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PROGRESS AND PROSPECTS AT THE NATIONAL ACCELERATOR LABORATORY

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ABSTRACT

A general review is given of the progress on the NAL 500-GeV synchrotron. Both the accelerator and experimental areas are discussed.

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I. THE ACCELERATOR

The National Accelerator Laboratory is located near Batavia, Illinois, a pleasant town on the Fox River, about 50 km west of downtown Chicago. The site covers 6800 acres of essentially flat land, formerly used mostly for farming. The houses in the former village of Weston have been rearranged and laboratory buildings added to form a temporary headquarters for design and administrative activities. Here Professor Robert R. Wilson has assembled an enthusiastic staff of physicists and engineers to build a 1-km radius proton synchrotron with a peak energy of 500 GeV and a design intensity of 5×10^{13} protons per pulse. Many simplifying features have been incorporated into the design, which helps to explain why so far we have been able to progress more rapidly and at less cost than originally planned. The accelerator consists of three major parts shown in Fig. 1: the 200-MeV linear accelerator, the 8-GeV rapid-cycling booster synchrotron, and the main ring.

This paper will review briefly the present status of each of the three major components of the accelerator, starting with the 200-MeV Alvarez-type linear accelerator, which has a 750-kV Cockcroft Walton preinjector. This high-voltage set was built in Switzerland. The linac is built in nine separate cavities and is approximately 150 m long.

On July 30 the first three tanks were successfully operated to accelerate a proton beam to 66 MeV, an energy for proton linacs surpassed only by the 100-MeV linac at Serpukhov. It is likely that near the beginning of next year the linac will be completed and in operation at 200 MeV.

The booster conventional construction is essentially complete. On July 27 the central utility pond was filled; it is a pleasant sight surrounded by the booster equipment galleries.

Booster magnets are being placed rapidly in the 75-m radius ring. On July 31 a significant milestone was reached when 1/4 of the booster ring was powered and a portion of the computer control system of the accelerator was used for the first time. The booster power supply was built in England. A prototype booster rf cavity has also operated successfully; by early spring of 1971 acceleration to 8 GeV should be possible.

Now we come to the main ring, a separated-function synchrotron. Since there are almost 5 km of bending magnets, a simple design is an important key to building the main ring at low cost. The magnet coil is split into three saddle-type coils, a pair of outers and an inner.

The total number of coils needed for both dipoles and quadrupoles is approximately 3400 and, in order to produce these in a short time, we have placed orders with seven different coil manufacturers, including two in England and one in France, as well as setting up our own fabrication shop in a village 10 km from the laboratory to manufacture the inner coils. Since the inner coils are next to the beam and strongly affect the field shape, tolerances of ±0.1 mm over the 6-m length must be maintained. In order to keep our schedule, it has also been necessary to manufacture some quadrupole coils ourselves. All the magnet coils are vacuum impregnated in an epoxy resin capable of withstanding in excess of 10^{10} rad.

Besides making coils, we have had to learn to build main-ring magnets. A shop has been set up on the site where the magnet components are assembled.

The half cores have been stacked from 1.8-mm thick laminations of low-carbon steel (H_c ~ 1.2 Oe). The tapered pole tips and small Rose shims are essential for maintaining a usable aperture up to 500 GeV. The feet are welded on the completed half-magnet cores when they arrive.

The assembly takes place on a pre-cambered table to remove sag in the completed magnet. We are successful in controlling the straightness to approximately 0.1 mm.

The whole magnet is assembled with the same basic epoxy used in the coils and cured at 90° C. Thus in the finished magnet, the coils are under tension because of copper-iron differential temperature coefficient.

The vacuum chambers are made of 1.2-mm thick stainless steel. Tests in a 60-meter long prototype have shown that with the 15-liter/sec titanium sputter-ion pumps on each magnet unit, average pressures better than 10^{-7} Torr are easily attained.

We have been able to make as many as 6 magnets per day. About 200 dipoles and quadrupoles are now complete. We need a total of 1014 for the ring so there is still a long road ahead.

Magnetic measurements are made on all completed magnets using measuring equipment on-line to a Varian 620i computer.

On each dipole, the field is integrated over the length. At 200-GeV excitation we are attaining an rms variation in $\int Bdl$ of $\lesssim 5 \times 10^{-4}$. Magnets are placed in the ring according to their magnetic measurements.

