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FUNDAMENTALS OF MAGNETIC MEASUREMENTS WITH ILLUSTRATIONS FROM FERMILAB EXPERIENCE*

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Abstract. - Techniques for measurement of magnets used in accelerators and beams are discussed with emphasis on principles and limitations of the various techniques. Selection of parameters to measure, mechanical, electronic and data collection issues will be discussed. Illustrations will primarily be selected from the experience in measuring more than 1200 superconducting and more than 600 conventional magnets for the Tevatron at Fermilab.[1,2]

TECHNIQUES AND PARAMETERS FOR MEASUREMENT

For typical high energy physics spectrometer work, as for many other efforts, the analysis of trajectories requires a detailed point map of the magnetic field through a large volume. For synchrotrons, storage rings and beam lines, the mathematical description which is employed involves a paraxial approximation in which the useful information is a measurement of the strength of the bending and focusing fields along a design trajectory plus a measure of the non-uniformity in nearby regions. Descriptions which provide the most insight into accelerator properties employ a harmonic description of the magnetic field errors integrated through an element. In most applications, an element which is conveniently built in a factory is suitably described by the integrated harmonic expansion of the deviations from a thin lens or point bending approximation. We have found that the end field measurements of representative magnets (at most) is sufficient to supplement the detailed integrated measurements on every magnet in the Fermilab Tevatron.

Existing magnet measuring systems employ three types of magnetic field sensors. Nuclear Magnetic Resonance provides a very high accuracy point measurement. Detecting the resonance requires care to avoid noise from power supply ripple and to acquire sufficient spacial uniformity and dynamic range. The absolute accuracy is sufficient that it is often used as a calibration point for other techniques. The Hall Effect is a less demanding point measurement technique when moderate accuracy and large dynamic range are required. However, to achieve high accuracy with this technique requires very careful attention to thermal and other effects which modify the fundamental response of the detector. The most general and widely used technique employs Faraday's Law applied to loops of wire constructed to measure the desired integrated field properties. These probes can measure change in magnet flux when rotated or translated in a static magnetic field or flux changes can be recorded with the probe stationary while the exciting current changes the magnetic field. To obtain integrated field properties from measurements of point maps implies accuracy requirements on the measurements of position in three dimensions. Properly evaluating field shape in this manner involves simultaneous accuracy in all three dimensions. Since the desired information is typically an integrated field strength, point measurements are typically used only for specialized measurements.

A SET OF PRODUCTION MEASUREMENT PARAMETERS

We give in Table I a list of measurements which are typically required for accelerator magnets. The accuracies shown are characteristic best cases for some existing systems. The actual requirements will depend upon particle type and energy as well as lattice design. Some additional properties such as the longitudinal bend center are critical to accelerator operation but for most magnets are uniform enough to not require measurement. Field angles and centers in iron magnets may not require magnetic measurement when iron location is well correlated to field location and angle. In superconducting magnets, these parameters must be measured and related to external survey points.

Table I

Magnetic Field Properties to Measure

Quantity	Accuracy Dipole	Accuracy Quad	Units
Integrated Strength	1/10,000	5/10,000	Rel.
Integrated Shape	3/100,000	3/100,000	Rel.
Field Angle	.00015	.00015	Rad.
Transverse Center		.1	mm.

SYSTEM DESIGN GOALS

A magnet test facility must be more than a magnetic field testing facility. Especially for superconducting magnets, this facility may be the only location prior to ring installation in which the magnets can be tested under operating conditions. Measurements of electrical insulation (HiPot) properties, maximum current (Quench), AC loss mechanisms such as eddy currents and hysteresis loss must be made along with the magnetic field measurements. Successfully cooling and powering a

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superconducting magnet provides a powerful test of its suitability for use.

If the first use of a magnet test facility is to see that a magnet has been powered, the only purpose of magnetic measurements is to put data in a form for evaluation and use by magnet and accelerator designers. Prototype measurements carried out to evaluate magnet designs also provide a basis for limiting production measurements to essential parameters (design dependent). Production quality control requires a well defined set of measurements which must be reproducibly made and evaluated with consistent data collection and calibration techniques. The uses of this data run along several lines: reject unacceptable magnets, correct deficient magnets when suitable modifications are identified, evaluate magnets for placement in the accelerator to minimize the collective effects of field errors (shuffling) and finally, record field errors for analysis of accelerator performance. Additional specialized measurements may be needed at any phase of accelerator design or operation. Each data use requires rapid feedback of information to design personnel.

