Directors Office

Fermilab TeV Program
Superconducting Magnet Ring

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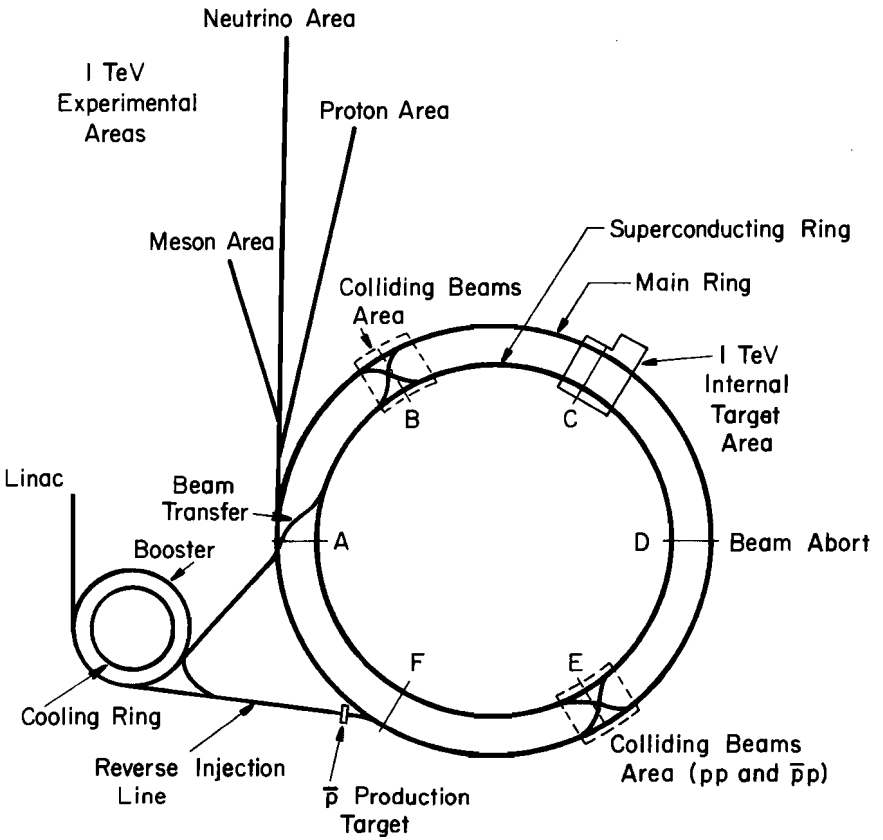


SCHEMATIC PLAN OF THE FERMILAB TeV PROGRAM

I. INTRODUCTION

A. Description of the Program and Outline of the Report

The Fermi National Accelerator Laboratory has a unique opportunity to make dramatic advances in the exploration of the structure of matter and of the forces that govern that structure. The capability to take these new steps stems from the existence at Fermilab of unique facilities for the production and study of high-energy interactions. An R&D project that is already approved and that is currently being funded will provide the Superconducting Ring of magnets that will be the central component required to make these new steps possible. It will also make it possible to save substantial amounts of electrical energy and money.

The Superconducting Ring will be in the same tunnel as the present Fermilab Main-Ring accelerator. With the completion of the second ring of magnets, three new areas of research become possible:

1) The study of interactions produced by colliding beams of protons and antiprotons with a $\bar{p}$-p center-of-mass energy of as much as 2 TeV.
2) The study of interactions produced by two colliding beams of protons with a p-p center-of-mass energy of about 1 TeV.
3) The study of interactions produced by particle beams with energies up to 1 TeV (1000 GeV) in the laboratory system.

The Frontispiece facing this page is a schematic representation of the TeV Program. A comparison of the center-of-mass energy and luminosity of the facilities described in this proposal with other existing or proposed facilities is given in Fig. I-1.

The TeV Program discussed in this Report consists of several distinct parts:

1) A 1-TeV (1000 GeV) Superconducting Ring to be built with operating funds as a research and development project and installed in the tunnel of the Main Ring of the Fermi National Accelerator

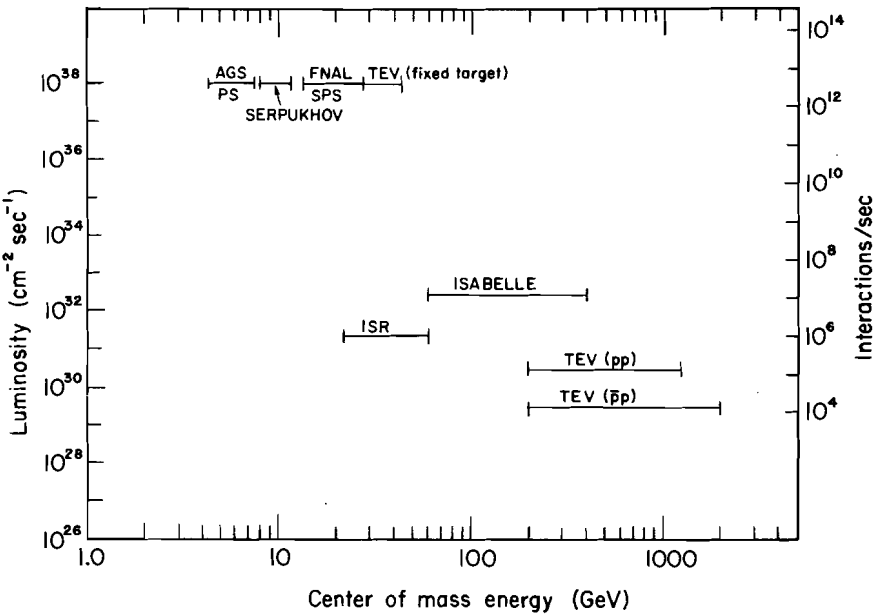


Fig. I-1. The TeV Program compared with other facilities.

Laboratory. At the conclusion of this R&D project, it should be possible to achieve coasting beam in the new ring at any energy up to 1000 GeV, but the installed rf and refrigeration will not be sufficient to support rapid ramping or rapid cycling of the accelerator.

2a) A construction project to make it possible to observe collisions between proton beams in the Main Ring and Superconducting Ring. The initial luminosity that might be expected for p-p collisions is approximately $10^{30}/cm^2$-sec. There are a number of studies through which this luminosity could be expected to be increased by more than an order of magnitude.

2b) A construction project to produce a source of antiprotons that can then be injected, with an oppositely rotating beam of protons, into either the Main Ring or the Superconducting Ring so that proton-antiproton collisions at very high energies can be observed and studied. The initial luminosity that might be expected for proton-antiproton collisions is approximately $3 \times 10^{28}/cm^2$-sec in the Main Ring and $10^{29}/cm^2$-sec in the Superconducting Ring. There are also a number of ideas through which this luminosity could be expected to be increased by more than an order of magnitude.

3a) A construction project to develop the Superconducting Ring into a full-fledged Energy Doubler/Saver. This requires additions to the rf and refrigeration systems to accommodate ramping of the magnets at a rate corresponding to about 50 GeV/sec.

3b) A construction project to modify the beam-extraction and switchyard systems and the experimental areas to use the 1-TeV beam on fixed targets.

There is a unity underlying the new program that Fermilab is proposing for its next step into the future. An energy of 1 to 2 TeV in

the center-of-mass will make available another large and important region of physics. It should be sufficient to produce intermediate bosons, if they exist. More importantly, it is so far beyond anything that can now be realized or that is now in the planning stage that the unexpected can almost surely be expected.

The program also makes accessible a large area of physics that can be explored by bombarding fixed targets with protons having a laboratory energy of 1 TeV. Such a program includes photon physics with photon beams of energy in excess of 500 GeV and, perhaps more important, incorporates neutrino physics with neutrinos of energy up to at least 700 GeV.

A few of the highlights of the physics associated with these three new areas of research are described in Part E of this chapter. In Parts B, C, and D we shall briefly describe the history of the proposed plan, its implementation, and several different possible modes of operation. Costs are summarized in Part F.

Chapter II of this report describes the work identified with the research and development project that will produce a superconducting ring of magnets installed in the tunnel and adequate for slowly accelerating a coasting beam. The facilities associated with the production and observation of the colliding beams are described in detail in Chapter III. Chapter IV describes the upgrading of the superconducting ring of magnets to a rapid-cycling accelerator with all the required associated facilities for extracting beam to the experimental areas. Chapter V describes the modifications to be undertaken in the experimental areas to prepare them to accommodate experiments in which the primary proton energy is as high as 1 TeV. Chapter VII gives the costs and schedules of all parts of the TeV program.

There are a number of options for longer-range development at Fermilab, including (a) a beam bypass, (b) the POPAE project, and (c) a site-filling ring that might go to as high an energy as 5 TeV on a fixed target or to as high as 10 TeV in the center of mass for

colliding beams. These options are discussed in Chapter VI.

B. Evolution of the TeV Plan

In the original design of the Fermilab accelerator, consideration was given to the use of superconducting magnets. With such magnets the peak magnetic field could be double that attainable with conventional copper and iron magnets, thereby doubling the maximum achievable energy. The technology of superconductivity was not yet sufficiently advanced at that time, a decade ago. The accelerator was therefore designed with conventional magnets, but space was left in the accelerator tunnel for the possible addition of a second ring at a later time. Serious development work on superconducting accelerator magnets at Fermilab began in 1972, after the Fermilab accelerator had achieved its design energy.

The present 500-GeV accelerator is actually an extension, within the initially authorized construction cost, of the 200-GeV accelerator originally specified for Fermilab. It has always seemed natural that when the technology of superconductivity was sufficiently developed, the extension in energy should be carried through another doubling, to the 1-TeV level. It has now become possible to achieve that goal by supplementing the original ring of conventional magnets with a second ring of superconducting magnets. Fig. I-2 is a cross section of the Main-Ring tunnel showing the proposed location of the Superconducting Ring. Fermilab has an opportunity to take this step toward higher energy and to do so in an economical fashion because of the existence of the 500-GeV accelerator.

The idea of a superconducting magnet ring had already been put forward well before the present energy crisis had been widely understood, but with the escalating cost of electrical energy, and with the limited operating budget and large cost of power at Fermilab, it became clear that another important attribute of such a ring of magnets would be its potential saving of energy and of operating costs.

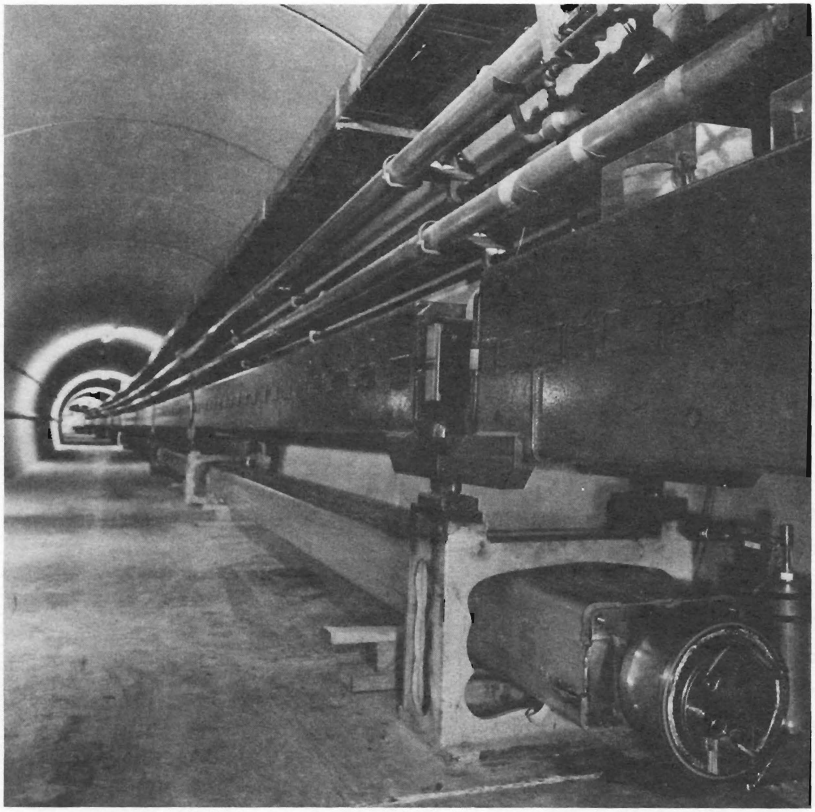


Fig. I-2. Location of the Superconducting Ring in the Main Ring Tunnel.

The combination of a doubling of the maximum proton energy to 1000 GeV with a saving of electrical energy required to operate the Fermilab accelerator systems suggested the name Energy Doubler/Saver for the new facility.

The idea of storage rings at Fermilab is not a new one. The size of a site for the laboratory, specified by the AEC, was increased during the site-selection process to make it possible to accommodate storage rings at some future time. In 1968, at the time the accelerator was positioned on the site, a design study was made of the construction of a pair of intersecting storage rings and a Design Report published in 1968. In 1972, as work proceeded on the early stages of development of magnets for the Energy Doubler/Saver, physicists became interested in the idea of a pair of intersecting storage rings that would accept the 1000-GeV beam from the Doubler/Saver.

At the end of 1973, acting in accordance with the guidance of its Long Range Advisory Committee, a nationally representative group of high-energy physicists, the Laboratory intensified its study of intersecting storage rings. That work culminated in a collaborative effort by staff members of the Argonne National Laboratory and the Fermi National Accelerator Laboratory. That working group produced a Design Study for POPAE (Protons On Protons And Electrons). That Design Report, dated May 1976, describes a possible pair of intersecting storage rings. The estimated cost, at an energy of 1 TeV on 1 TeV, was close to $250 million in FY 76 dollars. The design group also made an estimate for a project of reduced scope in which the intersecting storage rings would carry protons only up to an energy of 500 GeV, to give a center-of-mass energy of 1 TeV. The cost of such a facility was estimated to be around $150 million, also in FY 76 dollars.

Concurrently with the development of the POPAE design, the Laboratory was considering alternative and less expensive approaches to the achievement of collisions with very high energy in the center-of-mass.

One of these approaches has now been incorporated as an essential part of the Fermilab TeV Program discussed here. It involves two related physics goals and two independent methods.

Both methods hinge upon the use of the superconducting ring of magnets being developed for the Energy Doubler/Saver. One method is to obtain pp collisions between protons circulating in the new Superconducting Ring and protons in the existing Main Ring Accelerator. The second method provides for the production of high-energy proton-antiproton collisions either in the Main Ring or in the Superconducting Ring.

Compared with POPAE, the new approach has great advantages in achieving a much earlier look at the regions of physics that become available with super-high center-of-mass energies and in doing so with a relatively small financial commitment. In view of the great physics potential of this much less expensive approach, it is believed to be premature to proceed with POPAE. Instead, the proposed Fermilab TeV Program should be pursued with high priority.

C. Implementation of the TeV Program

1. Coasting Beam in the Superconducting Magnet Ring. The Superconducting Ring for the TeV projects has been the center of an active program of research and development at Fermilab since 1972. This program has had as its goal the completion of the Superconducting Ring and its installation in the tunnel, ready for testing by the end of FY 78. That would mark the end of the research and development project. The FY 78 budget now under consideration in Congress does not provide the funds required to meet that goal. In this report we shall assume the case of insufficient funding in FY 78 but completion of the Superconducting Ring in FY 79.

At that stage, it will be possible to inject a beam of protons from

the Main Ring into the new ring at an energy of approximately 100 GeV and to have that beam coast around the new ring for many hours. A small source of rf power will be installed in the new ring to increase the energy of the coasting proton beam at a slow rate to as high as the design energy of the new ring, 1000 GeV. Coasting beam can be achieved at any energy up to 1000 GeV.

2. Colliding Beams. The Superconducting Magnet Ring will have a cold bore, a very high vacuum, and a large enough aperture so that it can be used as a storage ring. The design that has been developed provides for the new Superconducting Ring's orbit to intersect the Main-Ring orbit at the locations of existing straight sections. With one new short beam-transport system that is already under construction, protons from the Booster Accelerator can be injected to circulate in the reverse (counterclockwise) direction in either of the two large accelerator rings. Then protons going in one direction in one ring can be made to collide with protons going in the other direction in the other ring. This realization of p-p colliding beams is implicit in the completion of the Superconducting Ring.

A second possibility for colliding beams at Fermilab stems from the invention by Budker at Novosibirsk, USSR, of the process of electron-beam cooling of a proton beam. With the application of this technique at Fermilab, it has been calculated to be possible to produce antiprotons by bombarding a fixed target with a beam of protons of approximately 80 GeV. That production target is now planned to be located in the short beam-transport section that is being constructed for reverse injection of the booster beam into the existing Main-Ring tunnel. The antiprotons that are produced at that target will be focused and transported to a new small ring of magnets to be installed inside the Booster tunnel. Within that magnet ring will be located an electron cooling device of the kind developed at Novosibirsk. After the antiprotons are

"cooled", a process by which their oscillations are reduced, they can be stacked in the cooling ring, then more antiprotons can be produced, collected and stacked until there is a sufficient number to be re-injected into the Superconducting Ring in the large tunnel in the reverse direction. At that point, protons can be injected in the normal way in the forward direction in the Superconducting Ring, and the oppositely circulating proton and antiproton bunches can be simultaneously accelerated to any energy up to 1 TeV. The protons and antiprotons can then be made to collide, giving a center-of-mass energy of up to 2 TeV.

3. Detector Facilities for Colliding Beams. The same detection facilities can be used to investigate the products of proton-proton and proton-antiproton collisions. Their construction, probably at straight sections B0 and E0, (and possibly at C0) would be the next step in the implementation of the TeV program.

4. Energy Saver. An essential facet of the TeV program will be the conversion of the Superconducting Ring into a rapid-cycling (one pulse per minute) accelerator with an extraction system. With the completion of that work, it will become possible to operate at present energies, in the Energy-Saver Mode. The resultant energy savings are expected to be at the rate of $5 million per year.

5. Energy Doubler. To exploit the potentialities of 1000-GeV fixed target physics the extraction system, Switchyard beam lines and experimental areas must be modified to accommodate particles with energies up to twice the present values. At that point the Superconducting Ring can be operated as an Energy Doubler for physics research with fixed targets. This complete accelerator will be called the Tevatron in this report.

D. Modes of Operation of the TeV Program

With the existence of either the Superconducting Ring or the antiproton source alone, several modes of operation become possible. When both are available, additional possibilities exist. Some of these modes are given in Table I-I and described in more detail in this section.

Table I-I. Modes of Operation of the TeV Program

BB = beam-beam; FT = fixed target;

MR = Main Ring; SR = Superconducting Ring

Mode	Particles		Collision Style	Ring	Energy (GeV)	Maximum Luminosity ($cm^{-2}sec^{-1}$) or Intensity (sec^{-1})	Maximum Duty Factor
1	$\bar{p}p$	(a)	BB	MR	500 CM	5×10^{28}	50%
2	$\bar{p}$	(a)	FT	MR	500 Lab	10^{6}	10%
3	pp	(b)	BB	MR-SR	800 CM	10^{30}	dc
3'	pp	(b)	BB	MR-SR	≤1200 CM	10^{29}	10%
4	$\bar{p}p$	(c)	BB	SR	2000CM	10^{29}	dc
5	p	(d)	FT	SR	500 Lab	10^{13}	25%
6	p	(d)	FT	SR	500 Lab	10^{12}	~100%
7	p	(d)	FT	SR	1000 Lab	10^{12}	10%

(a) $\bar{p}$ source only.
(b) R&D project alone will start this program at demonstration level.
(c) R&D project and $\bar{p}$ source required.
(d) Completion of rapid-cycling accelerator required.

Mode 1

Even before the completion of the R&D project, as soon as cooled antiprotons are successfully produced and stacked in the cooling ring, those antiprotons can be injected in the reverse direction into the Main Ring. Protons can also be injected in the normal direction. The protons and antiprotons can then be simultaneously accelerated to high energy and made to collide. Continuous operation at an energy of about 250 GeV appears to be possible; but, by ramping, a higher energy, up to 500 GeV, might be reached, at the expense of average luminosity. Of course, only preliminary calibrations and observations could be made until such time as adequate detection facilities are available. Then Mode 1 will become a possible research technique. This would, however, require a significant and probably costly Main-Ring vacuum improvement project. It is hoped that rapid completion of the Superconducting Ring

will make it unnecessary to resort to this limited option.

Mode 2

Before the completion of the Superconducting Ring, but following the successful completion of the antiproton source (as in Mode 1), it will be possible to transfer each bunch of antiprotons into the Main Ring in the forward direction where it can be accelerated, extracted and sent to an external experimental area for an experiment where a pure antiproton bombardment is desirable.

Mode 3

At the conclusion of the research and development project, it should be possible to store as many as 5×10^{13} protons of 1000 GeV circulating in either direction.

With 1000-GeV protons coasting in the reverse direction in the Superconducting Ring, the Main Ring can be operated in precisely its present mode. For example, protons can be accelerated to 400 GeV with a 10-sec repetition rate and extracted for delivery to the external experimental areas. During the acceleration cycle, those protons can be made to collide, at some selected energy, with the stored beam in the Superconducting Ring, just as accelerating protons in the Main Ring collide with protons in the hydrogen gas jet target in the Internal-Target Area. The time-average effective luminosity in such a mode of operation should be somewhat greater than $10^{28}/cm^2$-sec, and the center-of-mass energy can be as high as 1 TeV. Of course, only preliminary observations and calibrations could be expected until such time as adequate detection facilities are provided. Then both Mode 3 and Mode 1 will represent available research techniques. At that time, it might be desirable to run the two rings part of the time in a dedicated colliding-beam mode. Protons can be slowly accelerated and then stored in the Superconducting Ring, and accelerated to 250 GeV in the reverse direction and stored in the Main Ring. The two rings can then be run as intersecting storage rings with an expected luminosity of about $10^{30}/cm^2sec$.

Mode 4

With the completion of the R&D project and with the availability of cooled antiprotons, it will become possible to accelerate both protons and antiprotons slowly in the Superconducting Ring and to produce collisions there between the two oppositely circulating stored beams. Once again, only preliminary calibrations and observations would be possible until such time as adequate detection facilities are available. In Mode 4, while colliding-beam physics is being done using the Superconducting Ring, the Main Ring accelerator can be used to continue the present kind of fixed-target research program in the experimental areas.

Mode 5

With the high cost of electrical energy, an Energy-Saver mode is particularly attractive. Completion of the Tevatron makes this possible. In such a mode, the Superconducting Ring will be used as an accelerator, but the maximum energy will be set, for example, at 500 GeV. The intensity of protons accelerated can be about 10^{13} per second, and the duty factor can be in the neighborhood of 25%. The electrical power consumed would be only about 25 MW, compared with more than 100 MW required for such 500-GeV operation with the present accelerator. Even comparing the 500-GeV Energy-Saver mode with 400-GeV Main Ring operation an annual saving of as much as $5 million could be realized, depending on the mode of use.

Mode 6

The Tevatron can also be operated as a duty-factor stretcher, because it can run with a flattop of any length. Hence for experiments where counting rate is the limiting factor, each pulse can be extracted over a long flattop, making possible a duty factor approaching 100%. The power consumed would be reduced substantially below the present level. The average intensity in this mode will depend on the energy of the beam transfer from the Main Ring to the Superconducting Ring but should be about 10^{12} protons per second on very close to a continuous basis.

Mode 7

With the completion of the Tevatron portion of the TeV program, it becomes possible to run a fixed-target research program at double the energies now achievable. The accelerator system can be run in a dedicated fashion in this Tevatron mode. The fraction of time scheduled for such running would, of course, be determined by physics priorities. The flux of accelerated protons should be greater than 10^{12} pps, and the power consumed by the accelerator complex would be only about 25 MW, significantly less than that consumed at present.

E. Research Possibilities

The past few years have seen remarkable progress in particle physics. New phenomena (for example, weak neutral currents, charm, J/ψ particles) have been discovered and well understood. Other phenomena have been suggested by data (b quarks, neutral heavy leptons) and still other phenomena are suggested by present theories (intermediate vector bosons, Higgs particles, more new quarks and heavy leptons). These phenomena all make it of great interest to push on to experiments at higher energies. The TeV project at Fermilab offers several new ways to push on to this new energy region. These ways are complementary to one another. Physics with fixed targets cannot match the available energy that can be achieved in colliding beams, whereas physics with colliding beams cannot match the intensities or the variety of bombarding particles that can be achieved with fixed targets. Each of the approaches has its own special province of experiments for which it is well suited. We shall discuss some of these strong points below.

1. Fixed Targets. Neutrino beams of large intensity can be produced in fixed targets, up to energies of 700 GeV in the Tevatron. These neutrino beams are the best way to study weak interactions or interference from strong or electromagnetic interactions. In particular, neutrinos are well suited to searches for heavy charged or neutral leptons, which are suspected to occur in the mass range greater than

2 GeV/c^2. With sufficiently intense neutrino beams, one may study the quantum numbers and interactions of these new heavy leptons.

Neutrino beams can also be used as probes of the internal structure of the proton, because they are coupled to the quark structure of the proton by the weak interaction. Some of the evidence for the existence of quarks comes from neutrino scattering experiments at present Fermilab energies. The quark structure can also be probed with high-energy muon beams, which can also be produced in abundance up to 750 GeV in the Tevatron. Muons couple to quarks through both weak and electromagnetic interactions and one may learn much more about the structure of the proton by comparison of muon and neutrino scattering.

Scattering of hadrons on hadrons at present energies can be interpreted to some extent as the scattering of quarks in one hadron by quarks or antiquarks in the other. These quarks and antiquarks can annihilate to produce gamma rays, which produce muon-antimuon pairs. There are puzzles in the transverse momentum distribution of these muon pairs, which should reflect the internal momentum distribution of the quarks in the proton, and further experiments are needed with higher-energy protons.

Photons are also of interest in this new energy range, because they can create pairs of charmed particles. Charmed-particle spectroscopy has almost exclusively been done with e^+e^- storage rings until now, but it will be a rich field with the Tevatron, which will produce photons of energies of 500 GeV and more, yielding a center-of-mass energy greater than 30 GeV.

There is thus a large field of new and interesting particle physics to be explored with fixed targets at the Tevatron.

2. Colliding Beams. The attainment of a center-of-mass energy higher than 1 TeV for proton-proton collisions and 2 TeV for proton-antiproton

collisions permits a large number of new physics questions to be addressed. These include: What is the nature of the forces between quarks? Will free quarks be produced? Will qualitatively new strong interactions occur as suggested by cosmic ray evidence? What is the energy dependence of the pp or $\bar{p}p$ total cross sections? Will intermediate vector bosons be produced? All of these issues would seem to benefit more from an extension in energy rather than an extension in intensity. It is for this reason that the colliding-beam part of the TeV Project is compelling, an ultimate extension in center-of-mass energy by a factor of 20 (pp collisions) and 30 ($\bar{p}p$ collisions) beyond the CERN ISR.

At such energies, theories involving the existence of the intermediate vector boson will be strongly tested. Neutrino experiments at Fermilab have placed a lower limit of 20 GeV/c^2 on the mass. Theoretical arguments predict a mass of 50 to 150 GeV/c^2, with some difference between charged (W^+) and neutral (Z°). This is an energy region far beyond the reach of any proposed e^+e^- rings, but well within the region accessible with TeV colliding beams. Detection of this particle would be a very important step forward in the understanding of the weak interaction. Knowledge of the properties of such a particle could be crucial to a fundamental understanding of the structure of matter.

The same quark and antiquark distributions within the proton that were discussed above in connection with fixed targets are important in colliding-beams experiments. Conjectures about these distributions permit us to predict processes in which hadron-hadron collisions give rise to lepton pairs. For example, the process $p+p \rightarrow \mu^+\mu^+ + ..$ is predicted. It is plotted in Fig. I-3. It can be seen that the agreement of a model calculation with experiment is quite good.