The dipoles at 500 GeV have about 2.5 cm of usable aperture. The quadrupoles saturate at lower energy, but the separated-function design allows us, in order to have sufficient aperture during extraction, to run the tune of the machine at approximately 16 betatron wavelengths instead of the design value of approximately 20. In this condition, there is no problem with the quadrupoles. However, at the highest energy, if extraction is difficult or delayed beyond completion of the main ring, internal-target experiments are possible and are being discussed now.

Main-ring magnets will also be used in secondary beams. The capability we have developed for rapid production will be useful for building experimental equipment after the main-ring components are complete.

All major components of the main ring are ordered. On some items such as correction magnets, beam sensors, and elements of the control system, quantities to operate the first sector (1/6) of the ring are ordered while we are still seeking to improve the design.

We are optimistic that we can accelerate protons to almost 500 GeV soon after the synchrotron starts operation because of the efficient and economical design of two major components: bending magnets and power supply.

The advance in thyristor technology has made it possible to switch 1 MW of power in each of the power-supply modules. Each power supply contains six such modules.

There are 60 power supplies altogether, 48 for the dipoles and 12 for the quadrupoles places in 24 service buildings placed around the ring. The power supplies operate directly for the 13.8 kV power line.

The tunnel is built by first putting down a slab. Then using a geodilite, a laser ranging device, station marks are placed on the concrete slab to an accuracy of ±1 mm in 1 km. These station marks provide the starting point for accelerator alignment.

Then, precast hoops, fabricated on the site, are put in place. As of now about one-half the tunnel is complete and about one-fourth has been covered with dirt. Settlement has been monitored for two months now and was observed initially ~ 6 mm/month, but the relatively dense ground, a glacial till, is expected to stabilize.

The first magnet went into the main ring on April 15, 1970. We now have approximately 10% of the magnets in and are starting to hook them up. Installation is done with a special vehicle. This fall the first sector (1/6) will be completed. A tentative plan is to then accelerate protons in excess of 100 MeV, bring them one-half turn around the booster, then carry them down the 8-GeV transport system and into the main ring.

At the present rate of component delivery and installation we should have everything in place by late spring of 1971. Water cooling will probably not be adequate initially to run 400-500-GeV experiments at the full duty cycle, but this will vary considerably between summer and winter. There is a lot of hard work ahead, but it appears possible to have an accelerated beam next summer.

II. EXPERIMENTAL FACILITIES AND PROSPECTS

Figures 2(a), (b), and (c) show the master plan of the beam-transport and experimental-area layout. The beam will be extracted with 99.9% efficiency and split, using septa, into three independently controlled beams of variable intensity. These three beams will be transported about 2000 feet and used in the experimental areas to produce secondary beams. We may characterize these three experimental areas in the following way starting from the top and working down.

1. We call this Area 2. This area has been designed as a 200-GeV station with standard secondary beams. These beams will be roughly 1300 feet long and be of a semi-fixed nature. Experiments will essentially come to the beams rather than the other way around.

2. We call this Area 1 in which we use the straight-ahead proton beam. We regard this area as being quite fixed with very special long beams. Here we will target with protons up to 500 GeV. The principal feature here is a neutrino beam.

3. Area 3 will also be designed as a 500-GeV area.

We anticipate building further experimental areas beyond the initial complement of three.

The scheduled dates for experimentation using beams in these areas are July 1972 for Area 2, January 1973 for Area 1, and July 1973 for Area 3.

The initial round of proposals for experiments at NAL were submitted on June 15. Some statistical information on these proposals is quite interesting.

1. There was a total of about 90 proposals.

2. Fifty-four U. S. university groups submitted proposals.

3. The five major U. S. laboratories (NAL, BNL, ANL, LRL, and SLAC) each submitted several proposals.

4. There were proposals from the General Electric Company, USA, and NASA.

5. There were several proposals from foreign institutions: CERN, Orsay, Bari, Heidelberg, Max Planck Institute, Pavia, and Tohoku.

In many cases, these proposals were in the form of collaborations. The frequency distribution of the number of institutions involved in a proposal peaked at two or three and fell to zero above seven.

