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ABSTRACT

The test facility used for R&D testing of full scale development dipole magnets for the SSC is described. The Fermilab Magnet Test Facility, originally built for production testing of Tevatron magnets, has been substantially modified to allow testing also of SSC magnets. Two of the original six test stands have been rebuilt to accommodate testing of SSC magnets at pressures between 1.3 Atm and 4 Atm and at temperatures between 1.8 K and 4.8 K and the power system has been modified to allow operation to at least 8 kA. Recent magnets have been heavily instrumented with voltage taps to allow detailed study of quench location and propagation and with strain gage based stress, force and motion transducers. A data acquisition system has been built with a capacity to read from each SSC test stand up to 220 electrical quench signals, 32 dynamic pressure, temperature and mechanical transducer signals during quench and up to 200 high precision, low time resolution, pressure, temperature and mechanical transducer signals. The quench detection and protection systems is also described.

INTRODUCTION

Tests[1-6] of full scale R&D dipole magnets[7,8] for the Superconducting Super Collider (SSC)[9] have been carried out at the Fermilab Magnet Test Facility. This facility has previously been used for the production testing of superconducting magnets for the Tevatron. In this paper we will describe the cryogenic operation of the two SSC test stands, the high current DC power system, the quench protection system, the test stand and magnet instrumentation, and the data acquisition system. Because testing of SSC magnets has concentrated so far on quench performance and mechanical behavior, systems for magnetic field measurement have not been fully developed and will not be described here.

TEST STANDS

Two test stands, with somewhat different capabilities, have been constructed for the testing of SSC magnets, replacing two test stands previously used for testing Tevatron magnets. Each consists of two end boxes, whose ends simulate neighboring magnets in a magnet string, and a structure for supporting and aligning the magnet under test. The end

Table I

Test Stand Characteristics

Characteristic	Stand 4	Stand 5
Temperature range	3.2-4.8 K	1.8-4.8 K
Helium pressure	1.3-4.5 Atm	
Helium mass flow	30 g/s	50 g/s
Maximum magnet current	8 kA	9 kA
Voltage tap feed-through wires	200	200
Low voltage feed-through wires	330	330

