# Status of SST-1 Refurbishment

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Steady State Tokamak (SST-1) refurbishment at the Institute for Plasma Research has been recognized and accepted as a Mission activity since Jan 2009 with an ultimate objective of producing the first plasma by the end of 2011. Under the SST-1 Mission mandate, several refurbishment activities have been initiated and pursued vigorously on various sub-systems of SST-1. Developing reliable designs and processes leading to fabrication of leak tight low DC resistance joints, fabrication of bubble type supercritical cooled 80K shields, reliable electrical and thermal isolations amongst various subsystems of SST-1, modular testing of SST-1 machine shell in simulated scenarios, augmentation and reliability establishment in SST-1 vacuum vessel baking system, time synchronization amongst various heterogeneous subsystems of SST-1 etc, are few of the major activities being undertaken. SST-1 machine shell reassembly would begin by December 2009. During SST-1 refurbishment, all TF magnets equipped with sub n-Ω leak tight joints would be cold tested at nominal currents, all the repaired vessel sectors having baking channels would be tested in simulated scenarios, all the 80K thermal shield and 5K TF case shield sectors would be pre-assembly tested apart from some cryogenic lay-outs modification and GPS based time synchronization amongst heterogeneous sub-systems.

Keywords: SST-1 Tokamak, 80 K bubble shields, Leak tight sub n-Ω DC joint resistance, TF case shield, Time synchronization

## 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 (fig. 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.

SST-1 commissioning was attempted in 2006 with the TF magnets being cooled down to 4.5 K at the inlet and 6-8.8 K at the outlet. The helium inlet pressure was 1.8 bar and outlet was 1.3 bar with an over all cryostat pressure of $10^{-4}$ mbar. The helium flow was mostly in two phase flow regime. The SST-1 TF magnets could be charged up to 1000 A in these scenarios. From these attempts, it was evident that some of the subsystems did not perform satisfactorily. Understanding the limitations of these subsystems and rectifying the problems was found essential for successful commissioning of SST-1; especially in its magnet system, thermal shields and vacuum vessel. The limitations were mainly due to the (a) leaks in the cryogenic lines of Nitrogen and Helium circuits

Table 1: SST-1 Machine Parameters

| | |
|---|---|
| Major Radius | 1.1M |
| Minor Radius | 0.2 M |
| Elongation | 1.7-2 |
| Triangularity | 0.4-0.7 |
| Toroidal Field | 3T |
| Plasma Current | 220 kA |
| Aspect Ratio | 5.2 |
| Safety Factor | 3 |
| Average Density | $1{\times}1013cm^{-3}$ |
| Average Temperature | 1.5 keV |
| Plasma Species | Hydrogen |
| Pulse Length | 1000s |
| Configuration | Double Null |
| Heating & Current Drive | |
| Lower Hybrid | 1.0 MW |
| Neutral Beam | 0.8 MW |
| ICRH | 1.0 MW |
| Total Input Power | 1.0 MW |
| Fuelling | Gas Puffing |

(b) Heat loads on the magnets due to higher than expected temperature on the thermal shields. The leakages seen in both Nitrogen and Helium circuits were essential to be arrested and thermal shields were required to reach a temperature of ∼ 80 K for successful commissioning of the SST-1. Leaks present in the joints and termination region of the magnet winding pack as well as in some helium isolators were severely limiting and would not allow either an acceptable cryostat vacuum or operation of the magnets. Attempts with in-situ repair of the leaks with cold curing epoxies or with local repairs could not be feasible. The leaks in the terminations and joints on SST-1 winding packs were primarily in the (a) welding of the SS 304 L conduit with that of the ETP copper terminations on

