AIR-COOLED TRIM DIPOLES FOR THE FERMILAB MAIN INJECTOR

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Abstract

New horizontal and vertical trim dipoles have been designed for the Fermilab Main Injector (FMI) and are being assembled in the Fermilab Technical Division. Magnets are 42.6 cm in length (30.5 cm steel length) and have similar cross-section dimensions. The horizontal (vertical) magnet gap is 50.8 mm (127 mm) and the target integrated strength is 0.072 T*m (0.029 T*m). The major design effort lay in making air cooling possible for these magnets.

This report presents the magnets' thermal and magnetic properties and discusses the limitation on excitation current.

1 INTRODUCTION

The FMI lattice includes 104 horizontal and 104 vertical trim dipoles that perform fine close orbit correction [1]. The accelerator operation with 120 GeV energy requires 0.072 T*m integrated strength for the horizontal trim dipole and 0.029 T*m for the vertical one, but the dipoles must generate larger magnetic strength for 150 GeV operation, which will last about 10 minutes a day. The current duty factor, which is the ratio of the r.m.s. current to the maximum one, is 0.7.

The magnets must be less than 0.43 m long to allow their fitting into the space between the FMI dipoles and quadrupoles.

To simplify the mounting procedure and to increase reliability, the magnets were made air cooled. Maximum core temperature of 50° C was accepted to meet the safety requirements.

For air-cooled magnets, the surface temperature is a result of a balance between the coil power consumption and the power lost from the surface by radiation and convection. A simple estimate shows that if a magnet design uses traditional surface shaping, the coil total copper wire cross-section and the magnet core dimensions must be unreasonably high to meet the temperature specification.

2 THE DESIGN PRINCIPLES

The most obvious way to reduce the dipole coil cross-section is to increase significantly the magnet core surface. This was done by building the cores from E-shaped laminations with different width of flux return legs. The dipole half-cores were assembled from lamination packs. Each pack is 15 mm in thickness and contains 24 laminations die-stamped from 0.625 mm M15 ARMCO silicon steel sheets with two-side type C3 insulating coating. When being stacked together in a stacking fixture, alternating lamination packs were turned around the pole axis of symmetry. Due to the different widths of the flux return legs, this procedure resulted in half-cores with increased vertical surface. Prior to stacking, each lamination was coated with a thin epoxy layer. Curing in an oven in a stacking fixture with pressure applied to the whole assembly produced solid half-cores that were ready for the final assembly.

The coil has a simple racetrack configuration, rectangular 8 x 4 cm^2 cross-section, and is wound using ML-coated 6.56 mm^2 square copper wire. The coil leads are made using flexible insulated wires. After the coil was wound, it was ground insulated, vacuum impregnated with epoxy, and cured in an oven in a curing fixture. To avoid any air layers between the coil and the core, coils are glued into the core using room-cure epoxy. Figures 1 and 2 show the dipoles after final assembly.

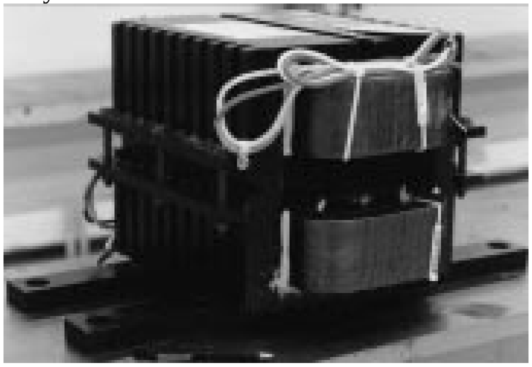

Figure 1: Horizontal Trim Dipole

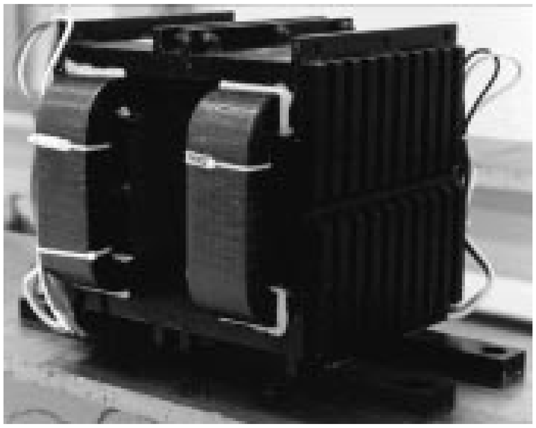

Figure 2: Vertical Trim Dipole

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The table 1 below presents the dipoles main parameters.

