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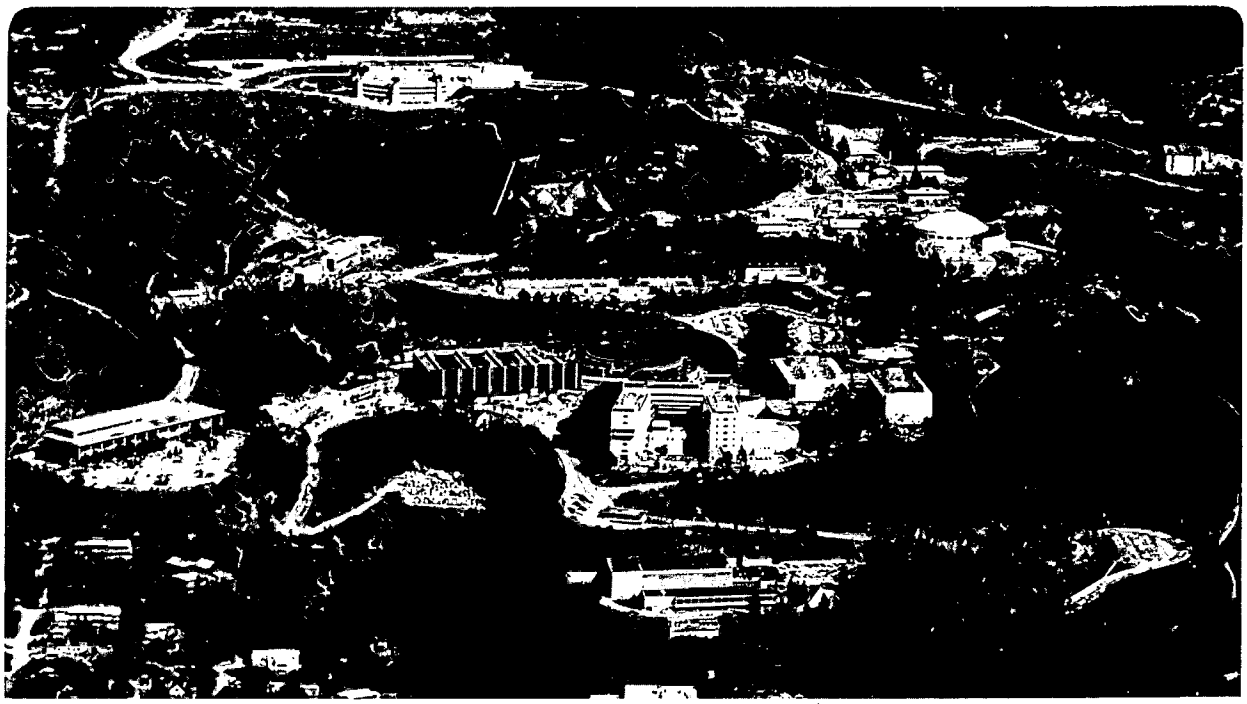

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SUBJECT: Accurate Determination of Dipole Phase Low Distribution - Appendix to MT 295 (Calibration Test Plan)

NAME

DATE: July 20, 1981

Authors: D.H. Nelson, M.I. Green & W.V. Hassenzahl

INTRODUCTION

The determination of the direction of the fundamental (dipole) component of magnetic-induction with respect to a fiducial (vector) associated with a magnet* was considered at the May 26th meeting of the Superconducting Magnet Measurement Planning Committee. We have decided to defer dipole phase measurements of the D8 magnet series. However, to preserve the information gained in the study and discussion that preceded the decision to defer the determination, we have prepared this report as an appendix to the test plan for determining the coils' areas (MT 295).

TASKS IDENTIFIED

There are several tasks required for determining the phase of the dipole field with respect to a mechanical fiducial on the magnet cryostat.

1. Define a suitable fiducial for later magnet installation and alignment.
2. Determine the phase of each search coil with respect to a fiducial on that coil.
3. Determine the phase of each search coil fiducial with respect to a fiducial on the coil array.
4. Determine the phase of the fiducial on the coil array, which will be completely enclosed and will not be visible from outside the cryostat, with respect to a fiducial on the drive shaft that extends outside of the cryostat.
5. Determine the phase of the shaft fiducial with respect to the magnet fiducial at the instant of a shaft encoder signal.

