# REPORT OF THE ACCELERATOR AND BEAM LINE OPTIONS WORKING GROUP*

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## 1. INTRODUCTION

This report summarizes work done before, during, and immediately after the conference. The group was led by Gerry Dugan, Gina Rameika, and Ernie Malamud. Malamud presented the group summary talk. The participants divided into six subgroups; leaders are shown in parentheses. The charge to each subgroup follows. The organization of this summary report is similar, but not identical to, the subgroup structure.

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Subgroup 1. COLLIDER OPERATION in the STANDARD UPGRADE PLAN (Glenn Goderre/Gerry Jackson). This subgroup considered the collider aspects of the Phase I and II upgrade plans[1-3]. Also considered were the collider aspects of a specific example of Phase III, namely the replacement of the Tevatron with a new ring providing 1.8 TeV per beam[4]

Subgroup 2. (a) MAIN INJECTOR (MI) DESIGN ISSUES; (b) MAIN RING (MR) ISSUES (Rod Gerig/Steve Holmes). This group considered specific improvements to the proposed MI which will enhance the performance of Phase II. Also considered were improvements which may be made to the present MR which will enhance the performance of Phase I.

Subgroup 3. THE FIXED TARGET PROGRAM in the STANDARD UPGRADE PLAN (Sam Childress/Craig Moore) This subgroup considered fixed target aspects of the Phase I and II upgrade plans[1-3] and a specific example of Phase III[4], namely the replacement of the Tevatron with a new ring providing 1.5 TeV fixed target operation.

Subgroup 4. EXTERNAL BEAM LINES IN THE EXPERIMENTAL AREAS (Gina Rameika). This subgroup considered the external beam lines associated with the upgrades.

Subgroup 5. MAGNETS for the UPGRADES and PUSHING THE LIMITS OF MAGNET TECHNOLOGY (Paul Mantsch) This subgroup considered new designs for superconducting magnets and associated large cryogenics systems connected with the accelerator systems proposed by the other subgroups.

Subgroup 6. BEYOND THE STANDARD UPGRADE PLAN (Chuck Ankenbrandt/Rol Johnson) This subgroup assumed the existence of Phase I and II upgrades[1,2], and considered new possibilities for Phase III such as new accelerators in new tunnels.

## 2. COLLIDER OPERATION IN THE STANDARD UPGRADE PLAN

### 2.1 Introduction

The discussions concerning the standard collider upgrades in the 1990's were segmented into the scheduled individual runs. The recently completed (1988-1989) and highly successful collider run II[5] was the starting point from which upgrade parameters were scaled. Figure 1 shows the assumed timetable for the discussions. Table 1 displays the evolution of many important collider parameters from collider run II through collider run VI. The details of the upgrades which correspond with future collider runs are discussed elsewhere [1-4].

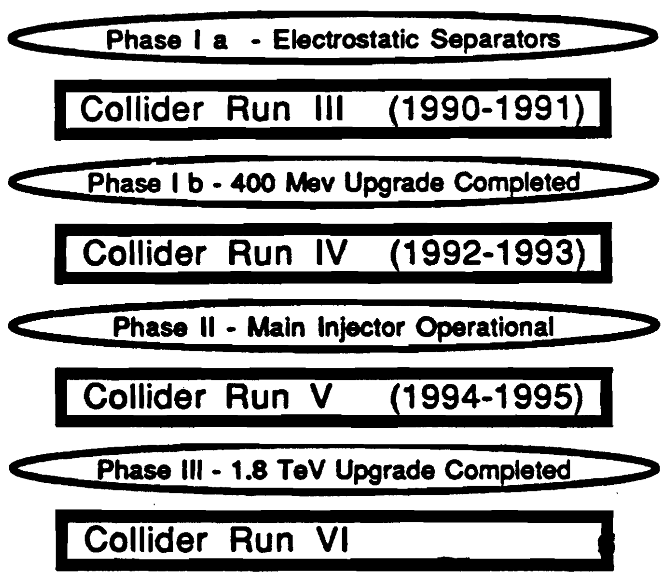


Figure 1. Assumed timetable for the standard collider upgrades

### 2.2 Collider Run III

2.2.1 Introduction. Collider run III occurs after the hardware modifications in phase Ia of the standard collider upgrade scenario. This phase is mainly concerned with the installation of electrostatic separators in the Tevatron, new low-$\beta$ systems at BØ and DØ, expansion of the Debuncher ring apertures, and the upgrade of the accumulator core stochastic cooling systems to 4-8 GHz. This work should increase the peak luminosity from $1.6 \times 10^{30}$ $cm^{-2}sec^{-1}$ in run II to somewhere between 6.6 and $9.4 \times 10^{30}$ $cm^{-2}sec^{-1}$ in run III. Because of the CDF[6] and DØ limitations on the minimum spacing between collisions, there are still six proton bunches circulating against six antiproton bunches.

2.2.2 Discussed topics. Given that run III is scheduled to occur in the next year, it is not surprising that much of the work at Breckenridge was centered on understanding the repercussions of the phase Ia upgrades. Most of the discussions centered on operation of the Tevatron with separated proton and antiproton orbits. The plan of separating the beams everywhere in the Tevatron except at the BØ and DØ interaction regions has been devised to reduce the number of head-on beam-beam

Table 1 The evolution of accelerator parameters through the upgrades.

| Parameter | | Run II | Run III | Run IV | Run V | Run VI | Units |
|---|---|---|---|---|---|---|---|
| Center of Mass Energy | | 1800 | 1800 | 2000 | 2000 | 3600 | GeV |
| Number of Bunches | | 6 | 6 | 18 (36) | 18 (36) | 18 (36) | - |
| Protons/Bunch at low-β | | 7 | 7-10 | 10-15 | 33-50 | 33-50 | $x10^{10}$ |
| Pbars/Bunch at low-β | | 2.9 | 7.2 | 3.4 (1.7) | 7.5 (3.7) | 7.5 (3.7) | $x10^{10}$ |
| Total Pbars from Core | | 26 | 60 | 98 | 142 | 142 | $x10^{10}$ |
| Pbar Transmision Efficiency | | 67 | 72 | 83 | 95 | 95 | % |
| Transverse emittance | Proton | 25 | 15 | 15 | 30 | 30 | 95% π |
| | Pbar | 18 | 14 | 19 | 22 | 22 | mm-mrad |
| Longitudinal emittance | Proton | 3 | 3 | 3 | 3 | 3 | eV-sec |
| | Pbar | 3 | 3 | 1 (.15) | .3 (.15) | .3 (.15) | |
| $\beta^*$ | | 0.55 | 0.5 | 0.5 | 0.5 | 0.5 | m |
| Pbar Stacking Rate | | 2.0 | 3.2 | 7.6 | 16.8 | 16.8 | $x10^{10}$ / hr |
| Calc. Luminosity Lifetime | | 36-55 | 14-36 | 14-32 | 11-26 | 9-22 | hrs |
| Ave. Stack before Transfer | | 64 | 82 | 137 | 198 | 198 | $x10^{10}$ |
| Optimum Stacking Time | | 24 | 25 | 17 | 12 | 12 | hrs |
| Linear Beam-Beam Tune Shift | | 0.025 | 0.007-0.010 | 0.010-0.015 | 0.016-0.024 | 0.016-0.024 | - |
| Prob. of >1 Interaction/xing | | 0.22 | 0.64-0.77 | 0.44-0.58 (0.25-0.35) | 0.94-0.986 (0.76-0.88) | 0.994-0.9995 (0.92-0.98) | - |
| Initial Luminosity | | 1.6 | 6.6-9.4 | 11.3-17 | 55-83 | 100-151 | $x10^{30}$ |
| Ave. Luminosity (60% Uptime) | | 0.31 | 1.3-1.8 | 2.4-3.7 | 11.3-17 | 20-30 | $pb^{-1}$ / week |

interactions from the present twelve to two. Schemes for the control of orbits, tunes, and chromaticities have been rechecked. The effect of long-range beam-beam interactions has been shown to be small and correctable[7,8]. The natural chromaticity generated by two low-beta insertions has been found to be quite large, but correctable[9].

