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STRENGTH AND SHAPE OF THE MAGNETIC FIELD OF THE FERMILAB MAIN INJECTOR DIPOLES*

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Abstract

Measurements of 230 6-meter and 136 4-meter dipoles constructed for the Fermilab Main Injector were carried out as part of the magnet production effort. An automated measurement system provided data on magnetic field strength and shape using several partially redundant systems. Results of these measurements are available for each individual magnet for use in accelerator modelling. In this report we will summarise the results on all of the magnets to characterise the properties which will govern accelerator operation.

1 INTRODUCTION

Over the last decade the Fermilab Main Injector and its magnets have been planned [1,2], designed [3,4,5,6] prototyped [7,8,9,10,11,12], produced [13,14], measured [15,16,17,18,19,20,21], installed [22], and commissioned [23,24]. Every dipole has been measured thoroughly, providing a rich set of data that is used for magnet assignments and beam modeling. Here we present an overview to give a flavor of the Main Injector dipoles.

In all, 230 6-meter and 136 4-meter dipoles were built and measured, including spares. These may be divided into several groups whose behavior differs for well-understood reasons: 1) Six 6-m R&D dipoles, 2) Six 4-m R&D dipoles, 3) the first 46 6-m dipoles, 4) the balance of the 6-m dipoles, and 5) the balance of the 4-m dipoles. Groups 1 and 2 were built with steel from Vendor A. Group 2 was built too long by 2.5-mm. Group 3 was built all or in part from steel from Vendor B's first production run. Groups 4 and 5 were built entirely with steel from Vendor B's later runs.

The integrated strength and the harmonic composition of the magnetic field was measured at multiple currents using a rotating tangential probe that extended through the magnet following the path of the beam. Field strength and shape were also measured using an integrating coil that could be held on center as the current ramped or moved transversely at a fixed current. A sample of magnets was further measured with an NMR and Hall probe package that scanned the magnet longitudinally.

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2 MAGNET STRENGTH

Groups 4 and 5 define our nominal magnet strength at each current. The mean strength, including the 4-m magnets weighted at 2/3 of the 6-m magnets, was calculated for each current. Deviations from that strength (for the 6-m magnets) or from 2/3 of that strength (for the 4-m magnets) are normalized to the nominal strength of the 6-m magnets. These deviations are quoted here in "units" of parts in 10^4.

Figure 1 shows the distribution of deviations of magnet strength from nominal for all magnets as a function of magnetic field. The profile is dominated by a narrow peak around the nominal strength composed primarily of Groups 4 and 5. The standard deviation of the distribution, due to variations in magnet length, magnet gap, steel properties, and random measurement errors, is in the range of 2 to 4 units.

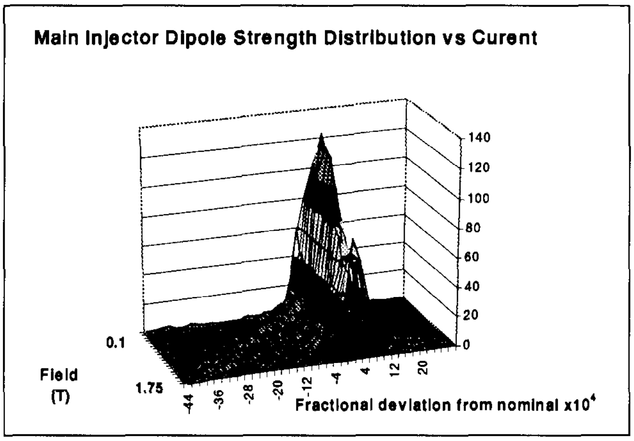

Figure 1: Main Injector dipole magnet strength distribution as a function of field. The field ranges from the injection value of 0.1 T to its peak of 1.75 T.