A HARMONIC REPRESENTATION OF 2-D FIELDS

Examination of Maxwell's Equations for magnetostatics in two dimensions reveals that a harmonic representation can exactly describe the field in any region free of sources. We choose the algebraic simplification of representing a 2-D vector by a complex variable. This paper will follow the work of Halbach.[3] MKS units will be used. In a region with no sources of magnetic field we may define a scalar potential U. With current sources parallel to the z axis we have a vector potential $\vec{A}$ with only a z component such that the following equations relate potentials and fields.

$$\vec{B} = -\mu_o \nabla U \qquad \vec{B} = \nabla \times \vec{A}$$

$$B_x = \frac{\partial A}{\partial y} = -\mu_o \frac{\partial U}{\partial x} \qquad B_y = -\frac{\partial A}{\partial x} = -\mu_o \frac{\partial U}{\partial y}$$

If we define a complex space variable $w = x + i\,y = r\,e^{i\theta}$ we may define a complex potential F and field B

$$F(w) = A + i\mu_o U \qquad B = B_x + iB_y$$

such that $B^* = iF'(w)$

where the * indicates a complex conjugate and F' is the complex derivative. In this notation the complex field B is not an analytic function of w. For an expansion we choose

$$F(w) = -\sum_{J=1}^{\infty} \frac{\mathfrak{C}_J}{J} w^J$$

$$B^*(w) = -\sum_{J=1}^{\infty} i\,\mathfrak{C}_J\, w^{(J-1)}$$

We also define a polar representation of the field $B = B_r + iB_\theta$ and find that

$$B = \sum_{J=1}^{\infty} iC_J r^{(J-1)} e^{-i(J\theta + \chi_J)} \qquad \mathfrak{C}_J = C_J e^{i\chi_J}$$

The properties of the harmonic expansion are manifest in this representation. The vector B has a magnitude which is constant on the circle of radius r and a direction which rotates J times as θ increases from 0 to 2Π. $\mathfrak{C}_J$ is identified as the 2J-pole component of the magnetic field. This leads naturally to characterizing shape imperfections of the field by comparisons of field at some reference radius a. We define normalized harmonic coefficients by

$$c_J = \frac{C_J a^{J-1}}{C_N a^{N-1}} = \frac{C_J a^{J-N}}{C_N}$$

where N identifies the dominant harmonic component. Some symmetry properties are most easily revealed by separating into cartesian form by defining

$$b_J = c_J \cos \chi_J \quad a_J = c_J \sin \chi_J$$

where b terms are "normal" and a terms are "skew" components. Changing the reference radius results in the transformation

$$c_J^A = c_J^a \left(\frac{A}{a}\right)^{J-N}$$

If the co-ordinate transformation $w' = \varepsilon w + \gamma$ is applied with $|\varepsilon| = 1$ (a rotation) then letting prime values indicate the values in the new frame

$$c_J' e^{i\chi_J'} = \sum_{I=J}^{\infty} \varepsilon^* c_I e^{i\chi_I} \frac{(I-1)!}{(J-1)!(I-J)!} \left(\frac{-\gamma}{a\varepsilon}\right)^{I-J}$$

To make this more concrete we calculate the first few terms for b_J with $\varepsilon = 1$, $\gamma = x$

$$b_J' = b_J - b_{J+1}\frac{Jx}{a} + b_{J+2}\frac{(J+1)J}{2}\left(\frac{x}{a}\right)^2$$

We speak of harmonic components resulting from "feed down" of higher components as expressed in other reference frames. We seek to understand magnets by expressing their harmonics referenced to magnet center defined <u>magnetically</u> by demanding that terms of harmonic N-1 be zero (the dominant N terms must not feed down to the next lower term).

