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LOCATING THE MAGNETIC CENTER OF THE SSC CDM USING A TEMPORARY QUADRUPOLE FIELD

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Abstract--The SSC dipole magnets must be very accurately aligned for the accelerator to work correctly. To align the magnets one must accurately know the center of the magnetic field. However, locating the center is difficult because of the extreme uniformity of the dipole field. A technique has been developed to determine the magnetic center of the SSC dipole magnet under ambient test conditions. This technique involves flowing current in the upper half of the coils in the direction opposite to the current in the lower half. This is done using a temporary lead connected to the splice joining the two coil halves and two matched power supplies. The resulting field is primarily skew quadrupole and has high field gradients which allow the center to be accurately located. The viability of this method has been verified by analysis using Taylor series expansion of the resulting magnetic field. Analysis has also verified that off-the-shelf power supplies have low enough mismatch to be used in this technique. The analytical results have been verified through the test of a short dipole magnet at the Brookhaven National Laboratory.

I. INTRODUCTION

In order for the Superconducting Super Collider (SSC) to meet its physics requirements, the magnetic center of each Collider Dipole Magnet (CDM) must be accurately aligned. The two most commonly used methods to find the center of a magnet are geometric and magnetic. The geometric method is based on the assumption that the magnetic center of the magnet is coincident with the geometric center. This is a good assumption for the CDM because the coils are extremely uniform and are two-dimensional in shape. Difficulty arises however after the magnet is assembled since the coils are not directly accessible. After assembly, one can use the beam tube as a reference but this introduces additional errors due to the tolerances of the tube and its locating method.

The magnetic method locates the center of the dipole field directly. This method uses a magnetic field measuring device, a one meter long rotating coil commonly called a "mole", in concert with feeddown analysis. Feeddown analysis is a technique which uses both high order allowed harmonics and lower order unallowed harmonics to analytically locate the magnetic center. While this technique generally gives consistent results, problems may arise if the higher order terms are not measured to sufficient accuracy or when the measuring coil radius is small compared to the magnet bore radius. Both of these problems occur in the CDM because of the extreme purity of the magnetic field and the fact that the moles have an average coil radius of 12 mm while the magnet bore radius is 25 mm.

An alternate technique has been developed which allows the use of direct magnetic centering while avoiding the problems associated with using feeddown on a dipole magnet. This technique involves flowing current in the upper half of the coils in the direction opposite to the current in the lower half. The resulting field is predominantly skew quadrupole, as shown in Figure 1, and has high field gradients which allow the center to be accurately located using a mole and feeddown analysis. It should be noted that this is not a true quadrupole, since symmetry about 45° and 135° axes is not satisfied, and substantial amounts of higher order terms are present. We shall, however, refer to this technique as the "skew quadrupole centering technique".

Reversing the current direction in the lower half of the magnet is done using a temporary lead connected to the splice joining the two coil halves. Locating the magnetic center of the CDM is performed warm during fabrication using approximately 10 A, and hence only a small copper temporary lead is required. The two coil halves are each connected to a matched power supply to ensure that each half has identical currents. Analysis presented in this paper shows that off-the-shelf power supplies have low enough mismatch to be used in this technique.

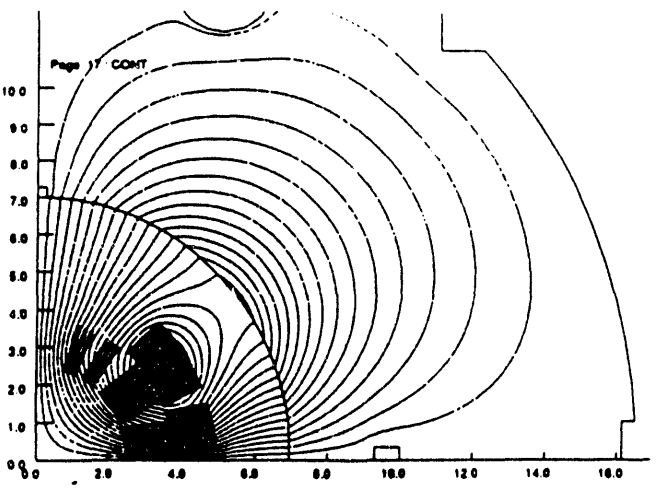

Fig. 1 90° model of the CDM connected in the skew quadrupole configuration.

