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Report on the Production Magnet Measurement System for the Fermilab Energy Saver Superconducting Dipoles and Quadrupoles

B. C. Brown, W. E. Cooper, J. D. Garvey, D. A. Gross,† R. Hanft, K. P. Kaczar, J. E. Pachnik, C. W. Schmidt, E. E. Schmidt, and F. Turkot
Fermi National Accelerator Laboratory*
P.O. Box 500
Batavia, Illinois 60510

The measurement system and procedures used to test more than 900 superconducting dipole magnets and more than 275 superconducting quadrupole magnets for the Fermilab Energy Saver are described. The system is designed to measure nearly all parameters relevant to the use of the magnets in the accelerator including maximum field capability[1] and precision field measurements.[2] The performance of the instrumentation with regard to precision, reliability, and operational needs for high volume testing will be described. Previous reports[3] have described the measurement system used during development of the Saver magnets from which this system has evolved.

MEASUREMENT SYSTEM

Six cryogenic test stands are connected to a 1500 watt refrigeration system[4] and to a dual data collection system based on PDP11/34 computers and CAMAC interfacing. Personnel safety is assured through a hardwired interlock system while more complex issues of equipment protection are monitored through a Texas Instruments 5TI Sequencer. Figure 1 shows a block diagram of the overall layout. The magnets are powered with Transrex power supplies configured to supply up to 5000 Amps at 100 Volts. Each supply is controlled through either a NIM or a CAMAC ramp generator. An amplified current shunt signal is digitized with a 12-bit ADC for high speed current measurements while for precision measurements the shunt is monitored with a digital voltmeter. The shunts have been compared by connecting both of them plus a third calibrated[5] shunt to the same power supply. They have also been compared by making NMR strength measurements in close succession on one magnet with the two systems. These comparisons agree on the relative calibrations and have revealed a slow change of the shunt on System 2 of about 3 parts in 10^{+4} in the two years of system operation. This drift has been monitored and corrected to 1×10^{-4}. All magnetic measurements are carried out within a two layer stainless steel warm bore tube of 1.950 inch inside diameter which is inserted into the beam pipe of the magnet and warmed by a nitrogen gas purge.

MAXIMUM FIELD CAPABILITY MEASUREMENTS

Spontaneous quenching of the superconductor will define the maximum current at which one can operate the magnet. A detected quench isolates the magnet from the power supply and shorts the leads with a 0.2 ohm reisitor. For a single magnet this is achieved with a 10 volt threshold on the resistive voltage. The resistive component is detected by subtracting an inductive voltage measured with a toroidal transformer on the current lead from the voltage on the magnet leads. Typically 40 kJ is dissipated in the magnet and 350 kJ in the water cooled reisitor at 4000 A.

Data on a quench is monitored with ADC's which are read into a 512 point circular buffer at typical rates of 250 Hz. Resistive voltage, magnet current, and dump voltage are monitored. These data plus

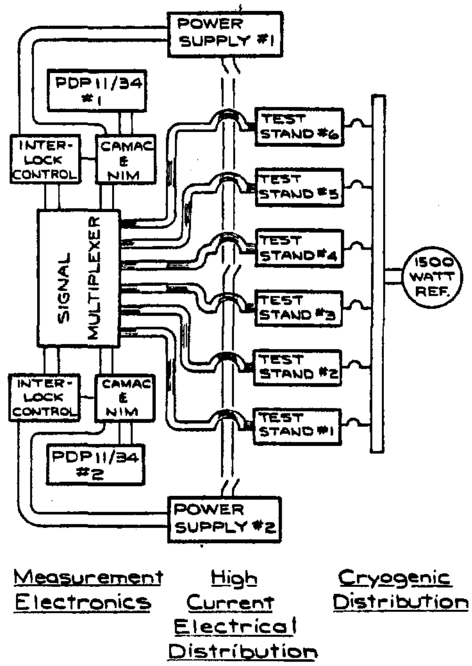

Fig. 1 Fermilab Dual Magnet Measrement System

energies and resistances calculated from them are presented typically from 0.4 sec before the quench to 1.6 sec after the quench[6]. Cooling conditions are recorded by observing the pressures and vapor pressure thermometers (VPT's) at both ends of the magnet in the single and two phase helium lines. Liquid nitrogen is placed in the warm bore tube for these tests to reduce the heat loss and simulate operating conditions.

