Conceptual Design Report

Fermilab Main Injector

Project No. 92-CH-400

Technical Components and Civil Construction

March 1991

Revision 2.3, Addendum

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Table of Contents

1. INTRODUCTION 3

2. THE MAIN INJECTOR 6
   - 2.1 Lattice - MI-16 6
   - 2.2 Acceleration Cycles 8
   - 2.3 Magnets 9
   - 2.4 Power Supplies 11
   - 2.5 Correction Elements 14
   - 2.6 Radio Frequency System (rf) 16
   - 2.7 Vacuum System 18
   - 2.8 Instrumentation 18
   - 2.9 Controls 19
   - 2.10 Abort System 20
   - 2.11 Slow Extraction 21
   - 2.12 Environmental and Shielding Considerations 23
   - 2.13 Utilities 24

3. BEAMLINES AND BEAM TRANSFERS 27
   - 3.1 The 8 GeV Line 28
   - 3.2 The 150 GeV Lines 29
   - 3.3 120 GeV Antiproton Production 32
   - 3.4 The 120 GeV Slow Spill Line 33
   - 3.5 Beamline Magnets and Power Supplies 34

4. CIVIL CONSTRUCTION 36
   - 4.1 Overview 36
   - 4.2 Main Injector Ring Enclosure 36
   - 4.3 Beam Transport Enclosures 37
   - 4.4 Main Injector Service Buildings 38
   - 4.5 F-Zero Beam Enclosures and F-Zero Service Building Addition 40
   - 4.6 Industrial Building No. 5 42
   - 4.7 Foundation Systems, Earth Retention and Active Soil Control 43
   - 4.8 Master Substatrion, Primary and Secondary Power Distribution 44
   - 4.9 Primary Cooling, Distribution and Mechanical Systems 46
   - 4.10 Drainage and Wetlands 48

5. COST ESTIMATE.....51
5.1 Methodology.....51
5.2 Technical Components.....51
5.3 Civil Construction.....52
5.4 Engineering Design Inspection and.....52
Administration (EDIA)
5.5 Contingency.....52
5.6 Other Project Costs (R&D, Pre-operating,.....53
Capital Equipment)
5.7 Spending Profile.....56

6. SCHEDULE.....57

1. INTRODUCTION

This addendum contains a description of Fermilab Main Injector (FMI) design, cost estimate, and schedule changes which have been implemented since the release of the most recent Conceptual Design Report, Revision 2.3 (CDR 2.3), in April 1990. The organization of this addendum parallels that of CDR 2.3, with only those sections which reflect changes to CDR 2.3 being incorporated into this document. It is intended that this addendum accompany CDR 2.3. A new Conceptual Design Report (Rev. 3.0) is in preparation with a tentative release date of May 1, 1991.

While changes have been incorporated into the design of technical and civil components, no change has been made to the location, circumference, energy, or operating scenarios of the Fermilab Main Injector. The scope of the overall project remains essentially unchanged. The updated Main Injector parameter list is given in Table 1-1

The primary function of the Main Injector remains the maintanence of growth in physics output of the Fermilab High Energy Physics (HEP) program during the pre-SSC era. As described in CDR 2.3 specific benefits expected from the construction of the Main Injector include:

1. An increase in the number of protons targeted for $\bar{p}$ production from 5.0×10^{15}/hour (following the Linac upgrade) to 1.2×10^{16}/hour.

2. An increase in the total number of protons which can be delivered to the Tevatron to 6×10^{13}.

3. The ability to accelerate efficiently antiprotons originating in stacks containing 2×10^{12} $\bar{p}$ for injection into the Tevatron Collider.

4. The ability to produce proton bunches containing up to 3×10^{11} protons for injection into the Tevatron Collider.

5. The reduction of backgrounds and deadtime at the CDF and DO detectors through removal of the Main Ring from the Tevatron enclosure.

6. Provision for slow extracted beams at 120 GeV year around and potential development of very high intensity, high duty factor ($\geq 1 \times 10^{13}$ protons/sec at 120 GeV with 34% duty factor) beams for use in high sensitivity K decay and neutrino experiments.

It is expected that with the construction of the Main Injector and the completion of planned improvements to the Antiproton Source the antiproton production rate will exceed 1×10^{11} $\bar{p}$/hour, and that a luminosity of 5×10^{31} $cm^{-2} sec^{-1}$ will be supportable in the existing collider.

Table 1-1: Main Injector Parameter List

Circumference	3319.419 meters
Injection Momentum	8.9 GeV/c
Peak Momentum	150 GeV/c
Minimum Cycle Time (@120 GeV)	1.5 sec
Number of Protons	3×10^{13}
Harmonic Number (@53 MHz)	588
Horizontal Tune	26.4
Vertical Tune	25.4
Transition Gamma	20.4
Natural Chromaticity (H)	-33.6
Natural Chromaticity (V)	-32.9
Number of Bunches	498
Protons/bunch	6×10^{10}
Transverse Emittance (Normalized)	20π mm-mr
Longitudinal Emittance	0.4 eV-sec
Transverse Admittance (at 8.9 GeV)	40π mm-mr
Longitudinal Admittance	0.5 eV-sec
β_{max}	57 meters
Maximum Dispersion	2.0 meters
Number of Straight Sections	8
Length of Standard Cell	34.3 meters
Phase Advance per Cell	90 degrees
RF Frequency (Injection)	52.8 MHz
RF Frequency (Extraction)	53.1 MHz
RF Voltage	4 MV
Number of Dipoles	216/128
Dipole Lengths	6.1/4.1 meters
Dipole Field (@150 GeV)	17.2 kGauss
Dipole Field (@8.9 GeV)	1.0 kGauss
Number of Quadrupoles	128/32/48
Quadrupole Lengths	2.1/2.5/2.9
Quadrupole Gradient	196 kG/m
Number of Quadrupole Busses	2

The primary design changes are described in Chapters 2, 3, and 4. These include:

1. A new lattice. The straight sections have been redesigned in a manner which provides significantly larger injection and extraction apertures. A consequence of the new lattice is that a second length of dipole (4.0 meters) will be required. While three lengths of quadrupoles are required as before, the lengths and quantities are different. The new lattice also increases the horizontal separation between the Main Injector and Tevatron by 7'.

2. The elevation of the ring has been lowered by approximately 6'. This was done in order to solve radiation shielding problems which resulted from the proposed floodplain mitigation plan. In addition the enclosure is now covered with 21' of equivalent earth shielding.

3. New beamlines have been designed. The biggest change is that the 150 GeV lines now provide an exact vertical dispersion match. This has allowed us to lower the elevation of the Main Injector ring as required above.

4. A third pulsed feeder loop was added to the ring and feeders are now housed in a ductbank rather than direct buried. This action followed further study of the power supply cycles and the need for access to and protection of feeder cables.

5. The width of the ring tunnel enclosure has been increased to 10'. This action followed a study of the requirements for transport of equipment within the enclosure during both installation and maintenance periods.

6. The cooling pond arrangement and water flow patterns have been modified in accordance with the requirements of the floodplain mitigation plan.

The Total Project Cost (TPC) of the Fermilab Main Injector is now estimated to be $197,000,000 including a Total Estimated Cost (TEC) of $177,800,000 and $19,200,000 in associated R&D, pre-operating, and capital equipment costs. The change from CDR 2.3 primarily arises from added escalation incurred by extending the construction schedule by a year. This, and details of the new cost estimate are given in Chapter 5.

It is currently proposed to construct the FMI over a 51 month period starting in October 1991. The schedule described in Chapter 6 results in a seven month to the Fermilab HEP program starting in April 1995.

2. THE MAIN INJECTOR

The Main Injector (MI) is a 150 GeV accelerator with a circumference 28/53 times that of the existing Main Ring. The primary design goals are to increase the admittance to 40π mm-mrad and lower the cycle time to 1.5 sec. The MI will be situated tangent to the Tevatron at the F0 straight section on the southwest side of the Fermilab site. Other possible sitings have been considered, including locations inside the existing Tevatron ring, but these were deemed less desirable than the site shown in this report. The MI, as described here, is constructed using newly designed (conventional) dipole magnets. The choice of building new magnets is based on considerations of field quality, aperture, and reliability. With the major exception of the dipoles, existing components from the Main Ring are for the most part recycled. Such components specifically include quadrupoles and the radio frequency (rf) systems. The use of all 18 existing rf cavities in a ring roughly half the size of the Main Ring will support an acceleration rate of 240 GeV/sec as compared to 120 GeV/sec in the present Main Ring. The power supply systems described are designed to support this rate.

2.1 Lattice

The design of the MI is driven by a number of considerations. Given the preferred siting, a maximum physical size of the ring is established by the proximity of the site boundary. This in turn leads to a minimum needed field strength in the magnets. The number and location of the straight sections is determined by the roles the ring is asked to play. In all phases of design the motivation has been to produce a lattice in which the transverse beam sizes are smaller than in the Main Ring over the energy range 8.9 to 150 GeV/c. The two lattice parameters which affect beam size are the beta function, β, and the dispersion, η. In this design β is kept small by using 90° cells with a short distance between quadrupoles. This is a cost effective approach because the quadrupoles will be taken from the existing Main Ring. The η is kept smaller in the MI than in the Main Ring in part due to the 90° cells, but more importantly due to careful dispersion matching around all straight section insertions. Dispersion matching insures that the maximum dispersion in the ring is no larger than the maximum dispersion in the standard cell. Of course the MI will not have overpasses, in contrast to the present Main Ring, and therefore the vertical dispersion will be zero.

<u>Lattice Design</u>

The present Main Ring lattice consists of FODO cells with four dipoles between adjacent quadrupoles. Two of these dipoles (B1) have a 1.5 inch vertical by 5.0 inch horizontal aperture and are placed nearest the horizontally focusing quadrupoles. The other two dipoles (B2) have a 2.0 inch vertical by 4.0 inch horizontal aperture, and are placed near the vertically focusing quadrupoles. The MI will use new dipoles with a 2.0 inch by 4.8 inch aperture.

Figure 2-1 shows the MI geometric layout. The standard cell of the MI is, like the Main Ring, a FODO design but with two dipoles between the quadrupoles as shown in Figure 2-2. The interelement spacing is the same as in the present Main Ring so that the length of the half cell is shorter by the length of two dipoles and the short drift spaces which follow them, i.e. by about half. Because of the shorter circumference, there are fewer than half as many dipoles as in the Main Ring.

The lattice now incorporates two different types of cells, the normal FODO cells, and the FODO dispersion-suppressor cells. The latter cells feature shorter dipoles, and reduce the horizontal dispersion to zero in the straight sections. There are 72 normal cells (including those within the straight sections) and 32 dispersion suppressing cells. This should be contrasted with the earlier design which had only 6 m dipoles, arranged in three different configurations.

The advantages of the new lattice include:

i. Zero dispersion in the straight sections. This reduces the horizontal beam size, which in turn makes beam transfers easier to accomplish.

ii. Smaller vertical β-functions both in the straight sections and in the dipoles surrounding the straight sections, affording more clearance for the beam and tolerance in steering at transfer time.

iii. A longer rf straight.

iv. A lattice which accommodates transfer lines to the Tevatron which match the vertical dispersion exactly and allow a ring which is lowered by an additional six feet.

v. An additional 6 feet of sheilding between the MI and the Tevatron.

Having fewer dipoles than the Main Ring leads to higher fields and a larger bending angle. The resulting sagitta in a 6 m dipole is 16 mm. The new dipoles will be built with a curvature which eliminates loss of aperture due to sagitta. A 90° phase advance per cell is chosen, resulting in a maximum β in the cells of 58 meters and a maximum η in the cells of 1.9 meters. By comparison the Main Ring has maximum β and η of 110 and 6.6 meters, respectively. Thus the beam size due to transverse emittance will be only 70% of what it is presently, and the maximum beam size due to momentum spread will be down by a factor of three from the Main Ring. The ring has been designed to have two-fold rotational symmetry; Figure 2-3 shows the MI lattice functions for one half the ring.

The MI contains eight straight sections. Their locations are shown in Figure 2-1 and a detail of the layout of the MI-60 straight-section is shown in Figure 2-4. Their numbering and their functions are as follows:

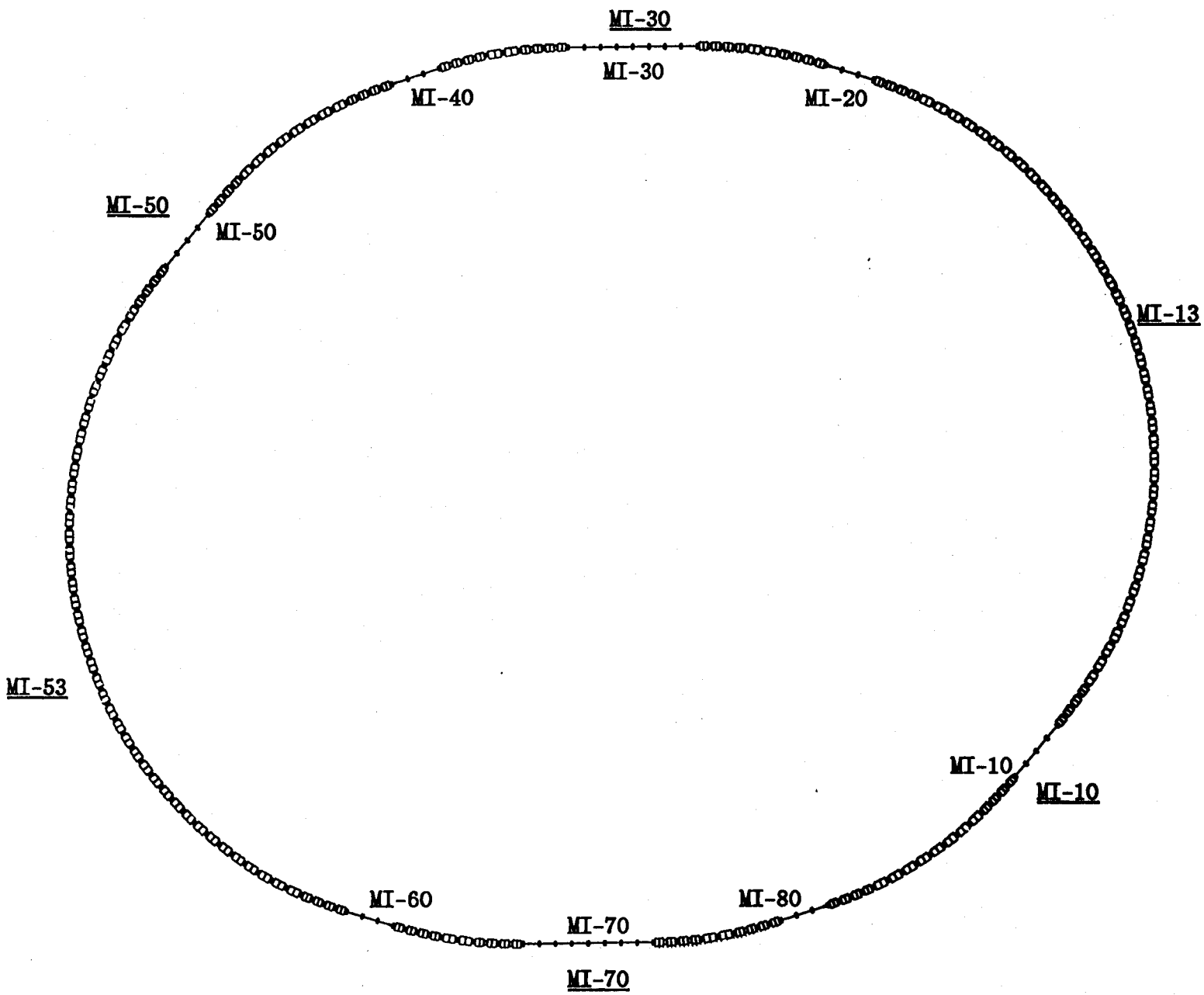


Figure 2-1. Main Injector Geometric Layout
showing Straight Sections (MI-xx) and Service Buildings (MI-xx)

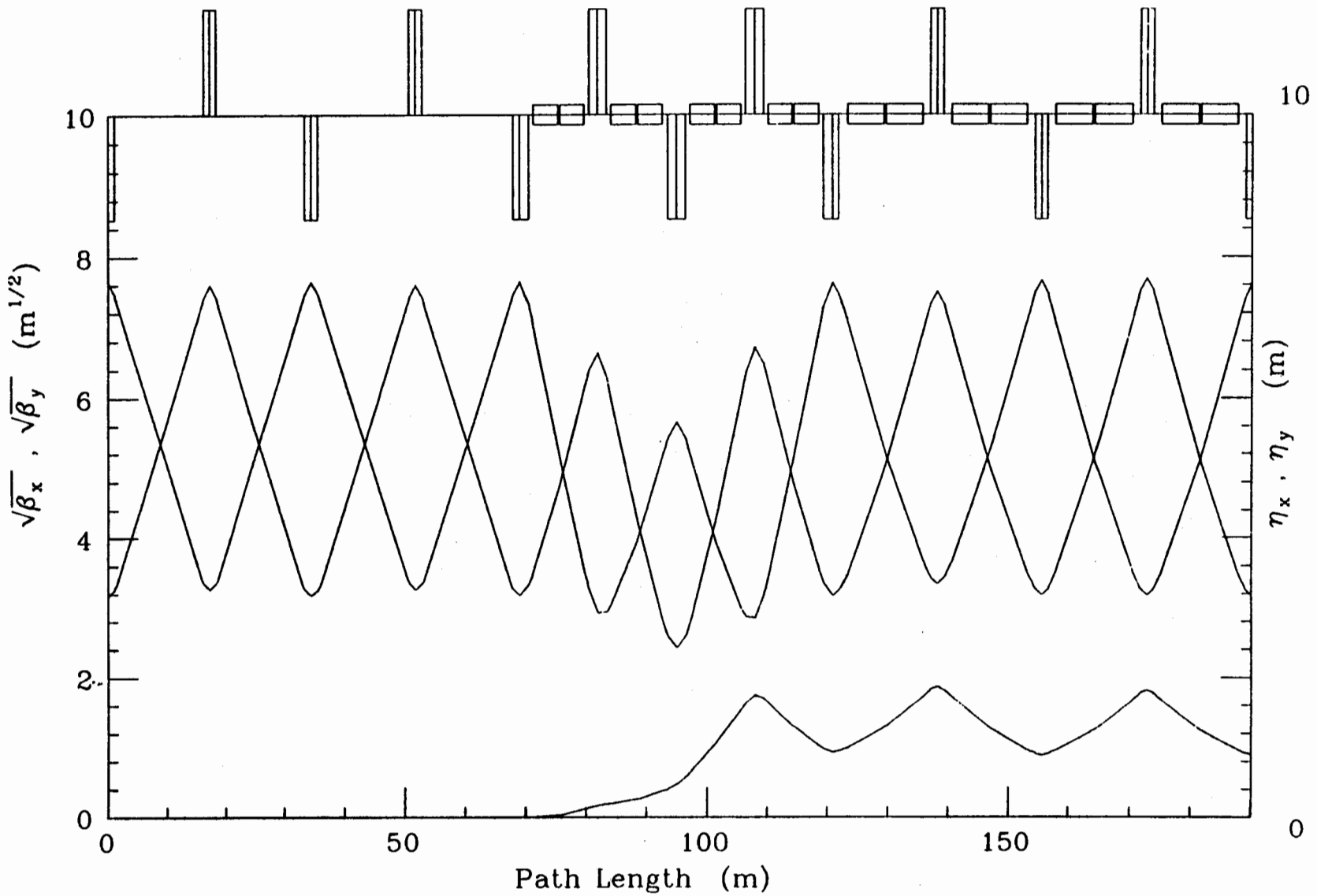


Figure 2-2. Main Injector FODO Lattice showing (left to right) 2 straight-section cells, 2 dispersion-suppressor cells and 2 normal cells.

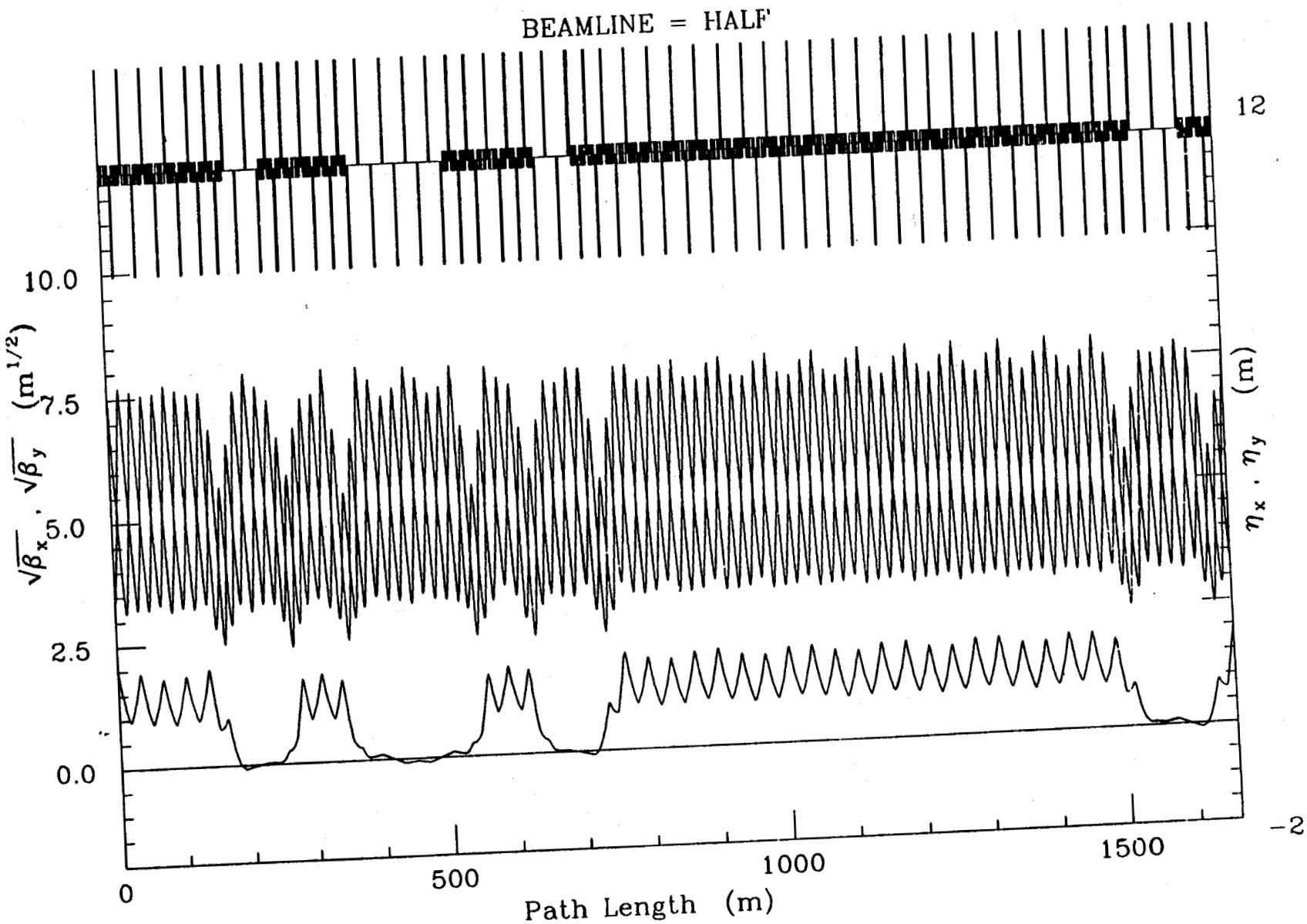


Figure 2-3. Main Injector Lattice Functions for one-half the Ring.

