D0 BETA MAGNET DECENTERING FORCES: AN "IMAGE SOLENOID" APPROACH

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ABSTRACT

We estimate the decentering forces on the the D0 β magnet by calculating the forces between the solenoidal currents in the magnet and their images in the WAMUS and SAMUS iron yokes, which are modeled as semi-infinite sheets of infinitely permeable iron.

1 BETA MAGNET PRELIMINARY DESIGN PARAMETERS

We refer to the 10/19/91 Draft Design Report for the dimensions of the β coil and its location with respect to the WAMUS and SAMUS iron:

D0 β Magnet Parameters	
Parameter	Value
L (coil length)	256.5 cm
R_i (Coil Inside Radius)	60.8 cm
R_o (Coil Outside Radius)	64.9 cm
N (# Turns)	1056
I (Operating Current)	4600 Amperes
Near Samus Iron Boundary	4.4 m (axially)
Near Wamus Iron Boundary	3.2 m (radially)

2 LORENTZ FORCE BETWEEN TWO SOLENOIDS

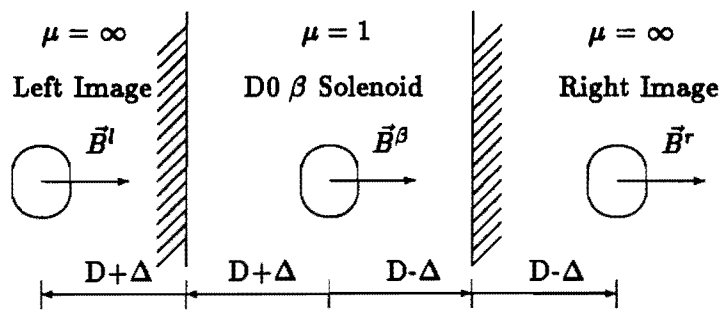
We subdivide the D0 β solenoid axially and radially into many current loops, and each loop into many phi segments, and calculate the Lorentz force on each segment from the fields produced by the two image solenoids in the respective WAMUS or SAMUS iron yokes. We sum over all segments and loops to obtain the total force on the β solenoid. We assume the magnetic permeability of the iron is infinite in order to replace it with air-core image solenoids located symetrically with respect to the original air-iron boundaries.

We calculate the fields of the image solenoids by subdividing them as we do the β solenoid and we use the CERNLIB elliptic integral package to calculate

the magnetic fields of the resulting current segments. The subdivision of the image coils is sufficiently fine to generate field values accurate to $\frac{1}{4}$%.
For each current element of the β solenoid, $d\vec{F} = dI\, d\vec{L} \times \vec{B}$; a sum over all current elements in the β solenoid yields the total force between the solenoid and its images in the iron.

3 AXIAL DECENTERING

For the axial case, the solenoid is located between two semi-infinite sheets of iron, and image currents are generated within the (infinitely permeable) steel by the currents of the D0 β solelnoid. When the solenoid is shifted off-center by an amount Δ to the right:



3.1 THE FORCES DUE TO THE AXIAL IMAGES IN THE IRON

The field at a current element at (r,z) of the β solenoid $\vec{B}(r,z)$ is a sum of $\vec{B}^l$ + $\vec{B}^r$, where, explicitly, $\vec{B}^r(r,z)$ = B(r,z-2(D-Δ)), and $\vec{B}^l(r,z)$ = B(r,z+2(D + Δ)). The β solenoid was subdivided into 20 axial and 10 radial current loops, and each loop into 40 phi segments.
When the parameter Δ is set to zero, we obtain

$$\begin{aligned} F_x &= -0.389x10^{-2}\, N \\ F_y &= +0.123x10^{-2}\, N \\ F_z &= +0.114x10^{-4}\, N. \end{aligned}$$

This gives us a measure of the precision of the calculations, since in this case the components of the force should all be zero. Evidently we have discretized the coils adequately.

