PROGRESS IN SLIP STACKING AND BARRIER BUCKET

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Abstract

The slip stacking [1] for pbar production has been operational in the Main Injector(MI) since December 2004 and has increased the beam intensity on the pbar target by more than 60%. We plan to use slip stacking for the NuMI neutrino experiment to effectively increasing the beam intensity to NuMI target by about a factor two in a MI cycle [2]. In parallel with slip stacking, we plan to study fast momentum stacking using barrier buckets [3-4]. One barrier rf system has been installed and tested, and a second system is being installed during the current shutdown.

INTENSITY UPGRADE FOR STACKING OPERATION

Antiproton production is essential in operationally Fermilab proton-antiproton collier experiments. The Main Injector accelerates protons from 8 GeV to 120 GeV and sends them to the target for antiproton production. In order to increase the proton intensity on target, slip stacking has been in operational in the MI since December 2004. The intensity from the Booster ring remained the same at 4.5E12 particles per pulse (ppp), but the intensity on the target was increased to 8.0E12 ppp with slip stacking.

Since the harmonic number of MI is 588 and Booster is 84, MI can accept more than two Booster pulses, one pulse has 84 bunches. MI stays at 8 GeV until two Booster pulses are injected and the two pulses are merged into one pulse, then accelerated to 120 GeV. Combining two Booster pulses into one and accelerating them in the same MI cycle increases the number of protons per pulse and the antiproton production rate.

Since the harmonic number of Debuncher is 84, MI can not send more than 84 bunches to target. Both methods of "Slip stacking" and "Barrier rf stacking" were studied to margin two Booster pulses to one at 8GeV in MI.

SLIP STACKING FOR ANTI-PROTON PRODUCTION

Operational status

MI operates a stacking cycle with slip stacking since December 2004.

The total beam intensity on target has been increased from 4.5E12 ppp to 8E12 ppp. Figure 1 shows antiproton production rate for the past one and half years as a function of proton intensity on target.

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Figure 2 shows a mountain range plot with a resistive wall current monitor (WCM) signal. The slip stacking process is shown from injection. The intensity of one Booster pulse was 4.25E12 ppp and total intensity at injection was 8.5e12 ppp as shown in Figure 3. A beam loss of 5e11 ppp (6%) was observed at the beginning of acceleration, around 9 GeV. The beam loss has been studied with both simulation and beam measurements.

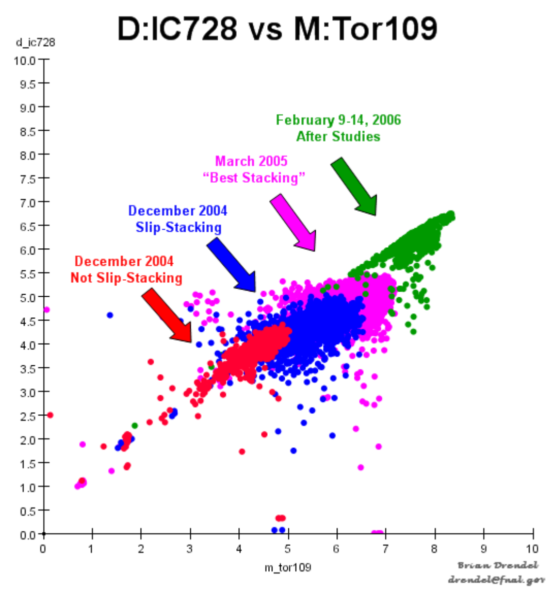

Figure 1: Antiproton production rate for the last one and half year as a function of proton intensity on target.

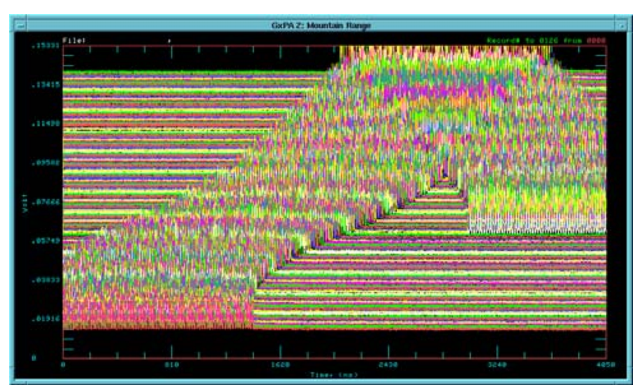

Figure 2: Mountain range plot with wall current monitor signals during a slip stacking process.