The QUENCH test records quench condition data on a linear current ramp terminated in a quench. CYCLE records quench currents and ramp history for a cyclical cycle of ramps with 20 sec flattops simulating an accelerator cycle. Successive pairs of ramps increase flattop current by 50 A. Verification of the quench protection heater strips and a heater induced 4000 A quench with the dump resistor shorted complete the maximum field strength evaluation.

HARMONIC ANALYSIS OF FIELD UNIFORMITY

The integrated transverse field shape of the magnets is determined by rotating a multiturn flat coil in the aperture. To achieve the desired resolution of 10^{-4} relative to the design multipole, the dominant field components are canceled by adding the signal from a second coil which samples the field at small radius (and is thereby less sensitive to high order multipole components). Figures 2a and 2b show the cross section of the dipole and quadrupole probes. Skew voltages due to probe imperfections are cancelled by a skew coil. For quadrupoles, the dipole signal due to the probe not being centered in the magnet must also be cancelled with normal and skew coils. The signals from various coils are summed through a resistive summing circuit and processed in an integrator[7] whose output is digitized by a 12-bit ADC.

* Operated by Universites Research Assn. Inc., under contract with the U.S. Department of Energy.

† Present address: General Electric Research Center, Schenectady, New York.

The probe is placed in the warm bore and rotated on the surface of the bore tube. The angle is obtained from a 1024 segment angular encoder. Voltage data is recorded at each change of the count from the encoder. After adjustment of the summing box resistances to achieve a sufficiently sensitive cancellation of the dominant components, switches and gains are set to record the outer coil signal alone. The Fourier analysis of this signal provides the calibrated reference amplitude A_s (and angle ϕ_s) for the measurement. This "standard amplitude" is recorded at 1000 A and scaled for measurements at other currents. The data is then recorded after setting switches and gains back to the sensistivity required for the harmonic measurement. After an initial hysteresis ramp to 4000 A, data is recorded for dipoles (quadrupoles) at 6 (7) successively higher currents to a maximum of 4000 A and then at 2 (6) points as the current is reduced.

To obtain harmonic coefficients relative to the fundamental component, the integrated voltage vs. angle data for one revolution is analyzed with the Fast Fourier Transform (FFT) method as

$$V(\theta)=\sum_{n=0}^{\infty} C_n \cos(n\theta - \phi_n)$$

The Fourier coeficients are rotated to the frame of the fundamental as determined by the outer coil ϕ_s and expressed as normal b_n and skew a_n harmonic components by

$$\alpha_n = (\phi_n - n\phi_s) \qquad a_n = b_n \tan \alpha_n.$$

For dipoles

$$b_n = \frac{(n+1)W}{r_o^{\,n+1}} \frac{C_n}{A_s} \frac{\cos\alpha_n}{1+(\frac{r_3}{r_o})^{n+1}-(1+(-1)^n)(\frac{W}{2r_o})^{n+1}}$$

while for quadrupoles

$$b_n = \frac{1}{2}(n+1) \frac{C_n}{A_s} \frac{\cos\alpha_n}{R_1^{\,n+1}} \frac{R_1^2 - R_4^2}{1-(\frac{R_4}{R_1})^{n+1}-2(\frac{R_2}{R_1})^{n+1}+2(\frac{R_3}{R_1})^{n+1}}$$

where the geometric parameters are defined by Figures 2a and 2b. Results are shifted to a co-ordinate system determined for dipole (quadrupole) magnets from the 18 pole (quadrupole) through elimination of the decentering induced 16-pole (dipole). Harmonic probes are 94" in length. Dipoles (long quadrupoles) must be measured in 3 (2) separate measurements and averaged.

Reproducibility of the harmonic components measured with this system is at the level of 0.3 x 10^{-4}. Systematic effects from probe imperfections and sliding on the warm-bore surface limit the measurement to accuracies of 1 x 10^{-4}.

NMR TESTS

A high precision Nuclear Magnetic Resonance (NMR) system is used to measure the magnetic field strength at points along the axis of the dipole magnets. Manufacturing defects such as coil dimension errors from coil clamping collars which close too loosely or too tightly are revealed by the axial structure of the field. Averaging this data over the body of the magnet provides a measure of magnet strength if one makes the assumption that the physical length of the magnets is constant. Field data from several magnets are shown in Figure 3.