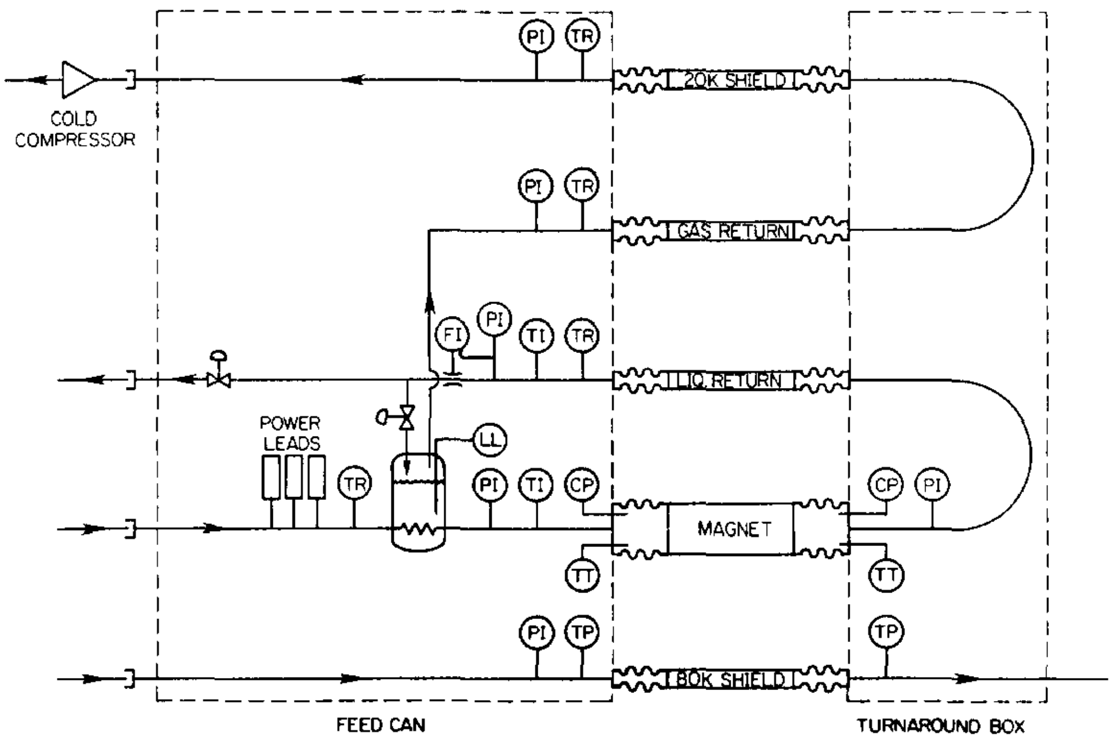

Fig. 1. Simplified flow schematic for test stand 4 showing locations of instrumentation. TR is a pair of carbon resistors. TT is a triplet of resistance thermometers: germanium, encasulated carbon and platinum. TP is a platinum resistor. TI is a vapor pressure thermometer. PI is a room temperature pressure transducer. CP is a cold pressure transducer. FI is a differential pressure transducer. LL is a liquid level probe.

boxes serve to route cryogens through the magnet, bring pressure tap capillary tubes to a room temperature gauge panel, and bring magnet power leads and instrumentation wires to the magnet under test. The characteristics of the two test stands are summarized in Table I.

Figure 1 is a flow schematic, including the locations of cryogenic instrumentation, of the first of two stands to be built (Stand 4). Helium at a temperature of approximately 4.6 K and a pressure between 1.3 Atm and 4 Atm is provided by a CTI-1500 refrigerator.[10] The helium enters the feed end box through the liquid supply line, where some of the flow is diverted to cool the power leads. The helium then passes through a boiling liquid subcooler, whose shell-side pressure sets the magnet test temperature. After passing through the magnet, the helium is routed by the return end box through the liquid return line of the magnet cryostat and back to the feed end box. Some of the flow passes through a J-T valve into the shell side of the subcooler, while the remainder returns to the refrigerator. Boil-off gas from the subcooler passes through the gas return line of the magnet and then the 20 K shield; in this mode of operation this shield actually operates at approximately the same temperature as the magnet. The helium passes through a cold compressor,[11] is warmed to room temperature and returned to the compressor intake of the refrigeration system. When the magnet is being operated at 4.4 K or above, the cold compressor is turned off. With the cold compressor on, the pressure on the shell side of the subcooler can be lowered to approximately 0.3 Atm, allowing the testing of magnets at temperatures as low as 3.2 K. The 80 K shield is cooled by liquid nitrogen which is vented to the atmosphere after a single pass through the magnet.

