# Design and Measurements of Prototype Fermilab Main Injector Dipole Endpacks

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## Abstract

The end field regions of the dipole for the Fermilab Main Injector contribute significantly to the overall field quality and magnet performance. The end effects which we must control are the variation in effective length as a function of current and the variation in field shape across the magnet aperture. We employed an iterative process of numerical calculations and prototype testing to refine the design of the endpack steel configuration.

The final design is an approximation to a Rogowski profile, which limits effective length variation to 1.8 mm per end between 0.1 T and 1.7 T, and includes small shims to compensate for the intrinsic negative sextupole of the ends. We discuss details of the design process and present the effective length, field shape, and harmonics measurements for various endpack designs.

## I. Introduction

The Fermilab Main Injector[1] (FMI) will use dipoles of a new design[2]. There will be 216 6-meter dipoles and 128 4-meter dipoles in the ring. All of the dipoles will be wired in series. In normal operation, beam will be injected at 8.9 GeV/c, accelerated to 120 GeV/c or 150 GeV/c, and extracted. The dipoles must provide a uniform or easily correctable magnetic field over the range of 0.1 T ($\sim$ 500 A) to 1.7 T ($\sim$ 9400 A).

We have built two prototype dipoles. After testing the bodies, we have built and tested a series of end packs, attempting to optimize the performance. The measurement and analysis techniques are described in Reference [3]. The results are presented in more detail in References [4] and [5].

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## II. Effective length of the ends

### A. Requirements

The parameter of prime interest is the integral through the magnet of the main component of the magnetic field, $\mathcal{I}(x, y, I)$. The bend angle of a particle traversing a magnet is proportional to this quantity and inversely proportional to the momentum. The FMI geometry assumes that the 6-m and 4-m dipoles have integrated strengths in the ratio of 3 to 2. To keep the beam on the same path throughout the acceleration cycle, the bend angle must remain the same in each of the magnets. Some variation can be accomodated by the 104 horizontal dipole correctors in the ring. However, it is not prudent to dedicate a large fraction of their range to adjusting for effects that could be avoided with a good magnet design.

Since the momentum of a particle does not vary as it traverses the ring, the relative values of $\mathcal{I}(I)$ need to remain constant as a function of current. Calling the field at the center of the magnet $B_0$, we can characterize the field integral as the product of the central field and an effective length, $L_{eff}$. Thus $\mathcal{I}(I) = L_{eff}(I) B_0(I)$.

We define the effective length of the ends as the difference between the measured effective length and $L_0$, a somewhat arbitrary constant length. For practical purposes we set $L_0$ to the maximum extent of the magnet steel in the axial direction.

$$L_{end} = (L_{eff} - L_0)/2$$

$$\mathcal{I}(I) = B_0(I)(L_{end}(I) + L_0 + L_{end}(I))$$

$B_0(I)$ and $L_{end}(I)$ should behave the same way for the 6-m and 4-m dipoles. The steel lengths do not change during the acceleration cycle. Therefore, to maintain the ratio of I(I) between the two lengths, we need to keep the effective lengths of the ends constant.

### B. Achievements

If the pole face of a dipole ends (as a function of $z$) with a hard corner, the steel there will saturate at a lower current than will the body. The effective length of the end will fall as the current increases. To combat this effect, the ends of magnet pole faces are often tapered. The initial design of the FMI dipoles had a single straight cut in the central 50 mm of the pole. The cut angle matched the angle of the sides of the pole. This produced an acceptable variation in the effective length of the end of 2.7 mm per end between 0.1 T and 1.7 T. This variation, along with some other representative endpacks, is shown in Figure 1.