There was a total of 487 individual Ph.D. high-energy physicists who were associated with these proposals. The total number of such physicists in the United States is about 1200. Thus, about one-third of the high-energy physics population of the U. S. was involved in the initial round of proposals at NAL.

The evaluation of these proposals is currently under way. Therefore, at this stage we can only give a general indication of what could be an attractive initial program of physics at NAL. In doing this, I will associate experiments with particular beams.

The parameters of the beams are shown in Table I.

<u>Area 2</u>: (i) <u>High-Energy, High-Resolution Hadron Beam</u>. It will be possible to perform total cross-section measurements for $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$, and p in this beam using liquid hydrogen and deuterium targets. The incident-particle mass will be identified using Cerenkov counters in the beams. These measurements will be performed from about 20 GeV/c to 200 GeV/c incident particle momentum. One can hope to achieve an absolute accuracy of better than 0.5% and a particle-antiparticle relative accuracy of at least 0.3%. On this beam line, it may also be possible to locate a strong-focusing 200 GeV/c particle spectrometer. This spectrometer will allow the study of inclusive reactions initiated by $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$, and p.

(ii) High-Energy, High-Intensity Beam. The program of elastic hadron-hadron scattering up to 200 GeV and in the momentum transfer range $0.1 \leq |t| \leq 5\ (\mathrm{GeV}/c)^2$ appears suited to this beam. A system of magnets with wire chambers and Cerenkov counters would detect the forward high-momentum elastically scattered particle. Another much smaller spectrometer would detect the recoiling low-momentum particle. It is anticipated that a polarized target will be used in this setup. The same apparatus would be able to study backward elastic scattering.

(iii) Diffracted-Proton Beam. This beam of 10^{10} protons per pulse at 200 GeV could be used to produce beams of short-lived charged and neutral hyperons. A survey would first be performed to ascertain the fluxes of these particles, Σ^-, Ξ^-, Ω^-, Δ^0, $\bar{\Delta}^-$. It is anticipated that these fluxes will be adequate to perform elastic-scattering measurements in the kinematic range

$$0 \leq |t| \leq 1\ (\mathrm{GeV}/c)^2$$

and for hyperon energies above about 100 GeV. By making measurements in the Coulomb region, both real and imaginary parts of the scattering amplitudes for these processes can be extracted and hence the total cross sections can be obtained. These measurements will give incisive tests of symmetry schemes.

This apparatus would also allow a search for new particles with lifetimes in excess of 10^{-11} seconds.

(iv) The Neutron Beam. This beam can be used to study the neutron-proton elastic scattering in the energy range 40 to 200 GeV and for $0 \leq |t| \leq 2\ (\mathrm{GeV}/c)^2$. Total cross sections for neutrons on hydrogen and deuterium targets can be made in the same energy range to an absolute accuracy of about 2%. In addition, this beam can be used to study neutron-proton charge exchange in the same energy range and with $0.002 \leq |t| \leq 1\ (\mathrm{GeV}/c)^2$.

(v) The Medium-Energy Medium-Resolution Beam. This beam may be used to study the reactions

$$\pi^- + p \rightarrow \pi^0 + n$$
$$\rightarrow \xi^0 + n$$

in the range $0 \leq |t| \leq 2\ (\mathrm{GeV}/c)^2$ up to 80 or 100 GeV. The Serpukhov data on the total cross sections of pions or nucleons suggest that the asymptotic region may be far off and hence the charge-exchange process will remain large up to high energy. In addition, these reactions are rather clean tests of certain features of Reggeism.

(vi) The K_L^0 Beam. Motivated particularly by the Serpukhov data on charged kaon nucleon total cross sections and the recent data on regeneration, it will be possible to measure the regenerative amplitude and phase of K_L^0 scattering on various targets, including hydrogen, in this beam. It will be possible to make measurements of the amplitude to 10% up to about 100 GeV.

Almost all of these experiments are in the category of total cross sections and elastic scattering. In addition to this basic program there will, of course, be searches for quarks, monopoles, etc.

Area 1: We turn our attention now to Area 1. In this area the dominant feature is a neutrino beam and a large bubble chamber. In addition, the design of the area includes a muon beam and a 500-GeV hadron beam to a small bubble chamber. The characteristics of the muon beam are given in Table I.