Temperatures are measured at the points indicated in Fig. 1 by resistance thermometers and vapor pressure thermometers. Pressures are measured by pressure transducers and mechanical gages at the room temperature ends of capillary tubes and by cold pressure transducers immersed directly in the helium in the two magnet interconnect regions. Helium mass flow through the magnet is measured with a venturi flow-meter in the liquid return line in the feed end box. The cryogenic instrumentation of this test stand has been described before.[12]

Figure 2 is a flow schematic for the more advanced test stand (stand 5). The cryogenic operation of this test stand is described fully in a companion paper[13] in these proceedings and will be described briefly here. Helium from the refrigerator passes first through a counter-flow heat exchanger (HX1), the other side of which contains the outlet flow from the magnet. The main flow then goes through the tube side of a boiling liquid subcooler (HX2) and then to the magnet. Helium exiting the magnet is routed back through the magnet liquid return line, passes through HX1, and is returned to the refrigerator. A fraction of the flow from the first heat exchanger is diverted to the shell side of HX2 to maintain the liquid level. Boil-off gas from the subcooler is warmed to room temperature and sent to a large vacuum pumping system. For 4.4 K testing, this pump is turned off; the pump is capable of lowering the pressure in the subcooler to 0.01 Atm, allowing testing of magnets to temperatures as low as 1.8 K. A fraction of the flow is diverted before the first heat exchanger to cool the power leads and is then sent through the 20 K shield, back through the gas return line and is returned to the refrigerator. This sets the 20 K shield at approximately 4.5 K. The 80 K shield is cooled by liquid nitrogen which is vented to the atmosphere at the outlet. Test stand instrumentation, indicated in Fig. 2, is similar to test stand 4.

