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Abstract Performance and performance limitations of the Tevatron proton-antiproton collider at Fermilab will be discussed along with plans for improving the performance by a factor of five by the end of the decade. The centerpiece of this effort is the Fermilab Main Injector, a new 150 GeV synchrotron now under construction. Status of the project will be presented.

Introduction Fermilab is in the midst of a program to raise the luminosity in the Tevatron proton-antiproton collider a factor of five above the currently achieved level of $1.2\mathrm{x}10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. The expected luminosity progression is given in Table 1.

The goals of Fermilab in physics are: to produce sufficient quantities of the top quark to allow determination of its fundamental properties; to provide a factor of two increase in the mass scale characterizing possible extensions to the Standard Model; and to support new initiatives in neutral kaon physics, b physics, and neutrino oscillations.

The goals established for the Fermilab accelerator complex in the 1990s are met through a series of steps which directly address identified limitations.

Time	*Apr. 1992* *May 1993*	*Dec. 1993* *Jun. 1995*	*Jul. 1998*	
Collider Run	Ia	Ib	II	
Energy (Center of Mass)	1800	1800	2000	GeV
Protons/bunch	$1.2\mathrm{x}10^{11}$	$1.8\mathrm{x}10^{11}$	$3.3\mathrm{x}10^{11}$	
Antiprotons/bunch	$3.1\mathrm{x}10^{10}$	$5.0\mathrm{x}10^{10}$	$3.6\mathrm{x}10^{10}$	
Number of Bunches	6	6	36	
Total Antiprotons	$1.9\mathrm{x}10^{11}$	$3.0\mathrm{x}10^{11}$	$1.8\mathrm{x}10^{12}$	
$\bar{p}$ Stacking Rate	$4.0\mathrm{x}10^{10}$	$5.0\mathrm{x}10^{10}$	$1.7\mathrm{x}10^{11}$	hour^{-1}
ε_p	20π	22π	30π	mm-mr
$\varepsilon_{\bar{p}}$	12π	14π	22π	mm-mr
β^*	35	35	25	cm
Luminosity*	$5.4\mathrm{x}10^{30}$	$1.2\mathrm{x}10^{31}$	$8.1\mathrm{x}10^{31}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Number of Crossings	2	2	2	
$\Delta\nu$ Total $(\bar{p})$	.009	.012	.016	
Integrated Luminosity	1.1	2.4	16.4	$\mathrm{pb}^{-1}/\mathrm{wk}$
Interactions/crossing (@45 mb)	0.8	1.9	2.1	
Bunch Spacing	3500	3500	396	nsec

*"Typical luminosity at the beginning of a store"--translates into integrated luminosity at about 55 hours/week.

Table 1: Expected Tevatron luminosity progression over the 1990s.

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

Improvements are incremental and lead to continuous significant increases in luminosity and/or other performance characteristics. Improvements at the various stages include:

Run Ia: Electrostatic separators in the Tevatron, new cooling system in the $\bar{p}$ source
Run Ib: Linac Upgrade, cold compressors
Run II: 36 bunch operations, main Injector

Performance Limitations Performance in the 1992-93 run Ia was enhanced relative to the previous run by improvements to both the Tevatron and the Antiproton Source, most noticeably the installation of electrostatic separators in the Tevatron and the installation of new cooling systems in the Source. The luminosity in the collider is given by the expression,

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

As seen, the luminosity achievable is generally proportional to the product of the proton phase density (N_p/ε_p) and the total number of antiprotons ($BN_{\bar{p}}$) in the collider. Following installation of separators (N_p/ε_p) is no longer limited by the beam-beam tune shift as it was previously. Space-charge at injection into the Booster provided in run Ia the fundamental limitation on this quantity. N_p itself was limited by 1) the Main Ring aperture at 8 GeV; and 2) a longitudinal coupled bunch instability in the Main Ring that limits coalescing efficiency. The number of antiprotons in the ring, ($BN_{\bar{p}}$), was limited by the number of protons the Main Ring can deliver onto the antiproton production target at 120 GeV. The capability was $2.1\mathrm{x}10^{12}$ protons every 2.4 sec. During the 1992-93 run Ia it was observed that the single most important factor determining the luminosity of a particular store was the stack size. In general the size of the stack reflected not only the stacking rate but the reliability of accelerator performance over past several days.

