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Development of the beam extraction synchronization system at the Fermilab Booster

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ABSTRACT

The new beam extraction synchronization control system called “Magnetic Cogging” was developed at the Fermilab Booster and it replaces a system called “RF Cogging” as part of the Proton Improvement Plan (PIP).[1] The flux throughput goal for the PIP is 2.2×10^{17} protons per hour, which is double the present flux. The flux increase will be accomplished by doubling the number of beam cycles which, in turn, will double the beam loss in the Booster accelerator if nothing else is done.

The Booster accelerates beam from 400 MeV to 8 GeV and extracts it to the Main Injector (MI) or Recycler Ring (RR). Cogging controls the beam extraction gap position which is created early in the Booster cycle and synchronizes the gap to the rising edge of the Booster extraction kicker and the MI/RR injection kicker.

The RF Cogging system controls the gap position by changing only the radial position of the beam thus limiting the beam aperture and creating beam loss due to beam scraping. The Magnetic Cogging system controls the gap position with the magnetic field of the dipole correctors while the radial position feedback keeps the beam on a central orbit. Also with Magnetic Cogging the gap creation can occur earlier in the Booster cycle when the removed particles are at a lower energy. Thus Magnetic Cogging reduces the deposited energy of the lost particles (beam energy loss) and results in less beam loss activation. Energy loss was reduced by 40% by moving the gap creation energy from 700 MeV to 400 MeV when the Booster Cogging system was switched from RF Cogging to Magnetic Cogging in March 2015.

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1. Introduction

Fermilab is going to provide 700 kW proton beam to the NOvA experiment. Prior to the 2012 shutdown, MI had been delivering 360 kW routinely and up to 400 kW of beam power to the NuMI target.[2] Booster had injected 11 batches of 4.3×10^{13} protons per pulse [ppp] to the MI. After the injection, the MI accelerated the beam from 8 GeV to 120 GeV every 2.2 s.

For NOvA operation, 12 batches are going to be injected into the Recycler Ring (RR) which is located on top of the MI in the same tunnel. The RR is an 8 GeV fixed energy synchrotron using permanent magnets. Two 53 MHz cavities were installed in the RR during 2012 shutdown for slip stacking. The harmonic number of the RR is 588 which is the same as MI. The MI power supply was upgraded and shortened the ramp from 1.6 to 1.33 s.

In the RR, 6 Booster batches are injected, and then another 6 batches are injected and are slip stacked. After the slip stacking doubles the beam density, the 6 batches are injected to the MI. This process takes 12 Booster cycles which are 0.8 s in total. In order to achieve 700 kW of beam power, the MI cycle has been shortened from 2.2 s to 1.33 s. This was accomplished by using the RR to manage the injection and stacking of beam from the Booster while the MI is ramping.

Booster is a 15 Hz resonant circuit synchrotron and accelerates proton beams from 400 MeV to 8 GeV. The required intensity in the Booster for NOvA operation is 4.3×10^{12} ppp, the same as it was for 400 kW operation. However, the cycle rate will be increased from about 7 Hz to 15 Hz to accommodate both NOvA and other users. The RF system and utilities are being upgraded to 15 Hz operations and are nearing completion. The plan is to start 15 Hz operations in 2016.

The beam loss limit has been set to 525 W to allow workers to maintain all elements in the Booster tunnel without excessive radiation exposure. Fig. 1 shows the historical beam loss in the Booster versus number of protons per hour and it shows that the total loss depends on the beam intensity. Given the required intensity of 2.3×10^{17} protons per hour, the loss rate has to be reduced to half by 2016.

The present operational beam intensities are 5×10^{12} ppp at injection and 4.5×10^{12} ppp at extraction at the Booster. The total energy loss is 0.075 kJ in one Booster cycle and hence 1150 W when the cycle rate is 15 Hz and it has to be reduced to half by 2016. Fig. 2 shows the intensity and energy loss during a normal operation cycle.

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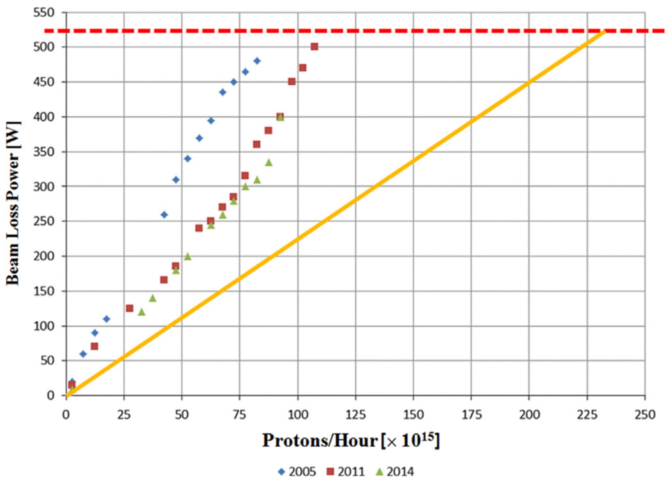

Fig. 1. The beam loss power and operational beam intensity in protons per hour for the three years, 2005, 2011 and 2014. The dash line is the beam loss limit and the solid orange line is the PIP operational goal.

