SST-1 Commissioning and First Plasma Results

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Abstract: The fabrication and assembly of the SST-1 tokamak, has been completed at the Institute for Plasma Research. Commissioning of SST-1 tokamak is currently in progress. A 10 kA DC power supply and associated energy dump system, has been commissioned for the super conducting (SC) toroidal field (TF) magnets of SST-1along with a self-protecting, quench detection system. A DC bus system, with appropriate switches, has been installed and tested for powering the Ohmic and vertical field coils of SST-1 from power supplies of ADITYA tokamak. Remote operation of the system from SST-1 control system has been established. One pair of current leads for operating current of 10 kA at 4.2K has been designed and manufactured indigenously and tested successfully for required ramp rate and steady currents. The leads have been integrated with the TF magnets. The cryogenic systems, at 4.2K and 80K, have been commissioned. The pumping systems for both the cryostat and the vacuum vessel have been installed. After completion of the assembly, initial leak tests and necessary repairs, the cryostat has been pumped down to a base pressure better than 10^{-5} torr. Leak tests in the main vacuum vessel have been completed and welding leaks repaired. Base vacuum better than 10^{-6} torr have been achieved. The thermal shields of the SST-1 have been successfully cooled down to 80K. Subsequently simultaneous cool down of the thermal shields and SC magnets has been achieved. Charging of TF coils is in progress. First phase diagnostics have been installed and the data acquisition and control system have been tested and commissioned. A pair of radially movable poloidal limiters has been installed in the vacuum vessel preparatory to production of circular plasma through Ohmic discharge. The operational experience of cooling down of the thermal shields and SC magnets of SST-1 is presented.

1. Introduction

The assembly of the Steady State Super conducting Tokamak, SST-1 [1], a modest size steady state device devoted to the study of very long pulse (1000 s), elongated, double null divertor plasmas in hydrogen has been completed in first quarter of 2005, and commissioning is in progress. SST-1 is designed to address both physics and technological issues relevant to steady state operation of fusion machines.

SST-1 aims at operating the super conducting magnet system (SCMS) comprising of TF coils in steady state operation, the poloidal field (PF) coils commensurate with the rapid plasma ramp up (~2T/s on the PF conductors), establishing feedback mechanism to stabilize highly elongated and triangular plasmas, sustaining currents in excess of 100 kA by lower hybrid and boot strap effects and active steady state heat removal at first wall with heat flux of the order of 1 MW m^{-2}.

Some of the key physics issues which will be addressed in SST-1 are the energy, impurity and particle confinement studies in long pulse discharges, controlled removal of heat and particles from the divertor region, maintenance of good confinement and stability, control of resistive wall modes in the advanced high beta regimes. The phase I operation of SST-1 shall involve various steps starting with ohmic circular plasmas to full power operation with divertor configuration. In phase IA, circular ohmic plasmas will be investigated. Later phase (IB) will experiment with circular plasmas assisted with LHCD and elongated LHCD plasmas at moderate and full power. In phase-II operation, advanced Tokamak configurations shall be tried out.

2. SST-1 Machine Commissioning

SST-1 has a major radius of 1.1 m, a minor radius of 0.2 m, a toroidal field of 3.0 T at the plasma center and a plasma current of 220 kA. Plasmas with elongation in the range of 1.7-1.9 and triangularity in the range of 0.4-0.7 in a broad spectrum of l_i have been envisaged for this machine. Auxiliary current drive is based on a 1.0 MW LHCD at 3.7 GHz whereas the heating will be accomplished with ICRH (1.0 MW, 22-91 MHz), ECRH (0.2 MW, 84 GHz) and NBI (0.8 MW, 10-80 KeV) [2]. The total incident power at a given time shall, however, not exceed 1.0 MW because of the limits of heat extraction at the first wall system.

