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MAGNETIC MEASUREMENT SYSTEM FOR HARMONIC ANALYSIS OF LBL  
SSC MODEL DIPOLES AND QUADRUPOLES\*

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**Abstract:** Specialized hardware and software have been developed to facilitate harmonic error analysis measurements of one-meter-long Superconducting Super Collider (SSC) model dipole and quadrupole magnets. Cold bore measurements feature cryogenic search-coil arrays with high bucking ratios that also have sufficient sensitivity to make room-temperature measurements at the low magnet currents of  $\sim 10$  A. Three sets of search coils allow measurements of the center, either end, and/or the axially integrated field. Signals from the search coils are digitally integrated by means of a voltage-to-frequency converter feeding an up-down counter. The data are drift corrected, Fourier analyzed, converted to physical quantities, and printed and plotted. A cycle of measurements including data acquisition, processing, and the generation of tabular and graphic output requires 80 seconds. The vast amount of data generated (several hundred measurement cycles for each magnet) has led to the development of postprocessing programs and procedures. Spreadsheets allow easy manipulation and comparison of results within a test series and between magnets.

### Introduction

The harmonic error analysis system we describe is routinely used as a research tool for diagnostics in the development of Superconducting Super Collider accelerator (SSC) model dipoles,<sup>1</sup> and recently the system has been expanded to allow measurement of SSC model quadrupoles. Operationally, the system is essentially the same for dipole and quadrupole measurements. The one-meter SSC models require both room-temperature and cryogenic magnetic measurements of the full magnet, central field, and end effects and, occasionally, differential scans along the axis.

The system that has been developed is just one configuration of the LBL general-purpose magnetic measurements Data Acquisition System (DAS). The DAS is also used for field mapping,<sup>2</sup> permeability measurements,<sup>3</sup> production-type quadrupole measurements,<sup>4</sup> and wiggler-magnet tuning.<sup>5</sup>

### Overview

This system generates, in "real time" ( $\sim 80$  seconds), magnet test and performance parameters. The test parameters include: date and time of run; magnet identification; search-coil identification and configuration; test-series and run descriptions; the operator's name; shunt resistances; data-set identification; initial, final, and average currents; period of revolution; and voltage-to-frequency converter range. All of the preceding, plus raw up-down counter outputs, are saved in a binary file on a hard disk.

The signal strength for each harmonic is printed as a guide to the significance of the data. Magnet performance parameters that are generated in real time include field strength, transfer function, the magnitude and phase of each harmonic relative to the fundamental, and the normal and skewed harmonics

relative to the fundamental. Magnet performance parameters are not saved, since they can be derived from the saved raw data and test parameters. Upon completion of measurements on each SSC model magnet, the data on hard disk are transferred to floppy disks for archiving.

### Program Options

The program prompts the operator to select "run" options from displayed menus. Alternatively, the system can be set up to run in an automatic mode in which the run options are read from a file and the measurement cycle repeats, either after a specified delay or at the operator's request. The operator is allowed the choice of three search-coil arrays. A single search-coil array is used for measuring both room-temperature and cryogenic quadrupoles,<sup>6</sup> whereas separate search-coil arrays are used for room-temperature and cryogenic dipoles. Each array consists of three search-coil sets. In response to options selected by the operator, coils may be connected to measure the center 10-cm length, either end, or the full length of the magnet. The system prompts the operator to specify the current-monitoring shunt resistance. The operator may also indicate that the search coil is cryogenic, in which case the program incorporates a shrinkage factor into the calculation of the sensitivity array for the search coil.

Another option is control of a low-current power supply used when making noncryogenic measurements.

### Measurement-Cycle Description

The changing flux linkage of a slowly rotating (usually 20-second period) search-coil array in a stationary magnetic field generates electrical potentials. A low-noise search-coil switching module (SCSM)<sup>7</sup> has been programmed to connect the selected coils to a bipolar voltage-to-frequency converter (V/F), which feeds an up-down counter. This combination of a V/F and an up-down counter forms a digital integrator. Pulses from an incremental optical encoder mounted on the shaft of the rotating search coil latch the contents of the up-down counter into a buffer and produce a CAMAC "LAM," an interrupt that informs the computer that it should read the buffer. We sample the up-down counter buffer 129 times for each 360-degree forward revolution, and then the search coil rotates backwards in preparation for another cycle. The first and last samples are at the same azimuthal coil position and are used to "drift correct" the raw data, providing 128 data points for fast Fourier analysis.