Operational questions focussed on the beam position monitoring resolution required at the intersection point[10], discussion of the optimal working point for collider run III[11], and the limits on separator performance[12].

Improvements to the Linac[13,14] and Booster[15,16] and implications of these improvements on collider operation are discussed in more detail in the references.

The upgrades of the Antiproton Source apertures and cooling hardware were reviewed. In addition, work was done to refine the calculation of core longitudinal emittance as a function of core intensity[17].

Finally, the calculations of luminosity lifetime expected in this and future runs were discussed[18]. The topics reviewed included intrabeam scattering, background due to particle losses at the collider detectors, vacuum lifetime, and the effect of bunched beam stochastic cooling in the Tevatron[19].

### 2.3 Collider Run IV

2.3.1 Introduction. The dominant project of which phase Ib is composed is the upgrade of the Linac energy from 200 MeV to 400 MeV[13]. The effect is to raise the intensity which can be injected into the MR from $2\times10^{10}$ to $4\times10^{10}$ protons per bunch. More protons per bunch, plus higher antiproton stacking rates and hence more antiprotons in the Accumulator core, combine to raise the luminosity to $11\text{-}17\times10^{30}$ cm$^{-2}$sec$^{-1}$ in run IV. CDF and DØ electronics and chamber upgrades, along with the increased number of available antiprotons and a new antiproton injector kicker system, will allow operation with either 18 or 36 bunches per beam[20,21]. Finally, it is expected that the Tevatron energy will increase from the present 900 GeV to 1 TeV with the installation of cold compressors[22].

2.3.2 Discussed topics. With the increase in proton intensity expected to be delivered from the Booster after the Linac energy upgrade, discussions centered on the questions of coherent instabilities generally in the Tevatron and specifically at transition in the MR[23]. In addition, the need for 18 or 36 bunches per beam to limit the number of interactions per crossing was highlighted. On the other hand, with 18 or 36 bunches per beam the occurrence of ions trapping onto the antiproton beam becomes more probable[24].

Because of the need for the bunches to be fully separated at the first crossings on either side of BØ and DØ, there is a minimum bucket spacing which is allowable (assuming no crossing angles at the interaction points). This bucket spacing is 21 buckets, or about 400 nsec. The current design for the abort kicker at AØ requires a beam gap of at least 2.2 μsec. Although for beam abort it is only necessary for one such gap to be present, two other gaps one-third of the ring apart are also required for the injection kickers. Although it is in principle possible for all these gaps to be of different length, it is preferable for reasons related to the beam-beam interaction to preserve threefold symmetric pattern for the bunch spacing[20]. Given these constraints, the maximum number of bunches in the collider is 36. For a 42 bucket minimum spacing, the number of bunches per beam is 18.

## 2.4 Collider Run V

2.4.1 Introduction. The projected luminosity in run V jumps up to approximately $55\text{-}83\times10^{30}$ $cm^{-2}sec^{-1}$ with the beginning of MI[3] operation. With apertures far greater than the MR, the proton intensity transmitted to either 120 GeV or 150 GeV increases greatly. This in turn allows an increase in the antiproton stacking rate and total extracted core intensity of approximately 45%.

2.4.2 Discussed topics. As was the case in collider run IV with the expected large increase in proton intensity, instabilities in both the MI and the Tevatron were of major concern. (See Section 3.1.6.) Another issue that was discussed was the rf requirements in the MI, especially at injection and during the bunch coalescing process. (See Section 3.1.2.) In addition, the development of the C∅ straight section as a 3rd interaction region in the Tevatron was studied, with special emphasis on its implications on peak luminosity at all three interaction regions[25].

## 2.5 Collider Run VI

2.5.1 Introduction. The standard version of Phase III assumes an energy upgrade of the Tevatron to a maximum beam energy of 1.8 TeV. This will result in an increase in luminosity to 100-151x$10^{30}$ $cm^{-2}sec^{-1}$ due simply to the adiabatic reduction of the beam emittance at the higher energy.

2.5.2 Discussed topics. The discussions concerned the feasibility and construction of dipoles, quadrupoles, and spool pieces capable of producing twice the field presently generated in the same or less longitudinal space. (See Section 6.1.) More drift space will be needed to allow more separator modules that will be required to maintain the same proton-antiproton beam separation (in units of rms transverse beam size). The effects of the energy upgrade on the Tevatron rf system and synchrotron radiation heat loading in the dipoles were also investigated.

# 3. MI DESIGN ISSUES AND IMPROVEMENTS TO MR PERFORMANCE

This subgroup concerned itself with an evaluation of, and possible enhancements to, the MI design, and with possible methods of improving the performance of the existing MR. The MI as described in the March 1989 Conceptual Design Report[3] was taken as the reference point. The Breckenridge workshop followed by one week a technical review of the MI project and its likely impact on the collider program. While a formal report from the review committee had not been received prior to commencement of the workshop, informal communication had revealed areas of concern regarding projected MI performance parameters. The subgroup specifically attempted to address many of these concerns. Even if funding of the MI were to proceed expeditiously, Fermilab will be utilizing the existing MR for at least two more collider runs. Hence, effort was also devoted to identifying possible means for enhancement of MR performance.

### 3.1 Evaluation and Development of the MI Reference Design

The MI has been designed as a replacement to the existing MR. Its primary purpose is to provide a factor of five increase (to $5x10^{31}$ $cm^{-2}sec^{-1}$) in proton-antiproton luminosity beyond that anticipated following the implementation of electrostatic separators and the completion of the Fermilab Linac Upgrade. This collider luminosity enhancement is realized through an enhanced ability to deliver protons onto the antiproton production target and to deliver high intensity proton-antiproton bunches from the Booster-Antiproton Source to the Tevatron. Secondary benefits of the MI include the potential for the delivery of slow spill beams year-round to the experimental areas for use either as test beams or in certain specialized high-sensitivity K-decay and neutrino experiments, and improved utilization of existing and future collider interaction regions through removal of the MR.

The design criteria for the MI include: 1) a transverse admittance of $40\pi$ mm-mrad (95%, normalized) at its injection energy of 8.9 GeV. This requirement is believed to guarantee the acceptance and efficient acceleration of beam from the Booster containing $6x10^{10}$ protons per bunch, and antiprotons from the Source originating from stacks as large as $2.5x10^{12}$; 2) a cycle time of 1.5 seconds for the delivery of 120 GeV onto the antiproton production target. Coupled with the increased intensity capability of the MI, this will provide a threefold increase in the number of protons targeted per hour for antiproton production; and 3) the ability to accelerate bunches containing up to $6x10^{10}$ protons with the capability of coalescing such bunches into single bunches containing $3x10^{11}$ protons.

The evaluation of the existing MI design was done within the context of assuring the achievement of the above-listed criteria.

