Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

CYCLE-TO-CYCLE EXTRACTION SYNCHRONIZATION OF THE FERMILAB BOOSTER FOR MULTIPLE BATCH INJECTION TO THE MAIN INJECTOR

R. Zwaska*, S. Kopp, University of Texas at Austin, Austin, TX 78712, USA
W. Pellico†, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract

We report on a system to ensure cycle-to-cycle synchronization of beam extraction from the Fermilab Booster accelerator to the Main Injector. Such synchronization is necessary for multiple batch operation of the Main Injector for the Run II upgrade of anti-proton production using slip-stacking in the Main Injector, and for the NuMI (Neutrinos at the Main Injector) neutrino beam. To perform this task a system of fast measurements and feedback controls the longitudinal progress of the Booster beam throughout its acceleration period by manipulation of the transverse position maintained by the LLRF (Low-level Radio Frequency) system.

INTRODUCTION

The Fermilab Booster accelerator [1] routinely delivers greater than 100 kW of 8 GeV protons to experiments and other accelerators. The beam is extracted in a single turn using a series of kicker magnets with risetimes of 30 - 40 ns; however the beam extracted from the Booster is bunched into 84 53 MHz buckets with a bunch spacing of only 19 ns.

To reduce the losses at extraction the charge is removed from several buckets early in the acceleration period, creating an abort gap or "notch". When the firing of the kickers is synchronized with the notch the extraction losses are reduced tenfold. Currently, the notch is created by firing a kicker and knocking out a few buunches at the start of the cycle. As the kinetic energy is one twentieth of its ultimate value the resulting radioactivation is correspondingly less, but still significant.

Synchronization Needs

In the past year, two significant users have come online using the Booster beam in the Main Injector (MI). The longitudinal slip-stacking of two Booster batches into one [2] is now used to increase antiproton production for Run II of the Tevatron. Also, the NuMI neutrino beam [3] will use 120 GeV protons for long-baseline neutrino experiments.

Each of the new uses involve injecting and accelerating more than one batch of Booster beam in the Main Injector – a process known as multiple batch operation. This operation maximizes proton power throughput by leveraging the shorter cycle time of the Booster and the high beam energy of the MI. To inject multiple batches the beam extracted from the Booster must arrive in the MI at a particular location relative to the beam already circulating. The Booster, however, ramps from 37 MHz to 53 MHz and longitudinal position of the notch is not naturally synchronized with the beam in the MI.

Synchronization Means

To synchronize the notch in the Booster and the beam in the MI the circulation frequencies of the two beams must be adjusted during the Booster acceleration cycle. By changing the horizontal ("radial") position maintained by the LLRF the beam's velocity and circumference are changed, inducing a longitidunal slip with respect to what would have otherwise occured – this process is known as "cogging".

The MI beam is coasting at 8 GeV, so it is already relativistic and would require unrealistically large changes in beam position to change the frequency quickly enough. The Booster, however, must accomodate the 400 MeV injected beam, so its available aperture increases rapidly through the acceleration cycle, enough to allow radial manipulations.

A proof-of-principle measurement and feedback system was implemented in 1998 [4]. This system established the magnitude of slippage to be corrected – about 200 RF buckets, or more than two revolutions. Also, the system demonstrated the expected longitudinal response (induced slippage) from radial manipulations.

The operational cogging system was under devlopment in 2003 and 2004 [5]. The sources of slippage were identified and quantified, improvements in various timings in the Booster reduced the slippage to be corrected to less than 80 RF buckets – less than one revolution. The notch creation was delayed by 5 ms allowing it to be created in anticipation of further slippage from measurements up to then. The feedback algorithm was improved to fully cog the beam.

ENHANCEMENTS

The cogging system became operational in Nov. 2004. Since our last report [5] several improvements have been made to the system to improve performance: the notch quality was improved by the installation of a new power supply; feedforward compensation of the gradient magnet

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[*] zwaska@mail.hep.utexas.edu

[†] pellico@fnal.gov

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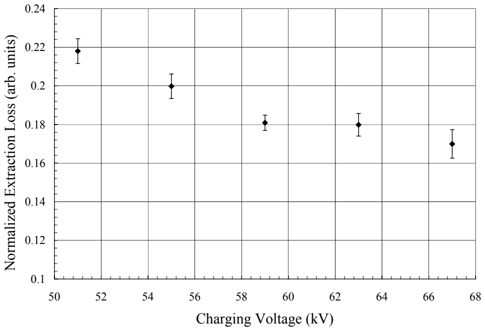

Figure 1: Total extraction losses normalized to beam intensity as a function of charging voltage – equivalent to magnet current or momentum kick magnitude. Error bars reflect cycle-to-cycle variations.

power supplies was established; feedforward radial manipulation is used before transition; the feedback manipulation algorithm was optimized; and baseline trajectories are established on the first batch of every multi-batch sequence.

