Design and Construction of the Bevatron

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ABSTRACT

This report summarizes the design and construction of the Bevatron (6-Bev proton synchrotron) with emphasis on the engineering problems. It includes specifications, outline drawings, and a bibliography of other reports concerning the subject. Operating results and changes made after the initial start-up in February 1954 are mentioned only briefly.

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INTRODUCTION

The principle of phase stability disclosed by Veksler[1] and McMillan[2], which removed the energy limitations on heavy-particle accelerators that had previously existed, was soon applied to the cyclotron,[3] where it was necessary to vary the frequency, and to the electron synchrotron,[4] where it was necessary to vary the magnetic field. Application of this principle raised the energy limits of both machines to the order of 300 to 500 million electron volts. By 1947, when the practicality of the synchrocyclotron and the synchrotron had been established, attention was turned to the possibility of the proton synchrotron in which both the magnetic field and the frequency would be varied. Preliminary studies of this type of machine made at the Radiation Laboratory indicated that proton energies higher by an order of magnitude than those of the synchrocyclotron could be obtained.[5] This work was encouraged by information from the group at Birmingham, England under Professor Oliphant[6] who, it was learned, had been working on the proton synchrotron since before the end of World War II. Discussions also took place with members of the accelerator group of the Brookhaven National Laboratory who were also interested in building such a machine. The possibility of building the machine in a series of magnet sectors with field-free regions between appeared very attractive from the mechanical standpoint. This possibility was being explored at the time by Crane at the University of Michigan[7] who, with the results of the analysis by Dennison and Berlin[8] and Serber[9] on the stability of the ion motion in an interrupted magnetic field, decided to proceed with the so-called race-track type magnet for an electron synchrotron. As a result of these studies by our own and other groups, it appeared that a large proton synchrotron would be

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*This report covers the design and construction of the Bevatron, with only brief mention of operating experiences and changes made after the start of operation in February 1954.

entirely feasible and that the size of the machine would be determined largely by the availability of funds.

Accordingly a proposal was made to the Atomic Energy Commission in February 1948 by the University of California Radiation Laboratory for the construction of a proton synchrotron. The machine was intended to be the largest that could be successfully built at the time. This, it was agreed, would mean a radius of approximately 50 feet and an energy of slightly over 6 billion electron volts. A factor in determining the size was the energy estimated for proton-pair production--approximately 5.6 Bev. The proposal called for a magnet of symmetrical return-yoke cross section consisting of four 90° quadrants of 50-ft centerline radius separated by field-free straight sections. The total quantity of steel was estimated at 10,000 tons and of copper, approximately 300 tons. The magnet power was to be supplied through flywheel motor-generator sets. The machine was to be located on the grounds of the Radiation Laboratory above the University of California campus in an area that was to be prepared by a rather large earth-moving operation. Although the site had some disadvantages from the standpoint of cost, it had the great advantage of proximity to the University campus. The cost of the machine, not including shielding or experimental facilities for using the accelerated beam was estimated to be 9.1 million dollars.

During the period that the site was being prepared and building construction started, a quarter-scale model of the accelerator was built and tested.[10] This smaller machine, whose maximum energy was only a few Mev, was used to study the injection period and to prove that ions could be stably accelerated through the interrupted magnetic field. The performance of this machine[11] verified the assumptions on which the large machine was based and showed that construction could proceed with assurance of a successful outcome provided the engineering problems were properly solved. During 1950 most of the steel for the yoke of the magnet was received and fabricated into plates which were assembled in a large shop operated by the laboratory in Oakland. Coil winding started in March 1951 and ended in June 1952. During 1951 and most of 1952 a minimum effort was devoted to the Bevatron due to other work in progress at the laboratory. The magnet power supply was tested using the magnet without pole pieces as a load during July and August of 1952, and delivery of pole-tip plates began at the end of that year.

Assembly of the plates in the slabs and their installation together with the installation of the vacuum tank took place during the year 1953. Also during 1953, work was resumed on the injector and the radiofrequency accelerating system. The injector first operated in June of 1953. The remainder of the year was spent on improving its output and on physics experiments with the 10-Mev proton beam. Construction was officially called complete at the end of January 1954, when all the basic elements of the machine had been tested individually and the process of looking for the beam began. The first low-energy beam was detected in February 1954, almost exactly 6 years after submission of the proposal for construction to the Atomic Energy Commission. This time could probably have been reduced to $4\frac{1}{2}$ years if diversion of effort to classified projects had not been necessary.

DESIGN POLICIES

Throughout the design, an effort was made to be as conservative as reasonably practical. It was expected that this machine would become extremely complicated and would necessarily involve a great many untried components. For this reason it was felt that where a proven solution could be used for any problem, it was desirable to use it so that a minimum number of untried elements would then be involved. Although the history of accelerator developments had generally been good, there had been long periods of trouble with some machines and every effort was to be made to avoid such a situation with the Bevatron. Following this policy of conservatism, it was desired to provide for almost any conceivable change without having to discard a large part of the machine. This meant designing a machine that could be assembled in a number of different ways. Associated with this was the ability to reverse the assembly procedure in case trouble appeared--to back up, make changes, and proceed again. For this reason irreversible processes such as cementing, welding, and riveting were avoided, and parts were generally assembled by bolting. For example, all the magnet plates, of which there are some 20, 000, could have been taken apart and reinsulated if necessary. In fact, many of the first few thousand were taken apart in order to improve their insulation resistance or accuracy of assembly. Avoidance of welding resulted in a less rigid structure in some cases, but it was considered to be worth its disadvantages.

Another example of the conservative approach was the method of deciding on the aperture of the machine. In the early discussions, it was felt by some that it would be rash to attempt to reach the 6-Bev final energy in the first design. The suggestion was made, for example, that the machine be first assembled on a 25-ft radius after which, if it operated satisfactorily, the radius would be increased to 50 ft by buying more steel and doubling the mass of the magnet. The more practical alternative, which was adopted, was to start the machine with the final 50-ft radius but with a much larger aperture than would be possible at 6 Bev. Much of the concern about the feasibility of the machine centered around the amplitude of the radial and vertical oscillations of the beam. Small machines such as the 50-Mev betatrons had apertures as great as 25% of the radius, and, at the time the aperture was under consideration, synchrotrons which had apertures of the order of 10% of the radius were still not in satisfactory operation. In fact there was a good deal of fear that such apertures were impractically small. The first design of the Bevatron therefore was based on an aperture 4 ft high and 14 ft in the radial direction, or 8 and 28% of the radius respectively. With the power supply planned, the energy with this aperture would have been only 1.3 Bev, but it was felt that this would insure that the beam could be contained. The plan was that after a beam had been obtained at this aperture, the vacuum tank would be changed, pole pieces installed, and a smaller aperture tested. It was at this time that it was decided to go ahead with the quarter-scale model, which was scaled to the 4-by 14-ft aperture, and the order for the main-magnet steel was held pending the results of the quarter-scale model test. The performance of the model was so satisfactory that it was felt that the 4-by 14-ft aperture would not be needed and that an aperture of 2 by 6 ft would be reasonably conservative. This would have provided a beam energy of about 3 Bev. The steel was accordingly ordered, based on the 2-by 6-ft aperture, and construction proceeded through 1949 and 1950 on this basis. When it was time to place orders for the pole steel, the aperture was again considered, and model tests were again reviewed. It was agreed that it would be safe to proceed on the assumption that the smallest aperture, the one that would give the 6-Bev energy, would be satisfactory. At this time the Brookhaven Cosmotron was within a few months of being tested. If Brookhaven ran into serious difficulties that were due to insufficient aperture, time would still be available, with some delay but with only moderate cost, to change the dimensions of the pole tips and to retreat to the 2-by 6-ft opening. Fortunately Brookhaven's testing proceeded with only minor difficulties, and the use of the smaller aperture was demonstrated to be practical.

A third point in which conservatism was followed was, of course, in construction of the quarter-scale model. The \$350,000 cost of this machine was considered very small as insurance for performance of the larger machine. Because it was constructed in 9 months, it probably caused no delay in completion of the final machine, as this time was spent preparing the Bevatron site.

GENERAL DESIGN

The theoretical considerations in the design of the Bevatron followed the principles previously analyzed in detail for the cyclotron, betatron, and synchrotron. Application of this theory to the Bevatron and investigation of certain special problems, including an analysis of the injection process, is covered in a report by Garren, Gluckstern, Henrich, and Smith.[21] The important choice of the field gradient was made in collaboration with the theoretical group working on the Cosmotron, and the value for $-\frac{dB}{dR}\ \frac{R}{B}$ of 0.60 was chosen for both machines.

As previously mentioned, the magnet consists of four quadrants of 50-ft centerline radius with an aperture 12 in. high by 48 in. wide, separated by 20-ft straight sections. The beam is injected in the east straight section from a 10-Mev linear accelerator supplied by a 480-kev Cockcroft-Walton accelerator, and is bent into the Bevatron orbit by an electrostatic inflector. A drift-tube electrode in the north straight section accelerates the beam. The radiofrequency, ranging from 360 to 2500 kc, is determined by a master oscillator tuned by a saturable reactor in the oscillating circuit.

Two alternative methods of frequency tracking were originally available. In one, the voltage induced in an induction pickup loop located in the magnet aperture, was used to control the saturating current. In the other, a fraction of the magnet current was passed through the saturable reactor. In either case, a correcting circuit was used to obtain the proper shape of the frequency-field relation and to permit adjustment of the radial position of the beam. The magnet is powered by two flywheel motor generators connected through an ignitron rectifier-inverter. The magnet current rises in about 2 sec to a peak of 8333 amp, at which point the generator output is 100,000 kw. The current flows through the magnet for approximately 4 sec out of 6 at maximum repetition rate. The magnet coils are wound with 137,000 ft of insulated cable and cooled by two large centrifugal fans supplying air through tunnels under the floor. The magnetic field at rated current is 15,500 gauss, and the beam energy 6.2 Bev. The vacuum system, which has an internal volume of 11,000 ft^3, is pumped by twenty-four 32-in. oil-diffusion pumps. The machine is housed in a building of 75,000 ft^2 floor area most of which is in the 220-ft-diam magnet room. Two 30-ton radial cranes cover the magnet-room area. Figures 1 to 11 show general views of the Bevatron. A more complete description of the design of the various parts of the machine with some of the thinking behind them is contained in the following sections. Technical specifications of the machine are given in the Appendix.

