Fermi National Accelerator Laboratory

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Achieving High Luminosity in the Fermilab Tevatron*

S. D. Holmes
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

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Stephen. D. Holmes
Fermi National Accelerator Laboratory*
P.O. Box 500
Batavia, Illinois 60510

Abstract

Fermilab has embarked upon a program, christened Fermilab III, to raise the luminosity in the Tevatron proton-antiproton collider over the next five years by at least a factor of thirty beyond the currently achieved level of $1.6\times10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. Components of the program include implementation of electrostatic separators, Antiproton Source improvements, installation of cold compressors, doubling the existing linac output energy, and the construction of a new accelerator--the Fermilab Main Injector. Basic limitations in the achievement of higher luminosity in the Tevatron, the strategy developed to achieve the Fermilab III goals, and the evolution of luminosity throughout the period will be discussed.

I. FERMILAB III GOALS

The Fermilab III program is designed to extend the discovery potential of the U.S. High Energy Physics program during the period leading up to the utilization of the SSC, and to ensure continued significant contributions from the Fermilab facility during the SSC era. Specifically, the goals of Fermilab III are to assure discovery of the top quark in the present decade assuming our understanding of nature as described by the Standard Model is correct, to provide a factor of two increase in the mass scales characterizing possible extensions to the Standard Model, to provide B-factory capability in a hadron collider, and to support new initiatives in neutral Kaon physics and neutrino oscillations. In order to attain these goals Fermilab is planning to attain by mid-decade a luminosity in excess of 5×10^{31} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ in the Tevatron Collider, supported by a new 150 GeV accelerator, the Fermilab Main Injector (FMI).

II. CURRENT PERFORMANCE LIMITATIONS

The Fermilab Tevatron is the highest energy particle collider in the world today. It will retain this position until the initial operation of either the Superconducting Super Collider (SSC) in the U.S. or the Large Hadron Collider (LHC) in Europe around the year 2000. At present in the Tevatron countercirculating proton and antiproton beams are brought into collision at 1800 GeV in the center-of-mass with a typical initial luminosity of 1.6×10^{30} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. Averaged over a multi-month running period typical initial luminosity translates into integrated luminosity with about a 33% duty factor.

The luminosity in a proton-antiproton collider is given by the expression,

$$\mathcal{L} = \frac{3\gamma f B N_p N_{\bar{p}}}{\beta^*(\varepsilon_p+\varepsilon_{\bar{p}})} F(\sigma_z/\beta^*) \qquad (1)$$

where γ is the relativistic factor of the proton (1066 at 1000 GeV), f is the revolution frequency (47.7 kHz), B is the number of bunches, N_p and $N_{\bar{p}}$ are respectively the number of protons and antiprotons per bunch, β^* is the beta function at the interaction point (assumed equal for horizontal and vertical), ε_p and $\varepsilon_{\bar{p}}$ are the proton and antiproton 95% normalized emittances respectively, and F is a form factor associated with the ratio of the bunch length to beta function at the interaction point.

The operating conditions which led to a luminosity of 1.6×10^{30} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ during the last collider run are given in the leftmost column of Table 1. The luminosity is limited by two quite different effects: 1)The beam-beam tune shift experienced by the antiprotons, which limits the useable phase space density, N_p/ε_p, of the proton beam; and 2)The availability of antiprotons, which is reflected in the product $BN_{\bar{p}}$. One can note by looking at equation (1) that as long as the proton and antiproton emittances are of comparable magnitude the luminosity achievable is proportional to the product of N_p/ε_p and $BN_{\bar{p}}$.

A. Beam-Beam Tune Shift

The beam-beam tune shift experienced by the antiprotons is given by,

$$\Delta\nu = .00733(N_p/\varepsilon_p)N_c \qquad (2)$$

where N_p is in units of 10^{10}, ε_p is in units of π mm-mr, and N_c is the number of bunch crossings per turn (=2B in the absence of orbit separation). As shown in Table 1 the achieved $\Delta\nu$ is .025. This is believed to be limited by the available working space in the tune diagram as delineated by the absence

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* Operated by Universities Research Association under contract to the U.S. Department of Energy

of resonances of ≤10th order. (The collider is operated with $\nu_x=\nu_y=19.42$, in a region bounded by the 5th order resonance 19.40, and the 7th order resonance, 19.428.) The Fermilab complex is actually capable of producing a proton phase space density approximately 60% larger than that reflected in the table. However, the use of such intense proton bunches has been found to have a deleterious effect on the antiproton bunches which makes the achievement of higher luminosities, accompanied by good lifetimes, impossible.

