THE MAIN INJECTOR TRIM DIPOLE MAGNETS

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Abstract

To correct field and alignment errors, provide full aperture steering at injection, and control the horizontal orbit in the straight section, a 0.060 T-m and a 0.090 T-m correctors were designed. The two magnets were chosen to have identical lamination cross section and identical coil packages, however the normal low field corrector has no cooling while a water cooled plate is incorporated to the high field one. Diffusion of the heat through the copper conductor, insulations, and magnet steel, with and without plate cooling, was analyzed, and temperatures were estimated. We report in this presentation the calculations of the various magnet parameters, and in particular, the procedure to optimize the temperature of the steel and the temperature of the inner copper coil.

I. Design requirements and constraints

Tracking studies at 8.9 and 120 GeV/c [1] have established that correctors with rms value of $\pm$ 35 μr in strength, will provide adequate correction at all energies. With a strength of 0.060 T-m, our normal corrector will provide 120 μr of steering at 150 GeV, a factor of 3.4 standard deviation at the highest energy. This should allow for correction for unexpected field/alignment errors and/or future orbit control requirements at high field. To reduce unexpected dipole field variations, we will consider shuffling the main ring dipoles during installation, and realigning the quadrupoles during commissioning. Stronger correctors around the straight sections are required to provide position and angle control around the electrostatic septa and Lambertsons during injection and extraction. To minimize corrector strengths at these locations, the high field orbit is first determined by quadrupole alignment. Then a corrector strength of only 0.090 T-m will provide 180 μr at 150 GeV/c and still provides a safety factor of about 2 above the required strength.

In addition to the beam requirements, the design of the trim dipole correctors was strongly restricted by first, the available space, and second, the necessity to accomodate existing power supplies. The horizontal trim dipoles are to be located upstream in the proton direction of each quadrupole, occupying a space of no more than 17 inches. For the normal trim dipoles, the maximum current allowed is 10 amperes with a duty factor of 0.7. To provide the stronger dipoles for injection and extraction manipulations, we investigated the possibility of having an optional water cooled plate added to the coil to be able to reach higher currents.

These specifications and constraints were used as a basis of a top-down optimization procedure that is described below. The allowed currents, given the desired ampere turns, precluded us from using copper tubing, but rather required low gauge solid

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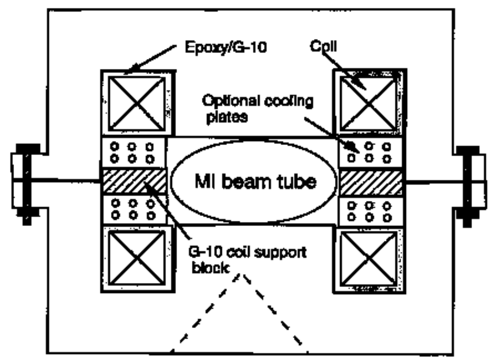

Figure 1. Horizontal magnet corrector cross-section. The dashed line shows an eventual way to increase the magnet area for better heat transfer.

copper wire. We therefore concentrated our efforts in modeling and evaluating the various mechanisms of heat transfer within the magnet components and convection at the outside surface. The main challenge in this optimization was to minimize the temperature of the inner copper to reduce the risk of insulation failure and the temperature of the steel surface for personnel safety consideration. We decided to limit the copper temperature to 95^o C (epoxy rating). We also plan in using Dupont Pyre-ML wire coating which can withstand 220^o C. The steel temperature is limited to 50^o C. Based on failure data of past dipole correctors and other small magnets, we do not believe that extra cooling is necessary for the normal corrector.

We assume an H type of magnet, with pancake coils around the poles. The magnet aperture to accomodate the Main Injector beam pipe is 2 inches for the gap and 5 inches for the pole width, and these define the pole gap and pole width in our magnet. The magnet cross-section is shown in Figure 1

II. Thermal model

The heat starting from the copper wire, flows through the wire coating, the epoxy potting and G10 around the coil, the steel core, and finally is dissipated by convection in the ambiant atmosphere at a 30^o C temperature. Each one of this processes generates a temperature differential that will be estimated. A simple series configuration is assumed, and alternate paths with higher resistance to thermal flow have been neglected. We should mention that a more elaborate thermal model of existing Fermilab corrector magnets has been attempted. In this circuit-like model thermal resistances and capacitances (heat capacities) are fitted to measurements.[2]

To start with, we may assume that good thermal contact between the coil and the steel can be realized only at the bottom or top coil surfaces. Using an electrical parallel circuit analogy, the thermal impedance between the side of the copper coil to the steel pole is much larger than its counterpart at the top or bottom interface. Alternatively, we also consider the possibility where good thermal contact is easier to accomplish at the two coil sides. It should be added that a small air gap will add a significantly high series resistance to the heat flow. Therefore, we plan to use thermal grease in all interfaces with the coil, as well as maintaining good contact pressure.

The conductor coil made of copper wire and coating around each wire is modeled as a distributed heat source with an effective thermal conductivity that depends on the coating conductivity, coating thickness, and wire gauge. This effective thermal conductivity can be derived by considering a unidimensional heat flow through a layer of copper, in between two layers of insulation. The accumulated temperature gradient is then:

$$\Delta T = \frac{P}{S}(\frac{2t}{\lambda_i} + \frac{g}{\lambda_c}) \tag{1}$$

where $\frac{P}{S}$ is the heat flow per unit area, t is the coating thickness, and g is the wire thickness (gauge); λ_i and λ_c are the respective conductivities. Since the copper conductivity is much higher than the insulator conductivity, the effective conductivity of this medium is :

$$\lambda_e = \lambda_i \frac{g}{2t} \tag{2}$$

More detailed calculations for the case of cylindrical wires can be found in [3].