MAGNET CORE

The flux path of the Bevatron magnet as shown in Fig. 2 consists of the yokes, the legs, the pole bases, and the pole tips. The yokes and legs are made of $\frac{1}{2}$-in. mild steel plate with no special requirements on composition other than maximum carbon and manganese contents of 0.15 and 0.40%, which were the minimum obtainable without extra cost. The thickness was selected in order to permit establishment of the eddy-current fields well before the injection period. The magnet is formed of 144 sectors of 2.5 deg each independent as far as the iron path is concerned. The yoke slabs, which taper from a thickness of 35 plates to 51 plates, are approximately 20 ft long and weigh 24 tons each. The plates of both the inner and outer legs are spaced to provide passages for cooling air to and from the coils. The $\frac{1}{2}$-in. plates are clamped together to form the slabs by 5/8-in. bolts on approximately 10-in. centers. The heads of the bolts and nuts are set below the surfaces of the plates in cup washers. Five-mil Kraft paper is used for interlamination insulation. The yoke plates are machined on one long edge and the leg plates are machined at opposite ends. The packages of

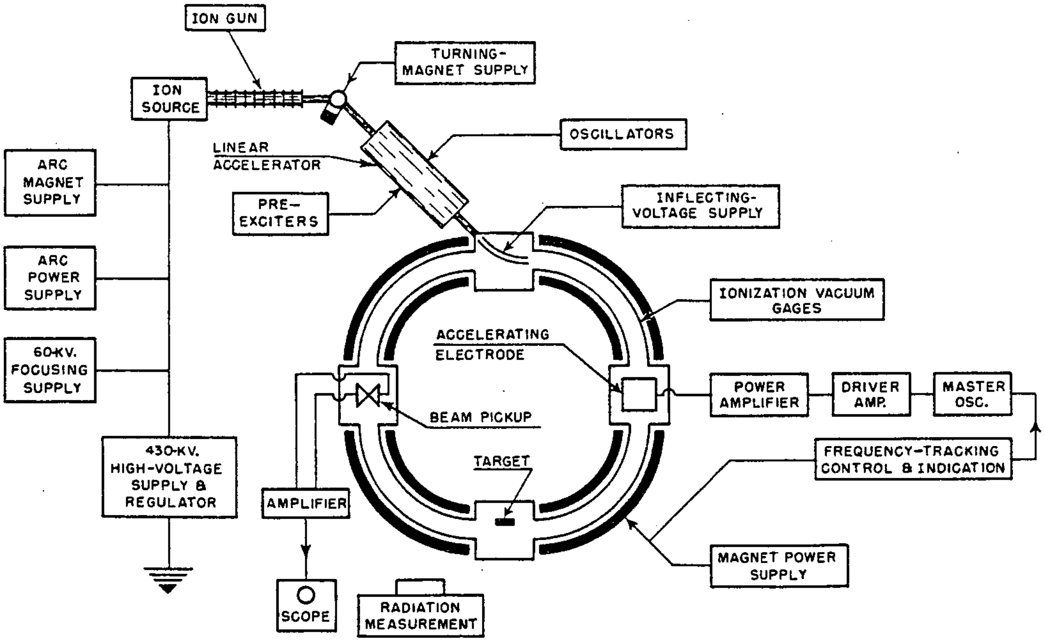

Fig. 1. Diagram of the Bevatron showing the principal electronic elements. Accelerating electrode and beam pickup are shown interchanged from their actual positions.

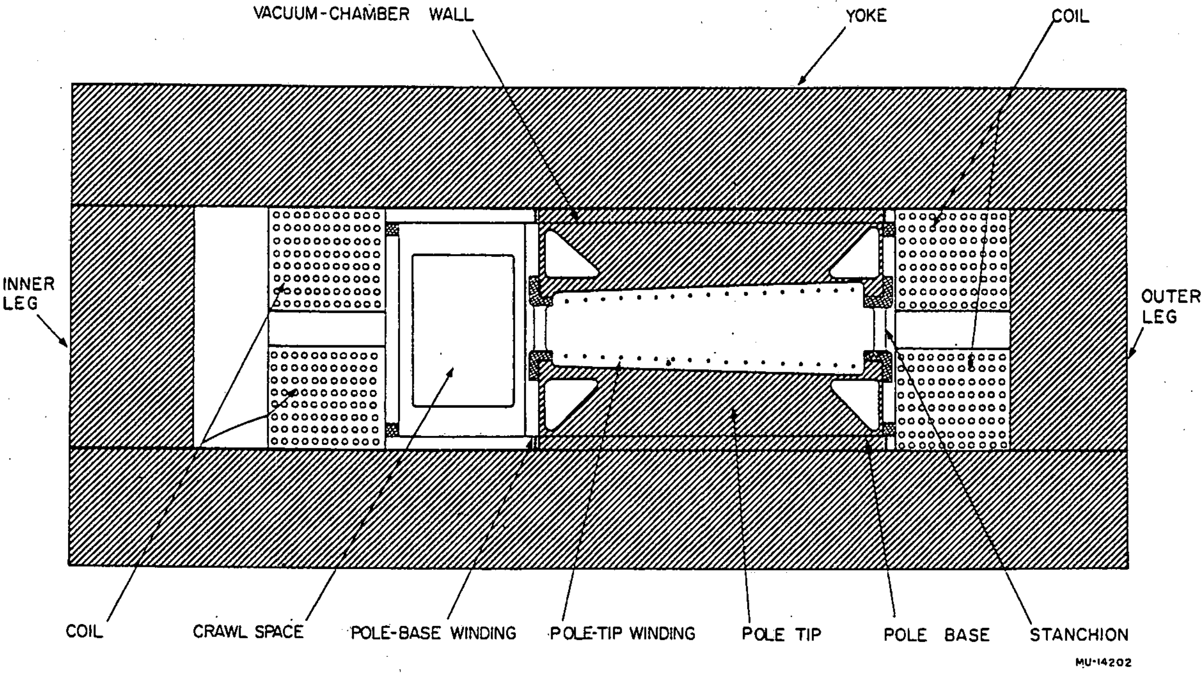

Fig. 2. Outline cross section of magnet. "Crawl space" and space between inner leg and coil would have been used with a larger aperture.

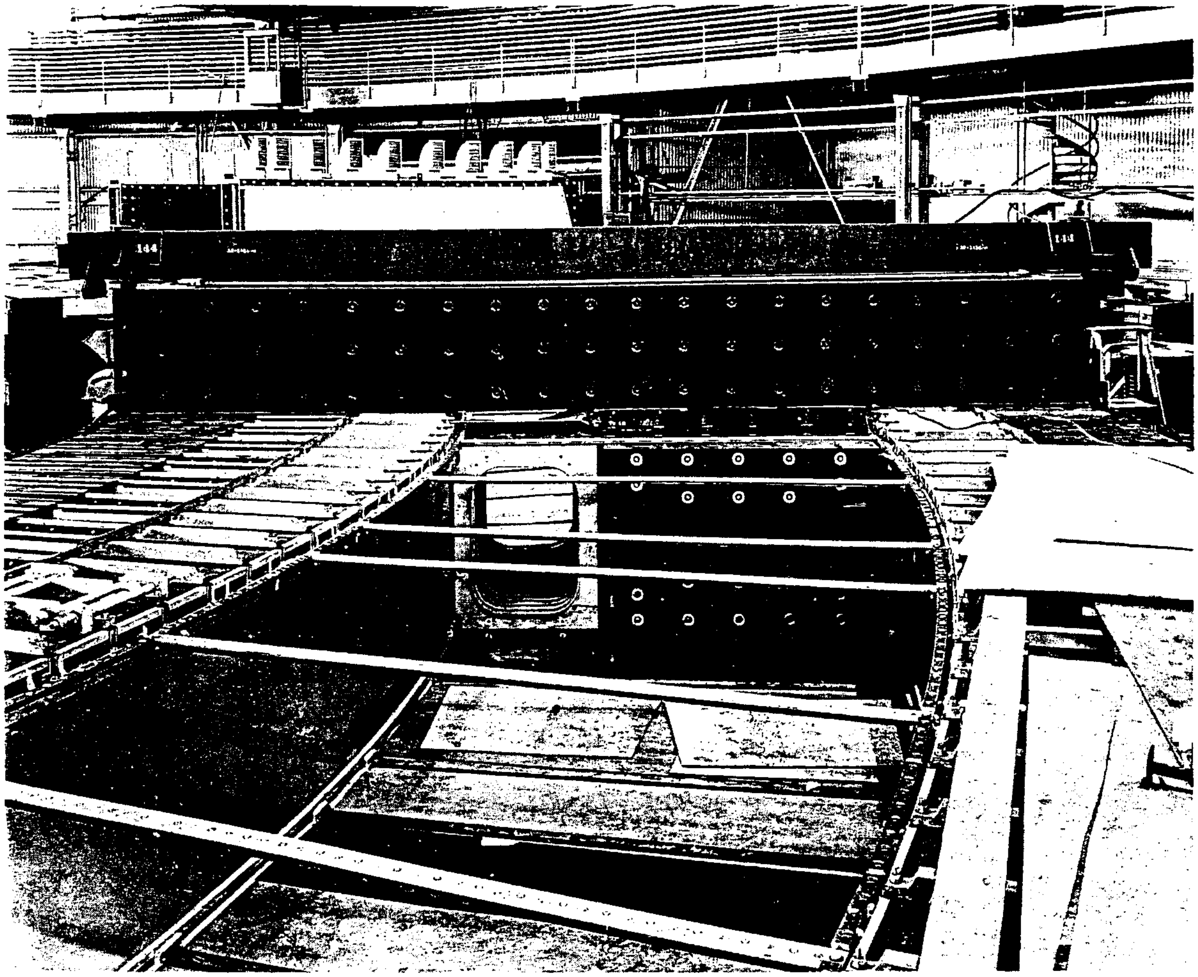

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Fig. 3. Magnet partially assembled. Note pole tips and base, stanchions, and vacuum-tube wall.

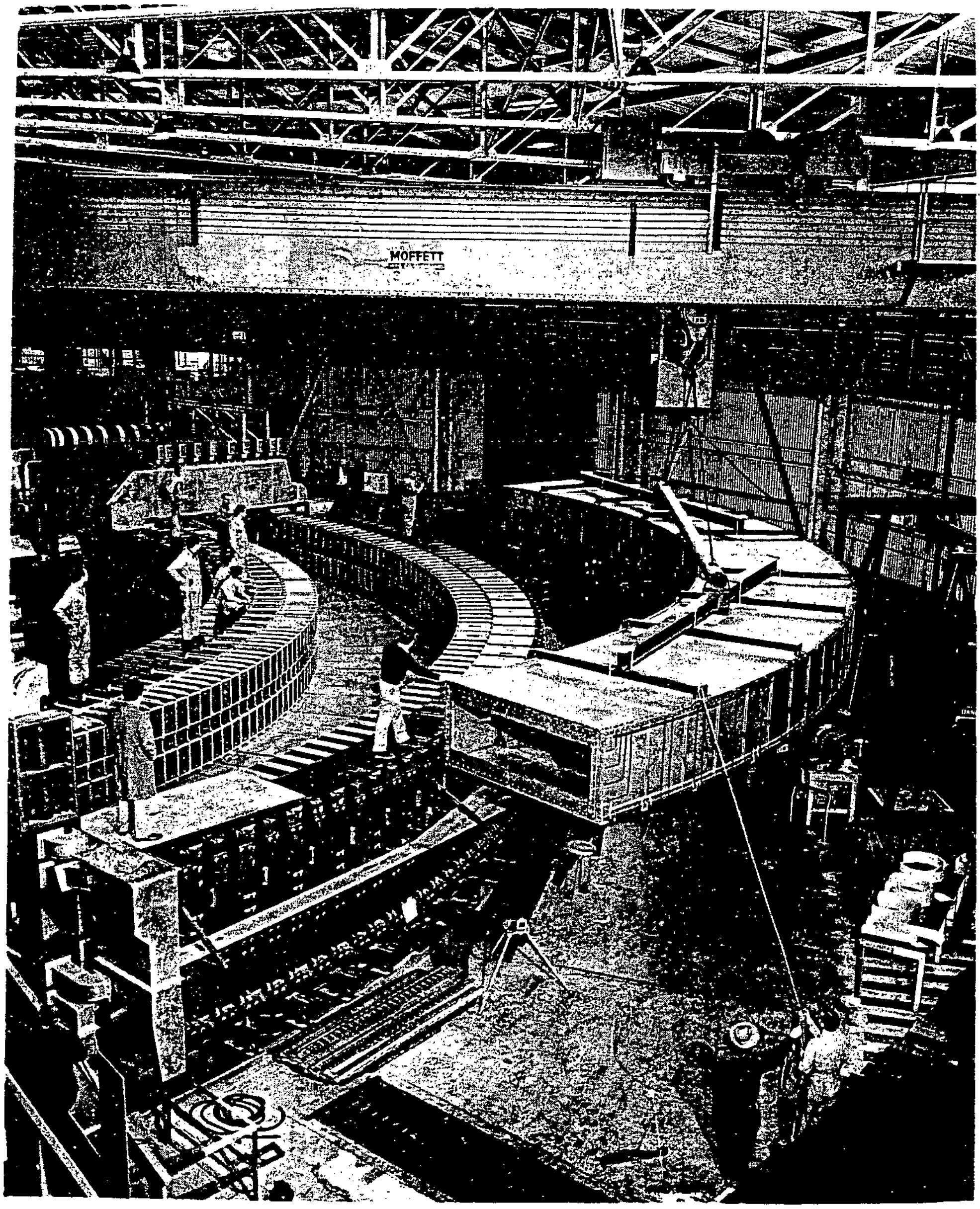

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Fig. 4. Installing a vacuum tube. Note pump-out lines on sides of tank.