SIGNAL DETECTED BY ROTATING A SIMPLE LOOP

Measurements based on Faraday's Law of induction begin with the relations

$$\frac{d\Lambda}{dt} = \frac{d}{dt}\int_S \vec{B}.\vec{n}da = \int_\ell \vec{E}.d\vec{\ell} = V_\ell$$

Where Λ is the magnetic flux. We begin with the simple radial loop probe shown in Figure 1a. We assume that the probe has rotated through an angle θ from its starting angle δ. If it is located in a magnetic field characterized by harmonic components C_J referenced to the probe axis, we find

$$\Lambda = \mathrm{Im}\left\{\sum_{J=1}^{\infty} iC_J \frac{La^J}{J} e^{-i(J\delta+J\theta+\chi_J)}\right\}$$

where the coil has length L and other parameters are as shown on the figure. If we measure the voltage V_ℓ as a function of θ in a 2N-pole magnet it will be sinusoidal with an amplitude

$$V_\ell = C_N La^N \frac{d\theta}{dt}$$

For example, rotation of a 1 cm radius by 1m long coil in a 2 Tesla dipole field with a rotation once every 4 seconds give a voltage amplitude of 31 mvolts. A measurement system which records flux (in Volt-Sec. or Tesla-Meters^2) will observe an amplitude of $C_N La^N/N$=20mV-Sec

If we re-express the flux in terms of normalized harmonic coefficients with a normalization radius equal to the probe radius, we have

$$\Lambda = \mathrm{Im}\left\{\sum_{J=1}^{\infty} iC_N LA^N \frac{c_J}{J} e^{i(J\delta+J\theta+\chi_J)}\right\}$$

giving a flux for the 2J-pole which is a fraction Nc_J/J of the dominant multipole field. Thus, for a sextupole distortion of the above 2 tesla field which is a part in 10000 at a probe radius, we have a voltage of 1 microvolt. Clearly, more sensitivity will be needed to measure fields of 400 gauss which might characterize the injection field of a conventional ring such as the Fermilab main ring. A limitation of this simple design is the effect of extraneous probe motions. A distortion of the probe motion by a part in 1000 of the probe radius (10 microns in the example given) will dominate field errors which are of the size we generally wish to explore. Some compensation for this effect must be found.

MEASUREMENT COILS WITH COMPENSATION

Some of the variety of measurement systems in use are shown in Table II. Where the accuracy is sufficient, the single loop coil is utilized. To achieve high accuracy, both the problems of large dynamic range and of compensation for motion errors make alternative designs of interest. The Morgan coil[4] achieves its suppression of unwanted multipoles by symmetry in angle. A Morgan coil with 2M-pole symmetry has 2M wires at angles of 360 / 2M degrees, with adjacent wires connected in opposite sense. The sextupole case is illustrated in Figure 1b. To measure the shape of a quadrupole magnet, a coil with quadrupole symmetry is used to measure the strength. Then the sextupole distortion is measured with a sextupole coil, etc. until all important distortions are measured. The flux intercepted by a Morgan coil of symmetry 2M is given by

$$\Lambda = \mathrm{Im}\left\{\sum_{J=1}^{\infty} iC_N LA^N \frac{c_J}{J}\ 2M\ e^{i(J\delta+J\theta+\chi_J)}\right\}$$

for $J = M(2u+1)$ $u = 0,1,2,\ldots$ with terms as defined above for the single loop. $\Lambda = 0$ for other values of J. A sextupole Morgan coil will suppress all except sextupole, 18-pole, 30-pole, etc. response. A real Morgan coil can be described through superposition as an ideal coil plus a collection of error loops. The sensitivity of the error loops to the dominant field limits the dynamic range and motional error suppression of the Morgan coil. Fermilab experience covering coils with diameters from 3 to 15 cm has typically observed suppressions of 200 to 800 in the dominant response. A recent 7 cm coil has achieved a suppression of quadrupole approaching 5000. Further compensation is obtained by analog addition of a fraction of signal from an orthogonal pair of coils for the dominant field. A typical quadrupole measuring probe might have a pair of dipole and a pair of quadrupole coils plus 6-P, 8-P, 10-P, 12-P and 20-P while a dipole probe would consist of two dipole, two quadupole, 6-P, 8-P, 10-P, 14-P and 18-P. The number of high order coils is limited by the available space for grooves and the cost.

The mechanical advantages of placing all wires on the surface of a cylinder can be maintained while improving the sensitivity of the Morgan coil with the design shown in Figure 1c.[5] This design is sensitive to the variations in the radial component of the field. This tangential coil can be fabricated with many turns to provide high sensitivity. The "belly-band" coil is used to provide dipole cancelation. This Fermilab design is used to allow analog summation of the tangential and dipole coils by choice of the turns ratio and angles. Both the dynamic range and motional cancelation are directly provided.

