CURRENT AND FUTURE HIGH POWER OPERATION OF FERMILAB MAIN INJECTOR*

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Abstract

Fermilab's Main Injector on acceleration cycles to 120 GeV has been running a mixed mode operation delivering beam to both the antiproton source for pbar production and to the NuMI[1] target for neutrino production since 2005. On January 2008 the slip stacking process used to increase the beam to the pbar target was expanded to include the beam to the NuMI target increasing the MI beam power at 120 GeV to 400KW. The current high power MI operation will be described along with the plans to increase the power to 700KW for NOvA and to 2.1 MW for project X.

FERMILAB ACCELERATOR COMPLEX

The Fermilab accelerator complex consists of an 400 MeV Linac, an 8 GeV Booster, the Main Injector (MI) and the Tevatron. The accelerator complex also includes a Pbar source and a Pbar storage Ring (Recycler) located in the MI tunnel. The Main Injector is used to accelerate protons and pbars to 150 GeV for injection in the TeV and protons to 120 GeV for pbar production and for the neutrino beam-line (NuMI).

MI MULTI-BATCH SLIP STACKING[2]

Since the ratio of the harmonic numbers between MI and Booster is 7 up to 7 Booster batches can be injected in MI at a time. Since we would like to maintain some spacing for kicker gaps the total number of Booster batches is limited to 6.

At the beginning of the MI mixed mode operation two Booster batches were slipped stacked into a double intensity batch and recaptured. After recapture 5 additional Booster batches were injected filling up the MI. Following acceleration to 120 GeV a bunch rotation was performed in order to reduce the bunch length and the double intensity batch was extracted to the pbar target. The rest of the beam was extracted ¼ of synchrotron period later to the NuMI target.

Since January 2008 we have extended slip stacking to include the beam to NuMI. A total of 10 Booster batches are now slipped stacked together in MI resulting in 5 double intensity batches. After recapture an additional Booster batch in injected. This way the total Booster batches to NuMI is increased from 5 to 9. A mountain range picture of the multi-batch slip stacking is shown in Figure 1. The beam power to the NuMI target is expected to increase to 320 KW from 190 KW while the total beam power at 120 GeV will be increased to 400 KW.

Following the end of the collider run we plan to use the Recycler storage ring for slip stacking while the MI is accelerating, increasing the final 120 GeV beam power to 700KW.

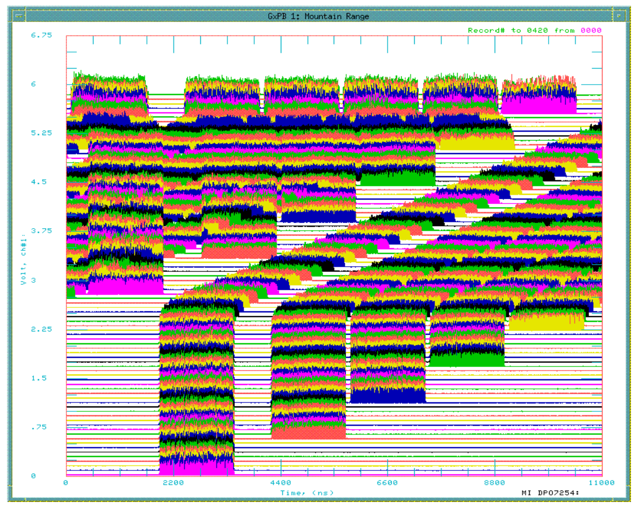

Figure 1: Mountain Range Picture of multi-batch slip stacking. The horizontal axis is time across the MI azimuth in nsec and the vertical axis time in machine turns.

UNDERSTANDING AND CONTROLLING LOSSES

Most of the losses are coming from slip stacking. With 95% efficiency if all of the losses were distributed uniformly around MI they correspond to about 0.5W/m average loss. Unfortunately the losses are localized and need to be controlled. Three types of losses were indentified and are currently being addressed.

1) *Un-captured beam loss.* The beam that is not captured after the slip stacking process is not accelerated and is getting lost when it hits the momentum aperture at 9.1 GeV. This loss is the largest in percent; 3-3.5% out of total loss of 5%. In order to address this loss a two stage collimation system was installed in MI [3]. This system is now operational and we have achieved collimator efficiencies 97% or better [4].

2) *Injection kicker gap loss.* During slip stacking some beam is spilling out in the gap left open for injecting new batches. This loss is localized at the injection kicker area

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MI-100. In order to address this loss we are building gap clearing kickers that will be fired just before the injection kickers and send the beam left in the gap in the MI abort. The construction of the kickers is under way and we currently planning to install them in the Summer of 2009.The kickers are expected to be operational in early 2010 when the new kicker building required to house the power supplies and cooling systems is ready.

