Superconducting Magnets of SST-1 Tokamak

Subrata Pradhan, Y. C. Saxena, B. Sarkar, G. Bansal, A. N. Sharma, K. J. Thomas, V. Bedakihale, B. Doshi, C. P. Dhard, U. Prasad, P. Rathod, R. Bahl, A. Varadarajulu, A. Mankani & SST-1 Team

Institute for Plasma Research, Bhat, Gandhinagar-382 428, Gujarat, India

e-mail contact of main author: pradhan@ipr.res.in

Abstract: Magnet System of SST-1 comprises of sixteen superconducting D-shaped Toroidal Field (TF) coils, nine superconducting Poloidal Field (PF) coils and a pair of resistive PF coils inside the vacuum vessel. TF magnets generate the basic 3.0 T field at the major radius of 1.1 m. Low resistance lap inter-pancake joints within and inter-coil joints between the coils have been made. Magnets are cooled with supercritical helium at 4 bar and 4.5 K, which is fed at the high field region in the middle of each of the double pancake over a hydraulic path length of 47 m. Voltage taps across joints and termination location are used for quench detection. The quench detection front-end electronics ensures fail proof quench detection based on subtraction logic. Quench detection system sends the quench trigger to the power supply system directly on a dedicated fiber optic link. Flow meters at the inlet of the TF and PF magnets, temperature sensors at the critical joint locations and at the outlet of the flow paths for enthalpy estimation, hall probes for field direction and magnitude measurements are the other sensors. A 20 V, 10 kA power supply will excite the TF magnets whereas the PF power supplies have voltages from few volts to in excess of 100 V to cater the fast current ramp-up of the PF magnets during start-up scenarios. All power supplies have been equipped with dump resisters of appropriate ratings in parallel with a series combination of DC circuit interrupters and pyro-breakers.

1. Introduction

The steady state superconducting Tokamak, SST-1 at Institute for Plasma Research (IPR) envisages steady state operation, with both the Single Null and the Double Null configuration [1]. The magnetic configuration and plasma shaping magnetic fields are provided by Superconducting Magnet System (SCMS) comprising of sixteen superconducting (SC), D-shaped, Toroidal Field (TF) coils and nine superconducting Poloidal Field (PF) coils [2] together with a pair of resistive PF coils, inside the vacuum vessel of SST-1. The PF coils are not used for plasma breakdown and initial current ramp up. An air-core ohmic transformer is used for this purpose. A pair of vertical field coils provides equilibrium during this phase. Figure 1 gives a schematic of the cross-section of SST-1 showing various magnets deployed.

2. SST-1 SCMS

2.1. Toroidal Field Magnet System

The TF system design requirements include the production of 3.0 T magnetic flux density at plasma axis with ripple < 2% within the plasma volume. The TF system consists of 16 numbers of SC, modified `D' shaped coils arranged symmetrically around the major axis and spaced 22.5^0 apart. The base conductor for these magnets is an NbTi based cable-in-conduit conductor (CICC) [3]. Each of the TF coils is made up of six double pancakes, each pancake having nine turns. The compacted winding pack of 6 double pancakes is shrunk fitted into a stainless steel (SS 316L) casing, which supports most of the electromagnetic loads. For a maximum current of 10 kA per turn the magnetic flux density at plasma center is 3.0T. All coils are connected in series and are protected against the quench by suitable dump resistance, switching and sensing system. The TF system stores 56 MJ in 17.28 MA-t in them. The maximum voltage developed during dump is ~1.2kV.

