Fantasies of future Fermilab facilities

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The author presents a perspective on possible future projects at Fermilab.

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> *Oh, fancie that might be, oh, facts that are*!
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> (Browning, 1889)

I. FOREWORD

Fancies can be fantasized for fabricating future facilities at Fermilab, but fulfillment will depend on the unfolding of physics, on finding funds, on the focus of other laboratories, on forceful personalities and fierce fights; but most of all it will depend on new facts, new findings, new fancies. Thus Fermilab physicists might find it futile to feel their way to 5 TeV, might find it more fun to fill in facts about physics at 50 GeV, or they might find more felicitous the flowering of photon physics at 500 GeV. In the following phantasmata, let me first figure on the most fruited fulfillment, let me flounder in a veritable fantasia of physics facilities; for realistic factors finally "little by little will subtract faith and fallacy from fact."

II. INTRODUCTION

The Fermi National Accelerator Laboratory was established in 1967 after the dramatic selection of a 7000 acre site located near Chicago, Illinois from the many sites presented throughout the nation. Figure 1 shows the site as it now appears; it is very flat and roughly rectangular, 5 km on a side. The proton synchrotron shown in Fig. 1 was brought into operation at 200 GeV in March 1972. It has supplied protons to the four experimental areas, also shown, which have successively been brought into operation. The synchrotron was designed to accelerate 5×10^{13} protons per pulse (ppp) to 500 GeV. Although the accelerator did reach an energy of 500 GeV, it regularly operates at 400 GeV and at intensities of about 2×10^{13} ppp, the maximum so far being 2.6×10^{13} ppp at a cycle time of about 10 seconds.

The characteristics of the accelerator and the experimental areas have been described in detail in a review article by J. R. Sanford (1976). As of July 1978 some 250 experiments had been completed of the 300 proposals for experiments which had then been approved. The results of those experiments have been published in about 225 articles, (Half of the articles about experimental particle physics appearing in Physical Review Letters during 1977 were about work done at Fermilab).

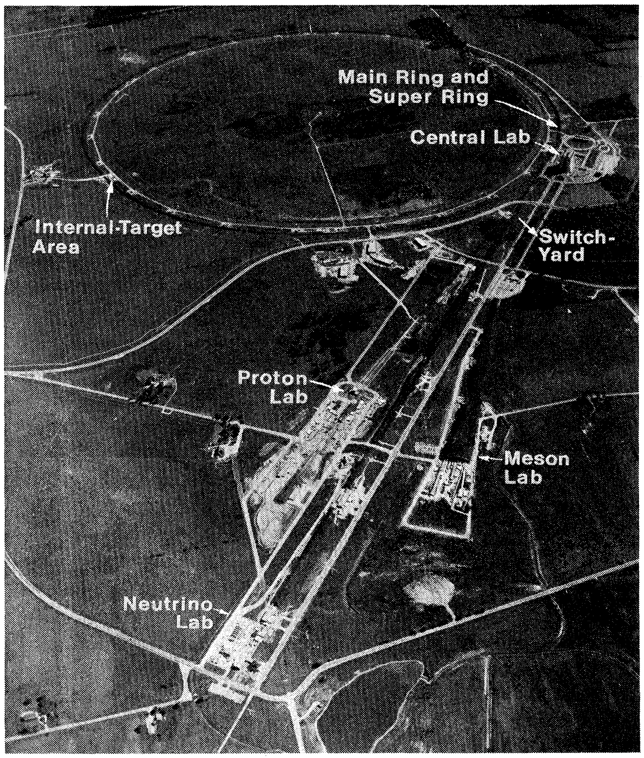

FIG. 1. Aerial view of the accelerator and experimental areas at Fermilab. Some improvements to the experimental areas have already been started to accomodate the extracted 1 TeV beam when available.

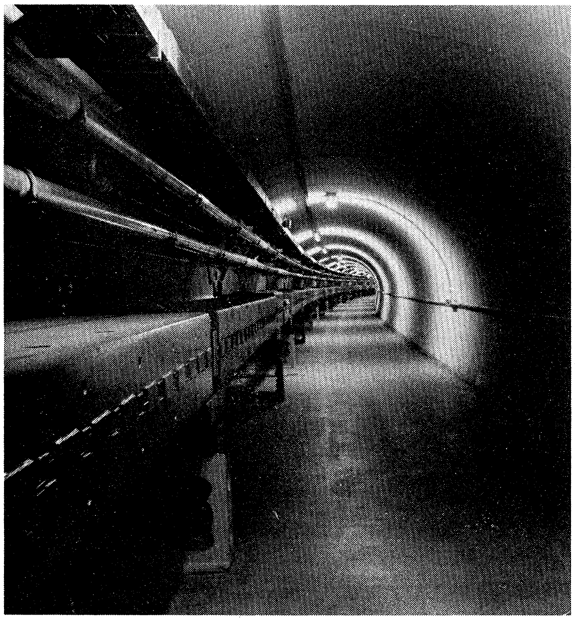

FIG. 2. The Main Ring accelerator tunnel magnets (Superperiod A) bend the proton beam into a circle with a circumference of 6.2 km.

FIG. 3. Superconducting magnets mounted directly below the conventional magnets of the Fermilab Main Ring, where extra space was provided for this installation at the time of the original construction around 1971. When the Super Ring is completed the 500 GeV proton accelerator will become the "Tevatron," with its energy increased to 1000 GeV (1 TeV).

The present emphasis at Fermilab is to carry out the experiments already underway or in preparation. Improving the reliability of the whole facility would probably contribute most to this, for an exceedingly complicated chain of circumstance must be favorable before a proton which has left the source finds its way through four tandem accelerators and through the maze of beam switches and beam splitters that directs it to the proper experimental area—perhaps one or two kilometers away—and then puts it on just the right target. Usually, a secondary beam of pions or photons or neutrinos must be produced and then guided to the experimental equipment. The experimental equipment itself may almost match the complexity of the accelerator—and all this must be working simultaneously and favorably if a good experiment is to result. Effort is also continuously given to increasing the intensity and the operating energy, for this opens new possibilities for experiments.

For the immediate future the fantasy of the Tevatron, a program to install a second ring of superconducting magnets in the Main Ring Tunnel as shown in Fig. 3 which should provide 1-TeV protons for fixed target experiments, and which should make possible colliding-beam experiments with c.m. energies up to 2 TeV, becomes less fantastic as actual superconducting magnets of high quality are installed in the tunnel. On the other hand, serious problems that are connected with any new technology are anticipated as the "dolce far niente" of fantasy turns to the "non posso far niente," or nearly so, of reality.

The Tevatron "variations" will be described, including the possibility of colliding 12 GeV electrons against one TeV protons and, of course, the improvement of the experimental areas so that experiments can be extended to one TeV. Success in any part of the Tevatron program will present the concomitant necessity of choosing between delectable alternatives, and an intense competition between colliding-beam and fixed-target experiments will inevitably ensue. The construction of Bypasses of the Main Ring would be one way to decouple colliding-beam experiments from the fixed-target program, for then, at least to some extent, both endeavors might proceed simultaneously.

A more complete decoupling of the programs as well as a major extension of beam-colliding facilities would result from the construction of an Inner Ring which might share the straight section of one of the Bypasses. A number of possibilities, such as higher luminosity and higher energy, will be discussed with regard to Bypasses. A brief epicedium will be celebrated for the ill-fated proposal to make a completely separate storage ring project, POPAE.

Because the site is large, a farther look into the future is taken in order to explore the limits of what might be attained at Fermilab. This might be the "Pentevac," a 5 TeV accelerator which would be composed of the largest ring of magnets, 5 km in diameter, which can be inserted within the present boundaries. Of course, by going deep underground in the manner of the Super Proton Synchrotron at CERN, the magnet ring might be completely freed of the confines of the site, but that possibility is so fraught with legal and political problems that it is not considered here. The Pentevac would be fed protons (or antiprotons) from the Main Ring or the Tevatron, and would open all the possibilities at 5 TeV which have been presented by the Tevatron for one

TeV. The large ring would also make high-energy electrons worthy of serious consideration. An electron–positron storage ring to give a c.m. energy of 100 GeV (or even twice that) is a distinct possibility.

Perhaps that is enough fantasy for now.[1]

III. THE TEVATRON

The general idea of the Tevatron (Wilson, 1977a; Tollestrup, 1978) is to use the present Main Ring accelerator as an injector for the Super Ring by accelerating protons to 100 GeV in the Main Ring and then transferring those protons to the Super Ring. The magnetic field in that ring would then be increased in about 20 sec from 4.25 kG to 42.5 kG, at which strength the energy of the protons should reach 1 TeV. The rest of a one-minute-long cycle might include a 20-sec flattop followed by a 20-sec ramp down to the injection field of 4.25 kG. For this typical cycle, if 6×10^{13} protons can be injected and accelerated in the Super Ring, the average intensity will be 10^{12} p/sec. Of course the length of the flattop can be adjusted to about any value, thereby offering the possibility of increasing the rate of data acquisition by an order of magnitude for experiments limited by counting rate.

As described elsewhere, (Wilson, 1977; Tollestrup, 1978) superconducting magnets of good quality have been developed at Fermilab and are being mass produced. As of September 1978, about 30 magnets of the 1000 magnets needed for the Tevatron had been produced and installed in the Main Ring tunnel (see Fig. 3). There are many lessons to be learned from the actual installation, about vacuum, about cooling, and about the radiation effects of the beam. A particularly interesting step will come when the first sector of supermagnets (one-sixth of the magnet ring, i.e., 130 bending magnets each about 21 feet long, and 40 quadrupoles each about 5.4 feet long) has been installed and cooled. At that time, the circulating beam in the Main Ring will be bypassed through the sector. This should provide a severe system test of the Tevatron concept. The schedule for supermagnet production and installation of the whole Super Ring depends critically on the funding and might take from a few to several years.

