First experiments with SST-1 Tokamak

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Abstract: SST-1, a steady state superconducting tokamak, is undergoing commissioning tests at the Institute for Plasma Research. The objectives of SST-1 include studying the physics of the plasma processes in a tokamak under steady state conditions and learning technologies related to the steady state operation of the tokamak. These studies are expected to contribute to the tokamak physics database for very long pulse operations. Superconducting (SC) magnets are deployed for both the toroidal and poloidal field coils in SST-1. An Ohmic transformer is provided for plasma breakdown and initial current ramp up. SST-1 deploys a fully welded ultra high vacuum vessel. Liquid nitrogen cooled radiation shield are deployed between the vacuum vessel and SC magnets as well as SC magnets and cryostat, to minimize the radiation losses at the SC magnets. The auxiliary current drive is based on 1.0 MW of Lower Hybrid current drive (LHCD) at 3.7 GHz. Auxiliary heating systems include 1 MW of Ion Cyclotron Resonance Frequency system (ICRF) at 22 MHz to 91 MHz, 0.2 MW of Electron Cyclotron Resonance heating at 84 GHz and a Neutral Beam Injection (NBI) system with peak power of 0.8 MW (at 80 keV) with variable beam energy in range of 10-80 keV. The ICRF system would also be used for initial breakdown and wall conditioning experiments. Detailed commissioning tests on the cryogenic system and experiments on the hydraulic characters and cool down features of single TF coils have been completed prior to the cool down of the entire superconducting system. Results of the single TF magnet cool down, and testing of the magnet system are presented. First experiments related to the breakdown and the current ramp up will subsequently be carried out.

1. Introduction

Steady State Superconducting Tokamak, SST-1, is a modest size steady state device devoted to the study of very long pulse (1000 s), elongated, double null divertor plasmas in hydrogen [1]. SST-1 has been designed to address both physics and technological issues relevant to steady state operation of fusion machines. 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 are some of the key physics issues which will be addressed in SST-1. Technologically, SST-1 aims at operating the superconducting magnet system (SCMS) comprising of TF coils in steady state operation, the poloidal field (PF) coils commensurate with the rapid plasma ramp up (as high as 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}. 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

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 cross-section of SST-1 is shown in figure 1.

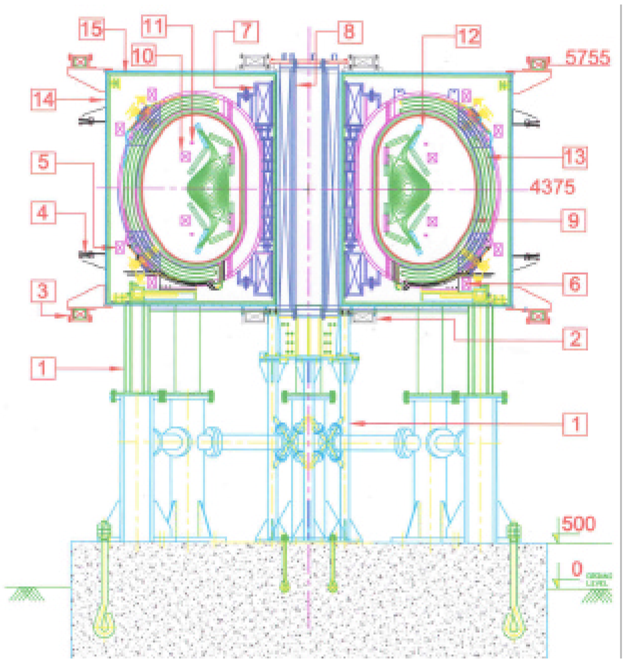

FIG.1 A cross-section of the SST-1 tokamak. (1 -Support Structure; 2-TR2 Coil ; 3-VF Coil; 4 -TR3 Coil; 5-PF5 Coil; 6-PF4 Coil; 7 -PF1, PF2 & PF3 Coils; 8-TR1 Coil; 9-Vacuum Vessel; 10 -PF6 Coil; 11-Feedback Coil; 12-PFC; 13 -TF Coil;14- Cryostat; 15- LN2 Panels)