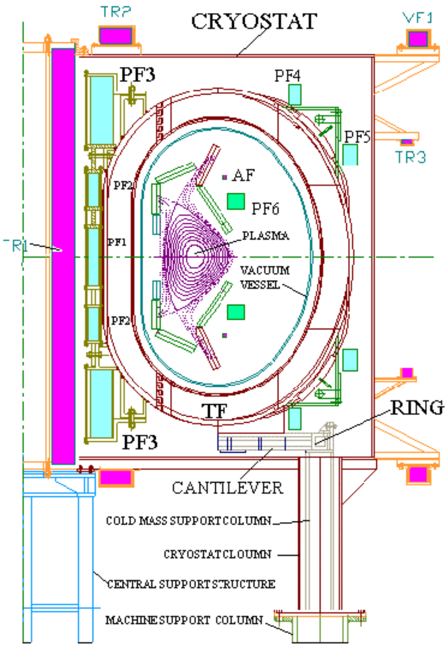

FIG. 1. A cross-section of SST-1 Tokamak

FIG. 2. A picture of SST-1 TF coil

Fig. 2 shows a picture of the TF coil in its casing. The TF coil casing consists of the side plates, the inner ring the outer ring and base plate. They are welded together to form closed shell within which the TF coil winding pack is housed. The TF coil casings are wedge shaped at the inner legs and form a cylindrical vault when all the 16 coils are assembled together. The outer vault is formed by connecting inter coil structures between the TF coils. These vaults resist the centering force and overturning torque experienced by the TF system.

2.2. Poloidal Field Magnets System

The SST-1 PF system [2] comprises of nine superconducting coils and two resistive coils. These coils allow for a variety of plasma equilibria with wide range of elongation and triangularity. Feasibility of limiter operation during plasma current ramp-up, double and single null operation at plasma current of 220 kA, double null operation at plasma current of 330 kA and various start-up scenario are the design drivers for PF system. A free boundary, axi-symmetric, ideal MHD equilibrium model based code has been used for locating and sizing of the PF system. The SC PF magnets are wound from the same CICC as that used for TF magnets and have a maximum nominal operational current rating of 10 kA. The SC PF coils are supported on the TF casings.

2.3. Conductor for Superconducting Coils

A unique feature of the SCMS of SST-1 is that the same basic conductor is used for both the SC TF and PF magnets. A SC Cable-in-Conduit Conductor (CICC), based on NbTi, has been designed [3]. CICC, with high copper to SC ratio in the strands, has been designed and manufactured, for the first time, for use in Tokamak Magnets. The cross-sections of the SST-1 strand and the CICC are shown in Fig. 3. The CICC consists of 135 NbTi/Cu strands of 0.86 mm diameter each, with a high copper to superconductor ratio of ≥ 4.9: 1. These strands are twisted in four stages before being jacketed inside a conduit made of stainless steel having a cross-section of 14.8 mm × 14.8 mm and a void fraction of 40 % inside the cable space for liquid helium to flow. A medium size Model Coil was wound from this CICC and was tested extensively for various SST-1 normal and off-normal operating events [4].

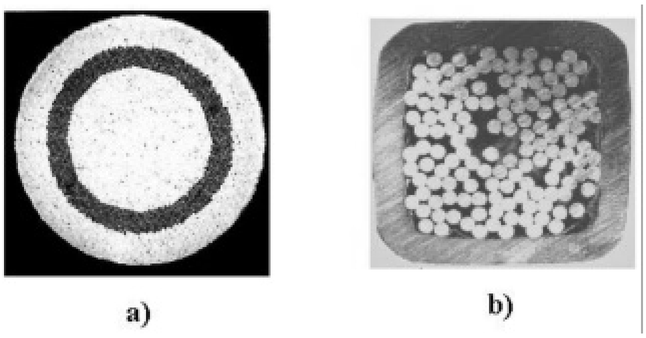

FIG. 3. Cross-section of a) the superconducting strand (0.86 mm diameter) and b) the CICC used for superconducting magnets of SST-1.