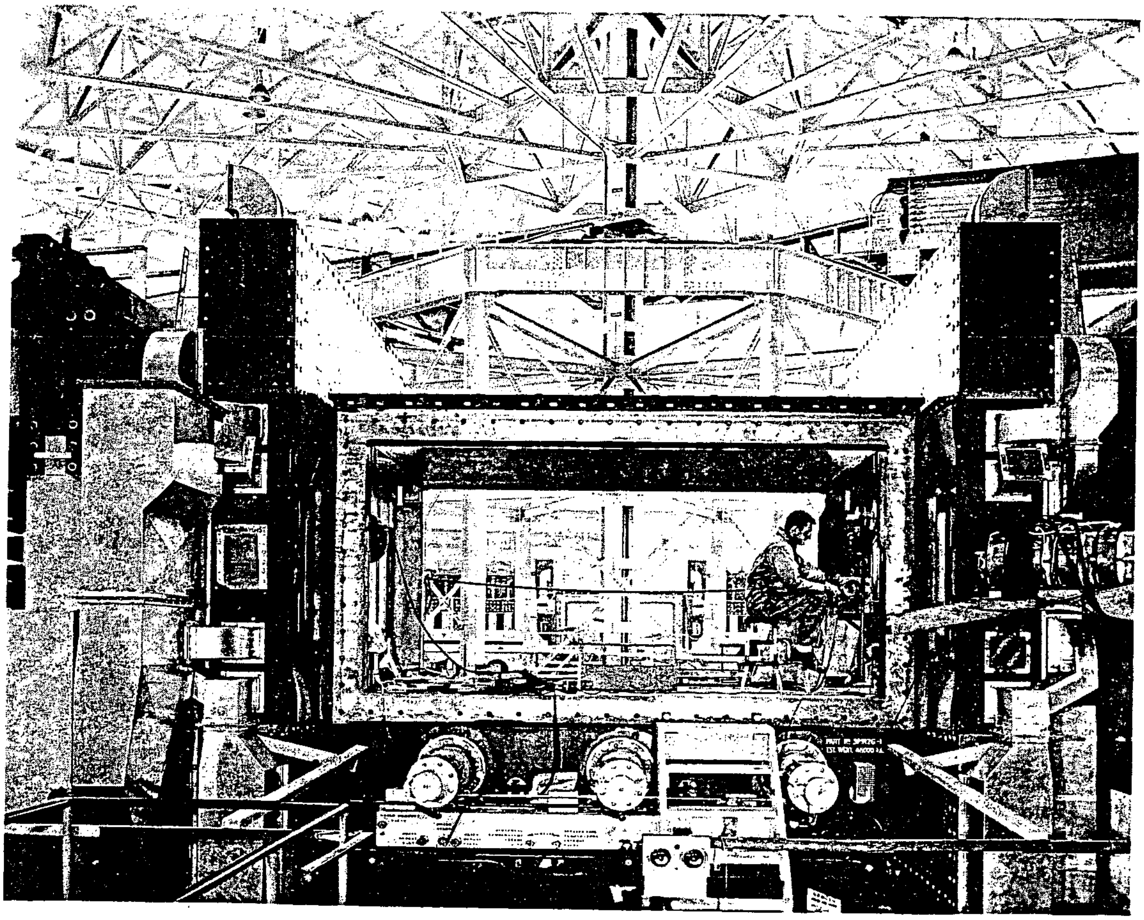

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Fig. 5. Injector straight section during assembly. Air ducts to end windings (top and sides) and alternating-gradient focusing magnet (right) are visible.

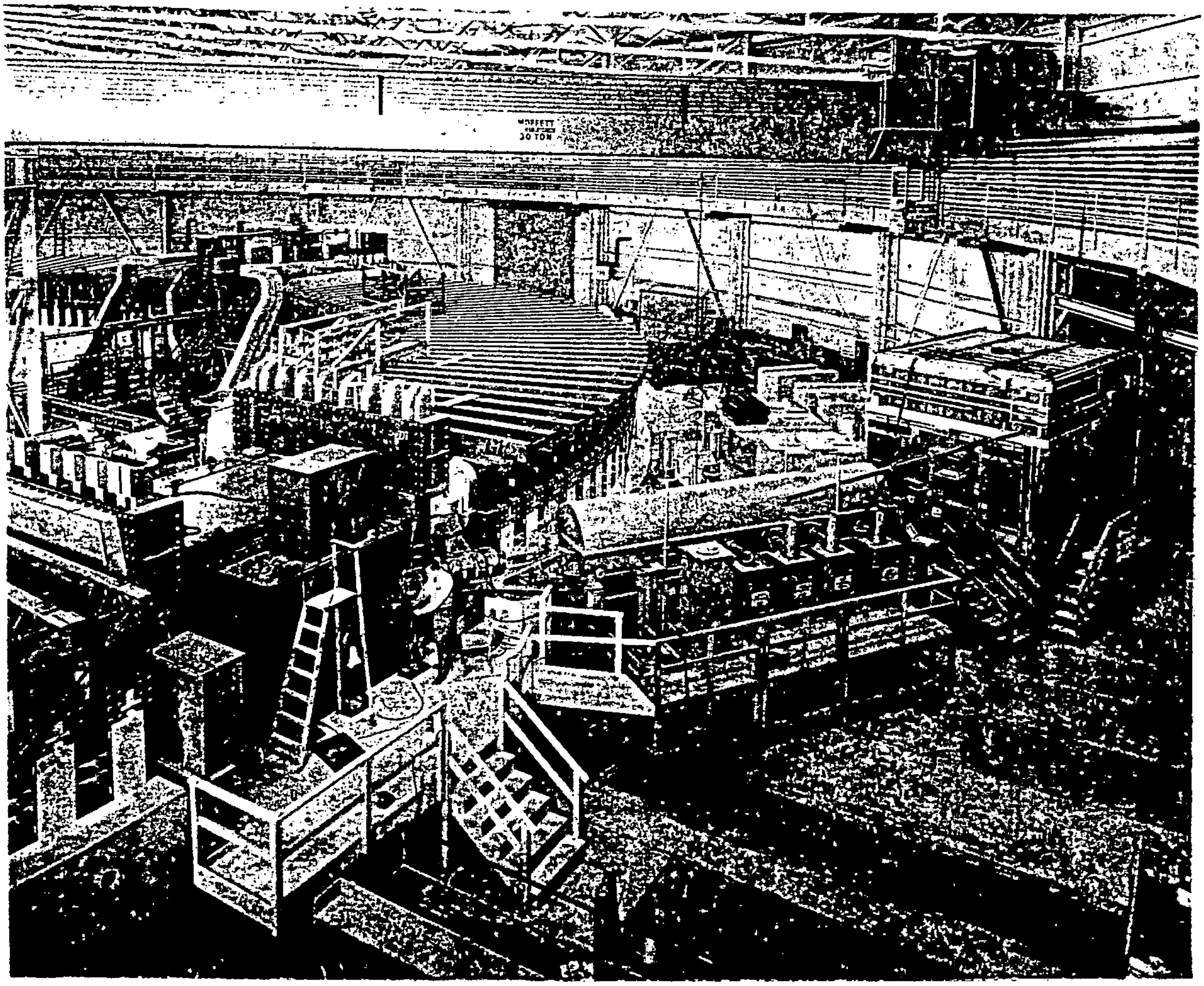

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Fig. 6. General view of injector area. Ion-gun housing (in right background) and linear accelerator with four self-excited oscillators and preexciter.