A DC bus system, with appropriate switches, has been installed and tested for powering the Ohmic and vertical field coils of SST-1 from power supplies of ADITYA tokamak. Remote operation of the system from SST-1 control system has been established. One pair of current leads for operating current of 10 kA at 4.2K has been designed and manufactured indigenously and tested successfully for required ramp rate and steady currents. The leads have been integrated with the TF magnets. The cryogenic systems, at 4.2K and 80K, have been commissioned. First phase diagnostics have been installed and the data acquisition and control system have been tested and commissioned. A pair of radially movable poloidal limiters has been installed in the vacuum vessel preparatory to production of circular plasma through Ohmic discharge.

2.1. SST-1 Vacuum System:

SST-1 has two vacuum chambers, (i) Vacuum vessel for plasma production and confinement and (ii) Cryostat to provide operational environment to all super conducting magnets. SST-1 vacuum vessel is ultra high vacuum chamber, which can be baked to 525 K by passing hot nitrogen gas through U-channels welded on its inner surface. Cryostat is high vacuum (HV) chamber, which encloses all super conducting toroidal magnetic field (TF) coils, poloidal magnetic field (PF) coils and the vacuum vessel. It is sixteen sided polygonal in shape and has rectangular poloidal cross-section.

For the first phase of SST-1 operation without diverters, vacuum vessel is pumped with two numbers of turbo molecular pumps each having pumping speed of 5000 l/s for air at inlet pressure $\bullet\ 1 \times 10^{-3}$ mbar for air. Net pumping speed achieved with these two pumps at vacuum vessel is 7000 l/s. There are also two numbers of closed cycle cryo pumps each having pumping speed of 10,000 l/s for water vapor and condensable vapors. Cryo pumps give net pumping speed of about 15,000 l/s pumping speed for water vapor at vacuum vessel. There are two fixed anodes mounted on inner surface of vacuum vessel for Glow Discharge Cleaning of vacuum vessel to remove wall impurities. Glow discharge is initiated at about 850 VDC and about 1×10^{-2} mbar pressure of 80 % hydrogen and 20 % helium gas mixture. Glow discharge is sustained at about 350 VDC between anode and wall, 10×10^{-6} Amp/cm^2 current density to wall and pressure of about 8×10^{-4} mbar. Ultimate vacuum achieved in vacuum vessel with two turbo molecular pumps is 8×10^{-7} mbar without baking. This will improve substantially after vacuum vessel baking.

2.2. TF Power supply and protection system:

A 10 kA DC power supply, using thyristor based, phase-controlled rectifiers, has been commissioned for the super conducting (SC) toroidal field (TF) magnets of SST-1. The schematics of the power supply are shown in Figure 1. On detection of quench in the TF coils, the current (and therefore, the coil energy) shall be rapidly discharged through a freewheeling thyristor group, included in the power supply. The TF energy dump system consists of a set of series connected DC circuit breakers (DCCBs) consisting of thyristor arrays with capacitor commutation circuits and a set of resistors across the DCCBs. In addition pyro-breaker are included in series with the DCCBs as second level of protection. Major parameters of the TF system are given in table 1.

The power supply and the energy dump system have been tested and commissioned using DC bus interface with short link before current leads in stable current range of 2-10kA. The tests have been repeated with the current leads (shorted at magnet end) and the DC bus interface. A self-protecting, fail safe quench detection system has been developed and tested.

