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Publication Date

1995-06-05



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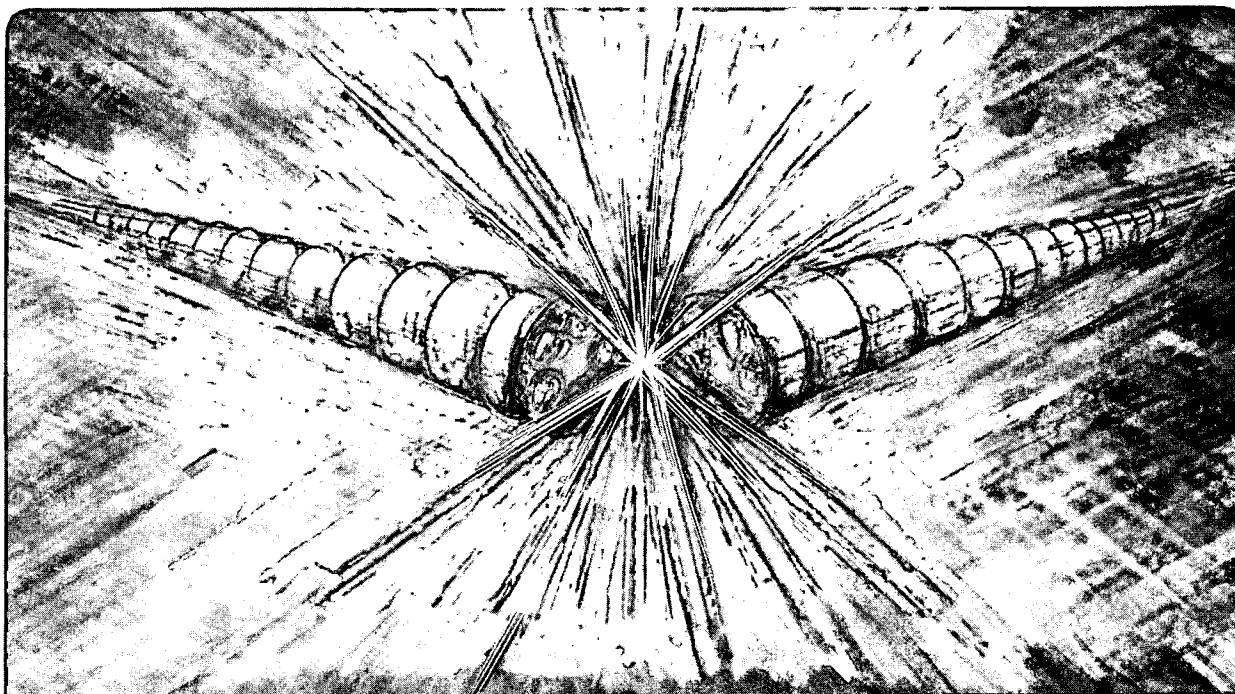
Accelerator & Fusion Research Division

Presented at the 14th International Conference on Magnetic
Technology, Tampere, Finland, June 11-16, 1995, and to
be published in the Proceedings

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**PASSIVE TEMPERATURE COMPENSATION IN HYBRID MAGNETS WITH
APPLICATION TO THE FERMILAB STACKER AND RECYCLER RING
DIPOLE DESIGN***

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June 1995

Paper presented at the 14th International Conference on Magnetic Technology,
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Temperature Compensation in Hybrid Magnets with Application to the Fermilab Stacker and Recycler Ring Dipole Design

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Abstract—Design theory of hybrid (permanent magnet plus iron) accelerator magnets with application to the proposed permanent magnet recycler and stacker rings at the Fermi National Laboratory is presented. Field stability in such devices requires that changes in the strength of the permanent magnet material with temperature be compensated. Field tuning techniques, including those employing variable capacitance between energized pole and magnet yoke and those employing variable energization of magnet pole pieces, are described. Mechanical configurations capable of achieving temperature compensation passively, including use of expanding liquids/gases and bimetallic springs are outlined. Active configurations, relying on an actuator, in addition to temperature compensation, have the additional benefit of enabling magnet tuning about a nominal operating field level.

