Design Considerations for a Large Aperture High Field Superconducting Dipole

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Introduction

The final phase of the Fermilab upgrade proposal calls for a new ring of superconducting magnets to be placed in the existing Main Accelerator tunnel. The goal of this design study is to specify a high field dipole (HFD) that is capable of supporting fixed target operation (ramping, resonant extraction) at a field of 6.6T (1.5 Tev) and colliding beam physics at 8.0T (1.8 Tev). The magnetic field quality at high field is set by the large amplitude orbits associated with resonant extraction. The field quality must therefore be at least as good as the existing Tevatron magnets which fulfill these criteria.

The high fields and large aperture of this magnet result in large forces on the coil and collar assemblies. Therefore, the cold mass design must be able to sustain these forces while providing sufficient cooling to the coils during 4.2 K fixed target operation, and a minimum heat load during 1.8 K collider operation.

The design work is still in progress but a cosine-theta, cold-iron dipole with a 70mm inner diameter coil has been tentatively adopted. This report presents details on the conductor and cable parameters, coil cross-section, projected manufacturing tolerances, iron yoke design, and cold mass assembly.

Conductor

The field uniformity and performance of a magnet depend on the coil geometry, iron geometry, and the current carrying capability of the conductor. Key features of a cosine-theta magnet design are the dimensions of the cable and the critical current density of the superconductor as they determine the maximum achievable field of the magnet. The primary objective in selecting the conductor for these magnets was to insure a performance margin of 5-10% over the nominal operating current. The cable specification is shown in Table I.

Table I. Conductor Specification

Strand diameter (in.)	0.0268 +0.0002 -0.0000
Number of strands	36
Copper-Superconductor ratio	1.5:1
Strand twist pitch (twists/in.)	2
Filament diameter (microns)	6
Filament spacing/diameter	<0.2
Number of filaments	~5000
Current density at 4.2 K, 5 T (A/mm^2)	>2800
Cable keystone (degrees)	1.03
Cable thickness, inner edge (in.)	0.0439
Cable thickness, outer edge (in.	0.0525

High fields in accelerator magnets require high current density. While superconductor current densities in Tevatron cables were near 1800 A/mm^2 (4.2 K, 5 T), recent advances have resulted in current densities that now approach 3000 A/mm^2. The experience with the Fermilab low-beta quadrupole program suggests that 2800 A/mm^2 is a reasonable specification for cable current density in production quantity.

A copper-to-superconductor ratio of 1.5:1 was chosen to maximize the amount of superconductor in the coil without compromising coil stability. A 6 micron filament diameter was chosen to minimize persistent current effects and hysteretic heating. To minimize the current per turn but yet have adequate width, a cable with a large number of strands, i.e. high aspect ratio, was selected. Since the forces on the cable are independent of the cable dimensions to first order, a wider cable reduces the pressure on the insulation. The strand diameter was chosen to give the necessary cable width.

The coil pressure during 8.8 T operation of the HFD is 2.4 times the peak operating pressure of the Tevatron dipoles. The integrity of the conductor insulation under high pressure is therefore crucial. The HFD insulation is based on the traditional Tevatron system; a Kapton wrap followed by a helical wrap of epoxy impregnated glass tape. A development program is underway to determine whether this insulation system will meet the difficult pressure requirement and will be resistant to creep.

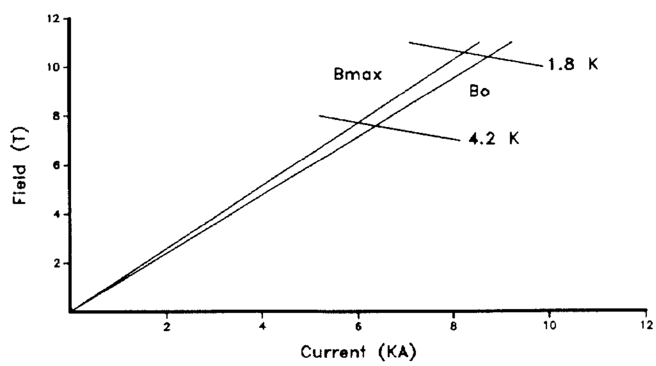

Figure 1. Load line and conductor characteristics.

