Control and materials characterization System for 6T Superconducting Cryogen Free Magnet Facility at IUAC, New Delhi

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Abstract. A system for carrying out automatic experimental measurements of various electrical transport characteristics and their relation to magnetic fields for samples mounted on the sample holder on a Variable Temperature Insert (VTI) of the Cryogen Free Superconducting Magnet System (CFMS) has been developed. The control and characterization system is capable of monitoring, online plotting and history logging in real-time of cryogenic temperatures with the Silicon (Si) Diode and Zirconium Oxy-Nitride sensors installed inside the magnet facility. Electrical transport property measurements have been automated with implementation of current reversal resistance measurements and automatic temperature set-point ramping with the parameters of interest available in real-time as well as for later analysis. The Graphical User Interface (GUI) based system is user friendly to facilitate operations. An ingenious electronics for reading Zirconium Oxy-Nitride temperature sensors has been used. Price to performance ratio has been optimized by using in house developed measurement techniques mixed with specialized commercial cryogenic measurement / control equipment.

1. Introduction

The 6T cryogen free superconducting magnet [1] developed at IUAC, New Delhi is designed to provide magnetic fields of up to 6T. The magnet is cooled by a two stage GM cry-cooler type SRDK-415D of 1.5W @ 4.2K. The magnet achieves a field of 6T at 102 A. A 50 mm diameter x 0.5 m deep working bore has been provided for sample insertion via suitable structures for materials property measurements at high magnetic fields for materials science research. A Variable Temperature Insert (VTI) designed to couple with the system using the warm bore has been fabricated and installed [2]. A sample holder inside the VTI has been incorporated with a Zirconium Oxy-Nitride [3, 4] based temperature sensor and a 50 W heater with connections provided for temperature control and sample measurement. The sample mounted on the VTI is exposed to the magnetic field. The VTI and magnet facility is being developed into a user facility with automation features for good operational efficiency and ease of use. For electrical transport measurements, Resistance vs temperature measurements,
current vs voltage measurements and current reversal 4 wire resistance measurements have been automated.

2. Instrumentation and control scheme
The process variables of the Magnet and VTI systems are acquired in real-time to carry out experiments. The magnet system parameters, the thermal radiation shield temperatures, the CCR stage temperatures and vacuums are constantly monitored and plotted. Hard disk data logging and automation functions have been implemented using algorithmic functions. Quench avoidance and detection is implemented by the software. For experimentation, a successive set-point temperature ramping algorithm has been incorporated.

2.1. Sensors and process instrumentation
The locations of various sensors and control points related to operation of the CFMS integrated with VTI are shown in Figure 1. Mostly Lakeshore™ DT470 Si diode temperature sensors [5] have been embedded inside the assembly at various locations. The radiation shield, CCR stages and some other temperatures are provided with Si diodes. For magnetic field prone areas, use of Si diodes is not possible because of their sensitivity to magnetic fields. Zirconium Oxy-Nitride [5] based temperature sensors (Cernox™ from Lakeshore Inc) are therefore used for VTI sample temperature, magnet coil temperature, bobbin temperature and other magnetic field prone locations. The connections are brought for control via various electrical feed-thrus.

![Figure 1](image)

**Figure 1.** Location of temperature sensors and other control measurement devices in CFMS-VTI system.

The instrumentation is shown in Figure 2. The Oxford Instruments Mercury iPS M power supply with IEEE 802.3 (Ethernet) [6] interfaces is used for charging, discharging and control of the 6T NbTi
magnet. Si diode sensors are monitored with a Lakeshore 218 temperature monitor interfaced over a serial port. The monitoring of Cernox™ sensors is done via an indigenously developed scheme described in a later section of this paper. Other additional instrumentation includes vacuum gauge controller interfaced via the serial port.

2.2. Instrumentation for Materials characterization with VTI

Four wire sample connections are brought from the sample contacts with proper electrical shielding via the feed-through port at the top. In some cases a two wire measurement configuration is used. As shown in Figure 2, the VTI sample connections are brought to a Keithley 2400 source measure unit [7] which is interfaced via the RS232 [8] serial port. The excitation current is fixed at the beginning of the experiment for resistance measurement and is ramped for current vs voltage measurements.

The Cernox™ temperature sensor and a 50 W heater installed on the VTI sample holder are connected to a cryogenic Proportional Integral Derivative (PID) [9] temperature controller of Lakeshore™ 331 type to form a closed loop control system. Lakeshore™ 331 temperature controller has capability of storing several different sets of Proportional (P), Integral(I) and Derivative (D) constants for several different temperature ranges (multi-zone temperature controller). The controller can drive a heater of up to 100 W to achieve temperatures from the mK range up to 400 K. The controller has been tuned using both the Ziegler Nichols method [10] as well as its own automatic tuning routines. The instrument provides a multi-purpose Ethernet interface for transferring sensor calibration tables from the control computer as well as remote control with its own proprietary command set.

![Figure 2. Scheme of the control and materials characterization system.](image)

2.3. Control System Hardware and Integration

A control computer running a 64 bit operating system forms the heart of the system as shown in figure 2. The main nodes of a control network are implemented by a 100 MBPS IEEE 802.3 (Ethernet)
hub and a high data rate multiple port serial interface hub on universal serial bus (USB). The 64 bit hardware and higher level drivers to enable accessing of instruments on the network are installed on the control computer.

The Oxford Instruments Mercury iPS magnet power supply and the Lakeshore 331 temperature controller are connected via the Ethernet hub. The Keithley 2400 source measure unit, the Lakeshore temperature monitors, the Cernox™ electronics and the vacuum gauges are connected through the USB multi serial hub.