B. Space-charge at Booster Injection

Even if the proton phase space density were not limited by the tune shift experienced by the antiproton bunches, it would still be impossible to create a density more than about 60% above that listed in Table 1. This is because the fundamental limit on proton density in the Fermilab complex arises from space-charge forces at injection into the Fermilab Booster. With the present 200 MeV injection energy the smallest proton emittance which can be produced for injection into the Tevatron collider is about 15π mm-mr. Any planned improvements which reduce the antiproton beam-beam tune shift can only affect the luminosity in a significant manner if it allows the creation of higher phase-space densities at the upstream end of the accelerator complex.

C. Antiproton Availability

Antiproton availability is limited by two effects, one obvious and the other more subtle. The obvious constraint is the antiproton production rate. During 1988-89 a rate of $2\times10^{10}\bar{p}$/hour was achieved. The transfer efficiency of antiprotons from the Antiproton Accumulator to 900 GeV in the Tevatron was in the range 60-70%. Since the average store lasted 13 hours, a total of 1.7×10^{11} antiprotons were typically available in the Tevatron Collider. The antiproton production rate is limited by the proton beam intensity delivered from the Main Ring onto the $\bar{p}$ production target, by the Main Ring cycle rate, and by the admittance of the Antiproton Source rings. The Main Ring beam intensity itself is limited by the Main Ring admittance.

Table 1: Tevatron Luminosity Evolution through the 1990s

	88-89	Ia	Ib	II	
Energy (Center of Mass)	1800	1800	2000	2000	GeV
Protons/bunch	7.0×10^{10}	7.0×10^{10}	1.2×10^{11}	3.3×10^{11}	
Antiprotons/bunch	2.9×10^{10}	7.2×10^{10}	1.2×10^{10}	3.7×10^{10}	
Number of Bunches	6	6	36	36	
Total Antiprotons	1.7×10^{11}	4.3×10^{11}	4.3×10^{11}	1.3×10^{12}	
$\bar{p}$ Stacking Rate	2.0×10^{10}	4.0×10^{10}	6.0×10^{10}	1.7×10^{11}	hour^{-1}
ε_p	25π	15π	15π	30π	mm-mr
$\varepsilon_{\bar{p}}$	18π	18π	18π	22π	mm-mr
β^*	55	50	50	50	cm
Luminosity	**1.6×10^{30}**	**5.7×10^{30}**	**1.1×10^{31}**	**5.7×10^{31}**	**cm^{-2}sec^{-1}**
$\Delta\nu$/crossing ($\bar{p}$)	.002	.003	.006	.008	
Number of Crossings	12	2	2	2	
$\Delta\nu$ Total ($\bar{p}$)	.025	.007	.012	.017	
Bunch Separation	3000	3000	395	395	
Interactions/crossing (@45 mb)	0.3	0.9	0.3	1.5	
What's New?	---	Separators, $\bar{p}$ Source Improv.	Linac Upgrade	Main Inject.	
When?	1988	1991	1992,94	1996	

new Accumulator stack-tail system will be required for Main Injector operations, leading to an ultimate capability of of stacks containing 2×10^{12} antiprotons and stacking rates of 1.7×10^{11}/hour.

C. The Linac Upgrade

The existing 200 MeV linac is in the process of being upgraded to 400 MeV by replacement of the second half of the existing drift tube linac with a side coupled structure generating 300 MeV in the same length. The result of the higher energy will be a reduction in the space-charge forces which lead to emittance dilution at injection into the 8 GeV Booster. It is anticipated that achievable proton transverse beam densities delivered from the Booster will increase by 75% following implementation of 400 MeV injection. This will benefit antiproton production by increasing the proton flux through the Main Ring, and will simultaneously allow for the creation of higher proton phase space densities in the Tevatron collider.

The Linac Upgrade was initiated in Fiscal Year (FY) 1990, and is schduled for completion in FY1992. Commissioning is expected to start in late summer of 1992.

D. The Main Injector

The Fermilab Main Injector is a proposed new 150 GeV accelerator which will replace the existing Main Ring. The purpose of the FMI is to remove forever the bottleneck that the Main Ring presents in the delivery of high intensity proton and antiproton beams to the Tevatron, and to increase the antiproton production rate sufficiently to be able to utilize this new capability.

The Fermilab Main Injector will be constructed tangent to the Tevatron in a separate tunnel on the southwest corner of the Fermilab site. The FMI will be roughly half the size of the existing Main Ring yet will boast greatly improved performance. The FMI will allow the production of about seven times as many antiprotons per hour (1.7×10^{11}/hour) as are currently possible using the Main Ring and will have a capability for the delivery of five times as many protons to the Tevatron (at least 3×10^{11} protons/bunch for collider operations). Additionally the FMI will support the delivery of very intense proton beams (3×10^{13} protons every 2.9 seconds with a 33% duty factor) for use in state-of-the-art studies of CP violation and rare Kaon decays, and for experiments designed to search for transmutation between different neutrino generations. Low intensity proton beams emanating from the FMI will support test and calibration beams required for the development of new experimental detection devices which will be required both at Fermilab and at the SSC. In contrast to the present situation at Fermilab, simultaneous antiproton production and FMI slow spill operation will be possible under normal circumstances, as will simultaneous FMI and Tevatron fixed target operations.