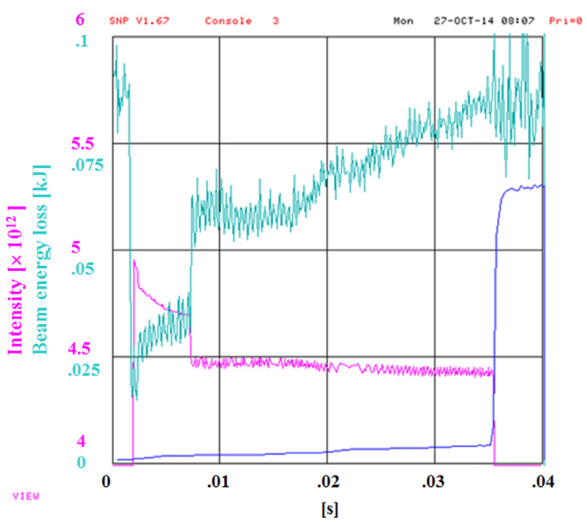

Fig. 2. The beam intensity during Booster pulse (magenta),the beam energy loss (Cyan) and the beam loss monitor signal near the extraction kicker (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The point where significant beam loss occurs is at 6 ms after the injection when the extraction kicker gap was created. The RF Cogging controls the position of the gap by changing radial position of the beam before and after transition time as shown in Fig. 3 [3,4]. The cycle-to-cycle variation of the Booster main dipole field is larger at lower energy. However, changing the radial position at low energy for RF Cogging is limited because of aperture.

The Magnetic Cogging is a beam extraction synchronization system developed at the Fermilab Booster and it can move the timing of the gap creation to 400 MeV from 700 MeV and reduce the energy loss and activation to beam line components. [5,6] It also can keep the beam orbit at the center, maximizing the beam aperture available, reducing losses due to beam scraping. We expected more than 10% energy loss reduction by employing the Magnetic Cogging.

2. Cogging in the Booster cycle

The 400 MeV beam is injected from the LINAC for 30 µs with a 200 MHz structure and it is captured within 37.7 MHz RF buckets

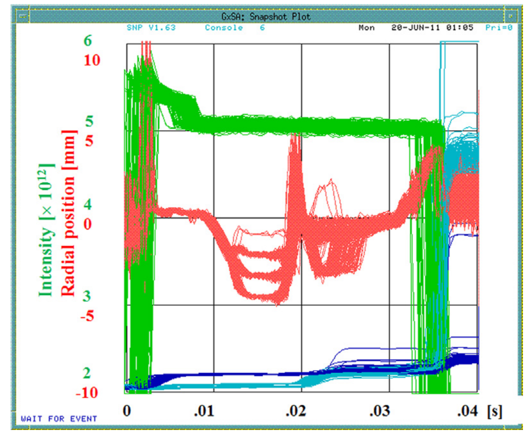

Fig. 3. The beam intensity during Booster pulse (green) and the radial position (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adiabatically over 400 µs. Since the Booster harmonic number is 84, the 84 bunches fill the Booster ring after the capture. The extraction kicker gap creation occurs at about 700 MeV, which is about 6 ms into the cycle. The Booster accelerates the proton beam from 400 MeV to 8 GeV and extracts to the MI or RR. The RF frequency at extraction is 52.8 MHz which is same as MI and RR injection frequency.

The Booster is a resonant circuit synchrotron with an operating frequency of 15 Hz, which is synchronized to the 60 Hz power line. Variations in the power line frequency and voltage result in deviation of the Booster cycle's length and the strength of the dipole field. The magnetic field error changes the revolution frequency through the cycle which results in a change in position of the extraction kicker gap. The cogging process controls the position of the extraction kicker gap through the cycle and synchronizes it to the MI or RR injection bucket.

2.1. Revolution frequency control with Cogging

The relationship between frequency, magnetic field and radial position is written as

$$\frac{\Delta f_{rev}}{f_{rev}} = \frac{1}{\gamma^2}\frac{\Delta p}{p} - \frac{\Delta L}{L} = \frac{1}{\gamma^2}\frac{\Delta B}{B} - \frac{\Delta L}{L} \tag{1}$$

where, f_{rev} is revolution frequency, p is momentum, B is dipole field and L is circumference.

The RF Cogging controls the revolution frequency by changing the radial position of the beam.

When the Booster radial position feedback is regulated to a fixed orbit the relationship in eq. (1) becomes

$$\frac{\Delta f_{rev}}{f_{rev}} = \frac{1}{\gamma^2}\frac{\Delta B}{B} \tag{2}$$

The magnetic cogging controls the revolution frequency by changing the magnetic fields of the dipole correctors while the radial RF feedback keeps the beam position at the central orbit.