2.4. Cernox™ sensor interface and measurement electronics

The Cernox™ sensors are installed to monitor temperatures at various points of the magnet and interfaced with an ingeniously developed electronic system as shown in the Figure 3.

![Figure 3. Measurement system for Cernox™ sensors.](image)

The designed measurement system uses high resolution Analog to Digital Converters (ADC) for reading the voltages generated across the Cernox™ sensors and Digital to Analog Converters (DAC) for controlling the excitation current through the sensors. The scheme is shown in figure 3. The DACs and ADCs are interfaced using the RS485[11] and MODBUS[12] protocol. Raw data from the ADC is read by the program and is linearized before calibration. The interpolation tables for the sensors are loaded into memory. The software controls and reads the raw data and does the calibration at a regular interval. The temperature data is displayed on the screen along with real time history and disk logging to a file. The measurement system has been able to provide a resolution of better than 1 mK at 4.2 K and of around 1300 mK at 300K at an accuracy of 0.1 % for the ADC. The acquired plots can be seen in the “RESULTS” section of this paper.

3. System operation and software development

3.1. General

The coordination of the 6T magnet operation with the VTI routine is done as shown in Figure 4. The primary responsibilities of the system are measurement of temperatures and vacuums on a regular basis, control of the superconducting magnet, parameter display, history plotting and data logging. Additional functions like magnet quench monitoring and protection are also included. The VTI control section consists of the source meter unit and a dedicated temperature controller for sample temperature control. User related experiment functions, mainly Resistance vs Temperature (R-T) and Current vs Voltage (I-V) characterization routines are developed. The R-T measurement system is closely linked to the temperature controller. In this measurement, the sample temperature is ramped through a number of temperature points, the temperature being stabilized at each point and Resistance reading taken subsequently.

The software works in the data logging mode or a sample control mode. A graphical user interface (GUI) based system implemented with Labview™ [13] provides ease of operation, user friendliness and minimization of human error. A snapshot of the GUI front panel is shown in Figure 4. A brief description of the software functions is given in the next section.
3.2. Magnet control and measurement
The Oxford iPS magnet power supply has been interfaced to the computer using the Ethernet interface provided with the system. The Magnet power supply uses a proprietary command set for Magnet ramp rate, ramp direction and status control. The quench status is constantly monitored by the software and a quench signal is flashed on the panel.

![Operational block diagram and GUI panel of the system](image1)

**Figure 4.** Operational block diagram and GUI panel of the system

3.3. Sample control and measurements with VTI
A method of temperature vs resistance measurements is implemented where a start, an end and a temperature increment value is set on the front panel.

![Flow chart of automatic Resistance vs Temperature measurements](image2)

**Figure 5.** Flow chart of automatic Resistance vs Temperature measurements.
When the start button on the GUI is pressed, the program sends the beginning set-point to the temperature controller and allows a settling time for the temperature. After the settling time is over and the temperature is reached, current reversal resistance measurement routine is executed with the help of the source measure unit. After the measurement, the next temperature set-point is calculated by incrementing the current set-point and the process is repeated. The iterations are carried out for successive incremented temperatures until the final temperature set-point of interest is reached and the program automatically stops the measurement. The resistance at every point is measured by applying the excitation current to the sample in both the directions and taking the average to ensure cancellation of thermally induced voltages. The data is saved in text files in multi column format. Online display of the resistance vs temperature plot is provided at the front panel.

3.4. Performance aspects

The data logging system and the VTI based automatic transport measurement systems have been extensively used. The Cernox™ measurement electronics developed with inexpensive high resolution ADC hardware has a resolution of <1mK at liquid Helium temperatures. The automatic R-T measurement system has also shown a sturdy and repeatable performance. The economically implemented system has been proven to be rugged and reliable.

4. Results and Discussion

The magnet has been charged up to 6T with a current of 102 A. A temperature history profile of magnet ramp up and ramp down at four locations near the magnet has been recorded with the automation system. The temperature history profile, as shown in figure 6 of the cold head, the magnet plate (T12), the magnet bobbin (T13) and the 6T superconducting magnet are as expected. At zero current, temperatures of the magnet and the CCR are 3.2K and 2.8K respectively. Whereas at 102 A temperatures of the magnet and the CCR shoot up to 3.9K and 3.2K respectively. The refrigeration load of the second stage of CCR at 3.2K and 3.9K are 0.7 W and 1.2 W respectively for corresponding first stage temperatures 40K and 44K.

![Temperature profile of the magnet and adjacent areas](image_url)

Figure 6. Temperature profile of the magnet and adjacent areas
A thin film of sample (20% Cd in ZnO) made by solgel spin coating method in IUAC is tested using the VTI setup.

![Figure 7. Resistance Vs Temperature Measurement of 20% CdZnO sample](image)

The results of the variation of resistance with temperature in heating and cooling are plotted in Figure 7. The sample shown here has been measured in the four wire mode with stepped temperature ramping method. The sample being a low resistance, four wire mode has been selected. The complete measurement took around six hours to complete. The sample is showing expected behaviour of negative temperature coefficient as it is semiconductor material at low temperature and constant resistance at room temperature [1].

5. Conclusion and future plans
The system for control of 6T superconducting magnet and automatic materials property measurements has been developed and implemented with a good performance. The temperature, magnetic field and sample related measurements and controls have been achieved as desired.

Several improvements are planned in future. A hall measurement system and an automatic van der Pauw[14] switching system measurements will be implemented in near future. Current vs Resistance measurements may be linked with automatic Resistance vs Temperature experiments.

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