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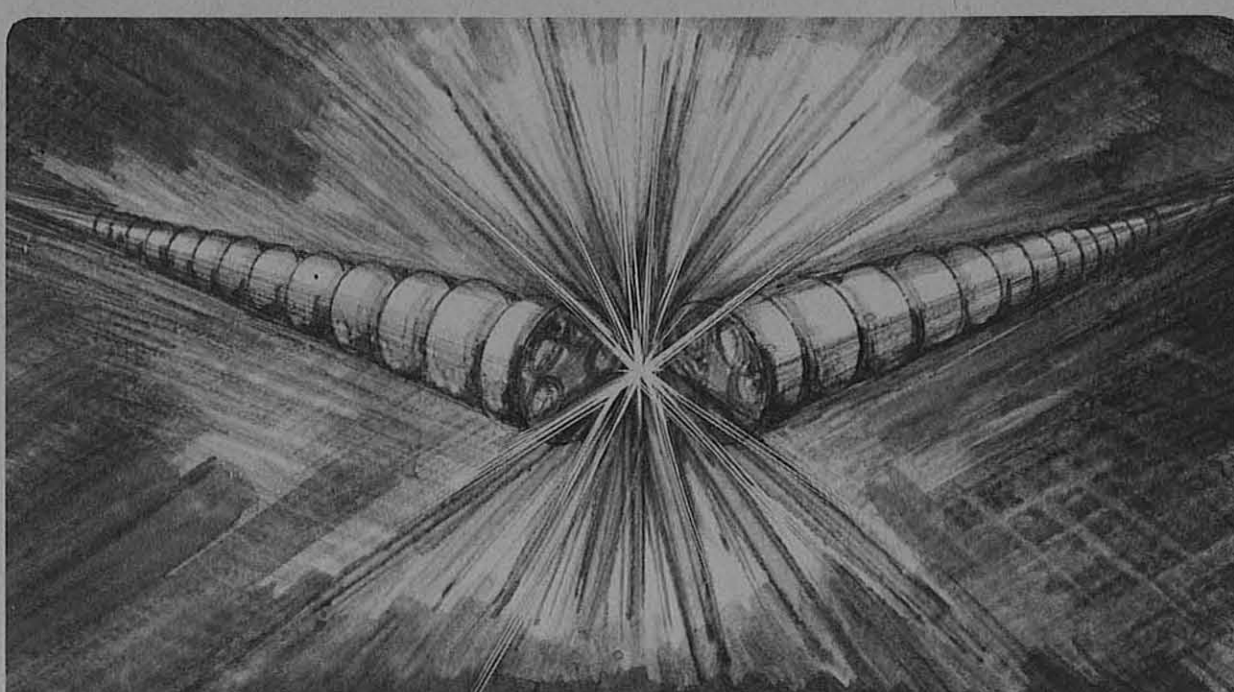

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Abstract

To qualify for use in the Superconducting Super Collider, the 8000 or so 16 m long dipole magnets must pass a series of tests. One of these will be a set of warm measurements of field quality, which must be precise to about 0.001% of the 100 G field produced by 10 A, the maximum current the coils are allowed to carry for an extended period at room temperature. Field measurements of better than this accuracy have already been carried out on 1 m long model dipoles. These measurements have included determinations of the dipole fields and the higher harmonics in the central or two dimensional region and in the total magnet. In addition, axial scans of the dipole and higher harmonic magnetic fields have been made to determine the local variations, which might reflect fabrication and assembly tolerances. This paper describes the equipment developed for these measurements, the results of a representative set of measurements of the central and integral fields and axial scans, and a comparison between warm and cold measurements. Reproducibility, accuracy and precision will be described for some of the measurements. The significance of the warm measurements as a part of the certification process for the SSC dipoles will be discussed.