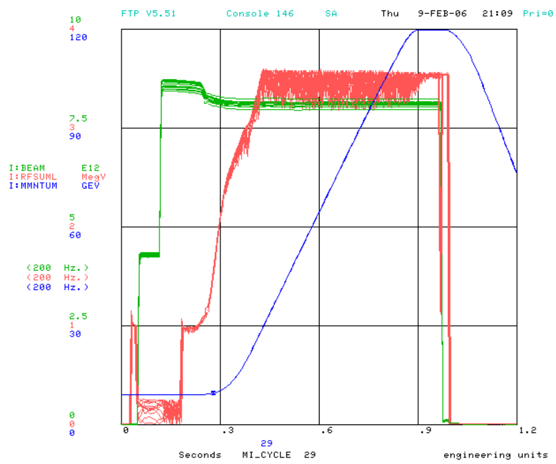

Figure 3: Beam intensity from injection to flat top. Beam intensity (green), RF voltage(red) and Momentum(blue).

Simulation for the beam loss

In order to estimate longitudinal acceptance with two frequencies used for slip stacking, a multi particle simulation was performed. Figure 4 shows the particles in the longitudinal phase space from injection to the point after 12000 turns which is about the same time duration of the slipping process (181 msec).

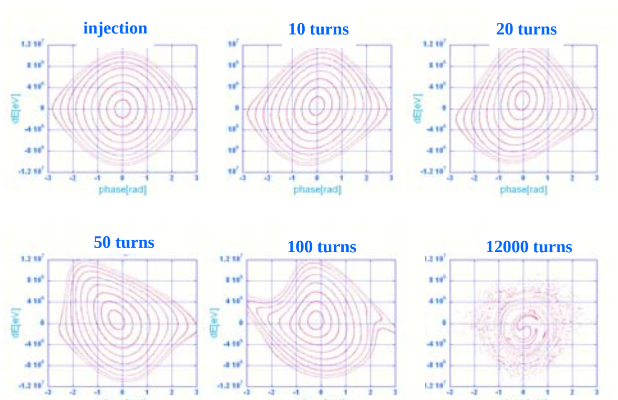

Figure 4: Longitudinal phase space during 1200 turns by simulation with two different frequencies.

For the operation, the frequency separation and the rf voltage for slipping were optimized to minimize beam losses. The optimum frequency separation is 1400 Hz and the voltage is 90 kV. The simulation with two frequencies was performed with these operation parameters. Figure 5 shows an injection distribution of particles which could stay around synchronus phase after 12000 turns. The maximum momentum acceptance with current operation parameters was +8 MeV from the result.

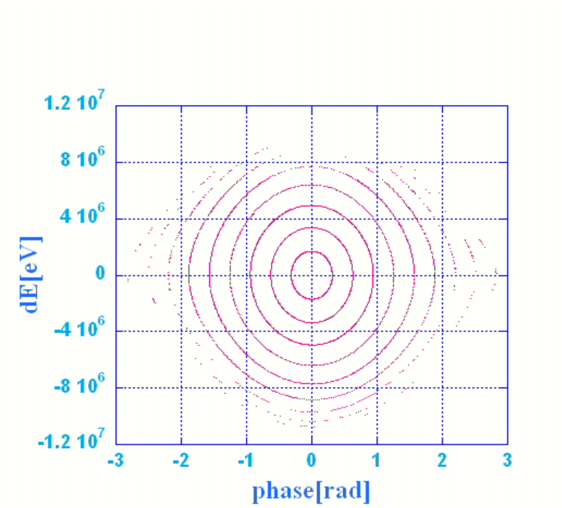

Figure 5: Injection distribution of the particles which could stay around synchronus phase after 12000 turns.

Emittance measurements at injection

In order to measure longitudinal emittance of the real beams, we used phase space tomography at injection. The tomography data of four different Booster bunches are shown in Figure 6. The results show different distribution in the longitudinal phase space from bunch to bunch and the 95% momentum spread was to be larger than +/-10 MeV. From the comparison between the simulation and measurements, there should be beam losses. Figure 7 shows the tomography data at recapture time. Particles were filling recapture rf bucket.

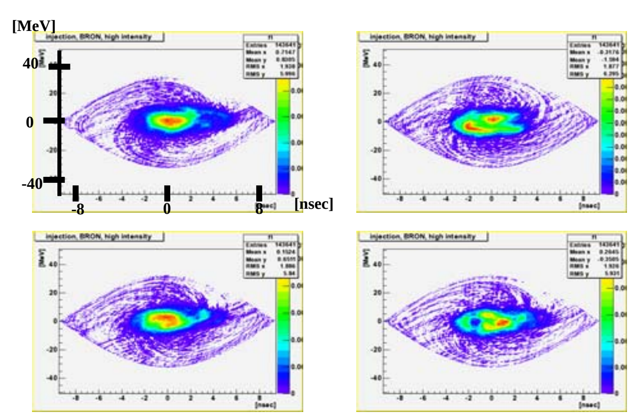

Figure 6: Longitudinal phase space tomography at injection.