2.4 Joints on Superconducting Magnets

A total of 228 terminations and 114 shake hand type low resistance joints have been made between the double pancakes as inter-pancake joints inside the winding packs and as inter-coil joints between the coils. A shake hand, overlap type joint has been adopted, which offers both a smaller DC resistance and fabrication simplicity. The joint locations in SST-1 magnets have been chosen in regions where rapidly changing magnetic fields are small, so that the AC losses on joints are small. The maximum temperature rise of the joint in the worst case of the plasma disruption of 330 kA is estimated as 0.4 K. The square shaped unconduited cable of 12.0 mm x 12.0 mm size is inserted inside a termination copper block (of RRR: 10) with hole size 12.5 mm x 12.5 mm and wall thickness 3.0 mm considering minimum current transfer path length and mechanical rigidity of the joint. As a thumb rule the overlap length of two terminations in a joint has been chosen to be 320 mm, which is equal to the last stage twist pitch length of the cable. Under this condition all the strands come into the direct contact with the septum (copper plate between two overlapped cables) ensuring the minimum current transfer path between two joining cables. The contact area between strands inside the copper termination block is increased by filling the silver solder (95Sn-05Ag) in the voids between inserted cable and copper termination block as this solder has low magneto-resistivity and low melting temperature of 220^0C. Two, prepared cable terminations are joined by 0.1 mm thick soft solder (60Sn-40Pb) layer. The joint resistance at 10 kA current and 4.5 K temperature has been estimated as ~2.0 nano-ohms. The joints are cooled in series with the magnet CICC by flowing supercritical helium through a 5.0 mm diameter channel provided inside the copper termination block. The overall size of the joint comes out to be 360 mm length x 37 mm width x 29 mm height. Suitable joint manufacturing processes and technologies had been developed and experimentally established in-house which were later extended to the actual SST-1 winding pack. The full size prototype joints have been successfully tested at liquid helium temperatures 4.2 K up to 13.5 KA current. The inductive current decay method has been adopted to measure the DC resistance of the joint [5]. The joint resistance of ~ 3.0 nΩ at 10.0 KA current and 4.2 K has been achieved.

3. Assembly and Integration of the SST-1 Magnets

During manufacturing, all SC winding packs had been qualified for a 2.5 kV DC (applied for 1 min) isolation with respect to casing and helium tightness at 10 Kg cm^{-2}. On the ground, all coil preparation work and qualifying tests had been carried out before they are released for assembly. Leads have been bent to suit the inter-pancake (IP) and inter-coil (IC) terminations and ensure joint overlapping length of 320mm. Three IP joints on top and two on bottom side had been made on each TF coil. IC joints were made after coils were assembled. PF-4 and PF-5 coils each had three inter pancake joints at 90^0 apart. Joints on TF are clamped in a comb like G-10 structure between them and through a 5 mm sheet between them and the coil case.

Each of the double pancakes in TF coils is fed the supercritical helium (SHe) at the high field region, in the middle of the pancake. The SHe exits at the inter pancake joints cooling them in series through supply and return manifolds mounted on each of the TF coils. The incoming and outgoing lines from these manifolds are connected to respective headers connected to the Helium flow control system. Each of the hydraulics lines is electrically isolated from the headers through specially designed cryo-compatible isolators-cum-helium feed-throughs, made of G-10 and stainless steel tubes, which are tested for 5 kV isolation and subjected to repeated cool down and warm up between 4.2k and 300 k. Each TF coil has 12 isolators. Hydraulics of PF-1 has 3, PF-2 has 2, PF-3 has 8, and PF-4/5 has 4 isolators. During the dumping of TF and PF coils, the helium plant, thus does not see the voltages.

