THE NAL PROTON SYNCHROTRON

R. R. Wilson

National Accelerator Laboratory Batavia, Illinois, USA

Introduction

Four years ago when this conference was held at Cambridge, Massachusetts, the National Accelerator Laboratory was three months old. A preliminary design for the proton synchrotron was presented to the Conference, but so tenuous was the project then, that the accelerator seemed little more than a dream. Now because of the efforts of so many determined people, the dream of that machine is turning into a reality of concrete and copper and steel.

The principal uncertainty then was money and how fast it would be appropriated.* July 11, 1969 was a big occasion for us for it was then that $250 million, the expected cost of the project, was authorized by our Congress. Previously though, enough pre-construction funds had been appropriated for some of the injector, and enough land of the site had been turned over to us that we could break ground on December 1, 1968 for the linac building. Exactly two years later, the very lively group under the direction of Don Young was able to demonstrate a fat beam of 200 MeV protons. The booster enclosure was started in February of 1969 and a group headed by Roy Billinge and Helen Edwards** set about building the parts to put in it. Little more than two years later, in May of 1971, they managed to deliver 8 GeV protons.

Meanwhile, yet a different group of hardliners, first directed by Frank Shoemaker and now by Ernie Malamud, set to the formidable task of building the main ring accelerator. The magnets of the main ring, one might say, have been built with more enthusiasm than prudence. The first of the roughly thousand magnets was installed in the tunnel only seven months after digging started in October 1969, and the last magnet was installed on April 16, 1971, three days after the tunnel had been turned over to us as complete inside.

The pace of this construction led me into the happy delusion that we might be able to bring the whole thing together and make it all work by June 31 of this year. Well, get it together we did - make it work at 200 GeV we did not, and have not yet. We did start testing rather early though and did manage to make the protons circulate some eight turns around the main ring by our target date - a rather remarkable accomplishment of my brave colleagues at NAL.

At present we are able to hold a circulating beam in the magnet for about one second, have been able to capture it by the radiofrequency voltage, have even been able to accelerate it a trivial amount. But before discussing our present operation further, let me bring up-to-date the description of the accelerator that was given to many of you four years ago.

Linac

The 200 MeV linac[1] is basically patterned after the Brookhaven Linac. The linac tanks are altogether some 450 ft. long, contain 295 accelerating electrodes and are excited at 200 Mc. One can say that it has very nearly achieved its design intensity and beam quality and that it is shaking down into a reliable and satisfactory source of 200 MeV protons for injection into the booster accelerator.

Booster Synchrotron[2]

The radius of the booster synchrotron (Fig. 1) was chosen rather arbitrarily to be 75 meters. That is large enough to provide an energy of 8 GeV at a reasonably low magnetic field, about 7 kG, and to allow room for long straight sections in which to place injectors, ejectors, RF accelerators, etc. The radius is small enough, though, that the RF voltage required to supply the required energy per turn need not be too large (about 0.7 MeV/turn).

A combined function lattice for the magnet was chosen as being simpler and more economic than the separate-function lattice used in the main ring, probably because of the lower field in the booster. The magnet design (Fig 2a,b)is patterned after the Cornell 10 GeV machine, the 96 ten-foot-long magnets being built up by stacking H-type laminations against an arc. The whole magnet is encased within a stainless

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* Perspectives change: We used to say, "If only we had a little money." Now we say,"If only we had a little skill!"

**A. van Steenbergen first headed this group; then Paul Reardon was in charge until he took over direction of our business activities.

steel skin, as shown in Figures 2a,b, with the coils potted in epoxy; thus it has no donut. A vacuum of several times 10^{-7} mm Hg is obtained when the booster is operating.[21] The magnets are pulsed at 15 cycles per second.

The RF system of the booster* dominates its construction, its cost, and its operation. Sixteen cavities (Fig. 3,4) are installed in pairs about the ring in various straight-sections. Each cavity is driven by a 100 kW amplifier which is a removable part of the cavity itself, and the frequency is changed from 30 MHz at 200 MeV injection to 53 MHz at 8 GeV by a current-biased ferrite tuner.

Multiple turns were observed soon after injection studies began on January 23, 1971 and a beam was accelerated by the RF almost as soon as it was turned on. We did experience some difficulty getting through the transition energy at 4.2 GeV. Although the booster is still not perfectly aligned - some of the magnets are out of position by several mm - it has already achieved an intensity of about 2×10^{11} protons per pulse using single turn injection. In order to realize the design intensity in the main accelerator of 5×10^{13} protons per pulse, 4×10^{12} protons must be accelerated in each booster cycle. (Twelve booster pulses are to be successively loaded into the main ring to produce a nearly completely filled single turn.) Since we plan to use four-turn injection into the booster, we will be looking for a factor of five improvement to reach design intensity. More careful tuning of the whole linac-booster system may do the job.

