STATUS OF THE FERMILAB MAIN INJECTOR AND RECYCLER

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Abstract

The Fermilab Main Injector is a new 150 GeV synchrotron under construction at the Fermi National Accelerator Laboratory. The FMI has been designed to support a factor of five increase in luminosity available from the Tevatron proton-antiproton collider while simultaneously providing a 2 mA resonantly extracted 120 GeV proton beam. Recently a new antiproton storage ring, the Recycler, has been incorporated within the scope of the project with an expected luminosity gain of a factor of two. Project status, schedule for completion, and expected performance characteristics of the Main Injector and Recycler will be presented.

1 INTRODUCTION

The Fermilab Tevatron is the highest energy collider operating in the world today. As such it is uniquely positioned as the world's forefront High Energy Physics "discovery facility"--a position it will retain until the advent of the LHC approximately eight years from now. Fermilab is committed to exploiting the Tevatron facility to the fullest extent possible over the period between now and 2005, and to that end has undertaken the construction of the Main Injector accelerator and the Recycler antiproton storage ring to provide improved Tevatron luminosity performance starting in 1999.

The Tevatron proton-antiproton collider currently operates at a center-of-mass energy of 1.8 TeV, accompanied by a luminosity greater than 1.5×10^{31}cm^{-2}sec^{-1}. The luminosity in the Tevatron collider is given by,

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

where γ is the relativistic factor, f is the revolution frequency, B is the number of bunches in each beam, N_p ($N_{\bar{p}}$) is the number of protons (antiprotons) in a bunch, ε_p ($\varepsilon_{\bar{p}}$) is the 95% normalized transverse beam emittance, σ_z is the rms bunch length, β^* is the beta function at the interaction point, and F is a form factor dependent on the ratio of the bunch length to β^*.

Under current operating conditions, the most important factor influencing luminosity performance is the total number of antiprotons in the ring, $BN_{\bar{p}}$. The second most important factor is the proton phase space density, N_p/ε_p. A large increase in N_p/ε_p is precluded by the beam-beam interaction. Hence, increasing antiproton availability remains, and will remain for the indeterminate future, the key to improving Tevatron collider performance.

2 RUN II PERFORMANCE GOALS

Run II is the name applied to the first operating period of the Tevatron collider following commissioning of the Main Injector. Goals established for this run include achievement of a luminosity of 5×10^{31}cm^{-2}sec^{-1} early in the run, ultimately growing to 2×10^{32}cm^{-2}sec^{-1} once the full capabilities of the Recycler ring are realized, accompanied by a capability of resonantly extracting 3×10^{13} protons per pulse at 120 GeV in support of a variety of fixed target experiments.

In order to achieve the collider goal the Fermilab complex will be required to support:

- More protons in collision
- Many more antiprotons in collision
- A significant increase in the antiproton stacking rate
- A capability for recovering antiprotons at the end of stores

The Main Injector, accompanied by a variety of improvements to the Antiproton Source facility, is designed to support a three-fold increase in the antiproton production rate, accompanied by good antiproton transmission efficiency from the Recycler to Tevatron and a modest increase in coalesced proton bunch intensity.

The Recycler is designed to capitalize on the existence of the Main Injector to extend further the performance potential of the Tevatron complex. The Recycler does this by relieving the Antiproton Source of responsibility for maintaining high stacking rate at high stacks, by doubling the effective stacking rate via antiproton recovery, and by providing a platform for further performance enhancements within the Tevatron complex.

Design parameters for the next Tevatron collider run (Run II) are listed in Table 1. For comparison typically achieved parameters and performance in the most recent collider run (Run IB) are listed in the first column. As can be seen from the table the factor of ten increase in luminosity is supported primarily through a factor of eight increase in the number of antiprotons in the collider. It should also be noted that the increased luminosity will require operations with 36 bunches per beam, rather than 6, in order to maintain the number of interactions per crossing as seen in the detectors at a reasonable level.

