SLIP STACKING*

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Abstract

Slip stacking has been onperational at Fermilab Main Injector (MI) since December 2004. The proton beam intensity for the anti proton production was increased by 70% with the stacking scheme. We plan to use it also for the Numi operation which is providing beams to the MINOS neutrino experiment. [1]

OPERATION STATUS

The MI sends protons with the energy of 120GeV to a pbar target and the Numi beam line in one MI cycle of 1.8 sec. Total 7 batches were injected from Booster at 8GeV, where one batch contained 84 bunches. The first two batches were merged into one batch by slip stacking and the other 5 batches were injected after the stacking process was completed as shown in Figure 1 and 2. There were one double-density batch going to the pbar target, and 5 single-density batches for the Numi in the MI at 8GeV. They were accelerated to 120 GeV at one cycle. The Booster cycle is 66.6msec and the MI cycle is 1.6sec at the minimum, so that accelerating 7 batches together increases beam efficiency effectively in the MI. The intensity for the pbar target is 9.0e12 and for Numi beam line is 22e12 particles per pulse (ppp) on the current operation.

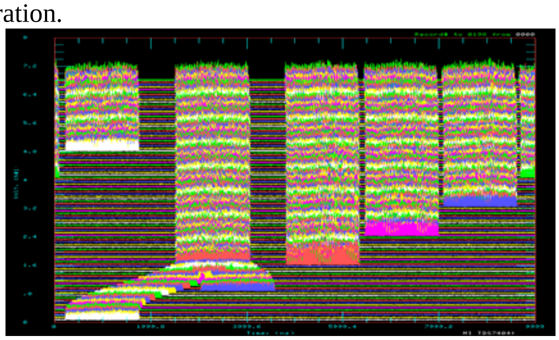

Figure 1: Mountain range plots with wall current monitor signals at 8GeV. The horizontal scale is 10µsec and the MI revolution is ~11µsec.

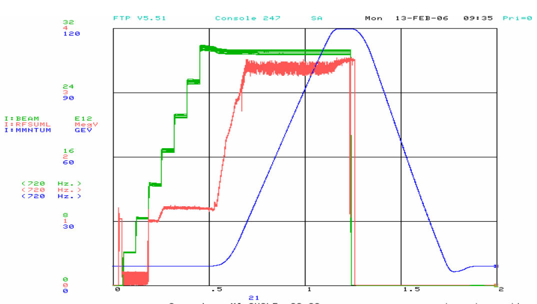

Figure 2: Total beam intensity in the MI (green), RF voltage (red) and momentum (blue).

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SLIP STACKING

In the slip stacking the beam at higher energy and the beam at lower energy are slipping each other, and they are captured by one rf bucket when they are lined up longitudinally.

RF system and MI momentum aperture

Two different rf frequencies were used for the slip stacking process. The MI has 18 53MHz rf cavities of three are driven at one frequency (lower) and three other at another frequency (higher). The rest of the cavities were off but were compensating for the beam loading effects. [2] The momentum aperture of MI is about +/- 1.0% so that the frequency can be changed by +/- 3000Hz from the central frequency. [3]

Table 1: The MI parameters

Harmonic number	588
RF frequency at injection	52811400 Hz
Transition Gamma	21.6
Kinetic energy at injection	8 GeV

Frequency curves and frequency separation

The frequency separation between higher and lower frequencies was studied by measurements and simulation. [3] In the case of the emittance of 0.08eV-sec and rf voltage of 60kV, the frequency separation of more than 1200Hz was necessary to avoid an emittance blow-up. Since a beam emittance depends on the beam intensity, the parameters were optimized by measurements of beam losses at high intensity. The frequency separation kept at 1400Hz with the RF voltage of 110kV in the operation. Both higher and lower frequency beams were captured with central frequency rf voltage of 1MV when they were at the same longitudinal location as shown in Figure 3.

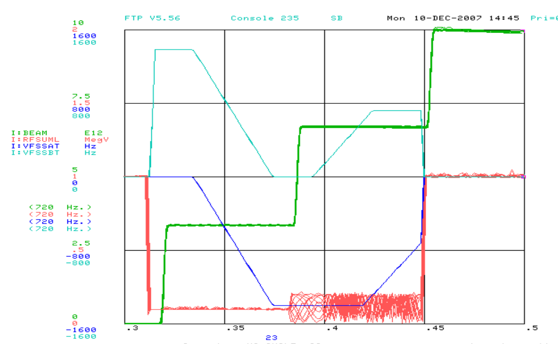

Figure 3: Higher (cyan) and lower (blue) rf frequencies, total beam intensity (green) and total rf voltage (red).

