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Slip Stacking

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Abstract. We have started beam studies for 'slip stacking'[1] in the Main Injector in order to increase proton intensity on a target for anti-proton production. It has been verified that the system for slip stacking is working with low intensity beam. For a high intensity operation, we are developing a feedback[2][3] and feedforward system.

INTRODUCTION

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

Higher proton intensities are needed to get more anti-protons 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 lightly lower energy, another train at lightly higher energy and bringing them together.

Since two bunch trains have different energies, MI must have an enough momentum aperture to accept both. The momentum aperture of MI is +/-0.7% at injection, that is, the rf frequency for each bunch train can be shifted by +/-3000Hz from the original value.

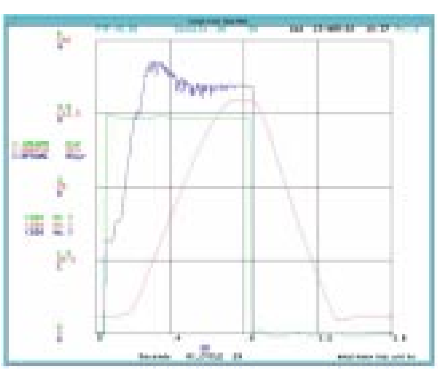

FIGURE 1. Typical operation cycle for anti-proton production. The green trace and red trace show a total intensity and momentum respectively.

TABLE 1. MI RF Parameters.

Rf frequency@njection	52.811400MHz
Number of rf cavities	18
Maximum total rf voltage @ injection	1.6MV
Proton energy @injection	8GeV
Harmonic number	588
Transition gamma	21.6
Mean radius	528.3m

STACKING PROCEDURES AND MEASUREMENT RESULTS

For slip stacking, we use three different rf systems and follow four steps. Step 1: the first bunch train is injected from 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 inside of the central orbit. Step 2: the second bunch train is injected on the central orbit and captured by the second rf system. Step3: As bunch trains have two slightly different energies, they can move relative to each other as they accelerated. Step 4: when two bunch trains coincide at the same longitudinal location, they are captured by the third rf system.

Optimum For Frequency Separation

Since there are two rf voltages during stacking, they act on both bunch trains. The bunch shape has been measured to demonstrate that the frequency separation between the first and the second rf systems is adequate.

In this measurement, one bunch train was injected, then two rf voltages were raised and the frequency separation was increased from 400 to 1200Hz. Figure 2 shows the bunch shape at injection and at 150msec after injection. The signals, plotted here with 5nsec/div, were obtained with a wall current monitor. It is clear that the frequency separation of 1200Hz is enough to keep the bunch shape unchanged.

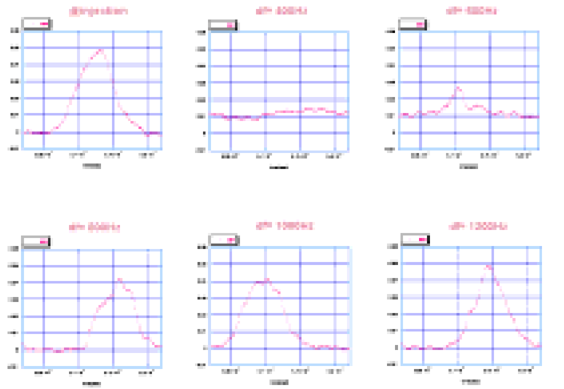

FIGURE 2. Comparison of the bunch shape, which is from a wall current monitor, at injection and after 150msec. The bunch on upper left was at injection. Other bunches were at after 2msec. The frequency separation was 400Hz(upper middle), 600Hz(upper right), 800Hz(Lower left), 1000Hz(lower middle), 1200Hz(lower right).

Simulation

A simulation study of the slip stacking has been curried out with a simulation code, ESME[4]. Two bunches each with emittance of 0.1 eV-sec were injected. An area corresponding to one bucket area of 0.1eV-sec was kept between lower and higher energy bunches. They then followed the four stacking steps and were captured by the third rf system which provided a bucket area of 0.3 eV-sec. At the end of these processes, we found a single bunch of emittance 0.3 eV-sec without beam loss, indicating an emittance growth of 50 %.

Measurement

The frequency and voltage as a function of time are shown in Figure 3 for the first and the second rf systems. Of 18 cavities at 53MHz, one was used for the first system, another for the second system. The frequency separation was kept at 1200Hz. 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. The intensity was low, $0.4*10^{12}$ppp, in order to reduce the beam loading effects. 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 the frequency 1200Hz lower than the original value. After 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 the third system, all 18 cavities. Figure 4, a mountain range picture of the signals from the wall current monitor, reveals the progress of slip stacking from the beginning to the end.

