DIPOLE CORRECTOR MAGNETS FOR THE LBNE BEAM LINE*

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Abstract

The conceptual design of a new dipole corrector magnet has been thoroughly studied. The planned Long-Baseline Neutrino Experiment (LBNE) beam line will require correctors capable of greater range and linearity than existing correctors, so a new design is proposed based on the horizontal trim dipole correctors built for the Main Injector synchrotron at Fermilab. The gap, pole shape, length, and number of conductor turns remain the same. To allow operation over a wider range of excitations without overheating, the conductor size is increased, and to maintain better linearity, the back leg thickness is increased. The magnetic simulation was done using ANSYS to optimize the shape and the size of the yoke. The thermal performance was also modeled and analyzed.

INTRODUCTION

The LBNE beam line magnets transport the proton beam to the target with the highest possible intensity feasible from the Fermilab Main Injector (MI) Accelerator. The recently proposed and discussed LBNE beam line design contains 43 ten-foot long quadrupole magnets [1]. To perform fine orbit corrections (for variations in the main dipole magnets and alignment imperfections in the quadrupole magnets), a total of 41 dipole corrector magnets (trim dipoles) are needed, one located at each focusing location.

The horizontal dipole correctors for MI, historically know as IDH [2], are first considered. The decision to use this dipole is primary determined by its modern design, simplicity and its operational reliability. About 128 units were built in the late 1990s; 104 are in use in current MI operation. The coils and cores were produced by the outside vendors, and the final assembly and testing of the magnets were done in Fermilab.

The recent experience of utilizing the current MI correctors for NuMI beam line showed a need of several modifications. In some beam line locations, an increase of the magnetic field was required to 0.10-0.12 T·m. Even with the magnets ramping the RMS current rises to ~15-16 A. Water cooling was added to cool the core, and indirectly the coils, of what had been an air-cooled magnet (IDHK). At these currents, the field vs current dependence deviates significantly from the straight line. While not fatal, this is an operational nuisance. The non-linearity is a larger problem for a few trims in the MI. These have been modified by the addition of steel plates to the top and bottom to provide a larger flux return path. (IDHE) To solve these problems cleanly for the LBNE beam line, changes to the existing IDH design were proposed.

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THE DESIGN OPTIMIZATION

Based on the existing IDH design shown in Figure 1, three parameters are kept, the aperture 50.8 mm, the core length 304.8 mm and the number of coil turns 812. The conductor size is increased to reduce the power consumption, which lowers the surface temperature. The steel leg thickness t_1 and t_2 vary to understand the magnetic field linearity response. The rough cross section of the IDH type correctors with different gauge wires is shown in Figure 2, with yoke thickness increased as well.

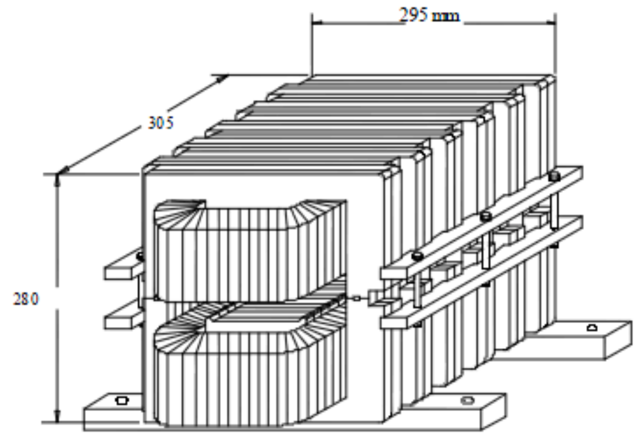

Figure 1: Sketch of the MI horizontal trim dipole.