I. INTRODUCTION

Permanent magnet (PM) accelerator magnets offer the advantage of being free of power supplies, cooling equipment, and operating energy costs. Fermilab is actively pursuing ferrite permanent magnet designs for stacker and recycler ring dipoles and quadrupoles. Issues that must be dealt with include magnet tunability and on-axis field stability under changing environmental conditions [1]. Passive temperature compensation to maintain on-axis field B_0 invariant is addressed here.

II. HYBRID MAGNET DESIGN

Figure 1 shows the first quadrant of a generic hybrid magnet consisting of a pole piece and a yoke comprised of soft magnetic material, typically iron or vanadium permendur and magnetized PM blocks, typically Neodymium-Iron-Boron, Samarium-Cobalt, or ferrite. Herein, the PM material with $\mu = 1$ is represented by magnetic charge sheets with charge density $\pm B_r$ on surfaces [2,3]. The permanent magnets deposit a "direct" flux into the pole

piece, which then assumes a scalar potential V_0 relative to the yoke and midplane, on $V = 0$. This potential difference drives an equivalent amount of "indirect" flux out of the pole, a portion of which crosses the device midplane, with the remainder entering the yoke. The equivalence of direct and indirect flux into the pole piece follows directly from $\nabla \cdot \mathbf{B} = 0$. The balance of direct flux and indirect flux in terms of the on-axis field B_0 , the PM's remanent field B_r , and the magnet's geometry (Fig. 1) is given by:

$$B_r \left(D_2 + \frac{D_1 h_3}{h_2} \right) = B_0 h_0 \left(\frac{D_1}{h_0} + \frac{D_2}{h_1} + \frac{D_1}{h_2} + E_c \right);$$

$$B_0 = \frac{(B_r)(h_3/h_0)(D_2/h_3 + D_1/h_2)}{(D_2/h_1 + D_1/h_2 + D_1/h_0 + E_c)} \quad (1)$$

where $E_c \equiv E(h_0/h_1) + E(h_1/h_0) + E(h_2/h_1) + E(h_1/h_2)$ is a known closed-form geometrical excess flux factor for the pole corners [2]. Three-dimensional effects from ends have been neglected; their inclusion is straightforward but do not change the gist of the development.

It is desired to keep B_0 invariant to within 0.01%. Ferrite's B_r , and thus the flux deposited on the pole, varies with temperature -0.2%/degree C.

III. TEMPERATURE COMPENSATION

Flux across the midplane can increase in-situ via two mechanisms:

1. If the direct PM flux into the pole is increased, indirect flux out of the pole likewise increases. If magnet geometry, including dimensions and permeabilities, is kept invariant, pole scalar potential V_0 and thus B_0 across the midplane (and incidentally, flux to the yoke) increase proportionally.
2. For a fixed direct PM flux into the pole, indirect flux out of the pole remains unchanged. However, if the capacitance from pole-to-yoke is decreased or if the capacitance from pole-to-midplane is increased, a larger fraction of this potential-driven indirect flux crosses the midplane, increasing B_0 . Capacitance changes are accomplished via an alteration of the system's geometry, i.e., either a change in a medium's permeability or a dimensional change.

Manuscript received June 13, 1995.

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Mat. Sci. Div., of the U.S. Dept. of Energy, Contract No. DEAC03-76SF00098.

