

## MAGNET DESIGN IN HIGH-ENERGY ACCELERATORS

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### Summary

The similarities and differences in magnet design of the presently existing multi-billion-volt accelerators are reviewed. Special emphasis is given to the requirements for alternating-gradient synchrotrons, particularly as exemplified by the Brookhaven AGS. Details include pole-contour shaping, choice of steel, coil design and power-supply requirements together with more general considerations of mechanical and electrical problems.

### I. Introduction

Of all the components in a circular high-energy particle accelerator, the magnet system, including the power supply, is predominantly the most expensive. Efforts to reduce the costs of magnets have, in fact, been a major factor in the development of new types of accelerators as higher and higher energies were contemplated.

One may mention, for example, the development of the ring magnet of the synchrotron instead of the solid-core magnet of the cyclotrons and the smaller cross section needed for the magnets in alternating-gradient synchrotrons compared with those for the constant-gradient type.

However, with these new developments, the precision required in the design of the magnetic system has increased markedly. In the early accelerators, simple calculations based on known engineering practice and, perhaps, a rough magnet model were all that was needed. For the accelerators of today, a large team of physicists, engineers and technicians must devote many man-years of effort on complex computations, on the design of many models scaled and full-size, on the development of newer, more precise measuring techniques both magnetic and mechanical, before a satisfactory and efficient system can be realized.

A report of this length cannot do more than try to touch on some of the problems that arise. In the time available, it will not be possible to cover the detailed features of magnets for all the

various types of accelerators, therefore, emphasis will be on the multi-bev synchrotrons and, more specifically, on the alternating-gradient type. Partly, this is because design studies for new, higher-energy machines of this sort are now in progress and it is probable that such an accelerator will be the next to be built. Moreover, the A-G magnets have required careful consideration of most of the problems that face a magnet designer for any accelerator and it is hoped that, although the solutions may be different, a review of these will be of benefit. Because of my association with its program, the Brookhaven AGS will serve as the chief example for the solutions to some of these problems but references to magnets of other multi-bev accelerators will provide alternates.

### II. General Design Considerations

The function of the magnet system is two-fold: first, to provide a bending force to keep the particles moving on a path that (in synchrotrons) is approximately circular and, second, to provide focusing forces that will restrict the horizontal and vertical motion of the particles so that they remain inside a vacuum chamber of relatively small cross section. The latter function has become increasingly important in recent designs.

It would be quite possible to separate these functions into two systems. For example, in an A-G accelerator, one could provide the necessary strong alternation in radial gradient of the magnetic field by the insertion of quadrupoles between constant-gradient (or zero gradient) bending-magnet sections. To date, however, synchrotron magnets have been built to combine the functions of bending and focusing by appropriate shaping of the pole-face contour. But an approximation to such separation has been made in the magnets of the Argonne Laboratory's 12.5-BeV, weak-focusing, proton synchrotron (the ZGS) where octant sections have a field that is radially uniform and focusing is achieved by shaping the ends of the sectors.

Obviously, although the magnet system is usually the largest and most costly component of a high-energy accelerator, it cannot be built as an independent entity. Its design is most strongly influenced, of course, by its effects on the particles' orbits and oscillations but, besides this, its design interacts with and is influenced by that of the other components: the injector, the radio-frequency accelerating system, the vacuum chamber, various control systems, and the design and costs of buildings to house the accelerator complex. In the higher-energy machines, it has become increasingly important, perhaps in some cases belatedly, to design the magnet for optimum use of the accelerator as a physics research tool with ample space for emergent secondary beams at all angles including those very close to zero, with provision for extraction of the primary beam, and the capability for these beams to arrive at detectors in bursts that can be of a duration comparable to the time required for acceleration. Thus, the group responsible for the design and ultimate performance of the magnet system must keep in close contact with those designing the other components and those trying to formulate the possible future research plans. Usually, this results in many compromises; an ideal solution for one component may be disastrous to another. On the other hand, arbitrary decisions may sometimes have to be made concerning solutions which are equally feasible merely because there is insufficient time and manpower to follow up alternate designs.