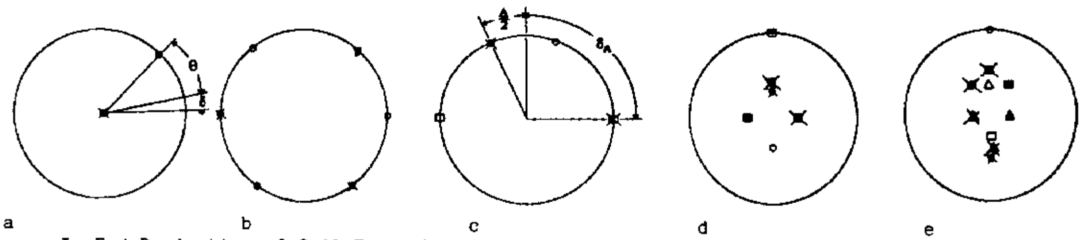

Figure I End Projection of Coil Forms For Harmonic Measurements. a) Simple Radial Loop b) Morgan Sextupole Coil[4] c) Tangential Coil With N_T turns in tangential coil & N' d) Tevatron Dipole Coil[1] e)Tevatron Quad Coil[1]

The flux intercepted by this coil in a multipole field is given by

$$\Lambda = \sum_{J=1}^{\infty} C_N a^N L \, c_J/J$$
$$\times\left[2N_T \sin J\Delta/2 + N_D\left(1-(-1)^J\right) \cos (J+1)\Pi/2\right]$$
$$\times \cos\left(J\theta + J\delta + \chi_J + J\delta_A - \Pi/2\right)$$

with terms as defined above or in Figure 1b. The choice of a wider tangential angle results in a greater sensitivity to lower order harmonics at the expense of a small span of harmonics which are measured before the sensitivity null.

The high field measurements of the superconducting magnets for the Fermilab Tevatron were made with coils which measure the azimuthal variation of the magnetic field. They are illustrated in Figure 1d and Figure 1e for dipoles and quadrupoles respectively. These coils achieve cancelation of the dominant fields with coils at smaller radii than the main sensing coils.

Much work is needed to relate mechanical errors in harmonic probes to errors in magnetic fields. If the field is so uniform that the main requirement is sensitivity, the problems with errors are minimized. In the case of the Fermilab Tevatron superconducting magnets, the horizonal aperture was improved at the expense of vertical aperture in a field which has suitable cancelation between normal components of 14-P, 18-P and 22-P fields. Determination of the skew component of the 18-P field was limited by probe fabrication and probe motion effects. A probe which sags along its length will have the effect of a different center of rotation at various points. This will mix multipole fields as shown in the formulas above. Again, if the higher order fields are small, there will be no "feed-down" effect. However, this is frequently not the case. Achieving machining accuracies of .001" (.025 mm) has required great care at all stages of the probe fabrication process including straightness of tubing, selection of cutting techniques and use of digital tooling for angle measurement. All error effects grow in importance as the probe diameter gets smaller. The angular errors for given machining tolerance grow linearly larger. Sag effects become more difficult at a higher rate forcing one to shorter probe lengths. Coil error terms will provide challenging problems for the 1 cm reference radii required for measurements of Superconducting Super Collider magnets.

ALTERNATIVES TO ROTATING COILS

Alternative coil geometries allow several types of specialized measurement. Precision absolute field measurements require geometrically precise probes. Fabricating probes with stretched tungsten wires held against precision crystal surfaces[1] (quartz or saphire) provides a geometry which can be precise to 10 microns. Achievable measurement accuracy is limited by wire motion and other problems. Measurement of field angle can be carried out by setting the loop in a very precisely vertical plane and measuring the flux induced into it while ramping magnet current. At the other limit, high sensitivity coils can be fabricated with many loops of wire on a form or from pairs of such coils in a gradient pair configuration. A variety of such systems are utilized for strength and shape measurements. NMR measurements provide high precision field shape information which is useful in examining fabrication details.