3.1.1 <u>Evaluation of cell length.</u> In the design of the MI, attempts were made to keep the beam size small leading to a large acceptance. A phase advance of 90°/cell was chosen to aid in this and to provide for straightforward dispersion matching. The 90° phase advance leads to a direct relationship between cell length and quadrupole gradient. The cell length chosen requires a quadrupole gradient that is near the maximum capability of the MR quadrupoles which will be used in the MI; any decrease in the cell length would entail the construction of new, higher gradient quadrupoles. Increasing the cell length would result in larger dispersion and a lower transition energy. (Dispersion scales as the square of, and $\gamma_t$ inversely with, the cell length.) The dispersion could probably be increased by 50% without impacting the required dipole aperture in a major way. However, the lower $\gamma_t$ which would accompany a longer cell is regarded as undesirable in that one would like to encounter transition as far from injection as possible.

Thus the cell length is optimized; it can not be shortened due to insufficient quadrupole gradient, and it should not be lengthened due to aperture and transition considerations.

3.1.2 Evaluation of rf design. The MI design was reviewed from the standpoint of rf requirements[26)]. With the exception of a tradeoff between bucket area and ramp rate to avoid synchrotron frequencies near 720 Hz during the beginning of the parabola, no problems are foreseen in matching to other machines, acceleration, or coalescing. It is possible that at intensities in excess of $3\text{x}10^{13}$ protons per second, power amplifiers will have to be installed on the cavities. A port for such a PA is incorporated into the design of the existing cavities.

3.1.3 Space-charge limitations and instabilities. The incoherent space-charge tune-shift was calculated for the design intensities and beam parameters. Using an emittance of 20$\pi$ mm-mrad, a per bunch intensity of $6\text{x}10^{10}$ protons, and a longitudinal emittance that is 0.25 of the bucket area results in a tune shift of 0.042. This is regarded as benign.

3.1.4 Lattice developments. A new, superperiodicity two, lattice was developed for the MI during the workshop[27)]. The lattice parameters are unchanged from previous versions, but the organization of the cells was modified. The essential change was that an additional cell was added between the rf straight and the extraction straights, while on the opposite side of the ring a cell was subtracted from this region. The circumference remains unchanged. The real impact of this change is to lengthen the beam lines between the MI and the Tevatron, and thus make the matching problem easier.

3.1.5 Beam line solutions. In parallel with the lattice modification, attempts were made to design beam lines for the reference MI lattice. Prior to the Workshop, attempts to design a beam line between the MI and the Tevatron had failed to produce a sufficiently matched line. In the course of the Workshop three proposals were made, each of which represented a potential solution to the problem. At present none of these specific solutions are being contemplated since the revised lattice has been adopted. However they do illustrate what can be done. One proposed solution utilized a modified lattice[28)] in the MI itself. This would result in larger betas in the extraction straight at the extraction energy. This solution was not perfectly matched, but calculations[29)] indicated an emittance growth of 0.3$\pi$ mm-mrad arising from the mismatch. This was (and is) considered acceptable. A second solution introduced multiple vertical bumps[30)] into the beam line. This solution did achieve exact matching. A final suggestion was that if all else failed, the proton injection into the Tevatron could occur at A∅ using the transfer line from the MI to the switchyard.

Work subsequent to the Breckenridge Workshop, with the longer beam lines associated with the superperiodicity two lattice, has yielded several potential beam line solutions with minimal emittance growth resulting from vertical dispersion mismatches.

3.1.6 Transition related issues. Because of the increased intensity in the MI, accelerating the beam through transition may pose problems. Two issues were addressed at the Workshop. The first relates to the increase in longitudinal emittance due to the high peak currents generated as the beam passes through transition. An analysis[31)], based on calculation of microwave growth rates, was done which indicated that indeed, at the top intensities assumed in the present design report, there will be emittance growth. The minimum longitudinal emittance produced after transition is expected to be 0.6 eV-sec for a beam containing $6 \times 10^{10}$ particles/bunch. This is larger than the design report value of

0.4 eV-sec, but is not expected to be of much practical significance. The analysis also showed that if a transition jump were added to the MI producing a $\Delta\gamma/\Delta t$ of 1./100 $\mu$sec, then a longitudinal emittance of 0.1 eV-sec could be preserved through transition.

The second issue addressed was the design of a transition jump system. It was shown[32)] that a system such as the one mentioned in the previous paragraph can indeed be incorporated into the MI lattice.

3.1.7 Magnet design. A post-Breckenridge contribution suggests the need for and a way to evaluate the MI magnet field quality[33)].

### 3.2 Enhancements to MI Performance

In the opening charge to the Workshop John Peoples challenged this group to explore what might ultimately limit the intensity of the MI[70)] - in particular, is the acceleration of beams containing a few times $10^{14}$ protons within the realm of possibility? During the course of the workshop several ideas were discussed, including an attempt to identify fundamental intensity limitations related to beam stability, space charge, and transition crossing, and possible high-intensity scenarios involving stretcher rings and/or pre-boosters[34)].

3.2.1 Ultimate intensity limitations. There are a class of instabilites[35)] introduced by the rf cavity impedance which will occur at very high intensities. Since in general such high intensities would be produced for fixed target running modes, the preservation of longitudinal emittance is not required but beam intensity must be preserved. A suggestion was made that it might be worth looking into the replacement of the ferrite in the tuners with the new YtGa material being developed for kaon factory rf systems. Use of this material would allow one to generate more voltage per cavity, especially at lower energies, and thus reduce the total cavity impedance associated with the generation of a given bucket area. As mentioned earlier, it is clear that a second PA would have to be added to each cavity to accelerate beams containing more than about $5\times10^{13}$ protons. Beam-loading compensation is also likely[36)] to become extremely challenging, if not impossible, at these intensities.

A more fundamental intensity limitation will arise from the incoherent space-charge tune shift. A beam containing $3 \times 10^{14}$ protons would have a Laslett tune shift of 0.42. This represents the outer limit of experience in high-intensity machines.

3.2.2 Transition avoidance lattices. If much higher intensities are to be encountered in the MI, then passing through transition may present insurmountable problems. It was felt that lattices which avoid transition, but still fit on site, need to be considered. Two approaches were examined. The first was a lattice with $\gamma_t$ below the injection $\gamma$[37]. This is accomplished by increasing the dispersion (without increasing the machine circumference). In the two lattices considered at the Workshop the maximum dispersion was 12 to 14 meters (as compared to two meters in the reference design). This would imply significantly larger aperture magnets than are presently designed and make the rapid cycling of the magnets more difficult.

A second approach is to make $\gamma^t$ imaginary[38]. This is accomplished by making the average dispersion in the dipoles negative. A cell structure for this sort of ring has been designed with a maximum dispersion (absolute value) of 1.3 meters. Straight sections have not yet been included. The drawback in this lattice is that the cell dipole packing factor is only 48%, as compared to 70% in the reference design, with much of the azimuth occupied by high strength quadrupoles.

3.2.3 Stretcher ring. An additional ring[39] could be installed in the MI tunnel which would benefit the MI fixed target program. This ring would be a storage ring at the fixed target energy, 120 GeV. The MI would cycle rapidly to fill the stretcher ring via a single turn injection. The stretcher ring would then slow spill this beam to the users. The improvement to the fixed target program would be twofold: the duty cycle would be essentially 100%, and the overall intensity measured in protons per second would be about 50% greater due to the decrease in MI cycle time accompanying the elimination of the MI slow spill flattop.

