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FIELD MEASURING PROBE FOR SSC MAGNETS*

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Introduction

The field probe developed for measuring the field in SSC dipole magnets[1] is an adaptation of the rotating tangential coil system in use at Brookhaven for several years[2]. Also known as the MOLE, it is a self-contained room-temperature mechanism that is pulled through the aperture of the magnet with regular stops to measure the local field. Several minutes are required to measure the field at each point. The probe measures the multipole components of the field as well as the field angle relative to gravity. The sensitivity of the coil and electronics is such that the field up to the full 6.6 T excitation of the magnet as well as the field when warm with only 0.01 T excitation can be measured. Tethers are attached to both ends of the probe to carry electrical connections and to supply dry nitrogen to the air motors that rotate the tangential windings as well as the gravity sensor. A small computer is attached to the probe for control and for data collection, analysis and storage. Digital voltmeters are used to digitize the voltages from the rotating coil and several custom circuits control motor speeds in the probe. The overall diameter of the probe is approximately 2 cm and its length is 2.4 m; the field sensitive windings are 0.6 m in length.

Field Description and Measurement

The two dimensional field at any point (r,θ) in the free aperture of a dipole accelerator magnet is expressed as a sum of harmonic amplitudes

$$\vec{B}(r,\theta) = \sum_{n=1}^{\infty} C(n) \left(\frac{r}{R}\right)^{n-1} \left[\vec{1}_r \sin n(\theta - \alpha_n) + \vec{1}_\theta \cos n(\theta - \alpha_n)\right] \quad (1)$$

where $C(n)$ is the magnitude of the n^{th} multipole field at a reference radius R, while α_n is the angular orientation of the multipole, with a value in the range $0 \leq \alpha < 2\pi/n$. The multipole expansion can also be expressed in Cartesian coordinates

$$B_y + iB_x = Bo \sum_{n=0}^{\infty} (b_n + ia_n)(x+iy)^n \ . \quad (2)$$

The coefficients b_n, a_n are called the normal and skew median plane multipole coefficients, respectively. For a dipole magnet, the median plane is defined by the dipole component $(C(1) = B_0, \alpha_1 = 0)$ and the median plane coefficients are related to the parameters $C(n), \alpha_n$ of Eq.(1) by

$$b_n = \frac{C(n+1)}{C(1)} \frac{\cos[(n+1)\alpha_{n+1}]}{R^n} \quad (3)$$

$$a_n = \frac{C(n+1)}{C(1)} \frac{\sin[-(n+1)\alpha_{n+1}]}{R^n}. \quad (4)$$

The multipoles of a magnetic field are commonly expressed by these coefficients, in "units" of 10^{-4} $(\mathrm{cm})^{-n}$.

A tangential winding is one that lies on the outer surface of a cylinder, $r = r_c$, (Fig.1) and is sensitive to the radial component of flux density (Eq.1). The magnetic flux linkage for an N turn tangential winding, of opening angle Δ, when it is centered at an angular position θ_c is

$$N\phi(\theta_c) = \sum_{n=1}^{\infty} NC(n) \left(\frac{r_c}{R}\right)^{n-1} \frac{2\ell r_c}{n} \frac{\sin n\Delta}{2} \sin n(\theta_c - \alpha_n). \quad (5)$$

For uniform rotation, where $\theta_c = -\omega t + \delta$, the accompanying induced voltage is

$$V(t) = -\sum_{n=1}^{\infty} NC(n) \left(\frac{r_c}{R}\right)^{n-1} 2\ell r_c \omega \sin\left(\frac{n\Delta}{2}\right) \cos n(\omega t - \delta + \alpha_n) \quad (6)$$

where the angle δ has been included to express the initial offset between the winding and the reference axis.

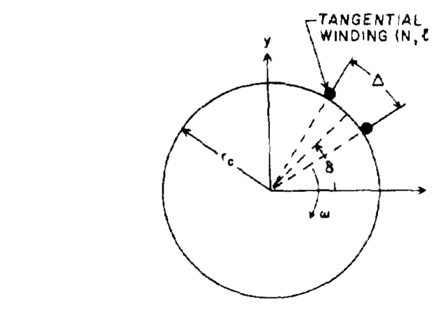

Fig.1. Parameters for a tangential winding.