Figure 1. Booster Synchrotron

* Designed and built by Quentin Kerns and his group.

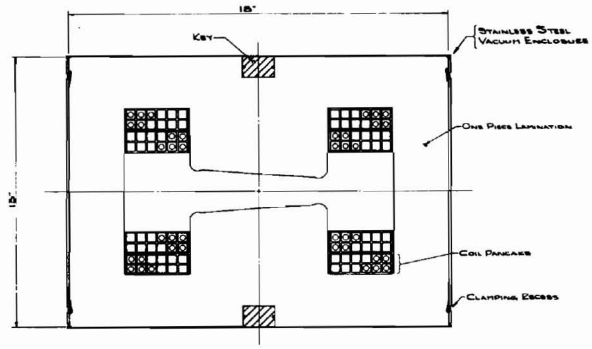

Figure 2a. Booster Magnet Cross Section

Main Accelerator

The main accelerator consists of 1014 magnets (See Fig. 5) disposed in a separate-function lattice about a ring of one kilometer radius (Fig. 6). The aperture of the magnets follows the changing shape of the beam that is characteristic of strong focusing. Thus half of the bending magnets have an aperture that is five inches wide and one and one half inches high while in the other half the aperture is four inches wide by two inches high. The magnet coil is split into three parts;* an inner part that fits in the gap of the magnet as shown in Figure 7, and a pair of outer parts that fit in the window of the magnet yoke. Because the inner coils are very close to the beam and can affect the field shape, very close tolerances, $\pm$ 0.1 mm, must be held in the relative positions of the individual turns. To do this we found it necessary to fabricate the inner coils in our own factory set up in a near-by town, but the outer coils were fabricated in a number of factories in England, France and the USA.

The yoke of the magnet consists of two half-cores which had been stacked and welded together at the same factory in which the 1.8 mm-thick laminations of which they are made had been punched.

The half-cores, the coils and a stainless steel donut were shipped to an assembly building at NAL where matching parts were given a thick layer of fixotropic epoxy and then assembled together on a precambered table (Fig 8). The same radiation resistant epoxy (good to 10^{10} rads) was used for this as was used in the fabrication of the coils.

* This was the idea of R. Sheldon who also was in charge of the factory that fabricated the inner coils.

Figure 2b. Booster Magnets

Figure 5. Main Accelerator Tunnel

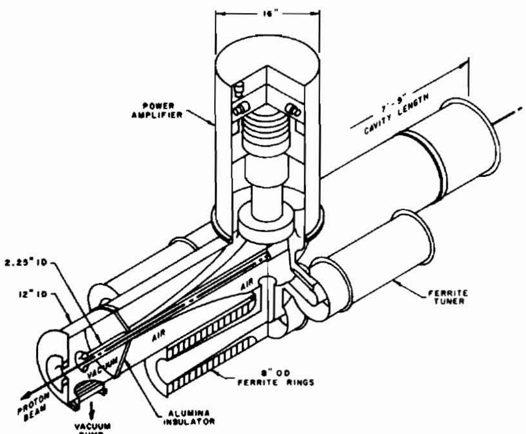

Figure 3. Booster R.F.Cavity Line

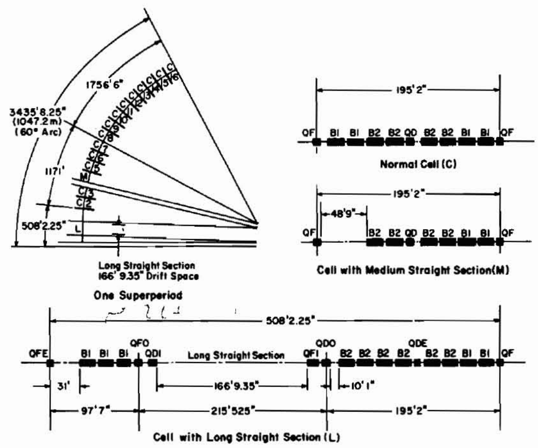

Figure 6. Main Accelerator Lattice

Figure 4. Booster R.F.Cavities 13 and 14 on Support Beam. The 200 MeV injection line appears in right background.

