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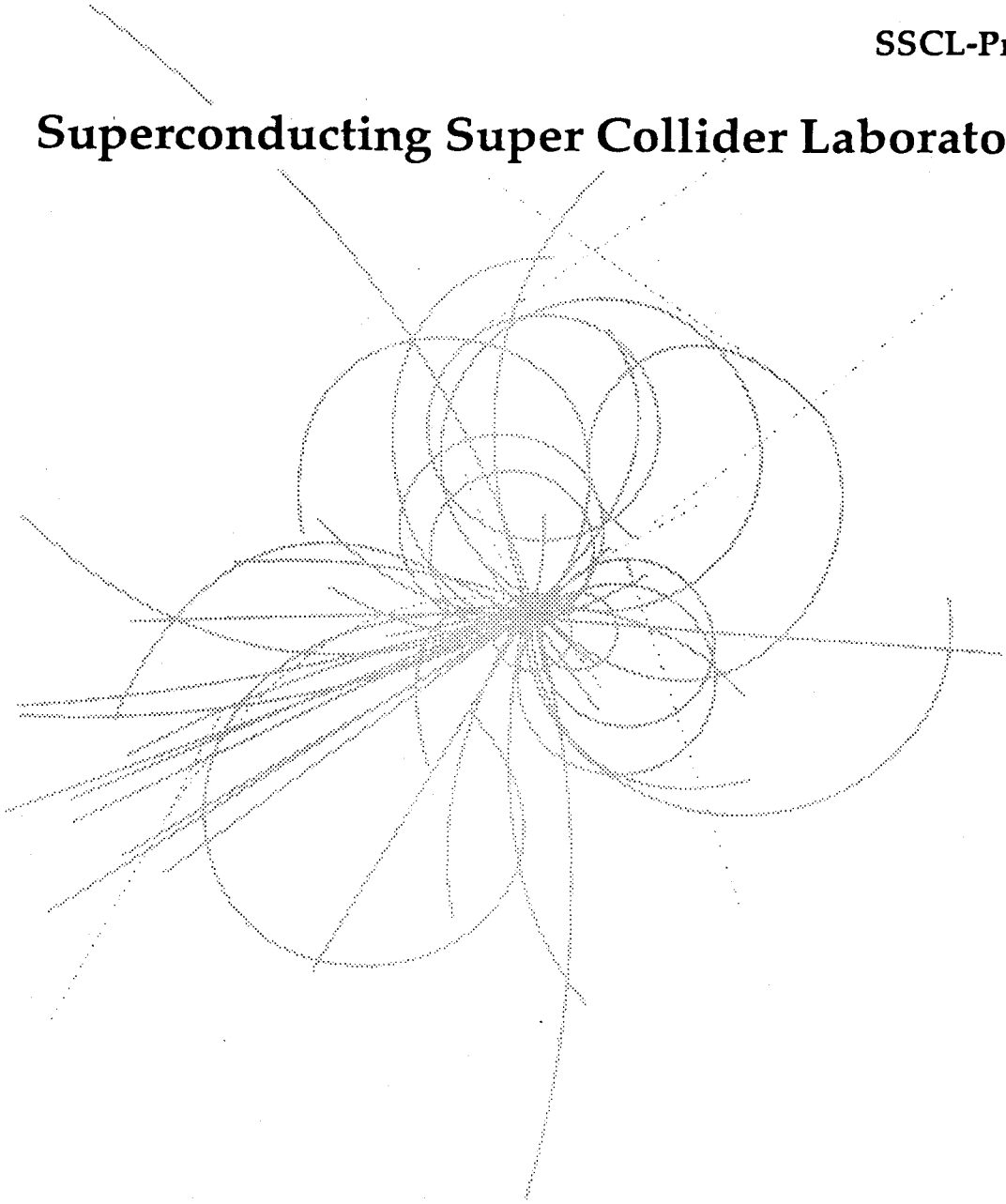

Magnetic Measurement Instrumentation Developments at the SSC

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MAGNETIC MEASUREMENT INSTRUMENTATION DEVELOPMENTS AT THE SSC

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ABSTRACT

We review the developments in magnetic measurement instrumentation that have taken place at the Superconducting Super Collider (SSC) Laboratory. The primary developments have been stretched wire systems for superconducting dipole and quadrupole alignment and field integral measurement, and our support of the "mole" that is being developed by Brookhaven National Laboratory (BNL).