Introduction

The type and extent of magnetic field measurements of accelerator and beam handling magnets are determined by the desired beam characteristics. Distortions in the beams are produced by the total variation from perfect bending (dipole) fields or focusing (quadrupole) fields. In storage rings such as the SSC, in which the beams may circulate for tens of hours, the cumulative effect of even small field perturbations could be disastrous. Thus, the field specifications, which are based on several calculations of beam performance,[1,2] are very strict for the small (40 mm bore) dipole of the SSC, as shown in Table I. This table is not complete, i.e, the list continues to higher multipoles (See reference 1 for a description of the multipoles). One question regarding such tight specifications is, "can the magnetic field be measured to this high an accuracy?"

TABLE I
Field Quality Requirements of SSC Dipole Magnets at 10 mm Radius

Multipole	Variance ($\times 10^4$)	Average ($\times 10^4$)
b_1	0.7	0.2
b_2	2.0	1.0
b_3	0.3	0.1
b_4	0.7	0.2
b_5	0.1	0.02
b_6	0.2	0.04
a_1	0.7	0.2
a_2	0.6	0.1
a_3	0.7	0.2
a_4	0.2	0.2
a_5	0.2	-

We discuss below the high precision measuring system developed and used at LBL and the results of system tests to determine its accuracy and precision of measurements. Then, some warm and cold measurements of SSC dipoles are presented and compared to the requirements of Table I. The multipoles at a radius of 10 mm are expressed in "units," or one part in 10^4 of the dipole field. The b's are the in phase components and the a's the out of phase components.

II. Description of Measurement System

A. Overview

The system used to make these measurements is the dipole configuration of the LBL general purpose magnetic measurements data acquisition system.[3] This configuration, shown in Fig. 1, allows us to measure field strength and quality with tabular and graphic output generated in "real time". Three pairs of search coils in a single coil array can be configured to make measurements of a 10 cm length of a 1 m dipole, either end, and/or an integral measurement. The first 10 cm measurement uses the pair of coils at the center of the array. Three general types of measurements are made with the basic system: 1. Cryogenic current sweeps, 2. Cooldown, warm up, and field decay at a fixed current for extended periods of time, and 3. Axial scans at a fixed current where the center 10 cm search coil pair is

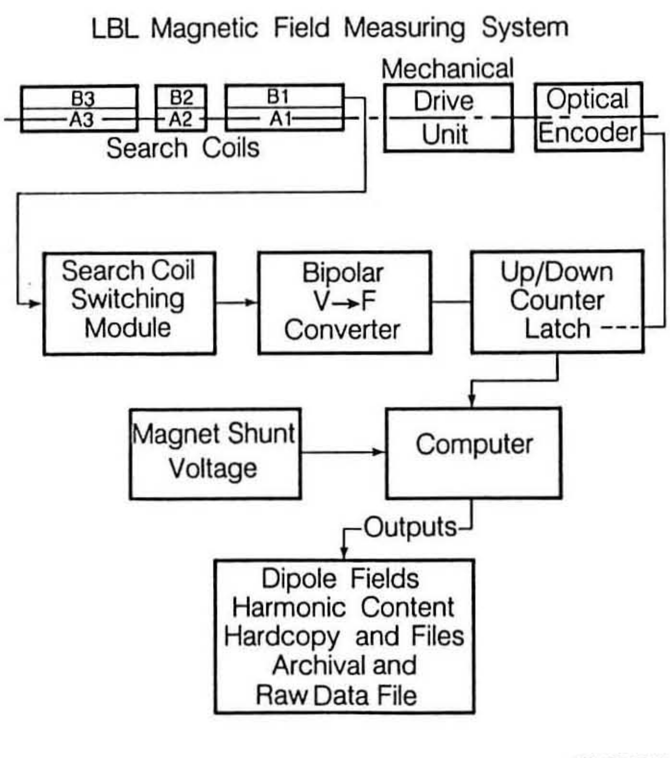

Fig. 1. Simplified Block Diagram of Harmonic Analysis Hardware

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used to measure the "local field" and to generate an axial profile of the dipole and the error harmonics.