At the same time, the magnet-design group must also investigate and keep in mind the capabilities of various industrial firms which might provide materials for or fabricate the various parts of the system. It is certainly preferable, if possible, to use materials of the standard sizes and shapes that are commercially available and if the fabrication techniques are fairly simple and straight-forward. Radical departures from normal industrial practice usually result in higher costs and in very frustrating delays and lengthening of delivery schedules.

Finally, the magnet group must plan its program to try to fit the overall schedule for completion of the whole accelerator. The time required for the manufacture and assembly of the magnet and its power supply can be of greater duration than that for any other component and, again, simple and standard procedures can result in significant saving of time. Schedule considerations may require the freezing of the magnet design before final decisions on the other components are made. I think that most of those who have been involved

in these matters will agree with me that there is seldom time to carry out all the computations and model measurements for an ideally efficient magnet system before the design group is pushed to state final specifications.

### III. Specific Design Problems

A. Circumference. The overall size of a circular accelerator is chiefly determined by the final energy desired and the choice of the maximum magnetic field. In synchrotrons, where the particles are to be confined to an annular region of approximately constant radius, the magnetic field must be increased from a low value which corresponds to the energy the particles have when they are injected to a high value which will still bend them when they reach the final desired energy. At all times during the period while they are being accelerated, the magnetic field,  $B$ , the radius of the particles' circular orbit,  $R$ , and their momentum,  $p$ , must follow the relation (in M. K. S. units):

$$R = p/(eB), \text{ or } R = \frac{\sqrt{E^2 - E_0^2}}{ecB} \quad \text{--- (1)}$$

where  $e$  is the charge on the particle,  $c$  is the velocity of light, and  $E$  and  $E_0$  are, respectively, the particles' total and rest energies. The majority of the presently existing synchrotrons have peak fields of the order of 15 kilogauss and, for this value, the radius of curvature of a proton's path is about 3 meters per BeV. Thus, for accelerators with energies in the tens or hundreds of BeV, the magnet's circumference becomes very large, even up to several miles.

It is, therefore, of considerable advantage to try to design the magnet to reach as high a field as possible and to keep the circumference to a minimum. This will not only reduce the cost of the iron and copper for the magnet itself, but will require lesser building costs for housing the magnet, less plumbing for cooling, less control and connecting cables, lesser communication problems, and so forth. On the other hand, some disadvantages arise if too much emphasis is put on achieving very high magnetic fields. For example, the demands on the magnet's power supply may be so great that extra complexity and cost accrue if higher ratings are called for than are readily available commercially. Or, the average power consumption during the years of the accelerator's operation may overbalance the additional cost of increasing the overall size. With very high currents, the magnetic forces on the

coils may be so great as to cause severe mechanical problems or even premature failures.

As already stated, the maximum guide field for most of the constant-gradient synchrotrons is around 15 kilogauss, or somewhat less. A notable exception is the Argonne proton synchrotron (the Z. G. S.) where a maximum field of 21.5 kilogauss is obtained by a very compact magnet design in the zero-gradient octants. The alternating-gradient proton synchrotrons have central guide fields that are somewhat lower because of the steep radial gradients. For example, the field at the central orbit position in the Brookhaven AGS is about 13.5 kilogauss but the gradient of about 10 percent per inch, over a radial width of approximately 7 inches, results in maximum flux densities in the high-field region of the poles of around 21 kilogauss. High-energy electron synchrotrons require a relatively much larger orbit radius and lower magnetic fields because of the radiation losses that are proportional to the fourth power of the energy but inversely proportional to the radius. For example, the Cambridge 6-BeV electron synchrotron has a peak field of only 7600 gauss.

Magnet designers have incorporated many devices in efforts to reduce or correct the effects of saturation in the iron and achieve higher maximum magnetic fields. Examples include separate pole tips of special iron, the addition of pole-face windings, crenelated poles (with alternate laminations or groups of laminations of different contours) or patterns of holes bored in the pole tips to give redistribution of the flux. The relative advantages and disadvantages of these schemes have given rise to much heated discussion and controversy. In the Brookhaven AGS, quadrupoles and sextupoles have been inserted between magnet sections to correct the gradient and the second derivative of the magnetic field. At CERN, the PS magnet has pole-face windings together with quadrupoles, sextupoles, and octupoles.

