A PROPOSAL FOR IMPROVING THE QUALITY OF THE FNAL SUPERCONDUCTING MAGNETS

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ABSTRACT

A system for reducing the errors in superconducting dipoles, as made at FNAL, is proposed. Implementation of this system is being investigated and if successful could result in a reduction of random field errors by perhaps a factor of 3 or more.

The FNAL superconducting magnet is a two-shell magnet. The basic philosophy of the production scheme has been to construct a "factory" that makes coils reproducibly. The absolute accuracy is not important because after a coil has been produced, it can be measured and the sector angles changed according to a perturbation calculation to correct the measured lower harmonics b_1, b_2, b_3, b_4 and a_1, a_2, a_3, a_4 to the desired value. Here:

$$B_y(x) = B_o \sum_{n=0}^{\infty} b_n x^n \quad \text{Normal terms.} \tag{1}$$

$$B_x(x) = B_o \sum_{1}^{\infty} a_n x^n \quad \text{Skew terms.} \tag{2}$$

The most important point realized at FNAL was that the absolute accuracy of the coils is not important since any "nearby" shape can be shimmed, as will be described below, to give the desired field. For the moment, we assume the "factory" reproduces the geometry exactly from coil to coil. A block diagram then looks like:

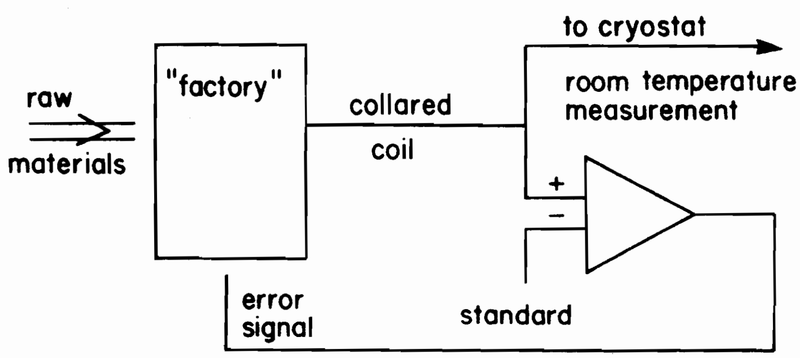

Fig. 1

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In the present FNAL factory, a collared coil cannot be changed without removing the collar - an expensive and time consuming operation. The feedback loop, therefore, has a delay of at least one unit. However, since we assume for the present that there is no noise in the system, the error signal decreases to zero after one magnet.

How do we use the error signal? To answer this question, consider a single shell of the coil (see Fig. 2). The angles are specified by 4 coordinates. These 4 coordinates may be changed by small amounts δy_1, δy_2, δy_3, and δy_4. As in normal modes, the symmetry of the problem leads to 4 combinations that are useful:

$$\delta_1 = 1/4 \left[\delta y_1 + \delta y_2 + \delta y_3 + \delta y_4\right] \quad (3)$$

$$\delta_2 = 1/4 \left[\delta y_1 + \delta y_2 - \delta y_3 - \delta y_4\right] \quad (4)$$

$$\delta_3 = 1/4 \left[\delta y_1 - \delta y_2 + \delta y_3 - \delta y_4\right] \quad (5)$$

$$\delta_4 = 1/4 \left[\delta y_1 - \delta y_2 - \delta y_3 + \delta y_4\right] \quad (6)$$

These combinations have the advantage that they couple into the harmonics as shown below:

$$\delta_1 : b_2, b_4 \quad (7)$$

$$\delta_2 : b_1, b_3 \quad (8)$$

$$\delta_3 : a_2, a_4 \quad (9)$$

$$\delta_4 : a_1, a_3 \quad (10)$$

It is empirically true that these perturbations mainly affect the lower 2 harmonics. The higher terms are mainly determined by the corners of the current blocks, and the designer has no control over them without introducing more current blocks. Also, remember that we have 2 shells and, hence, 8 independent coordinates. δ_3 looks like a rotation, but since there are 2 shells, it only represents a rotation if the inside and outside δ_3's are the same. The coordinate system is picked to make $a_o = 0$.

