Permeable Materials in the CLEO III Magnetic Field

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Two pairs of superconducting magnets will be inserted into CLEO as part of the CESR/CLEO phase III upgrade. Stray fields from the superconducting magnets will affect the field quality of the solenoid in the sensitive region of the CLEO detector. This problem was analyzed in [1]. In addition, the superconducting magnets will be supported by an active, high precision positioning system. Parts of the positioning system will be made from permeable materials which will magnetize in the CLEO field and generate undesireable fields. These fields could affect beam dynamics as well as the calibration of the drift chamber. An analysis of these effects is presented in this paper.

Description of Problem

The cryostats of the superconducting interaction region magnets will be kinematically supported on roller bearings. The bearings will be held by stainless steel rails mounted to the fixed (pylon) portion of the CLEO return yoke. There will be two rails for each cryostat. The bearings are made of a hard bearing steel and are ferromagnetic. The rails will be made of 316L stainless steel and are slightly permeable. Because the rails are large (about 550 lbs each) the effect of even slight permeability can conceivably be significant. The rails and the bearings are approximately 30-35 cm from the beam axis. The rails start about 1300 mm from the interaction point and end at the CLEO yoke. The bearings are on the IP end of the rails. See figure 1

Magnetization of the Bearings

Adjacent to each other, on the end of each rail are a cam bearing and a support bearing. They will be treated as if lumped together for the purpose of analysis. When the CLEO solenoid is energized the bearings will magnetize and cause field distortions. An upper limit to the magnetization is assumed to be equal to the saturation magnetization pure unit volume of pure iron $M = 1830$ G, [1] corresponding to an internal field of $4\pi M$ 23,000 G [2]. This is be an overestimate of the actual bearing magnetization because the bearings are not pure iron. In fact the assumed degree of magnetization is about what you could expect from the high performance material vanandium permadur [3].

The total dipole moment m for a bearing pair is estimated by taking the saturation magnetization per unit volume and multiplying by the volume of the bearings. In the positioning system the two types of bearings together weigh 2.61 lbs

[1] I will use cgs units in this discussion. Magnetization will be in units of gauss, dipole moment will be in units of gauss cm^3.

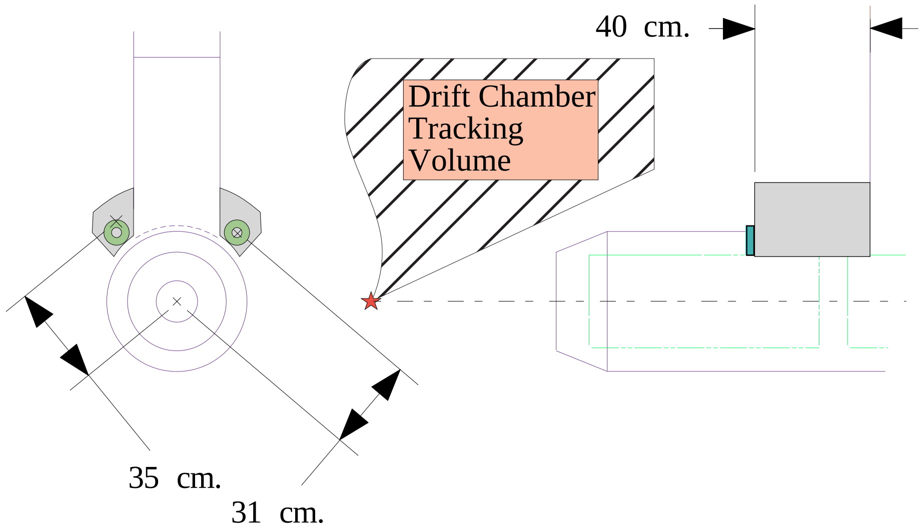

Figure 1: Distortions of the cleo solenoid field by the positioning system bearings.

which is 152 cm^3 per bearing pair. This gives a total dipole moment m of

$$m_{bearings} = 2.78 \times 10^5\ G\ cm^3 \quad (1)$$

located on the end of each rail.

Magnetization of the Rails

Magnetization measurements of the raw material to be used for the rails were done at a field level of 4580 G [4]. At this field the induced magnetization corresponds to permeability $\mu(H = 4580\ G)$ ranging from 1.0076 to 1.0273, depending of samples measured. We do not know what the magnetization will be at the CLEO field of 15000 G. In many magnetic materials, the magnetization saturates at fields below about 1000 Oe [3]. If this were true for the 316L stainless for the rails then the permeability at 15000 G would be less than about 1/3 of the permeability at 4580 G. To be conservative I will assume the permeability holds constant up to 15000 G and is equal to the highest of the measured value, i.e. 1.0273.

Field Calculations

The distance from the bearings to either the beamline or the tracking volume is much larger than the size of the bearings, so far field approximations of the field distortions are valid in the regions of interests. This greatly simplies estimates of the their effects because the magnetize bearings can be replaced with single magnetic dipole so long as the total dipole moment is correct. The CLEO steel yoke is far enough away from the bearings to be neglectable.