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its square section interfaces (b) brazing of the SS 304 L helium exit tubes on to the termination with a 0.5 mm step (c) the end copper plates and the copper solder tubes used for solder filling. This dissimilar welding was done in-situ after the solder filling of the termination region in a reduced temperature range of $\sim$ 350 C and hence could possibly having improper fusion of materials as well as tin and other inclusions in the weld region and thereby did not allow a leak proof welding in cold. Similarly, probable improper polymerization and defects in the raw material (G-10) of the isolators as well as their cold bonding with stainless steel ends leaked in few cases. There was a severe pressure drop imbalance and thermal run-away observed amongst parallel nitrogen flow paths primarily caused by the hydraulic impedance mismatches, which could not be controlled. After a thorough review of the issues and problems associated with SST-1, a decision of dismantling SST-1 was taken primarily driven from the distributed nature of the leaks and flow imbalances. It called for new joints and terminations replacing the old ones on the winding pack ensuring (a) leak proofness in operating conditions (4 bar, 4.5 K) and in off normal conditions like quenches (b) DC resistance ensuring $< 5$ n$\Omega$ at 5 K on the fabricated magnets, new leak tight helium and nitrogen isolators in the envisaged strain scenarios, new 80 K thermal shields ensuring flow uniformity and temperature uniformity with acceptable pressure drops across the hydraulic paths, repairing of baking channels welded on the vacuum vessel sectors and modules etc. Further, upon dismantling of SST-1, it was realized that the un-cooled TF cases could be shielded with a bubble type supercritical helium cooled panels against plasma current disruptions and vertical displacement events so that the edge-most pancakes inside the TF winding packs do not get heated up and the magnet operation becomes more reliable. The 80 K system could be cooled with single phase LN2 ensuring better temperature uniformity. Also an in-principle decision was adopted at testing each of the components and sub-systems before they are made assembly ready. It was decided to test all the joints and terminations in cold with the nominal transport currents for their DC resistances and leak tightness, to test all the isolators and manifolds, to test all the sectors of the 80 K thermal shields, to test all the helium cooled thermal shields on the cases, to test all the vacuum vessel sectors and modules having baking channels apart from redesigning the current lead assembly chamber that houses the current leads for better access and ease in installations. The insulation strength of the magnet winding packs in cold with currents in presence of the field, characteristics of the current leads in fast current ramping scenarios as per the SST-1 ramp-up sequences etc would also be validated through dedicated experiments. Augmentations on central machine controls have also been taken up, such as time synchronization between various heterogeneous sub-systems of SST-1 through dedicated GPS based protocols as well as integrated validations of the threshold plasma diagnostics with data acquisitions and triggers in experimentally simulated sources.

All these aspects constitute the refurbishment spectrum of SST-1. The refurbishment tasks thus comprises of redesign/modified design of some selected components and sub-systems, limited engineering and technology trials, processes validations and establishment, precise fabrication with enhanced QA/QC and precision assembly measurements etc. The refurbishment aspects have begun since 2008 and have been recognized and accepted as a Mission starting January 2009.

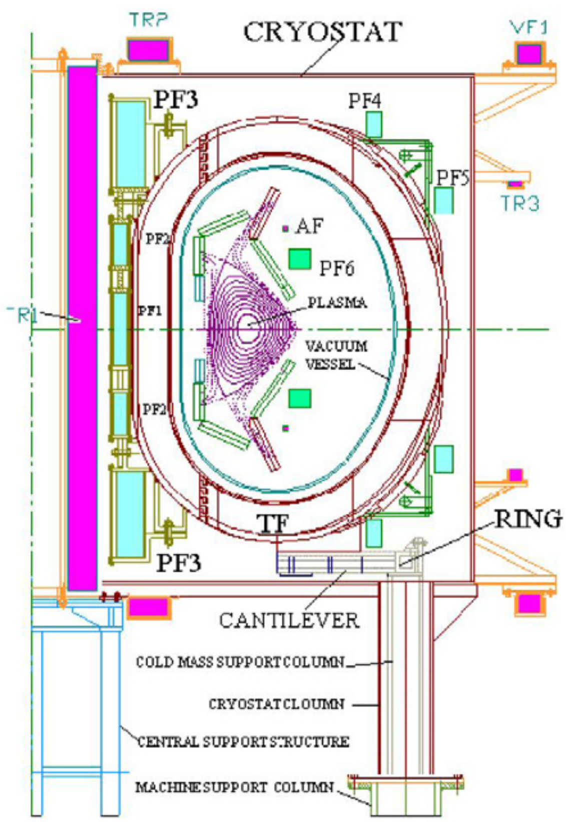


Fig. 1 Cross-sectional view of the Major components of SST-1

Under the mandate of the SST-1 Mission, a $\sim$ 100 kA, limiter assisted circular plasma with superconducting TF magnets & PF Magnets would be realized in the first phase. Plasma breakdown will be accomplished with the available V-s of the Ohmic Transformer (OT) system, the plasma equilibrium shall be maintained with equilibrium field (BV) magnets. The expected plasma duration shall be $\sim$ 300 ms with a TF field of $\sim$ 1.5 T and in q $\sim$ 3. Prior to the first plasma all sixteen assembled series connected TF Magnets shall be tested in supercritical (SHe) flow conditions (4 bar, 4.5 K, 1.25 g/s at inlet) at 10KA of transport current producing 3 T at a major radius of R =1.1 m and 5.1 T on the conductor without any plasma and VV sectors being un-welded but assembled inside the cryostat in a vacuum of $10^{-5}$ mbar or better. As an auxiliary activity, all the Poloidal Field (PF) magnets would be tested in certain reference envisaged operational scenario currents and ramp rates in SHe flow conditions (4 bar, 4.5 K at inlet) and the influence of the reflected voltages on the PF magnets as well as on the power supply shall be investigated, which may lead to measures on over-voltage protection. Elongation of the SST-1 plasma duration, shape and sizes shall be carried out in the subsequent phases. The mission schedule envisages the conclusion of the refurbishment activities by 2011 followed by the test on the assembled magnets and the first plasma.