In addition, there are arguments that lead us to anticipate a new level of narrow vector mesons of mass above 10 GeV/c^2. Such mesons will be important in the understanding of charmed states. We may also

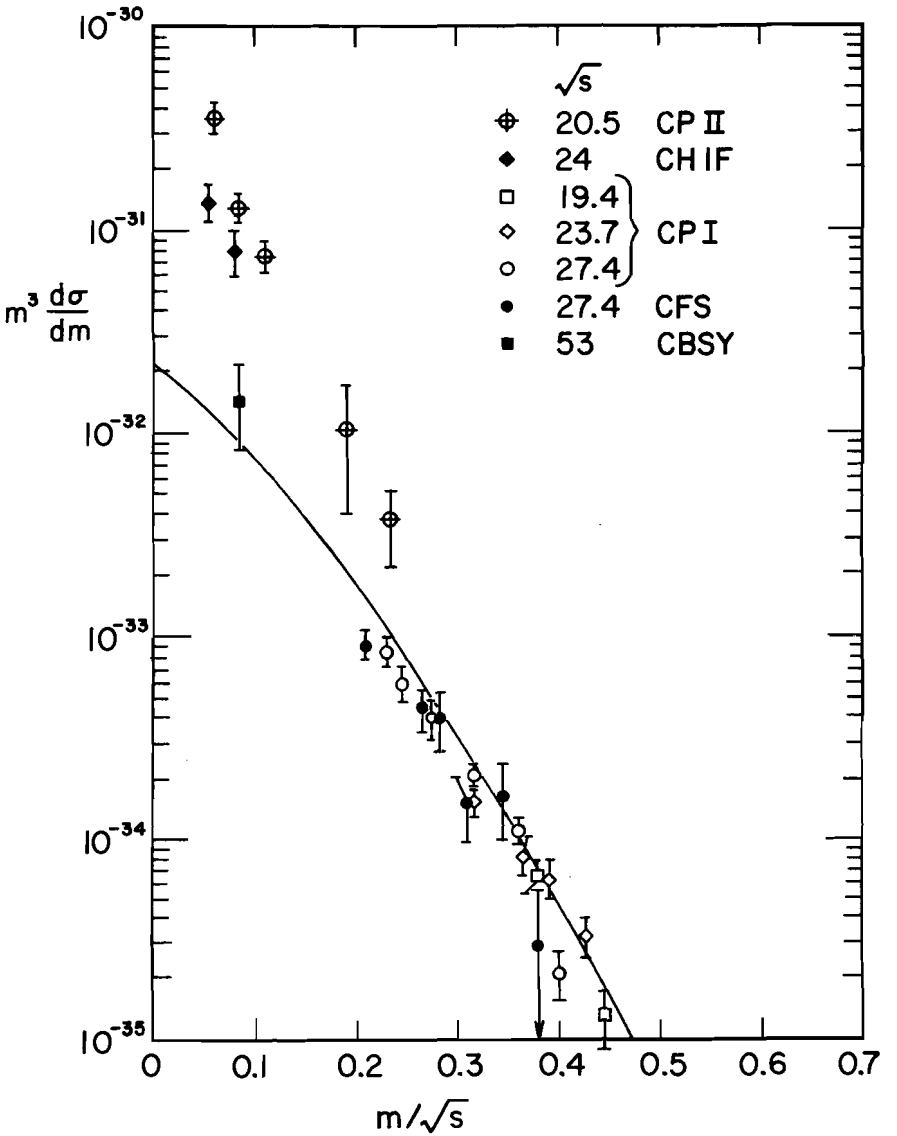


Fig. I-3. Measured cross sections of $p + p \rightarrow \mu^+\mu^+ + \ldots$

expect further information about quark dynamics, because the vector mesons will decay above quark thresholds. It may also be that there are new massive quarks to be found. In fact, there may be a complex spectrum of heavy leptons and one of quarks to be explored.

One might expect initial luminosities of $10^{30}cm^{-2}sec^{-1}$ for pp and about a factor 20 less for $\bar{p}p$. We estimate the W^+ production rate, with these luminosities and reasonable assumptions about branching ratio and detector, to be 0.45 events/hour for pp. The background of muon pairs is estimated to be small and the intermediate vector boson should be observable in our colliding-beams systems.

For all these studies, the energy available in colliding beams for both pp and $\bar{p}p$ offers an experimental tool unmatched by any other proposed device. At such TeV energies it may well be the unexpected phenomena that will dominate the physics.

The most-often discussed experiment with colliding beams has been one to search for charged and neutral intermediate bosons. The existence of these mediators of the weak interactions has become most compelling because of the recent advances of gauge theories, which unite the weak and electromagnetic interactions. The energy and luminosity required for a pp or $\bar{p}p$ colliding beam facility are crucially tied to the estimates of the masses and production cross sections for these bosons. In a $\bar{p}p$ collision, one expects a higher probability of energetic quark-antiquark collisions and therefore different production cross sections. Fig. I-4 shows predicted production cross sections for W^+ and Z° for pp and $\bar{p}p$ collisions.

F. Cost Estimates and Schedules

Table I-II presents a summary of the estimated costs of the three parts of the Fermilab TeV program and the estimated expenditures by year assuming FY 78 funding as proposed in the President's Budget. It will be seen that on this basis the research and development program will be completed at the end of FY 79. With more rapid funding, it

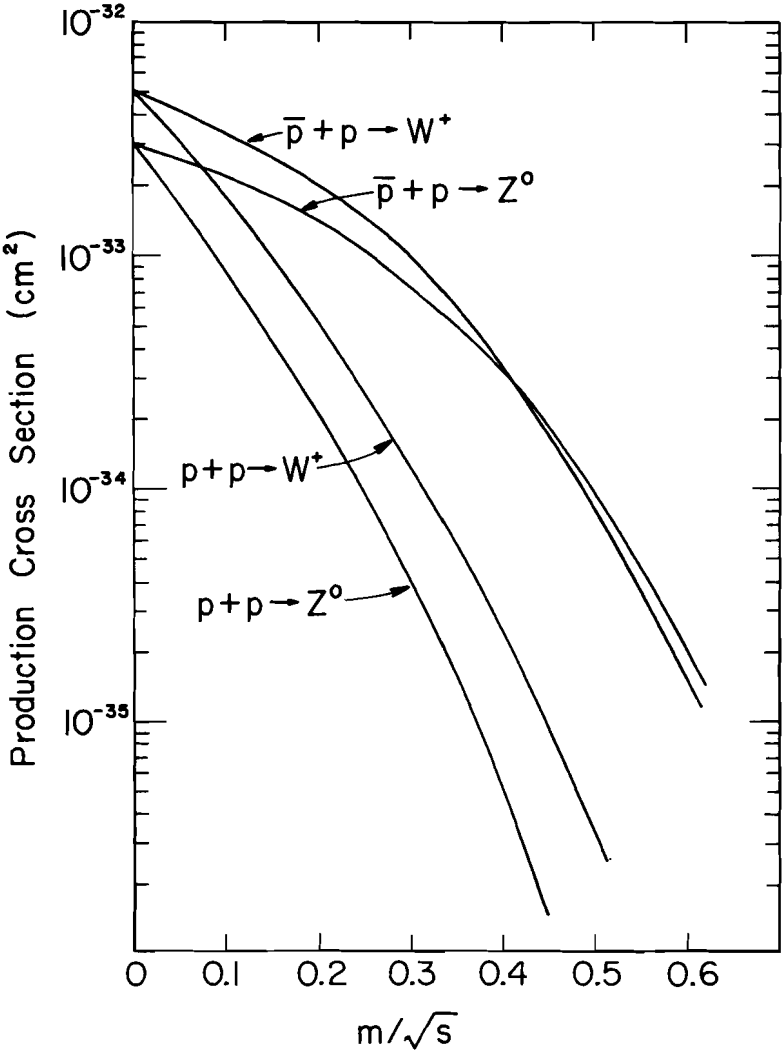


Fig. I-4. Predicted production cross sections for W^+ and Z^0 intermediate bosons.

might be completed by the end of FY 78. Both proposed construction projects, the Colliding-Beams Experimental Facilities, whose total cost is estimated to be $10 million, and the Tevatron and Associated 1-TeV Facilities project, whose total cost is estimated to be $40 million, could be completed by the end of FY 81, or faster with earlier funding. A more detailed schedule and cost estimates are given in Chapter VII.

Table I-II. Summary of TeV Program Cost Estimates by Fiscal Year

(Assuming FY 1978 Funding as Proposed in President's Budget
(In Millions of Dollars)

	FY77	FY78	FY79	FY80	FY81
A. SUPERCONDUCTING RING (R&D Program)	7.0	10.0	23.0		
B. COLLIDING-BEAM EXPER. FACILITIES (Construction Project)			4.0	5.0	1.0
C. TEVATRON AND ASSOCIATED 1-TEV FACILITIES (Construction Project)			10.0	15.0	15.0
	7.0	10.0	37.0	20.0	16.0

It should be noted that the two major construction projects identified in Table I-II can each be subdivided and undertaken piecewise. Separate, significant physics objectives can be achieved at various stages. The production, cooling and injection of antiprotons is one part of the Colliding-Beams Facilities and can be built at a cost of only $1.5 million.

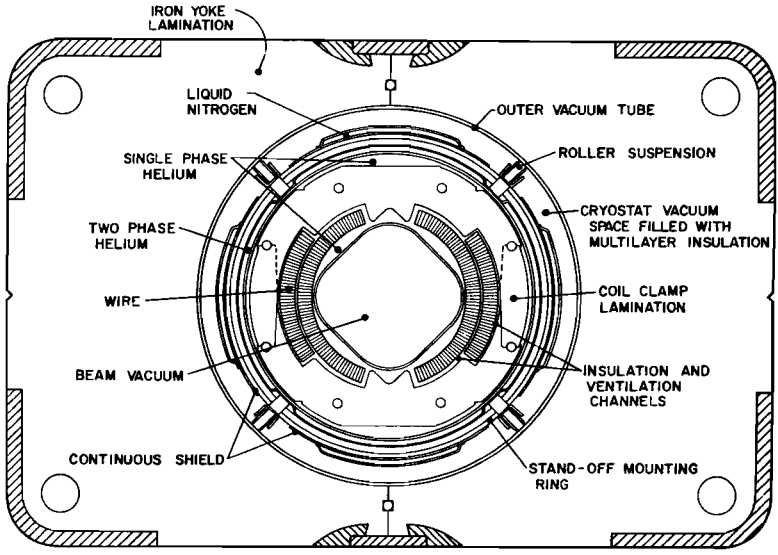
Under item C, the Tevatron accelerator can be completed at a cost of $10 million and substantial energy savings could be realized. Separate costs are then involved in the modification of each external experimental area in order to accommodate 1000-GeV experiments in that location.

II. SUPERCONDUCTING RING RESEARCH, DEVELOPMENT AND DEMONSTRATION

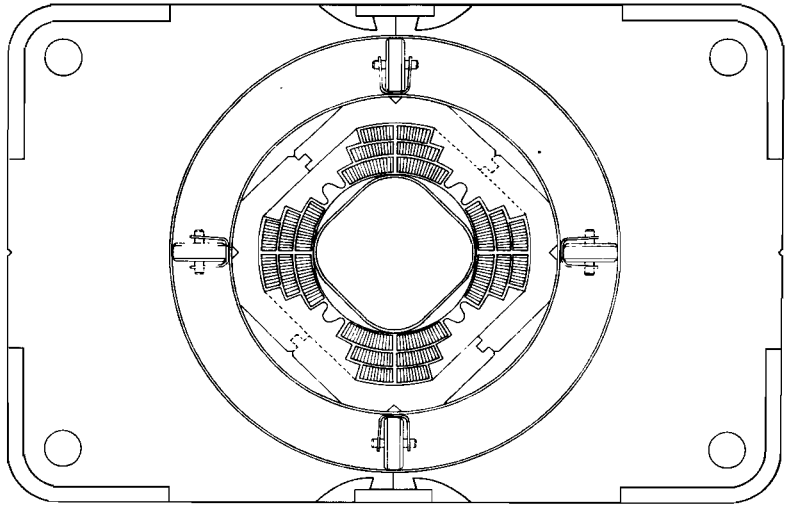
A. Introduction

This chapter describes the research, development and demonstration phase of the Fermilab TeV project. This phase has the objective of demonstrating coasting 100-GeV proton beam in a completed superconducting magnet ring in the existing main-ring tunnel and of accelerating the beam slowly (with an acceleration-cycle period of approximately 4 minutes) to 1 TeV. Fig. II-1 shows cross sections of the dipole and quadrupole magnets of the Superconducting Ring. This beam can be used with a Main-Ring beam in colliding-beam tests. These initial tests would have relatively low luminosity, several orders of magnitude less than that of other proposed colliding-beams devices, but a center-of-mass energy of 1000 GeV. The subsequent construction project described in the later chapters of this report will improve the ring to provide acceleration on a more rapid cycle, the extraction of 1-TeV beams to appropriately modified experimental areas, targeting for 10^{12} protons per sec, and higher-luminosity colliding beams with experimental areas for their use at two long straight sections.

In order to provide the coasting beam, slow acceleration, and colliding beams that are the objectives of the demonstration, the research and development includes superconducting magnets (dipoles, quadrupoles, and correction magnets) arranged in a lattice with desirable properties, beam-transfer systems, a vacuum system, a refrigeration system for the dc operation, a modest rf accelerating system, a beam-abort system, and controls. All these components must be designed so they are compatible with the later construction program. The research and development program on these components and their design are described in the remainder of this chapter. We have collected the major parameters of the Superconducting Ring in Table II-I.



Dipole



Quadrupole (suspension shown for illustrative purposes only)

Fig. II-1. Cross sections of Superconducting Ring magnets.

Table II-I. Superconducting-Ring Parameters

Average Radius	1000 m	
Final Energy	1 TeV (1000 GeV)	
Intensity	5×10^{13} protons/pulse	
Injection Energy	100 GeV	
Lattice	Separated function with 6 long straight sections (almost identical to Fermilab Main Ring)	
Magnets	Number	Peak Field
Dipoles	774	42.3 kG
Quadrupoles	240	24.2 kG/in.

B. Progress of the Program to Date

During the original design of the Fermilab accelerator in 1967 and 1968, space was left in the main-ring tunnel for another magnet ring, intended from the start to utilize superconducting magnets, and in the main-ring service buildings for the associated cryogenic equipment. A small group began to work on superconducting-magnet development in 1972, after the Fermilab accelerator had achieved its design energy of 200 GeV. This work has continued and been expanded in effort up to the present.

At the outset, a number of tentative design principles were established. Among these are:

(i) The Superconducting Ring cycle time was picked with the realization that the first ramping supermagnets to be developed might be ramped more slowly than conventional magnets. It was deemed that a desirable goal would be to achieve an average intensity of about 10^{12} protons per sec, which implies a cycling time of several minutes. At this cycling rate, the thermal load originating from induced currents is a small part of the refrigeration load. It should be emphasized that there is always an option of increasing the repetition rate and hence the average proton intensity by increasing the rf capability and the refrigeration capacity. Another method of increasing the average proton intensity is to stack additional Main-Ring pulses in the Superconducting Ring prior to acceleration.

(ii) The magnet dewars would themselves play the role of transfer lines carrying coolant from and back to the refrigerators located in the service buildings.

(iii) The magnets would have a cold beam tube, since the relatively low proton beam current would not have stringent vacuum requirements. Later, it was determined that it would be possible to have vacuum of high enough quality for colliding beams in the Superconducting Ring.

(iv) The magnet iron used to enhance the magnetic field would be at room temperature and would always be below saturation, thus insuring field linearity with excitation.

(v) The current in the conductor would be consistent with utilization of existing Main-Accelerator power supplies for superconductor excitation at the highest practical current density.

(vi) The protons would be extracted and transported into the present external experimental areas.

The possibilities of producing colliding beams between the Superconducting Ring and the Main Ring and of colliding proton-antiproton beams in the Superconducting Ring were realized in the mid-1970's and provisions for these colliding beams have since been incorporated into the design.

1. Magnets. The major thrust of the program to this time has been the development of the elements of the accelerator that are new, the superconducting magnets and their refrigeration. Our work has concentrated on the development of dipole magnets, but the lessons learned in this work are applicable to higher-multipole magnets and a quadrupole has been designed and is now being fabricated. Work has also been carried out on the lattice, beam transfer, beam abort, extraction, vacuum system, rf system, and all the other systems of a complete accelerator.

The more conventional elements that are part of the Research and Development phase are discussed in part C of this chapter, while those that are part of the later construction project are discussed in Chapter IV below.

More than 70 test magnets 1 ft or 5 ft in length have been built to understand the behavior of superconducting accelerator magnets and to develop mechanical structures and refrigeration systems. From this work, we have reached a better understanding of the phenomenon of training and are now able to build magnets that reach or exceed their design fields with only minimal training. The test program is discussed in detail in the 1976 Design Report. We may summarize by saying that training appears to come from very small relative conductor movements during excitation. Frictional local heating coming from these movements causes quenching of the superconducting state. Knowing this, one can design to minimize training. Magnets remember their training over long periods of time and through many temperature cycles, provided that the basic coil-support structure is not disturbed.

Several methods of coil support have been explored in our development program. We have settled on a structure utilizing external stainless-steel collars, which give satisfactory support during cooldown and excitation.

In the last year, we have wound, assembled, and tested 17 full-scale 22-ft dipole magnets. Keystone wire, improved end configurations and improved collars have been incorporated in these magnets. We are now engaged in extensive field measurements and studies of coil motion both under cooldown and under excitation. These studies have led us to incorporate greater constraining forces and to provide preloading of the coils in the design. These improvements have made it possible to reduce unwanted field multipoles to within acceptable limits for particle orbits.

These improvements have also made it possible to reduce the assembly work by automating the coil-forming and collaring operations. In

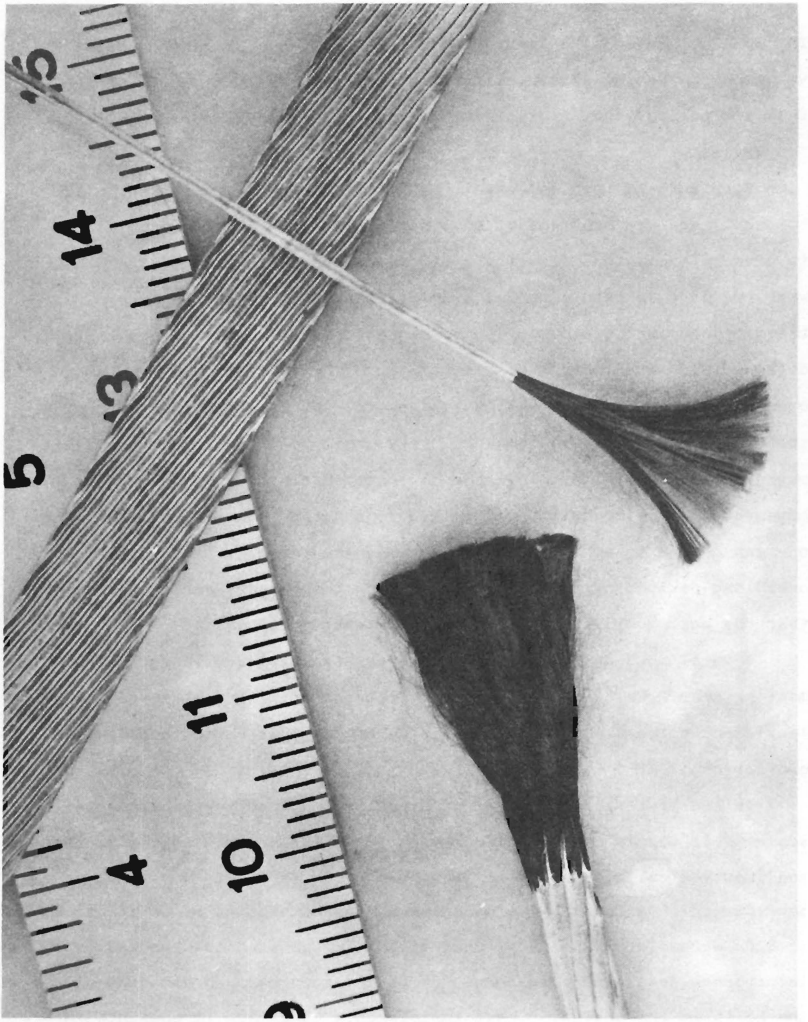


Fig. II-2. Superconducting cable.

addition, a new pancake technique is used in which coils are wound flat, then formed to the desired saddle shape by being pressed in a mandrel. This technique has been tested on 5-ft magnets and is now being phased into 22-ft magnet production. The pressing technique is new to superconducting-magnet construction. It is expected to improve field quality and speed of fabrication.

Production methods have been studied in great detail. We have set up a production line to assemble supermagnets at Fermilab from parts that have been fabricated by private industry. Production is now at the rate of one 22-ft magnet per week and increasing rapidly as more tooling comes into operation. We also expect to develop the capability in private industry to produce complete magnets.

We have also studied conductors of many varieties and have settled on a niobium-titanium superconductor stabilized in copper, shown in the photograph of Fig. II-2. This is wound into a Rutherford style cable. Each of the 23 strands of 0.027-in. diameter in the cable has 2100 filaments of 8 μm diameter. We have worked with domestic fabricators of superconductor to improve their quality control. They are now able to meet our specifications. We have developed cleaning and taping procedures and have successfully transferred this technology to private industry. All cable is now received ready for winding into coils.

Each magnet has a stored energy of approximately 0.5 MJ at design current and a means is needed for extracting this energy safely in the event of a quench. A prototype system has been built and recently tested successfully. This system detects a quench by sensing the onset of an ohmic voltage. Thyristors are then fired to shunt magnet currents through a water-cooled dump resistor. In recent tests, a large fraction of the energy stored in a 4-magnet string was successfully dumped many times. There was no evidence of quench propagation into neighboring magnets. The remainder (10 to 20% of the stored energy), which is dumped into the quenched magnet itself, does no damage.

2. Refrigeration. The ring will be divided into 48 magnet strings, which will be cooled by sub-cooled one-phase liquid helium. In order that the temperature rise along the cooling path be kept within bounds, the magnet vessel is surrounded by a return channel filled with boiling helium. A string of magnets between heat exchangers is thus at a constant temperature. The demand for power around the ring is reduced from almost 10 MW with separate refrigerators to approximately 5 MW with a liquefier and satellite-refrigerator system. This system has been developed as part of the research and development of the Superconducting Ring.

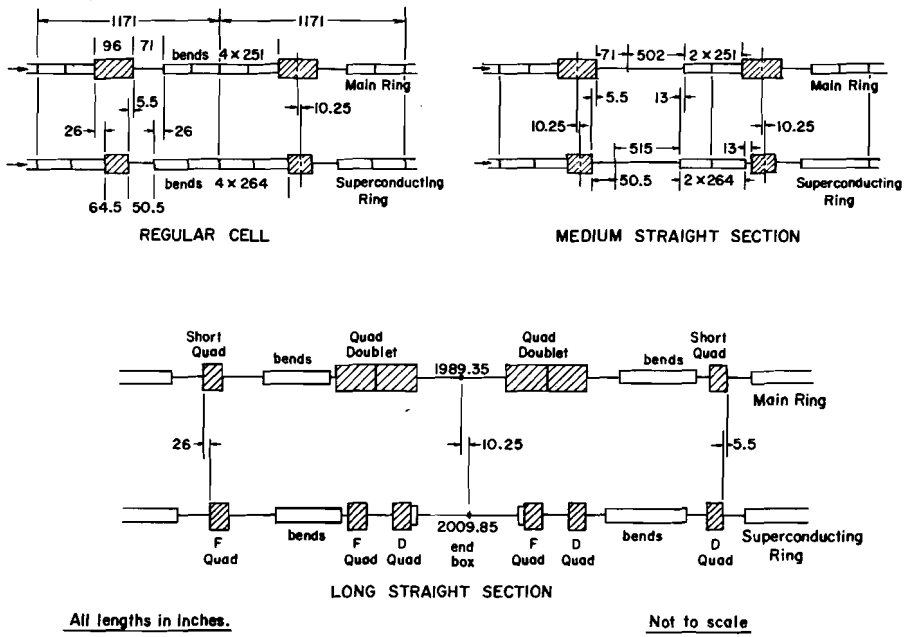


Fig. II-3. Lattice of the Superconducting Ring.

Tests of the system concepts have been carried out. The commissioning of a prototype satellite refrigerator is complete and reliability runs are in progress. The satellite refrigerator has shown that it can satisfy the design requirements (700 W at 4.5 K). Strings of several full-size magnets have been operated to test the cooling-system concept. The building for the central helium liquefier has been completed. Equipment has been obtained from a surplus USAF liquid-oxygen plant in California and is being reconditioned and assembled at Fermilab.

The research, development and demonstration phase will have 12 satellite refrigerators, plus three spares. The construction phase will add 12 more to give a total of 24 installed for the complete rapid-cycling accelerator.

C. Superconducting Ring Design

1. Lattice. The lattice design of the Superconducting Ring is tightly constrained by the fact that it must fit within the Main-Ring tunnel and must therefore follow very closely the bending of the Main Ring. At the same time, experience with the Main Ring and the development of superconducting magnets has made it possible to fit 22-ft dipoles into the longitudinal space in the support structure of the 21-ft dipoles of the present Main Ring. A lattice incorporating these 22-ft dipoles has been designed. It is shown in Fig. II-3. Except in the long straight sections, bending centers are superimposed so that the Superconducting Ring beam lies directly below the Main-Ring beam. In the long straight sections, the beam is parallel to and slightly outside (0.392 in.) the Main Ring. Nothing in the ring intrudes into a clear space directly below the clear space of the Main-Ring long straight section. An extra space of 12 in. just outside this clear region is provided for the doubler "warm-up" box, which makes the transition from 4K to room temperature. This lattice is matched at a tune of 19.4.

There are six long straight sections, just as in the Main Ring. It is planned to utilize them as follows:

A. 1. Beam transfer from Main Ring

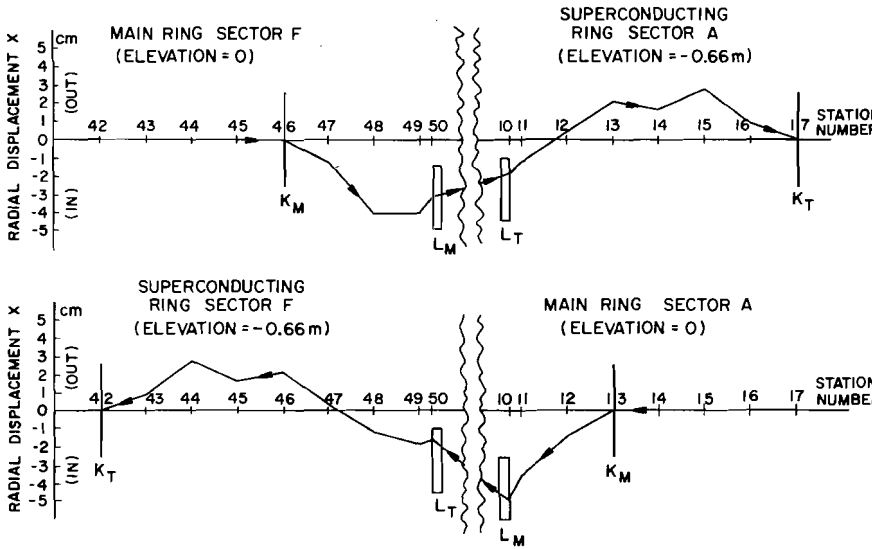


Fig. II-4. Forward and backward beam-transfer systems, Main Ring to Superconducting Ring.

2. Beam extraction to external experimental areas

B. Colliding-beams interaction region

C. 1. Internal Target Area

2. Possible future colliding-beams interaction region

D. Forward and reverse beam-abort septa, dc magnets and targets

E. Colliding-beams interaction region

F. RF acceleration system

2. Beam-Transfer Systems. There are two beam-transfer systems, one for each direction of beam in the Superconducting Ring. In addition, there is a system for reverse injection of 8-GeV beam from the Booster into the Main Ring. This last system is not a part of the programs described in this report. A schematic plan of these systems is shown in Fig. II-4. The orbits in the two rings are separated vertically by 26 in. (0.66 m). The beam can be transferred at any momentum up to 100 GeV/c. The parameters given below correspond to a transfer momentum of 100 GeV/c.