A second, lower ridge branches from the main stem at about 0.3 T and diverges to lower strength roughly linearly. These are Group 3 magnets with early steel from vendor B. [25] A handful of magnets appear below the nominal peak at 0.1 T, and the same magnets appear above the peak around 1.5 to 1.6 T. These are Groups 1 and 2 showing first a lower remanent field and then slower saturation. A modification to the back leg has allowed us to match the nominal field at 1.4 T and at 1.7 T, though it runs high in between.[26] The identity of

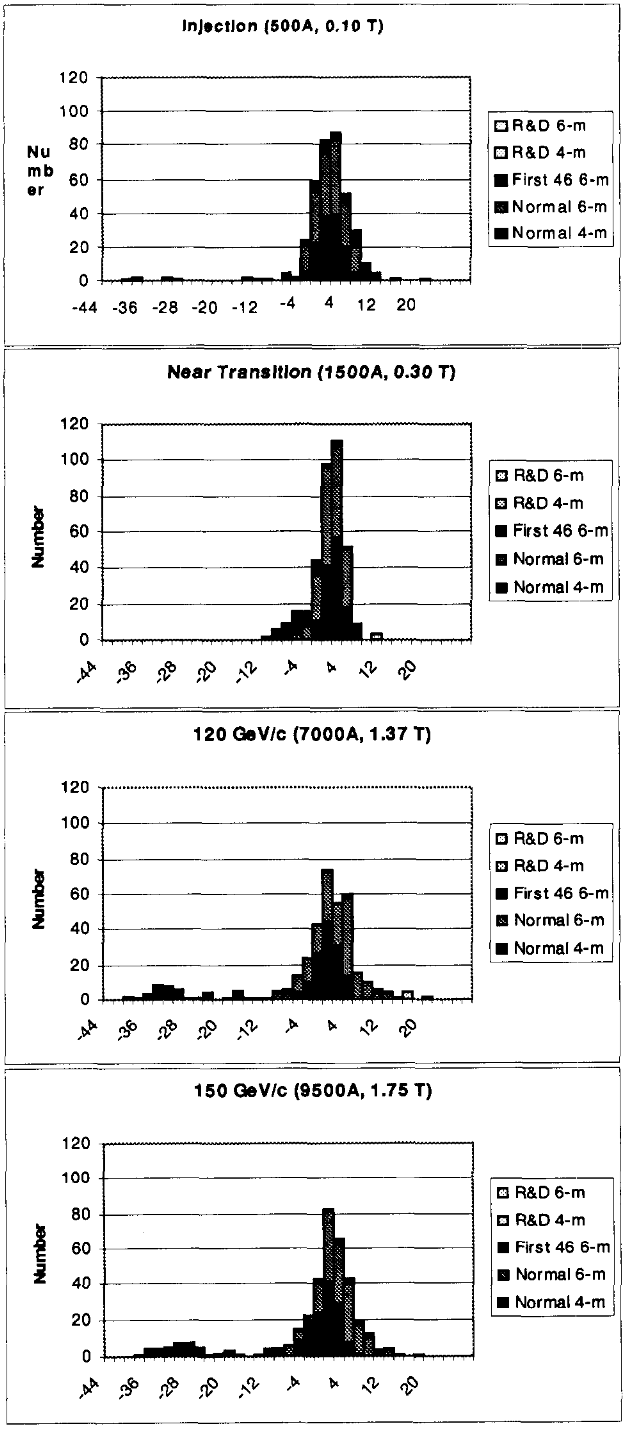

Figure 2: Distribution of magnet strength at four key excitations.

