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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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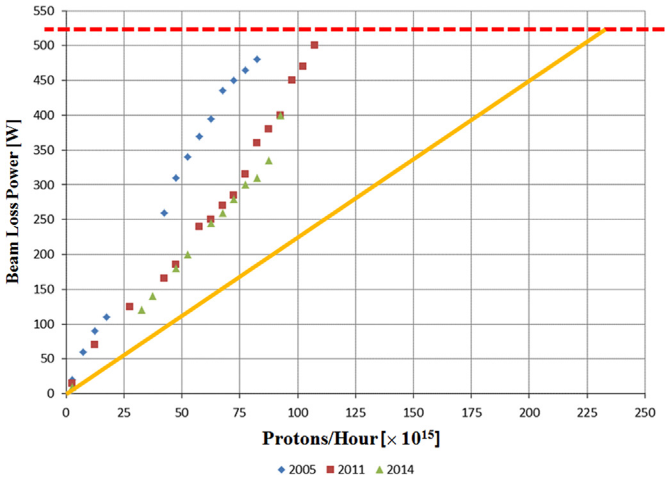

Fig. 1. The beam loss power and operational beam intensity in protons per hour for the three years, 2005, 2011 and 2014. The dash line is the beam loss limit and the solid orange line is the PIP operational goal.

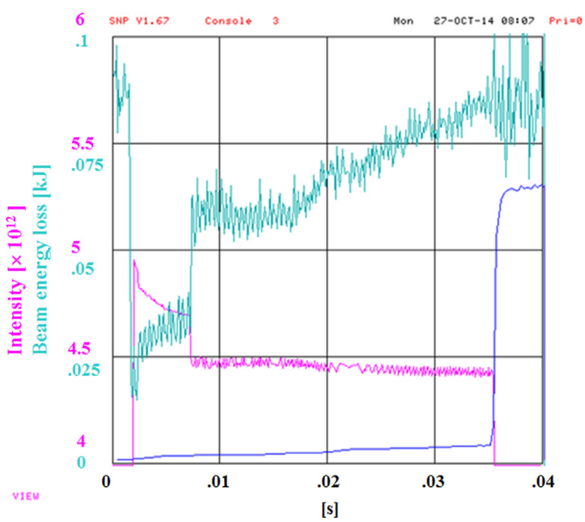

Fig. 2. The beam intensity during Booster pulse (magenta),the beam energy loss (Cyan) and the beam loss monitor signal near the extraction kicker (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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

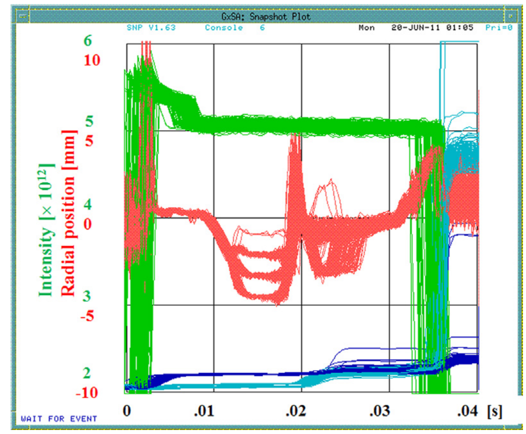

Fig. 3. The beam intensity during Booster pulse (green) and the radial position (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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