The design of the bubble chamber is proceeding rapidly. The length of the chamber will be fifteen feet and it will be capable of cycling at least twice per second. Two sets of three cameras are being incorporated in the design. The magnetic field will be about 30 kG. The superconducting coils are now under contract to be made at the Argonne National Laboratory. The expansion system will be made at the Stanford Linear Accelerator Center. The vacuum-chamber construction is now under contract. Assembly of the vacuum chamber and support structure will be made at NAL next summer. The first cool-down of the chamber is scheduled for July 1972. It is hoped that by January 1973 that the chamber will be ready to be tested with beam tracks. Simultaneous with the construction of the chamber, electronic detectors for particle identification will be constructed and will be located outside the sensitive volume of the bubble chamber. The bubble chamber will be used for studying both neutrino interactions and high-energy hadron interactions. It is anticipated that in the study of weak interactions the use of a neon filling of the chamber will be important. The design of the chamber will ensure this possibility and also the use of track-sensitive targets within the chamber. Finally, it is expected that the additional smaller bubble chamber will be brought to NAL and operated for high-energy hadron exposures as soon as beam is available.

(i) Neutrino Beam. The neutrino-beam design is characterized by about a 1200-foot hadron decay distance and a 3300-foot muon-shield thickness constructed of soil. The 500-GeV full-intensity proton beam will strike a target located at the beginning of this decay region and the pions and kaons produced in this target will be magnetically focused down the decay pipe. This focusing system will be of two distinct types, first, a wide-band system in which hadrons of essentially all momenta are focused and allowed to decay, producing neutrinos of all energies up to the kinematic limit into the detector. Second, a narrow-band system will be used in which hadrons within a narrow momentum interval will be focused and allowed to traverse the decay region. Neutrinos produced within the solid angle of the detector have a rather unique energy from the pions and kaons. This monochromatic aspect of the beam will be extremely useful in determining the energy dependence of the total cross section for neutrino interactions. Useful rates for study of the total cross section can be obtained up to at least 300 GeV. It is envisaged that a 100-ton spark-chamber detector will be located in the neutrino beam at an early stage. The event rate of W-meson production in the same detector will allow a search for the intermediate boson up to 15-GeV boson mass.

(ii) The Muon Beam. The muon beam will be used to extend the range of deep-inelastic electromagnetic scattering by about an order of magnitude in energy beyond SLAC energies and by about a factor of five in momentum-transfer squared. Thus the validity of the observed scaling law observed at SLAC will be explored in a range extended by roughly an order of magnitude. In addition, the muon beam has controllable longitudinal polarization from less than zero to essentially 100%. This feature may prove to be of great value in probing the fundamental properties of these phenomena.

These experiments represent a good sampling of the prospects at the National Accelerator Laboratory. This summer we have had two guests from Serpukhov with us at NAL. It is our hope that this represents only a beginning of a fruitful collaboration at NAL between scientists of the Soviet Union and the United States in this exciting field of human endeavor.

Table I.

Area	Beam	Production Angle (mrad)	Max. Mom. GeV/c	Solid Angle (μsec)	Max. Resolution (Δp/p)	Max. Momentum Band Pass (Δp/p)	Approximate Flux Per Pulse 10^{13} Interacting Protons
2	H. E. H. R.	2.5	200	1.9	±0.03%	±1.0%	10^6 π at 100 GeV
2	H. E. H. I.	3.5	200	2.0	±0.2%	±2.5%	10^7 π at 100 GeV
2	Proton/ Neutron	1.75	200	0.28	±0.1%	±1.2%	10^{10} P at 200 GeV
2	M. E. M. R.	15.0	80	5.3	±0.1%	±0.45%	6×10^6 π at 30 GeV
2	K_L^o	10.0		0.04			10^4 K_L^o/GeV at 80 GeV
1	Neutrino	0.0					10^7 ν/m^2 integrated $E_\nu > 40$ GeV
1	μ Beam	0.0	300		±3%	±3%	2×10^7 μ at 100 GeV