The field is measured by rotating the tangential loop in the field at a constant angular velocity and digitizing the voltage [Eq.6] induced in the loop 128 times during each revolution. The trigger to digitize is derived from an optical encoder attached to the rotating coil. A marker pulse from the encoder defines the reference axis. The resulting time spectrum of the voltage is Fourier analyzed to give the harmonic content of the field. In practice, several wire loops (Fig.2) are employed to differentiate between the large fundamental dipole and the much smaller multipoles. Each signal is separately digitized and the bucking of the fundamental is performed digitally in the computer (Fig.3). Note that the voltages from the measuring coils pass directly to the DVM's without conditioning or modification. The high input impedance of the DVM's minimizes problems from slip ring and wire resistance. The voltmeters integrate the signal over one 60 Hz line cycle to reduce common mode noise, present in most environments. These various features together with the internal calibration capability of the voltmeters give the measuring system good inherent accuracy, stability, and reproducibility.

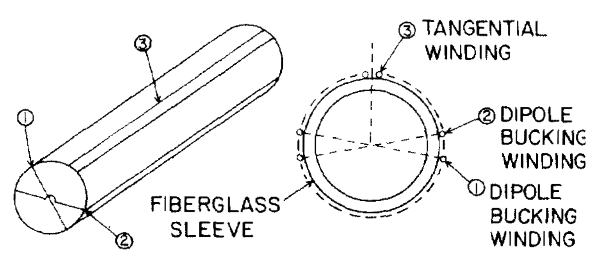

Fig.2. Windings on a tangential coil.

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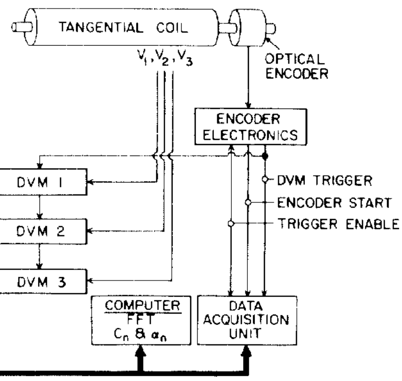

Fig.3. Readout electronics for tangential coil.

The sensitivity of the field probe to the various multipole fields, as used to measure SSC dipole magnets, is as follows

MULTIPOLE	SENSITIVITY (V/T)
Dipole	0.0903
Quadrupole	0.2160
Sextupole	0.3866
Octupole	0.6133
Decapole	0.9098
⋮	⋮
26-pole	8.4622

General Description

A schematic representation of the field probe is given in Fig.4. An air motor rotating at $\sim$ 7000 rpm provides the driving force to rotate the coil. The gas pressure to the motor is controlled in a feedback loop to maintain constant rpm. The speed is geared down in several stages so that finally, the required 15 rpm is achieved. The high speed moving parts are non-metallic to avoid deleterious effects from eddy current forces. Vibration

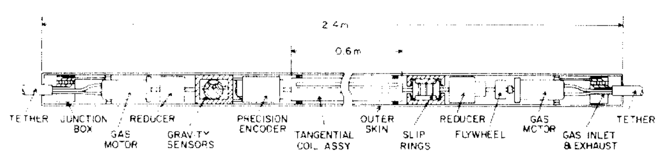

Fig.4. Schematic drawing of field measuring probe.

dampers are used in several places along the shaft of the device to reduce torsional vibrations, which are the source of the most significant errors in this device. The optical encoder housing is coupled to a gravity sensor which gives the angular orientation of the device in space. Since the field probe housing can rotate as it is drawn through a magnet, and since the gravity sensor precision is maximized near zero output, a drive system is incorporated to orient the gravity sensor to zero angle.

Mechanical Structure

The frame of the field probe is made from a thin walled brass tube comprised of three sections. The drive end section covers the drive train including the air motor, speed reducers and slip rings, the coil section covers the rotating coil form, and the final section covers the encoder gravity sensor subassembly. These three sections are connected with brass splice sections using fine machine threads on the respective components. Inside the brass tube are a series of stainless steel threaded cylinders supporting the drive train and other components where added strength is required. Several of the commercial components have been remanufactured at BNL to eliminate metallic pieces. Precision alignment is required throughout to prevent drag and to minimize vibrations.