After completion of a test series, the processed data from individual runs are put into spreadsheets and further reduced to provide, as needed, graphs and tables of transfer function, field, harmonics, etc. as a function of current, time, axial position, etc.

B. Hardware/Block Diagram

Figure 1 is a simplified block diagram of the hardware. The slowly rotating (usually 20 s period), search coil array generates a voltage proportional to the vector potential of the magnet field. This voltage is fed into a bipolar voltage to frequency converter.[4] The up/down counter integrates the counts from the converter. Pulses from an optical encoder on the shaft of the search coil array latch the contents of the counter into a buffer, which is read by the computer. The value of the up/down counter is recorded 129 times in a single revolution of the coils. The first and last samples are taken at the same azimuthal position and are used to drift correct the raw data. After the drift correction, which is linear, the data is scaled to a 16 bit maximum signal, Fourier analyzed: via a Fast Fourier Transform (FFT), converted to physical quantities and then printed and plotted. During the printout the search coil array rotates in reverse for the next cycle.

For each measurement there are two cycles. During the first, the search coil A, which centered is on the symmetry axis, is monitored to determine the dipole term. For the second rotation, the A and B coils are connected in a series opposing mode so that the dipole signal is mostly cancelled. The B coil is as similar to A as possible and is mounted at a larger radius but in the same plane as the A coil. This bucking, which reduces the dipole signal by a factor of about 500, allows the error harmonic terms to be measured with much higher resolution than if they were sitting on top of a large dipole signal. Simultaneous with the field measurement, other parameters, such as shunt voltages, are being monitored and recorded by a multiplexer/DVM combination.

C. Accuracy

Errors in the measurements of the multipole and dipole field come from several sources. These sources will be discussed below in the logical order in which they affect the signal and its later analysis leading to a final field value. Before addressing the errors in detail, it is important to realize that the errors must be determined relative to two very different measuring conditions -- cryogenic and warm. The warm measurements are done routinely at a low current, 10 to 20 A. They detect gross winding problems such as shorts, and magnet winding and hookup errors. In addition this measurement may be used to give a direct indication of the expected cold results. Note that the harmonics in the magnetic field of a cold magnet will be different from that warm because of mechanical changes in the coil and support structure due to cool down contraction and Lorentz forces. The individual search coils are mechanically measured to 0.001" at 300K and their areas are magnetically calibrated to 0.05%. Based upon the magnetic measurements the coils are paired. The pairing of the coils in this manner results in an analog cancellation of the dipole fields to a part in 500 or better. (This is referred to as a "bucking ratio" and is monitored as one characteristic of the health of the system.) The search coil arrays have different sensitivities to the different harmonics. These depend on the as fabricated coil geometry and are included in a sensitivity array for each coil. The errors in the final analyzed dipole and harmonic fields associated with the coils and several other components of the measuring system are given in Table II .

The analog signal from the coils is carried to a connector, which is at room temperature. For the cold measurement this thermal transition, i.e. the conductor used, is extremely important. A single spool of Teflon insulated, conductor is used for all 12 wires in the 6 twisted pairs. This procedure helps to minimize thermal emf's.

The signal enters the search coil switching module in which all components are thermally grounded and an equal number of relays exist in each circuit. It then goes to the Precision Bipolar Voltage to Frequency Converter (V/f). The V/f has 13 full scale ranges from 1 millivolt to 10 volts per megahertz in a 1, 2, 5 sequence. In addition, the Search Coil Switching Module (SCSM) incorporates a preamplifier that extends the full scale sensitivity to 100 microvolts/megahertz on the low end and also has *10 and *100 attenuation extending its highest full scale range to 1000 V/MHz. This gives a full scale range variation of 10^7. The calibration accuracy is 0.1% on the 100 microvolt range and improves to 0.01% on the 10 volt range. The value of the counts in the up/down counter are recorded 129 times per revolution and, along with a multitude of test parameters, are entered in a data file on the computer. In the technique used here the velocity of the measuring coil is not important, only the angular position at which the data is recorded has significance as the V/f converter and up/down counter combination integrates the signal.