INTRODUCTION

Several developments in magnetic measurement instrumentation have taken place at the SSC Laboratory. We have developed a stretched wire technique for precision alignment of dipoles and quadrupoles. In addition, this technique should give the integrated field strength of dipoles and the integrated gradient of quadrupoles. The technique works at currents over the entire range from 10 A to 6500 A. We can use the same instrument to do alignment and field integral measurements on warm and cold magnets to get the warm-cold correlations.

We are also aiding the "mole" development effort at BNL. We have performed an extensive computer simulation of the mole to establish its crucial design parameters. The errors in multipole measurements were determined for various mechanical imperfections. We present construction tolerances that must be met to keep the errors on the multipole measurements below 0.01 unit. We are also looking into several ways to simplify the mole and to calibrate it.

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STRETCHED WIRE DEVELOPMENTS

Magnet fiducialization, the alignment of the magnetic field with respect to external markings on the magnet cryostat, is a fundamental step in accelerator alignment. The measurement of the dipole-integrated field strength and the quadrupole-integrated gradient are also important. The fiducialization and integrated field determination for the SSC magnets are complicated by the fact that only a fraction of the magnets will be tested under operating conditions. Most magnetic measurements will be made at room temperature with low energization current. The magnets tested cold must provide correlations between the measurements at room temperature with low energization current and the measurements at the operating temperature with full energization current. In developing instrumentation to do the fiducialization and integrated field determination, we were looking for a very sensitive device capable of working at the low field strengths of a warm magnet. In addition, we wanted a device with a large dynamic range so the same device could be used to make all the measurements necessary to determine the warm-cold correlations. We believe a stretched wire system is ideally suited to our needs.

The technique we came up with involves oscillating the wire in the magnet. The wire is oscillated at different positions and orientations. Null measurements give the alignment. The magnet is energized with direct current. This allows us to avoid problems with eddy currents, yet take advantage of the sensitivity of AC electronic techniques. The technique was devised after R. Schermer's advocacy of AC techniques for these measurements,[1] and after visits to DESY and Stanford Linear Accelerator Center (SLAC) to observe their methods of magnet fiducialization.[2,3] In particular, our technique is an adaptation and extension of Gerry Fischer's quadrupole centering technique used at SLAC.[3] We have used our technique on dipole and quadrupole magnets to date. We expect the technique could be used on higher-pole magnets. We review the technique for dipoles and quadrupoles and discuss our initial results.

Dipole Fiducialization

The specification on the dipole roll angle measurement is that the average field direction be given within 1 mrad with respect to fiducial markings on the cryostat.[4] Our stretched wire system measures the dipole roll angle in the test bench coordinate system. A companion system finds the fiducial marks also in the test bench coordinate system. The stretched wire system, therefore, can use only a fraction of the 1-mrad error budget. We wish to determine the dipole roll angle at the few tenths of a milliradian level. A specification on the integrated field value is that at full field it must be within 0.3 Tm of the specified[4] value of 100.1 Tm, or within 0.3%. We thus wish to measure it to a few parts in 10^4. In this section we describe our stretched wire system and its ability to meet these specifications. A more complete description can be found in the references.[5]

The basic idea behind the stretched wire dipole alignment technique is illustrated in Figure 1. If a wire is oscillated parallel to the dipole field, no voltage is induced in the wire. If the plane of wire oscillation makes a small angle with respect to the dipole field direction, a voltage given by

$$V^{rms} = \frac{1}{\sqrt{2}} B_0 L_m \omega A(\theta - \theta_0)$$

is induced in the wire. In this expression, V^{rms} is the rms voltage (including the relative phase) induced in the oscillating wire, B_0 is the dipole field strength, L_m is the magnetic length, ω is 2π times the frequency of wire oscillation, A is the wire

oscillation amplitude, and $\theta - \theta_0$ is the angle between the direction θ of the wire motion and the direction θ_0 of the dipole field. Sample values for the parameters in this equation are $B_0 = 0.01$ T ($I_{mag} = 10$A), $L_m = 15$ m, $\omega = 6.28$ 1/s ($f = 1$ Hz), and $A = 3$ mm. The 1-Hz oscillation frequency was chosen to be well below the wire's fundamental frequency of vibration, which is around 10 Hz. Inserting the parameter values, the expected signal is $V^{rms} = (2.2\mu\text{V/mrad})(\theta - \theta_0)$.