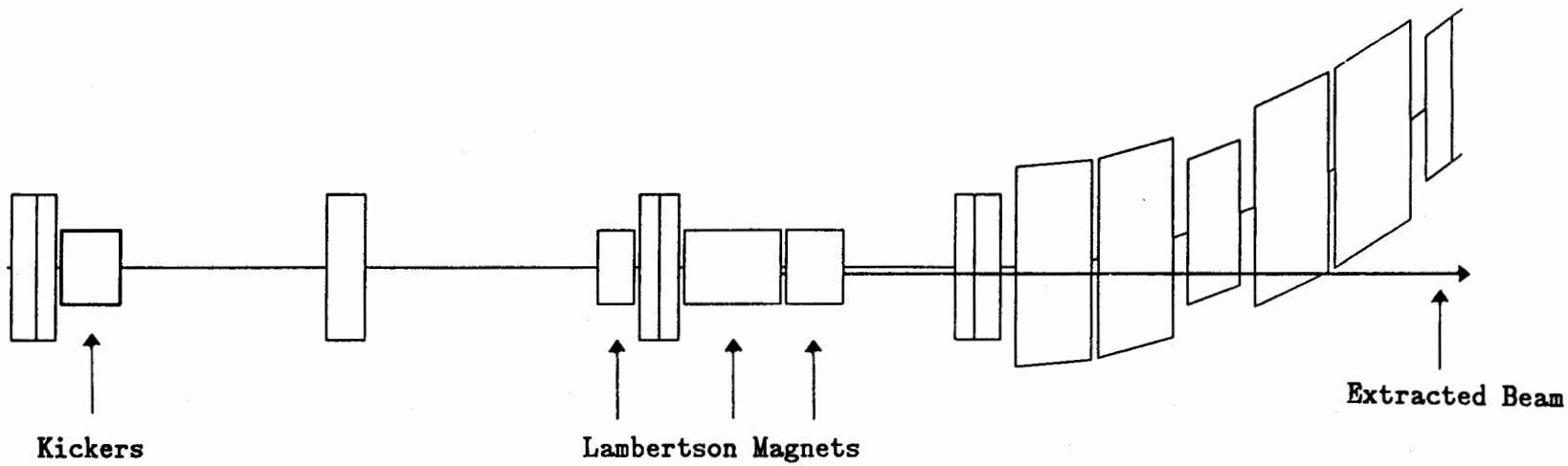


Figure 2-4. Detail (Plan View) of MI-60
used for 8 GeV Antiproton Injection and 120/150 GeV Proton Extraction

10 - 8 GeV proton injection
20 - (unused)
30 - (unused)
40 - (unused)
50 - proton abort
60 - 150/120 GeV proton extraction; 8 GeV antiproton injection
70 - MI RF section
80 - 150 GeV antiproton extraction

All straight sections are obtained by omitting dipoles while retaining the standard 17.3 m quadrupole spacing. There are three different lengths of straight sections. Straight sections 10 and 50 are 68 m long (two cells), straight sections 20, 40, 60, and 80 are 51 m long (one and one-half cells), and straight sections 30 and 70 are 136 m long (four cells). Straight section 70 is used for the rf; its length will allow flexible spacing of the rf cavities and provide generous free space for diagnostic beam pickups.

Three different quadrupole lengths are required: 2.13-m quadrupoles for the normal cells, 2.95-m quadrupoles for the dispersion-suppressor cells, and 2.54-m quadrupoles at the boundary between the two types of cells. The lengths have been adjusted so that all quadrupoles are powered off the two main quadrupoles busses. All straight section insertions are dispersion matched to the cells. With at least 135° of phase advance in each straight section, there is space within the long straight for kickers and septa, a situation not provided for in the present Main Ring lattice or the earlier Main Injector lattice.

The six long straight sections are capable of beam extraction at the highest MI energy. Due to the fact the ring lies 10 meters from the Tevatron, two of these (60, 80) are required to provide injection into the Tevatron, one each for protons and antiprotons. On the opposite side of the ring two straight sections (20, 40) are added for symmetry. MI-10 is necessary for injection of protons from the Booster, and MI-50 is placed symmetrically for the proton abort.

2.2 Acceleration Cycles

There are four basic acceleration cycles, shown in Figure 2-5, serving each of the four operational modes of the MI:

(a) The antiproton production cycle: 1.5 second cycle, peak energy of 120 GeV.
(b) The 120 GeV slow spill cycle: 2.9 second cycle with a one second slow spill at 120 GeV to the fixed target area.
(c) The Tevatron fixed target injection cycle: 2.4 second cycle for Tevatron injection at 150 GeV.

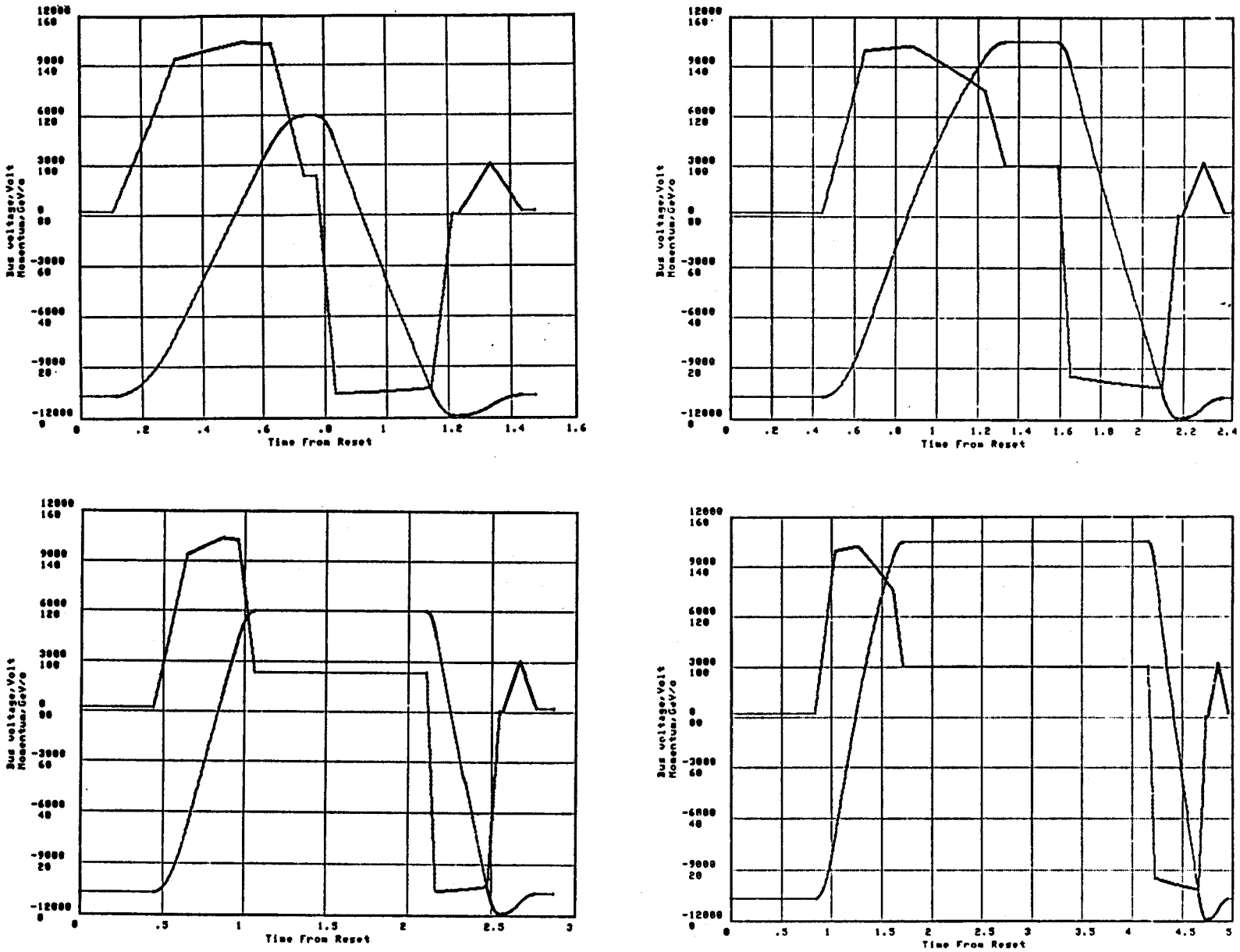


Figure 2-5. Acceleration Cycles

a. 120 GeV Antiproton Production
b. 120 GeV Slow Spill
c. 150 GeV Fixed Target Injection
d. 150 GeV Collider Injection

(d) The Tevatron collider injection cycle: 5.0 second cycle with a 2.4 second flattop at 150 GeV for coalescing and cogging.

The operational limits for the rf cavities and power supply systems are discussed in Sections 2.4 and 2.6 respectively. The 18 existing Main Ring cavities in their current running mode are adequate for all of the above cycles.

2.3 Magnets

The MI uses conventional iron core magnets. A total of 216 6-m dipole, 128 4-m dipole, 128 2.13-m quadrupole, 48 2.95-m quadrupole, 32 2.54-m quadrupole, 108 sextupole, and 208 correction dipole magnets are required. The magnet apertures need to be sufficient to provide a transverse admittance of 40π mm-mr and a momentum aperture of ±1% at transition. The dipole and sextupole are newly designed and manufactured magnets. The 2.1-m quadrupoles and correction magnets are to be recycled from the Main Ring. Dipole and quadrupole parameters are listed in Table 2-1. The sextupole and correction dipole magnets are described in Section 2.5.

The decision to construct the MI using newly designed dipole magnets is made for several reasons. First, the existing Main Ring magnets are straight. Recycling these magnets into the MI would result in a loss of about 16 mm of aperture due to sagitta. This aperture is recovered by constructing curved magnets. Second, the existing magnets suffer from reliability problems. Most of the failures in the existing magnets occur at conductor joints within the coil. The number of such joints per magnet will be reduced in the new magnet and at the same time the reliability of the joints improved. Third, it is believed that higher field quality can be achieved in a newly constructed magnet so that the dynamic aperture is only limited by the magnet physical aperture - a situation not achieved in the existing Main Ring.

Table 2-1: Main Injector Magnet Parameters

	Dipole			Quadrupole		
Strength (@150 GeV)	17.2 kG			196 kG/m		
Full Aperture	15x5 cm^2			7.6 cm		
Turns/pole	4			4		
Maximum Current	9375 A			3630 A		
Length	6 m	4 m	2.1 m	2.5 m	2.9 m	
Coil Resistance	0.8	0.6	4.5	5.2	6.0	mΩ
Coil Inductance	2.0	1.3	1.3	1.5	1.7	mH
Peak Power	75	50	59	69	79	kW
Number Required	216	128		128	32	48
Newly Constructed	Yes	Yes		No	Yes	Yes

Once it was decided to build new dipole magnets, a cost optimization was performed which minimized the sum of construction plus operating costs over five years. The result is a magnet with twice as much conductor and half as many turns as the existing Main Ring B2 magnet. The dipole magnet cross section is shown in Figure 2-6. The longer magnet is 6.09 meters long, 1" longer than the Main Ring magnets. The core is constructed from 0.060" thick laminations which are split on the magnet midplane. The coil consists of four turns per pole of a 1" x 4" conductor. Since no conductor is contained in the median plane of the magnet, the coil can be wound as two "pancakes" with no bends along the long dimension of the conductor. This conductor is available in 20 foot lengths so each coil can be made with eight joints. The joints will be of a type with demonstrated reliability in which conductors are brazed together with a ferrule inserted between the conductor water holes. The water hole is 0.5 in. in diameter. A single water circuit in each pancake (two circuits per magnet) provides sufficient cooling.

A four terminal construction has been chosen for the dipole magnet. In a magnet of this design the role of return bus is filled by one of the conductor turns within the magnet. This has the advantage of removing the need for approximately 12,000 ft of 4 in^2 copper bus (@ $40/ft) in the MI enclosure. The price paid for this benefit is the requirement that the insulation be sufficient to withstand 2000 volts between conductors within the coil, and 1000 volts to ground.

Prototype Magnet

The dipole lamination shape is designed to provide a field at the injection energy which varies by no more than 1×10^{-4} over the range $-1.75" < x < +1.75"$. The body field of the first prototype dipole has been measured using four systems: a narrow loop moved in across the aperture ("flatcoil"); a rotating coil positioned at three locations across the aperture; a Hall probe; and an NMR probe. From each measurement the field By(x) has been reconstructed. Figure 2-7 shows the relative variation from the central field at the injection energy calculated by PE2D, measured with flatcoil, and measured with with the rotating coil. Agreement is quite good.

At injection energy the field shape is dominated by the lamination shape, and at transition by lamination shape and eddy currents. At the 120 GeV energy used for antiproton production and slow spill some saturation has started to set in on the edges of the aperture, but the 1×10^{-4} tolerance still holds over the range $-0.9" < x < +0.9"$. The beam only stays briefly at 150 GeV before transfer to the Tevatron, so the shrinkage of the 1×10^{-4} region to $-0.3" < x < +0.3"$ is perfectly acceptable. Figure 2-8 shows the measured field shape for 8 GeV, 120 GeV, and 150 GeV. Both flatcoil data and fields reconstructed from the harmonics data are plotted, again demonstrating the good agreement. The high-field deviations in field shape are predominantly a sextupolar field; the strength of the horizontal chromaticity-correcting sextupoles is driven by the desire to correct this deviation.

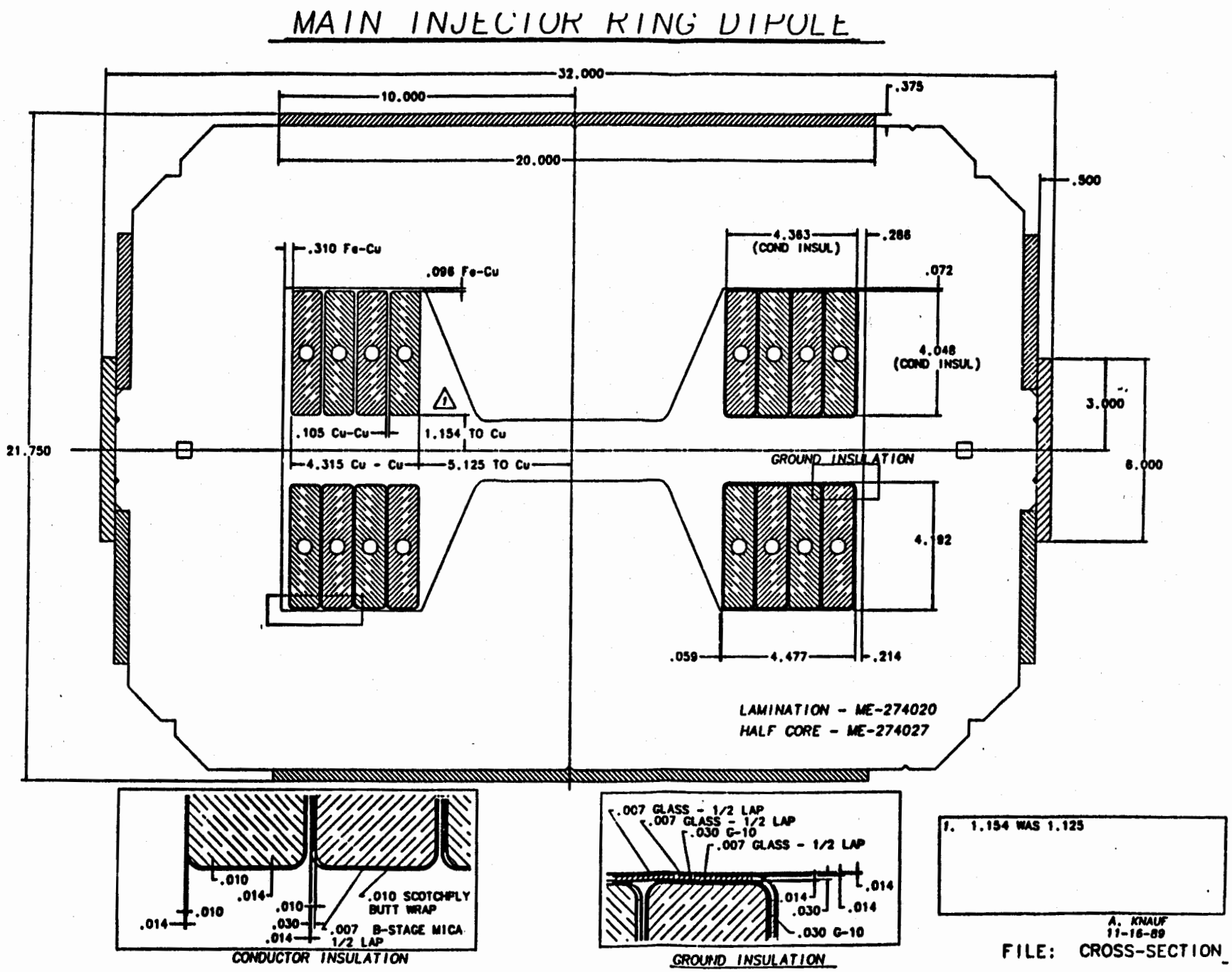


Figure 2-6. Main Injector dipole magnet cross section.

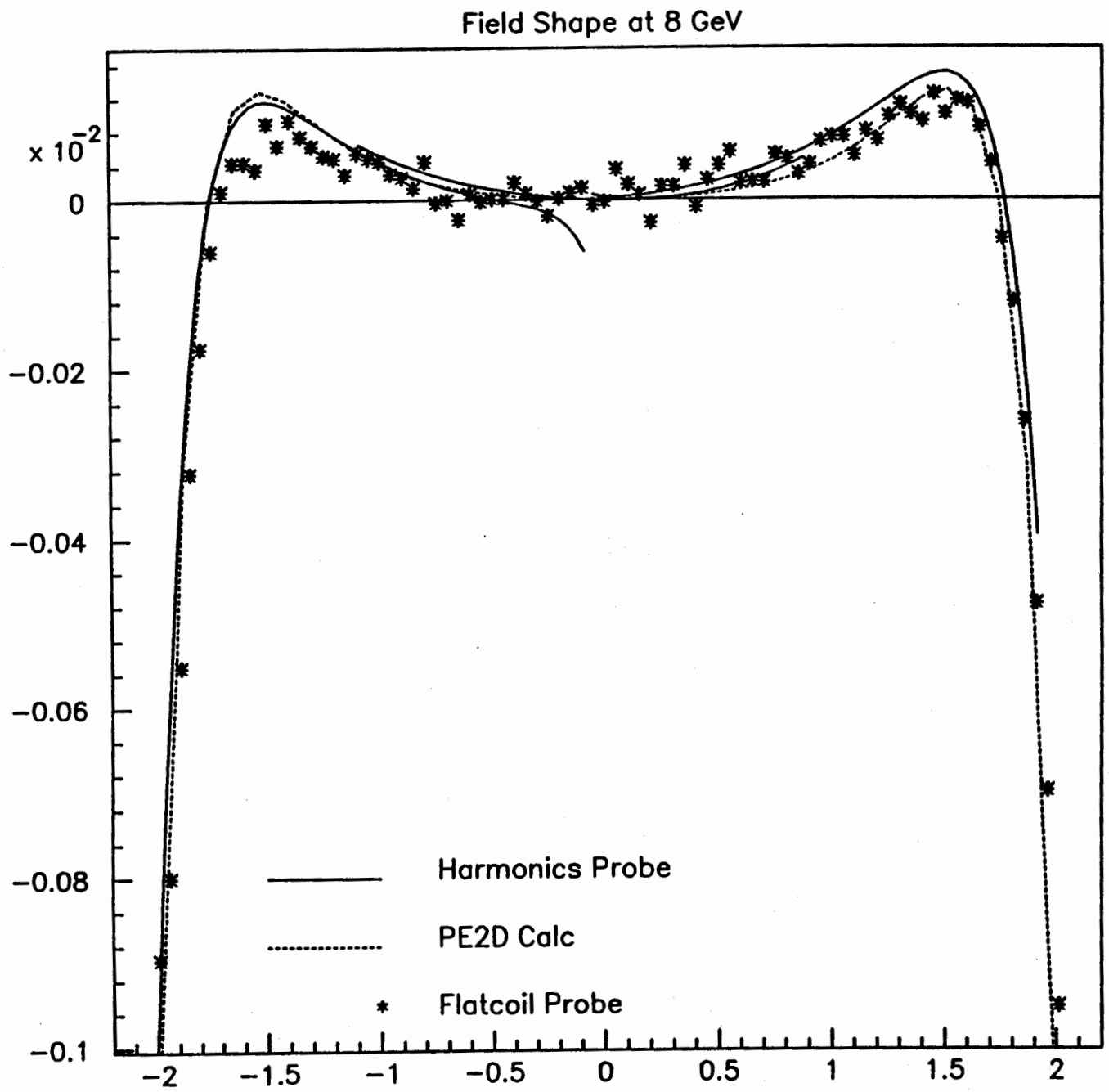


Figure 2-7. Magnetic Measurements at Injection Energy

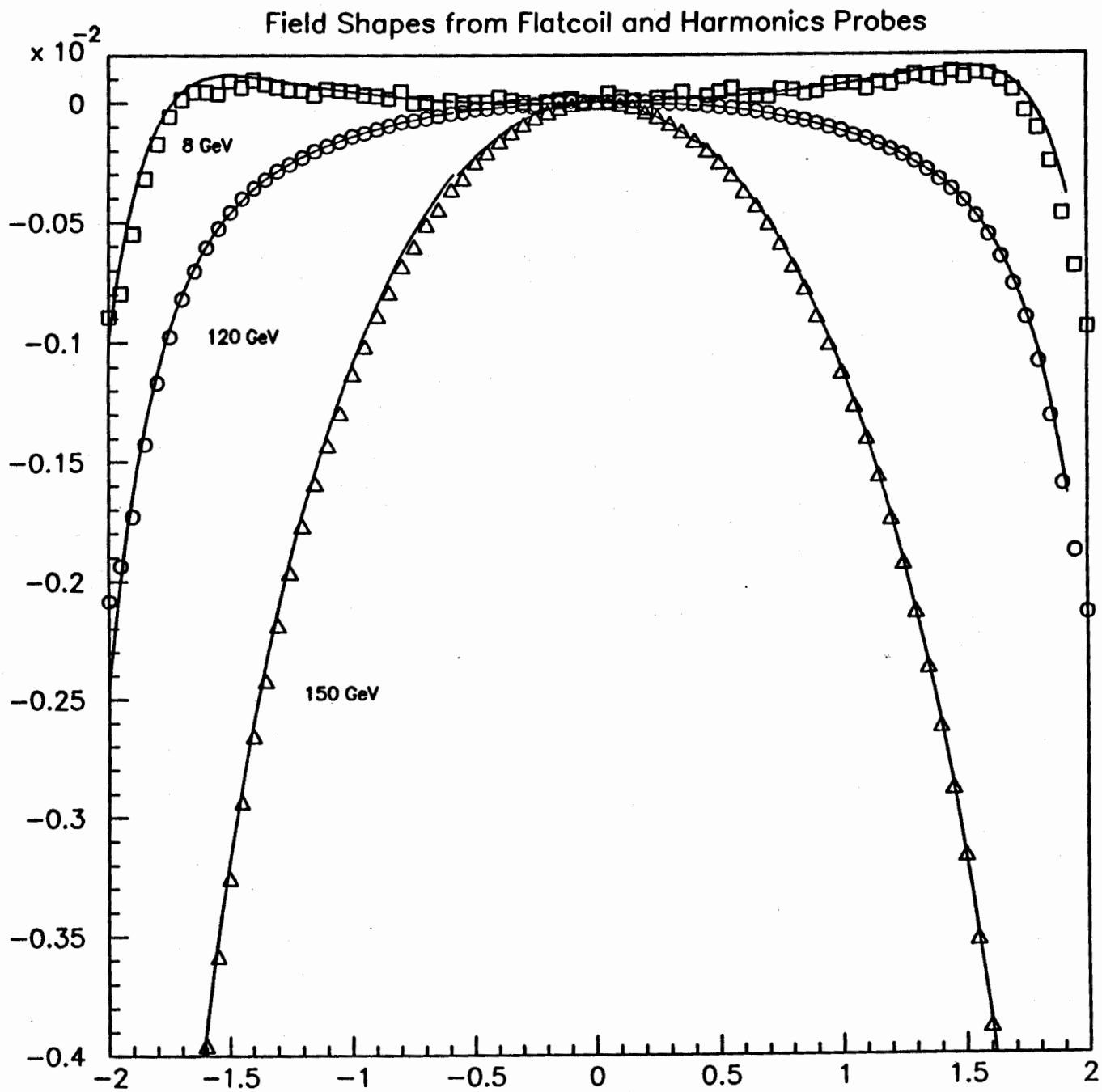


Figure 2-8. Magnetic Measurements at various Energies

The end packs of the magnets will be tailored to match the field shape of the body of the magnet at injection energy. This will allow use of the same end pack on both the 6-meter dipoles and the 4-meter dipoles. The precise steel length of the 4-meter dipoles will be chosen so that the integrated field strength, including the ends, will be exactly 2/3 of the strength of the 6-meter dipoles.