Notch Improvements

Creation of the notch is delayed to 5 ms after injection in such a way as to compensate the predicted slippage from the first 5 ms. At that point beam momentum has increased 45 % and requires a correspondingly larger kick to fully create the notch.

The kicker magnet that creates the notch is powered by the discharge of a high voltage pulse-forming network (PFN). For notching at 400 MeV, a charging voltage of 43 kV was typically enough, suggesting that this implementation of cogging requires as much as 70 kV. The existing supply could not operate reliably in excess of 57 kV.

A new power supply capable of 70 kV charging voltage was procured and installed. Figure 1 shows measurements of extracion losses with cogging as a function of charging voltage with the new supply .

Magnet Sag Compensation

Measurements of slippage over multiple cycles in a batch train showed systematic variations from batch to batch. Further measurements showed that the pulsing of the RF anode supplies was causing the supply voltage to the gradient magnets to sag, causing the injection current to vary pulse-to-pulse.

The grandient magnets have a feedback system, but it takes a few pulses to correct the minimum magnet current. In this situation each subsequent cycle has a consistent magnet offset that led to slippage very early in the cycle that interfered with the prediction procedure. For a current variation of one part in 10,000 we expect slippage at the rate of 1.8 buckets / ms at injection, rapidly decreasing, integrating to a total slip of 10 buckets (see ref. [5] for details). We saw variations up to nine parts per 10,000 at injection. The absolute variation is about the same at extraction, so the relative variation is a factor of ten smaller.

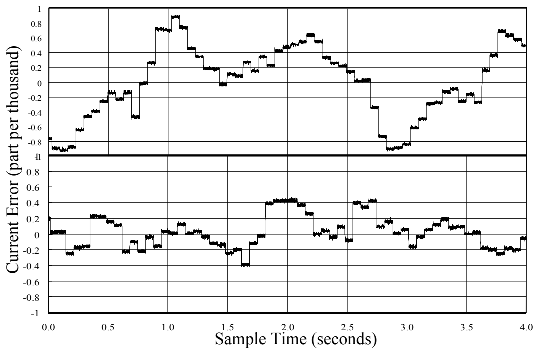

Figure 2: Measurements of minimum gradient-magnet current error. Above is without compensation, below is with compensation. These measurements were taken within minutes of eachother with the same machine conditions. The minimum current is only sampled at 15 Hz, causing the box profile.

To combat the variation, a feedforward magnet current compensation system was implemented. The compensation consists of a pulse generated on each cycle modulating the magnet current regulation. The pulse is a half-sine wave offsets to the magnet current throughout the cycle, increasing the magnet current at injection.

This simple system reduced the variation of the measured minimum current by more than a factor of two, improving the quality of the prediction used to create the notch. The effect of the compensation on current varition is shown in figure 2.

Pre-Transition Radial Manipulation

The bulk of cogging has been done after transition when the available aperture is large and the possibility for unplanned slippage is small. However, the radial excursions necessary (>4 mm) caused occasional beam loss at high batch intensity.

Feedforward radial maipulation is now used before transition to reduce the excursions necessary after transition. The radial offset magnitude and direction are based on a prediction of future slippage – similar to the prediction used for notch creation.

The magnitude of the bump is small (<2 mm) as the available aperture is still small. However, the slip factor is larger than after transtion: about 1.0 instead of 0.4 buckets / mm / ms.

Gain Optimization

The gains from the feedforward pre-transition bump reduces the cogging necessary after transtion. The magnitude of the larget post-transtion bump is now 3.4 mm, with a typical bump being 1.7 mm.