A. 1 TeV protons on fixed targets

Let us first consider the Tevatron as a fixed-target accelerator (Fermilab, 1977). The earliest experiments to be made in this mode will probably make use of the internal target. This is a narrowly collimated beam of hydrogen or helium gas that intersects the circulating proton beam in the synchrotron donut. Many of the experiments in the Internal Target Area have been made as Soviet-American collaborations (Malamud and Nezrick, 1975), and all such experiments can be extended from 400 to 1000 GeV, essentially without any change of the experimental equipment.

In order to make use of the external experimental facilities, obviously the proton beam must be extracted from the synchrotron. Now a beam of 6×10^{13} protons at 1 TeV energy has a total energy of 10 MJ which highlights a problem already serious at 400 GeV: objects tend to vaporize or melt when exposed to the intense energy of such a beam. The extraction problem will be more difficult for the Tevatron than it is now, because in addition to parts of the ejector melting, scattered protons due to the inefficiency of extraction can be absorbed in the superconducting coils and cause them to "go normal." Because of this, either very fast (one turn) or very slow extractions will be easiest to do.

Once extracted, the proton beam must be split and guided to the various experimental areas. This is done in the "switchyard" area shown in Fig. 1. To raise the capability of the switchyard from 0.4 to 1 TeV will require the replacement of the conventional magnets (nearly 200 of them) by superconducting magnets. The first magnets being made for the Super Ring are expected to be inferior to those made after the assembly facility has been adjusted for the best precision. Since in the switchyard the beam passes through the magnets only once rather than hundreds of thousands of times, the precision required is less, and hence the first production magnets should be quite adequate for use in the switchyard. The first production magnets will also be useful in the experimental areas for guiding secondary beams of particles and as part of experimental apparatuses.

On the positive side, just bringing 1 TeV protons to the targets of the various experimental areas will cause a substantial increase in the intensity of the secondary beams. This is partly because the multiplicity of secondary particles increases with energy and partly because the production cone folds forward as the energy increases. As an example, with 1 TeV protons on target, rather than 400 GeV protons, the intensity of 250 GeV neutrinos will increase by an order of magnitude.

The main improvement in the experimental areas will be to raise the energy of various secondary beams. In most cases this can be done by replacing conventional magnets in the beam lines with supermagnets. The shielding for such beams in some instances must also be hardened, for example, by replacing earthen shielding with iron shielding. Thus in the Meson Laboratory it appears possible to raise the energy of the small-angle pion beam ($M2$) from 400 to 1000 GeV, of the medium-resolution beam ($M1$) from 400 to 600 GeV, and of the high-resolution beam ($M6$) from 200 to 400 GeV.

In the Proton Laboratory, many of the present experiments can be repeated at 1 TeV without change just by bringing the protons on target. The new high-intensity pion beam has been designed from its inception to go to 1 TeV when all the supermagnets have been installed. It is designed to yield about 10^{10} pions per 10^{13} protons on target. It will also have the capability of operating as an intense high-purity electron beam because the energy loss due to synchrotron radiation by the electrons as they pass through the magnets will make possible their separation from pions which lose very little energy by synchrotron radiation.

Photon beams, too, will become considerably more powerful tools of research with 1 TeV protons on target. In the broad-band beam (Sanford, 1976), the flux of photons at 250 GeV should increase by a factor of

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[1] Most of the ideas presented here have been borrowed from my fantastically talented colleagues at Fermilab.

about 100, depending on how the extrapolation is made. The beam of 250 GeV electrons should be about 10^8 per 10^{13} incident protons, which is relatively intense. These electrons can be used in the tagged-photon facility which will enable the experimenters to extend their precise measurements of photon interactions (Caldwell *et al.*, 1978) from the present photon energy of 185 to about 500 GeV.

In the Neutrino Area, by adding iron shielding and iron magnets in appropriate combination, it is anticipated that neutrino measurements can be extended to about 750 GeV (Fermilab, 1977). A new muon beam is being designed that should provide a flux of about 10^8 muons/ per 10^{13} protons at an energy of 500 GeV (Cole, 1978), and muon energies up to about 800 GeV should be available with useable intensities.

B. 250 GeV protons colliding with 1 TeV protons

The Tevatron can also be used as a colliding-beam facility. The possibility of colliding beams presents the exciting prospect of a tremendous increase in the center-of-mass energy in nucleon–nucleon collisions, i.e., from about 30 GeV typical of fixed targets to as much as 2000 GeV for colliding beams. This prospect can be effected by using both the Main Ring and the Super Ring as storage rings. In one mode of colliding beams, we can imagine filling the Super Ring with protons from the Main Ring and then, after acceleration to 1 TeV, clamping the magnet current so that the protons circulate continuously. Then protons can be injected into the Main Ring in an opposite direction and accelerated to, say, 250 GeV at which time that ring too would be clamped. It should then be possible to bring the counter-rotating beams into collision in a few of the straight sections, and with expected luminosities[2] as high as 10^{32} $\text{cm}^{-2}\,\text{sec}^{-1}$. There are six straight sections, each 50 m in length, of which three are used for such things as injection and extraction of the beam, rf acceleration, or beam-abort equipment. The remaining two or three straight sections could be available for colliding-beam studies. At 250 GeV in the Main Ring, the center-of-mass energy will be about 1 TeV. A 40% increase in the c.m. energy could be attained by pulsing the Main Ring to 500 GeV, but at the cost of average luminosity. This c.m. energy is roughly equivalent to that available were 10^6 GeV protons to be incident on a fixed target.

Will the vacuum in the rings be adequate for serious colliding-beam experiments? The donut of the Super Ring is to be made vacuum tight with respect to the thermally insulating vacuum of the cryostat in order to achieve the best vacuum, and advantage will be taken of the cold bore at 4.6 °K to use cryosorption pumping between magnets. It is estimated that a vacuum of about 10^{-10} Torr (room temperature equivalent, i.e., about 10^7 helium atoms/cm^3) will obtain in the donut, and this should correspond to a beam lifetime at 1 TeV of many days, but we do not yet know about resonant effects.

The vacuum in the Main Ring, presently about 10^{-7} Torr, is not so critical for storing a beam because the Main Ring can frequently be refilled. At present a beam life of a few hours has been observed on clamping the Main Ring energy at 200 GeV. However, gas scattering in the Main Ring donut gives rise to a serious radiation background in the tunnel; the vacuum can be improved by a factor of about 10 by eliminating the many tiny leaks that exist, by outgassing the donut in place with heating, and if necessary by adding cryogenic pumping. The lifetime may be limited by resonant effects induced by magnetic imperfections. How much these can be corrected is still to be explored.

Can the beams stored in the two rings be brought into collision? Two possibilities are shown in Fig. 4. The "kissing scheme" is limited to relatively low c.m. energies, perhaps less than 1 TeV, by the strength of magnets. A more satisfactory arrangement without an energy limitation is to lower the Main Ring magnets to floor height for one or more sectors (there are six) of the Main Ring. For these lowered sectors of the Main Ring, the supermagnets would be mounted *above* the conventional magnets. The beams of the two rings would then be caused to transpose up and down at the straight sections by tilting, or "rolling," a few bending magnets in the near vicinity of the straights. The tilting of the magnets would produce a horizontal component of the magnetic field which would cause the vertical motion. The desired result is the crossing of the beams at all energies and hence the easy possibility of bringing them into collision as illustrated in Fig. 4. Lowering one sector produces beam crossings in two adjacent straights, for example, in straight sections B and C. Alternately lowering three sectors will produce crossings in all six straight sections, and would make for a more symmetrical lattice.

In the crossing scheme, the angle between the beams is about 15 mrad, and at this angle of crossing the luminosity is less by an order of magnitude than that which would obtain for head-on collisions. Smaller crossing angles, down to zero, can be produced by placing magnets in the straight section. As an example, for an angle of 5 mrad between the beams, all but 12 meters of the 50-meter-long straight section would be used up if 18 kG magnets were deployed, but the luminosity would be increased by a factor of 2 or 3. Going to head-on collisions would require nearly all of the free space to be filled with conventional magnets, but the luminosity would be increased by a factor of 10 or 20.

If we assume single-turn injection in the Tevatron of 2×10^{13} protons and that the orbit function has the normal value of 70 m, the luminosity should be about 0.4×10^{30} $\text{cm}^{-2}\,\text{sec}^{-1}$ for proton energies of 1 TeV in the Tevatron and 250 GeV in the Main Ring.[3] For this lum-

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[2] The synchrotron radiation by the protons begins to become significant at 5 GeV. The 2 KeV per turn of radiation will cause a "cooling" of the beams to half size in about one day.

[3] The luminosity in $\text{cm}^{-2}\text{Sec}^{-1}$ for colliding the Main Ring beam with the Super Ring beam is given by $L\approx 7.5\times 10^{24} n_1 n_2/(\sigma_1^2+\sigma_2^2)$ which applies for colliding beams bunched at the same frequency (53.1 mHz) into 1113 bunches. The number of proton stored in the rings n_1 and n_2, is measured in units of 10^{13}. The mean squared Gaussian widths of the beams, σ_1^2 and σ_2^2, are in *mm* and are given by $\epsilon\beta/6\pi$, where β is the orbit function (in meters), and the emittance ϵ is given roughly by $13\pi/E$ in mm-mrad, E being the proton energy in GeV. Thus we can see that the luminosity should increase approximately linearly with the energy of the least energetic protons.

