Fermi National Accelerator Laboratory

FERMILAB-Conf-95/112

The Main Injector Chromaticity Correction Sextupole Magnets: Measurements and Operating Schemes

C.M. Bhat, A. Bogacz, B.C. Brown, D.J. Harding,
S.J. Fang, P.S. Martin, H.D. Glass and J. Sim

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

May 1995

Presented at the *1995 Particle Accelerator Conference*, Dallas, Texas, May 1-5, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

THE MAIN INJECTOR CHROMATICITY CORRECTION SEXTUPOLE MAGNETS: MEASUREMENTS AND OPERATING SCHEMES

C. M. Bhat, A. Bogacz, B. C. Brown, D.J. Harding, Si J. Fang,
P.S. Martin, H. D. Glass and J.Sim
Fermi National Accelerator Laboratory*
P.O. Box 500, Batavia, IL 60510

Abstract

The Fermilab Main Injector (FMI) is a high intensity proton synchrotron which will be used to accelerate protons and antiprotons from 8.9 GeV/c to 150 GeV/c. The natural chromaticities of the machine for the horizontal and the vertical planes are -33.6 and -33.9 respectively. The Δp/p of the beam at injection is about 0.002. The chromaticity requirements of the FMI, are primarily decided by the Δp/p = 0.002 of the beam at injection. This limits the final chromaticity of the FMI to be ± 5 units. To correct the chromaticity in the FMI two families of sextupole magnets will be installed in the lattice, one for each plane. A sextupole magnet suitable for the FMI needs has been designed[1] and a number of them are being built. New chromaticity compensation schemes have been worked out in the light of recently proposed faster acceleration ramps. On an R/D sextupole magnet the low current measurements have been carried out to determine the electrical properties. Also, using a Morgan coil, measurements have been performed to determine the higher ordered multipole components up to 18-poles. An overview of these results are presented here.

I. Chromaticity Compensation Schemes for the FMI

Previously a scheme for chromaticity compensation in the FMI had been worked[2] out taking into account the effect of beam tube eddy current, the dipole saturation, and the end-pack sextupole fields generated by the dipole magnets. The data were taken from measurements on R&D dipole magnets. Since then, several developments have taken place:

1. The measured[3] combined contribution of the saturation and static fields in the dipoles showed a slightly negative sextupole component (i.e., b_2 = -0.05 m^2) at low fields (which is in contrast with the earlier scheme).

2. The material of the FMI beam tube is selected to be 316L stainless steel (resistivity of 74×10^{-8}Ohm m)[4].

*Operated by the Universities Research Association, under contracts with the U.S. Department of Energy

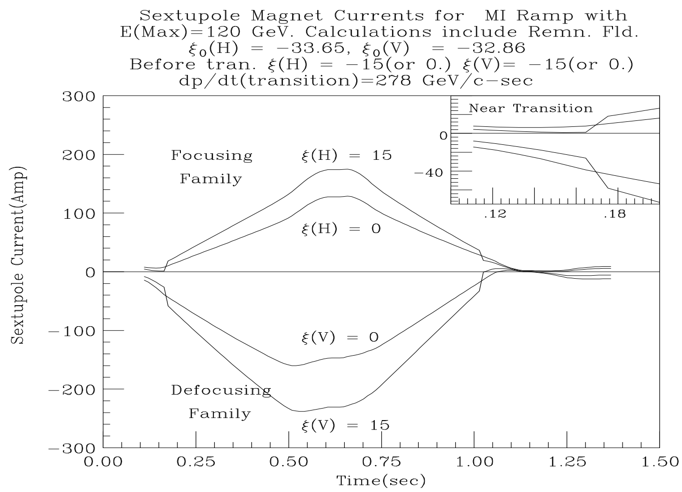

Figure 1: The FMI sextupole magnet operating scheme for 120 GeV/c fast ramp. The 8.9 GeV/c beam is injected at 0.1 sec extracted at 0.64 sec. The total cycle time is 1.4 sec. The chromaticity sign changes at transition from negative to positive.