The description given above fits the actual measurements quite well. The lower 8 harmonics are sensitive to construction tolerances and the higher ones, which are determined

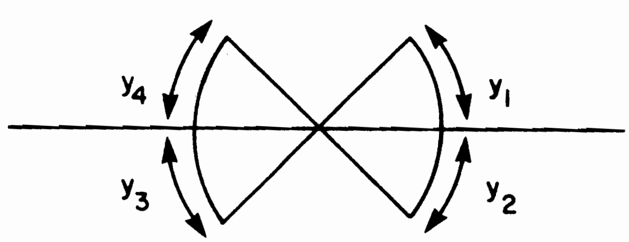

Fig. 2

by the coil corners, fluctuate by rather small amounts. The matrices coupling the δ's with δb_n and δa_n are given below:

δ_1 = .01 in.

n	Inner δb_n	Outer δb_n
0	7.2	4.0
2	7.1	5.8
4	4.1	1.7
6	1.4	.005

δ_2 = .01 in.

n	Inner δb_n	Outer δb_n
1	20.7	6.8
3	- 3.8	3.6
5	- .2	.5

δ_3 = .01 in.

n	Inner δa_n	Outer δa_n
0	35.8	20.4
2	- 7.4	6.3
4	.29	- .2

δ_4 = .01 in.

n	Inner δa_n	Outer δa_n
1	10.9	13.8
3	- 6.5	1.7
5	2.4	- .6

The units in the above table are 10^{-4} $(\text{in.})^{-n}$. It is evident that as stated above, the effect of changing the key angles only affects the lowest harmonics.

We can now see how the feedback works in Fig. 1. A coil is made and measured. The appropriate changes δ_1 . . δ_4 in the coil angles for inner and outer coils are calculated and fed into the "factory". The next coil should then be perfect.

We now must face the real world. There is noise in both the "factory" as well as the measuring process. Thus, an averaging time must be introduced into the feedback loop in order for the system to be stable. In practice, the noise in the factory is the most serious. This results in some coils being outside the limits of acceptability. At present, the room temperature measurements do a rather good job on the terms b_1, b_2, b_3, b_4. The skew terms are not measured, but the apparatus is being modified to make these measurements.

As an example of how a coil can be corrected, consider Magnet No. 214. Its room temperature tests produced the following:

	b_1	b_2	b_3	b_4
After first collaring	-3.4	-7.5	-3.3	.74
Desired	0	0	0	2
	±2.5	±3		
After remolding	-1.3	-1.1	-3.2	.9

The remolding operation involved cutting the collars off and then heating the coil in a mold to change its size. Appropriate new shims were installed when it was recollared in order to give the desired field. It is seen that the sextupole almost came to the desired value of 0. Thus, experimentally the method will work.

It is worth noting that small corrections to the terms b_1 and a_1 can also be made by placing the coil off center in the iron yoke. We have used this procedure, and quadrupole errors of ±5 units can be corrected easily by asymmetric shimming of the cryostat in the yoke.

However, a new scheme which could improve the field quality by perhaps a factor of 3 or more is easily visualized. After the coils are molded, they are placed in a temporary collar and measurements at room temperature are made. The perturbations to the coil angles are then calculated and appropriate shims placed in the final collars. The temporary collar could be a relatively simple insulated device that holds the 2 coil halves together for the measurement. Since at the time of collaring, about 1/3 of the total cost of the magnet has been expended, there are also strong economic reasons for eliminating the production of out-of-tolerance coils.

It should be clear from the above discussion that the most sensitive overall measurement of small harmonic errors in the conductor placement is made by measuring the harmonic content of the field. This is then easily corrected by adjusting the current block angles before final assembly. Small quadrupole errors can be corrected by off-axis assembly in the iron yoke. The overall improvement in quality will be determined by how well the room temperature measurements predict the final magnetic field. It has been observed that training the magnet causes changes in the field harmonics. This effect is not large but will limit the improvement to be expected.