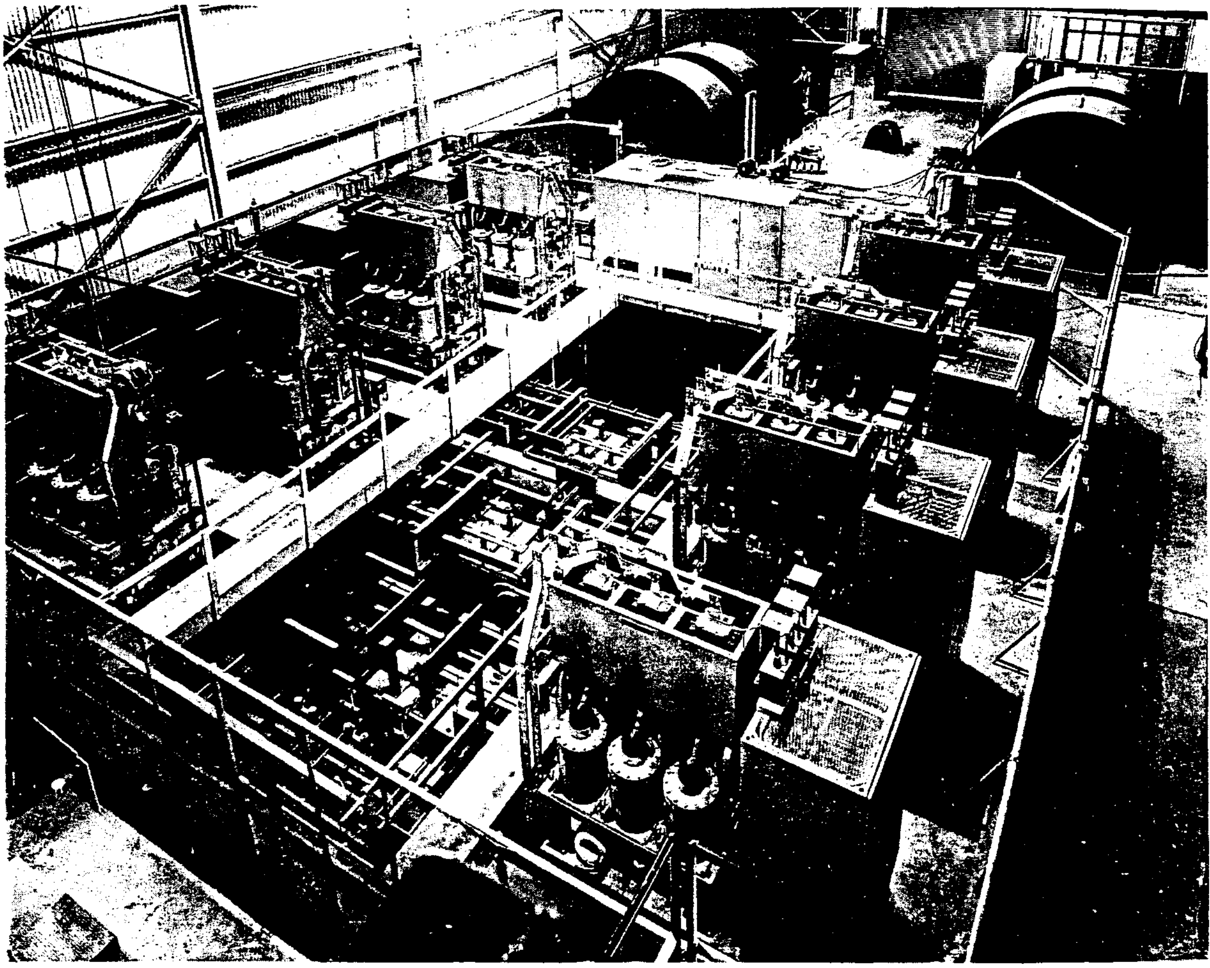

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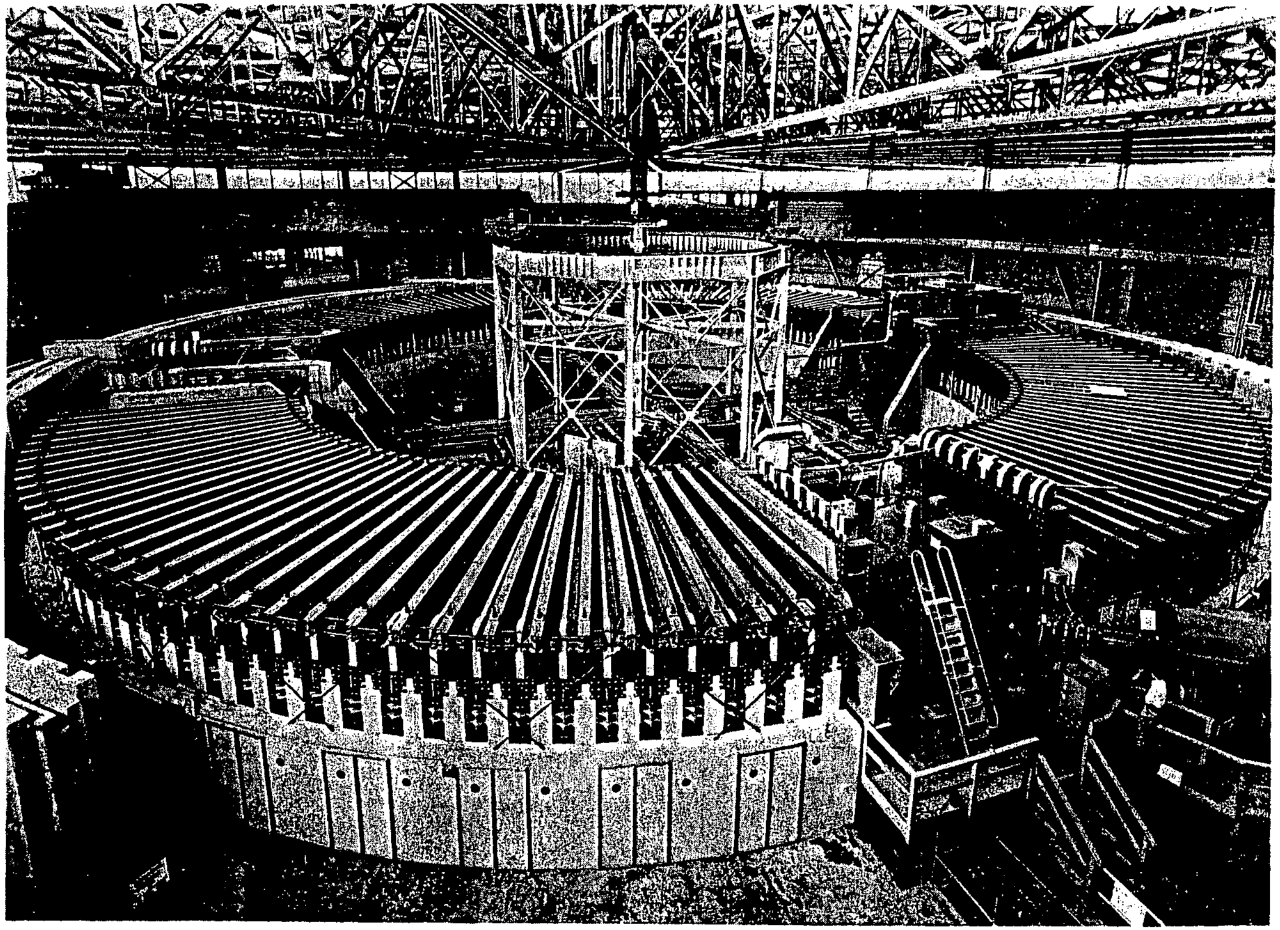
Fig. 7. Magnet power supply. Ignitron rectifier-inverter is in the foreground. A man can be seen beside the flywheel of the west motor generator.



ZN-1524

Fig. 8. Over-all view of the Bevatron. The straight section in the foreground is used for injection, that at the far right for acceleration, and the one at the left for the induction electrodes.

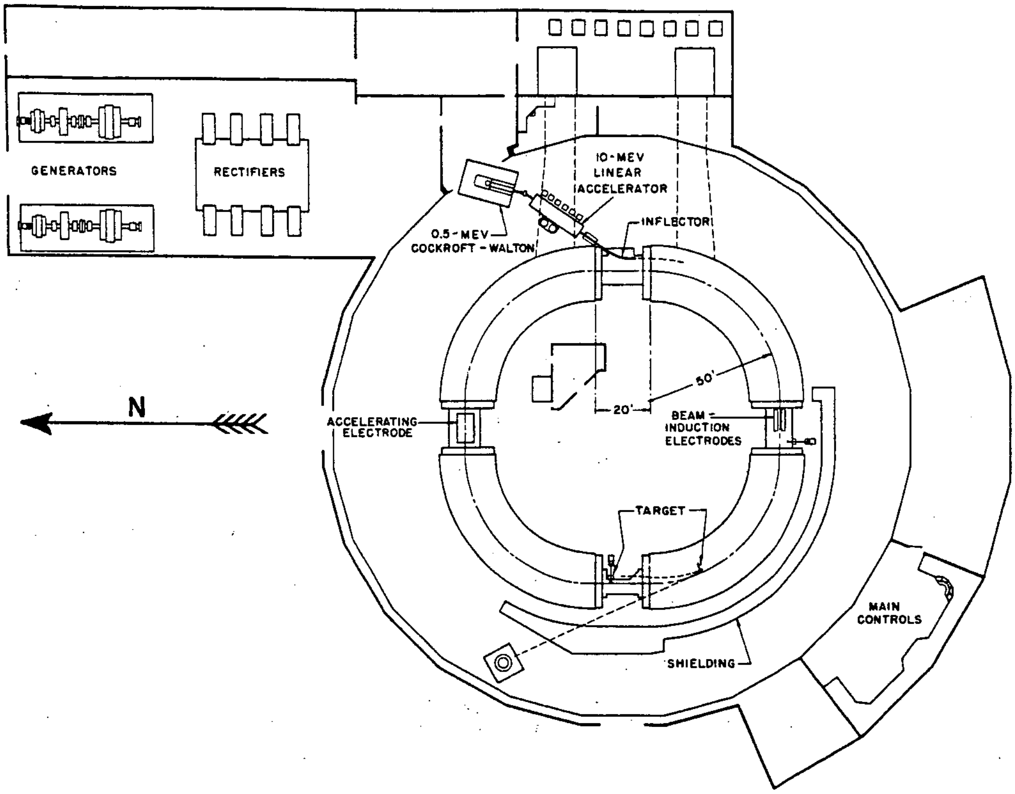


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Fig. 9. Floor plan of the Bevatron building. The power-supply wing is to the left and the fan room is directly beyond the magnet room.

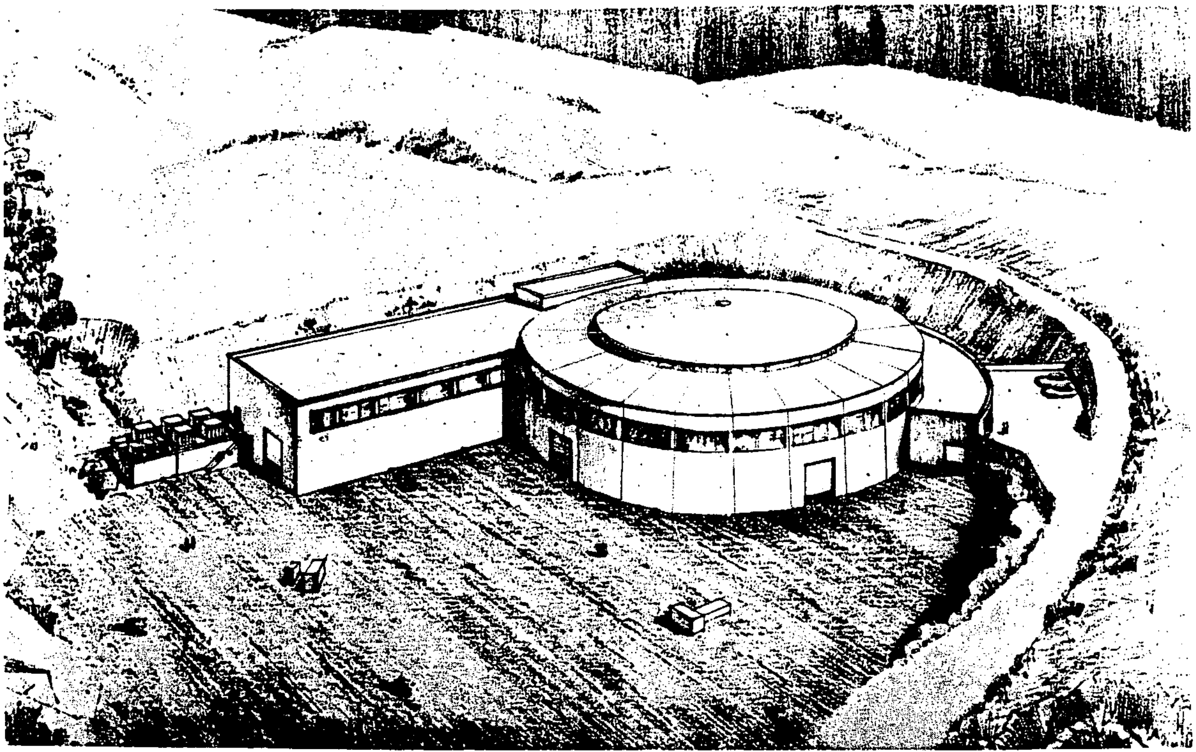

Fig. 10. Architect's drawing of the building.