The most significant interruptions included power outages, Main Ring magnet failures, and quench protection monitor system problems.

Approximately 2/3 of all stores were ended intentionally. The average store length was 12.8 hours and about 110 hours of stored beam was provided each week.

Luminosity lifetimes were typically 11 hours at the beginning of a store, increasing by about 0.3 hour/hour. Maintenance of the lifetime required eternal vigilance to identify noisy power supplies. Occasional episodes of 8 hour lifetimes were observed due to such effects.

In an effort to improve the lifetime, bunched beam stochastic cooling as an R&D project was developed. Hardware for a proton/vertical damping system was installed and operated during the run. Based on promising results the remaining proton and antiproton systems were installed in summer 1993. The potential gain from this system is up to 50% in integrated luminosity. Parameters achieved in collider run Ia were a new world best.

Collider Run Ib Collider Run Ib started in the fall of 1993. The primary modifications to the Fermilab accelerator complex for this run include implementation of the 400 MeV linac upgrade and the addition of cold compressors in the Tevatron refrigeration system. The purpose of the linac upgrade is to double the 8 GeV Booster injection energy to 400 MeV by replacing the second half of the existing drift tube linac with a modern side-coupled structure. The phase space density of protons delivered from the Booster increased by 25% as a result of reduced space charge forces at injection. New hardware was installed in the summer of 1993. Following this upgrade the 8 GeV Booster has delivered beams containing up to $4\mathrm{x}10^{12}$ protons to the Main Ring, and the Main Ring now delivers typically $2.75\mathrm{x}10^{12}$ protons every 2.4 sec. to the antiproton production target.

Also, in the summer of 1993, hardware was installed that allowed operation of the Tevatron at 3.6^0 K, a full degree lower than the current operation. This improvement should ultimately allow us to raise the energy of the Tevatron to 1000 GeV.

As a result of these improvements the Tevatron is delivering a luminosity in excess of $1 \mathrm{x} 10^{31}$ cm^{-2}sec^{-1} in Run Ib (2 pb^{-1}/week), still with six proton and six antiproton bunches.

The Fermilab Main Injector, Run II The Fermilab Main Injector (FMI) Project is the centerpiece of Fermilab's initiative for the 1990s, Fermilab III. The parameter list is given in Table 2. In order to attain goals in physics, Fermilab is planning to attain by the end of the decade a luminosity in excess of $8 \mathrm{x} 10^{31}$ cm^{-2}sec^{-1} in the Tevatron $\bar{p}$-p Collider, supported by a new 150 GeV accelerator, the Fermilab Main Injector. Concurrent with first operation of the Main Injector the Tevatron will be shifted to 36 bunch operation. This step will be taken in order to minimize the number of interactions per crossing in the two experimental detectors and results in a minimum spacing between bunch crossings of 396 nsec.

Circumference	3319.4 m
Injection Energy	8.9 GeV
Peak Energy	150 GeV
Minimum Cycle Time(@120 GeV)	1.5 sec
Number of Protons	$3 \mathrm{x} 10^{12}$
Number of Bunches	498
Protons/Bunch	$6 \mathrm{x} 10^{10}$
Horizontal Tune	26.4
Vertical Tune	25.4
Transition Gamma	20.4
Natural Chromaticity (H)	-33.6
Natural Chromaticity (V)	-33.9
Transverse Emittance (95%, normalized)	20π mm-mr
Longitudinal Emmittance	0.4 eV-sec
Transverse Admittance (@8.9 GeV)	40π mm-mr
Longitudinal Admittance	0.5 eV-sec
β_{max}	57 m
Maximum Dispersion	2.0 m
Number of Straight Sections	8
RF Frequency (Injection)	52.8 MHz
RF Frequency (Extraction)	53.1 MHz
Harmonic Number	588
RF Voltage	4 MV
Number of Dipoles	216/128
Dipole Lengths	6.1/4.1 m
Dipole Field (@150 GeV)	17.2 kG
Number of Quadrupoles	128/32/48
Quadrupole Lengths	2.1/2.5/2.9 m
Quadrupole Gradient	196 kG/m
Number of Quadrupole Busses	2

Table 2: Main Injector parameters.

