MI HIGH POWER OPERATION AND FUTURE PLANS*

Ioanis Kourbanis, Fermilab, Batavia, IL 60510, U.S.A.

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 both the beam intensity and power. The current high power MI operation will be described along with the near future plans.

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 beamline (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(See Figure 2). A mountain range picture of the multi-batch slip stacking is shown in Figure 3. 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.

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A picture of the Fermilab Accelerator complex is shown in Figure 1.

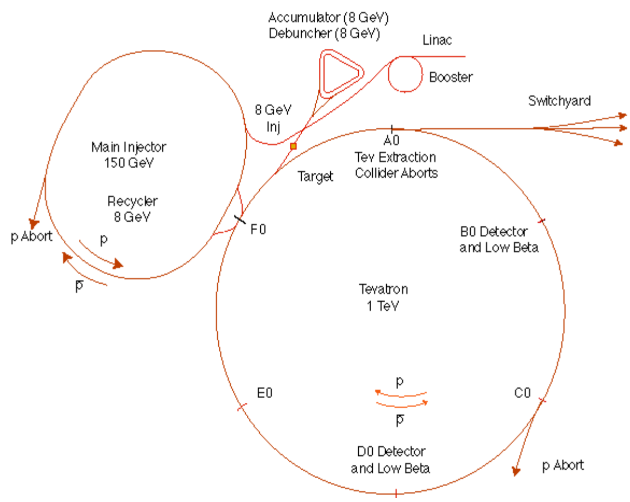

Figure 1: Fermilab Accelerator Complex

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.

The increase to the MI 120 GeV power is mainly achieved by the reduction to the MI cycle time. The evolution of MI power at 120 GeV is illustrated in Table 1.

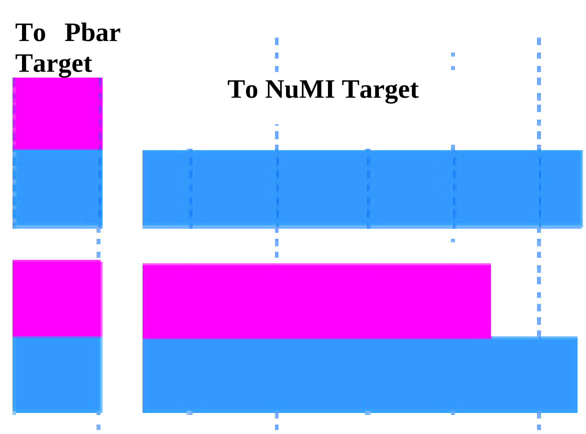

Figure 2: Schematic of the MI loading during the mixed mode operation. 2+5 operation on top and 2+9 operation on the bottom.

	2007 Conditions Two-batch slip-stacking in MI	Proton Plan (2008 conditions) Multi-batch slip-stacking in MI	NOvA Multi-batch slip-stacking in Recycler
Booster intensity (protons/batch)	**4.3-4.5×10E12**	**4.3×10E12**	**4.3×10E12**
No. Booster batches	**7**	**11**	**12**
MI cycle time (s)	**2.4**	**2.2**	**1.333**
MI intensity (ppp)	**3.3×10E13**	**4.5×10E13**	**4.9×10E13**
To anti-proton source (ppp)	**8.8×10E12**	**8.2×10E12**	**0**
To NuMI (ppp)	**2.45×10E13**	**3.7×10E13**	**4.9×10E13**
NuMI beam power (kW)	**192 (263)**	**320 (400)**	**700**
PoT/yr to NuMI	**2×10E20**	**3×10E20**	**6×10E20**

Table 1:MI Power evolution. The numbers in parenthesis indicate the total MI beam power at 120 GeV.

Figure 3: Mountain Range Picture of multi-batch slip stacking.

ISSUES WITH MULTI-BATCH SLIP STACKING OPERATION

Most of the issues with multi-batch slip stacking are related with losses. 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. In order to better understand the different type of losses a simulation of the slip stacking process was performed [2]. A sequence of simulation pictures starting from the point after the deceleration of the first 5 batches till after the recapture if shown in Figure 4.