### 3.3 Improvements to the Existing MR

The MR will play a central role in Fermilab operations for at least the next three years. Effort was expended at Breckenridge on identifying ways in which MR performance might be improved. This is an ongoing effort and many ideas exist. The basic approaches include: ideas which provide compensation for magnetic errors in the MR dipoles, thus improving the dynamic aperture; solutions which reduce the beam size in the MR, thereby improving all effective apertures; and exotic ideas which attack specific operational modes.

3.3.1 Compensation of magnetic field errors. The existing MR dipoles are known to have a large systematic decapole component. It has been postulated that the installation of dedicated correction decapoles within the ring might result in a significant increase to the machine[40)] dynamic aperture. Such correction elements were found difficult to construct and install. In any case tracking studies of the MR indicate that dynamic aperture reduction comes primarily from even higher multipoles and that such elements are likely to be of marginal utility. Another suggestion[40)] is to build "anti-B1" magnets, devices that add field at the edges to patch up the sagging field, and thus remove all multipoles.

3.3.2 New lattice ideas. New lattice ideas were discussed and to some extent were implemented prior to the workshop. Included are modifications to the horizontal dispersion functions and the tune using existing correction sextupoles, and also more radical changes such as removing and/or replacing some of the dipoles[33)]. These ideas will be pursued further during the winter fixed target startup.

3.3.3 RF manipulations for improved $\bar{p}$ production. A scenario was suggested in which rf manipulations might be implemented in the Booster and MR which could double the proton intensity delivered to the antiproton production target without increasing the transverse beam emittance in the MR[41)]. The general idea is as follows: protons are adiabatically captured in the Booster by an h=42 rf system, and then squeezed and captured in the buckets of the existing h=84 acceleration system. Following acceleration this Booster batch is delivered to the MR with every other 53 MHz bucket populated. A second such batch is delivered and loaded into the MR following the first batch. After acceleration to 120 GeV, rf manipulations in the MR interleave the two batches resulting in a train of 84 bunches containing twice the normal Booster batch intensity. Unfortunately, calculations indicated that the rf manipulations expended enough time to more than outweigh the gain in intensity.

## 4. FIXED TARGET PROGRAM WITH THE MI

### 4.1 Extraction from the MI

The main concern about extraction from the MI has been the magnitude of beam losses on the electrostatic septum. An optimized solution has been achieved that is difficult to significantly improve without a high beta insertion[42]. This solution benefits from some numerical coincidences relating the current state of the art in septum design and the relatively low momentum of the MI extracted beam. The concept is straightforward; the momentum is low enough that the effective length of the septum can be sufficiently short that not all protons that hit the septum will interact. This effect then reduces the extraction inefficiency below what one would calculate from the wire size and step size alone. The inefficiency is a function of the effective wire size divided by the step size. We have achieved a step size of 14 mm which is well matched to the 20 mm gap in typical septa used at Fermilab; 100 KV applied across this gap can be practically achieved with present septa design. If one increases the step size one must also increase the gap so that beam does not hit the cathode of the septum. Since the bend angle of a septum is proportional to the electric field, if one holds the voltage constant and increases the gap then the angle per unit length decreases. To get the same total angle one must then increase the length of the septum.

With these considerations we can calculate an extraction inefficiency of 0.5%. However, there is also an additional effect due to net field in the wire plane causing a proton motion out of the wire plane before interacting. This effect could lower the losses to approximately 0.35%. These losses are low enough to run a high-intensity fixed target program from the MI without calling for special remote handling techniques. If we scale from fixed target running conditions in the Tevatron, we could expect to have some elements in the extraction region reaching 200 mRem/hour @ 1' for $3x10^{13}$ extracted protons every 1.5 seconds.

### 4.2 The Fixed Target Program from the MI

Two major external beam lines and physics programs are envisioned: a neutrino program and a K-physics program[43]. The neutrino target is designed for $3.3x10^{13}$ protons every 1.5 sec (neutrino fast spill) and it is believed that $10^{14}$protons/sec is achievable. An exciting and unique K-physics program for the MI has been developed. This program will benefit from almost complete debunching of the beam[26]. Approximately 10% bunching will remain to maintain use of rf-sensitive instrumentation.

## 5. THE TEVATRON FIXED TARGET PROGRAM IN THE STANDARD UPGRADE PLAN

### 5.1 Extraction and Switchyard Intensity Limits

The existing Tevatron extraction and external beam line systems can readily accommodate the much higher intensities which would be available with the MI as a source.

For the extraction system, beam intensity limits due to slow spill extraction losses should be significantly greater than $10^{14}$ protons per Tevatron cycle. As example, with a slow spill energy deposition limit of 8mW/g, for superconducting magnets, the intensity limit would be $3.6x10^{14}$ protons/spill for magnets downstream of the DØ extraction septa.

Significantly higher beam intensity capability than presently utilized is also feasible with the existing Switchyard beam-splitting system. Current radiation levels from septa beam loss are typically an order of magnitude less than those present in the MR Switchyard environment. The limit to Switchyard intensity is expected to be due to septa beam loss at the cryogenic magnet strings. Detailed computer modeling of these limits has been initiated.

5.2 Target Intensity Limits for Tevatron Beams

For beam energies to 1 TeV, target stations in the existing Proton, Meson, and Muon areas (not counting NC or PW) can all safely target up to a few $x10^{12}$protons; NC can target $1.4x10^{13}$protons. However, one can assume that NC may be used for the 120 GeV neutrino program from the MI. If the Proton-West primary target is used (i.e. secondary instead of primary line downstream of it) then it can handle $>10^{14}$. The best existing high-intensity target is PW, but the present experiments do not utilize this high-intensity capability. The flattop can also be made longer as the total intensity increases, to enable experimental use of more intense beams. Table 2 lists target station intensity limits for the existing external beam-line system[44].

Table 2 800 GeV Intensity Limits for External Beam Target Stations

| Beam | Groundwater p per year | Muons p per year | Target Heating ppp |
|---|---|---|---|
| MW/MT | $3.4x10^{18*}$ | $5.7x10^{17}$ | $4x10^{12}$ |
| MC | $3.4x10^{18*}$ | $2.7x10^{17}$ | $2x10^{12}$ |
| MP | $3.4x10^{18*}$ | $1.5x10^{18}$ | $3x10^{12}$ |
| ME | $4.0x10^{18}$ | NA | $5x10^{12}$ |
| NW | $4.6x10^{18}$ | NA | $1x10^{12}$ |
| NC | $4.6x10^{18}$ | NA | $1.5x10^{13}$ |
| NE | $5.5x10^{17}$ | $1.0x10^{17}$ to NE8 | $1x10^{12}$ |
| | | $1.9x10^{16}$ in NE4 | |
| NM | $4.9x10^{17}$ | $1.4x10^{18}$ | $6x10^{12}$ |
| PW | $1.4x10^{19}$ | $2.5x10^{18}$ | $1x10^{14}$ |
| PC | $1.1x10^{17}$ | NA | $4x10^{12}$ |
| PE | $1.0x10^{19}$ | $4.2x10^{18}$ | $2.3x10^{12}$ |
| PB | $5.7x10^{18}$ | $1.3x10^{19}$ | $4x10^{12}$ |

* Limit applies to the sum of these three beam lines.

## 5.3 High Energy Options for the Fixed Target Program

Previous study has shown that up to 1.5 TeV fixed target beam operation would be feasible[45], if the Tevatron were upgraded with a new ring of at least this energy capability.