2.2. Dipole corrector and Booster lattice

Booster has 24 periods. Each period consists of a 1.2 m straight section (short straight section), a focusing combined function main dipole magnet (F magnet), a defocusing main dipole magnet (D magnet), a 6 m straight section (long straight), and another D magnet and F magnet. 48 correctors were installed in the long and short straight sections in 2006.[7] Each corrector has horizontal and vertical

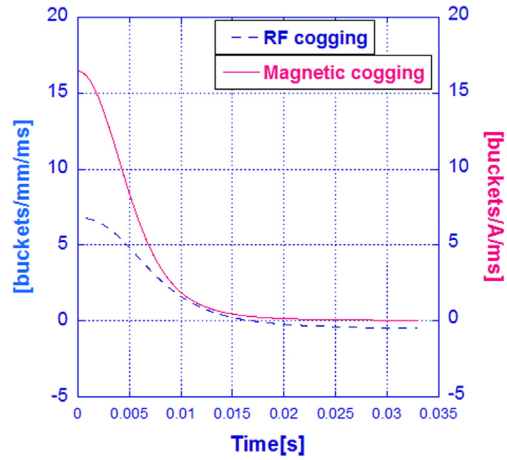

Fig. 4. The number of buckets which RF Cogging can move a notch with 1 mm radial position offset for 1 ms and that for Magnetic Cogging with 1A offset on 48 dipole correctors for 1 ms.

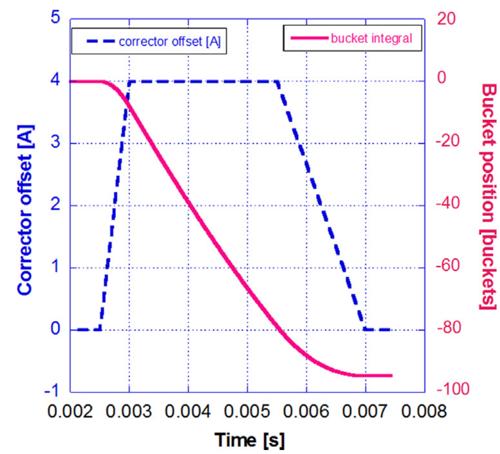

Fig. 5. The corrector current offset which was applied to 24 correctors at short locations and the estimated position change in buckets.

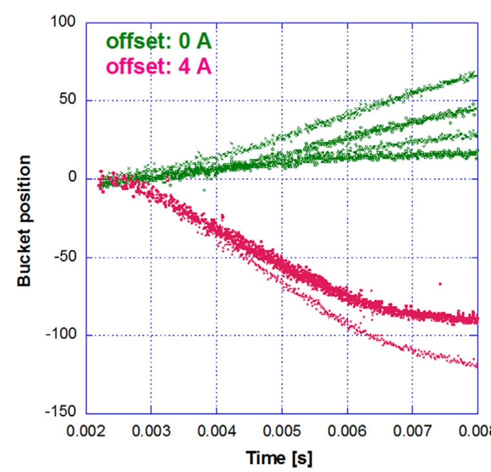

Fig. 6. The magenta points show the measured bucket positions with the 4A dipole corrector offset during the 6 ms. The green points show bucket positions without additional dipole field. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dipoles, a quadrupole, a skew quadrupole, a sextupole, a skew sextupole and horizontal and vertical beam position monitors.

A corrector has a length of 0.6 m and the dipole field strength is 0.009 T-m with 24.4 A, and the slew rate is 3.24 T-m/s. Maximum corrector current is ± 40 A. The ratio of the field from 48 dipole correctors with 10A compared to the average Booster field at injection is 0.0088, therefore the corrector should be able to compensate for 1% field error at injection.

Fig. 4 shows the bucket slippage in 1 ms, calculated for RF Cogging with 1 mm offset and Magnetic Cogging with 1A offset on each corrector.

2.3. Creation of the extraction kicker gap with the 'Notcher'

The Notcher is a horizontal kicker which creates a gap in the Booster beam and sends the beam into absorber. The kicker pulse length is 70 ns which is 2.5 buckets at the injection energy and 3.5 bucket at extraction. Three bunches are kicked out with the Notcher and the rest of the 81 bunches are sent to the MI and RR. The final gap position has to be within ± 1 target bucket before the Booster to MI phase lock process begins approximately 4 ms before beam extraction from the Booster.

2.4. Beam study of revolution frequency control with dipole corrector

Beam studies have been performed using 24 correctors at the short straight sections. A known current offset, which was expected to make a bucket position change by 95 buckets, was applied to the correctors from 2.5 ms to 7 ms (Fig. 5). A gap was created at 2.3 ms and the position was measured with a resistive wall monitor. Five sets of data were taken with and without the 4 A offset. One set of data, taken without the offset, was used as a reference. The marker position changed by 90 buckets with the 4 A offset (Fig. 6). Variations in traces with the same offset came from the cycle-to-cycle variation of the main dipole field. Beam position signals were also measured with and without an offset. Fig. 7 shows the closed-orbit error with the offset in vertical (upper) and horizontal (lower). The horizontal error was about ± 1 mm.

3. Magnetic field feedback on the Magnetic Cogging

The Magnetic Cogging controls the revolution frequency by changing the dipole corrector fields. Fig. 8 shows the block diagram of a control loop. The RF count difference (Δcount) between current cycle and the reference cycle is determined approximately every 10 µs and this difference is integrated through the entire Booster cycle. *A* gain, *G*, is applied to the integrated count difference and the resulting signal is sent to the corrector power supplies. The total dipole field in the Booster is then the sum of the fields due to the dipole correctors and the main gradient magnets.