During the first forward rotational cycle the strength of the fundamental is determined. While the search coil is rotating backwards, the raw data are saved on hard disk, drift corrected, plotted, Fourier analyzed, converted to physical quantities, and then printed and plotted.

On the second forward rotational cycle, the search-coil sets are connected in series opposition so that the fundamental output signal is dramatically reduced ("bucked out"). This allows measurement of the harmonics with much higher resolution, since the harmonics are not sitting on top of a fundamental signal that may be three orders of magnitude larger than the harmonics of interest. While the search coil is rotating backwards, the raw data are again saved, drift

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corrected, plotted, Fourier analyzed, converted to physical quantities, and printed and plotted.

For each harmonic number we print the signal magnitude, phase and magnitude of the harmonic relative to the fundamental, and also the skewed and normal harmonics relative to the fundamental. We plot the unbucked and bucked raw data versus azimuthal position and produce a semilog bar graph of the magnitude of the harmonics relative to the fundamental.

#### Hardware

Figure 1 is a block diagram of the hardware. A DEC LSI-11/73 microprocessor is interfaced to the rest of our equipment by means the DEC Q-BUS. On the Q-BUS are 4 Mbytes of ram, CAMAC and GPIB interfaces, a clock calendar, a 10-Mbyte RLO2 hard disk, a 40-Mbyte Winchester hard disk that emulates 4 RLO2's, a DLV11ED connected to a modem attached to a phone line that allows us to communicate with other computers and/or operate the DAS remotely, and two DLV11J 4-line RS-232 interfaces. Connected to the DLV11J's are a laser printer, a LA-120 printer/terminal, an Epson dot-matrix printer, a Hewlett-Packard plotter, and several graphics terminals. NIM and GPIB modules are used for

high-precision analog-data acquisition. CAMAC modules are used mainly for digital I/O, such as control and monitoring of motors, reading up-down counter modules, etc.

#### Software

We use the S&H, Inc. TSX-Plus time-sharing operating system. This operating system is used on DEC PDP-11 and LSI-11 computers and operates "on top" of the DEC RT-11 operating system. This multiuser system allows simultaneous data acquisition, program development, and postprocessing of data. All application programs are written in FORTRAN 77. Commercial software packages used include DEC Laboratory Subroutines, DEC Scientific Subroutines, Tektronix Plot 10, National Instruments GPIB library, Standard Engineering CAMAC library, S&H, Inc. RTSORT, Columbia University Kermit, and Saturn Systems, Inc. Spreadsheet/Graphics/Word processing Office Automation Package.

Short structured programs are written that are primarily only calls to subroutines or groups of short subroutines. Structured programming has significantly reduced the effort necessary to design, debug, maintain, and modify complex real-time data-acquisition systems.