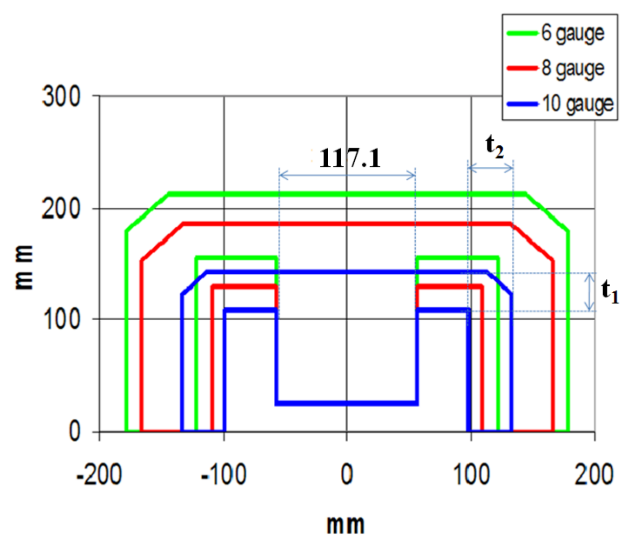

Figure 2: The cross section of the IDH type correctors.

Table 1: Parameters of IDH Type Correctors

Characteristic	Values		
Conductor (gauge)	#10	#8	#6
Resistance (Ohm)	2.16	1.41	0.93
Power @ 12A (W)	311	203	134
Conductor weight (kg)	50	80	130
Steel weight (kg)	201	322	392
Magnet weight (kg)	251	402	522

Conductor Size

The parameters of IDH type correctors with different conductor sizes are listed in Table 1. Besides the original IDH design using #10 copper gauge wire, #8 and #6 wires are selected, because their lower resistance can reduce total power consumption so that the magnet can be cooled by air. Increased wire size leads to increased weight for the conductor and the steel. For easy handling and installation, the weight is required to be less than ~454kg. Note that in Table 1, the weight of the steel for #10 was measured based on IDHE, and the weight of the steel for #8 and #6 is calculated approximately with the thickness t_1 and t_2 increasing by the ratio of $D_{\#8}/D_{\#10}$ and $D_{\#6}/D_{\#10}$, respectively. A corrector with #8-gauge wire is the better candidate to start the optimization.

Steel Leg Thickness

Based on the IDH type corrector, #8 gauge wire is used as the conductor. To improve the linearity of the magnet at higher current, the thickness of the steel needed to be increased to enlarge the flux return path. To find the best solution, the parameters t_1 and t_2 are set as the variables shown in Table 2. The maximum t_1 and t_2 are specified as 85.1 mm so that the total magnet weight is just below the required handling weight.

The trim correctors for LBNE beam line will be operated in the range of +30 A to –30 A. The linearity of the magnetic field strength is specified based on the parameter dBL/dI, where BL is the integrated field strength and I is the corresponding current. When the current is below 15 A, the deviation of dBL/dI shall be within 4% of the desired amount across the range of operation of the magnets. From 15 A to 20 A, the deviation of dBL/dI shall be within 8%, and from 20 A to 30 A, within 15%.

Table 2: Thickness and Weight of the Steel

Name	t_1 (mm)	t_2 (mm)	Weight (kg)
#10	27.2	27.2	130.0
#8-1	27.2	27.2	155.6
#8-2	50.8	50.8	235.0
#8-3	68.6	68.6	302.4
#8-4	85.1	85.1	370.9

The magnetic model was built in ANSYS, shown in Figure 3, to calculate the field strength and the deviation of dBL/dI with different iron thickness. The simulation results are compared and shown in Figure 4. From #8-2, the thickness of the iron meets the linearity requirement. The simulation results are also compared with the measurements of IDH104, IDHE126 and IDHK104. As the reference, #10 is the simulation for IDH104. Taking account of the difference of the simulation results and the measurement of the magnet, #8-3 is the best candidate that meets the linearity requirement.