FIG. 4. TF Module with tackle

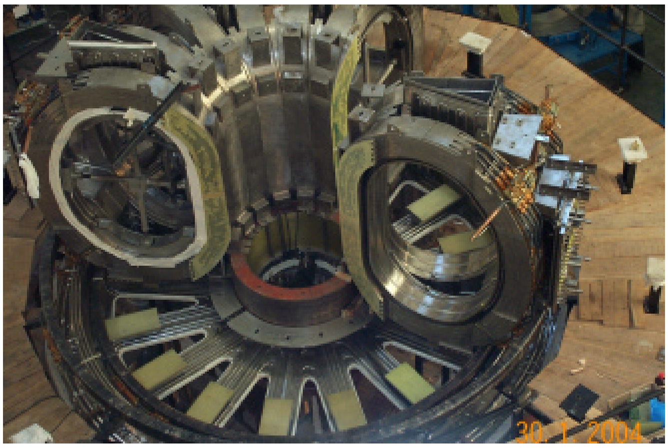

FIG. 5. TF modules on the support beams

As an assembly strategy, a pair of TF coils, together with the vacuum-vessel module, LN_2 panels and outer-inter-coil-structures (OICS) are assembled on the ground before being mounted on machine structure. The Coils are nosed on their in-board side with 1.0 mm of insulation bonded with low temperature compatible `CRYOSEAL' resin glue, between them. Coil case to LN_2 panel gap was maintained at 20 mm minimum. All 8 such modules were tested for 1.25 kV isolation. A special handling fixture lifted the integrated module without disturbing the ground alignment as seen in fig. 4. No thermal shorting between any two surfaces were allowed. The modules were then sequentially placed on the support beams as shown in fig. 5. A co-configured current return current loop was made to cancel the current loop generated by the IC joints. Fifteen numbers of IC joints were made in-situ between the TF coils.

4. Sensors, Diagnostics and Quench Detection in SCMS

The magnet system is equipped with nearly 520 sensors. There are 300 shielded twisted pair cables as voltage taps across winding packs primarily for quench detection. A total of 173 temperature sensors (CERNOX type) are mounted on TF and PF Helium inlets, OICS, joints and bottom ring largely for cool-down and warm-up monitoring purposes. Flow meters have been installed at the inlet of each of TF coils and PF-1 and PF-3 coils for flow measurement purpose and as a secondary quench detector. Absolute pressure transducers placed at the inlet and outlet of the TF coils measures pressure. Two hall probes, placed diametrically opposite, in the TF bore will measure the field intensity and eight displacement transducers will measure the cool-down and warm-up induced contraction/expansion of the support and TF coil cases. All leads from the sensors have been thermally anchored at 4.5 K and 77 K following a particular anchoring procedure. Minimum, maximum and average temperatures are used for controlled cool-down and warm up of the magnets.

Signal conditioning for the voltage taps in TF coils have incorporated multilevel of high voltages protection up to 5kV. A combination of RC filters in fault current limiting mode followed by a combination of Metal oxide varistors and back to back zener diodes prevents voltage tap burn out as well as suppresses the high voltage spikes. A subtraction logic based quench detection has been adopted for the SST-1 magnets as shown for a typical TF card in fig- 6.