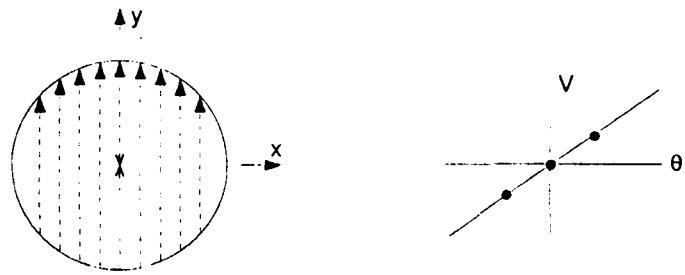

Figure 1. Illustration of the measurement by which the dipole roll angle is determined.

After establishing the stretched wire measurement concept, we assembled equipment to do a proof-of-principle test. We stretched a 150-μm (6 mil) CuBe wire through a full-length dipole. At each end of the dipole the wire was moved by an assembly consisting of a synchronous motor turning a cam that pushed a slide connected to the wire. The magnet was energized with 10 A. The voltage in the wire was measured with a lock-in amplifier. We rotated the magnet and recorded the voltage as a function of magnet roll angle. Figure 2 shows our results. The voltage has the expected rate of change with angle and the phase goes through a 180° change, as expected. A fine scan of the voltage vs. angle demonstrated a measurement sensitivity of about 0.1 mrad. Our next step is to calibrate the system to bring the accuracy in line with the sensitivity. A complete discussion of these preliminary results can be found in the references.[6]

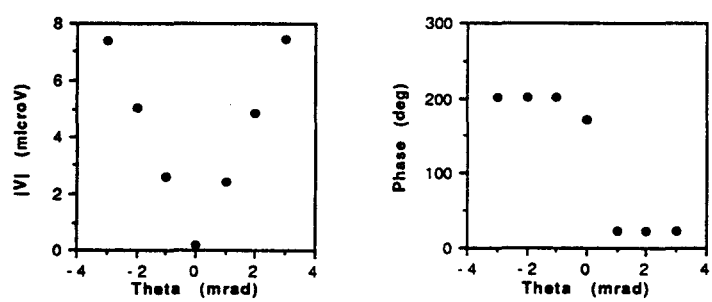

Figure 2. Measured voltage, magnitude and phase, induced in the wire as a function of dipole roll angle.

We envisage doing the integrated field strength measurement by oscillating the wire perpendicular to the dipole field and measuring the voltage with a precision voltmeter. The induced voltage in the wire is given by $V^{rms} = (1/\sqrt{2})B_0 L_m \omega A$. Unlike the null measurement for alignment, V^{rms}, ω, and A in this expression must be measured to 1 part in 10^4 if we are to determine $\int Bdl = B_0 L_m$ to a few parts in 10^4. We have ordered equipment with the required accuracy, but we have not performed this measurement yet.

Quadrupole Fiducialization

The specifications on quadrupole alignment are more stringent than on dipole alignment. The quadrupole center must be determined within 0.2 mm with respect to fiducial markings on the cryostat.[7] The quadrupole roll angle must be determined within 0.5 mrad.[7] As in the dipole measurements, the stretched wire system can use only a fraction of this error budget. We thus need to make measurements with accuracies a few tenths of these specifications. A specification[7] on the integrated gradient is that the rms variation between magnets be within 1 part in 10^3 of the average value. We thus require our measurement accuracy to be a few parts in 10^4 for the integrated gradient measurement. We now describe our stretched wire system for quadrupole measurements and its ability to meet these specifications. A complete analysis of our measurement techniques can be found in the references.[8]

Our procedure for doing the quadrupole alignment is illustrated in Figure 3. The x-position of the quadrupole center is first determined by the method indicated in Figure 3a. The wire is oscillated in the x-direction, and the center of oscillation is moved through the magnet. The voltage induced in the wire is given approximately by

$$V_\omega^{rms} \simeq \frac{1}{\sqrt{2}} G L_m \omega A_x (x_{e0} - x_0),$$

where V_ω^{rms} is the rms voltage (including the relative phase) at frequency ω, G is the quadrupole gradient, L_m is the magnetic length, ω is the angular frequency at which the wire is oscillated, A_x is the oscillation amplitude, x_{e0} is the x-position of the center of wire oscillation, and x_0 is the x-position of the quadrupole center. This equation is a simplification of the exact expression which can be found in the references.[8] Scanning x_{e0} gives a voltage null at the x-position of the quadrupole center.