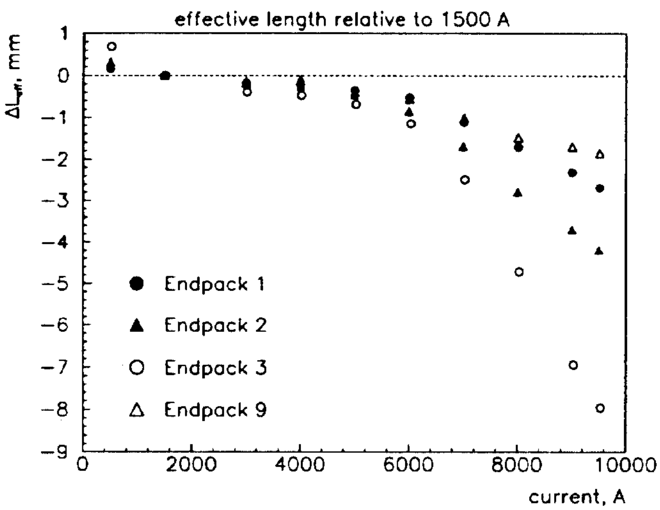


Figure 1: Effective length (relative to 1500 A) vs current for endpacks #1, original straight cut; #2, stepped approximation to straight cut; #3, Borda profile; and #9, Rogowski profile.

The rest of the end pack had a more complicated shape, making machining somewhat expensive. We therefore decided to fabricate the production end packs by building them from laminations trimmed in advance to produce the desired contours. Fermilab has successfully used this technique in the past. We built a set of endpacks that approximated the straight cuts of the initial design with steps three laminations (4.5 mm) deep. This stepped approximation to the straight line produced an unacceptable variation of 4.5 mm per end, as shown in Figure 1.

We then tried an end pack following the Borda profile[6], which we hoped would reduce effective length variations by making the saturation uniform along the pole profile. The stepped approximation to the Borda profile produced an even larger variation of 8.6 mm over the range of interest, as shown in Figure 1. A retrospective analysis showed that we had failed to recognize problems with nonuniform saturation in the bulk of the end pack.

Finally we tried the Rogowski profile[6] and made an end pack which approximated the Rogowski profile (with steps) in the central region. To reduce the iteration time we machined an existing set of end packs, carefully cutting just to lamination boundaries. This shape produces an acceptable variation. After the adjustments described below to the sides of the end pack, the effective length variation is only 2.0 mm, as shown in Figure 1.

Our computer 3-D models have not been able to accurately predict the changes in effective length. We attribute this to difficulty in modeling the anisotropy of the laminations and insufficient computing resources to model a large enough volume with fine resolution.

# III. End Field Shape

## A. *Requirements*

The body field of the FMI dipoles is quite uniform as a function of x, especially at low current. The goal of the end pack design was to not degrade that uniformity in the total field integral. We expect and ignore a quadrupole component of the end field due to the magnet being constructed with parallel ends rather than as a sector. Any sextupole or higher component is of concern. The end field shape must be studied in concert with the shape of the body field and the shape of the field generated by eddy currents in the beam pipe. We wanted to get the sextupole component of the end field low enough so that the chromaticity correction sextupoles could adjust the chromaticy over the desired range without changing polarity[7].

## B. *Achievements*

When it is normalized with respect to its value at $x = 0$, the field of a magnet naturally falls off on the sides of the end region. To first order, this effect is purely geometric and introduces an excitation-independent negative sextupole contribution in the integrated field expansion. Since the rate of fall off of the field is larger when the gap to width ratio increases, profiled ends tend to have an even larger sextupole than a plain rectangual end. To compensate for that effect, the original design provided large bumps on each side of the end pack protruding from the flat tapered surface. These provided additional effective length to the sides by keeping the field stronger.

Measurements of the end field shape on the original end pack and the stepped approximation to it agreed quite well with each other[5]. However, the variation with position was unacceptably large, comprising about half of variation in total field integral at the critical injection field (I=500 A). As expected, the shape was not a strong function of current.

The 3-D computer model of the field was able to reproduce the measured field shape qualitatively fairly well. However, the same considerations that limited the effective length calculations affected the shape calculations as well.