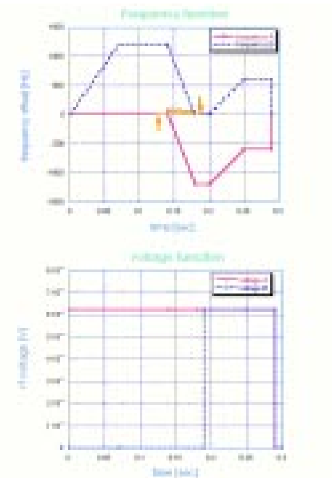

FIGURE 3. Frequency (upper) and voltage (lower) as a function of time. Red lines are for the first rf and blue line are for the second rf.

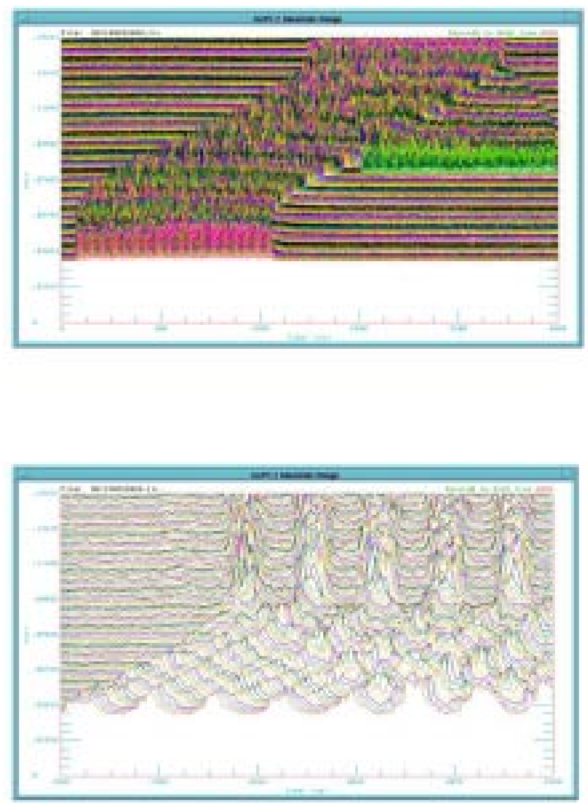

FIGURE 4. Measurement results of the whole slip stacking cycle. The lower figure shows the expanded signal at just after recapture by the third rf.

BEAM LOADING COMPENSATION

For high intensity operation, beam loading compensation is the key issue. A simulation was carried out to compare the beam with and without compensation of beam loading effects. Two trains of 84 bunches with the total intensity of $5*10^{12}$ went through the slip stacking process. At the end of stacking, with no compensation, the bunch shape became distorted and many particles were left outside of the bucket. When there was compensation of 40 dB of loop gain, there were no particle losses.

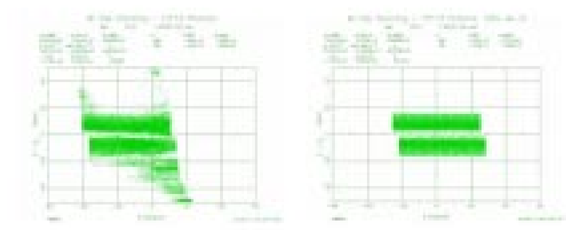

FIGURE 5. Simulation results comparing the beam after the slip stacking with (right) and without (left) a compensation of beam loading effects.

Development Of Beam Loading Compensation

We are developing feedback and feedforward systems for beam loading compensation. Figure 6, in which the center frequency is the fundamental, shows frequency spectra from a gap voltage monitor. The gain for feedback system was –20dB. One can see from this that the feedforward system reduces the revolution sidebands by 20dB.

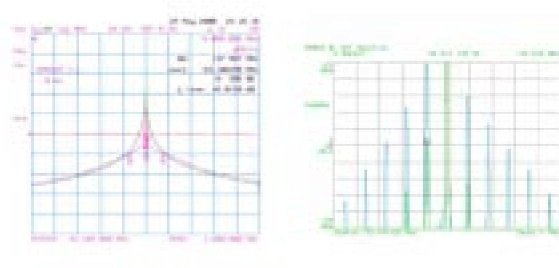

FIGURE 6. Measurement of the beam spectra from a gap voltage monitor. On the left graph, the green and red traces show without and with feedback system, respectively. On the right graph, the blue and green traces show without and with feedforward system, respectively.

SUMMARY

In order to achieve an increase in proton intensity, Fermilab Main Injector will use a stacking process called "slip stacking". The intensity will be doubled by injecting one train of bunches at a slightly lower energy, another at a slightly higher energy and then brining them together for the final capture. Beam studies have stared for this process and we have already verified that, at least for low beam intensity, the stacking procedure works as expected. For higher intensity operation, development work of the feedback and feedforward system is under way.

REFERENCES

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