Table 1

Feature Description	Horizontal Dipole	Vertical Dipole
Magnet size: (mm)		
length	426	426
width	295	380
height	280	305
Core length (mm)	305	305
Magnet weight (kg)	180	220
Coil cross-section (mm)		
width	40	40
height	80	80
Average wire turn length (m)	1.02	1.12
Number of turns per magnet	812	812
Total copper weight (kg)	50	55
Magnet resistance (Ohm)	2.2	2.4
Magnet inductance (H)	1.1	0.9
Nominal power (W)	180	200
Cooling surface area (cm^2)	8200	9300

3 MAGNETIC PROPERTIES

Figures 3 and 4 show the relative magnetic field distribution in a transverse (X, Y) plane for the horizontal and vertical trim dipoles found using the OPERA-2D magnetic modeling program. The integrated field measurement performed using a rotation coil have shown that the magnet end field adds some negative sextupole to the body field harmonic content. It makes the integrated field distribution differ slightly from the body field distribution. Nevertheless (and partly due to this effect), for both dipoles, the magnetic field meets the field quality requirement. Due to relatively low field level, the magnets do not have saturation problems.

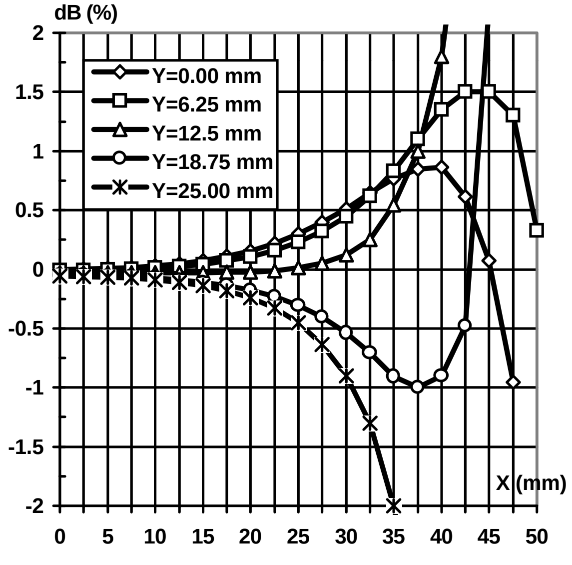

Figure 3 Horizontal trim dipole magnetic field.

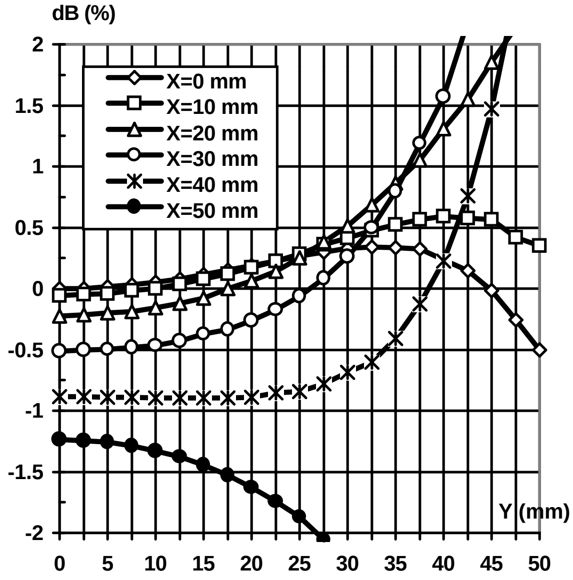

Figure 4 Vertical trim dipole magnetic field.

4 STATIC THERMAL PROPERTIES

The factor that can put a natural limit to the magnet strength is the coil temperature. The normal regime current density for both of the magnets is approximately 1.8 A/mm^2, so it is necessary to insure proper coil cooling to avoid overheating. The maximum temperature inside the coil

$$T_m = T_{core} + \frac{p \cdot a}{2} \cdot [\frac{a}{k_{eff}} + \frac{g}{k_{ins}}], \qquad (1)$$

where **p** (W/m^3) is the coil power consumption; **a** (m) is the coil thickness; **g** (m) is the gap between the coil and the core, filled with a material with a thermal conductivity $\mathbf{k_{ins}}$; $\mathbf{k_{eff}}$ is the effective thermal conductivity of the coil. Calculating the power consumption, one should apply all the coil power to the coil volume inside the core, because thermal conductivity of the coil along wire layers is much larger than that across the coil. For the dipoles' normal operation, the coil power consumption **p** = 41000 W/m^3. The effective thermal conductivity $\mathbf{k_{eff}}$ can be found if we know thickness **d** and thermal conductivity **k** of copper and insulating layers:

$$\frac{d_{Cu} + d_{epoxy} + d_{ML}}{k_{eff}} = \frac{d_{Cu}}{k_{Cu}} + \frac{d_{epoxy}}{k_{epoxy}} + \frac{d_{ML}}{k_{ML}}. \qquad (2)$$

Table 2 lists the thermal conductivity values for the materials used in the coil [2]:

Table 2

Material	Units	Value
Copper	W/(m*°C)	386
Dupont Pyre-M.L.	W/(m*°C)	0.155
Epoxy	W/(m*°C)	0.65
Air	W/(m*°C)	0.024

