MODIFICATIONS TO THE EXCITATION CHARACTERISTICS OF FERMILAB MAIN INJECTOR DIPOLES BY MACHINING

P.S. Martin, R. Baiod†, D.J. Harding, J.F. Ostiguy, A.D. Russell
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

Abstract

Twelve dipole magnets were built under the R&D phase of the Fermilab Main Injector project using steel from a different vendor than the production vendor. These dipoles exhibited an excitation-dependent difference in strength relative to the production magnets, with a maximum difference of about 1% observed at high field. This difference was too large to allow them to be used in the project. From calculations based on the differences in the B(H) curves of the two types of steel, the high-field strength of the twelve R&D dipoles was reduced by machining the back-legs of the cores. The machining technique will be described, and excitation curves before and after machining will be compared.

1 INTRODUCTION

The Main Injector accelerator [1] will be constructed using 344 new conventional dipole magnets [2-3]. An extensive R&D program was carried out [4] to assure the quality of the magnets and to determine the desired end geometry to minimize the effective length variation with excitation and the sextupole content of the ends. Twelve full-length, pre-production dipoles (six six-meter and six four-meter dipoles) were built using steel supplied by Armco. When the FMI project was ready to begin fabrication of the production magnets, LTV Steel submitted the low bid and was awarded the production contract for approximately fourteen million pounds. The steel specification is discussed elsewhere [5].

2 STRENGTH COMPARISONS

The twelve pre-production dipoles were quite uniform in strength. The six, 6-m dipoles had a full width of about 0.14% at 1.38 T, while the spread in strengths of the 4-m dipoles was even less. There was, however, a difference at all fields of about 0.08% between the average of the 6-m dipoles and one and one-half times the average of the 4-m dipoles. This effect was corrected in the production magnets by reducing the stacking length of the 4-m dipoles by about 3 mm. However, compared to the production dipoles, the pre-production ones were stronger by as much as 0.9%, in a current-dependent manner. The averages of the strengths of the 6-m and the 4-m dipoles, relative to the strength of the production magnets, are shown in Figure 1; the upper two curves in that figure show the dipole strengths before the modifications which are discussed below. The impact on the closed orbit distortion in the Main Injector ring was determined to be too large to allow using these magnets.

Since the strength deviation is a function of current, the cause is a difference in the magnetic properties of the steel as opposed to a geometrical difference. The permeability of the Armco steel was somewhat higher than the LTV steel at all values of H. Based on this difference, it was plausable to try to reduce the strength of the pre-production dipoles by removing steel.

Although several locations on the cores were candidates, the easiest location to access while still maintaining symmetry was the backleg at the parting plane. According to Ampere's law, the field in the gap is given by:

$$B\ gap = \frac{\mu_o}{gap}\left[nI - \int \frac{B_{steel}}{\mu_{steel}} dL \right]$$

where the integral is over the steel along a flux line. We can manipulate the value of B in the gap by changing B in a section of steel with length L:

$$\Delta B_{gap} \approx -\frac{\mu_o}{gap} L \ \ \Delta\left(\frac{B_{steel}}{\mu_{steel}} \right)$$

Modifying the cross-section of the backleg such that

$$B_{steel} \times (backleg \ \ width) \approx B_{gap} \times \left(poletip \ \ width/2 \right)$$

(flux conservation) we obtain a variation of B in the gap that depends upon the length of the section of backleg which is reduced in width. Also, one sees that at low excitation, where μ is large the change in B is small, but that as the excitation increases the effect increases.

The above equations suggest the starting point. It was determined through OPERA2D calculations that removing a rectangular region 2.69 cm wide by 5.08 cm high on each backleg (see Figure 2) should reduce the field at 1.38 T by the desired amount. The width of the flux-carrying region in the steel in the backleg, taking into account the keyway on the parting plane, was reduced from 13.0 cm to 10.3 cm. Removing steel from a rectangular region was done for simplicity of machining. While the height of the cut determines the absolute change in strength and mostly shifts the strength curve vertically, the depth of the cut controls its general shape, i.e. the level of current at which saturation effects become important.

