BEAM INTENSITY UPGRADE AT FERMILAB*

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Abstract

The performance of the Fermilab proton accelerator complex is reviewed. The coming into operation of the NuMI neutrino line and the implementation of slip-stacking to increase the anti-proton production rate has pushed the total beam intensity in the Main Injector up to ~ 3×10^{13} protons/pulse. A maximum beam power of 270 kW has been delivered on the NuMI target during the first year of operation. A plan is in place to increase it to 350 kW, in parallel with the operation of the Collider program. As more machines of the Fermilab complex become available with the termination of the Collider operation, a set of upgrades are being planned to reach first 700 kW and then 1.2 MW by reducing the Main Injector cycle time and by implementing proton stacking.

INTRODUCTION

The Fermilab accelerator complex has recently seen substantial improvements in proton throughput.

The short-baseline neutrino oscillation experiment MiniBoone has accumulated in the last few years 7.2×10^{20} protons from the Booster.

In 2005 the Main Injector (MI), a 120 GeV proton synchrotron, has started operation for the NuMI long-baseline neutrino facility [1], achieving a maximum delivered beam power of 270 kW. The anti-proton source, part of the Tevatron Collider complex, has witnessed a steady increase in proton intensity. Up to 8×10^{12} protons/pulse (ppp) have been delivered on the anti-proton target by means of slip-stacking [2] two Booster batches in the Main Injector. Implementation of slip-stacking over multiple batches will increase the beam power on the NuMI target to 350 kW.

The future experimental neutrino program [3], devoted to long-baseline electron-neutrino appearance searches, will require a substantial upgrade in proton beam power.

With the conclusion of the Collider program, several machines will become available to be used, in conjunction with the Booster and the Main Injector, to increase the beam power delivered to the NuMI facility.

We foresee a first stage up to 700 kW beam power, which makes use of the Recycler ring as a proton pre-injector to the Main Injector, and a second stage up to 1.2 MW by adding in the chain the Accumulator ring, presently part of the anti-proton source, to perform momentum-stacking of several Booster batches.

THE ACCELERATOR COMPLEX

A sketch of the Fermilab accelerator complex is shown in Figure 1 .

The Booster is effectively the proton horsepower of the complex. Fed by 400 MeV H$^-$ ions from the Linac, it accelerates protons to 8 GeV kinetic energy at 15 Hz rate. Booster batches (set of proton bunches accelerated in the Booster, typically up to ~5×10^{12} protons) are transferred through the MI8 line into the Main Injector or sent to the MiniBoone neutrino target.

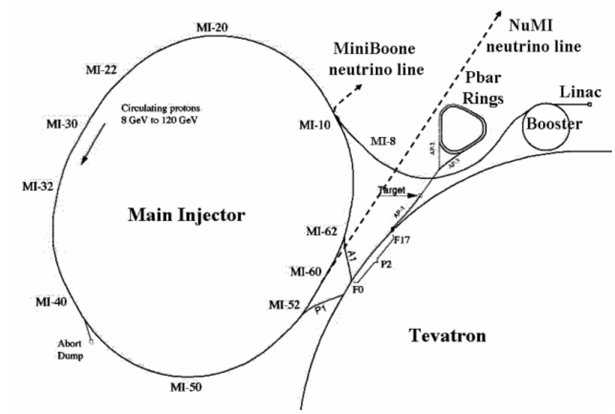

Figure 1: The Fermilab accelerator complex.

The Main injector is seven times the circumference of the Booster. Six Booster batches are required to fill up the machine, leaving one seventh of the circumference available for the rise-time of the extraction kicker. Table 1 summarizes the MI parameters.

Table 1: Main parameters of the Main Injector

Circumference (km)	3.319	Harmonic number	588
Injection momentum (GeV/c)	8.9	RF frequency at injection (MHz)	52.8
Extraction momentum (GeV/c)	120	RF frequency at extract. (MHz)	53.1
Transition gamma	21.8	Maximum RF voltage (MV)	4.3

The Main Injector is the central machine of the complex, equipped with a complex set of injection and extraction lines to connect to the other machines of the complex. It provides protons for anti-proton production, it has a dedicated extraction to the NuMI line and it is connected to the Tevatron for proton and anti-proton transfers.