The data is adjusted by a scale factor to fit in the 16 bit Fast Fourier Transform. This latter adjustment can lead to some error for the harmonic signals that have a low value, but will have little effect on the dipole.

TABLE II
Error Sources and Their Effects on the Central or 2 Dimensional Dipole and Harmonic Fields, Warm, 20A

Error Source	Dipole	Quadrupole	Sextupole	Octupole
Coil Area	0.05%	0.05%	0.05%	0.05%
Coil Position	NA	0.18%	0.35%	0.52%
V/F	0.1%	0.1%	0.1%	0.1%
16 Bit FFT	0.006%	-	-	-
Shunt/Current Measurement	0.01%	0.01%	0.01%	0.01%
PS Noise	0.01%	NA	NA	NA
Electronic Noise and Ambient Temperature	0.03%	0.75 units	0.25 units	0.15 units

Examples

Figure 2 shows the variation of the transfer function (T/kA) at 6000 A for an SSC model dipole MD-2 over a 40 minute period. The point-to-point variations are about 6 parts in 10^5 and are probably due to the 16 bit resolution of the FFT subroutine. The drift is due to other effects such as current shunt heating or real effects in the magnet such as mechanical motion or slowly decaying currents. The sextupole term b_2 is shown in Fig. 3 for the same set of data and give a similar feel for the precision of measurements. The total variations is about ± 0.01 units during a 40 minute period, $b_2 = 6.990$, $\sigma = 0.006$ units. A summary of data on fields and standard deviations is given in Table III.

The variations of some other harmonics are given in Fig. 4 for a similar set of measurements but for a different magnet D-14B-5 at 10 A at room temperature.

At low currents the accuracy of our system is limited by noise, which ranges from approximately 100 nanovolt seconds for the $n = 3$ (sextupole) term to under 5 nanovolt seconds for the $n = 19$ term. In general, we get reproducibility for the sextupole term of a few tenths of a unit and better than a tenth of a unit for harmonics greater than 6.

Magnetic Fields of SSC Dipoles

Several types of measurements have been made on the model SSC dipoles. These are all based on the measurement system described above. The goal in a series of measurements include the following:

- To determine the fields produced by transport currents -- usually a room temperature test, or at a current of several thousand amps where iron saturation and superconductor magnetization have little effect.[5,6]
- To determine the fields cold including iron saturation and magnetization effects.[5,6]
- To assess the effectiveness of warm measurements in predicting low temperature performance.

TABLE III

Observed Variation in Central Field Transfer Function and Harmoncs

Magnet	D-14B-4	MD-2	MD-2
Current (A)	20	300	6000
σ		0.26	1.32
Transfer (T/kA) Function	1.0300	1.0289	1.00464
σ	0.00028	0.00080	0.000036
b_1	2.351	2.831	0.437
σ	0.528	0.008	0.006
a_1	2.169	-2.833	-1.022
σ	0.488	0.032	0.024
b_2	-6.040	-4.360	6.990
σ	0.1526	0.020	0.006
a_2	1.180	3.643	0.894
σ	0.142	0.029	0.023
b_4	0.597	4.204	0.027
σ	0.052	0.017	0.010
b_6	0.091	-0.501	0.032
σ	0.0146	0.003	0.0012