† Present address AT&T Corp., Middletown, NJ

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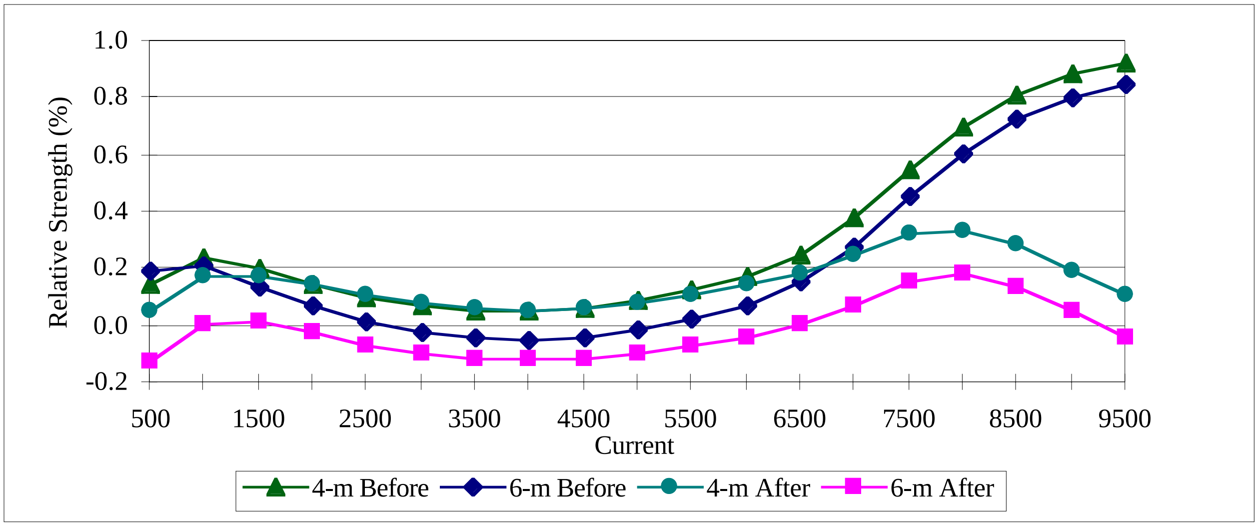

Figure 1. Dipoles strengths, relative to production magnets, for the pre-production magnets before and after machining.

The method chosen for removing the steel in the backleg was to remove twenty-six of the thirty tie plates which join the half-cores together (sixteen of twenty for the 4-m dipoles), leaving one tie plate in each of the four corners. After machining, the magnet was reclamped in the assembly press and stainless steel tie plates were welded to fasten the half-core together. It was verified during the modification of the first dipole that if the tie plates are replaced with steel tie plates after machining, the reduction in field in the gap is much smaller than expected; i.e. the presence of a parallel flux path drastically diminishes the reduction in field. However, simply replacing the tie plates on a dipole which has not yet been machined has almost no effect on the field. Leaving the corner tie plates in place allowed shipping the magnet with the coils still intact. The machining was done by outside firms at a total cost of less than 5% of the value of the magnet, including Fermilab labor.

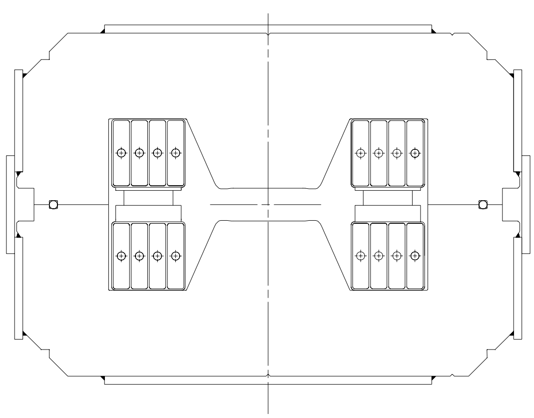

Figure 2. Cross-section of machined dipole. For scale, the lamination is 78.1 cm x 26.7 cm.

The procedure was first tested on one of the two prototype dipoles which were totally unsuitable for use in the ring: the endpacks were bolted on rather than being an integral part of the cores, and had the wrong profiles; the coils were not of the final configuration, and their impregnation was inferior. They were, however, fabricated from the same steel as the twelve pre-production dipoles. When this test proved to be successful, the same procedure was done to one of the pre-production dipoles. In both cases, the machining was done as a series of straight cuts which approximated the 15 mm sagitta of the dipole in 3 mm steps. For the remaining eleven pre-production dipoles, a different vendor was found who had larger capacity, and whose machines could follow the sagitta precisely. In both cases, the machining was done over the length of the cores except for the last 24 cm on each end where the tie plates were still in place.

Figure 1 also shows the strength deviation as a function of excitation for the machined dipoles, again relative to the production dipoles. The dipoles were reduced in strength very close to the desired amount. The residual strength variation is not a problem: by placing them in pairs the local closed orbit distortion is about 2 mm, which is less than the expected errors due to misalignment, and is within the range of the individually-powered correction dipole system to correct.

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