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FLATTENING THE FIELD DURING INJECTION IN THE FERMILAB BOOSTER USING DIPOLE CORRECTOR MAGNETS*

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Abstract

The FNAL Booster is a fast cycling 15 Hz resonant circuit synchrotron accelerating proton beam from 400 MeV to 8 GeV. The linac pulse injected into the Booster is 32 µs long and fills the ring by multi-turn charge-exchange injection. As part of the PIP-II project, the Booster injection energy and repetition rate will be increased to 800 MeV and 20 Hz respectively. Due to much reduced average current in the new superconducting PIP-II linac, the injection time will increase to 550 µs. A shorter machine cycle coupled to a longer injection time make flattening the injection porch B-field during injection an important requirement for successful PIP-II operation. We aim to achieve: (1) flattening of the net bending during injection using dipole correctors, and (2) using a new system based on an Altera FPGA board, reduction of the cycle-to-cycle bending field variation caused by current jitter in the Gradient Magnet Power Supply (GMPS). While the flat injection scheme is essential to future PIP-II operations, it should also noticeably improve efficiency for present HEP operations.

FERMILAB BOOSTER AND INJECTION

The Fermilab accelerator complex delivers proton beams to multiple high-energy experiments. The process begins with H- ions accelerated to 750 keV in the Radio Frequency Quadrupole, the initial stage of the accelerator chain. Subsequently, the H- beam is accelerated to 116 MeV in a Drift Tube Linac, and then to 400 MeV in a Side Coupled Linac. The output current from the linac is approximately 25 mA. At Booster injection, the H- ions are transformed into protons by stripping away electrons with a carbon foil.

The Booster operates as a resonant circuit synchrotron, where the bending field sinusoidally ramps at a frequency of 15 Hz. The Booster then accelerates the 400 MeV proton beam to 8 GeV. Following this, the beam is accelerated from 8 GeV to 120 GeV in the Main Injector before being directed to a target for neutrino production in the Nova neutrino experiment. The intensity of the beam from the Booster is 4.8×10^{12} protons per pulse (ppp), resulting in a beam power of 1 MW on the target.

Present 15 Hz Operation

The beam intensity is modulated by adjusting the pulse length according to experimental requirements, typically around 32 µs for the intensity of 5.0×10^{12} ppp. Injection occurs approximatel 200 µs prior to the bottom of the bending field, as depicted in Fig. 1. The beam is then adiabatically captured within the RF bucket for a duration of 200 µs. Throughout the capture process, the radial beam position shifts by 2 mm due to the changing bending field.

Requirement for PIP-II Injection

An 800 MeV superconducting linac is currently under construction at Fermilab, slated to replace the existing 400 MeV linac [1]. In order to boost the beam power to 1.2 MW, the beam will required to be increase to 6.5×10^{12} ppp and elevate the repetition rate to 20 Hz. Additionally, the injection energy will be raised to 800 MeV to mitigate space charge effects. The PIP-II continuous wave (CW) capable linac will provide a beam current of 2 mA, necessitating an extension of the pulse length to the Booster to 550 µs. Due to the elongated injection pulse, the bending field will undergo approximately a 0.13 % change while the beam energy remains constant from the linac. Throughout the injection process, the radial beam position shifts by 5 mm due to the evolving bending field as shown in Fig. 1.

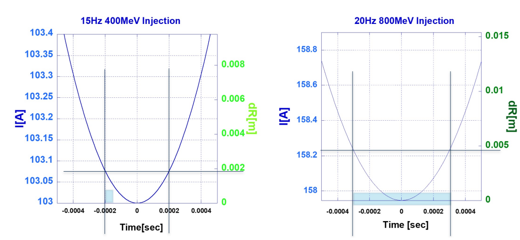

Figure 1: GMPS current and radial position shift with constant RF frequency. Left: Present 15 Hz operation, Right: PIP-II 20 Hz operation.

BEAM ORBIT CONTROL WITH CORRECTOR DIPOLES

The Booster comprises 24 periods, with each period featuring two combined-function focusing magnets, two combined-function defocusing magnets, and short and long straight sections arranged in a FODOODOF lattice configuration [2]. Each straight section includes a corrector package, total of 48. The corrector dipole field strength is 3.7×10^{-4} Tm/A. At 10 A excitation, the corrector field represents 1 % of the main bending field. The objective is to counteract the main bending field change with the corrector dipole field, aiming to flatten the net bending during injection.