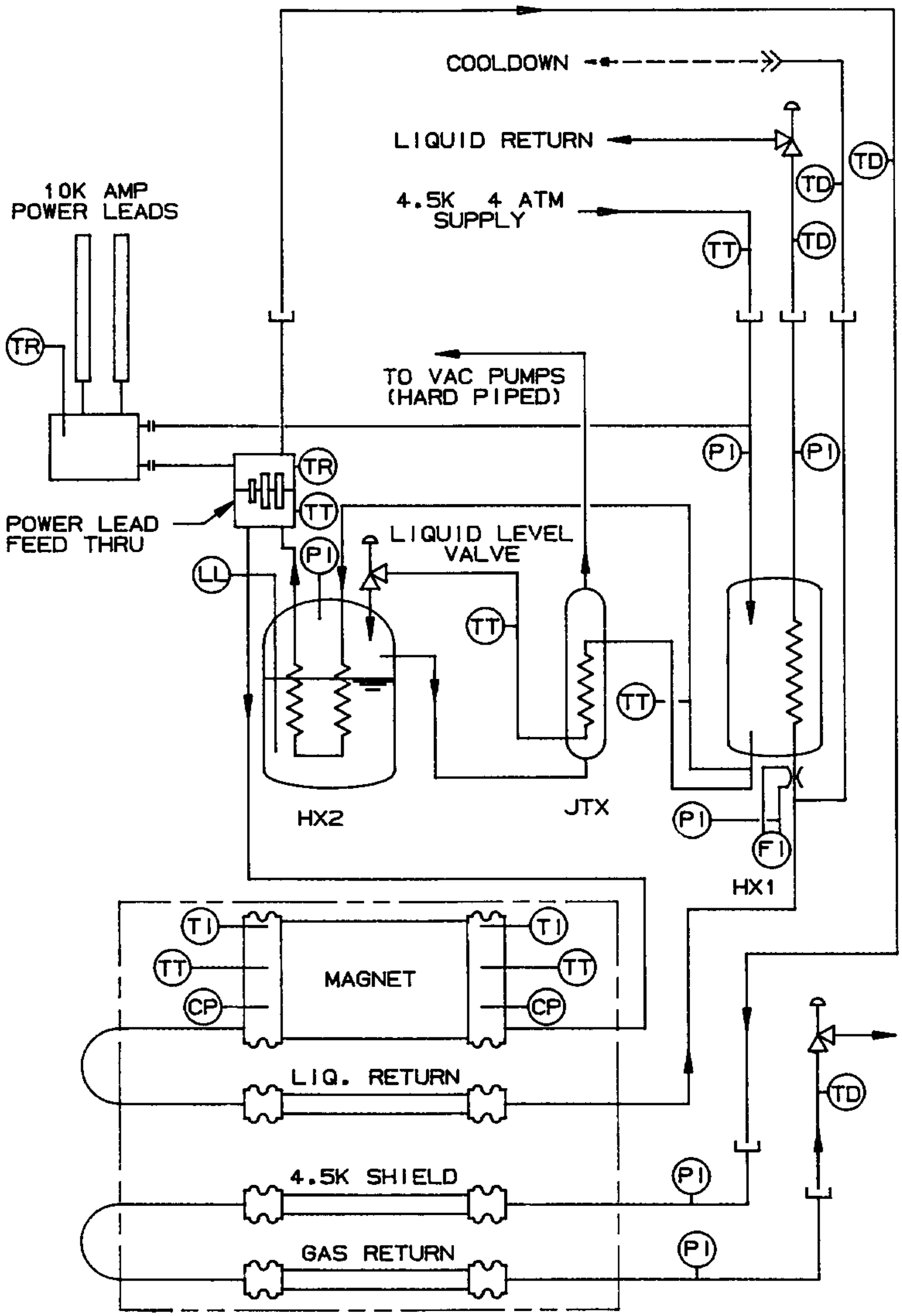

Fig. 2. Simplified flow schematic for test stand 5 showing locations of instrumentation. The notation is the same as in Fig. 1, with the addition that TD is a pair of resistance thermometers: germanium and encaulated carbon.

A simplified schematic diagram of the power system is shown in Fig. 3. The system is based on two Transrex 500 kW power supplies, each with its own filter, series SCR, and dump resistor circuits, which are put in parallel near the test stands. Current is directed to the test stand in use by mounting the appropriate copper plates in a "switch-yard." The LC filter consists of the 8 mH choke (a Fermilab main-ring magnet) and the parallel 22500 μF and 4500 μF capacitors. The diode in the filter protects the electrolytic capacitors from being back-biased during quenches, while the 3 Ω resistor conducts enough DC current to keep the diode on.

Magnet current is measured both by a shunt[14] and a zero-flux current transformer[15] (transductor). The time derivative of the current is measured using an air-core transformer ("dI/dt coil"). The primary is a 5-turn solenoid in the main bus and the secondary is a 1000 turn solenoid inside the primary, yielding a mutual inductance of 0.11 mH. The dI/dt signal is used for subtraction of the inductive component of the magnet voltage both for quench protection (see below) and for analysis of quench data. A soft ground is provided through a 1 Ω and a 25 Ω resistor. Voltage across the 1 Ω resistor is used to detect ground faults, while the voltages across both resistors are monitored by the quench data acquisition system.

Under normal conditions, the series SCR Q2 is gated on while Q1 is off. When a quench is detected (see next section), the power supply is turned off, Q2 is gated off and Q1 is gated on. The -400 V on the