The actions of the two transfer systems are identical, except in opposite directions. Sequentially in the direction of the beam, the 100-GeV/c beam in the Main Ring is first kicked radially inward by a kicker magnet K_M across the iron septum of a Lambertson septum magnet L_M approximately one-fourth of a horizontal betatron oscillation downstream. The septum magnet L_M deflects the beam downward toward a similar septum magnet L_T in the Superconducting Ring that deflects the beam back to the horizontal plane. Both L_M and L_T are located in long straight section A near the upstream and downstream ends respectively. In addition to the vertical dog-leg in the beam, the two septum magnets are also rolled slightly about the beam axis to form a small horizontal double bend in the beam, so that the beam will enter the Superconducting Ring in the horizontal plane at the proper horizontal displacement and angle to intersect the Superconducting Ring orbit approximately three-fourths of a betatron oscillation downstream of L_D. At the

intersection point, a horizontal kicker magnet K_T will kick the beam onto the Superconducting Ring orbit. The transfer systems for both directions are located in long straight section A on the radially inward side. The parameters of the transport elements are given in Table II-II and the layout and geometry in Table II-III.

Table II-II. Beam-Transfer System Parameters

Kicker Magnets	K_M	K_T	
Length	1	1	m
Peak Field	1.5	1.0	kG
Kick Angle (h)	0.45	0.30	mrad
Rise Time	0.2	0.2	μsec
Aperture (v × h)	4×6	3×5	cm^2
Location forward (clockwise)	F46(MR)	A17(SR)	
Location backward (ccw)	A13(MR)	F42(SR)	
Construction	Terminated ferrite-core window frame		
Lambertson Magnets L_M and L_T			
Length (6 sections)	6		m
Field	8.33		kG
Bend Angle (v)	15		mrad
Aperture	2×2		cm^2
	L_M	L_T	
Location forward	F50(MR)	A10(SR)	
Location backward	A10(MR)	F50(SR)	
Construction	Conventional dc iron septum magnet		

Table II-III. Beam Transfer Layout and Geometry

	Upstream of L_M	Downstream of L_T	
Forward			
location	F50(MR)	A10(SR)	
horiz. displace (x)	-31.0	-19.3	mm
horiz. angle (0_x)	- 0.086	0.025	mrad
vert. displace (y)	0 (MR level)	-0.66 (SR level)	m
vert. angle (0_y)	0	0	
Backward			
location	A10(MR)	A50(SR)	
horiz. displace (x)	-48.4	-15.8	mm
horiz. angle (0_x)	0.43	0.35	mrad
vert. displace (y)	0 (MR level)	-0.66 (SR level)	
vert. angle (0_y)	0	0	

At present, there are interferences between these magnet elements for beam transfer and equipment already installed in the Main Ring at F46, F50 and A13. These interferences can all be resolved by modifying the Main-Ring equipment. It would be possible to avoid all interferences by simply locating the beam-transfer systems in an unoccupied long straight section, such as E, but, on the other hand, it is desirable to

reserve as many straight sections as possible for colliding-beam experiments (see Chapter III). In the Superconducting Ring, the mini-straight at F42 and A17 where kickers K_T are located will either be made warm-bore or K_T will be designed to operate in the cold.

3. Beam Dynamics and Aperture Considerations.

a. Magnetic field corrections. The Superconducting Ring has a magnet lattice that is almost identical to the Main Ring and the beam dynamical effects arising from constructional errors are therefore the same for the two accelerators and have, thus, already been determined (see Section 4.4 of the 1968 NAL Design Report). Furthermore, the tuning and operating experience gained from the Main Ring is applicable in detail to the Superconducting Ring. Finding and improving the closed orbit with a properly instrumented beam-position monitoring system is a well-understood problem. Given good magnetic-measurement data, a careful survey, and reliable means for beam steering, it is likely that a circulating beam can be obtained without unusual difficulty, insofar as effects due to magnetic-length and placement errors are concerned.

Harmonic multipole errors excite resonances. Low-order resonances cause excessive growth in beam size and must be avoided. But with reasonable care in the fabrication of magnets and with the corrections provided by the trim-magnet packages, the widths of these resonances caused by harmonic errors can be reduced to tolerable values, and with proper regulation of the power supplies, these resonances can be avoided. This is especially true with a superconducting magnet system, for which the response of the field to power-supply ripple is small and slow.

The chromaticity, the variation of betatron tune with momentum, must be adjusted to ensure that the ring has a reasonably large momentum aperture. The natural kinematic chromaticity of the ring is $\frac{\Delta\nu}{\Delta p/p} \simeq 22$. To first order, ignoring space-charge instability problems, this chromaticity can be reduced to zero. Landau damping of coherent space-charge

instabilities introduces other requirements on chromaticity. An average sextupole field is provided by the trim-magnet packages located in the ministraight sections to adjust chromaticity to the desired value. Higher-order dependences of ν on $(\Delta p/p)^2$m $(\Delta p/p)^3$, etc., can be corrected by higher-order average multipoles, but in all likelihood these corrections will not be necessary. Dependence of tune on amplitude limits the betatron aperture of the ring. This dependence is compensated by average octupole fields also produced by the trim-magnet packages.

b. Aperture. The most severe aperture requirement is imposed by the operation of an efficient slow beam-extraction system. In a resonant-extraction scheme, the aperture has to be large enough in the extraction plane to permit an unstable betatron oscillation of sufficient amplitude to develop so that the amplitude-dependent step size becomes sufficiently large to jump across an extraction septum with high efficiency. The half-integer resonant extraction system currently in use on the main accelerator takes up about 2 in. of aperture for the unstable betatron oscillation to build up and another 0.75 in. (step size 0.375 in.) to accommodate the stepped-over beam that enters the septum aperture at the proper phase of oscillation. At present, the extraction efficiency is close to 99% on a long-term average and is limited by the effective thickness of the electrostatic septum.

For a superconducting magnet ring with negligible field ripple, it is more advantageous to employ a third-integer scheme. In this kind of scheme, the stable betatron amplitude is not enlarged near resonance, as in the half-integer scheme, so that more of the available aperture can be used for the buildup of unstable betatron amplitude. Moreover, the step size is the accumulation of the amplitude growth in three turns instead of two. Thus one can obtain larger step size for the same available aperture or the same step size with a smaller total aperture. The slow-extraction system for the Superconducting Ring described in Chapter IV below requires a horizontal good-field aperture of

2.25 in.

c. Space-charge effects. The incoherent space-charge tune shift for a beam intensity of 5×10^{13} protons per pulse is negligible at energies above 100 GeV.

Intensity-dependent collective effects in the Superconducting Ring can be estimated by scaling from knowledge of the same effects in the Main Ring. We can expect longitudinal as well as transverse coherent instabilities to occur in the same manner as they do there. Since both the tune spread and the momentum spread in the beam decrease roughly linearly as energy increases, the tolerable transverse and longitudinal coupling impedances of the vacuum enclosure for the Superconducting Ring will be about half those for the Main Ring. Conversely, for the same coupling impedances, the 1000-GeV beam in the Superconducting Ring can be expected to be twice as unstable in the 500-GeV Main-Ring beam.

Longitudinally, the tolerable impedance in the Main Ring is given by $Z/n \sim 10\Omega$, where n is the mode number. The major contribution to this coupling impedance comes from parasitic modes in the rf cavities. This instability was cured after these parasitic modes were properly damped and the inactive cavities were properly shorted on the flattop. Similar precautions will be taken in the design of the rf cavities. In addition, a wide-band longitudinal feedback damper may be necessary for the full intensity of 5×10^{13} protons/pulse. There is such a damper already in use in the Main Ring.

On the other hand, since both the ring aperture and the rf of the Tevatron can contain much larger momentum spread, it should be possible to increase the momentum spread intentionally as the beam is being accelerated. One can keep the momentum spread at 1000 GeV as large as or even larger than that of 500 GeV. The larger momentum spread will maintain stability through Landau damping.

Transverse coherent instabilities in the Superconducting Ring can be cured in the same manner as in the Main Ring by using a wide-band feedback damper. This technology is well-developed and straightforward.

In addition to the damper, which will take care of the lower modes, the chromaticity of the lattice must be adjusted by the trim sextupoles to positive values throughout the acceleration cycle to insure stability of the higher head-tail modes.

4. RF System. A minimal rf system is required to demonstrate synchronous beam transfer, stable containment of the beam at all energies, and acceleration of the beam to energies up to 1 TeV. The acceleration rate can be almost arbitrarily low. Radial-position detectors and a beam-current phase detector will be required in the superconducting ring. A minimal low-level rf system capable of being phase-locked to the Main Ring will also be needed.

One slightly modified Main-Ring rf cavity will be installed in the Superconducting Ring in long straight section F. The beam transferred to the Superconducting Ring will be synchronously captured into the rf buckets created by this cavity. The Main Ring normally operates with 18 cavities at a synchronous phase angle of 50° and an acceleration rate of 150 GeV/sec. To supply the same bucket area with one cavity, the synchronous phase angle must be reduced to 19°. The acceleration rate is then

$$\frac{\sin 19°}{\sin 50°} \cdot \frac{150 \text{ GeV/sec}}{18} = 3.54 \text{ GeV/sec}.$$

To match the beam-bunch shape, the Main-Ring ramp will be reduced prior to beam transfer to that corresponding to 3.54 GeV/sec and the rf voltage reduced adiabatically to the equivalent of one cavity. Approximately 4-1/4 minutes are required to accelerate the beam from 100 GeV to 1000 GeV. Ramping the Superconducting-Ring magnets at this low rate will make negligible additional demand on the refrigeration system, which is designed primarily for dc operation.

Starting from 100 GeV, the total frequency modulation required is only 4.3×10^{-5}. Hence a simple low-level rf system with a rough program will suffice.

The larger rf system needed for the complete Tevatron is discussed in Chapter IV below.

5. Beam-Abort System. In a superconducting magnet ring, a fast, high-efficiency beam-abort protective system is essential. One must be able to eject the beam rapidly and bury it in a beam stopper in case of component failure or when desired for other reasons. If the superconducting magnets are not properly shielded from stray particles, either primary or secondary, heating by those particles in the magnet coils will cause the coils to quench.

The most efficient and reliable beam-abort system is, in essence, a simple fast beam-extraction system. The system we have designed is shown schematically in Fig. II-5. The operation of the forward and the backward systems is identical. We will describe only the forward abort system.

To abort the forward circulating beam, it is kicked downward by a fast kicker K_A located at B50 in long straight section C. The vertical oscillation induced will displace the beam downward at C50 in long straight section D across an iron-septum Lambertson magnet S_A. The Lambertson magnet will deflect the beam radially outward to clear the ring quadrupole at D10 and enter a beam stopper buried in the wall of the tunnel. At both B50 and C50, the vertical β-function has its maximum value of approximately 120 m, and with a betatron tune of $\nu = 19.4$, these two locations are separated by 2π (3.23) in betatron phase. Thus a kick at B50 of 0.18 mrad will result in a displacement at C50 of 2.15 cm, adequate to clear the septum. The septum magnet S_A is composed of a chain of ten sections of dc Lambertson magnets and deflects the beam radially outward by an angle of 6.0 mrad, which will bring the beam far enough out at D10 to clear the ring quadrupole. The beam will enter the tunnel wall just upstream of the first dipole after D11, where the beam stopper is buried. If desired, it is of course possible to bend the beam downward after it clears the ring using additional dipoles and

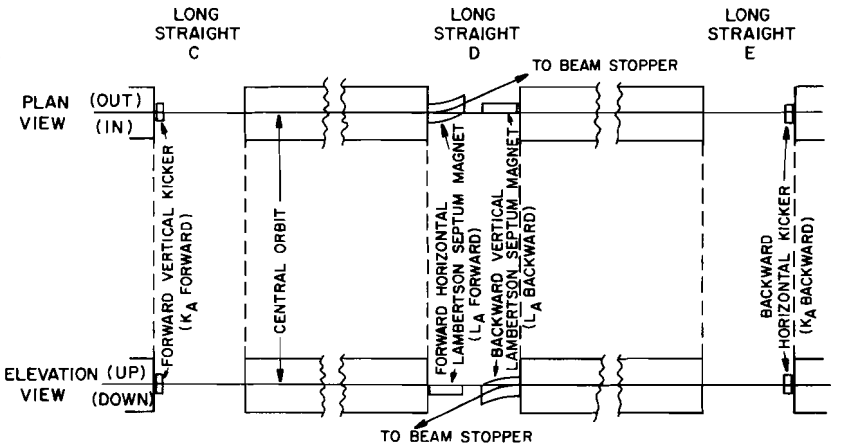


Fig. II-5. Forward and backward beam-abort systems.

direct it into a stopper buried in the floor of the tunnel.

For the backward abort system, the kicker is placed at E10 and the septum is located at D10. The deflections of the beam should now be radially outward to take advantage of the large horizontal β value at D10 and E10. The Lambertson magnet will then deflect the beam downward to the beam stopper buried in the floor of the tunnel. The parameters of the kicker and the septum magnets are given below for a 1-TeV beam.

Table II-IV. Beam-Abort Magnet Parameters

Kicker Magnet K_A		
Length (4 sections)	4	m
Peak Field	1.5	kG
Kick Angle	0.18 (vertically down for forward; radially out for backward)	mrad
Rise Time	0.2	μsec
Aperture (v × h)	4 × 6	cm^2
Location	B50 (forward) E10 (backward)	
Construction	terminated ferrite-core window frame	
Lambertson Magnet S_A		
Length (10 sections)	20	m
Peak Field	10	kG
Bend Angle	6.0 (radially out for forward; vertically down for backward)	mrad
Aperture (v × h)	2 × 4	cm^2
Septum thickness	2	mm
Location	C50 (forward) D10 (backward)	
	conventional dc iron-septum magnet	
Beam Stopper		
Construction	Steel cylinder with Al core inserted from front	
Al core diameter	0.1	m
length	1.5	m
Steel cylinder diameter	1	m
length	3	m
Geometry of Aborting Beam		
Angle kicked by Kicker K_A	0.18 (vertically down for forward; radially out for backward)	mrad
Displacement at entrance to septum magnet S_A	2.15	cm
Angle at entrance to S_A	-0.20	mrad
Bending angle of S_A	6.0 (radially out for forward; vertically down for backward)	mrad
Displacement at ring quadrupole downstream of S_A	24 (9.4)	cm

With a revolution time of 21 μsec, a kicker rise time of 0.2 μsec, a beam displacement at the septum of 21.5 mm, and a septum thickness of 2 mm, the fraction of beam hitting the septum is

$$\frac{0.2\ \mu\text{sec}}{21\ \mu\text{sec}} \times \frac{2\ \text{mm}}{21.5\ \text{mm}} = 0.09\%.$$

The efficiency of the abort system is thus better than 99.9%.

The present Main-Ring beam abort system is in long straight section D, making this area somewhat radioactive. By aborting the Superconducting-Ring beam in this same area, we limit the radioactivity to one long straight section and leave all other straight sections cool. The kicker magnets placed at the ends of long straight sections C and E are only 4 m long each and should not handicap the utility of these straight sections for colliding beam experiments.

6. Vacuum System.

a. Introduction. The decision to use the Superconducting Ring as a storage ring to collide beam with the Main Ring places stringent requirements on the vacuum system. In addition, the vacuum system is unconventional because it is a cold-bore accelerator. There are many advantages and some disadvantages of a cold-bore ring. Among the advantages are:

(i) Maximum use of the beam-tube aperture. This is an advantage even if the magnetic field is not uniform throughout the aperture, because this space can be used for injection and extraction of beam when the Superconducting Ring is operating as an accelerator.

(ii) Cryopumping of all residual gases except for helium and hydrogen. The vapor pressure of hydrogen if approximately 10^{-6} Torr at 4.6K.

The major disadvantages of a cold-bore system are lack of access to the beam tube and lack of experience with cold-bore systems.

b. Pumps. Since liquid helium is readily available, it seems advantageous to use cryosorption pumps throughout the system. These pumps can have a very high pumping speed and capacity for both helium and hydrogen, and can be built into the cryostat in many places. It is planned to locate cryosorption pumps at warm-cold interfaces. Although this scheme provides lower net pumping speed than more frequent pumps, it should be more than adequate, provided there are no helium leaks into the tube directly from the liquid-helium regions of the cryostat.

We have tested this system in the last year with good results. The system can indeed be made leak-tight.

c. Beam-off Vacuum. If there are no leaks into the beam tube from the liquid, the pumps must still be capable of handling the outgassing of the beam tube and leaks from the insulating vacuum into the tube. Our tests have shown that hydrogen desorption from the beam-tube walls is the largest problem. The beam tube itself will therefore be chemically treated, vacuum baked, and stored in dry nitrogen before installation. With this treatment, outgassing rates at room temperature of hydrogen from stainless steel can be held to less than 10^{-12} Torr-liters $cm^{-2}sec^{-1}$. At 4.6K, the outgassing should be many orders of magnitude less.

The other problem will be small leaks from the insulating vacuum region into the bore tube. A string of magnets will be leak-checked when warm and with the pressure in the insulating region at one atmosphere or more. This sets a limit on leaks of $Q_{leak} \lesssim 10^{-9}$ atm-cc/sec. Sensitive regions, such as bellows and feedthroughs, can be cold-shocked to liquid-nitrogen temperatures during the leak-detection procedure. We assume that undetected leaks will be small, $Q_{leak} \lesssim 10^{-13}$ atm-cc/sec and if we assume a total leak rate Q_{leak} of 10^{-12} atm-cc/sec and pumps of speeds of 500 ℓ/sec at every quadrupole, then the peak gas density at the position of a leak (15 meters from a pump) will be less than 10^7 helium molecules/cm^3, which is equivalent to a room-temperature pressure of less than 2×10^{-10} Torr. This is clearly adequate for any storage

ring, and would give a beam lifetime against multiple scattering and nuclear interactions of many days.

d. Beam-on Vacuum. The most severe limitation to current in the Tevatron will be the pressure-bump instability. Dynamically, this is caused by ions made by beam-gas collisions and accelerated to the beam-tube well by the electrostatic potential of the beam. When the ions hit the wall, they release gas molecules that are absorbed on the wall causing a local increase in pressure. At some beam current, $I_{critical}$, this becomes a runaway process that destroys the beam.

One of the uncertainties of cold-bore systems is the possibility that the desorption coefficient η, the number of desorbed molecules per incident ion, might be very high. Theory predicts that for a cold-bore system with high sticking probability, the product $\eta I_{crit} \approx 10^4$ amps. The only data for desorption of hydrogen from cold surfaces were taken using protons of a few keV to bombard films of frozen gas. The coefficient η was measured to be approximately 5×10^4 for hydrogen and helium and much less for nitrogen and argon. Since the ions in our case will be a few hundred electron volts, we expect that an η of approximately 5×10^3 is realistic, giving $I_{crit} \approx 10$ A. The current in the Superconducting Ring at 5×10^{13} protons per pulse is 0.4 A if the bunching factor is one, so we believe we are well below the limit for the pressure-bump instability.

e. Warm Regions. The long straight sections will be pumped by cryosorption pumps or titanium getter-ion pumps. These regions can and will be baked in situ. A coaxial pumping region with chevron baffles can be installed in the beam tube to decrease the migration of gas into the cold region, and to reduce the heat leak due to radiation. With sufficient pumps, the pressure in the straight sections can be held to 10^{-9} to 10^{-10} Torr.

f. Valves. At the end of each cryogenic string, halfway between service buildings, there is a short (1 m) region for Joule-Thomson valves. This region will have a warm-cold interface, with a fast-acting vacuum

valve to isolate the regions.

g. Insulating Vacuum. The vacuum in the insulating region should be between 10^{-4} and 10^{-5} Torr and should be able to be attained quickly. In order to get lateral pumping of the superinsulation, we will use aluminized Mylar with prepunched holes. These holes increase the pumping speed by orders of magnitude over edge pumping, without significantly increasing the effective emissivity. We will use a system similar to the present Main-Ring roughing system (perhaps even share the same one). This system consists of a mechanical pump and diffusion pump at each service building.

7. Refrigeration System. As was discussed in part B of this chapter, the decision was made early in the development to cool with one-phase helium and to utilize the magnet ring itself as the helium channel. In addition, we have developed the design of a system of a central helium liquefier and 24 satellite refrigerators. Only 12 of these satellite refrigerators are needed for the demonstration phase. The system is shown in schematic form in Fig. II-6.

a. Central Liquefier. The use of a central plant gives high efficiency and consequent power saving, as well as ease of maintenance. The plant we have obtained, partly from USAF surplus, consists of three large compressors, a helium reliquefier, and a nitrogen reliquefier. Our plan is to use two of the compressors for helium instead of liquid-air service (as they were previously), which will necessitate operating them at one-half of their rated horsepower. The other compressor, providing flow for the nitrogen reliquefier, will run at nearly full power. Under these conditions, the design output of the plant is approximately 1,300 lb/hr (5,000 ℓ/hr) of liquid helium with both compressors running. The design output of the nitrogen reliquefier is 5,000 lb/hr (2,800 ℓ/hr) of liquid nitrogen. The current plan is for the central helium liquefier to be operational in the fall of 1977.

Many possible uses exist for the central liquefier. It can provide

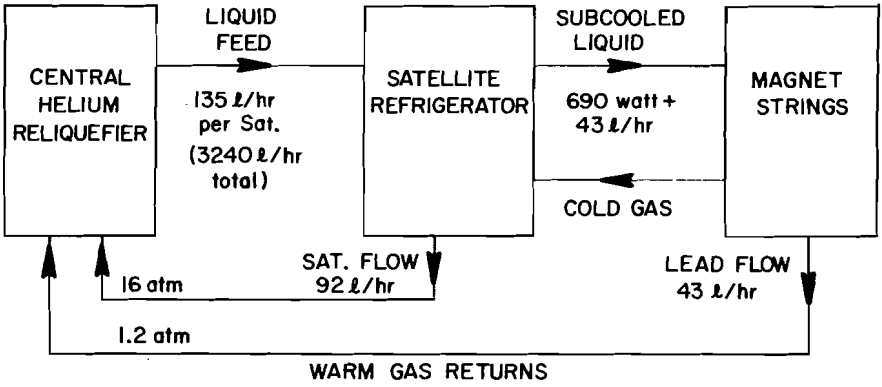


Fig. II-6. Refrigeration schematic.

refrigeration for beam-line magnets. Depending on the actual heat loads developed by the accelerator system, it may be possible to run only one helium compressor at a time. In the event of a future increase in liquid-helium requirements, it would be possible to rearrange the cylinders on the helium compressors and to approximately double the plant output. This would require an expenditure of approximately $200,000 to buy some additional cylinders.

b. Satellite Refrigerator. The satellite refrigerator unit has three possible modes of operation, as shown in Table II-V and in Fig. II-7.

Table II-V. Satellite-Refrigerator Operation

Mode	Consumption	Production
Satellite	91 ℓ/hr He	690 W
Refrigerator	37 ℓ/hr N_2	445 W
Liquefier	60 ℓ/hr N_2	90 ℓ/hr He

In the satellite mode, the system is continuously supplied 3.2 g/sec of liquid helium from the central liquefier. In the refrigerator and liquefier modes, which are used when the central liquefier is not operating, liquid nitrogen is used instead of liquid helium.

Reliability of the satellite refrigerator system is high, for the following reasons:

(i) The compressor package consists of ammonia refrigeration compressors. These machines are commercially produced and have a proven record of reliability.

(ii) The expanders are installed in separate canisters. This allows quick removal and replacement with a spare unit. During the absence of an expander, the satellite refrigerator can produce the same amount of refrigeration through the addition of more liquid helium at a rate of 400 ℓ/hr coming out of storage. While the expander is being repaired, the central liquefier will liquefy the extra gas.

8. Control System. The Superconducting Ring will be controlled

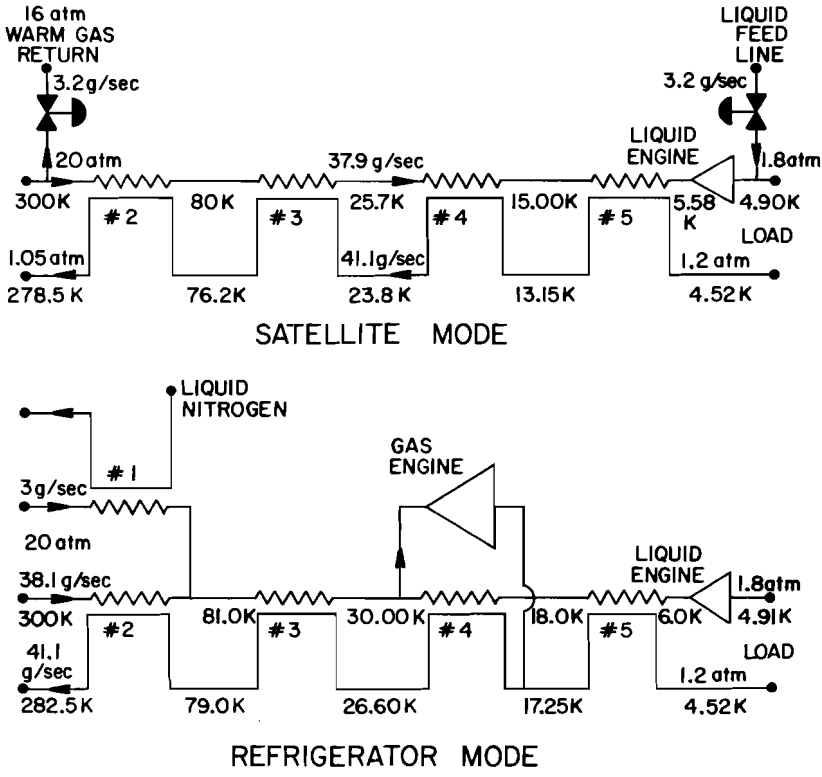


Fig. II-7. Satellite-refrigerator modes.

completely through the present Main-Ring control network. No new central-control or transmission facilities will be needed.

D. Plans and Schedules

The rate at which the research and development phase of the Superconducting Ring will be completed and how much it will cost depend on the rate at which funding is provided for fiscal years FY 78 and FY 79. The Laboratory's initial cost estimate for the project, starting in FY 77, was $35 million, based on the availability of $10 million in FY 77 and $25 million in FY 78. It was stated that a slower schedule would result in a higher cost. The FY 78 budget which is now under consideration in Congress would bring the funding total for FY 77 and FY 78 to less than half the required amount. Although a case has been made for increased funding in FY 78, the President's budget may be passed as submitted. In that case we assume that the funds required to complete the project will be provided in FY 79. Nevertheless, that delay will raise the total cost to $40 million. Both alternatives are discussed below.

1. FY 77

   a. Assemble and test first quadrupole
   b. Assemble 120 dipole magnets. Install in tunnel as completed.
   c. Complete correction-magnet design.
   d. Qualify vendors for coil-assembly production.
   e. Complete Central Liquefier Plant.

In FY 78 and FY 79, we discuss:

Case A: Fermilab Recommended Plan

Case B: President's Budget

2. FY 78

   Case A

   a. Assemble and install 680 dipole magnets.
   b. Assemble and install 240 quadrupole magnets.
   c. Commission Refrigeration System.
   d. Complete Vacuum System.
   e. Complete RF System.
   f. Complete Controls System.

Case B

a. Assemble and install 180 dipole magnets.
b. Assemble and install 50 quadrupole magnets.
c. Commission Refrigeration System (half of satellites).
d. Complete Vacuum System.
e. Complete RF System Design.
f. Complete Controls System Design.

3. FY 79

Case A

Commission Superconducting Ring with beam at beginning of year.

Case B

a. Assemble and install 500 dipole magnets.
b. Assemble and install 190 quadrupole magnets.
c. Complete Refrigeration System.
d. Complete RF System.
e. Complete Controls System.
f. Commission Superconducting Ring with beam at end of year.

Cost estimates for Cases A and B are given on the next page.