Each magnet-design group must make its own decision as to the relative merits and necessity of such corrections. Pole-face windings increase the vertical aperture and, thus, the magnet cross section and the ampere-turn requirements. Separate pole tips, crenelations and hole patterns add complexity to the fabrication, which certainly increases costs and may cause considerable delays. Most correcting devices add further variables to be studied and adjusted while bringing the accelerator into operation and keeping it in operation stably and at optimum intensity. With no intention of stirring up further argument, I would add that it is my

personal opinion that correcting devices should be either nonexistent or kept to an absolute minimum.

The actual circumference in most accelerators is somewhat larger than that given by Eqn. (1) for the top energy and the peak magnetic-field value because of the addition of field-free regions (straight-sections) between magnet sections. These regions are used for injection, for rf accelerating stations, for beam-observation and beam-control devices, for correcting magnets and for targeting and beam extraction. For example, in the Brookhaven AGS, although the radius of curvature of the particles' orbit is only 280 ft, the overall radius of the accelerator is 421.5 ft, i. e., the magnet occupies only about two-thirds of the total circumference. Not only is space needed for the equipment mentioned above, but each of the 240 individual magnet units requires an extra 2 ft of space just for the coil ends. Larger accelerators will probably have even larger fractions of their circumference devoted to field-free regions. It would seem that, at every accelerator now in operation, the conclusion has been reached that the straight sections used for targeting purposes are too short, particularly for the emergence of small-angle secondary beams, and new designs contemplate regions many times the present size of 10 or 15 ft. However, greater circumference is not entirely a disadvantage. In the A-G accelerators, that can have injection of beam for only one or a few turns, a greater circumference means the ability to inject a greater total amount of charge and, thus, the possibility of attaining higher intensity.

B. Cross Section and Pole Contour. The cross-sectional size and pole shape of the magnet is chiefly determined through studies of the dynamic motion of the particles. The aperture inside the vacuum chamber must be sufficient to accommodate the oscillations arising from the spread in space, angle and energy of the injected beam; in addition, radial space is needed for the excursions of the phase oscillations. In constant-gradient synchrotrons, this aperture can be as much as several feet wide and over a foot high; the pole shape is usually a simple taper that will give the small radial decrease in field that provides the focusing. Such an aperture requires very large cross-sectional dimensions; for example, the 3-BeV Brookhaven Cosmotron has outside dimensions 8 ft by 8 ft.

One considerable point of argument has concerned the merits of a C-shaped magnet cross section, where the magnetic return path is located on only one side of the aperture and the other side is left open with the vacuum chamber exposed, as opposed to H-shaped or "picture-frame" magnets with magnetic returns on both sides of the aperture. The latter type is certainly more efficient magnetically and higher fields can be reached before the effects of saturation destroy the desired field shape but, in the experimental use of an accelerator, such a magnet design is inconvenient because the beam is relatively inaccessible and it is more difficult to observe and extract primary and secondary beams. During the construction stage, the open C-shape is also more convenient for the installation of equipment in the magnet gap. Of the presently operating, constant-gradient synchrotrons, the score is about evenly divided with those at Brookhaven and Princeton in the United States, at Birmingham and the Rutherford Laboratory in Great Britain, and at Saclay, France, having C-shaped magnets; the Berkeley Bevatron and the Dubna (U. S. S. R.) Synchrophasatron have H-shaped magnets with poles and the Argonne ZGS and the Delft (Holland) zero-gradient machines have poleless picture-frame magnets.

In alternating-gradient synchrotrons, because of the strong focusing, the apertures required for containing the motions of the beam are much smaller. But two other demands for space become more important. Together with the particles' oscillations about an equilibrium orbit, the orbits themselves may have radial excursions of comparable size due to azimuthal nonuniformity of the magnetic fields in the individual sectors and due to their misalignment. Also, with such small apertures, it must be kept in mind that there should be sufficient space for moving the final accelerated beam onto various targets. The ability to carry out several research experiments simultaneously can depend upon sharing fractions of the beam between several targets which may need to be located at different radial positions and further radial space may be needed for the proper maneuvering of the beam onto them.