The NMR circuit has been adapted from that described by Borer[8]. The proton sample (rubber), resonance coil, field sweeping coil and amplifier section are mounted in a copper box driven through the magnet by a threaded rod. A locking circuit (with

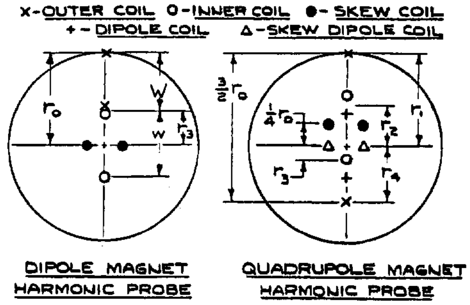

Fig. 2a,b Cross Section of the Harmonic Probes

manual guidance) seeks and locks to the resonance. Commercial CAMAC scalers record the on-resonance frequency (about 84 MHz) by counting for precise 100 ms intervals gated by a crystal controlled clock. The shunt voltage is recorded along with the frequency and longitudinal position information obtained from an encoder attached to the threaded rod.

The current is set to 2000 A after ramping to 4000 A and back to zero. The field uniformity is recorded with a resonance frequency found and recorded approximately every 1 inch. A measurer controls the probe advance, assists the resonance locking circuit if required, and certifies the resonance condition. Since the supply current may change by up to 1 A during the 30 minute measurement, the data are presented as a field transfer function (Gauss/Amp).

The uniformity tests are limited in the current reading least count accuracy of 0.5 x 10^{-4} (0.1 A). The magnet strength results are limited by the systematic effects in the shunt reading described earlier. A comparison of average transfer functions from successive testing on the same day yields differences with a standard deviation of 0.4 x 10^{-4}.

STRETCHED-WIRE INTEGRAL FIELD PROBES

Unlike conventional electromagnets, the field angles of saver dipoles and quadrupoles and quadrupole centers are determined relative to the iron yokes only by the precision of assembly. This precision is not sufficient for accelerator requirements. Using 2 wire (or 4 wire) probes, the integral of the fundamental dipole (or quadrupole) field is measured, resolving the normal and skew components with respect to gravity (and centering the quadrupole probe in the magnet). Eccentric survey lugs encode the angle of mounting in the accelerator to correctly orient the field. The quadrupole field center is surveyed with respect to the iron yoke and this information also encoded into survey lugs.

Figures 4a and 4b illustrate the loop fixtures. Tungsten wires (0.004" in dia.) are stretched through the bore tube, placed on the fixtures and tensioned to 1600 grams. The dipole fixtures creates a precision loop through the dipole spaced by 1" quartz or sapphire rods. For the field angle measurements, the loop is rotated and a 1/4" rod inserted which references to a precision level surface on the fixture. A split bubble level with <10 microrad precision is used to orient the fixture. The quadrupole fixture uses a precision square reference block to hold four 3/16" dia quartz rods. Four wires are stretched through the quadrupole in a square pattern 1.128" on a side. The four wires are connected to relays allowing various electrical loops. With the probe rotated to the diamond orientation, vertical or horizontal two wire loops can be selected and the fixtures positioned to find the flux nulls which define the quadrupole center. The four wire loops can be created in two configurations and data are recorded for both and averaged. In the square orientation the four wire loop measures the normal quadrupole component; while in the diamond orientation the four wire loop measures the skew quadrupole component referenced to gravity. Electronic levels with a precision better than 10 microradians are affixed to the quadrupole probe fixtures.

The loops are connected to a precision integrator[7] whose output voltage is read by a digital voltmeter. Data is collected by ramping the curent in 20 A steps, waiting for the induced oscillations to damp and recording the result when successive voltage reading agree adequately. A linear drift correction is applied. The integral remnant field is obtained by rotating the loop at zero current.

A coil is installed on the symmetry plane of dipole yokes in a groove in the laminations. During fabrication, this yoke coil is used to align the magnet coil to the yoke to an accuracy of a few milliradians. An integrated voltage induced in the yoke coil is recorded during the dipole field angle measurement and correlated with the field angle obtained. Data on dipoles are collected with both wire probe and yoke coil using a 0.6 A sinusoidal excitation at 11 Hz and lock-in amplifier techniques. Data is collected at superconducting and room temperatures. Changes in field angle with time can be monitored with 11Hz measurements of the yoke coil.

The offset angle of the vertical reference surfaces is calibrated by an autocollimation procedure using a survey level with a resolution of 10 microradians. Loop widths are measured with a digital micrometer fixture which is brought into electrical contact with each wire in succession.

The field strength measurement has a repeatability of 3×10^{-4} run to run. Integrator calibration and mechanical measurements of the quartz rod fix the scale of the dipole measurements to 3×10^{-4} accuracy. Loop width measurements on quadrupoles provide nearly the same accuracy. Undetected fixture wear problems limited the accuracy of some dipole measurements. Small systematic inaccuracies are caused by finite loop width coupled to higher harmonic field content. Since the stretched wire is straight, the .250" sagitta of the Saver dipoles adds further systematic higher multipole contributions. Field angle is determined to 150 microradians and field center for quadrupoles to 0.004".

