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Focusing Properties of The Booster Extraction Septa

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Abstract

The MP02 septum which was installed into the Booster L3 extraction area in Jan 2003 has been measured. The focusing properties of the Booster Extraction septum field non-uniformities are expressed in terms of the $k1$ parameter for use in lattice calculations. Measurements in the fringe field region and comparisons with the measurements reported for the earlier design are included.

1 Introduction

To extract the 8 GeV protons from the Booster, they are kicked above the copper septum of a pulsed dipole. This dipole bends them up through an angle of 50 mRad in order that they can enter the transport line. At Booster L3 they enter the MI8 transport to the Main Injector tunnel whereas at L13 they are extracted to the Radiation Damage Facility or to the Booster dump.

The field near the septum is sufficiently non-uniform as to encourage one to consider the focusing effects. The MP01 septum which is installed at L13 and the MP02 which was installed since the beginning of Main Injector operations at L3, are of the design described by Cosgrove *et al.*[1]. A modified design was employed for magnets built in 2002. Measurements of the magnet installed in Jan 2003 are used to examine the magnitude of the effect.

2 Mathematical Description

One can find the focusing properties of the septum in terms of the field shape, expressed as normalized harmonics and the bend angle. We begin by noting that the bend angle θ provided by the septum is given by

$$\theta = \frac{BL}{B\rho} \tag{1}$$

where BL specifies the integral bend field of the septum magnet and $B\rho$ is an expression for the momentum of the beam which is 29.65 T-m for the Booster beam which is extracted at 8 GeV or 8.88889 GeV/c. We express the magnetic field as

$$B_x(x) = B + B_2 y = B(1 + b_2 \frac{y}{a}) \tag{2}$$

where B_2 is the harmonic quadrupole field, b_2 is the normalized quadrupole harmonic and a is the Harmonic reference radius. From measurements of the field one obtains the normalized quadrupole term from

$$b_2 = \frac{\Delta B}{B} / \frac{\Delta y}{a} \tag{3}$$

The (geometric) quadrupole focusing parameter k_1 for a magnet of effective length L_{eff} as defined for MAD (for example) is

$$k_1 L_{eff} = \frac{\int B_2\, ds}{(B\rho)} = \frac{B_2 L}{(B\rho)}. \tag{4}$$

Using the definition for b_2 we have

$$k_1 L_{eff} = \frac{b_2}{a} \frac{BL}{(B\rho)} = \frac{b_2}{a}\theta. \tag{5}$$

The expression which includes the next term in a fit of B_x vs. y is a skew term.

$$B_x(x) = B + B_2 y + A_3 y^2 = B(1 + b_2 \frac{y}{a} + a_3 (\frac{y}{a})^2) \tag{6}$$

When viewed from above, the Booster circulates protons in the counterclockwise direction. the coordinate system for MAD (or TRANSPORT) defines s or z in the beam direction and y up. Since it is a right-handed coordinate system, x is radially inward. The MP02 septum bends the beam up. This requires B_x to be positive[1].

3 Data

3.1 MP02 Bend Field

The magnet is constructed using "C" laminations with a 1.1″ gap. The length of the steel of the magnet is 65.25 inches (1.65735 m). A septum is attached at the mouth of the "C" with a return coil at the opposite end of the gap. The magnet is curved with a radius corresponding to a 43 milliradian bend angle. The beam transport line is constructed to utilize a 50 milliradian bend angle so that the beam is deflected away from the septum such that is it nearly 0.25″ away at the end of the magnet.

[1]MAD describes all dipoles as bending in the horizontal plane and then rotated by some angle. In this note we describe all fields in terms of a standard reference frame so the dipole field of the septum is described by B_x.