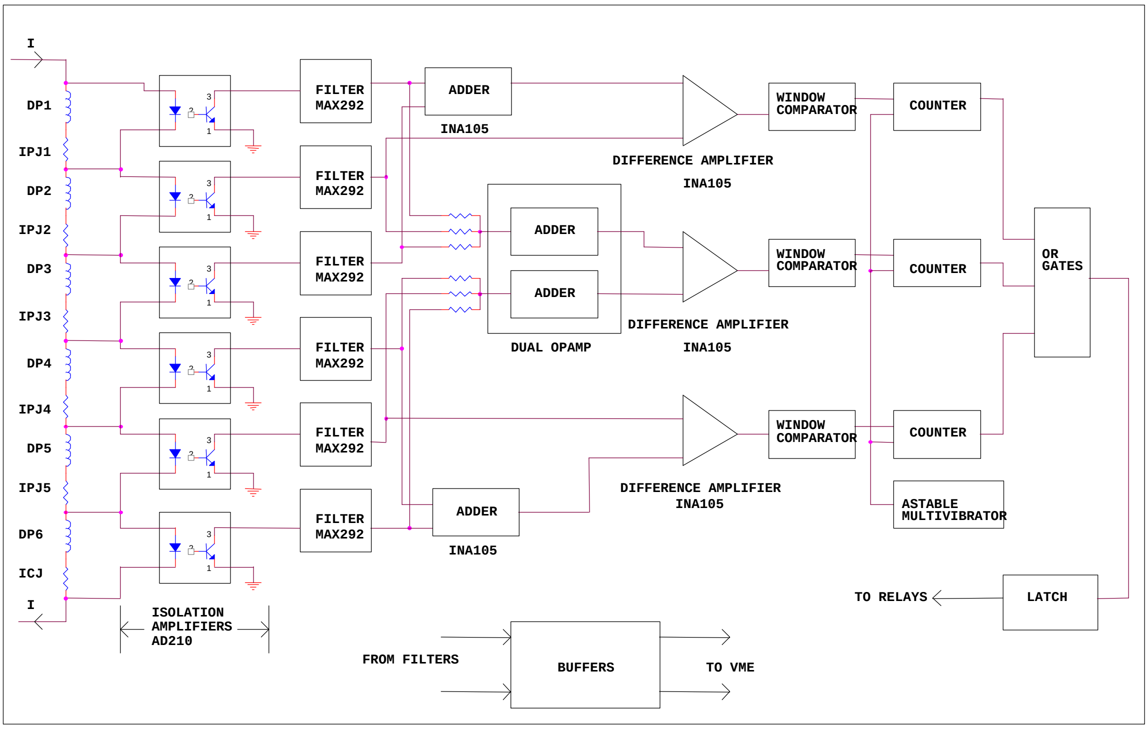

FIG. 6. Circuit diagram for the quench detection in TF coils

A quench is announced only if the signal remains high (≥ 100 mV) for a time exceeding 100 ms as dictated by the normal zone characteristics of the magnet winding pack and the maximum heating permissible prior to the initiation of the current dumping. The signals from various quench detection circuits are combine in “OR” logic and sent to the latch and relay circuit from where it is hardwired to the power supply-breaker circuit through potential free contacts and optic-optic links. The hardwired logic also detects the coil/winding pack, which has initiated the quench. The voltage signals across each magnet section, during the quench, are recorded in VME based data acquisition system for post analysis.

Multi channel cards had been developed specially for these sensors comprising of individual amplifiers, low pass filters for noise filtering and optical isolation for ground isolation. A real time, stand alone data acquisition system incorporating 448 analog input channels, 16 analog output channels and 128 digital I/O channels has been successfully realized for SST-1 magnet system. As a secondary quench detection other than the redundant voltage taps, transients induced inlet flow reduction measurements through venturimeters is also being implemented in SST-1 magnets.

5. Cooling system for SCMS

In an operational environment such as SST-1, the conductors of SCMS are subjected to various external disturbances, which reduce the operational temperature margin of the conductor. It is therefore, necessary to provide a sufficient cooling for the SCMS. Coolant adopted for all the superconducting coils for the SCMS of SST-1 is forced flow supercritical helium (SHe) at 4 bar and 4.5 K. The source of the coolant is a 650 W/200 l/h refrigerator/liquefier (R/L) supplied by M/s Air Liquide DTA, France as per the SST-1 cryogenic requirement [6]. A cold circulator (CC) has been incorporated with the cold-box of the R/L to maintain a constant flow rate through the SCMS. Based on estimates of the energy margin and operational temperature margin of the CICC, the mass flow rate requirement for the whole magnet system have been estimated [7]. The stability margins in the CICC demand a flow rate of 240 g/s for the TF magnet system. The heat loads on the PF magnet system require a total of 35 g/s mass flow rate through the cooling channels. A total of 300 g/s mass flow rate has been provided.

