# THE FERMILAB UPGRADE

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## Abstract

Fermilab has considered several possible directions for upgrading the performance of the existing Tevatron complex so as to effectively double the mass range accessible to experiment. Alternatives examined include luminosity and/or energy enhancements and the possibility of providing proton-proton collisions. New construction required and performance parameters for the preferred option will be discussed.

## Introduction

The purpose of the Fermilab Upgrade is to provide the opportunity for new physics exploration during the decade leading up to the advent of operations at the Superconducting Super Collider (SSC). Fermilab currently operates the highest energy collider in the world. This situation will remain unchanged until the initial operation of the SSC (or possibly CERN's Large Hadron Collider) sometime in the late 1990's. Today at Fermilab antiprotons and protons are brought into collision at 1.8 TeV in the center of mass with peak luminosities routinely 50% in excess of the design luminosity of $1\times10^{30}$ $\text{cm}^{-2}\text{sec}^{-1}$. It is expected that the current collider run will yield an integrated luminosity, recorded on tape, of about 8 $\text{pb}^{-1}$. This level should be sufficient for observing the top quark if its mass is less than about 100 GeV and heavy Z's and W's up to a mass of about 300 GeV. Fermilab would like to provide the potential for experimenters to double this mass reach during the 1990's.

The planned upgrade of the Fermilab Complex will take place in three phases. The first phase is based on optimizing and improving existing facilities. It involves the implementation of new low beta systems at the two interaction regions designated B0 and D0, the use of separators to run a large number of proton and antiproton bunches in the Tevatron, upgrades to the Antiproton Source, implementation of cold compressors to get the beam energy to 1.0 TeV, and the upgrading of the Linac energy from 200 to 400 MeV. All of these projects are presently in progress and are expected to be fully implemented by the end of 1992. The luminosity is expected to rise to about $1\times10^{31}$ $\text{cm}^{-2}\text{sec}^{-1}$ as a result of these improvements.

Pushing the luminosity up another factor of 5-10 will require the construction of new facilities at Fermilab. Three approaches have been examined over the past year: 1)Proton-Antiproton collisions at 2 TeV (center of mass) with a luminosity of $5\times10^{31}$ $\text{cm}^{-2}\text{sec}^{-1}$ based on the construction of a new antiproton accumulator ring and a new booster ring both operating at 20 GeV. 2)Proton-proton collisions at 2 TeV with a luminosity of $3\times10^{32}$ $\text{cm}^{-2}\text{sec}^{-1}$ based on a replacement of the Fermilab Main Ring and construction of a second superconducting accelerator. 3) Proton-Antiproton collisions at 3.6 TeV with a luminosity of $1\times10^{32}$ $\text{cm}^{-2}\text{sec}^{-1}$ based on a replacement for the Main Ring and a new higher energy superconducting accelerator located in the existing tunnel. The third option is the one

Table 1: Upgrade Parameters

| | Phase 1 | Phase 2 | Phase 3 | |
|---|---|---|---|---|
| Energy (Center of Mass) | 2.0 | 2.0 | 3.6 | TeV |
| Protons/Bunch | $6\times10^{10}$ | $3\times10^{11}$ | $3\times10^{11}$ | |
| Antiprotons/Bunch | $2\times10^{10}$ | $5\times10^{10}$ | $5\times10^{10}$ | |
| Number of Bunches | 22 | 22 | 22 | |
| Total Antiprotons | $4\times10^{11}$ | $1\times10^{12}$ | $1\times10^{12}$ | |
| Antiproton Stacking Rate | $7\times10^{10}$ | $14\times10^{10}$ | $14\times10^{10}$ | p/hr |
| Proton Transverse Emittance (95%) | $12\pi$ | $30\pi$ | $30\pi$ | mm-mr |
| Antiproton Transverse Emittance | $12\pi$ | $22\pi$ | $22\pi$ | mm-mr |
| $\beta^*$ | 0.5 | 0.5 | $\leq0.5$ | meters |
| Proton Beam Size (rms) at IR | 31 | 48 | $\leq36$ | $\mu$m |
| Antiproton Beam Size | 31 | 41 | $\leq31$ | $\mu$m |
| **Luminosity** | **$8\times10^{30}$** | **$5\times10^{31}$** | **$\geq1\times10^{32}$** | **$\text{cm}^{-2}\text{sec}^{-1}$** |
| Beam-beam $\Delta\nu$/crossing | .004 | .007 | .007 | |
| Number of Crossings | 2 | 2 | 2 | |
| $\Delta\nu$ Total | .007 | .015 | .015 | |