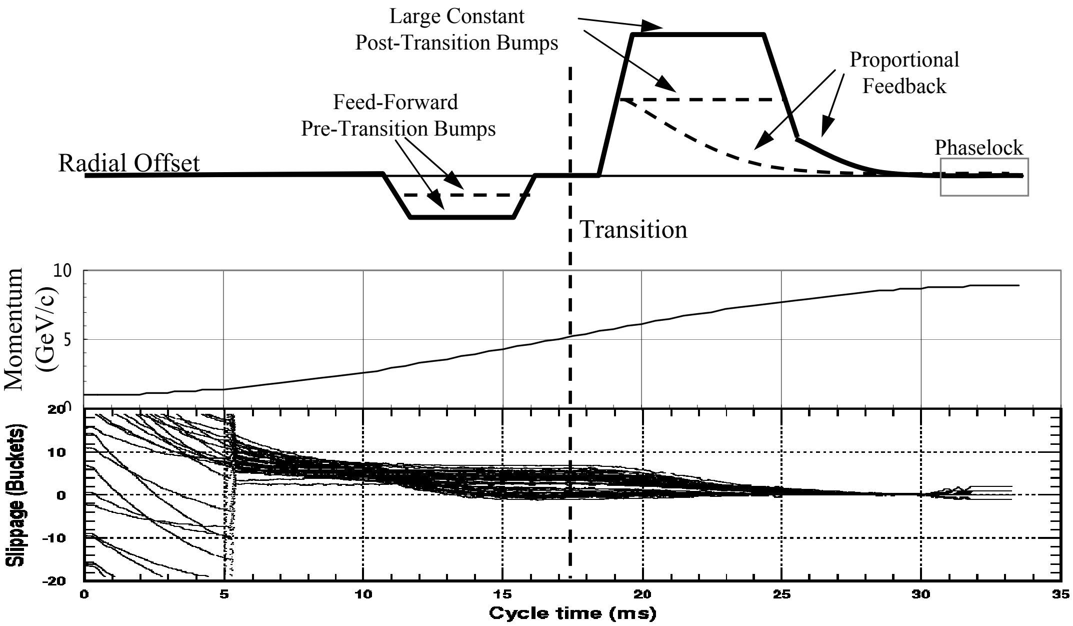

Figure 3: (above) Outline of radial manipulation throughout the Booster cycle. Pre-transition manipulations use a prediction of further slippage later in the cycle. Post-transition cogging consists of a large constant offset (when the error large) followed by proportional feedback with a large gain. (below) Measured slippage from 50 cogged cycles. They start at an arbitrary positon around the ring. The notch is created with the prediction at 5 ms, causing the discontinuity in the slippage. The slippage rapidly flattens out, but is modified by radial manipulations to reduce the error to zero at the end of cogging. Phaselock starts at 30 seconds and can cause further slippage.

The gain on the proportional feedback was increased, to allow faster cogging. Still, the offset is never greater than 1 mm. The feedback signal is also passed through a 10 kHz low-pass filter to reduce the effects of toggling.

When the bucket error is 1 the proportional feedback offset is about 0.3 mm. If the maximum magnet current is off by about 2 parts per 10,000 the slippage from the two effects will cancel out, preventing further error reduction. As such, the gain is doubled when the error is 1. Figure 3 summarizes the different feedback regimes.

Learning

Changes in the hardware handshaking procedures betweeen the Booster and Main Injector now allow every first batch of a multibatch cycle to be used as a baseline. This avoids radial manipulation on the first batch and removes all sources of error that vary over seconds or longer time periods.

PERFORMANCE

Figure 3 shows the performance of cogging over the Booster cycle. The system reliably reduces slip error to zero buckets by the end of acceleration. However, the phaselock system applies radial feedback in the last few ms and causes a final slip error of up to two buckets.

The current phaselock system cannot be retuned to reduce this distortion. We plan to implement a system that will take into account the measured variation at the end of the cycle at the cost of movemment of the beam by up to two buckets in the MI. This motion is probably acceptable. Additionally, a new phaselock system is being considered that can be retuned to take cogging needs into account.

The error from phaselock notwithstanding, extraction losses are reduced 85-90 % by cogging. Another 4-6 % reduction would be possible with the improvement of the phaselock system. The remaining losses are from large amplitude beam being collimated in the extraction septum magnet and cannot be reduced by cogging.

CONCLUSION

The synchronization system described above is operational and has now synchronized over ten million beam pulses. Improvements have allowed extraction losses to be maintained beneath predetermined limits allowing safe operation of the Booster. A few improvements can still be made, but this system is expected to meet the demands of the next several years.

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