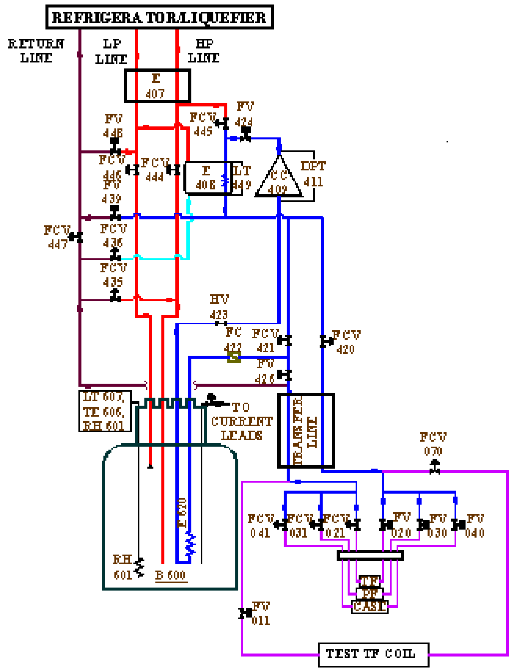

FIG.2. The schematics of the Helium Refrigerator/Liquefier with the integrated flow distribution system.

2.1. Magnet System

The magnet system of SST-1 [3] comprises of both the SCMS and resistive water cooled magnets. The SCMS include the TF coils (16 Number) and PF coils (9 number), while the resistive magnets include one pair of PF coils (PF6) inside the vacuum vessel, an Ohmic transformer, the vertical field coils and position control coils. The SCMS of SST-1 is described in an accompanying paper in this conference [4]. An Ohmic transformer, having a storage capacity of 1.4 Vs, is to be used for plasma start up and initial current ramp up. These coils are made from hollow copper conductors. A pair of vertical field (VF) coils will keep this circular plasma in equilibrium during the initial phase. Vertically elongated plasma is inherently unstable to perturbations in the vertical direction. A set of passive stabilizers, placed inside the vacuum vessel, slow down the growth rate of this vertical instability to. Further stabilization of the instability is provided by active feedback using a pair of coils placed inside the vacuum vessel. PF6 will also be used for radial position control in addition to equilibrium and shaping.

2.2. Cryogenic System

The SCMS during normal operation is maintained at 4.5 K at 4 bar (a) pressure using supercritical helium (SHe). The current leads will be cooled with liquid helium at 4.4 K, 1.2

bar (a). A helium refrigerator/liquefier (HRL) with ≅1 kW capacity (400 W refrigeration and 200 l/h liquefaction) at 4.5 K has been designed, procured, installed and commissioned to meet these requirements [5]. The main components of the HRL are the compressors with oil removal system, an on-line purifier, a cold box, a main control dewar (MCD) and the warm gas management system. Figure 2 shows the over all arrangement of the HRL with the integrated flow distribution and control (IFDC) system for the SHe to the TF and PF coils. There are 3 numbers of compressors, each providing a flow rate of 70 g/s with 14 bar (a) outlet pressure. Three medium pressure (14 bar (a)) storage tanks made of carbon steel & painted inside with anti rust epoxy, each of 68 m^3 inner volume, are used as buffer tanks during the operation of HRL. One storage tank made of SS is exclusively used to store the helium gas coming from the magnet quench. Two storage tanks, at 150 bar (g), each of 25m^3 inner volume are used for the inventory of the helium gas. These tanks are also used to store helium gas coming from various applications using the recovery system comprising of a recovery compressor of capacity 100 Nm^3/h and two gas bags each of 40 m^3 capacity.