The Fermilab Main Injector parameter list is given in Table 2. The FMI will perform at a significantly higher level than the existing Main Ring as measured either in terms of protons delivered per cycle, protons delivered per second, or transmission efficiency. For the most part expected improvements in performance are directly related to optics of the ring. The MI ring lies in a plane with stronger focussing per unit length than the Main Ring. This means that the maximum betas are half as big and the maximum (horizontal) dispersion a third as big as in the Main Ring, while vertical dispersion is nonexistent. 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, and improved field quality in the dipoles will all have a beneficial impact on beam dynamics. The construction of new, mechanically simpler magnets is expected to yield a highly reliable machine.

The FMI is seven times the circumference of the Booster and slightly more than half the circumference of the Tevatron. Six Booster cycles will be required to fill the FMI and two FMI cycles to fill the Tevatron. The FMI is designed to have a transverse aperture of 40π mm-mr (both planes, normalized at 8.9 GeV/c). This is 30% larger than the expected Booster aperture following the 400 MeV Linac upgrade, and a factor of three to four larger than that of the existing Main Ring. A single Booster batch will be accelerated for antiproton production while six such batches are required to fill the FMI. Yields out of the FMI for a full ring are expected to lie in the range $3\text{-}4\times10^{13}$ protons ($6\text{-}8\times10^{13}$ delivered to the Tevatron.) By way of contrast the existing Main Ring is capable of accelerating 1.8×10^{13} protons in twelve batches for delivery to the Tevatron.

The power supply and magnet systems are designed to allow a significant increase in the number of 120 GeV acceleration cycles which can be run each hour for antiproton production, as well as to allow a 120 GeV slow spill with a 35% duty factor. The cycle time at 120 GeV can be as low as 1.5 seconds. This is believed to represent the maximum rate at which the Antiproton Source might ultimately stack antiprotons and is to be compared to the current Main Ring capability of 2.6 seconds.

The Total Estimated Cost of the Fermilab Main Injector is \$177.8 M. The FMI is included in the President's proposed FY1992 budget with \$43.4M of funding in the first year. This proposal is now before the Congress. With the proposed funding profile the FMI would become operational on or about January 1, 1996.

Magnet R&D was initiated on this project in 1990. A full-scale prototype was built and is undergoing measurement at the Fermilab Magnet Test Facility. Measurements show that this magnet is very well described by the computer models and satisfies the magnet field quality specification.

Environmental permitting is well advanced on this project. A Clean Air and Water, Section 404, joint permit application was submitted to the U.S. Army Corps of Engineers, Illinois Environmental Protection Agency, and the Illinois Department of Transportation in September of 1990. These permits are expected well in advance of construction. In addition an

Figure 1 displays the correlation between intensity delivered from the 8 GeV Booster and the beam emittance. The correlation appears to be due to the space-charge effect mentioned earlier. As can be seen from the figure, the Main Ring is currently incapable of accelerating the full quantity of beam which the Booster is capable of delivering due to the restricted admittance. As a result the Booster is typically run at two-thirds of its ultimate capability for antiproton production.

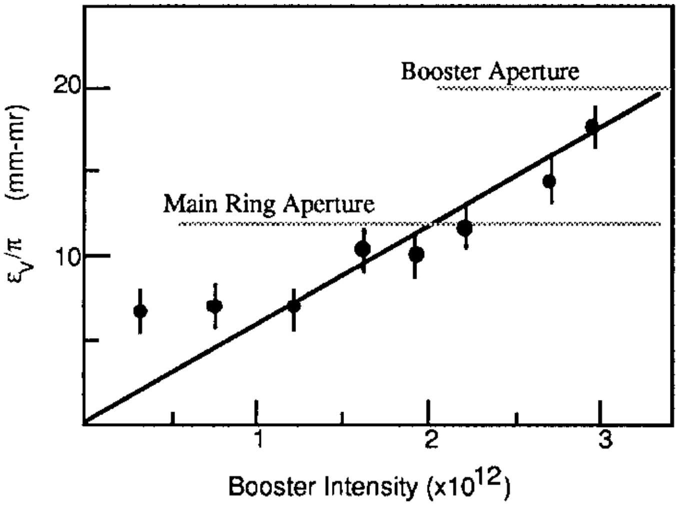

Figure 1: Transverse emittance delivered from the Fermilab Booster as a function of intensity.