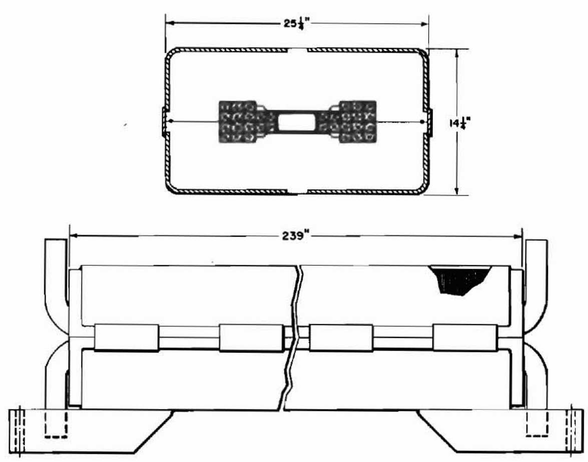

Figure 7. Main Accelerator Magnet Cross Section.

The finished magnet was cured at 90°C. After cooling down, the coils are under tension because of the copper-iron differential coefficient of expansion. On being removed from the precambered assembly table, the magnets would sag by just the right amount to bring all parts exactly level. In a good week we could assemble more than 50 magnets.

The quadrupole magnets, Figure 9, all have the same cross section but come in two lengths: regular seven-foot long magnets for insertion in the ring between groups of four bending magnets, and irregular four-foot long quadrupoles to be used in various combinations with themselves and regular quadrupoles to match the long straights to the ring-lattice. The quadrupoles were also assembled on the site in a manner similar to that used for the bending magnets.

The magnetic length, $\int B\, dl$, was measured for each completed magnet, and was found to have an rms variation of about 5×10^{-4}. The residual field was also measured. The placement of magnets in the ring was partly determined by such magnetic measurements - and partly just by expediency. After assembly, the coils of the magnets were "highpotted" at 2.5 kV and their resistance to ground was measured.

The bending magnets were found to withstand a magnetic field of 22.5 kG without excessive heating or mechanical failure. The field shape is excellent up to about 20 kG and there are yet a few cm of good field at 22.5 kG. Thus the magnet system should be able to accommodate 500 GeV protons if the current and cooling can be provided.

Alignment

In order to expect a closed orbit within the donut without correction coils, the position errors of quadrupole magnets, transverse to the beam, must be less than about $\pm$ 0.5 mm. Actually it is only the higher harmonics of the position errors that are important; for example, for harmonics less than about the sixth, errors of several cm are unimportant. For harmonics between the 20th and 100th, though, exact positioning becomes critical; this means that the position of each quadrupole relative to its nearest neighbors must be made precisely; that of course is what is easiest to do.

To do this an offset method is used in which a laser is mounted on one quadrupole and a centering detector is mounted on a distant quadrupole as shown in Figure 10; the offset is then measured by a centering detector mounted on the quadrupole between the other two. The random fluctuations presently achieved in setting the magnets are only slightly better than $\pm$ 1 mm - the spread being due to refractive effects in the air and to actual ground motions during the survey. Both of these effects are diminishing with time as equilibrium sets in, and it is felt that an accuracy approaching a few tenths of a millimeter may eventually be achieved. At present it is necessary to correct the injection field by the use of correction coils and it will be necessary to move individual magnets on the basis of the measured position of the beam with respect to the magnets.

Power Supplies[3] *

The power supplies for the magnets are located in 24 service buildings uniformly placed around the ring. There are 60 identical separate power supplies, 48 for the bending magnets and 12 for the quadrupole magnets. They operate directly from our 13.8 kV power line which is connected through a transformer to the 345 kV line that brings the electrical power to the site. Each power supply consists of six modules, Fig. 11, containing 8 thyristors. The modules, although compact, being 20" x 24" x 12", deserve respect - each one can switch over one megawatt of power.

Just before construction of the modules, a new development in the technology of thyristor rectifiers raised their current capacity to 1400 ampere rms. Although we had originally intended to install only enough capability (28 mW rms) to reach 200 GeV, the very good price on the supplies and transformers enabled us to install enough capacity to reach 500 GeV excitation (80 mW rms) for about the price we had originally anticipated for the 200 GeV level. The major uncertainty about exceeding 200 GeV is the arrangement we have with Commonwealth Edison, the supplier of electrical power, which provides only for operation at 200 GeV. Exceeding that level must be done on an empirical basis that may require us to install enough energy storage to prevent too great a voltage-drop on their power lines. The other uncertainty is the cooling. On cold winter days, our circular cooling canal should be quite adequate for any kind of operation. Air coolers (similar to automotive radiators) are being installed to supplement the cooling ponds (as well as to save water). On a very hot summer day, we will have to drop either the energy of the accelerator or the repetition rate.

R.F.

Sixteen R.F. cavities are located in the long straight just south of the transfer straight, about 1,000 meters away.