The HRL has 7 nos. of heat exchangers and three nos. of turbines, where, first two turbines are connected in series. A cold circulator (CC) capable of providing 300 g/s flow rate at 4 bar (a) has been placed on the down stream of the third turbine. Further down stream of the CC, the IFDC system is used to distribute the required flow to the SCMS. The MCD of 2500 l, is also used to house the heat exchanger, which absorb the transient heat load arising from the SCMS, during PF ramp up-down as well as plasma shots. The HRL has different operating modes like controlled cool down & warm up of the SCMS, maintaining SCMS at 4.5K during tokamak operation, safe handling of the SCMS quench, higher SHe flow rate at higher pressure drop in the SCMS, absorption of high transient heat loads of the SCMS, compressor power saving for lower cooling requirements in standby mode, and operation without liquid nitrogen.

A liquid nitrogen (LN_2) management system has been designed, fabricated, installed and commissioned to take care of the LN_2 requirement. The system consists of 3 nos. of LN_2 storage tanks with 300 m long super-insulated vacuum transfer lines, followed by a phase separator before LN_2 is distributed to sub-systems. All the cryogenic systems have been automated with a SCADA based control system on PLC.

2.3. Vacuum Vessel, Cryostat and Pumping System [6]

The vacuum vessel, an ultra high vacuum system, is a fully welded vessel made from sixteen modules, each module consisting of a vessel sector, an interconnecting ring and three ports. The ring sector sits in the bore of TF coil, while the vessel sector with ports is located between two TF coils. The vessel is made of SS304L material. It has a height of 1.62 m, the mid-plane width of 1.07 m, a total volume of 16 m^3 and a surface area of 75 m^2. The cryostat, is a high vacuum chamber, encloses the vacuum vessel and the SC magnets. It is a sixteen-sided polygon chamber made of SS304L with a volume of 35 m^3 and surface area of 59 m^2. The base pressure inside the cryostat will be maintained at less than $1x10^{-5}$ torr to minimize residual gas conduction losses on the SCMS. Liquid Nitrogen cooled panels (LN_2 panels) are placed between all surfaces having temperature higher than 85K and surfaces at 4.5K to reduce the radiation loads on SC magnets and cold mass support system. The total surface area of all the panels is 126 m^2. Each of the panels is made up of 8 mm diameter tubes, vacuum brazed to a 1 mm thick SS304L sheet. The cooling method is based on latent heat of vaporization. During normal operations 10,000 l/s pumping speed is required to achieve base pressure of less than $1x10^{-8}$ torr in vacuum vessel. Two turbomolecular (TM) pumps, each of

5000 l/s speed, will be used for this purpose. Two closed cycle cryo pumps will be used during wall conditioning of vacuum vessel. The main gas load from vacuum vessel is during steady state plasma operation. Sixteen numbers of TM pumps, each with a pumping speed of 5000 l/s at 10^{-3} torr for hydrogen, are to be connected to sixteen pumping lines on the vacuum vessel. The net speed of each pumping line is estimated to be 3900 l/s. The net pumping speed provided for cryostat using two TM pumps is 10000 l/s. Vacuum vessel and cryostat will be pumped down from atmospheric pressure to 10^{-3} torr using two separate root pumps of 2000 m^3/hr capacity.

2.4. Plasma Facing Components

The PFC of SST-1 [7], comprise of divertors & baffles, poloidal limiters and passive stabilizers. The normal incident peak heat flux on inboard and outboard strike point is 1.6 MW/m^2 and 5.6 MW/m^2 respectively. The poloidal inclination of the outboard divertor plates is adjusted so as to have the average heat flux at the strike point to be less than the allowed limit of 0.6 MW/m^2. The target points of inboard as well as outboard divertor plates have been chosen at a distance as large as practicable from the null point. A baffle has been incorporated in the design so as to form a closed divertor configuration that helps in increasing the neutral pressure in the divertor region. A pair of poloidal limiters is provided to assist plasma breakdown, current ramp-up and current ramp-down and for the protection of RF antennae and other in vessel components during normal operation and during VDEs and disruptions. The outboard limiters are made movable to protect RF antennae. On the inboard side, a safety limiter is placed 30 mm away from the seperatrix. Passive stabilizers comprising of conducting structures surrounding the plasma are provided to reduce the growth rate of the vertical instability. The stabilizers are located close to the plasma to have greater mutual coupling with it when the plasma moves from its equilibrium position. The top and the bottom stabilizers are connected in saddle configuration with a current bridge at the location of this break. The passive stabilizers are designed to handle heat fluxes of 0.25 MW/m^2. Isostatically pressed fine-grain graphite is chosen as the base line armor material for PFC of SST-1 tokamak. The PFCs are actively cooled so as to keep the surface temperature of plasma facing surface less than 1000 ^{0}C. The PFCs are also designed for baking up to 350 ^{0}C.