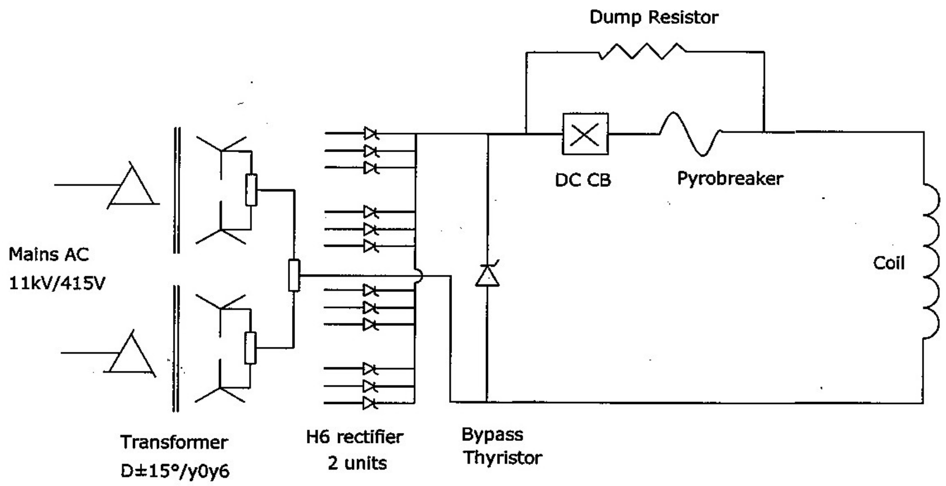

FIG. 1: Schematics of the TF power supply with quench protection system.

Table 1: Parameters of TF system of SST-1

Parameters	Value
Coil Inductance	1.128 H
Circuit Resistance	1.2 m ohm
Natural Time Constant	~1000 s
Maximum Power supply voltage	16 V
Maximum Current	10kA
Stored Energy at 10 kA	56.4 MJ
Fast Dump Time Constant	12 s
Energy dump resistance at operating Temperature	0.094 ohm

3. Current Leads for TF system:

One pair of conventional current leads to supply 10 kA current to TF coils of SST-1 have been designed, fabricated and tested in house [3]. The special features of the leads are simple fabrication techniques, a bottom liquid helium (LHe) can & control valve at the top of each of the leads, making them independent for helium flow control. The lead has LHe consumption rate of 3.9 l/hr/kA/pair with pressure drop of ~5 mbar at 10 kA current. The heat exchanger is a bundle of 35 similar copper rods, each inserted in a concentric tube of SS304L material, to guide the helium flow in the annular space between the rod and the tube. The tubes are kept in position by spacer and the heat exchanger assembly is inserted into a jacket of SS304L having outer diameter of 76 mm. NbTi-based super conducting strands are used to transfer current from rods to the bottom copper flange. The bottom part of the lead is inserted into a jacket having outer diameter of 128 mm and length of 465 mm which acts as LHe can for the lead. The bottom flange has a thick copper plate to transfer current from leads to the bus bars of the magnet. This thick copper plate is bolted with another copper plate into which the super conducting strands of the bus bar are soldered. This joint is covered with the jacket similar to the LHe can, which is fed with supercritical helium (SHe) to cool the joint and the bus bar.

The helium plant [4] meant for SST1 was used to test the pair of current leads and establish the interfacing of controls and logics involved in the operation of helium plant along with current lead. The specially designed cryostat having 900 mm outer diameter and 1800 mm height with LN2 shield and flange for turbo-molecular pump was used. During the testing, two current leads were electrically shorted at the bottom, by use of super conducting strands and these are cooled by conduction to the LHe bath of the lead. Test set-up was equipped with sufficient number of calibrated instruments at strategic locations (Figure 2) to monitor the behavior of the lead. Cool-down of the current lead from 300K to 4.2K is done in a controlled manner along with Master Control Dewar (MCD) of helium plant at an average cooling rate of ~14 K/hr. After cool down phase, liquid level in header is controlled very precisely by inlet valve with active dependency of header level and passive dependency of discrete liquid levels of leads. Header pressure is also controlled with the outlet control valve.