An additional machine, an 8 GeV anti-proton storage ring, denominated Recycler, is located in the Main Injector tunnel above the MI ring and with the same basic cell geometry. Antiproton transfers in and out of the Recycler Ring take place through two transfer lines connecting the Recycler to the Main Injector. Figure 2 shows the Main Injector tunnel in the MI-60 region, where the NuMI extraction is located.

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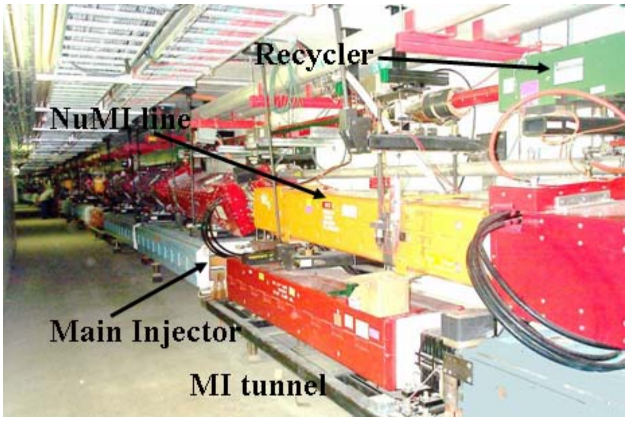

Figure 2: A photo of the Main Injector tunnel in the MI-60 region, showing the NuMI extraction line between the Main Injector at the bottom and the Recycler on top.

PRESENT OPERATION

Currently the Main Injector has to satisfy simultaneously the needs of the Collider program and of NuMI operation. Two main cycles are operational in the Main Injector most of the time, 'mixed-mode' and 'NuMI only' cycles.

The default mode of operation is the 'mixed mode' cycle. Protons for the anti-proton target and for NuMI are simultaneously accelerated in the same cycle. Seven booster batches are injected into the Main Injector. The first two are slip-stacked together into a single batch for anti-proton production and then followed by five additional batches for NuMI. At 120 GeV/c flattop momentum, first the slip-stacked batch is extracted to the anti-proton target by means of a fast kicker, followed after ~1ms by a single turn extraction (~8 μs) of the five remaining batches to NuMI, for a total intensity of up to 2.5×10^{13} ppp.

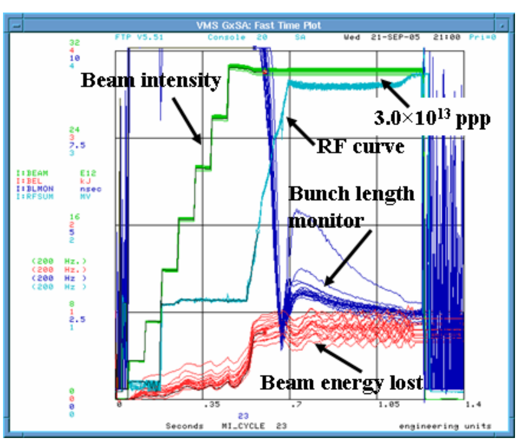

Figure 3: 'mixed-mode' cycle in Main Injector

Figure 3 shows beam intensity, RF acceleration curve, bunch length monitor and beam energy lost during a mixed-mode cycle. The seven steps in the beam intensity monitor correspond to the seven injected batches from the Booster at 15 Hz rate.

The slip-stacking process, shown schematically in Figure 4, and described in detail in [2] has been made operational in the Main Injector at the beginning of 2005, achieving 8×10^{12} protons/pulse on the anti-proton target with a slip-stacking efficiency of 94%.