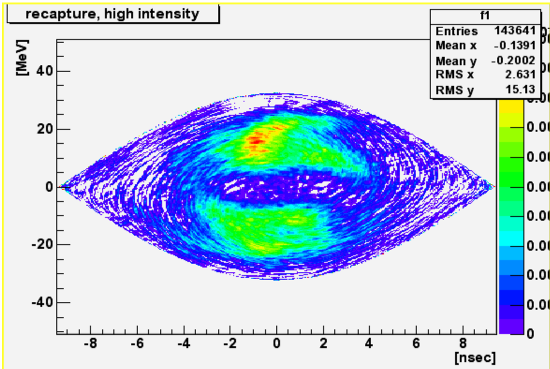

Figure 7: Longitudinal phase space tomography at recapture.

Simulation with acceleration

In order to estimate how much beam loss was caused by the large longitudinal emittance at injection, the phase space tomography results were used in the simulation. The particles were slipped, recaptured and accelerated from 8 to 9 GeV. Figure 8 shows phase space at 9 GeV. The vertical scale is the same for the left and right pictures but the horizontal scale is 600 buckets for the left and 10 buckets for the right. The left picture shows that there was a gap vertically between particles around synchronus energy and in lower energy. The right picture shows that most of the particles were captured in acceleration bucket. The lower energy particles were going to hit momentum aperture of the MI and then tuning into beam losses at 9 GeV. There was 3.5% beam loss at 9 GeV in the simulation.

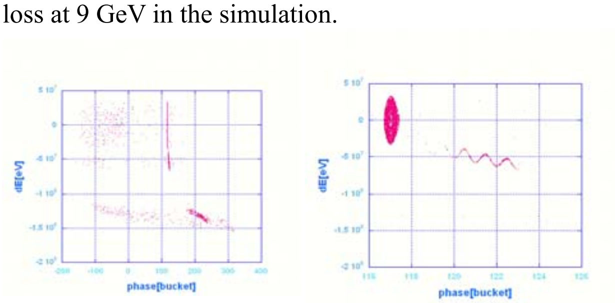

Figure 8: Longitudinal phase space at 9 GeV. Vertical scale was from -20E7 to +5E7 eV. Horizontal scale was 600 buckets for left and 10 buckets for right.

BARRIER BUCKET STACKING FOR ANTI-PROTON PRODUCTION

Barrier bucket rf

The barrier bucket stacking is another method to increase the intensity for a stacking cycle. We have been doing beam studies using a barrier bucket cavity which is a coaxial cavity consisted with seven finemet cores. The cavity was installed into MI in 2002. A pulse generator sent power of 10 kW to the cavity with the repetition of 90 kHz for 0.4sec. The output voltage was +/-8 kV with width of 10 microsec.

Machine studies

We injected two Booster pulses next to each other in the barrier bucket, and The rf voltage of 53Mhz cavities was reduced adiabatically to debunch the 53MHz bunches from Booster. The width of barrier bucket was reduced to squeeze two injection pulses. After 0.2 sec, the total pulse length became half. The 53 MHz rf voltage was then raised adiabatically to recapture beam in 53MHz rf buckets. The total process time was 0.4 sec and Figure 9 shows the whole process from injection.

Total beam loss was 20 % at the beginning of acceleration and the emittance at extraction was 0.8eV-sec.

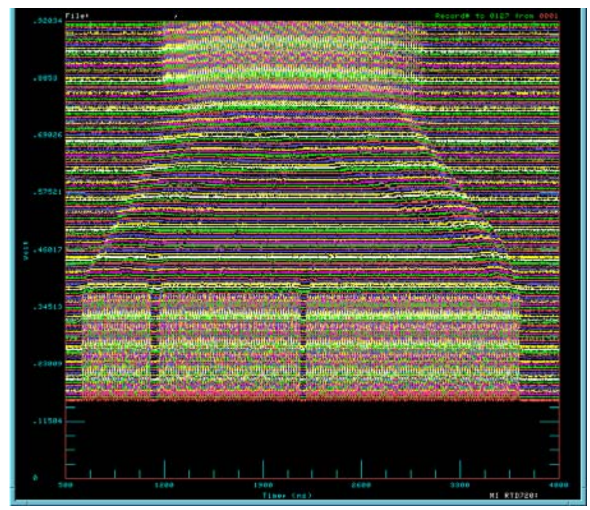

Figure 9: Mountain range plot at 8 GeV on Barrier bucket stacking process.