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* R. Cassel has been responsible for the design, fabrication, installation and mise-au-point of the main ring power supply.

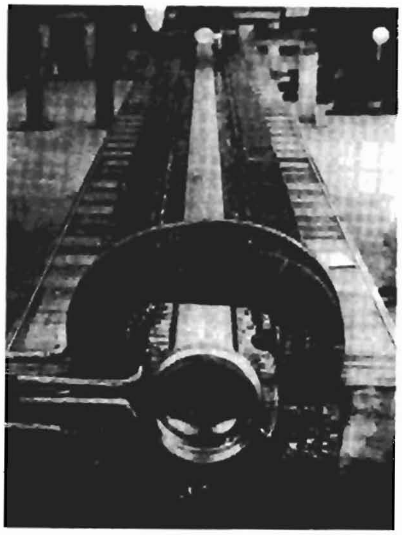

Figure 8. Main Accelerator Magnet Assembly.

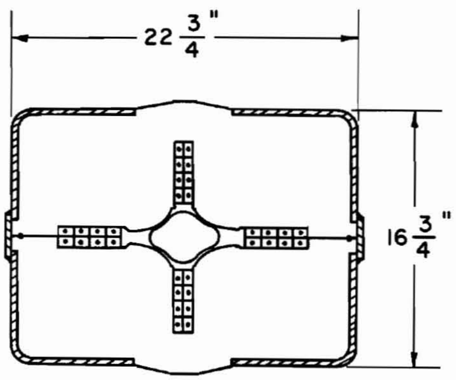

Figure 9. Main Accelerator Quadrupole Cross Section.

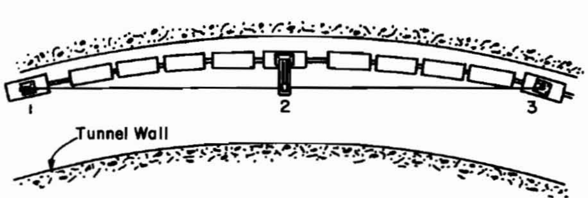

Figure 10. Alignment fixtures on three successive quadrupoles. 1) Laser positioned over first quadrupole. 2) Offset measuring fixture. 3) Centering detector. There are four bend-magnets between each two quadrupoles.

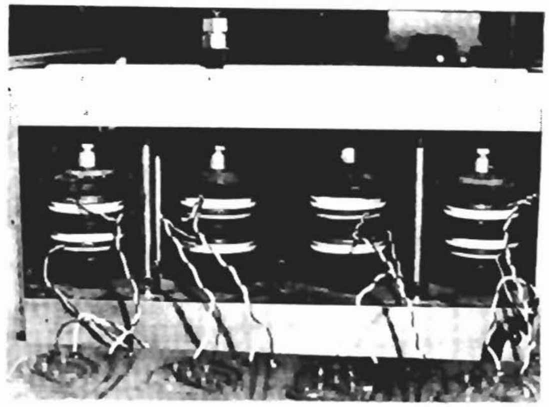

Figure 11. Main Accelerator Power Supply.

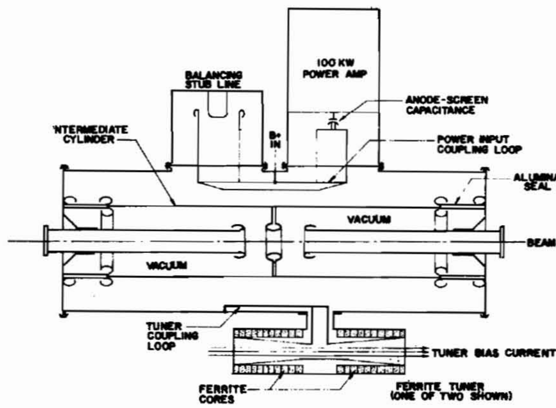

Figure 12. Main Accelerator R.F. Cavity.

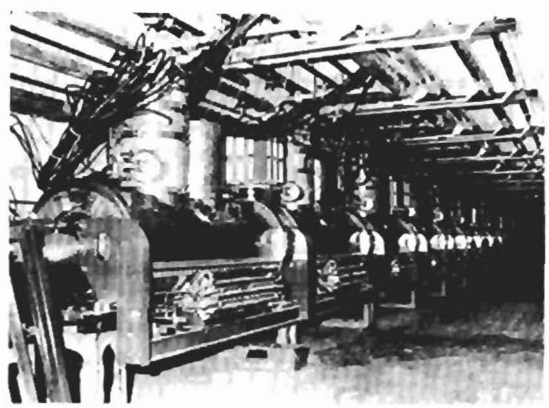

Figure 13. The 15 Main Accelerator R.F. cavities looking downstream in the R.F. straight section.