The air motor is a vane-type device manufactured by the Micro Motor Co., Santa Anna, CA The shaft is machined from 4301 torlon composite, selected for strength, machining properties and dimensional stability. The vanes are machined from Hostalen plastic, selected for its abrasion resistance to ensure adequate lifetime of the air motor. The rotor is mounted on two ball bearings made of silica nitride balls and beryllium copper races. These will be replaced with silica nitride races at a future date. Approximately 6 psi pressure and 10 cfm gas flow are required to drive the motor. The air motor is connected to a carefully balanced flywheel made of molded polymer whose function is to smooth out transient variations in motor speed. Following the flywheel are two speed reducers, the first a 4:1 in line spur gear unit manufactured by Portescap, U.K. and the second a 110:1 3-stage planetary gear unit manufactured by Portescap, W. Germany. In this way the 0.3 in. oz. output torque of the air motor is reduced to drive the coil form, which is made of glass reinforced epoxy with precision wire slots for the tangential windings.

The eight ring slip ring assembly, manufactured by the Airflyte Co. of Bayonne, N.J., is located between the speed reducers and the coil. Between the slip ring assembly and the coil is a vibration damper, consisting of a hollow section sealed with rotary seals and filled with vacuum grease that forms a viscous circumferential shear plane with two boundary layers. This serves to dampen torsional vibrations as do the tygon tube connections between the various components in the drive train.

Beyond the coil is the encoder gravity sensor (EGS) subassembly. The precision optical encoder is manufactured by Teledyne Gurley, Troy, N.Y. and the gravity sensor, a vial containing electrolytic fluid, by Spectron Glass and Electronic Co., Hauppauge, N.Y. The EGS actually contains several gravity sensors, a fine resolution sensor to cover the angular range $\pm 2°$ and a coarse sensor to bring the EGS within this range. A reversible air motor coupled through speed reducers to the EGS is used for this task. A multiturn potentiometer ensures that the control system, regulating the air flow through solenoid valves, recognizes the maximum angle available to the EGS. The system is designed to obtain a gravity sensor reading near zero degrees, no matter how much the probe housing has rotated in its traversal of the magnet.

A block diagram of the gravity sensor readout scheme is given in Fig.5.

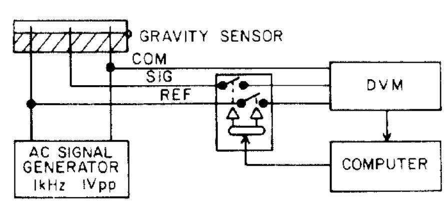

Fig.5. Gravity sensor readout scheme.

Performance

As seen in Eq.6, a constant angular velocity ω is required for accurate voltage measurements. To enhance the accuracy, the time between encoder trigger pulses is digitized and the voltage measurement is corrected using these measured time intervals, typically a 1% correction. A plot of the measured times is shown in Fig.6. The rms variation in the data shown is 0.323 msec, a typical number; if this variation becomes large, data taking is halted until the source of the variation is corrected. To maximize accuracy, the gravity sensor is rotated so as to give readings near zero degrees. The linearity of this device for small angles is shown in Fig.7. As can be seen, it is quite linear so that readings somewhat other than zero are still valid.

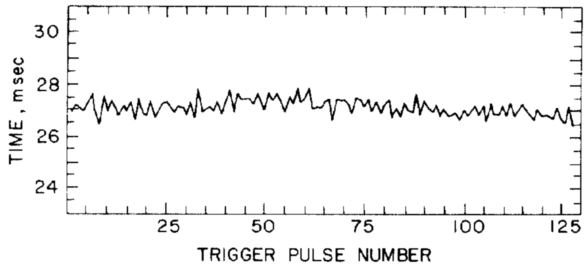

Fig.6. Time variation in trigger pulses from probe.

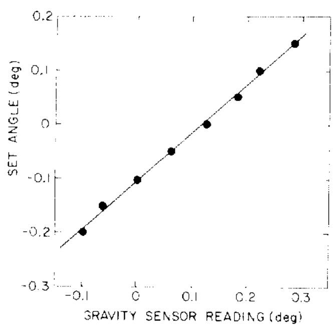

Fig.7. Gravity sensor linearity.