Bucket acceptance for Slip stacking

The bucket size was estimated by particle simulations with applying two frequency rf voltages. [4] All particles were located on the bucket trajectory of central frequency rf at input. Because the higher frequency rf was applied, only the particles shown in Figure 4 was able to stay in the bucket after 120msec. The bucket acceptance with current operational parameters was +/-5 nsec in the phase and +/- 7.5 MeV in the energy directions in order to avoid beam loss.

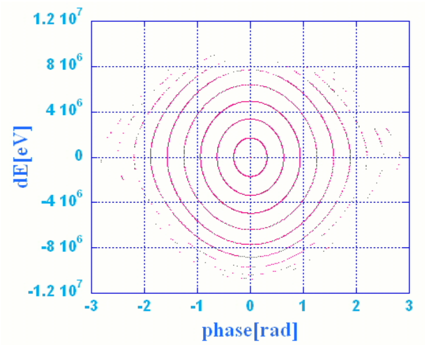

Figure 4: Bucket acceptance with rf voltage of 110kV and frequency separation of 1400Hz.

Emittance growth

A longitudinal emittance per bunch of 0.12 eV-sec with momentum spread of +/-9.4 MeV was measured at injection with the intensity of 4.23e12 ppp out of Booster. The longitudinal phase space was measured at recapture time and shown in Figure 5 (left). Figure 5(right) shows the phase space at recapture by simulation using the same injection emittance as measurements. The emittance at recapture was measured to be 0.35 eV-sec agreeing the simulation. There was no unexpected emittance blow-up during slip stacking on operation with beam loading compensation according to the specification. [2]

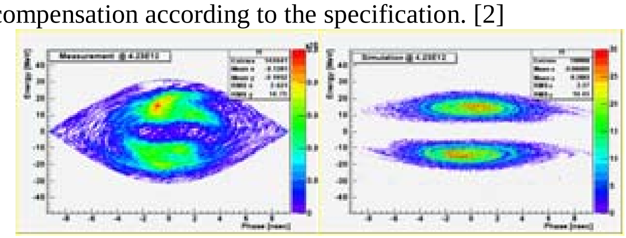

Figure 5: Phase space tomography at recapture time on measurement (left) and simulation (right).

MULTI BATCH SLIP STACKING

The slip stacking scheme was extended for the “Proton plan” project in order to increase intensity for the Numi operation. Eleven batches will be injected from the Booster to the MI. One slip stacking batch is going to the pbar target, while four doubled batches and one single batch are going to the Numi beam line. Total beam power is expected to increase from 300 to 400kW with repetition rate of 2.2sec. The intensity for the pbar target will stay at 8.0 - 9.0E12 ppp and that for the Numi will be increased to 36.0E12 ppp. The total beam loss has to be less than 5%.

Multi batch slip stacking and Status of studies

Multi batch slip stacking uses two different frequencies as shown in Figure 6. The multi batch slip stacking scheme was already verified in the mountain range plots of the whole process was shown in Figure 7. Beams were sent to the pbar and NuMI targets with intensity of 8.2E12 (Pbar) and 30E12 (Numi) with an efficiency of 95.5%. A record intensity of 4.6E13 ppp was accelerated to 120 GeV as shown in Figure 8.

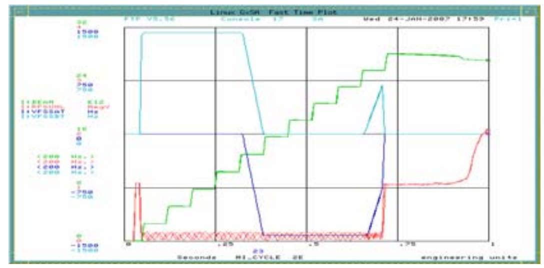

Figure 6: Higher rf frequency (cyan), lower rf frequency (blue), total beam intensity (green) and total rf voltage (red) on multi batch slip stacking.

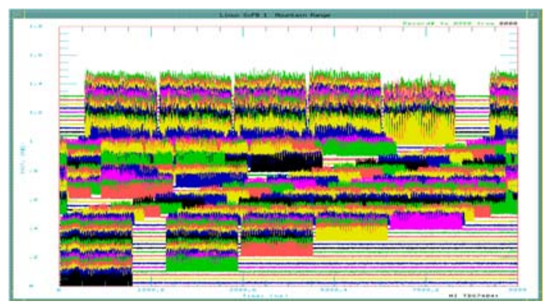

Figure 7: Mountain range plots with wall current monitor signals at 8GeV of multi batch slip stacking. The horizontal scale is 10µsec.

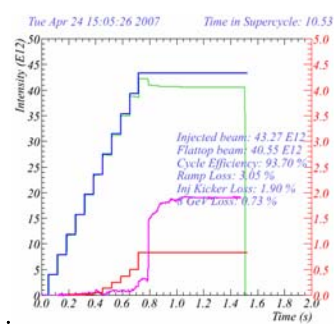

Figure 8: Total intensity injected from Booster (blue) and total intensity in the MI (green).