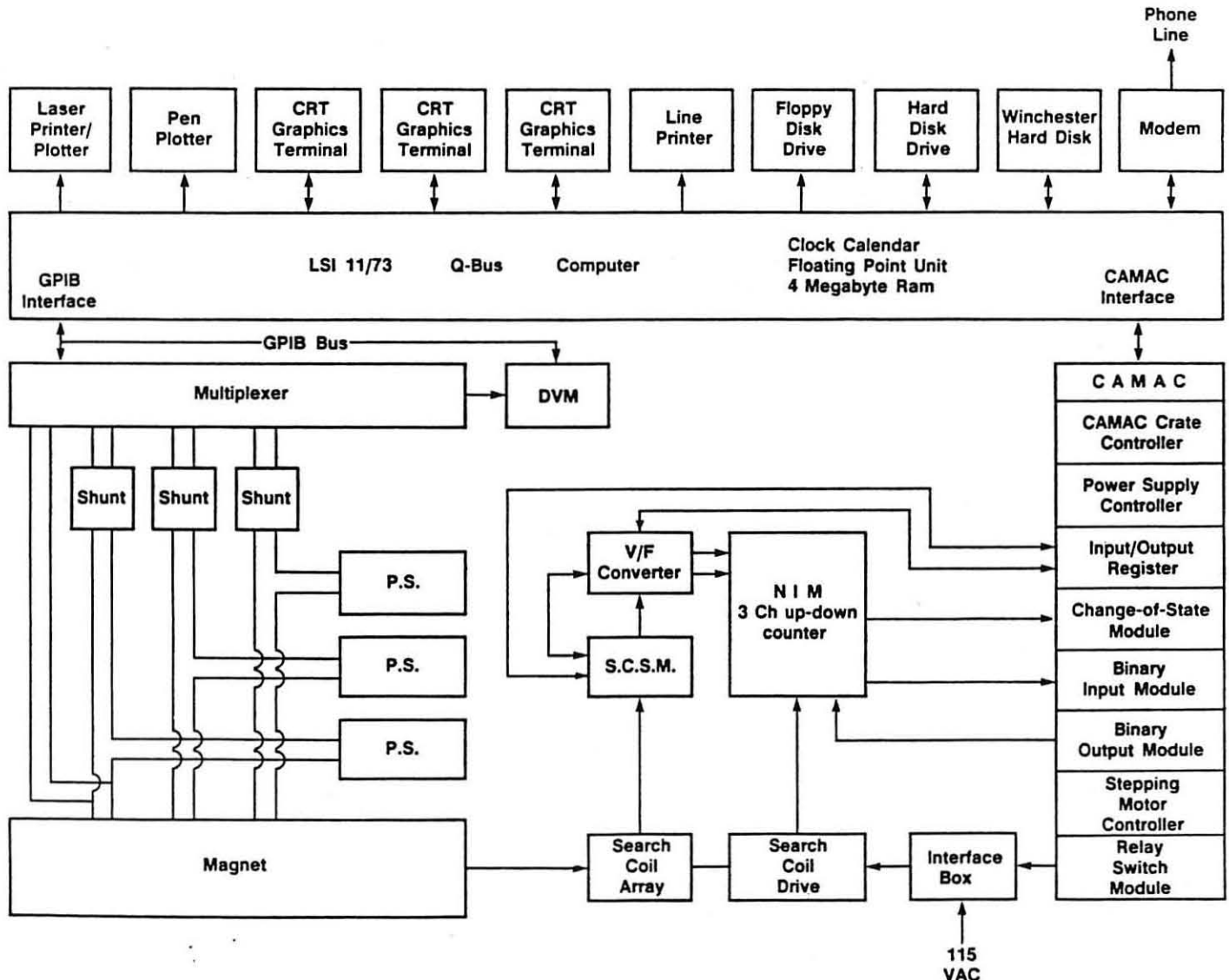


Fig. 1. Block diagram of SSC model magnets harmonic analysis system.

### Data Postprocessing

We have developed three types of postprocessing for the dipole and quadrupole systems: 1) re-creation of the real-time output, 2) generation of an SSC "prompt report," and 3) production of general-purpose spreadsheet/graphical output.

First, the real-time output can be regenerated in toto from the saved test parameters. Plots and printouts that are identical to the original output can be produced. An option also allows printing of the raw counts stored from the buffer of the up-down counter.

Second, "transportable" data files are generated, each consisting of a test series encompassing a set of real-time acquisition runs (from 1 up to 99). These files are routinely generated after SSC model magnet runs and are transported from the DAS by modems and telephone to IBM AT personal computers, loaded into a LOTUS spreadsheet, and used to generate SSC magnet prompt reports. LOTUS processing of these files has been semiautomated using macros. In particular, we use routine procedures for producing reports on magnet behavior during cooldown (from room temperature to 4.3 K), warmup (from 4.3 K up), decays (a series of measurements at a single magnet current taken over time), current sweeps (measurements taken at various current levels while ramping the magnet current up to a specific value and then back down again), and Z-scans (measurements taken with the center search-coil pair at various axial positions along the dipole). The output produced for one of these prompt reports includes a table of magnet data (field strength, transfer function, major harmonic values) and a series of graphs relating to the specific nature of the test (e.g., graphs relating main field and harmonics to magnet current for current sweeps and graphs of main field and harmonics vs. time for decays).