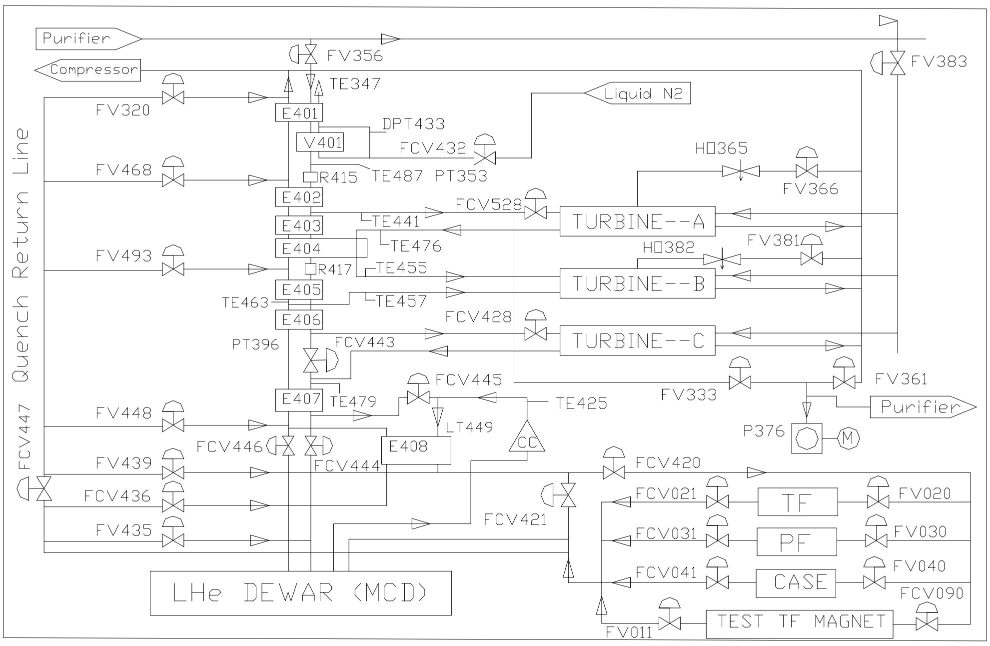

FIG.7. P & ID diagram of the cold box and flow distribution system of SST1 SCMS.

A P & ID diagram of the SCMS cooling system is shown in Fig. 7. The three control valves named as FCV021, FCV031 and FCV041 at the return lines of TF and PF magnet system and TF case system not only maintain the required flow rate in each system during the normal operation of the machine, but also help in controlling the required flow rate in each system according to its heat capacity for simultaneous cool-down of all the coils. During the initial cool-down of the magnet system, the helium temperature at the inlet of the SCMS would be lowered sensing the maximum value from the temperatures sensors placed on the coils/structure, keeping a temperature difference of 50 K to avoid excessive thermal stresses on the magnet.