Secondary fluxes for existing beam lines have been calculated for targeting of 1.5 TeV primary protons[46]. As shown in Figure 2, dramatic gains are achieved by this increase of primary beam energy.

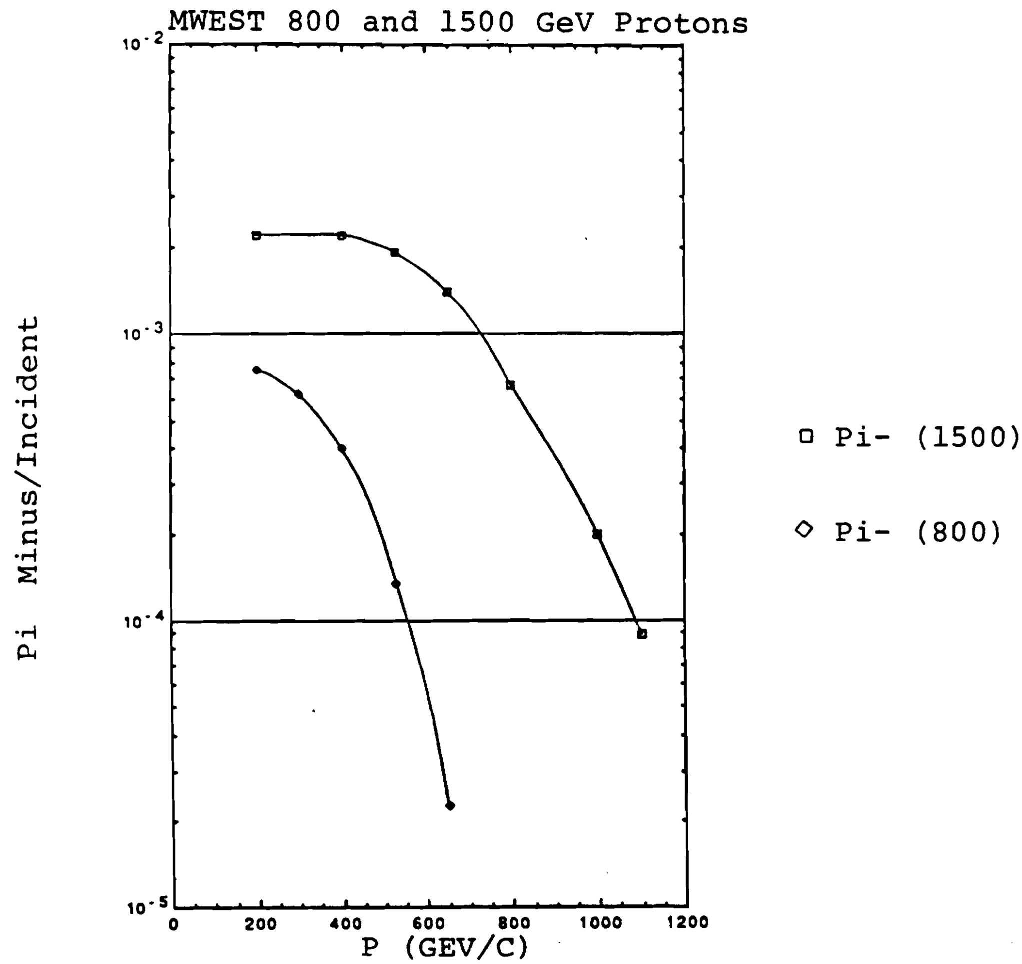


Figure 2 Secondary Flux Comparison for 800 and 1500 GeV in MWEST Beam Line.

## 5.4 Other Extracted Beam Options

Crystal extraction from the Tevatron is being investigated. This is a way to obtain a very low-intensity (a few kHz) test beam into the Switchyard during collider runs and also can be considered as an R&D

project for doing the same thing from the SSC[47].

# 6. MAGNETS FOR THE TEVATRON UPGRADES

## 6.1 Magnets for the "Standard" Upgrade

Phase III of the standard upgrade plan replaces the existing Tevatron ring in the same tunnel with a ring of higher-field magnets. A magnet has been designed which provides 6.6 T (1.5 TeV) for extraction with the machine at a temperature of 4.6 K and up to 8.88 T (2 TeV) for colliding beams with the machine at 1.8 K[48,49]. This magnet features cold iron, a 7.0 cm aperture, and an SSC-style cryostat. A few of these magnets would find immediate application in providing needed warm space in the present lattice for specialized devices such as separators and kickers and for experiment components (Roman pots). The Phase III dipole is shown in Figure 3.