3. Machine Integration and Assembly

SST-1 machine integration for phase-I operation of SST-1 has the broad objectives of the cool-down of the magnet system along with the cold mass support structure, charging of the magnets and carrying out physics experiments with circular plasmas. Accordingly, the assembly and integration of the entire machine support system, entire magnet system, entire vacuum vessel and cryostats have been completed. Cryogenic system has been integrated. Installation of limiter system and ECRH pre-ionization system would follow very soon. As a strategy definite assembly sequences have been followed. Consequently, tight installation tolerances associated with each of the sub-systems have been possible. Measuring templates, Electronic Co-ordinate Determination System (ECDS) etc have been used to ensure the assembly and integration accuracy. Integration philosophy also incorporated the feasibility of sequential testing of each sub-system, accurate positioning of the components in the radial, toroidal, poloidal and vertical direction to meet the tolerances. These would facilitate proper alignment of the plasma facing components. The machine base frame, comprising of 8 columns and central support structure, has been grouted and the bottom cryostat panel have been integrated with 0.5 mm of planarity along with LN2 panels.

Eight of the vessel sectors have been welded with the interconnecting ring on either side. One such module along with the LN2 panels mounted on it is shown in figure 3. 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. The modules were then sequentially placed on the cantilever beams in the supporting bottom ring, which in turn is freely supported on cold mass support in the outer support columns. The remaining vessel sectors are then assembled in-situ and welded from inside the vessel to form the full vacuum vessel. The vacuum vessel sectors, inter-connecting ring sectors and cryostat panels have been inserted and mounted around the TF coils maintaining a minimum gap of 15 mm between the 4.5 K to 77 K surface and 77 k to 300 K surface. The verticality and perpendicularity of the cases are within 0.3^0. The radial ports have been placed perpendicular to the major axis within 0.1^0 and with a twist less than 0.1^0. The coils have been nosed in the inboard side generating a smooth bore of 1024 mm in diameter (Figure 4). The PF1, PF2 and PF3 coils have been supported on the TF cases with insulation between them. TF cases are fixed at out-board side with OICS both on the bottom and top with insulating bolts. PF-4 and PF-5 are placed on the OICS. A view of the complete assembly of the vessel and TF coils with OICS and LN2 panels is shown in figure 5.

