PROGRESS IN MULTI-BATCH SLIP STACKING IN THE FERMILAB MAIN INJECTOR AND FUTURE PLANS

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Abstract

The multi-batch slip stacking has been used for operations since January, 2008 and effectively increased proton intensity to the NuMI target by 50% in a Main Injector (MI) cycle. The MI accepts 11 batches at injection energy from the Booster, and sends two batches to antiproton production and nine to the NuMI beam line. The total beam power in a cycle was increased to 340 kW on average. We have been doing beam studies in order to increase the beam power to 400 kW and to control the beam loss. We will also discuss 12 batch slip stacking scheme which is going to be used for future neutrino experiments.

INTRODUCTION

The beam studies for slip stacking were started in 2001 in order to increase proton intensity of the antiproton production cycle for Tevatron collider experiments. The beam intensity from the Booster stayed at 4.5E12 particles per pulse (ppp), but the intensity for the antiproton production was increased to 8.5E12 ppp by combining two Booster batches into one in the MI using the slip stacking scheme. Slip stacking became operational in the MI in December 2004. This was the first time it had been implemented in any accelerator. Slip stacking increased the beam intensity to the antiproton production target by 70 %. [1]

The slip stacking scheme was extended to multi-batch stacking for the NuMI neutrino experiment in order to increase the proton intensity at the NuMI target. The MI is sending a total beam power of 340 kW to both antiproton and NuMI targets as a daily operation. We plan to increase the beam power to 400 kW.

The Fermilab has a plan to use the slip stacking scheme for the NOvA neutrino experiment which is going to require 700 kW of proton beam power. The Recycler Ring (RR) will accept 12 batches from the Booster and will merge them into six batches with slip stacking. Beam studies have been done in MI at low intensity and it has been verified that this longitudinal stacking process works as expected.

STATUS OF 11 BATCH SLIP STACKING OPERATION

MI used to send one slip stacked batch to antiproton production and 5 normal batches to the NuMI beam line on the mixed mode operation cycle. Multi-batch slip stacking has been in operation since January 2008. A total of 11 Booster batches are injected in the MI. Two batches are sent to antiproton production and nine to the NuMI beam line. The intensity on the pbar target stayed at 8-8.5E12 ppp, but the intensity to NuMI target was increased from 22.5E12 to 32-33E12 ppp. The total intensity at 120 GeV is 41E12 ppp with a cycle efficiency of 95 %.

Figure 1 shows a mountain range plot during the 11 batch slip stacking process. The process of slip stacking, merging 10 batches to 5 batches and then injecting an 11th batch, are done in 0.733 sec. The beam was accelerated to 120GeV with a MI cycle time of 2.2 sec as shown in Figure 2. Figure 3 shows the total beam power was increased from 250 to 340 kW with 11 batch slip stacking on the mixed mode operation.

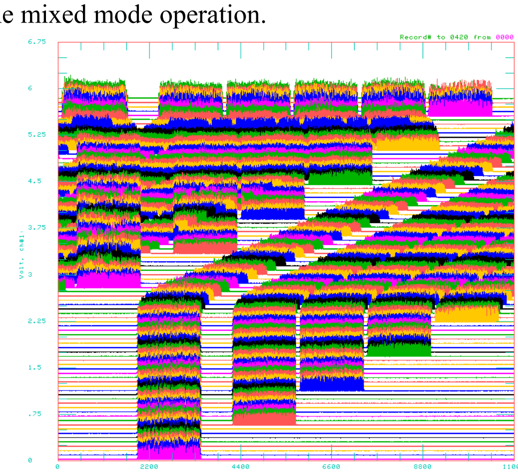

Figure 1: Mountain range plot showing the 11 batch slip stacking process in the mixed mode cycle. Horizontal scale is a MI revolution of ~11 μsec.

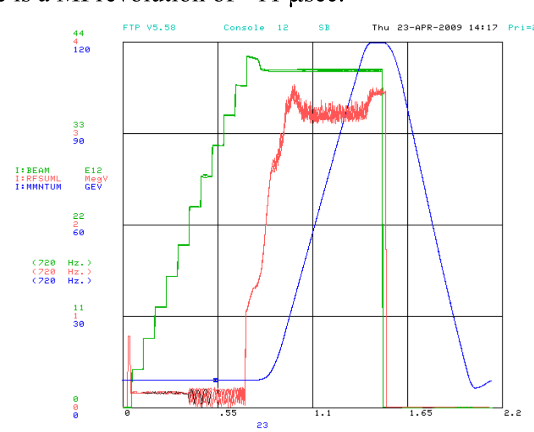

Figure 2: The total intensity (green), rf voltage (red) and momentum in the MI (blue) on the mixed mode cycle.