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Table 1: Collider operational achievement in Run IB and goals for Run II. Run II is the first run supported by the Main Injector and Recycler rings.

RUN	IB(1993-95)	II(1999-)	
Protons/bunch	2.32×10^{11}	2.70×10^{11}	
Pbars/bunch	5.50×10^{10}	7.00×10^{10}	
Total Pbars	3.30×10^{11}	2.5×10^{12}	
Pbar Production Rate	6.00×10^{10}	2.00×10^{11}	pbar/hour
Proton emittance	23π	20π	mm-mr
Pbar emittance	13π	15π	mm-mr
β*	0.35	0.35	m
Energy	900	1000	GeV
Bunches	6	36	
Bunch length (rms)	0.60	0.38	m
Form Factor	0.59	0.70	
Typical Luminosity	1.6×10^{31}	2.0×10^{32}	$cm^{-2}sec^{-1}$
Bunch Spacing	~3500	396	nsec
Interactions/crossing	2.7	5.8	
(@ 50 mb)			

3 MAIN INJECTOR AND RECYCLER PERFORMANCE GOALS

The Main Injector is a 3319 meter circumference, 150 GeV, conventional-magnet-based accelerator. It is designed to perform all duties currently assigned to the Main Ring, the original 400 GeV accelerator at Fermilab, but with significantly improved performance. In addition the Main Injector creates a new capability at Fermilab for modest energy (120 GeV), high average intensity extracted beams.

Improved performance relative to Main Ring is largely attributable to a larger design aperture. The Main Injector is designed to provide an admittance of 40π mm-mr (normalized at 8.9 GeV) as compared to approximately 12π in the Main Ring. This improvement is the result of implementation of a lattice with beta functions reduced by a factor of two (55 meters vs. 110 meters) and dispersion reduced by a factor of three (2 meters vs. 6 meters), and by elimination of vertical dispersion. In addition better field quality is being achieved at injection through the use of lower coercivity steel (<1 Oe) and a higher injection field (0.1 Tesla vs. 0.04 Tesla).

As a result of these improvements the Main Injector is anticipated to have a capability of delivering more protons per cycle (5×10^{12} vs. 3×10^{12}) at a faster cycle rate (1.47 sec. vs. 2.4 sec.) than currently achieved in the Main Ring. A new capability of slow extracting 3×10^{13} protons per pulse at 120 GeV is also provided. Fast or slow resonant extraction cycles are planned with a 1.93 and 2.93 second cycle time respectively. A parametric description of the Main Injector is given in Table 2. It is expected that after some years of operation the delivered intensities may rise by a factor of two to three beyond the formal project goals.

Table 2: Main Injector parameter list

Circumference	3319.4	m
Injection Momentum	8.9	GeV/c
Peak Momentum	150	GeV/c
Cycle Time (@ 120 GeV)	1.5	s
Cycle Time (@150 GeV)	2.4	s
Protons/Bunch	6×10^{10}	
Number of Bunches	498	
Number of Protons	3×10^{13}	
Average Current	433	mA
Maximum Beta Function	57	m
Maximum Dispersion Function	1.9	m
Nominal Horizontal Tune	26.425	
Nominal Vertical Tune	25.415	
Transverse Emittance (Normalized @ 8.9 GeV/c)	20π	mm-mr
Transverse Admittance	$>40\pi$	mm-mr
Harmonic Number (@53 MHz)	588	
RF Frequency (Injection)	52.8	MHz
RF Frequency (Extraction)	53.1	MHz
RF Voltage	4	MV
Transition Gamma	21.8	
Longitudianl Emittance (95%, per bunch)	0.2	eV-s
Longitudinal Admittance	>0.5	eV-s
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
Quad. Gradient (@150 GeV)	200	kG/m