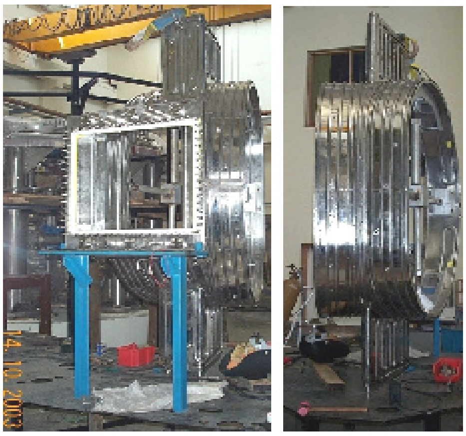

FIG. 3. Views of Vessel Module

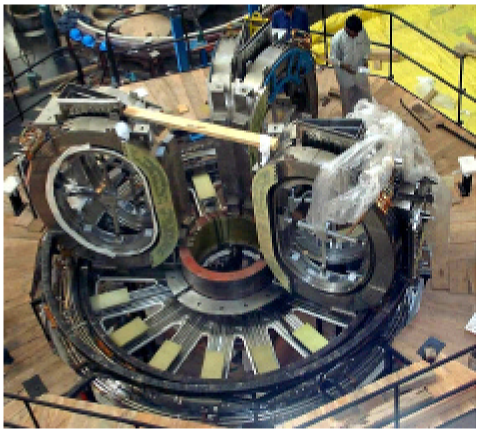

FIG. 4. TF modules on support structure

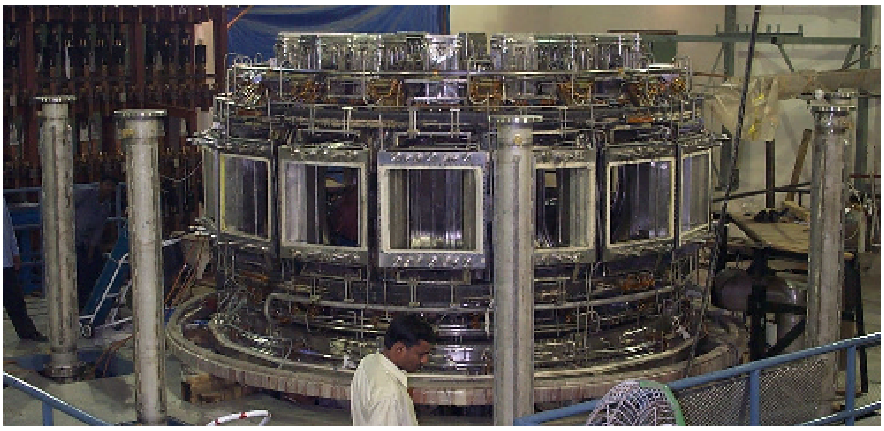

FIG. 5. A view of complete assembly of the SCMS, vacuum vessel and LN2 panels

4. Cryogenic System Performance

The cryogenic system for the SST-1 has been commissioned and is presently under operation for carrying out various tests. Apart from establishing the operating parameters for normal operations, all other operational modes have also been established [8]. Figure 5 shows the refrigeration vs liquefaction capacity of the HRL obtained during commissioning. It is observed that the HRL is optimized as a refrigerator.

During testing it was observed that before starting the CC, it is necessary to cool down the CC cooling loop to 4.5 K temperature, for it's safe control and speed change. Two-phase cooling scheme for the SCMS was tested with 50 g/s flow rate. The heat load (up to 400 W for steady state condition and 600 W for transient state) was supplied by the heater connected to the IFDC. It was observed that process parameters for MCD and associated heat exchangers were within the required value.

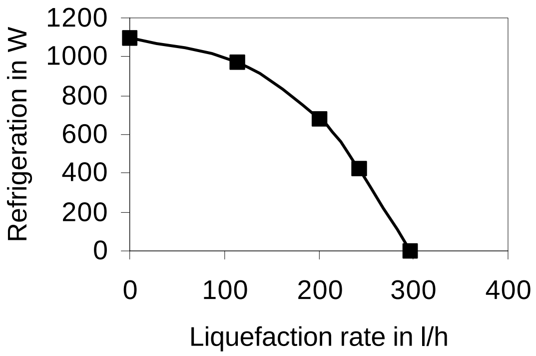

FIG. 6. Liquefaction Vs Refrigeration capacity of the Plant

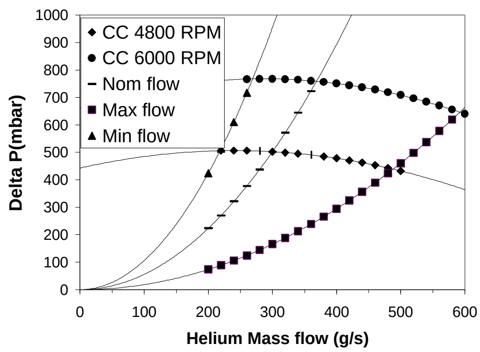

FIG. 7. Characteristics of cold circulator for the different speeds from test data

The CC was operated first by bypassing the IFDC, to find the pumping heat load due to CC for nominal operation. The heat load was found to be 250 W. Subsequently CC was tested with different speed and flow rate through IFDC with it's heater power variation and data are presented in Figure 7. The operating point of CC is found, where these two curves meet. Test data shows that, for nominal flow of 300g/s, the pump can operate at a speed at 80 Hz with pressure head of 500 mbar and 360 g/s at pressure head of about 750 mbar for speed at 100 Hz, which satisfy the design requirement.