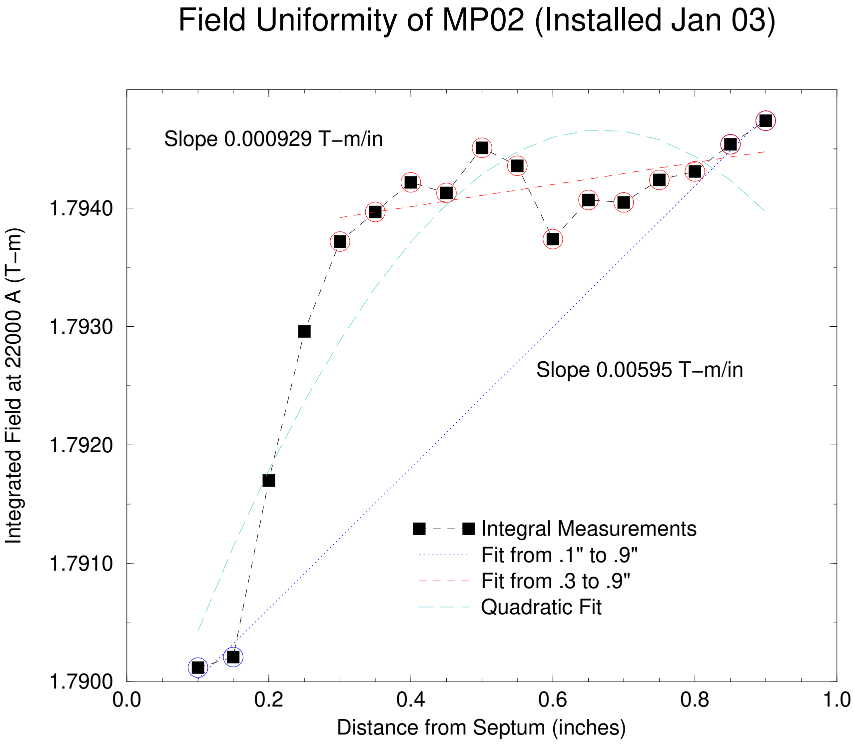

Figure 1: Measurements of the field shape of MP02 in the bend field region (inside the magnet) as described in the text. A quadratic fit and linear fits to selected subsets of the data are identified by the lines.

Using a curved coil which was longer than the magnet length, the field integral was measured using the flux induced by the standard 1/2 sine wave excitation. The coil was positioned parallel to the septum and moved perpendicular to the septum to the positions indicated in the graph in Figure 1.

Figure 1 shows the resulting field integrals for a peak current of 22000 A. Using a gap of 1.1″ one calculates a body field (assuming infinite mu iron) of 0.989 T. The measured field integral of 1.79 T-m implies an effective length of 1.809 m (71.22″) which is substantially longer than the iron length. The typical rule of thumb for a magnet with square ends (this one should be less) is $L_{eff} = L_{iron} + g$. $L_{iron} + g = 66.35''$ so the results shown are more

Fit region	d(BL)/dx	b_2	$k_1 L_{eff}$	a_3
	T-m/in		1/m	
Fit 0.1″ to 0.9″	0.00595	0.00332	0.00654	
Fit 0.3″ to 0.9″	0.00093	0.00052	0.00102	
Fit all (Quadratic)		.00975		-.00728

Table 1: Analysis results for MP02 (installed Jan 2003 at L3) measurements in the Bend Field at 22000 A. Data is shown in the figure. Note that the excitation for measurement is sufficient for a 60 mRad bend whereas the $k_1 L_{eff}$ is based on the excitation required for the 50 mRad bend required to put the beam onto the design transport line.

than 7% above expectations.

The field varies by about 0.22% from the point adjacent to the septum to the point 0.5″ from the septum. The beam width is reported to be about $\sigma = 2.2$ mm so 6σ is 13 mm or 0.52″. Since the beam is in this region where the field varies substantially, we would like to express the non-uniformity in terms of integrated normalized harmonics which can be used in beam optics programs to understand their significance.

Using the xmgr program, fits to some of the data in Figure 1 were performed. Using the formulas shown above, these results were converted to normalized harmonics and geometric (k_1) focusing properties. Table 1 shows the fit results and converted values. If we assume that the beam is placed about 3σ from the septum on the upstream end, the difference in curvature of the beam and the septum will place the orbit in a more uniform field over much of the length of the septum. These are integral measurements. we would need separate body and end contributions for a more quantitative evaluation.