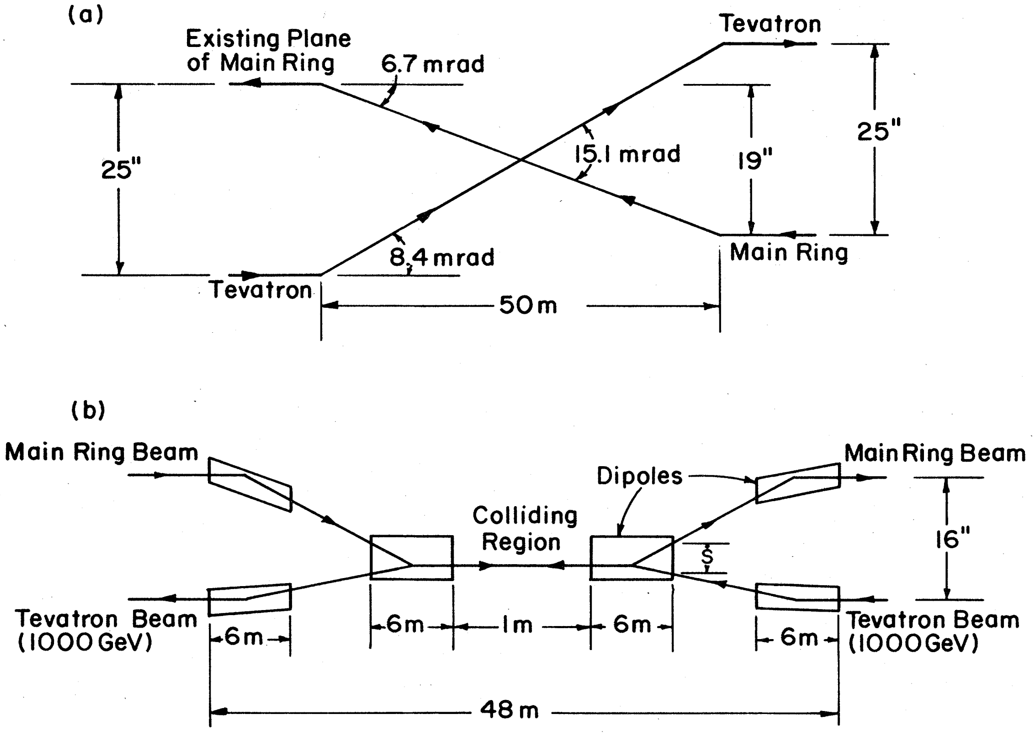

FIG. 4. Two schemes for colliding beams. In the transposition scheme (a), the Main Ring magnets will be lowered to the floor in one or more of the six sectors of the ring, and the supermagnets mounted above them (the opposite arrangement to that of Fig. 3). Beam crossover at the straight sections will be caused by tilting a few magnets near these points. The "kissing" scheme (b) keeps the Main Ring above the Super Ring in all sectors, and brings the two beams together over a "colliding region" of length 1 m in one or more of the straight sections.

inosity there should be about 20 000 interactions per second. Now there may be adequate phase space in the Tevatron in which to stack protons, so ten turns might be stored at 100 GeV before accelerating to 1 TeV. In that case the luminosity just calculated would increase to 4×10^{30} $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$. However, the energy stored in such a beam would be 30 MJ—a frightening prospect.

Another way to increase the luminosity is by decreasing the width of the beams at the center of the straight section. T. Collins (1976) has invented a very simple scheme for reaching an orbit function of 2.5 m (instead of the normal value of 70 m) by separately powering the present quadrupole magnets adjacent to the Main Ring straight section. This will work for energies up to about 150 GeV without any changes, and it will go to higher energies by replacing, or by supplementing, the present quadrupole magnets with superconducting ones. If all this is done, including stacking, the luminosity might increase to about 5×10^{32} $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ corresponding to a total rate of about 10^{7} interactions per second (mostly forward) in which case there might be trouble with the counting rates in the detectors. The beams would be typically a few tenths of a millimeter in width, and because of the rf bunching of the protons, the collisions would occur over a length of several tens of centimeters.

We have seen that the beams can be brought into collision in the straight sections with reasonably high luminosity, but it is fair to ask if there is room and time for significant experiments to be made. Now there can be little doubt that if the beams were colliding as described, then the ingenuity of physicists would be challenged; they would doubtlessly find methods of utilizing even the present cramped space of the tunnel at the straight sections; they would fill the space with a solenoidal magnet and with detectors of great resolution; they would place muon detectors in holes dug in the vicinity of the tunnel. They would catch an intermediate boson and they would see the unseen and unimagined!

Poetry aside, good physics requires a combination of high luminosity *and* of sensitive detecting equipment—both must be optimized. There is little reason not to enlarge the tunnel at a straight section into a substantial experimental hall in which a rather elaborate detector can be installed. This was done at the Internal Target Area when a substantial enclosure was added contiguous to the tunnel and without losing operating time of the synchrotron.

A study was held in Aspen during the summer of 1977 to consider specific colliding-beam experiments that might be made in the straight sections. An elegant device was designed which would have universal application, but which specifically could be used to search for the intermediate boson. Although the cost, about six million dollars, appeared to transcend the probable financial resources of Fermilab, the exercise did show what could be done—perhaps even what had to be done. The exercise also emphasized the serious nature of constructing, installing, debugging, and then using such an

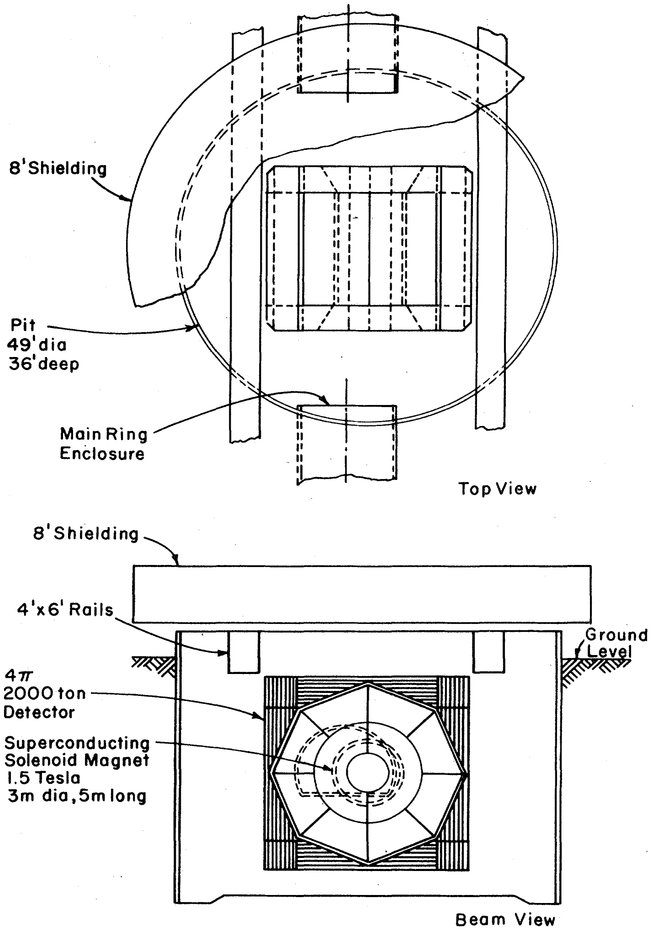

FIG. 5. (a) Colliding-beam detector and pit. (b) Colliding-beam detector and pit—beam view.

instrument in view of the expected heavy demand for fixed-target physics.

A group has been formed at Fermilab under the leadership of Alvin Tollestrup to organize the design and construction and use of a major detector facility. Figure 5 illustrates the group's present thinking about the detector and its enclosure. This detector would consist of a superconducting axial magnet with very open return yokes in order to facilitate the insertion of the various moduli which would contain the usual mixture of detector elements that identify the kind, the tracks, and the momenta of the multiplex of particles coming out of a collision. In order to allow for construction and debugging of the detector simultaneously with the use of the Tevatron for other experiments, the possibility is envisaged that the whole facility, magnet, and detectors (some 2–4 thousand tons) could be raised to the surface where it could be shielded from the radiation of the accelerator.

It should be emphasized that there is much more of nature to be explored than just to search for the intermediate boson. For one thing there are the mysterious phenomena observed in cosmic rays: the Centauro event at about 1000 TeV with practically no electromagnetic component; the Bristol event at 100 TeV with practically no nuclear component; or the increase in mean penetration observed in the Tien-Shan experiments at energies greater than 100 TeV. All these occur at much less equivalent energy and at tremendously less luminosity than will be available in the Tevatron in its colliding mode. Also available for study is small-angle scattering, or the interesting jet phenomena which should occur when two quarks collide, not to mention the possibility of actually producing a quark, or something even more exotic.

C. 1 TeV antiprotons colliding with 1 TeV protons

A quite different approach to colliding beams has been made possible by the development of "beam cooling" by the late Gersh Budker and his colleagues at Novosibirsk (Budker, 1967; Dikansky *et al.*, 1977). Beam cooling refers to the effect that occurs when an ion beam is caused to interact with a "cold" beam of electrons traveling together with the ions with the same average velocity. The transverse components of velocities of the particles in an ion beam can be reduced by this effect so that the beam can be injected into an accelerator. A scheme to apply this effect at Fermilab has been put forward by Rubbia, McIntyre, and Cline (Rubbia *et al.*, 1977; see also Mohl *et al.*, 1976). Thus antiprotons can be produced by having 100 GeV protons from the Main Ring collide with a target near the Booster Accelerator as shown in Fig. 6. The resulting antiprotons can then be captured, cooled, and stored in a small auxiliary ring, and this can be done for thousands of pulses of the Main Ring. When enough antiprotons have been collected, they can be injected back into the Booster for acceleration and transfer to the Main Ring where they can again be accelerated and then transferred to the Tevatron. After the antiprotons have been injected from the Booster into the Main Ring, a pulse of protons would also be injected in the opposite direction, and the two counter-rotating beams would then be accelerated to a desired energy, up to 1 TeV. Collisions between the protons and antiprotons could thus be studied in the straight sections up to a c.m. energy of 2 TeV. Although, in principle, collisions up to 1 TeV c.m. could also be studied in the Main Ring by this method (the vacuum and luminosity might be marginal) it appears that the Super Ring is much better matched to this application, as well as providing twice the c.m. energy. Using the Super Ring has the further advantage that the Main Ring might be used in its present mode to supply high-energy protons to the external experimental areas while the Super Ring was being used for colliding-beam experiments.