The HFD load lines are shown in Fig. 1. The central fields at critical current and the corresponding operating margins are as follows:

Operating Temp.	Design Field	Maximum Field	Operating Margin
4.2 K	6.6 T	7.18 T	9%
1.8 K	8.8 T	9.90 T	12%

Coil Cross-section Design

Two recent developments in coil design techniques, wedges and offset placement, permit the construction of coils that generate better field quality than that achieved in the Tevatron dipoles. Conversely, smaller diameter coils (and hence smaller, less expensive magnets) can be used to generate the same field quality. Both of these techniques modify the current distribution in the cosine-theta style coils to more closely resemble the perfect current density distribution (no multipoles). The proposed coil cross-section using both of these features is shown in Fig. 2. The coil diameter is 70mm, 6mm less than the Tevatron magnets. The inner shell uses two wedges and the coil offset is 4.45mm. This design achieves a field of 6.6T at a current of 6176 amps.

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

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The peak field in the coil windings is 7.93% greater than the dipole field which results in a magnet with a 9.0% safety margin. This coil deviates by less than one part in 10^4 across 85% of the coil aperture compared with the Tevatron dipole that obtains only 60% of the coil aperture as a good field region. The calculated multipoles in this magnet are:

Pole	6	10	14	18	22	26	30	34
Mean	0.00	0.00	2.10	-1.07	1.94	-2.27	0.23	0.08

In general two wedges and one offset should allow the first three harmonic coefficients to be made zero. In this design, however, the offset was used to minimize the $\delta B/B$ by letting the 14-pole cancel the next three terms.

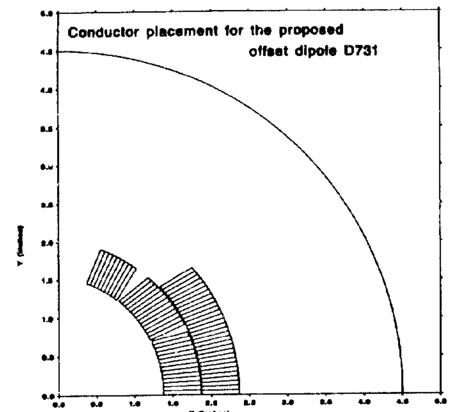

Figure 2. High field dipole coil cross-section.

Tolerances and Coil Motion

An analysis[1] that relates coil dimensional errors to their field multipoles has been done. The analysis concluded: Multipoles higher than decapole are not significantly affected by typical construction errors. The inner coil key angles and parting line must be within 1.0 mil and 0.5 mils respectively to limit the quadrupole through decapole multipoles to 2 units or less; the corresponding outer coil dimensional tolerances are a factor of 2 larger. The radii of inner and outer coil need to be within 1.0 mil to limit the dipole error to 10^{-3}.

These tolerances are easily satisfied by the tooling and coil containment collars, which are assembled out of fine-blanked laminations with a final assembly accuracy of 0.5 mil. The dimensional tolerance of insulated cable is also nominally 0.5 mil. This tolerance is cumulative in the azimuthal direction of the coils, and results in variable sizes and elastic moduli of the molded coils. When assembled in collars, the median plane adjusts to accommodate the up-down differences unless the coils are premeasured and matched. The Tevatron experience[2] indicates that matching of coils reduces the multipole errors to a fraction of a unit.

The HFD conductor motion due to the influence of the magnetic field on the transport current has been calculated for a field of 8.8 T, an azimuthal elastic modulus of 3 mpsi, and the assumptions of a rigid collar and adequate preload to hold the coil ends in contact with the collar keys. The peak position error of the inner and outer coil conductors is 1.4 mil and 0.6 mil respectively. These displacements will increase the sextupole multipole by approximately 2.5 units which can be compensated by the the sextupole resulting from iron saturation.