2.4 Power Supplies

The MI power supply system has been designed to ramp the magnet system from an injection level of 8.9 to 120/150 GeV/c excitation at a repetition rate adequate to meet requirements for Antiproton Source stacking, Tevatron injection, and slow spill operation. The power system consists of 12 new rectifier power supplies for the bend bus, reuse of existing equipment on the quadrupole bus including six main bus supplies, a new power feeder system for all the supplies, a new harmonic correction system, and the reuse of many smaller items from the present Main Ring. A summary of the MI power supply requirements is given in Table 2-2.

Power supply spacing for minimum voltage to ground requires an equal impedance between power supplies on the dipole bus. The proposed system will have six service buildings with two dipole supplies per building, one on each of two busses and one quadrupole supply. The buildings are spaced so that there are 25 6-m dipole magnets (or an equivalent mixture of 4-m and 6-m dipoles) between each supply, with the magnets on a folded bus loop. The third supply in each of the six buildings is configured such that three are in series with the focussing quadrupole magnet bus; three are similarly used with the defocussing quadrupole bus.

Table 2-2: Power Supply Summary for the MI System

	Power Supplies	Voltage	Maximum Current
Bend	12 new	1000 V	9375 A
Quad F	3	850 V	3630 A
Quad D	3	850 V	3630 A
	Other Equipment Needed:		
Quad regulator	2 new	300 volts	500 A
Regulation			
Transductors	2 new		10,000 A
Transductors	2 new		5,000 A
Computer link	1 new		
Harmonic filter	1 new		

Criteria for Ramps and Constraints on Power Supply Layout

The overriding design criterion was to design a combined magnet and power supply system that would be cost effective during operation. A system was chosen to have low power consumption and a safe power supply voltage without being unduly expensive to construct and unwieldy in physical size. Two new 40 MVA power distribution transformers located at the new Kautz Road Substation will be used in the new installation with an operational limit set at 120 MVA peak and an rms value less than 15 MW. There will be a 13.8 kV feeder cable system installed in a triple loop around the Main Injector ring. The rms current rating of the entire system is 2700 amps.

The maximum rate of rise will be set by the use of the existing Main Ring rf system which has at present an operational limit of about 240 GeV/sec. The maximum ramp repetition rate is set by the 2700 amp feeder current limit and a chosen rms dipole bus current of 5000 amps.

The dipole configuration is two busses internal to the new magnets with a fold at MI-70 allowing for six upper bus supplies and six lower bus supplies. The impedance of the magnet load in the Main Injector dipole bus is 0.6 Henries and, with the use of 4 in^2 cross section copper for the magnets and power supply bus, will have a dc resistance of 0.32 ohms. The required peak power supply voltage is 12 kV for the bend bus.

The quadrupole configuration is two separate busses in continuous loops around the injector with current flowing in opposite directions, one focusing and one defocussing, each having three supplies for ramping and a transistor regulator supply for injection current regulation. Each quadrupole magnet loop impedance is 0.15 Henries, and with the use of 2 in^2 power distribution bus, will have a dc resistance of 0.3 ohms. Thus the required peak power supply voltage is 1500 volts for each quadrupole bus.

Ramp Details

The ramp details are determine by a number of limitations which enter at various points in the ramp: rf voltage, power supply voltage, feeder currents, etc. For antiproton stacking the voltage and number of power supplies are chosen to provide a repetition rate of 1.5 seconds with a maximum rate of rise of 240 GeV/sec. Figure 2-5 and Table 2-3 give details on the four modes of operation. The fixed target injection ramp requires only a short flattop. The collider injection ramp will need a longer flattop, but is only run at a low repetition rate. The fixed target injection ramp is intended to be run twice in succession, once a minute, with 120 GeV cycles the remainder of the time. The transformers for the Main Injector are being sized for a current (average between peak and rms) of 6500 A. If the fixed target injection ramp is run repetitively (for studies) the repetition rate must be slowed to reduce the rms current to ~3600 A (~5.4 sec rep rate).

With 12 kV maximum power supply voltage, the ramp rate will need to decrease above 80 GeV from 240 GeV/sec to 225 GeV/sec at 108 GeV. This is required due to the lack of power supply voltage to maintain high inductive voltage and high resistive voltage at the same time. The lower rate of rise slightly increases the rms current in the magnets and feeders.

Feeder current limitations require the ramp rate to decrease more dramatically above 120 GeV, to 120 GeV/sec at 144 GeV. The result of this restriction is that as one approaches the parabola coming into flattop, no more than nine power supplies can be turned on. Ramp regulation which puts supplies into bypass is required. While this lowers the peak feeder currents, it raises the peak voltage to ground and bus to bus voltage that the magnets experience.

Power Supply Control

The power supplies are assumed to be controlled differently on different cycles. For the fast cycling 120 GeV cycle (with very short flattop) one power supply is used at 8 GeV, but as the ramp begins, the remaining power supplies are turned on simultaneously. For the 150 GeV cycle, the supplies are turned on and off as required by voltage demands, with either 1, 4, 8, 10 or 12 supplies on at once. For the 120 GeV slow spill cycle, 1, 3 or 12 supplies are energized. This sequential turn-on is required to minimize voltage to ground distributions and rms feeder currents.

Studies on the Main Ring supplies indicate that the regulation will not be degraded in going to a ramp rate of 240 GeV/sec, twice that of the Main Ring, with no changes in the power supply control. The regulation of the Main Injector power supply system could be further improved by providing two 24-pulse power supplies, one of which would be used as the regulating power supply and the other as a spare. The remaining ten supplies would remain 12-pulse. The cost for such a modification would be minor, but is not presently included.

Power Feeder Loading

The main 13.8 kV power feeders have an operating limit of 2700 amps rms. The power supplies around the ring will be supplied in a three feeder loop to ensure proper current sharing. More details are given in Section 2-14.

The use of rectifier power supplies on this system draws current pulses from the feeders which then drive harmonic resonances, causing higher voltages at the resonant frequencies to be imposed on the power equipment. The present Main Ring has an harmonic filter to limit the peak voltages of

higher frequencies superimposed on the 60 Hz line voltage. The MI will run with 12 power supplies at 120 MVA peak versus 70 MVA for the Main Ring, requiring the filter to damp more harmonic power. Therefore, in the MI a new filter needs to be designed to correct for the higher harmonic driving force of the system. This new filter will be installed at the switch in the feeder system where the feeders change from direct feed to loop feed (at the Kautz Road Substation), and will consist of a new section in parallel with the Main Ring filter.

Table 2-3: Fixed target, pbar production & slow spill ramp parameters

Ramp	Fixed Target	Collider Injection	Antiproton Production	Slow Spill	
Peak Energy	150	150	120	120	GeV
Cycle time	2.40	5.0	1.4667	2.8667	sec
Time (Booster cycles)	36	75	22	43	
Injection Dwell	.441	.841	.108	.441	sec
Flattop	.250	2.45	.040	1.04	sec
DIPOLE BUS					
Max. Current	9375	9375	7100	7100	A
RMS Current	5434	7295	3765	4988	A
Power	9.4	17.0	4.5	8.0	MW
RMS Feeder Current	1991	1796	2054	1473	A
Peak Feeder Volt-Amps	98	98	94	94	MVA
Average Feeder Volt-Amps	48	43	49	35	MVA
QUAD BUS (sum of both)					
Max. Current	3630	3630	2904	2904	A
RMS Current	2095	2812	1540	2040	A
Power	4.8	8.5	2.5	4.4	MW
RMS Feeder Current	444	649	316	336	A
Peak Feeder Volt-Amps	21	21	16	16	MVA
Average Feeder Volt-Amps	11	16	8	8	MVA

2.5 Correction Elements

The MI correction element inventory includes steering dipoles, trim quadrupoles, sextupoles, and skew quadrupoles. Wherever possible existing components will be reused. The steering dipoles, trim quadrupoles, skew quadrupoles, skew sextupole and resonance-compensating sextupoles will be recycled Main Ring components. The chromaticity-controlling sextupoles will be a modified version of the Antiproton Source sextupole. Correction

elements will be placed next to each quadrupole. A horizontal (vertical) steering dipole will be placed at each focussing (defocussing) quadrupole. Sextupoles will be placed next to quadrupoles in the arcs where the dispersion is large. The trim quadrupoles and skew quadrupoles will be placed around the ring as needed. In addition, a small number of sextupoles to cancel harmonics due to the chromaticity sextupoles will be located in the straight sections. A typical installation, showing the ends of two dipoles, the lattice quad, a chromaticity sextupole, a trim quadrupole, and a correction dipole, is seen in Figure 2-9.

Steering Dipoles

The steering dipoles correct the closed orbit. The primary sources of orbit distortion are quadrupole placement errors, dipole strength errors, and dipole rotation. These errors cause orbit distortions proportional to β, and, if uncorrected, would yield an rms error of 1.5 mm. If the gap in the existing Main Ring horizontal steering dipoles is increased from 1.9" to 2" they will produce a field strength of 32 G-m per ampere. Use of these magnets will allow insertion of bumps of up to ±30 mm at 8.9 GeV/c, which will easily correct closed orbit errors and permit aperture scans and closed orbit bumps. The vertical steering dipoles will be shimmed to enlarge their gap from 4.1" to 4.9", with a resulting strength of 17 G-m/A. The correction element power supplies to be relocated from the Main Ring will allow programming of the steering dipoles throughout the acceleration cycle. If correctors are installed at every quadrupole, a total of 104 correctors in each plane are required.

Trim Quadrupoles

The main quadrupoles of the MI will run on two separate busses and will be used for all necessary tune adjustments. Trim quadrupoles are needed for harmonic generation or cancellation. A sufficient number of Main Ring trim quadrupoles will be installed around the ring to cancel half-integer stopbands, if they are significant. In addition, slow extraction will require a small number of trim quadrupoles for excitation of the half-integer resonance.

Sextupoles

Sextupoles will be used primarily for correction of the MI chromaticity. The natural chromaticities of the MI are -33.65 horizontally and -32.87 vertically. The lattice has been designed to have low β and η (58 m and 2.2 m are the maximum values in the arcs). Thus, very strong sextupoles will be needed to cancel the natural chromaticity. The configuration chosen places an F(D) sextupole at each F(D) main quadrupole in the arcs where η is large. Fifty-four of each sextupole type will be needed. There are also large sextupole components in the dipole magnet induced by saturation of the steel as the beam energy approaches 150 GeV

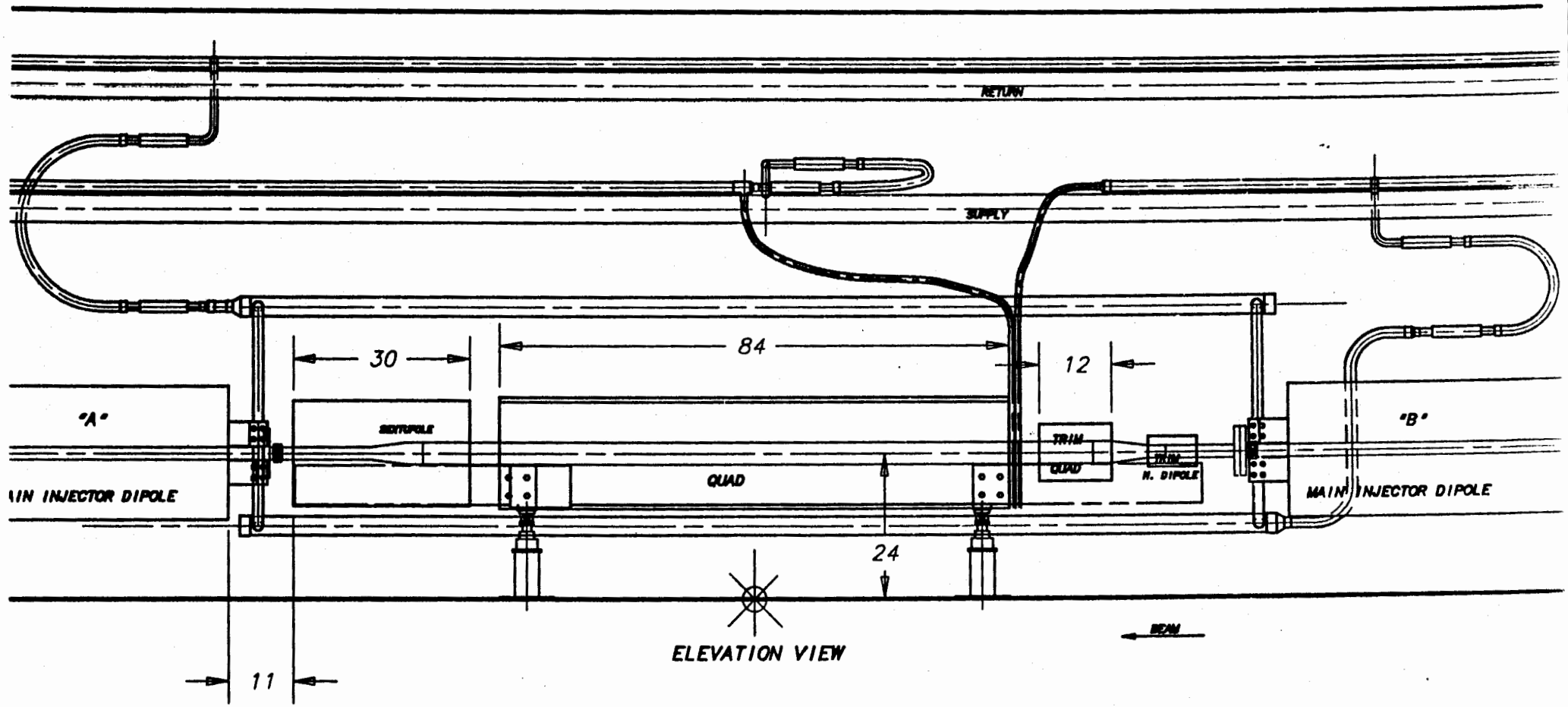


Figure 2-9. Layout of a typical Main Injector Quadrupole and Trim Magnets.

(horizontal sextupole) and by eddy currents in the beam pipe (vertical sextupole). These effects produce "natural" chromaticities of -77 horizontally (at 150 GeV) and -55 vertically (near 20 GeV). The correction sextupole magnets must also be capable of compensating this effect. Based on a requirement that the sextupoles be capable of producing a corrected chromaticity of +20 in each plane, the sextupoles are designed to have a maximum field strength of 625 kG/m^2-m. These magnets will be similar to the Debuncher Sextupoles built for the Tevatron I project, but with a reduced aperture (4.25" vs. 5.625") and increased length (30" vs. 8").

With the strong sextupoles required in this ring there may be some concern that the dynamic aperture of the machine might be adversely affected. Tracking studies completed to date indicate that there is no loss of dynamic aperture due to the sextupole correction system. However, we will still distribute eight individually powered sextupoles for control of third order resonant driving terms.

Skew Quadrupoles

Prelimary work has begun on calculating the magnitude of the coupling in the MI. Twelve skew quadrupoles, representing 3% of the strength of a normal 2.1-m quadrupole, will be installed to cancel coupling. They will be recovered from the Main Ring.

2.6 Radio Frequency System (rf)

h=588 cavities

The 18 existing 53 MHz Main Ring rf cavities will be installed in straight section MI-70 and operated at harmonic number 588. The operating levels below transition are determined by an interplay between cycle time, bucket area, and synchrotron frequency. A bucket area of at least 0.5 eV-sec is required to accept beam out of the Booster. Historically, it has been necessary to keep the synchrotron frequency in the Main Ring below 720 Hz to avoid resonance with power supply ripple at the sixth harmonic of the line frequency. Figure 2-10 shows the rf voltage, bucket area, synchrotron frequency, and synchronous phase through the 120 GeV antiproton production cycle. A bucket area of 0.5 eV-sec is maintained, but with the synchrotron frequency rising above 720 Hz. The ramp would have to be slowed down to avoid this. The momentum spread in the beam, $\delta p/p$ (95% half width), is ±0.2% at injection, increasing to about ±1.4% near transition, and decreasing to ±0.1% at extraction.

Since the Main Injector must accelerate antiprotons as well as protons, a degree of simplicity can be achieved in the fanout/fanback system by placing the cavities at spacings that are multiples of one-half the rf wavelength. The elimination of the present switching system will increase

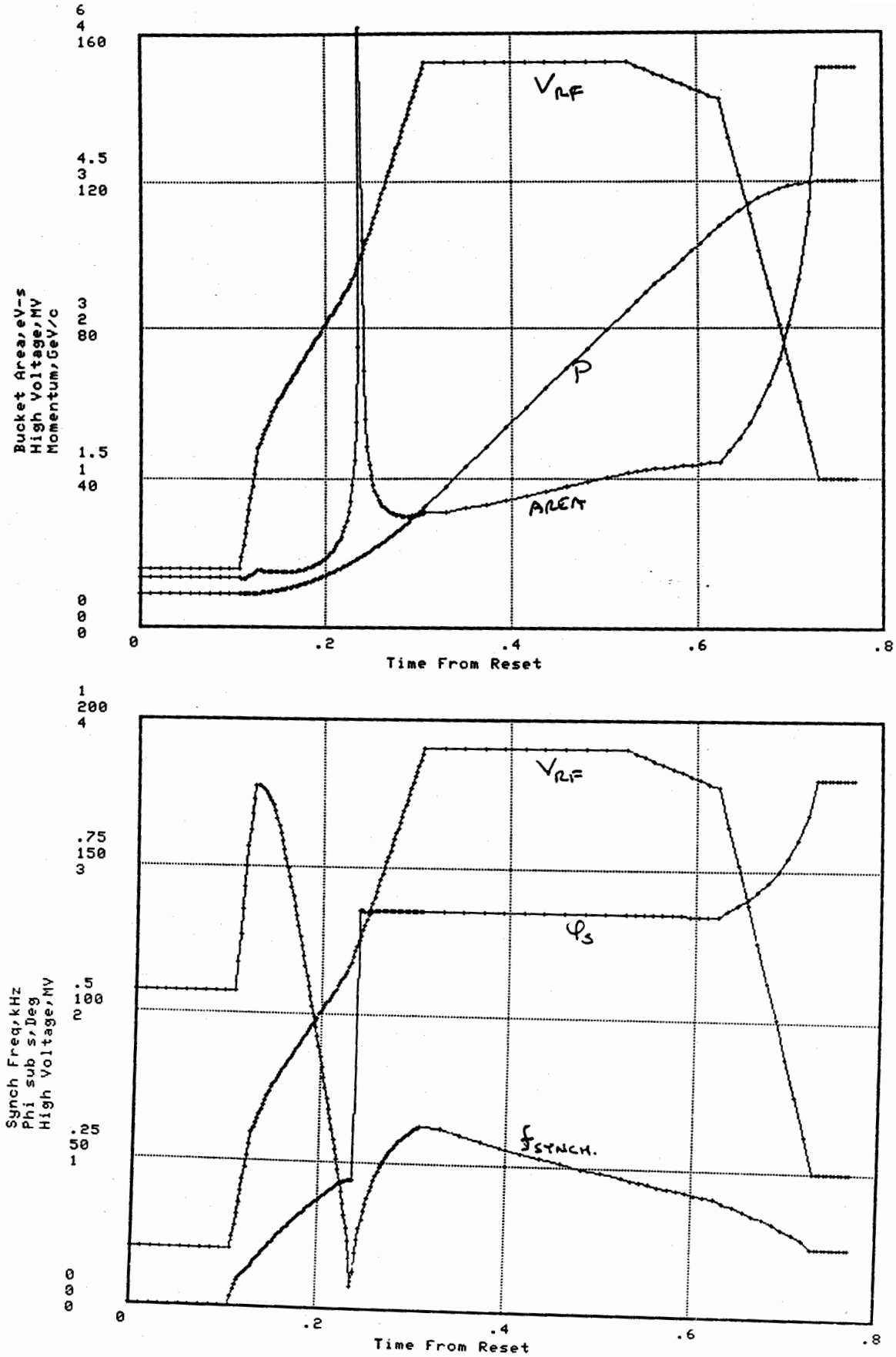


Figure 2-10. RF Parameters for the 120 GeV Antiproton Production Cycle.

the system reliability and provide greater flexibility in cavity control during coalescing.