The main-ring rf cavities (Fig 12) are somewhat similar to those of the booster, possibly because both systems were built by Quentin Kerns and his group. In both systems, the power amplifiers, drivers, and ferrite tuners are mounted on the cavities while the power supplies and controls are in a gallery outside the shielding. The main-ring cavities have less ferrite, because they modulate only 0.5% in frequency. The peak energy gain per turn is 2.5 MeV in the main ring.

At this time, all the cavities are installed (Fig 13) and five are operating. We are doing experiments to pick up and accelerate the beam.

Beam-abort system

The energy in a single pulse being accelerated in the main ring is enough so that considerable damage, thermal as well as radiation, can result were something to go wrong; for example, the beam might smack into a magnet coil. We expect to be able to detect the kind of fault that would cause this sort of thing soon enough to abort the beam out of the donut and deposit it in a controlled way on a beam dump.

This is to be done by bumping the beam onto an aluminum block 15 x 15 x 220 cm long. The beam bump results from discharging a condenser bank through two bending magnets, one located just before and one just after D straight. The 200 GeV beam will move over 2 cm in about one millisecond and there encounter the aluminum block. Some of the energy is deposited in the aluminum; the rest will be caught on two regular bending magnets (not excited) that are placed downstream from the block so as to intercept the remaining part of the shower that develops in aluminum.

Controls

A design goal of the system being developed at NAL is that one person be able to operate the entire accelerator from one simple control console.* A computer-assisted system is used, with control possible at various levels. At a basic level there are standard controls and meters at the location of each device such as a power supply. Thus, in principle at least, an army of men, one stationed at each piece of equipment, could turn on and run the machine if all were in contact by telephone with a hydra-headed operator receiving information and barking orders to them.

At a higher level are a collection of digital-to-analog and analog-to-digital converters, multiplexers, binary sense circuits, etc., that enable local minicomputers (Lockheed MAC-16's) to monitor and control pieces of equipment.[4,5] There are about eight of these minicomputers which control sub-systems of equipment such as the Booster RF or the Main-Ring magnet or the beam extraction equipment. Little or no computation is carried out by the minicomputers; rather they perform regulation and control functions. Access to them locally is by teletype peripheral equipment.

A central control computer (XDS Sigma-2) assists the operator to communicate with the minicomputers, stores running conditions, produces displays of accelerator parameters, gives warnings, etc.

A very simple control console has been developed. It consists of a few generalized knobs and control buttons that can be hooked to whatever components are typed on the keyboard of the console. Information is displayed in alphanumeric form or as graphs by a number of TV monitors. Thus one can "hook" several correction coils to one knob so as to produce a localized "bump" in the beam orbit. The TV display indicates where the bump is made on the orbit, and how large it is. The effect of the beam bump can be observed then on beam position detectors that can be called up, or by the effect on the beam intensity. By pressing a button, all of the current conditions are fed into the computer memory. These can be held in the memory to be set back into the accelerator if subsequent tuning should degrade the beam, or they can be stored on tape for future use.

The control console can be located anywhere, can even be controlled over the telephone. When the central computer becomes inoperative, for whatever reason, the accelerator continues to run at its last setting. It is still possible to operate it, but much more awkwardly, from the several minicomputers located in various rather distant parts of the accelerator. Even were some of the minicomputers inoperative, most of the accelerator components continue to function at the last settings.

The controls are actually more complex than indicated by the above simplified description. The Linac was brought into operation before this system was developed, and uses an XDS-Sigma 2 that communicates directly with the equipment to be measured and controlled.[6] The Linac computer operates in real time whereas in the other system, the central computer communicates sequentially in time. At present we are trying to meld the best features of both systems into one overall system. I don't

* The development of this system was carried out under the direction of Donald A. Edwards.

know why it is that a camel keeps appearing on the TV display.

Extraction System [7] *

An important part of the design of the accelerator is the extractor which must work at an efficiency greater than 99% so that radiation and residual radioactivity will not limit our beam intensity to less than 5.10^{13} protons per pulse. Extraction occurs in the same long straight as does the injection. A growth rate in betatron oscillation of 1 cm per revolution can be induced by inducing a third-integral resonance by the use of trimming sextupoles. To start with the beam will be moved onto the septum by means of a beam bump. The first element that the beam encounters in the donut is an electrostatic septum located some 100 feet upstream of the ejection straight (a magnet has been removed from the lattice at this point making a 30 foot long free space). The electrostatic septum consists of a vertical array of 0.05 mm tungsten wires spaced at 1.25 mm intervals, the length of the array being about 300 cm. Opposite this a solid electrode to which a potential is applied provides a field of the order of 100 kV/cm which deflects the beam horizontally outward. After drifting about 100 feet the beam enters a Lambertson septum magnet which bends the beam downward. A series of C and H magnets then deflect the beam out of the 167 foot long straight and guide it to a pipe in the tunnel wall that leads to the Proton Switchyard.