ENERGY DOUBLER OPERATING COST ESTIMATE*
(To Coasting Beam)

CASE A. FERMILAB PREFERRED	FY 1977	FY 1978
MAGNETS		
Number of 22-ft Dipole Magnets	120	680
Number of Quads & Correction Elements	-0-	240
Dipole Cost	$ 3,570	$16,000
Quads & Correction Elements Costs	-0-	2,400
Subtotal - Magnet Cost	$ 3,570	$18,400
OTHER COMPONENTS		
Vacuum	$ 80	$ 300
Controls	-0-	300
RF	-0-	200
Power Supplies	-0-	300
Beam Transfer	-0-	400
Extracted Beam	-0-	-0-
Supports	70	700
Conventional Utilities	-0-	1,000
Subtotal - Other Components	$ 150	$ 3,200
ANNUAL R&D (INCLUDING SWF)	$ 2,850	$ 4,200
REFRIGERATION SYSTEM	$ 400	$ 2,200
CONTINGENCY	-0-	-0-
TOTAL for Energy Doubler (less Central He Liquefier)	$ 6,970	$28,000

CASE B. PRESIDENT'S BUDGET	FY 1977	FY 1978	FY 1979
MAGNETS			
Number of 22-ft Dipole Magnets	120	180	500
Number of Quads & Correction Elements	-0-	50	190
Dipole Cost	$ 3,570	$ 4,500	$13,500
Quads & Correction Elements Costs	-0-	500	2,000
Subtotal - Magnet Cost	$ 3,570	$ 5,000	$15,500
OTHER COMPONENTS			
Vacuum	$ 80	$ 150	$ 200
Controls	-0-	150	150
RF	-0-	200	-0-
Power Supplies	-0-	200	100
Beam Transfer	-0-	200	200
Abort Beam	-0-	-0-	-0-
Supports	70	200	600
Conventional Utilities	-0-	200	850
Subtotal - Other Components	$ 150	$ 1,300	$ 2,100
ANNUAL R&D	$ 2,850	$ 3,000	$ 3,400
REFRIGERATION SYSTEM	$ 400	$ 700	$ 2,000
CONTINGENCY	-0-	-0-	-0-
TOTAL for Energy Doubler (less Central He Liquefier)	$ 6,970	$10,000	$23,000

* In Thousands of Dollars

III. COLLIDING-BEAMS FACILITY

A. Introduction

There are two kinds of colliding-beams facilities planned as part of the TeV program, proton-proton (pp) and antiproton-proton ($\bar{p}p$). These two kinds of facilities will make use of the same long straight sections for experiments, but are achieved in quite different ways. The pp collisions will use a beam stacked in the reverse (ccw) direction in the Tevatron and accelerated, then made to collide with the forward (cw) circulating beam in the Main Ring. The $\bar{p}p$ collisions will use an antiproton beam that is produced by the Main Ring proton beam, then "cooled" to small oscillation amplitudes and stacked in a special ring in the Booster tunnel. The antiproton beam can be accelerated in the reverse direction in the Main Ring and Tevatron simultaneously with a proton beam circulating clockwise.

The two colliding-beams facilities will be discussed separately below.

B. Proton-Proton Colliding Beams

For pp collisions, an intense p beam is stacked, accelerated, and stored in the Tevatron at 1 TeV in the reverse direction. The Main Ring is then operated in the normal mode, accelerating a proton beam to 400 or 500 GeV in the forward direction. On the flattop of the Main Ring, the two beams are brought together to collide in long straight sections. We have designed all beam-manipulating systems necessary for accelerator functions in such a way that only three straight sections are occupied. Straight sections B, C, and E are left available for use as three colliding-beam experimental areas. For this mode of operation, the necessary modifications and additions are:

(i) Modification of the backward beam-transfer system and adding the stacking rf system to enable stacking many Main Ring pulses in the momentum space in the Tevatron.

(ii) Modification of the Tevatron rf system to accelerate the more intense stacked beam and to keep the beam bunched

during storage.

(iii) Addition of beam colliding systems in long straight sections to bring the beams together to collide and modification of the long straight section quadrupoles for low β^* to enhance luminosity.

(iv) Modification and enlargement of the tunnel sections at the colliding-beam straight sections to accommodate particle-detection equipment and addition of the detection equipment.

The luminosity that can be obtained with low β^* insertions, but without beam stacking, will be sufficient to carry out some colliding-beams experiments. Some initial colliding-beam operation without beam stacking is planned. With or without stacking, an rf system capable of keeping the beam bunched during storage will be needed.

1. Backward-stacking beam-transfer system. For stacking in momentum (longitudinal) phase space, the beam should not be injected onto the central orbit. Instead, it should be injected onto an orbit corresponding to a momentum slightly below (in our case) the central value. The injected beam will then be accelerated by a stacking rf system to or slightly above the central momentum to stack. In order that the already stacked beam not be affected by the injection kicker K_T, the dispersion function must have a high value at K_T, and the kicker must have an open aperture (a C cross section instead of an H or window frame) to allow the beam to be accelerated out. In addition, an eddy-current shield must be placed around the stacked beam over the length of the kicker to attenuate the leakage field from the kicker. We have already chosen a high-dispersion location for K_T. The modifications required are therefore:

(i) Retuning of the strength of the transfer magnets L_M and L_T (see Table II-II) for beam displacement and angle at F50 appropriate to the non-central injection orbit.

(ii) Replacement of the window-frame K_T by the open-aperture

kicker and the eddy-current shield.

(iii) Addition of the stacking rf system. The voltage and frequency-modulation requirements on this rf system are minimal, but the precisions required are high.

The lateral geometry of the injection and stacking orbits is shown in Fig. III-1. Cross sections of the orbits, the kicker, and the shield are shown in Fig. III-2. Parameters are given below for 100 GeV/c.

Table III-I. Proton-Stacking Injection Parameters

Kicker magnet K_T (in the Tevatron)	
length	1 m
peak field	1.5 kg
kick angle (h)	0.45 mrad
rise time	0.2 μsec
aperture (v × h)	1 cm × 1.5 cm
construction	terminated ferrite-core open(C) cross section
location	F42
radial position	lip of the C at 1.5 cm radially outward from central orbit
Eddy-current shield	
length	1.2 m
aperture (v × h)	1 cm × 4 cm
construction	high-conductivity Cu open(C)cross section
location	F42, with C-opening facing that of kicker
Orbit and beam characteristics	
injection orbit	
$\Delta p/p$ from central mom.	-3.5×10^{-3}
horiz. displ. at F50	-6.0 mm
horiz. displ. at F42	-20.0 mm
stacking orbit	
$\Delta p/p$ from central mom.	3.5×10^{-3}
transferring beam	
$\Delta p/p$ from central mom.	-3.5×10^{-3}
horiz. displ. at F50	-29.6 mm
horiz. angle at F50	0.61 mrad
displ. from inj. orbit at F50	-23.6 mm
angle from inj. orbit at F42	-0.45 mrad
Stacking rf system	
stacking mode	stacking on top
frequency	53.1 MHz
frequency-modulation range	1 kHz
accuracy of stacking frequency	10 Hz
voltage amplitude	25 kV
capture mode	synchronous capture into stationary buckets
accelerating synchronous phase ϕ_s	55°
bucket area (in $\Delta\phi\Delta p/p$ units	0.158×10^{-3}
bucket area (in $\Delta\phi\Delta E/\omega$ units	0.0478 eVsec (>beam bunch area)
acceleration rate	20.5 keV/turn
total energy gain	0.707 GeV
acceleration time	0.72 sec

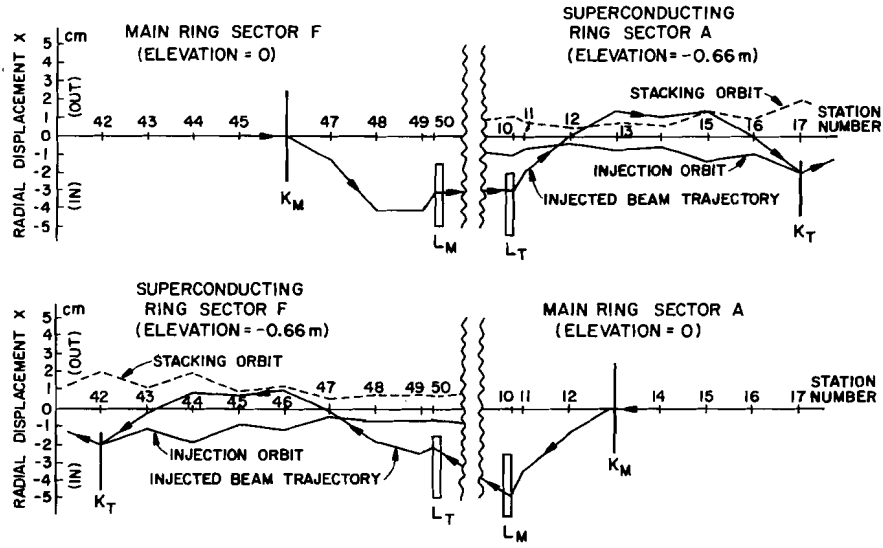


Fig. III-1. Lateral geometry of injection and stacking orbits.

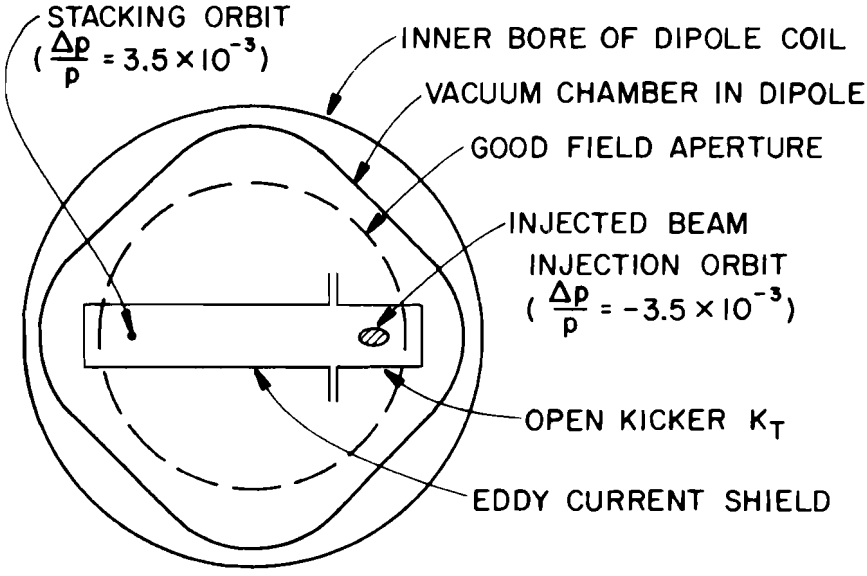


Fig. III-2. Cross section at injection.

For the stacking rf, a single modified Main-Ring rf cavity will suffice. The total number of turns that can be stacked is determined by the capacity of the rf system used for accelerating the stacked beam to 1 TeV. This will be discussed below in connection with the accelerating rf system.

The forward beam-transfer system can be modified in a similar manner to stack a clockwise high-intensity beam if desired.

2. The Accelerating rf System. For colliding with the Main-Ring beam, which is bunched at 53.1 MHz, the Tevatron beam should be bunched at the same frequency. The harmonic number of this rf system should therefore also be 1113. We shall see that the rf system described in Chapter IV to accelerate the beam for fixed-target experiments can also be used for this application.

During stacking, the rf bucket area (in $\Delta\phi$ $\Delta p/p$ units) is 0.158×10^{-3} and the full height is $\Delta p/p = 0.123 \times 10^{-3}$. Although the beam-bunch area is expected to be slightly smaller than the bucket area, we shall assume that the bucket is full. Then the first turn contributes a momentum spread of 0.123×10^{-3} and each subsequent turn contributes a momentum spread of 0.0251×10^{-3}. Stacking 10 turns, we get a total momentum spread of 0.349×10^{-3}. In addition, in stacking at a synchronous phase of 55°, one gets a dilution of a factor 2.5. Hence, the 10-turn stacked beam will have a total momentum spread of 0.87×10^{-3}.

To capture this beam adiabatically and accelerate it at a synchronous phase of $\phi_s = 10°$, one needs a minimum rf voltage of 470 kV/turn. To provide some tolerance, we will take an rf voltage of 900 kV/turn. This will produce an acceleration rate of 7.5 GeV/sec. It will therefore take 2 min to accelerate the beam from 100 GeV to 1 TeV. With 2×10^{13} protons per turn, the 10-turn stack will contain 2×10^{14} protons and correspond to a current of 1.52 A. During acceleration, the power imparted to the beam is 240 kW. Both the voltage and the power can be supplied by 3 of the modified Main-Ring rf cavities described in

Chapter IV. When flattopped at 1 TeV, the stationary rf bucket area will be over 6 times that of the beam bunch and will be ample for keeping the beam bunched during colliding-beam operation. The rf parameters are summarized in Table III-II below.

Table III-II. Acceleration and Stacking Parameters

Characteristics of stacked beam	
No. of turns in stack	10
No. of protons in stack	2×10^{14}
stack current	1.52 A
momentum spread ($\Delta p/p$)	0.87×10^{-3}
Acceleration of stacked beam	
rf frequency	53.1 MHz
harmonic number	1113
frequency modulation	4.32×10^{-5}
cavity	4 MR cavities
capture mode	adiabatic capture
peak voltage per turn	900 kV
synchronous phase	10°
acceleration rate	7.5 GeV/sec
power to beam	240 kW
acceleration time (100 GeV to 1 TeV)	2 min
accelerating bucket area at 100 GeV (in $\Delta\phi \cdot \Delta p/p$ units)	7.57×10^{-3}
beam bunch area at 100 GeV ($2\pi \cdot 0.87 \times 10^{-3}$)	5.47×10^{-3}
stationary bucket area at 1 TeV	3.40×10^{-3}
beam bunch area at 1 TeV	0.55×10^{-3}
bunch length	1.805 rad (1.62 m)
bunch full momentum spread	0.39×10^{-3}

We have taken a conservative beam stack of 10 turns. It would be possible to stack 20 turns to get a stacked current of more than 3 A. To accelerate such a stack at the same rate, the power to the beam would be 480 kW and 5 modified Main-Ring rf cavities would be required.

3. Luminosity. Luminosity calculations must involve an estimate of the beam size in the accelerator. We take for the Main-Ring emittance ε

$$\varepsilon_v = \varepsilon_h = 13\ \pi/E \text{ mm-mrad},$$

where E is the beam energy in GeV. The beam shape is close to Gaussian. The Gaussian rms width σ is given by

$$\sigma^2 = \varepsilon\beta/6\pi \ (\text{mm}^2),$$

where β is the orbit function (in meters).

For head-on collisions, the luminosity is given by

$$L = \frac{n_1 n_2 \times 10^{26} f_o}{2\pi h} \frac{1}{\sigma_1^2 + \sigma_2^2},$$

where $n \times 10^{13}$ protons are in h bunches with revolution frequency f_o. Inserting numerical values, we have

$$L = 7.44 \times 10^{26} \frac{n_1 n_2}{\sigma_1^2 + \sigma_2^2}$$

An obvious way to increase the luminosity is to reduce σ^2 by focusing the beam to lower β. A very easy and practical low β for a Main-Ring straight section can be achieved for energies up to 155 GeV by simply powering the present quads in that straight section from three separate programmed power supplies. The important properties are:

(i) β at the center of the long straight section is reduced to 2.5 m compared with the normal 70 m.

(ii) Continuous adjustment is possible with beam in the accelerator.

(iii) Starting normally and adjusting the quadrupole currents as the energy increases keeps the maximum beam size (in one of the quads) smaller than the injection size.

(iv) A small adjustment of the regular quad current keeps the tune constant with a very small change of β in the rest of the accelerator.

(v) The off-momentum displacement $\eta\ \Delta p/p$ can be made small at the center.

(vi) Nothing is added to or removed from the tunnel and no straight-section space is lost.

Above 155 GeV, some of the quads are driven too hard for continuous operation and β must be returned to normal. If these quads are

replaced with superconducting quads, a small β can be achieved up to 400 GeV.

The momentum spread in the Main-Ring beam is also approximately Gaussian. A value of 0.1 eV-sec is generally used for the longitudinal emittance, although measurements usually give a smaller value. Converting to $\Delta p/p$ and bunch length, one finds, with no acceleration

$$\frac{\sigma_p}{p} = 3.6 \times 10^{-3}\ V^{1/4}/E^{3/4}$$

$$\sigma_\ell = 44/(VE)^{1/4}\ \text{cm},$$

for a beam bunched by V MeV/turn.

Table III-III summarizes the luminosity calculations for several possible running conditions. In all cases a bunched beam of 2×10^{13} and a β of 2.5 m was assumed for the Main Ring. Case A is the most straightforward; it assumes:

(i) Single-turn injection into the Tevatron (2×10^{13} protons),

(ii) Tevatron operation at 400 GeV to permit low β^* (5 m) operation and

(iii) Main-Ring operation at 150 GeV allowing both low β^* (2.5 m) operation with the present quads and continuous collisions (without ramping for cooling reasons). This yields a luminosity of $4.2 \times 10^{30}/\text{cm}^2\text{-sec}$ for head-on collisions at $\sqrt{s}$ = 490 GeV, or about 2×10^5 interactions per second. (Actually the crossing angle will be at a very small angle α<1 mrad to avoid collisions at the next bunch points and consequent background in the experiments.)

For Case B, the energy of the Tevatron beam is set at 1000 GeV, with no special effort to focus the beam (β^*=70 m). This gives L = $1.4 \times 10^{30}/\text{cm}^2\text{-sec}$ at $\sqrt{s}$ = 775 GeV.

Case C assumes that six superconducting quads are used to focus down the Main Ring to β = 2.5 m for 400 on 1000 GeV ($\sqrt{s}$ = 1265 GeV) operation. The smaller Main-Ring emittance at 400 GeV only helps the

instantaneous luminosity slightly (at 400 GeV the Main Ring must be pulsed for cooling reasons, so the time-average luminosity at this energy will be reduced).

A considerably higher luminosity can be achieved with stronger Tevatron focusing; at 400 GeV this can be achieved in a manner similar to that used for the Main Ring, and an instantaneous value of 6.6×10^{30} is found for 400 on 400 GeV ($\sqrt{s}$ = 800 GeV) operation (Case D). If such focusing can also be achieved at 1000 GeV (Case E), the smaller emittance will boost this value to 1.1×10^{31} for head-on collisions. Such focusing will probably require the addition of quads in the long straight section, in which case a finite crossing angle may be required, with a subsequent reduction in the luminosity.

The last two cases assume ten-turn stacking in the momentum space of the Tevatron to give 2×10^{14} protons. For energies of 400 on 1000 GeV, Cases F and G show $L = 1.5 \times 10^{31}$ and 1.1×10^{32} for Tevatron $\beta^* = 70$ and 5 m, respectively. The latter number corresponds to nearly 10^7 interactions/sec and may be difficult to achieve, because it depends not only on stacking, but also on simultaneously achieving zero crossing angle and low β^*.

Table III-III also shows some typical beam parameters. The rms spreads in the transverse dimensions are typically ±0.2 mm. These small spreads will be useful in eliminating backgrounds originating from outside the interaction volume and may also make it possible for the beam to serve as a line source for magnetic spectrometers bending in the vertical plane. The rms bunch lengths σ_ℓ are typically ±10 cm; the rms length of the interaction volume for head-on collisions is given by

$$\sigma_L = (\sigma_{\ell_1}{}^2 + \sigma_{\ell_2}{}^2)^{1/2}/2$$

and is typically ±7 cm.

The beam-beam tune shifts are generally small, but in a few cases are in the $\Delta\nu \cong 0.01$ region. Although these cases are somewhat larger than the very conservative limit of 0.005 often quoted, it seems likely

Table III-III. Parameters for different modes of pp operation. For all modes β^*_{MR} = 2.5 m and 2 × 10^{13} protons in each ring (2 × 10^{14} in ESD for modes F and G).

		A	B	C	D	E	F	G
E_{MR}	(GeV)	150	150	400	400	400	400	400
E_D		400	1000	1000	400	1000	1000	1000
β^*_D	(m)	5	70	70	5	5	70	5
σ_{MR}	(mm)	0.19	0.19	0.12	0.12	0.12	0.12	0.12
σ_D		0.17	0.40	0.40	0.17	0.17	0.40	0.11
V_{MR}	(MV/turn)	3.0	3.0	3.0	3.0	3.0	3.0	3.0
V_D		0.5	0.5	0.5	0.5	0.5	1.0	1.0
$(\sigma_p/p)_{MR}$	(10^{-5})	11.0	11.0	5.3	5.3	5.3	5.3	5.3
$(\sigma_p/p)_D$		3.4	1.7	1.7	3.4	1.7	9.0	9.0
$\sigma_{\ell MR}$	(cm)	9.6	9.6	7.5	7.5	7.5	7.5	7.5
$\sigma_{\ell D}$		11.7	9.3	9.3	11.7	9.3	35	35
σ_L	(cm)	7.6	6.7	6.0	6.9	6.0	18	18
$\Delta\nu_{MR}$	(10^{-3})	1.2	0.2	0.1	0.5	1.2	0.8	12
$\Delta\nu_D$		0.7	3.9	10.4	1.8	0.7	10.4	0.7
$\sqrt{s}$	(GeV)	490	775	1265	800	1265	1265	1265
L_o	($10^{30}/cm^2 sec^1$)	4.6	1.4	1.7	7.2	12	16	120

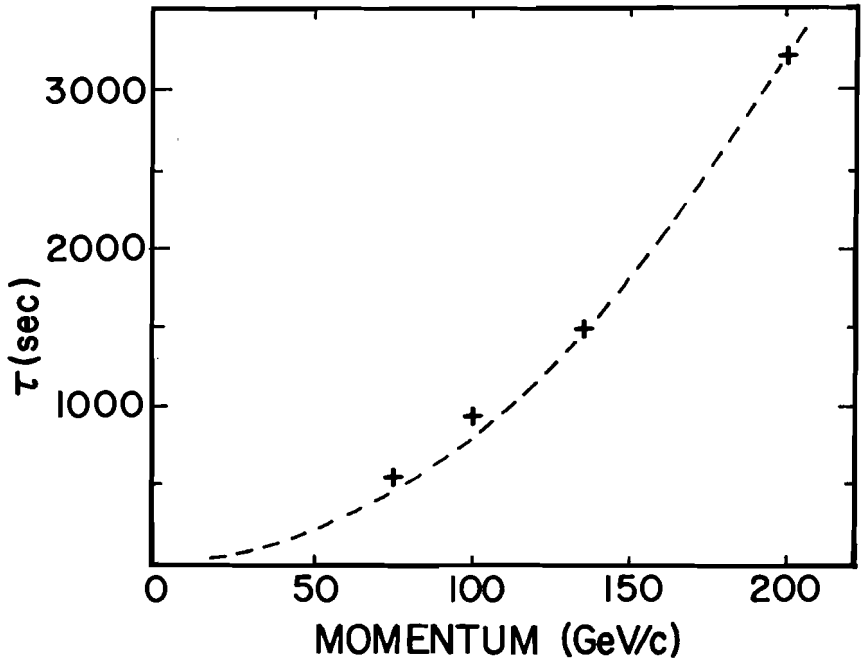


Fig. III-3. Measured Beam lifetime in the Main Ring as a function of momentum.

that this effect will not affect the performance substantially.

There are also problems of lifetime of stored beam with rf on and of radiation background. These problems are being studied experimentally. Fig. III-3 gives some preliminary results on lifetimes of stored beam in the Main Ring. There is rough agreement between experiment and the diffusion theory of multiple scattering. Beams have been stored for as long as 1 hour with rf on. Preliminary results on radiation background indicate that it can be reduced significantly at a particular location by careful attention to the tune of the accelerator.

4. Colliding Geometry. Bringing the beams together in the 50-m straight section is not trivial, especially at the top energy of 400 on 1000 GeV. The most straightforward way is to allow the Main Ring and Tevatron to cross one another vertically, with the two accelerators remaining transposed for one-sixth of the ring, and then recrossing at the next long straight section. In this sextant, the Main-Ring magnets and their adjustment jacks are removed from their normal stands and placed on the tunnel floor, a vertical displacement of about 19.5 in. as indicated in Fig. III-4, while the Tevatron magnets change position from their usual 25 in. under the Main Ring to 25 in. above it.

The vertical bending of each beam will be accomplished by a partial rotation of sets of bending magnets at each end of the straight section. The scheme outlined in Fig. III-4 gives a vertical angle of 6.7 mrad for the Main Ring and 8.4 mrad for the Tevatron for a crossing angle between the two beams of 15.1 mrad. Additional horizontal bending must be added to make up for the $1-\cos\phi \approx 3\%$ loss in horizontal bending power caused by the twist angle ϕ (typically 15°) and to line up the two beams in the horizontal plane. Although some of this additional bending could come from powering the rotated magnets differentially, the scheme shown in Fig. III-4 is able to accomplish these objectives solely with the addition of steering magnets in free space along the two beams.

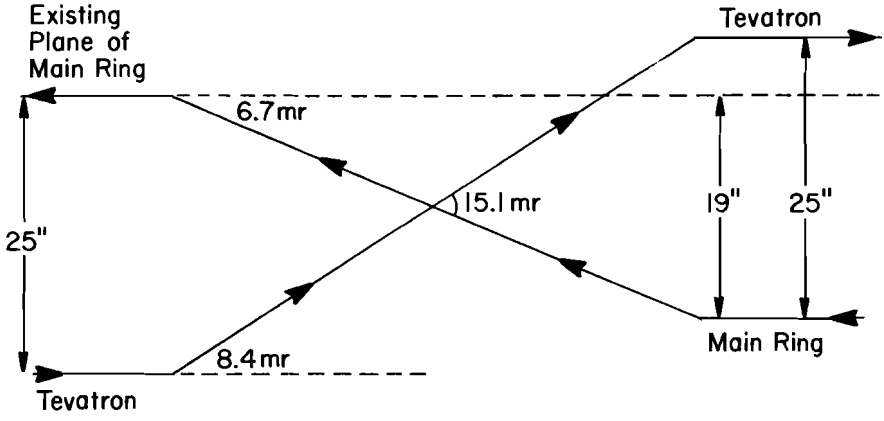


Fig. III-4. A cross geometry for pp collisions.

This scheme then results in a free space of 50 m for experimental apparatus; some of this space could also be used for additional quads to improve Tevatron focusing. The natural crossing angle of 15 mrad in this scheme does reduce the luminosity somewhat. As shown in Fig. III-5, the luminosity for the various cases drops from the head-on range of (1.4 to 110) $\times 10^{30}$ down to (0.5 to 6) $\times 10^{30}$. This loss is partly balanced by the fact that the length of the interaction diamond shrinks by the same ratio.

Although the luminosity obtained with α = 15 mrad is adequate for many experiments, we have also investigated the possibility of squeezing down this angle with the scheme shown in Fig. III-6. This method uses somewhat idealized conventional 18-kG dipole magnets with a broad gap. Even in the case of full-energy operation at 400 GeV on 1000 GeV, head-on collisions can be obtained by filling most of the space available with dipoles to leave approximately 5 m free for experiments. An intermediate value of α = 5 mrad would allow a free length of approximately 12 m and a range of luminosities of (1 to 20) $\times 10^{30}$.

This scheme has the advantage that the beams can always be made to cross one another at the same point when collisions are desired, even though the beams do move about as the beam energies or magnetic fields are varied. The maximum excursion is shown by the dotted straight-through lines in Fig. III-6. Trim coils will steer the beams horizontally to avoid collisions when the Main Ring is at low energy, where the beam-beam tune shift would cause losses.

We have also examined geometries in which the rings do not transpose. Such geometries ("kissing" schemes) naturally result in head-on collisions, but ramped superconducting magnets are required at the full energy of 400 GeV on 1000 GeV, including large (approximately 10 in. diameter) superconducting magnets common to both beams. We are continuing to investigate the relative merits of the two beam-collision schemes.