The rf system has the capability of generating enough voltage at injection to produce a 1.0 eV-sec bucket area at injection. In this mode the synchrotron frequency lies well above 720 Hz at injection and descends rapidly, crossing 720 Hz when the beam energy is about 15 GeV. Operational experience will dictate which scenario is used.

One drawback of the existing Main Ring rf system is the power that it can deliver. The present requirements are 55 kW per cavity, which will grow to 70 kW after the Linac upgrade. The Main Injector will require 112 kW for accelerating the full intensity at 240 GeV/sec, which is close to the present capability. To overcome this limitation, new 200 kW power amplifiers and 30 kV series tube modulators will be provided. The new 200 kW amplifiers will be a cathode-driven, grounded-grid design with the cathode having a dc bias voltage. The design will retain the existing Main Ring final PA tube module. The cathode of the final tube will be biased by a new 20 A, 500 V supply and be driven through a matching network by a new solid state 5 kW rf driver. A Tevatron power amplifer (grid biased to -230 V) has already produced more than 200 kW of output power when the final tube cathode was driven by 4 kW of rf drive power. This demonstrates the feasibility of the new design and is also a possible alternative to the biased cathode design.

The transient beam loading from 6×10^{10} protons per bunch will require about 1.25 A delivered to the cavities, supplied by 15 A (12:1 cavity step-up ratio) of rf current generated by the power amplifier. A 200 kW rf power amplifier operated at a dc plate voltage of 20 kV will produce a peak rf current of approximately 21 A, providing 40% surplus capability.

Coalescing cavities

The Main Ring coalescing rf cavities (2.5 MHz and 5 MHz) will also be employed in the Main Injector for use during collider loading. The change in harmonic number, coupled with the change in γ_t, results in the coalescing cavity bucket height increasing by a factor of 1.5 relative to the Main Ring. This should improve the coalescing efficiency, enhancing the ability to make bunches of the desired intensity for delivery to the Tevatron Collider. Alternatively, if the need arose the voltage in these cavities could be reduced keeping the coalescing bucket height the same as currently used in the Main Ring.

Transition crossing

Concerns over emittance dilution (Johnsen and Umstätter effects) during transition crossing have led to a prosposal for a higher harmonic cavity which will avoid the rf-focussing effects which contribute to the dilution.

Simulations of transition crossing in the presence of a third harmonic rf voltage are very encouraging and work is underway to modify a spare Main Ring cavity for use in studying this behavior. If such studies successfully demonstrate the ability to transmit large emittance beams through transition without blowup, a dedicated cavity will be constructed.

2.7 Vacuum System

The vacuum system for the MI will be similar to the Main Ring system. Each dipole magnet chamber will have two ports for 30 liter/sec ion pumps, with three pumps installed on each pair of dipoles. The fourth port will be blanked off or fitted with a valve for connecting temporary pumping capacity. The straight sections will have a port approximately every six meters for the same type of pump. Care will be taken in the design of the vacuum chamber to limit the impedance presented to the beam. Ion pumps and their power supplies from the Main Ring will be reused. The stainless steel vacuum chambers will be electro-polished and baked at 400°C. Since two inch aperture magnets are used throughout the MI, the conductance will be higher, and an average pressure lower than the Main Ring should be achievable. The design goal is an average pressure of 1×10^{-8} Torr. With this pressure the beam lifetime will be an order of magnitude larger than in the Main Ring.

Gate valves will be used to divide the MI into sectors. There will be a gate valve at the end of each straight section with appropriate interlocks. There will be a total of 32 gate valves in the system.

The beamlines will use 30 liter/sec ion pumps of the same type as the MI, spaced approximately every 12 meters.

Vacuum pressure during pump down will be monitored by a combination of thermocouple and cold cathode gauges; high vacuum will be monitored by the current readout of each ion pump. Vacuum pump down will be done using portable turbomolecular units that can be wheeled to any area being worked on. Ten units are provided.

2.8 Instrumentation

<u>Beam Position Detector (BPM)</u>

The beam position system for the MI is patterned after the existing Main Ring system. At each F(D) main quadrupole there will be a horizontal (vertical) pickup. New beam position detectors will be built for the MI. The processing electronics are the Fermilab standard amplitude-to-phase conversion style with a center frequency of 53 MHz. The system will be capable of producing first turn orbits, turn-by-turn readouts, and closed orbits.

Beam Loss Monitors (BLM)

The loss monitor system will utilize the recently constructed Main Ring ion chambers at each quadrupole in the ring and be of the same type as the present Tevatron system.

Other Special MI Diagnostics

The MI will employ a second harmonic dc current transducer. This will enable accurate acceleration efficiency measurements and will also be used for dc storage studies.

In order to analyze longitudinal and transverse instabilities, the MI will be equipped with a broad band longitudinal pickup and two broad band transverse pickups, one for each plane. These detectors should be very useful in studies of coupled bunch and head tail instabilities common to such high intensity rings.

The MI will also be equipped with three flying wires to allow dynamic emittance and momentum spread measurements during acceleration.

Dampers and Scrapers

The MI damper systems will be patterned after the Tevatron bunch-by-bunch system. The system will allow damping of injection oscillations and coherent instabilities, as well as providing the capability of knocking out selected bunches or heating the beam transversely in either plane.

The MI will have beam scrapers for measuring the acceptance of the machine in both planes and a momentum scraper to aid in beam transfer function measurements.

2.9 Controls

The entire accelerator complex, from the ion source to the Tevatron and antiproton rings, is controlled by a uniform system known as ACNET (shown in Figure 2-11). As shown each accelerator subsystem has a front end computer which drives a link attached to all appropriate hardware for that subsystem; all links constructed recently are CAMAC while some older systems utilize different technologies. Application programs and file storage, as well as a central database detailing all electronic components, are under control of VAX computers networked to the front ends. Also connected to this network are a number of operator consoles, attached in such a manner that any console can monitor and control any accelerator.

ACNET is currently being upgraded in a number of important aspects, with more modern hardware and software being added. However, the basic

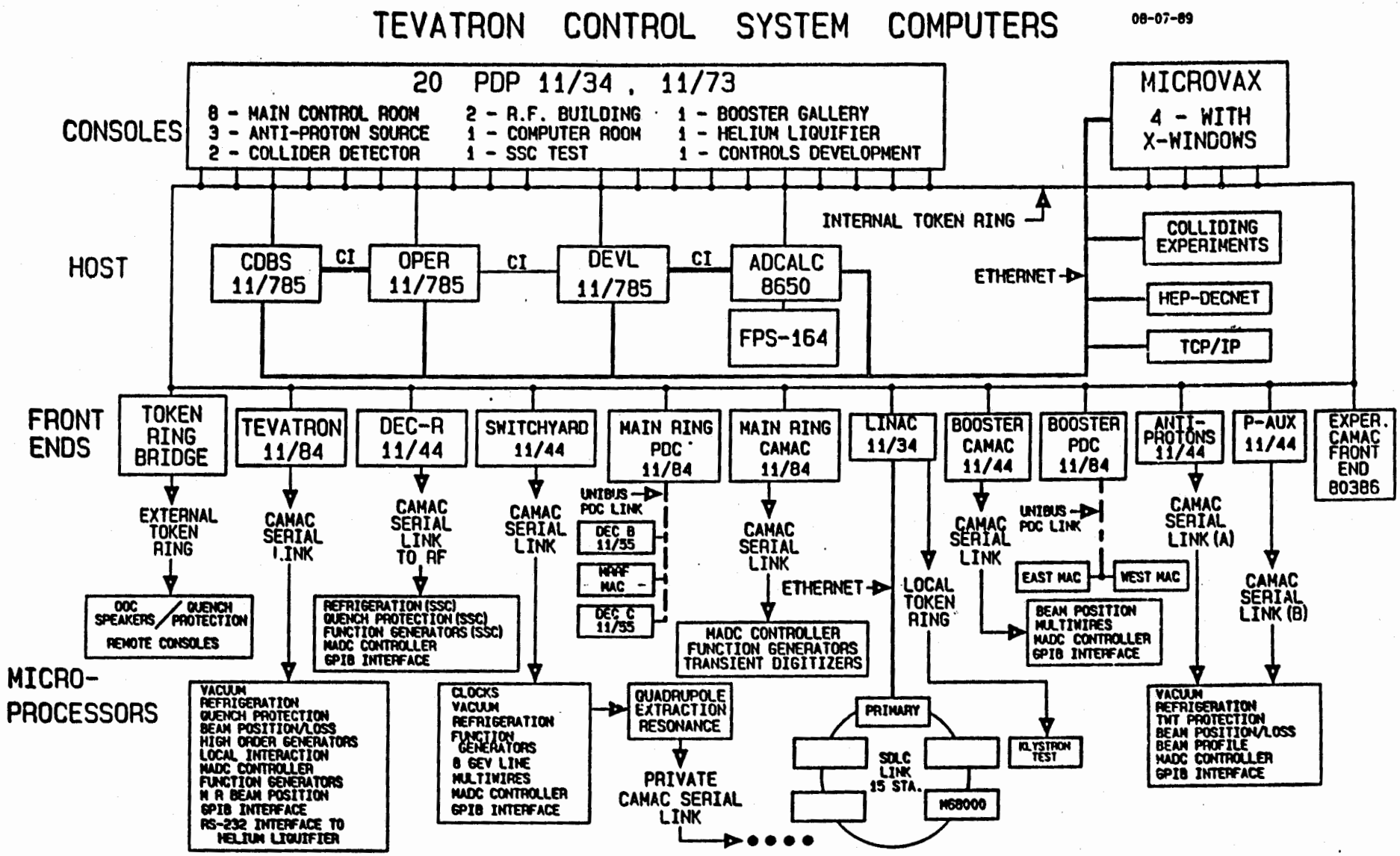


Figure 2-11. Schematic diagram of the Accelerator Controls Network (ACNET).

structure described is not being changed. A major upgrade is the reworking of Main Ring controls in CAMAC. Much of the MI hardware will be these CAMAC modules and associated equipment, moved to the new location. Also ongoing as part of the Main Ring upgrade is the installation of 24 channels of fiber optic cable as the conduit for various controls and timing links. Similar cable will be used for the MI, with a path from the Cross Gallery roughly along the 120 GeV beamline. This path is chosen so that beamline controls can be handled by these same links.

The MI fits naturally into the existing system. To the current complement of ten front ends will be added one for the MI; there exists sufficient network bandwidth and VAX computer cycles that this addition can be made with minimal impact. (Remember the Main Ring will be disappearing.) A new front end is needed because the one installed for the Main Ring system cannot be easily moved since it has been convenient to attach some Tevatron devices to it. The new computer will drive a CAMAC link running to and around the MI; this link will connect to a number of crates and relay racks, and will have a number of cable terminations, scaled according to experience with the Main Ring. Twelve thousand feet of fiber and 84 repeaters are appropriate to provide this link, as well as to distribute timing signals and real-time accelerator data, and to extend the laboratory wide Token Ring network.

Since most of the new hardware connected to the control system will be copies of existing modules, the software effort necessary for support is expected to be manageable. Applications and front end code should be straightforward migrations of what is currently being created for the Main Ring. However, there are other computers associated with the current Main Ring beyond those normally associated with data collection. The ramp is presently generated by a pair of PDP-11's (DEC-B and DEC-C), which are in the process of being replaced with 68040-based processors. With the variety of MI operational modes some software effort may be needed in transferring these machines to the MI, although the initial implementation of these will be done with the Main Injector in mind.

The Main Ring high level rf is controlled by one of the few remaining Lockheed "MAC" computers in the Laboratory, along with its associated MIU (module interface unit). A new computer and hardware system, and associated software effort, will be required for this function.

2.10 Abort Systems

The proposed proton abort system for the new MI relies heavily on the technology and design utilized in the existing Main Ring abort system commissioned in 1983. This system has successfully provided clean single-

turn abort capability for all subsequent Main Ring proton beam operation. The abort system for the new MI reuses much of the hardware of the present Main Ring system, with the exception of the beam dump. Because of the low intensities transported, there is no $\bar{p}$ abort.

The system will track the energy of the MI ring, and be capable of aborting the beam at any point in the 8.9 - 150 GeV/c range, within 50 μsec (5 turns) of the abort command. A 1.5 μsec abort kicker risetime matched to a corresponding minimum gap in the circulating beam allows abort efficiency approaching 100%.

Two 2.2 m long kicker magnets are located at the upstream end of long straight section MI-50. The peak kicker field required is 1.9 kG with the 90° phase advance between the kicker location and three Lambertson magnets at the center of the long straight section. The first of these will be located upstream of the quadrupole in the middle of the straight section. A horizontal displacement of the aborted beam of about 44 mm at the first Lambertson magnet positions the beam appropriately for the abort channel.

The three Lambertsons, with peak fields of 11 kG, deflect the aborted beam vertically downward at an angle of 11.7 mr so as to clear the quadrupole at the downstream end of straight section MI-50 and exit the MI tunnel toward the abort beam dump. For low energy beam abort, only the middle of the three Lambertsons is excited, with a current program which tracks the Main Injector ramp. For higher energy beams, the other two Lambertsons, whose lengths have been adjusted so their bend center is in the center of the middle Lambertson, are ramped. This avoids having low energy beams with their larger physical sizes passing vertically offcenter through the quadrupole. The geometry of the MI-50 straight section is shown in Figure 2-4.

The beam dump will be constructed with a graphite core of length 4.4 m, similar to the existing Main Ring beam dump. The kicker power supplies will be located in the MI-50 service building, which will be situated so that relatively short cables (<25 m) can be used between pulsing units and kicker magnets. This is crucial for maintaining the kicker pulse shape.

2.11 Slow Extraction

The slow extraction system has been designed to provide 120 GeV/c resonant extracted beam with a uniform spill over times of one second with losses of less than 1%. Slow spill of the entire beam is easily achieved with half-integer extraction. Extraction is implemented by using special quadrupoles and octopoles to bring the beam onto the half-integer resonance in such a manner that the amplitude of betatron oscillations will grow in a

controlled fashion until the particles are deflected by an electrostatic septum. The kick supplied by the electrostatic septum provides enough space between the circulating beam and the extracted beam to allow magnetic septa to be used to extract the beam.

Septa

The extraction septa are located in straight section MI-60. This region must accommodate transfers of 8 GeV, 120 GeV and 150 GeV beams. The geometry of the Lambertson magnets is identical to that of the abort, except the bend of the Lambertsons is vertically upwards. For 8 GeV transfers, only the middle of the three Lambertsons is excited.

The placement of the electrostatic septum is made easy by the fact that the straight section has sufficient phase advance that both the septum and extraction kicker magnets can be placed within the straight section. It is desirable to have a separation of 6 mm at the magnetic septa between the circulating beam and the extracted beam. A 120 μr kick from the electrostatic septum will achieve this with an applied voltage gradient of 40 kV/cm.

Harmonic Elements

The appropriate harmonics for quadrupoles (53rd) and octopole (0th) will be provided by special magnets designed for this purpose. Quadrupoles will be located at points equidistant in phase around the ring, while the special octopoles will be located in phase with the quadrupoles. Air core quadrupoles are sufficient to provide the necessary stop band width to ensure total extraction of the beam. Required strengths for the quadrupoles are 60 kG-in @ 1 inch, and for the octopoles 116 kG-in @1 inch.

Phase Space

Extraction starts by raising the normal horizontal tune from 26.4 towards 26.5, while turning on a 0th harmonic octopole. The octopole is used to produce an amplitude dependent tune; thus a larger amplitude has a larger tune and is closer to the half-integer. Then a 53rd harmonic quadrupole is used to increase the width of the half-integer stop band. Small amplitude (smaller tune) particles are stable while larger amplitude particles stream out along the separatrix until they encounter the electrostatic septum. Phase space distributions produced by these elements at the electrostatic septum and at the magnetic septa are shown in Figure 2-12. The rough angle of 45° exhibited by the beam is a compromise between high extraction efficiency (where the angle would be zero) and aperture considerations at the location of the magnetic septa. For the extracted phase space shown the emittance is 6π, with an extraction inefficiency of 1%.

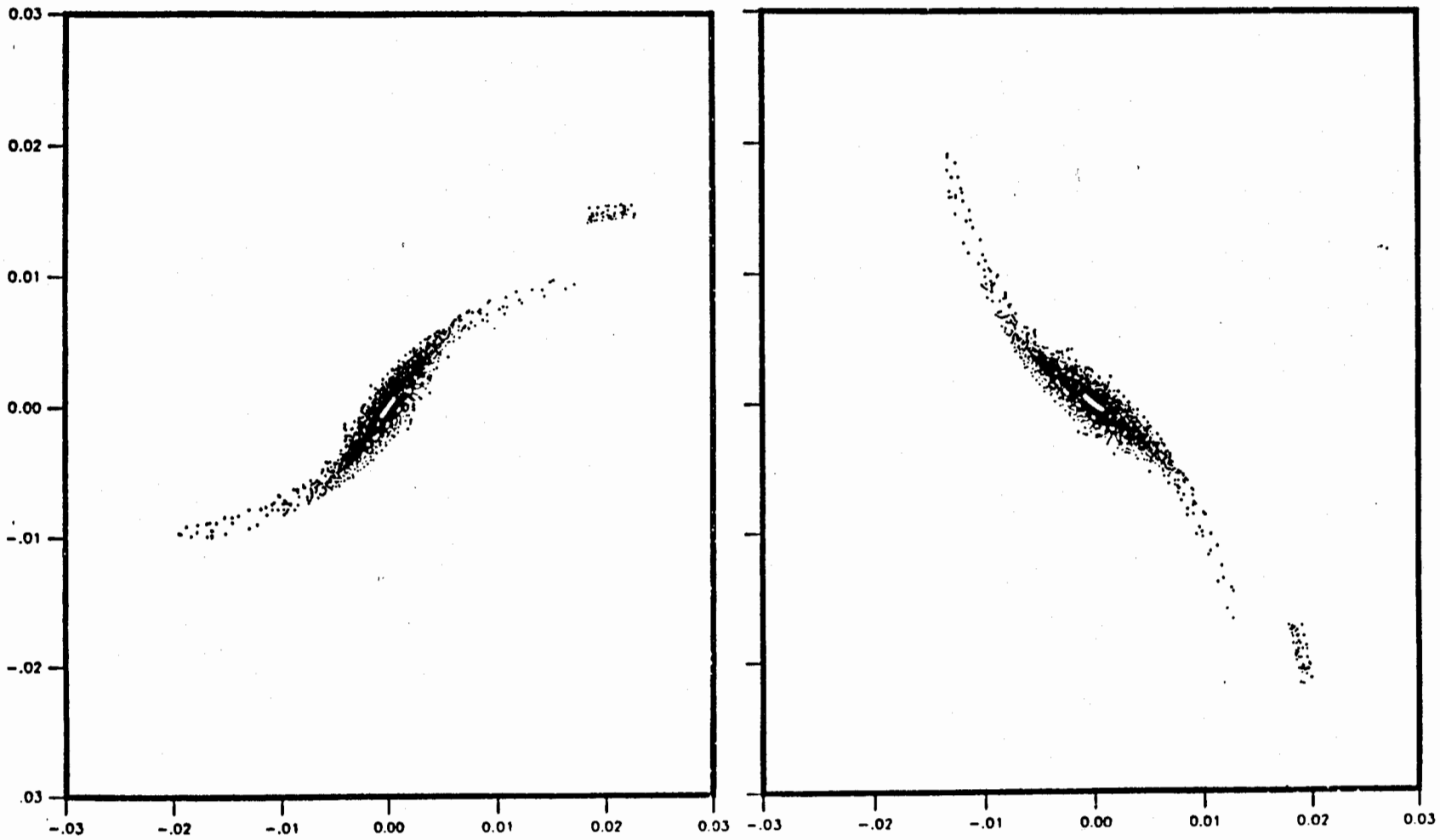


Figure 2-12. Phase space distributions at the electrostatic septum (left) and at the extraction Lambertson (right) during slow extraction.

Quadrupole Extraction Regulator System (QXR)

The goal of the slow extraction system is to provide a constant rate of extraction during the slow spill. This is accomplished by moving the stop band smoothly through the beam using the quadrupole extraction regulator system, QXR. There are two parts to this system, distinguished by strength and bandwidth. The stronger, lower bandwidth components are tied to a normal beam intensity monitor which is insensitive to fast fluctuations. After the signal is sampled during the spill and compared to an ideal signal, the resultant smoothed error signal is used to modify the power supply output. This system is the base from which the weaker, faster responding system works. Monitoring is based on a fast reacting detector in the extracted beamline itself. Power supply ripple up to 360 Hz can be compensated by this system.

2.12 Environmental and Shielding Considerations

The proposed construction of the MI lies in approximately 400 acres southwest of the existing Main Ring tunnel, between the F0 building and the site boundary. Access to the construction project will be via the existing Kautz Road. Efforts will be made throughout the construction period to protect and enhance the local conditions. Details are discussed in Appendix C.

Calculations have been made of radiation dose near the tunnel when beam is lost on the magnets or dumped intentionally. The dose is estimated both on the surface of the earth berm covering the tunnel and at the site boundary at the point of closest approach (approximately 75 m) to the MI. A berm thickness of 21 ft, 4 ft more than that of the present Main Ring, is assumed. The ring has been lowered by 6 ft from the previous description; part of this is in response to particular problems at culverts crossing over the ring. The additional 4 ft of shielding reduces the radiation at those points to acceptable levels. The dose rate in the vicinity of the abort dump (Section 2.10) is also investigated and found to be lower than required.

The highest muon dose is only 0.3 mR and occurs about 70 m downstream of the loss point, where the berm meets grade level (assumed to be 10 ft above the center of the tunnel). The average exposure rate due to muons during routine operation at the surface of the berm is also small and amounts to approximately 12 mR/year. The dose at the site boundary is estimated at 0.3 mR for the worst case loss scenario and at 10 mR/year for routine operation. See Appendix C for details.

The most important component of radiation for shielding considerations is hadrons. Appendix C contains details of the assumptions made in calculating hadron dose and required shielding. For accidental loss the

prediction is 3 mR at the surface of the berm, thus requiring this area to be defined as minimal occupancy. Further from the berm the dose falls off rapidly so that 60 feet from the berm the dose is below the minimal occupancy limit of 1 mR. A small amount of beam is lost continuously. This results in integrated levels of less than the 500 mR/year limit for permanent occupancy. By adding an extra 3 feet to the berm at the closest approach to the site boundary, the off-site dose is a factor of 5 below the required limit of 10 mR/year.