Proton Switchyard

The protons have yet to travel roughly a kilometer before reaching the targets in various of the laboratories. A series of beam splitters and magnets directs the protons through the maze of buried pipes and tunnels that lead to the targets. (Fig.14) The magnets, hung á la Budker from the ceiling of the tunnel, will exceed in number the magnets in the booster accelerator.

Experimental Laboratories**

The procedure customarily followed with accelerators is to build the machine, get it to work, and then sensibly to get on with the business of building appropriate experimental facilities. Although originally we expected to proceed in just this manner, in fact it turns out that we are trying to bring the whole facility into operation at once, full-blown, as Aphrodite from the sea. We have been motivated to do this by the enthusiasm, the attention, and the help of the physicists who expect to use the facility. When we called for proposals for experiments a year and a half ago, we were inundated with some 100 submittals, the number now exceeding 150. A Program Advisory Committee was set up, and on the basis of hard work on their part some 50 experiments have been approved.

Experimenters swarm all over the place, and from all over! Soviet physicists are collaborating with U.S. counterparts on a proton scattering experiment to be made in the donut of the main ring. For this, Nikitin is to bring his gas jet target from Russia; a teletype machine busily trades factors of 2.54 with one at Serpukhov as the physicists try to normalize millimeters and inches at the interfaces of their respective equipment. A gung-ho group from Caltech, expecting to do a counter experiment on neutrinos, started to assemble their equipment last spring in the Illinois mud. By now they have a considerable amount of sophisticated experimental equipment put together and working in a minimal "Wonder" building (Fig 15) which is still without a concrete floor - and in various trailers (Portacamps). I am ashamed that their experiment is nearly ready to go, and we are not yet sending them the neutrinos that they were led down the garden path to expect by now. Perhaps a half-dozen pioneering (excuse the pun) efforts are in various stages of development on the site. Three principal laboratories (Fig 14) are being built in which to do these experiments: A Neutrino Laboratory, a Meson Laboratory and a Proton Laboratory; we hope to bring them into operation in that order. The names are only indicative of a characteristic but not exclusive activity in a particular place.

Meson Laboratory

The Meson Laboratory [8] will be used to provide a variety of general purpose secondary particle beams produced by bombardment of metal targets by protons of energy up to 200 GeV. Many of the secondary beams will be various kinds of mesons, but there will also be a neutron beam and a diffracted proton beam. We tried to follow more conventional planning in designing the Meson Lab because it could be expected that several relatively fixed beam lines would be of considerable use for many years. The Laboratory starts at the Meson Target Hall, where a railroad can transport the target and its auxiliary shielding and magnets into a well shielded target box. These targets can be expected to become exceedingly radioactive, $\sim 10^4$

* The extraction system was built by a group under the direction of A. W. Maschke.

**Developed by Experimental Services Group under direction of J. R. Sanford

R/hr; adjustments of the target are made by remote control using mechanical manipulators and cranes. The secondary beams will emerge from the Target Box and be guided by a transport system to the Detector Building (Fig 16, 17) some 1000 feet distant, the enclosures being covered by earth for shielding. The energy of the bombarding protons is limited to a nominal 200 GeV, depending on the experiments being done, by the length of the shielding (about 1000 ft of dirt) against muons produced in the target.

The Meson Laboratory is nearly completed except for the Detector Building which will be erected over experiments in progress. Experimental equipment is being assembled in various of the enclosures that are already finished.

The Neutrino Laboratory *

The Neutrino Laboratory (Fig 18) starts at the Neutrino Target Building which is almost identical to the Meson Target Building except it is somewhat longer (See Fig 14). Mesons (K's and π's) are produced by the protons and are guided into a 600m long decay pipe at the end of which they strike a beam stop. An elongated mound of dirt then filters out all particles except neutrinos, the muons being the next most penetrating. At the end of the mound, some one kilometer distant, a 15 foot bubble chamber is being constructed, and behind it is located a laboratory for neutrino counter experiments. Midway down the mound, in a cut, is located another laboratory (the "Wonder" building described above), where at somewhat lower energy neutrino counter experiments will be done. Off to the side of this laboratory is the Muon Laboratory, and a beam transport system can lead muons or pions into it. As part of an experiment on muon scattering, the Chicago University cyclotron magnet is being moved to provide momentum analysis.