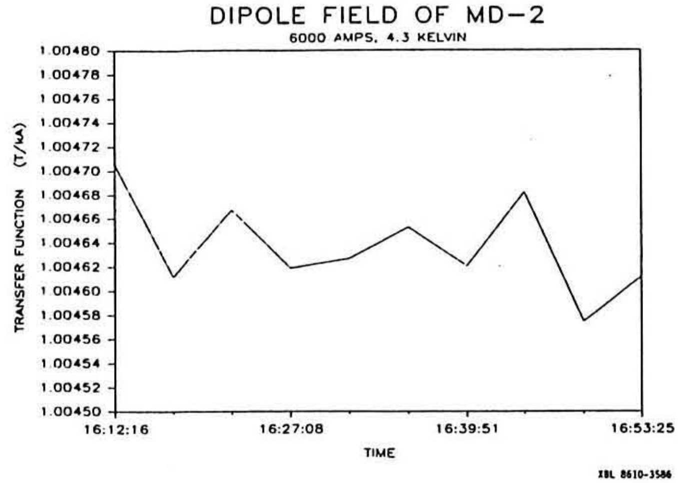

Fig. 2. Transfer Function Variations at 6000 Amps

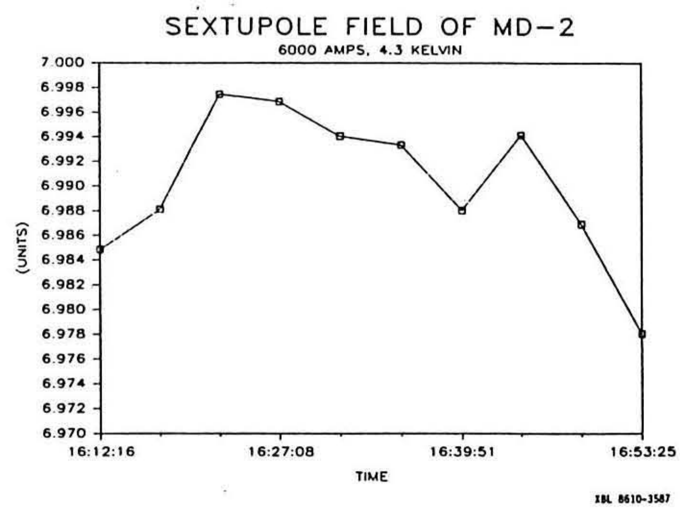

Fig. 3. Sextupole Variation at 6000 Amps

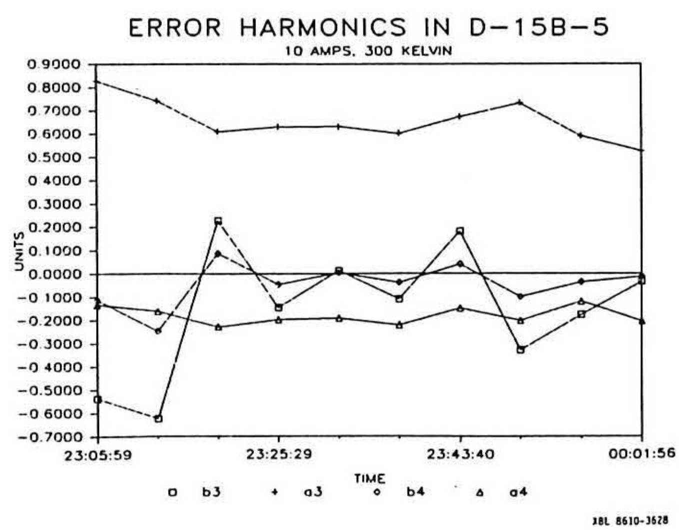

Fig. 4. Some Harmonic Variations at 10 Amps

- To determine field variation due to high current cycling that may result in field changes as the coil undergoes permanent relaxation.

- To evaluate multipole correction elements mounted on the boretubes.[7]

- To determine the end section design.[8]

The results of some of these measurements have been described elsewhere and are referenced accordingly. Here we discuss some of the measurements that will form a data base for the final, SSC production magnets. Data are available on some 20 or so magnets.