COMMENTS

Task 1 difficulty depends on the meaning of suitable.

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*I.e., the determination of the "dipole phase"

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COMMENTS (continued)

Task 2 may be accomplished with a minor increase in the effort required for coil calibration if the appropriate positioning hardware is fabricated. A procedure for accomplishing task 2 is described below.

Task 3 is a relatively easy mechanical exercise.

Task 4 appears difficult (if possible). It is complicated because the dynamic orientation may vary from static orientation and the relative orientation of the coil and shaft may change as the coil is cooled.

Task 5 is a straightforward alignment problem that can be accomplished with reasonable effort.

COIL PHASE DETERMINATION
(Procedure for Accomplishing Task 2)

GENERAL

The technique to be described depends on the accuracy of four fiducial surfaces. The first two, the top and bottom surfaces of the coil, should be parallel* within the accuracy with which we hope to determine the coil phase. The other two surfaces are on separate fixtures, each capable of accurately locating the coil to the same position within the magnet except that when the coil bottom (or top) is in contact with fixture 1, the coil's electrical axis is nominally perpendicular to the lower pole surface and when in contact with fixture 2, the electrical axis is nominally parallel to the lower pole surface. The reproducibility of the two fixture surfaces and the ability to reproducibly locate the coil is essential to this procedure.

*These surfaces must be flat and the deviation from parallelism known to the accuracy we hope to determine coil phase.

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The description of this procedure is facilitated by introducing a coordinate system defined by the two fixture surfaces and two vectors: 1) the vector defining the electrical-axis of the coil and 2) the vector associated with the average magnetic induction over the volume occupied by the coil (when in place).

Figure 1 shows the coordinate system and the vectors defined above. In Figure 1, we have assumed that the two fixture surfaces are perpendicular and therefore define a cartesian coordinate system.* $z = 0$ defines a plane parallel to the lower pole tip. $x = 0$ defines a plane perpendicular to the lower pole tip. $y = 0$ is the center of the long dimension of the coil (when in place, i.e., centered with respect to magnet poles). $\vec{B}_{AVG}$, the vector associated with average magnetic induction, must be constant (both in magnitude and direction) during the procedure described (to the accuracy of the determination of the coil-phase). Finally, six vectors, associated with three coil orientation pairs, are shown as 1, 1', 2, 2', 3, 3'. We have assumed that the vector $\vec{B}_{AVG}$ is at an angle β with respect to $\vec{z}$ and that the electrical axis of the coil is at an angle α with respect to the outward normal of the coil's top surface.

QUALITATIVE EXPLANATION OF PROCEDURE

Briefly, we will install fixture 1 and measure an electrical quantity (integrator output potential) which is proportional to $\cos(\beta - \alpha)$. This is done by flipping the coil between position 1 and 1'. Next we install fixture 2 and measure an electrical quantity proportional to $\sin(\alpha - \beta)$ by flipping between orientations 2 and 2'. Finally, we rotate the coil about $y = 0$ and measure an electrical quantity proportional to $\sin(\alpha + \beta)$ by flipping between orientations 3 and 3'. We will use trigonometric identities and reasonable approximations to determine α and β from the measured electrical quantities.

*It is not necessary that the two fixture surfaces are perpendicular but it simplies the discussion and is easily achieved.