3.2 MP01 Bend Field

The fields measurements of MP01[1] employed a short coil and end fields as well as integrated fields are shown in the published paper. In Figure 2 we have re-plotted the integral data and fit it with a quadratic and the region from 0.3″ to 1.1″ with a linear function. Fit results are shown in Table 2.

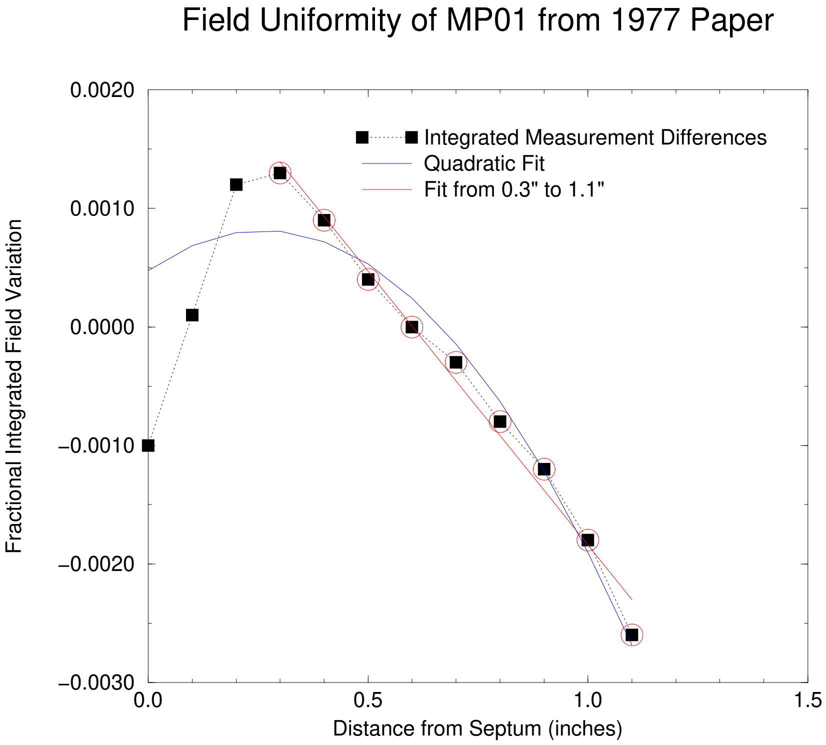

Figure 2: Measurements of the field shape of MP01 as described in Reference 1. A quadratic fit and linear fits to selected subsets of the data are identified by the lines. Results are shown in Table 1.

Fit region	d(BL)/dx	b_2	$k_1 L_{eff}$	a_3
	T-m/in		1/m	
Fit 0.3″ to 1.1″		-0.004617	-0.00909	
Fit all (Quadratic)		0.002599		-0.00497

Table 2: Analysis results for MP01 (as reported in 1977 Paper).

3.3 MP02 Circulating Beam Field

Using a straight probe, the field in the circulating beam region below the septum was measured for the MP02 which was installed in January 2003. Position was measured with respect to the bottom of the septum with y