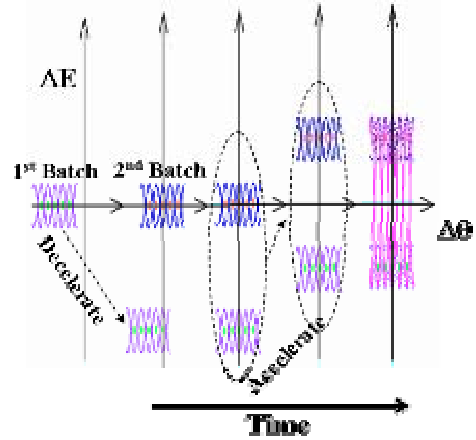

Figure 4: Mechanics of slip-stacking two Booster batches in the Main Injector.

'NuMI only' cycles are run whenever the anti-proton source is not operational or when the spacing of the 'mixed mode' cycles is such to allow insertion of additional cycles. In this case the Main Injector is loaded with six Booster batches and all of them are extracted to NuMI in ~10 μs. In this mode a total intensity of 2.8×10^{13} ppp every 2 s has been achieved (see Figure 5), corresponding to a beam power of 270 kW.

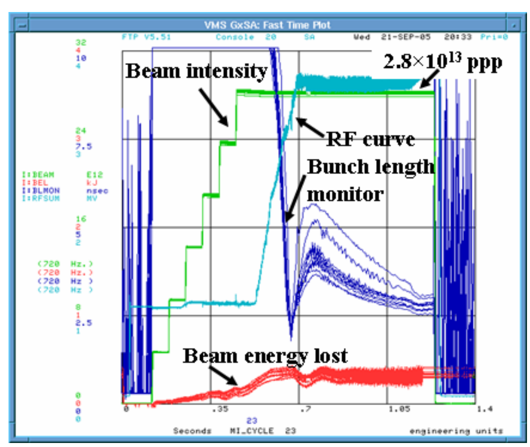

Figure 5: 'NuMI only' cycle in Main Injector

A bunch-by-bunch digital damper system in MI

The implementation of a transverse and longitudinal bunch by bunch digital damper system in the Main Injector has been essential to insure reliable running conditions at high intensities ($\geq 2\times10^{13}$ ppp) [4].

A schematic of the damper hardware is shown in Figure 6. Transverse dampers utilize 1 m long stripline pickups and kickers. The stripline kickers are each driven by a pair of 500 W, 10 kHz to 100 MHz amplifiers. For the longitudinal dampers, the input signal is provided by a resistive wall current monitor, while three broadband cavities, each driven by a 3.5 kW, 10 kHz to 100 MHz amplifier, are used to kick the beam. A large FPGA, to do all the damping calculations, is installed on the same board as the 212 MHz ADC's and the 424 MHz DAC's. The bandwidth of the system is such to allow an effective bunch by bunch damping. The board also includes large FIFOs to store the raw ADC samples and the damping calculations, providing a very useful diagnostic tool.

We achieved a much better lifetime at 8 GeV by using the transverse dampers to control the resistive wall instability, while running with chromaticities close to 0. Injection oscillations are successfully damped in ~0.5 ms.

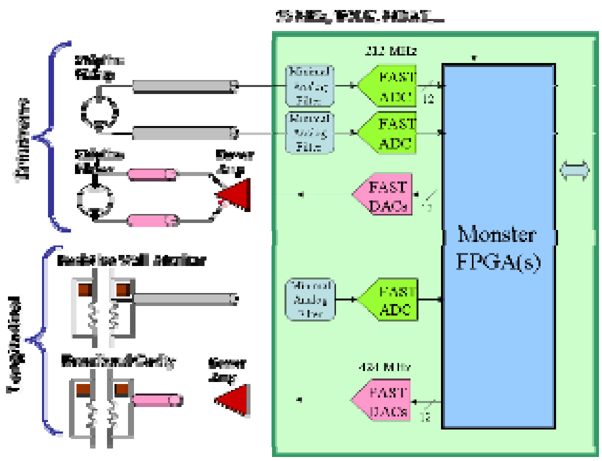

Figure 6: Schematic of the digital damper board.

NuMI operation

NuMI [1] is an acronym that stands for 'Neutrinos at the Main Injector'. The neutrino line points from Fermilab to a detector installed in the Soudan mine, in Northern Minnesota, at a distance of 735 km from the neutrino target.

