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national accelerator laboratory

THE 200 BILLION VOLT ACCELERATOR

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The largest scientific instrument in the world is now being planned and designed at the National Accelerator Laboratory, to be located at Weston, Illinois. The instrument will be a proton synchrotron producing particle beams of 200-GeV energy, capable of future extension to 400 GeV. The purpose of the laboratory is to provide particle beams and experimental support for research studies of the elementary particles, and on the origin of the nuclear force which binds these particles into atomic nuclei. The Laboratory will become a field station for scientists from many universities, and is intended to support a significant fraction of high-energy particle research in this country. The staff is presently located in temporary quarters at Oak Brook, Illinois. The Director is Professor Robert R. Wilson, formerly of Cornell University. The parent organization which will contract with the U. S. Atomic Energy Commission for Federal funds to support the construction and operations of the Laboratory, is the Universities Research Association (URA) consisting of 46 member universities spread throughout the United States. The President of the Board of Trustees of URA is Professor Norman F. Ramsey of Harvard University.

Planning:

The conceptual planning of an accelerator of this energy range started in 1959 at a MURA (Midwestern Universities Research Association) summer study in Madison, Wisconsin. The first memorandum on the concept was circulated that fall by Professor Matthew Sands, then at Cal Tech; it described a possible 300-GeV synchrotron utilizing the principle of alternating gradient focusing. This concept was a challenge to planners and designers in other laboratories. By late 1960 a design group at the Brookhaven Laboratory, where the 30 GeV AG synchrotron had just been completed, started thinking about much larger machines and developed basic parameters for accelerators of 300, 700 and 1000 GeV; they issued two preliminary reports of these studies in August, 1961. Scientists from several universities and other national laboratories cooperated in these studies. Also, at the Lawrence Radiation Laboratory in Berkeley, where they had been thinking about a machine in the hundred-GeV range for some years, a request for support of a design study in the 100- to 300-GeV range was submitted to the AEC in February of 1962, and renewed in December of that year.

These preliminary reports and proposals were considered, along with other aspects of the national program in high-energy physics, by an advisory panel appointed by the AEC and the President's Science Advisory Committee. The report of this panel, known as the "Ramsey Report" for the Panel Chairman, made favorable recommendations for the support of very high energy machines. In April, 1963, the AEC authorized the Lawrence Radiation Laboratory to proceed with a more thorough design and cost analysis, and an experienced staff was assembled. This effort resulted in a two volume report, "200 BeV Accelerator Design Study," dated June, 1965, which was submitted to the AEC as a Proposal for construction. Hearings before the Subcommittee on Research, Development and Radiation, of the Joint Committee on Atomic Energy, were held on March 2 to 5, 1965, in Washington, at which the several design studies and a preliminary form of the LRL Report were presented and discussed by a wide representation of scientific and administrative witnesses. The emphasis at these Hearings was on the high-energy physics research program and on the importance of a higher energy accelerator to maintain progress in the field.

Meanwhile, a group of the experienced accelerator staff at CERN have developed designs and a proposal for a 300-GeV accelerator which has been submitted to the CERN Council to be considered as the next step in the European program. And in the U. S. S. R., although the major emphasis has been on completing the 70-GeV machine at Serpukhov, tentative design planning has started for 1000-GeV energy.

As these design studies developed it became clear that the basic principles of the AG synchrotron, used successfully at two laboratories in the 30-GeV range, could be extended with confidence to the highest energies envisioned. The magnets and beam aperture of an AG synchrotron do not increase in transverse dimensions with increasing energy and orbit radius. Synchronous stability during acceleration is maintained to any chosen energy, and beam control techniques are available to focus and retain the circulating beams within small magnet apertures. The increased engineering requirements for higher energy are within the known capabilities of present technology.

The only limitation to the energy of particle accelerators is that of cost. The cost of most components is nearly proportional to energy, including power sources and the housing for the accelerator. The initial "unit cost" of the CERN and Brookhaven machines was about $1 million per GeV for the initial installations, including laboratory facilities, although costs at both machines have increased with later modifications and improvements. A unit cost of this magnitude can be anticipated for larger machines of this type, and it should vary about linearly with energy.