## 2. Magnet System

The performance objectives of the terminations and joints in SST-1 winding pack must necessarily fulfill the functionality requirements of the magnet system in several operating, normal and off normal scenarios of SST-1. These essential requirements includes guaranteeing the leak tightness of the winding pack during the cool-down and warm up, leak tightness during the charging and nominal operations of the assembled magnets, acceptable resistances of each of the inter-double pancake and inter-coil joints as well as assuring that the joints and terminations being not the weak links (i.e. initial quench zone) at any instances during magnet operation etc. Thus, the new design of the termination and joints in the SST-1 magnet winding pack must respect the existing constraints of the SST-1 machine assembly and build-up as well as must meet the following objectives:

- An assured/tested DC resistance of the joints (inter-double pancake as well as inter-coil) < 5 $n\Omega$ at 5 K with transport current up to 10 kA in the conductor.
- Leaks from any part of the terminations and joints below the detectable limit of the sniffer probe at room temperature with an internal pressure of 12 bar eliminating the probability of any real leaks.
- Integrated leaks from any part of any of the joints in a complete winding pack below the detectable limit of the sniffer probe at room temperature with an internal pressure of 12 bar.
- Integrated leaks from any part of the joints in a complete winding pack below the detectable limit of the sniffer probe at 4.5 K with an internal inlet pressure of 4 bar with SHe flowing inside the winding pack.
- The joints location does not become a region of Initial Quench Zone (IQZ) and thereby does not limit the operational performance of the magnets in the envisaged SST-1 scenarios. The temperature of the joints from the joule heating (caused by the 10 kA DC transport current) as well as from the steady state heat loads (from the 80 K shield) must be at least 1 K below the current sharing temperature (The joint region experience a maximum field of 0.7 T and the current sharing temperature is $\sim$ 8 K)
- The joint fabrication methodology does not degrade the superconducting performance of the winding pack (current carrying ability and stability margin)

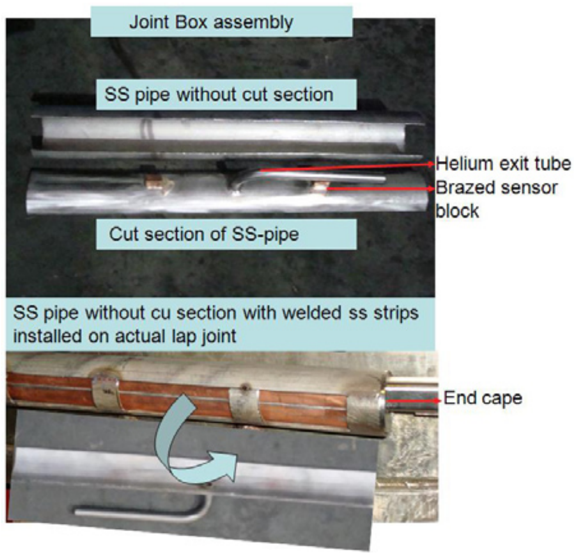


Fig. 2 New Joint Scheme of SST-1

While the first four performance requirements are necessarily to be established quantitatively on each magnet through tests, the last two criteria are required to be ensured through processes and designs. New joints as shown in fig.2 have been successfully validated both in laboratory as well as on a spare TF coil in representative operating conditions. The result obtained on the spare coil is shown in fig.3 indicating resistance of $\sim 0.2 n\Omega$ at $\sim$ 10 kA of transport current with an average temperature of $\sim$ 6 K. The resistance values are repeatable.