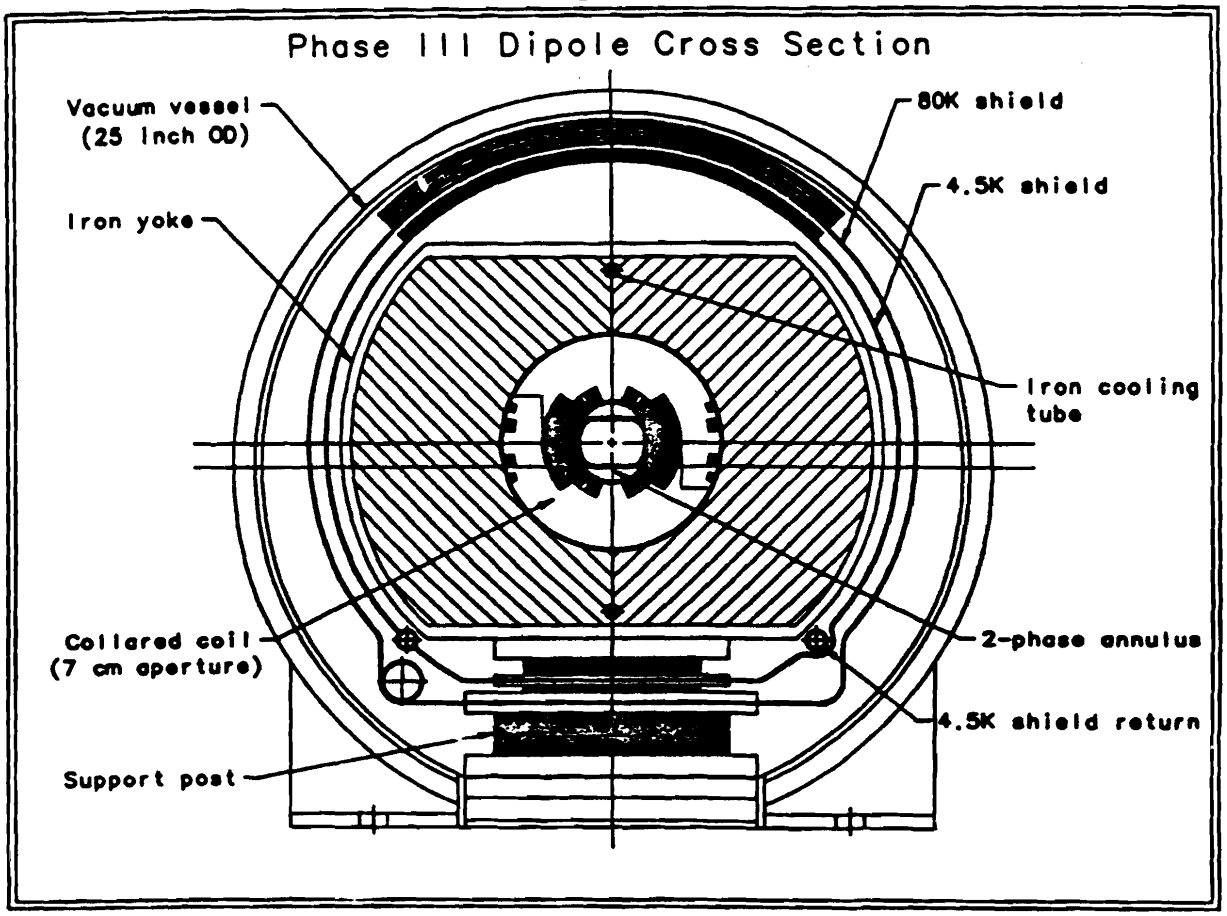


Fig. 3. Cross Section View of Phase III Dipole

6.2 Magnets for the Beyond the Standard Upgrade

A proposed site filler "LINCOLN" (see Section 7) requires a dipole of 5 cm aperture and the highest possible field. However, without further investigation, it is not clear that sufficient field quality can be obtained with this small an aperture[33]. The design goal would be an 8.8 T field at 1.8 K. Unlike the Phase III dipole, ramping is not required. Because of the similarity to the present SSC collider dipole, the question arose as to the possibility of using SSC dipoles for this ring. This does not appear to be an attractive option because of the required sagitta and the limitation of SSC dipoles to temperatures above 3.8 K. A concept has been worked out based on the extrapolation of the Phase III dipole and SSC designs[49]. Figure 4 shows the proposed cross section for this magnet. A study has been made of the superfluid cryosystem required for this machine[50]. Such a system seems quite feasible.

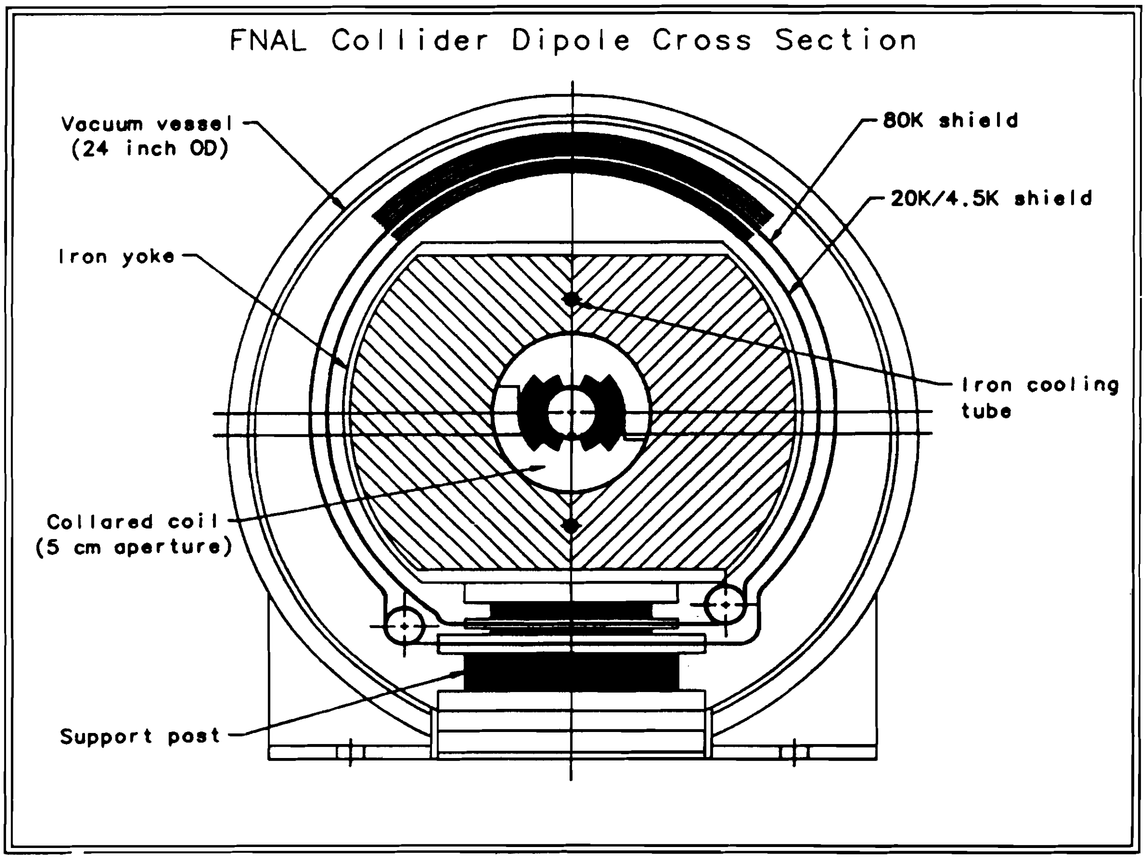


Fig. 4. Cross Section View of Fermilab Collider Dipole

6.3 Comparison of the Requirements of SSC and Tevatron Upgrade Magnets

The requirements of the Phase III collider and High-Energy Booster are sufficiently similar that a common design may be possible. Both magnets ramp and have similar aperture and field requirements. The desire to go to low temperature (1.8 K) in the Phase III dipole to achieve high field (8.8 T), however, results in some difference in the size of the return iron and the cryostat cryogenics. Whether these differences can be resolved in order to gain an economic advantage requires further study.

The Fermilab MI and SSC Medium-Energy Booster are probably even closer in their magnet requirements. Since a recent decision was made to ramp the MEB rapidly, it seems clear that a common set of parameters for these two machines could be defined. The MI cycle is 1.5 seconds from 8 to 150 GeV compared to the MEB that takes 4 seconds to go from 12 to 200 GeV. The bending radii are in the ratio of 4:3 so the field swing is the same. Therefore the only difference is in the curvature (required sagitta) in the magnets: 16 mm in the MI vs. 12 mm in the MEB. The difference could likely be split to make the magnets for both machines identical. The number of dipoles required is 300 for the MI and 500 for the MEB.

6.4 Exploring the Limits

There is a clear motivation to increase field strength in accelerator magnets. It is important to investigate the performance limits of these magnets in order to guide machine designers. For example, can a 20 T accelerator dipole be built?

The optimization of performance of superconducting magnets begins with increasing the current and then trying to accommodate the higher forces. There are indications that at least a factor of two in current density in conductor is possible in NbTi and higher if NbSn is used[53]. The geometry of coils and coil ends must ensure that this current density is not compromised and that the conductors can be adequately supported. It is also important that the insulation must withstand high pressures. There may also be limits on the mechanical structure that will restrict the ultimate field. Many of these issues have been addressed[51-57].

The flux return iron starts to become very large at 10 T and contributes a decreasing increment to the field. An iron-free magnet with a superconducting shield (possibly with high $T_c$ superconductor) has been proposed[58].

Another concern is that the bending in these magnets will be so high that in a high-intensity proton machine the field would be limited by synchrotron radiation[59].

## 7. BEYOND THE STANDARD UPGRADE PLAN

### 7.1 Introduction.

Phase III of the standard upgrade is the installation in the present tunnel of a new Tevatron providing 1.8 TeV/beam for collider runs, and an extracted 1.5 TeV beam for fixed target and test-beam operation. An alternative to Phase III is proposed. The crux of the new plan is the construction of a new tunnel for a 4 TeV-on-4 TeV $\bar{p}p$ collider. The new collider has contemporary superconducting magnets, which have higher field and smaller aperture made possible by the 1 TeV injection energy provided by the present Tevatron. Unconstrained by the existing tunnel, the new collider can have several well-designed interaction regions. The present Tevatron will continue to exist to provide year-round beams for fixed target experiments and test beams.