It appears that a luminosity of between 10^{28} to 10^{29} $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ might be achieved for the antiproton–proton colliding mode (Rubbia *et al.*, 1977; Mohl *et al.*, 1976), and there are possibilities of reaching even higher values (Cole, 1978). Although such luminosities are less than can be expected for collisions of protons on protons there are advantages beyond the independence of the operational mode just mentioned. For example, it is expected that the interaction between nucleons can be reduced to interactions between the constituent quarks. An interaction between a quark and an antiquark ought to be more interesting than an interaction between two similar quarks because all the quantum numbers are an-

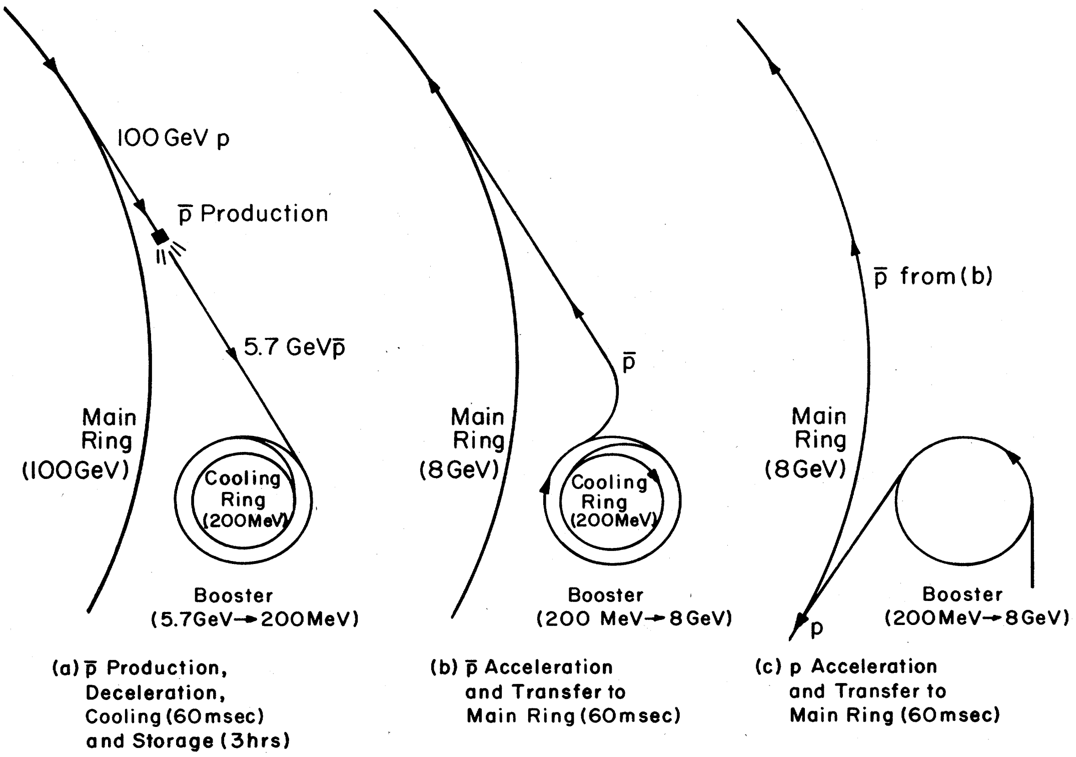

FIG. 6. Scheme for producing "cooled" antiprotons.

nihilated as in e^+e^- collisions. Theoretical considerations (Quigg, 1977) indicate an enhancement of W^+ production in $\bar{p}p$ collisions over that in pp collisions.

A moderate project is underway at Fermilab to confirm the Novosibirsk cooling results (see the cooling ring in Fig. 7), to apply them to cooling antiprotons, to accelerate those antiprotons, and then to study collisions of antiprotons with protons (Gray *et al.*, 1977; Cole, 1978). At CERN a similar project (Van der Meer, 1972; CERN, 1978) is underway with an emphasis on "stochastic cooling." Stochastic cooling implies that the average position of a segment of the beam is sensed and then that the deviation is corrected by an electrical signal which outruns the beam by taking a shortcut across the ring. Because stochastic cooling should be very effective in cooling synchrotron oscillations, it is probable that both

FIG. 7. Aerial view of antiproton test cooling ring.

methods will eventually be used at Fermilab. One can expect new ideas and inventions yet to occur with regard to reducing the size of colliding beams because of the importance of the experiments which would result at the higher luminosities which would then obtain.

D. 12 GeV electrons colliding with 1 TeV protons

Rich possibilities exist at Fermilab for the highly desirable study of electron–proton collisions. These possibilities have been taken very seriously since 1973 when a Fermilab Long Range Advisory Committee recommended the evolution "through a 1 TeV fixed target accelerator to include both a 1×1 $(\text{TeV})^2$ *pp* device and a 0.02×1 $(\text{TeV})^2$ *ep* device." The committee pointed out that with such energies it should be possible to penetrate the region in which the weak interactions could be expected to overtake electromagnetic interactions in strength. For a while, consideration was given to bringing the Cambridge Electron Accelerator synchrotron to Fermilab and rebuilding it to be tangential to the Main Ring. It would have been used as a 3 GeV circulating "electron target" for the 400 GeV circulating proton beam in the Main Ring (Collins, *et al.*, 1973). This experiment was abandoned at the recommendation of the same Long Range Advisory Committee; they did not feel it to be worth the cost or effort for the expected results. The next attempt was to follow the Committee's advice and include an *ep* option in the POPAE (Protons on Protons and Electrons) project which will be described in Sec. VI. That project did not become viable either.

At the 1976 Fermilab summer study at Aspen concerned with experiments using the Tevatron, there was a recrudescence of interest in *ep* collisions, an interest which had also surfaced in 1973 (Edwards, 1973). It was pointed out that with a suitable electron injector, the Main Ring itself could be used to accelerate and store electrons at energies up to about 12 GeV, and that in collisions of these electrons with the 1 TeV protons in the Tevatron, a luminosity of as much as $10^{32}\,\text{cm}^{-2}\,\text{sec}^{-1}$ might be obtained (Griffin and Ruggiero, 1976; Ruggiero, 1973). Significant counting rates could be anticipated for values of transfer momenta squared, Q^2, higher than 10^4 $(\text{GeV}/c)^2$.

Ruggiero and others (Griffin and Ruggiero, 1976; Ruggiero, 1973) have investigated in considerable detail the acceleration of electrons in the Main Ring, and a concentrated effort in 1978 has resulted in a conceptual design study of an *e-p* colliding-beam facility (Ruggiero *et al.*, 1978). The scheme is illustrated in Fig. 8. In the first phase, the Main Ring would be used for about one minute as an injector of protons into the Tevatron; it is envisaged that 10 pulses would be stacked at 100 GeV to give a total of 2×10^{14} protons which would then be accelerated slowly to 1000 GeV, at which energy they would be stored in a bunched mode at the standard frequency of 53 mHz. In the second phase, a 75 MeV electron linear accelerator would be used to inject electrons into the Cooling Ring, which is already being constructed to produce an intense beam of antiprotons. The electrons would be accelerated in the Cooling Ring to 750 MeV, transferred to the Booster where they would then be accelerated to 4 GeV, and then transferred to the Main Ring in the opposite direction to that of the protons. The Booster cycle would be repeated many times, as it is for protons, until the Main Ring had been filled. Then the electrons would be accelerated to 12 GeV using the same rf system as for protons, except the frequency would be held constant at 53 mHz. By installing more rf accelerators, a higher electron energy could be reached, but rf power considerations might very probably reduce the luminosity that could be attained.

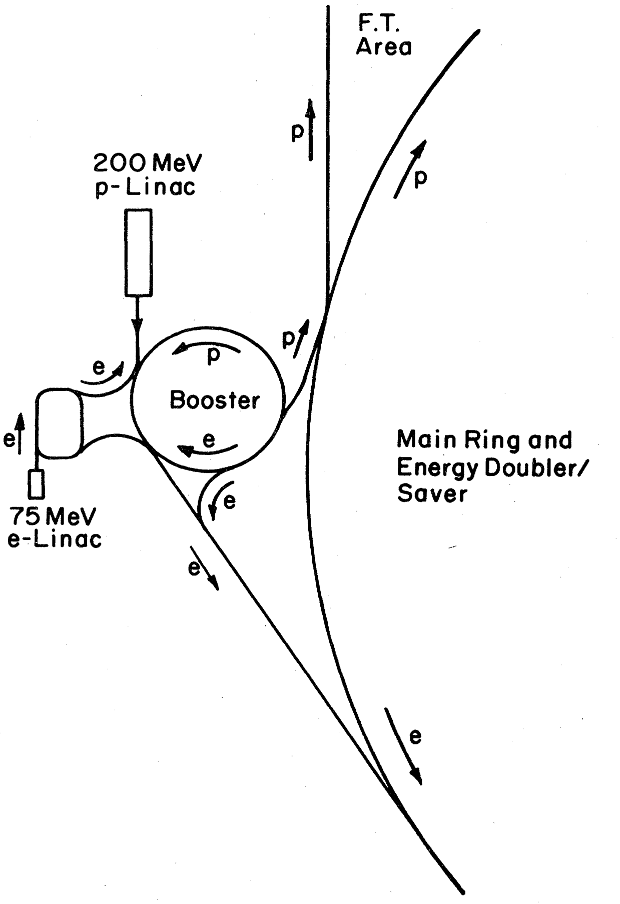

FIG. 8. The *e-p* colliding-beam facility.