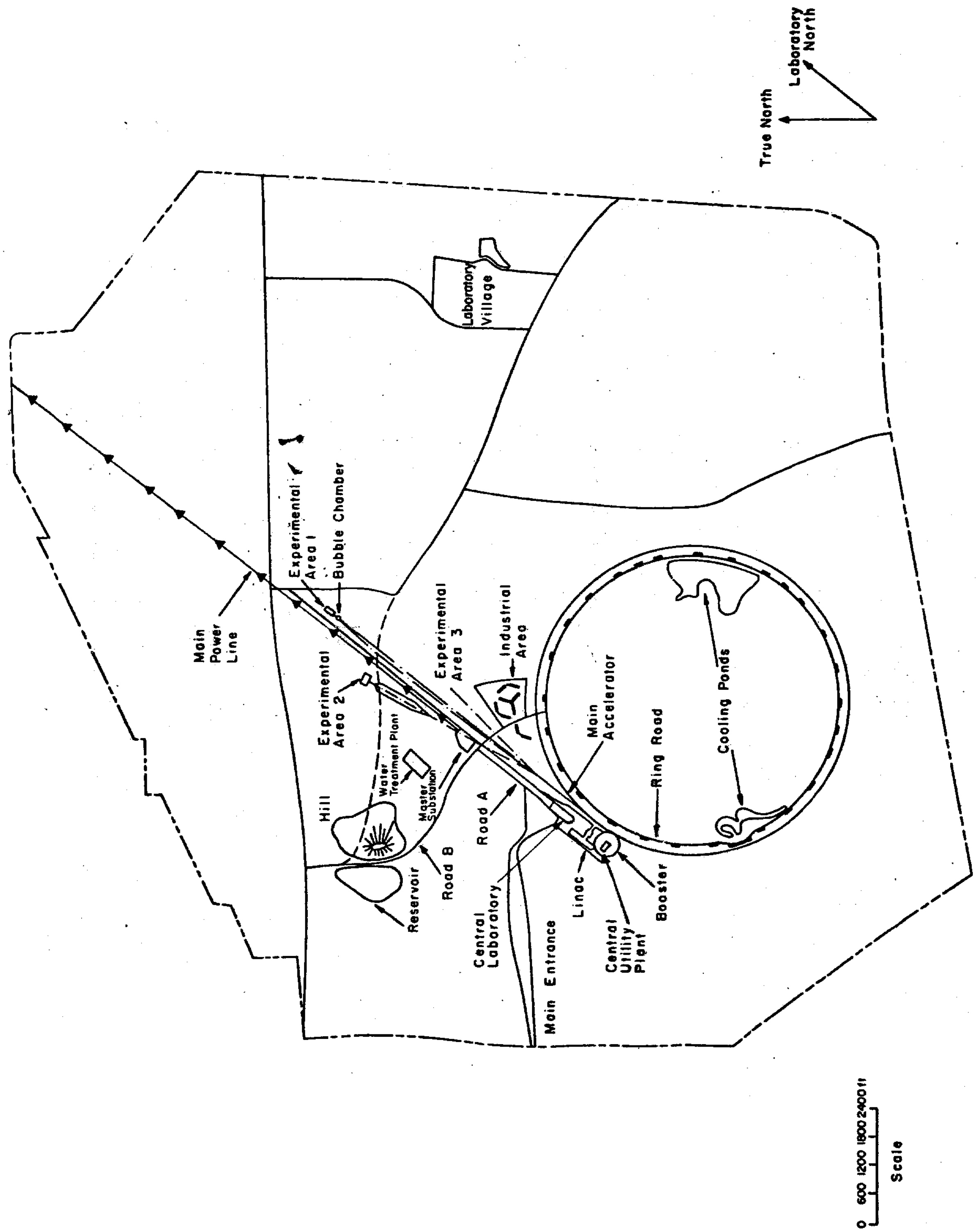

Fig. 1. Master Site Plan, April 1, 1970.