Beam Orbit Response with DC Dipole Corrector at DC Main Bending Field

The equation for the beam radial position R change due to the bending field B change under the fixed RF frequency

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can be expressed as (1).

$$\triangle R/R = \frac{1}{(\gamma^2 - \gamma_t^2)} \triangle B/B \qquad (1)$$

Figure 2 shows the beam radial position when the main bending field was held constant at 400 MeV while the dipole corrector was scanned from -3.4 A to 3.4 A. The measured beam positions closely follow the estimated values.

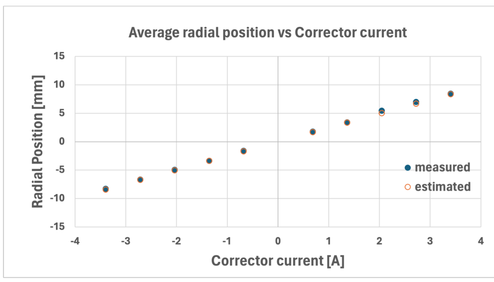

Figure 2: Radial position vs corrector dipole current at 400 MeV. Blue: measured, Orange: calculated.

Beam Orbit Response with Pulsed Dipole Corrector

To measure the response of the dipole corrector field, the field at the magnet's center was measured using a gauss probe. The power supply current was pulsed with a rise and fall time of 10 µs. The flat-top current was set to 1 A, 2 A, and 4 A. However, the load current did not precisely track the programmed current due to the output voltage being limited to 180 V and the response of the current regulation loop, thereby constraining the slew rate, as shown in Fig. 3.

The measurements are repeated with a beam pipe placed within the corrector, resulting in the lower two plots in Fig. 3. In this scenario, Eddy currents opposed and delayed the magnetic field.

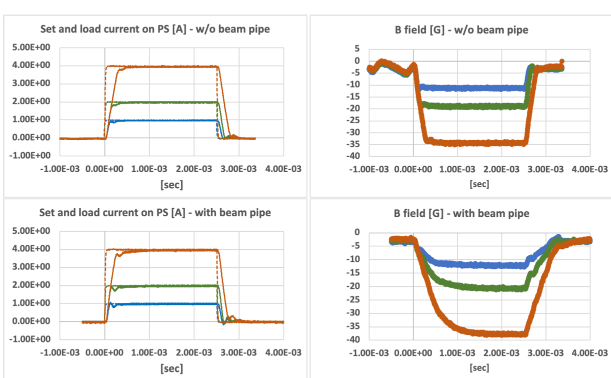

Figure 3: Set and load current on corrector power supply (left). Measured magnetic field (right). Top: without beam pipe, Bottom: with beam pipe.

Similar measurements were conducted with beam studies, focusing on measuring the beam position instead of the magnetic fields while RF frequency and main bending field were kept at constant. The beam position shifted by 8 mm when the power supplies carried 3.4 A, aligning with expectations (refer to Fig. 4). The results consistent with the position shift with DC current on corrector shown in Fig. 2.

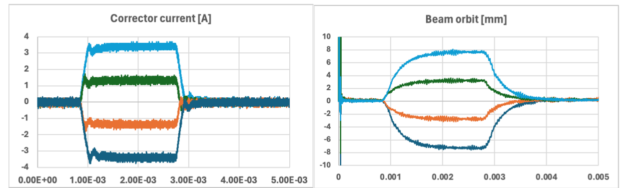

Figure 4: Measured beam position with applying +/- 3.4 A and +/- 1.63 A on the corrector.

Flattening the Net Bending Field with Shorter Pulse

A beam study was conducted with the main bending field ramping at 15 Hz. All feedback loops were deactivated, and the RF frequency remained constant. The beam orbit shifted by 2 mm, as indicated by the orange line in Fig. 5 (right). This shift corresponded with the calculated excursion shown in Fig. 1.

Given the time response of the corrector field, aligning it with the sinusoidal main bending field is not straightforward. To mitigate this, the pulse applied to the corrector power supply in Fig.4 (left) was shortened to 500 µs to approximate a sine-like field. The beam position was assessed on the DC main bending field by varying the current from 0 to 1 A, creating the dipole field configuration depicted in Fig.5 (left). Applying 0.62 A flattened the net bending field, resulting in an orbit excursion change of less than 1 mm, as shown by the blue line in Fig.5 (right).

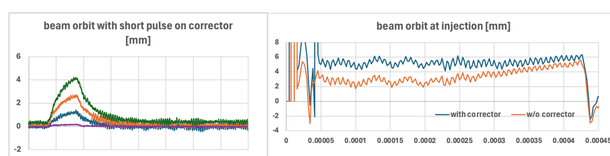

Figure 5: Left: Beam orbit with shorter pulse on corrector. Right: Effective bending field flattening with corrector. Beam position with correction (blue) without correction (orange).

