# ESTIMATION OF THE REQUIRED DIPOLE CORRECTOR MAGNETIC FIELD FOR PIP-II INJECTION BASED ON BEAM STUDIES*

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## *Abstract*

The Fermilab Booster will accept a 550 µs beam pulse from the new superconducting Linac for PIP-II operations. The Booster is a rapid-cycling synchrotron that uses a resonant magnet circuit ramping at 15 Hz. For PIP-II, the cycle rate will increase to 20 Hz, and the injection pulse length will expand from 40 µs to 550 µs due to the lower output current from the new Linac. Because the Booster main bending field follows a sinusoidal waveform, the magnetic field is not constant during the extended injection window. The longer pulse length and higher repetition rate modify the beam orbit and can lead to increased beam losses.

The Booster contains 48 dipole-corrector packages distributed across its 24 periods. Each package includes horizontal and vertical dipoles, quadrupole, sextupole, skew-quadrupole, and skew-sextupole elements. By driving the dipole correctors with an appropriately shaped sinusoidal waveform during injection, we can compensate the changing average main field and create an effectively flat bending field—referred to as *flat injection*.

Over the past several years, machine studies have been performed to characterize the required correction fields and to determine the corresponding power supply specifications needed for PIP-II operation. In this presentation, we will summarize the study results and discuss the estimated magnetic field requirements and power supply parameters for achieving flat injection in the Booster.

## REQUIRED CORRECTOR FIELD BASED ON BEAM MEASUREMENTS

The goal of this work is to compensate the average bending field during injection so that it is effectively flat over an 800 $\mu$s interval along the sinusoidal ramp, using dipole corrector magnets. Before estimating the required compensation field for PIP-II operation at 20 Hz and an injection energy of 800 MeV, beam studies were performed under the current operating conditions of 400 MeV injection energy and a 15 Hz ramp [1, 2].

The bending field at injection was inferred from beam orbit measurements. The power supply currents required to generate the corresponding magnetic fields in the dipole corrector magnets were determined through offline test bench measurements. This approach established an indirect relationship between beam orbit displacement and corrector power supply current, and the observed beam response was verified to be consistent with the expected dipole corrector field behavior.

### *Main Bending Magnet Field vs Beam Orbit*

The Booster uses 96 combined function magnets to provide the main bending field [3]. Using the Booster circumference and assuming an injection energy of 400 MeV, the average bending field was calculated.

The injection magnetic field was evaluated by measuring the beam orbit at ±0.5 ms relative to the field minimum, as shown in Fig. 1 (bottom). Beam orbit measurements were performed with the RF feedback loops turned off for different power supply current. The orbit was reconstructed using the averaged signals from 48 beam position monitors (BPMs) located under the corrector packages and distributed in the short and long straight sections over 24 periods. The beam orbit shifted by approximately 2 mm when the main magnet power supply current was changed by 0.1 A.

Figure 1 (top) shows the calculated beam orbits when the bending magnet power supply current was scanned +/- 0.2 A by assuming that magnetic field is ideal sinusoidal curve. The calculation agrees with the measurements, which conclude that the main bending field follows a sinusoidal curve, as expected.

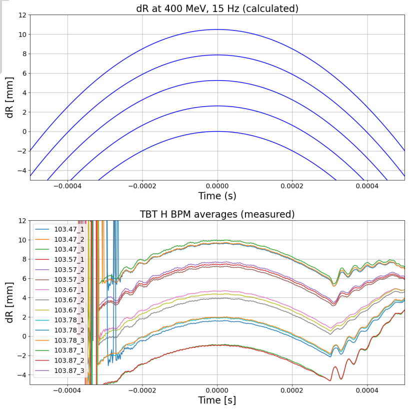

Figure 1: Calculated beam orbit for a change in magnet power-supply current from 103.47 to 103.87 A (top) and the corresponding measured beam orbit (bottom).

### *Dipole Corrector Magnet Field vs Beam Orbit*

The dipole corrector magnetic field was measured and documented in a technical note [4], which reports an integrated field of 0.009 T·m at a current of 24.4 A.

A DC current ranging from −3.4 to +3.4 A was applied to 48 horizontal dipole correction magnet, and the resulting

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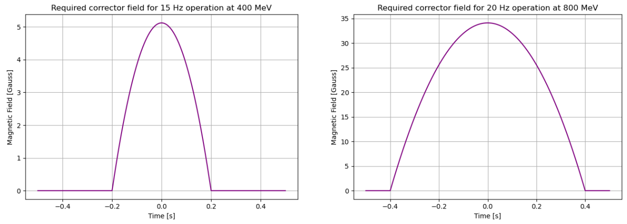

Figure 2: Estimated ideal corrector field for 15 Hz operation at 400 MeV over a ±200 $\mu$s interval (left) and for 20 Hz operation at 800 MeV over a ±400 $\mu$s interval (right).

beam orbit displacement was measured and reported in the reference [2]. The calculated scale factor between orbit displacement and corrector current was in good agreement with the measured value.