3. A faster ramp[5] is selected to reduce the emittance dilution at transition. The $\dot{p}$ at transition in the present FMI operating scheme is about 280 GeV/c-sec (fast ramp) which is nearly 70% larger than the previously proposed ramp (viz., $\dot{p}_t$ = 167 GeV/c-sec, slow ramp).

Hence, a new chromaticity compensation scheme has been developed. Here we essentially adopt the method outlined in Ref. 2.

Figures 1 and 2 show the examples of operating schemes for two different types of FMI accelerating ramps viz., fast and slow ramps respectively. The Fig. 1 illustrates the fast ramp. Here, a 8.9 GeV/c beam will be injected into the FMI at about 0.10 sec in to the accelerating cycle and the beam will reach its peak momentum of 120 GeV/c at 0.61 sec. The required sextupole magnet currents as a function of the cycle time for two chromaticities, viz., 0 and 15 units, are shown for both focusing and defocusing families of sextupole magnets. The Fig. 2 displays the expected sextupole magnet current for the slow ramp. In this case the maximum momentum reached is 150 GeV/c.

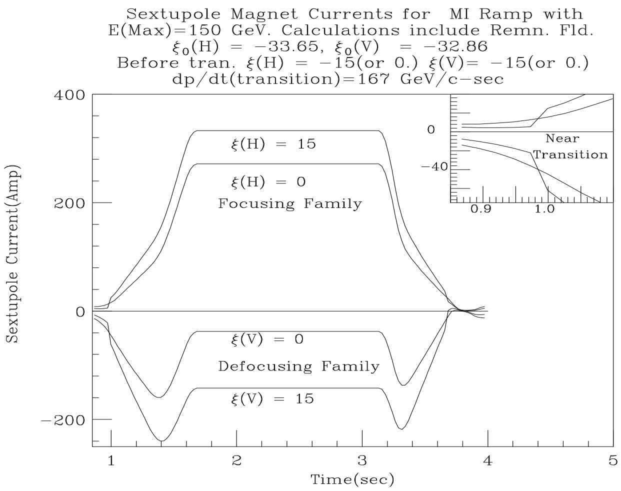

Figure 2: The FMI sextupole magnet operating scheme for 150 GeV/c slow ramp. The 8.9 GeV/c beam is injected at 0.84 sec and extracted at 3.10 sec. Here the total cycle time is 4 sec. The chromaticity sign changes at transition from negative to positive.

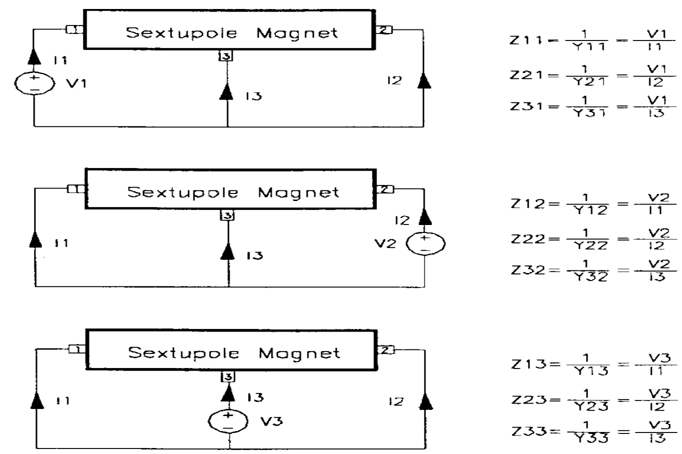

Figure 3: Impedance Matrix Measurement.