Following the submission of the LRL Proposal, the AEC started on selection of the site. Recommendations for site locations were requested from all of the States, and eventually 160 or more site proposals were received. The AEC requested assistance in evaluating these proposals from the National Academy of Sciences, which appointed a Committee (E. Piore, Chairman) to recommend a site. This Committee reported 6 sites as meeting the essential requirements, representing 6 major regions in the U. S., in March, 1966. From this list the Atomic Energy Commission selected the site at Weston, Illinois, announcing it in December, 1966. Meanwhile, the Universities Research Association had been organized, and was authorized by the AEC to proceed with a design study and to name a Director. During the winter there had been several discussions between the AEC, the Bureau of the Budget, the Joint Committee on Atomic Energy, and the President, during which the conditions for favorable action by the Administration and the Congress had been clarified. The URA was expected to submit a revised Proposal for a 200-GeV accelerator, with a construction cost of the order of $240 million, with an initial intensity which could be less than the ultimate intensity and with an initially limited scope of experimental facilities. The URA announced the appointment of Wilson as Director in March, 1967, and called a meeting of potential 200-GeV scientific users at the Argonne Laboratory in April.

By June 15, 1967, Wilson started a summer study group on design at the newly acquired 10th floor of the Executive Office Building at Oak Brook, involving 30 or more accelerator experts from LRL, Brookhaven, Argonne and other laboratories. This group, with the permanent staff members who have arrived, has met the first deadline of an AEC "Construction Data Sheet" on October 15. The cost estimate is for $242 million, with an estimated $60 million more for experimental equipment. The estimated date of completion is 1972. The next deadline is a written Proposal by mid-December.

Description of the Accelerator:

The accelerator is a proton synchrotron utilizing alternating gradient focusing, designed for initial operation at 200 GeV and capable of extension to 400 GeV at a future date. The main accelerator is formed of a ring of magnets of 1 kilometer radius (1-1/4 miles diameter) in a tunnel-shaped underground enclosure. Straight sections without magnets are symmetrically spaced around the ring; these are used for injection, radiofrequency acceleration, internal targets, ejection of emergent beams, and for magnets and other devices for controlling the beam. The enclosure for the magnet sectors is

10 ft. across and 8 ft. high. Larger structures are used at straight sections, designed to accommodate the specific function at each location.

A sequence of three preaccelerators will be used to bring the proton beam to the injection energy of 10 GeV. A Cockcroft-Walton set operating at 750 keV will be obtained commercially. Then a proton linac of 200 MeV will be built, similar to the one designed at Brookhaven in the AGS improvement program. The linac beam will be injected into a fast-cycling (15 cps) booster synchrotron operating at 10 GeV, with a radius of 75 meters (about 500 ft. diameter). A sequence of 13 single-turn pulses from the booster will be ejected and diverted into the main synchrotron to fill the orbit. During the injection interval the magnets in the ring will be maintained at the 10-GeV injection field of 489 gauss. The magnets will be excited with a flat-top pulse in a cycle: 0.8 sec. injection, 1.6 sec. rise to peak, 1.0 sec. flat-top, 0.6 sec. fall. The 4 second cycle means a repetition rate of 15/minute. The beam duty factor is 25%. The design intensity is 5×10^{13} protons/pulse or a time average of 1.5×10^{13} protons/sec. This is about 20 times the intensity at the Brookhaven AGS, and beam power will be 100 to 200 times that at the AGS.

One innovation in this design is the use of separated function magnets rather than the hyperbolic-pole-face magnets used in earlier AG synchrotrons. There are several reasons for this choice. Bending magnets with flat poles can be operated at much higher fields than gradient magnets, so the bending radius is reduced and the magnet circle is smaller for a given energy.

Construction is simpler and cheaper for magnets with flat poles, and the weight of iron is less. The desire for relatively longer straight sections for ejection of the high-energy beams requires a larger "beta" function, which calls for a reduced betatron wave number, and so reduces the required gradients. The quadrupoles needed to substitute for the gradient magnets are widely spaced and relatively short. Total cost for the AG magnet system is considerably reduced below that with combined function magnets.

Another change from earlier designs is the use of "H"-frame magnets with iron returns on both sides, rather than the "C"-frame used in the AGS and PS machines. With symmetrical magnets there is no need for alternating back-legs from inside to outside the orbit. All installation and handling can occur from one side. Tunnel dimensions can be reduced significantly, by locating the magnet ring close to one wall. This is chosen to be the outside wall, since it is expected that beam spillage and radiation from induced radioactivity will be less inside the orbit. A full-scale model of the tunnel, and a section of magnet has been built in the NAL design office, which gives a good feeling for the size and the ample space for handling equipment.

The AG magnet ring will consist of nearly 1000 separated function magnet units in a BOFOBODO focusing order. The number of 20-foot bending magnets will be 744; a set of four 20-foot units forms a single sector of bending magnets (B). One hundred ninety two quadrupoles (F and D) located in short straight sections (O) between bending magnets provide the focusing, resulting in about 20.25 betatron wavelengths per turn.