6. Magnet Power Supplies and Quench Protection for SCMS

The SCMS power supplies (one for TF and one each for each of the PF coils) are twelve-pulse controlled rectifier type. The twelve-pulse rectifier design facilitates for inherently lower dc ripple and mitigated ac line harmonics. TF power supply is continuously rated for 10 kA at 18 V dc. PF coils are also rated for 10 kA at various voltages ranging between 20 V and 140 V dc and can be operated at a maximum duty of 1000 seconds every hour. All power supplies are designed for two-quadrant operation. The current polarity for the power supplies can be reversed by off-load links. All the power supplies are designed and constructed for stable operation within 0.1% of the current set point. High precision, high bandwidth hall-probe based transducers provide the dc current measurement. The coils are isolated from the power supply or earthed to ground bus by suitably rated off-load isolator cum grounding switches during non-operation phase. Necessary interlocks between the mains input breakers, converter transformers, cooling, auxiliaries, off-load switches are included. All monitoring and control are implemented with a standalone mini-PLC in each power supply. An important feature in the power supplies is the controlled bypass, which plays a major role in the inductive current management during faults. Battery backed control voltage sources are provided for the reliable operation of the controlled bypass. Protections for SCMS quench are included in the dc circuit of the TF and PF coils. In the event of quench detection, the dc current in the power supply is commutated to the controlled bypass, which provides a reliable and stable path. The dc circuit is, then opened with on-load mechanical DC breaker and the current is commutated to the dump resistor connected in parallel to the DC breaker. An explosive triggered opening switch (pyro-breaker) is provided as a back up for the mechanical breaker. For both simplicity and reliability, no off-line switches are included in the scheme. Both the dc opening switches are type tested for the parameters including operational duty. The energy dump resistor elements are of stainless steel material assembled in a robust construction for repetitive operations in every hour. During TF dump, the voltage developed across is ± 600 V. The dump resistor has a value of 0.1 Ohm and the dump time constant is 12 s for the TF coils. A schematic of the power supply with quench protection is shown in figure 8.

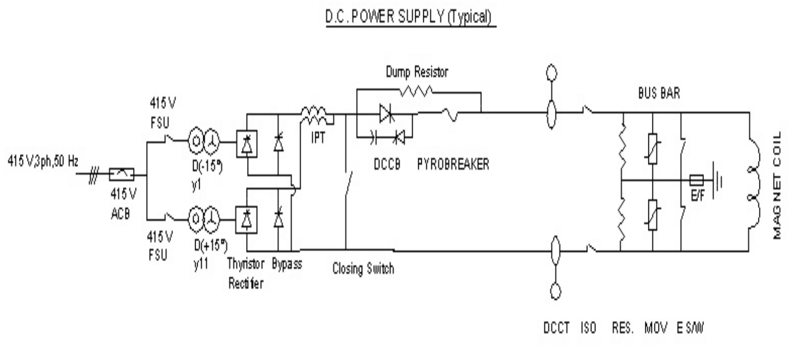

FIG. 8. A schematic of the power supply with quench protection.

Integrated control of the power supplies with tandem control of the SST-1 machine central control is inevitable. The power supply digital controllers are integrated on a PROFIBUS interface. The PLCs are separately integrated on a different PROFIBUS interface. This allows reliability and provide for better bandwidth for the feedback control. The power supply control is centralized on a VME platform RISC processor based computer. This VME-based computer is integrated to the SST-1 machine control by a Reflective Memory bus interface. All the critical communication including the quench event relaying and switching are implemented with optic fiber cables for immunity against EM interference.

7. Summary:

Sixteen superconducting TF and nine PF magnets in SST-1 have been manufactured and assembled. All 228 terminations and 114 low resistance lap joints have been made on the winding packs. Helium hydraulics with supply and return manifolds been integrated with isolators validated up to 5 kV. Magnets have been fully integrated with SST-1 machine. The cryogenic supply to the magnet system has been completely established with the TF winding packs receiving nearly 240 g/s and PF winding packs receiving 30 g/s at 4 bar and 4.5 K through a cold circulator. Magnet system is equipped with 300 voltage taps for quench detection, 173 CERNOX temperature sensors for temperature monitoring, 8 displacement transducers, 19 venturi flow meters and a couple of hall probes. The front end electronics and signal conditioning has been completed. The quench detection is based on subtraction logic. The quench signal is hardwired to the power supply-dump circuit through contact free fiber-optic link. Quench detection circuits also drive the voltage signals across each magnet section to VME data acquisition system for post analysis. A real time, stand alone data acquisition system incorporating 448 analog input channels, 16 analog output channels and 128 digital I/O channels has been successfully realized. Suitable power supplies for the TF and PF systems have been established with their respective dump resistors and redundant circuit breakers. The power supply control is centralized on a VME platform RISC processor based computer and is integrated to the SST-1 machine control by a Reflective Memory bus interface.

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