# STATUS OF SLIP STACKING AT FERMILAB MAIN INJECTOR *

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*Abstract*

To achieve an increase in proton intensity, the Fermilab Main Injector (MI) is using a stacking process called "slip stacking" [1]. The intensity will be doubled by injecting one train of bunches at a slightly lower energy, another at a slightly higher energy, then bringing them together for the final capture. Beam studies have been performed for this process and we have verified that, at least for low beam intensities, the stacking procedure works as expected [2]. For high intensity operation, an upgrade of the 4kW solid state drivers to 8kW was done during the last machine shut down, from August to November 2004. Slip stacking became operational in December 2004.

## INTRODUCTION

MI accelerates protons to 120GeV for antiprotons production. In the stacking cycle, 84 bunches are injected from Booster to MI, accelerated from 8GeV to 120GeV and extracted to production target. The total beam intensity has been around $4.5*10^{12}$ particles per pulse (ppp) on a 1.5 sec cycle.

Run II upgrade has an intensity goal of $8.0*10^{12}$ protons in 84 bunches from the MI to be achieved with the scheme called "slip stacking". Two bunch trains are injected from Booster and merged to one batch at an injection energy of 8GeV, and then accelerated to 120GeV.

The intensity is going to be almost double the non-slip stacking value. After antiprotons are produced on target, the beam is sent to the Debuncher for bunch rotation and momentum cooling. The bunch length on the target is limited to less than 1.5 nsec because the Debuncher cooling system has a momentum acceptance of 4%[3]. MI is providing 120GeV beam not only to the pbar target, but also to fixed target experiments. Since we have to inject additional bunch trains from Booster to MI, the whole slip stacking process has to be completed in less than two 15Hz Booster cycles.

This paper explains the development of the feedback and feedforward systems and operation status of slip stacking.

## BEAM STUDIES WITH LOW INTENSITY

Fist, beam studies for the slip stacking process have been done with low intensity, $\sim 1.0*10^{12}$ppp, and we have verified that the stacking procedure to work as expected.

There was no beam loss during the process, but there was emittance growth when two bunch trains were recaptured. The emittance growth expected from simulation was a factor of 3.2. There was no emittance growth before the two trains were recaptured by one RF bucket but there was a factor of 4.0 emittance growth after the recapture.

Simulation studies have indicated that the emittance growth was caused by RF phase variation. The RF phase variation was eliminated and the emittance was measured again. No undesirable emittance blow up has been observed. The beam has been accelerated to 120GeV with a beam loss of ~2% at the beginning of acceleration.

## BEAM LOADING COMPENSATION

### *Beam Studies*

After beam intensity was increased to $4*10^{12}$ ppp, beam loading effects were observed on bunch signal in a mountain range plot as shown in Fig. 1. The signal from the wall current monitor (WCM) reveals the progress of slip stacking from the beginning to the end. The signal was measured with a resolution of 0.5 ns/sample and the data were obtained every 2.1 msec for 0.24 sec. There was feedback with gain of 14 dB and no feedforward beam loading compensation on Fig. 1; some particles were outside the RF bucket and the length of train was longer than 84 RF buckets. Feedforward beam loading compensation of 14dB was applied on the case of Fig. 2; the bunches were now kept the same shape from injection to the end of slip stacking. [4]

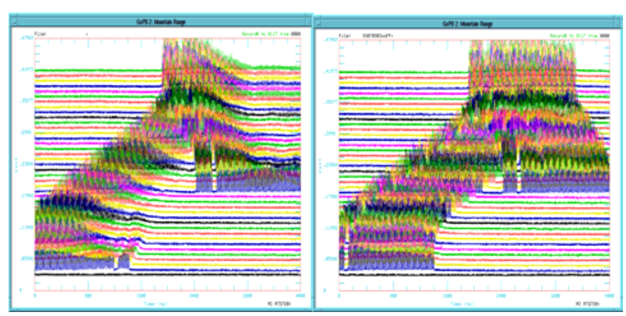

Figure 1 and 2: Mountain range plots of the WCM signal. The plots on the left and right show signal without and with feedforward beam loading compensation.

### *Simulation*

In order to estimate the required gain for beam loading compensation, simulation studies were carried out using the code ESME [5] with beam loading effects. In the simulation studies, two bunch trains of 84 bunches each were put in upper energy and lower energy with a total intensity of 1.0E13. Different frequencies were applied to each bunch trains and beam shape was measured after 70 msec as shown in Fig. 3. Some particles were outside the

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RF buckets and total train length became longer than 84 RF buckets because of the beam loading effects.