For the rails the situation is similar in that the relevent distances are much bigger than the transverse size of the rails, but the length of the rail is comparable with the distance to the beam axis. To calculate the effect of the rails I will integrate over a line distribution of magnetic moments. The CLEO steel yoke will have an effect in this case.

The vector potential from a magnetic dipole of strength m pointing in the $+z$ direction is

$$A_\phi = \frac{m \sin\theta}{r^2} \tag{2}$$

where r is the distance from the dipole to the observation point and θ is the spherical coordinate system angle from the z axis to the observation point.

The magnetic field is obtained by taking the curl of A_ϕ. The result is

$$B_r = \frac{2m\cos\theta}{r^3} \tag{3}$$

$$B_\theta = \frac{m\sin\theta}{r^3} \tag{4}$$

$$B_\phi = 0 \tag{5}$$

Notice the field drops with the cube of the distance.

It is useful to derive the field parallel to the axis of CLEO but offset some distance b from a magnetic dipole, as well as the field perpendicular. The results are:

$$B_\perp = B_r \sin\theta + B_\theta \cos\theta \tag{6}$$

$$= \frac{3mbz}{(b^2+z^2)^{5/2}} \tag{7}$$

$$B_\parallel = B_r \cos\theta - B_\theta \sin\theta \tag{8}$$

$$= \frac{m(2z^2-b^2)}{(b^2+z^2)^{5/2}} \tag{9}$$

where z is the axial distance from the magnetic moment to the observation point.

Bearings effect on CLEO

From the geometric layout the nearest point of the detector tracking volume is about 24 cm away, with $b = 9.4$ cm and $z = 22.4$ cm. Using equation 9, at this point the contribution to the CLEO solenoid field in the direction of the solenoid field is

$$B_{bearings} = 32\ G \tag{10}$$

which is slightly more than two parts per thousand change in the solenoid field. Because of the inverse cube dependence, the bearings affect only a small portion of the tracking volume, nearest the beam axis and furthest from the interaction. A few centimeters deeper into the drift chamber the field distortion drops rapidly below the part per thousand level. Thus magnetic bearings are not expected to produce significant effects on CLEO tracking.

Bearings Effect on Beam Dynamics

On the question of effects of the bearings on beam dynamics it is important to keep in mind that the distance to the beam from the positioning system bearings, 31 cm, is much larger than the size of the bearings, 4 cm, so the lowest order multipoles are most significant. Because there is no special symmetry all multipoles will be present. The two lowest order multipoles are dipole and quadrupole. These are essentially of no importance other than to shift the closed orbit slightly and slightly change the required setting of the quadrupole.

Another important point is that the beam integrates the effect of the bearings along its trajectory. Upstream and downstream of the bearings the effect is opposite, so a straight integration of the force due to the magnetic field from the bearings along the beam axis yields exactly zero. However, all particles do not follow the design axis so there can be more subtle effects on

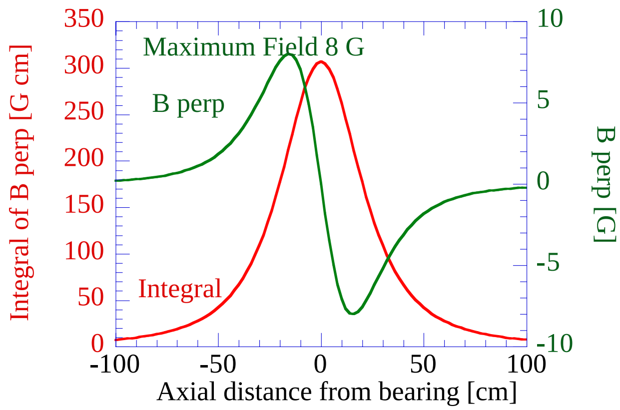

Figure 2: The magnetic field perpendicular to the beam axis due to nearby magnetic bearings.

beam dynamics, even if the integral of the field distortion cancels out.

The field perpendicular to the beam axis is plotted in figure 2. The maximum perpendicular field occurs at position upstream of the bearing $b/2$, where b is the distance of closest approach (31 cm) between the design axis and the bearing center. The value of this peak field is 0.859 m/b^3 which is 8 G. This field will locally shift the quadrupole magnetic center of Q1 by 18 μm, which illustrates the insignificance of the dipole component.

To evaluate the significance of the nonlinear fields on the beam dynamics I will use the field quality specification for the nearby superconducting interaction region magnets as a reference. That was based on tracking studies and holds that non-quadurpole and non-dipole fields at 5 cm from the beam axis be less than 5×10^{-4} of the quadrupole field. This works out to be is 11 gauss at 5 cm, or when integrated over the effective length of 65 cm, 715 Gcm.

The integral of the perpendicular field along the beam axis is:

$$\int_{-\infty}^{z} dz' B_{\perp}(z') \quad = \quad \frac{-mb}{(b^2 + z^2)^{3/2}} \qquad (11)$$

Starting at $-\infty$, this integral is maximal just opposite the bearing where it has the value of -289 Gcm. If the integral is continued to $+\infty$, to get the entire kick to the beam, it would give zero result. However, as mentioned above, to be conservative, I will evaluate the maximum value of the integral and interpret it as a worst case.