Two types of warm measurements have been made on these dipoles. Figure 5 is an example of an axial scan (some of these are also shown in Ref. 8) to measure end effects. The other is a series that includes determining the central and end fields at either + and -20 A or + and -10 A, and at 0 A. These results give several pieces of information about the magnet. Comparing measurements before and after a cold cycle will indicate movement of the conductors in the windings and of the entire collared magnet in the iron. Table IV shows the results for D-14B-2 before and after a test at 1.8 K and 9000 A.

Comparison of Warm and Cold Measurements

Another goal of the warm measurement program is to be able to predict the cold magnet characteristics based on the room temperature measurements. The reason for desiring a good correlation is the hope that one can avoid measuring the magnetic fields of the entire ~8000 SSC dipoles. Thus, we give in Table V a comparison of warm and cold measurements for several of the models tested at LBL. The correlation is very good in general and the one significant variation is for magnet D-14B-4, which was constrained at the midplane in iron at room temperature. This gave about 2 units of positive sextupole.

Conclusions

This assessment of the performance of the LBL field measuring system is the beginning of the process of learning the effectiveness of measurements of the SSC dipoles. Further effort will be required to give a complete analysis of the exact precision and accuracy of the measurement, but it would appear that the technique should yield adequate data for the ssc dipoles, and in addition the warm/cold correlation observed in the magnets indicate that not all will need to be tested cold.

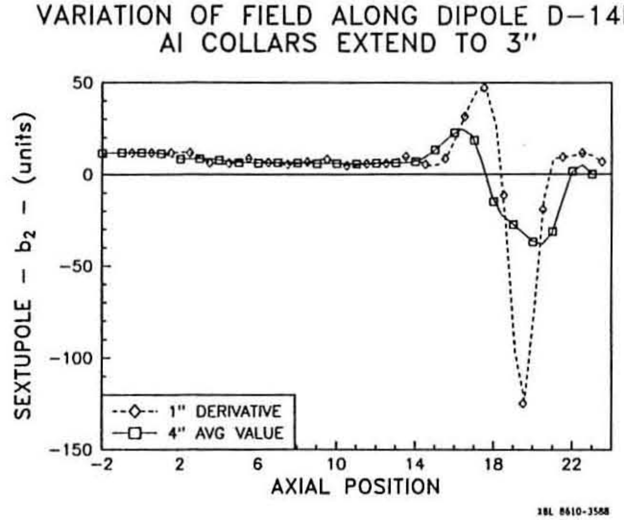

Fig. 5. Axial Scan of a Sextupole Field at 10 Amps

TABLE IV

	Before +20A	Before −20A	After +20A	After −20A
Trsf fn	1.0300	1.0240	1.0406	1.0339
b_1	−0.08	−0.38	+0.32	−0.90
b_2	+1.85	+1.39	+2.02	+1.67
b_3	+0.14	+0.20	+0.12	+0.15
b_4	+0.38	+0.42	+0.48	+0.45
a_1	+0.07	−0.19	−0.22	−0.28
a_2	+0.50	+0.48	+0.42	+0.38
a_3	+0.14	+0.19	+0.12	+0.15
a_4	+0.08	+0.05	+0.04	+0.06

TABLE V

Warm and Cold Magnetic Fields of SSC Model Dipole Magnets

	Transfer Function (Tesla/kA) Cold	Transfer Function (Tesla/kA) Warm	b_2 (units) Cold	b_2 (units) Warm	b_4 (units) Cold	b_4 (units) Warm
MD2	1.0046	1.035	7.0	6.1	0.0	0.0
D-14B-3	1.021	1.030	-4.1	-3.8	0.1	0.6
D-14B-4	1.029	1.024	-2.4	-0.4*	0.5	0.5
D-14B-5	1.029	1.029	-1.4	0.3	0.5	0.9
D-14B-6	1.027	1.028	1.4	1.4	-0.1	0.0

*Aluminum collared magnet constrained in warm iron.

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