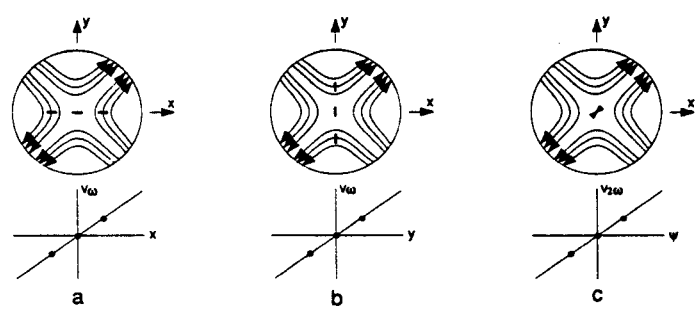

Figure 3. Illustration of the measurements in our prototype alignment procedure by which we determine the a) x-position of the quadrupole center, b) y-position of the quadrupole center, and c) roll angle of the quadrupole.

The y-position of the quadrupole center is found in a manner similar to the x-position. The procedure is illustrated in Figure 3b. The wire is oscillated in the y-direction, and the center of oscillation is moved through the magnet. The voltage induced in the wire is given approximately by

$$V_\omega^{rms} \simeq -\frac{1}{\sqrt{2}} G L_m \omega A_y \left(y_{e0} - y_0 - \frac{2}{3}\delta \right).$$

The quantities in this expression have similar meaning to those used in the previous expression for finding x. In this expression, however, the sag of the wire, δ, enters and must be accounted for. We anticipate using the DESY technique of varying the wire tension and extrapolating to infinite tension. The extrapolated position of the voltage null gives the y-position of the quadrupole center.

The quadrupole roll angle is found in the manner illustrated in Figure 3c. The wire is oscillated at angles near the 45° line. For this measurement, we use the voltage induced at twice the frequency of the wire oscillation. This voltage is given by

$$V_{2\omega}^{rms} \simeq -\frac{1}{\sqrt{2}} G L_m \omega A^2 (\psi - \theta_0).$$

In this expression, ψ is the angle of wire motion relative to the 45° line, and θ_0 is the roll angle of the magnet. The other variables have been previously defined. There is a voltage null at $\psi = \theta_0$.

We set up equipment to do a feasibility study of this technique. We were able to measure the y-position of the quadrupole center with a sensitivity around 20 μm, as shown in Figure 4. The roll angle could be determined only to around 1 mrad, as shown in Figure 5. We have several improvements planned for the roll angle measurement. The voltages for both measurements had the expected magnitudes and dependencies. As for the dipole measurements, we still need to calibrate the system to bring the accuracy in line with the sensitivity.

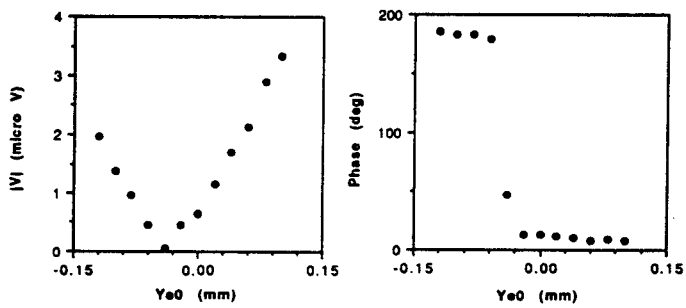

Figure 4. Measured voltage, magnitude and phase, induced in the wire in a scan to determine the sensitivity for finding the y-position of the quadrupole center.

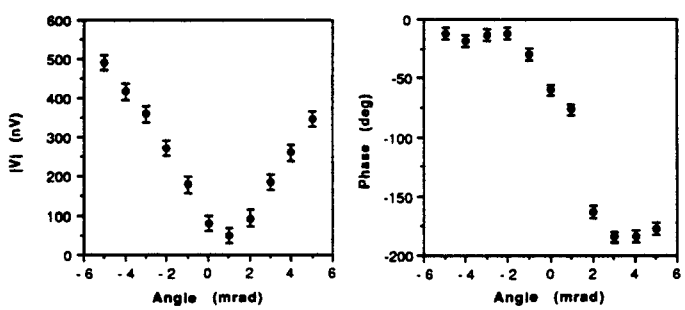

Figure 5. Measurement indicating our present sensitivity to the quadrupole roll angle. The plot shows the magnitude and phase of the induced voltage as a function of roll angle.