The 120 GeV/c primary proton beam, single turn extracted from the Main Injector, is transported by a large acceptance primary proton line over a distance of 350 m, brought to a pitch angle of 58 mrad in order to point to the neutrino detector in the far location, and focused onto a water-cooled graphite target. Fractional beam losses along the primary proton line have been kept below 10^{-5} during operation [5].

A 'beam permit system' has been set up to allow a reliable and safe operation at high beam power, where repeatedly misdirected beam could cause severe hardware damage. The beam permit is a complex system monitoring ~240 inputs from magnet power supplies, loss monitors, beam positions in front of the target, miscellaneous inputs like cooling water, vacuum valves … and 'beam quality' inputs from the Main Injector. In particular several quantities are monitored in the Main Injector to insure a lossless extraction: no beam present in the position corresponding to the rise time of the extraction kicker, kicker current, beam positions in the extraction region and loss monitors at flattop time.

The beam permit system will inhibit the current pulse if any of the quantities is out of tolerance at specified times, as close as few 100 μs to extraction. Anything failing the limits in the course of the extraction, i.e. fractional beam losses in the NuMI primary proton line larger than few 10^{-5}, will inhibit the following pulse. Moreover, in order to keep the primary proton line properly tuned, an 'auto-tune' program acting on the trim magnets of the line runs continuously to keep the beam within specified limits. In particular the beam positions on target are maintained within 125 μm.

The first year of NuMI operation is summarized in Figure 7, showing daily average protons/pulse and beam power. The bars indicate the RMS values over a day. Also shown is the curve of integrated protons on target versus time. A total of 1.4×10^{20} protons have been collected on the NuMI target during the first year of operation.

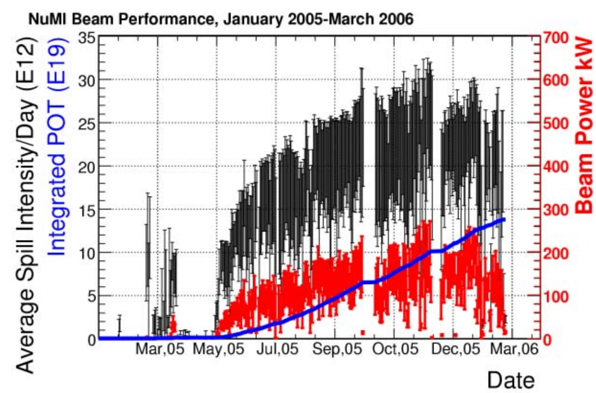

Figure 7: Spill intensity, beam power and integrated protons on target for the first year of NuMI operation.

In the last part of the run, from October 15 to January 31, we have achieved an average beam power of 170 kW, with a peak power of 270 kW. Lower intensity periods have been requested by the experiment in the last month of running to investigate possible systematic effects on the neutrino near detector.

Ongoing and forthcoming upgrades

In the ~30 years of operation prior to the MiniBoone experiment, the Booster has delivered a total of 5×10^{20} protons. Since the startup of MiniBoone in November 2002, the Booster has delivered a total of 8.6×10^{20} protons, keeping the activation in the tunnel within a factor of two of what it was before MiniBoone start-up. This has been achieved through a strict control of Booster losses [6].

Collimators have been installed in the Booster since 2004 [7]. In spring 2006 the H^- injection region of the Booster has gone through a complete reconfiguration, allowing the removal of a septum magnet. A complete new set of correctors will be installed in the Booster in 2007 to achieve better closed orbit control. These upgrades are expected to increase the Booster peak proton throughput, currently at $\sim9\times10^{16}$ protons/hour, by about a factor 2.

In spring 2006 two collimation stations, 90° apart in phase, have been installed in the MI-8 line to clean up beam halo before injection into the Main Injector.

The Main Injector is being upgraded to handle the larger beam power associated with the implementation of slip-stacking and NuMI operation. In spring 2006 quadrupole magnets at all injection and extraction locations have been replaced by larger aperture quadrupoles, running on the same bus current, with a gain in pole tip radius from 41.7 to 55.2 mm. A collimation system for the Main Injector is presently at the design stage.