The postprocessing program also extracts a small subset of the test parameters from the raw-data files and creates an index file of the data sets. This index file is incorporated into the prompt reports.

The third postprocessing function is similar to the prompt-report generation, except that it uses a local (on the DAS) spreadsheet and graphics package (Saturn Calc and Saturn Graph). The data base created here is much more extensive than the LOTUS data base and is completely general purpose. All test and performance parameters are available in two standard spreadsheets, one of magnet performance parameters and one of test parameters. The test-parameter spreadsheet allows the scanning of data sets for problems such as high drift, unusual module configurations, etc. As yet, no automatic routines have been developed or implemented for use with this system. In general, it is used to promptly examine particularly interesting real-time runs or to investigate abnormal data sets, series, or runs.

All postprocessing functions can be operated simultaneously with real-time acquisition operations.

### Performance

The precision bipolar V/f converter has 13 full-scale ranges from 1 mV/MHz to 10 V/MHz in a 1, 2, 5 sequence. In addition, the Search Coil Switching Module (SCSM) incorporates a preamplifier that extends the low-end full-scale range to 100  $\mu$ V/MHz. Furthermore, the SCSM has attenuation factors of 10 and 100, which extends the highest full-scale range to 1000 V/MHz. The calibration accuracy is 0.1% on the 100- $\mu$ V range and improves to 0.01% on the 10-V range.

The dimensions of the individual search coils are mechanically measured to  $\pm 0.001$  inches, and their areas are magnetically calibrated at room temperature to better than 0.05%. On the basis of the magnetic

measurements of effective dipole area, the coils are matched. The matching of coils in this way results in a "dipole bucking ratio" of 500 or better and a "quadrupole bucking ratio" ranging from 100 to 250.

Figure 2 is a plot of the noise signal vs. harmonic number obtained by a stationary 10-cm center coil pair configured in the bucking mode. The line joins average values. At low currents the accuracy of the LBL system is limited by noise, which ranges from approximately 100 nV-s for the  $n = 2$  (quadrupole) term, to approximately 2 nV-s for  $n = 19$ .

The reproducibility of the dipole system at 20 A and room temperature is presented in Table 1. The deviations are greater for the central field values because of the relatively small size of the coil (10 cm long) and the resulting small signals. At SSC operating currents, the reproducibility for the sextupole term plotted in Fig. 3 is approximately  $\pm 0.01$  units (1 unit = 0.0001 of the fundamental magnitude). Figure 4 shows that the reproducibility for higher harmonics is approximately  $\pm 0.002$  units.

### Improvements

Time, personnel, and funds permitting, the following expansions and/or improvements are planned: 1) set up a real data-base system for magnet comparison instead of using spreadsheets, 2) replace the existing 16-bit, fast Fourier transform with a double-precision version, 3) shorten the measurement cycle by taking data in both the forward and reverse directions and/or use multiple V/f up-down counters to acquire bucked and unbuckled data simultaneously, 4) automate the axial positioning of the magnet relative to the search-coil array for making measurements of harmonic content as a function of axial position, and 5) expand the use of Saturn spreadsheet/graphics and consolidate the existing postprocessing code (this should reduce the time for producing prompt reports).