### 7.2 History and Rationale for a New Collider.

Over the last two years, there has been a constant evolution of ideas for the next steps in the long-range physics program at Fermilab. First, a luminosity goal of $5\times10^{31}$ $cm^2$/sec led to the concept of two 20 GeV rings[60] to achieve $\bar{p}p$ collisions. One of the new rings was to improve the transmission of the present MR and the other was to improve the accumulation capability for antiprotons.

A second idea was the concept of a 1 TeV-on-1 TeV proton-proton collider[61] which would operate at very high luminosities. This concept included the construction of a second superconducting ring in the Tevatron tunnel which would occupy the same space as the present MR. The functions of the MR would be taken over by the MI in its own tunnel.

The third idea was based on the realization that higher energy could provide a physics reach equivalent to higher luminosity but with fewer requirements for major detector improvements. Thus the present 3-phased plan for a Fermilab upgrade is based on the idea that a higher energy $\bar{p}p$ collider will provide the most significant improvements to the accelerator complex. The first phase includes improvements to the Linac and Antiproton Source. The second phase is the construction of the new MI which would free needed space in the Tevatron tunnel for Phase III, a higher-energy replacement for the Tevatron Collider[62)].

The discussion of an attractive alternative to Phase III began with a consideration of previous proposals involving new tunnels on the Fermilab site: the "Pentavac"[63)], "POPAE"[64,65)], the "Dedicated Collider"[66,67)] and a proton-proton version of the Dedicated Collider[68)]. The proposal presented here is an updated version of the $\bar{p}p$ Dedicated Collider.

## 7.3 Physics Motivation.

7.3.1. The physics "niche." We assume that the SSC will start producing physics around the beginning of the next millenium and for its first decade or so will be busy with a small number of generic detector experiments. By generic we mean a large multipurpose $4\pi$ detector. We further assume that UNK will begin a multi-faceted fixed target program at 3 TeV before the end of the century. What is the physics niche for Fermilab? One possible niche is to provide facilities for non-generic experiments. Specialized insertions, different from those available elsewhere, will be required. These special insertions will be the starting point for the accelerator lattice design. Since the experiments are not all-purpose, it is important to provide many collision areas that can (though are not required to) run simultaneously. Construction of a new proton-antiproton collider at Fermilab will allow Fermilab to do forefront research in the pre-SSC era and continue to make unique contributions during the time of the SSC.

7.3.2. Non-generic experiments. A starting point for the design is to consider a set of non-generic collider experiments such as the menu suggested in a recent letter from James Bjorken[69]. The next step would be to design insertions that accommodate experiments like these and have a high degree of flexibility. The straight sections need to be completely matched so they are "invisible" to the rest of the accelerator. One of the design issues for the small $\beta^*$ regions would be to examine their feasibility in terms of achievable quadrupole gradients and free space from the detector. In the medium to high $\beta^*$ regions, (a) either the particles of interest travel in an enlarged accelerator aperture and the accelerator magnets are used for momentum analysis, or (b) very small outside dimensions are required of some of the accelerator lattice elements near the experiments.

7.3.3 Mass reach at high luminosity. One scenario, depending on the opportunities at the time, is to run maximum luminosity at one experiment, perhaps removing collisions at other straight sections in order to minimize the beam-beam tune shift. An example of a non-generic high luminosity detector is a steel ball with good muon detection optimized to search for new physics that reveals itself in multi-muon signals. "What does one do to the Tevatron if $m_{top} > 200 - 250$ GeV?"[70]. Although a "top" or "Higgs" search is not the primary motivation of this machine, it can, if needed, extend the mass reach significantly as shown in Table 3[71].

Table 3 Mass reach for various cm energies

| Center-of-Mass Energy (TeV) | Integrated Luminosity ($pb^{-1}$) | $m_Q$, (heavy quark mass, GeV) (discovery limit, 100 pairs) |
|---|---|---|
| 2.0 (1992-3) | 100 | 220 |
| 3.6 (standard phase III) | 500 | 410 |
| Alternative to Phase III: | | |
| 6.0 (LINCOLN-4.2) | 500 | 560 |
| 8.0 (LINCOLN-1.8) | 500 | 660 |

## 7.4 The LINCOLN Proposal

This new collider has been given the acronym LINCOLN, an acronym for Large INdependent COLlider Nearby. LINCOLN-4.2 has magnets operating at 4.2 K and accelerates the beams to 3 TeV. However, the magnets can run at superfluid temperatures; therefore, an "upgrade" to LINCOLN-1.8 is an upgrade to 1.8 K helium and 4 TeV per beam.

A new $\bar{p}p$ collider in a new tunnel, capable of 4 TeV on 4 TeV collisions with luminosities approaching $10^{32}cm^{-2}sec^{-1}$ will greatly enhance the physics capabilities of Fermilab. Continuing to do $\bar{p}p$ collisions is a natural extension of Fermilab's program, and will be a unique capability in the world. Having one ring is relatively inexpensive; the source and injector exist. The CDF and DØ detectors exist and could be "reincarnated" at the new collider.

By using the Tevatron, the world's highest-energy accelerator, as an injector one can have a smaller aperture which reduces magnet costs. A small energy range implies smaller persistent current effects. Since it is not planned to extract the beam, a smaller magnet aperture may be adequate. This reduces magnet and cryogenics system costs. There will be no conflict between detector operation and $\bar{p}$ production.

By putting the new collider in a new tunnel the radius becomes a free parameter in its design. There are many other advantages to avoiding existing tunnel constraints. The Collider and Fixed Target programs are independent. The Tevatron can continue doing 1 TeV fixed target experiments and provide test beams during times when the new collider runs. There will be minimal downtime to the ongoing program for construction.

Injection is from EØ in two opposite directions into a specially designed utility straight section. There needs to be enough distance for a good match but not too much to keep the length and cost of the 1 TeV transfer lines down. Some design questions to address are (1) how much elevation difference is necessary and (2) can one inject/abort at the same place? Kickers should be placed to avoid cogging and provide the ability to selectively replace bunches, further relieving the $\bar{p}$ economics problem.

The major accelerator parameters are a bending radius of 1.5 km and an average radius of 2.3 km, implying a total circumference of 14.5 km. The shape is an oval, incorporating eight straight sections, with some bending in between to decouple them in terms of background. Six of these straight sections will be devoted to experiments. The maximum dipole field, $B_{max}$, will be 6.6 T, rising to 8.8 T after a cryogenics upgrade. Building superfluid helium capability into the magnets allows an energy increase after a few years of running if warranted by the physics.

The rf frequency would be 53 or 106 MHz (equipment is readily available commercially). RF voltage requirements are very low so one can aim for short bunches (shorter luminous region). The synchrotron frequency is 1 - 10 Hz. This makes the ring very sensitive to ground noise and power supply noise (as in any large collider). Another possible improvement, more easily incorporated in a new design with long straight sections, is electron cooling[72)].

The lattice will be designed with 90°, low-dispersion cells. The separator system will benefit by producing "smoother" helices. A new regular lattice will make the separators more effective. One can probably inject into the collision optics so selective replacement of bunches will be possible and the experiments can study the energy dependence of processes. Luminosity lifetimes will be long. There is a much slower growth of emittance from intrabeam scattering because of the higher energy.