At present, with the terminations and joints being fully validated, the fabrication of the terminations and joints on the SST-1 TF winding packs have begun. The SST-1 winding packs are vacuum pressure impregnated and shrunk-fitted into its cases. The helium inlet region as well as the emerging leads regions would insulation strengthened with bisphenol-A epoxy resin and fiber-glass tapes in a specially designed vacuum oven to ensure the winding pack to ground insu-

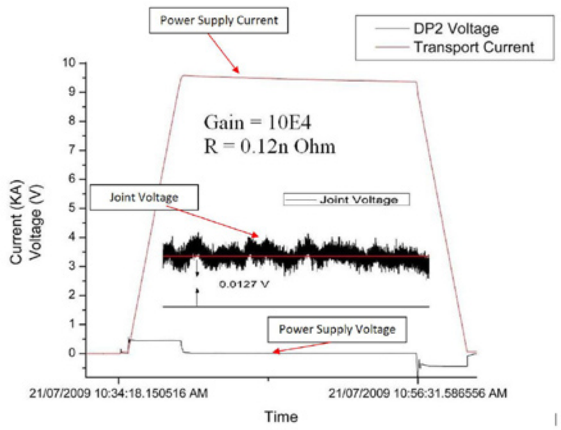


Fig. 3 Voltage Drop in joint box1 During 10KA 1000Sec Shot

lation in excess of several tens of MΩ in cold conditions. This technique was implemented and validated in spare TF coil test campaigns.

A bubble type supercritical helium cooled thermal shield shall be installed in the inner bore of each of the SST-1 TF magnets to reduce the plasma current disruption and VDE induced disturbances and the resultant heating of the edge most pancake. These shields will also reduce the direct radiation from the 80 K shield falling on the high field region of the TF magnets. These shields are 6-8 mm in overall thickness and will be flowing SHe (at 4 bar, 4.5 K) with a nominal mass flow rate of 1 gm/s. The expected temperature rise due to eddy current heating of these panels are below 1 K over all. The electromagnetic forces acting on these panels shall be contained by spot welding these panels on the edges with the casing. The procurement of these panels is currently going on. The quench detection system of SST-1 magnets are continuously being improved and validated with stable reference generator, increase in the counter size, input filter protections, opto-isolation between analog and digital sections and digital driver for driving quench signals etc. The signal conditioning cards are improved with long term offset stability $< \pm$ 1 mV. Temperature measurements are validated for sensitivity better than $\pm$ 0.01K at 4.5K in subsequent spare coil test. Precision low resistance measurements practices have also been validated with several magnet test campaigns repeatedly.

As a strategy, presently the testing of two TF coils together with assembled vacuum vessel sectors and 80 K shield sectors have been planned in the test facility at IPR with the vacuum vessel sectors and thermal shields. Suitable supports would be provided at the joint locations against electromagnetic forces. Accordingly, the test facility has been augmented with appropriate hardware. Such a test would ensure an integrated test such as inter-pancake & inter-coil joint validations and response characteristics of helium plant due to unforeseen events of one octant of the SST-1 as well as would validate the magnet protection system. The first trial on such a test is envisaged in April 2010.

## 3. Vacuum Vessel & First Wall

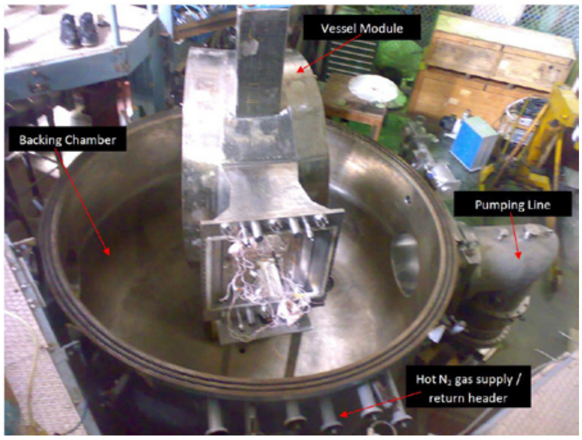


Fig. 4 Vessel Sector assembled in baking facility

Few leaks were observed in the baking channels welded on the vacuum vessel sectors and modules. These leaks have mostly originated due to improper fusion between joint of parent material of the baking channel with that of the vessel. These leaks have been subsequently repaired following a developed and defined process and QA. Each of these vessel sectors shall be tested in representative heating cycles in a specially developed baking facility in vacuum as shown in fig.4. This heating cycle will be carried out with a ramping rate of $50^0C/h$. Average temperature of $150^0C$ will be maintained in the vessel module surface for at least 6hours and then the module will be allowed for natural cool down to room temperature. The objectives of these exercises shall be not only to validate the baking channel repairs but also to experimentally establish the spatial temperature distribution on the vacuum sectors as a result of baking, as well as freezing the baking parameters (i.e. inlet temperature, inlet pressure & flow of the hot nitrogen gas) in representative nominal scenarios. Testing of these vessel modules would begin in Nov 2009 and would end by Jan 2010. The baking of the vessel sector would be carried out up to 150 C for extended duration. The baking facility has already been augmented with appropriate feedback mechanisms and is PLC controlled. The first plasma will be leaning against a movable toroidal limiter system, which has been fabricated and standalone tested. In the first phase of the Mission, no first wall components other than the above are envisaged. The vacuum vessel and the cryostat shall be pumped with two and two numbers of turbo-molecular pumps respectively. The vacuum controls have been automated and monitored remotely in SST-1 vacuum control console through on a PXI platform.