The 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 Main Injector will allow the production of about four times as many antiprotons per hour ($1.7\mathrm{x}10^{11}$/hour) as are currently possible using the Main Ring and will have a capability for the delivery of two times as many protons to the Tevatron (at least $3\mathrm{x}10^{11}$ protons/bunch for collider operations). Additionally the Main Injector will support the delivery of very intense proton beams ($>3\mathrm{x}10^{13}$ protons every 2.9 seconds with a 33% spill duty factor, or every 1.9 seconds with a few millisecond fast spill) 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 Main Injector will support test beams required for the development and calibration of new experimental detection devices. In contrast to the present situation at Fermilab, simultaneous antiproton production and Main Injector slow spill operation will be possible under normal circumstances.

FMI Project Status

R&D Program A comprehensive magnet R&D program has been completed. Two prototype and ten pre-production dipole magnets have been successfully constructed and tested. These magnets are conventional iron/copper magnets designed with a low number of turns (4 turns/pole) in order to support the rapid cycle rate at 120 GeV. Magnetic measurements have verified the field quality of the magnets as being sufficient to support a dynamic aperture at injection in excess of the required 40π mm-mr, and as being of sufficient quality to allow resonant extraction at 120 GeV. Typically the deviation of the magnetic field relative to the central value is less that $1\mathrm{x}10^{-4}$ over an aperture of ±3.8 cm (±1.5").

Prototype quadrupole and sextupole magnets have also been constructed and tested. Each shows acceptable field quality. A prototype model of the 1000V/10,000A supply required to power the dipole magnets has been successfully tested and the first pre-production unit is now under construction. The prototype supply is currently ramping a string of ten of the preproduction dipoles. Twelve of these supplies are required for powering the completed accelerator dipole string. Three prototype 200 kW rf power amplifiers, of eighteen required to accelerate the beam, have been fabricated. One unit is currently in service in the existing Main Ring rf system.

Production Finally, with confidence in the design, the fabrication process, and the subcontractors, production of the balance of the dipoles for the project began. The total quantity, 344, to be built will include the number required for the Main Injector ring plus spares. Six production dipoles were assembled by September, 1994. The first production dipole was measured magnetically and the quality of the field was confirmed.

After an initial ramp up period, dipole production is planned to run at a steady rate of ten magnets per month.

The key to the plan is that the major subassemblies of the dipole magnets are being fabricated by industry but the final assembly is being done at Fermilab. The major subassemblies are the steel for the laminations, laminations themselves, the stacked half cores, the bare coils, the insulted coils, and the beam tubes.

Production of quadrupoles and sextupoles is ongoing now at Fermilab. The first production units were measured and the quality of the magnetic fields was confirmed to be within specifications.

Civil Construction Following the official groundbreaking on March 22, 1993 the project rapidly awarded contracts for other civil construction activities. Contracts for the underground enclosure housing the rf straight section and the large service building/rf gallery at the point of tangency, and for general site preparation were awarded in the first half of 1993. Work on these projects is now complete. The largest single construction package on the project, the underground accelerator ring enclosure, was awarded in January 1994. The overall construction strategy for the project has been established as constructing the northern half of the ring enclosure in 1994 and the southern half in 1995. Work on the ring enclosure was initiated in April 1994. Construction of the beamline connecting the Main Injector to the existing 8 GeV Booster and of the above grade service buildings will be initiated in late 1995 and in 1996. By the end of FY94 1500m of tunnel was excavated.

Summary The Tevatron Collider is running beautifully. Luminosity goals for the 1993-94 run Ib have been met. Building upon this successful run, Fermilab has a well considered plan for increasing the luminosity by another factor of five over the remainder of the decade. Linac and low temperature upgrades were installed in summer 1993, preparations for 36 bunch operations in the following collider run II, and finally operations with the Main Injector near the end of the decade. The future offers new research opportunities for the Tevatron complex, both during the coming decade and into the 21st century.

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