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which has been deemed to offer the best combination of physics potential and flexibility.

Phase 2 of the upgrade thus involves the construction of a new 150 GeV accelerator, designated the "Main Injector", and removal of the Main Ring from the Tevatron enclosure. This phase can be completed by the end of 1993 and should yield a luminosity in excess of $5x10^{31}$ $cm^{-2}sec^{-1}$. The third, and ultimate, phase is then implemented through the construction of a 1.8 TeV per beam accelerator/storage ring based on 8 Tesla superconducting dipoles. This accelerator could become operational sometime in the latter half of the 1990's. Parameters for the three phases are given in Table 1.

## Phase 1: Low Beta, Separators, and Linac Upgrade

A single low beta area is currently installed in the Fermilab Tevatron in the BO straight section. This is the area in which the CDF detector is taking data. Because the insertion presently in use is not matched optically to the Tevatron lattice, the installation of a second low beta region at the DO straight section requires a new optical solution both at BO and at DO. An insertion has been designed which provides fully matched optics in both these regions. The low beta regions are identical and rely on 1.4 Tesla/cm quadrupoles currently under construction at Fermilab. When implemented in September 1990 both the BO and DO areas will have the capability of running with $\beta^*$ down to 25 cm although this full capability will not be utilized initially due to the finite bunch lengths.

Electrostatic separators are also under development at Fermilab at this time with implementation scheduled for the September 1990 run. The collider is presently running with six proton and six antiproton bunches. In this mode we appear to be tune-shift limited (at $\Delta\nu$ total = .02) and are actually forced to dilute the proton phase space in order to stablize the antiprotons. Increasing the luminosity can be achieved by increasing both the number of bunches and the proton phase space density while using electrostatic separators to keep the proton and antiproton beams apart outside of the interaction regions. A design has been completed which utilizes twenty-one 3 meter long modules each running at voltages up to 40 KV/cm. Separators will be installed to deflect the beam in both horizontal and vertical planes resulting in helically separated orbits.

Work is currently underway to upgrade the energy capability of the existing Linac from 200 to 400 MeV. The goal of the upgrade is to increase the beam density out of the 8 GeV Booster by 75%. It is believed that the current limitation on the number of particles per unit phase space which can be delivered to the Main Ring arises from space-charge forces at injection into the Booster. Raising the injection energy should allow the squeezing of the same number of protons into a phase space area 57% as large as at present. Operation in this mode should directly result in smaller beam emittances in the collider and a corresponding increase of 75% in luminosity. Implementation of the Linac Upgrade is based on replacing the second 100 MeV of existing drift tube linac with a modern side-coupled structure producing 300 MeV in the same physical length. Construction is to begin in October 1989 with completion in September 1992.

## Phase 2: The Main Injector

The Main Injector (MI) is a new 150 GeV accelerator which will replace the existing Main Ring in all its functions. The ring is approximately half the circumference of the Main Ring and will be situated on the southwest side of the Fermilab site, tangent to the Tevatron at the FO straight section. Following construction of this ring all Main Ring operations will cease. Major impacts on both the collider and fixed target programs at Fermilab are expected as detailed below.