Yoke Design

One major problem in designing high field magnets is saturation of the iron yoke at high fields changing the field distribution. The approach taken in this design is not to avoid or reduce saturation in the magnet, but to control the way the iron is saturated. For this purpose different yoke designs have been analyzed and a final design suggested.

Saturation effects: These effects are described analytically in Halbach's paper.[3] Given a relation between B and H in the iron, there will now be an azimuthal field component H_ϕ on the surface associated with a varying scalar potential. This results in the generation of harmonics, which are nothing but the Fourier coefficients of the azimuthal field component at the inside surface of the iron shell.

When applied to a symmetrical dipole (N=1) the sextupole effect is given by the term:

$$b_3 = -\frac{4i}{\pi R^2} \int_0^{\pi/2} \cos(3\phi) H_\phi(\phi)\, d\phi \qquad (1)$$

It is noted from Eq. (1) that the integral is the sum of a positive and a negative contribution, simply because the term $\cos(3\phi)$ changes sign at $\pi/6$ and H_ϕ is always either positive or negative (for a circular inner iron geometry). Depending on the distribution of H_ϕ, the two contributions can balance out, leading to a small sextupole value. At magnetic fields of this magnitude, it is not, therefore, a question on whether the iron is saturated, but more a question on how the iron is saturated. Also, the value of sextupole by itself is not a measure of how much the iron is saturated. The amplification factor is still a good representative number for that purpose. In the next sections we shall look at different designs and see what effect they have on mainly the sextupole.

Inner/outer diameter effects: By varying the inner radius of the iron we will affect the way the iron inner surface saturates. For a given inner radius, the sextupole variation versus central dipole field seems to have one of two general shapes. The first and most common shape is where the sextupole magnitude increases to a maximum and then decreases. This behaviour is due to the saturation in the immediate vicinity of the pole causing the increase in sextupole. Saturation on either side of the coil will cause the sextupole magnitude to decrease. Tollestrup[4] had similar observations. It is important to note that such a behavior is very much dependent on the inner radius value. For a relatively higher inner radius value, the notion of immediate vicinity vanishes and the sextupole peak will start to disappear resulting in a monotonically decreasing sextupole versus central field. Figure 3 illustrates this behavior for different inner radii. As the inner radius increases the peak vanishes.

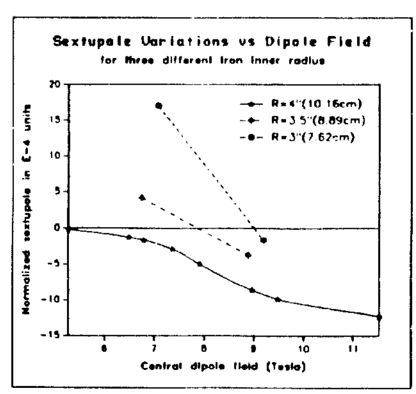

Figure 3. Sextupole component vs coil i.d.

Based on these two types of behavior we then have two options in our yoke design. Either select a radius such that the two lower ends of the peak correspond to a low sextupole value with a limited maximum value for the peak, or have a monotonically increasing value that will not exceed critical values at high fields.

The effect of the outer radius is less predictable. Up to now we have used an iron outer radius of about 22 cm. By reducing the thickness of the iron we will significantly increase the sextupole component while reducing the dipole field (higher amplification factor) for a similar exciting current. By contrast increasing the iron thickness has the opposite effect. These behaviors are shown in Fig. 4.

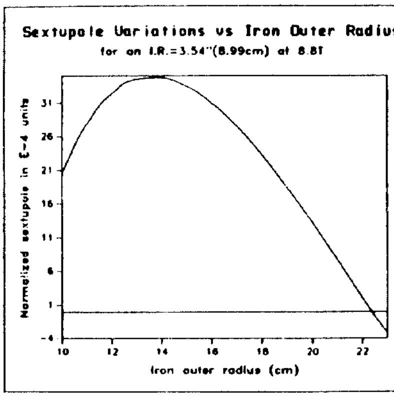

Figure 4. Sextupole component vs iron thickness.