The average epoxy layer thickness can be calculated using the data from Table 1: d_{epo} = 0.45 mm. The thickness of the wire insulation d_{ML} = 0.1 mm. Then, the estimate of the coil effective thermal conductivity

$$k_{eff} = 1.6\ \text{W/(m*°C)}.$$

It is relevant to say that for an epoxy-impregnated coil, the wire film insulation has two times larger thermal resistance than the epoxy filled gap between the wires. If we do not use epoxy to fill the gaps, the air layers will dramatically increase the coil thermal resistance. With no epoxy inside the coil, we would have a maximum coil temperature of about 300°C, which is not acceptable from the point of view of the wire insulation reliability.The same effect will take place if we leave air gaps between the coil and the core after the coil is installed into the core. Assuming that these gaps are equally distributed and filled with epoxy (g_{av}= 2.3 mm), using (1), we can estimate the coil temperature rise as ΔT = 23°C. So, using the epoxy impregnation technique, and eliminating any air gaps between the coil and the core, we can eliminate the problem of coil overheating.

To evaluate the magnet static thermal properties, measurements were performed at different current levels for the Horizontal and Vertical trim dipoles. The measurement results are in a reasonably good agreement with predicted numbers. The table 3 below compares the measured and calculated coil and core temperatures for the Horizontal trim dipole tested using 15 A D.C. excitation current. The coil power consumption in this case was almost 4 times larger than the magnets nominal power. The measured average coil temperature in the table was calculated based on the measured rise of the coil resistance. Surface-to-air heat transmission coefficient α = 13 W/(m^2 °C) was used for the core surface temperature rise calculation [3].

Table 3

Feature	Calcul.	Measured
Power consumption at 15 A.	714 W	720 W
Core surface temp. rise (above ambient)	64°C	62°C
Core surface temperature	84°C	82°C
Maximum coil temperature	148°C	--
Average coil temperature	127°C	105°C

As it is possible to see from the table 3, the core temperature is the main component contributing to the coil maximum temperature. The magnet design and manufacturing technology helped to reduce the problem of coil overheating. On the other hand, as it was mentioned earlier, the yoke cross-section, which was chosen to insure the magnet rigity, can tolerate much more magnetic flux without saturation. It provides a significant reserve for the magnets integrated strength increase. By accepting higher core surface temperature, or by using forced air flow or water for additional core cooling, we can significantly increase the average current before degradation to the magnet would occur.

5 DYNAMIC THERMAL PROPERTIES

The dynamic thermal properties of the magnets can be described by the heating characteristic time index τ, which provides a scale to the exponential temperature change, according to the expression

$$\Delta T(t) = \Delta T_0 \cdot (1 - e^{-\frac{t}{\tau}}), \qquad (3)$$

where ΔT_0 is the maximum temperature rise. For the coil, which mainly releases deposited energy into the core, the estimate that takes into the account the numbers from the table 2 gives for both magnets $\tau_{coil} \approx$ 25 min. For the steel core, τ_{St}= 130 min. Because $\tau_{coil} << \tau_{St}$, we can expect that the coil maximum temperature will follow the core temperature after about 25 minutes of a magnet operation. The core temperature after t minutes of the magnet operation with the increased current can be found from the expression:

$$\Delta T(t) = \Delta T_{nom} \cdot \frac{I_m^2 - I_{nom}^2}{I_{nom}^2} \cdot \frac{t}{\tau_{St}}, \qquad (4)$$

where I_{nom} and I_m are nominal and increased current values, and ΔT_{nom} - the core temperature rise at nominal current. Calculation gives ΔT(10 min)=0.73°C.

Dynamic temperature measurements performed with the Horizontal Trim Dipole gave the results that are in very good agreement with the calculated predictions. Measured coil-core characteristic time was about 25 minutes, core heating time - 2 hours; core temperature rise after 10 minutes of operation with the increased current was less than 1°C.

6 CONCLUSION.

A strict limit on the magnet core temperature forced us to increase the magnet's cooling surface, arranging vertical air passages along the core sides. Using epoxy for the coil impregnation and gluing the coil into the core nest with epoxy compound helped to keep maximum wire temperature at a reasonable low level. The dipole cores saturation properties allow operation at more then twice the nominal field. The 15 A DC horizontal dipole operation with the power consumption almost 4 times as larger than at the nominal 12 A maximum current (0.7 duty factor) operation has confirmed the magnet reliability.

References:

[1] - Fermilab Upgrade: Main Injector. Technical Design Handbook, August,1994.

[2] - Handbook of Chemistry and Physics, Thirtieth Edition, Chemical Rubber Publishing Co., Cleveland, Ohio, 1947.

[3] - R. Baiod, private communication.