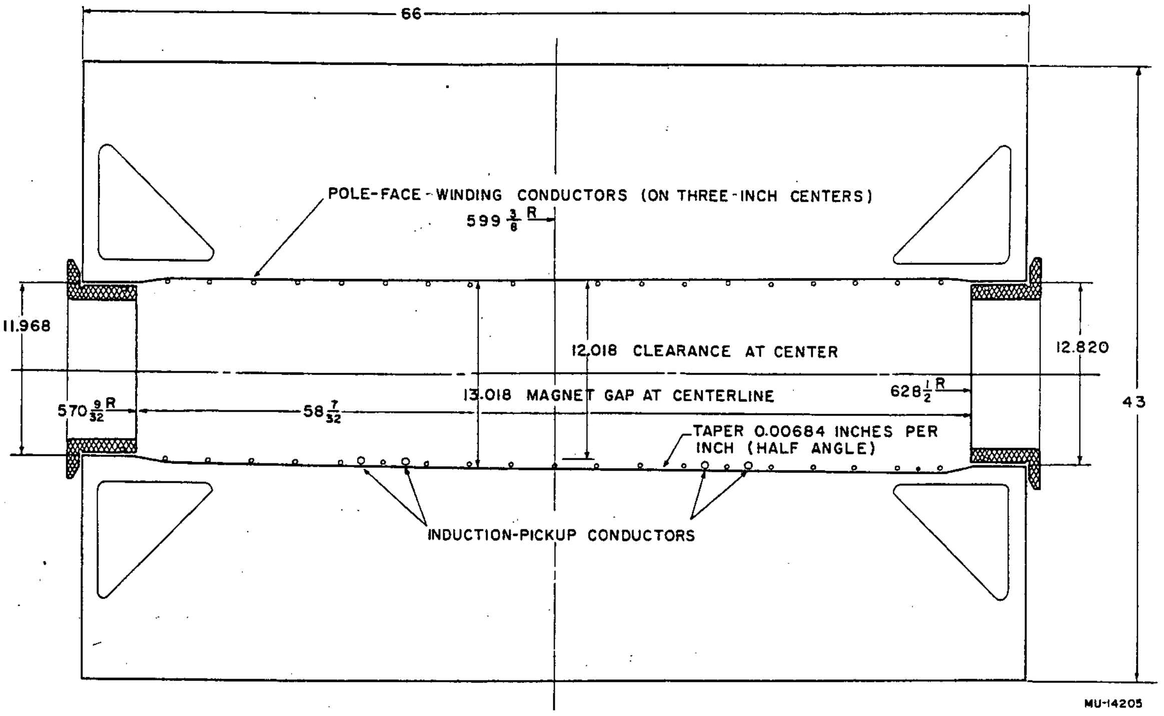

Fig. 11. Dimensions of magnet aperture. All dimensions are in inches.

plates forming the yokes and the legs were assembled in large hydraulically operated fixtures that held the plates square while the bolts were being tightened. Before the slabs were removed from the fixtures, the interlamination resistance was checked and corrected if less than 100 ohms. This value provided a large factor of safety over the resistance that would cause trouble due to current flow between the laminations, but it was felt that if the resistance were less than 100 ohms, some incipient trouble might be occurring. The assembled slabs were dipped in varnish to prevent short circuits from dirt and chips picked up on their surfaces.

The magnet poles, laminated of $\frac{1}{4}$-in. plate, are made up of the paper-insulated pole bases outside the vacuum space and the vitreous-enamel-insulated pole tips inside the vacuum space. The pole tips are shaped to provide a magnetic field index of 0.6. The gap is slightly reduced at the inner and outer radii to increase the radial width of the uniform field, and, in addition, triangular cutouts are made at either end of the pole tips in order to provide the maximum width of field at injection without increasing the stored energy as was suggested by Crane.[13] The pole-base and -tip slabs are also clamped by 5/8-in. bolts with recessed washers. Special attention had to be given to plates that did not extend all the way across the aperture to avoid their being pulled into the gap by the magnetic field. This was done for the pole plates by casting Araldite resin around the bolts and cup washers. For the yoke plates, shear plugs welded to the long plates and fitting in holes in the short plates were used. The pole plates and base plates were die-cut from enameling-grade iron with maximum carbon, manganese, and silicon contents of 0.12%, 0.40%, and 0.10%, respectively. Each of the sectors is clamped by beams extending radially above and below the yokes with tie bolts extending vertically between the beams at the inner and outer radii. The vertical tie bolts are tightened to a standard load measured by a strain gauge. The clamping force as well as the magnetic force between the poles is supported by nonmagnetic cast iron spacers called stanchions, as shown in Figs. 2 and 3. The sectors are spaced tangentially by bolts between the clamp beams and by jack screws between the pole-base and between pole-tip slabs. Tie rods are used to space the pole tips and pole bases from the legs in a radial direction. The legs in turn are located by brackets on the clamp beams. All these parts are made adjustable so that the magnet can be disassembled at any time and reassembled without damage.

The entire magnet is supported through the bottom clamp beams on jacks, three jacks being used under each sector, two at the outside radius and one on the inside. The sectors can be leveled and can be moved radially or tangentially by adjusting and tilting the jacks. The magnet was releveled once during the construction of the machine and once shortly after it started operation. The tie rods connecting the clamp beams as well as the jack screws between the pole tip and base slabs are all insulated to avoid eddy-current circuits. In the insulation system, circuits are generally broken in two points so that resistance checks can be made at any time. To provide for the large magnetic forces at the end of the quadrants, tangential jacks are used between the bracing structure inside the straight-section tanks and the end yokes, pole bases, and pole tips. These tanks are of especially heavy construction to carry this tangential load around the straight section without interfering with access. A series of diagonal tie rods at the inner and outer radius of the magnet holds the yokes upright and takes the tangential component of earthquake forces while the radial component is taken through the jacks. The magnet is designed to resist a horizontal earthquake acceleration of 15% of gravity.

A special plate-distribution scheme was followed in order to randomize possible variations in the magnet steel. As plates were machined they were stacked in a series of piles, the first plates machined being at the bottom and the last at the top of the piles. When the plates were assembled into slabs they were taken successively from the tops of the piles. This was done for each quarter of the steel order. As the core frame was erected, an equal number of slabs from each quarter of the steel order was used in each quadrant.

The pole slabs were assembled as the plates were received and each assembled slab was weighed. These slabs were then distributed so as to hold the average weight of the top and bottom of each quadrant the same. Samples were cut from all the $\frac{1}{2}$-in. plates received from the steel mill, but only a few of these were tested for permeability. Samples were also cast with each of the nonmagnetic cast-iron stanchion castings and measured as a check on their permeability. The permeability of these castings was about 1.05 at 1000 gauss.

MAGNET COIL

The Bevatron magnet coil consists of 88 turns of two parallel stranded insulated conductors and provides 733,000 amp turns at the rated magnet current. Both water- and air-cooled coil designs were studied. Water cooling would have provided an improved space factor both for the coil space and the iron core, because air passages through the magnet legs would not have been needed. However, it was felt that the reliability of insulation wound at the construction site would be inferior to that of the insulation applied to the cable in the factory. Also, expansion of the water-cooled coil and end connections to the water circuits, and provision for sufficient leakage path at the coil ends appeared to be considerable design problems. Air-cooled coils of the type used had operated successfully on the synchrotrons, and scaling up of the size appeared to involve no new problems. Water-cooled coils with conductor lengths of the order of 80 ft had not been approached in any other design to our knowledge, and it was felt that the larger scale and the rather poor conditions under which insulation might have to be applied made the successful performance of water-cooled coils somewhat uncertain. Another advantage of the air-cooled cable-wound coil was the ability to rewind the coil in a different shape if this proved to be necessary. Some of the early plans for changing the aperture involved such rewinding.

The cable is supported on asbestos-bakelite insulating spacers. Each coil is anchored to a sector nearest the center of the quadrant, and both ends are allowed to expand. The end turns pass above and below the aperture and are contained in boxes that permit azimuthal motion. The strands are not individually insulated, as calculations indicated that eddy currents in the conductor would be unimportant. The cable insulation is 1/8 in. of varnished cambric in eight layers followed by two layers of canvas tape. The windings are transposed and connected so that any difference in current between the two parallel paths is averaged out among the four quadrants and there is no net vertical component of current.

A sample section of cable was tested with a motor-driven loading device to determine the effect of the pulsating mechanical force on the insulation. This test showed the importance of keeping the cable tightly clamped and led to the use of heavy springs to hold the bakelite support.

spacers tightly against the cables. Springs could not be used on the end windings so that it is necessary to tighten the end coil clamps periodically. The coil connections are brought out at the north and south straight sections to terminal boxes where connection is made to lead-covered cables running to the generator room. Forced-air cooling is applied to these cables also.

The time-average copper loss at the maximum output is 3500 kw. This power is carried away by air supplied by two fans each of 280,000 cfm capacity at 5-in. static pressure. Air enters the fans through an oil-coated screen-type filter in the east wall of the building. The filter face area is 1200 ft^2. The fans discharge into a tunnel running under the entire magnet ring. Air from the tunnel passes to the coils through the spaces between the plates in the legs of the magnet core. Exhaust air passes radially outward through the magnet legs and is discharged into the room, leaving the building through a monitor in the roof. Much care had to be taken in ducting the air to make sure that leakage was not excessive. The coil banks have masonite covers with spring-supported sealing strips. No reliance was placed on flexible nonmetallic materials. As the air flow is all in parallel, obstruction over a length of only a foot or two could cause overheating which probably would not be detected before damage to the insulation occurred. Thermocouples are installed at a number of points to sample the coil temperatures, but it would be impossible to check the entire length of all the cables in this manner. Insurance against failure of air flow in the parallel passages is provided by frequent checks on the velocity of the exhaust air. The maximum cable-surface temperature has not exceeded 55° C in the hottest weather in which the machine has operated thus far.

The iron loss is estimated at approximately 500 kw. The part of this loss that appears in the pole pieces has to pass through several insulating barriers before reaching the outside air, and it appeared from calculations that, to be conservative, it would be necessary to provide cooling for the magnet yoke to hold the temperature rise of the pole pieces to a small value. This cooling has not yet been used, and there is no indication that it will be needed.

The magnet has two sets of correcting windings. One, the pole-face windings, consists of conductors running azimuthally along the surfaces of the top and bottom pole pieces at a radial spacing of 3 in. To permit shaping the maximum field as was thought might be required for beam deflection, 5/16-in. copper tubes with provision for air or water cooling are installed. These tubes are supported by stainless steel tubes fastened to but insulated from the pole-slab laminations. They were pulled with a wire rope in continuous 80-ft lengths through a sizing die and into the stainless steel supporting tubes. As only low current corrections have been required, a much simpler winding of insulated wire could have been used. The second set of windings consists of coils of 10 turns of No. 10 wire wrapped around each upper and lower pole base to provide azimuthal variations in the strength of the field. These windings have been found useful to compensate for the stray fields of auxiliary magnets and to displace the beam radially. In addition to the correcting windings, two pickup windings of RG9U coaxial cable are used on the lower pole face providing loops 24 in. wide over the entire circle. One of these windings is used in connection with the frequency-control system to be described later.

MAGNET TESTS

The model testing which started early in 1948 and continued until just before the start of operation involved the construction of six direct[14] and three alternating current models. All but the last alternating current model were constructed to approximately 1/12 scale and had a length corresponding to approximately 22.5 deg of arc. The first five direct current models were used principally to study major changes in the shape and placement of the coils. Model DC-6 was curved, made in sectors , and was made in versions modeling the 4-by 14-ft and the 1-by 4-ft apertures. It went through twelve major changes.