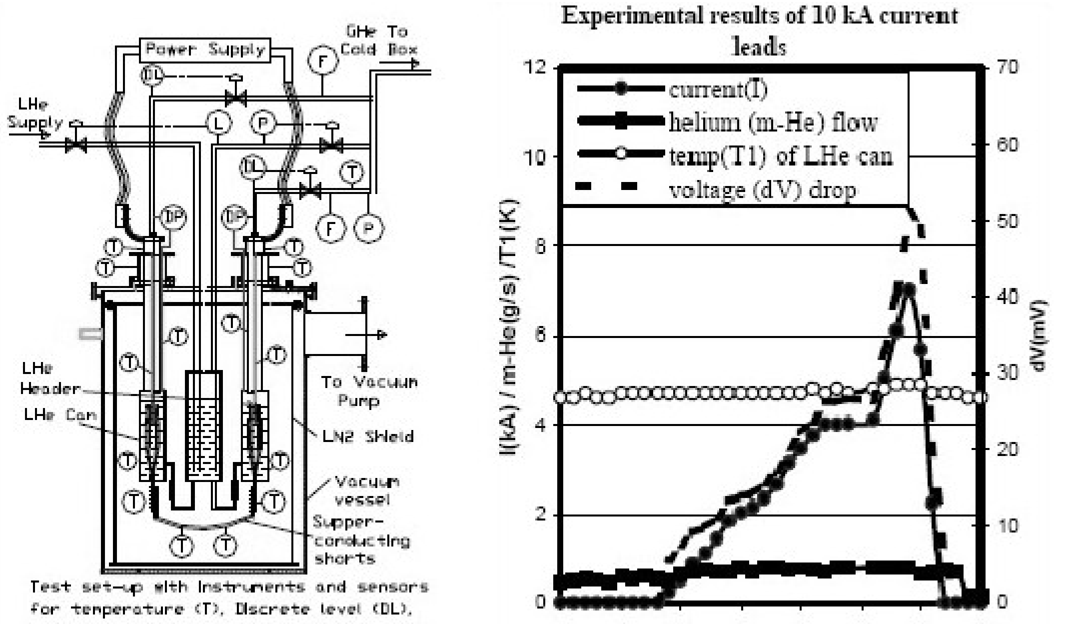

FIG. 2: Schematics of test setup (left) and test results (right) of the current leads for TF Coils

During the testing a very smooth current charging was made upto 7.4 kA. A very good vacuum of 3.8 $\times 10^{-8}$ mbar was achieved in the cryostat showing that current leads and test set-up are highly leak-proof. The ramp-down of the current was done at a very fast rate (~600A/min) to check the suitability of the leads for PF coils, for which current ramping will be done at a faster rate compared to TF coils. During this testing, neither helium flow fluctuation nor increase in helium flow rate was observed ensuring that the leads are robust to sustain the high current ramping. Test results show a higher LHe consumption rate of 5 l/hr/kA/pair compared to the design value of 3.5 l/hr/kA/pair. This is ascribed to the joule heating of the joints at the bottom of the lead and the external radiation heat load coming to the joint and the super conducting strands at the bottom of the leads, estimated to be a total of 3 W per lead. If we exclude this, which will be removed by SHe in real application, the actual consumption of leads comes to be 3.9 l/hr/kA/pair. This value is marginally higher than the design value.

4. Cool down of super conducting magnets

4.1 Cool down scenario of SST-1:

The super conducting magnet system of SST-1 (SCMS), consisting of 35 ton cold mass of toroidal (TF) field coils, poloidal field (PF) coils and support structure has been subjected for cool down along with the helium refrigerator. The fluid from the refrigerator is divided into three supply headers, namely, TF, PF and support structure [5]. The TF header supplies to all sixteen TF coils through the supply sub-headers with equal distribution probability. There are 12 flow paths per coil, each of 48 m length and a flow of 1.25 g/s per path is required. Similarly, the flow paths in PF coils are also divided as per equal flow probability and connected to the PF coil header. Table 2 summarizes the flow coils.