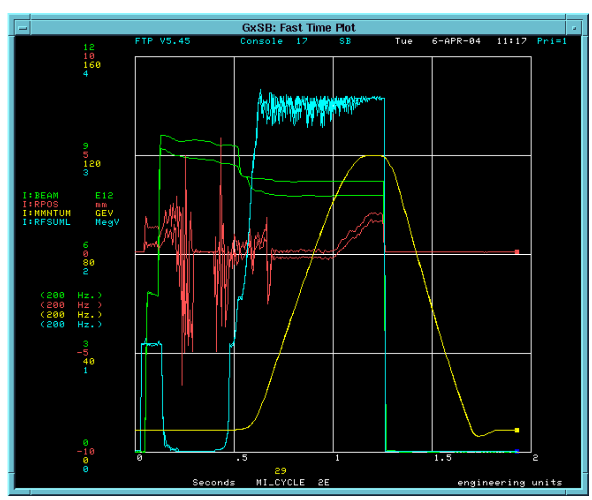

Figure 10: Total intensity (green) and 53 MHz rf voltage(cyan) on Barrier bucket stacking cycle.

INTENSITY UPGRADE FOR NUMI OPERATION

The Main Injector also accelerates and sends protons to the Numi beam line target for the MINOS neutrino experiment. The MI sends 5 Booster pulses, the total intensity 2.5E12 ppp, to Numi. The beam to antiproton target and the beam to Numi were accelerated together in one cycle to increase beam powers on target. On this cycle, first two Booster pulses are merged with slip stacking and after recapture five more Booster pluses are injected and accelerated. Fermilab has a plan to double the intensity of beam to Numi with the "proton plan" project. The MI is going to accept 11 Booster pulses at injection energy and accelerates them to 120 GeV. By using Slip stacking or barrier bucket stacking, two of them are merged into one and send to Anti-proton production, while 9 of them, as one single and four merged pulses, are going to be sent to the Numi beam line.

With Slip stacking

We are going to use two frequencies. Five pulses are injected on the central frequency and decelerated. After the frequency has lowered, the 6th pulse is injected on the central frequency. Since the 6th injection pulse and the other five have different frequencies, they move on different orbits and slip each other. After the pulse train slips by one pulse length, the 7th pulse is injected on the central frequency. Figure 11 shows the scheme of the multi-batch slip stacking and first five pulses (blue) keep changing their locations but the other 6 pulses are not.

Machine studies have begun with low intensity, the total intensity was about 4E12 ppp, and the beam was accelerated 120 GeV. Figure 12 shows mountain range plots during a 11-pulses slip stacking at injection energy and Figure 13 shows WCM signals at 120 GeV.

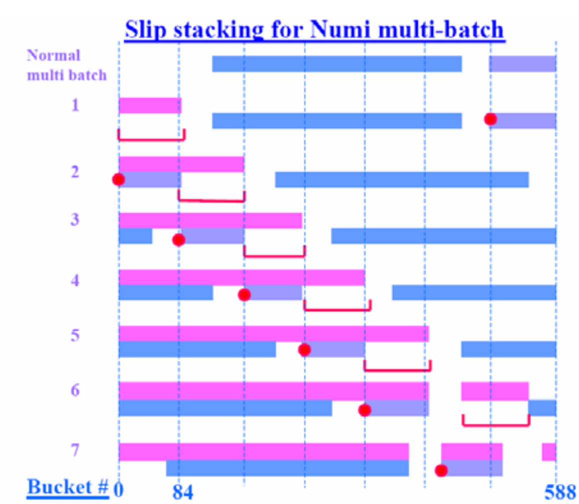

Figure 11: The scheme of 11 pulses slip stacking.

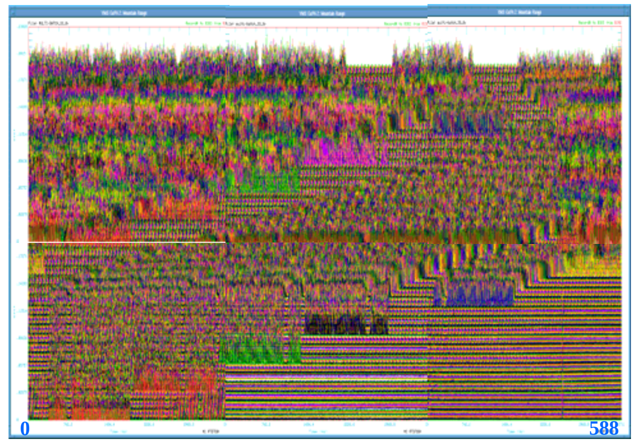

Figure 12: Mt. range plots during 11 pulses slip stacking at injection energy.