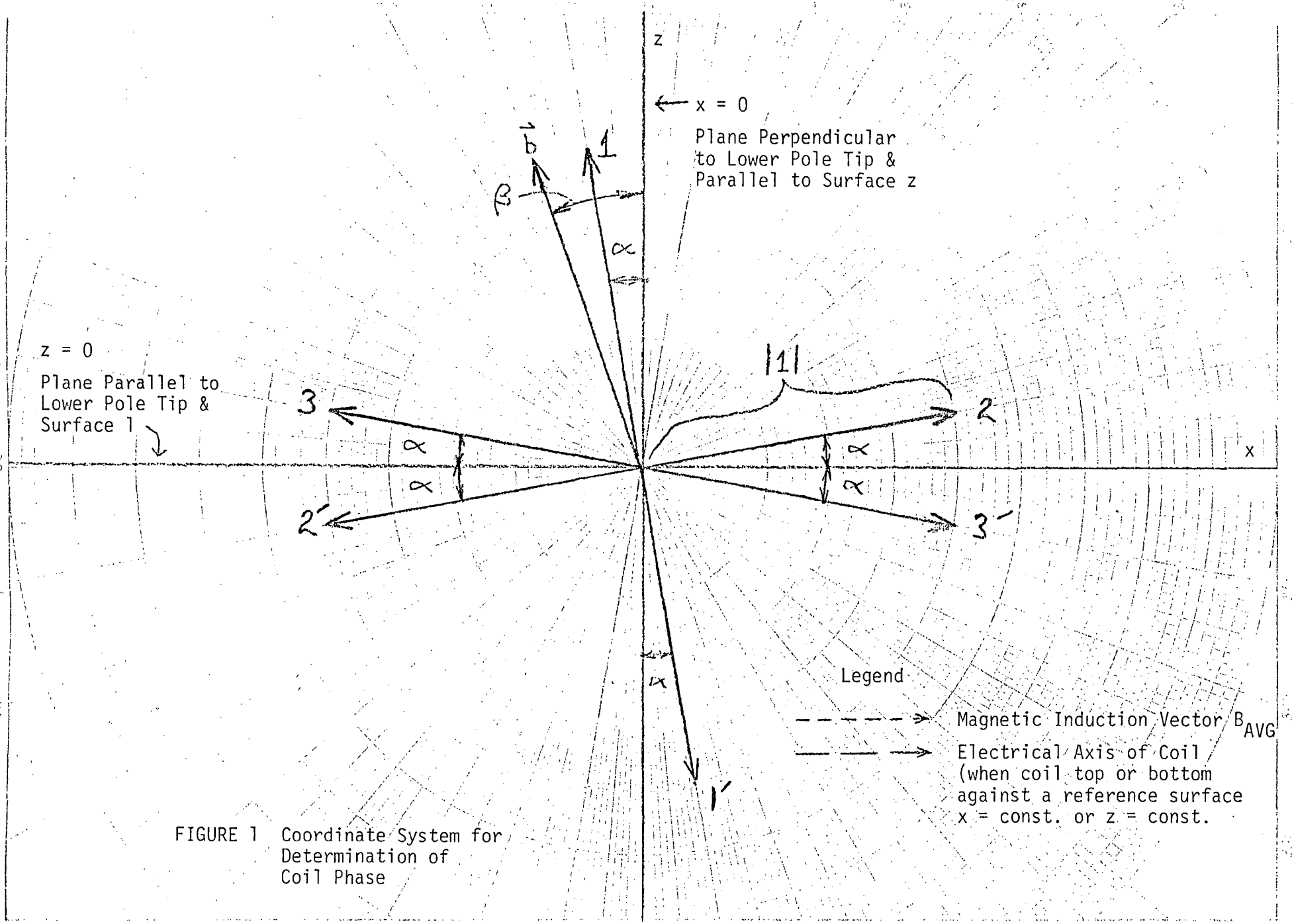

FIGURE 1 Coordinate System for Determination of Coil Phase

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QUANTITATIVE EXPLANATION OF PROCEDURE

Let flux linkage be defined by the scalar product $\vec{nA}\cdot\vec{B_{AVG}}$ where:

1. $\vec{nA} = |\vec{nA}|\,\vec{na}$, $|\vec{nA}|$ is the turns-area product of the coil, $\vec{na} = \vec{nA}/|\vec{nA}|$ is the unit directional vector denoting the electrical axis of the coil (nominally normal to the top and bottom surfaces of the coil).
2. $\vec{B_{AVG}} = |\vec{B_{AVG}}|\,\vec{b}$ is the average magnetic induction over the volume occupied by the coil. $\vec{b}$ is the unit vector describing the direction of $\vec{B_{AVG}}$.