The A-G magnets built to date have been C-shaped although there is really no fundamental reason why properly shaped poles could not be designed for an H-shape. However, the latter might prove to be unwieldy in manufacture, installation and operation and the magnetic advantage, in this case, may be questionable. A typical cross section is shown in Figure 1. The solid line represents a contour for a so-

called "open" section, with the field gradient decreasing to the right, and the dotted curve that for a "closed" section with the gradient increasing. If the center of the accelerator were at the far left, the open contour would be vertically focusing and the dotted one would be radially focusing. In the Brookhaven AGS, the pole width is 12.5 in., the gap height at the central-orbit position is 3.5 in. and the external dimensions are 33 in. by 39 in.

Although the vacuum chamber is only about 7 inches wide, the greater pole width is needed to provide the strong, uniform, radial gradient that (for the AGS) is about 10 percent per inch. For the contour shown by the solid line in the figure, the field (at any given time, i. e., for a given value) will increase as one moves radially to the left, but to keep the slope accurately uniform over the aperture and to offset the leakage effects due to the gap, it must continue to rise, but with decreasing slope, before the maximum is reached and before dropping to the low values at and beyond the pole's edge. The effects of saturation in this high-field region can be minimized by rounding the corners of the pole tips to give a more uniform distribution for the flux.

A significant quantity, for studying saturation characteristics in such an A-G magnet, is the average maximum field in the pole tip. This quantity,  $B_{\max}$ , is related to the field at the center of the aperture,  $B_0$ , by a relation:

$$B_{\max} = f(\mu)PK(1 + ka/2)B_0 \quad \text{--- (2)}$$

where  $f(\mu)$  is a function of the permeability,  
 $P$  is the inverse of the packing factor of the steel in a magnet unit,  
 $kB_0$  is the gradient of the magnetic field,  
 $a$  is the total radial aperture,  
 $K$  is a constant (always greater than unity) that depends on the profile and is a kind of efficiency factor for the rounding off of the pole tip.

In tailoring the profile for the Brookhaven AGS, an effort was made to reduce  $K$  to a value as small as possible; in final form, the rounded portion is almost parabolic in shape and  $B_{\max}$  is about 1.6  $B_0$ . However, optimum shaping for constant gradient to the highest fields, and over the widest radial extent, was limited by the fact that the minimum vertical distance between the

poles had to be large enough to permit installation of the individual pancakes of the exciting coils.

Another way in which the effects of saturation were reduced and the pole width kept to a minimal size, was the displacement of the central orbit position to a radial position 1 inch away from the geometrical center toward the low-field side. This has the effect of adding more iron on the high-field side of the magnet where there is the greater flux and of subtracting it from the low-field side where it is not needed. This also means that the open magnet units and the closed units are displaced radially from each other by 2 inches but, since each was a separate unit with its own coil, this caused no particular problems.

The pole shape that will produce a field with constant radial gradient is approximately hyperbolic. However, the leakage effects of the gaps and the proximity of current-bearing coils require some modification of the hyperbolic shape and a fairly extensive computational program was carried on at Brookhaven to arrive at the final optimum contour. There were three main reasons for this. First, one can obtain results which are difficult to measure in models. For example, a knowledge of the fields inside the coil is helpful for the determination of the forces on the coil and for estimating the eddy currents that may be induced there. Some knowledge of the fields inside the iron, even if calculated for constant permeability, provides information on the way the iron saturates. Second, one can reduce the number of magnet models required. At Brookhaven, some 20 or more various pole contours were studied on paper in the search for optimum characteristics and only a few models were made to check the results, to give the time-varying behavior, and other necessary electrical and mechanical specifications. The third reason is understanding. If the measurements and calculations do not agree, either something is wrong with the measurements or one does not understand the behavior.

The calculations were carried out by means of the relaxation method, using a modified potential function<sup>1</sup>; they were relatively simple, requiring the services of only two human computers and a desk calculator. Recently, much more sophisticated techniques using high-speed electronic computers have been developed, particularly by R.S. Christian and others at the MURA Laboratory, which can give very precise results for quite complicated pole shapes and that take into account the inter-relationship between field and permeability inside the iron.

For the AGS magnets, however, relatively simple calculations sufficed to determine a pole shape that would provide a cross-sectional area about 7 in. wide and about 3 in. high, where in the ratio of the gradient to the central-field value remained constant to better than 1 percent.