We assume a 4 mil thick Dupont Pyre-ML wire coating which can sustain higher temperature (higher glass transition at which mechanical properties change drastically). For this material the thermal conductivity is about 0.16 watt/m.^{o}C. The coil will be dipped in epoxy to reduce air pockets.

The assumption of only one coil-steel contact simplifies the heat transfer within the copper source to an inhomogeneous 1-dimensional Poisson equation that can be solved easily:

$$\frac{d^2T}{dx^2} = -\frac{p}{\lambda_e} \tag{3}$$

p being the heat production rate in a unit volume of copper. In the case of top/bottom contact, the temperature difference between the hottest point ($\frac{dT}{dx} = 0$), on one side of the coil, and the opposite point closest to the steel interface at a distance h (the coil height) is:

$$\Delta T = \frac{p}{2\lambda_e}h^2 \tag{4}$$

In the alternate case of side coil-steel contact, the temperature depends on w (the coil width):

$$\Delta T = \frac{p}{2\lambda_e}(\frac{w}{2})^2 \tag{5}$$

Next, the heat flow through the epoxy and G10, described by an equation similar to Equation 1, assumes a thermal conductivity of 0.65 watt/m.^{o}C. The respective thicknesses are 30 mils and 1/16 inch.

Finally, the convection at the steel surface is described by:

$$\Delta T = \frac{P}{AH} \tag{6}$$

A is the external magnet area, and H is the heat transfer coefficient by natural convection. Vendor painted aluminum plates can reach about 14 watt/m^2.^{o}C. Our magnet will be painted, and we will assume this optimum value.

III. Optimization of the copper and steel

The size of the copper cross-section, and the length of the steel core are dictated by the necessity to simultaneously

- reduce the power needed to energize the normal corrector.
- minimize the temperature of the hottest spot inside the copper,

The total length of the magnet, coil and steel being restricted to 16 inches, we loose steel length as the coil package increases in width. We are left with only the coil width w and coil height h as free parameters.

For a given magnet strength, the power and the inner coil temperature scales like:

$$power \sim \frac{1}{wh}(\frac{1}{L-2w})^2 \tag{7}$$

where $L = 16$ inches, and

$$\Delta T \sim \frac{1}{w^2(L-2w)^2} \tag{8}$$

for a top/bottom contact, or

$$\Delta T \sim \frac{1}{4h^2(L-2w)^2} \tag{9}$$

for a contact from both sides. These relations are plotted in Figure 2.

Figure 2. suggests that a square coil of size 2 inch is a good compromise that does not overdesign the magnet size. This is the value adopted in the present design. The backleg and yoke are fixed to a thickness of about 1 inch to have enough mechanical strength. No saturation is expected given the low value of the field in the gap.

The magnet core as well as the copper coil are sufficiently defined now to derive other parameters. In particular the amount of heat produced when the magnet is powered to the required

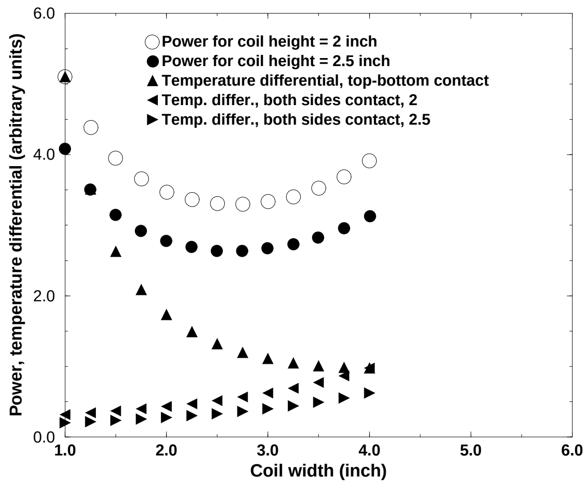

Figure 2. Effect of coil size on the amount of heat and on hot spot temperature

strength and duty factor allows us to estimate the temperature of the different components using the above model.

The steel temperature is found to be 58^o C. This temperature will be decreased by increasing the magnet area. We are exploring two possibilities. The first one is to have wide endplates while the second one is to have a wedge on the top and bottom of the magnet. The latter reduces the weight of the magnet. The former may create a bottleneck for the heat flow, and increase temperature gradients. In any case, we assume that the temperature of the steel can be maintained below 50^o C.

Next, the temperature of the epoxy at the copper coil interface is evaluated. The epoxy is a vulnerable component. If the contact between the steel, G10, and epoxy is tight (thermal grease is utilized), then this interface will be at temperature of about 57^o C. An air gap of 5 mils with the same heat flow, will raise this temperature by 12^o C.

Last, the inner coil temperature is found to be around 81^o C. This is below the limit we specified. At this point we should say that some gradients are short-circuited if we put a water-cooled plate against the bottom or top of the epoxied coil winding. For this option, with a higher current of 15 ampere and the same duty factor we reach a temperature of about 91^o C. This is to be compared to 120^o C with no plate cooling.

IV. Summary

The modeling of the trim dipole has been dominated by the desire to minimize the temperature of sensitive components. It gave us the following directions in which to orient the engineering efforts:

- There must be as much contact as possible between the coil and the steel.
- The winding impregnation should get rid of the air pockets to maximize the effective thermal conductivity.
- The insulating materials are limiting components, and their thermal conductance and temperature resistance should be as high as possible.
- The lamination design should maximize the external magnet surface.
- The steel should preferably be painted in black.

In addition to the thermal calculations we are in the process of adding bumps in the poletip to maximize field uniformity. This design will have to take into account the sextupole captured at the ends since our magnet steel is rather short, 12 inches.

V. Acknowledgements

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References

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