

SLIP STACKING EXPERIMENTS AT FERMILAB MAIN INJECTOR

K. Koba, T. Berenc, B. Barnes, B. Chase, I. Kourbanis, J. MacLachlan, K. Meisner, J. Steimel
 FNAL, Batavia, IL 60510, USA

Abstract

In order to achieve an increase in proton intensity, Fermilab Main Injector will use 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 started for this process and we have already verified that, at least for a low beam intensity, the stacking procedure works as expected[2][3][4]. For high intensity operation, development work of the feedback and feedforward systems is under way[5][6][7].

INTRODUCTION

The Fermilab Main Injector (MI) accelerates protons and extracts them to a target to produce antiprotons. In the operation cycle for the antiproton production, 84 bunches are injected from Booster to MI. Bunches are accelerated from 8GeV to 120GeV and extracted to hit the production target. The total beam intensity is $4.5 \cdot 10^{12}$ particles per pulse (ppp) with a cycle of 1.5 sec. The Main Injector parameters are listed in Table 1.

Run IIb will follow Run IIa and has a luminosity goal $4.1 \cdot 10^{32} \text{ cm}^{-2}\text{sec}^{-1}$ requiring $9.634 \cdot 10^{12}$ total antiprotons in the Tevatron. In order to achieve this goal, we need $9.0 \cdot 10^{12}$ protons in 84 bunches in the Main Injector for antiproton production. Higher proton intensities are required to get more antiprotons and higher stacking rates in the accumulator. In order to achieve this, we are planning to use a scheme called "slip stacking". With slip stacking, the intensity of the bunches can be doubled by injecting one bunch train at slightly lower energy, another train at slightly higher energy and bringing them together.

Beam studies of the slip stacking process have started and we have already established that the stacking procedure works as expected.

Table 1: Main Injector parameters on stacking cycle

RF frequency @ injection	52.811400Hz
Proton energy @ injection	8GeV
Proton energy @ extraction	120GeV
Harmonic number	588
Transition gamma	21.6
Mean radius	528.3m

RF PARAMETERS

For slip stacking, we use three different radio frequency (RF) systems and follow four steps. Step 1: The first bunch train is injected from the Booster on the central orbit and captured by the first RF system. To make a room for the second bunch train, the first bunch train is then decelerated until it circulates on the inside of the central orbit. Step 2: The second bunch train is injected on the central orbit and captured by the second RF system. Step 3: As the two bunch trains have slightly different energies, they can move relative to each other. Both bunch trains are accelerated till they are separated by the same amount from the central energy. Step 4: When the two bunch trains coincide at the same longitudinal location, they are captured by the third RF system.

Since two bunch trains have different energies, MI must have an enough momentum aperture to accept both. The momentum aperture of MI is $\pm 0.7\%$ at injection, corresponding to the frequency separation of $\pm 3000\text{Hz}$ from the central value of 52.8114MHz.

MI cavities and Injection Matching

MI has eighteen 53MHz cavities. These are separated into the two groups, each with 9 cavities. Low level RF (LLRF) signals go to two groups of cavities individually. For the slip stacking, we are using one out of 9 cavities in each group at injection. The RF voltage at injection is adjusted so that one cavity produces 62 kV in order to achieve a low momentum spread.

At extraction, the Booster RF voltage is 380kV, which matches to a MI injection voltage of 1MV for normal operation. Since the MI injection RF voltage is 62 kV for the slip stacking, a bunch rotation is carried out in Booster before extraction so that the bunch shape will be matched to the RF bucket of MI at injection. As the Booster RF voltage is rapidly reduced, the bunch starts to rotate in the phase space. After a quarter of synchrotron period, the bunch is injected into MI.

Frequency Curve

The frequency as a function of time is shown in Figure 1 for the first and the second RF systems. The frequency separation was kept at 1200Hz which is enough to keep the bunch shape unchanged.

The first bunch train was injected on the central orbit with nominal frequency at 0.13msec and captured by the first RF system of 62kV. At this time, the frequency of the second RF system was 1200Hz higher than the first RF system. The first bunch was then decelerated to a frequency 1200Hz lower than the original value. After

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one Booster cycle of 66.7msec, the second train was injected on the central orbit and captured by the second RF system. After slipping, both bunch trains were captured by all 18 cavities with 800kV and 0 frequency separation.