Model AC-8 on which the final core dimensions were determined was made after the tests of the quarter-scale model and was based on apertures of 2 by 6 ft and 1 by 4 ft. It was made with laminations modeling the full-scale plates, and all the principal conducting parts of the tank and the magnet structure were included to determine the eddy-current effects. This model was made to simulate one end of a quadrant starting from the straight section, and in some of the tests a straight-section tank was modeled also. The model was powered by a condenser bank of 10,000 μf at 1200 v. Measurements were made of the total field, the azimuthal and radial variations, stray field, and total flux. Absolute field measurements were made by bucking the voltage induced in a coil placed in the gap against the voltage of a coil placed in a solenoid in series with the magnet. The current was observed by bucking the voltage across a shunt in the magnet circuit against a standard voltage. The current signal was placed on the vertical-deflection plates of an oscilloscope, and the unbalance of the pickup-coil voltage was placed on the horizontal plates. An attenuator across one of the pickup coils was adjusted until the current and pickup-coil voltage were simultaneously balanced. The magnitude of the field was obtained from the attenuator setting. For measurements of the field variation in the gap, the reference pickup coil was placed at a fixed point in the gap instead of in the solenoid. These measurements failed to show a region about 6 in. wide below 2,000 gauss in which the n value[*] was low by 0.2. In retrospect, it would seem to have been preferable to use a pair of coils spaced a constant small distance apart to observe the slope rather than to observe the departure of the field from a fixed point. The former method was used in the full-scale test in which the error was picked up. The last model made was built to 1/7th rather than 1/12th scale to check the final shape of the pole pieces. There were no significant differences observed between it and the smaller models.

Residual-field measurements were made on the models. With the 2-by 6-ft aperture, the shape of the residual field was such that demagnetizing pulses between the accelerating pulses would probably have been required. With the 1-by 4-ft aperture, this was not necessary.

Full-scale magnetic-field tests were made before looking for the accelerated beam.[15] The apparatus consisted of search coils mounted on trucks which could be pulled through the aperture by ropes for observation of the strength and radial and azimuthal uniformity of the field. The signals from the coils were electrically integrated and displayed on an oscilloscope during the magnet-current pulse. Marker pips from the current-measuring signal system appeared on the oscilloscope trace. The scale of the oscilloscope trace was changed a number of times during the pulse to obtain the necessary accuracy. The position of the median plane was observed by measuring the horizontal component of the field at three heights above the

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[*] $n = -\frac{r}{B}\left(\frac{\partial B}{\partial r}\right)$

pole piece. Residual field was measured with a radiofrequency flux meter. Results of the radial-uniformity measurements are shown in Fig. 12. Azimuthal variations were on the order of $\frac{1}{4}\%$.. The height of the median plane was within $\frac{1}{4}$ in. of the geometrical centerline over most of the radial aperture. Although the n value was within the required range of 0.63 ± 0.1 over 3 ft of the aperture at injection, a large improvement in the beam was made by increasing the slope an additional 0.1.

MAGNET POWER SUPPLY

The large energy to be stored in the Bevatron magnetic field made the selection of the magnet power supply an extremely important question. Early in the design work, all the methods that might conceivably be practical were looked into to some extent. These included condensers, storage batteries, DC generators, and direct-coupled AC generators, as well as AC generators coupled to the magnet through ignitron tubes, which was the system adopted.[16, 17] A principal advantage of this system was the use of large rotating machines of conventional type. Rectification by ignitrons was known to be reliable, and inversion, during the period of decreasing current, had been tested extensively by manufacturers of the tubes. The preliminary calculations indicated that with a rise to full current in one second, the power rating of the equipment would be about 100 Mw. This rating was not changed, although later, as shown by model tests, the current rise time had to be increased to about two seconds. It was desired to have two independent power supplies, either of which could be operated without the other. The original plan was to operate the two generators with their rectifier inverters in parallel so that operation on one supply would mean a limitation in maximum current, but not maximum voltage. The first power supply test showed it to be impossible to balance the current between the two generators during inversion, and it was necessary to connect the generators in series. With the series connection, it was necessary to reduce voltage as well as current when running on one machine, the current limitation being set in this case by the energy storage of the rotating equipment. Because of this voltage limitation as well as the current limitation, operation on a single machine has not been very satisfactory. The maximum circuit

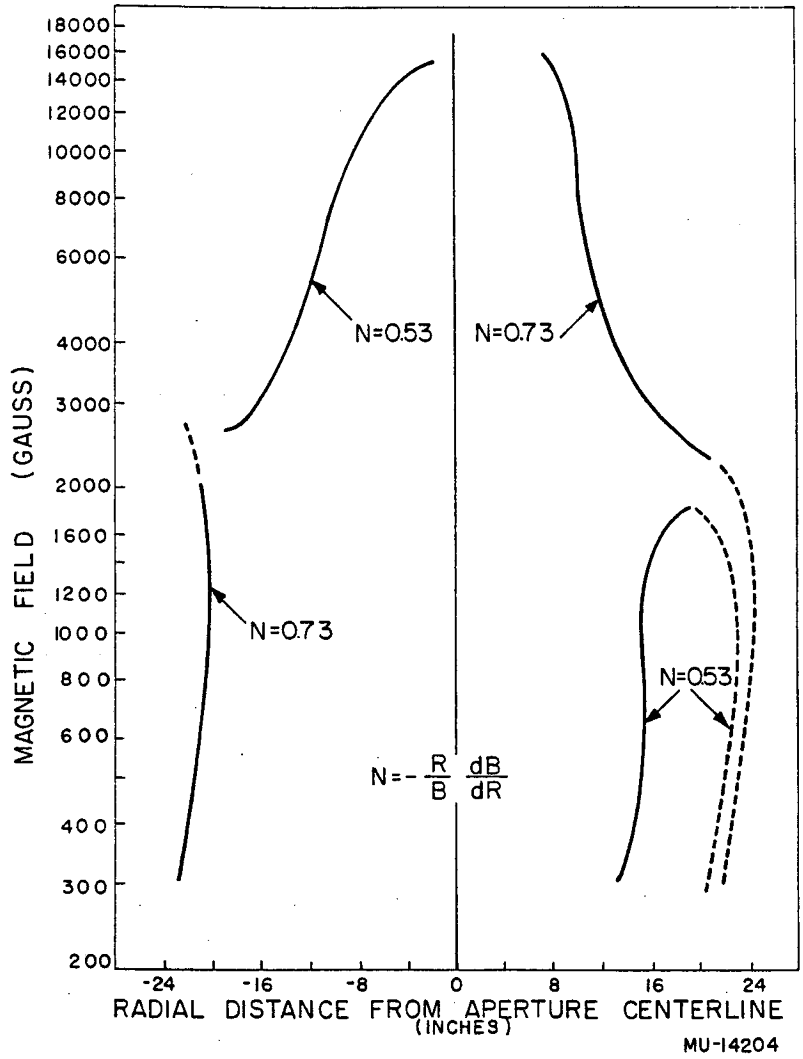
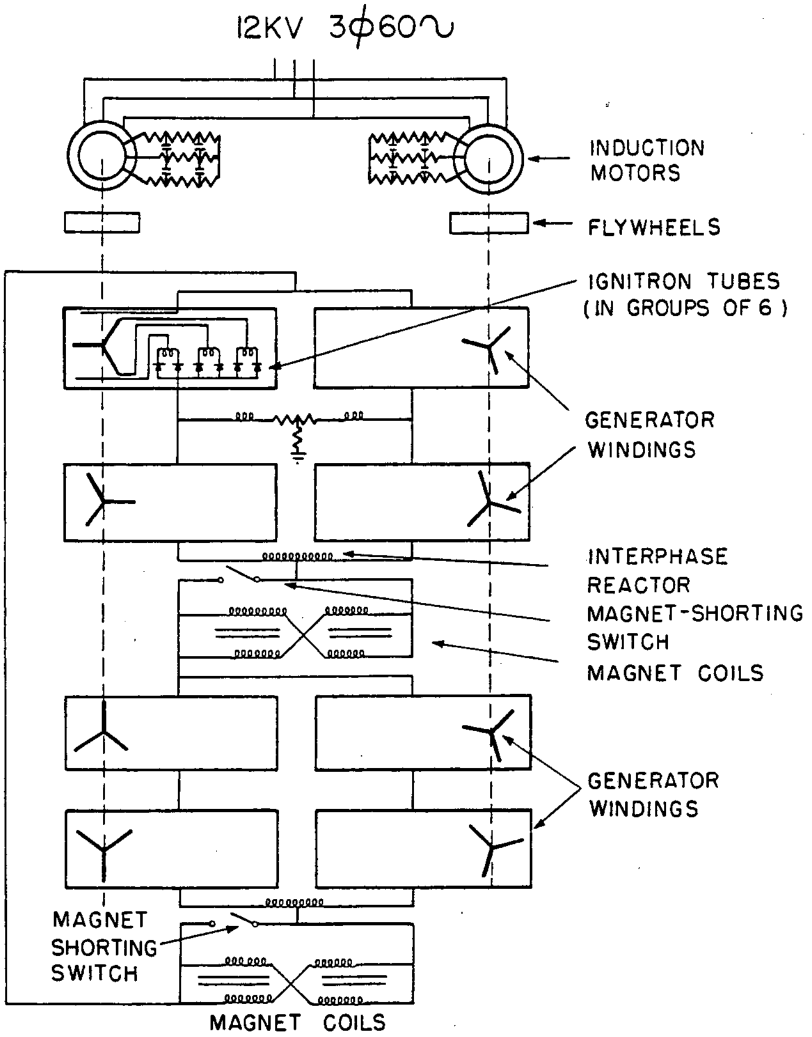


Fig. 12. Predicted limits of useful field.

voltage was specified as 18,000, divided through the use of the magnet windings and the rectifier units so as to limit the voltage above ground to 4500. Ground potential occurs at four points in the system; one of which, between two of the magnet coils, is grounded through a protective resistance. The other points are floating grounds which may have considerable voltages on them during pulses. The circuit is shown in Fig. 13. Each motor generator set consists of a 3500-hp wound-rotor induction motor, a 67-ton 10-ft-diam flywheel, and a generator rated at 50,000-kw peak power output. The rotational energy of each machine at synchronous speed is 340 megajoule. . Each generator has four separate Y-connected windings, with a pair of ignitrons in parallel on each leg of the Y. Paralleling of the individual tubes of the pair, and of the tubes on each winding of the two generators, is through interphase transformers, of which twenty-seven are used. The magnet is protected by spark gaps and short-circuiting switches that close across the windings in the event of a fault. The rotor windings of the motors are controlled by contactors for starting the set and to hold the input power fluctuation to 3000 kw during pulsing. The rectifier firing circuits are energized by transformers connected across the generator windings. No transformers are used in the main power circuits between the generators and the rectifier. The machines are provided with dynamic braking, which dissipates the energy in the motor-starting resistors. This cuts the stopping time to about 15 minutes from the 3 hours that would otherwise be required.

The equipment was designed so that the voltage would fall from 18,000 at zero current to 12,000 at the peak current of 8,330 amp. In operation, however, the voltage has been made more nearly constant around 14,000 v. It has been found desirable to regulate the voltage to 1/3% during the initial part of the magnet pulse. The generator speed fluctuation during the pulse is approximately 7%, the synchronous speed being 900 rpm.

During the initial operation of the Bevatron, considerable trouble was experienced from arc-through in the ignitrons during the inversion part of the cycle. This necessitated reducing the peak current and the repetition rate. During the year 1954, the equipment was gradually improved by alterations in the firing circuit and by mechanical changes to some of the tubes, until practically the full rated output has been obtained. However, faults



MU-14203

Fig. 13. Bevatron magnet circuit.

resulting in automatic closing of the magnet-shorting switches are still a major cause of outage.