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II. FEEDDOWN ANALYSIS

A. Feeddown

Feeddown occurs when the measuring coil center is not coincident with the magnet center. The measured values of magnetic field, when broken down into harmonic coefficients b_n and a_n, include the effects of feeddown from higher order terms.

The ability to find the magnetic center using feeddown from high order harmonics is limited by the accuracy of the harmonic measurements. With the re-optimized CDM cross-section, the high order harmonics are extremely small. Using a required magnetic field center location accuracy of 110 μm, the required measurement accuracy of b_9 and b_{10} is better than 0.0014 units in the dipole configuration. The mole may be able to measure the field this accurately. Currently, the accuracy of the mole is believed to be better than 0.01 units; how much better is unknown. In addition, due to the difficulty in calibrating the mole, its accuracy may remain unknown throughout the SSC program. Consequently, use of the skew quadrupole centering scheme has been investigated as an alternative technique.

B. Feeddown Definition

The purpose of the following analysis is to determine the required tolerance for mole harmonics measurement. The magnetic fields can be represented either by a Fourier series or Taylor series expansion. For feeddown analysis it is convenient to use the Taylor series representation.

$$B = B_x + iB_y = \sum_{n=0}^{\infty} (D_n)\,(z^*)^n \; ; \tag{1}$$

$$z = x + iy \tag{2}$$

The feeddown effect is produced by measuring the magnetic field with an origin that has an offset from the magnetic center. For this analysis the offset is a complex number. Replacing z with $(z' + \delta)$, where z' is the measurement variable and δ is the offset from the magnetic center, the series can be transformed to show the harmonic produced by measuring off center.

$$B = \sum_{n=0}^{\infty} (D_n)\,([z' + \delta]^*)^n \; ; \; z = z' + \delta \tag{3}$$

$$B \approx \sum_{n=0}^{\infty} (D_n)\,[(z')^*]^n \left[1 + n\frac{\delta^*}{z'^*} \right] ; \tag{4}$$

taking the first two terms of the binomial expansion

Since the δ/z' multiplies the $(z')^n$ term, it appears to produce a $z'^{(n-1)}$ component. This is the method in which feeddown is produced.

$$B \approx \sum_{n=0}^{\infty} [(z')^*]^n \,[\,(D_n) + (n+1)\,\delta^*\,(D_{n+1})] \tag{5}$$

If D_n' is the measured harmonic,

$$B = \sum_{n=0}^{\infty} [(z')^*]^n \,(D_n') \tag{6}$$

$$D_n' \approx (D_n) + (n+1)\,\delta^*\,(D_{n+1}) \; ; \tag{7}$$

comparing coefficients

For the SSC dipole magnets odd coefficients, when considered from the magnetic center, are produced by coil asymmetries. When considering higher order harmonics, odd harmonics should be very small. They can therefore be ignored. Feeddown to D_{n+1} is small for two reasons. First, D_{n+2} is very small because it is odd harmonic for odd n. It is therefore a weak feeddown source. Second, feeddown from D_{n+3} and higher terms are reduced by $(\delta/z)^{k-(n+1)}$, where k is n+3 or larger; they can be ignored if δ/z is small. This is same reason used for truncating the binomial expansion in equation (4). Consequently, measured D_{n+1}' is approximately equal to D_{n+1}. Using this information the origin displacement can be found.

$$\delta \approx \frac{1}{n+1}\,\frac{(D_n')^*}{(D_{n+1}')^*} \tag{8}$$

C. Requirements on Measurement Accuracy

The CDM alignment plan requires the magnetic center to be located to within 110 μm. This tolerance sets the accuracy of measurements required of the harmonics. Since $\Delta\delta$ is small, derivatives can be used to determine the sensitivity to D variation. Since the requirement on δ is isotropic, only magnitudes need to be considered.