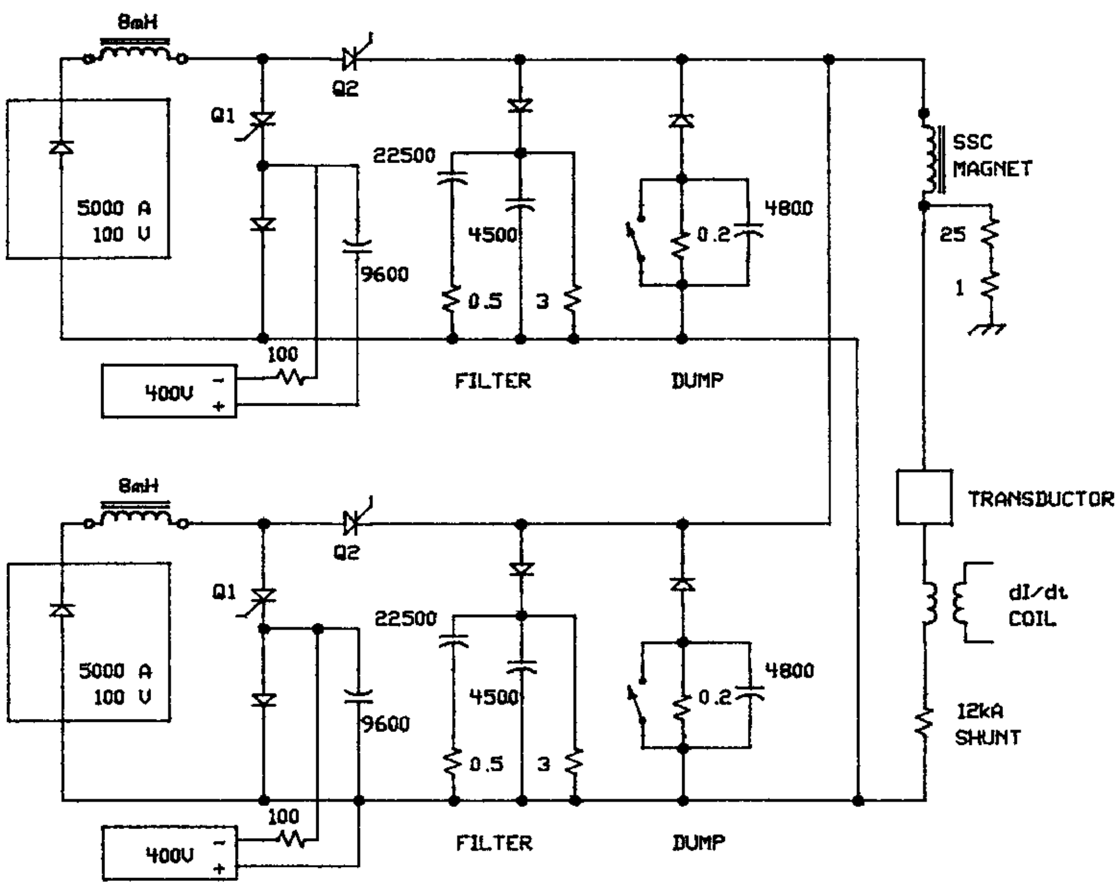

Fig. 3. Simplified power system diagram. All resistances are indicated in Ohms and all capacitances in μF.

9600 μF capacitor back biases Q2 to turn it off, while Q1 and the diode in series with it provide a discharge path for the energy stored in the 8 mH choke. The magnet discharges through the dump resistor. A switch allows the dump resistor to be shorted, causing the magnet to absorb its full stored energy. This is equivalent to using a single diode across the magnet leads for quench protection. Most tests of SSC magnets have been performed in this mode.

QUENCH PROTECTION SYSTEM

Magnet and test stand quench protection is provided by a set of analog comparators, which detect non-zero resistance in the magnet coil or power leads, excessive resistance in the gas-cooled copper leads, or non-zero ground current. The protection system requires the detection of a non-zero resistive voltage while being insensitive to the inductive component. A quench detection circuit module (QDC) accepts two signals, amplifies or attenuates each independently and sets a latch if the difference between the amplified signals lies outside an adjustable window centered on zero. The relative gains are adjusted so that the difference signal has no inductive component.

Figure 4 shows the voltage taps on the magnet and power leads used in the quench protection system. Signals from the whole main coil, the two half coils, the two superconducting power leads, the two gas-cooled copper power leads, the 1 Ω resistor between the negative bus and ground (see Fig. 3), and the trim coil (not shown), are brought to the control room through isolation amplifiers. Signals from the two SSC test stands are routed through a relay multiplexer to a common set of quench detection circuits.

Table II(a) lists the quench detection circuits used, their inputs and thresholds and Table II(b) indicates the actions taken when each is triggered. The most sensitive QDC takes the difference between the upper and lower half coils. To protect against the possibility of a symmetric quench, a second QDC measures the voltage across the whole main coil and

