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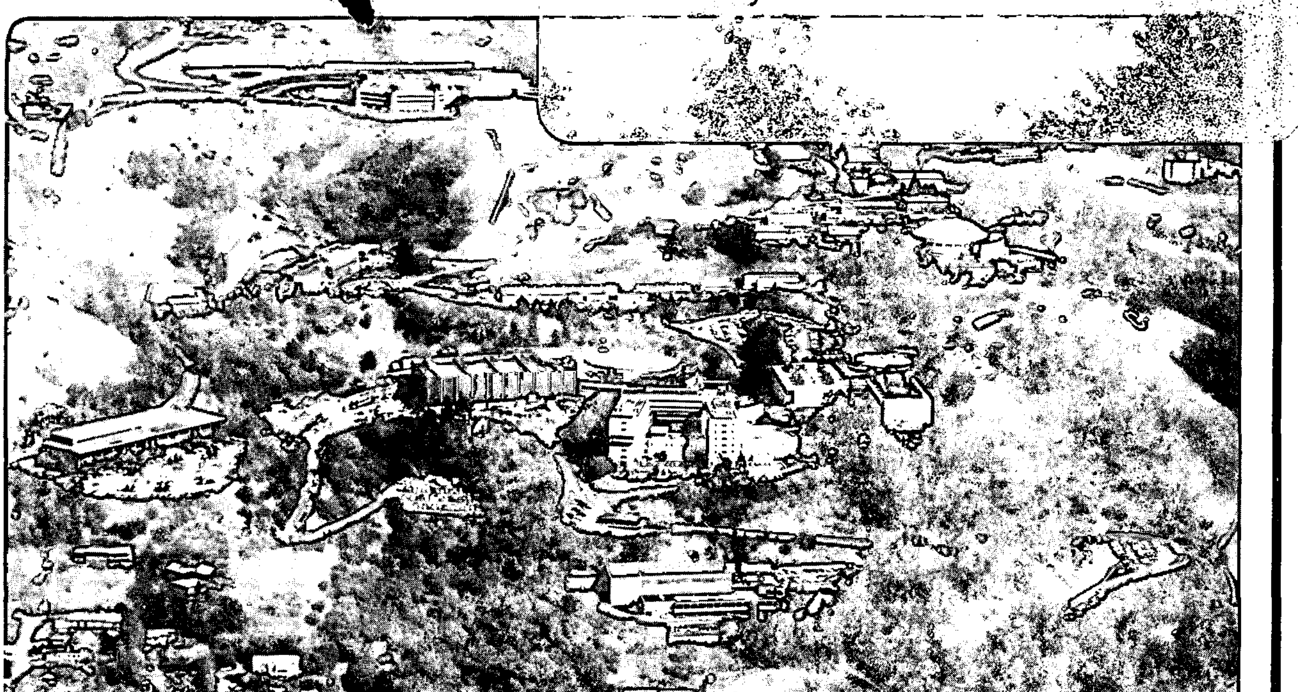

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DISCLAIMER

THE LAWRENCE BERKELEY LABORATORY MAGNETIC-MOMENT SORTING SYSTEM*

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Abstract - The Magnetic Measurements Engineering Group at Lawrence Berkeley Laboratory (LBL) has designed and built, and is currently using, a Magnetic-moment Measurement and Sorting System (MMSS). The MMSS measures magnetic moments of permanent-magnet material and sorts the material according to selected criteria. The MMSS represents the latest application of the LBL General Purpose Magnetic Measurement Data Acquisition System reported on at MT-8. We describe the theoretical basis for the MMSS, the analog and digital components, and a unique method of calibrating the MMSS using only measured electrical quantities. We also discuss the measurement and sorting of permanent-magnet material to be incorporated in beam-line elements (dipoles and quadrupoles) in the Lawrence Livermore National Laboratory Advanced Test Accelerator Beam Director.

INTRODUCTION

The increased use of permanent magnets for providing magnetomotive force for beam-line elements has prompted the Lawrence Berkeley Laboratory (LBL) to develop a computer-controlled system [1] for measuring the magnetic moment of permanent magnets. The Magnetic Measurements Engineering Group at LBL has designed and built and is currently using a Magnetic-moment Measurement and Sorting System (MMSS).

This paper provides the theoretical basis for the MMSS and describes the measurement system and a unique calibration method. Results of measurements of three components of magnetic moment for 400 permanent magnets for use in the Lawrence Livermore National Laboratory Advanced Test Accelerator (ATA) Beam Director [2] are reported.

THEORY

Figure 1 shows a "point" dipole ($\vec{m}$) at the origin of a cylindrical coordinate system. The dipole produces axial magnetic induction (B_z; at any point in space) represented by (1) [3].