One to twelve Booster cycles are injected to the MI/RR in one MI/RR cycle and the first Booster cycle is used as a reference cycle. RF count through the reference cycle is captured and written to a memory table every MI/RR revolution, which is approximately every 10 µs. The cogging process makes the total number of RF counts through a cycle same as the reference cycle.

3.1. Programmable VXI controller module

A Programmable VXI controller module was developed for the Magnetic Cogging operation (Fig. 9). The module has two RF inputs which convert the RF signals into logic level clocks for counting, 8 digital I/O, 4 ADC inputs and 4 DAC outputs. A digital to analog, DAC, output which has 14 bits and output voltage of ± 5 V transmit the feedback signal for the dipole correctors. Three digital

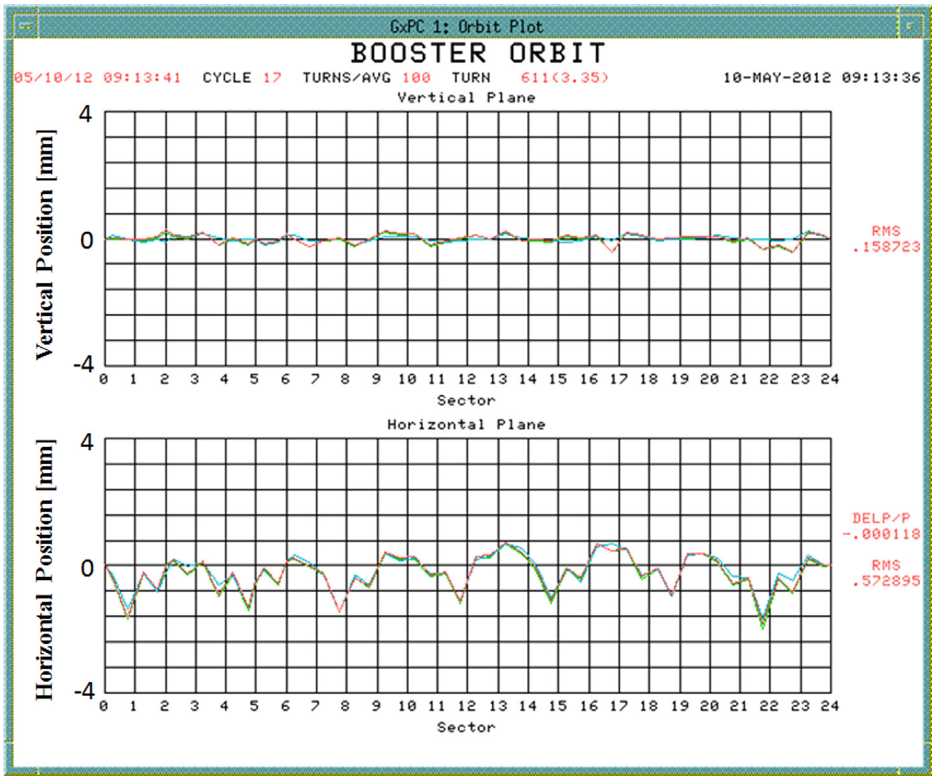

Fig. 7. The closed-orbit error with dipole offset.

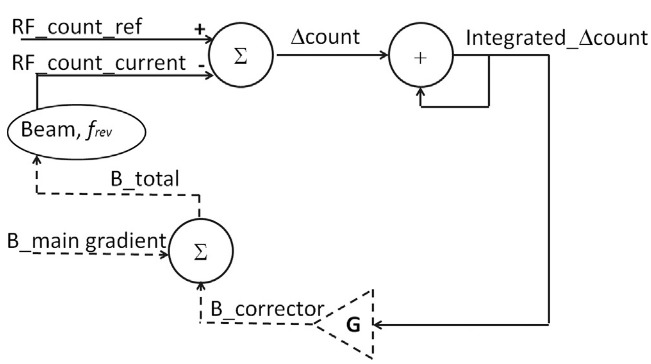

Fig. 8. Block diagram of the Magnetic Cogging feedback system with dipole corrector field.

outputs are used to trigger the notching kicker and extraction kicker, and the MI Low Level RF (LLRF) system.

3.2. Dipole corrector field feedback

The controller uses 2 RF input signals. One for the Booster RF signal (BRF) and one for the MI/RR RF signal (MIRF). It uses 4 digital inputs. These are Bdot (beginning of acceleration), OAA (MI revolution markers sent from the MI LLRF), Tclock (event that identifies the booster cycle which needs cogging) and Beam Gate (indicates beam exists on the cycle). The control process is as follows

1. Start counting BRF at Bdot.
2. Start counting MIRF and create the FOAA signal every 588 MIRF counts, starting at Bdot. The OAA signal is not synchronous to Bdot, or the Booster RF, but FOAA and OAA have the same period.
3. Count the BRF cycles that occur within every FOAA (approximately 10 μs).
4. Compare the count with the one from the reference cycle and take their difference.
5. Integrate the difference.
6. Take 32 turn average.
7. Multiply the integral by a gain from a gain table.
8. Multiply by an adjustable constant gain.
9. Send the product via the DAC output to the correctors.

The VXI controller module has 4 DAC outputs and each has 14 bit resolution. Fig. 10 shows output signals from the DAC's; integrated count difference, the gain curve, the adjustable constant gain and the product of the multiplication of the three signals. The integrated count difference multiplied by the two gains is the cogging feedback signal which is sent to the external buffer amplifiers and distributed to the dipole corrector power supply controllers around the Booster Gallery.