Since D_n' and D_{n+1}' are close harmonics measurements, one would expect that measurement accuracy for both would be similar. Assuming this to be exactly true, a tolerance can be determined. Determining the sensitivity to measurement from equation (8) and adding in quadrature,

$$\Delta\delta \approx \Delta D\,\frac{1}{n+1}\sqrt{\frac{D_n'^2}{(D_{n+1}')^4} + \frac{1}{(D_{n+1}')^2}} \; ; \tag{9}$$

ΔD is the harmonic measurement accuracy

Since D_n is a feeddown produced term, it can be replaced with its feeddown source function, from equation (8). By substituting this function in for D_n', ΔD can be found. Substituting and using $D_{n+1}' \approx D_{n+1}$

$$\Delta D \approx \frac{\Delta\delta\,(n+1)\,(D'_{n+1})}{\sqrt{[\delta\,(n+1)]^2 + 1}} \tag{10}$$

In the CDM cross-section selected for the first seven prototype magnets, the value of b_{10} is large compared to other harmonics in its neighborhood. Consequently, it is a logical choice for a feeddown source. Assuming a value of 0.018 units for the 22-pole term, and a offset of δ=1 mm, we get the required accuracy of measurement of 0.0014 units for high order terms in order to achieve $\Delta\delta$=110 μm. It is important to perform the previous calculation with lengths in terms of centimeters since centimeters is implicit in "unit". The term "unit" indicates 10,000 times the field gradient in terms of Tesla per centimeter to the nth power normalized by the central field in terms of Tesla.

D. Power Supply Requirements

While locating the magnetic center, two matched power supplies, set up as master and slave, are used to ensure that equal currents flow in the top and bottom coil halves. Commercial power supplies are available off-the-shelf with a maximum mismatch specification of 0.1%. An analysis has been performed to determine if these commercial power supplies meet the requirements for the skew quadrupole centering technique.

When a current mismatch is introduced, changes in the field harmonic values result which translate into errors in the offset calculations. The change in the calculated offset can be determined from the change in the harmonic. An analysis has been performed using the computer code PE2D and a 180° model of the 50 mm aperature CDM, similar to the one shown in Figure 1. Current values were scaled to 10.00 A (10.01 A in the upper coils of the mismatch configuration) in the simulations. The results of the simulation are shown in Table 1 which lists the magnitudes of the lower order harmonic coefficients, D_0, D_2 and D_4, for the matched and unmatched current situations. Higher order harmonics are so small that feeddown from them can be neglected.

Table 1. Harmonics Coefficient Magnitudes (G/cm^n)

n	$\lvert D_n \rvert$ (matched)	$\lvert D_{n+1} \rvert$ (matched)	$\lvert D_n \rvert$ (unmatched)	$\lvert D_{n+1} \rvert$ (unmatched)
0	0.00020	20.1034	0.05188	20.1134
2	1.93E-5	0.62620	2.06E-5	0.62650
4	2.13E-5	0.03797	2.11E-5	0.03799

The largest change in calculated offset is 25.7 μm stemming from the change in the D_0 harmonic. None of the other harmonic changes affect the calculated offset by more than 0.015 μm. Therefore, a 0.1% maximum current mismatch requirement is not excessively stringent and current mismatch should not be a limiting factor in using the skew quadrupole centering technique.

III. TEST RESULTS

The feasibility of using the skew quadrupole centering method was investigated experimentally in a short magnet DS0204. This is a short SSC dipole magnet with coils of 40 mm inner diameter. In normal operation of the magnet, there is an external splice between the upper and lower coils. For this experiment, this splice was taken apart. This facilitated measurements in either the usual dipole mode, or the skew quadrupole mode, by using suitable jumper cables and a single power supply. This also ensured that the currents in the upper and the lower halves of the magnet are the same in both the modes. In an actual application for the collider magnets, however, two independent power supplies will be needed to power the upper and the lower coils in the skew quadrupole mode.