We assumed that the shape measurements on the Borda profile endpack, which had no transverse variation in steel profile, would be our best approximation to what the Rogowski profile would produce with no transverse structure. We compared the measured sextupole component of that end field with the sextupole expected (from a 2-D calculation) due to a notch in the pole face. We found that a notch of the depth and length of the first step required for the Rogowski profile produced approximately the right amount of sextupole to compensate for the corner saturation. While this approach has the advantage of being easier to calculate than a complicated 3-D shape, we expect it to saturate at a lower current. At that point the body sextupole will be dominating the total integral, so a deterioration of the end will be acceptable.

We carefully trimmed off the original bumps, step by step, measuring the end field after each step. We reduced the sextupole component each time, until we were left with only one set of laminations that were not flat. We adjusted the width of the central notch to reduce the sextupole a little more, and declared victory. The final end pack is shown in Figure B.. The resultant field shapes are shown in Figure 1 of [3]. The difference between the final shape and the shape of a tapered endpack with no transverse shaping is in excellent agreement with the integrated field predicted by multiplying the result of a 2-D calculation by the length of the notch.

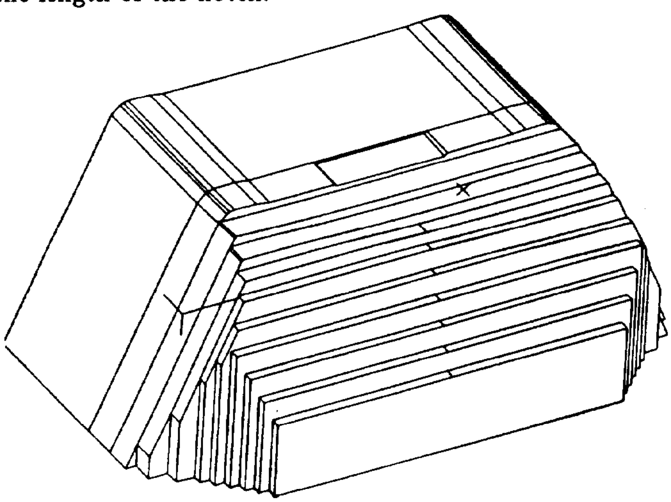

Figure 2: Isometric drawing of the final endpack design.

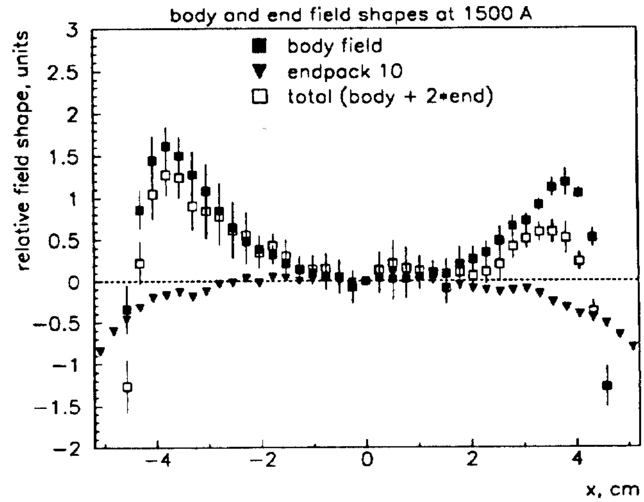


Figure 3: Relative shapes at 1500 A of the body field and integrated field for Endpack 10 (Rogowski profile). The estimated total field shape is superimposed.

## IV. CONCLUSIONS

After a lengthy development program, we have settled on an end pack design for the FMI dipoles and have started production with that design. The design meets all of the magnetic requirements of the accelerator. Figure 3 shows the field at 1500 A of a single end, of the body of the magnet, and of the sum of two ends plus the body. With the simplified method of controlling the sextupole in the end field that we have adopted, machining might have been cost effective compared to building the shape from trimmed laminations. Time constraints prohibited further investigation of that approach.

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