The electrostatic separator system will be designed so each of the six collision regions can be turned on and off independently. The insertions will be designed so that $\beta^*$ can be independently varied at each experiment. The peak luminosity = $10^{32} cm^{-2} sec^{-1}$ but this may only be achievable when not all collision regions are running simultaneously because of the beam-beam tune-shift limit. Aperture requirements are determined by the need to separate protons and antiprotons in both planes with electrostatic separators, and closed orbit errors.

A fundamental limit in any antiproton-proton collider may be the large average number of interactions per crossing. The need to place electrostatic three-bumps between collision points to keep the beams apart imposes a geometric lower limit on bunch spacing for head-on collisions. A crossing angle may alleviate this.

There are many factors that will determine siting; level difference of rings for injection, topography, crossing through (or over or under) the MI tunnel. A large component of the expense will be in the experimental halls. Since 2-phase cooling is not needed in the magnet (since the magnets do not ramp), the cryogenics system can work even if the plane of the ring is tilted. An important constraint requiring considerable attention early in the design is the site boundary radiation (muon) shielding requirement.

## 7.5 BEYOND LINCOLN

In considering large increases in collider energy, beyond LINCOLN, and beyond even the mass reach of the SSC, it is useful to recall the approximate factors relating hadron-hadron cm energy to parton-parton c.m. energy[73)]. These are shown in Table 4.

Table 4 Relationship of h-h cm energy to parton-parton c.m. energy.

| | Hadrons | Partons |
|---|---|---|
| pp | 40 TeV | 3000 GeV |
| pp | 18 | 1500 |
| pp | 6 | 600 |
| $\bar{p}p$ | 3.6 | 600 |
| $\bar{p}p$ | 2.0 | 400 |
| $\bar{p}p$ | 1.8 | 300 |

In considering accelerators of the future, beyond LINCOLN and beyond SSC, electrons may be the most effective way to reach super-high, parton-parton c.m. energies. A particularly interesting idea[74)] that could be uniquely exploited here at Fermilab is the use of protons in a two-beam accelerator structure to accelerate electrons. A wakefield 2-beam accelerator using a proton beam driver is power efficient. It is timely that the Fermi National Acclerator Laboratory begin an R&D program in new methods of charged particle acceleration.

## 8. CONCLUSIONS

### 8.1 Collider Operation in the Standard Upgrade Plan

Various open issues in the standard plan were discussed and explored in detail. A steady increase in collider luminosity is expected as improvements to different elements in the accelerator complex are incorporated. At the Workshop, progress was made in identifying and focussing in on a number of key issues, which will be addressed in the near future by calculations, accelerator experiments, and measurements of device properties. Primarily these concern stability issues in the Tevatron, optimal location of the separators, and continued work on beam-beam effects. A bunch spacing scenario has been defined, and a plan was discussed for implementing a third interaction region in the Tevatron.

8.2 MI Design Issues

The parameters of the MI were re-examined and a number of changes and additions were discussed. New lattices have been developed which make beam lines easier to design; a matched solution has been found for the 150 GeV injection line. Calculations show that the presently designed MI lattice is compatible with a $\gamma_t$ jump. Cell optimization calculations confirm that the existing cell design is optimized. A detailed analysis of the rf system confirms that the plan to reuse the MR cavities will work.

There was considerable examination of the capability of the MI to reach higher intensities, perhaps as high as a factor of 10 above the current design. The $\gamma_t$ crossing at 22.4 becomes a serious problem. A package of additions and changes to solve this problem and reach higher intensities was proposed. This package consists of a pre-Booster, a holding ring in the Booster, a weak focussing MI, and a stretcher ring. The stretcher ring can be considered independently of the other additions, and has some significant advantages. With a 2 sec cycle instead of a 3 sec cycle, it raises the intensity by 1.5, and the spill duty factor by 3x, which particularly benefits the K-physics program. Other limits to higher MI intensity requiring additional study are (1) rf cavity loading and cavity driven instabilities, (2) space charge limit (tune shift), (3) other instabilities, and (4) the limit for fast extraction.

8.3 MR Issues

Two alternative approaches to fixing the MR are increasing the good field aperture and decreasing the beam size. It is known, based on field measurements and dynamic aperture measurements at 20 GeV, that there are systematic multipoles of many orders in the B1 magnets. Proposals are being examined to install correctors.

8.4 The Fixed Target Program from the MI

Extraction from the MI of high intensity beams was examined and the extraction inefficiency was estimated at ~0.35%. The neutrino target, designed for $3.3 \times 10^{13}$ protons every 1.5 seconds (neutrino fast spill), could go up to $10^{14}$ protons/sec. Leaving 10% of the 53 MHz rf bunching in the slow spill will be satisfactory for the proposed K-physics program as well as allowing accelerator instrumentation to continue to function.

8.5 The Fixed Target Program from the Tevatron

An in-depth review was made on the implications of upgrading the Switchyard and the beam lines for higher energy and intensity. Existing Proton, Meson and Muon areas (not counting NC or PW) can safely target a few $\times 10^{12}$. NC at 800 GeV can target $1.5\times 10^{13}$ protons. If the PW primary target is used then it can handle $>10^{14}$ protons. Flattop can be made longer as the total intensity increases. Secondary flux rates for existing beam lines for 800 GeV and 1.5 TeV incident primary energy have been calculated.

8.6 Magnets for Upgrades

Conventional dipoles for MI and SSC-MEB have close enough requirements so a common set of parameters can be defined. The dipole for Phase III requires an aperture of 7 cm. Requirements for this dipole were compared to the 2 TeV SSC-HEB design. Since the requirements are almost the same, design and development could be done common. Dipoles for LINCOLN, the on-site 4 TeV-on-4 TeV $\bar{p}p$ collider in a new tunnel, have the following requirements: 5 cm aperture; 6.6 T @ 4.2 K; 8.8 T @ 1.8 K. A new design for these dipoles can be a straightforward extrapolation of earlier work (SSC and Phase III). Superfluid cryosystems of the scope required seem possible.

The limits of superconducting technology were explored. The results of these studies and discussions are as follows. Another factor of two is possible in $J_c$ in NbTi (~6000 A/mm$^2$, 5 T, 4.2 K) based on recent work at IGC. NbSn is required however, to achieve fields above 11 T. Insulation schemes are good for magnets with 12-15 T. Mechanical structure limits for cosine$\theta$ magnets are also in the 12-15 T range. Synchrotron radiation is not a problem for magnets of less than 15 T at the highest conceivable $\bar{p}p$ beam intensity. These studies indicate that 15 T seems to be an upper limit with the current coil designs.

## 8.7 LINCOLN and Beyond

An alternative to the standard upgrade plan for Phase III was discussed. This consists of a new tunnel and $\bar{p}p$ collider with energy up to 4 TeV per beam. Injection would be at 1 TeV from the existing Tevatron. The physics motivation is to provide facilities for a diverse program of $\bar{p}p$ collider physics. This is accomplished by an oval geometry having a relatively large number of intersection regions. These regions would be designed with great flexibility and be able to incorporate different kinds of "non-generic" detectors. This collider has been named LINCOLN, Large INdependent COLlider Nearby.

In considering steps beyond LINCOLN and SSC, it is felt worthwhile for Fermilab to begin an R&D program in new methods of particle acceleration complementary to ongoing work elsewhere and capitalizing on the unique capabilities present at this laboratory.

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