Field measurements were made in the magnet DS0204 in both the dipole and the skew quadrupole configurations at a current of 10 A. The dipole field at this current is about 100 Gauss in the dipole configuration. In the case of the skew quadrupole configuration, simple analytical estimates can be obtained by assuming a $|\cos\theta|$ dependence of the magnitude of current density. Such an estimate gives field strengths of 25.9 and 1.3 Gauss at 1.0 cm radius for the skew quadrupole and the skew octupole respectively in this magnet at 10 A. These are substantial field levels, and can be measured very precisely. The dipole, sextupole, etc., terms are unallowed, and are expected to be negligible in comparison. However, there may be a significant permanent dipole field from the iron yoke. The data can be corrected to subtract this permanent field by making measurements at both +10 A and -10 A. The magnet was taken through three AC cycles of ±10 A in the beginning of each run, before taking data, to minimize the residual fields. Seven sets of data, each consisting of a +10 A and a -10 A measurement, were taken for each configuration.

A. Experimental Results

Figure 2 shows the typical harmonic fields contributed by the coil (filled boxes) and the iron yoke (crosses) in one of the measurements in the skew quadrupole configuration. The separate contributions were calculated by using the +10 A and the -10 A data. It is seen that the residual dipole field can be even greater than the dipole field (due to feeddown) from the coil. Thus, quadrupole feeddown can not be used for centering, unless the iron effect is subtracted out from the data. As a check on sensitivity, the histogram in Figure 2 depicts the detection limits of various harmonic fields assuming a conservative voltage sensitivity of 0.1 μV. It is seen that all the harmonic field from the coil, including the unallowed terms up to the 20-pole, are well above the detection limit. Also, the measured quadrupole and octupole strengths at 1.0 cm radius were 25.6 and 1.2 Gauss respectively, in very good agreement with the approximate analytical calculations.

B. Centering Parameters

In the case of the usual dipole configuration, the centering parameters (r_0,ω) describing the vector δ in eq. (8) were obtained by minimizing feeddown from the allowed 22-pole and 18-pole terms to the unallowed 20-pole and 16-pole respectively. The resulting r_0 values are shown in Figure 3 by crosses for all the 14 records in the run (no averaging of +10 A and -10 A data was done in this case). The average r_0 was 0.497 mm and the standard deviation (s.d.) from the 14 records was 143 μm. The $\pm 1\sigma$ range is denoted by the dashed lines in Figure 3. The scatter of the r_0 values is quite large in

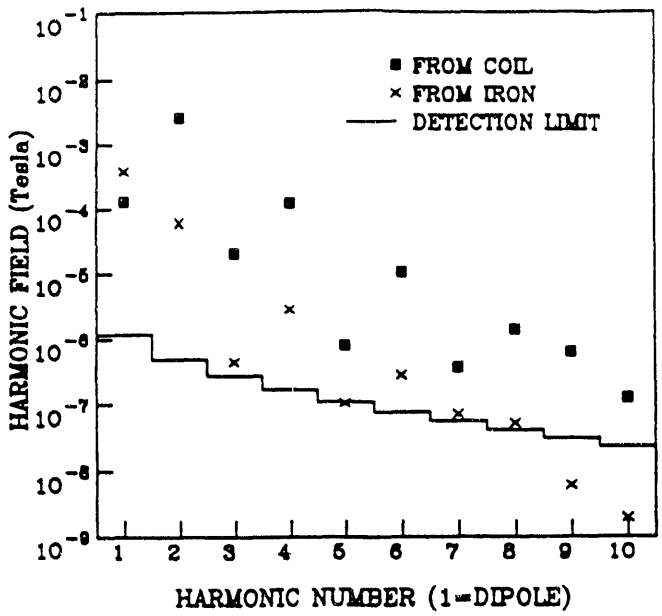

Fig. 2 Detection limits of various harmonic field numbers assuming a voltage sensitivity of 0.1 μV.