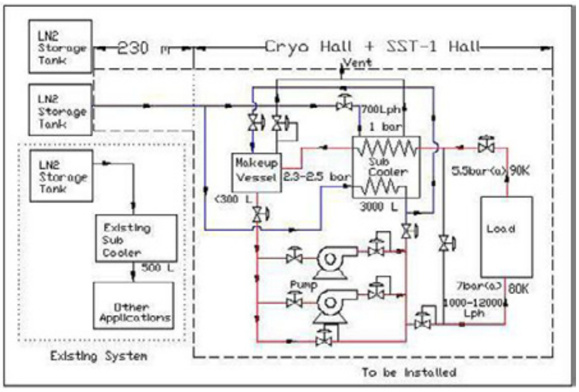


Fig. 5 Conceptual layout with PID of LN2 Booster system

## 4. 80 K thermal shield

Severe flow imbalance as a result of impedance mismatch and spatial temperature non-uniformity was observed on the SST-1 80 K system in the last campaign. The temperature non-uniformity has been planned to be eliminated by employing bubble type construction of the 80 K panels, which will be cooled with liquid nitrogen in single phase at 80 K and 6 bars at the inlet. The single phase nitrogen will be provided through 80 K booster system, which is currently being designed at SST-1 cryogenics hall. The conceptual PID of the booster system is shown in fig.5. This system shall have features of providing variable flow ranging from 2000 lph to 12000 lph with a continuous duty cycle of three months minimum and would be equipped with couple of booster pumps and an auxiliary vessel with heat exchanger and cryogenic valves.

The 80 K thermal shield will be grouped suitably to have equal flow distribution amongst them and would be additionally equipped with control valves. Presently, the thermo-hydraulics of such groups of panels is being carried out after which, the fabrication of these panels would commence with the validation of 1:1 prototypes. The prototype testing is expected in the beginning of 2010.

## 5. Cryogenic System

In the last SST-1 campaign, the magnets were cooled with two phase helium as a result of leaks in the magnet joints, electrical isolators and in the helium and nitrogen circuits since increase in the inlet pressure was resulting a deterioration of the cryostat vacuum. SST-1 helium cryogenics system [3, 4] has a 1.3 kW Helium Refrigerator / Liquefier system capable of providing supercritical helium with a nominal flow rate of 300 g/s at 4 bar, 4.5 K with a cold circulator.The total cold mass of the system is about 35 tons. This requires typical cool down time of about 15 days without any interruption of utility. The temperature difference ($\Delta T$) of $\leq$ 50K is maintained across the inlet and outlet of the magnet system.