A coil pair with Helmholtz geometry (see Fig. 1) may be used to measure the flux-linkage generated by the dipole; (2) describes this flux-linkage. In theory, one may determine three components of magnetic moment by bringing a magnet from "infinity" to the origin of the coil's coordinate system, orienting the magnet in each of three mutually orthogonal positions, and measuring the corresponding induced flux-linkage. Only $B_z(r, \theta, z = \pm R_m/2)$ contributes to flux-linkage. The radial component of magnetic moment (m_r) generates $B_z(r, \theta, z)$, which is an odd function of both r and z and therefore makes no net contribution to the flux-linking symmetrically located coils connected in "series aiding." Helmholtz geometry minimizes errors in flux-linkage due to both the finite size of the magnet and magnet position errors (random and systematic). For Helmholtz geometry the constant of integration introduced in (2) is: $G = (1 + 0.5^2)^{3/2} = 1.398$:

$$B_z(r, \theta, z) = \frac{m_z(2z^2 - r^2) + 3m_r(rz)}{4\,(r^2 + z^2)^{5/2}} \quad (1)$$

$$\Psi = n(\phi_1 + \phi_2) = n\left(\iint \vec{B}_1 \cdot \vec{ds}_1 + \iint \vec{B}_2 \cdot \vec{ds}_2\right)$$

$$= n \int_{\theta=0}^{2\pi} \int_{r=0}^{R_m} \Big[B_z(r, \theta, z = -R_m/2)$$

$$+ B_z(r, \theta, z = +R_m/2)\Big]\, dr\, d\theta$$

$$= m_z n/(R_m G) \quad (2)$$

where: r, z = cylindrical coordinates defined in Fig. 1 (m)

θ = third cylindrical coordinate (not shown) (radians)

m_z = axial (z) component of magnetic moment (Wbm)

m_r = radial (r) component of magnetic moment (Wbm)

B_z = z-component of magnetic induction (T)

ϕ_i = $\iint \vec{B}_i \cdot \vec{ds}_i$ = magnetic flux intersecting each coil (i = 1,2) (Wb)

n = number of turns per coil (dimensionless)

Ψ = $n(\phi_1 + \phi_2)$ = total magnetic flux-linkage (Wb)

G = constant of integration (dimensionless)

R_m = mean radius of each coil = axial separation of coils (m)

MEASUREMENT SYSTEM

Figure 2 is a block diagram of the test equipment used for measuring magnetic moment. Essentially, flux-linkage in the Helmholtz coil pair is measured with the electronic integrator. The flux standard [4] provides a flux-linkage reference for calibrating the integrator system. The Data Acquisition and Control Unit (DACU) reads both integrator output potential and temperature and sends information to the computer by means of the IEEE-488 Bus.

The magnets tested for the ATA Beam Director are shaped as shown in Fig. 3 and Table I. Each ferrite magnet is machined so its easy axis (of magnetization) lies nominally along one of 16 azimuths in the x'-y' plane. To measure its magnetic moment we install a magnet in a positioning fixture as shown in Fig. 4.

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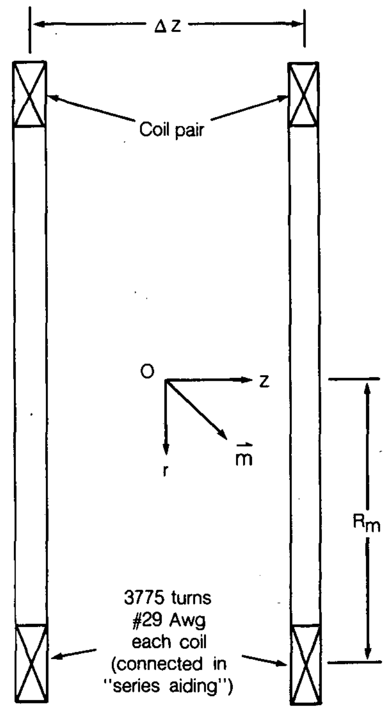

Fig. 1 - A magnetic dipole ($\vec{m}$) at the origin of a cylindrical coordinate system centered on a Helmholtz coil pair; the axial separation (Δz) equals the mean radius of the coil bundle (R_m)

