored electrically, sufficient in all to diagnose various harmonic distortions of the equilibrium orbits. On the basis of such information the correcting multiple magnets and windings to be attached, if necessary, to the outside of the vacuum chamber can be powered to hold the orbits near the center of the vacuum chamber and to compensate, to a degree, for field distortions due to magnet saturation toward the end of acceleration.

The magnets are being positioned on the ring with reference to the primary survey monuments shown in Fig. 10. Each primary monument is driven into the underlying sand and is mechanically separate from the tunnel base and ring piles. From each monument straight lines of sight are available within the tunnel walls to the two adjacent monuments on either side. By means of a high-precision survey, distances between adjacent monuments have been determined to a thousandth of an inch; triangle closures, to one-third of a second. Periodic resurveys will be carried out to monitor stability and possible movements of the soil.

## Particle Accelerator Development

In this brief description of the Brookhaven alternating gradient synchrotron we have tried both to outline the principal physical ideas involved and to indicate the organization, precision, and range of special technologies involved in a large project of this sort, all aimed at penetrating nature's secrets in the fantastically small atomic nucleus.

The development of particle accelerators (*4*) has been essential to the advances in nuclear physics and high-energy physics that have been made in the past few decades. Increases in both energy and beam intensity are ardently sought by workers in these fields.

Figures 11 and 12 show graphically how peak energy has increased with the year of initial operation for various accelerators and how the intensity, measured by the average beam current, tends to decline with increasing energy. Parentheses in Fig. 12 indicate machines which are only in the planning or construction stage, even though some (for example, Saclay and Bonn) are scheduled for completion this year.


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