The supercritical operation of the SST-1 cryo-

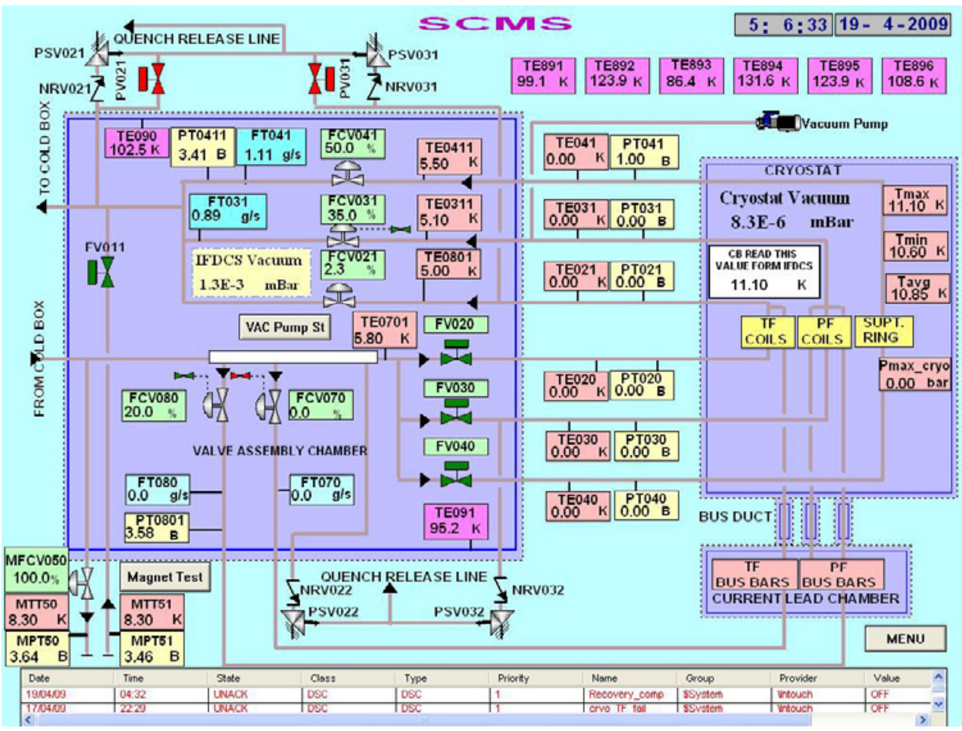


Fig. 6 MIMIC for Supercritical Helium operation with a load as CICC loop

genic system with a load has been demonstrated for long duration exceeding one hour. The mimic of the supercritical operation is shown in fig. 6 and the cold circulator operation is shown in fig.7 respectively. The reliability of the SST-1 cryogenic system for long operations envisaged during repeated SST-1 magnet tests are currently being emphasized. It is planned to use SST-1 cryogenic system for magnet testing up to eight months a year.

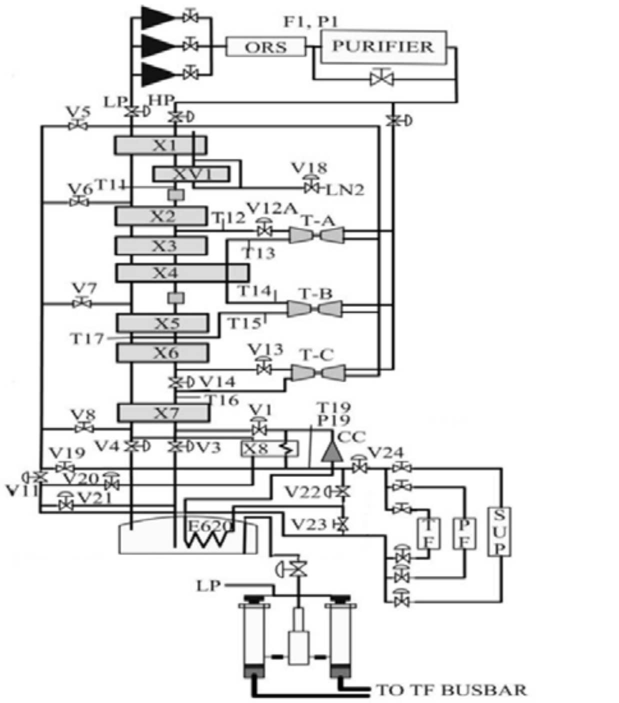


Fig. 7 Flow diagram of Helium Refrigerator / Liquefier system for Cold circulator operation with a load

SST-1 cryogenic recovery system is also being augmented to handle higher outputs envisaged during the combined operation of the SST-1 as well as SST-1 neutral beam systems.

The helium isolators are being procured from IPP, China for the helium circuits. These isolators suitable for operations up to 5 kV at 4 bar, 4.5 K in supercritical helium will be installed in the supply and return manifolds of the SST-1 magnet system and will undergo a detailed QA tests before being integrated. In the manifold design, appropriate flexibility is being provided to cater to the expected thermal contraction and expansions during the cool-down and warm-ups.

## 6. SST Auxiliaries

SST-1 TF magnets were only charged during the last campaign and consequently only pair of current leads was installed in a separate TF current lead chamber near to the SST-1 machine. In the Mission, as stated earlier, poloidal magnets will also be charged in representative start-up scenarios. This necessitates