The electrons would be brought into collision with the protons in the Tevatron about 25 inches below by bringing the electrons down through a short vertical Main Ring bypass (see Fig. 6) to become tangent to the Tevatron beam (actually the beams would intersect at a horizontal crossing angle of 2 mrad). A low-beta insertion would be included in the bypass lattice to give a beta value of about 30 cm, which would imply a luminosity of about 10^{32} $\text{cm}^{-2}\,\text{sec}^{-1}$.

Now assuming that problems of injecting into the Main Ring at 4 GeV, and maintaining an adequate vacuum in spite of evolution of gas by synchrotron radiation, and of getting an adequate beam of 1000 GeV protons can all be solved, how about the physics? There can be little question that the electron is and will remain an excellent particle with which to probe the structure of the proton. If the electron continues to behave as a simple

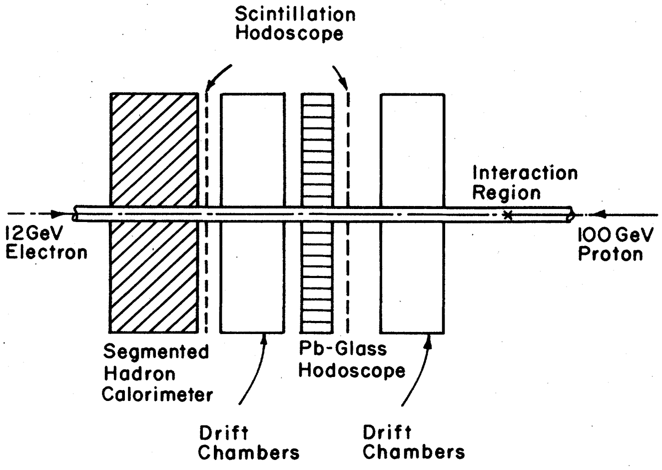

FIG. 9. An example of a nonmagnetic *ep* detector.

particle, the *e*-*p* colliding beam should be able to resolve distances within the nucleon of the order of about 10^{-16} cm. With the proposed muon beam of the Tevatron, Q^2 values of the order of about 500 $(\mathrm{GeV}/c)^2$ might be reached. The *e*-*p* facility should allow exploration to Q^2 values about four times higher—forty times that of any present μ-scattering experiment. In the *e*-*p* study report of Ruggiero *et al.* (1978), consideration is given to experiments on deep-inelastic scattering, on electro- and photoproduction, and on weak interactions; it is concluded that each of the fields of study would be importantly accessible to the *e*-*p* facility. They give the design of two detectors: (1) a nonmagnetic detector suitable for exploring the neutrino reaction which is characterized by the lack of a scattered electron and by the large transverse momentum of the final-state hadron; and (2) a magnetic detector suitable for the exploration of deep inelastic scattering which is characterized by a very high-energy electron in the backward hemisphere of the incident electron. A schematic diagram of the nonmagnetic detector is indicated in Fig. 9, the overall dimensions of the detector being about 3 m wide by 5 m long.

The difficulty, of course, is that this beautiful *ep* physics would be in competition both with the *pp* and $\bar{p}p$ colliding-beam experiments and the fixed-target experiments—equally beautiful. On the other hand the cost of the project is modest; perhaps the electron linear accelerator can be found on surplus, or, if new, it is estimated to cost $1.4 million. The other components and the two detectors are estimated to cost about $6 million. The total cost might be about $10 million.

Although there is every reason now to be optimistic that antiprotons can indeed be cooled, nevertheless, that process is very complicated and, in the sum of all the delicate operations, might flounder and fail to produce high-luminosity colliding beams. In that case, or even in the case of a significant delay, the *ep* facility would provide a very welcome alternative option. In any case, the physics available will eventually become irresistible and will be done, perhaps in the Inner Ring, to be discussed later, if not in the Tevatron.

IV. ACCUMULATOR RING

The Accumulator Ring is a low-energy ring to be placed in the Main Ring tunnel, for example at the top of tunnel, in order to improve the average intensity of the Main Ring accelerator and of the Tevatron. It might increase the luminosity of the Tevatron in the colliding-beam mode; it might further decouple the use of the Main Ring as a fixed-target accelerator while using the Tevatron as a $\bar{p}p$ collider; it might offer an alternative way of accelerating and storing electrons in the Main Ring tunnel; and finally it has also been suggested as a colliding-beam facility when used either with the Main Ring or with the Super Ring. The Accumulator Ring would be modest in that the maximum energy sought is only about 30 GeV. For a lattice similar to the Main Ring, the maximum field would be about 1.4 kG so a higher energy might also be considered, i.e., 100 GeV. Actually shorter magnets at correspondingly higher fields and arranged in a lattice specifically designed for both electrons and protons might be used.

To increase the proton intensity, the Accumulator could be storing pulses from the Booster Accelerator and be accelerating them, say, to 30 GeV, during the same time that the Main Ring would be accelerating a previously injected pulse from the Accumulator. Because of this simultaneous operation, the pulses could overlap in time, hence the cycling rate of the Main Ring and thus the average intensity would be increased. More importantly, the optical quality of the beam would be better in each dimension at 30 GeV than at the present injection energy of 8 GeV, hence the possibility of stacking, say, ten turns in the Main Ring would be opened. There is also an advantage of injecting above the critical energy of the Main Ring, about 25 GeV. Protons from the accumulator could also be used directly to make antiprotons, thus freeing the Main Ring for almost independent use as a fixed-target accelerator while the Super Ring was being used as a $\bar{p}p$ colliding beam facility.

The Accumulator can be considered as an improvement to the present accelerator, rather than as a separate accelerator project, and if it is made, it will probably be done in that spirit. It might cost about $8 million.

An Accumulator Ring might also be built into the Booster Tunnel. One such ring in which to cool and stack antiprotons has already been discussed. That ring might also be used to stack protons from the 200 MeV linac and then to accelerate them to an energy where space-charge effects in the Booster Accelerator would not limit the beam intensity as they appear to do now.

Another possibility would be to install a ring of superconducting magnets in the Booster tunnel. Using exactly the same lattice but a slower cycling rate, it should be possible to make 50 GeV protons. These protons could be accelerated between Main Ring injection pulses and could be used, for example, to produce an intense beam of low-energy neutrinos, or an intense K^0 beam. The 50 GeV protons might also be used to produce antiprotons without interfering with the Main Ring fixed-target program. The Accumulator Ring, of course, could also be built in a separate tunnel to reduce the general congestion.

V. BYPASSES

The colliding-beam experiments using the Tevatron, even with the Accumulator, will inevitably be in conflict with a vigorous program for use of the Tevatron as a source of 1 TeV protons for fixed-target experiments. It is not just a question of running a colliding-beam experiment; the installation of an experiment and then bringing it into operation can also be very time consuming. Furthermore, the average luminosity of the Tevatron as a collider will be decreased because of its alternating use in colliding and then fixed-target modes. The straight section length 50 m may also be somewhat constricting for some experiments.

A modest first step to provide a greater decoupling between programs, and a greater accessibility to the colliding experiments, would be to build a Bypass (Wilson, 1977b) as shown in Fig. 10. This would consist of a new section of tunnel that would bypass a third of the Main Ring going from straight section *F* to straight section *B*. The radius of the curved part of the tunnel as shown would be about 0.8 of that of the Main Ring on the assumption that by the time the Bypass would be built, the superconducting magnets installed in it would reach a 20% higher field strength than for those installed in the Main Ring tunnel.

It can be seen that a particularly long straight section (400 m) would then become conveniently available right in the vicinity of the Central Laboratory Building. Clearly a longer or shorter length of the Bypass straight section could be arranged by choosing a different radius of curvature. Alternatively, the Bypass straight section could be broken down into a number of shorter straight sections isolated from one another by a small number of bending magnets to be placed between them. Another possibility would be to have a number of parallel straight sections so that the beam could be switched from one to another, thus permitting a greater independence of installing and running different experiments.

Very likely it is possible to invent schemes of pulsed magnets and magnet placement so that the beam could be switched at any time from the Main Ring to the Bypass. I doubt that any such arrangement would really be necessary, and assume for simplicity that it would be adequate to choose to run in one mode or the other for periods of weeks or months. In that case, at the points where the Bypass leaves and rejoins the regular magnet ring, i.e., at SS-F and SS-B of Fig. 10, the interfering magnets would be physically moved so that *either* the regular magnets would be connected, *or* the Bypass magnets would be connected. Only one cell (eight bending magnets) need be moved at each end, so the changeover from one mode to the other should require only about one day. This simple scheme would require that the beam transfer from the main ring to the superconducting ring be changed from SS-A to one of the other straight sections.

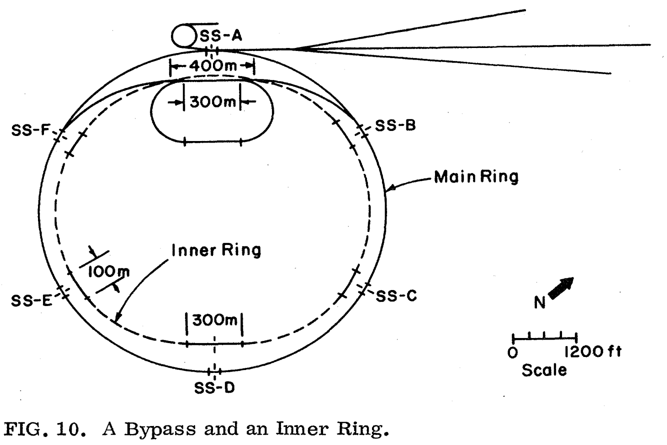

FIG. 10. A Bypass and an Inner Ring.

The Bypass magnets, as they bend away from the main ring, would be a source of inconvenience, for they would snake along the floor, obstructing passageway along the Main Ring tunnel. The inconvenience need not be major, however, for it will be easily possible to step over the Bypass magnets—or even to lift a bicycle over them.