We expect[8] to be able to measure the quadrupole-integrated gradient with the stretched wire technique. As in the case of the dipoles, we have ordered equipment with the required accuracy to make these measurements, but have not performed the measurements yet.

MOLE SIMULATION STUDY

We have developed a simulation program to study magnetic multipole measurements using a tangential coil with dipole bucking windings. In this study, our focus was on the errors arising from imperfections in the rotating coil.

A typical coil is shown in Figure 6. The simulation program generates the voltage vs. time data from a given input magnetic field and a set of configuration data about

the coil. The analysis program takes these data as input and calculates the magnetic field. The input magnetic field[9] is shown in Table 1. The given values of a_n and b_n represent the limit on the allowed mean value plus 3 standard deviations. In the simulation program, we can take the imperfections of the coil construction into account. Examples are gravity sag, bowing, wire twist, etc. The program simulates their effect on the measured harmonics. When we study one particular effect, only those parameters related to this effect change, and others are kept constant with their nominal values. The results are compared with an ideally built coil in order to give us some design guidance. Table 1 shows the output magnetic field after the simulation and analysis program with all parameters set at their nominal values. The small discrepancies are due to the fact that the coil windings in any particular wire bundle are not at the same radial and angular position, as shown in Figure 6.

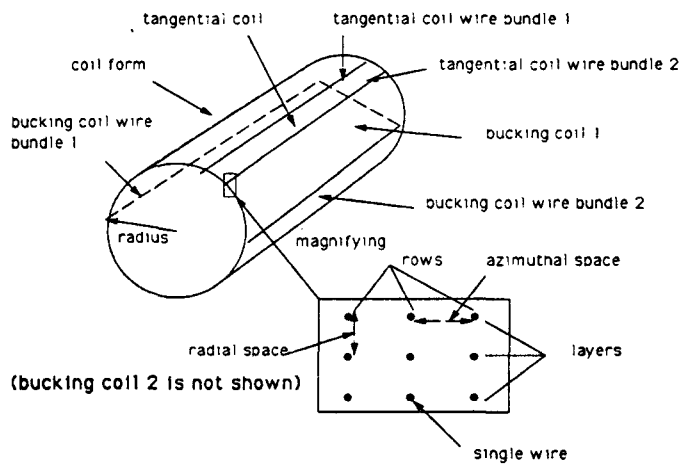

Figure 6. Illustration of the rotating coil used for multipole measurements in dipole magnets.

Table 1. Comparison of the input and output multipole coefficients.

Multipole	Input skew a (units)	Input normal b (units)	Output skew a (units)	Output normal b (units)
0	0.0	10000.0	0.0	10000.0
1	3.79	1.54	3.804	1.545
2	1.082	5.45	1.089	5.484
3	0.986	0.506	0.9958	0.511
4	0.17	0.74	0.1723	0.7496
5	0.166	0.076	0.1685	0.07716
6	0.043	0.08	0.04379	0.08144
7	0.04	0.04	0.04077	0.04076
8	0.0305	0.0425	0.0311	0.04335

The digital bucking technique was used in our analysis program. Usually the voltage induced in a rotating coil is dominated by the fundamental component of the magnetic field. In order to calculated the higher-order multipoles accurately, we need to buck out the fundamental component. Figure 6 shows a typical configuration of dipole-bucking coils in which one tangential coil and two bucking coils are used.

The induced voltage in the tangential coil can be written as[10]

$$V_T(t) = -\sum_{n=1}^{\infty} NC(n)\left(\frac{r_c}{R}\right)^{n-1} 2lr_c \sin\left(\frac{n\Delta}{2}\right)\cos n(\omega t - \beta + \alpha_n),$$

where N is number of turns of the tangential coil, $C(n)$ is the magnitude of the nth multipole field at the reference radius R, l is the length of the tangential coil, r_c is the radius of the tangential coil, ω is the angular velocity, β is the initial offset angle, and α_n is the angular orientation of the multipole. The induced voltages on the two bucking coils are given by a similar expression. The skew and normal harmonics are defined as

$$a_{n-1} = -\frac{C(n)\sin(n\alpha_n)}{C(1)R^{n-1}}; \qquad b_{n-1} = \frac{C(n)\cos(n\alpha_n)}{C(1)R^{n-1}}.$$

For a detailed discussion of digital bucking and the error analysis, please see the references.[10,11] In the following we discuss the effects of several imperfections in the measurement coil.