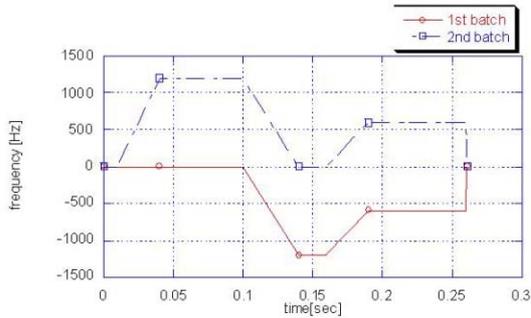


Figure 1: Frequency for first bunch train and second bunch train as a function of time.

PREVIOUS BEAM STUDY

Two bunch trains, each with 82 bunches, were injected into MI. The total intensity for two trains was low, $0.8 \cdot 10^{12}$ ppp, in order to reduce beam loading effects.

Figure 2, a mountain range picture of the signals from the wall current monitor (WCM), reveals the progress of slip stacking from the beginning to the end. The WCM had a resolution of 0.5ns/sample. The data were obtained every 1.42ms for 0.18s. There was no beam loss during the slip stacking process.

The length of the first bunch of the first bunch train shown in Fig. 2 was used to calculate the emittance. Figure 3 shows the calculated 95% emittance during 0.18s. Since there was an empty space between upper and lower bunches, there should be an emittance growth. The emittance growth expected from simulation is a factor of 3.2. From the plot, we see that there is no emittance growth before the two batches are recaptured by one RF bucket but there is a factor of 4.0 emittance growth after the recapture.

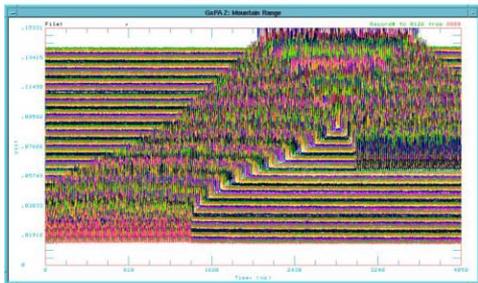


Figure 2: Mt range plot. The signal came from WCM with a resolution of 0.5ns/sample. The data were obtained every 1.42ms for 0.18s.

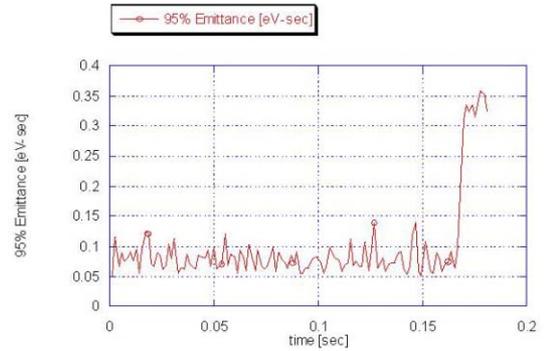


Figure 3: The 95% emittance calculated by bunch length shown in Fig.2.

SLIP STACKING PHASE VARIATION

Frequency curves (Fig.1) applied to the beam are calculated assuming that, at the time of recapture, two bunch trains are sitting exactly on the same longitudinal location, that is, two cavities are in phase. However, MI slip stacking studies revealed cycle to cycle variation in the RF system phase slip. This produced an unreliable RF voltage for recapture.

The largest phase variation was traced to timing jitter on the 720Hz line locked Tevatron Clock event. A MI LLRF system Digital Signal Processor (DSP) generates the frequency curves from user tuned tables. The frequency curves are a function of time and are integrated by the DSP to apply phase modulation to the RF systems that slip the bunch trains. The DSP processes run at 720Hz, $23 \cdot 720$ Hz, and $138 \cdot 720$ Hz via a scheduler that is synchronized with the Tevatron Clock event by a phase lock loop (PLL). As the PLL input jitters and the DSP follows the jitter, the frequency curves output and its integral (RF phase) varies.

The RF phase variation was reduced to 0° by changing the frequency curve generation from the Tevatron Clock time base to accurate LLRF internal time.