5. TF Coil Cool-down Results

In order to validate the cooling configuration of the SSST-1 TF coils, an experiment has been carried out on a spare TF magnet. The TF coil is mounted inside a specially designed cryostat (3 m diameter, 3.2 m height), from the support bars with specially designed hangers on four support columns with thermal break, and hydraulically connected to the HRL through vacuum insulated transfer line and appropriate cryogenic valves for the process flow control. The TF magnet assembly is surrounded by an actively cooled liquid nitrogen (LN_2) shield. Figure 8 shows the assembly of TF magnet in the cryostat on the support bars with hangers. Figure 9 shows the location of the temperature sensors mounted on the hydraulic paths and on the casing of the TF magnet. All the temperature sensors are calibrated CERNOX sensors suitable to measure temperature in the range of 300 K to 4.2 K. Temperature Sensors, designated with tag nos. T1 to T 27 has been placed on the hydraulic inlet/outlet/inter pancake joints as well as on the casing on strategic locations (Figure 9). Two numbers of KELLER make absolute pressure sensors at the inlet and outlet paths have been mounted to monitor the entry and exit pressures of the TF magnet, and the pressure drop across the coil. The total flow across the magnet is measured with a calibrated orifice flow meter.

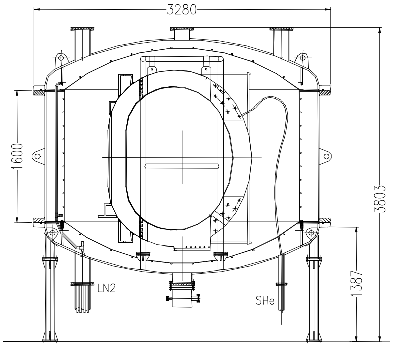

FIG. 8. Schematic diagram of the test set up for TF coil cool down.

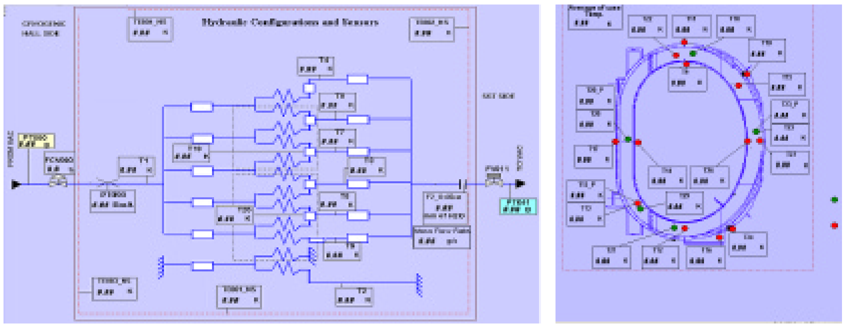

FIG.9. Position of temperature sensors in hydraulic paths (left) and casing (right).

The cryostat along with a 12 m long transfer line is pumped to a base vacuum of $2{\times}10^{-5}$ with the help of 1000 l/s TM pump. The maximum of all the 27 temperature sensors is fed to the control loop as one of the controlling parameter for opening of valve for LN_2 supply.