The change from rectification to inversion involves a change in the direction of the torque between the flywheel and the generator which imposes an alternating stress on the shaft. A timing circuit is arranged to make the transition in two steps; first, from full forward torque to zero, followed after an interval of about $1\frac{1}{2}$ cycles to full negative torque. The time delay is adjusted so that the second torque impulse will come in such a phase as to reduce rather than increase the amplitude of torsional vibration. In addition, a torsional-vibration damper is fitted to each machine. The shafts are inspected for cracks by the magnaflux method after every 200,000 pulses.

As the equipment was originally installed, the noise level in the generator room was approximately 110 decibels. Although personnel do not have to spend long periods in this room, it was felt that some sound control would be desirable and, accordingly, shrouds have been made for the generators and motors. In addition, silencers have been installed on the air-exhaust stacks to reduce the noise outside the building.

Control of magnet pulsing is provided through varying the bias on the ignitron pulse-forming transformers. This is done by equipment through which the repetition rate and current-rise time can be accurately controlled. 18
There are a large number of protective interlocks that stop pulsing,, close the magnet-shorting switches, and, in some cases, shut down the motors.

Equipment was provided to control the angular relation between the two generator rotors so as to cancel as far as possible the 1440-cps ripple in magnet voltage. This synchronizer compared pulses received from magnetic pickups responding to the position of teeth of gear wheels attached to the two shafts. Control was effected by varying the generator field excitation. Even between pulses there is sufficient hysteresis and eddy currents induced to provide control of the generator speed by means of the field current. It was later found possible to damp the magnetic field ripple by use of the pole-face winding, making synchronization unnecessary.

VACUUM SYSTEM

As in all synchrotrons, the problem in designing the vacuum tube was to use a minimum amount of the aperture for the structure of the tube and to avoid excessive eddy currents. In addition, in the case of the Bevatron, it was desired that a vacuum-tank design be developed that would, if possible, be usable for both the 2-by 6-ft and the 1-by 4-ft apertures. This problem was finally solved by a scheme in which the vacuum-tank wall was sandwiched between sections of the pole pieces. In the final 1-by 4-ft aperture used, approximately 15 in. of the length of each pole is inside the vacuum and 6 in. is outside as shown in Fig. 2. In this way, the internal pole pieces support the atmospheric-pressure load on the tank, and a very thin wall is practical. The top and bottom walls are made of 50-mil stainless steel insulated from the pole pieces by bakelite sheets on both sides of each stainless steel sheet. In order to keep the eddy currents to a sufficiently low value, the top and bottom walls of the tank are broken by radial insulated joints every 5 deg. The vertical walls of the tank are made of 60-mil stainless steel sheets extending continuously for the length of each quadrant. The joint between the horizontal and vertical sheets are made by Hycar gaskets set in 1.5-in. square dural bars, called corner bars. Double gaskets, 0.25.in wide, are used, with a pump-out space between. At the ends of the quadrants, these bars butt against aluminum end frames to which flexible bellows-type sections approximately 2 ft long are attached. These bellows, called transition tanks, are bolted to the end walls of the magnetic steel "tangent tanks" used in the straight sections and provide some flexibility to permit assembly. Three-way gasket joints are required between the corner bars and the end frames, and between the corner bars and the radial bars at which the insulated joints in top and bottom plates are made. These three-way joints, which use a molded Hycar gasket in the form of an H, have been quite satisfactory.

When the gaskets are compressed, electrical clearances are on the order of only 1/16 in., and leakage distances over the insulation are about the same. During construction, we found that it was not possible to keep these joints insulated due to the inevitable accumulation of dirt and chips. To provide more insulation, we had to disassemble several of the tanks and paint the metal surfaces with plastic paint which was then baked. In addition, a very thorough deburring job was done, and the exposed surfaces of the joints were covered with tape. The integrity of the insulation of these joints is very important because currents of several thousand amperes could flow across them in case of electrical failure. For certain critical joints a monitoring system has been installed, so that if a breakdown occurs during pulsing, an alarm will be provided. Considerable time has been spent in clearing short circuits across these joints with consequent interruption of operation. Greater leakage distance, more frequent interruption of the circuits by insulated joints, and better protection against the accumulation of dirt and chips would have been desirable.

The pump-out spaces between the gaskets are divided by cross dams into lengths of the order of 10 to 15 ft. Each of these spaces is provided with a separate vacuum connection, about a hundred of which are used in each quadrant. The tightness of the joints was checked using these pump-outs before the tanks were installed, because it was not considered economical to design a structure to handle the atmospheric-pressure load that would have occurred if the tanks had been evacuated without the support of the pole pieces. A number of leaks have occurred in the inner gaskets which required sealing the corresponding pump-out tube. However, pumping continuously on the inter-gasket space has not been required.

Each insulated section of the tank is connected through resistors to a grounding system that runs through each quadrant. The pole-tip plates are also all individually grounded, as are all other metal parts that can "see" the beam. The insulation of the vacuum joints can be monitored by checking resistances in these grounding circuits.

The corrugated transition tanks are made of 1/8-in. stainless steel sheets, and each carries a port in the inner- and outer-radius walls. Vacuum joints to the flanges of these tank sections are made by continuous "dumbbell" cross-section gaskets. The straight-section tanks are approximately 12 ft long by 7 ft high by 8 ft wide in inside dimensions and have cover plates for the full area of the top and side walls.

The pumping system consists of twenty-four 32-in. oil-diffusion pumps with 8-in. boosters backed by seven 300-cfm mechanical pumps. Six diffusion pumps are located beneath each tangent tank and are connected to the tanks through individual air-operated gate valves. Between the valves and pumps are baffles cooled to -40° C by a common Freon refrigeration system. The linear accelerator is pumped by two 20-in mercury-diffusion pumps, each of which is provided with a -40° Freon-cooled baffle, a carbon dioxide-cooled baffle, and a chilled-water system for the pump-barrel cooling circuit. Only one of the two pumps has been found necessary in operation. In addition, small liquid-nitrogen traps are used in the tank. The ion gun is pumped by a 10-in. mercury-diffusion pump with the same combination of traps and temperatures.

Flange-mounted ion gauges are used in the main Bevatron straight-section tanks to observe the high vacuum. Safety circuits are provided to shut off the ion gauges and close the pump valves in case of failure of the vacuum.

As originally installed, the vacuum system required approximately 72 hours to reach 10^{-5} mm pressure. This was with the use of liquid nitrogen in small traps in the tangent tanks. The time to reach a pressure at which the diffusion-pump valves could be opened was on the order of 16 hours. Many changes of the mechanical-pump oil were required to remove the water evolved from the system during pump down. The large water absorption appeared to be due to the use of phenolic insulation in the vacuum system. In order to reduce the pump-down time, a system has been installed to dry the air admitted to the tank while open to the atmosphere. With this system, the time to get on the diffusion pumps has been reduced to 1 hr and the time to reach 10^{-5} mm to 12 to 24 hours after a shut-down of a few days. Operation of the machine is possible at approximately 10^{-5} mm but improves considerably as the pressure is reduced below this value. Normal operation is around 2×10^{-6} mm.

Remotely operated shut-off valves are used between the ion gun and the linear accelerator, and between the linear accelerator and the main vacuum system. These are closed in the case of failure of vacuum in any one of the systems.

INJECTION SYSTEM

The injection system consists basically of the three units: the ion gun, the linear accelerator, and the electrostatic inflector. The ion gun is a Cockcroft-Walton-type accelerator providing a proton beam of 3 to 5 ma at 480 kv. The high-voltage structure is supported by phenolic plastic insulating tubes extending horizontally from the wall of the surrounding metal housing. The machine operates in ordinary atmospheric air without dehumidification or additives. Sparking directly to ground has never been observed with the existing electrical clearance of $4\frac{1}{2}$ ft. The Cockcroft-Walton-type voltage-multiplying power supply forms a column extending vertically from the floor of the enclosure to the high-voltage shell. It consists of 24 stages of multiplication using RCA 8013A tubes. Filaments are heated by a 60-kc oscillator, and plate voltage is provided by an 800-cy motor generator. The supply of this type first developed used oil insulation, but the one now in use is air insulated and operates very satisfactorily. The ion source is the cold-cathode PIG type. The voltages for the source are supplied from power units in a "file-drawer" type of mounting. Primary power comes from a permanent-magnet 400-cy generator in the high-voltage shell, belt-driven by a 10-hp motor at the low-voltage end. The condensers in the power-supply stack have a capacity of $\frac{1}{4}$ μf each.

The vacuum tube is made of insulating sections of the type used in the Van de Graaff machine at this laboratory. Joints between the insulating rings are made with Hycar O-ring gaskets.

The beam leaving the linear accelerator passes through a 20-deg turning magnet, which provides some focusing effect.

LINEAR ACCELERATOR

The linear accelerator is of the Alvarez type operating at a frequency of 202.5 Mc, which corresponds to a diameter of 42 in.[19] It increases the proton energy from 450 kv to 9.9 Mev using 43 drift tubes. Focusing is accomplished by grids which, in total, stop approximately one-half of the beam. The linear accelerator is preceded by a buncher which brings the injected ions into the acceptable radiofrequency phase angle, thereby increasing the beam output by about a factor of three. The output of the linear accelerator is 300 to 400 μamp. The length of the machine is 19 ft, corresponding to an energy gain of $\frac{1}{2}$ Mev per ft. This gradient has resulted in very steady operation after a comparatively short bake-out period. The accelerator can be powered by as many as 4 single-tube oscillators using Eimac 3-W 10,000 A-3 triodes. However, two oscillators are ordinarily used. The peak power required to excite the cavity is 500 kw. The cavity is preexcited by a tuned oscillator using an Eimac 4-W 20,000 tetrode. Plate power for the oscillators is provided by a pulse line providing 12-kv pulses for 700 μsec. A smaller pulse line is used for the preexciters. The resonant cavity is tuned by dishing the end diaphragms. Voltage pickups are provided at a number of points along the cavity to monitor the uniformity of the field. The injector is pulsed at an approximate rate of two pulses per second; each pulse injected into the Bevatron being triggered from the Bevatron magnet current. Pulses not used for injection are monitored by inserting a collector cup at the exit of the inflector. Thus, at a Bevatron repetition rate of 10 pulses per minute every twelfth pulse is accelerated by the Bevatron, most of the others being used for monitoring purposes.

INFLECTOR

The inflector bends the beam through an angle of 35 deg at an 18-ft radius, its gap width is 7/8 in., and it operates at approximately 80 kv. It is adjustable mechanically for radial position, rotation about the axis of the injected beam, and vertical height with respect to the center plane. Best operation is obtained with the exit lip at 621 in. radius. When the height adjustment is made, the linear accelerator and ion gun must also be moved vertically. In addition, the section of the high-voltage electrode nearest the exit end is connected to a separate power source so that changes in the angle of deflection can be made by varying its voltage. Clearance in the vacuum for the inflector voltage is 5/8 in. minimum and the length of the stand-off supporting insulators is 3.5 in. Power for the inflector electrode is supplied by a regulated radiofrequency Cockcroft-Walton system.

A set of strong-focusing magnets is used between the linear accelerator and the inflector to decrease the divergence of the injected beam. Probes can be moved into the beam by remote control at the exit of the ion gun and at the entrance as well as the exit of the inflector. The beam at the exit of the inflector is 200 to 300 μamp during the pulse.