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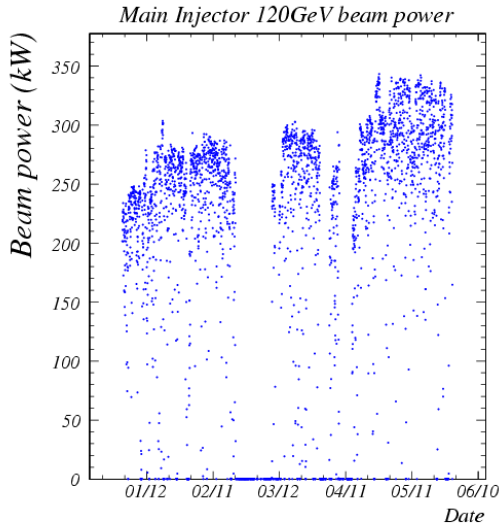

Figure 3: The total beam power of mixed mode cycle from January to July 2008. Plot shows before and after the 11 batch slip stacking process became operational.

BEAM LOSS

There are four types of beam losses, injection kicker loss (~1%), ramp loss (~3%), extraction kicker loss (less than 0.5%) and lifetime loss at 8GeV (~1%), on the cycle. The loss mechanisms are in good agreement with simulations. [2]

Injection kicker loss comes from the beam which is not captured by slipping rf buckets and is kicked by the injection kicker for the following injection batches. The loss is localized at the injection kicker area. A new kicker which is called the gap clearing kicker is going to be implemented to send the beam in the injection kicker gap to the MI abort line before the injection kicker is fired. [3]

The ramp loss comes from the beam not captured by the rf buckets during acceleration and stayed at the injection energy during the ramp. Four collimaters were installed and have localized 99% of the loss. [4]

The extraction kicker loss comes from the beam in the extraction kicker gap which was not captured by slipping rf buckets but captured by acceleration buckets at 8GeV. Since the beam was accelerated, the beam could be a high loss at 120GeV even though it was small amount of beam. The beam on the gap was fuzzed transversely by using damper and swiped at 8GeV. A kicker is going to be used as a fuzzer and it should fuzz beam effectively five times more than the current damper. [5]

The lifetime at 8GeV loss is from transverse emittance blow up. Lowering chromaticity with the transverse damper during first 5 batch injections, before bunches started overlapping longitudinally, reduced this loss.

Beam studies are going to be continued to improve the efficiency to greater than 95% and the beam power to 400kW. The longitudinal beam emittance from the Booster is essential to the high efficiency operation.

12 BATCH SLIP STACKING FOR NOVA EXPERIMENT

The MI is going to accelerate 48E12 ppp in a 1.33 sec cycle in order to provide 700 kW proton beam for the NOvA neutrino experiment. The RR is going to be used as an injector to the MI, accept 12 Booster batches and combine them into 6 batches with slip stacking. [6]

The 12 batch slip stacking process was studied in MI and worked as expected at low intensity. Two rf systems with different frequencies were used for the 12-batch slip stacking. Figure 4 shows the frequencies which are applied for the beam, total rf voltage, and beam intensity in the MI.

Six batches, each with 84 bunches, were injected on the central frequency of the first rf system, captured with 100 kV rf voltage and then decelerated. The second rf system was off during the 6 batch injections. After the frequency of the first system has lowered, the 7th batch was injected on the central frequency of the second rf system and captured with 100 kV rf voltage. Since the 7th batch and the proceeding six have different frequencies, they move on different orbits in the ring and slip each other. The 6 batch train had to slip by one batch length before the 8th batch was injected. Since a new Booster batch is injected every 15 Hz, the frequency separation between two rfs has to be 1260Hz. After the 12th batch was injected, both frequencies were moved up to around the central frequency to wait for the higher and lower energy batches lined up longitudinally, then bunches were captured with 1 MV of rf voltage with the central frequency. Figure 5 is a mountain range plot showing 12 batch injections and 6 combined batches after the slip stacking process. The process has been done within 0.8 sec, which is shorter than one MI cycle.