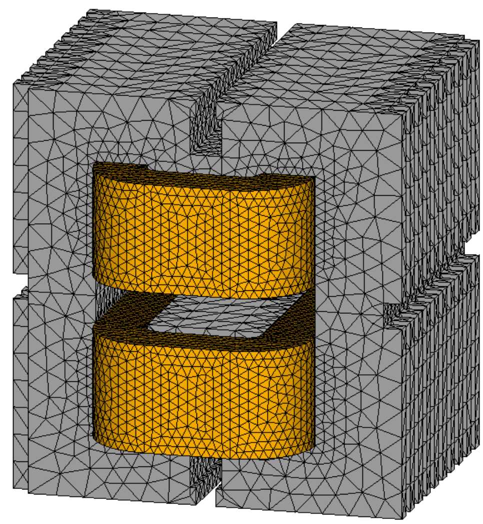

Figure 3: The corrector magnetic model in ANSYS.

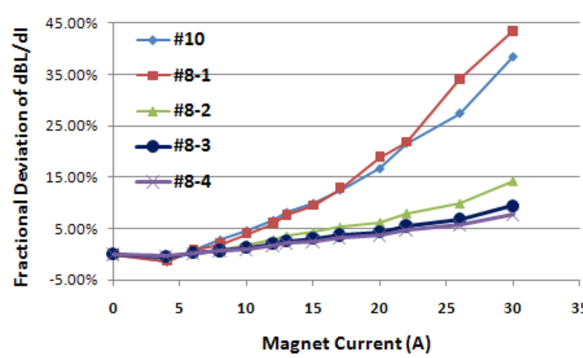

Figure 4: Iron Optimization for #8 Trim Dipole

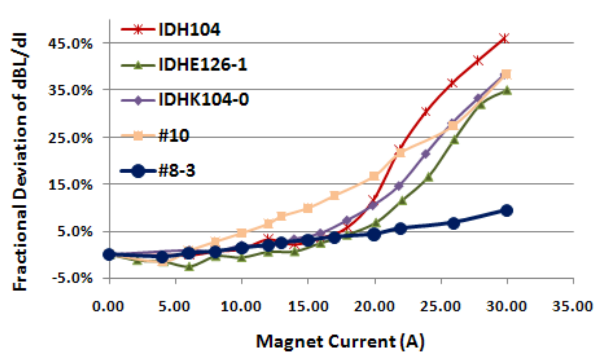

Figure 5: Comparison of Simulation and Measurements

MAGNET THERMAL EFFECT

Joule heating is generated during the operation of the trim dipoles. In the current MI operation at ~8.5 A RMS without additional cooling, the maximum core temperature is less than 50° C, which is acceptable for the safety requirements. The trim dipole designed for LBNE beam line is also an air cooled magnet. The thermal model was built in ANSYS based on the design of #10 and #8-3. The RMS current was applied to the conductor. The electrical resistance of the copper was defined as temperature dependant, and the other material properties used in the simulation are listed in Table 3. The thermal conductivities of Mylar and epoxy were used to calculate the effective thermal conductivity across the coil [2].

Table 3: Material Properties for Thermal Calculation

Material	Specific Heat (J/kg-°C)	Thermal Conductivity (W/m-K)	Heat transfer coefficient (W/m^2-K)
Copper	--	386	--
Mylar	--	0.155	--
Epoxy	--	0.65	--
Coil Assembly	200	386 (//) 2.5 (⊥)	4.5
Steel Core	175	45	2

The specific heat and the surface heat transfer coefficients of the coil and the steel laminations were tuned based on the comparison between the simulation with #10 gauge wire and the measurements of IDH104 at 10 A RMS. The results are shown in Figure 6. The temperature was measured at points on the core and coil surfaces during one hour of operation and the maximum temperature was used. The data was taken from the simulation in the same way. After ten hours' operation, the rise is slowing, but has not reached a plateau.

The simulation model was verified by comparing the results with the measurements of IDH104 at 12 A, shown in Figure 7. In 10 hours, the core temperature reaches 88 ˚C for 12 A.