The bending magnets will be a modified "picture frame" type with parallel pole faces and iron returns on both sides of the gap. The coils will be formed of water-cooled copper bus and located in the magnet "windows." The vertical betatron oscillations have a nearly sinusoidal variation in amplitude and the vertical aperture will match this variation roughly. One set of bending magnets (B_1) will have a gap length of 2 in. and have 16 turns of windings; the following set (B_2) will have a gap of 1-1/2 in. and 12 turns. When connected in series the two types produce the same peak fields. The iron cores will be formed of die-stamped punchings of laminations of about 1/16 in. thickness, assembled and welded in blocks and mounted on a supporting girder to form a unit of 20-foot length. External dimensions of the laminations will be 14 in. (high) x 25 in. (wide). The coils will be insulated with radiation resistant oxide coatings and cast into the magnet windows with an epoxy resin. All magnets will be built and installed in the orbit and powered to provide a field of 9 kilogauss for operation at 200 GeV; additional power must be provided to reach 400 GeV. The weight of a 20-foot unit is about 13 tons; the total weight of iron in the magnet ring will be 11,000 tons, and of copper 900 tons. The magnet will require about 50 megawatts peak power for 200 BeV. Present plans call for direct take-off from the power lines, without using motor-generators to store and average the power. The Commonwealth Edison Company has tentatively agreed to this procedure.

The quadrupole magnets will have about the same dimensions as the bending magnets but are shorter (5.5 ft.). Die-punched laminations will be shaped to provide the four poles and the coils will be formed of smaller copper bus. The quadrupoles will provide gradients of about 150 kilogauss/meter for 200 MeV, over an aperture of 2 in. x 5 in. They will also be designed to operate at a higher power level for 400 GeV.

The magnets will be mounted on supports resting on the floor of the tunnel-shaped housing, which will be a thick concrete slab. They will be aligned by means of stretched-wires and optical surveys. Sensing coils around the current-carrying wires will provide a continuous measure of any magnet settling or misalignment; motor-driven jacks can be used for readjustment if required. The decision to mount the magnets on a slab floor rather than on piles is based on experience with other accelerators and on the properties of the soil at the Weston site; it will reduce the cost of foundations.

The vacuum chamber will be installed as an integral part of each magnet unit. The chamber for the 2-inch gap magnets will be an oval tube of 5 cm. x 10 cm. cross section, made of 30 mil nonmagnetic stainless steel; that for the 1-1/2 -inch magnets will be 3.5 cm. x 12 cm. At magnet ends the chambers will terminate in circular flanges which can be welded to adjacent chambers or pump manifolds with automatic machinery. When installed in the magnet, they will be prestressed to anticipate deflections when under vacuum. Vacuum pumps of the titanium discharge type will be located at frequent intervals, with welded connections to the pump manifolds. The design pressure in the ring is 10^{-7} torr. Rough-vacuum manifolds will be distributed around the ring from 30 fore-pump stations. Removal of a magnet or a vacuum unit can also be handled by automatic machinery to grind off the welds.

The radiofrequency system for acceleration during the 1.5 sec. rise-time of the magnet will provide a peak of 3.6 MeV per turn, at a frequency of about 50 megacycles. The velocity increase of protons from 10 GeV to 200 GeV is only 0.4% and requires a frequency modulation of only 0.2 megacycles during the cycle. The entire accelerating system of 16 cavities occupies a length of 92 ft. and fits in one of the long straight sections. The peak rf power during the cycle will be about 2 megawatts, provided by high-power triodes.

The beam will be phase focused and bunched into an rf substructure at 50 megacycles, with 1120 bunches around the orbit. Orbital frequency in the circle of 1 kilometer radius is about 50 kilocycles; the period of revolution is 20 microseconds. During the 1.6-second acceleration interval the particles will traverse 80,000 revolutions or a distance of about 300,000 miles.

Three types of straight sections are planned: long, medium and short. There will be 6 long straight sections, each 180 ft. long, matched to give a parallel beam with small momentum spread by the use of Collins-type quadrupoles; these will be used for internal targets, rf cavity systems and for the removal of emergent beams. Six medium straights, each 95 ft.

long provide space for injection and for auxiliary devices; these are provided by omitting a single 80-ft. bending magnet sequence in the lattice. There will also be 192 short straight sections, each 8-ft. long, in which short trimming quadrupoles and sextupoles can be mounted for control of betatron frequency and momentum spread. This arrangement results in 6 super-periods, each containing 16 focusing cells; each focusing cell includes 8 20-ft. bending magnets and two quadrupoles and is about 200 ft. long.