### *Required Corrector Field for Flattening the Average Dipole Field*

In the previous two subsections, the beam orbit response to variations in both the main bending field and the corrector field was verified. After confirming that the beam responds as expected, the ideal corrector field required to achieve a flat effective injection field can be calculated. The required corrector field as a function of time is given by

$$B_{\mathrm{corr}}(t) = \frac{2\pi R}{LN}\left(B(t) - B_{\mathrm{target}}\right), \tag{1}$$

where $L$ is the corrector length, $N$ is the number of correctors, and $B(t)$ is the time-dependent Booster average field. Here, $B_{\mathrm{target}}$ denotes the Booster field at the start of the flat region.

The estimated corrector fields for 15 Hz operation at 400 MeV over a ±200 $\mu$s interval and for 20 Hz operation at 800 MeV over a ±400 $\mu$s interval are shown in Fig. 2. The required peak corrector field for PIP-II injection is approximately 33 G.

## CALCULATION OF THE DIPOLE CORRECTOR FIELD AND POWER SUPPLY VOLTAGE WITH EDDY CURRENT EFFECTS

The magnetic field response of the corrector magnet was measured on a test bench with a 360 V supply. A 2.5 ms current pulse with varying amplitudes was applied to a corrector dipole magnet, while the load current, load voltage, and magnetic field were recorded. The dipole magnetic field was measured with a hall probe positioned at the center of the magnet. Figure 3 shows measured magnetic field step responses. Due to the presence of the beam pipe inside the magnet, eddy current effects were observed, resulting in a delayed magnetic field response.

The measured magnetic field data were fitted using the step-response model

$$B(t) = B_0\left(1 - e^{-t/\tau}\right), \tag{2}$$

where $B_0$ is the steady-state magnetic field and $\tau$ is the time constant. The fit yields a time constant of $\tau = 0.38$ ms.

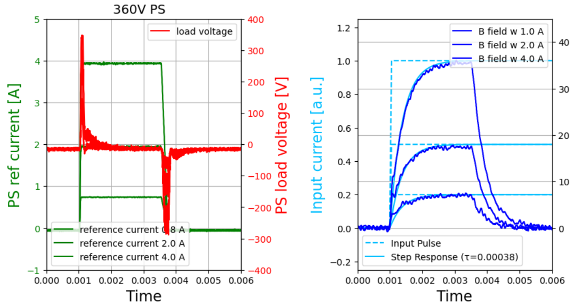

Figure 3: Measured and fitted magnetic field step responses using a 360 V power supply.

### *Discrete-Time Convolution Model*

In practice, the input current and magnetic field were sampled at a fixed sampling interval $\Delta t$. The discrete-time impulse response is therefore given by

$$h_B[n] = \frac{k}{\tau} e^{-n\Delta t/\tau}, \tag{3}$$

where $n$ is the discrete time index.

The output magnetic field was estimated using discrete-time convolution,

$$B_{\mathrm{out}}[n] = \sum_{m=0}^{n} I_{\mathrm{in}}[m]\, h_B[n-m]\, \Delta t, \tag{4}$$

where $I_{\mathrm{in}}[m]$ is the measured input current waveform.

The magnetic field estimated using the convolution model was compared with the magnetic field measured by the hall probe at the magnet center, as shown in Fig. 4 (left). The measured field follows the estimated value, indicating that the model provides a reasonably good representation of the system response.

### *Load Voltage of the Power Supply*

The load voltage of the power supply was measured while varying the rise time of the reference current from 4 A in 10 $\mu$s to 4 A in 1000 $\mu$s. Using the known inductance and resistance of the magnet, the load voltage was estimated using

$$V(t) = L\frac{dI(t)}{dt} + RI(t), \tag{5}$$

where $L$ is the magnet inductance and $R$ is the magnet resistance. The values used were $L = 0.014$ H and $R = 0.272\ \Omega$, as reported in the reference [4].

The same 2.5 ms pulsed current was applied to the power supply. The load voltage estimated using Eq. (5) was then compared with the measured load voltage, as shown in Fig. 4 (right), demonstrating reasonable agreement.