Table 2: 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 | $3x10^{13}$ |
| Harmonic Number (@53 MHz) | 588 |
| Horizontal Tune | 22.42 |
| Vertical Tune | 22.43 |
| Transition Gamma | 20.4 |
| Natural Chromaticity (H) | -27.5 |
| Natural Chromaticity (V) | -28.5 |
| Number of Bunches | 498 |
| Protons/bunch | $6x10^{10}$ |
| Transverse Emittance (Normalized) | $20\pi$ mm-mr |
| Longitudinal Emittance | 0.25 eV-sec |
| Transverse Acceptance (at 8.9 GeV) | $40\pi$ mm-mr |
| Momentum Acceptance | 2.0 % |
| $\beta_{max}$ (Arcs) | 57 meters |
| $\beta_{max}$ (Straight Sections) | 80 meters |
| Maximum Dispersion | 2.2 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 | 300 |
| Dipole Length | 6.1 meters |
| Dipole Field (@150 GeV) | 17.2 kGauss |
| Dipole Field (@8.9 GeV) | 1.0 kGauss |
| Number of Quadrupoles | 202 |
| Quadrupole Gradient | 196 kG/m |
| Number of Quadrupole Types | 3 |
| Number of Quadrupole Busses | 2 |

The Main Injector Parameter List is given in Table 2. The primary design criterion for the MI is that it remove the existing bottleneck in the delivery of intense proton beams either to the Tevatron or to the antiproton target imposed by the Main Ring. The aperture of the Main Ring ($12\pi$ mm-mr as measured in normalized units) is significantly smaller than that of the 8 GeV Booster ($20\pi$ mm-mr). As a result the Booster is typically run at about two thirds of its capability during normal operations. The restricted aperture in the Main Ring is due to perturbations to the ring which have been required for the integration of overpasses and new injection and extraction systems related to operations with antiprotons. Following the 400 MeV Linac upgrade the Booster aperture will increase to $30\pi$ mm-mr due to increased adiabatic damping within the new linac and the Booster/Main Ring mismatch will become even more dramatic. The Main Injector is designed to have a transverse acceptance ($40\pi$ mm-mr) larger than that of the Booster following the Linac upgrade. The Main Injector should be capable of accelerating $5x10^{12}$ protons per Booster batch for antiproton targetting, as compared to $1.7x10^{12}$ in the Main Ring, and should be capable of delivering up to

$6\text{x}10^{13}$ protons in two MI batches to the Tevatron, as compared to $1.8\text{x}10^{13}$ in the Main Ring.

It is anticipated that the MI will not only perform at a significantly higher level than the Main Ring in terms of protons delivered per cycle, but also in terms of cycle rate for antiproton production and transmission efficiency. The MI will cycle to 120 GeV every 1.5 seconds as compared to 2.6 seconds in the Main Ring while the aperture is sufficient for 100% transmission of antiprotons from the largest stacks imaginable. For the most part expected improvements in performance are directly related to the optics of the MI. The MI lies in a plane with stonger focussing per unit length than the Main Ring. This means that the maximum betas are half as large and the maximum (horizontal) dispersion a third as large as in the Main Ring, while vertical dispersion is non-existent. As a result physical beam sizes associated with given transverse and longitudinal emittances are significantly reduced compared to the Main Ring. The elimination of dispersion in the RF regions, raising the level of the injection field, elimination of sagitta (through the construction of new, curved dipoles), and improved field quality will all have a beneficial impact on beam dynamics.

The major impact of the Main Injector on collider operations will be to increase the luminosity by a factor of 5-10 and to eliminate backgrounds in the collider detectors currently arising from the proximity of the Main Ring (which is delivering protons for antiproton production during stores). The impact on luminosity is twofold and is seen in Table 1: 1)An increase in the antiproton stacking rate, due to a threefold increase in the number of protons targetted per hour, which will support a larger number of antiprotons in the collider; and 2)An increase in the number of protons which can be delivered to the Tevatron in a single bunch. The second of these is important because in Phase 1, with separators implemented, the inadequacies of the Main Ring will not allow the beam-beam limit to be approached.