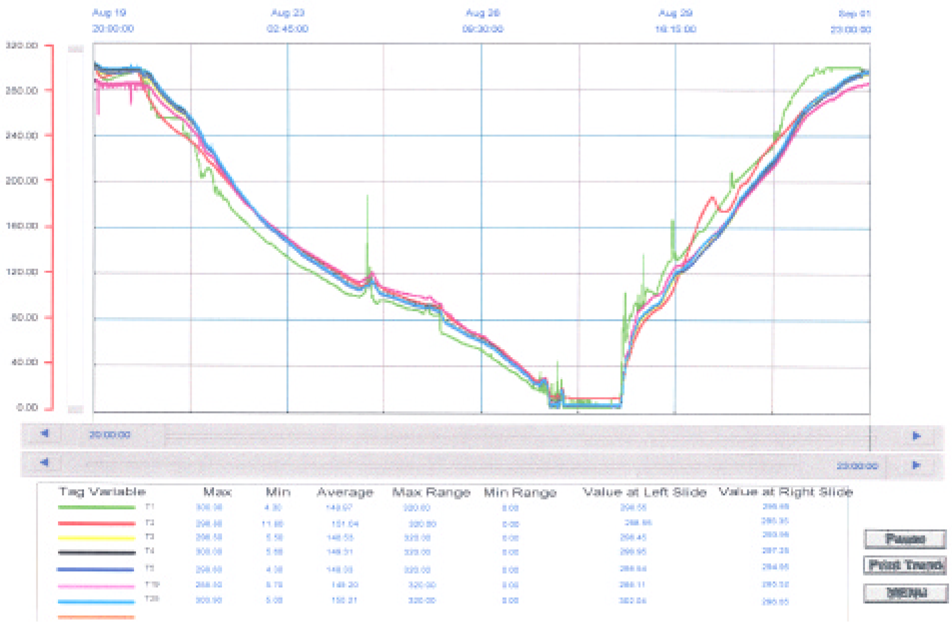

FIG.10. Cool down and warm up curves for the single TF coil

The coil was successfully cool down to 4.5 K with two-phase helium in eight days. It is observed (figure 10) that all temperature sensors at the outlet of the hydraulic path follow the inlet temperature, indicating that the hydraulic path pressure drop are identical and follow the inlet temperature variation. The TF casing is expected to be cooled only by conduction from the winding pack, as active cooling is not provided on the casing. A theoretical simulation cool down was carried out assuming overall distributed contact between the winding pack and casing to be 5 % and 10 % respectively. Experimental results (Figure 11) show that contact between the winding pack and casing is better than 15 %.

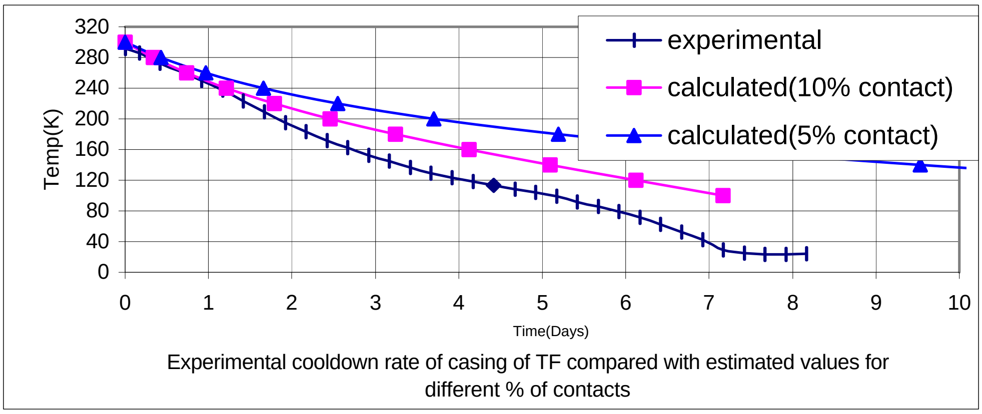

FIG. 11. Rate of cool down of the TF coils (experimental observations and theoretical estimates)

6. Summary

SST-1 is now getting ready for the final stages of assembly for stage IA. The welding of the cryostat plates will be completed in November 2004 and will be immediately followed by its evacuation and the SCMS cool down. Helium refrigerator has been commissioned and tested for its design parameters and operational modes. Cool down characteristics of the TF coil have been studied and hydraulics found to be satisfactory. If the SCMS are commissioned successfully we expect Ohmic Plasma shots in early 2005.

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