2.13 Utilities

Main Injector Low Conductivity Water System and Magnet Bus Connections

The proposed system for connecting the power and water to the MI is similar to the Main Ring. This system requires minimum maintenance. Stainless steel headers supply low conductivity water (LCW) to copper pipes which conduct both power and cooling water to the magnets. Ceramic feedthroughs, with flexible metal braid hoses, electrically insulate the piping from the copper bus system. All connections are either brazed or welded.

The MI components and associated utilities are grouped together at the outside wall of the tunnel leaving most of the enclosure space for servicing, as shown in Figure 2-13. All connections to the magnets are designed so they are accessible from the inner space of the tunnel. There will be six utility buildings uniformly spaced along the perimeter of the Main Injector. These are labelled MI-10, 13, 30, 50, 53, and 70. Each utility building will supply power and cooling water to about 1815 feet of circumference in the MI.

Four service building will have three pumps each, and the remaining two buildings will have four pumps all connected in parallel. Each pump has a 50 HP motor, and delivers 300 gpm of LCW with a pressure head of 162 psi (375 TDH). The heat from the magnets is transferred to the LCW and dissipated in a tube and shell heat exchanger placed above the pumps in each service building. Pond water is circulated in the tube side of the heat exchanger to remove the heat by evaporation.

From the existing LCW system in the Main Ring, 12 pumps with starters and controllers, and six heat exchangers will be reused for the MI. Seven existing spare pumps will also be used, and one new pump will be required. The remaining water cooling equipment in the Main Ring will remain as part of the Tevatron. New extra strong copper bus (2.875" o.d. by 1.771" i.d. for the dipoles, and 2.00" o.d. by 1.2" i.d. for the quadrupoles) will be used for the MI. The old copper bus from the Main Ring (1.625" o.d. by 0.187" wall) with the porcelain clamps will be reused for the beamlines.

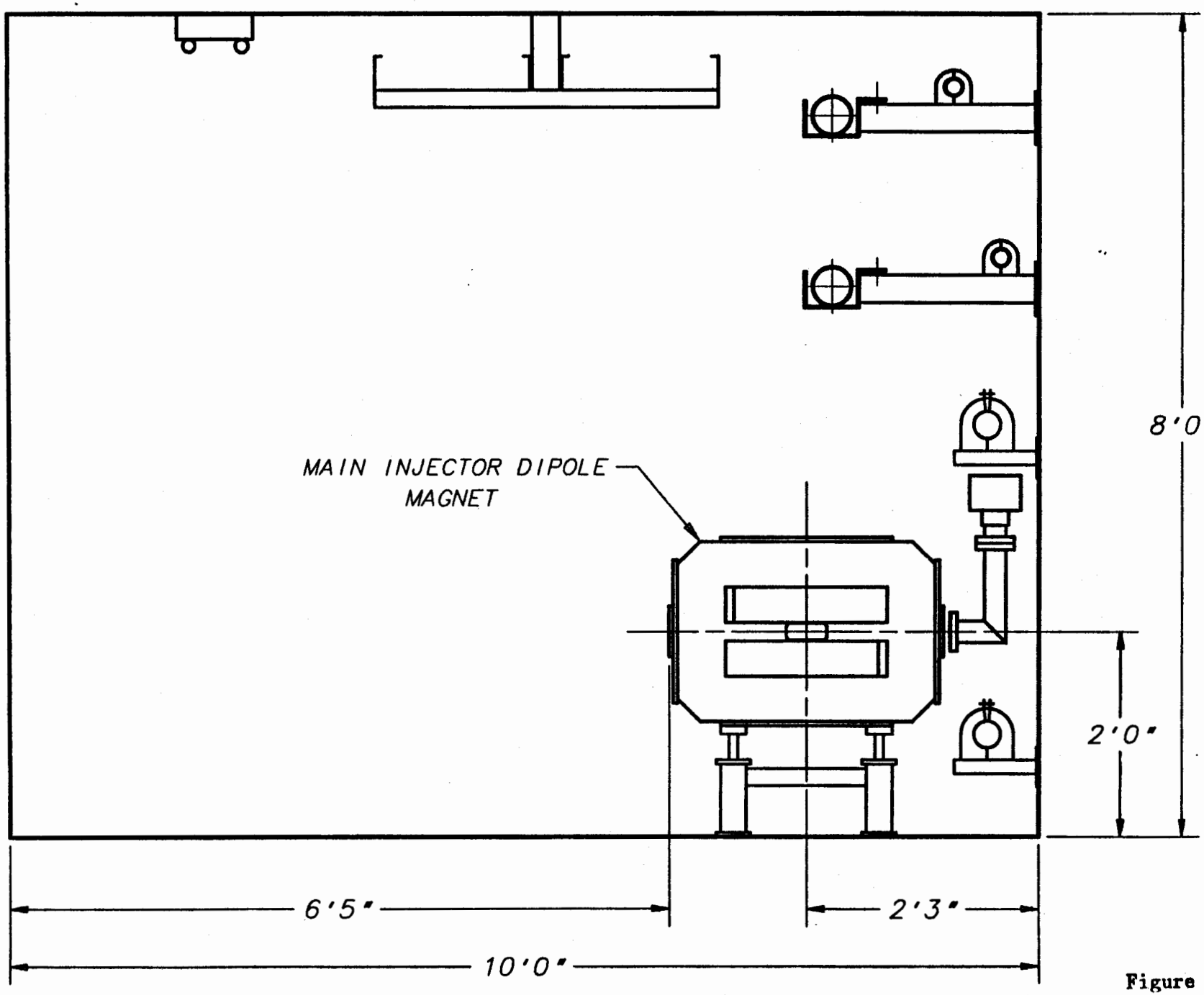


Figure 2-13.

Two 4 in. stainless steel pipe headers will be installed over the magnets along the 10,891 ft circumference of the MI. A total of 20 pumps (300 gpm each) will be connected in parallel across the supply and return pipes. All magnet and bus systems will also be connected in parallel across the LCW headers. Flow control devices, used in the Main Ring, will be altered and can be reused in the new injector to limit the water flowing to 8 gpm through the dipole magnets. For 120 GeV operation (4342 amps rms), the water temperature rise across the magnets is calculated to reach about 7°C. An average of 950 GPM of LCW from each of the six service buildings will be required to cool magnets, bus, power supplies, chokes, and electronics equipment. The heat load removing capacity per building is about 2 MW limited by the cooling pond.

At each utility entrance, as well as at locations half-way in between, the enclosure will have a ceiling one foot higher than the regular tunnel. The purpose of this extra space is to make room for expansion joints for the 4 in stainless steel pipes, copper bus, and trays. At this position the enlarged enclosure allows the utilities to cross over without obstructing the regular tunnel clearance for the magnet moving vehicle.

A net counterclockwise flow in the ring will be accomplished with restricting valves at each of the entrances. In one of the larger service buildings (MI-70), a LCW processing system will be installed. A continuous polishing flow action is required to keep low conductivity in the water. Two mixed bed de-ionizers will be used with about 80 gpm flow going through one of the beds. An average of 9 MΩ-cm resistivity of the LCW will be maintained in the ring. An expansion tank and a 3,000 gallons storage tank are also to be used. The MI will required an estimated 29,000 gallons of low conductivity water to fill the pipes, tanks, bus, and magnets.

Power Distribution for the MI

There are three separate power systems associated with the MI system: 1) power system for pulsed power supplies; 2) conventional power system; and 3) power system for beamlines. The power distribution system is shown schematically in Figure CDR-28 (Appendix E).

Power System for Pulsed Power Supplies

This system consists of two new 50 MVA transformers at the Kautz Road Substation and a new 13.8 kV distribution system to the MI. A 13.8 kV switchgear area, located within the Kautz Road Substation, allows sectionalizing of the system. From this switchgear, three loop feeders, situated within a ductbank, are used for the pulsed power to the ring.

At each service building, there is a disconnect switch to supply power to the power supplies. From the disconnect switch to the power supply transformers, the feeders are routed in a ductbank. A paralleling switch at the south side of the ring enables uneven loading of each segment without overloading the feeders. This switch can also be used for feeder isolation for maintenance purpose.

Each feeder consists of three 750 MCM aluminum 15 kV power cables, each 2000 feet long so that no splices are needed between service buildings. Feeder construction will be cross-linked polyethelene, concentric neutral with overall jacket.

A new harmonic filter will be installed at the Kautz Road Subtation between the feeders to ground, to prevent possible component damage due to excessive harmonic distortion caused by the non-linear power supplies. The filter will consist of a section similar to the existing filter in the Main Ring pulsed power system, installed in parallel with the Main Ring filter.

Conventional Power System for the MI

This system will consist of one 15 kV feeder around the MI ring, with a 500 kVA transformer at each of the six service buildings. The conventional power will be used for building power, lights, pumps, etc. Power is derived from the existing 82B transformer relocated to the Kautz Road Substation and is delivered to the MI-70 switchgear area by backfeeding through the existing feeder 45. From this switchgear, the feeder will continue as a direct buried feeder to the six service buildings. At each service building there will be a disconnect switch with a ductbank connection to the 500 kVA conventional power transformer.

Power for Beamlines

Total rms power required for the beamlines is 1.5 MW. This requires one feeder and a total of four 500 kVA substations. This power is delivered via a feeder in the ductbank from the Kautz Road Substation to the switchgear area at the MI-70 Building. In the switchgear area there is a switch module supplying power to substations at F0 (three substations adjacent to the switchgear area) and the North Hatch Building. In addition, power is required for operation of the beamline elements located in the Main Ring tunnel between F1 and A0. This power is supplied from existing Main Ring feeders and power supplies.

3. BEAMLINES AND BEAM TRANSFERS

Five new beamlines with a combined length of about 1600 meters are required to integrate the Main Injector into the existing Fermilab accelerator complex:

1. A 730-meter beamline for transport of 8.9 GeV/c protons from the Booster to the MI.

2. A 260-meter Tevatron injection beamline for injection of 150 GeV protons from the MI into the Tevatron.

3. A 260-meter beamline for injection of 150 GeV antiprotons from the MI into the Tevatron.

To link the new Main Injector complex to the Antiproton Source and Switchyard, the existing magnets and power supplies in F sector (from F0 to A0) of the Main Ring and of AP1 will for the most part remain in place. Two additional sections of beamline are required to integrate these sections of magnets into the MI complex:

4. A 210 meter section of magnets to provide beam transport between the Main Injector and Main Ring station F11. This section of beamline lies directly above the 150 GeV Tevatron injection beamline for protons (2 above) and transports 120 GeV protons from the MI for antiproton production, 8 GeV antiprotons (protons) from (to) the Antiproton Source to the Main Injector, and slow extracted 120 GeV protons from the MI for delivery to the Switchyard.

The 120 GeV protons used for antiproton production will be transferred from F17 into the existing AP1 beamline using the present Lambertson system. The 120 GeV protons used for the "test beam" are transported through the entire F sector to A0 where the fifth beam line is to be installed:

5. A 130 meter section which connects F49 to the upstream end of Switchyard.

The site coordinates of all beamline elements have been determined and the beamline layout is shown in Figure CDR-10 (Appendix E). Optical designs currently exist for the 8.9 GeV/c Booster to Main Injector line and the two 150 GeV/c Main Injector to Tevatron beamlines. Optical designs of the other lines are in progress. Longitudinal beamline sections showing the disposition of the elements with the beam transfer lines are shown in Figures CDR-13 to CDR-18.

3.1 The 8 GeV Line

The 8 GeV line is composed of three major sections: a matching section from the Booster into the beamline, a section of three major achromatic bends incorporated in a periodic FODO lattice, and a final matching section into the MI. The primary geometrical constraints in the design of the 8 GeV transfer line are minimizing the total beamline length and minimizing the impact on existing roads and structures.

Protons are extracted horizontally from the Booster at straight section L3 at an elevation of 726'6". A horizontal bend of 8.5°, 8 m downstream of the Booster extraction point, steers the beam into the existing AP4 enclosure. A second bend of 3.8°, 21.8 m further downstream bends the beam onto a line 2.5' from and parallel to the wall of the existing AP-4 enclosure. This line extends another 29 m to the end of the enclosure. Two major bends totalling 29°, complete the matching section to the Booster; Figure 3-1 shows this part of the beamline. The design does not consider connection to the AP-4 line or to the existing dump in the AP-4 enclosure. Sufficient space exists to connect to the AP-4 line, while the Main Injector removes the need for the L3 dump.

The three achromatic bends are incorporated into a 615 meter FODO lattice selected to match the Main Injector cells. The first and second bends are separated by a 100 meter straight section. The first bend deflects the protons approximately 30° towards the west, commencing the trajectory around the existing Antiproton Source complex. The second bend, which is still at the Booster altitude of 726.5', bends the protons through 43°, taking them 72" beneath the existing AP2/SP3 beamlines. Immediately following this section the 8 GeV line descends by 1.64 meters over one 90° cell of the FODO lattice. This corresponds to half the altitude difference between the Booster and Main Injector. An achromatic horizontal bend of 60° finalizes the approach to the Main Injector in the horizontal plane. The second 1.64 meter altitude drop is achieved in the final 90° FODO cell, terminating at the Main Injector. The phase difference between the two altitude changes ensures that the total vertical bend is also achromatic.

The lattice functions for the 8 GeV line are shown in Figure 3-2; the horizontal (vertical) beta and dispersion functions are shown by the solid (dashed) curves. The maximum β (dispersion) through the arcs is 64 m (10 m). For a 95% normalized transverse emitance of 40π mm-mr and $\Delta p/p = .002$, this corresponds to approximately 25 mm transverse beam size. The maximum β in the Booster end matching section is 140 m. Figure 3-3 shows the 6σ beam envelopes as well as the physical apertures of the bending magnets and the beam pipe.

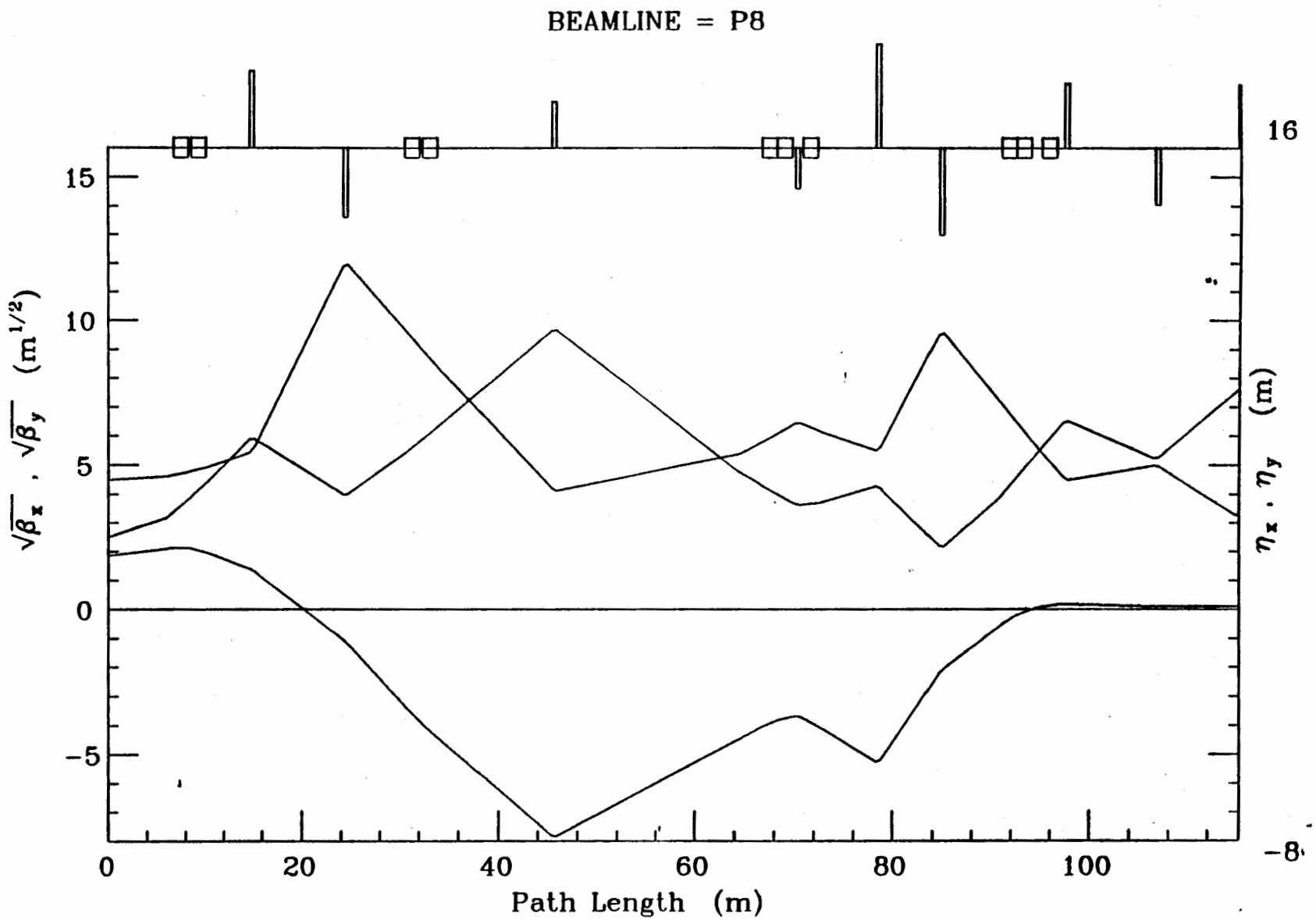

BEAMLINE = P8
15
10
5
0
−5
16
−8
0
20
40
60
80
100
Path Length (m)
$\sqrt{\beta_x}$, $\sqrt{\beta_y}$ (m$^{1/2}$)
η_x , η_y (m)

Figure 3-1.

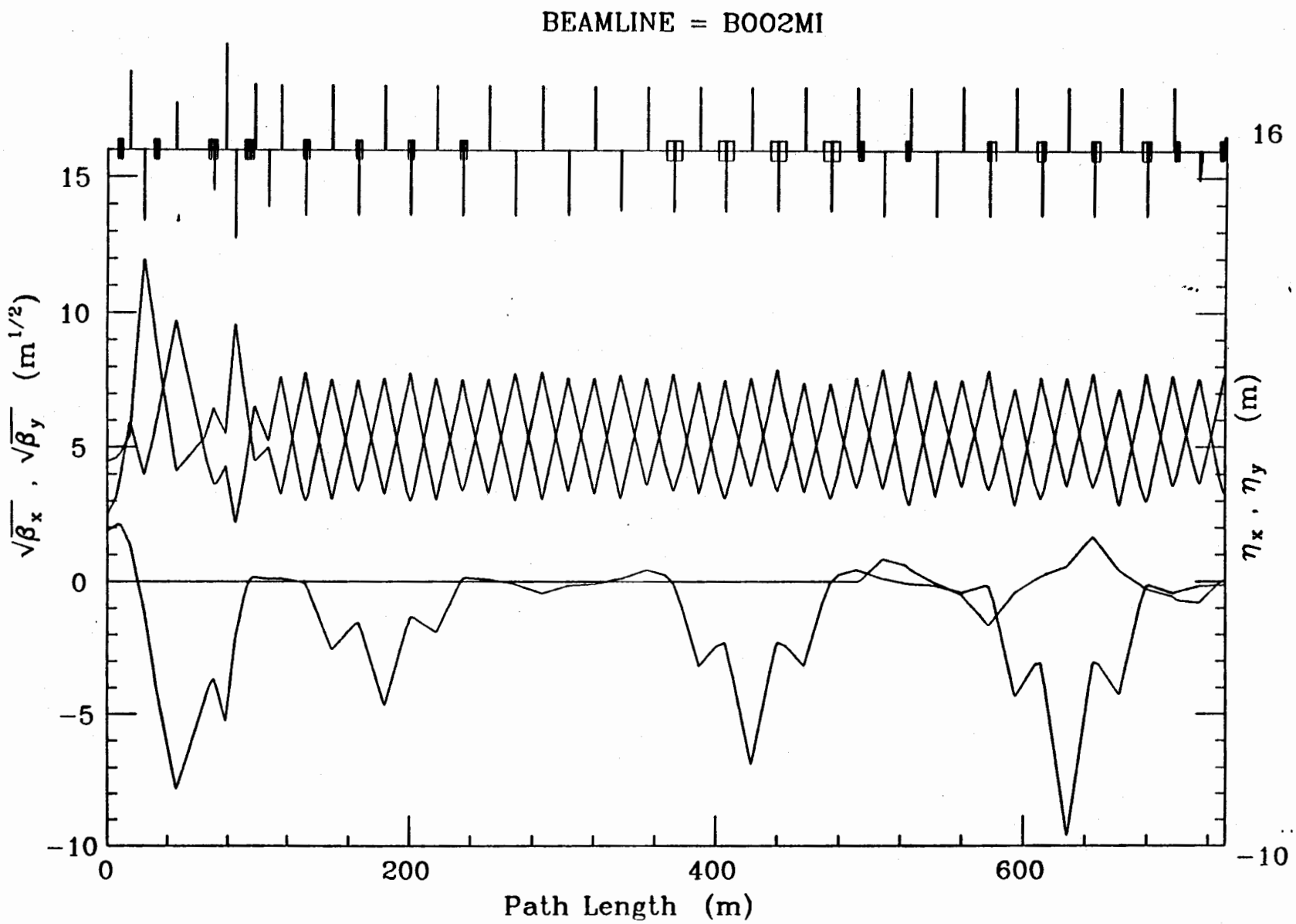

BEAMLINE = B002MI
16
15
10
5
0
−5
−10
$\sqrt{\beta_x}$, $\sqrt{\beta_y}$ (m$^{1/2}$)
η_x , η_y (m)
−10
0
200
400
600
Path Length (m)

Figure 3-2.

MI Injection

Injection of 8.9 GeV/c protons is accomplished in the MI straight section, MI-10. Plan and elevation views of the injection straight section are shown in Figure 3-4. The straight section is approximately 68 meters long and has to accomodate two vertical injection Lambertsons and the horizontal kickers. The Lambertsons are located just upstream of the center of the straight section. The beam trajectory at the entrance to the Lambertson is 37.7 mm above center with a downward 33 mr vertical angle and 40 mm outside the center of the aperture; the circulating beam is displaced 20 mm inside. The Lambertson removes the 33 mr vertical angle to bring the beam onto the vertical closed orbit of the MI.

Four horizontal kicker magnet modules located 90° downstream of the Lambertson removes the 60 mm horizontal offset present at the Lambertson. The kickers provide a 1.5 mr bend to place the injected protons onto the horizontal closed orbit of the MI.

No other magnetic elements are required for the injection of 8.9 GeV/c protons. The injection of 8.9 GeV/c antiprotons from the Accumulator takes place in straight section MI-60 which is also used for extraction as discussed in Section 3.3. The antiproton injection process uses the same vertical Lambertson and horizontal kicker which are used for proton extraction.