Figure 4 shows the simulation results with beam loading compensation. Most particles captured in the RF buckets and the total train length remained 84 buckets. In this simulation feedforward and feedback were applied with gains of 20 dB and 14dB respectively. From these results we estimated that we needed to increase the feedforward compensation gain by 6 dB.

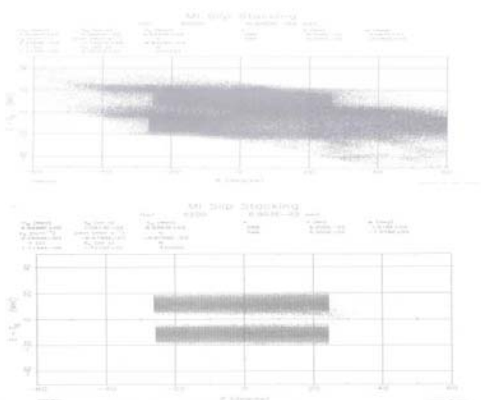

Figure 3 and 4: Simulation results in phase space plots. The vertical axis is 40MeV/div and horizontal is 20 degree/div. The upper shows no beam loading compensation. The lower shows the effect of 14dB feedback and 20dB feedforward beam loading compensation.

### *RF Stations Upgrades*

In order to increase the gain of RF feedforward loop, more RF current was required. The combination of increasing the power and changing the PA operation point from class AB to class A at injection energy was needed to increase the current.

During machine shut down, solid state driver was upgraded from 4kW to 8kW by adding four more modules for each RF station. Figure 5 shows a frequency spectrum of gap voltage with and without feedforward compensation on one of the eighteen cavities and the reduction was 24dB. The reduction was different on each of the cavities but the average is about 20dB.

The PA grid bias system was also improved to program the current up the ramp. Figure 6 and 7 show the phase detector signal between input and output RF gap voltage on one of the RF cavities. The signal was measured from injection to flat top. After we installed full beam loading compensation and having the grid bias programmed, the phase difference was almost 0 degree from injection to flat top.

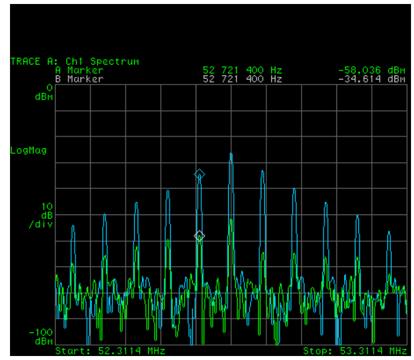


Figure 5: Frequency spectrums of gap voltage monitor on one of the eighteen cavities. Blue and green traces show signals without and with feedforward beam loading compensation. The vertical scale is 10dB/div.

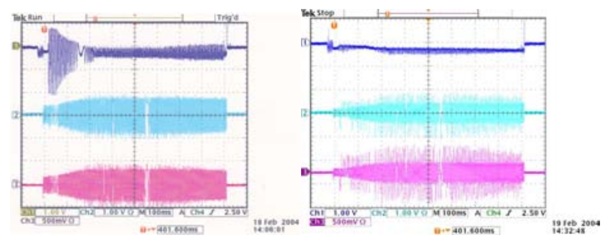

Figure 6 and 7: The top traces are phase detector signal between input and output gap voltage. The vertical scale is 9[degree/div]. The middle and bottom traces are cathode voltage and forward power respectively. The left plot is without and right is with feedforward beam loading compensation.

## OPERATION STATUS

Since December 2004, the MI has been operating all stacking cycles with slip stacking. Total intensity injected from Booster is $8.0*10^{12}$ppp as shown in Fig. 8 and beam on the target is $7.0*10^{12}$ppp. The bunch length at MI extraction is 1.8 nsec. Total time of slip stacking process is 133 msec which is less than two Booster cycles. We have not achieved our goal of intensity and bunch length yet, but we have seen considerable improvement in pbar stacking rate. Figure 9 shows the number of pbars as a function of the number of protons on target. Since December 2004, the number of pbars was increased up to almost 30%.

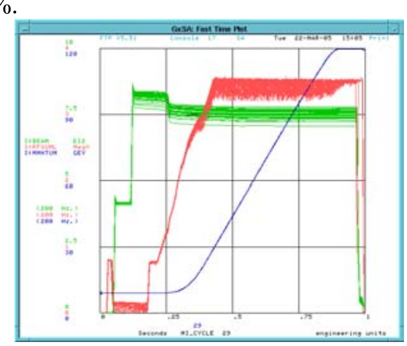

Figure 8: RFSUML: RF voltage[MV], MMNTUM: momentum[GeV/c], I:BEAM: total beam intensity [$*10^{12}$ ppp]

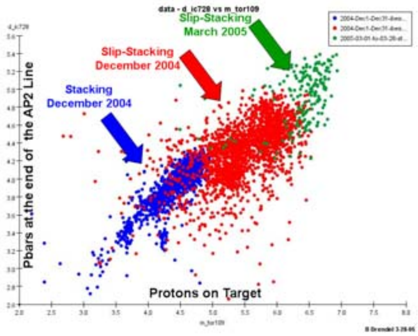


Figure 9: Number of pbars in an ion chamber after the target as a function of the number of protons on target. Blue points are with non slip stacking in December 2004, red is with slip stacking in December 2004, green is with slip stacking in March 2005.