Briefly, the shape departs from the hyperbolic by having a narrower gap on the high-field side and a wider gap on the low-field side. The coils situated so close to the gap on the low-field side have considerable influence and tend to make the gradient too high; thus, iron needs to be removed on this side. The coils on the high-field side have very little influence on the field; the pole contour is the chief influence on the field shape. The same contour (but reversed in radial direction) was used for both the open and closed magnet sections. This resulted in some small assymetries because of slight differences in the magnetic flux paths. However, with the frequent alternations of the magnets in the AGS, these differences were not large enough to have any harmful effects on the beam's behavior.

The widths of the top, bottom and back legs of the AGS magnets were made the same size as the pole width since rough field calculations showed that this did not result in serious saturation. In fact, it is possible that some saving in iron could be made by making at least the back leg somewhat narrower. But it was felt that the saving was so small that it was not worth the delay that would result from the time required for computations or modelling.

C. Choice of Steel. In the design of A-G magnets, the choice of steel has much greater importance than has been the case for constant-gradient magnets where costs have been a major determining factor. In the early days of design at both Brookhaven and CERN, since each of the many magnet units in the AGS or PS was required to have fields that would be identical to about 0.1 percent or better for all values of these fields during the acceleration period, non-uniformity in the magnetic characteristics of the steel was a worrisome problem. Previous measurements that had been made at Brookhaven, during the construction of the Cosmotron, showed variations among the different heats of steel (and even among samples from the same heat) up to  $\pm 20$  percent and with the additional troublesome fact that  $\mu_{vs} B$  curves for the different samples exhibited one or more cross-overs as B increased from low to high values.

At both Brookhaven and CERN, the groups working on the linac injectors felt that an energy of about 50 MeV was about the highest that they would propose in view of the state of the art at the time; this meant that the injection field in the synchrotron would be only of the order of 100 gauss. Thus, permeability values at low inductions and their variations were of even greater interest than the permeability values for steel at high inductions. For such low injection-field values, an important role is played by the remanent field that is left in the gap when the pulsed current in the magnets is reduced to zero, and its value is directly proportional to the value of the coercive force in the steel. Remanent fields for the contemplated A-G design would be of the order of 20 gauss for a coercive force of about 1 and would, therefore, be a large fraction of the total injection field. Experience had already shown that coercive force might have the greatest variation of all the magnetic parameters of the steel.

For these reasons, both at Brookhaven and at CERN, an extensive program was carried out to investigate the properties of various types of steel. In this country, the large steel manufacturers were very cooperative during this program and some of them made many pertinent measurements in their own laboratories. However, it was not practical to have a truly custom-made steel since the approximately 4000-ton order was sufficiently large that it would require the facilities of a large plant and yet was not so great that the processing could be very different from normal industrial practice.

Of the commercial grades of sheet steel, one can say in general that those which have the higher permeability values for low inductions also have lower values of coercive force, but lower permeabilities for high inductions. For example, the silicon steels of dynamo grade (about 3 percent Si) have permeability values over 1000 at 100 gauss and  $H_C$  close to 0.5; the electrical-grade silicon steels (about 1-1/2 percent Si) have permeabilities at such inductions of around 750 and  $H_C$  near 0.9; the low-carbon steels (including so-called "pure" iron) have permeability values of 250 to 500 and  $H_C$  values of 1.5 to 2.

Many undesirable effects result from the choice of a steel which has a low value of the permeability at the injection-field values. The lower the value of the permeability, the greater is the reluctance of the iron in the magnetic circuit and it can become an appreciable fraction of the total reluctance that includes the

air gap. With an A-G design like that of Fig. 1, the reluctance in the iron can be over 5 percent of the total reluctance if the average permeability is about 500 and will be over 12 percent for a permeability of 200. This can mean that the effects of nonuniformity will be greater. For instance, if two magnets have average permeabilities that differ by 10 percent, their fields will differ by 1-1/4 percent if this permeability is close to 200, whereas they will differ by only about 1/2 percent if it is closer to 500.