The flux linkage when the coil is in orientation 1 is given by equation 1.

$$\psi_1 = \vec{nA_1}\cdot\vec{B_{AVG}} = |\vec{nA}|\,|\vec{B_{AVG}}|\,\vec{na_1}\cdot\vec{b} \qquad (1)$$

For any of the six orientations, the flux linkage may be described by equation 2.

$$\psi_i = |\vec{nA}|\,|\vec{B_{AVG}}|\,\vec{na_i}\cdot\vec{b} \qquad i = 1, 6 \qquad (2)$$

The six equations differ only by the scalar product of the unit vectors which are summarized in Table I along with identical simplified quantities.

Orientation (i)	$\vec{na_i}\cdot\vec{b}$ Scalar Product See Figure 1	Trigonometric Identity
1	$\cos(\beta - \alpha)$	$\cos(\beta - \alpha)$
1'	$\cos(180 - \{\beta - \alpha\})$	$-\cos(\beta - \alpha)$
2	$\cos(90 + \{\beta - \alpha\})$	$-\sin(\beta - \alpha)$
2'	$\cos(90 - \{\beta - \alpha\})$	$\sin(\beta - \alpha)$
3	$\cos(90 - \{\beta + \alpha\})$	$\sin(\beta + \alpha)$
3'	$\cos(90 + \{\beta + \alpha\})$	$-\sin(\beta + \alpha)$

TABLE 1 Scalar Product of Unit Vectors and Identical Terms

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The coil leads are connected to the input of an electronic integrator whose output potential is proportional to changes in flux linkage. By flipping, we determine the following flux-linkage differences.

$$\psi_1 - \psi_1' \sim^* 2\cos(\beta - \alpha) \tag{3}$$

$$\psi_2 - \psi_2' \sim -2\sin(\beta - \alpha) = 2\sin(\alpha - \beta) \tag{4}$$

$$\psi_3 - \psi_3' \sim 2\sin(\beta + \alpha) \tag{5}$$

Using the identities

$$\sin(A + B) = \sin A\cos B + \sin B\cos A$$

and

$$\sin(A - B) = \sin A\cos B - \sin B\cos A,$$

equation 6 is the sum of equation 4 and equation 5; and equation 7 is the difference of equation 5 and equation 4.

$$5 + 4 \sim 2\sin\alpha\cos\beta - 2\cos\alpha\sin\beta + (2\sin\alpha\cos\beta + 2\cos\alpha\sin\beta) = 4\sin\alpha\cos\beta \tag{6}$$

$$5 - 4 \sim 2\sin\alpha\cos\beta + 2\cos\alpha\sin\beta - (2\sin\alpha\cos\beta - 2\cos\alpha\sin\beta) = 4\cos\alpha\sin\beta \tag{7}$$

So far no approximations have been made and it is possible to solve equations 3, 6 and 7 numerically for α and β. One approach to solving the equations is to first assume α, β, and $(\alpha - \beta)$ are small enough such that $\cos\alpha = \cos\beta = \cos(\alpha - \beta) = 1$, and $\sin\alpha = \alpha$, $\sin\beta = \beta$, and then replace the indicated values for α and β into equations 3, 6 and 7 and iterate. We will carry out only the first step, assuming that the approximations are adequate.

$$1/2 \text{ Eq.6/Eq. 3} = \quad 1/2 \frac{4\sin\alpha\cos\beta}{2\cos(\beta - \alpha)} \sim \sin\alpha \sim \alpha \tag{8}$$

$$1/2 \text{ Eq.7/Eq. 3} = \quad 1/2 \frac{4\sin\beta\cos\alpha}{2\cos(\beta - \alpha)} \sim \sin\beta \sim \beta \tag{9}$$

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* $\sim$ means "proportional-to" in this discussion.

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DISCUSSION

The question of vertical axis orientation was discussed with the Fermi Lab staff. Fermi Lab has an effective solution that should be applicable to any accelerator magnet, but which is not compatible with the LBL horizontal test cryostat. They claim to determine this orientation to ±0.5 milliradians, but the coil, which operated at an ambient temperature, is completely different from those used for harmonic field analysis. Several of the tasks described above are complicated by the measuring coil being cold. This difficulty goes away when all the measuring gear is warm.

We will not attempt to determine the vertical axes of the D-8 series magnets.

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