ADDITIONAL ISSUES WITH THE BEAM AT INJECTION

Further beam studies revealed two additional primary issues at injection.

After the beam is adiabatically captured for 200 µs at injection, the beam orbit is expected to be constant with radial position feedback. Additionally, the frequency curve should ideally be synchronized with the bending field. However, due to extensive tuning of the Booster over decades to minimize beam loss, the orbit, RF frequency curve, and bending field may deviate from ideal conditions. As a result, the beam orbit shifts 8 mm within the first 1 ms from injection as shown in Fig. 6 (left).

Figure 6 (right) shows the fluctuation of the GMPS current at the injection, with inverted polarity, shifting from pulse to pulse and drifting by 0.2 A over several hours. Furthermore, Fig.7 (left) indicates a correlation between beam loss and GMPS amplitude error.

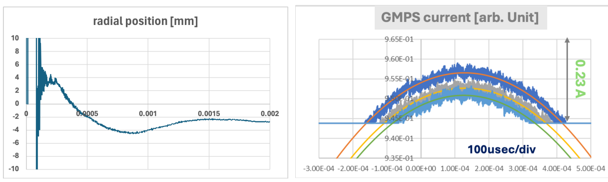

Figure 6: Left: Radial position for 2 ms after the injection. Right: GMPS current signal with inverted polarity.

GMPS Amplitude Jitter Compensation

Utilizing a system based on an Altera FPGA board, the GMPS amplitude jitter was effectively compensated. Since 2014, a programmable VXI controller module has been developed for the Magnetic Cogging system, facilitating the synchronization of beam extraction from the Booster to the Main Injector/Recycler Ring [3]. The FPGA-based module enables adjustments to the dipole corrector current and the revolution frequency of the beam.

Equipped with one of 4 available 14-bit ADC inputs, the module can accurately read the GMPS current (in Fig. 6, right) with a precision of 0.007 A. The GMPS current was measured 100 µs prior to beam injection, allowing for the calculation of the necessary offset at injection, followed by the application of additional current to the dipole corrector magnets.

In Fig. 7 (right), the GMPS amplitude error(in blue), measured GMPS current with FPGA module (in magenta), and calculated offset (in green) are illustrated. The beam orbit was measured around the Booster ring with and without compensation, with the results depicted in Fig. 8. This figure demonstrates that the beam orbit jitter was reduced from +/- 4 mm to +/- 2 mm with the compensation.

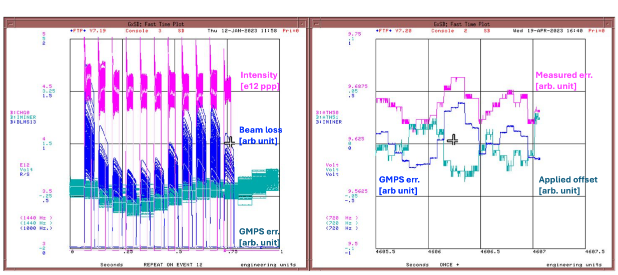

Figure 7: Left: Beam loss with GMPS amplitude error. Right: GMPS error, GMPS current measured 100 µs prior to beam injection and estimated offset in arbitrary units.

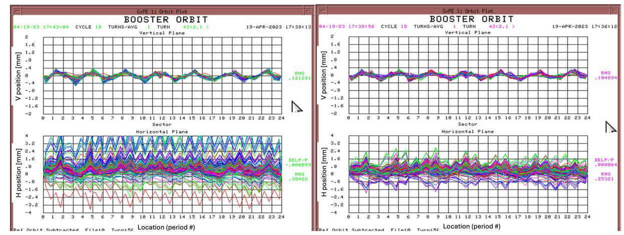

Figure 8: Beam orbit jitter without (left) and with (right) the amplitude compensation using corrector dipole.

CONCLUSION

In preparation for the upcoming PIP-II operation, efforts were made to flatten the effective bending field at injection. During beam studies, the orbit response to the dipole corrector field was measured. Due to limitations in the power supply, the output voltage was restricted, thereby reducing the slew rate. Additionally, the corrector field was observed to be affected by the Eddy current. Using the limited time response, the bending field was canceled resulting in a change in orbit execution of less than 1 mm.

Further beam studies revealed two additional primary issues. Firstly, during normal operation, the beam orbit moves more than 8 mm within the first 1 ms of injection. Secondly, the bending field exhibited jitter of more than 0.2 %, causing the beam orbit to fluctuate +/-4 mm. To address the field jitter, a feedforward approach utilizing an FPGA module was implemented to resulting in a reduction of jitter to less than half of its original magnitude.

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