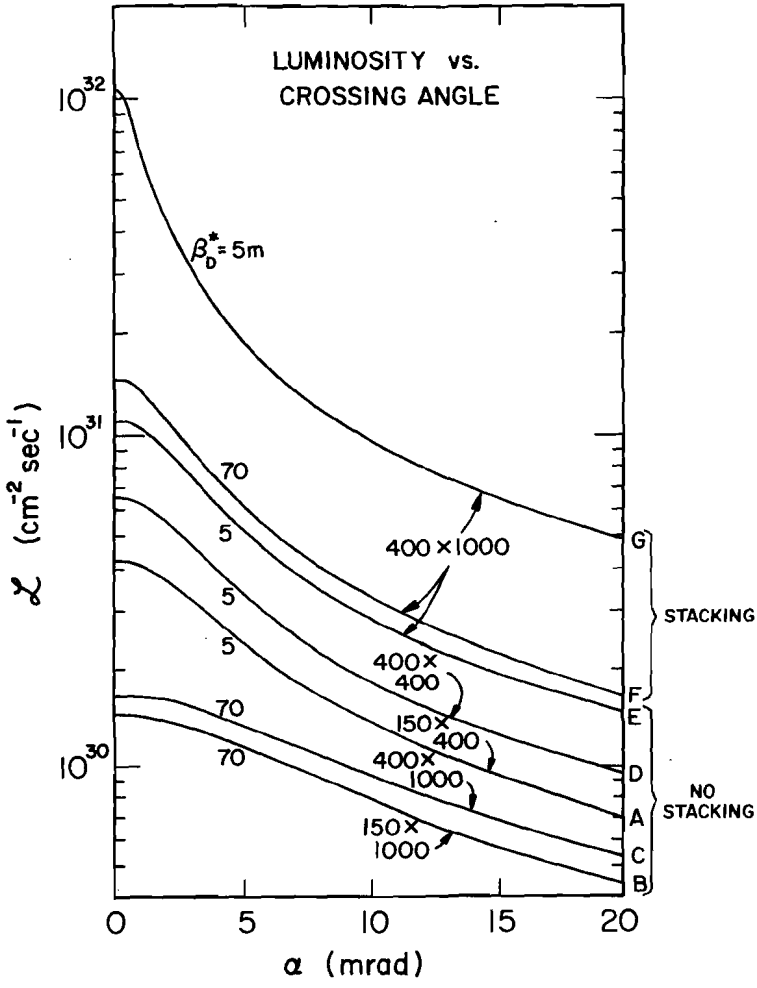


Fig. III-5. Luminosity vs crossing angle.

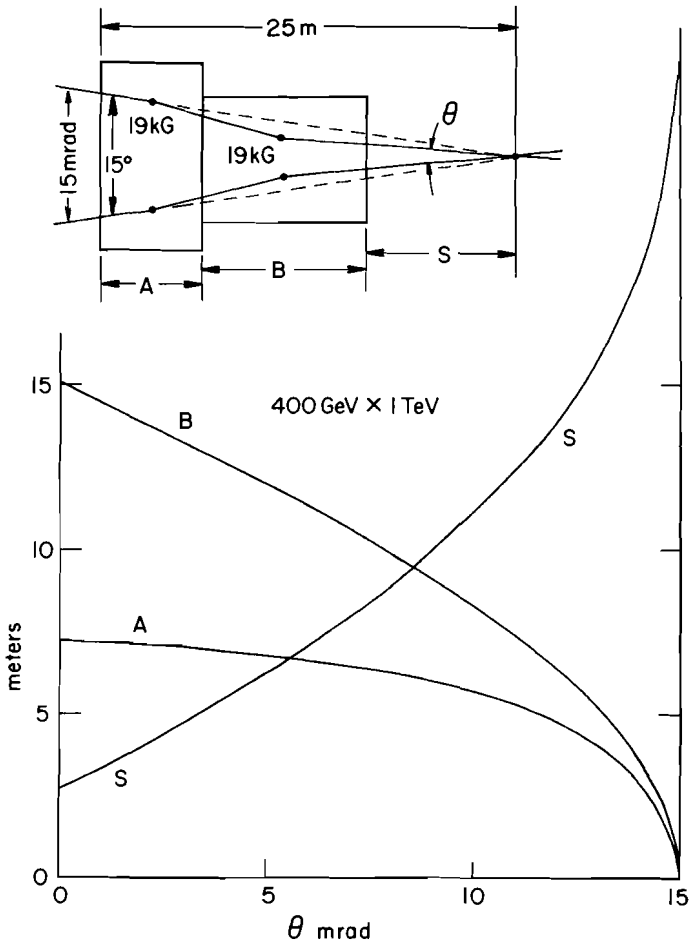


Fig. III-6. A method of reducing crossing angle.

C. Antiproton Source

1. Introduction. Recent experimental work[1] on electron cooling of a proton beam at the Institute of Nuclear Physics, Novosibirsk, USSR, has given rise to suggestions that it will be possible to produce an intense circulating antiproton beam at Fermilab for use in proton-antiproton colliding-beam experiments. This section describes the Fermilab work and plans.

Electron cooling was suggested by Budker[2] and has been brought to fruition by him and his colleagues at Novosibirsk. If an electron beam is directed parallel to a heavy-particle beam, so that their relative velocity is very small, the two beams will move toward a "temperature" equilibrium. That is, under favorably chosen initial conditions, the transverse oscillation amplitudes and longitudinal momentum spread of the heavy-particle beam will decrease.

One may repeatedly "cool" the heavy-particle beam as it circulates in a storage ring or accelerator. One can then envisage producing antiprotons from protons in the Main Ring, cooling them and stacking them to produce a more intense circulating beam in the Main Ring or the Tevatron[3,4]. The direction of circulation is, of course, opposite to that of protons, so that it is possible to produce colliding beams in a single accelerator.

There are several reasons why antiproton-proton collisions may have advantages over proton-proton collisions. First, only one accelerator ring is needed. Second, the superconducting ring at Fermilab will have a very good vacuum and will therefore be ideal for a storage ring. Third, the two intersecting beams can both have the maximum energy, 1 TeV, thus giving 2 TeV in the center of mass. Fourth, as discussed in Section E of Chapter I of this report, there may be distinct physics advantages associated with particle-antiparticle collisions. The chief disadvantage is the difficulty of achieving an interaction rate competitive with that in proton-proton colliding beams.

The Novosibirsk group has demonstrated in their NAP-M ring that

cooling actually occurs and that there is at least rough agreement of theory with experiments. The rate of cooling depends, of course, on the parameters of the electron system and measured cooling times have been in the range 50 msec to 1 sec. Cooling is most efficient at low energy.

In order to verify the Novosibirsk results and to investigate some aspects of electron cooling in more detail for purposes of design, we are building a small storage ring at Fermilab to carry out cooling and accumulation experiments. Protons will be injected from the Fermilab 200-MeV linac while it is not in use for injection into the booster. Some of the components being built for this ring will be reusable in the antiproton cooling ring to be built as part of this proposal, if the cooling experiments give successful results. The cooling experiments are not a part of the present proposal and will not be discussed further. They are described in detail in Refs. 3 and 4.

2. Proposed Antiproton Cooling Scheme. The design of the proposed cooling scheme is constrained by the sharp increase of cooling time with energy. This increase makes it necessary to cool at low energy. The procedure planned is therefore to:

(i) Produce antiprotons of approximately 5.2-GeV energy by bombarding a solid target with protons of 80 to 100 GeV energy extracted from the Main Ring at F17.

(ii) Carry the antiproton beam to the booster in the tunnel constructed for reverse injection into the Main Ring.

(iii) Inject the 5.2-GeV antiprotons into the Booster and decelerate them to 200 MeV.

(iv) Transfer the antiproton beam to the cooling ring to be constructed in the Booster tunnel.

(v) Cool the antiproton beam and move it to a storage orbit.

(vi) Repeat the previous steps with more antiprotons, stacking an antiproton beam.

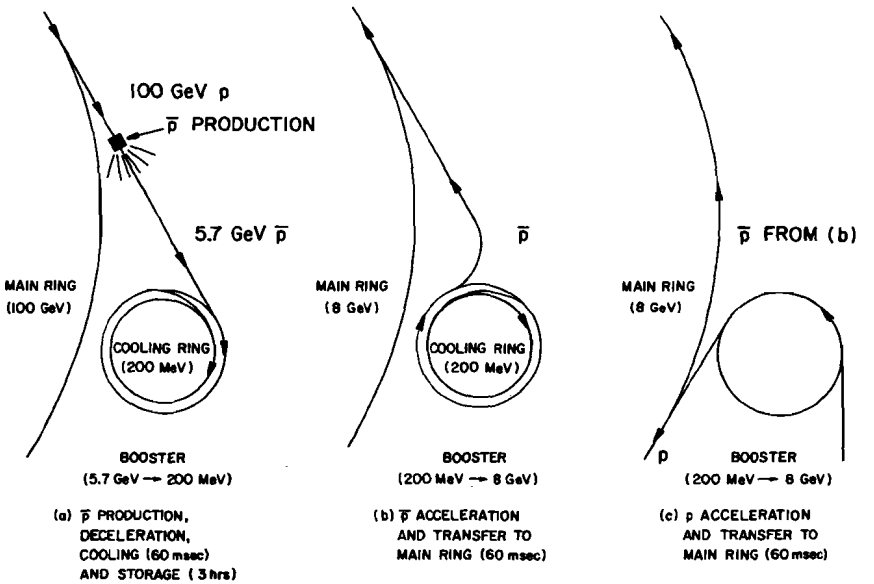


Fig. III-7. Antiproton cooling scheme.

(vii) Accelerate the stacked antiproton beam to 8 GeV in the Booster, transfer it to the Main Ring in the reverse direction and accelerate it to 100 GeV.

(viii) Transfer the antiproton beam to the Tevatron and store it.

(ix) Accelerate a normal proton beam to 100 GeV in the Main Ring, transfer it and store it in the forward direction in the Tevatron.

(x) Accelerate both proton and antiproton beams to 1 TeV in the Tevatron. The two beams will collide in straight sections B and E.

This plan is shown schematically in Fig. III-7.

We estimate that we will collect and cool approximately 1.5×10^7 antiprotons/pulse at a Main-Ring intensity of 2.5×10^{13} protons/pulse.[4] It is planned to accumulate antiprotons for 5 hours to give a beam of 10^{11} antiprotons to be accelerated and collided with the proton beam, which is, of course, one Booster ring worth or 2×10^{12} protons. These beams will give luminosities of approximately $5 \times 10^{28}/\text{cm}^2\text{-sec}$ at an energy of 250 GeV in each beam in the Main Ring and more than $10^{29}/\text{cm}^2\text{-sec}$ at an energy of 1000 GeV in the Tevatron.[4]

This luminosity is smaller than those usually estimated for proton-proton systems. It must be remembered, however, that this figure is attainable in a unique system, protons and antiprotons, and that it can certainly be improved by development of the system. We can improve the luminosity achievable in the following ways:

(i) <u>Transition γ</u>. The booster $\bar{p}$ bunch coming from 100-GeV protons is mismatched to the 8-GeV Main-Ring bunch in longitudinal phase space. By moving γ_t to the neighborhood of the $\bar{p}$ injection energy, the beams can be matched. This increases $\Delta p/p$ by a factor 2 and will increase the $\bar{p}$ collection rate correspondingly. A scheme that is essentially the same is in routine operation on the CERN PS. There γ_t is shifted by 2.3 units; here we need to shift it by only one

unit.

(ii) Targetry. The targetry assumed in our estimates is not optimum and improvement can probably be found, particularly in greater demagnification of the proton beam and magnification of the $\bar{p}$ beam. At present, the proton angular spread is approximately 20 times less than the $\bar{p}$ spread used. A factor of 2 might be gained by improving the match.

(iii) Main-Ring intensity improvement. If the Main-Ring intensity is doubled, then the rate of production of $\bar{p}$'s is doubled.

(a) For example, improvement of Booster-beam brightness without enlargement of aperture leads to a factor of 2 in N_p without enlarging the emittance ε and the luminosity quadruples.

(b) On the other hand, enlarging the emittance without increasing the brightness yields a factor of 2 in collection rate. Thus achieving 5×10^{13} protons/pulse in the Main Ring leads to a factor of 2 to 4 in $\bar{p}p$ luminosity.

(iv) Beam stacking, longer accumulation time. We can momentum-stack protons in the Tevatron, gaining a factor of 2 to 4 in proton density.

Putting all these factors together, it is reasonable to expect a luminosity of 10^{30} after some development. The initial Tevatron luminosity of 10^{29} will be acceptable for initial exploratory work.

3. Cooling-Ring Design.

a. Lattice. The lattice must have long straight sections for cooling regions. It is desirable that these cooling regions have large β_x and β_y and small η. The lattice is also constrained by the fact that it must fit in the Booster tunnel and must therefore have at least twelve-fold symmetry. The lattice we have designed to fit these constraints is outlined in Table III-IV and shown in Fig. III-8.

b. Magnets. The lattice is composed of 60 quadrupoles and 24 dipoles.

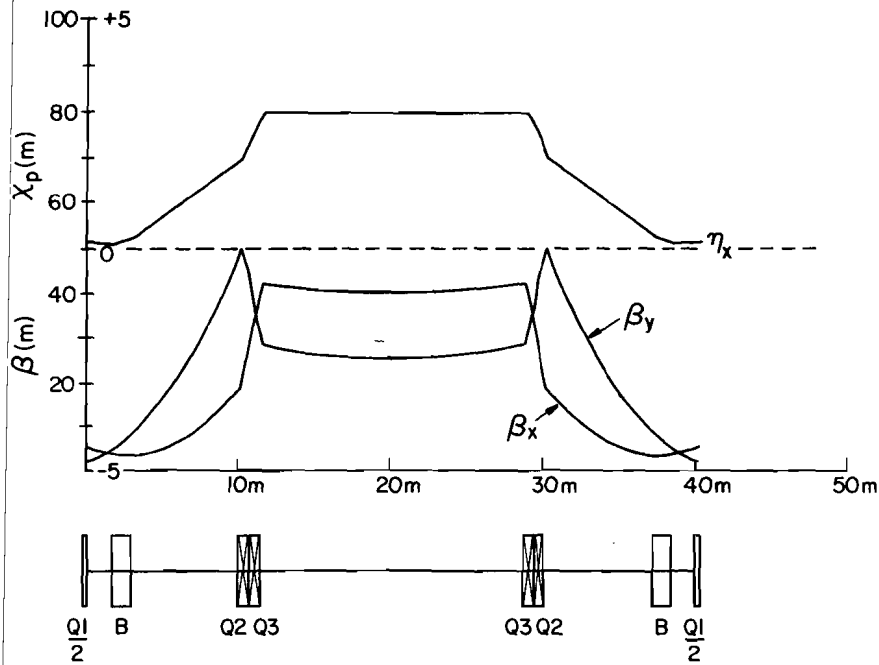
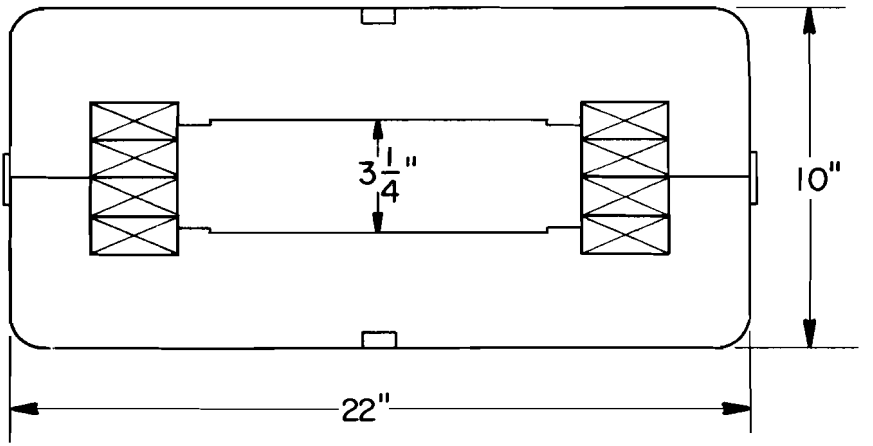


Fig. III-8. Cooling-ring lattice.

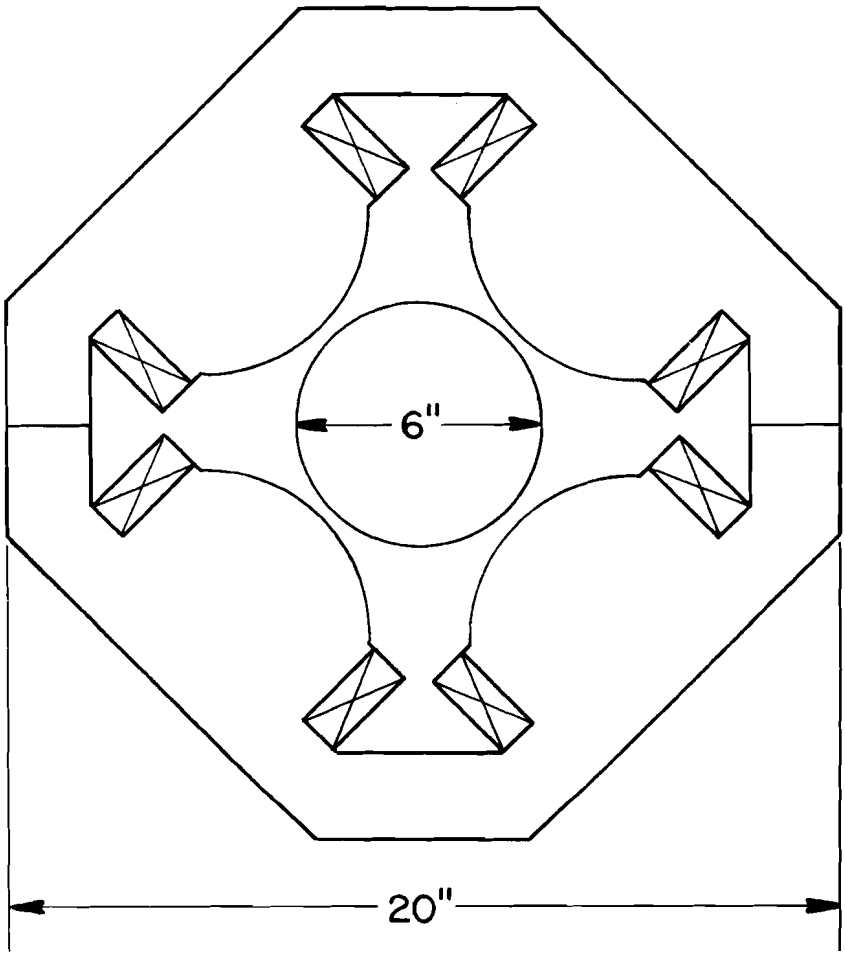
The dipole magnets are 4 ft long, 10 in. high, and 22 in. wide. Their gap region provides sufficient space for the beam and its sagitta and for the vacuum chamber and insulation required for baking at high temperature. The fringe-field region is used to provide distributed ion pumping. The magnets are stacked in halves, with the laminations and end plates welded to let-in keys. With the coils in place, top and bottom halves are welded together with clamp blocks, similarly to the Main-Ring magnets. The coils are wound as double pancakes, with two pancakes top and bottom, then the ends are bent out of the median plane region prior to insulation. A cross section of the magnet is shown in Fig. III-9 and properties are given in Table III-V.

The quadrupole magnets are 2 ft long and 20.5 in. in width and height. Their bore is sufficient to contain a 6-in. beam pipe plus thermal insulation for baking. The laminations are stacked in half-cores with end plates and welded to keys. Top and bottom halves are welded together with clamp blocks. The coils are solenoid-type, insulated before winding. Their dimensions are chosen so that they can be installed into the half-cores prior to final assembly. A cross section of the quadrupole magnet is shown in Fig. III-10 and properties are given in Table III-V.



COOLING RING DIPOLE

Fig. III-9.



COOLING RING QUADRUPOLE

Fig. III-10.

Table III-IV. Cooling-Ring Lattice Parameters

Regular 12-sided polygon	12 × 40.4 m
Straight sections (free)	12 × 17.2 m
Energy	200 MeV
Magnets:	24 4-ft dipoles @ 4.6 kG
	60 2-ft quadrupoles @ 15 kG/m
No. superperiods	12
ν_x	7.85
ν_y	5.85
β^*_x (cooling region)	40 m
β^*_y	25.6 m
η^*	2.97 m
η'^*	0
$\beta_x$max	41.9 m
$\beta_y$max	49.6 m
η max	2.97 m
No. of quadrupole supplies	

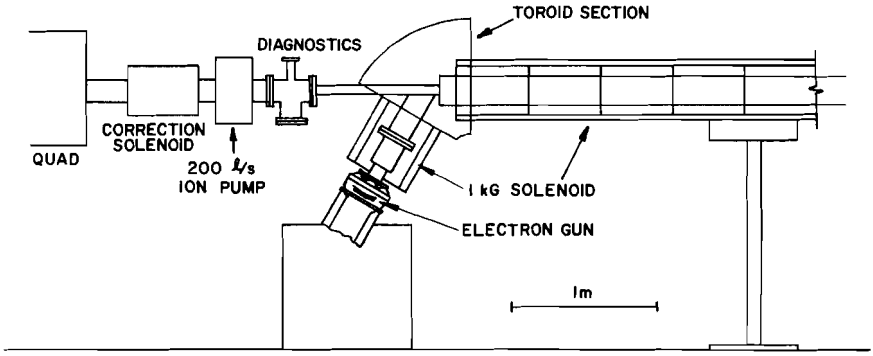
Table III-V. Magnet Specifications

a. Dipoles

Field Strength	5	kG
Magnet Length	48	in.
Magnet Gap	3.25	in.
Field Aperture	±6	in.
Field Quality (ΔB/B within ±3 in.)	± .005	%
Coil Turns (top and bottom)	40	
Copper Conductor Cross Section	0.46 in. by 0.46 in.	
Water Cooling Hole Diameter	0.250	in.
Conductor Corner Radius	0.063	in.
Conductor Current	775	amps
Magnet Inductance	12	mH
Coil Resistance	.025	Ω
Voltage Drop	19.5	V
Power	15.1	kW
Cooling Water Pressure	65	psi
Number of Water Paths	4	
Water Flow	4.4	gpm
Temperature Rise	13.1°	C
Outside Dimensions	10 in. by 22 in.	
Iron Weight	2145	lbs
Copper Weight	266	lbs
Lamination Thickness	0.059	in.

b. Quadrupoles

Field Gradient	.50	kG/in.
Magnet Length	24	in.
Aperture	6.5	in. dia.
Width of Good Field Gradient	±4.0	in.
Gradient Quality (ΔB/B at 1 in.)	±0.02	%
Coil Turns Per Pole	10	
Copper Conductor Cross Section	0.46 × 0.46 in.^{2}	
Water Cooling Hole Diameter	0.250	in.
Conductor Corner Radius	0.063	in.
Conductor Current	535	amps
Coil Resistance	0.0135	Ω
Voltage Drop	7.2	V
Power	3.9	kW
Cooling Water Pressure	65	psi
Number of Water Paths	2	
Temperature Rise	7.2°	C
Total Weight	1500	lbs
Outside Dimensions	20 in. × 20 in.	
Water Flow	2	gpm
Lamination Thickness	0.059	in.



ELECTRON COOLING STRAIGHT SECTION

Fig. III-11.

c. Vacuum System. The vacuum must be good enough to allow accumulation and storage over a period of a day. There will be cooling, which will compensate the emittance growth of multiple scattering, but nuclear interactions of antiprotons will limit the accumulation time. The ultimate vacuum in the ring should be of the order of 10^{-10} Torr. A system has been designed to provide this pressure, with the following features:

(i) Stainless steel.

(ii) All-welded.

(iii) In-situ baking to 400° C.

(iv) Distributed ion pumps in all dipoles.

The chamber will be insulated from the magnets by a ceramic-fiber material. The distributed pumps planned for use are a type developed at the Physical Sciences Laboratory of the University of Wisconsin. Some lumped pumping will also be provided. Turbomolecular roughing carts will be used.

d. Accumulation. In order to accumulate many groups of particles, it is necessary to provide an injection region, separated by a real or virtual septum from a stacking region, which can also be the cooling region, and a means to transport the particles from one region to another. This will be accomplished by stacking in momentum space. A total of 60 to 100 kV of rf at 30 MHz is required to contain the phase space of the beam, and this will transport the beam through a 1% momentum shift to the stacking region in 3 msec with a 3° stable phase angle. In order to avoid moving septa, injection is achieved with two kickers placed 90° upstream and downstream in radial betatron phase. The small uncancelled kick to the stacked beam will be removed by the cooling system.

e. Cooling Straight Sections. The typical cooling region contains an electron gun, magnets to bend the electron beam in and out, and a drift region with a solenoidal magnetic field, and a collector. Fig. III-11 is a view of the cooling straight section.

(i) Electron gun. We have chosen to use a gun design developed

for the SPEAR klystron, a 26-A, 20-cm^2 beam at 110 keV. The gun has a Pierce geometry, with postacceleration and focusing. Design work in collaboration with SLAC has shown that it is possible to achieve a transverse beam temperature of the order of 1 eV in the electron rest frame.

(ii) Drift region. The beam from the gun is bent 60° by a crossed toroidal (6.7 kG/m) and dipole (80 G) magnetic field to superpose it with the antiproton beam. In the drift region, the electron beam is confined by a uniform 1-kG solenoidal field. The ground-potential surface in this region is produced by a 6-in. drift tube split into four 90° segments, each connected to an independent voltage source to control the ground potential and introduce dipole and quadrupole fields if desired. One can also trap ions by depressing the ground below that of the adjacent bends. It is desired to be able to neutralize the electron-beam space charge with low-temperature hydrogen ions.

(iii) Collector. After a second 60° bend, the beam is decelerated and absorbed in a collector assembly. This collector is operated at a potential slightly lower than that of the electron-gun cathode. The collector geometry must closely approximate that of the gun itself, because any energy coupled into gyration in the deceleration process is difficult to recover.

(iv) Correction elements. The solenoidal field induces gyration in the protons, which will be compensated by a small (0.5-m) solenoid located just beyond each 60° bend. The ring correction elements will be used to compensate other perturbations.

D. Intersecting Regions

1. Design Goals of the Areas. The colliding-beams areas are to be used for both pp and $\bar{p}p$ experiments. Some desirable features of the areas are:

(i) Installation and removal of experiments from the area should take as short a time as possible to allow operation of the normal research program to continue with little interference. Space transverse to the beam line is needed for setup and modification of detectors. Good accessibility by a truck ramp and ease of material handling with a crane is required because of the limited accessibility time.

(ii) The experimental areas should extend the full length of the long straight section (50 m). The areas should have uniform elevation, other than a pit area, to allow easy movement of detectors with the use of rollers or other devices. The depth of the pit below beam height at the center of the area should be 4 m. In the rest of the area, 2 m below beam height is adequate. It is expected that some experiments will use the special magnets that bring the beams together as analyzers and will therefore need more space below the beam than is possible in the present tunnel.

(iii) An adjacent assembly building is desirable to allow experimenters to pre-assemble detectors and fully check them with their associated data-acquisition and computer system. Assembled detector modules may be lowered from the assembly building directly into the experimental area.

(iv) A bypass around the experimental area at the Main-Ring tunnel-floor elevation is needed for normal tunnel traffic. Beyond these requirements, the areas must comply with radiation and fire-safety requirements and have adequate utilities for experimental operations. Measurements of the radiation level in the earth berm of the main ring will be carried to permit the most economical design of the area.