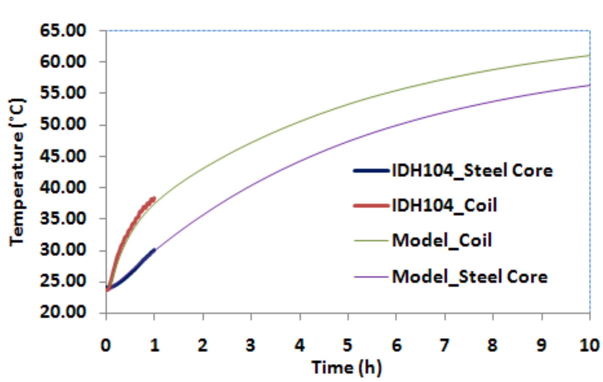

Figure 6: Temperature comparison at 10 A.

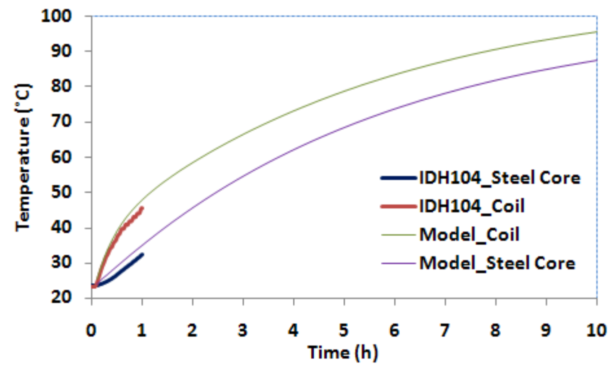

Figure 7: Temperature comparison at 12 A.

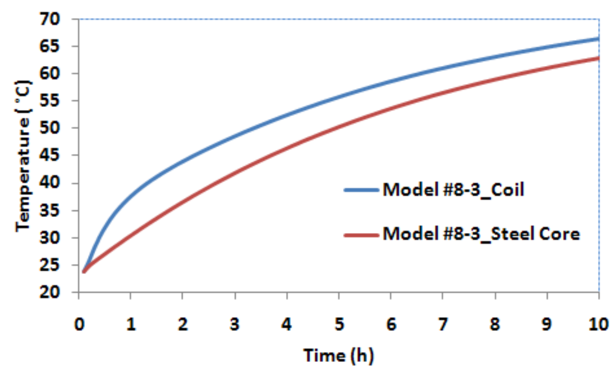

Figure 8: Model #8-3 simulation results at 15 A.

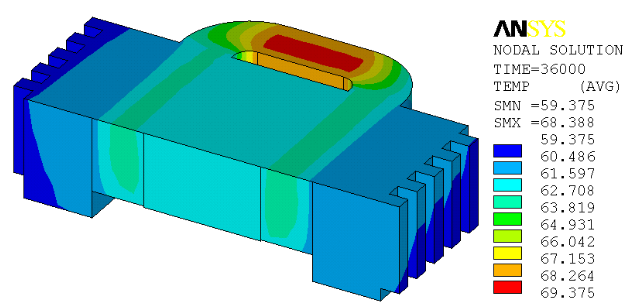

Figure 9: Temperature distribution in cross-section view.

The simulation results of the design model #8-3 are shown in Figure 8 and Figure 9. In ten hours, the core temperature reached 63 ˚C. The simulation still needs to be verified by the test of a prototype.

CONCLUSION

The conceptual design of a trim dipole for LBNE beam line has been modeled. The excitation linearity meets the requirements over the full range of currents. Long term operation at the peak fields approaches our informal temperature limits, but peak fields are only anticipated for short periods of beam tuning.

REFERENCES

[1] http://lbne.fnal.gov/
[2] D.J. Harding et al, "Air-Cooled Trim Dipoles for the Fermilab Main Injector," PAC1997, pp 3291.