## ISSUES

We still have beam loss at the beginning of acceleration. Intensity at injection is $8.0*10^{12}$ppp, at extraction is $7.5*10^{12}$ppp and intensity on pbar target is $7.0*10^{12}$ppp. At the beginning of acceleration, there is beam loss on the oder of $5*10^{11}$ppp and then at extraction, $5*10^{11}$ppp were sent to MI abort line after stacking beam was sent to target.

### *Beam Loss at Injection and Leaks from Stacking Bunches*

Mountain range plots as shown in Fig. 10 and 11 were measured for 47 msec from the point of injection. The figures show picture the beginning and the end of bunch train respectively. Some beam is seen to leak from the RF buckets on left side after injection time in Fig. 10. The direction of the leak depends on beam energy from Booster and the loss never goes away from both sides. Longitudinal emittance was measured at MI injection and it was larger than MI bucket area. Also, the bunch rotation in Booster which is used for emittance matching to the MI bucket, was not optimized with high intensity. The leaks were caused by large and mismatched emittance from Booster.

Since we recaptured the beam with RF voltage of about 1MV after slipping, and there were leaks around the RF bucket of 90kV, some of the leaking beam was captured with the large rf bucket at recapture time and accelerated to 120 GeV. Figure 12 shows the WCM signal before MI extraction with vertical scale of 300 mV/div and horizontal scale is 500 nsec. Figure 13 shows the WCM signal with vertical scale of 10mV/div and the leak is visible outside 84 buckets. After 84 bunches were extracted to the target, the left over beam was sent to the MI abort. An intensity monitor on the MI abort line shows an intensity of $5*10^{11}$ ppp, which agrees with the difference between the intensities of MI extraction and on target.

### *Study and Operation Plans*

Beam studies in the Booster to reduce longitudinal emittance and optimized bunch rotation are in progress. A plan to install collimation system is being considered in MI to get rid of the higher momentum beam.

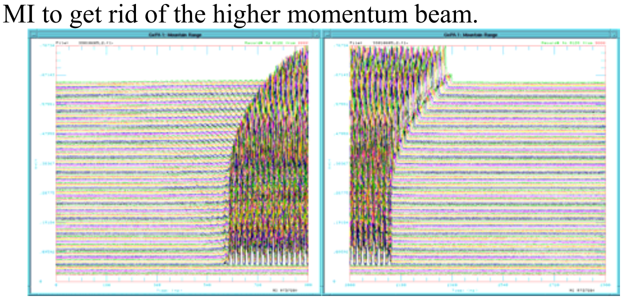

Figure 10 and 11: Mountain range from injection to 47 msec later. The left figure is the beginning of bunch train and the right is the end of bunch train.

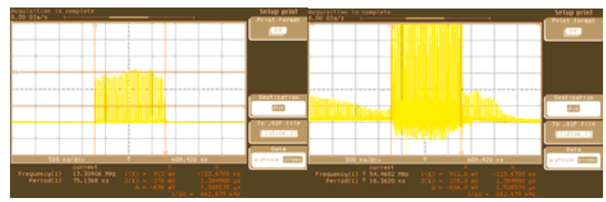

Figure 12 and 13: WCM signal before MI extraction with vertical scale of 300 mV/div (left) and 10mV/div (right).

## CONCLUSION

We have done beam studies and simulation studies to estimate how much beam loading compensation is needed for high intensity slip stacking operation. The gain of feedforeward system was increased by doubling the power of solid state driver and by programming of the PA grid bias. The effects were observed on beam and gap voltage signals.

Since December 2004, slip stacking is operational and the intensity on the pbar target is $7.0*10^{12}$ppp. The bunch length at MI extraction is 1.8 nsec and total time of slip stacking process was 133 msec which is less than two Booster cycles. We have already seen a almost 30% increase in anti proton production.

There is beam loss at the beginning of acceleration and there is also seen to be leaks from stacking bunches at flat top. Intensity at injection is $8.0*10^{12}$ppp, at extraction is $7.5*10^{12}$ppp and the intensity at target is $7.0*10^{12}$ppp. Beam studies are underway to fix those beam loss.

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