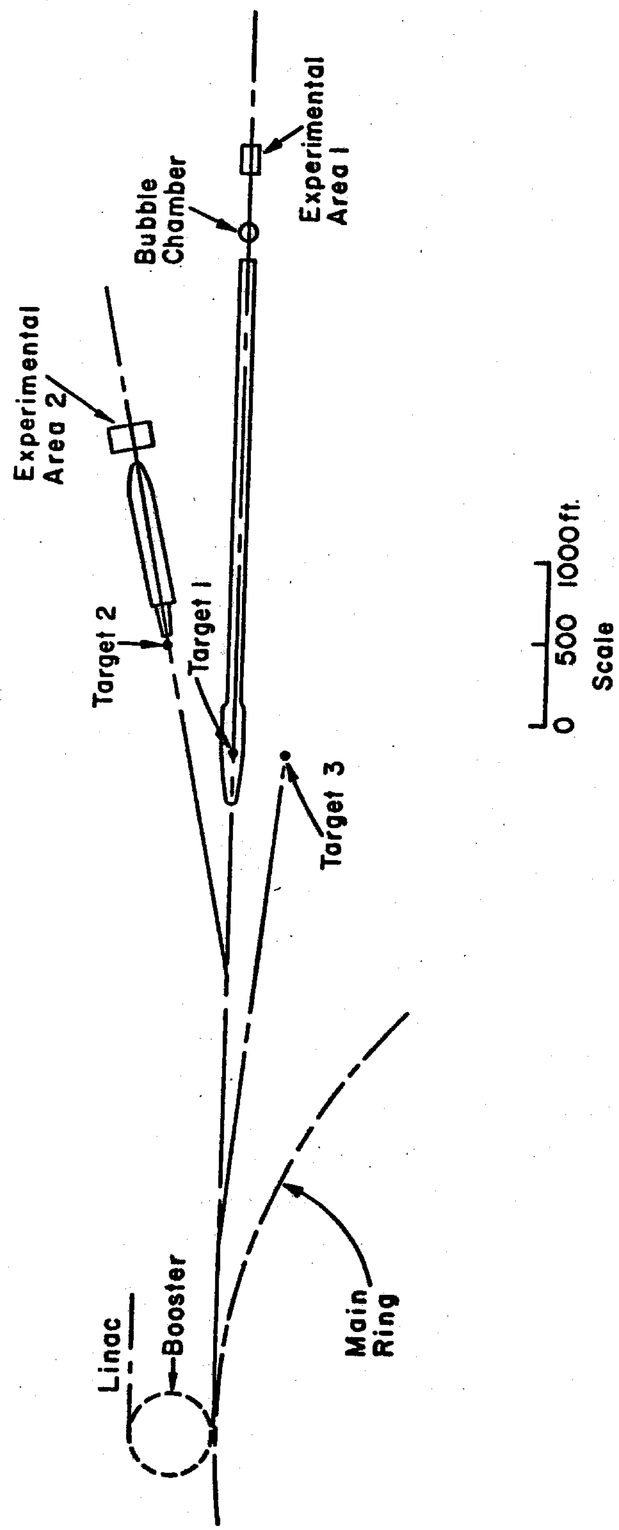

Fig. 2(a). Layout of experimental-beam areas.