Table II

Some Systems for Harmonic Measurements

Coil Type	Motion Speed	Readout	Record Data	Location
Loop	High	DVM	A	SLAC
Morgan	AC(1Hz)	Lock-In	A	FNAL
Morgan	High	V/f	B	BNL/FNAL
Morgan	High	Lock-In	A	FNAL
Morgan	Interm	ADC	A	FNAL
Radial	Low	V/f	A	LBL
Morgan	Low	Int/ADC	A	FNAL
Tangential	Low	Int/ADC	A	FNAL
Radial	Low	Int/ADC	A	FNAL
Tangential	Interm	DVM	C	BNL

A=Computer B=Gated Scalars C=Instrument Memory

SIGNAL PROCESSING ELECTRONICS

Measurement of the voltages induced by flux changes is carried out in a variety of ways in existing magnet measurement systems. Traditional integrator systems based on operational amplifiers provide high sensitivity, especially if followed by a high quality amplifier. Digitizing the resulting signal in coordination to position changes provides a straightforward signal processing system. 12 bit ADC's have been used to provide rapid conversions. Alternative signal processing has been carried out with a low noise amplifier followed by a voltage to frequency converter. The integration of flux changes is carried out with a scaler. Data recording by using a latching scaler provides the same pattern of information provided by the integrator/ADC system. Harmonic information can be obtained directly by providing a suitable system of scalers with inverting and non-inverting gating signals based on signals from the angle encoder. With modest optimization in computing, direct integration of the voltage signal can be carried out with traditional amplifier/ADC combinations or the data can be recorded at speeds limited by DVM conversion times directly in memory associated with selected digital volt meters. Finally, lock-in amplifier techniques can be used to provide high sensitivity for measurements by generating suitable locking signals from angle encoders.

For iron free magnets, lock-in techniques can also be used with AC magnet excitation.

DATA HANDLING TECHNIQUES

Although the data collection requirements of a magnet measurement system are far removed from the megabaud data transfers required for modern particle physics experiments, the useful data which can and must be collected will easily overwhelm techniques with logbook and pencil. Modern software engineering techniques and available data management tools are readily applicable to the magnet measurement problem. Most important to the successful management of the results is a consistent database system for both hardware calibration and configuration information together with unprocessed and fully processed measurement data. Monitoring and analyzing data with these tools can be very effective. Some hardware calibration drifts can be tolerated if monitoring of effects is straightforward. Modern tools for screen management, graphics and database management are cost effective additions to the basic programming environment.

FUNDAMENTAL PROBLEMS

To provide precise and accurate magnetic field measurements, the mathematical model of the probe and its motion must closely match the mechanical implementation. Tolerances in coil fabrication are only one of the limits. Asymmetries and non-uniformities of sag or deflection properties demand that these effects must be kept small. In similar fashion, the problem of relating the position of a rotating probe to the center (suitably defined) of a magnet is made difficult by the ratio of length to diameter of typical accelerator magnets and by the encumbrances of beam pipes and other items fabricated with finite tolerances. The magnitude of field errors which will need to be measured and the accuracy with which they need be measured will have a major impact on the needed coils and electronics. If only "good" magnets need to be evaluated, many problems associated with coupling signals from large harmonic error terms into the nearby small terms need not be considered. As in all measurement systems, the full dynamic range which must be measured sets a scale for the difficulty of the problems.

SPECIAL CONSIDERATIONS

Current control deserves special attention. The current regulation, day to day reproducibility and ripple reduction are less critical than for accelerators, however, the hysteretic effects, particularly the effects on field shape are frequently important and small current overshoot in achieving a new current setting can have devastating effects on measurements. For superconducting magnets, quench detection/ protection/recording during all phases of a measurement cycle is highly desirable. As in any complex QC problem, it is very important to provide as often as possible for redundancy of measurements. Redundancy allows problems to be spotted as they occur and the correct hardware cause identified. The problem of providing rigid quality assurance testing software in the same package with flexible prototype and study software is a knotty one. The rewards for solving it are a consistent feedback from each to the other for better quality in each. By facing the need in the design stage of the software, suitable choices can allow this to be the cost effective solution.

FUTURE OPTIONS

The only radical new technology for which I see immediate applications to the problem of magnet measurement is NMR imaging. The developers of resonance imaging systems are developing magnet field mapping systems for large volume systems. The possibility of applying such systems to accelerator type magnets should be explored. The general problem of providing systems whose geometry can be mathematically modeled with sufficient accuracy may remain the dominant problem. The rapidly maturing technology of SQUIDS provide an extremely sensitive technique to sense fields. Unfortunately, the sensitivity of these devices imply systems with extremely high dynamic range if the simplest concepts of using SQUIDS are to be applied. Modern developments in electronics and software continue to provide convenient tools to develop traditional magnet measurement systems.

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