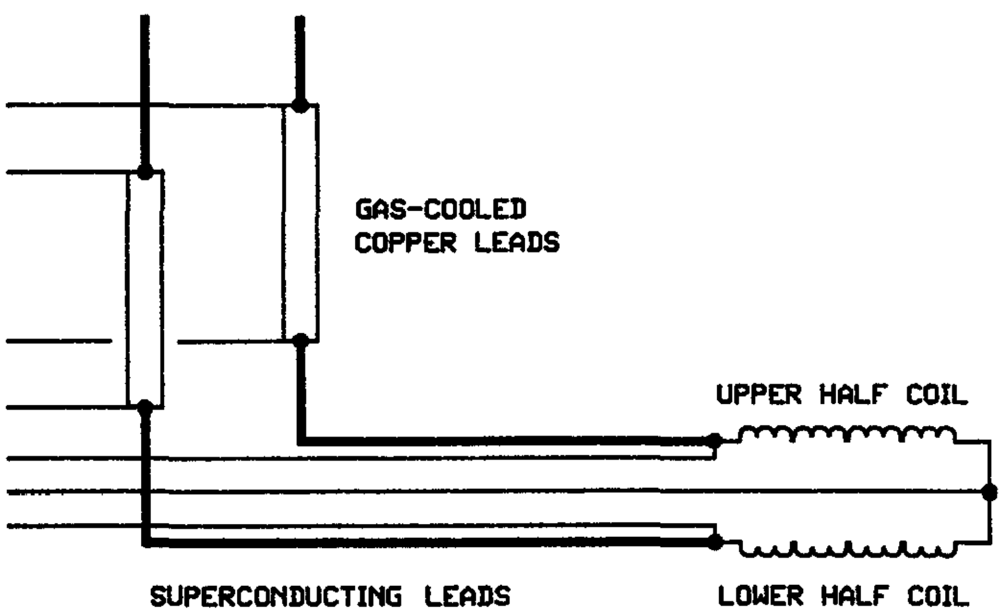

Fig. 4. Voltage taps used in the quench detection system.

Table II

a) Quench Detection Circuits

QDC	Inputs			Threshold	Group
1	Upper Half Coil	-	Lower Half Coil	0.25 V	A
2	Whole Main Coil	-	dI/dt Coil	4.0 V	A
3	Whole Main Coil			11 V	A
4	Superconducting Leads	-	dI/dt Coil	0.01 V	B
5	Copper Leads	-	Shunt	0.03 V	B
6	Trim Coil			0.5 V	C
7	1 Ohm Ground Resistor			0.10 V	C

b) Magnet Quench Protection

QDC Group	Action	Delay Range
A	Phase back power supply SCRs	0-2 sec
	Energize energy extraction system	0-2 sec
	Energize protection heaters	0-2 sec
	Turn off correction coils	0
B	Phase back power supply SCRs	0-2 sec
	Energize energy extraction system	0
	Energize protection heaters	0
	Turn off correction coils	0
C	Ramp main current to 0 at 200 A/sec	0
	Turn off correction coils	0

uses the signal from the dI/dt coil (see Fig. 3) to cancel the inductive component. Because the frequency response of the superconducting magnet (considered as an inductor) is different from that of the dI/dt coil, they respond differently to the power supply voltage ripple, so the threshold cannot be placed as low as on the first QDC. The third QDC monitors the total magnet voltage and protects against excessive ramp rates that might result if the power supply were to go out of regulation. Between the bottom of each gas-cooled copper power lead and the magnet, the current is carried by 2 (stand 4) or 3 (stand 5) Tevatron superconducting cables, which do not have any additional copper stabilizer. Quench detection circuit 4 measures the sum of the voltages across the positive and negative superconducting leads and subtracts the inductive component using the dI/dt coil. The fifth QDC protects the gas-cooled leads from thermal run-away that could result from inadequate helium flow. A signal proportional to the current and is subtracted from the sum of the lead voltages, placing a window about the nominal resistance of the leads. Quench detection circuit 6 monitors the voltage across the correction coil uncorrected for inductive effects. Ground current is detected by QDC 7 which is sensitive to voltage across the 1 Ω resistor in the system ground.

When any one of the quench detection circuits 1 through 5 (groups A and B in Table II) is triggered, several actions are taken to protect the magnet and power leads. Both the main and correction coil power supplies are turned off, the dump resistor is switched across the magnet leads, and protection heaters (strip heaters) in the magnet are energized to cause the quench to propagate throughout the coil. To allow studies of quench protection methods and of quench propagation, each of these actions may be delayed independently by up to 2 seconds for quenches detected by the first three QDCs (group A). Because lead quenches may take a substantial time to be detected, most of the delays are bypassed if QDC 4 or 5 (group B) is triggered. Quench detection circuits 6 and 7 (group C) cause the main coil current to ramp to zero at 200 A/sec and the trim coil power supply to be turned off. No delays are allowed. If the trim coil quenches, there is no need to quench the main coil. If a ground fault occurs without a quench, it is undesirable to quench the magnet or switch in a dump resistor, since either of these actions would generate considerable voltage to ground in the coil.