For $\Delta = 10$ cm. we obtain

$$\begin{aligned} F_x &= -0.389x10^{-2}\,N \\ F_y &= +0.102x10^{-2}\,N \\ F_z &= +0.625x10^{3}\,N. \end{aligned}$$

Since the displacement was 10 cm, we have

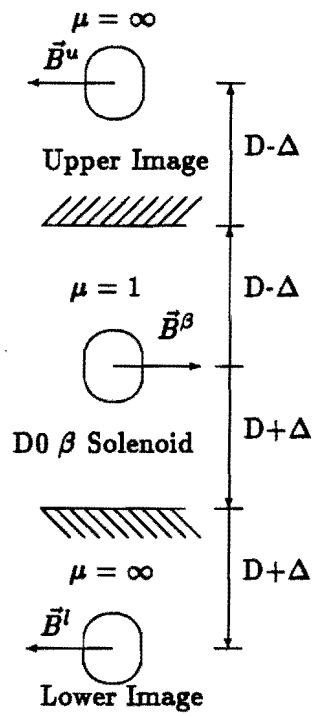
$$\left.\frac{F}{\Delta}\right)_{axial} = 6.25 \times 10^3[\frac{N}{m}], \quad (1)$$

$$= 35.7[\frac{lb}{in}] \quad (2)$$

in the direction of Δ.
We recall that the "image dipole" model developed in an earlier note gave a decentering force of $6.72x10^3\,[N/m]$. We would expect the "image solenoid" results to be more realistic than the "image dipole" calculations since although both assume the iron can be replaced by image currents, the "image solenoid" model does not make any "dipole field" approximations for the magnet or its images. The close agreement of the two calculations is perhaps due to the inherent small magnitude of the decentering force, which is itself due to the relatively large distances between the magnet and the SAMUS iron.

4 RADIAL DECENTERING

For the radial case, the solenoid is located between two semi-infinite sheets of iron above and below it, and image solenoids are generated within the (infinitely permeable) steel by the currents of the D0 β solenoid. When the magnet is shifted upwards by an amount Δ:



4.1 THE FORCES DUE TO THE RADIAL IMAGES IN THE IRON

The field at a current element at (r,z) of the β solenoid $\vec{B}(r,z)$ is a sum of $\vec{B}^u + \vec{B}^l$, where, explicitly, $\vec{B}^u(r,z)$ = B(r-2(D-Δ),z), and $\vec{B}^l(r,z)$ = B(r+2(D+Δ),z). We note that the image currents circulate in the opposite sense of the β solenoid.
When the parameter Δ is set to zero, we obtain

$$\begin{aligned} F_x &= -0.609x10^{-2}\,N \\ F_y &= -0.969x10^{-3}\,N \\ F_z &= -0.191x10^{-5}\,N. \end{aligned}$$

Again, a null result is expected and we see that our discretizations yield adequate precision. However, for Δ = 10 cm. we obtain

$$\begin{aligned} F_x &= -0.109x10^{-1}\,N \\ F_y &= +0.801x10^{3}\,N \\ F_z &= +0.181x10^{-4}\,N. \end{aligned}$$

Since the displacement was 10 cm, we have

$$\left.\frac{F}{\Delta}\right)_{radial} = 8.01 \times 10^3 [\frac{N}{m}], \tag{3}$$

$$= 45.7[\frac{lb}{in}] \tag{4}$$

in the direction of Δ. We recall that the "image dipole" model gave a radial decentering force of $1.1x10^4$ $[N/m]$. As in the axial case we would expect the "image solenoid" results to be more realistic than the "image dipole" calculations, as discussed in section 3.1 above.

5 CONCLUSIONS

The important assumption in the foregoing is that the β solenoid is imaged undiminished in the SAMUS and WAMUS iron. As was shown in the earlier note of the "image dipole" model, this assumption is likely to be conservative by a few percent.

As in that note, and reinforced by the rather close agreement between the "image dipole" and "image solenoid" models, we remain certain that designing for decentering forces a factor of 10 greater than those provided by the models is conservative:

$$\left.\frac{F}{\Delta}\right)_{axial} = 360\,[\frac{lb}{in}] \tag{5}$$

$$= 700\,lbs \tag{6}$$

for a 5 cm axial displacement. And

$$\left.\frac{F}{\Delta}\right)_{radial} = 460\,[\frac{lb}{in}] \tag{7}$$

$$= 900\,lbs \tag{8}$$

for a 5 cm radial displacement.