Apart from nonuniformity effects from magnet to magnet, too low a value of average permeability will result in variations of its value across the pole tips and may alter the shape of the field at injection from that which would be present at high fields. Rough calculations showed that for the AGS design, if the steel in the poles had an average permeability as low as 200, the gradient of the magnetic field at injection would not only be reduced by about 2 percent but would have a varying slope of about 0.5 percent per inch across its radial extent.

Another problem that arose during these studies on the properties of steel, concerned the effects of aging: both the values of the low-induction permeability and the coercive force change with time and subsection of the samples to higher temperatures for a short time accelerated the effects. The greatest change was in the coercive force where, particularly for the low-carbon steels, changes of over 2 to 1 were observed. However, even the silicon steels showed changes in samples that the manufacturers claimed would not age. Unfortunately, the changes were usually for the worse, i. e., the coercive force increased and the low-induction permeability decreased.

The steel finally chosen for the Brookhaven AGS was an electrical grade of sheet steel known as M-36 which contains about 1-3/4 percent silicon. Its choice was based not so much on its magnetic properties as on its mechanical ones. Pilot lots of this type of steel had shown a high degree of flatness and a uniformity of gauge and other mechanical properties greater than other types. It was somewhat higher in bulk price than a low-carbon steel but its mechanical superiority made fabrication of the magnet units easier. Its somewhat lower high-induction permeability was offset by the high packing factor that was achieved so that the high-field performance was quite satisfactory. Uniformity of the magnet units was obtained by distributing the sheets so that those from the same coil in any given heat were located at the

same spot in each of the units. This was done by stacking the sheets into the number of piles required for the units prior to fabrication. The result was a uniformity from magnet to magnet of about 2 parts in  $10^4$ .

D. Structure and Fabrication. Because synchrotron magnets are pulsed, the magnet cores must be laminated. For rapidly pulsed machines, like those at Princeton and Cambridge, the laminations must be thin in order to reduce eddy-current effects but in the other accelerators, where the magnetic field usually takes about 1 second to reach its peak value, thicker plates can be used. However, for the Brookhaven AGS, thin laminations of thickness 0.035 in. were chosen because it was felt that, through a stamping process, stricter tolerances could be met in obtaining the desired pole shape and in fulfilling the requirement of high uniformity between the units. It is possible that an equally satisfactory magnet could have been made from plates, of perhaps 1/4-inch thickness, with a machined profile.

The laminations can be held together by either one or a combination of two techniques: by chemical bonding or by strictly mechanical means. At Brookhaven, although a magnet model that had been bonded with a vinyl resin appeared to be quite satisfactory, it was believed that the temperature control during the bonding cycle would not be sufficient to ensure the necessary uniformity. Therefore, the laminations were stacked under pressure and held in place by welded straps as shown in Figure 2. A carefully symmetrical program for the welding was maintained to prevent any distortion of the magnet's gap. The laminations were stamped out by a carbide die that would not require sharpening during the entire process and, to offset the effects of any vertical assymetry in the die, the laminations were turned end for end every 20 sheets in the stack.

Nearly all synchrotron magnets are composed of sections which are arcs of circles. In the constant-gradient machines, these may be quadrants or octants but the higher-energy alternating-gradient type consists of many more units. Although at CERN the magnet units were assembled in circular arcs, at Brookhaven the units were made straight for mechanical simplicity. They are sufficiently short that there is no serious effect on the particles' orbits which move slightly from one side to the other in their passage through each unit.

The supporting structure for the magnet will depend greatly upon the nature of the soil where the accelerator is located and upon the specified tolerances of stability. These tolerances are more severe for the A-G type of synchrotron where the magnet's location must remain constant to a few mils both radially and vertically. We were fortunate, at Brookhaven, to have very uniform sand to a considerable depth with no perceptible earth movements. The magnet support consisted of a set of simple box girders, as shown. Each girder holds two magnet units and rests on concrete caps that cover 50-ft long steel piles driven into the sand.

Some means for positioning the magnets must be provided. Each of the AGS magnets has, on its top, three ground plates defining a plane which determines the precise level and vertical position of the unit. Also on top are two reamed holes situated directly above the aperture's center line in the gap; these serve as locating sockets for radial positioning.