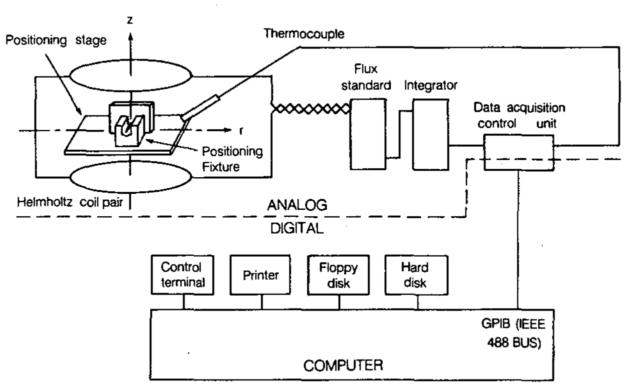

Fig. 2 - Magnetic-moment measurement and sorting system (MMSS) schematic diagram

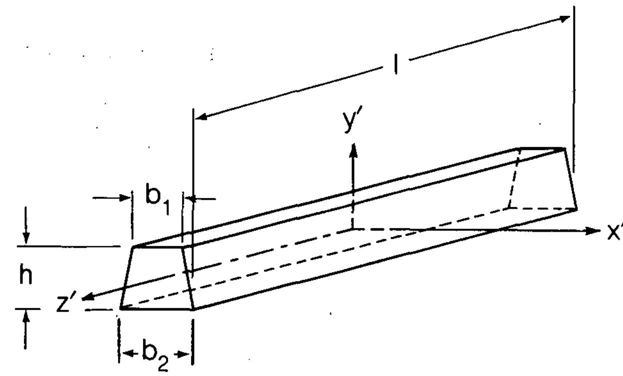

Fig. 3 - Representative magnet--ATA beam director

Table I. Magnet Dimensions (see Fig. 3)

(Brobeck) Drwg. No.	Base 1, b_1 [cm]	Base 2, b_2 [cm]	Height, h [cm]	Length, l [cm]	Volume, $V=lh(b_1+b_2)/2$ [cm^3]
95D1733-1	0.645	0.937	0.786	10.630	6.609
95D1733-2	0.645	0.937	0.786	5.315	3.304
95D1732	0.645	0.937	0.786	10.630	6.609
95D1734	0.645	0.888	0.641	8.999	4.421

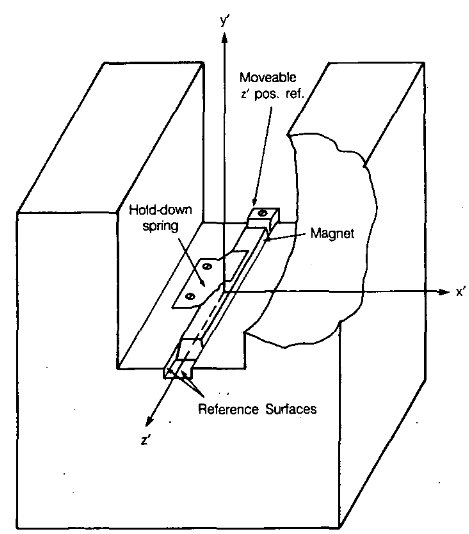

Fig. 4 - Magnet positioning fixture

The magnet positioning fixture, a key element of the MMSS, is a precision cube of aluminum into which a slot has been milled to accept a magnet. Reference surfaces, parallel to outer surfaces of the cube, mate with magnet fiducials, and a phosphor bronze spring constrains the magnet's centroid and axes to correspond to those of the cube. The cube's outer surfaces determine the location and orientation of the magnet under test as we measure three orthogonal components of magnetic moment.

SYSTEM CALIBRATION

Equation 2 indicates that magnetic moment may be derived from the geometry of the coil pair and a measurement of flux-linkage. Although we can measure flux-linkage with an accuracy of 0.1%, it is difficult to define coil-pair geometry precisely. Instead, we employ the following argument (based on the Reciprocity Principle [5]) to enable us to calibrate the system using only electrical quantities: Given a point on the perpendicular axis of symmetry of a circular, closed path, the expression that describes the ratio of axial magnetic moment at the point to the flux linking the path is the same expression that describes the ratio of current in the path to axial magnetic intensity at the point. For the special case of the Helmholtz coil pair shown in Fig. 1, where the coil pair represents the closed path and the origin of the coordinate system represents the point, this relationship is expressed by (3)

$$m_z/\Psi = I/H_z = R_m G/n \qquad (m) \qquad (3)$$

where: m_z = (axial, z-component, of) magnetic moment (Wbm)
Ψ = flux-linkage due to magnetic moment at the origin (Wb, i.e., V-s)
I = current (A)
H_z = (axial, z-component, of) magnetic intensity at the origin (A/m)
R_m = (mean) radius of coil pair (m)
G = Geometric factor; for Helmholtz geometry: $G = (1 + 0.5^2)^{3/2} = 1.398$ (dimensionless)
n = number of turns per coil (dimensionless)

We determined the sensitivity of our Helmholtz coil pair to magnetic moment at the origin by determining the ratio of the magnitude of current in the coil pair to magnetic intensity at the origin (I/H_z).* Then, $m_z = (I/H_z)\Psi$; we measure $2\Psi = \int_{+\Psi}^{-\Psi} e dt$. The emf generated in the Helmholtz coil pair due to manually reversing the magnet positioning fixture (rotating it 180° about the y axis) is $e = -d\Psi/dt$.