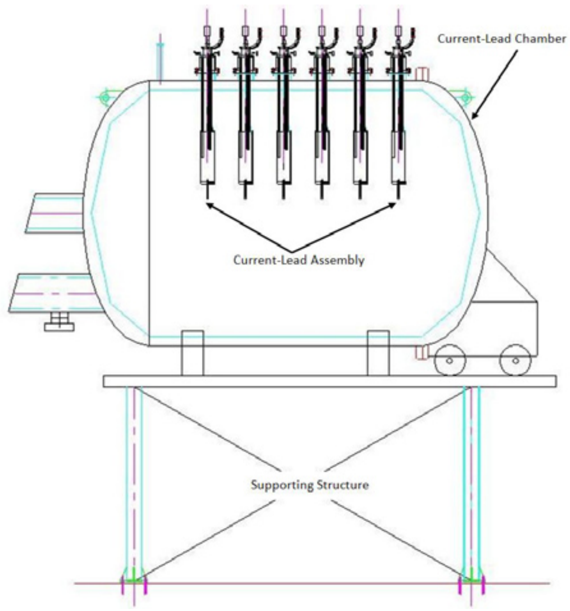


Fig. 8 Current Leads Assembly Chamber

a dedicated current leads assembly chamber with appropriate plumbing for the PF magnets apart from the TF magnets. The current leads assembly chamber (CLAC) has been housed about 10 meters away from the SST-1 machine shell in the SST-1 cryogenic hall. The CLAC cryostat has been modified to be a horizontal mounted chamber as shown in fig.8. The bus-bars from the SST-1 magnet system till the CLAC consists of the SST-1 CICC and are laid inside vacuum chambers with a suitable vacuum barrier isolating the SST-1 cryostat vacuum to that of the CLAC vacuum. These bus-bars being potential break down regions will be suitably insulated with possible conducting screens, if necessary. The bus-bar leads will be terminated below the current leads with sub-divided joints configurations. The CLAC will be equipped with suitable inlet and outlet cryogenic lines for the current leads, baths for containing liquid helium for the current leads, isolators for maintaining electrical isolations between the helium plant and the magnets as well as the gas return lines.

The current leads for the SST-1 TF and PF magnets are conventional type and are indigenously developed. Same current leads shall be employed for TF and PF magnets. The current leads have been tested for representative TF coils charging scenarios as well as for fast charging scenarios of the SST-1 PF coils typical of the start-ups for their design parameters of voltage drops, pressure drops and helium consumptions for each KA of currents as well as for high voltage withstanding ability. A representative result for the 3 KA start-up scenarios is shown in fig. 9. It is planned to test few more pairs of the current leads in a dedicated test facility after which the batch production of the current leads would commence with an established QA.

## 7. SST Control System

SST envisages a central control while being operated where all the essential sub-systems shall be monitored. SST-1 central control has been in place since last campaign. However, various sub-systems of SST-1 operate in various heterogeneous platforms. The SST central control system runs on LINUX whereas the SST-1 Vacuum System is PXI running RT-Labview based with acquisition rate of 1 KHz, SST-1 Magnet System is PXI RT-Labview and VME based with acquisition rate of 1 KHz, SST-1 Power Supply System is VME based on VxWorks with an acquisition rate of 1 KHz and the SST-1 Cryogenic System is SCADA


Fig. 9 3000 A/S Ramp Rate Current and Temperature profile.

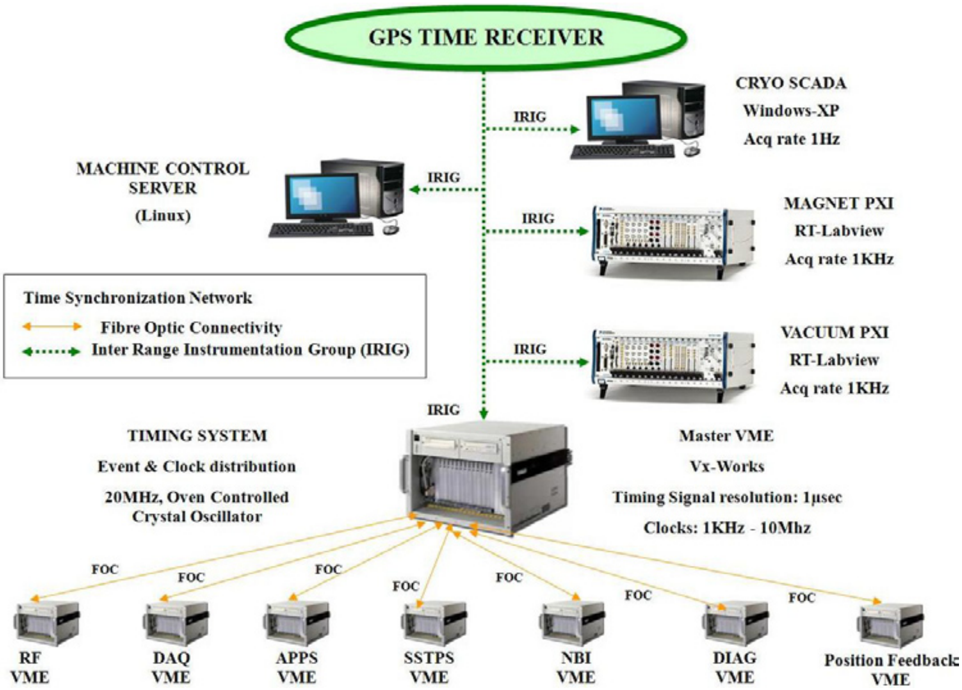


Fig. 10 GPS based Time Synchronization System for SST-1

based with PCs running on Windows XP with an acquisition rate of 1 Hz.