2. Description of the Experimental Areas. It is our present intention

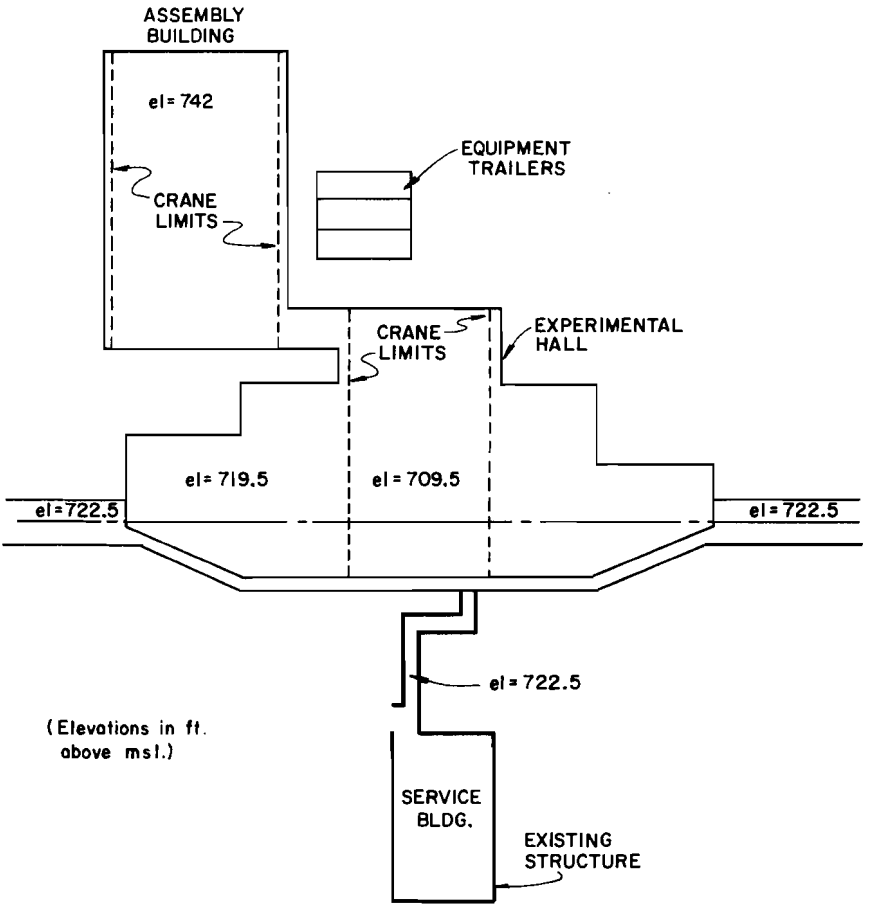


Fig. III-12. Colliding-beams experimental area.

to have the two initial experimental areas constructed identically. This will allow maximum flexibility of the research program. Parameters of the design are given below.

Table III-VI. Experimental-Area Design Parameters

	Experimental Area		Assembly Building	
	Pit	Total		
Length	12	50		25 m
Width				15 m
inside ring	4	4		m
outside ring	8	10		m
Height				
maximum crane hook clearance above beam	6		hook clearance above floor	7 m
beam elevation above floor	4	2		m
Crane	30	none		30 tons
Power	Total installed capacity 3.0 MW			
Loading Access	Via truck ramp and crane from assembly building			

Access to the assembly building is from a yard located on the outside of the ring and the building itself is offset longitudinally from the center of the interaction straight section and laterally from the beam line. Materials may be brought directly into the experimental area via truck ramp or lowered from the assembly building onto rollers and brought under the pit-crane coverage. A plan view of the area is shown in Fig. III-12. The data-acquisition systems will be set up in adjacent portable buildings.

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IV. CONSTRUCTION OF THE TEVATRON

A. Introduction

This chapter describes the construction proposed to turn the Superconducting Ring into a complete accelerator, the Tevatron. The research, development, and demonstration project discussed in Chapter II above has as its goal completion of the superconducting magnet ring and demonstration of the ability of this ring to accept protons synchronously transferred from the Main Ring, contain them stably, and accelerate them slowly to 1 TeV with a borrowed Main-Ring rf cavity. After this demonstration, it is necessary to make the Superconducting Ring into a complete 1-TeV accelerator, useful for fixed-target experiments. For this purpose, the following systems must be added:

(i) An rf system capable of accelerating the beam in the Tevatron at a rate up to 50 GeV/sec.

(ii) Sufficient refrigeration capacity to handle the ac heat load caused by ramping the ring at repetition rates up to 1 pulse/minute.

(iii) A beam-extraction system that can extract the clockwise-circulating 1-TeV beam from the Tevatron in both slow and fast modes and transport it to the external proton beam line of the present Switchyard.

(iv) Modifications of the present Switchyard and experimental areas to handle 1 TeV.

Item (iv) is not directly related to the accelerator and hence will be discussed separately in Chapter V. Here we will describe the design of items (i), (ii), and (iii).

B. RF System

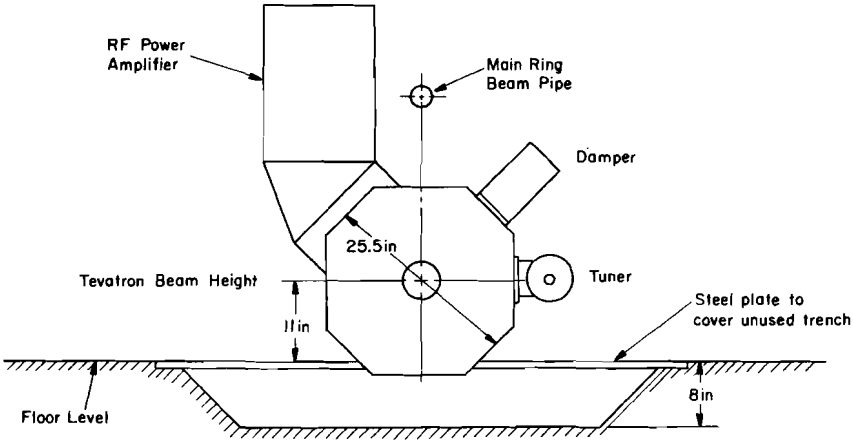
In order that the Tevatron be useable as a 1-TeV accelerator for fixed-target experiments, it should be capable of being operated at a wide range of ramp rates, depending on the requirements of the application. The rf system is designed to have the capability for accelerating

5×10^{13} protons at rates up to 50 GeV/sec. With a revolution period of 21 μsec, this corresponds to an energy gain of 1.05 MeV/turn and a power to the beam of 400 kW.

It is planned to transfer beam synchronously from Main Ring into Tevatron rf buckets to avoid beam loss during capture. For this synchronous transfer, the harmonic number of the Tevatron should be an integral multiple of that of the Main Ring. Thus the Tevatron accelerating frequency must be an integral multiple of that of the Main Ring. Because of the limited space available for Tevatron rf accelerating cavities, consideration has been given to operating it at the second or third harmonic of the Main Ring frequency, where higher accelerating gradients per unit length can be developed. Storage-ring operation and beam stacking are more easily accomplished at the fundamental frequency. Colliding beams between the Main Ring and Tevatron will also work more efficiently if they are at the same frequency. It is therefore planned that the Tevatron will be operated at the same frequency as the Main Ring, 53.104 MHz.

With a harmonic number of 1113, a synchronous phase angle of 60° and a ramp slope of 50 GeV/sec. the rf system must develop 1.2 MV. This will provide a bucket area of 0.2 eV-sec, adequate to contain the beam-bunch longitudinal emittance of 0.1 eV-sec. To match the shape of the Main-Ring beam bunches to that of the Tevatron buckets, the Main-Ring ramp rate will be reduced to 50 GeV/sec and its rf voltage reduced adiabatically to 1.2 MV prior to beam transfer.

The required 1.2 MV is to be developed by four accelerating cavities, each developing 300 kV and delivering 100 kW to the beam. These cavities will be slightly modified versions of existing Main-Ring cavities. Because of the very small tuning range required of the cavities (about 2.3 kHz between 100 GeV and 1000 GeV), the existing Main-Ring tuners can be removed from the cavities and replaced by very small tuners. The quality factor Q of a Main-Ring cavity with its tuners



Note: Cavity support not shown.

Tevatron RF Cavity

Fig. IV-1.

removed is approximately 8000 and its gap shunt resistance is 840 kΩ. Consequently each cavity will dissipate

$$P_{cav} = \frac{V_{gap}^2}{2\,R_{sh}} = \frac{9 \times 10^{10}}{1.7 \times 10^6} = 53 \text{ kW}.$$

Each cavity must therefore be supplied with 153 kW of rf power.

The modified cavity-power-amplifier combination must be mounted so that the existing Main-Ring beam pipe can pass directly above it. In order to accomplish this with a minimum of enclosure modification, the cavities can be rotated by 45° about an axis along the beam and new power amplifiers fitted to the existing flanges. The final amplifier tubes must be mounted vertically and the input power-coupling system will therefore have to be extended slightly. This extension would cause complications in the self-resonance of the input coupling system if the presently used 4CW100000 (Fermilab designation Y 567) tubes were to be used. This problem will be resolved by replacing the single power amplifiers presently used by two power amplifiers using 4CW50000 tubes. The slightly smaller output capacitance of these tubes will compensate for extension of the coupling system. This modification is shown in Fig. IV-1. The presently existing Main-Ring cavities already have two mounting flanges upon which the two amplifiers can be mounted. The total anode-dissipation capability of 100 kW will require that the two tubes develop the required 153 kW of rf power with an efficiency of 61%, well within existing design capability.

Power dissipation in the cavities will be raised from the present design level of 33 kW to 53 kW, necessitating some modification of cavity cooling and a slight increase in the cooling-water requirement for the combined Main Ring and Tevatron rf systems.

The low-level rf-control system and power-amplifier excitation system are simple extensions of existing Main-Ring systems. During beam transfer the Main Ring and Tevatron rf systems will be phase-locked to each other. Such a system is presently employed for beam transfer

from the Booster into the Main Ring at 8 GeV and the technology is well developed.

C. Refrigeration System

The design considerations and choices of the refrigeration system were discussed in Section 7 of Part C of Chapter II above. The only addition to be made in the construction project is 12 more satellite refrigerators to remove the heat generated from ac losses in ramping the magnets.

The ac losses of a dipole have been measured and are shown in Fig. IV-2. With a full-size dipole loss of 500 J/cycle, the total ac losses in all dipoles at the design ramp rate of 1 pulse/minute are 500 × 784/60 = 7500 W. The ac loss of an individual quadrupole is estimated to be at most one-third that of a dipole. The maximum ac quadrupole loss is then 500 × 240/60 × 3 = 670 W. The total ac loss is then 8200 W.

Each satellite refrigerator has a capacity of 700 W when supplied with 100ℓ/hr of liquid helium. The twelve additional refrigerators will therefore be sufficient to remove this additional dissipated power.

Recent investigations of wire manufacturing indicate that the ac losses can be reduced as much as 15% by increasing the number of twists per inch of the wire before cabling. Magnets made with this superconductor will be available for measurement in the late spring. This improvement should produce a significant safety factor in refrigeration.

The added refrigerators will be located in the existing Main-Ring service buildings, just as the original twelve of the research and development phase are. The completed system was shown schematically in Figure II-6.

D. Beam-Extraction System

Both slow and fast modes of beam extraction are required to optimize the use of the Tevatron for physics experiments with fixed targets. The extracted 1-TeV beam will be transported to the existing Main-Ring external beam line and Switchyard, the modifications of which will be

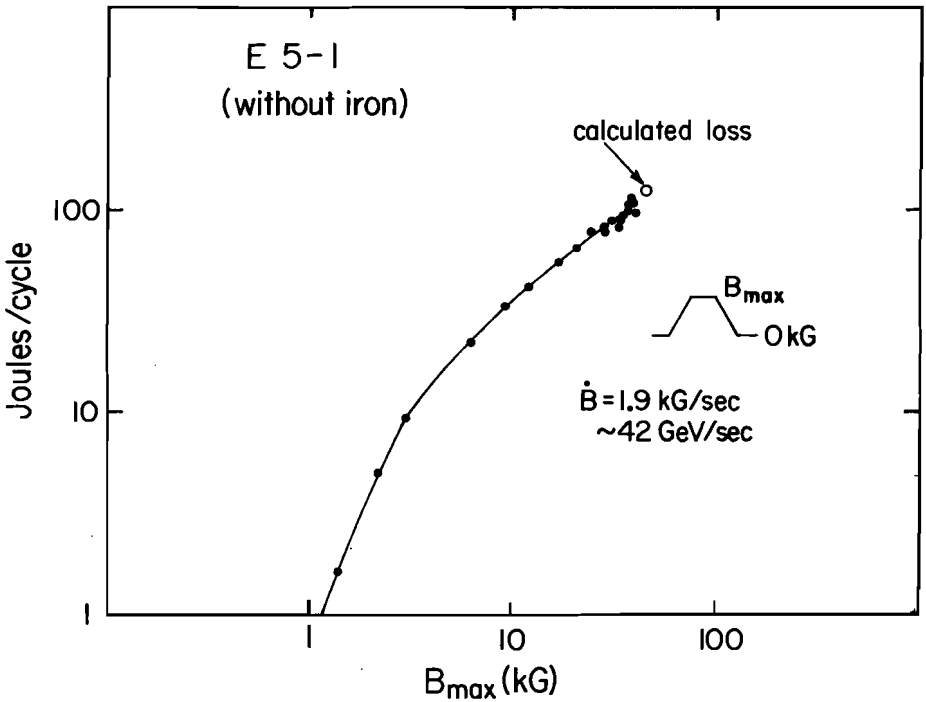


Fig. IV-2. Measured ac cycling losses of a superconducting magnet.

discussed here.

1. Slow Extraction. The horizontal third-integer resonant-extraction scheme operating at ν = 19-1/3 will be used for slow extraction. In this scheme, the horizontal width of the beam is resonantly excited by a sextupole magnet to grow at an increasing rate. The outer part of the beam then steps across an electrostatic wire septum and is deflected further outward by the septum to enter an extraction channel, which begins at F10. The electrostatic septum is located at A10 and positioned so that the septum is 2 cm radially outward from the central orbit. The sextupole is also placed in long straight section F, 30° in horizontal betatron phase upstream of the electrostatic septum. With a sextupole strength of $B''\ell = 2.4 \times 10^4$ kG/m at 1 TeV and a betatron tune of ν = 19-1/3, the beam half-width at the septum will step from 2.0 cm to 2.9 cm in three turns, when the particles return to the same phase. The 9-mm wide part of the beam that is inside the aperture of the electrostatic septum is deflected radially outward 0.06 mrad by the septum. As it arrives at the entrance of the extraction channel, this deflected beam will be 4.2 mm wide and separated from the undeflected part of the beam by a gap of 3.2 mm. This separation is adequate to clear the iron septum of the Lambertson magnet that is the first element of the extraction channel. The part of the beam passing just outside the channel aperture will continue to circulate around the ring and be extracted three turns later. The largest beam excursion is 31 mm and occurs only in the ring quadrupole immediately downstream of F10. The horizontal half-aperture on the mid-plane of the vacuum chamber is 1.4 in. = 35.6 mm and is thus adequate. Note that the good-field region does not have to extend out to 31 mm for this beam, which is on the way out of the ring in less than one sector anyway.

During extraction, the horizontal betatron tune is shifted from 19.4 to 19-1/3 by a conventional extraction quadrupole placed at the

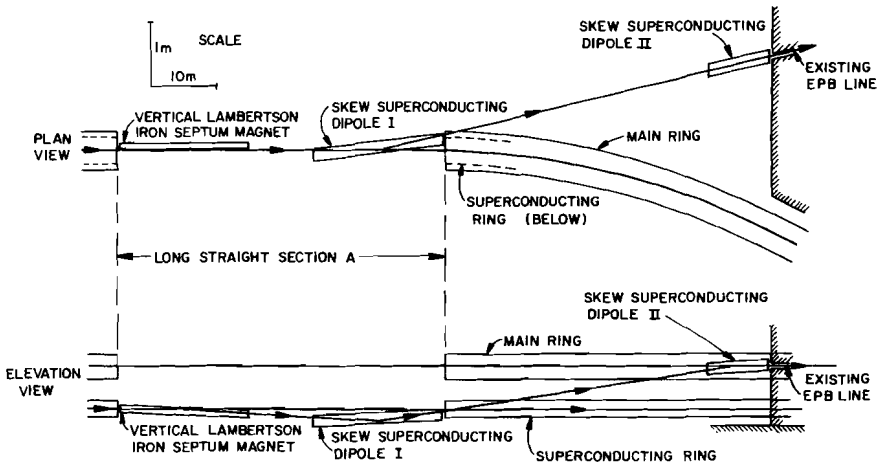


Fig. IV-3. Extraction channel to experimental areas.

proper betatron phase relative to the electrostatic septum. This system can also be employed for the medium-fast extraction (coherent extraction) in the same manner as is done on the Main Ring. With a step size of 9 mm and an effective electrostatic-septum thickness of 0.1 mm, the slow extraction efficiency should be close to 99%.

2. Fast Extraction. Fast (single-turn) extraction is accomplished simply by a fast kicker magnet located in the medium straight section at E17. The kicker kicks the beam by 0.09 mrad, thereby displacing the beam at the entrance to the extraction channel by 6 mm, adequate to clear the channel septum. For both fast and slow extraction, angle and position bump magnets must be installed upstream and downstream of long straight section A to place the beam immediately next to the channel septum before the fast kicker is fired. The fast-extraction efficiency should be very close to 100%.

3. Extraction Channel. The extraction channel is shown in Figure IV-3. Beginning at F50, the first elements are sections of Lambertson iron-septum magnets totalling 20 m in length and deflecting the beam vertically downward by 6 mrad. The beam is initially deflected downward instead of upward in order to avoid interference with the Main-Ring to Tevatron beam-transfer system, which has beam pipes and transport elements crisscrossing the region between the Main-Ring and Tevatron orbits. The beam is 12 cm below the Tevatron orbit at a distance of 10m downstream of the exit from the Lambertson magnets. This separation is large enough for the extracted beam to enter a small-aperture, high-field superconducting dipole. Two chains of these dipoles, each positioned at a proper skew angle with respect to the normal horizontal and vertical axes, are needed to impart the proper two-dimensional displacement and angle to the beam to make it enter the existing external proton beam line some 75 m beyond A0. These dipoles are far enough downstream from all the septa so that there is no danger of their being sprayed by stray beam. Superconducting quadrupoles will be

installed in the transport line between the 2 chains of dipoles to produce the desired beam optics.

Parameters of the entire beam-extraction system are given below for 1 TeV.

Table IV-I. Beam-Extraction System Parameters

Slow Extraction	
Sextupole	
length	2m
strength B''	1.2×10^{4} kG/m^2
location	long straight section F, 30° horizontal phase upstream of entrance to electrostatic septum
Electrostatic Wire Septum	
length	6 m (in 2 sections)
field	100 kV/cm
deflection angle	0.06 mrad
location	F10, septum is 2 cm radially outward from central orbit
construction	array of 0.05 mm diameter wires with 1 mm spacing
effective thickness	< 0.1 mm
Beam Characteristics	
resonance	ν_x = 19-1/3
step size at entrance to wire septum	20 mm to 29 mm in 3 turns (on resonance)
horizontal width at entrance to wire septum	9 mm
optics at entrance to wire septum	$x'/x = 0.01$ m^{-1} (diverging)
horizontal width at F50	4.2 mm (x = 12.5 mm to 16.7 mm)
Optics at F50	$(x'/x) = 0.008$ m^{-1} av. (converging)
Separation from undeflected beam	3.2 mm
Fast Extraction	
Kicker Magnet	
length	3 m (in 3 sections)
peak field	1.0 kG
kick angle	0.09 mrad
location	E17 (medium straight section E)
Beam Characteristics	
horizontal betatron phase to F50	5.75 (2π)
beam displacement at F50	6 mm

Extraction Channel

Lambertson iron-septum magnet	
length	20 m (in 10 sections)
field	10 kG
bend angle	6 mrad (downward)
location of bend center	15 m upstream of A0
septum position	11 mm radially outward from central orbit
Superconducting dipole I	
length	20 m (in 5 sections)
field	54 kG
bend angle	32.4 mrad
direction of bend	up and out, 48.9° to vertical
location of bend center	15 m downstream of A0
"good field" aperture radius	1 cm
Superconducting dipole II	
length	9.54 m (in 2 sections)
field	54 kG
bend angle	15.5 mrad
direction of bend	down and in, 8.93° to vertical
location of bend center	5 m in front of entrance to EPB line (70 m from A0)
"good field" aperture radius	1 cm

V. MODIFICATION OF EXPERIMENTAL AREAS FOR FIXED-TARGET PHYSICS AT 1 TEV

A. Introduction

The most significant attributes of a fixed-target experimental program are the intense secondary beams of leptons, photons and mesons that are produced by primary-beam collisions on a fixed target. The 400-GeV program at Fermilab has produced many results of great physics interest. To mention only a few, there are the unexpected energy dependence of the ratio of neutrino to antineutrino cross sections, neutrino-induced dileptons and dimuons, neutral currents, charmed baryons and, recently, trimuons. Many results indicate that there will be new phenomena that can be found when the energies of lepton, photon, and meson beams are extended almost to 1 TeV. Previous chapters have discussed construction of the accelerator and colliding-beams facilities. In this chapter, we shall describe modifications that will bring the 1-TeV proton beam to the external fixed-target experimental areas and the upgrading of these areas to make 1-TeV experiments possible to them.

Just as the present Main-Ring tunnel is capable of containing a second ring of superconducting magnets, thereby doubling the proton energy, the present experimental areas are capable of handling the doubled energy with only modest changes. The essential elements required are replacement of some conventional dipole magnets in the Switchyard with superconducting magnets, modification of the existing target stations to handle 1-TeV protons, addition of shielding to reduce muon background brought on by 1-TeV protons, and the replacement of conventional magnets in the secondary beams with superconducting magnets to double the secondary-beam energies.

This plan utilizes the existing utility-distribution network, service buildings, cooling systems, power supplies, buildings for experimental detectors, and nearly all the existing beam-line tunnels, while preserving the special character of each of the three experimental areas. Because these features can continue to be used, the cost of converting the experimental areas is quite modest. During the Summer Study of 1976,

a plan to construct a special 1000-GeV Area, the Quark Area, was examined and rejected as being expensive and without advantage over the upgrading program in the existing areas. The Quark Area was originally proposed in 1968 as the candidate for a 1000-GeV area.

Improvements now being constructed at Fermilab have been designed with 1 TeV in mind. For example, the Switchyard Service Building (SSB) has been enlarged in size as part of the program to convert the vertical-bend dogleg to Neutrino to superconducting magnets. The SSB is now large enough to house a satellite refrigerator that is being constructed to cool these magnets. In addition, the High-Intensity Laboratory that is now being constructed for high-intensity pion beams can be modified for 1-TeV use by merely adding magnets; the building need not be changed. Third, a project to replace the two power-consuming horizontal bends in the M6 beam of the Meson Area with superconducting magnets has just been started.

The TeV program will thus gain a great deal from existing facilities at Fermilab. It must be recognized that there are possible interferences between the ongoing 400-GeV research program and the installation of new components for 1 TeV in the experimental areas. We plan to carry out the installation with minimal interference. The 400-GeV research program has reached a state of continuity in which there are planned shutdowns of a month or more for improvement work in individual experimental areas. Installation work can be done during these shutdowns. Switchyard tunnel modifications and new tunnel construction in P-East will be scheduled during colliding-beam operation.

In the sections below, we shall describe the physics programs of each of the three experimental areas, the Neutrino, Proton, and Meson Areas and the modifications needed in each area to carry out this physics program. There are some parts of the upgrading program that are common to all areas. All parts of the program will make use of Tevatron superconducting dipoles as elements in external beams where possible. There are locations where Tevatron dipoles may not be applicable,

because of restricted access or because greater aperture is needed, as is true in the vertical bends. The superconducting-magnet work now being done by the Switchyard group has the goal of developing a magnet for these applications. Quadrupole magnets will largely remain as conventional iron magnets, because in many cases they are located in isolated enclosures (manholes). Some superconducting quadrupoles will be used in locations close to superconducting dipoles, so they can utilize the same helium lines. All the superconducting magnets in external beam lines will make use of the satellite-refrigerator design developed for the Tevatron.

Another element common to all areas is sharing of the slow spill. Beam sharing by splitting the beam with electrostatic septa is presently done and can be done at 1 TeV by doubling the length of the septa. Splitting has always been a source of beam loss and radioactivity, even with high splitting efficiency, and it is attractive to consider "branching", directing the beam alternately to each area for a second or so on every pulse or on successive pulses. This kind of operation might be particularly good for the Neutrino-Proton or Neutrino-Meson split. We are not considering branching as a substitute for the split within any one area; in particular, we plan to upgrade the triple split in the Proton Area. The final choice will depend on the results of the continuing work of the Switchyard group.

We now turn to consideration of the individual experimental areas.

B. Neutrino Area

1. Physics of the 400-GeV Neutrino Area. The era of 400-GeV physics has been fruitful for the study of weak and electromagnetic processes with neutrino and muon beams. The exciting results include the discovery, with CERN, of the existence of neutral currents, the observation of dimuons in neutrino collisions, the excess number of charged-current antineutrino events with a large energy transfer to the nucleon (high-y anomaly), the violation of Bjorken scaling in muon scattering, and the excess of neutral kaons in neutrino bubble-chamber pictures with two

final-state leptons.

In the most recent neutrino work, the discovery of trimuon events, there may be evidence for new leptons with a mass of 2 GeV or more. If this hint is confirmed, it will usher in an era of investigation of super-heavy particles for which only Tevatron beams will be appropriate.

Together with these particularly dramatic results, there have been many solid measurements in more conventional neutrino, muon and hadron physics that have been made during the five years since the Neutrino Area began to operate, resulting in a deeper understanding of both weak and hadronic interactions. This incomplete list of 400-GeV physics gives a taste for the kind and variety of physics that will be possible at 1 TeV.

2. Physics of the 1-TeV Neutrino Area. The advent of a 1-TeV proton beam will have a major effect on the physics of the Neutrino Area. From kinematic considerations alone, there will be a gain in event rate for both neutrino and muon scattering of a factor 2.5. More important however, will be the far larger gains in production of very heavy particles such as charmed mesons, heavy leptons and other possible more massive states of matter. Some of the specific processes that will be studied are neutrino total cross sections up to 700 GeV, dimuon and trimuon production in neutrino and muon interactions, charmed-particle production by neutrinos, deep-inelastic scattering of muons and neutrinos, heavy-lepton production, and systematic hadron study of final-state neutrino and muon scattering by protons.

In addition to these lepton-scattering topics, it is expected that a program of 1-TeV hadron physics will be maintained in the Chicago Cyclotron Spectrometer (CCM) and the 30-in. Bubble Chamber Spectrometer. The future location of the 30-in. Chamber remains to be resolved, since there is interference between the neutrino and hadron physics experiments at the end of the muon shield. Possible locations for the 30-in. include the new muon beam and the Meson Area. The specific topics that

will be interesting for these facilities include pp and $\bar{p}p$ total cross sections at energies above 400 GeV (30-in. chamber) and high $P_\perp$ and rare-process studies for π, K, $\bar{p}$ beams (CCM spectrometer).

As is almost always the case in high-energy physics, it is probably not possible to anticipate the most startling and exciting results that will emerge from the 1-TeV Neutrino Area. Nevertheless, a mix of beams and facilities has been planned that should be powerful tools for the investigation. The single most dramatic upgrade is for the 750-GeV muon beam, which will improve on its predecessor by two orders of magnitude. With this tool, precision measurements of nucleon structure can be made down to distances of order 10^{-17} cm. In this regime, it will be possible to confirm or deny the asymptotic-freedom picture for quark-quark forces and perhaps to exceed the limit for quark-quark binding, so that free quarks could be produced at last.

3. The 400-GeV Neutrino Area.

a. Primary-proton transport. The primary beam to the Neutrino Area follows a straight-ahead path after emerging from the extraction channel, as shown in Fig. V-1. The Neutrino Area uses both fast-spill and slow resonant extraction beams. The fast spill has been of two types: single-turn extraction, which provides a pulse of protons of 21 μsec duration, and fast resonant extraction at a half-integral resonance, which provides a pulse width of 1 to 2 msec duration. The former has been used exclusively with the 15-ft bubble-chamber neutrino experiments. As the use of an external muon identifier, an electronic device, has become more important for the 15-ft program, the value of the single-turn extraction has declined. It is planned that by 1978 the Neutrino counter program and the Neutrino bubble-chamber program will use fast resonant extraction exclusively.