MEASUREMENTS

We measure $2\Psi = \int_{+\Psi}^{-\Psi} e dt$ by electronically integrating the emf pulse due to rotating the positioning fixture about the y axis. Computer-generated instructions instruct the operator to measure 2Ψ corresponding to six 180° rotations (12 different orientations of the positioning fixture). For each component, we measure 2Ψ, first with the fixture upright, then with the fixture inverted (about the z axis). These measurements are processed with an algorithm that minimizes the effects of misalignment of the positioning stage with respect to the measurement coordinate system. While calculating the three components of magnetic moment, the algorithm cancels the effects of systematic rotational errors about the x and y axes.

*Sensitivity based on this calibration was 0.54% lower than sensitivity based on the nominal geometry of the coil pair.

We compute $\theta_{x'y'}$ (the direction of magnetization in the x'-y' plane) as follows:

$$\theta_{x'y'} = \tan^{-1}(m_{y'}/m_{x'}).$$

We measured three components of a total of 400 magnets for the ATA Beam Director.

ACCURACY

Early in our measurement program for the ATA Beam Director magnets we tested the MMSS for zero resolution (the noise level of a measurement sequence with no magnet in the fixture), reproducibility, the effects of translation along the x, y, and z axes, and the effects of rotation about the x, y, and z axes. The zero resolution tests were made without a magnet in the positioning fixture. The remaining tests were conducted on two magnets--one with its easy axis along the x' axis and the other with its easy axis along the y' axis. For each test we measured three components of magnetic moment. Results of these tests are included in [6]. We summarize the results below:

Error Test	Maximum (Measured) Error
Zero resolution	20 [Maxwell cm] (1 Wbm = 10^{10} Maxwell cm)
Displacement (5 cm along the x, y, or z axis)	5 [Maxwell cm/cm]
Rotation (100 milliradians about the x, y, or z axis)	0.5 [Maxwell cm/milliradian]

The absolute accuracy of our determination of magnetic moment ($m_{x'y'}$) or any component ($m_{x'}$, $m_{y'}$, or $m_{z'}$) is 30 Maxwell cm. The uncertainty in our determination of θ_{xy} is limited by physical magnet tolerances to 5 milliradians.

RESULTS

Table II summarizes test results for the ATA Beam Director magnets. Figure 5 is a schematic cross section of a 16-piece quadrupole [7].

Table II. Test Summary

(Brobeck) Drwg. No.	Number measured	Average moment, m_{xy} [Maxwell cm]	Standard deviation, σ [% m_{xy}]	Average magnetization, $M_{xy} = m_{xy}/V$ [10^3 Gauss]
95D1733-1	80	22626	1.40	3.423
95D1733-2	47	11336	0.73	3.431
95D1732	96	22725	0.87	3.438
95D1734	176	not available at publication time		

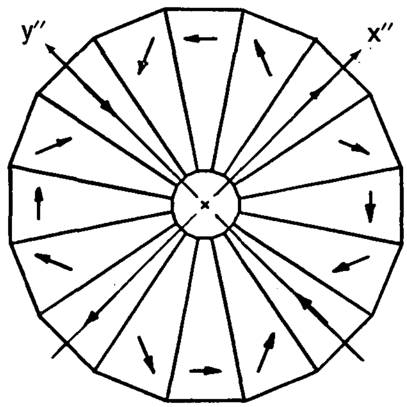

Fig. 5 - Schematic cross section of a 16-piece quadrupole

SUMMARY

We determine 3 components of magnetic moment with absolute accuracies of 30 Maxwell cm (30 x 10^{-10} Wbm). Our calibration method is independent of geometry and is based on measured electromagnetic quantities. We minimize the effect of rotational misalignment of the positioning stand with respect to the Helmholtz-coil coordinate system. A computer-instructed sequence of measurements of flux-linkage corresponding to rotating the measurement fixture about selected axes is processed by an algorithm that effectively cancels the errors due to systematic rotation.

The 400 magnets have been selected for installation in a total of 21 beam-line elements (10 dipoles and 11 quadrupoles). At the time of publication, the Magnetic Measurements Engineering Group at LBL has begun measuring these elements for strength and quality. These measurements will be the subject of a future report.

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