With only the supermagnets installed, the Bypass would be available for $\bar{p}p$ collisions on a nearly stand-alone basis. Once the superconducting ring in its bypassed mode has been filled, the Main Ring could continue to operate simultaneously in its present-day mode to feed protons of energies up to 500 GeV to the external experimental areas.

It would also be possible to bring protons from the Main Ring into the Bypass for proton-on-proton colliding-beam experiments by installing a string of conventional magnets above the superconductor magnets, just as in the rest of the Main Ring. However, it is doubtful that either of these modes would justify by themselves the construction of the Bypass, for by the time it is built the initial low-luminosity experiments most likely will already have been done and we will be reaching for higher luminosity or higher c.m. energy, or both. The Bypass opens possibilities for further steps to be taken in both of these directions.

Presumably the Bypass tunnel, exclusive of the experimental enclosures at the straight section, would cost about one third as much as did the Main Ring tunnel, costs being appropriately inflated from 1970 to the time of construction, say 1980. This would bring the price of the tunnel to about $5 million. All Tevatron supermagnets and refrigeration are estimated to cost about $25 million in 1978, so we might guess that one-third of this would cost about $10 million in 1980. The experimental enclosure could cost about $3 million and if we add $2 million for utilities, etc., we would get a total price for the Bypass of very roughly $20 million, exclusive of any detector equipment—which might cost another $10 million.

A more modest version of a Bypass has been designed by F. R. Huson (1977). In his version only a part of one section is bypassed instead of two, and it has the advantage of not bypassing straight section A where the beam is injected into and extracted from the synchrotron. The cost would be roughly one-third that of the Bypass shown in Fig. 6. We could also consider building two independent small bypasses which would make for greater independence of access and use of the experimental equipment.

VI. INNER RING

The construction of the larger Bypass described above would lead naturally to a next step, the Inner Ring (Wilson, 1977), which would be a magnet ring placed concentrically within the Main Ring, as shown in Fig. 10, so as to share the Bypass straight section. The Inner Ring would be a stand-alone 3 TeV center-of-mass colliding-beam facility with high luminosity and with ample room for experiments. It should be modest in cost because it would utilize the straight section of the Bypass as injector and because it could make use of the utilities, services, and refrigeration capability already installed for the Main Ring and the Tevatron. It would also continue to make use of the experimental facilities already installed for the Bypass.

The average radius of curvature in the Inner Ring would match that of the Bypass, 0.8 of that the Main Ring. A number of geometries are possible for the Inner Ring. Thus a symmetrical arrangement with four straight sections, each about 300 m long, fits nicely in the available space circumscribed by the Main Ring cooling ponds. I have chosen instead to show the Inner Ring with six straight sections in an arrangement with twofold symmetry in which two of the straight sections, IRA and IRD of Fig. 10, are about 300 m long, and in which the other four straights are about 150 m in length. The principal reason for this choice is that it brings the straight sections and hence the experimental facilities of both rings into close conjunction and makes possible a greater use of already installed utilities, roads, and buildings. The larger number of straight sections would also provide for a greater flexibility in developing facilities for experiments. Again, the lengths of the straight sections appear to be on the large side, and they could be made smaller by choosing a larger radius of curvature both in the Bypass and the Inner Ring.

As a first step, the Inner Ring might contain one high-current storage ring which could be filled at the Bypass straight section. We can assume that considerably higher magnetic fields, say 80 kG, can be designed into the inner Ring magnets so that the injected protons or antiprotons could slowly be accelerated from an injected energy of between 0.1 TeV and 1 TeV to about 1.5 TeV. Thus *pp* collisions could be studied at a c.m. energy of about 2.5 TeV by colliding the 1 TeV protons achievable in the bypassed Tevatron ring against the 1.5 TeV protons of higher intensity available in the Inner Ring. These studies would be confined to the common Bypass straight section, IRA. Antiproton collisions with protons could be studied at any of the straight sections, at center-of-mass energies up to 3 GeV, and at much higher luminosities than in the original ring.

The highest luminosity and the greatest center-of-mass energy for *pp* collisions could be achieved by installing a second high-current storage ring in the Inner Ring tunnel. This stage of development would be almost the equivalent of the Fermilab POPAE proposal of 1975. The Inner Ring might cost between $100 and $200 million, depending upon how elaborate the facility is made.

Electron–proton collisions could also be studied in the Inner Ring, either by leading the 12 GeV electron beam from the Main Ring into the Bypass by the addition of some very modest magnets in the Bypass tunnel, or by adding a separate electron accelerator and storage ring in the Inner Ring tunnel. This would decouple the Inner Ring from the Main Ring and Tevatron, would make it possible to reach higher electron energy (perhaps as high as 30 GeV, depending on the expenditure of electrical power and money), and would open all the straight sections to *ep* experiments.

VII. POPAE

POPAE is an acronym for Protons on Protons and Electrons. It refers to a "1×1 (TeV)^2" proton–proton colliding-beam facility with a "0.2×1 TeV^2" electron–proton colliding-beam option as recommended by the Long Range Advisory Committee of Fermilab in 1973. The POPAE concept is the result of a study carried out in 1975–76 as a collaboration between scientists at Argonne National Laboratory and Fermilab led by Robert Diebold (Diebold *et al.*, 1976).

The project was to consist of two rings housed in a common tunnel of circumference 5.5 km (average radius 0.87 km) to be located at some distance from the Main Ring as shown in Diebold *et al.* (1976) Fig. (I-2, p.7). The magnetic field in the bending magnets was designed to be 60 kG, corresponding to stored beams of 1000 GeV each. Luminosities as high as 10^{34} cm^{-2} sec^{-1} were anticipated in six colliding regions.

The estimated cost of the project, assuming it would be authorized in October of 1977 and finished by March 1982, was $294 million. A very rough estimate for an *e-p* option that would provide a luminosity of 10^{32} cm^{-2} sec^{-1} for 10-GeV electrons was $25 million. An alternative plan which would provide for 500 GeV upon 500 GeV clashing beams of protons in an identical tunnel was estimated to cost about $155 million.

The project is essentially moribund at this time, largely because of a decision of the Department of Energy to proceed with an alternative project for a similar device at Brookhaven National Laboratory... "eppur si muove." POPAE is included here as a carefully worked out illustration of what can be done at the Fermilab site using the Tevatron as an injector for a storage ring facility. The more gradual approach to high-energy colliding beams which has been described earlier in this article has been adopted instead.

VIII. PENTEVAC

The Fermilab site is large and one might ask, "What is the largest accelerator that can be built within its confines?" The ring shown in Fig. 11 has a radius of 2.5 km, and, although a slightly larger circle would also fit, it is well to stay some distance away from the site boundaries. The rigid off-site radiation limitation, whether it be due to muons or neutrons, presents a serious problem. Starting with a tunnel 2.5 km in radius, we can ask what might go into the tunnel. Rather than putting three magnet rings in the tunnel so we could attempt every possibility at once, we might instead imagine a scenario in which we would install only one or two rings at a time, in a sequence most likely to develop the information about particles that we want, and thereby drawing out a view of nature as a novelist draws out

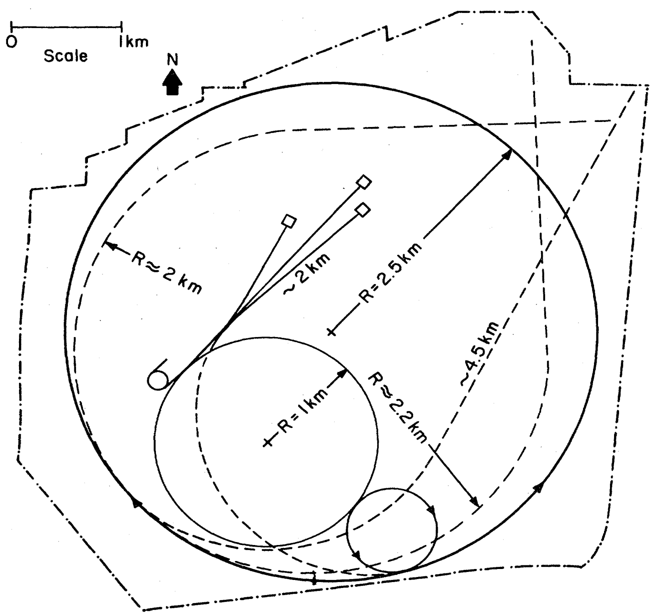

FIG. 11. The Fermilab site with a ring 2.5 km in radius inscribed and with possible external beam lines indicated.

his story, for the maximum satisfaction of his reader—or in this case, for the maximum of insights about the physical world within the limitation of available funding.

A. 5 TeV protons on fixed targets

Let us consider first the accelerator as a source of protons to be incident on fixed targets. Because it will not be built in the immediate future, we must ask what magnetic field can we anticipate might be attainable in the magnets at the time, say ten years from now, when such a large accelerator might be started. Although by the use of new materials there is no obvious reason not eventually to reach fields of the order of hundreds of kilogauss, I suggest that a factor of two beyond the field of 42.5 kG which obtains in the Tevatron magnets, i.e., to 85 kG, is nearly within the state of the art right now. In that case 5 TeV protons could be produced, hence the name Pentevac.

The present limitation of the field in the Tevatron magnets is imposed primarily by three factors: (a) the current density that can be reached using the present superconductor NbTi; (b) the mechanical distortion caused by the tremendous magnetic force on the conductors; and (c) the removal of the large amount of magnetic energy intrinsically stored in each magnet without melting the conductor. Doubling the magnetic field in the present Tevatron magnets by simply doubling the current density, were that possible, would quadrupole the forces and the stored energy.