MANAGEMENT OF PRODUCTION MEASUREMENT

The FERMILAB Saver project has produced and measured more than 900 dipoles and 250 quads. This has required a system which has the capability to measure more than 20 magnets per week. In order to accomplish this, from a total staff of 60 persons, 30 technicians have been employed on a continuous basis during peak measurement periods to install, cool, measure, warm and remove the magnets. An additional staff of 5 have examined and archived the data.

Measurements typically take 13 to 17 hours per magnet. Figure 5 shows production measurement output for the years 1981 and 1982. The second measurement system became available in June of 1981. Much of the variation shown is limited by availability of magnets for test or the need to utilize the measurement stands for development and/or specialized testing. During March through May, 1982, an average of 12.6 dipoles and 6.3 quadrupoles per week for a total of 18.9 magnets per week were measured.

Review of the measurement system reveals several areas for potential improvement in planning such production systems. A higher degree of automation and computer review of data at the time of collection would improve data quality by reducing the chance for human error. To maintain very high accuracy, substantial redundancy must be built into the system to provide cross checks which allow one to discover the inevitable subtle system failures. This same need requires frequent measurment of . standards and justifies automated checks on system equipment of all types. The flexibility to continue special developmental measurements has been utilized repeatedly.

FOOTNOTES AND REFERENCES

1. F. Turkot, et al., Maximum Field Capabilities of Energy Saver Superconducting Magnets, This Conference.
2. R. Hanft, et al., Magnetic Field Proprties of Fermilab Energy Saver Dipoles, This Conference; E. E. Schmidt, et al., Magnetic Field Data on Fermilab Energy Saver Quadrupoles, This Conference.
3. M. Wake, et al., Cryogenics, 21, 6,341 (June 1981); D. Gross, et al., IEEE Trans on Magnetics, MAG-15,137 (1979).
4. W. Cooper, et al., Cryogenic System for Production Testing and Measurement of Fermilab Energy Saver Superconducting Magnets, This Conference.
5. This shunt was calibrated by the National Bureau of standards up to a current of 1 kA to an accuracy of 2×10^{-4}.
6. This system has also been used to make AC Loss measurements, see M. Wake, et al., IEEE Transactions on Magnetics, Mag-15,141 (1979).
7. A conventional operational amplifier integrator of Fermilab design is used based on an Analog Devices AD234L op amp and a Component Research Co. Model J11C 105FXA Teflon capacitor.
8. K. Borer and G. Fremont, NMR Circuit Design, CERN Publication 77-19; see also R. Yamada, et al. IEEE Trans on Nuc. Sci. NS-24,1312(1977).

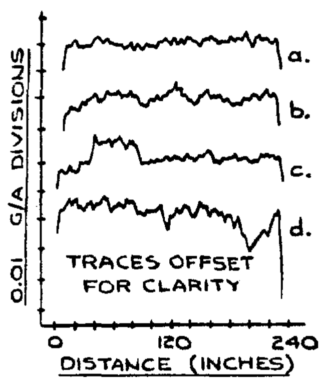

Fig. 3 NMR Transfer Functions
Collars: a,b) OK c) Overclosed d) Underclosed

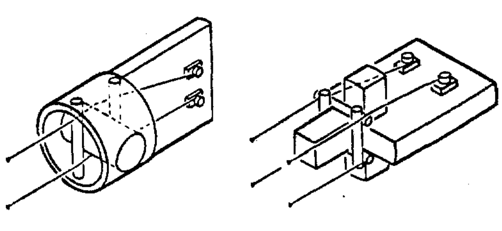

Fig. 4 Stretched Wire Fixtures
a) Dipole b) Quadrupole

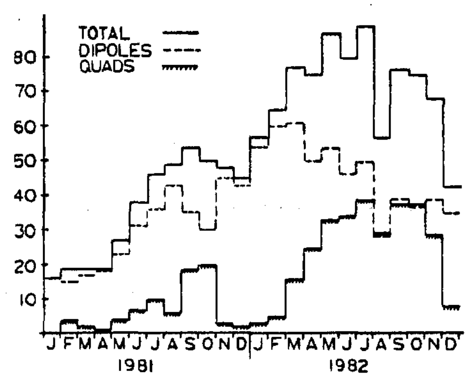

Fig. 5 Number of Magnets Measured each month at Fermilab MTF, 1981-2.