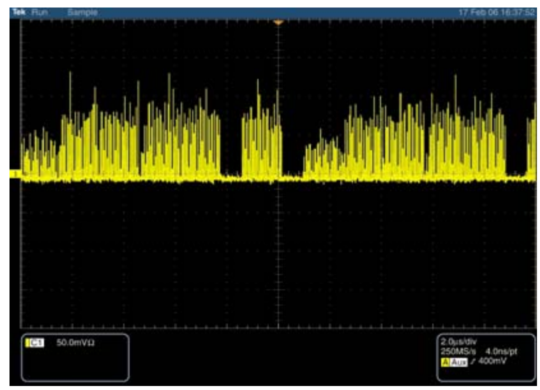

Figure 13: WCM signal at 120GeV.

With Barrier bucket rf

In parallel with slip stacking, we plan to study fast momentum stacking using barrier buckets. Two barrier bucket cavies are required for this scheme and the second system is being installed during the current shutdown.

As Figure 14 shows, two barrier buckets, one is changing the bucket length (moving barrier) and the other is not moving longitudinal location (stopping barrier), are used for the process. A Booster pulse is injected on a separatrix of the moving barrier rf bucket and it starts a synchrotron oscillation around the rf bucket. After the particles reach a fixed point, they started to drift and are blocked by stopping barrier bucket. At the end, the beam is kept in between the moving bucket and the stopping bucket.

Particle simulation was performed. The longitudinal phase space after the barrier bucket stacking with 12 pulses injection is shown in Figure 15. After the stacking, the beam has to be captured in 53 MHz rf in order to be accelerated to 120 GeV.

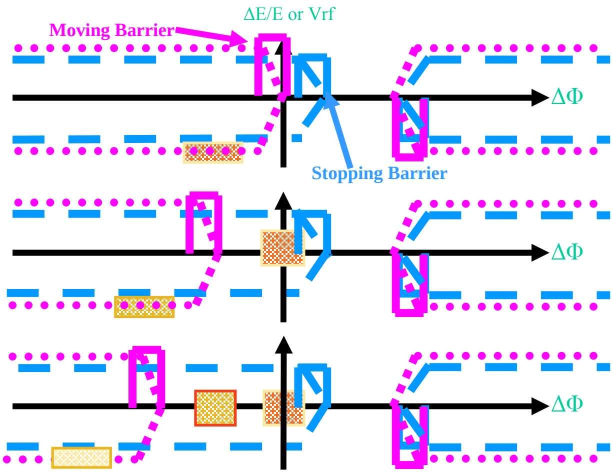

Figure 14: The scheme of fast momentum stacking using barrier buckets.

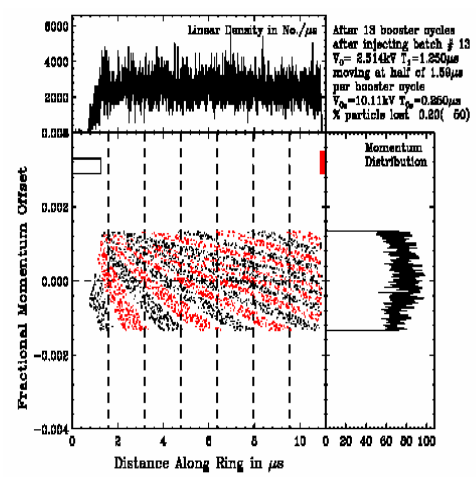

Figure 15: Longitudinal phase space after 12 pulses injection into the barrier buckets.

SUMMARY

- Slip stacking has been operational since December 2004 on antiproton production cycle.
- Intensity on the target was increased from 4.5E12 to 8.0E12 ppp and increasing the antiproton production rate by more than 60%.
- Barrier bucket cavity was installed and the scheme was studied with a beam intensity of 10E12 ppp.
- In order to increase the proton intensity to the Numi, the MI is working on slip stacking with multiple pluses.
- Low intensity beam studies have begun with 11 pulse injections. Total intensity of 4E12 ppp was accelerated to 120 GeV.
- A second barrier bucket system is being installed for fast momentum stacking using barrier buckets.

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