A long-range view of the arrangement of magnets in the AGS is shown in Figure 3. Two vertically focusing units are followed by two radially focusing units in alternation around the approximately half-mile circumference. The units are arranged in groups of 10, each group being separated by a field-free region 10 feet long. The back legs of the magnets are alternately located inside the orbit for one group of 10, and then outside the orbit for the next group of 10, in order to allow secondary beams to emerge at all angles.

E. Coils. The design of the exciting coils for large accelerator magnets also involves many conflicting choices. The primary function, of course, is to provide the magnetomotive force, or the appropriate number of ampere-turns required to give the chosen maximum field in the magnet's gap.

The cross-sectional size of the winding will influence the overall cross-sectional size of the magnet and its cost but very compact coils with high current densities will need greater insulation, more extensive cooling and result in higher costs of operation because of higher power dissipation. The number of turns in the winding must be adjusted to match the ratings of the magnet's power supply and it is desirable to keep the number small to keep the voltage down. But this may result in a conductor size that is so large that it will not only be very costly but may have eddy currents that will be high enough to distort the magnetic fields inside the magnet's gap. In coils that are of considerable length,

there will be a large number of welded or brazed joints that can leak or even fail under continual pulsing; on the other hand, if the magnet is of many units with shorter coils, the number of inter-connections will be greater and the amount of conductor is increased. For example, the connecting bus for the 240 magnets of the Brookhaven AGS is of such an extent that it has a resistance that is 6 percent of the resistance of all the coils.

The mechanical structure and specifications of the coil are also important. The electromagnetic forces can be very large and can cause motion that, even though small, may be troublesome. It is fairly well known, I think, that the coils of the Brookhaven Cosmotron suffered fatigue failure after about 7 million pulses from small motions in the fringe fields of the quadrant ends. Such motions can be prevented by the practice in common use today of casting preformed coils with epoxy or polyester resins to form a rigid, monolithic structure of good mechanical stability. Unfortunately, some of the bonding materials that have the best mechanical strength have poor electrical properties and it is usual to wind the coils with layers of glass cloth or other good insulating material prior to the bonding.

As a numerical example of typical specifications, the coil units for the Brookhaven AGS magnets were expected to be able to withstand tensile forces of 500 psi and shear forces of 1000 psi between turns or layers. The turn-to-turn and layer insulation was required to stand a 1500-volt peak high-frequency or 5000-volt peak impulse test and the ground insulation to withstand 20,000 volts, rms, at 60 cycles. All the firms solicited to make the coils were requested to submit samples of their proposed construction in order to give them such mechanical and electrical tests.

Most of the large synchrotrons have fairly simple coil structures with conductors of rectangular cross section and a central hole for water cooling. The Berkeley Bevatron is an exception that is cooled by rapid air flow. The coils for the machines with high cycling rates present special problems, particularly with respect to eddy currents. At the Cambridge electron accelerator, for example, the coils are made of a bonded structure with stranded cables to carry the current and small tubes inserted between the cables for water cooling.

F. Magnet Power Supply. Another large and costly item in the magnet system for multi-bev accelerators is the power required for excitation. Such large magnets have stored energies of many tens of megajoules which must be removed at the end of each pulse. If this were to be dissipated each time, the operating costs would be enormous, so some method of storing this energy and reusing it is essential. The magnetic field must rise at an approximately constant rate during the acceleration period and the repetition rate should be rapid in order to provide higher average intensity in the accelerator and thus reduce the amount of time necessary to complete the research experiments.

The rate of rise of the magnetic field is a choice between conflicting interests. A short rise time will increase the peak value of the kva required and so increase the cost of the power supply but, for a fixed repetition rate, it decreases the average power demand by reducing the heat in the windings and allows a greater fraction of the energy to be recovered when the magnet is discharged. The rise time should be short compared with the magnet's time constant but a higher rate of change of the magnetic field in the gap requires higher accelerating voltages in the radio-frequency system. Rapid rates of rise also produce large eddy-current effects. The decay of the current from its peak value to zero should also be as rapid as possible to keep the losses down. Moreover, the power supply should provide this build-up and return of energy without causing serious fluctuation in the primary electrical supplying system.