Other benefits anticipated from the construction of the Main Injector include an increase in the total number of protons deliverable to the Tevatron to $6\text{x}10^{13}$, freeing up of a third Tevatron straight section for eventual installation of a third interaction region, provisions for slow extracted 120 GeV test beams year around and potential development of very high intensity/high duty factor ($\gtrsim 1\text{x}10^{13}$ protons/sec at 120 GeV with 34% duty factor) beams for use in high sensitivity K decay and neutrino experiments, and the creation of space in the Tevatron enclosure for eventual installation of a second superconducting accelerator.

Fermilab has proposed that construction of the Main Injector begin in October, 1990 with operations commencing in late 1993.

## Phase 3: The New Tevatron

The New Tevatron exploits the full potential of the Main Accelerator complex with a new ring of high field superconducting magnets replacing the old Main Ring. As shown in Table 1 Phase 3 nearly doubles the energy and luminosity achieved in Phase 2 of the upgrade. Planning for Phase 3 has not yet been developed to the same level as Phases 1 and 2. It is felt, however, that this phase could be implemented sometime in the second half of the 1990s.

Table 3 lists parameters for the New Tevatron. The primary differences between the New and existing superconducting accelerators are the energy, the increased field strengths required, and the increased phase advance per cell and matched dispersion which lower $\eta_{\max}$ from 5.8 meters in the existing machine to 2.5 meters in the new machine.

Table 3: New Tevatron Parameter List

| | | |
|---|---|---|
| Circumference | 6283 | meters |
| Injection Energy | 150 | GeV |
| Peak Energy | 1500-1800 | GeV |
| Harmonic Number (@53 MHz) | 1113 | |
| Horizontal Tune | 25.6 | |
| Vertical Tune | 25.6 | |
| Transition Gamma | 23.0 | |
| Number of Bunches (Collider) | 6-44 | |
| Protons/bunch | $3\text{x}10^{11}$ | |
| Transverse Emittance (Normalized) | $30\pi$ | mm-mr |
| Longitudinal Emittance/Bunch | 2.0 | eV-sec |
| $\beta^*$ | 0.25 | meters |
| $\beta_{\max}$ (Arcs) | 100 | meters |
| $\beta_{\max}$ (IR, Injection Lattice) | 280 | meters |
| $\beta_{\max}$ (IR, Low Beta Lattice) | 1650 | meters |
| Maximum Dispersion (Arcs) | 2.5 | meters |
| Maximum Dispersion (IR) | 6 | meters |
| Number of Straight Sections | 6 | |
| Number of Posssible IRs | 3 | |
| Length of Standard Cell | 59.4 | meters |
| Phase Advance per Cell | 90 | degrees |
| RF Frequency | 53.1 | MHz |
| RF Voltage | 1 | MV |
| Dipole Field (Max) | 6.6-7.9 | Tesla |
| Dipole Length | 8.1 | meters |
| Quadrupole Gradient (Cell, Max) | 140-168 | Tesla/m |
| Quadrupole Length | 1.7 | meters |
| Quadrupole Gradient (IR, Max) | 200-240 | Tela/m |

The dominant design issue is the supeconducting bending magnet to be used in the New Tevatron. Since the overall geometry is fixed by the existing tunnel, the achievable energy is determined by the dipole magnet field. At 1.5 TeV the required field is 6.6 Tesla and the magnet design is relatively straightforward, representing a continuation of the Tevatron, HERA, SSC line of progress. At 1.8 TeV, 8 Tesla is needed. With present technologically well developed superconducting materials 2° K refrigeration is implied. Since the magnet aperture must be large enough to satisfy the demands of slow extraction in fixed target operation and separated orbits in the collider mode, the resulting stresses are approaching material yield strengths. A high field magnet development program is underway at Fermilab to address these problems and to develop workable designs.