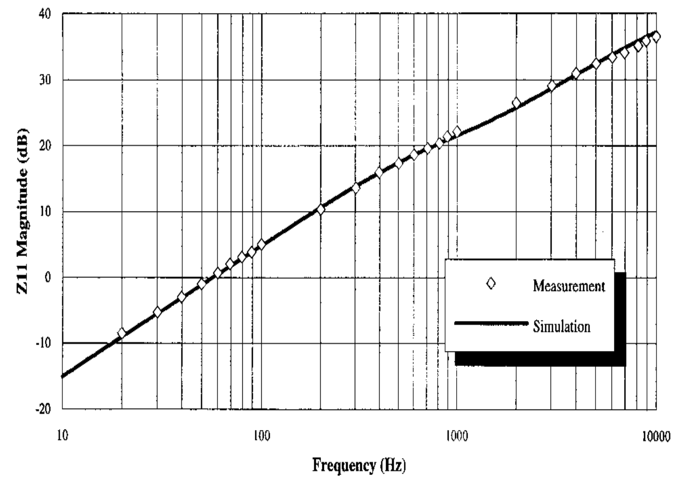

Figure 4: Z11 Magnitude Plot.

The selection of $\dot{p}_t \approx$ 280 GeV/c-sec has resulted in a very large amount of eddy current contribution to the sextupole field component at low B fields. For instance, near the transition energy the contribution to the sextupole component b_2 arising from the eddy current reaches a maximum value of 0.8 m^2 for the fast ramp, and about 0.5 m^2 for the slow ramp. The effect of this 60% increase in the sextupole field strength on the operating scenario is quite noticeable near transition energy as shown in the insets of Figs. 1 and 2. This suggests that in order to have enough safety margin for the operation of the FMI below 25 GeV/c we might need a bipolar power supply for the focusing family of sextupoles. However, for the defocusing family of sextupoles a unipolar power supply should be sufficient.

II. Electrical Model

The sextupole magnet is a three-terminal device with two coil terminals and one magnet case ground. The electrical characteristics of the magnet can be described by a 3×3 impedance matrix at non-saturation. The equations for this three-terminal device network can be written as

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} Y11 & Y12 & Y13 \\ Y21 & Y22 & Y23 \\ Y31 & Y32 & Y33 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

The elements in the matrix are frequency dependent variables. The magnet equivalent circuit can be determined by measuring the impedance matrix as shown in Fig. 3.

Terminal 1 and 2 are coil bus terminals and terminal 3 is the case ground. Z11, Z22, Z12 and Z22 measure the coil bus impedance. Total bus to ground capacitance is measured by Z33. Z13 and Z31 measure the capacitance between terminal 1 and ground while terminal 2 is shorted to ground. Similarly, Z23 and Z32 measure the capacitance between terminal 2 and ground while terminal 1 is grounded. The Z13, Z23 and Z33 are capacitance measurements since the slope of the measurements data is -20 dB/decade in Bode plot.

The circuit simulation program Spice is used to curve fit the sextupole magnet electrical model into its impedance matrix as shown in Fig.4 for Z11.

Figure 5 shows the sextupole magnet electrical model. R1 represents the copper loss and R2 is for the core loss. L1 and R3 are the air core inductance and skin depth effects respectively.

III. Magnet Measurements

The magnets are measured at the Fermilab Magnet Test facility (MTF) using a rotating Morgan coil with the data base-controlled MTF software[6]. The coil is rotated at

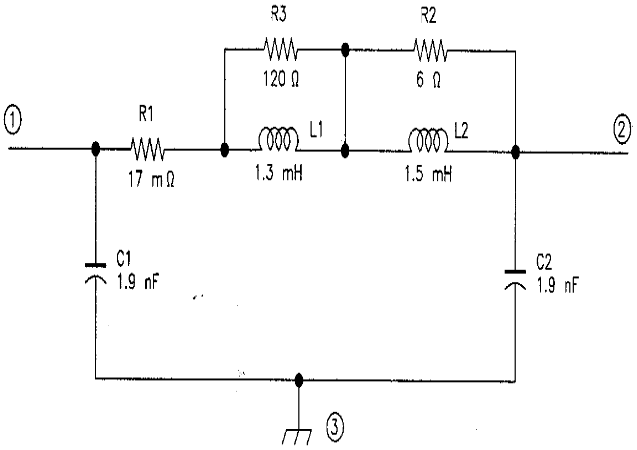

Figure 5: Main Injector Sextupole Electrical Model.