## POWER SUPPLY LOAD VOLTAGE REQUIREMENTS FOR PIP-II INJECTION

Based on beam studies and analytical calculations, the required corrector magnetic field profile to achieve an 800 $\mu$s flat field was determined. This target profile is referred to as

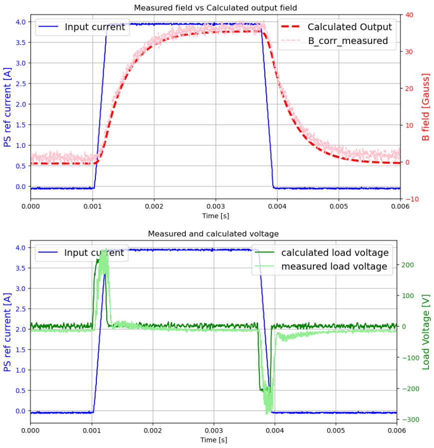

Figure 4: Comparison between the magnetic field estimated using the convolution model and the magnetic field measured by the hall probe.

the *ideal magnetic field*. Using deconvolution of the measured magnet impulse response, the input current waveform required to produce this ideal field was estimated.

### Estimation of the Input Current

The output magnetic field of the dipole corrector magnets can be expressed as the convolution of the input current and the system impulse response, as given in Eq. (4).

The required input current can therefore be obtained by deconvolution:

$$I_{\text{in}}[n] = \text{deconv}(B_{\text{out}}[n], h_B[n]). \tag{6}$$

Assuming $h_B[0] \neq 0$, the input current can be computed recursively as

$$I_{\text{in}}[n] = \frac{1}{h_B[0]} \left( \frac{B_{\text{out}}[n]}{\Delta t} - \sum_{m=0}^{n-1} I_{\text{in}}[m]\, h_B[n-m] \right). \tag{7}$$

The estimated input current required to generate the ideal field is shown in Fig. 5 (top). The deconvolved waveform exhibits a step-like increase of approximately 7 A at the beginning of the pulse. Such an abrupt change would require an infinite load voltage and is therefore not physically realizable. To obtain a realizable solution, the rise time of the input current was decreased, limiting the rate of change $dI/dt$ as shown in Fig. 5 (bottom). With this modified waveform, the required power supply load voltage is reduced to below 320 V.

### Measurements with Adjusted Input Current

The adjusted input current waveform was implemented experimentally, and the resulting magnetic field and load voltage were recorded.

Figure 6 compares the measured and calculated results, showing that the adjusted waveform achieves the desired field. The power supply load voltage remained below 320 V, within the supply limits.

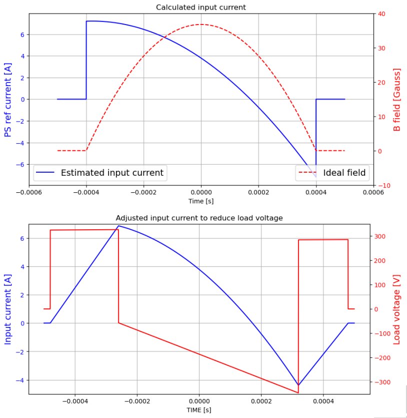

Figure 5: (top) Estimated input current waveform obtained from deconvolution to achieve the ideal magnetic field. (bottom) Adjusted input current waveform with finite rise time to ensure feasible power supply operation.

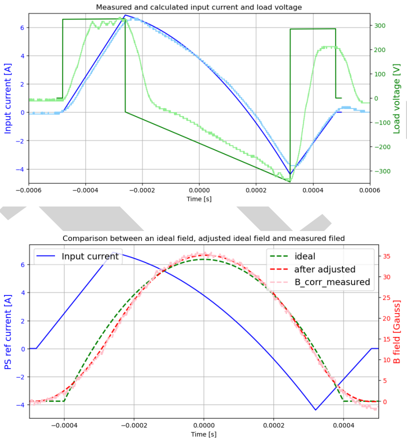

Figure 6: Validation of the adjusted input current: Top, measured and calculated load voltage; Bottom, measured and calculated magnetic field compared with the ideal field.

## SUMMARY

Based on beam studies, analytical calculations, and measurements of the corrector and main bending fields, the required magnetic field profile to achieve an 800 $\mu$s flattop has been determined. The corresponding power supply requirements were derived from this target profile.

It is concluded that a power supply capable of delivering approximately ±320 V, with currents in the range of −5 A to +7 A over a time window of ±500 $\mu$s, is sufficient to produce the 800 $\mu$s flat region for PIP-II injection.

These estimates do not include additional effects such as the injection bump or cogging [5], which may impose further demands and should be considered in future studies.

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