MAGNET INSTRUMENTATION

Recent SSC magnets[4-6] have been heavily instrumented with a variety of measurement devices which must be accommodated by the test facility. Strain gage based devices and linear potentiometers have been used to measure stress, force and motion in various magnet components, resistance thermometers have been used to measure the thermal performance of the cryostat[16] and several magnets have included up to 133 voltage taps for quench localization and propagation measurements. Coil azimuthal stresses at the collars have been measured with both direct compression and bending beam[17] load cells. Direct compression load cells[17] have been used to measure the axial force between the coil end and the magnet end plate, while bending beam motion transducers and linear potentiometers have been used to measure the deflection of the end plates, motion of the end of the coil relative to the cold mass skin, and overall length changes of the magnet with both temperature change and excitation. Strain gages have been applied directly to the cold mass skin and to many cryostat components[16] to measure stresses due to thermal effects and excitation. Depending on the application, results may be reported as strain, stress, force or displacement. The strain gages may be wired as full- or half-bridges with voltage or current excitation, or may be read as individual gages by a 4-wire resistance method.

DATA ACQUISITION SYSTEM

The data acquisition system can be divided into two main sub-systems: one for electrical quench signals and one for cryogenic[12] and mechanical signals. The two systems conform to similar philosophies: front-end electronics are located as close to the test stand as is practical, amplified signals are brought to digitization electronics and data are collected and transmitted via serial CAMAC to programs running on a MicroVax II.

Hardware

To reduce the load on the MicroVax and eliminate need for the MicroVax to perform real-time operations, intelligent readout electronics with local memory are used for digitization. A complete set of electronics exists for each test stand;[18] multiplexing between the two test stands is done by the readout programs selecting the appropriate CAMAC modules. Fast digitization of signals during quenching is provided by 32-channel, 12-bit analog-to-digital converters[19] (ADCs) with 1024 words of memory per channel. These are operated in a "ring buffer" mode, with digitization stopping after a pre-selected number of data samples have been taken following a quench trigger. Currently nine such modules are used for each test stand for electrical signals and one for cryogenic and mechanical signals. The sampling clock frequency and number of post-trigger samples can be controlled on-line by the magnet tester. Clock periods used typically range from 0.2 to 2 msec while normally 128 or 256 pre-trigger samples are stored. Cryogenic and mechanical data are measured with higher precision but poorer time resolution by a digital voltmeter[20] (DVM) with signals multiplexed through a relay scanner.[21] Once a scan is started, the DVM and scanner trigger each other and data are stored in memory in the voltmeter; the MicroVax need only initiate a scan and collect the data at the end. Up to 1400 channels can be multiplexed into one DVM in this manner. We currently have hardware to read 360 channels from the two test stands.

The number of channels that can be read is ultimately limited only by the number of feed-through wires. On each test stand there are approximately 330 low voltage instrumentation wires and 200 voltage tap wires available for magnet data taking (in addition to a smaller number for monitoring signals within the end boxes). In addition, signals from instrumentation in the insulating vacuum (for example, strain gages mounted on the cold mass skin or thermometers mounted on cryostat components) are typically brought out through the magnet cryostat wall, increasing the number of signals possible.

To be able flexibly to accommodate the different configurations of instrumentation on the R&D magnets, a modular system has been developed for voltage tap, strain gage, thermometer, and linear potentiometer readout. Voltages across segments of the magnet coil are measured by constructing signals from pairs of voltage taps. The ADCs are protected from the potentially large common- and differential-mode voltages by transformer-coupled isolation amplifiers.[22] A single width NIM module includes two isolation amplifiers and a differential amplifier, which gives the difference between the two input signals. The inductive voltage from two coil segments of equal inductance is eliminated in taking the difference, allowing greater sensitivity to small resistive voltages. The gains of the individual and difference amplifiers are independently selectable by a combination of internal and external switches.