Experimental Facilities:

One of the long straights will be equipped with heavy movable concrete shielding and can be used for a target in an internal beam. The major experimental facility will be the extracted beam, ejected at another long straight by fast kicker magnets and pulsed deflection magnets. Focusing quadrupoles will maintain a parallel beam to the location of the first target, which is one-half mile from the ejection section. Two switching magnets along the beam path will divert the beam into two other target stations. Each of the three target stations will be enclosed and equipped with heavy movable shielding. Secondary beams from the targets will branch off through shielding channels to sites for experiments with mesons or other secondary radiations. It should be possible to operate ten or more experiments simultaneously. Beam stops will be provided beyond each of the target locations. The muons penetrating the stops will be absorbed in enormous earth mounds at the end of the emergent beam run. Total length available in the emergent beam run is about two miles.

The synchrotron magnet tunnel will be shielded with an earth mound over the tunnel of about 20-ft. thickness. Radiation intensities during operation will be minimized by observing beam spills and eliminating them by suitable beam control devices. Except for target areas, the beam spillage around the orbit should be less than 1%. At the internal target and at beam ejection straight sections, thicker earth fills will be used. A serious problem arises from build-up of induced radioactivitiy in the vicinity of deflecting magnet septums; this can lead to intensities during maintenance or modification shut-downs which exceed the tolerance levels for personnel. Here, the development of more efficient devices for extracting and handling the beam will be necessary, before design intensities can be allowed. The most serious radiation problem will be radioactivity produced in the vicinity of targets, which will require the development of techniques for remote handling and removal of "hot" material.

Description of the Laboratory:

Consideration of the distances involved in the synchrotron ring (4 miles around) and along the emergent beam run (2 miles long) has led to an attempt to group the active areas as closely as possible. The linac and booster synchrotron are placed outside the orbit at a medium straight used for injection; the next long straight downstream will be used for ejection of the emergent beam. The major building will be a high-rise (15-floor) office, laboratory and control center, centrally placed within a few hundred feet from each of these active areas. It will be about 80 x 400 ft. in size. The control center will be located in this building, as well as a computer center, offices, cafeteria, electronic laboratories and light shops. Separate buildings will house heavy shop facilities, equipment assembly areas, warehousing, central heating and air conditioning equipment, etc. Electric power substations will have about 200 MW capacity. A railroad spur will connect with a nearby railroad.

The site is in gently rolling farm country with several ponds and streams. Wooded knolls reasonably close to the center complex may provide pleasant locations for future visitor housing. The highest elevation is 790 ft. and the lowest 710 ft. above sea level; at the synchrotron site it varies from 730 to 750 ft. Beam elevation is chosen as 725 ft. in the synchrotron, and the emergent beam will be deflected up to a higher level (740 ft.) at the experimental areas.

<u>Options for the Future</u>

The accelerator ring has orbit radius sufficient to reach 400-GeV energy, or possibly even higher at a reduced duty cycle. All magnets, cabling and services for 400 GeV will be installed in the tunnel initially, to minimize down-time during the modification. The additional costs for 400 GeV will be largely for increased power and cooling, but will probably also include a large (but presently unknown) increase for experimental facilities at the higher energy.

Another option is for future addition of storage rings and a colliding-beam facility. Space is reserved at two of the unused long straights to provide for ejection and return of the beam through an external by-pass sector. The spacing between the by-pass and the ring is sufficient to install a storage ring for 50 GeV protons. This could be used to store beams of this energy from the main ring in successive cycles to build up the circulating intensity to 10 to 100 times that in the main ring, limited only by space charge effects. One use of the stored beam could be to arrange for collisions between this 50-Gev beam and a 50GeV or 200 GeV beam in the main ring. Another use would be to re-inject the high-intensity stored beam into the main ring at 50 GeV and then to accelerate it up to maximum energy at a reduced cycling rate. Space is also available outside this by-pass for a much larger ring, of the CERN two-orbit type, to provide colliding beams up to 400-GeV energy each way, if this energy range becomes important in the future.

The National Acceleragor Laboratory is now off to a running start. The number of scientists and engineers on the staff is about 30, and growing every week. A feeling of optimism and enthusiasm has developed which makes it an exciting place to be. I expect that several of you will be priviledged to work with the Laboratory or join in research experiments when it is completed.

This work was done under auspices of the U. S. Atomic Energy Commission.