BEAM LOSSES IN MULTI BATCH SLIP STACKING

Beam losses in the multi batch slip stacking were studied by measurements and simulations. [5] Four different categories of beam losses were identified:

- Injection kicker gap loss.
- Loss at beginning of acceleration.
- Extraction kicker gap loss.

- 8 GeV life time loss.

The first three losses were created by longitudinal motion. Longitudinal particle simulations were carried out with rf parameters. The last one was created by transverse effects and has not been simulated yet.

Emittance measurements at different intensities

The longitudinal emittance was measured by using phase space tomography of wall current monitor signals at injection. The tomography pictures for three different intensities from Booster are shown in Figure 9. At the highest intensity of 4.3e12 ppp the phase space distribution is varying from pulse to pulse as shown in Figure 10. The distributions of energy and phase were fit to Gaussian, and two sigma were listed in Table2.

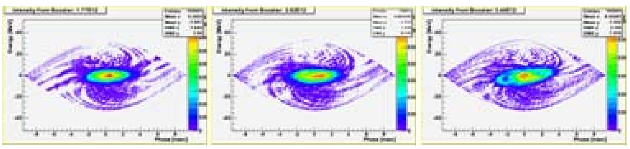

Figure 9: Tomography with intensity of 1.77(left), 2.65(middle) and 3.44 e12 ppp(right).

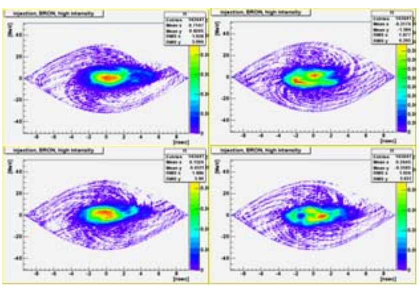

Figure 10: Tomography with intensity of 4.23E12 ppp for four different pulses.

Table 2: Measured beam size at different intensities

intensity	Energy spread	Bunch length
1.77e12 ppp	+/-6.88MeV	+/-2.94nsec
2.65e12 ppp	+/-7.62MeV	+/-3.36nsec
3.44e12 ppp	+/-8.99MeV	+/-3.56nsec
4.23e12 ppp	+/-9.37MeV	+/-3.58nsec

Measurement and Simulation results for the beam loss

The longitudinal particle simulation was curried out in order to estimate injection kicker gap loss and acceleration ramp loss with the emittances listed in the table2. The Figure 11 shows the results of measurements and simulations as a function of intensity. The simulation results are following those of measurements. The measurements at 4.23 ppp were changing from pulse to pulse because of the emittance at injection as shown in Figure 11. Figure 12 shows simulation of extraction kicker gap losses on the left and right side of the batch going to the pbar target. The losses on the right side are higher than the left, which agrees with what was measured by the WCM signal at the MI extraction. The three losses depend on the beam size at injection.

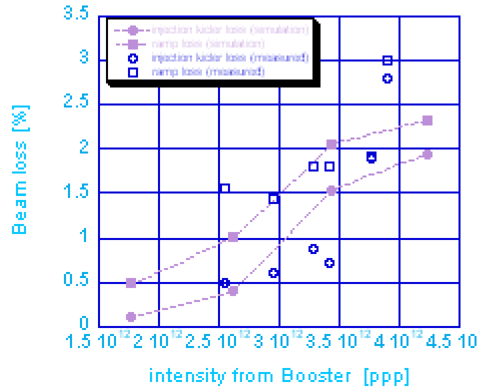

Figure 11: Simulation (blue) and Measurement (purple) results on injection kicker gap loss and loss(circle) at the beginning of acceleration(square).

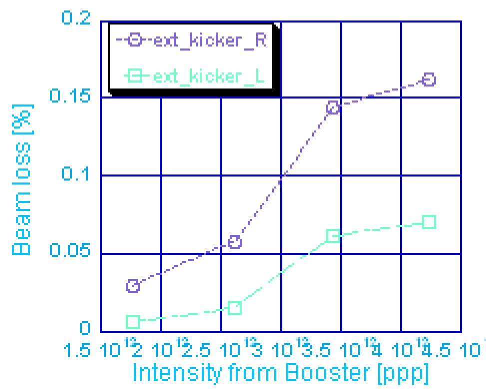

Figure 12: Simulation results on extraction kicker gap loss in the left (purple) and right (cyan) side of the pbar batch.

SUMMARY

Slip stacking is in operation for pbar stacking since December 2004. Multi batch slip stacking scheme has been verified and sent beam to the pbar and NuMI targets. Beam loss issues have been studies with measurements and simulations. The results shows to require small emittance beam at injection to lower beam loss.

REFERENCES

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