Bucket position delay and timing for notch creation, and a constant gain can be changed via the accelerator control system, ACNET. Four 4096 × 16 bit memory buffers are available for diagnostics. This data can be plotted and saved as files using custom programs written in JAVA, running in ACNET.

3.3. Notch creation and beam extraction synchronization

The extraction kicker gap is supposed to line up with a revolution maker (OAA) which represents the MI and RR desired injection bucket. Since the MI and RR stay at their injection energy, the period of OAA stays constant at approximately 10 μs during the Booster cogging cycle. Since the MIRF and OAA do not synchronize to the BRF and BDOT, the difference between OAA and FOAA has to be taken into account when the trigger signal is

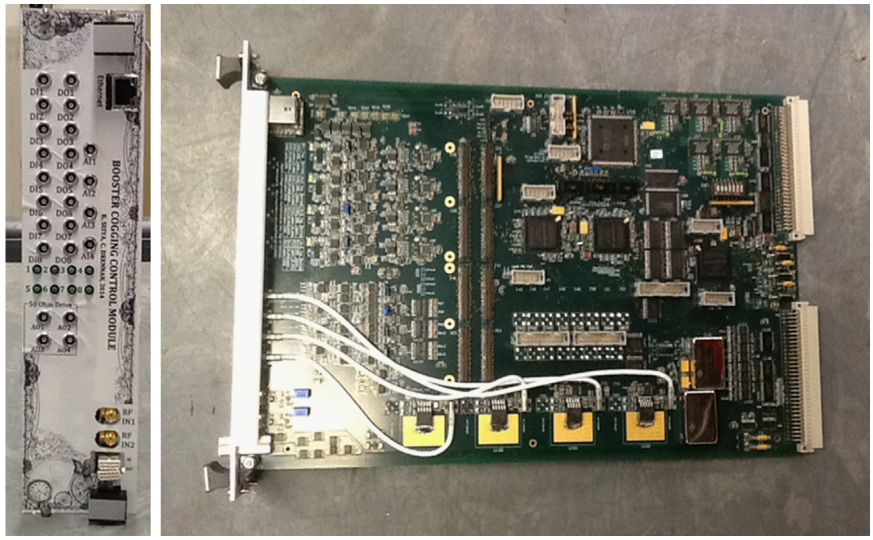

Fig. 9. The top and side view of the developed programmable VXI controller module.

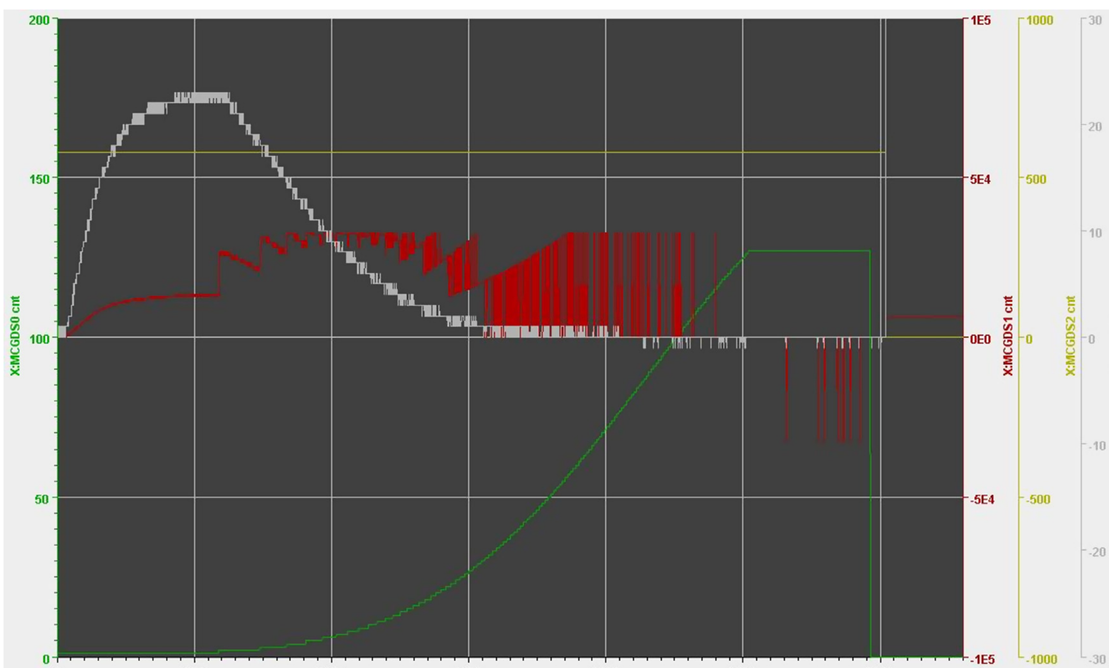

Fig. 10. The four signals on a JAVA display are integrated bucket error (white), gain curve (green), adjustable constant gain (yellow) and the product of these three signals which is sent to the dipole correctors (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

created for the Notcher. Three delays determine the trigger time for the Notcher firing system.