The Recycler is a 3319 meter, 8.0 GeV (kinetic energy), permanent-magnet-based storage ring situated within the Main Injector enclosure [1,2]. The choice of permanent combined function (or “gradient”) magnet technology for this ring was based on considerations of construction and operational cost and reliability. The purpose of the Recycler is to improve the stacking capability of the existing Antiproton Accumulator by relieving this facility of the responsibility of maintaining a high (> 2×10^{11} antiprotons/hour) stacking rate at high stacks (> 5×10^{11} antiprotons). Perhaps more importantly the Recycler will create the capability to recover unspent antiprotons at the end of collider stores. Since typically >70% of all antiprotons initially stored in the Tevatron remain at the end of a collider store, a significant increase in available antiprotons will be made possible through recycling. This operation will require deceleration of antiprotons from 1000 GeV to 8 GeV followed by transfer to and cooling in the Recycler.

Specific design goals for the Recycler include a stacking capability of 2×10^{11} antiprotons/hour up to a total stack size of 3×10^{12} antiprotons. The initial implementation is based on stochastic cooling. An R&D program aimed at developing electron cooling at 8 GeV is currently underway. Electron cooling will be required to support stack sizes in the range 3-10 $\times10^{12}$ antiprotons at stacking rates up to 10^{12} antiprotons/hour for future applications.

Table 3: Recycler parameter list

Circumference	3319.4	m
Operating Momentum	8.9	GeV/c
Total Antiprotons	3×10^{12}	
Number of Bunches	498	
Average Current	43	mA
Maximum Beta Function	55	m
Maximum Dispersion Function	2.0	m
Nominal Horizontal Tune	24.425	
Nominal Vertical Tune	24.415	
Transverse Admittance (Normalized @ 8.9 GeV)	> 40π	mm-mr
Momentum Acceptance (full)	0.6	%
Number of Gradient Magnets	216/128	
Dipole Lengths	4.5/3.1	m
Number of Quadrupoles	72	
Quadrupole Length	0.5	m

A detailed description of the lattice is contributed to these proceedings [3].

4 PROJECT STATUS

The Fermilab Main Injector Project is currently in its sixth year of funding. Funding over the period FY1992-97 amounts to \$198.65M, with \$30.95M scheduled for the final year of funding, FY1998. Currently (March 31, 1997) the project is 66% complete by cost and project completion is scheduled for March 1999.

4.1 Construction and Installation Status

Civil construction on the Main Injector is well advanced following completion of the underground ring enclosure and above ground service buildings in 1996. Currently under construction are the cooling ponds, a new substation, and the transmission line required to deliver 345 KV power to the substation. The major outstanding civil construction job involves the final connection of the Main Injector beam lines into the Tevatron at the interface between the two machines. This work is scheduled to start in the fall of 1997.

Magnet production is now nearing completion [4, 5]. Of the 344 dipole magnets required, 307 have been built and 280 are now installed in the ring. In addition all 80 new quadrupole magnets have been completed. These will be augmented by 128 quadrupoles recovered from the Main Ring following the shutdown of that machine in the fall. Dipole power supply installation is nearly complete and testing should be initiated in June. Prototype power amplifiers and modulators required to drive the 53 MHz cavities have been constructed and placed in service in the Main Ring where they have accumulated 24,000 and 14,000 hours respectively of failure free operations [6]. The actual accelerating cavities used in the Main Injector will be recovered from the Main Ring.

In September of 1995 it was decided to construct the 8 GeV transfer line connecting the Fermilab Booster to the Main Injector utilizing permanent magnets [7]. This choice was made in order to gain experience with the technology under consideration for the Recycler ring. The permanent magnets (about 120 in total) required for the 8 GeV line have now been constructed and installed, and procurements for Recycler permanent magnets have commenced.