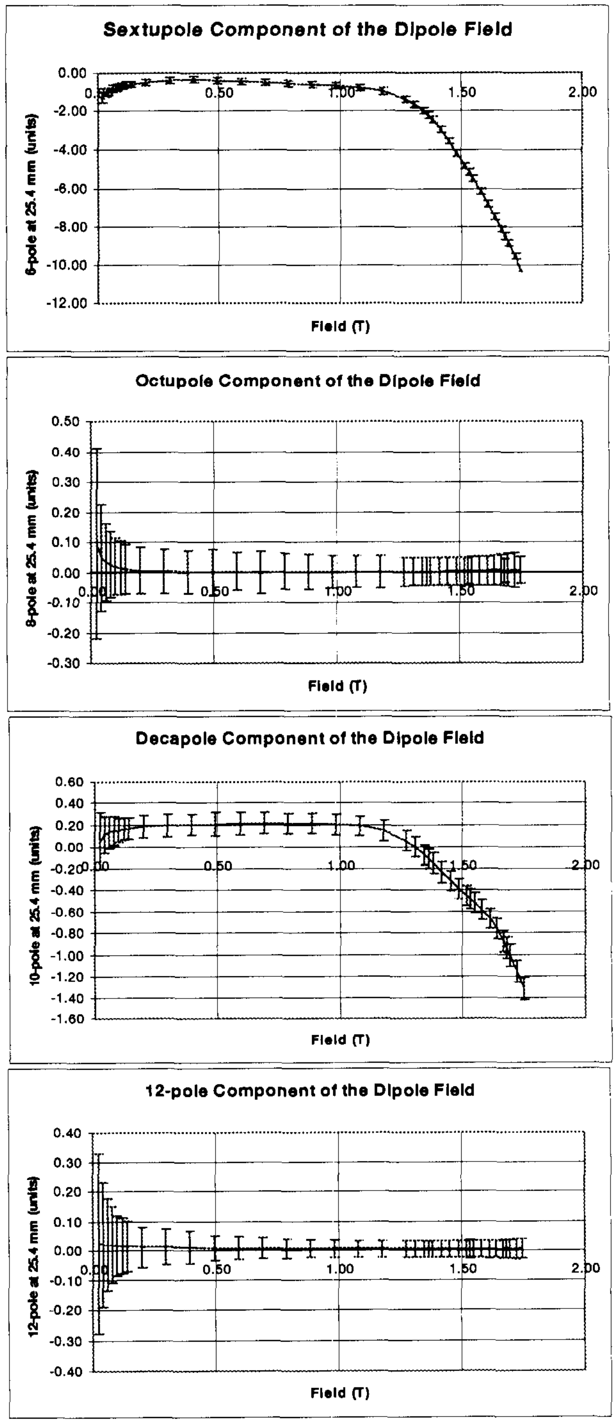

Figure3: Multipole components of the dipole magnets as a function of magnetic field. The ordinate scales vary.

these groups of magnets is clear in the histograms of Figure 2 which represent slices though the Figure 1 mountain range. The hysteresis in the dipoles has been studied and is included as an operational factor

3 HARMONICS

We characterize the variation of the magnet field across the aperture by the coefficients of its harmonic decomposition. The coefficient we quote is the fraction of the field due to the component in question at 25.4 mm (typical of the maximum beam size) relative to the dipole component in "units" or parts in 10^4.

Figure 3 shows the distribution of the normal sextupole, octupole, decapole, and 12-pole as a function of magnetic field. The error bars represent one standard deviation.

Note that the plots extend below the injection field of 0.10 T. As expected, we see some contribution of even terms as the steel saturates, reflecting the symmetry of the magnet, but the design and fabrication process minimizes the antisymmetric terms.

In operation, a significant sextupole field is also generated by eddy curents in the beam tube.[27,28]

4 CONCLUSION

Although the variation in steel properties prevented the overall Main Injector dipole strength variation from meeting expectations, within a steel run the uniformity was excellent. The field shapes meet the project requirements.[3] The non-standard magnets have been assigned locations in the ring where they produce small, local two-bumps, minimizing their impact on the closed orbit.[29]. Care has been taken to reserve a suitable collection of spare magnets to allow replacement of any magnet with a like magnet.

Purchasing all the steel before the project was funded would have alleviated the strength variation by reducing the increasing the uniformity of the steel and permitting homogenization of the magnet cores. In the end, the cost and schedule savings enabled by the phased steel purchases justify the extra effort required.

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