RADIOFREQUENCY ACCELERATING SYSTEM

The Bevatron accelerating frequency must vary from approximately 360 kc at injection to 2500 kc at final beam energy. The rate of change is 12 Mc $\sec^{-2}$ at injection decreasing to 16 kc $\sec^{-2}$ at 6 Bev. The tolerance on the relation of frequency to magnetic field is on the order of one part in a thousand corresponding to a change in the average beam radius on the order of 1 in. The frequency is determined by a master oscillator tuned by a saturable reactor. The saturating current may be obtained from either a shunt in the magnet circuit or an amplifier which integrates the voltage induced in one of the induction pick-up loops located in the magnet gap. Controls are provided that effectively vary the slope of the frequency-field relation, the frequency at the starting field or current, and the maximum frequency. The frequency-current or frequency-field relation produced by the reactor -tuned oscillator does not have the required shape without correction. For this reason in the oscillating circuit a subsidiary reactor is used whose bias is varied during the pulse to provide a fine adjustment of the frequency-current relation under control of the operator, as described in the following paragraph.

Signals are obtained at 30 fixed values of magnet current through the current-peaking transformer system for control and monitoring purposes. Each magnet-current peaking transformer, of which two are used, consists of 3 Ferroxcube rings carrying toroidal magnet windings through which passes a single turn carrying half the magnet current. The bias current in each winding is changed in steps; each step occurs after the corresponding signal pulse has been transmitted. Ten signals are thus provided by each toroid. Adjustment of the frequency-current relation was originally provided by an independent control for each of the 30 current steps. This equipment has recently been replaced by a time-based analogue correction that is less flexible but much more reliable in operation. The saturable reactors, the peaking transformer, and the shunts are all cooled by a circulating-oil system. Temperature regulation to 0.01° C has been found necessary in the case of the reactors, the inductances of which are sensitive to temperature. Great care was taken to avoid stray magnetic pickup by making the shunts and peaking transformers coaxial and interleaving the high-current conductors.

The master-oscillator signal is applied to a 3-stage wide-band driver amplifier. The driver output is applied to the final amplifier which is tuned by a saturable reactor whose saturating current is controlled by the phase shift across the stage. The final amplifier tube is an RCA A2332S, which is a shield-grid version of the RCA 5831 with a short electrode structure. The output circuit of the final amplifier consists of the drift-tube accelerating electrode hanging in the north tangent tank resonated by the large Ferroxcube saturable reactor. This reactor contains 350 lb of Ferroxcube III in the form of rings 1.75-in. inside diameter, 2.5-in. outside diameter, and 1-in. thick. The saturating winding consists of 5 turns of bus-bar conductor through which a current of up to 1000 amp is passed. The sections of the reactor are connected in series-parallel so that radiofrequency voltage is cancelled out of the saturating supply circuit. The reactors are cooled by a circulating-oil system which is maintained under vacuum for maximum dielectric strength. The reactor sections are mounted in insulating cases to keep the capacity to ground to the minimum. The system is designed to provide 40 kv peak on the electrode with 14-kw plate input power.

The saturating power supply for the final amplifier is basically a 3-phase full-wave selenium rectifier in series with a 3-phase full-wave vacuum-tube rectifier. The output voltage is varied by varying the load on the vacuum-tube rectifier. This load consists of a triode whose grid signal is obtained through the circuit that controls the reactor bias. In addition, fast regulation is provided by transformer coupling to the reactor circuit.

Equipment was provided to monitor the frequency-current relation by comparing the frequency at each current pulse with the output of a crystal oscillator, displaying on an oscilloscope the error at each of the 30 correction points on each pulse.[21] This instrument was helpful in the initial startup, but has not been needed in normal operation.

INSTRUMENTS AND CONTROLS

The Bevatron operating controls are located in four rooms: the main control room, the generator control room, the injector control room, and the radiofrequency control room. Operators are ordinarily present only in the generator and main control rooms during operation. The generator operator sets the repetition rate and maximum current from telephone instructions from the main control room. All other operating controls are from the latter position. The radiation field at the injector control room is higher than desirable during running so that it is ordinarily not manned. The radiofrequency control room, located inside the magnet ring in the vicinity of the north straight section, is used only for testing the radiofrequency equipment. Selsyn-type remote controls for the high-voltage end of the ion gun are available in the injector and main control room. In addition to the controls and instruments already described, the main control room is provided with dual beam oscilloscopes which can be switched by push-button control to any one of a large number of monitoring circuits. Oscilloscope signals use coaxial cables terminating in patch panels in the various control rooms.

The beam current is observed on collector cups when testing at low energy and on the induction-pickup electrodes. These electrodes, connected through wide band amplifiers to a fast oscilloscope, provide the most useful indication of the accelerating beam. Timing controls operate from the magnet-current signal pulses with fixed or adjustable time delays. An indicator board monitors the arrival of the timing pulses.

The counting-equipment room is adjacent to the main control room. Discussion of the extensive counting equipment and other experimental facilities used with the Bevatron is not part of this report.

CONSTRUCTION COSTS AND EFFORT

Table I shows the distribution of the construction cost of the machine according to the Laboratory's accounting practice. Of the total, 22% was spent within the Laboratory. The total of 9.7 million dollars is to be compared to the 1948 estimate of 9.1. Fortunately the major commitments were made before the price rise that occurred during the Korean war.

The accounting practice effective at the time charged Laboratory overhead primarily to the operating accounts and not to construction accounts such as the Bevatron construction.

If the Bevatron construction had been carried out by its own organization without the assistance provided by the operating funds, the overhead would have had to be charged at something like 100% of direct labor, which would have added about 1.5 million. In addition, a charge of 5% on the contracted work would have been needed to cover administrative expenses, which would have amounted to $380,000. The total construction cost as an independent project including the required overhead can thus be estimated at $11,580,000.

Table II summarizes the total Laboratory technical effort applied during construction. This included the extensive testing and building of the quarter-scale model.

Table I

Bevatron cost summary (kilodollars)

Building (including magnet foundation, cranes, emergency generator, power distribution)	1,389	
Site preparation and outside utilities	400	
Architect-engineering for building	114	
Total building		1,804
Magnet core	2,547	
Magnet coil	710	
Magnet power supply	1,400	
Magnet miscellaneous	536	
Total building		5,193
Injector		503
Accelerating system		395
Controls		248
Shielding		159
Quarter-scale model		350
Miscellaneous		644
Total project		9,696

Table II

Laboratory direct effort		(man years)
Scientific groups[a]		25
Mechanical engineering[b]	101	
Electrical engineering[b]	55	
		156
Mechanical shops	106	
Mechanical technicians	31	
Electrical shops and technicians	43	
Construction trades[c]	53	
		233
Other		2
Total laboratory effort		416 ?

Laboratory indirect effort (purchasing, personnel, transportation, etc.) was not charged to the Bevatron project.

[a] Includes some technicians' time

[b] Includes drafting

[c] Electricians, plumbers, carpenters, etc.

ACKNOWLEDGMENTS

Extending over six years, the design and construction of the Bevatron was the work of a large number of able and devoted people. Professor Lawrence, director of the Laboratory, had the over-all responsibility and was the one who determined how large a machine should be build, how conservatively it should be designed, and how thoroughly each step should be tested. At the beginning of the project a group of scientists and engineers including Drs. E. M. McMillan, R. L. Thornton, W. K. H. Panofsky, L. W. Alvarez, W. M. Powell, Robert Serber, and Kenneth McKenzie, Mr. W. B. Reynolds, and the writer met with Professor Lawrence frequently to arrive at the basic design specifications.

Dr. Edward J. Lofgren returned to the Laboratory in the spring of 1949 to spend full time on the Bevatron project. He made many important contributions to the design of the machine. He was in charge of operation of the quarter-scale model and has been in charge of the operation of the Bevatron since completion of construction.

Dr. Lloyd Smith devoted much of his time during the construction period to beam dynamics, gas scattering, and other analytical problems.[22] Duane Sewell performed the magnetic measurements on the models, and Glen Lambertson under the direction of Wilson Powell made the full-scale magnetic measurements. Mechanical design was supervised by James Bell, Hayden Gordon, Ralph Peters, and the writer. The mechanical shops were supervised by the late Andrew Harvie. Supervisory electrical engineers were George Farly, William Baker, Dick Mack, and C. A. Harris. James S. Norton headed the electrical engineering and shops. Mechanical field engineering and mechanical assembly of the machine was under the direction of William Twitchell, whose untimely death prevented him from sharing the satisfaction due him on the completion of the exacting job.

Space does not permit mentioning the many others who made important contributions to the project. Approximately 300 Laboratory people have been listed as deserving credit for the direction and prosecution of the work.

The firm of Maston and Hurd, architects, and Huber and Knapic, engineers, were responsible for the Bevatron building and solution of the difficult site and foundation problems.

The project was authorized and financed by the Research Division of the U. S. Atomic Energy Commission headed at the time by Dr. James Fisk whose enthusiastic support was of the greatest value in initiating the project.

APPENDIX

Bevatron Design Specifications

Characteristic	Unit	Quantity
Nominal aperture in vacuum	ft	1 × 4
Radius to center of aperture	ft	50
Length of straight sections	ft	20
Length of orbit	ft	394
Maximum magnetic field	gauss	16,000
Maximum proton energy	Mev	6,440
Magnet gap at 50-ft radius	inches	13
Injection energy	Mev	10
Injection radiofrequency	Kc/sec	364
Maximum radiofrequency	Kc/sec	2,460
Frequency ratio		6.75
Injection field	gauss	299
Useful width of field at injection ($0.5 < n < 1$)	inches	48
Acceleration time	sec	1.85
Initial rate of rise of field	gauss/sec	9,600
Final rate of rise of field	gauss/sec	5,900
Magnetic-field exponent "n"		0.60
Initial energy gain per turn	ev	1,750
Final energy gain per turn	ev	1,075
Initial rate of change of frequency	$\mathrm{Kc/sec}^2$	11,600
Injection time (time for beam to cross half width of useful field)	μsec	498
v/c at injection		0.146
v/c at maximum energy		0.992
Turns during injection time		181
Radial motion per turn during injection (rf off)	inches	0.133
Scattering loss at 10^{-5} mm air pressure	%	22
Distance between accelerating gaps	ft	10
Electrical angle between accelerating gaps	deg	9.1

Characteristic	Units	Quantity
Initial peak accelerating-electrode voltage*		22,300
Final peak accelerating-electrode voltage*		13,600
Stored energy in magnetic field (approx.)	mega-joules	80
Peak magnet current	amp	8,333
Number of series turns on magnet		88
Peak ampere turns		732,000
Initial voltage on magnet	volts	18,000
Voltage at maximum current	volts	12,000
Peak instantaneous power	kw	100,000
Allowable time-average dissipation in magnet	kw	3,500
Conductor weight	tons	347
Conductor cross section	in^2	1.31
Number of conductors in parallel		2
Conductor length	ft	137,500
Coil resistance at 65° C with 98% conductivity copper	ohms	0.267
Rf cycles per phase oscillation		
At injection		160
At maximum energy		2,140
Rf cycles per betatron oscillation		
Vertical		1.15
Horizontal		1.44
Damping of phase oscillations: amplitude at final energy/initial amplitude		0.027
Damping of betatron oscillations: amplitude at final energy/initial amplitude		0.135
Distance of particle travel during acceleration	miles	305,000
Number of revolutions during acceleration ($\times 10^6$)		4.1

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*At 30° equilibrium phase angle

Characteristic	Unit	Quantity
Frequency tolerance at injection		
for 100% loss	%	1.6
for 10% loss	%	0.16
Frequency tolerance at final energy		
for 100% loss	%	3.2
for 10% loss	%	2.9
Repetition rate at full energy	pulses per min	10

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