3) *Beam in the extraction kicker gap.* After the slip stacking process there is some beam captured between the batch for pbar production and the train of NuMI batches. This beam is accelerated to 120 GeV and is getting lost when the batch to the pbar target is extracted. Even if this loss in percentage is very small (0.2%-0.3%) since it happens at 120 GeV it represents an important fraction of our power loss. It is concentrated at the extraction area for pbar production MI-520.

The bunch by bunch transverse damper [5] is used to reduce the beam in the gap between the batch used for pbar production and the batches used for NuMI. The beam in the gap is anti-damped by driving the damper at the tune value. Since the damper is limited in voltage the anti-damping is most effective at low energies. Recently we were able to reduce this loss an order of magnitude by adding another kicker.

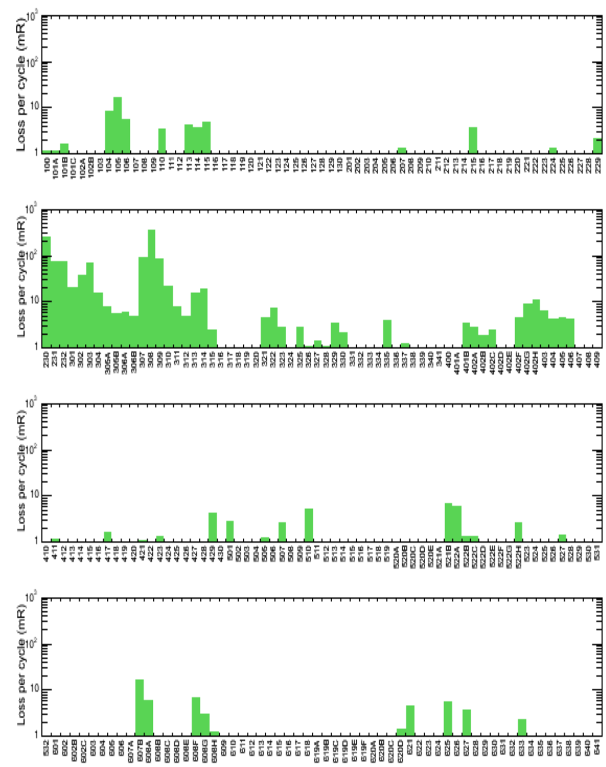

Figure 2: MI loss plot. The vertical axis is the integrated loss at each MI beam loss monitor at the end of each cycle (in log scale). Most of the losses are concentrated at the collimator region 229-309. The injection kicker gap loss (104-106) is also evident.

CURRENT STATUS

Since January 2008 when we switched to the multi-batch slip stacking we have made great progress in increasing the MI intensity and beam power. A typical plot of the MI intensity with the percentages of the various losses is shown in Figure 3. The beam intensity to the NuMI target has been increased by 30% and the MI beam power at 120 GeV has reached 340KW; 85% of the design goal of 400KW. We are now running routinely with beam power greater than 320 KW (Figure 4). Currently the Injection kicker gap loss is preventing us from further increasing the beam intensity.

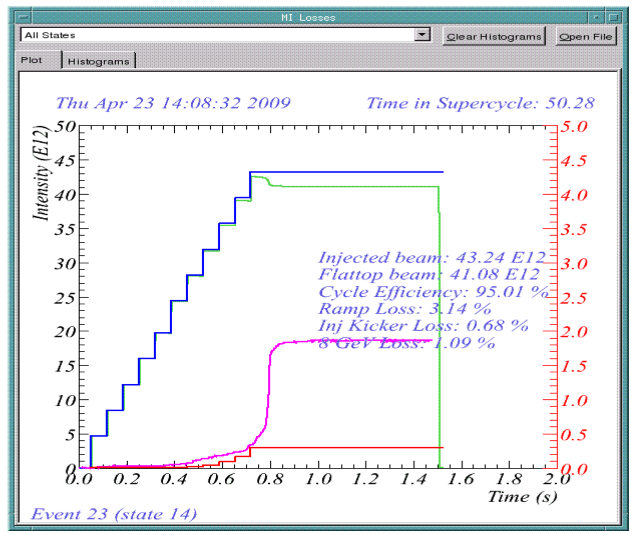

Figure 3:Typical plot of the MI beam intensity (green). The blue line shows the sum of the injected beam, the red trace indicates the injection kicker gap loss and the purple trace shows the lost beam.

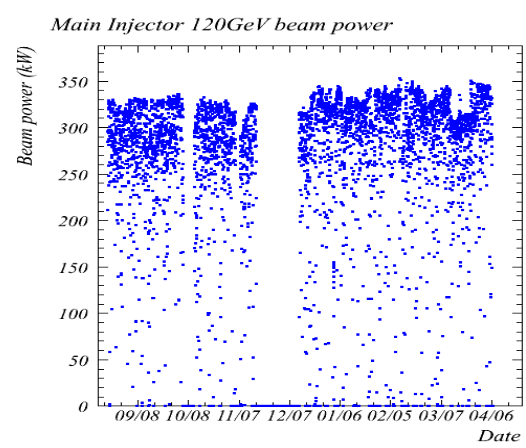

Figure 4: MI beam power at 120 GeV since August 10 2008. The gap in the middle represent a period where the NuMI horn was changed.