The ability of the probe to measure magnetic fields has proven quite good. The observed rms reproducibility in the range B = 1-2 T is generally several parts in 10^6 of the main field for the lower multipoles and equal to or less than one part in 10^6 for multipoles above the decapole. Repeated measurements over several days in a dipole field of 1.8 T gave $\Delta B/B = 3.6 \times 10^{-4}$ (rms) and Δ (dipole angle) = 0.13 mrad (rms). A measure of the accuracy of the probe has been obtained from measurements in a calibration dipole field with all multipoles expected to be at or near zero. The observed multipoles for B = 1.8 T are several parts in 10^6 of B for the quadrupole and sextupole terms and less than one part in 10^6 of B for higher multipoles.

Magnetic Field Measurements

Measurements using the field measuring probe have been carried out on a number of SSC dipole magnets. To illustrate the probe's performance, several are shown here. Figure 8 shows the sextupole component measured in three repeated scans of an SSC magnet powered with 10A excitation (approximately 100 G dipole field). Figure 9 shows the dipole angle

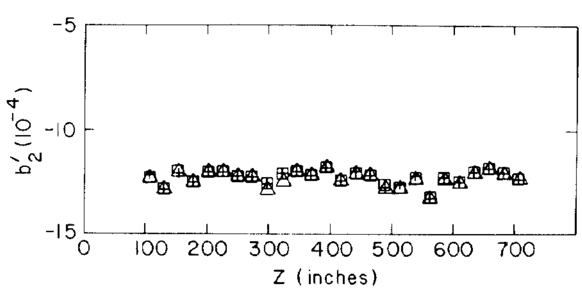

Fig.8. Repeated measurements of sextupole field in a 17 m SSC magnet.

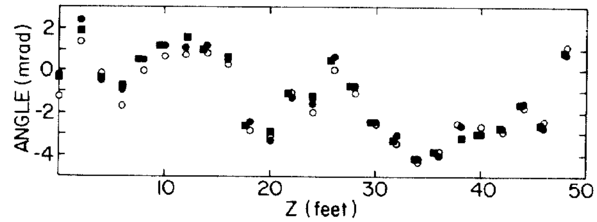

Fig.9. Repeated measurements of dipole angle in a 17 m SSC magnet.

measured several times over the length of the magnet. The reproducibility of the measurements is seen to be good in spite of the extremely low signal strength inherent in these low field conditions.

A measurement of the sextupole field as a function of current is shown in Fig. 10. Due to magnetization of the relatively large filaments in the superconductor used in this magnet, there is a substantial difference in the up-ramp and down-ramp values of the normal field component shown here, with the up-ramp values more negative. This effect persists to very high multipoles; it is seen in the 26-pole measurement as well. The clear-cut difference measured between up and down ramps shows that the probe is sensitive to these high multipoles. The figure illustrates that the point-to-point measuring repeatability of the probe is excellent.

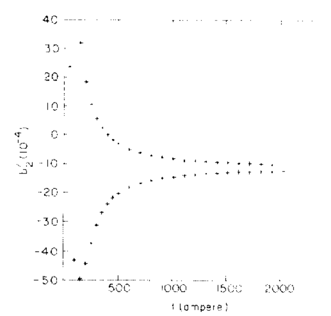

Fig.10. Sextupole field vs current in an SSC magnet.

Conclusion

The field probe described has been under development for several years. It has proven capable of measuring the field in SSC dipole magnets, both warm and cold, with adequate precision to meet the program requirements. The major hurdles that have been overcome are the required small diameter to fit the magnet aperture, the need to remove metallic components in the rotating structures of the device, and the damping of torsional vibrations. Modifications and improvements are underway to make the probe more reliable and easier to use, in anticipation of the large number of magnets that must be measured in the SSC program.

References

[1] J.Herrera, H.Kirk, A.Prodell, E. Willen, "Magnetic Field Measurements of Superconducting Magnets for the Colliding Beam Accelerator", 12^{th} Int. Conf. on H.E. Accelerators, FNAL, Aug. 11-16, 1983.

[2] The requirements for measuring the field in SSC magnets are discussed more completely in "Proceedings of The SSC Magnetic Measurements Workshop", SSC-SR-1025, LBL, Nov. 18-20, 1986