Table 2:Flow rates in PFCoils

Coil Type	No. of Coils	Flow paths/coil	Path length (m)	Flow per Path (g/s)	Total Flow (g/s)
PF1	1	2	109 117	0.90 0.87	1.77
PF2	2	1	113	0.89	1.78
PF3	2	8	67-84	1.19-1.05	17.84
PF4	2	4	113	0.89	7.12
PF5	2	4	130	0.82	6.56

Controlled cool down of SCMS from 300 K to 4.5 K is achieved using the helium refrigerator/liquefier in the normal cool down mode [6]. The SCMS is equipped with more than 100 numbers of temperature sensors at the strategic locations on TF, PF & support structure. The refrigerator operates in a feedback loop with T_{max} from the SCMS and generates T_{min} from the refrigerator for the SCMS inlet. SCMS cool down up to 90 K is achieved using the LN2 heat exchanger of the helium refrigerator, with 15 kW capacity. Automatic setting of the valves with integral time constant controls the gradual cool down of SCMS. Further cool down from 90 K is achieved by authorizing the turbines. The helium refrigerator/liquefier of SST-1 is equipped with two turbines in series and one hyper-critical turbine connected in series with the JT valve.

The thermal shields are cooled with sub-cooled liquid nitrogen. The flow to thermal shield is divided to three parts, namely, cryostat, vacuum vessel and inner cylinder. The inlet control valves control flow division to each path. The thermal shields are also equipped with temperature sensors at many locations in each sub-section. The flow channels in the thermal shield decide the initial flow distribution in each path. The cool down of the thermal shield is started prior to the SCMS cool down. The flow of helium gas at ambient temp is established first in the SCMS. After achieving flow in the SCMS, the cool down of the thermal shield started. Once the average temperature of 250 K is achieved in the thermal shield, order for SCMS cool down is initiated through the logic and then the cool down of both thermal shield and SCMS follows.

4.2. Results and discussion

The first cool down of SST-1 SCMS and thermal shields was started during July 2005. The thermal shield was cool down up to 80 K maintaining the vacuum in cryostat. The temperature in the SCMS was lowered as the thermal shields were cooled, restricting the temperature differential of less than 50K in SCMS. The helium circuits were successfully pumped and purged to achieve a purity level of better then 10 ppm prior to this. Partial vacuum failure was observed in the cryostat at a minimum temperature of 63 K in the SCMS. Leaks have been identification and repaired. A couple of leaks could be attributed to inadequate flexibility for contraction during cool down. Helium circuit has been modified to incorporate additional flexibility during the cool down.

Second cool-down of the thermal shield and SCMS started again during Sept 2006. Figure 3 shows the cool down plot of the thermal shield with time for the thermal intercept (T18), cryostat (T19) and vacuum vessel (T24). It can be seen that gradual cool-down of different segments were achieved within the reasonable time. The temperature distribution on different parts of the thermal shield shows uniformity within the tolerable limit.

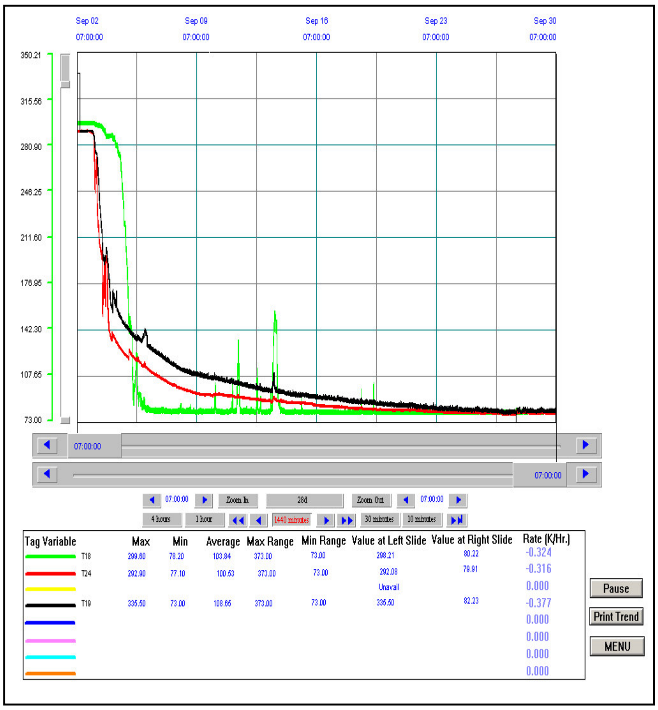

FIG. 3. Cool down plot of the thermal shield
T18: Thermal intercept, T24: Vacuum vessel, T 19: Cryostat