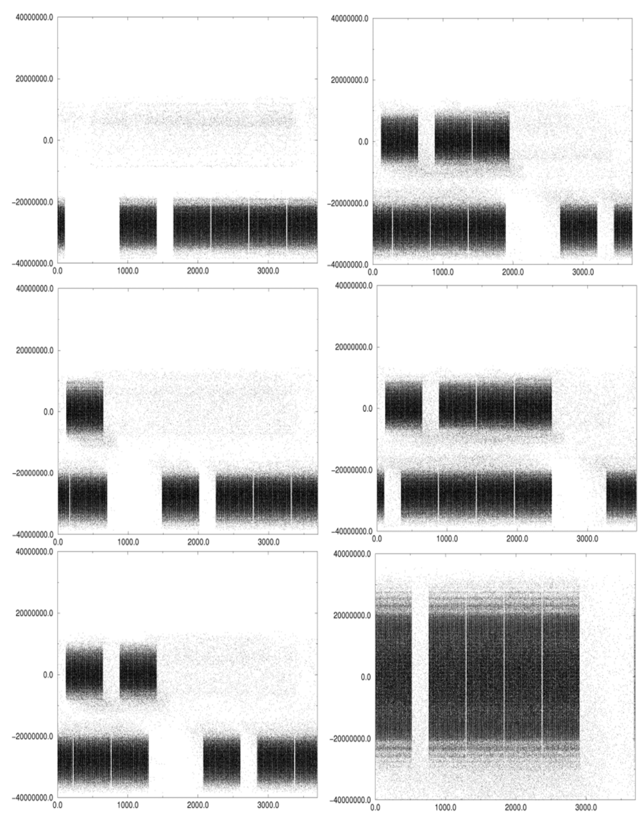

Figure 4: Simulation pictures starting at the moment the first group of the 5 batches has been decelerated.

From this figure we can identify 3 different types of losses. First we see that there is beam left in the injection kicker gap for the batches 6-11. Second there is beam that is not captured and third that some beam is captured in the gap between the beam for pbar production and NuMI.

Un-captured beam loss

The beam that is not captured is not accelerated and it is getting lost when it hits the momentum aperture at 9.1 GeV. This loss is concentrated at the high dispersion points and the injection/extraction Lambertson magnets. 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 92% or better. The effect of the collimation system on the acceleration losses is illustrated in Figure 5.