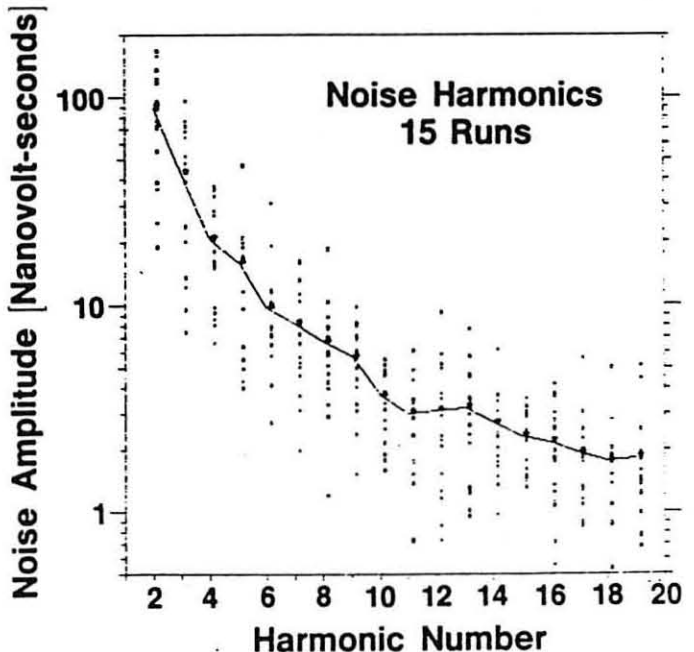


Fig. 2. Harmonic analysis of noise from a stationary coil pair in "bucked" configuration.



TABLE I. STANDARD DEVIATIONS OF MAIN AND HARMONIC FIELDS FOR THE LBL MEASURING SYSTEM (18 CONSECUTIVE RUNS AT 20 A).

Search-Coil Configuration	Transfer Function ( $10^{-4}$ Tm/A)	Error Harmonics ( $10^{-2}$ Units)					
		$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$
End 1	0.5	2.6	2.5	0.9	0.8	0.3	0.2
Central	2.8	33.2	16.2	9.9	5.2	4.9	1.5
End 2	1.0	1.5	1.4	0.5	0.4	0.2	0.3
Integral	1.9	1.8	1.9	1.8	0.4	0.3	0.2

Note:  $C_2$  refers to the amplitude of the quadrupole field at 1-cm radius.

D-14B-11 Normal Sextupole

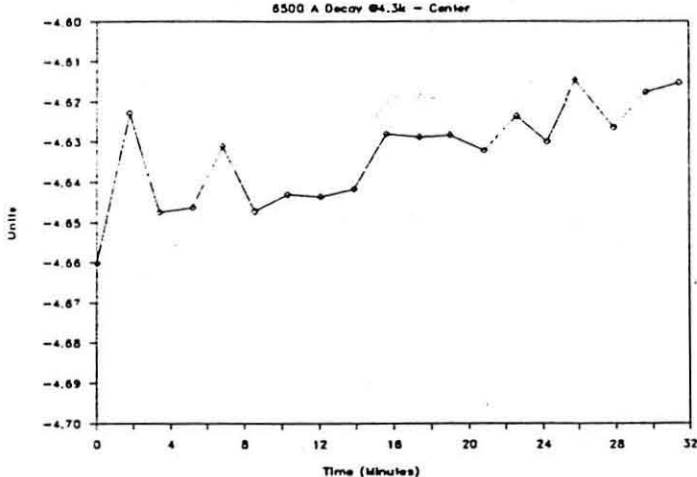


Fig. 3. Sextupole variation at 6.5 kA.

D-14B-11 Error Harmonics

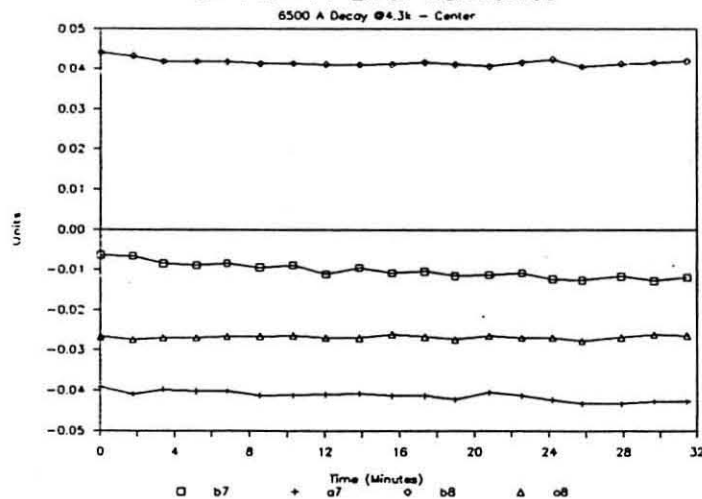


Fig. 4. Some harmonic variations at 6.5 kA.

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