Figure 4 shows the flow distribution scheme of SCMS and different operating parameters. The current lead path was also was simultaneously cooled down along with the SCMS through the main control Dewar of the refrigerator. Figure 5 shows the cool down graph from 300 K to 4.5 K. As shown in figure 5(a) (spikes in temperature value), during cool down few power failures were observed, which led to longer cool down period. The refrigerator has been able take care the disturbance and resumed normal operation with in the estimated time span of 2 to 3 hours. No improper transition was observed in the temperature during the transition from LN2 pre-cooling of helium gas to turbine authorization, which shows stability in the control sequence of the refrigerator. Figure 5(b) shows the temperature distribution in TF coil within the cryostat.

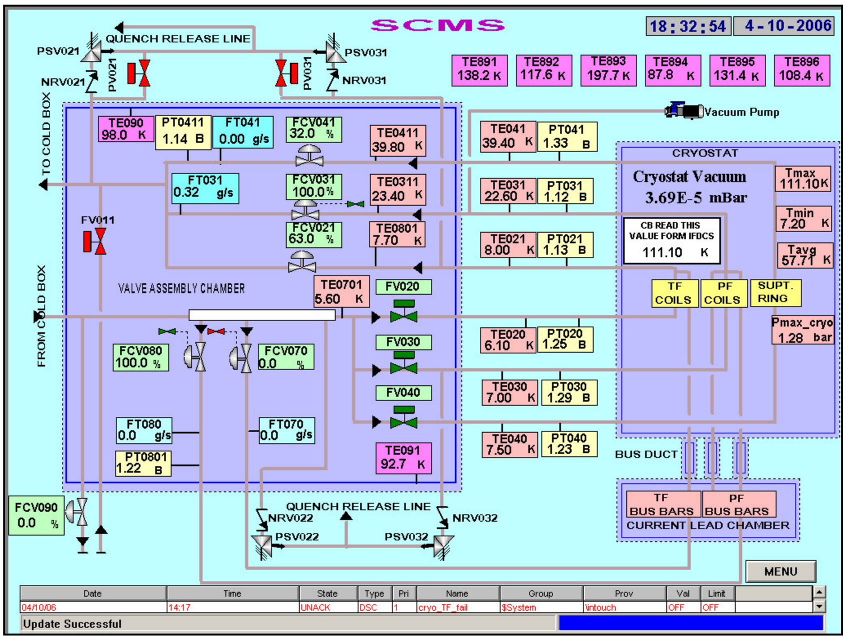

FIG 4. Flow distribution scheme of SST-1

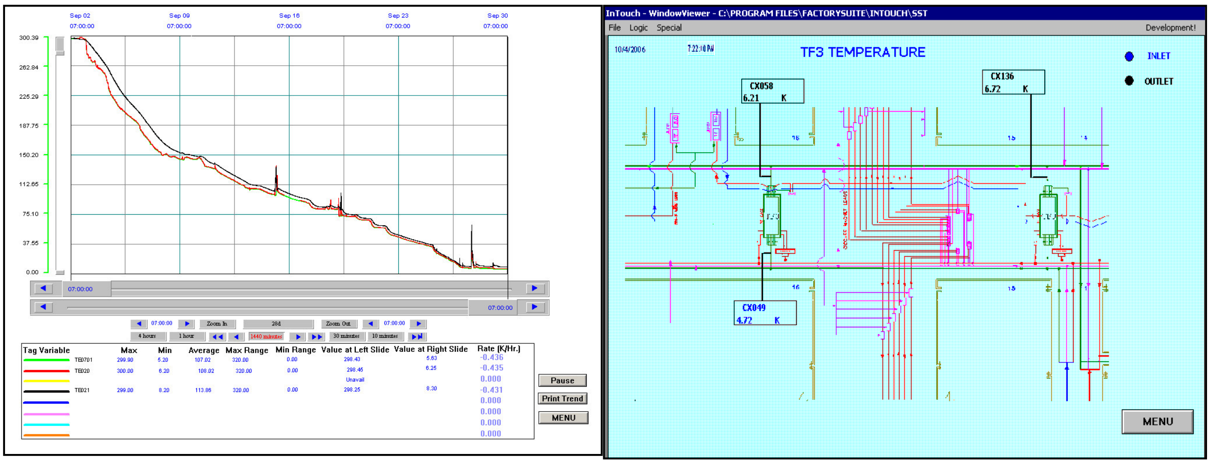

FIG 5(a)Cool down plot of SCMS of SST-1 (b) Typical temperature distribution in TF coil

Figure 6(a) shows the arrangements of one pair of lead connected to the TF coils, a view from the mimic page of the SCADA system. The system is well equipped with the necessary instrumentations, such as, temperature, pressure and flow as well as discrete liquid helium level inside