Mole Construction Tolerances

In the process of constructing the mole, the coil may be bent. Since the coil is rigid, the bend direction is fixed with the coil and rotates with it. We set the bowing angle to 0° with respect to the coil symmetry axis. The values of bowing sagitta were set to 3, 6, and 12 mils, respectively. Figure 7 illustrates the effect. Since the largest change occurs linearly in b_2, the bowing should be less than 1.6 mils if we require $|\Delta b_2|$ less than 0.01. From Figure 7, the relative changes of the sextupole are $\delta a_2/a_2 = -0.098$ and $\delta b_2/b_2 = -0.11$. We can also estimate these changes analytically[11] using a first-order approximation, which results in $\delta a_2/a_2 = -0.10$ and $\delta b_2/b_2 = -0.10$. The two methods are consistent.

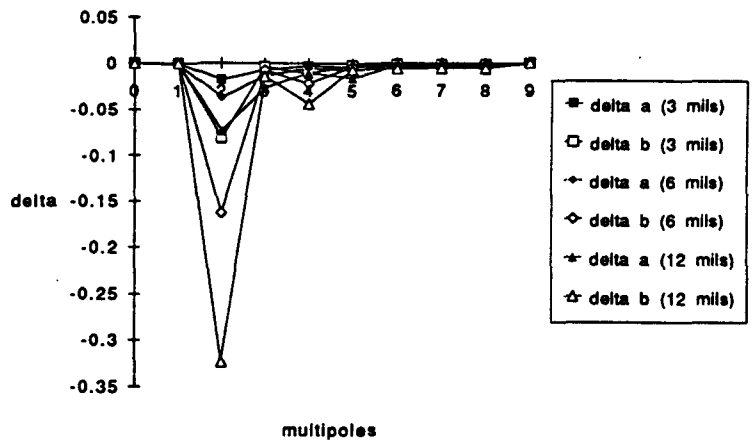

Figure 7. Measured multipole error with coil bowing at zero degrees.

Some other sources of mechanical imperfections are: (1) the angular or radial position of the coil winding may be offset parallel to the rotating axis; (2) the coil winding may have a cone shape; and (3) the bearing of the coil may be offset from the geometrical center of the coil. The multipoles are sensitive to these effects, and the simulation and analysis can be done similar to the bowing. If the required maximum tolerance on any multipole is less than 0.01 unit, then the coil has to satisfy all the mechanical tolerance requirements in Table 2. All these simulation results are in good agreement with the analytical calculations.[11]

Table 2. Tolerance requirements for the coil.

effect	physical parameter	tolerance
bowing	$\|bow\|$	1.6 mils or 0.041 mm
tangential coil radius	$\|\Delta r_T\|$	0.24 mils or 0.0061 mm
bucking coil radius	$\|\Delta r_B\|$	0.53 mils or 0.0135 mm
tangential coil cone	$\|\Delta r_{Tcone}\|$	0.48 mils or 0.012 mm
bucking coil cone	$\|\Delta r_{Bcone}\|$	2.0 mils or 0.052 mm
bucking 1 angle	$\|\Delta\theta_B\|$	7.1 mrad
bearing offset	$\|\Delta x\|, \|\Delta y\|$	0.24 mils or 0.0061 mm
sag	sag	40 mils or 0.10 mm
twist	$\|\Delta\phi\|$	40 mrad
tangential angle	$\|\Delta\theta_B\|$	130 mrad
angular velocity of coil	$\|\Delta\omega\|$	1%

We also studied other imperfections, such as coil sagging, coil twist, and angular speed variations. These effects are either very small or can be corrected using the measurement data. From Table 2, we see that harmonics are very sensitive to the radius errors. Therefore, the most demanding requirements are on the radius tolerance.

Using the above fabrication tolerances as guide, we put together a machining fixture that is now being used to fabricate coil forms.

CONCLUSION

We are in the process of developing a fast, accurate method of aligning magnets and measuring the integrated field values. The fundamental ideas of the stretched wire system appear sound. We have much work to do, however, to automate the system and to prove its accuracy.

We have provided insight into the characteristics of the mole. The crucial design parameters have been identified. Improvements in the mole construction are being made.

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