In order to provide for long bursts of both extracted and secondary beams for certain types of research experiments, it is useful to be able to keep the current in the magnet near its peak value for durations of several hundreds of milliseconds, i. e., the magnet pulse should have a so-called "flattop". During this time any ripple in the resultant magnetic field can have deleterious effects by causing the secondary beams to emerge with erratic intensity. Obviously, the longer the duration of the flattop, the greater will be the power dissipated and the higher the operational costs; moreover the heat load may be so high that the rate of repetition of the pulses may have to be reduced. Sometimes, it is also advantageous to introduce a constant-current step in the rising pulse, i. e., to provide a flattop at intermediate energies, target there, and then to continue to accelerate the beam to its peak energy and, perhaps, have another flattop region there. All of these modifications naturally tax the power supply and should be considered in the initial plans.



In most of the large synchrotrons, the power supply consists of an alternator-flywheel-motor generator combination. The energy stored in the flywheel is supplied to the magnet during the acceleration period and is returned to the flywheel via the generator, acting as a motor, when the current in the magnet is restored to zero. The usual time taken to reach the maximum current is about 1 second and rates of repetition are some 10 to 20 pulses per minute. Commercial rectifiers, such as ignitrons, are used and serve also as inverters at the end of the pulse. A totally different power supply is used for the magnets in the accelerators which have high cycling rates of many pulses per second. In these cases, the magnet is part of a resonant circuit which includes large capacitor banks and chokes.

#### IV. Conclusion

A report of this kind usually concludes by making some sort of statements about what can be expected in the way of future developments. As far as magnets are concerned, a favorite contender in such discussions is the possibility of using superconducting or super-cooled coils for

the production of much higher fields and for reduction of power costs. Recently, there have been some promising developments, some of which are to be reported later at this meeting. At present it appears to be more likely that superconducting magnets may be used for auxiliary equipment such as bubble-chamber or beam-transport magnets before they are used for accelerators, but this could be a pessimistic outlook.

There are certainly many improvements that could be made in most of the components of a magnet system over those that have been presented here from the existing accelerators. However, in new designs, the group responsible will still probably have to face many of the same problems of the conflicting advantages and disadvantages of some contemplated procedure and to decide whether a higher initial cost will be balanced by savings during operation.

#### References

- 1 M. S. Livingston and J. P. Blewett, Particle Accelerators (McGraw-Hill, New York, 1962), pp. 253-4.

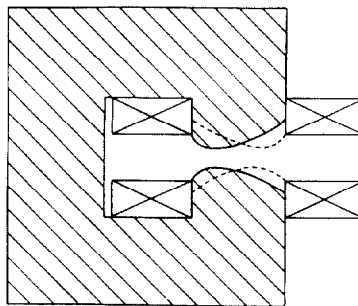


Figure 1. Typical cross section of an alternating-gradient magnet. The solid contour has a magnetic field that decreases with radius as one moves to the right; the dotted profile has a field that increases toward the right.

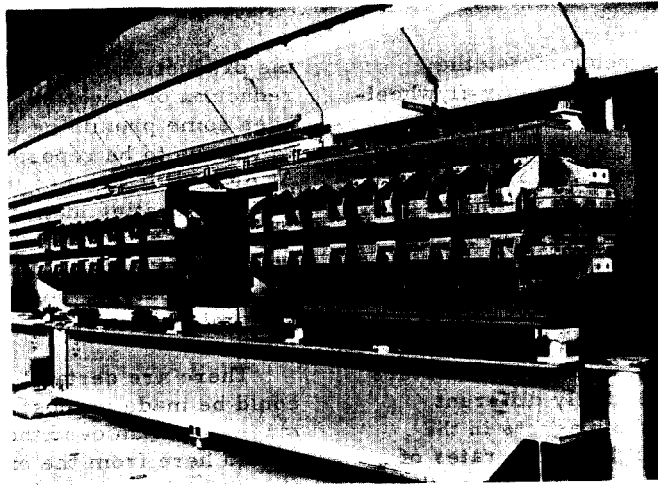


Figure 2. Two magnet sections of the Brookhaven AGS that show the type of construction and supporting structure.



Figure 3. The Brookhaven AGS complete magnet system is shown in place in the ring tunnel. In the foreground is a 10 ft. straight section (with one of the rf accelerating stations); the back legs of the groups of magnets are alternated between positions inside and outside the orbit at these straight sections.