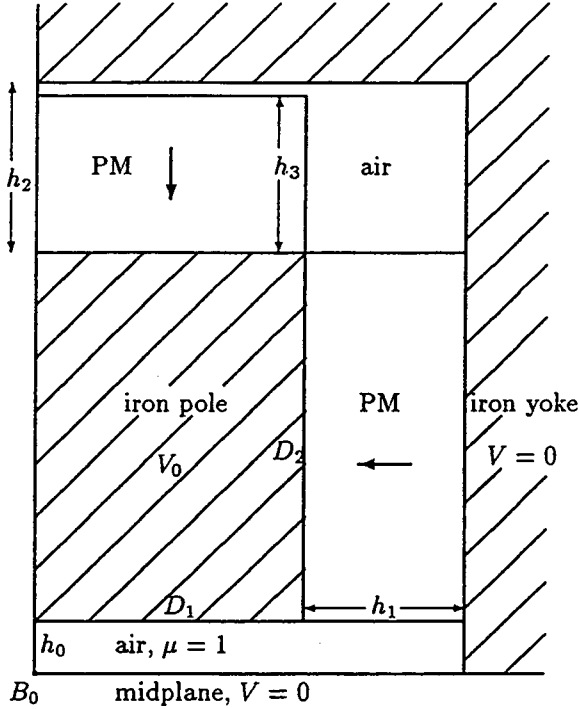


Fig. 1. First quadrant of generic hybrid PM dipole; variable h_2 enables temperature compensation/ field tuning (beam axis is into paper at lower left corner)

The first mechanism occurs naturally whenever ambient temperature changes. For a temperature rise, the ferrite's B_r decreases resulting in a reduced B_0 . A method for compensating this temperature effect that utilizes the second mechanism, specifically, altering a medium's permeability to effect a pole-to-yoke capacitance change has been described previously [4]. It entails bleeding off a fraction of the indirect flux via a pole-to-yoke shunt whose permeability varies inversely with temperature. As temperature rises pole-to-yoke capacitance is reduced, so as to increase V_0 and the fraction of flux crossing the midplane. B_0 rises just enough to offset its decrease via the first mechanism, due to the PM's lowered B_r .

A. Dimensional change in yoke

Here we proffer an alternative technique that relies on a dimensional change which, via the second mechanism, alters the pole-to-yoke capacitance and via the first mechanism, alters the direct flux into the pole. Specifically, a positive vertical displacement of the top portion of the yoke in Fig. 1 changes B_0 via both mechanisms: (1) The direct flux into the pole decreases due to the increased fraction of flux deposited on the pole from the negative charge sheet surface at the top of the uppermost PM block. This effect lowers B_0 (and incidentally the indirect flux from pole-to-yoke as well). (2) Pole-to-yoke capaci-

tance decreases, thus the fraction of indirect flux to the midplane increases, effecting a rise in B_0 . Assume that $h_3 = h_1$ and $h_2 \simeq h_3$ for the optimally designed magnet of Fig. 1. Net change in B_0 as h_2 is incrementally increased from its initial value $h_2 = h_1$ is

$$\left. \frac{dB_0}{dh_2} \right|_{h_1} \equiv B'_0 = \left(\frac{-B_r D_1}{h_0 h_1} \right) \left(\frac{(1 - B_0 h_0 / B_r h_1)^2}{w_1 / h_0 + E_c} \right) \quad (2)$$

where the negligible dE_c/dh_2 term has been dropped. Assume the PM operating point in the optimized magnet design is at $\sim B_r/2$:

$$B_{PM} = B_0 h_0 / h_1 = B_r / 2. \quad (3)$$

Then fractional changes in B_0 and in h_2 are given by:

$$\frac{\delta B_0}{B_0} = \frac{(-\delta h_2 / h_0)(B_r / B_0)^2}{8(1 + E_c h_0 / D_1)} \quad \text{and}$$

$$\frac{\delta h_2}{h_2} = -4(B_0 / B_r)(\delta B_0 / B_0)(1 + E_c h_0 / D_1). \quad (4)$$

Note that the change in the direct flux dominates the opposing effect of the pole-to-yoke capacitance change. For our strawman design $E_c h_0 / D_1 = 0.5$ and $B_0 / B_r = 1.25$. Per degree C temperature rise, $\delta B_0 / B_0|_{\delta B_r}$ is -0.002; we desire the dimensional change to exactly negate this on-axis field drop. Inputting these numbers into Eqn. (4) gives the fractional change in h_2 required to compensate for the change in strength of the PM material with temperature:

$$\frac{\delta h_2}{h_2} = -1.5\% \quad \text{per degree C temperature rise.} \quad (5)$$

Various means can passively effect this required closing of the yoke-to-pole gap as temperature rises, including use of bimetallic springs or expanding liquids. Liquids, for example, with a coefficient of cubical expansion $\sim 0.1\%$ per degree C, filling a cavity of height h_4 beneath a fixed strongback and necking down by a factor $r = 15h_2/h_4$ to a cylinder with a piston attached to the top of a moveable, low friction upper yoke section could adequately provide the dimensional change. We are currently exploring practical, inexpensive designs that implement such a passive temperature compensation feature.