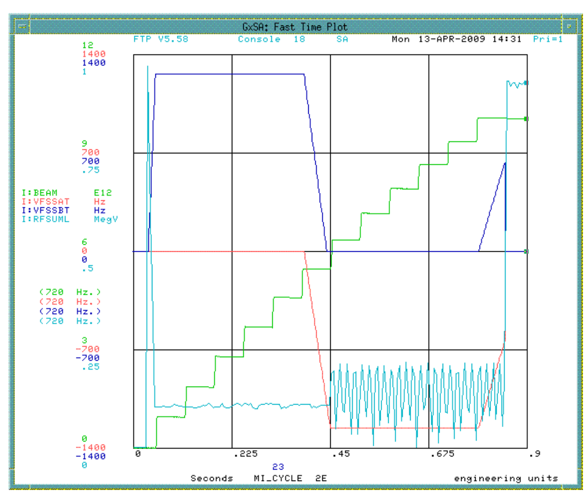

Figure 4: The frequency functions for the first rf system (red) and the second rf system (blue), the total rf voltage (cyan), and the beam intensity (green) in the MI.

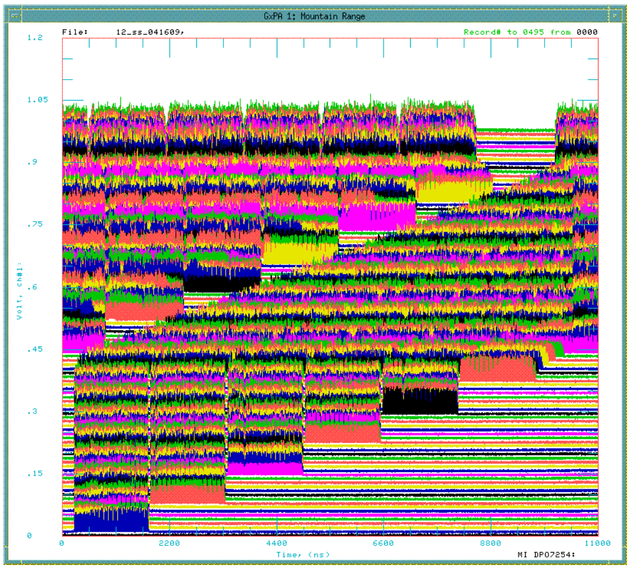

Figure 5: Mountain range plot showing a 12 batch slip stacking process at 8 GeV in the MI. Horizontal scale is a MI revolution of ~11 µsec.

RF System for Slip Stacking in the RR

The RR is a fixed energy machine at 8 GeV and located on the top of MI with same circumference of 3.3 km. RR is currently using a wideband rf system with the frequency rang of 90 kHz - 15 MHz and has no 53 MHz rf. Since the RR has enough momentum aperture of +/- 0.75% for the frequency manipulation, the slip stacking scheme could be applied in the RR by installing new 53 MHz rf cavities. [7]

Three 53 MHz cavities have been designed for the RR slip stacking. Two cavities, produce up to 150 kV each, are going to be installed in the RR and one will be used as a spare. The RR parameters compared with the current MI system are listed in table 1. 20 dB of beam loading compensation is required. The slip stacked beam is going to be sent to the MI before recapturing with high rf voltage. A new low level rf system is also necessary to control two rf frequencies and voltages with required accuracy. [8] Wall current monitor and Beam position monitors will also need to be modified for 53 MHz operation.

Table 1: Comparison Between the Current MI System and the Designed rf System for the RR.

	MI	RR
frequency	52.8114 MHz	52.809 MHz
Harmonic number	588	588
Number of slipping cavities	6	2
Maximum voltage for each frequency	180 kV	150 kV
R/Q	104	20
Q	3400	7000

Beam Loss on the RR Slip Stacking

The beam loss issues in the RR are going to be almost same with the MI. The gap clearing kicker is going to be necessary for the losses in the injection kicker gap and extraction kicker gap.

A chromaticity control and transverse damper are also required for lifetime loss.

SUMMARY

Multi-batch slip stacking has been in operation since January 2008. The total intensity at 120 GeV is 41E12 ppp with a cycle efficiency of 95 %. The MI is sending a total beam power of 340 kW to both antiproton and NuMI targets as a daily operation.

The beam loss mechanism was explained by measurement and simulation results. Further beam studies are going to be continued to improve the efficiency to better than 95% and increase the beam power to 400 kW.

MI is going to provide 700 kW of proton beam power to the NOvA neutrino experiment. The RR is going to be used as an injector and accept 12 batches from the Booster and merge them into six batches with the slip stacking scheme. The beam study has been done in the MI at low intensity and it had been verified that this longitudinal stacking process works as expected. Rf cavities have been designed for the slip stacking in the RR.

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