The Neutrino proton beam contains pulsed magnets that make it possible for fast pulses to be directed around the Neutrino-Proton and Neutrino-Meson splitting stations, thereby making it possible to send

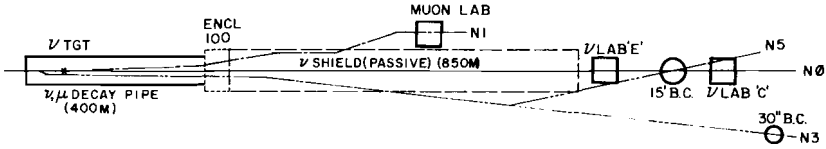


Fig. V-1. Present Neutrino Area layout.

all the fast beam to the Neutrino Area.

An electrostatic septum located in the G-3 manhole splits the proton beam vertically. After the two beams have traversed the second half of the vertical dogleg in Neuhall, a set of Lambertson magnets separates the beams horizontally. The part of the beam that bypasses the neutrino beam target then traverses the target tube and decay pipe until it reaches a target either at the end of the decay pipe or in enclosure 100, as shown in Fig. V-1. This beam has been used to produce mesons for the muon beam (N1) when it is not being used as a muon beam, and for the N3 and N5 beams which run to the 30-in. Chamber and the 15-ft chamber respectively.

b. Neutrino-area target systems and beams. The present scheme for targeting protons and forming tertiary beams of neutrinos and muons is shown in Fig. V-2. The first stage of the muon beam and the neutrino beam consists of a set of focusing elements mounted on 20 narrow-gauge railroad cars to form a beam train. The train is inserted into a 60-m long, 1.8-m diameter steel tube buried in an earth berm. The purpose of the focusing elements is to focus the mesons produced on the primary target into a parallel beam that can then traverse the 400-m long, 0.9-m diameter decay tube. The mesons that decay into muons and neutrinos provide the source of tertiary particles for the muon beam and the neutrino beam. In the former case, a simple magnet transport system collects the muons reaching Enclosure 100, guides them out of the earth muon shield, and then along the edge of the shield to the Muon Laboratory. All particles except neutrinos that proceed straight ahead toward the Neutrino detectors 1000-m further downstream are intercepted by the muon shield.

The neutrino and muon beams were designed to share a common target, first-stage focusing system and decay pipe. It was originally intended that these beams could operate simultaneously by sharing a compatible set of focusing and beam-forming elements after the target, but this has been possible for only one of the three major focusing systems, the

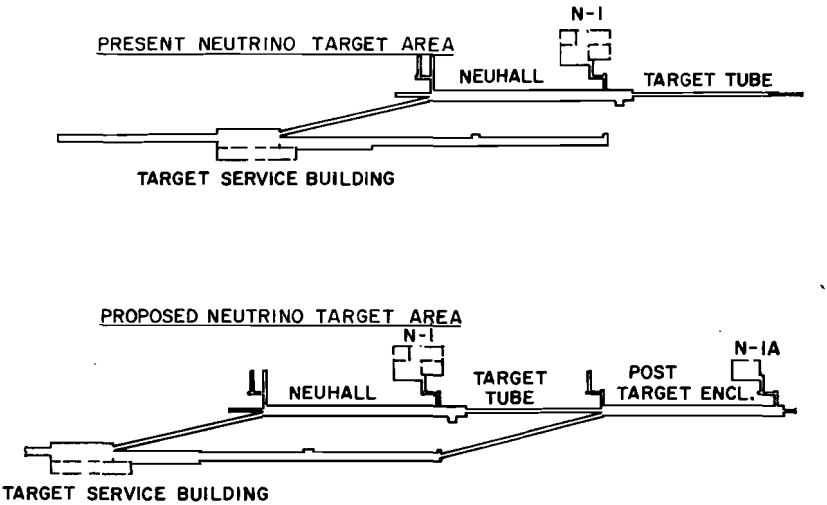


Fig. V-2. Proposed changes in the Neutrino target area.

quadrupole-triplet train. The other two, the double horn and narrow-band dichromatic, have not been useful for forming muon beams.

A still more serious problem created by the operation of the muon beam with any of the focusing systems is an unwanted flux of muons entering the 15-ft Bubble Chamber and the neutrino counter experiments. It arises because the muon beam elements transport muons that emerge from the decay pipe around the muon shield and into the detectors. Thus an essential incompatibility has developed between the running conditions for muon and hadron physics and the neutrino bubble-chamber program. This conflict has severely limited the muon-physics program at Fermilab and has had a negative impact on the neutrino program as well. The solution to this conflict is to construct a muon beam that shares no enclosures with the neutrino beam and that has an independent, spatially separated target.

c. The muon shield. The present muon shield is designed to stop all muons that emerge from Enclosure 100 before they reach the neutrino detectors, which are 1000 m further downstream. The present constitution of the shield is 640 m of earth, 92 m of 1.8 m × 1.8 m iron and 260 m of gaps. The shield also has a 50 cm × 50 cm needle of iron located at the beginning of the shield just downstream of Enclosure 101. The ionization loss of a particle that traverses the earth and the 92 m of iron is estimated to be 375 GeV. The shield has been demonstrated to be effective at 500 GeV.

In addition to the neutrino and muon physics program, there has been a modest but rewarding program of hadron physics in the Neutrino Area. Unfortunately, the hadron beams on the east side create background problems at the 15-ft Bubble Chamber for the same reason that the muon beam does.

4. The 1-TeV Neutrino Area.

a. Primary-proton transport. The transport of a 1-TeV beam to the Neutrino Area involves two kinds of changes in the Neutrino line, first,

the superconducting magnets discussed in the Introduction to this Chapter and second, a new proton-beam split that will be developed to enable the new muon beam to have its own targeting station (the Mu0 line). This modification is particularly important because it will allow full utilization of all the Neutrino Laboratory apparatus. The elements necessary to transport these two beams are compared with the existing 400-GeV proton beam and N7 bypass in Table V-I.

Table V-I. Proton Transport to Neutrino-Area Targeting Stations

	400 GeV		1 TeV	
Element	N0	N7	N0	Mu0
Vert. Bend to Neutrino Target	8-10 ft dipoles 11 kG	-	6-10 ft SC dipoles 36 kG	-
Right Bend to Muon Target	-	2-10 ft dipoles 12 kG	-	3-22 ft SC dipoles 41 kG
Transport Quads	3-10 ft quads 3.0 kG/in.	1-5 ft quad 3.8 kG/in.	6-10 ft quads 5.2 kG/in.	8-10 ft quads 3.0 kG/in.
Targeting Quads	4-10 ft quads 3.2 kG/in.	6-10 ft quads 4.1 kG/in.	4-5 ft quads 10 kG/in.	6-10 ft quads 6 kG/in.
Splitting Dipoles	-	4-10 ft Lamb. 6 kG	-	5-10 ft Lamb. 5.6 kG

Both the large vertical dogleg and right bend can be achieved with superconducting dipoles run at conservative currents. Use of superconducting magnets permits both proton transports N0 and Mu0 to be built with minimal modification of existing enclosures. In particular, Enclosure C needs to be widened by 6 ft over a distance of 70 ft, the G-2 manhole needs to be extended by 90 ft on its downstream end and one new manhole, Mu-1, must be constructed for quadrupoles transporting the Mu0 beam.

Refrigeration for the superconducting magnets will be accomplished in the following way. The lower half of the vertical bend is combined with the Meson left bend and cooled by Tevatron satellite refrigerators located in the SSB. The top half of the vertical bend, the right bend and the N0 targeting quadrupoles are cooled with a satellite refrigerator located in the Neuhall Service Building. The N0/Mu0 split is

accomplished with six (6) ten-foot electrostatic-septum sections in Enclosure C, followed by a string of five Lambertson magnets in Enclosure G-1.

b. 1-TeV Neutrino Target and Beam Forming. The utility of the neutrino beam is considerably enhanced if it is designed to have a narrow momentum spread. If the focusing system forms a monochromatic meson beam, it will give a dichromatic neutrino beam. The neutrino energy will depend on only whether the parent was a pion or a kaon. The dichromatic beam that is under construction will provide neutrino energies up to 300 GeV. A new 700-GeV version of this beam will be constructed for 1-TeV operation.

A 700-GeV monochromatic meson beam with conventional magnets would be longer than the target tube. The use of superconducting magnets was considered, but rejected because of the high-radiation environment in the target tube. A 75-m concrete enclosure will therefore be added to the target tube. Servicing of this new beam will also require modification of the Target Service Building (TSB). Fig. V-2 gives a schematic representation of the required changes, showing the present targeting area and its modifications. Most of the remaining target systems can continue to be used without change.

c. Muon Shield at 1 TeV. The major problem that 1 TeV presents for the Neutrino Area is the problem of hardening the muon shield. There are three possible approaches that have been considered:

(i) Dense iron shielding with a cross section 4 m × 4 m for the first 300 m, with the present earth and iron shielding in the last 700 m.

(ii) Focusing of the dominant-sign Neutrino so that a small cross section of steel, approximately 2.5 m × 2.5 m, can be used for the first 300 m. The present earth and iron shielding remains in the last 700 m.

(iii) A large magnetized-iron shield located at the present site of Enclosure 100.

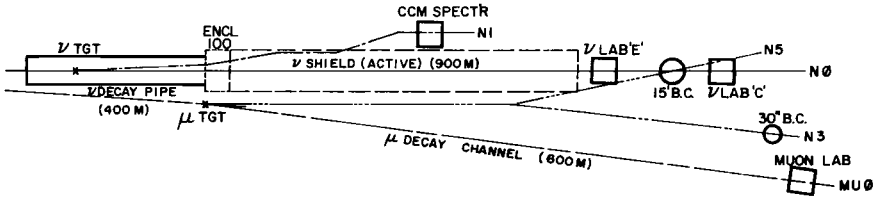


Fig. V-3. Layout of proposed muon beam in Neutrino Area.

Each scheme calls for all gaps to be filled with steel or earth. Thus each scheme requires between 1,000 and 10,000 tons of steel. Each solution has certain advantages and disadvantages. The first is straightforward, but involves the greatest cost, because it requires the largest transverse shield dimensions. Since the cost of the muon shield increases as the square of the transverse dimensions, every effort must be made to contain the most penetrating muons in the decay pipe before it enters the shield. The second proposal makes use of magnetized toroids inserted on rollers into the existing decay tube. The toroids will be set to focus the same charge as the focusing device in the target tube, thereby containing the largest portion of the muon beam. Steel shielding will be placed immediately downstream of the decay pipe, and will extend a distance of 300 m. Gaps in the shielding created by beam-line enclosures and the Wonder Building will be filled in with steel at the center of the berm. About 1000 tons of steel will be installed in this location. Similar remarks apply to the third option.

During 1977 and 1978, tests are planned to evaluate the effect of toroidal magnets on the muon problem. Toroids will be located at Enclosure 100 and the background of muons will be measured at the Wonder Building, halfway down the shield. These tests and calculations will provide the information necessary to design the preliminary shield.

d. 1-TeV Muon Target and Beam Transport. The primary-proton targeting station for the new muon beam is simple and straightforward. Fig. V-3 shows the site location and beam layouts. The new muon beam will be underground in order to utilize the natural earth shielding to range out all muons well within the site boundaries. The 1-TeV protons are focused onto a target in a new Enclosure, Muhall, using conventional quadrupole magnets.

Pions from the target are collected by a conventional quadrupole doublet and passed through a dipole bend to separate the primary proton beam prior to dumping it. The first focus of the beam is at the proton

beam dump. A beam port in this dump functions as the momentum-selection slit for the pions that are the parents of the muon beam. After the proton dump, two sets of dipoles and a quadrupole triplet recombine the momenta of the pions and match them into the decay-pipe section of the beam. The decay region will contain three quadrupole enclosures spaced approximately 500 ft apart to confine the beam. The final set of quadrupoles focus the muons of required momentum onto the pion absorber.

The muon transport consists of a set of dipoles giving a 10-mrad bend upward, followed by a quadrupole triplet. This allows muons of the desired momentum bite to be bent upward, away from the off-momentum muons. The quadrupoles gather the muons together after the absorber, counteracting at the same time the dispersion introduced by the dipoles to maintain the 10% momentum bite of the muons. A final doublet of quadrupoles in the beam transport focuses the muon beam through a set of dipoles into the experimental area. This final set of dipoles bends the beam into the new Muon Laboratory.

The muon beam as described, will produce the yields shown in Table V-II. The yields are compared with the existing muon beam at Fermilab.

Table V-II. Muon Yields for 400-GeV and 1-TeV Proton Beams

Proton Energy (GeV)	Muon Energy (GeV)	Yield (per 10^{13} interacting protons)
400 (Existing Beam)	150	1.8×10^6
400 (Existing Beam)	225	1.2×10^6
400 (Existing Beam)	275	0.8×10^6
1000 (New Beam)	250	100×10^6
1000 (New Beam)	450	90×10^6
1000 (New Beam)	750	6×10^6

It is seen that improvements of a factor three in energy and two orders of magnitude in intensity are achieved. The gain comes from two sources. First, the phase-space capture of pions from the primary target is increased significantly over the present beam and second, the present unfocused decay pipe is replaced by a quadrupole channel to capture and contain a large momentum bite of the charged particles.

The muon beam is partially polarized by the kinematics of parity violation in the pion decay. By momentum selection of forward and backward decays (in the center of mass), the spin polarization of the muon (helicity) can be varied from an average of +61% for forward to -53% for backward decays.

The pion absorber will be 40 interaction lengths long. It will probably consist of 40 ft of beryllium so that the average multiple scattering is limited to 0.8 mrad at 100 GeV. At energies in excess of 500 GeV, this is negligible compared with the beam divergence.

Muon beams are notorious for their halo, but this problem is much less serious in the 100-GeV energy range than in the 10-GeV energy range, as has been learned empirically in Fermilab experiments. It is important to limit the halo to the order of 1% or less of the beam in order to make effective use of the new high intensity. To eliminate halo in the Muon Laboratory, the hadron beam will be absorbed before any of the muon transport system using magnetized spoilers.

A list of the magnets necessary for the muon beam transport is given in Table V-III.

Table V-III. Magnets for Muon-Beam Transport

Element	Number	Dimensions (in.)	Field or Gradient (kG) (kG/in.)
Dipole	13	4 × 4 × 240	15.0
Quadrupole	19	3 × 84	6.0
Quadrupole	27	4 × 120	5.7

e. New Muon Laboratory. A new laboratory building is planned for utilizing the new muon beam. The muon beam is located 3 ft above the floor of the building and slopes downward at an angle of 2 mrad to insure that the beam buries itself deep in the ground beyond the Muon Laboratory. The beam itself is at an elevation of 730 ft above sea level, an elevation that places it approximately 10 ft below local ground level. It would otherwise be necessary to erect an earth berm to shield halo muons escaping from the beam.

Location of the beam below ground level requires that the floor

have an elevation approximately 13 ft below ground level. The building is 30 ft by 180 ft.

The building construction will be of conventional type with corrugated steel walls and a concrete-pad floor. The building requires conventional services such as electric power, cooling water, heating and lighting. Air conditioning for electronic equipment can be provided locally in the manner already established at Fermilab.

The building outlined above will accommodate two muon experimental setups, one behind the other. This tandem scheme has been used in the present Muon Laboratory with good success. This pattern of two basic classes of muon experiments, which can be roughly divided into low-mass experiments and high-luminosity experiments, will continue at 1 TeV. The spectrometers demanded by the two classes of physics are sufficiently different that it is effective to have two setups of different character rather than a single facility of compromised design.

C. Proton Area

1. Physics in the Proton Laboratory. The Proton Laboratory has produced a wealth of valuable physics results. The first evidence for a charmed baryon was found in the Proton Laboratory wide-band proton beam. The same facility was used to demonstrate the first photoproduction of the J/ψ particle, the essential clue to identifying the particle as a hadron. Experiments investigating high transverse-momentum inclusive production in Proton East and Proton Center keynoted the unexpectedly high direct-lepton production at Fermilab energies. Later, a series of experiments there helped to demonstrate that most of this production was due to dilepton production. These experiments searched out to dilepton masses of more than 10 GeV/c^2. Recently another experiment designed to measure photon-photon correlations has observed diphoton masses up to 7 GeV/cm^2. There data suggest a possible state that decays into a pair of photons. Many other key experiments, such as the measurement of photon total cross sections and the high-t proton-proton elastic scattering have been performed in the Proton Area.

All these experiments will be significantly enhanced by the availability of 1-TeV protons and the possibility of a spill duty factor of nearly 50%. The higher energy helps by increasing the center-of-mass energy to 43 GeV, offering the possibility of opening channels for new processes. The greater energy also boosts the useful energies and fluxes of secondary and tertiary beams. In particular, the fluxes of tertiary particles increase dramatically. The flux in the high-energy pion beam increases by a factor of 20 while the usefulness of the beam as a source of antiprotons from antilambda decay increases by a factor of 10. The flux of photons in the tagged-photon beam increases by a factor of 100.

At 1 TeV, each branch of the Proton Area will offer attractive opportunities for physics. The broad-band photon beam in P-East can be used to look for new high-mass vector mesons. Charmonium-like states with masses up to 15 GeV/c^2 should be accessible. The interactions of the known and new vector mesons with hadrons can only be studied with photon beams, which in turn can only be produced in a fixed-target area. This same beam can also be used as a source of high-energy K^0 and n. When the Tevatron operates at 1 TeV, an intense flux of tagged 300-GeV photons will be available in P-East. This should prove very valuable for charmed-particle spectroscopy. The photon-energy tag makes possible experiments in which the energy balance from a photon-produced event is determined. This feature will make this beam a unique tool to study the pair production of heavy leptons. It will be possible to study carefully leptons of mass 1.8 GeV/c^2, if they are found.

In P-Center, the hyperon facility now under construction will be helped by the increased energy. Ω^- hyperon fluxes will reach intensities large enough that the strong interactions of a particle made up of only strange quarks can be studied. The P-Center target box could also be used to extend the continuum dilepton pair-production measurements with a two-arm spectrometer. The higher incident proton energy should push these measurements out to masses of 25 GeV/c^2.

In P-West, the high-intensity beam now under construction has 1-TeV flexibility built in. This beam will be a unique source of high-energy, high-intensity beams of antiprotons and mesons. This new facility offers the opportunity to extend massive lepton pair production, particle production at very large transverse momentum and experiments using, in effect, antiquarks. Intense beams of mesons will play an important role in the study of quark-quark and quark-antiquark interactions, which manifest themselves most clearly when at least one hadron has large transverse momentum. In addition, the upstream proton-proton experimental station will continue to offer unique opportunity for experiments needing clean intense proton beams.

2. Implementation of 1000 GeV in the Proton Area. The existing Proton Laboratory consists of separated underground areas, each receiving an independent proton beam directly from the accelerator. This arrangement makes possible direct experimentation with the beam from the accelerator as well as the ability to produce specialized 0° beams such as photon, hyperon, and antiproton beams.

The upgrading of the Proton Laboratory to 1000 GeV makes significant use of these existing facilities, resulting in many economies. It is useful to review first the existing facilities in some detail in order to discuss the 1-TeV modifications.

a. The 400-GeV Proton-Beam Transport and Proton-Area Configuration. The Proton Area normally operates at 400 GeV although it has operated at 500 GeV and as low as 100 GeV. The Proton Laboratory Beam Transport begins with the Proton-Neutrino split in Enclosure B in the beam-extraction area. After being split, the extracted proton beam passes through a set of thirty-four 10-ft 12-kG dipoles. These magnets bend the proton beam to the east as it passes through Enclosures B, C, and D. Intermixed with the dipole string are quadrupoles that focus the beam so that it can be contained within the aperture of the dipole magnets and to prepare the beam for subsequent splitting. When the beam enters

Enclosure E, it is made parallel and directed onto a set of five electrostatic septa that split it vertically into three parts. These parts are then deflected vertically upward into Enclosure H by a common set of dipole magnets. The beam elevation in Enclosure H, which is the final elevation of the three proton beams, is 5 m below the local ground surface.

In Enclosure H, the three vertically separated beams are separated horizontally, first by a set of three-way magnets and then by standard EPB dipoles. After a distance of 2000 ft, the three beams are sufficiently separated so that independently accessible primary targets can be used. These three target stations and the associated experimental enclosures are 5 m below ground. The independent targeting and the underground enclosures constitute the unique features of the Proton Area. Each area contains a quadrupole doublet in a pre-target tunnel (four 10-ft quadrupoles per area), which focuses the beam to a 1-mm spot on a target about 200 ft downstream.

A plan view of the Proton Area is shown in Fig. V-4. In Proton East, at the bottom of Fig. V-4, the beam is then switched either east to the broad-band photon/neutron-beam target, or west to the tagged-photon-beam target. Both of these beams are semi-permanent facilities. The broad-band beam is filtered by 100 ft of liquid deuterium (to reduce the fractional content of neutrons) and arrives in EE-4 for use by experiments. The electron beam, which is capable of transport up to 300 GeV, provides electrons to the Tagged-Photon Laboratory (TPL) where a tagged-photon beam is produced by bremsstrahlung in a thin radiator. The energies of the photons are determined by measurement of the angle and energy of the scattered electrons.

In Proton Center, the beam presently services a two-arm dilepton experiment. This will be replaced within the next two years by a charged-hyperon facility, starting from the same target position and ending in a 200-ft extension of the Proton Center pit. The capability of doing pp experiments in this area will be maintained.

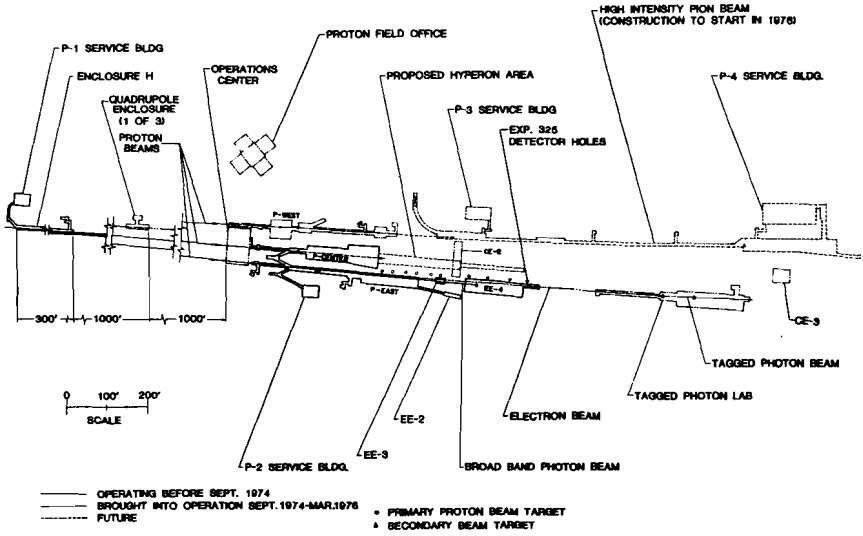


Fig. V-4. Plan view of the Proton Area.

In Proton West, near the top of Fig. V-4, the primary beam is shaped and collimated in the West Focusing Enclosures in order to provide a very halo-free beam in the West Pit for transmission-target experiments that have apparatus extremely close to the beam in the upstream enclosures (PW1).

The first area to be designed specifically for 1-TeV capability is now under construction in the West Area, the High-Intensity Laboratory. It is shown in dotted lines at the top of Fig. V-4. This beam, which begins at the end of the present Proton West, can target up to 10^{14} protons per pulse, will produce about 10^{10} pions and 10^{8} $\bar{p}$'s per 10^{13} targeted protons, and has "good" optics (sextupole-corrected).

b. The 1-TeV Configuration.

(i) Primary Proton Transport. Since the Proton Line already has 500-GeV capability, it is only necessary to double the product of the magnetic field and length everywhere. The 34 EPB dipoles that form the right bend will be replaced by superconducting dipoles, the Lambertson magnets will be doubled in number, and the quadrupoles will be either doubled in number (space permitting) or replaced by superconducting quadrupoles. The resulting free space can be used to double the conventional quadrupole lengths. The number of Lambertson magnets need only increase from 5 to 7, since the field can be increased by increasing the current.

(ii) Enclosure E Branching or Electrostatic-Splitting Station. Enclosure E presents special challenges because it contains the three-way split electrostatic septa, which requires either that the voltage be doubled, which may not be possible, or that the length be doubled, which can be done in a straightforward way. The present split employs two sets of electrostatic septa separated by a drift space. In order to maintain the triple split at 1000 GeV, ten electrostatic septa must be installed plus two extra conventional quadrupoles. The upstream half of the Proton vertical bend can be achieved by increasing the number of conventional magnets from three to six, using magnets obtained from

Enclosure H. Conventional magnets will be used here, because there is not much power involved and this avoids having to power superconducting elements from a distance of at least 1000 ft.

(iii) Enclosure H - Magnetic Splitting/Branching. The 1-TeV upgrade of Enclosure H can be accomplished without enlarging Enclosure H, although an enlarged access hatch will be needed. It will require three large-aperture superconducting dipoles to complete the vertical bend dogleg, an additional six three-way split magnets, and seven 22-ft Tevatron supermagnets to deflect the three beams toward the East, Center, and West target stations. The vertical bend magnets must be wide-gap in order to contain the three vertically spaced beams, which are spread over 5 in. Since there is at present no superconducting analog of the three-way split magnet, the string of these magnets must be lengthened from the present four to a total of ten.

Fortunately, the P-1 service building is close to Enclosure H, thereby making it possible to transfer liquid helium efficiently to superconducting magnets using the same type of refrigeration system that is being developed for the Tevatron and the High-Intensity laboratory. The P-1 service building already has enough room to accommodate the necessary refrigerator. A new penetration will be made for the transfer line.

(iv) Proton-West Quadrupole Enclosures. Initially Proton West Operation at 1 TeV will be used primarily for the Pion Beam. If experiments taking place in the present P-West transmission target can tolerate a factor 5 increase in beam halo, then no upgrading is needed. The first quadrupole doublet is adequate to refocus the beam, the second doublet is turned off, and the magnets and collimators in PW-B are raised 2 in. to accommodate vertical doglegging which is reduced by a factor 2.

At a later stage, the present halo-free feature of the West beam may be restored by replacing the quadrupoles and possibly the dipoles with superconducting magnets. This area presents a special problem with regard to refrigeration because it is spread out over 600 ft and is far

from any service building. A service shed 20 ft by 15 ft would be needed to house a small refrigeration system. Alternatively, a long helium transfer line could be constructed from P1 or the Pagoda.

(v) P-East Branch Point. During the revision of the Proton Area to accommodate 1 TeV, it would be natural to extend splitting or branching to P-East, thereby permitting simultaneous operation of the tagged-photon beam and the broad-band photon beam for the first time.

With the extra room opened up in Enclosure H by the installation of superconducting magnets, 20 ft of electrostatic septa can be placed in the P-East beam line in Enclosure H. This will produce enough vertical splitting of the beam to allow the use of Lambertson magnets 1000 ft downstream of H for horizontal separation. In order to make a place for these Lambertsons, a new enclosure, 100 ft long, will have to be constructed. For 2 ft of separation of the incident proton beams in the P-East pre-target area, three 2-way Lambertson magnets will be required at 1 TeV. The power for these magnets will be provided from the existing 1.5 MW substation at the quadrupole enclosures.

(vi) Pre-Target Areas - PE, PW, PC. All magnets will be replaced with superconducting magnets. The present low-gradient quadrupoles must be replaced on a one-for-one basis with superconducting quadrupoles. The 6-in. bore of these magnets provides adequate aperture to avoid the proton beam halo. The necessary refrigeration for these magnets will be housed in the Pagoda pump room, if suitable reduction of the large LCW system is made. Need for the LCW system will be much reduced by the introduction of superconducting magnets.