1. The delay between FOAA and OAA.
2. The delay between FOAA and OAA on the reference cycle.
3. The constant signal delay between the digital output of the cogging controller and the input to the Notcher firing system.

Two parameters, Notcher timing with the resolution of Booster revolution and Booster bucket delay, are adjustable from consoles.

4. From machine studies to machine operation

The main dipole field error was measured and compared with the simulation. The feedback gain was optimized based on the simulation and measurements. The Magnetic Cogging became operational in March 2015.

4.1. Field error estimation and measurements

The variations of the main dipole magnet field resulted in variations of the revolution frequencies. In order to understand the size of the variation, simulations and measurements were performed. Four sources of field error, each error respective to their ideal field, were assumed and used for simulations. RF cycles were counted every FOAA which was approximately 10 μs and compared with the one from the reference cycle as explained in Step 3 in the Section 3.2 in the simulation. The integration of the RF counts error through the Booster cycle was calculated for cases with 0.1% field error at injection, 0.1% field error at extraction, 1 μs delay on cycle and 0.001 Hz error on cycle length as shown in Fig. 11. Also, the RF count error was measured 10 times for the 6 Booster pulses and this is plotted on Fig. 12. The total bucket error was varied from 5 to 160 buckets at extraction on the 10 measurements. The measured error was expected to be created with combinations of the four sources which were mentioned above.

4.2. Optimization of the feedback gain

There are two different functions for the feedback gain, a fixed gain and a time varying gain curve. These two functions were applied to measurements and simulations. The number of RF buckets that the dipole correctors can move in 1 ms with 1 A through each corrector magnet was calculated and is shown in Fig. 4. Since more current on the dipoles is required to move the same number of buckets at a higher energy, the time varying gain curve (Fig. 13) was determined using the inverse of the results in Fig. 4. Fig. 14 shows results from 10 measurements where the final notch positions had a variation of ± 2 buckets with the fixed gain and ± 1 bucket with the time varying gain curve. Fig. 15 shows results from simulations which we assume a 0.1% field error at injection and it shows a one bucket error with the fixed gain and no error with the time varying gain curve. One RF count results in 0.2 A through the correctors with the fixed gain in both simulations and measurements. The time varying gain curve was chosen for the operation and used on Step 7 in the Section 3.2.

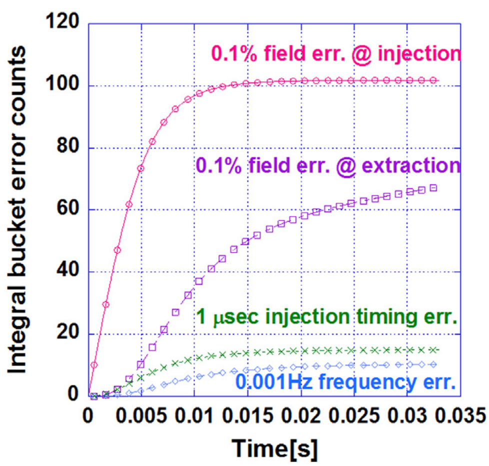

Fig. 11. Integrated bucket error from the 4 simulations.

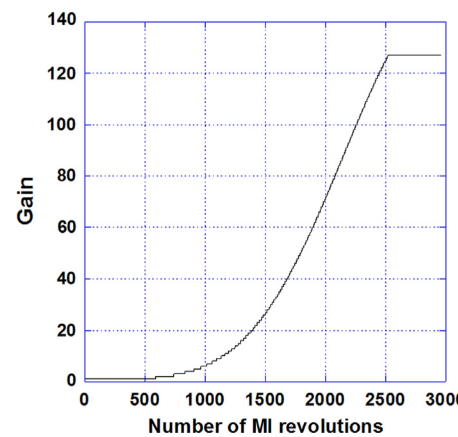

Fig. 13. The gain curve used for the measurements and simulation.