SIMULATION FOR RECAPTURE

To understand what caused the emittance growth at recapture, simulation studies were carried out using the code ESME[8]. In the simulation studies, the time and voltage to recapture bunches were varied to match the observed RF phase variation.

The delay was changed from 0 to 250 μ sec causing a ± 60 degrees phase variation and the 95% bunch length after 15msec was measured. The emittance plotted in Fig. 4 was estimated from the bunch length. It increased by a factor of 3.2 to 7.0 with increasing delay. Since the RF phase variation produced errors as large as 45 degrees, it could cause the emittance growth.

The recapture voltage was changed from 0.5 to 1.0MV because the voltage is changing from 0.8 to 1.0MV after the time to recapture. The 95% emittance plotted in Fig. 5 shows the emittance growth by a factor of 3.2 to 3.6.

By the two simulation studies, it was verified that the emittance growth was mainly due to the RF phase variation produced by the time error of Tevatron Clock event.

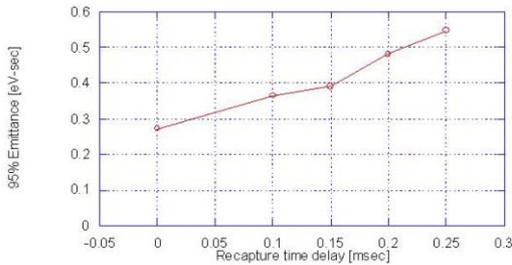


Figure 4: The estimated 95% emittance vs. recapture delay time.

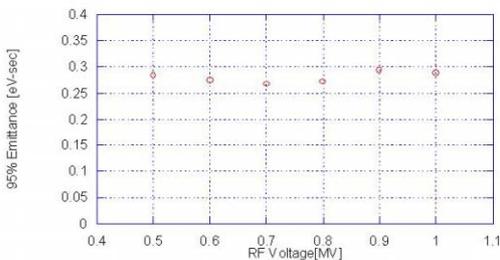


Figure 5: The estimated 95% emittance vs. recapture RF voltage.

BEAM STUDY

Previous beam studies have reported that there is an emittance growth when two bunch trains are recaptured. Simulation studies have indicated that the emittance growth is caused by variation in the final RF system phase. The phase variation was eliminated and the 95% longitudinal emittance was measured again. A factor of 3.2 in the observed emittance growth is the same as simulation results and there is no unexpected emittance growth during slip stacking.

ACCELERATION

Acceleration was also tried. Figure 6 shows the beam intensity during beam acceleration. Approximately 1.0×10^{12} total particles were injected, slip stacked and

accelerated to 120GeV. There was a beam loss of ~2% at the beginning of acceleration.

The emittance at 120GeV was measured. The observed value of 0.24eV-sec is less than the one we currently have in the normal operation cycle.

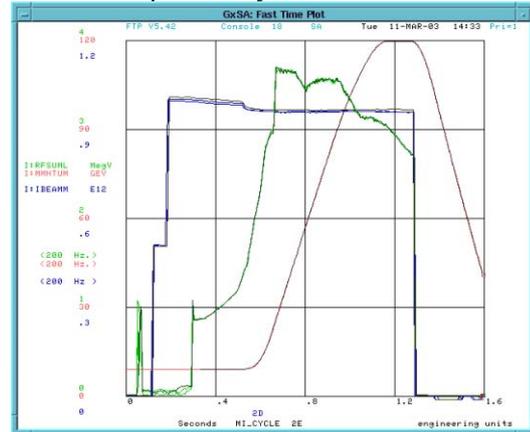


Figure 6: RFSUML: RF voltage[MV], MMNTUM: momentum[GeV/c], IBEMM: total beam intensity [E12 ppp]

CONCLUSION

Beam studies have started for the slip stacking process, and we have already verified that, at least for low beam intensity, the stacking procedure works as expected.

There was no beam loss during the process, but there was emittance growth when two bunch trains were recaptured. Simulation studies have indicated that the emittance growth is 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.

Beam has been accelerated to 120GeV with a beam loss of ~2% at the beginning of acceleration.

For higher intensity operation, development of the feedback and feedforward system is under way.

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