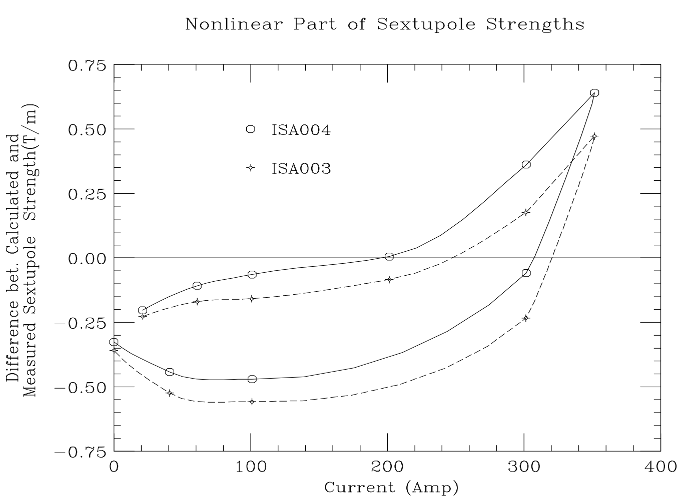

Figure 6: The nonlinear part of the sextupole strengths is obrained by substracting the measured field integral from the value calculated from normal geometry and infinite mu. Results are shown for two R&D sextupole magnets. Extraction of the nonlinear components is carried out by using a method outlined in Ref.6.

the center of the magnet at a constant current. Activating different coil windings on the probe allows the measurements of the sextupole strength and the contributions to the field shape from other harmonic components up to 18 poles. We have made measurements of both normal as well as skew components. We find none of the components are of significant importance for FMI operation scheme except the remanent field. A remanent field of -0.3 (Tm/m^2) is seen for the magnet that is ramped up to 350 Amp. Using the scheme outlined in Ref.6 we have extracted the non-linear part of the sextupole field. The result is shown in Fig. 6. In our chromaticity compensation scheme developed for FMI in section I, we have included this non-linear part of the sextupole field. The sextupole field arising from the eddy current and the remanent field of the sextupole magnet counteract. Hence, the focusing sextupole magnet power supplies need not go much negative.

Authors would like to thank the MTF personnel for their help during the magnet measurements.

REFERENCES

[1] D.J. Harding, N.Chester, and R. Baiod, Proc. of the 1993 IEEE Part. Accel. Conf. (1993) 2826

[2] S.A. Bogacz, Proc. of the 1993 IEEE Part. Accel. Conf. (1993) 77.

[3] D.J. Harding R. Baiod B.C. Brown J.A. Carson N.S. Chester E. Desavouret J. Dimarco J.D. Garvey H.D. Glass P.J. Hall P.S. Martin P.O. Mazur C.S. Mishra A. Mokhtarani J.M. Nogiec D.F. Orris J.E. Pachnik A.D. Russell S.A. Sharonov J.W. Sim J.C. Tompkins K. Trombly-Freytag D.G.C. Walbridge and V.A. Yarba, "Magnetic Field Measurements of the Initial Production Main Injector Dipoles", (Procedings this conference).

[4] D. G. Walbridge and M. E. Bleadon and B. C. Brown and H. D. Glass and D. J. Harding and and P. O. Mazur and J. W. Sim, "Measurements of Beam Pipe Eddy Current Effects in Main Injector Dipole Magnets", "Int. J. Mod. Phys. A (Proc. Suppl.)" Vol. 2B, (1993) 617 and Proceeding of the XVth International Conference on High Energy Accelerators, Hamburg, July 20-24, 1992 also available as FERMILAB-Conf-92/220

[5] The Main Injector Technical Design Handbook 1994.

[6] J.W. Sim et. al., 'Software for a Database-Controlled Measurements System at Fermilab Magnet Test Facility' (these proceedings)

[7] B.C. Brown, Analysis of Magnet Strengths from Steel B-H Curves and Geometry' Fermilab MTF-94-0078,(1994).