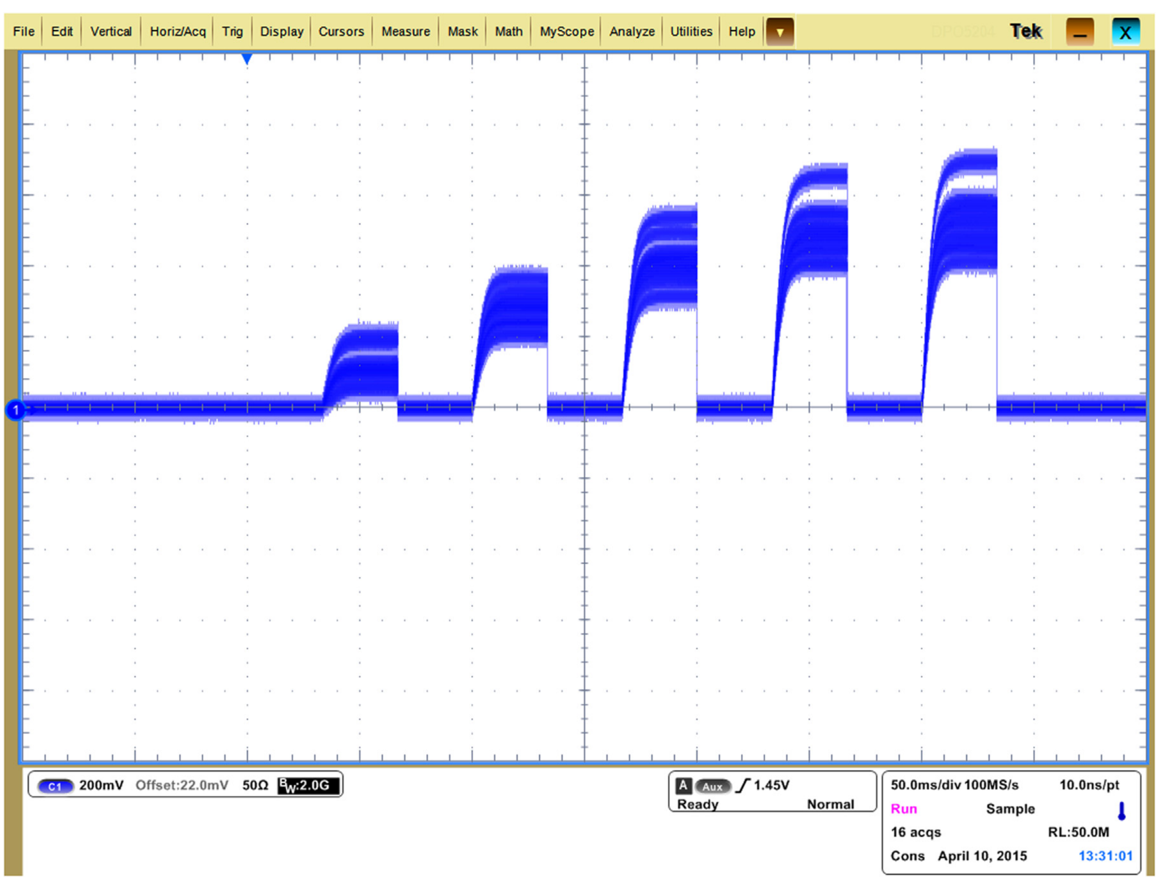

Fig. 12. Integrated bucket error from the measurements. Horizontal scale was 50 ms/div and vertical was 45 buckets/div.

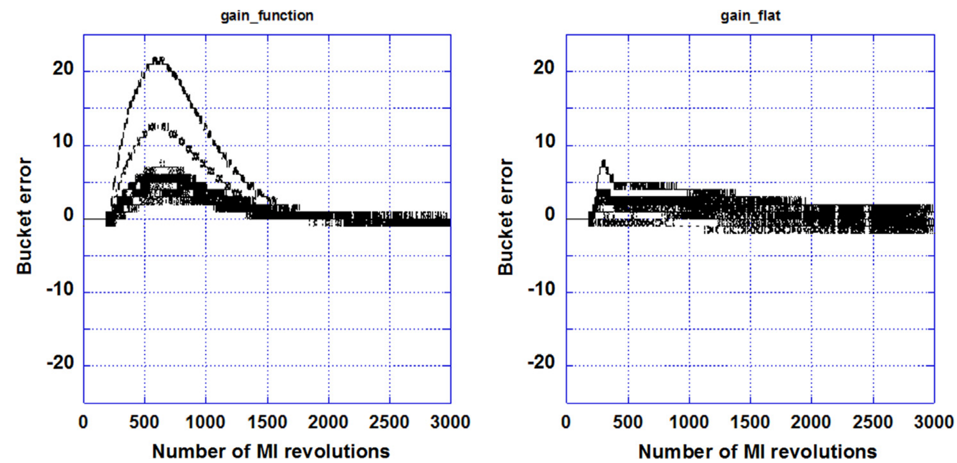

Fig. 14. Integrated bucket error with gain feedback curve (left) and constant gain feedback (right) from the measurements.

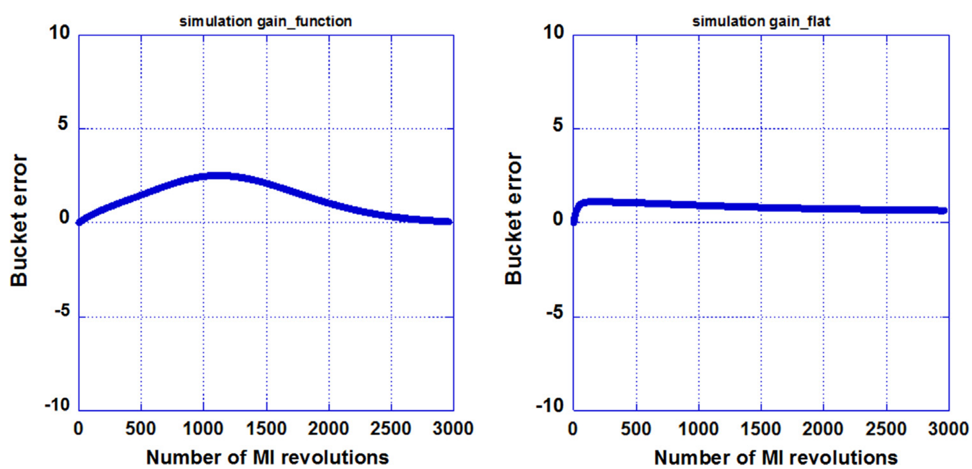

Fig. 15. Integrated bucket error with gain feedback curve (left) and constant gain feedback (right) from the simulations.