Thus, the time synchronization has become essential right before, during and after the plasma shots between various subsystems. Trials have shown that the time synchronization can be achieved in sub-micro second order amongst various subsystems. Implementation of a GPS based time synchronization system as shown in fig. 10 is currently being done. The reference time for all synchronous and asynchronous events for the plasma shots are derived from a precision crystal oven oscillator. A terabyte level data storage and archival system is also being implemented for the data handling and manipulations purposes.

## 8. SST Data Acquisition System

Several threshold diagnostics have been identified for the SST-1 first plasmas. The SST-1 Data Acquisition System tries to establish communication interfaces amongst the front end signal conditioning and electronics, Data acquisition and Control for automated information exchange during tokamak operation under the over all Central Control. Several integrated diagnostics tests with simulated sources on distributed and laid out signal conditioning, data acquisition modules interfaced with central timing systems have been initiated. In the first phase of the SST-1 Mission plasmas, the electromagnetic diagnostics, soft X-ray diagnostics, Bolometry, Microwave Diagnostics, Spectroscopy diagnostics are the primary diagnostics, which will be employed for the immediate plasma characterizations. At later stages, advance diagnostics shall be employed with elongated and shaped plasmas. A dedicated Network Attached Data Storage Server is being used to store SST-1 Diagnostics data for post shot data analysis.

## 9. SST-1 Power Supplies

SST-1 power supplies (one each for TF and 11 PF coils) are twelve-pulse controlled rectifier type. TF power supply is continuously rated for 10 kA with no load voltage of 18 V dc. This power supply has been tested with spare coil load for extended durations along with VME controls and acquisition. With these operations, the magnet protection system sequence along with the energy dump function has been verified. Critical FO communications between the Magnet System, Cryogenics System, Vacuum System and Power Supply have been validated for prescribed operating scenarios.A typical TF pulse as employed during the spare coil test has been shown in fig. 11. SST-1 PF coils have also been rated for 10 kA at various voltages ranging between 7 V and 160 V dc and can be operated at a maximum duty of 1000 seconds every hour. These power supplies are under integration and

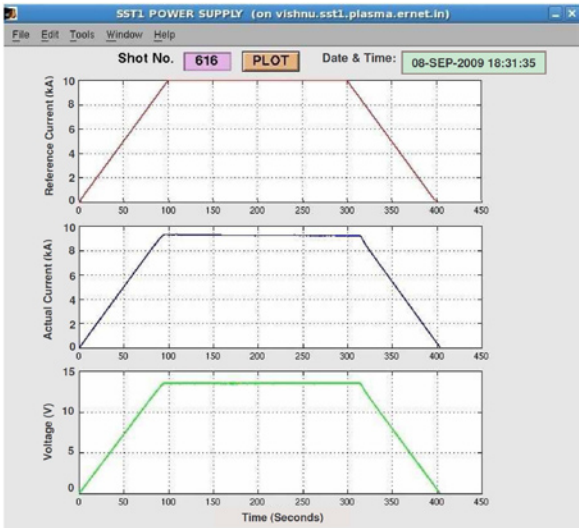


Fig. 11 A 200-sec 10kA pulse with ramp up & down rates @ 10A/sec: (top) reference current, (middle) actual current & (bottom) actual voltage

will be made ready for the SST-1 Mission.

## 10. SST-1 Refurbishment Schedule

SST-1 refurbishment is based on meticulous testing at component level, at sub-system levels at system level before they are integrated onto the machine without compromising the quality but within the existing constraints of using most of the available hardware. The 80 K shield fabrication and prototyping is expected to begin by December 09 as well as the TF thermal screen by Jan 2010. Magnets preparations with new terminations and joints have already been initiated. The commencement of the test activities with a pair of TF coils, intervening vacuum sectors together with 80 K shield components is envisaged by April 2010 with baking channels validations in the baking facility being completed earlier. The reassembly activities of the SST-1 are expected to begin from Dec 2009 onwards for a period of twenty four months. Cool-down of the magnet system and commissioning activities are expected soon after that by end of 2011 and would be followed with first plasma soon after.

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