MULTI-BATCH SLIP-STACKING

In parallel with the operation of the Collider program, a plan is in place to increase the power on the NuMI target by implementing slip-stacking on the NuMI batches.

While running in 'mixed-mode', a scheme [2] has been devised to slip-stack 4 out of the 5 NuMI batches, in addition to a slip-stacked batch for the anti-proton source.

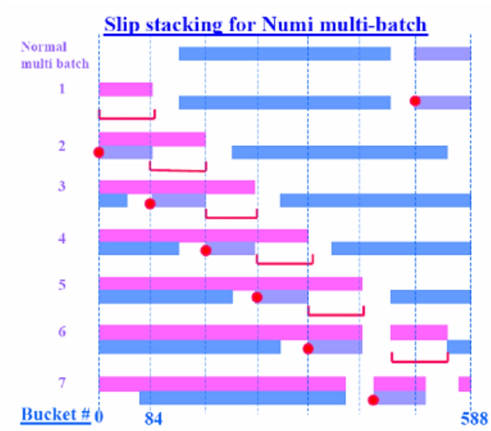

Figure 8: Slip-stacking scheme over multi-batches

For a Booster batch size of 4.7×10^{12} protons and a slip-stacking efficiency of 95%, the Main Injector would accelerate 4.9×10^{13} ppp every 2.2 s, for a total beam power of 430 kW, of which 350 kW delivered on the NuMI target. The gain in beam intensity is partially offset by the increase in cycle time due to the injection of 4 additional Booster batches.

A test at low intensity has been successfully performed, demonstrating the mechanics of the process.

FUTURE UPGRADE PLAN

A rise in beam power to NuMI is anticipated with the conclusion of the Collider program. The operation of the Main Injector would be largely simplified. NuMI would gain that portion of beam presently sent on the anti-proton target.

Substantial additional gains are possible through a reconfiguration of the present accelerator complex and an upgrade of the Main Injector RF system.

In the present operation of the Main Injector, the duration of a 'mixed-mode' cycle is 2 s, of which about 20% is spent waiting for batch injections from the Booster. It has been proposed [8] to use the Recycler ring as a proton pre-injector, accumulating proton batches from the Booster while the Main Injector is accelerating beam.

The Main Injector would then cycle as fast as allowed by magnets, power supplies and RF system. The 120 GeV cycle time would be reduced to 1.47 s by eliminating the loading time.

The other main factor affecting the Main Injector cycle length is the acceleration rate. Magnets and power supplies of the Main Injector have been designed for a conservative maximum rate of 240 GeV/s. The present RF system, consisting of 18 stations, retrieved from the decommissioned Main Ring, has enough power to stably accelerate up to 6×10^{13} ppp at a rate of 205 GeV/s [9]. The system is presently operated in this mode.

The addition of two RF cavities in the Main Injector ring, available as spares, would allow to increase the maximum acceleration rate to 240 GeV/s [9] and hence reduce the Main Injector cycle time further, down to 1.33 s, with an additional gain of ~10%.

Beam intensities in the Main Injector in excess of 6×10^{13} ppp will require an upgrade of the Main Injector RF system. The present RF cavities have an available port to add a second power tube. Calculations [10] show that adding a second tube provides sufficient power to accelerate up to $\sim1\times10^{14}$ ppp.

Batch intensities from the Booster are limited to $\leq5\times10^{12}$ because of limits on activation of components in the Booster tunnel. Stacking more than two Booster batches into one is not possible with the process of slip-stacking. It has been proposed [11] to use the Accumulator ring in the anti-proton source to perform momentum-stacking of multiple batches into one.

The Recycler ring as proton pre-injector

The construction of a short transfer line between the MI-8 line and the Recycler ring allows using the Recycler as proton pre-injector to the Main Injector.