The 30" Argonne bubble chamber has been moved to a position near the 15 foot bubble chamber but off to the other side of the mound. A hadronic beam of particles can be led from the Neutrino Target by a transport system either to the 30-inch bubble chamber or to the 15 foot bubble chamber. The 30 inch bubble chamber is expected to be ready to start operations by November of this year. The 15 foot bubble chamber, being designed and built by a group led by W. Fowler, is scheduled to be finished and running by January 1973.

Proton Laboratory **

The Proton Laboratory (Fig 19) represents more of an innovation. Here the protons are raised above the level of the beam in the Main Ring by eight feet which still leaves them about 15 feet below normal ground level. The idea is to use dirt as the principal shielding material, to tailor the sunken enclosure to the particular experiment proposed. Thus steel sheet-piling is driven into the dirt to make a retaining wall appropriately close to the experiment. The dirt is excavated and the experiment is installed. At the end of the experiment the sheet piling is removed, the dirt filled in, and the ground is ready for the next experiment.

The Proton Laboratory begins at a beam splitter which directs the beam into any of three 2000 foot-long pipes that lead to permanent concrete structures that contain utilities. The experiments extend out from these structures within the temporary sheet-piling structures as much as another 1000 feet depending on the experiment.

These laboratories as well as the main ring tunnel in which some experiments can be made represent about the scope of experimental facilities envisaged at the start of the project. We are hopeful that, after some experience with their use, we will have enough funds left over to build one or even two more such laboratories.

Some Topical Problems

Apart from our principal problem, which is just keeping the many components of such a newly built and complicated system ready and going at the same time, two difficulties appear to be particularly critical at this time. First, there are obstacles inside the donut! This is indicated by a steady depletion of the circulating beam after each turn and by the small momentum acceptance of the ring. Now the decrease could be caused by a number of things; for example, by the magnet being near a betatron oscillation resonance, or standing wave modes in the magnet ring, or random ground currents, but obstacles in the donut are the best explanation. Now a four-mile long, welded together, stainless steel tube is not the easiest place to have to find one or more necessarily tiny obstacles (we do get many successive turns). Indeed just opening the donut more or less at random in a few places soon revealed a circular piece of plastic, about 10 cm in diameter and about 0.5 mm in thickness, neatly tucked into one of the quadrupoles so as to obstruct a significant part of the aperture. Further careful looking has turned up a number of very thin (0.2 mm OD) steel wires. It turned out that these wires were formed at rare intervals by

*Being installed under direction of T. Toohig

**The conception of A. Maschke and L. Read

-Figure 14. Experimental Areas. The Meson Laboratory is above the Neutrino Laboratory. The Proton Laboratory is below. The lowest two areas are far in the future.

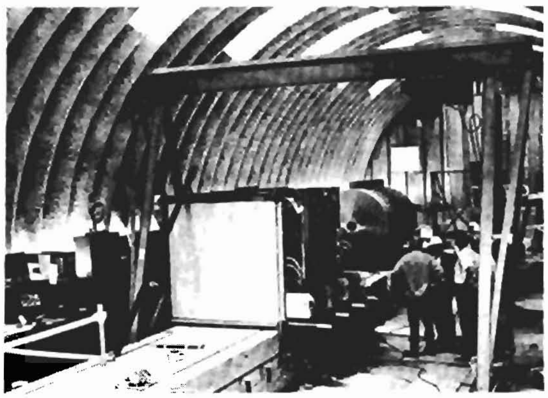

Figure 15. "Wonder" Building. An improvised laboratory in which the Caltech-NAL neutrino experiment is being set up.

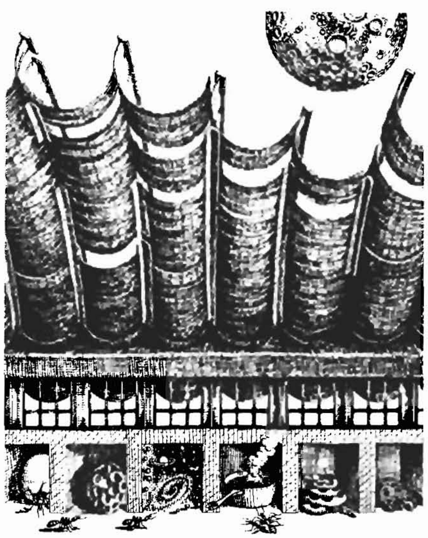

Figure 16. An artist's (Angela Gonzales) view of the Meson Laboratory and the activities therein.