We must subtract off quadrupole and dipole contribution to this integral before comparing it with the specification. After a bit of algebra, it can be shown that, when expanded about the beam axis, the first non-linear component (sextupole) of the integrated bearing field is $3\delta^2 m/b^4$ where δ is the distance from the beam axis to the point where the field is evaluated at, i.e. 5 cm. This works out to 22.6 Gcm for a bearing pair — about 3% of the specification limit for the nearby superconducting quadrupoles. This amount is not trivial, but given that it is canceled out almost immediately, and that it is a reasonable upper bound, it would seem that the effect of the bearings on beam dynamics is ignorable. Higher components of the bearing field are less important. The field from the bearings at this distance is relatively smooth and the multipole expansion rapidly converges.

Field from Rails

I will calculate the fields generated by one rail including the effects of the CLEO steel. Each rail starts at the CLEO steel and extends into the CLEO detector field a length $L = 40.6$ cm. Radially the center of the rail is 35.1 cm from the beam axis. I assume that I can simulate the field distortion by a linear distribution of magnetic dipoles located at the center of the rail and extending the full length of the rail.

Using the assumed worst case permeability of 1.0273 as mentioned above, we have $B = \mu H = H + 4\pi M$ so $M = H(\mu - 1)/4\pi = 32.6\ G$. The cross-sectional area of the rail of $A = 309\ cm^2$ so the magnetic moment per unit length along the rail is $MA = 1.01 \times 10^4$ in cgs units. The effect of the CLEO steel is to create an image of the line of dipoles, with dipole moments in the same direction. This means the source integration extends over a distance $-L$ to L. See figure. Using equation 7 we obtain the net field perpendicular to the beam axis is at position z, where $z = 0$ is the beginning of the CLEO steel:

$$B_\perp = \int_{-L}^{L} dz' \frac{3MAb(z - z')}{(b^2 + (z - z')^2)^{5/2}} \quad (12)$$

$$= -MA\{\frac{1}{(b^2 + (z + L)^2)^{3/2}} - \frac{1}{(b^2 + (z - L)^2)^{3/2}}\} \quad (13)$$

for $z < 0$. For $z > 0$ the CLEO steel approximately shields the beam from the effect of the rail permeability. The field is plotted in figure 3

The peak value of the perpendicular field on the beam axis occurs just beyond the end of the rail at 41.4 cm from the CLEO steel and has a value of 0.22 G. The integrated effect on the beam is obtained by integrating $B_\perp$ from $-\infty$ to 0. We get:

$$\int_{-\infty}^{0} dz B_\perp = -\frac{2MAL}{b^2\sqrt{b^2 + L^2}} \quad (14)$$

This evaluates to 12.4 Gcm. If this is averaged over the length of an interaction region magnet (65 cm) it would have an average strength of 0.19 G.

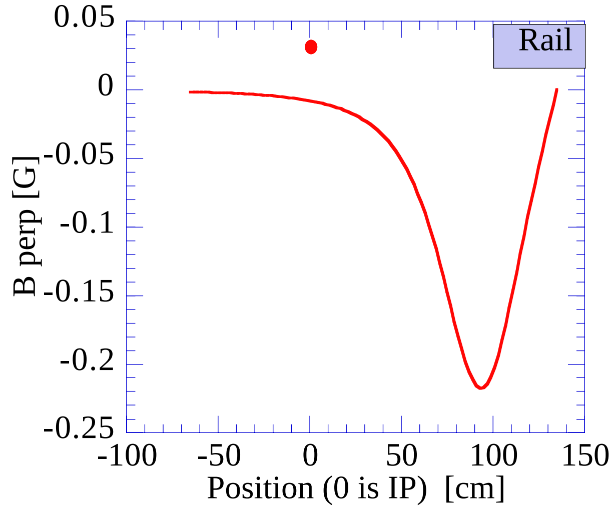

Figure 3: Field generated by magnetization of a stainless steel rail.

The total magnetic moment of the rails is $MAL = 4.10 \times 10^5\ Gcm^3$ which is about 1.5 times more than magnetic moment of a bearing pair. In the case of the rails, the linear distribution of magnetic moments generates some cancelations which were not included in the bearing estimate.

Higher moments of the rail generated field can be calculated but are very small. The quadrupole moment will be of order $0.19 \times 5/35 = 0.03\ G$ at 5 cm radius. The sextupole contribution will be of order $\frac{1}{2}\frac{5}{35} times 0.03 = 0.002$ G. Etc. These higher moments are much smaller than the specified limit for the interaction region magnets (11 G) We may conclude that the nonlinear effects of the rail permeability are not significant.

References

[1] G. Dugan and J.J. Welch, *Stray Fields in*

CLEO from the Phase III Superconducting Quadrupoles,CBN 96-4, (1996)

[2] Purcell, page 395

[3] G.E. Fischer, *Iron Dominated Magnets* AIP Conf. Proc. 153, Vol 2, pp 1201 (1985).

[4] Internal note/memo