Moreover the momentum acceptance of the Recycler is sufficiently large (1.5% full span) to allow slip-stacking of Booster batches. It is foreseen to slip-stack six on six batches, and, at the time they line up, extract them in the Main Injector in a single turn, where they would be recaptured and accelerated. A relatively simple and inexpensive 53 MHz RF system needs to be added in the Recycler to perform slip-stacking.

Momentum stacking in the Accumulator ring

The Accumulator was designed to perform momentum stacking of anti-protons. Injection kickers are located in a region of 9 m dispersion and do not affect the core beam.

It is proposed [11] to perform momentum stacking of Booster batches in the Accumulator. At 15 Hz rate, a new Booster batch is positioned in the low momentum orbit of the Accumulator and then accelerated towards the core orbit, where it is merged and debunched into the core beam. Given the very large momentum aperture of the machine (~84×2.8 eV-s), it is possible to momentumstack at least 3-4 Booster batches with a longitudinal emittance dilution of only ~20%.

In sequence six Accumulator batches are loaded into the Recycler and from there single-turn transferred into the Main Injector.

An injection line from the Booster into the Accumulator and an extraction line back into the MI-8 line, together with substantial modifications to the RF system, are the major upgrades necessary to utilize the Accumulator ring.

Upgrade scenarios and time scale

Table 2 summarizes the set of operating scenarios possible with the reconfiguration of the accelerator complex after the conclusion of the Collider program.

A tentative schedule foresees a year-long shutdown in 2010 to complete all the upgrades necessary to get to 1.2 MW.

Over a couple of years, beam power would gradually ramp up from 400 kW, achievable at start-up without implementing slip-stacking, first to 700 kW and later to 1.2 MW with the addition of the Accumulator.

Table 2: Foreseen operating scenarios.

	Recycler without slip stacking	Recycler with slip stacking	Accumulator momentum stacking
Booster intensity	4.7×10^{12}	4.3×10^{12}	4.6×10^{12}
No. Booster batches	6	12	18
MI cycle time (s)	1.333	1.333	1.333
MI intensity (ppp)	2.8×10^{13}	4.9×10^{13}	8.3×10^{13}
NuMI beam power (kW)	400	700	1200
Protons/hr	7.6×10^{16}	1.3×10^{17}	2.2×10^{17}

CONCLUSIONS

The present operation of the Fermilab proton accelerator complex has been described, reporting in detail on the performance of the NuMI neutrino facility.

A set of staged upgrades to increase the beam power on the NuMI neutrino target has been presented.

In parallel with the operation of the Collider program, a plan is in place to implement multi-batch slip-stacking in the Main Injector for up to 400 kW beam power.

With the conclusion of the Collider program, a plan is being developed to reconfigure the accelerator complex to shorten the Main Injector cycle time and to perform stacking of multiple Booster batches. First 700 kW beam power is achieved by using the Recycler as proton pre-injector, then 1.2 MW by performing momentum-stacking over several Booster batches in the Accumulator.

Figure 9 shows proton beam power of past neutrino experiments and the present performance of the NuMI neutrino line, together with the projections for the upgrades. Also shown are the planned performances of the CNGS line and the first phase of J-PARC.

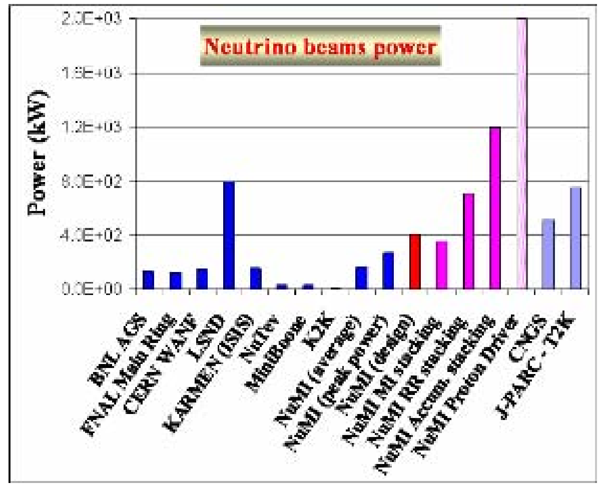

Figure 9: Proton beam power of neutrino experiments.

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