Elliptical cross-sections: The peak in the sextupole coefficient is due mainly to the saturation of the pole in the immediate vicinity of the coil. It is therefore natural to assume that a change in the pole shape in that region might drastically affect the result. As an example, we selected a flat pole, leaving the sides circular. As shown in Fig. 5, the improvement from a circular pole relative to a flat pole is apparent. One can argue that a flat pole will lead to more saturation. Again, the strategy is not to avoid saturation but to control how the saturation occurs. The flat pole with circular sides, similar to an elliptical shape, makes this design a strong candidate.

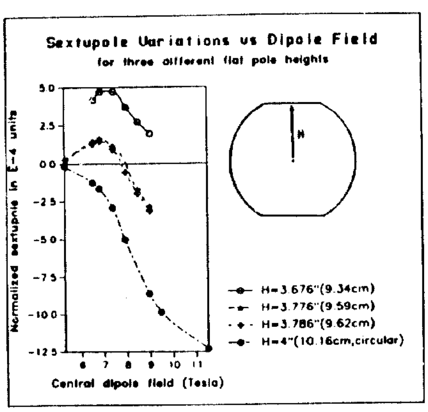

Figure 5. Sextupole component vs iron cross-section.

Initial work on the iron yoke demonstrates that it is possible to maintain a small sextupole component at high fields. Different parameters affecting the sextupole variations have been considered together with methods to control these variations. Two different designs are suggested. The first one uses a circular iron shape at 4.5 in. and eliminates the peak in the sextupole variations. To further reduce the sextupole coefficient a thicker iron yoke is necessary. An alternative design uses a smaller inner radius, 4 in., with a flat pole to reduce the peak sextupole variation.

Cold Mass Assembly

The coil collar has to be designed to contain the Lorentz forces at the 8.8 T maximum field of the HFD. At this field, the peak inner and outer azimuthal Lorentz forces are 7900 lb/in. and 3950 lb/in. respectively. Allowing some margin for loss of preload during cool-down, this represents a pressure of 20,000 psi on the inner coil and 10,000 psi on the outer coil during collaring.

Our initial designs have considered collar outer diamenters of 7.2 in. to 8.0 in. The corresponding iron yoke diameters are 17.3 in. to 22.0 in. For these size collars, the stresses are limited to 50,000 psi; high for aluminum but concentrated in a small, non-critical area of the key slots. Steel tapered keys are used to join the upper and lower coil packs. Spot-welded aluminum laminations are used to reduce the preload loss during cool-down. Unless braced by the more massive iron yoke, the vertical and horizontal diameters of the collars will deform 0.011 in. and 0.003 in. respectively.

The cold mass cryogenic design work is still in progress. The cold mass must have sufficient cooling to minimize the temperature rise along the length of the magnet during 4.2 K fixed target ramping. The cold mass also requires minimum liquid helium volume and heat leak to the 1.8 K liquid helium during colliding beam operation. Cooling during ramping can be achieved by heat transfer to a contiguous two-phase helium shell, either outside the collar or from the inside of the magnet through a double-walled bore tube. The 1.8 K volume can be reduced by a containment skin between the collars and the iron, or by filling the iron laminations with epoxy. Heat conduction to the 1.8 K liquid helium can be reduced by supporting this volume within a 4.2 K surface.

Conclusions

The initial stages of this design work have shown that it is possible to achieve the required field uniformity over the proposed operating range of this magnet. Conductor placement errors, coil motion, and iron saturation will all modify the design field but within operating tolerances. A cable designed specifically for this magnet is required. The large aperture and high fields produce large forces and stresses on the coil assembly which require detailed attention to the mechanical design of the magnet, and will probably be the limiting factor in the magnet performance. Two distinct cryogenic operating regimes provide another significant challenge to the cold mass design.

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