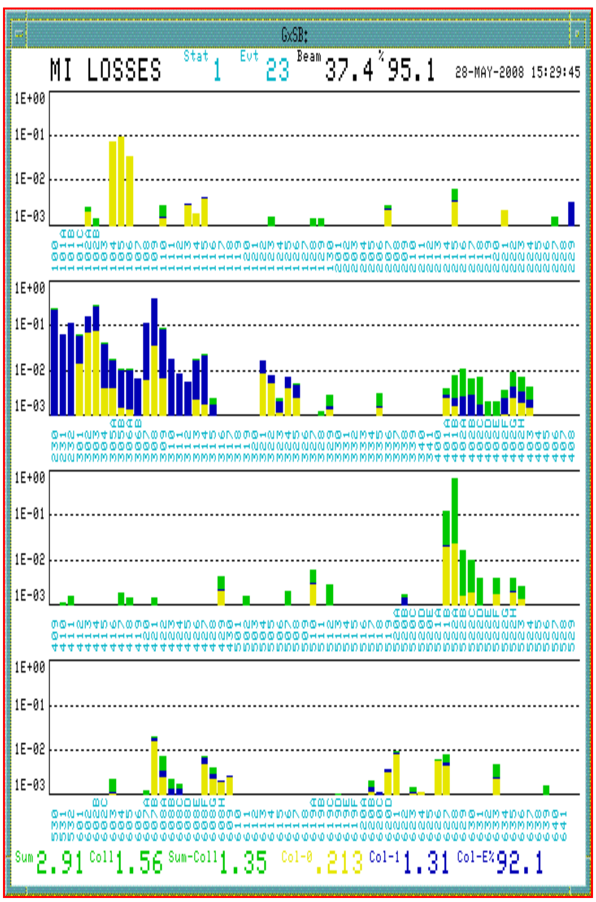

Figure 5: MI loss plot and collimator efficiency. The vertical axis is the integrated loss at each MI beam loss monitor at the end of each cycle (in log scale). The yellow color indicates the contribution to the total loss from injection, the blue from the losses during acceleration from un-captured beam and the green from extraction. The MI collimator efficiency is indicated in the bottom right corner.

Injection kicker gap Loss

This loss is localized at the injection kicker area MI-10. 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 Spring of 2009.

Extraction kicker gap loss

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 at MI-52.

The bunch by bunch transverse damper [4] 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. Efforts are in place to increase the damping power by adding another kicker.

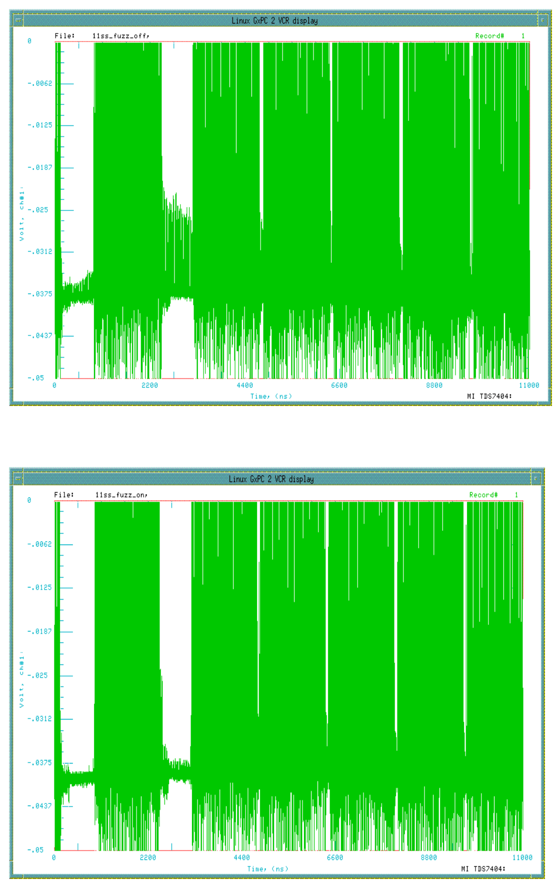

Figure 6: Beam between the pbar production batch and the NuMI batches without (top) and with (bottom) ant-damping.

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 7. A plot of the MI 120 GeV beam power as a function of time is shown in Figure 8. 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. Currently the Injection kicker gap loss is preventing us from further increasing the beam intensity.

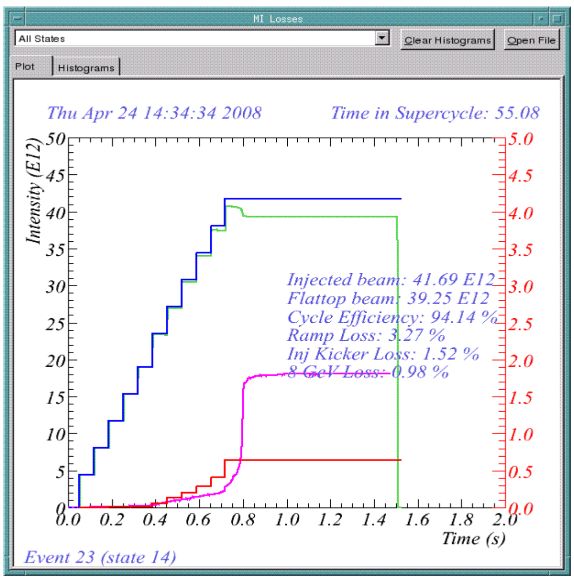

Figure 7: Typical plot of the MI beam intensity (green). The blue line shows the sum of the injected beam, the red trace indicates the injection kicker gap loss and the purple trace shows the lost beam.