Figure 12 shows in cross section a suggested design of a dipole supermagnet for the Pentevac which might reach 85 kG; it is based on the present Tevatron magnet design. Instead of NbTi, Nb_3Sn would be used as superconductor, for it will in principle reach the required current density at the required field strength. The present difficulty with Nb_3Sn is that practical conductors made of it are not ductile enough so that sharp bends in the coils can be made without destroying the superconducting property of the wire. Although this problem may be solved, for example, by making the filaments of the superconductor much finer than at present, there is even at present a technique for fabricating the coil. Bronze is used as the matrix material in which fine filaments of pure Nb have been imbedded. This material is ductile so that coils made of it can be wound in the appropriate shape. Then if the temperature of the material is raised to about 750°C, the tin component of the bronze will migrate and interact with the Nb to form Nb_3Sn. The coils must be insulated after having been formed and heat-treated and then installed within the stainless steel collars. The present coil structure of NbTi and insulator tends to be "squishy," and might not withstand a quadrupling of the force without collapsing. However, loading the epoxy heavily with alumina makes a much stiffer material than the present epoxy-fiberglass (B-stage) material now is use, and there is some empirical evidence that the alumina-loaded material is satisfactory. Sprayed-on glass might also be a good insulator for use with Nb_3Sn, and one which might withstand the heat conditioning. The cable is shown to be much larger than in the Tevatron magnets, in order to reduce the number of turns and thereby also reduce the voltage on the coil during ramping and quenching. This would also reduce the work of insulating the turns, and would require less space for the insulation and hence give a larger average current density.

The free opening in the coil shown in the design is roughly elliptical in shape, $2\frac{1}{2}$ in. wide by 2 in. high; it is smaller than the opening of the Tevatron magnets,

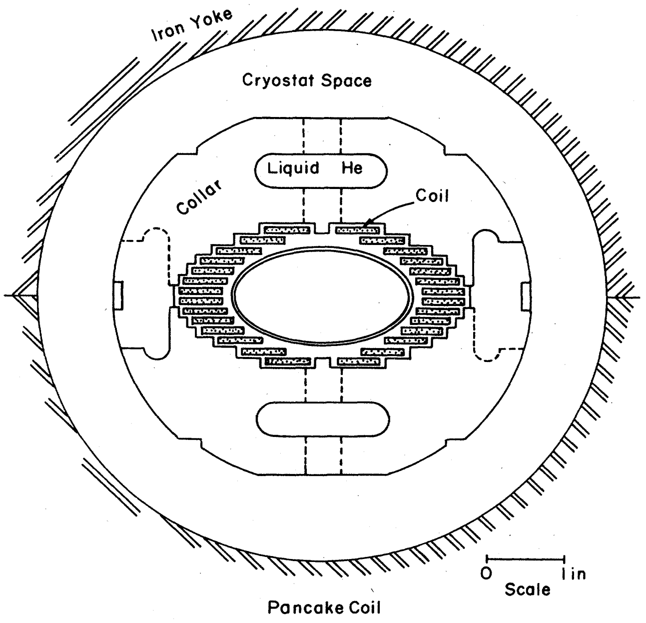

FIG. 12. A possible design for an 85 kG magnet for the Pentevac.

which is circular in shape and 3 in. in diameter. The smaller opening should reduce the stored energy for a given value of the magnetic field by nearly a factor of two and the total force on the conductors would also be reduced accordingly. The "good" magnetic field aperture as indicated by the calculations of S. Snowdon is about 0.75 in. wide instead of being about 1 in. wide as in the Tevatron magnets. The reduction in aperture should be possible because the injected beam of 300–1000 GeV protons would be somewhat smaller in size and stiffer than the beam of about 100 GeV protons which are to be injected into the Tevatron. A stronger lattice might also be used to reduce the size of the beam.

The energy stored in the magnetic field, about 1 MJ per magnet assuming the same length as for Tevatron magnets,[4] must be rapidly disposed of in the event of an accidental quench in order to prevent the superconducting cable from melting. Nearly all of the stored energy in the present Tevatron magnets, 0.5 MJ per magnet, is absorbed in the coil when it goes normal. It is important that the whole coil be driven normal by means of a heater once a quench is detected. This method can still be expected to work even for the higher field design because the coil is still capable of absorbing about twice as much energy without melting or burning the insulation.

As shown in Fig. 11, protons can be transferred from the Main Ring or the Tevatron to the Pentevac through an intermediate filling ring, average radius 0.5 km. A different possibility, not shown, would be to build an external bypass on the Main Ring so as to be tangent to the Pentevac ring at one of its straight sections.

A typical cycle might require 60 seconds: it would be comprised of a 10-sec dwell-time at low field while three pulses of 300 GeV protons from the Main Ring were successively injected to fill the Pentevac ring head-to-tail fashion, then a 15-sec ramping period to full field, then a flattop of any length (but let's say 20 sec), after which the cycle would end with a 15-sec ramp back to the injection field. By using tricks such as stacking multiple turns in the Tevatron and then transferring these to the Pentevac, the injection time could be reduced to a few milliseconds, and then, by using a faster rise time for the magnets, the total pulse time of the Pentevac, apart from the flattop, might be reduced to about twenty seconds, i.e., comparable to the present pulse time for Main Ring operation at 400 GeV. If we assume that each injected pulse from the Main Ring would contain 3×10^{13} protons, the total pulse intensity of the Pentavac would be about 10^{14} protons. When these have been accelerated to 5 TeV, the total beam energy would be a frightening 100 MJ per pulse. Clearly should such a pulse of protons get out of control it could destroy many of the supermagnets. The experience with the present one megajoule level of beam energy is that seldom does the beam get out of control, and, although what is now called "out of control" would correspond in the 5 TeV case to an inadvertent loss of only about one percent of the beam, my judgment is that the beam abort system could be tightened up enough to abort the beam reliably before a dangerous beam loss could occur. Even a smaller loss, as little as about 10^{-6} in one magnet, may be enough to quench the supermagnet. This does not mean that the problem of containing a large beam of protons is impossible, but it does mean that new techniques of sensing a small abnormal growth of the beam would be required. Tuning the machine would necessarily become a much more sophisticated exercise than it now is—but not an impossible one.

Beam extraction and targeting are the really serious problems. One solution is to limit the intensity of the beam to levels for which solutions have already been found, and then, as new techniques are developed, slowly to raise the beam intensity. For short flattops, this would mean reducing the envisaged intensity by a factor of about 100. For longer flattops, the rate of energy deposition would be reduced, and thermal cooling could then occur; however, radiation damage and induced radioactivity would still be important. The solution to the problem of extraction lies in increasing the efficiency of extraction. One measure to help increase the efficiency of the extraction process would be to make an insertion of large-aperture magnets in the vicinity of the extractor. These could be arranged in a lattice insertion that would locally increase the betatron oscillation amplitude which would help the extraction process. The large aperture would also decrease the interception by local magnets of the beam lost in the extraction process and thereby allow the radiation to be intercepted by an inert shield or at lower density in the following magnet structure. The downstream magnets in which the greatest loss can be expected to occur could be of conventional design, and hence capable of absorbing much greater radiation. They would constitute a form of magnetic beam scrapers.

Increasing the targeting capability is difficult but more straightforward. Both the thermal energy and the radioactivity deposited would be ten times greater per proton than is presently the case, but present techniques can very likely be extended by that factor—although with considerable difficulty.

Without having to confront problems of beam extraction, an internal target area could be built in the Pentevac so that the kinds of experiments which have been done in the Main Ring internal-target area could be extended to new energies—but a less-dense gaseous target would have to be used to minimize beam loss in the magnets just downstream from the target.

Assuming that the extraction and targeting problems can be solved, what about the external proton beam and its experimental areas.[7] There are numerous possibilities. Several tangents can be drawn to the ring having lengths to the site boundary of between 2 and 3 km, as can be seen in Fig. 11. For comparison, the present distance from the Main Ring extraction point to the 15 foot bubble chamber is about 2 km. By extracting the proton beam inward instead of outward and by bending it as shown in Fig. 11 with a 20% stronger magnetic field than exists in the bending magnets of the Pentevac, a 4-km-long straight beam line can be drawn to the site boundary. The proton beam would be pointed downward at a slight angle so as to direct muons into the earth.

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[4] It is suggested that the magnets be made about 25 m in length rather than the 7 m length of the present Tevatron magnets.

Alternatively, by bending the beam radially inwards with a short radius, about two-thirds of that in the Pentevac, the 5 TeV protons could be brought into the present switchyard where, with stronger magnets, the protons might be led to the present experimental areas where some of the present experiments could be repeated at a higher energy, but probably not at the full energy.

It appears that the distances available on the site are large enough to do almost any experiment presently envisaged for 5 TeV protons or their secondary particles. It is interesting to note that a 5 TeV muon has an average range in earth of 2–3 km. At these energies the stopping power is dominated by the radiation of photons and electron pair production rather than by ionization loss, and the range is given by $R = \log(E+1)$, where R is measured in muon interaction lengths and E the muon energy is measured in critical energy units given by $E_{\text{TeV}}/35$. The tunnel must be placed at a low enough level so that the muons produced by an inadvertent loss of protons will remain well below the deepest inhabited level. This requirement suggests that the plane of the tunnel should not be absolutely level, but rather should tilt slightly to correspond to the average tilt of the ground around the site. There may be some economic advantage to be gained by having the accelerator follow the average contour of the surface so that it is not in a plane at all. There are small chromatic effects introduced by this procedure but these might be compensated by a careful choice of the contour. Of course, where the protons were aimed upwards, care would have to be given to the possibility of muon radiation near the surface.

It appears from the above discussion that eventually 5 TeV protons might be produced in copious amounts at Fermilab and that the site is large enough for most of the fixed-target experiments which can presently be envisaged. With regard to the experimental areas and the experiments that could be made in them, almost everything that was said about the Tevatron in extrapolating from 0.4 to 1 TeV could be further extrapolated in the same way to 5 TeV. The full nature of the physics to be explored at such energies, of course, cannot be foreseen or there would be small reason to build the Pentevac.