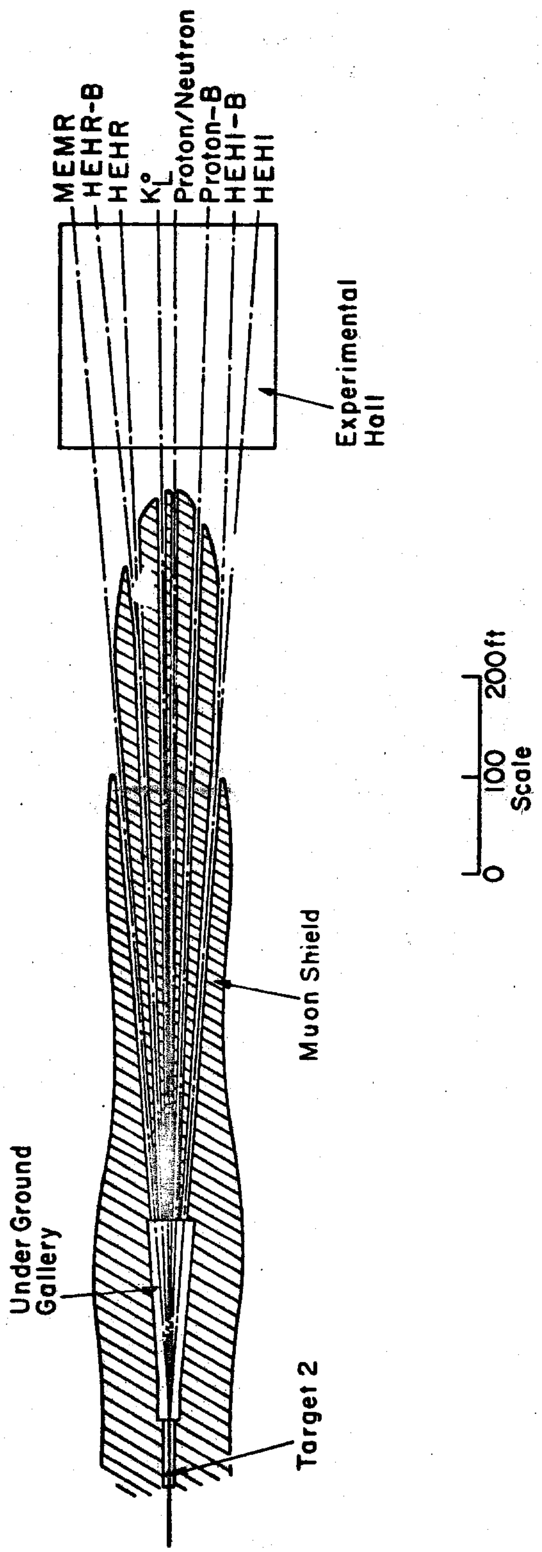

Fig. 2(b). Experimental-area 2.

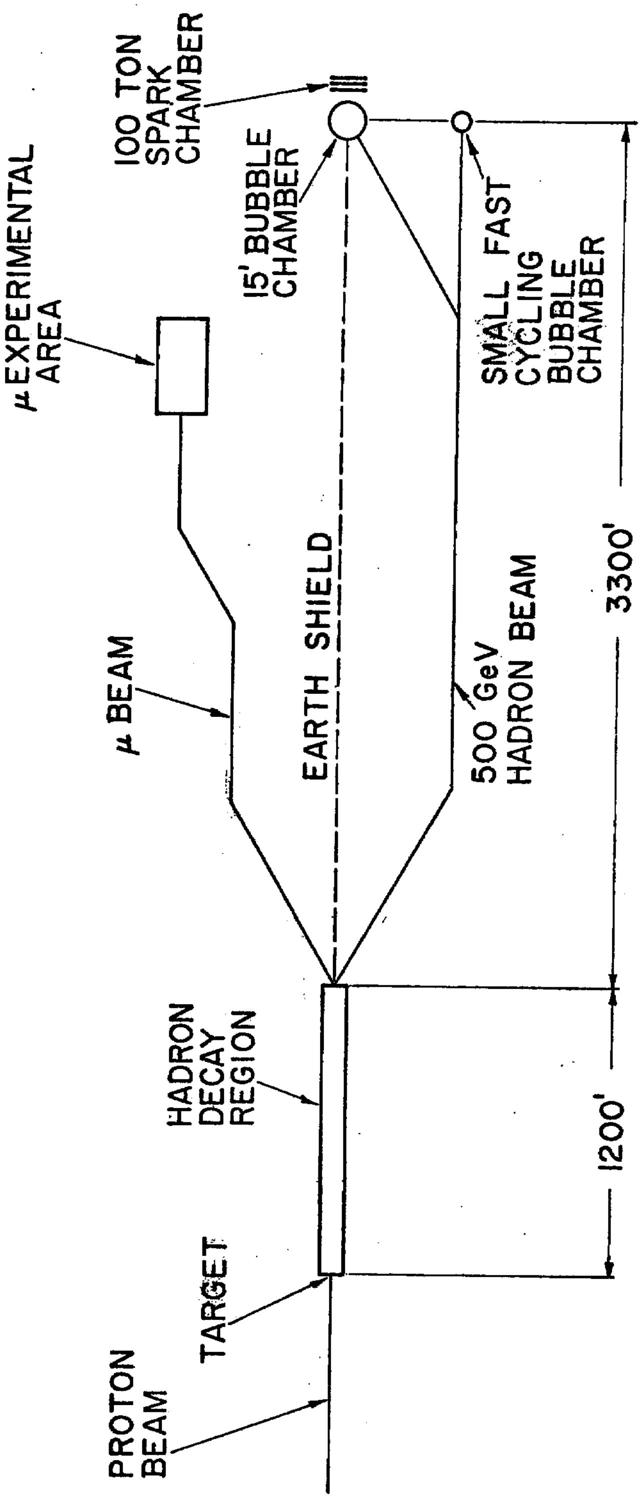

Fig. 2(c). Area one.