the can of the current leads and voltage taps at different locations. All these instrumentations were considered necessary for operation of the current feeder system. Feedback loops were generated for controlling the valves used to maintain the pressure, differential pressure and flow. Superconducting bus bars were connected from the cold terminal of the current leads to the magnets system. Active cooling of the bus bars is ensured and temperature at the joint location has been monitored out side the housing can of the joint.

Figure 6(b) shows the cool down plot of the TF current feeder system. It can be seen from the plot that smooth cool down in the current feeder system is achieved simultaneously with the SCMS, which shows that the cold power of the refrigerator can be controlled as per the operating mode and pre-defined requirements [7]. Spikes in temperature values are observed due to power failures.

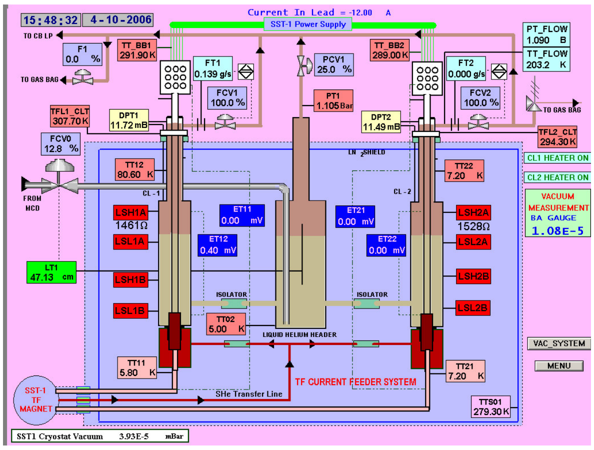

FIG. 6(a) Arrangement for one pair of Current leads in the current feeder system

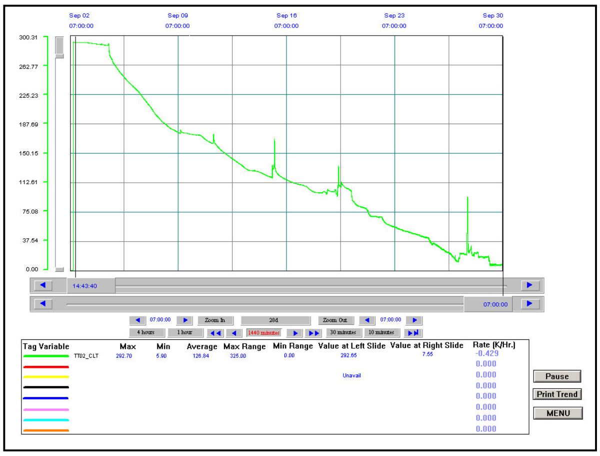

FIG 6(b) Cool down plot of CFS

5. Summary

SST-1 commissioning is in underway. The super conducting magnets have been successfully cooled down to 4.5K. Charging of TF magnets is in progress.

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