Antiproton availability is also limited by a more subtle effect having to do with the correlation between the antiproton transverse beam emittance and stack size in the Accumulator. The beam emittance arises as a result of the attainment of equilibrium between intrabeam scattering and stochastic cooling. As the stack size increases, the heating due to intrabeam scattering increases, while the effectiveness of the cooling system decreases. The resultant antiproton beam emittance rises as the stack size increases. Unfortunately, the Main Ring admittance is less than the emittance emanating from the Accumulator at a stack size in excess of 6×10^{11}. In general this guarantees that accumulated antiprotons in excess of 6×10^{11} will not be transmitted through the Main Ring on their journey to the Tevatron. Since we are currently capable of delivering about 40% of the antiproton stack from the Accumulator, with 60-70% transmission to the collider this also limits antiproton availability in the collider to 1.7×10^{11}.

III. LUMINOSITY EVOLUTION THROUGH THE 1990S

Fermilab has initiated a series of improvements to the existing accelerator complex to provide a luminosity capability in excess of 5×10^{31} cm^{-2}sec^{-1} by 1996. These improvements are aimed at attacking the above-described limitations associated with the beam-beam tune shift, space-charge in the Booster, and antiproton availability. Specifically included are: 1)implementation of electrostatic separators in the Tevatron; 2) a series of Antiproton Source improvements; 3)upgrading the Linac energy from 200 MeV to 400 Mev; and 4)construction of a new accelerator, the Fermilab Main Injector, to replace the existing Main Ring.

The expected progression of luminosity throughout the decade is summarized in Table 1. Note that in addition to the items listed above the table reflects the implementation of cold compressors which will lower the operating temperature of the Tevatron magnets by about 0.5°K and provide an energy of 1000 GeV per beam.

A. Electrostatic Separators

Electrostatic separators will create helically separated orbits in the Tevatron which will keep up to 36 proton and antiproton bunches separated everywhere but at the B0 and D0 collision points. This will reduce the total beam-beam tune shift, as given in equation (2), by providing N_C=2 with B up to 36.

Each separator is 3 meters in length and is capable of generating 250 kV over a 5 cm aperture. Twenty units are required to create the desired orbits. The peak field, 50 kV/cm, is required only during injection--during a proton-antiproton store no unit will be required to operate above 40 Kv/cm.

Several units have been tested in the Tevatron with protons and antiprotons stored at 150 GeV. These studies have shown no anomolous behavior, i.e. unexepcted tune shifts, emittance growth, or lifetimes, for separations as low as 1σ.

Thirteen of the required twenty units are installed at this time. The remaining units, which are located in the region currently occupied by slow extraction equipment, will be installed following the completion of the current fixed-target run. All separators will be in place and operational for the collider run scheduled to start in late 1991.

It should be noted that separators themselves do not create higher luminosity in the collider. They only create the potential for raising the luminosity if one has the capability of raising the proton phase space density and/or the number of antiprotons in the Tevatron.

B. Antiproton Source Improvements

Improvements implemented in the Antiproton Source since 1989 have beem aimed at increasing the accumulation rate and reducing the emittance characterstic of a given stack size. An enlargement of antiproton collection line and Debuncher ring apertures, and implementation of Debuncher momentum cooling are expected to increase the antiproton stacking rate by a factor of 2-3 beyond that achieved in 1988-89. A 4-8 GHz core cooling system has replaced the original 2-4 GHz system in the Accumulator Ring. The new system will reduce the emittance at a given stack size relative to that currently achieved. Future improvements to the targeting system and a

Environmental Assessment has been prepared and is currently under review by the Department of Energy. A Finding of No Significant Impact (FONSI) is expected in late summer.

Table 2: Fermilab 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	2.2	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	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	meters
Quadrupole Gradient	196	kG/m
Number of Quadrupole Busses	2	

IV. SUMMARY

The Fermilab Tevatron Collider currently operates at a luminosity of 1.6×10^{30} cm^{-2}sec^{-1}. Luminosity limitations in the collider are well understood and a coherent plan has been formulated for increasing the luminosity by at least a factor of 30 in several steps over the next five years. All elements required for achievement of 5×10^{31} cm^{-2}sec^{-1} are in place or funded with the exception of the Fermilab Main Injector which is currently before the Congress.

The research program based on the Fermilab III program will allow High Energy Physicists to extend their understanding of the basic structure of matter over the decade leading up to utilization of the SSC. In parallel many of the detector techniques required for utilization of the SSC will be developed and proven in the Tevatron Collider over the next decade. The construction and operation of the Fermilab Main Injector will leave Fermilab well positioned for continuing contributions to the field of High Energy Physics during the SSC era.