The MI high power operation has also been very reliable. From January1, 2008 to April 3, 2009 the total MI downtime was 325 Hrs, i.e. 3.8% of the total running time. A pie chart with the sources of the downtime is shown in Figure 5.

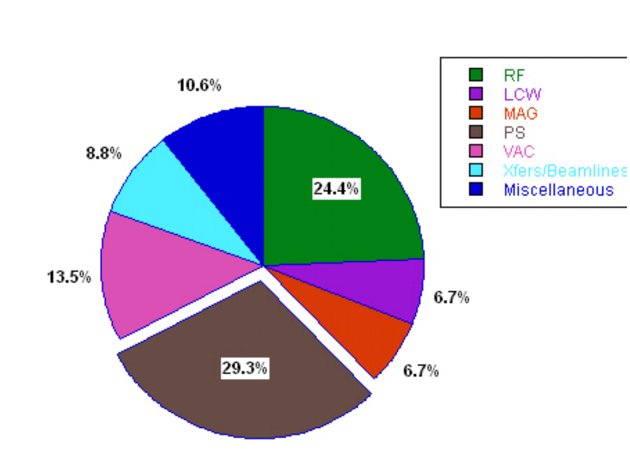

Figure 5: Sources of MI downtime.

700 KW OPERATION (NOVA)

When the collider programs concludes we plan to use Recycler as proton Injector, accepting beam directly from the Booster. The Recycler momentum aperture is large enough to allow slip stacking operation for up to 12 Booster batches injected. Six Booster batches are slipped with respect to the other six and, at the time they line up, they are extracted to MI in a single turn, are captured and accelerated. The MI cycle time can now be reduced to 1.33 sec from 2.2 sec increasing the 120 GeV beam power to 700KW. Since the power increase comes mainly because of the cycle time reduction and not the increase in MI intensity no new problems with beam instabilities and transition crossing in MI are expected. The MI collimators are designed to handle the additional power.

The main elements of this upgrade are outlined below:

- New Injection line from Booster into Recycler
- New Extraction line from Recycler to MI.
- New Injection, Extraction and Abort kickers for Recycler.
- New 53 MHz rf system for slip stacking.
- New Low Level rf system for Recycler.
- Two extra rf cavities in MI (from spares).
- MI quad power supply upgrade.
- Cooling and power supply upgrades in the NuMI beam line.
- New NuMI targets and horns.

All these modifications are scheduled to be in place in 2012 and the NOvA detector will be ready for beam in 2014.

2.1 MW OPERATION (PROJECT X)[6]

As part of the Project X upgrade, the Fermilab's Proton Source will be replaced with an 8 GeV superconducting Linac operating at 5 Hz and delivering 1.6E14 H- ions per pulse. The H- ions are stripped at injection into the Recycler in a manner that "paints" the beam both transversely and longitudinally to reduce space charge forces. Following the 1.25 ms injection, the proton beam is moved off the stripping foil and is transferred in a single turn into the Main Injector where are accelerated to 120 GeV and fast extracted to a neutrino target. The 120 GeV MI cycle takes 1.4 sec, producing 2.1 MW of beam power. MI will be able to provide the same beam power throughout the energy range 60-120 GeV by adjusting the cycle time. Accelerating 3 times the intensity required for NOvA represents a major challenge for MI. We have developed an R&D program to address the major issues[7]. Work has already started in designing a new MI rf system, simulating and measuring electron cloud effects [8],[9] and designing a transition jump system In addition we plan to install a 3ft long piece of pipe coated with TiN during this summer shutdown for electron cloud studies.

REFERENCES

[1] Sam Childress, "The NuMI Beam at Fermilab: Successes and challenges" proceedings of HB2008.

[2] K. Seiya et al. "Multi-batch Slip Stacking in the Main Injector at Fermilab" PAC'07, Albuquerque, New Mexico, June 2007, p. 742-744

[3] Bruce Brown, "Collimation System for Beam Loss Localization with Slip Stacking Injection in the Fermilab Main Injector" proceedings of HB2008.

[4] Bruce Brown et al. "Fermilab Main Injector Collimation Systems: Design, Commissioning and Operation " these proceedings.

[5] P. Adamson et al. "Operational Performance of a bunch by bunch Digital Damper in the Fermilab Main Injector" PAC'05, Knoxville, Tennessee, June 2005, p. 1440-1442.

[6] http://projectx.fnal.gov/

[7] http://projectx.fnal.gov/RnDplan/index.html

[8] Nathan Eddy et al. "Measurement of Electron Cloud Development in the Fermilab Main Injector Using Microwave Transmission" These proceedings.

[9] Miguel Furman et al. "Status of Electron-Cloud Build-Up simulations for the Main Injector " These proceedings.