In the pre-target area in P-East, construction work will be needed to enlarge the tunnels to accommodate two independent sets of pretarget focusing magnets. Each set will consist of four superconducting quadrupoles for focusing and two dipoles for steering the beams onto the broad-band and tagged-photon beam proton targets. The target box can remain approximately as now configured, with the exception that the horizontal separation of the target will be increased from 1 ft to 2 ft.

The initial stage of the two beams can be moved to accommodate this shift.

(vii) Target Systems/Radiation Problems. The present concept of target boxes require no special hardening for 1 TeV for current intensities. Hadronic-shower development will not change strikingly between 300 and 1000 GeV. Hadron leakage from the target boxes is not a source of above-ground radiation at 400 GeV nor is it expected to be at 1000 GeV.

Penetrating muons are the principal problem at 400 GeV and will be the most serious problem at 1000 GeV. Because the experimental area is below ground, it will present no hazard to the people on the surface, although it will make experiments more difficult. The worst problem for experiments will be the penetration of muons into the tagged-photon laboratory and EE-4 when either of these beams is operating. Muons that emerge from the earth will be the major environmental radiation problem when the electron beam is running with 6×10^{12} protons on target.

The muon densities in the tagged-photon pit are approximately 1 to 3×10^5 muons/m^2 per 10^{12} primary protons when the broad-band beam runs. The above-ground dose rates from muons at the Tagged Photon Counting Room are 0.1 mrem/hr per 10^{12} primary protons when the electron beam runs. It is anticipated that these two rates increase approximately proportional to energy, in which case there will be no difficulty at 1 TeV. If, however, the muon rates increase by a factor 60, as calculated in the 1976 Summer Study, additional muon hardening at the end of the P-East Enclosure will be necessary.

A more serious problem with 1000-GeV protons and 0° beams is deflection into the dumps inside the target boxes. The target-box system designed for the new facility in P-West is capable of handling this problem. Similar geometries can be installed in P-East and P-Center.

(viii) Broad-Band Photon Neutral K°_L Beam. The broad-band photon/neutral-K° beam in Proton East can go to 1 TeV with no additional magnets because it is a neutral beam. There will, however, be an increase in background from the more energetic neutron interactions and from the

increased bremsstrahlung of the higher-energy electron pairs in the 100-ft liquid-deutrium filter. The filter, which will continue in use, is embedded in nine sweeping magnets that remove electron pairs and charged particles from neutron interactions. The addition of another sweeping element at the end of the first Proton East enclosure will help decrease any increase in charged-particle backgrounds. It will continue to be possible to transport protons in this beam to a target in EE-4.

(ix) Tagged Photon-Electron Beam. To upgrade the electron beam to 700 GeV, which can be done at a later phase, the components in EE1 and the Tagged Photon Lab will be made superconducting while the few elements in the broad-band beam experimental enclosure (EE-4) can be doubled in length and remain conventional. Since the flux at 700 GeV will be small, this upgrade will use superconducting elements with the widest possible aperture in order to increase the solid angle of the beam. New superconducting elements required are: Five low-current Proton Department 10-ft superconducting dipoles and four low-current Proton Department 10-ft superconducting quadrupoles. The superconducting elements in the first Proton East enclosure will be cooled from the Pagoda, while the magnets in the Tagged-Photon Laboratory (TPL) will be cooled from a refrigerator in TPL.

One challenging problem is that of making the major bend at the end of the Proton East enclosure superconducting, because the neutral beam dump is at this point and massive shielding will be required. The final problem to be overcome, if the upgraded electron beam is still intended to make a tagged-photon beam, is an upgrade of the tagging-system magnets. This will require large-aperture magnets.

(x) P-West High-Intensity Laboratory. As noted above, this facility has already been designed for 1-TeV operation. By the time the 1-TeV beam is available, a superconducting 400-GeV transport system will be operating in the new High-Intensity Laboratory. The increase in the energy capability of the transport to 1 TeV will be straightforward. At that time, the 1.25-m superconducting dipoles will be taken out and

reused as trim magnets in the pre-target areas in PE, PC, and PW and in the secondary beams in the Proton Area. These dipoles will be replaced with 3-m versions and the number of 3-m quadrupoles in the beam line will be doubled. Eleven additional quadrupoles and eleven additional dipoles will be needed. An additional four sextupoles will be needed to apply the same level of correction at 1 TeV as is applied at 400 GeV. The installed refrigeration system is adequate for 1 TeV. The new P-West target system has been designed for 1 TeV.

(xi) P-Center Hyperon Beam. In Proton Center, the charged-hyperon facility, designed to transport charged hyperons up to 400 GeV, will be in place when 1 TeV protons are available. Two operational phases are envisaged:

(1) utilization of the increased flux at a secondary momentum of 400 GeV with 1-TeV incident protons and no changes in the secondary system, and

(2) upgrade of the secondary system to higher momenta.

The upgrade of higher momenta will require a redesign and an approximate doubling of lengths.

(xii) Cryogenics Needs. For Phase I of the upgrade, that is, upgrading Enclosure H and the pre-target areas, but not the West focusing enclosures, electron beam or hyperon area, the equivalent of a satellite refrigerator (450 W at 4.5°K) is needed in the P1 Service Building and the Pagoda. In addition, two satellite refrigerators will already be in place for the High-Intensity Laboratory. The combination of the Pagoda refrigerator and the upstream refrigerator in the High-Intensity Laboratory will provide liquid helium for the 400-GeV hyperon facility. Upgrading the West focusing enclosures and the electron beam (Phase 2) will require two additional refrigerators.

D. Meson Area

1. The Physics of the 400-GeV Meson Area. The Meson Area was constructed to provide a laboratory for flexible studies of hadronic processes. The Area was originally built to handle the projected 200-

GeV energy of the Main Accelerator, and was later modified to handle 400 GeV. This revision was accomplished without significant interruption of the experimental program. A number of important experiments have been carried out in the Meson Laboratory. These include observations that rising total cross sections are common to all hadron-hadron collisions, that many two-body inclusive reactions are quantitatively described by leading Regge-Pole trajectories at high energy, and that single-particle inclusive cross sections obey the general predictions that emerge from the Muller-Regge Analysis. In addition, fundamental properties of hadrons have also been measured, such as the charge radius of the π and K mesons and the magnetic moment of the Λ°. This last measurement, which will eventually be done to better than 1%, is a consequence of the fact that Λ°'s have been observed to have significant transverse polarization in a Meson Laboratory Experiment.

Experience has shown that useful clues for unraveling hadronic processes have also come from other types of experiments performed outside the Meson Laboratory, such as inclusive scattering of electrons and muons and the 30-in. bubble-chamber exposures to hadrons. This has resulted in a change of emphasis in the Meson Area's physics role at Fermilab. Future Meson Laboratory activities may be weighted toward complicated multiparticle processes with relatively high cross sections. In addition, it is relatively simple to insert a simple dipole target load into the Meson Target Tube to produce a ν_e beam, taking advantage of the relatively large solid angle available at the Detector Building. This development will enhance the capabilities of the Meson Area, while complementing the physics of the Neutrino Area.

2. <u>The Physics of the 1-TeV Area</u>. The significant transverse polarization of Λ's is but one example of the fact that collisions of hadrons resulting in the outgoing particle having transverse momentum greater than 1 GeV/c appear to be related to the scattering of the constituents in the hadrons. Is the fact that the Λ° is transversely polarized

evidence that the spin dependence of the quark-quark forces is very large? During the past few years evidence has accumulated for a two-step description of hadron collisions in which a quark in the projectile first scatters off a quark in the target and then the scattered quarks react strongly with themselves and the remaining spectator quarks in the projectile and target. If the original scattering of the two quarks is a violent collision causing the scattered quarks to have a large transverse momentum, the creation of quark-antiquark pairs will occur along the direction of the scattered quarks. This will give rise to a pair of collinear jets of hadrons in the center-of-mass system of the scattered quarks. In the laboratory the jets will not be collinear, but they will balance transverse momentum.

Experiments in the Meson Area designed to look for these jets of hadrons are beginning to find evidence for them. These results suggest that the study of hadron-hadron collisions, particularly at higher energy, may still lead to important insights into strong-interaction dynamics.

So far, no charmed hadrons have been detected in hadron-hadron collisions. The comparison of charmed-particle production may give important information because the charmed quark is so much heavier than the strange quark. These cross sections are expected to be extremely small and they are likely to require energetic as well as intense beams.

In addition, many of the present Meson Laboratory experiments will be well served by higher energy. Obvious examples are the total cross-section experiment and the form-factor experiments. Rare decay modes of the K_o may be studied in the intense K_o flux available in the M3 neutral beam line.

3. <u>The 400-GeV Meson Area</u>. The present proton transport from the split to the Meson Area target consists of 64 10-ft dipoles, which operate at 12 kG, and 19 10-ft quadrupoles. This provides a west bend

from the extraction trajectory. A pair of vertical bends provide a dogleg to bring the beam up to ground level.

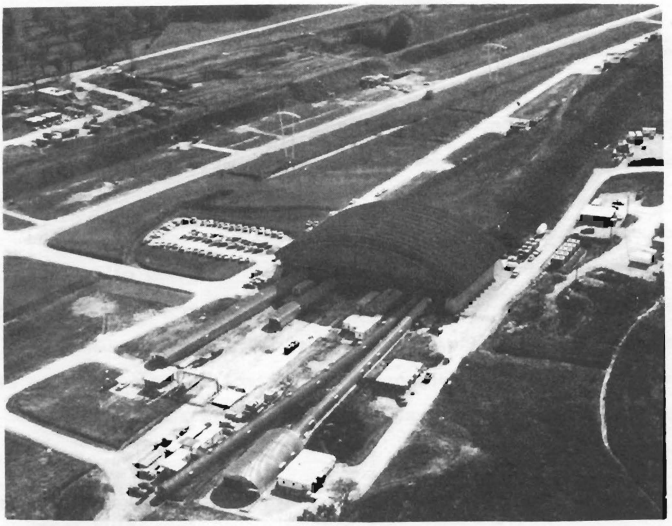
The existing Meson Area consists of a Target area, a beam area encompassing six secondary-beam lines radiating out from the single target, and an experimental area to house the experiments. The target area includes beam elements to focus the primary proton beam on the production target, the target, a series of beam-defining collimators, and a beam dump, then a target box into which the target and collimators are inserted on narrow-guage railroad cars. The secondary-beam area includes the beam-forming, monitoring and control equipment for the six secondary beams. The properties of these beams are summarized in Table V-V.

Table V-V. Summary of Existing Meson Area Charged Beams

Name	Peak Energy	Production Angle	Flux (per 10^{13} 400-GeV Protons)
M1	400	3.5 mrad - East	$10^7 \pi^-$ @ 200 GeV
M2	400	3/4 mrad - Up	10^{10} p @ 400 GeV
M3	400	3/4 mrad - Up	$10^6/cm^2$
M4 chgd neutral	100 400	7.5 mrad - Down	@ 100 GeV $10^6/cm^2$
M5	50 (test beam)	25 mrad	@ 50 GeV
M6	200	3.0 mrad - West	$10^7 \pi$ @ 150 GeV

M6 is now being upgraded to 400 GeV with Tevatron superconducting magnets. This should be completed by April, 1979.

The experimental area consists of the Meson Detector Building, which houses power distribution, control systems and utilities, and a series of prefabricated buildings ("fingers") to house the experiments extending north from the Detector Building. Fig. V-5 illustrates the experimental and beams areas.



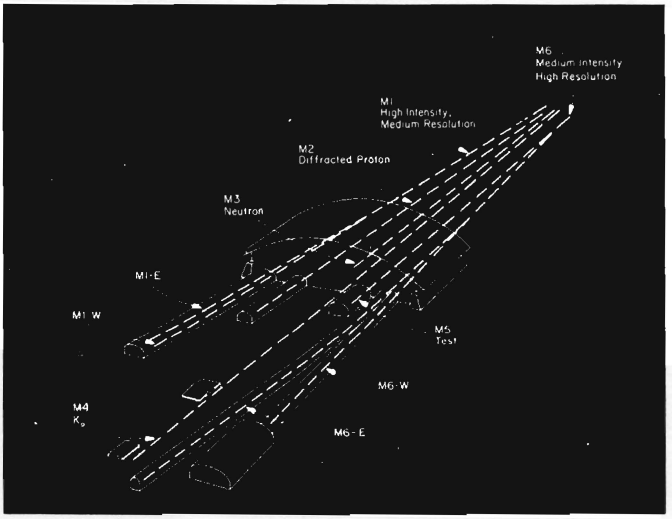


Fig. V-5. The Meson Area.

4. The 1-TeV Meson Area.

a. Beam-Line Upgrading. Utilization of Tevatron magnets to increase the peak-energy capability of the M6 beam line is presently being pursued as an energy-conservation project. The nature of the beam is such that this conversion to superconducting magnets for 400-GeV operation will actually bring the beam to a peak energy of 600 GeV. This installation is projected for the FY78 shutdown of the Meson Area. Modification of the simple optics of the M2 diffracted proton beam with superconducting magnets for improved 400-GeV optics will actually provide 1-TeV capability. At the end of that shutdown period, the 400-GeV Meson Area will actually have the M2 and M3 beams at 1 TeV and the M6 line with its complement of large spectrometers capable of 600 GeV. This will involve approximately 15 Tevatron dipoles. A major installation project would be necessary to convert the M1 beam line to 900-GeV operation. The range of secondary-particle fluxes available in M1 would, however, be greatly extended by 1-TeV proton targeting.

b. Shielding at 1 TeV. Extrapolation of measurements in the experimental area at 400 GeV indicate that the present Meson Area shielding will be adequate even at 1000 GeV. The worst condition in the experimental area lies along the axis of the area in the vicinity of the M3 beam line. This results from muons arising from the decay of mesons produced in the target and pointing along the direction of the incident proton beam. The levels in this vicinity would be 2×10^6 muons/m^2 for 4×10^{12} 1-TeV protons on the target with no change in the present shielding. This flux, while large, would not compromise experiments. Radiation measurements at 400 GeV indicate that the muon levels away from M3 are considerably less. This condition would be expected to persist at 1 TeV.

c. 1-TeV Target in Meshall. The components of the Meson Target system are mounted on 20-ft long narrow-gauge railroad cars. Modification of this system is straightforward and has been done several times since

1972. Steering magnets are now being added to permit the reduction of the production angle in M1 with a simultaneous increase in production angle in M6 or vice versa. This will allow the M1 beam to be as high as $10^9\pi^-$ per 4×10^{12} protons, if needed. Development will continue on plans to make the production angles in the M1 and M6 beam independently variable. No additional changes of this type are contemplated for 1-TeV operation.

The cooling of the target load has been studied to estimate what level of intensity the current target configuration can stand at 1000 GeV. The deposition of energy will be approximately unchanged, with the shower maximum moving slightly downstream in the C2 collimator. The present target load has been run with 10^{13} 300 GeV protons per spill, so that 4×10^{12} protons at 1 TeV would be manageable. Current experience, coupled with the estimated secondary-beam intensities, lead one to believe that this would be a quite satisfactory intensity. It is indeed possible that downstream muon problems, not target heating, will set the upper limit on useable intensity at 1 TeV.

d. The 1-TeV Proton-Transport System. Superconducting magnets will be used for the left bend, while the 10-ft magnet presently being developed by the Switchyard Group will be used for the vertical bend. The quadrupoles that are now used in the F1, F2, and F3 manholes will be retained. The strength of the lenses in these locations will be increased by adding more quadrupoles. The enclosures containing these quadrupoles will be lengthened where necessary. Since this type of quadrupole uses little power and the quadrupoles are widely spaced, it is not sensible to use superconducting magnets for these applications.

The superconducting dipoles in enclosure C, the left bend and the lower half of the vertical dogleg bend, will be cooled by a Tevatron satellite refrigerator located in the Switchyard Service Building. The superconducting magnets in the Meson Target Hall (Meshall) will be cooled

by a satellite refrigerator in the M1 service building.

It is possible to accomplish beam splitting at the Neutrino-Meson branch by adding additional electrostatic septa and magnetic septa in the space presently occupied by conventional dipole magnets.

VI. OPTIONS FOR THE FUTURE

The TeV Program discussed in the previous chapters is planned for the near future. To place this program in a broader perspective, in this Chapter are presented some of the longer-range opportunities for development, some inherent in the TeV Program itself and others inherent in the present Fermilab accelerator and site.

One option for a future extension of the Fermilab program is the construction of a Bypass in the Main Ring or in the Superconducting Ring. Such a Bypass could provide a colliding-beam straight section that would be isolated from the normal path of accelerating protons. It would therefore be readily accessible without interference with other accelerator operations. It could house more elaborate experimental facilities and could be associated with an electron ring that could be used for electron-proton collision studies. A possible location for such a Bypass is sketched in Fig. VI-1.

A second option for a future extension is the pair of intersecting storage rings, POPAE. That project has been the subject of extensive discussions and studies and is described in some detail in a Construction Data Sheet and in a Design Report that were submitted to ERDA in 1976. As indicated above, in view of the newly developed gradual approach to colliding beams, it is now felt to be premature to proceed with POPAE. Nevertheless, the opportunity to build a high-luminosity, high-energy pair of intersecting storage rings at Fermilab still remains. By taking advantage of existing facilities, such a pair of storage rings could be built most economically at Fermilab. By taking advantage of the Superconducting Ring now under construction, a center-of-mass energy of 2000 GeV could be achieved in POPAE, a proton-proton energy that is neither planned nor proposed elsewhere.

A third option is a multi-TeV fixed-target accelerator, suggested in the reports of the 1974 and 1975 HEPAP Subpanels on New Facilities. The site boundaries of Fermilab were modified in 1967 to accommodate

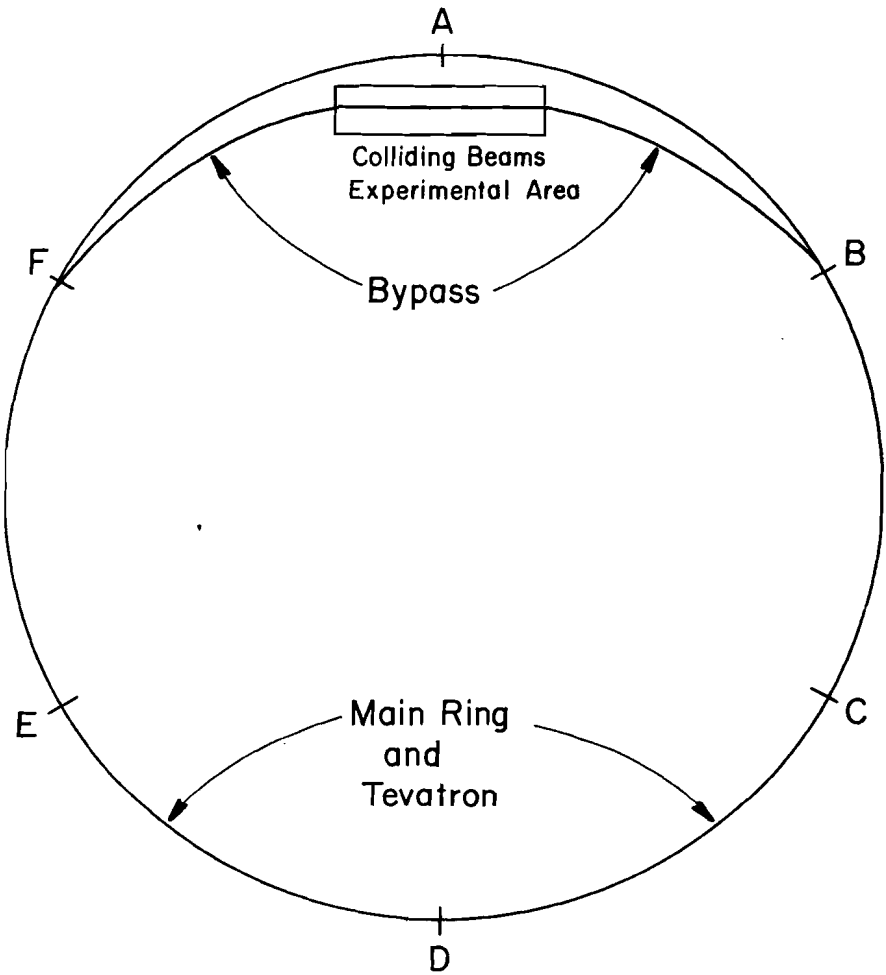


Fig. VI-1. Possible Location for a Beam Bypass.

the largest possible accelerator within the area provided. This accelerator has sometimes been referred to as the Site-Filler Ring. The site will hold a ring of radius 2.5 km. With superconducting technology that might be possible at that time, one might construct an accelerator with a peak energy of 5 TeV.

It has further been assumed that the Site-Filling tunnel could be used for colliding-beam experiments either with proton-antiproton collisions in the superconducting ring or with proton-proton collisions, which would require an additional storage ring in the same tunnel. An electron option could also eventually be added.

Fermilab is a uniquely attractive location for a multi-TeV accelerator because a large site is already available and because there exists in place an excellent injector in the form of the present Fermilab accelerator; the site-development and injector costs would be a large fraction of the total cost of such a project at a new location.

The importance of a multi-TeV accelerator in the long-range development of high-energy physics was emphasized by the HEPAP Subpanels on New Facilities in both 1974 and 1975. Furthermore, those Subpanels both identified Fermilab as the natural site for such a development. The Laboratory is in full agreement with the HEPAP Subpanels as to the importance of the long-range multi-TeV goal. The most logical steps that can be taken at this time toward reaching that objective are the development of the Energy Doubler/Saver and the Colliding-Beam Facility of the presently proposed TeV Program for Fermilab.

It is not intended, by the above listing, to imply any priority ranking of these available options. They are simply presented in random order as examples of the flexibility inherent in the TeV Program.

VII. SCHEDULES AND ESTIMATED COSTS

The preceding chapters have discussed three different parts of the Fermilab TeV program, first, the research, development, and demonstration leading to the Superconducting Ring, second, the construction of colliding-beams facilities, and third, the construction of the Tevatron and 1-TeV fixed-target experimental facilities. In this chapter, we collect information on costs and schedules of these programs.

Table VII-I is a summary of the estimated costs by fiscal year. It is estimated that the present program of Research and Development will cost a total of $40 million over three fiscal years. The Laboratory originally estimated the cost to be $35 million if $10 million were made available in FY 77 and $25 million in FY 78. The difference between $35 million and $40 million represents the cost of stretching out the schedule.

The colliding-beams facilities construction project is estimated to cost $10 million over three fiscal years FY 79 through FY 81. The Tevatron construction project is estimated to cost $40 million over the same three fiscal years, largely for 1-TeV experimental facilities. More detailed cost estimates for these three programs are given in Tables VII-II, VII-III, and VII-IV.

The schedule of the entire TeV program (all three projects) is given in Fig. VII-1.

Table VII-I SUMMARY OF TEV PROGRAM COST ESTIMATES BY FISCAL YEAR
(Assuming FY 78 Funding as Proposed in President's Budget)
(In Millions of Dollars)

	FY77	FY78	FY79	FY80	FY81
A. SUPERCONDUCTING RING (R&D Program)	7.0	10.0	23.0		
B. COLLIDING-BEAM EXPER. FACILITIES (Construction Project)			4.0	5.0	1.0
C. TEVATRON AND ASSOCIATED 1-TEV FACILITIES (Construction Project)			10.0	15.0	15.0
	7.0	10.0	37.0	20.0	16.0

Table VII-II. SUPERCONDUCTING RING (To Coasting Beam) ESTIMATED COSTS*

A. R&D Program - Consistent with President's Budget, Case B of Chapter II.

MAGNETS	FY 1977	FY 1978	FY 1979
Number of 22-ft Dipole Magnets	120	180	500
Number of Quads & Correction Elements	-0-	50	190
Dipole Cost	$3,570	$4,500	$12,000
Quads & Correction Element Costs	-0-	500	1,700
Subtotal - Magnet Cost	$3,570	$5,000	$13,700
OTHER COMPONENTS			
Vacuum	$ 80	$ 150	$ 200
Controls	-0-	150	150
RF	-0-	200	-0-
Power Supplies	-0-	200	100
Beam Transfer	-0-	200	200
Beam Abort	-0-	-0-	200
Supports	70	200	400
Conventional Utilities	-0-	200	850
Subtotal - Other Components	$ 150	$1,300	$ 2,100
ANNUAL R&D	$2,850	$2,900	$ 3,400
REFRIGERATOR SYSTEM	400	800	3,800**
CONTINGENCY	-0-	-0-	-0-
TOTAL for Energy Doubler (less Central He Liquefier)	$6,970	$10,000	$23,000

* In Thousands of Dollars

** Allows Ramping Magnets at 4 min Repetition Rate

Table VII-III. COLLIDING-BEAM EXPERIMENTAL FACILITIES CONSTRUCTION PROJECT ESTIMATED COSTS

(In Millions of Dollars)

a.	EDIA	1.0
b.	Conventional Construction	3.0
c.	Facilities & Technical Components	3.5
d.	Anti-Proton Production Facility	1.0
e.	Contingency and Escalation	1.5
	Total Estimated Cost	10.0

Table VII-IV. TEVATRON AND ASSOCIATED 1-TEV FACILITIES (CONSTRUCTION PROJECT) ESTIMATED COSTS
(In Millions of Dollars)

I. Complete Energy Doubler/Saver, extract to Neutrino Area:		
Refrigeration	5.8	
Power Supplies and Controls	0.6	
RF	1.2	
Extraction	0.9	
Conventional Construction and Utilities	1.0	
		9.5
II. Neutrino Area:		
Upgrade of neutrino beams for 1000 GeV	3.5	
Beam Branching Station and Beam Transport for Muon Target	0.5	
Upgrade of Muon Target Station and Muon Beam	4.5	
		8.5
III. Proton Area:		
Beam Branching Station and Beam Transport to Proton Target	1.0	
Upgrade of Proton Area to 1000 GeV	6.0	
		7.0
IV. Meson Area		
Beam Branching Station and Beam Transport to Meson Target	2.0	
Upgrade of Meson Area to 1000 GeV	2.5	
		4.5
Total Conventional Facilities and Technical Components		29.5
EDIA		3.0
Contingency		3.0
Escalation		4.5
Total Estimated Cost		40.0

It should be noted that the work incorporated within Tables VII-III and VII-IV can be subdivided and undertaken in a stepwise fashion. For example, within the Colliding Beams project the Antiproton Production Facility could be separated out and construction undertaken at a cost of about $1.5 million.

Within the Tevatron and Associated 1-TeV Facilities Project, completion of the accelerator could be undertaken separately and would yield substantial energy savings, as well as some new physics, at a cost of $10 million. Similarly, the upgrading of each of the experimental areas could be separately undertaken.

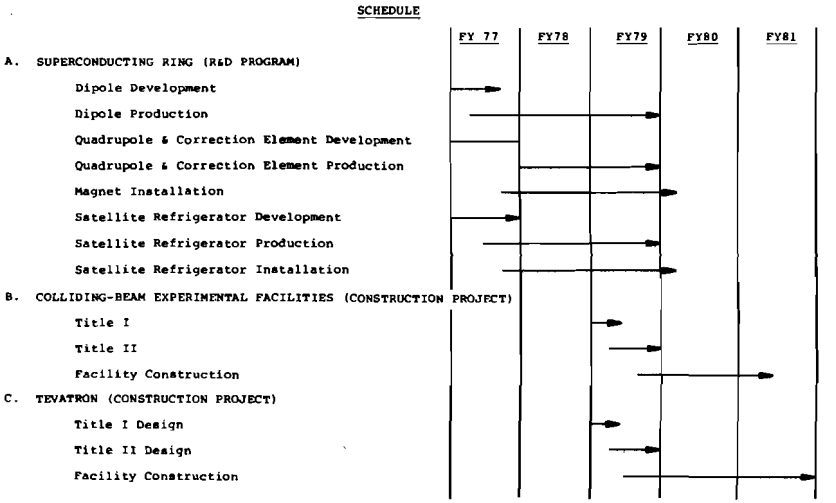


Fig. VII-1. TeV-Program Schedule.

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