Proton Injection Magnets and Power Supplies

The Lambertson magnet and power supply currently being used for 8.9 GeV/c proton injection into the Main Ring will be used without any major modifications. The injection kicker magnets will be constructed following the existing Booster extraction kicker technology. The magnets will have a 2.5"x 2.5" aperture to allow room for a 2.25" (i.d.) ceramic beam tube. The four kicker magnets are each capable of a 0.5 mr kick. The existing injection kicker power supply will be used with minor modifications.

3.2 The 150 GeV Lines

Two beamlines connect the Main Injector to the Tevatron. One of these simply provides transport of the 150 GeV antiprotons. The other, in addition to delivering 150 GeV protons to the Tevatron, must share an extraction system in the MI with the beamline delivering 120 GeV protons to the antiproton target or to the Switchyard. These additional functions are described in the following sections; here are described only the two optically similar beamlines which transport particles from the MI to the Tevatron. The difference between the proton and antiproton transfer lines originates in the slight asymmetry of the injection point in the Tevatron with respect to the two particles: the two beamlines must match into different lattice functions.

The elevation of the MI is 2.3 m below the Tevatron. Protons (antiprotons) are extracted by kicker magnets which deflect the beam across the septa of vertically bending Lambertson magnets located in the MI-60 (MI-80) straight section. The Lambertson magnets deflect the beam upward by 23 mr and are followed by a vertical pitching magnet which can be used to direct the beam upwards into the 120 GeV line. The total beamline length is 260 meters. Each of the lines includes eight recycled 6-m Main Ring B2 dipoles, eight 4-m B2 dipoles obtained by reworking existing magnets, and sixteen quadrupole magnets, thirteen of which are new.

The lattice functions for the 150 GeV proton Tevatron injection line are shown in Figure 3-5. The horizontal (vertical) beta and dispersion functions are shown by the solid (dashed) lines. The current optical solution has all lattice functions well matched including the vertical dispersion generated by the vertically bending dipoles in the line. The vertical dispersion match is accomplished by rolling magnets (as three families) in the transfer line. The maximum roll angle is 12.8°. The cells containing the dipole magnets encompass 360° of phase advance. This yields a simple transformation of the input β functions, and decoupling of the vertical dispersion matching from the β-matching.

In the previous beamline design, the mismatched vertical dispersion resulted in emittance growth for coalesced beam injected into the Tevatron at 150 GeV/c (assuming a full momentum spread of ±0.2% and a rms distribution of 0.1%) of approximately 1π mm-mr.

MI Extraction

Extraction takes place at the two long straight sections near Tevatron straight section F0: MI-60 (proton extraction) and MI-80 (antiproton extraction). Figure 2-4 shows a plan view of long straight MI-60 and the beginning of the extraction line.

Transfer into the Tevatron is initiated by a kicker (or electrostatic septum in the case of slow extracted protons) located 90° upstream of the Lambertson septum magnets. The kicker displaces the beam horizontally across the Lambertson septa; the Lambertson magnets deflect the extracted beam upward by 23 mr for both the 150 GeV/c Tevatron injection lines and for the 120 GeV/c extraction lines. The 23 mr angle is the minimum required for just clearing the top of the MI quadrupole at the end of the long straight section.

The requirements on the proton extraction Lambertson aperture are dictated not by the 150 GeV/c extraction, but by its use as the injection Lambertson for 8.9 GeV/c antiprotons. Thus a Lambertson magnet of the "F17

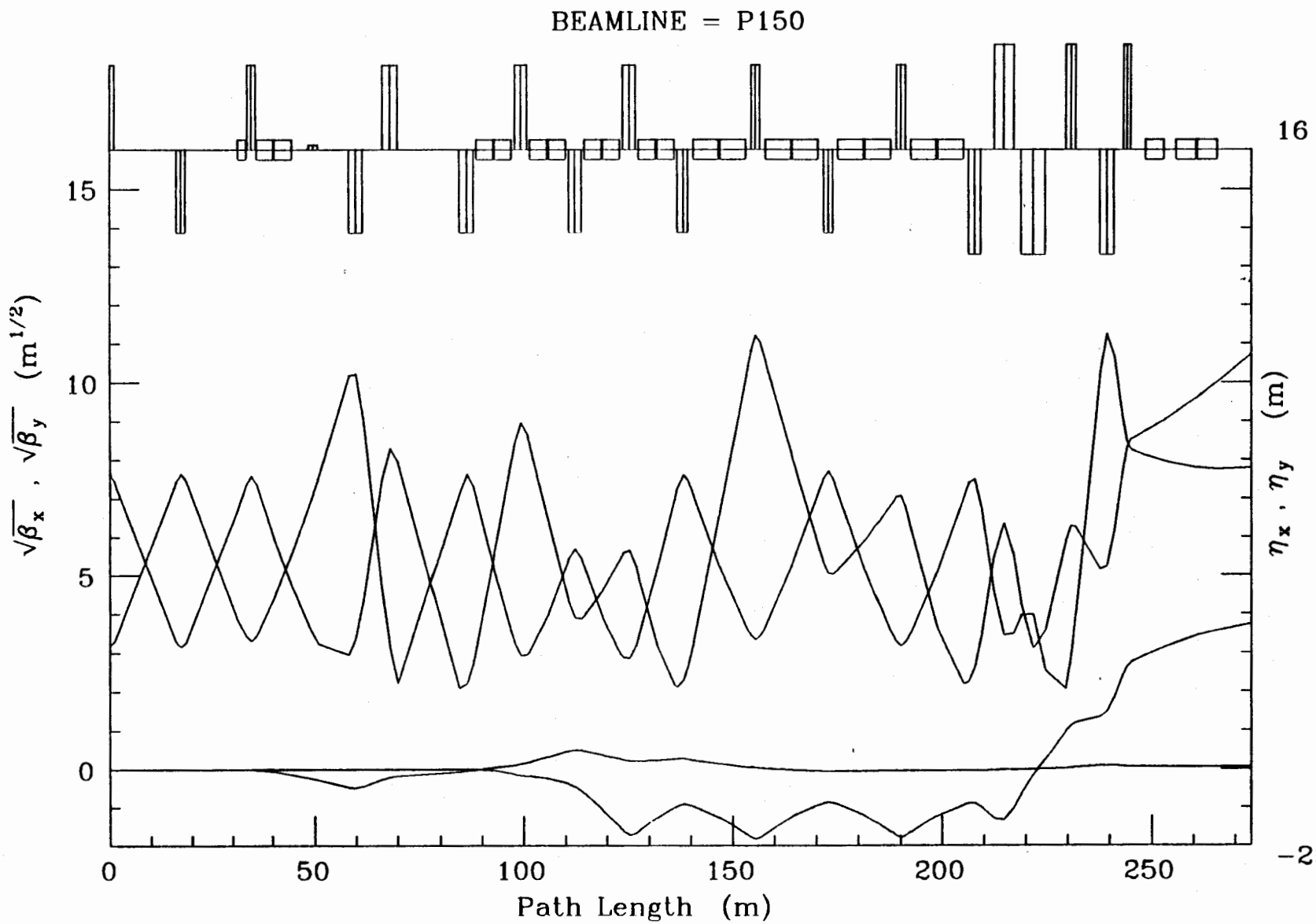


Figure 3-5. 150 GeV Proton Beamline and Lattice Functions

style" design will is used at MI-60. This is the magnet currently used for injection of 8.9 GeV/c antiprotons into the Main Ring. With the reduced β fucntions at the straight section, the aperture is sufficient for the acceptance of 40π mm-mr antiproton beams from the Antiproton Source. The Lambertson magnets are the same type as those used for the abort in MI-50. Figure 3-6 shows the Lambertson and quadrupole magnet apertures and 40π mm-mr beam profiles at 8 GeV and 150 GeV. Generous clearance for the injected and circulating beams is afforded. Only the center Lambertson magnet is excited for 8 GeV beam transfers, so the beam passes through the quadrupole with no vertical offset. The antiproton transfer line to the Tevatron, which only transports 150 GeV beams, is not as demanding in its aperture requirements, and existing Lambertson magnets will be used if suitable ones are available.

Tevatron Injection

Injection into the Tevatron is moved from its present location in the E0 straight section to the F0 straight section. This move leaves the E0 straight section completely free for possible use as an interaction region or for other purposes.

The F0 region will continue to be used to accomodate the Tevatron rf systems. By rearranging the accelerating cavities in the upstream end (proton beam direction) of the straight section, the proton and antiproton injection lines can converge toward a common set of injection septum magnets located at the downstream end of the straight section. This reduces the number of such elements needed in the Tevatron. In the present Tevatron, the accelerating cavities are arranged in a manner such as to ensure proper phasing between the proton and antiproton systems and to minimize the effects of cavity trips. Thus, a new layout of the cavities is necessary and its consequences must be investigated.

The most appropriate injection scheme into the Tevatron is one in which the incoming beam approaches the accelerator horizontally, the last horizontal bend being produced by a magnetic septum magnet, and closure onto the vertical orbit being produced by a kicker magnet downstream of the injection point. The nearest points on either side of the long straight section where kickers may be placed are the F17 medium straight section (for clockwise proton injection) and the E48 short straight section (for counterclockwise antiproton injection). Both of these locations have larger horizontal β functions, favoring horizontal kickers, but presently available kicker strengths are sufficient for vertical kicks.

Since the short straight section E48 is very close to the F0 region, the logical location of the injection point is at the downstream end of the straight section. This generates the largest amount of betatron phase

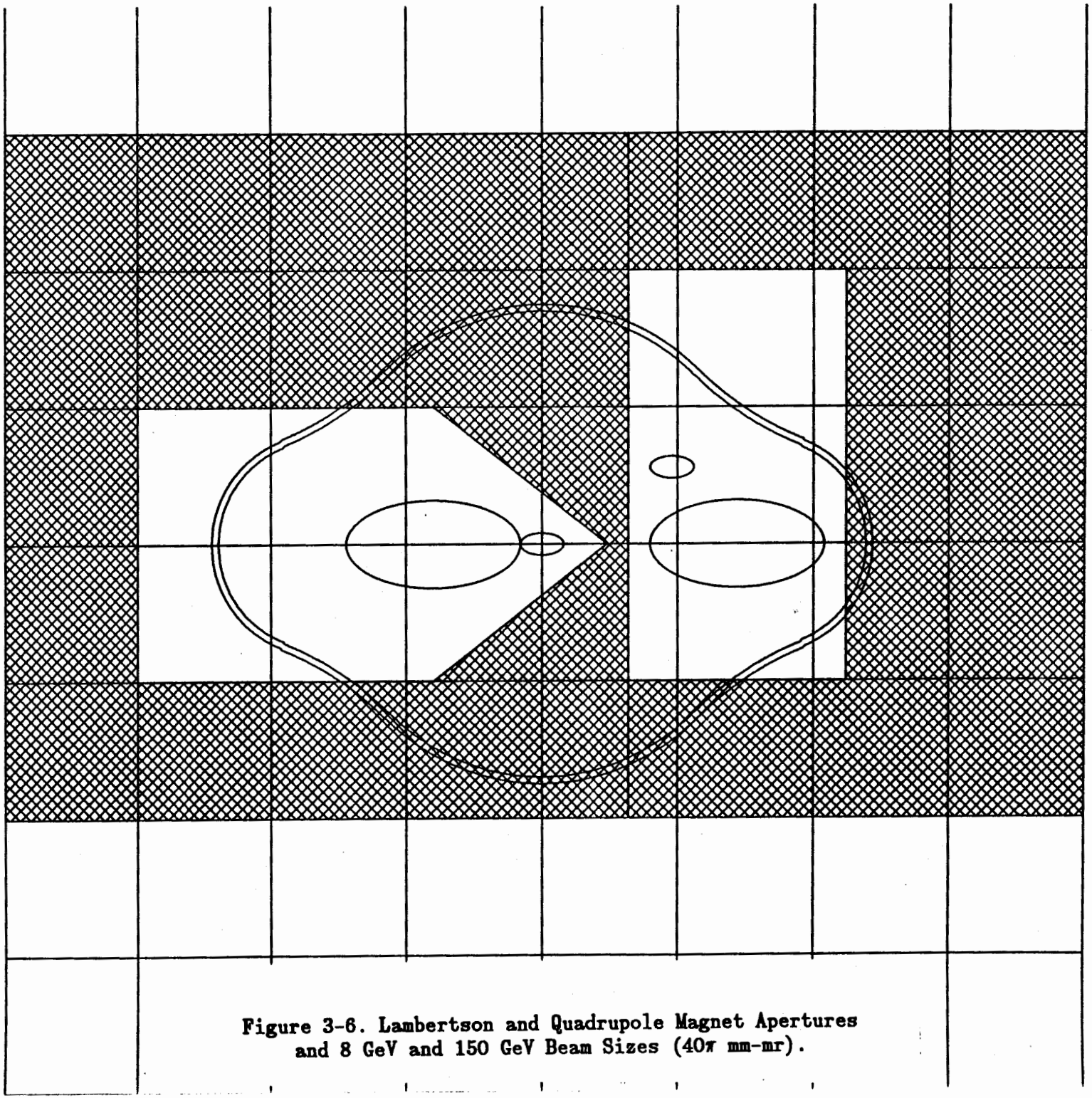


Figure 3-6. Lambertson and Quadrupole Magnet Apertures and 8 GeV and 150 GeV Beam Sizes (40π mm-mr).

advance between the injection magnetic septa and the kickers for the counterclockwise injected beam. The phase advance between this injection point and the F17 medium straight for the proton beam is also favorable.

Injection System Layout

The Tevatron rf system occupies roughly 26 m of the 52 m straight section. In the remaining 26 m, two Lambertson magnetic septa are placed symmetrically about a point 13 m upstream (proton direction) of the end of the straight section. These Lambertsons are two of four used in the present Tevatron injection system at E0. Both the proton and antiproton beams pass through the field region of these magnets upon injection. To provide more clearance at the ends of the free space, each of the injection lines incorporates one ''C'' style magnet just in front of the Lambertsons. As stated earlier, the vertical injection kicker magnets will be located at the E48 and F17 straight sections. These magnets will be moved into E48 and F17 from their present Tevatron locations. A plan view of the F0 region is shown in Figure 3-7.

3.3 120 GeV Antiproton Production

The existing AP-1 beamline, which is used to target 120 GeV protons for antiproton production and transport 8.9 GeV/c antiprotons back into the Main Ring, will remain intact. The Main Ring magnets from F11 to F17 will also be used in their present locations, with only minor modifications to the bus and power supplies. A new section of beamline, from the Main Injector to the old Main Ring F11 station (MI-F11 beamline), will be required to complete the beamline for antiproton production. This new section of beamline will transport 120 GeV protons to the antiproton target, transport 8.9 GeV/c antiprotons into the MI, and will also be used in the transport of 120 GeV slow extracted beams. Delivery of protons to the Switchyard is discussed in Section 3.4.

The MI-F11 beamline

This beamline lies directly above the 150 GeV proton transfer line for the majority of its length (see Figure 3-6). Since the MI-F11 and 150 GeV/c beamlines share the same extraction channel, a vertical bend is required to produce the required separation. The location and strength of this bend is driven by the elevation difference between the MI (715'8.7"), Tev (723'4.5"), and MR-F11 (725'6",) and the requirement of a matched vertical dispersion function in both beamlines. The design of this beamline is still under study.

Modifications to Main Ring F11 to F17 magnet string

This section of magnets will be used in their current location. Only minor modifications to the magnet bus will be required to power the dipole

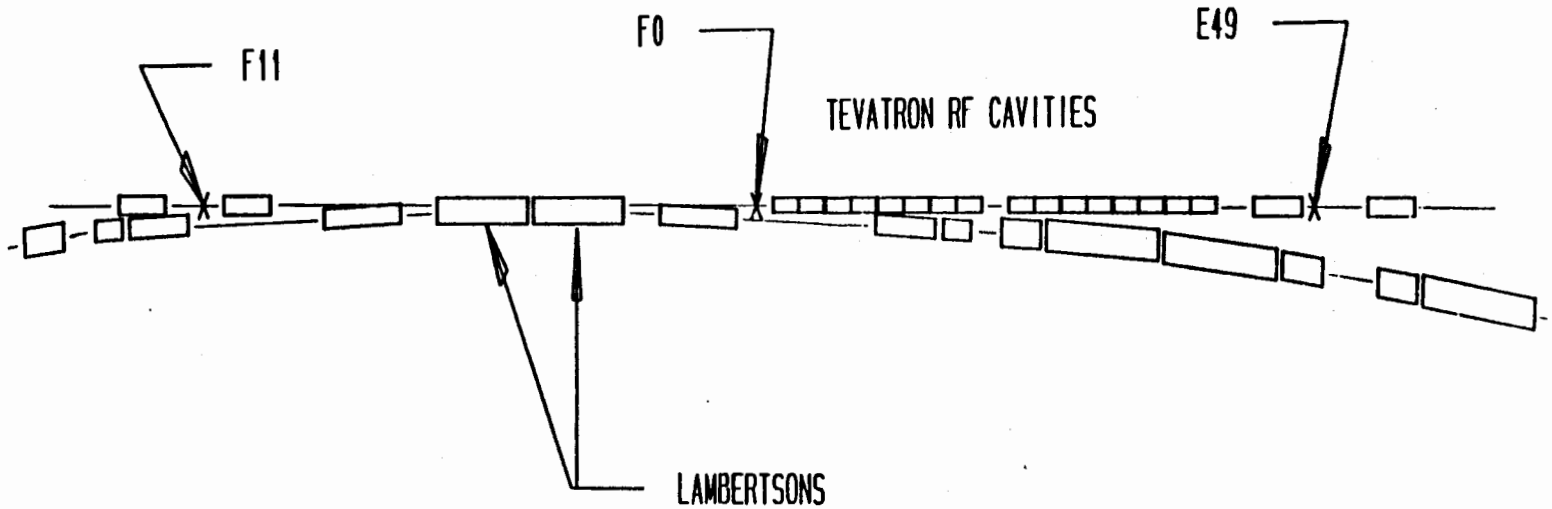


Figure 3-7. Plan view of the F0 region in the Tevatron with the 150 GeV proton and antiproton injection lines shown.

and quadrupole circuits. The B1 magnets (1.5"X5" beam pipe) will be replaced with B2 magnets (2"X4" beam pipe) to increase the acceptance for antiproton transfers. In addition, it may be determined advantageous to replace the six B2 magnets at the largest vertical β-function locations with B3 magnets (3"X5" beam pipe). The quadrupoles at F11 and F12 will be replaced to make them look like regular cells in order to simplify the optics and reduce the beam sizes. A Main Ring power supply located at F1 will be used to power the bending magnets in this section. The focussing and defocussing quadrupole busses will be powered in series by a new supply. The dipole correction elements in this section will remain for use in smoothing the orbit for 8 GeV antiprotons.

Connection with the Existing AP-1 Beamline

Currently, a kicker at E17 is used to supply the required orbit distortion necessary to place the beam in the field region of a Lambertson magnet at F17. The Lambertson will be replaced by a vertically deflecting B3 to bend the beam up to miss the first downstream MR dipole and enter the AP-1 line. The match between the MR F17 and the AP-1 line will not be altered. The advantage of the B3 magnet is to provide a larger aperture for the 8 GeV antiprotons. The B3 magnet must be turned off for slow spill to Switchyard.

3.4 The 120 GeV Slow Spill Line

The 120 GeV Slow Spill Beamline is used to transport slow and fast extracted beam from the MI to the experimental areas for a variety of purposes during collider and/or fixed target runs. This beamline uses four beamline sections: 1) MI-F11, 2) F11-F17 magnet string, 3) F18-A0 magnet string, and 4) the new section of beamline between F49 and Switchyard.

Modifications to F18-A0 Magnet String.

The magnet string will remain in its current location. Two additional bending magnets will be added to the MR bus on either side of the 7' quadrupole at F49 to move the beamline trajectory for matching into Switchyard. Minor bus work will be needed to connect the four power supplies required to ramp the bending magnets in this section. One MR power supply at F3 will be used to power the two quad busses in series. The correction dipole magnets can be removed from this section for use in the Main Injector, since they are not useful at 120 GeV. A savings in operating cost could be realized by replacing the B2 magnets in this section with B1 magnets, which have a lower impedance.

F49 to Switchyard

Approximately 130 meters of new beam transport are required to join F49 to the existing upstream end of the Switchyard without interfering with fixed target operation from the Tevatron. In addition to the two MR B2

magnets added in series with F18-A0 string, a second horizontal bend center (or 2 B2 magnets) is required for the proper horizontal trajectory. Two vertical bends located at the Switchyard interface and 40 meters upstream provide the necessary vertical trajectory for entrance into the Switchyard.

3.5 Beamline Magnets and Power Supplies

Magnet requirements for all beamlines are summarized in Table 3-1. Decommissioning the Main Ring and the existing 8 GeV line will provide a major source of magnets for the beamlines.

The new 8 GeV line requires construction of new TeV I style bending magnets, SDB and SDC. The SDB is a 10 ft dipole with a sagitta of 2.5" and bend angle of 0.175 radians; the SDC is a 5 ft dipole with a sagitta of about 0.6" and a bend angle of 0.087 radians. These magnets are chosen for their reliability and low power consumption. All 54 quadrupoles in the 8 Gev line are of the SQA type. About 20 of these quadrupoles exist in the current 8 GeV line, and can be reused. The remainder (34) will be newly constructed.

The two Tev injection beamlines, the MI-F11, and the F49-SY beamlines reuse existing dipole magnets for almost all the bends.

The MI and beamlines use 170 of the 192 existing 3Q84 quadrupoles.

The required trims for both the 120 GeV and 150 GeV beamlines will be constructed utilizing a current Fermilab design. These will be made using 40" of standard EPB dipole laminations.

Table 3-1: Beamline Magnet Requirements

	Length	Number	Magnet Style	Status
MI-F11 magnet string				
Dipoles		12	6-m B2	Exist
Dipoles		4	4-m B2	New
Dipoles (V)		1	6-m B3	Exists
Trims (H)		3	4-2-40" EPB	New
Trims (V)		3	4-3-40" EPB	New
Quadrupoles			3Q84	Exist
F11-A0 magnet string				
Dipoles (H)		129	B1 & B2	Exist
Trims (H)		4		Exist
Trims (V)		4		Exist
Quadrupoles		34	3Q84	Exist
A0-SY magnet string				
Dipoles		4	B2	Exist
Trims (H)		1	4-2-40" EPB	New
Trims (V)		1	4-3-40" EPB	New
Quadrupoles		4	3Q84	Exist
150 GeV				
Lambertson		2	E0 Type	Exist
Dipoles		16	6-m B2	Exist
Dipoles		16	4-m B2	New
Trims (H)		8	4-2-40" EPB	New
Trims (V)		8	4-3-40" EPB	New
Quadrupoles		6	3Q84	Exist
		2	3Q100	New
		6	3Q116	New
		18	Various lengths	New
8 GeV				
Dipoles (H)		12	SDB	New
		14	SDC	New
		1	Vernier	Exist
		1	4' dipole	Exist
Dipoles (V)		1	AP-4 bend	Exist
		3	B1(MOD)	Exist
Quadrupoles		20	SQA	Exist
		34	SQA	New
Trims (H)		5	DTRIM	New
Trims (V)		2	DTRIM	Exist
Lambertson		1	A0	Exist
Kicker		4	Booster style	New

4. CIVIL CONSTRUCTION

4.1 Overview

The Civil Construction for the Main Injector includes all below-grade beamline enclosures, shielding, above-grade buildings, roads, parking, ponds, utilities, and services to accommodate the equipment for, and operation of, the Main Injector. The Civil Construction also includes the removal and replacement of a portion of the existing Tevatron Ring Enclosure to accommodate the new Proton and Antiproton Injection Beamline from the Main Injector into the Tevatron.