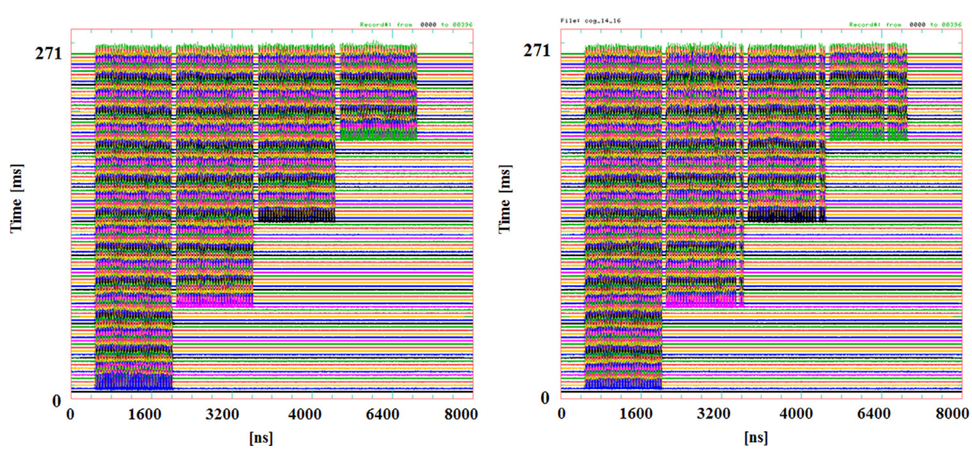

Fig. 16. Resistive wall current monitor signals every 2.7 ms at the MI injection with Magnetic Cogging (left) and without Magnetic Cogging (right).

4.3. Beam extraction with Magnetic Cogging

Four Booster batches were sent to the MI on machine study cycles using the dipole field feedback. The mountain range plot, in Fig. 16, shows that the 4 batches (each batch had 81 bunches) were injected from the Booster to the MI every 66.6 ms. The resistive wall monitor signal was recorded for 8 μs on each trace and a trace is recorded every 2.7 msec in the vertical direction. The 4 batches were supposed to be next to each other with a 3 bunches spacing in the MI. The left plot in Fig. 16 shows that the kicker gaps synchronized to an edge of the batch with cogging while the right plot shows the kicker gaps in the middle of the batch without cogging. Beam losses were created at the Booster extraction without Magnetic Cogging because the extraction kicker gap did not synchronize to the kicker rising edge and the kicker kicked an extra 3 bunches.

4.4. Notch at 400 MeV and beam energy loss

After the feedback gain was optimized, the Magnetic Cogging was applied to the Booster operation. The trigger timing for the

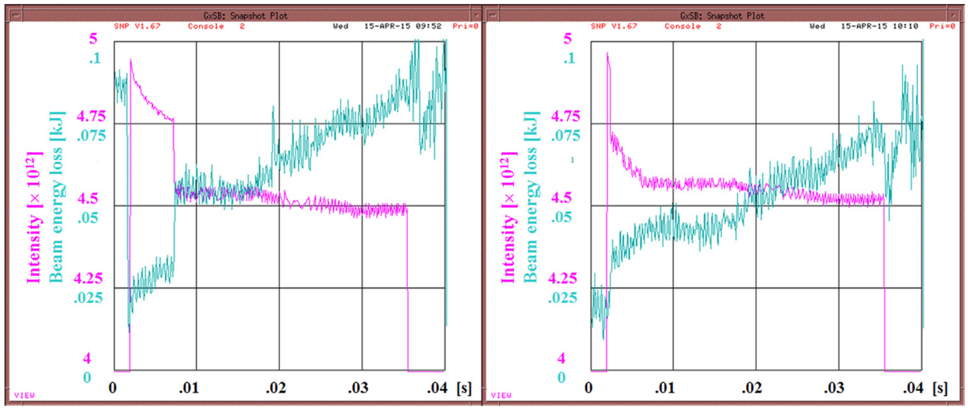

Fig. 17. Beam intensity and beam energy loss in the Booster with the 700 MeV Notch (left) and with the 400 MeV Notch (right).

Notcher with the RF cogging system was set to 700 MeV. However, the Magnetic Cogging system is able to set the timing at any time in the Booster cycle. The timing of the Notch creation was moved earlier, from 700 MeV to 400 MeV and beam intensity and beam energy loss were compared (Fig. 17). This reduced the total energy loss by 0.1 kJ which was 40% of the energy loss the 700 MeV Notch created.

5. Summary

New beam extraction synchronization system called "Magnetic Cogging" was developed at the Fermilab Booster. The main dipole field error causes variation of the revolution frequency pattern during the cycle and changes the final position of the extraction bucket from cycle to cycle. The Magnetic Cogging controls the position of the extraction kicker gap by changing the dipole corrector fields. The feedback system was built with a new programmable VXI board and the gain was optimized using the simulation results. The gap creation used to be at 700 MeV with the RF Cogging and it was moved to 400 MeV with Magnetic Cogging. The Magnetic Cogging reduced beam energy loss at the Notch creation. The system was successfully implemented to the operational in March 2015.

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