Double width NIM modules provide constant voltage or current excitation for up to eight full- or half-bridge strain gages. Constant voltage modules provide for remote sensing of the excitation voltage, while constant current modules include a precision, high stability, resistor for measuring the excitation current. The strain gage voltage is routed to front panel connectors for digitization by the digital voltmeter. These modules also include bridge completion resistors for half-bridges and optional amplifiers with switch selectable gains of up to 500 to allow dynamic readout by ADCs. The modules are configured for a specific test by internal terminals.

Other double width NIM modules provide constant 2.5 mA excitation for up to 12 individual gages read by the 4-wire resistance method. Again the current is measured by a precision resistor in each module. In this readout method, thermal and magnetic field effects on the active strain gages are corrected by subtracting the apparent strain measured on a compensating gage, which is in the same environment as the active gage but is unstrained.

If the active and compensating gage are excited by the same current source, the effect of small uncertainties in the absolute calibration of the current measuring resistor will tend to cancel. To allow dynamic readout, the analog difference between the active and compensating gage voltages can be amplified. The configuration of the module is set by internal jumpers.

Similar modules[12] provide excitation and optional amplification for resistance thermometers, except the current is in the range 1-25 μA. Excitation and signal conditioning for pressure transducers is provided by commercial electronics.[23]

Software

Three cooperating programs[12] on the MicroVax are used to collect and store the data. Cryogenic and mechanical transducers are read through the DVM-scanner system and one 32-channel ADC by a program called CRYO_MONITOR, which responds to requests from the other two programs. CRYO_LOGGER makes requests for high resolution quasi-static data at fixed time intervals, typically every 10 minutes, logs the data to disk and displays the cryogenic data on a terminal screen for use by the refrigerator operators and magnet test personnel. Both raw voltages and values after conversion to physical units are recorded and each type of data is written in both binary and ASCII formats. Complete configuration and calibration data are written at the beginning of each file and whenever CRYO_LOGGER is restarted.

The magnet test and measurement program SSC controls the power supplies, measures the main and correction coil currents from shunts or transductors via digital voltmeters, collects, analyses and logs quench data from the ADCs, collects (via CRYO_MONITOR) and logs strain gage and other cryogenic data as a function of magnet current, and has structures to allow for magnetic field measurements when such systems become more completely developed. An ASCII "log" file records time-stamped information about the test, including changes in magnet current, the writing of data files, the occurrence of quenches and operator comments. Magnet and power system electrical signals from each quench are written as raw ADC counts in a binary file, which contains full configuration and calibration information to allow off-line programs to convert the data to physical units. The quench data files also contain information about the cryogenic state of the magnet before the quench, results of simple on-line analysis of the data (e.g. quench current, maximum voltages and $\int I^2 dt$) and operator comments. Mechanical and cryogenic data as a function of magnet current are written in ASCII files, which have a format similar to the ASCII files written by CRYO_LOGGER.

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16. T. H. Nicol, Structural Performance of the First SSC Design B Dipole Magnet, presented at the International Industrial Symposium on the Super Collider, New Orleans, LA, February 8-10, 1989.
17. A. D. Anerella, et. al, Measurement of Internal Forces in Superconducting Accelerator Magnets with Strain Gauge Transducers, presented at the Applied Superconductivity Conference, San Francisco, CA, August 22-25, 1988.
18. Six ADC modules for multiple voltage tap readout on highly instrumented magnets are shared between the two test stands. Nine eight-conductor cables must be changed at a patch panel to switch between the two test stands.

19. Model 8212A 32 channel, 12-bit fast data logger with model 8800A memory module, LeCroy Research Systems, Spring Valley, NY.
20. Model 3457A digital multimeter, Hewlett-Packard Co., Palo Alto, CA.
21. Model 706 scanner with model 7064 low-voltage relay scanner cards, Keithley Instruments, Inc., Cleveland, OH.
22. Type AD210BN, Analog Devices, Norwood, MA.
23. Dynisco, Norwood, MA.