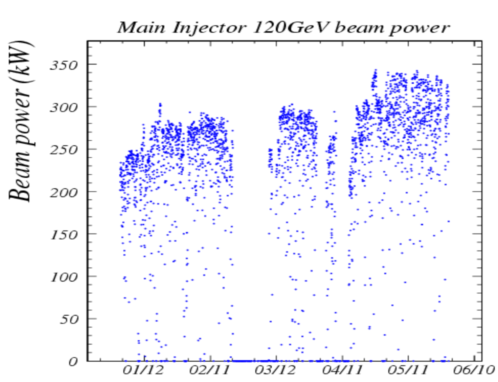

Figure 8: MI beam power at 120 GeV since January 1 2008.

The MI high power operation has also been very reliable. From January1, 2008 to June 2, 2008 the total MI downtime was 144 Hrs, i.e. 3.8% of the total time. A pie chart with the sources of the downtime is shown in Figure 9.

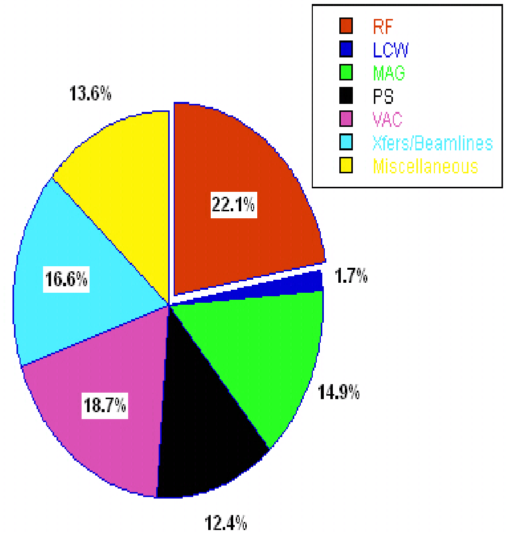

Figure 9: Sources of MI downtime.

FUTURE PLANS

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. The difference between the two MI 120 GeV ramps is illustrated in Figure 10. 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.

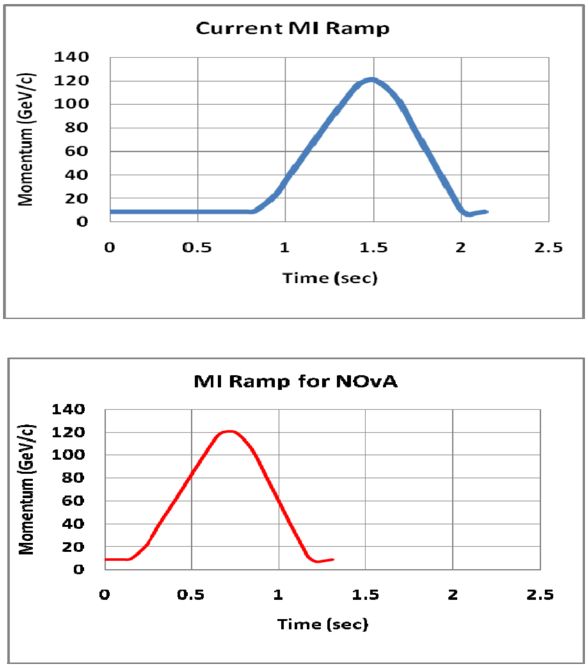

Figure 10: Difference in the MI 120 GeV ramp between the current (top) and future (bottom) MI operation.

CONCLUSIONS

We have successfully switched to multi-batch slip stacking in MI an operation that would allow us to achieve 400KW beam power at 120 GeV.

We have already achieved 85% of the design beam power and we are already addressing the beam loss issues that are preventing us from achieving our goal.

After the end of the collider run we plan to use the Recycler as a proton pre-injector allowing us to decrease the MI ramp time by 40% and increasing the beam power to 700KW.

Controlling the beam losses and limiting the activation of MI will continue to be our largest challenge.

REFERENCES

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