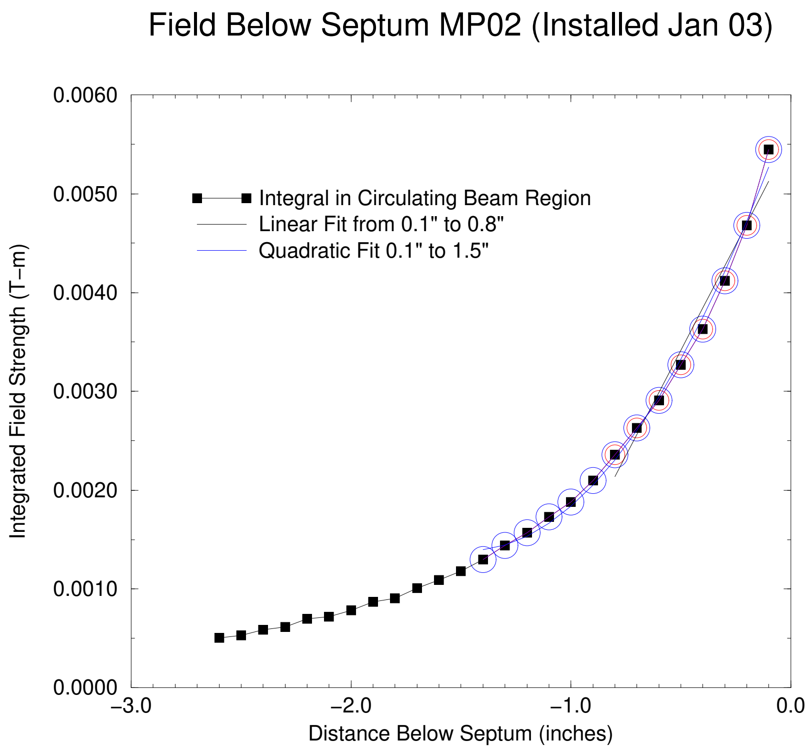

Figure 3: Measurements of the field shape of MP02 below the septum. A quadratic and a linear fit to selected subsets of the data are identified by the lines.

Fit region	d(BL)/dx	B_2L	k_1L_{eff}	A_3L
	T-m/in	T-m/m	1/m	T-m/m^2
Fit 0.1″ to 0.8″	0.00427	0.1681	0.00567	
Fit 0.1″ to 1.5″ (Quadratic)	0.00612	0.2409	0.008126	3.2478

Table 3: Analysis results for MP02 External Field

pointing up. Figure 3 shows these data. Again, the data was fit using xmgr and the results are shown in Table 3. We express the harmonic fields in unnormalized form and convert to geometric fields (k_1) using $B\rho = 29.65$ T-m suitable for 8 GeV beam.

Orbit effects from the pulsing of MP02 have been observed. Let us see what these measurements imply for the distortion at MP02 due to the angle it introduces into the circulating beam. The usual expression for this distortion is

$$d(s) = \frac{\sqrt{\beta_i \beta(s)}\theta_i}{2\sin(\pi\nu)} \cos(|\Psi_i - \Psi(s)| - \pi\nu) \tag{7}$$

where ν, β and Ψ are the usual tune, amplitude function and phase function for a strong focusing lattice, and θ_i is the bend angle error at location i. We simplify for the case where we examine the displacement at the location of the error field to

$$d_i = \frac{\beta_i \theta_i}{2\sin(\pi\nu)} \cos(-\pi\nu) \tag{8}$$

Taking the beam center to be about $0.3''$ below the septum we observe that the resulting integrated field is 0.004 T-m. At 8 GeV ($B\rho = 29.65$ T-m), this will produce a bend angle of 135 μRad. Assuming β_v of 20 m and a fractional tune near 0.75 we find $d_i = -1.3$ mm which is comparable with the observed deviation.

4 Conclusions

The field shape of the new MP02 septum has been measured. We report those measurements and express the non-uniformity of the field in terms of the usual harmonic components. For the field below the septum (which affect the circulating beam), the measurements are carried out with a straight probe and provide a reasonable measure of the fields seen by the beam. Measurements in the bend field region of MP02 were carried out using a curved probe positioned parallel to the septum. Since the septum is curved with a larger radius than that experienced by the beam, the beam moves away from the septum and into a more uniform field region as it passes through the magnet and out of the downstream end. Consideration of these components will permit examination of the effects they may have on the Booster and the MI8 transfer line beam optics. If they are found to be significant, the available information on body-end separation will be used to provide a more careful determination of the focusing fields seen by the extracted beam.

5 Acknowledgments

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References

[1] D. F. Cosgrove, R. P. Johnson, and S. C. Snowdon. A Pulsed Septum Magnet for Extraction From the Fermilab Booster. *IEEE Trans. on Nuc. Sci*, NS-24:1263, 1977.