4.2 Recycler Status

A proposal to incorporate the Recycler into the Main Injector project, without modification to the project budget or schedule, was presented to the Department of Energy in November 1996. As part of the proposal four prototype gradient magnets were built with field uniformity sufficient for use in a storage ring. These magnets culminated a nearly eighteen month period of R&D on permanent magnets for this application. The proposal was approved in February 1997 and work on Recycler construction commenced in April.

The Recycler itself is estimated to cost \$12.6M. The low cost results from the utilization of permanent magnets and the already existing Main Injector enclosure and service buildings. The goal is to complete installation of the Recycler in the spring of 1998 and to commission over the remainder of the year.

4.3 Commissioning activities

The 8 GeV line is now completely installed over ~80% of its length. Commissioning with beam commenced on February 20, 1997 and beam was observed at the entrance to a temporary dump situated at the ~60% point after two hours of tuning. Currently beam transmission is measured at 95±5% with most losses coming in the upstream, electromagnet, matching section where the most restrictive apertures are located. A measurement of the average bending in the line indicates that the dipole field in the permanent magnets is 0.4±0.2% less than that required for "8 GeV" beam delivered from the Booster. This offset is well within the acceptance of the line and will be corrected in the future by either realigning the gradient magnets or by reducing the Booster energy.

Commissioning of the 8 GeV line has occurred nearly a year ahead of schedule--the original plan called for utilizing magnets recovered from the Main Ring during the upcoming shutdown. Commissioning activities in the ring itself are expected to start in late winter/early spring 1998

5 SCHEDULE TO COMPLETE

The current working schedule to completion of the project is given below.

April 1997	Start Recycler construction
May 1997	Award F0 construction contract
September 1997	Start shutdown (Main Ring off)
October 1997	Start F0 construction (demolition)
March 1998	Start half turn commissioning of the Main Injector
June 1998	Main Injector under vacuum, start full turn commissioning
Summer 1998	Recycler under vacuum, start commissioning
July 1998	F0 partial occupancy. Start F0/beamline reinstallation
September 1998	Start Tevatron cooldown
November 1998	Complete F-0 construction. Start delivery of beam to the Tevatron. Parasitic commissioning of remaining beamlines.
January 1999	Complete Recycler installation & commissioning
March 1999	Project complete

We are planning to shut down the Main Ring for the final time on September 15, 1997. At this time equipment removal from the Main Ring and Tevatron will start, followed by demolition and reconstruction of the Tevatron enclosure with its connections to the Main Injector. During the same period Main Ring components destined for reuse in the Main Injector, primarily quadrupole magnets and rf cavities, will be removed, refurbished, and reinstalled.

It is anticipated that 50% of the Main Injector will be intact by February 1998, allowing half turn beam delivered to the permanent dump starting in March. The entire ring should be installed and under vacuum by May 1998. In parallel, but somewhat behind the Recycler magnet and vacuum systems will be installed, allowing commissioning with beam to commence in the summer of 1998. Final installation of beamlines and Recycler rf and stochastic cooling will not happen until the fall of 1998, to be followed by commissioning. Current planning calls for startup in fall 1998 with the Tevatron in a fixed target configuration. Parasitic collider commissioning activities will continue until the late spring of 1999 followed by a changeover to collider configuration.

6 SUMMARY

A plan for enhanced utilization of the Fermilab complex in the upcoming decade(s) is now well underway. By the end of the century the Fermilab community can expect to see:

- A luminosity in the range of $5\text{-}20\times10^{31}$ $cm^{-2}sec^{-1}$ in the Tevatron Collider.
- A new capability for study of neutrino oscillations and rare K decays based on 120 GeV resonantly extracted beams
- 120 GeV test beams to the experimental areas coincident with collider operations.
- A complex capable of being upgraded to $\sim1\times10^{33}$ $cm^{-2}sec^{-1}$ with further improvements to antiproton targeting and cooling.

Following the recent enhancement represented by the addition of the Recycler ring, the Main Injector project is proceeding rapidly to conclusion, with installation now well underway and completion scheduled for spring 1999.

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