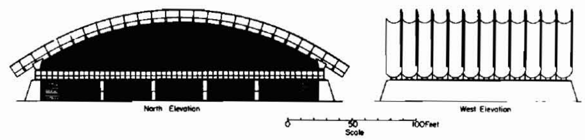

Figure 17. Detector Building of the Meson Laboratory

Figure 18. View of neutrino beam looking toward accelerator from Bubble Chamber. The Meson Laboratory is to the right; the Proton Laboratory is to the left.

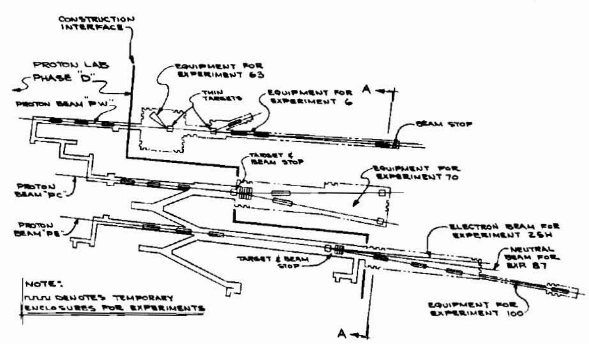

Figure 19. Proton Laboratory experiments layout.

the tool that cuts open the stainless steel donut at the weld point. Furthermore the wires inexplicably get into the magnet gap, and because of cold-working, are magnetic enough to stand up in the magnetic field at injection. Several have been found by now, and the expectation is that there are several more yet to be found. With some of the obstacles removed, the beam has been made to last as long as about one second - the momentum acceptance indicating an open aperture of the order of 1 cm. We are still searching the donut for more obstacles. Various techniques are used: radiation detectors placed around the ring (200 of them) sometimes indicate larger objects; blowing gas through the donut removes some. Felicia, our friendly little ferret, is anxious to help us, but she turns out to be especially good at getting mice out of the donut, and has not yet developed a taste for steel wire. She earns her keep by pulling a string through long pipes in the experimental area (Fig.20). We are buckling down to a long systematic visual search, working inch-by-inch at every part of the donut.

Another serious problem encountered so far has been the electrical failure of magnets apparently caused by moisture in the tunnel. Although the magnet coils have been regularly "high-potted," that is, tested at 2.5 kv for arc-over to ground at the time of production in our factory, after being for some time in the tunnel some of them have developed arcs to ground, even when a voltage of the order of a few hundred volts is applied. The difference is that the factory is dry, - the tunnel has on occasion been very wet. This is because it was finished during the coldest weather of last winter and was then sometimes covered over with frozen dirt. A considerable length of magnets was installed and tested to 200 GeV excitation last winter, with no problems. However, the rest of the magnets were installed this spring into a very cold tunnel and when they were excited arc-overs occured. The hot, humid Illinois air got into the tunnel - produced a veritable rainstorm by condensation on the tunnel walls - but especially also soaked the magnets by condensation. Each magnet coil has about 80 sq. ft. of area (about 6 sq. meters) exposed to ground, and a single crack in the epoxy insulation (produced by stress, or crazing, or whatever) if filled with water could become a short circuit to ground. Alas, there were such cracks, there was water to fill them, and when filled, short circuits did occur in some of the magnets.

The answer of course is to dry out the tunnel, and to dry out the magnets. To really dry out a magnet is not easy. We find it necessary to bake the magnet at 90°c in a vacuum for many hours. In that case we can catch nearly a liter of water from each wet magnet, and then the insulating properties of the magnet are good. However, we know that the crack is still there, so we are vacuum impregnating all the magnets that have shown low resistance to ground. For those in which an arc has occured, it is usually necessary to take the magnet apart and replace the faulty coil. It turns out to be possible to save all the basic materials of a damaged magnet, and the copper coils can be reinsulated and used again in the old iron cores. About 5% of the magnets have had catastrophic arc-overs and been replaced. Another 15% have been replaced because of showing a low resistance to ground or because of a vacuum problem. The remaining magnets should now be capable of withstanding the operating voltage and so tests are begining at higher excitation. In general, as the excitation is raised, the voltage to ground does not increase very much for increase comes by switching on more supplies around the ring.

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Figure 20. Felicia

DISCUSSION

V.P. DZHELEPOV: Can you give a preliminary estimate for the time required to finish the work on the magnet system and to obtain a full-energy proton beam?

R.R. WILSON: At NAL we have learned how to make our construction and adhere to a tight schedule. It is obvious that we have not yet learned how to make everything we build to work on the scheduled time. Until we do, I prefer to make no estimates.