A rough estimate of the cost, assuming one pulse per minute and an intensity of 10^{14} protons per pulse, might be about \$500 million in 1980 dollars. Of this, \$100 million might be identified for conventional facilities connected with the accelerator, \$200 million might be identified for the accelerator components, i.e., magnets, extraction, etc., and \$200 million might be identified for the experimental areas. For a rough comparison, the Main Ring in 1970 cost about \$75 million and the present experimental areas cost about \$50 million. Multiplying the Main Ring cost by 2.5 and adding \$100 million to provide for roughly the same amount of experimental areas gives \$287 million in 1970 dollars. When a factor of 1.8 is allowed for inflation, this comes to about \$500 million. My expectation is that the superconducting magnets might be less costly and that the conventional facilities might be constructed at somewhat lower cost because of the magnitude of the job. In summary, it should be possible to construct the Pentevac to first beam in about three years after it is funded and for a cost of less than \$500 million, and—with the creative imagination of younger designers—for considerably less.

B. 5 TeV antiprotons on 5 TeV protons

By the time the Pentevac is constructed, we can assume that techniques for cooling antiprotons will have been developed and will have been used for colliding-beam experiments in the Tevatron. These beams could be transferred directly to the Pentevac ring for slow acceleration to 5 TeV each. Thus we can contemplate the exciting prospect of reaching a center-of-mass energy of 10 TeV in colliding-beam experiments in the Pentevac at similar or even greater luminosity. There would be adequate space available along the 15 km peripheral length of the Pentevac tunnel in which to design and install colliding-beam experimental areas.

The Pentevac magnet ring becomes ready for beam collision studies as its first phase of operation because at that stage, just as with the Tevatron, it is not necessary to solve the problems of extraction, of beam targeting, and of fast acceleration. Thus studying $\bar{p}p$ collisions in the Pentevac becomes a particularly attractive possibility, especially if such studies have already been feasible in the Tevatron, because the problems of antiproton production would have been solved, and because there would be little interference with the Tevatron or the Inner Ring experimental programs.

If it should turn out for some unexpected reason that the cooling of antiprotons is more difficult than is now anticipated and we have not realized high-luminosity beams of antiprotons in the Tevatron, then a fallback position would be to consider collision studies between the 5 TeV protons of the Pentevac with the 1 TeV protons of the Tevatron in an external bypass which might have been built to load the Pentevac in any case. Alternatively, the transfer ring shown in Fig. 8 could be used as a storage ring for 1 TeV protons (85 kG) which could be collided against the 5 TeV protons—both schemes giving about 4 GeV in the center of mass.

C. 50 GeV electrons on 50 GeV positrons

The large diameter of the Pentevac tunnel brings up the possibility of constructing an electron storage ring as one of the stages of the Pentevac. The maximum electron energy is sharply dependent on the amount of rf power that is installed. Although 100 GeV is conceivable, something like 50 GeV would be more optimal. At that energy the electrons would radiate about 300 MeV per turn, which is modest.

The study group at CERN has examined the possibility of constructing a large electron–positron storage ring (LEP) and concluded that a $(100\times 100\ \text{GeV})^2$ facility could be built which would reach a luminosity of 10^{32} $\text{cm}^{-2}\,\text{sec}^{-1}$. It would have an average radius of about 8 km. The group gives a curve of the cost and radius as a function of energy and it is interesting that the 50 GeV point occurs at about 2.5 km, and that the corresponding cost would be about 1000 million Swiss francs (500M\$). For details the reader is referred to the LEP study report (CERN, 1978b). It does appear possible to build a demi-LEP at Fermilab.

D. 10-50 GeV electrons on 5 TeV protons

Colliding 50 GeV electrons against 5 TeV protons would be highly desirable, however, a stored beam of 50 GeV electrons might be almost as expensive, or perhaps about half as expensive, as an electron–positron storage ring. Because of the E^4 variation of synchrotron radiation, the cost will have a rapid dependence on the electron energy, hence a gradual approach is indicated. For example, 12 GeV electrons will doubtlessly exist in the Main Ring, as we have seen, and these could be brought directly into collision with the 5 TeV protons of the Pentevac in the congruent external bypass of the Main Ring already referred to in Secs. VII A and VII B, and at very little extra cost.

The 12 GeV/5TeV e-p colliding-beam experiments could also be done at minimal extra cost, but the results of these experiments would have to be interesting indeed before the next step, say the installation of a 40 GeV electron storage ring in the Pentevac tunnel would be taken. The magnetic field for a 40 GeV electron (540 G) would be the same as in the LEP magnets for 100 GeV, so we might take over the ingenious LEP design directly. The CERN estimate for the magnet system, when scaled down for the smaller radius, comes to about $80 million. This cost might be reduced because the synchrotron radiation per meter for a 40 GeV electron would be an order of magnitude less than for 100 GeV electrons.

To the magnet cost must be added the cost of the radio-frequency cavities, power supplies, electrical power, etc. The energy radiated by a 50 GeV electron would be about 300 MeV per turn—which implies an expenditure of electrical power of very roughly 30 MW in order to obtain a luminosity of about 10^{32} cm^{-2} sec^{-1}. This power would decrease with the fourth power of the electron energy, if the number of cavities used at each energy were proportional to that needed, or with the eighth power of the electron energy if all the cavities for 50 GeV were to be installed at the beginning. Scaling the CERN costs indicates that about $75 million might be required for 50 GeV operation, but this cost would plummet rapidly were lower energies to be used.

In summary, it appears that there is a wide range of possibilities for studying *ep* collisions, but with rapidly increasing cost from the very economical 12 GeV× 5 TeV *ep* experiments. The opportunities for turning up new insights about the nature of particles will make some level of study of *ep* collisions irresistible.

IX. L'ENVOI

....

Thoughts hardly to be packed
Into a narrow act,
Fancies that broke through language and escaped....

....

So take and use thy work;
Amend what flaws may lurk,
What straing o' the stuff, what warpings past the aim!
My times be in thy hand!
Perfect the cup as planned!
Let age approve of youth......

(Browning, 1864)

....

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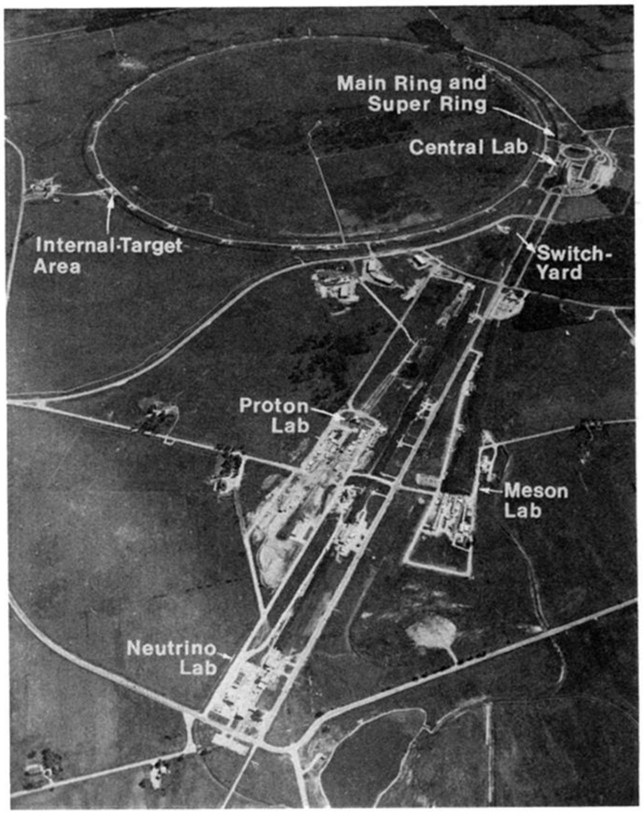

FIG. 1. Aerial view of the accelerator and experimental areas at Fermilab. Some improvements to the experimental areas have already been started to accomodate the extracted 1 TeV beam when available.

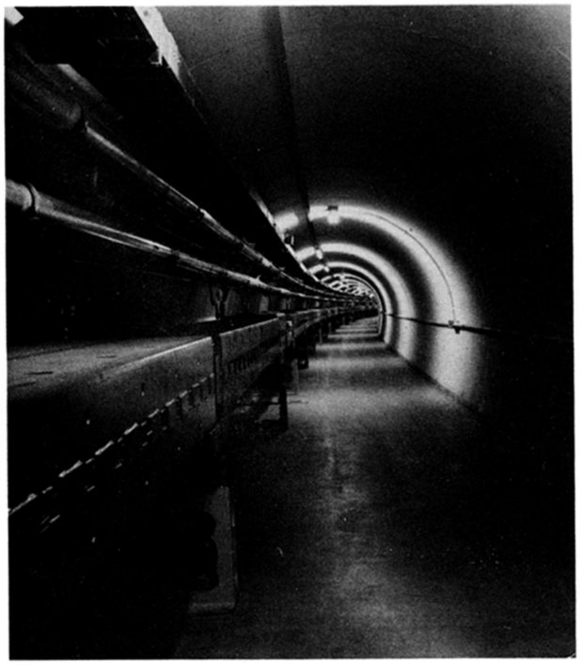

FIG. 2. The Main Ring accelerator tunnel magnets (Superperiod A) bend the proton beam into a circle with a circumference of 6.2 km.

FIG. 3. Superconducting magnets mounted directly below the conventional magnets of the Fermilab Main Ring, where extra space was provided for this installation at the time of the original construction around 1971. When the Super Ring is completed the 500 GeV proton accelerator will become the "Tevatron," with its energy increased to 1000 GeV (1 TeV).

FIG. 7. Aerial view of antiproton test cooling ring.