The below-grade enclosures include the Main Injector Ring Enclosure and the various Beam Transport Enclosures which provide for the following beam transport lines:

1. 8 GeV protons from the Booster to the Main Injector.

2. 150 GeV protons from the Main Injector to the Tevatron.

3. 150 GeV antiprotons from the Main Injector to the Tevatron.

4. 120 GeV protons from the Main Injector to the Antiproton Source.

5. 8 GeV antiprotons from the Antiproton Source to the Main Injector.

6. 120 GeV protons from the Main Injector directly to the Beam Extraction Lines for the Fixed Target Areas.

New construction is similar to presently used and proven construction methods at Fermilab. The architectural style of the new buildings reflects, and is harmonious with, existing adjacent buildings. Existing topography, watersheds, vegetation, natural habitat and site boundaries have been carefully observed in the layout of the new construction.

Safety provisions for radiation, fire protection and conventional safety are included in this conceptual design. Energy-efficient construction techniques will be incorporated into all new structures. Quality assurance provisions will be part of all project phases, conceptual, preliminary, and final design, construction, and construction management.

4.2 Main Injector Ring Enclosure

The Main Injector Ring Enclosure is an oval-shaped, below-grade enclosure, approximately 10,900 ft. long, with a 10'-0" wide and 8'-0" high

cross-section. At utility alcoves under service buildings, heights are increased to 9'-0" and widths are broadened. Additional utility alcoves will be provided along the inside wall of the enclosure midway between the service building locations. The enclosure Plan and Sections are shown on Drawing Nos. CDR-6, CDR-7, CDR-10 and CDR-12. The floor of the enclosure is at Elevation 714'-0" or 19' to 31' below existing grade. The Main Injector Ring equipment is centered on Elevation 715'-10" or 1'-10" above the floor and is positioned 2'-0" to 2'-3" from the outer curved wall. The MI-70 enclosure is 10' high and widens to 15'. Earth shielding berms over the Main Injector Enclosure provide the required 21' earth equivalent shielding.

The Main Injector Ring Enclosure is constructed on a reinforced concrete cast-in-place (CIP) base slab on 3" thick lean concrete mud slab over compacted granular fill or undisturbed glacial till. Both CIP and precast reinforced concrete wall and roof construction are used, but 9,936' of the ring will be built with precast concrete inverted ''U'' wall/roof sections which are welded to the CIP base slab. Nearly 26,000' of this type precast have been economically constructed at Fermilab during the past two decades. The enclosures beneath service buildings and the alcoves will consist of CIP base slab, walls, and roof. Underdrains, moistureproofing, and granular backfills are used to insure a dry enclosure.

Cable trays, power bus, piping, lighting, and other utilities are ceiling- or wall-mounted on outer walls. Numerous penetrations connect to the service buildings constructed above the Main Injector Enclosure's utility alcoves.

Equipment access to the Ring Enclosure is provided by an open hatch and semi-circular labyrinth from the RF/MI-70 Service Building crane bay. Personnel access stairs to the Main Injector are provided at six service buildings including the RF/MI-70 Service Building. Stairs occur at the two Abort Service Buildings. Ventilation equipment is near these stairs and is described in Section 4.11 below.

A common earth berm above the Main Injector Enclosure defines the location of the below-grade Ring Enclosure. The top of berm will generally be at elevation 743'-0" except at the higher terrain of the western quadrant where the berm will be constructed at an elevation 3'-0" above the existing grade.

4.3 Beam Transport Enclosures

Although there are six functionally different beam transport lines, only three distinct beam enclosures are required through the use of shared beam elements and shared enclosures. Drawing Nos. CDR-10 through CDR-18

illustrate the enclosure configurations in Plan, Section and Elevation views.

The 8 GeV Beam Enclosure is a 2,060 foot long structure, 8'-0" high and 10'-0" wide in straight sections and 11'-0" wide in arcs. The floor is slightly sloping to follow the beam elevations. Earth shielding of 21'-0" is used above this enclosure except at roads where steel shielding is used to reduce the earth requirements. In the area of Well Pond Road, existing steel shielding will be removed and replaced to maintain shielding integrity. Access is from a shielded hatch under the North Hatch Building crane bay. Earth shielding of 16'-0 is currently provided at the North Hatch Building, but the final shielding design for this building will be studied further.

The two 150 GeV Injection Beam Enclosures for proton and antiproton transfer from the Main Injector to the Tevatron are each 740 feet in length, 10'-0" to 20'-0" in width and 8'-0" high with sloping floors. Earth shielding of 21'-0" to exterior berms and 15'-0" to interior building floors is currently proposed. This area of shielding is also under study. While shielding at the MI-70 Service Building can easily be accommodated by relocating the structure further from MI-70 Enclosure, the relative position of the Tevatron RF Enclosure and the RF Service Building are fixed so that increased shielding would require steel plate shielding or a concrete haunch inside the service building. Access is from the Main Injector Ring Enclosure in each case. The 120 GeV protons from the Main Injector to the Antiproton Production Target and the 120 GeV Extracted Proton Test Beam to the Fixed-Target areas are also transported from the Main Injector through the Proton Injection Enclosure. These beams travel to the Tevatron Enclosure at F-Zero where both beams are injected into a beamline arc consisting of the former Main Ring accelerator components as far as either F-17 in the case of the antiproton production or to A-Zero and the start of the Switchyard for Fixed-Target beams in the case of the test beam. The 8 GeV antiprotons are transported to the Main Injector following the 120 GeV antiproton production line in reverse from F-17 to F-Zero and back into the Main Injector.

Construction details of the Beam Transport Enclosures are very similar to the Main Injector Ring Enclosure. Additional personnel stairs are provided for the 8 GeV Enclosure as well as the interrupted Antiproton Transport Enclosure.

4.4 Main Injector Service Buildings

Ten service buildings in five size configurations contain equipment, services, and utilities for the Main Injector and various beam transport

lines. Other equipment for the beam transport lines will be contained in the existing Transfer Gallery. Locations of the ten service buildings are shown on Drawing No. CDR-6.

Service Buildings MI-13, MI-30, MI-50 and MI-53 are four identical buildings that are illustrated on Drawing Nos. CDR-19 and CDR-20. These buildings are located outside the shielding berm, approximately 1,800' apart. Since the buildings house the magnet power supplies, the locations occur following every 50 dipole magnets in the beam enclosure below. The buildings also contain control racks, pumps, and heat exchangers, and include a CIP concrete passageway over the berm and a stair enclosure to provide personnel and equipment access to the beam enclosure. Conduits to a utility alcove off the beam enclosure below provide for dc bus, power cable, control cable, and LCW piping via the aforementioned passageway.

The four buildings are 38'-4" wide and 47'-4" long in plan with 10'-0" clear interior heights. Construction is insulated metal siding on a steel frame with built-up roof and concrete floor. The concrete passageway will be designed to provide a tornado shelter. The electrical and mechanical systems for these buildings are described in detail in Sections 4.11 and 4.12 below.

Service Building MI-10 is similar to the above four buildings in construction, but is 50'-0" wide and 50'-0" long. The increased size is necessary to house additional power supplies for nearby 8 GeV beam transport line.

Service Buildings MI-20, MI-40 and F-17 Kicker Building are small, single-purpose buildings containing the pulsed power supplies for the Main Injector Beam Abort and Beam Transfer Kickers. These buildings are 20'-0" square with 10'-0" clear interior height. There is stair access to the beam enclosure below at MI-20 and MI-40. Construction is similar to the other service buildings.

Service Building MI-70 is a large, multi-purpose service building that is connected to the rebuilt Tevatron Service Building F-Zero. Both buildings are shown on Drawing Nos. CDR-21 and CDR-22. The construction scenario is described below in Section 4.7.

Service Building MI-70 includes a 50' by 75' by 24' high bay served by a 25-Ton crane, and low bay areas of 75' square and 25' by 300'. Within the high bay is the 8' by 30' equipment hatch and a 5-Ton freight elevator connecting to the curved access labyrinth into the Main Injector Ring Enclosure. Studies are underway to optimize the high bay space requirements including magnet storage and hatch location which could result in a larger

or reconfigured space. In the low bay areas are housed Main Injector and beamline power supplies, Main Injector RF power supplies, LCW pump and deionizer equipment, HVAC equipment and access stairs.

The North Hatch Building is sited approximately midway along the 8 GeV Beam Enclosure in the immediate vicinity of the existing AP-50 Service Building. The exterior treatment is therefore similar to and consistent with, the Antiproton Source Service Buildings. This configuration is shown on Drawing No. CDR-23.

The North Hatch Building is 46' wide by 120' long with 16'-0 clear interior height. A 25-Ton crane serves the high bay area which includes a shielded access hatch 7'-2" by 24'-2". The hatch and adjacent stairs independently connect to an access enclosure leading into the 8 GeV Beam Enclosure. Power supplies, LCW pumps and control racks are located in the designated areas shown on Drawing No. CDR-23.

4.5 F-Zero Beam Enclosure and F-Zero Service Building Addition.

The F-Zero Beam Enclosure contains components from the accelerator(s) to be relocated from the existing Main Ring, as well as from several beam transport lines. Functionally these are elements of the 150 GeV Proton Injection Line, the 150 GeV Antiproton Injection Line, the 120 GeV Antiproton Production Line, the 8 GeV Antiproton Accumulator to Main Injector Line, and the 120 GeV Extracted Test Beam Line. As mentioned above, some of these lines share common elements at certain locations, or share common enclosures at other locations. In the immediate F-Zero location, a back-to-back double ''Y'' must be constructed as seen in Drawing No. CDR-11.

The existing F-Zero Enclosure has insufficient space for the new transport beams to be included in addition to provisions for the accelerator(s) to be located in the Main Ring. Hence it must be completely demolished and rebuilt. In order to do this construction work, a portion of the existing F-Zero Service Building directly above the F-Zero Enclosure must also be demolished and then rebuilt. Refer to Section 4.9 for a description of the earth retention system planned to accomplish this work, which is a three-stage process: 1) the new Main Injector Enclosure is built, and most of the MI-70 Service Building constructed, 2) The existing F-Zero Enclosure and Buildings on top are demolished, and a new F-Zero Enclosure constructed which connects to stubs left incomplete when the Main Injector was constructed, and 3) The F-Zero Service Building is rebuilt and a connecting link to the MI-70 Service Building constructed. All these steps may be seen in Drawing Nos. CDR-9, CDR-11, CDR-21 and CDR-22.

The demolished section of the existing F-Zero Enclosure will be approximately 400' long, and it will be replaced with the aforementioned double ''Y''-shaped structure as seen in Plan view in Drawing No. CDR-11. The width of the common structure varies from 17'-0" to 24'-0" and the height is either 8'-0" or 10'-0". Of the four ends in the double ''Y'', two will reconnect to the existing Main Ring tunnel, and two to the stubs left from the earlier construction of the Main Injector and the Beam Transport Lines. The floor of the enclosure under the Main Ring Accelerator(s) will be at Elevation 722'-6" and the floor of the enclosure under the Beam Transport elements will be at a lower elevation, requiring a step across the width of the enclosure as seen in cross-section in Drawing No. CDR-22.

The F-Zero Enclosure is constructed of CIP reinforced concrete. Since no portion of the existing base slab can be re-used due to the increased span loads, a completely new base slab will be poured. The glacial till and the existing granular sub-base is adequate. Underdrains from the existing Tevatron/Main Ring Enclosure and the new Beam Transport Enclosures will be routed to new sump pits. Moistureproofing and granular backfills will be used similar to the Main Injector.

An existing freight elevator, stairs, and curved labyrinth from the re-used portion of the F-Zero Service Building will remain to service the new beam enclosure on the Tevatron side. Access on the opposite side will be through the beam transport lines, and stairs and freight elevators in the MI-70 building. Numerous penetrations connect the building and the enclosure below and are shown in the drawing sections.

The F-Zero Service Building Addition and the connection to the MI-70 Service Building can be built only after the F-Zero Beam Enclosure below is completed and backfilled. A 25'-0" wide, 237'-0" long, 12'-0" clear height addition is built on top and parallel to the F-Zero Enclosure for RF power and controls for the accelerator(s) in the Tevatron/Main Ring Enclosure. A 50'-0" wide, 50'-0" long, 12'-0" high addition at Elevation 745'-6" crosses the space between the two accelerator enclosures as projected to the surface, connecting the F-Zero Service Building to the MI-70 Service Building. This structure is seen in Drawing Nos. CDR-21 and CDR-22. The final connected structure encompassing MI-70 and F-Zero buildings is at three different elevations; Elevation 742'-6" for the preserved ''front or southeast'' portion of F-Zero, Elevation 745'-6" for the reconstructed Tevatron RF and connection section, and Elevation 741'-0" for the MI-70 Main Injector RF and service section.

The construction of the F-Zero addition is similar to the existing structure, with insulated metal siding over a steel frame, built-up roof and concrete floor. Equipment access doors are provided to all large equipment areas.

The co-joined F-Zero/MI-70 building contains the RF cavity power supplies for the Main Injector and the Tevatron accelerator(s), magnet power supplies, an existing helium compressor room, LCW cooling systems, control racks, test areas and small technical work areas. The space allocation is shown on the drawings.

4.6 Industrial Building No. 5

The Industrial Building No. 5 will be used for component fabrication and final assembly for many of the Main Injector magnets. The addition of this building in the Fermilab Industrial Area allows magnet production to be completed according to the schedule without impacting other Fermilab on-going magnet programs.

Industrial Building No. 5 will be located north of the present Industrial Area rear parking lot and immediately west of the present Industrial Building No. 3. Refer to Drawing No. CDR-33. Siting the new building in this location will allow for use of the existing parking areas and will provide convenient access to the facilities and personnel in the Industrial Area. Utilities and services are available nearby for extension to the new building. Minor reworking of a drainage ditch and extension of a storm sewer are required. Based on soil borings and previous construction at the Industrial Center Building, shallow concrete caissons are an economic choice for the building foundation.

The exterior of Industrial Building No. 5 will match the appearance of the four sister Industrial Buildings No. 1 through No. 4. The steel frame building will have a high bay 60 feet wide by 300 feet long with a roof height of 30 feet, serviced by a 30 ton bridge crane. A 30 foot wide by 90 foot long single-story side bay will extend from the south side of the building to provide space for mechanical equipment, toilets and a lobby area. A 5'-1" high concrete kicker wall at grade is topped by flush metal vertical siding to the roof. Vertical window areas will be provided on the north wall of the high bay. Equipment access will be provided at either end of the high bay with personnel doors spaced around the building perimeter to provide proper exiting.

All areas in Industrial Building No. 5 will be air conditioned. Lighting levels and power outlet distribution will be similar to the North Hatch Building. A 1500 kva substation will be installed near the west end of the building and will connect to a 2000 Amp switchboard for the various power needs within the new building.

4.7 Foundation Systems, Earth Retention and Active Soil Control

All base slabs and piers under Main Injector Enclosures will be founded on glacial till with high bearing capacity. Soil boring logs near the Main Injector perimeter indicate the unsuitability of shallow foundations if founded on high water bearing strata above the glacial till. Soil boring locations, elevations of glacial till, and unconfined compressive strengths are shown on Drawing No. CDR-4. During Title I, additional borings will be made to better define the sub-surface conditions.

Although the glacial till varies in depth of 4 to 21 feet below grade, the requirements for various beam enclosure structures place the base slab excavation well into the till except at a very few isolated areas. In these areas, a compacted granular backfill or lean concrete will replace the several additional feet required to reach glacial till.

The foundations for the six service buildings around the Ring will be shallow concrete strip and spread footing approximately 4 feet below grade. The concrete passageways over the berm will be partially supported by two concrete piers extending to the top of the Ring Enclosure below. The North Hatch Building will be supported by concrete shaft walls bearing on the Ring Enclosure below as well as drilled concrete piers bearing on the same till strata.

Earth retention systems will be used during the various construction phases in order to retain foundations for existing beam enclosure structures. In addition, the retention systems will contain and confine much of the active soil adjacent to these existing beam enclosures. With these methods, the Main Injector Ring Enclosure and much of the Beam Transport Enclosures may be built during normal accelerator operations.

Sheet piling, driven in Phase 2 beside the existing Tevatron F-Zero Enclosure and RF Service Building will allow construction of the Main Injector Ring Enclosure and MI-70 Service Building during accelerator operations. This sheet piling will be driven parallel to and 21 feet beyond the outer radius of the the Tevatron Enclosure to approximately 42 feet depth and 440 feet length. Refer to Drawing Nos. CDR-9, CDR-11, CDR-21 and CDR-22.

A second row of parallel sheet piling will be driven along the southwest wide of the proposed Main Injector MI-70 Enclosure during Phase 2 to be supported by horizontal bracing between the two piling rows and to permit excavation and construction work. After the MI-70 Enclosure is completed and partially backfilled, both the horizontal bracing and the southwest piling will be removed and re-used as part of Phase 3 work.

The salvaged sheet piling and horizontal bracing will be re-installed during the scheduled accelerator downtime which signals the commencement of Phase 3 work. After demolition of the existing RF Service Building above the Tevatron F-Zero Enclosure, sheet piling will be driven approximately four feet away from the RF Service Building foundation to approximately 40 feet depth and 370 feet length. The horizontal bracing will be installed between the two rows of sheet piling and the F-Zero Enclosure, MI Injection Enclosure and P-Bar Injection Enclosure will be built.

Soils excavated from areas adjacent to existing Tevatron Enclosures that exhibit low levels of activity will be carefully segregated, controlled and subsequently backfilled into areas by the reconstructed enclosures. Soil storage pits next to required excavations will be dug as a repository for all active soils removed during construction. The active soil bulk will be covered with an umbrella of clay soil for temporary protection and containment during the construction period. Surface water will be controlled and diverted away from these storage pits.

4.8 Master Substation, Primary and Secondary Power Distribution

Power is provided to the Main Injector through a new 345 KV overhead transmission line, a new outdoor 345 KV master substation and through 13.8 KV power feeders in ductbanks to various substations and secondary distribution for three Main Injector power systems. These systems as discussed in Section 2.14 above are: 1) Pulsed Power Supply Power System, 2) Conventional Power System and 3) Beamline Power System.

A new 345 KV switching station will be installed at the southeast corner of the Fermilab site along the Commonwealth Edison Co. transmission line corridor paralleling the E.J. & E. railroad tracks. Refer to Drawing No. CDR-1. Two manually-operated 1600 Amp, 345 KV switches will connect to Commonwealth Edison Co. Transmission Lines No. 11119 and No. 11120.

A new overhead transmission line, approximately 13,000 feet long will be installed along the southern boundary within the Fermilab site, at least 1000 feet from Illinois Highway 56, Butterfield Road. The line will bend northward along Kautz Road and will terminate at the new Kautz Road Master Substation (KMS). Double arm steel poles at an average span of 1,000 feet will carry a single 345 KV circuit with static shield wires above.

The new Kautz Road Master Substation (KMS) will be located east of Kautz Road approximately 700 feet from nearest arc of the Main Injector, 0.2 miles from the south site boundary and 1.6 miles from the existing Master

Substation (MSS) at Road A-1 and Road B. The new substation area is well drained, has been in recent cultivation and lies south of wooded areas that abut the Tevatron Ring between E-3 and E-4.

The new Master Substation (KMS) will be 400 feet by 400 feet rock base enclosed with a security fence with access gate to Kautz Road. Within this area will be the 345 KV dead-end structures, aluminum tubular bus bars and insulators, motor operated 345 KV switches, SF6 main circuit breaker, three transformers, a walk-in structure for secondary equipment and Main Injector harmonic filters and switchgear. Foundation pads and vaults, oil containment sumps, lightning and ground grid are also included.

One new transformer and two existing transformers from the present Master Substation (MSS) will be installed in the new Master Substation (KMS). Refer to Drawing No. CDR-29. The new transformer will be 40 MVA capacity (40/53/66.6 MVA-OA/FA/FOA), 345/13.8 KV, 3 phase, 60 Hz oil filled and will be used for the Main Injector Pulsed Power Supply and Beamline Power Systems. An existing 60 MVA Transformer 82B, that will be retired from Main Ring Pulsed Power Supply service, will be used for the Main Injector Conventional Power System. Another existing 40 MVA Transformer 84A, currently an MSS on-line spare, will be moved and reinstalled in the new Master Substation (KMS) as an on-line spare.

The secondary sides of the three transformers will be connected by 3,000 Amp, 13.8 KV non-segregated outdoor bus to 13.8 KV, SF-6 type main and feeder breakers with sufficient interrupting capacity for the available short circuit currents. These breakers, together with metering, relaying and communication equipment are all housed in an enclosed metal walk-in structure.

Underground concrete-encased ductbanks with precast concrete manholes will route the 13.8 feeders from the new Master Substation (KMS) to the various Main Injector power systems. Refer to Drawing No. CDR-30. Other ductbanks will connect back to the Main Ring Duct Bank near E-2 and F-2. With these connections and the use of six existing Main Ring feeders, approximately 40 MVA of primary power may be back-fed to the Master Substation (MSS).

The Pulsed Power Supply System is fed from the new 40 MVA transformer in the Master Substation (KMS) through four 13.8 KV feeders for MI Ring pulsed power and one 13.8 KV feeder for MI Beamline power. The MI Ring uses three loop feeders carried through an underground ductbank, the ends of which connect through switchgear at the KMS and near the MI-70 building area. At each service building, there is a disconnect switch to supply power to the power supplies. This routing is shown in Drawing No. CDR-19.

A paralleling switch at MI-30 will enable uneven loading of each segment without overloading the feeders. This switch can also be used for feeder isolation for maintenance purposes. The power for the beamlines will require one feeder with 1500 KVA Substations at F-Zero and one 500 KVA Substation at the North Hatch Building.