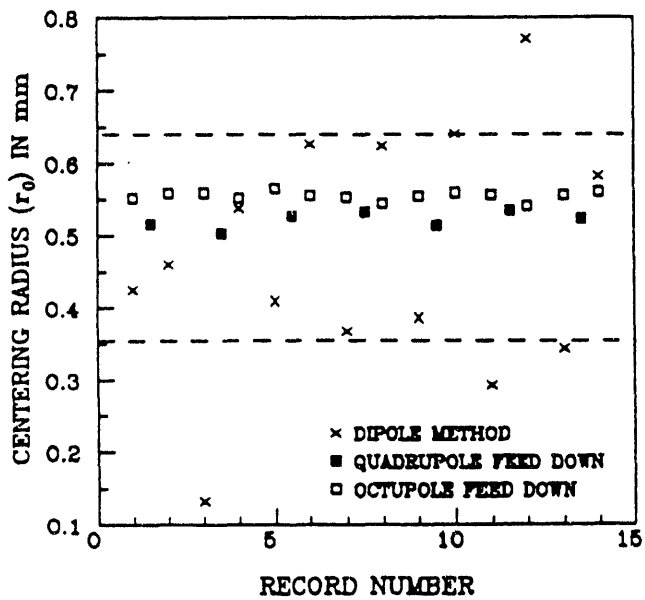

Fig. 3 Centering radius (r_0) in DS0204 for both dipole and skew quadrupole centering methods.

this case. The angle parameter ω shows a similar scatter and the mean value is 327.6 degrees with a s.d. of 26.1 degrees. If the +10 A and -10 A data are averaged to subtract the residual fields, the scatter can be reduced to a s.d. of 60 μm in this case.

In the case of the skew quadrupole configuration, (r_0,ω) were obtained by requiring no feeddown from the quadrupole term. The 14 records of the run give only 7 values of (r_0,ω) in this case, since the data from +10 A and -10 A must be averaged in this case to get rid of the residual iron fields. The scatter in this case is remarkably small, and the mean r_0 is 0.521 mm with a s.d. of 11 μm. The mean value of ω is 314.2 degrees with a s.d. of 1.1 degrees. These values are consistent with those calculated from the usual method of high order terms feeddown in the dipole configuration. The improved statistics in the new method is a direct result of working at field levels which are several orders of magnitude higher than typical detection limits (see Figure 2).

Although excellent results are obtained by the quadrupole feeddown method, the accuracy may still be compromised by the fact that the residual dipole field is higher than that from the coil, making accurate subtraction difficult. A close look at Figure 2 suggests that the best choice in this case would be to use feeddown from the octupole (n=4) term. This is because for both n=4 and n=3, the field levels are still much higher than the detection limits, and the residual fields from the iron are negligible compared to the fields from the coil. Also, it is not essential (although still preferable) to average the +10 A and the -10 A data. The centering parameter r_0 obtained by octupole feeddown is also shown in Figure 3 by open boxes. The s.d. in this case is only 6 μm, even though no subtraction of residual fields was performed.

The skew quadrupole method of centering has also been tested with two independent power supplies for the upper and the lower coils in measurements at 15 K and 4.35 K with equally consistent results.[1]

IV. SUMMARY AND CONCLUSIONS

The skew quadrupole centering technique has been developed to accurately locate the center of a dipole magnet during fabrication. Tests results on magnet DS0204 have shown that this method can provide extremely reliable centering parameters, which can then be used to analyze field data in the usual dipole configuration.

ACKNOWLEDGMENTS

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REFERENCES

[1] R. Howard, A. K. Jain and P. Wanderer, "Centering Parameters in DRS8", BNL Magnet Division Note 434-11 (RHIC-MD-145), April 14, 1992.

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