B. Rotation of a PM tuning block

Another technique we have pursued also relies on a dimensional change which, via the first mechanism, alters the direct flux into the pole. It entails the rotation of a PM tuning block, most likely positioned in the air space near the upper-right corner of the pole piece as shown in Fig. 2. In the orientation shown, the PM tuning block has

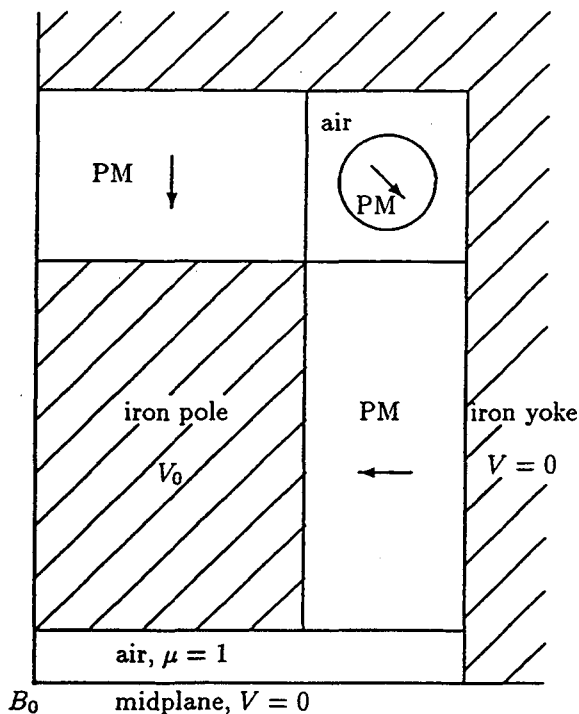


Fig. 2. First quadrant of hybrid dipole showing temperature compensating/ field tuning stud (beam axis is into paper at lower left corner)

no net effect on direct flux into the pole; identical fractions of negative and positive surface charges enter the pole, so their contributions cancel.

Since with this mechanism, all soft iron dimensions (i.e., the pole piece and the yoke) are fixed, capacitances do not vary; change in B_0 results solely from a change in the V_0 pole excitation change due to a change in direct flux from the PM blocks. The design objective here then is to compensate for the decrease in direct flux into the pole due to a decrease in PM strength with temperature by reorienting the magnetization direction of our PM tuning stud so as to increase its contribution of direct flux into the pole piece.

Again, various means can passively effect this required rotation as temperature rises, including use of bimetallic springs or expanding liquids/solids attached to a piston connected to the PM tuning block. We are currently exploring practical, inexpensive mechanical designs that implement such a passive temperature compensation feature.

C. Active compensation

Before we leave the subject of temperature compensation in PM accelerator rings, recall that the primary motivation for such devices is that they offer the advantage of being free of power supplies, cooling equipment,

and operating energy costs. Having “disconnected the plug”, in the same vein of thought, we then attempt to temperature-compensate these accelerator elements passively. It should be noted, however that powering an actuator connected to a temperature sensor so as to effect a change in the positioning of a yoke section or the rotation of a PM tuning stud is nowhere comparable to the electrical power requirements for generating the magnetic fields themselves. Furthermore, such low-energy active control would enable remote in-situ tuning capability of magnets, since they are no longer fixed at a single nominal field level. This is a substantial benefit.

IV. SUMMARY

Herein, we have presented the theory of hybrid magnet design and made use of its nuances to proffer two attractive temperature compensation schemes to maintain field stability. Potential techniques for accomplishing the requisite geometry perturbations passively have been outlined. Choosing between completely passive temperature compensation and low-energy active control must be driven by relative economic and technical merits.

ACKNOWLEDGMENT

Defining the issues surrounding the construction of permanent magnet rings and evaluating solutions to design challenges raised has been and continues to be a collaborative effort between physicists and engineers at Fermilab, LBL, and private companies. We are pleased to thank these colleagues for their expertise in addressing these issues.

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