The conventional power system will be fed from the relocated Transformer 82B and will consist of one 13.8 KV feeder around the Main Injector Ring, with a 500 KVA (1500 KVA at MI-70) transformer at each of the principal Ring service buildings and North Hatch Building. The conventional power will be used for building power, lights, pumps, etc. The existing Main Ring conventional power feeder will be intercepted at F-2 and will be extended to the Main Injector switchgear area located at MI-70 through an underground ductbank, as shown in Drawing No. CDR-31. From this switchgear, the feeder will continue as a direct buried feeder to the six service buildings. At each service building there will be a disconnect switch with a ductbank connection to the conventional power transformer. The conventional feeder to the North Hatch Building will be routed through ductbank.

Conventional power will be connected to power distribution panelboards in each service building. 480/277 volt, 3 phase branch circuits will power the water pumps, heating and ventilating equipment, control racks and service outlets. Step-down transformers and panelboards provide 208/120 volt power for lighting and outlets. Separate panelboards for isolating beam equipment at 480/277 volt and 208/120 volt are provided. Refer to Drawing No. CDR-19.

4.9 Primary Cooling, Distribution and Mechanical Systems.

The primary heat rejection medium for the 12 MW generated by the Main Injector is cooling pond water (PW). Drawing Nos. CDR-6 and CDR-26 show the two new interconnected cooling ponds that roughly encircle the Main Injector Road and provide 16.0 acres of cooling surface. The ponds total 10,400' in length, are 60' wide, and the average to maximum depth is 4'-6" to 7'-0". Transverse concrete dams near each service building provide intake and discharge piping separation and elevation control. Pond water level varies from Elev. 739' matching the Tevatron ponds at F-Zero down to Elev. 732'. Cross-connect piping between the Main Injector ponds and the Tevatron Ponds allow load shedding and water level control.

As described in Section 2.14 the Low Conductivity Water (LCW) system is a closed piping loop exchanging heat from the Main Injector and Beam Line magnets and power supplies to the pond water. Much of the equipment now in

the present Tevatron Service Buildings will be re-installed in the new Main Injector Service Buildings and perform in a similar capacity. New LCW piping will be installed in the Main Injector Beam Enclosure. System-wide deionizers are located at the RF Building and the North Hatch Building for slip stream polishing.

Existing chilled water (CW) in the F-Zero Service Building which comes from the Central Utility Building will be retained and re-used, and extended into the attached MI-70 building. The new combined loads on the chilled water system are comparable to the present loads.

The underdrain system for all new beam enclosures is similar to the design used for the Antiproton Rings. Perforated drain piping surrounded by granular material and covered with geotextile fabric is installed on both sides of the enclosure base slabs. Duplexed pump sump pits connect to the underdrain piping and discharge into surface ditches.

The fire detection/suppression systems for the Main Injector are proposed to be similar to those systems used for the Tevatron enclosures and buildings. Industrial Cold Water (ICW) will serve fire hydrants and hose cabinets in the F-Zero, MI-70, and North Hatch Service Buildings. These buildings will also be equipped with smoke detectors which report to the site-wide FIRUS system, as will be the other service buildings. The Main Injector tunnel enclosure, and the Beam Line Enclosures will be equipped, as is the present Main Ring, with ''derivative thermal detectors'' and link to the FIRUS system. An independent fire protection consultant has been engaged by Fermilab to review the safety requirements of the Main Injector project including fire protection/suppression and exiting designs with respect to recognized codes and standards.

Moderate ventilation rates with dehumidification will be used in the Main Injector Beam Enclosure. Refer to Drawing Nos. CDR-24 and CDR-25. Ventilation fans will be placed at alternate service buildings to supply/exhaust air through underground ducts to the alcove areas of the Main Injector enclosure. Two air changes per hour will be used when needed during non-operating periods. Periodically placed dehumidifiers about the beam enclosure will control humidity. Also, air will be circulated through the longer beamlines by a push-pull ventilation system.

The Main Injector and North Hatch Service Buildings are equipped with a variety of HVAC equipment to accommodate the required occupancies. Local, self-contained air conditioners will be used to cool Control Rack areas. Unit heaters will heat the power supply and water system areas when operations are off. Roof fans and wall louvers will provide ventilation to these areas when the temperature requires.

4.10 Drainage and Wetlands

The construction site is mainly open cropland with approximately one-third recently removed from leased cultivation. The overall drainage pattern is to the southwest into Indian Creek. There are isolated areas of trees and fence rows, shallow ditches meander the site and abandoned agricultural tiles are in evidence.

The Federal Emergency Management Agency's National Flood Insurance Program Maps indicate that part of the construction site is within the Indian Creek floodplain for a 100-year storm. A 500-year storm would only increase the 100-year crest elevations by 18" or less. The construction area also contains wetlands, though less than 10 acres would be disturbed. The wetland areas shown on the site drawings CDR-4 and CDR-5, are based on definitions and classifications obtained from a survey and report by an environmental consultant engaged by Fermilab in the fall of 1990. These areas overlap the 100-year storm floodplain and occupy small areas within the construction zone. The two types of wetlands that would be affected, as defined by the Illinois State Natural History Survey Division, are in the Palustrine System. The dominant vegetation types are Emergent Herbaceous Angiosperms and Forested with Large Broad-leaved Deciduous Trees. Both types of wetlands are classified as either temporarily flooded or seasonally flooded.

Detailed and specific definitions of the wetland areas, floodplain and storm water management have been identified by environmental consultants and the proposed mitigation and compensatory plans have been included in a Floodplain/Wetland Assessment Report now being reviewed by the U.S. Army Corps of Engineers, Illinois Environmental Protection Agency, and the Department of Water Resources of the Illinois Department of Transportation, with anticipation of a Section 404 Permit later this spring.

The Main Injector impacts the site with three salient features; the shielding berm, the new road and the cooling ponds. The site drainage will be designed to minimize any impact according to the following design goals during both construction and operations phases:

1. <u>Maintain the Existing Watershed Characteristics</u> within the project area and the surrounding topography.

   Construction Phase:

   The flow at Indian Creek and its tributaries will be diverted temporarily as required to keep immediate construction areas

dry. The normal water courses will be restored as construction work in the Indian Creek areas is completed. The normal flows through the center of the Main Injector will be unimpeded.

Operations Phase:

The flow at Indian Creek and its tributaries will continue unimpeded as it passes through the Main Injector area except in cases mentioned below. Special attention will be given to maintain the watershed characteristics in the center of the Main Injector Ring to maintain satisfactory environment for the resident wildlife. Any wetlands that will be disturbed during the course of the project will be restored as closely as possible to their original condition. Mitigation plans for any disturbance and/or loss of wetlands will only be finalized after consultation with the Corps of Engineers. Compensatory wetlands will be created in the vicinity of the disturbed wetlands in a ratio of 1-1/2 to 1 of existing wetlands removed from the Main Injector site.

2. Control Surface Runoff into Indian Creek so as to create no adverse impact on downstream off-site residential areas.

Construction Phase:

There will be no reduction in the retention capacity of the Indian Creek drainage basin during the construction of the project. Temporary retaining ponds will be created to counteract reduced capacity during construction. These ponds will hold only diverted excess storm water and will provide the same retention capacity as the areas temporarily disturbed by construction work. Normal flow characteristics of the basin will be not disturbed.

Operations Phase:

There will be no reduction in the retention capacity of the Indian Creek drainage basin. The Illinois State Water Survey has supplied the surface water information that will be used for the development of surface runoff control plans. The cooling ponds will be designed with an additional storage capacity in order to retain excess storm water runoff. The stored water would be released at a controlled rate in order to reduce flow peaks that most severely affect downstream sites. Compensatory 100-year floodplain areas will be created

to replace areas removed from Main Injector site.

3. Provide for Collection of Surface Runoff when required into the cooling ponds using pump stations to meet project requirements for cooling loads.

4. Elevate all Buildings, Roads and Ponds above any potential high water levels.

In general, drainage structures will be placed through and under the shielding berms, road beds and ponds to maintain the normal surface water flow through the interior ring area of the Main Injector. Pump stations, control dams and weirs will be provided for seasonal adjustment of the drainage patterns needed to maintain the watershed characteristics. Operations of these controls will be coordinated with the existing Swan Lake and Booster Pond cooling systems which also connect to Indian Creek.

5. COST ESTIMATE

The Total Estimated Cost for construction of the Main Injector, associated beamlines, and required modifications to existing facilities is $177,800,000 in then-year dollars. The cost estimate is summarized in Table 5-1. An additional $19,200,000 will be required in direct R&D, pre-operating, and capital equipment costs to support the project. The cost estimate methodology is based on a Work Breakdown Structure which has been modified since CDR 2.3. Our recent experience with the TeV I (Antiproton Source) and Main Ring overpass construction projects forms the basis for a large fraction of the cost estimate of this project.

5.1 Methodology

A Work Breakdown Structure (WBS) is set up in order to identify all required components of the Main Injector project and to insure that each component is adequately specified and incorporated into the estimate. The WBS through third level is shown implicitly in Table 5-1. The actual WBS used for the cost estimate extends through the seventh level.

All components are estimated at the lowest applicable level in 1991 dollars and then summed upwards. At the lowest level materials costs and labor hours are entered separately along with the basis for the estimate. Labor estimates are associated with a craft code specifying the type of labor to be used. When materials costs are based on previous purchases of identical components they are escalated to 1991 prices using standard DOE inflation factors. The translation of craft codes into hourly costs is based on current local labor rates and is given in Table 5-2. Through this approach a categorized estimate of the total manpower required for completion of the project is created at the same time as the cost estimate. The manpower estimate is given in Table 5-3.

The cost estimate is produced in 1991 dollars. The TEC in $1991 is $155,200,000. Escalation to then year dollars is accomplished through a convolution of the cost spending profile with DOE construction project escalation rates. (See Section 5.7.)

5.2 Technical Components

The technical components of the rings and beamlines include magnets, power supplies, vacuum, RF, diagnostics, controls, and safety systems. Included in the estimate are materials, fabrication, and installation costs. The total cost estimate for these components is $77,100,000 (1991). Engineering design and inspection (ED&I) are included in the component cost. All components are similar to components already built and installed at

other locations within the Fermilab complex. The only extraordinary items are the new dipole magnets and the 9000 Amp power supply. A modest R&D effort is associated with these items.

5.3 Civil Construction

The civil construction cost estimate includes the Main Injector ring enclosure, beamline enclosures, service buildings, modifications to the Main Ring enclosure and service building at F0, and all associated utilities including primary power and water distribution. Also included are the requisite sitework and road development, as well as a new industrial building required for magnet assembly. Specifically provided for are new cooling ponds, environmental restoration of impacted wetlands, and the new 345 KV Kautz Road Substation.

The total civil construction is estimated at $46,000,000 (1991). Included is $600,000 specifically targeted for environmental mitigation (accounted for in WBS 1.2.1 and 1.2.2). Standard estimating guidelines (Means) are used. The cost estimate includes contractor overhead and profit at 20%. The ED&I component of the cost assumes the use of an outside architectural and engineering (A&E) firm for design work on all civil components removed from the interface between the Main Injector ring and existing facilities.

5.4 Engineering Design Inspection & Administration (EDIA)

ED&I is incorporated into component costs at the lowest applicable WBS level and summed upwards. Project management costs are explicitly estimated under WBS 1.3. Total estimated EDIA as a fraction of the total components cost is 18.2% (including 13.1% for ED&I, 3.8% for Project Management, and 0.7% for G&A). The G&A rate is the established incremental overhead on construction projects at the laboratory. EDIA is estimated at $19,800,000 (1991).

5.5 Contingency

Contingency is assigned to all technical components on the basis of the cost estimating procedure. Estimates based on previous actual purchases, on vendor quotes, or on catalog prices are assigned a 15% contingency. Estimates based on undocumented engineering estimates (approximately 25% of the total materials cost estimate for the project) are assigned a 25% contingency. An across-the-board 25% contingency is applied to all labor estimates. Civil construction contingencies are assigned at the third WBS level on the basis of previous experience with similar projects.

The total contingency assigned to the project is $26,600,000 (1991). This represents 20.7% of all construction, installation, and EDIA costs. This level of contingency is felt to be appropriate for the conceptual design stage of a project with minimal technical risk.

5.6 Other Project Costs (R&D, Pre-operating, Capital Equipment)

Specific R&D required to support the Main Injector is limited to the areas of the dipole magnet, the 9000 Amp/1000 Volt power supply, the special quadrupole magents required at the MI straight sections, RF power amplifiers (PAs), and 53 MHz vernier cavities. Twelve dipole magnets, two special quadrupole magnets and tooling, one 9 MVA power supplies, three new PAs, and two low voltage, low impedence cavities will be constructed using R&D funds. Total estimated cost of this effort is $11,900K. These costs are included in the TPC as is a 37% G&A surcharge, 30% contingency, and escalation.

Pre-operating costs ($6,300K) include the operation of the MI ring and beamlines during a three month commissioning period and servicing of equipment to be removed from the Main Ring and used in the Main Injector. Capital equipment required in support of R&D is estimated at $1000K.

5.7 Spending Profile

Both obligations and cost profiles have been developed based on the construction and installation schedule described in Chapter 6. The profiles are developed at WBS level 3 for all technical and civil components. The project obligations and cost profiles are given in Table 5-4.

Table 5-1: Main Injector Cost Estimate (Dollar amounts in thousands)

WBS	Description			Total
1.	**MAIN INJECTOR CONSTRUCTION (TEC)**			177800
1.1	**Technical Components**		77060	
.1	Magnets	43044		
.2	Vacuum	672		
.3	Power Supplies	9271		
.4	RF Systems	3276		
.5	Aborts	59		
.6	Kickers	1090		
.7	Slow Extraction	267		
.8	Instrumentation	1384		
.9	Controls	821		
.10	Safety Systems	562		
.11	Electrical Utilities	9612		
.12	Mechanical Utilities	3163		
.13	Installation	3843		
1.2	**Civil Construction**		46050	
.1	Phase 1	6402		
.2	Phase 2	30376		
.3	Phase 3	8116		
.4	Phase 4	1155		
1.3	**Project Management**		5530	
.1	Project Management	3502		
.2	Accelerator Physics	1134		
.3	G&A	894		
1.4	**Contingency**		26610	
1.5	**Escalation**		22560	
OTHER PROJECT COSTS (escalation included)				19200
2.	**R&D**		11850	
3.	**Capital Equipment**		1000	
4.	**Pre-operating**		6300	
	TOTAL PROJECT COST (TPC)			197000

Table 5-2: Cost Estimate Labor Codes & Rates ($/hour)

Fabrication		
Technician, Conventional Magnets	T1	27.50
Technician, Accelerator Division	T2	18.70
Technical Support	T3	29.00*
Shops, average capability	S1	33.00*
Shops, specialized/precision	S2	38.00
Installation		
Plumber, steam fitter, sheet metal	IP	41.10
Electrician	IE	38.20
Rigger, crane operator	IG	42.80
Laborer	IL	27.20
Surveyor	IA	31.10
EDIA		
Physicist	PH	33.90
Engineer	EN	32.40
Engineer, Construction Services	CE	40.00*
Designer/drafter	DC	32.00*
Drafter, Accelerator Division	DR	22.20
Programmer	PR	30.90
Project Management	PM	40.00
Architectural Engineering	AE	50.00
Administrative Support	AD	20.00

*Fermilab Service Center chargeback rates

Table 5-3: Total Labor Effort (Man-years, R&D included)

Fabrication		
Technician, Conventional Magnets	T1	290
Technician, Accelerator Division	T2	40
Technical Support	T3	52
Shops, average capability	S1	2
Shops, specialized/precision	S2	4
Installation		
Plumber, steam fitter, sheet metal	IP	10
Electrician	IE	61
Rigger, crane operator	IG	5
Laborer	IL	1
Surveyor	IA	2
EDIA		
Physicist	PH	30
Engineer	EN	58
Engineer, CES	CE	40
Designer/drafter	DC	23
Drafter, Accelerator Division	DR	31
Programmer	PR	4
Program management	PM	13
Architectural Engineering	AE	42
Administrative support	AD	18
Total		726

Table 5-4: TEC Spending Profiles (Dollar Amounts in Thousands)

Fiscal Year	Obligations		Costs	
	1989	Then-year	1989	Then-year
1992	41373	44016	26623	27821
1993	39244	43989	39494	43364
1994	37448	44016	43083	49977
1995	37177	45782	42611	52198
1996	0	0	3431	4443
Total	155200	177800	155200	177800

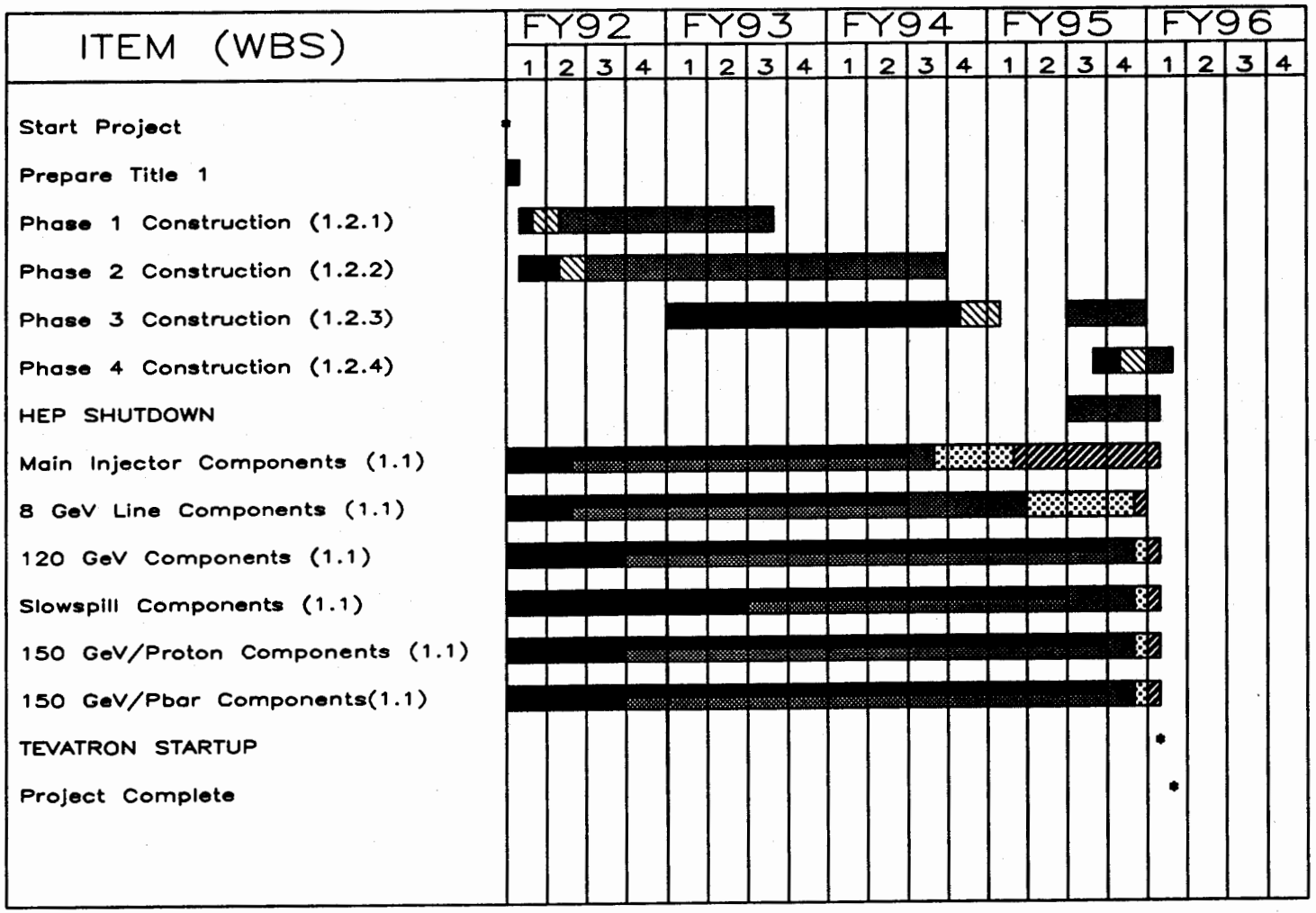
6. SCHEDULE

It is proposed that the Main Injector project be completed over the period October 1, 1991 through December 31, 1995. The schedule is shown in Figures 6-1 (project schedule). The period October 1, 1989 through September 30, 1991 will be devoted to preconstruction R&D and to the completion of all required environmental documentation and the securing of required permits. Preparatory engineering in support of construction will begin on October 1, 1991. The schedule shown reflects the spending profile given in the Construction Project Data Sheets (Appendix A) and the total manpower estimate shown in Table 5-3. The schedule results in a seven month disruption to HEP operations. This disruption will start on April 1, 1995.

A set of project milestones is given in Table 6-1. As can be seen the Main Injector ring and 8 GeV beamline can be largely installed without disturbing Tevatron operations. The length of the HEP shutdown is tied to the civil construction in the area of F0. Overall downtime has been minimized by situating the Main Injector 12 meters away from F0 so that commissioning can actually begin prior to completion of construction in this area.

Table 6-1: Major Project Milestones

	Milestone	Date	Description
1989	1	October 1	Start Magnet R&D
1990	2	September 1	Submit Request for COE Section 404 (Wetlands) Permit
	3	October 1	Environmental Assesment First Draft
	4	October 1	Complete First Dipole Prototype
1991	5	April 1	Receive 404 Permit
	6	August 14	DOE Publication of Finding of No Signifcant Impact (FONSI).
	7	October 1	Start Project, Start Title 1 Design
1992	8	March 1	Start Magnet Production
	9	April 1	Start Civil Construction
1993	10	March 1	Beneficial Occupancy (BO) of IB-5
	11	March 1	BO of Kautz Road substation.
1994	10	June 1	Complete dipole production.
	11	June 1	BO of Main Injector Enclosure, MI-70, and North Hatch Building. Partial Occupancy of 8 GeV Enclosure. Start MI and 8 GeV Installation.
	12	July 1	BO all MI Service Buildings.
	13	December 1	Complete Dipole/Power Supply Installation. Start Power Test.
1995	14	April 1	Complete Full Dipole Power Test. Begin HEP Shutdown. Begin Equipment Removal at FO. Start Quadrupole Rework.
	15	April 15	Start FO Construction.
	16	July 15	Complete 8 GeV BO. F17 Kicker BO.
	17	September 1	Complete MI Installation. Start System Test. BO of FO and 150/120 GeV Beamline Enclosures. Start 150/120 GeV Installation.
	18	September 15	Complete 8 GeV Installation. Start 8 GeV Commissioning. BO of RF/FO Wave Guide Penetrations. Start Tevatron RF Installation.
	19	October 1	Complete 150/120 GeV Installation. Start MI Beam Commissioning.
	20	October 15	Main Injector Slow Spill Startup.
	21	November 1	Tevatron Startup.
	22	December 31	Paving and Landscaping Complete. Project Complete.



BID: FABRICATE/CONSTRUCT: INSTALL: COMMISSION:
DESIGN: