IAEA-CN-94/FT/2-2

Test Results on Systems Developed for SST-1 Tokamak

D. Bora, and SST-1 TEAM

Institute for Plasma Research,
Bhat, Gandhinagar 382 428, INDIA

e-mail: dbora@ipr.res.in

Abstract. Steady state Superconducting Tokamak (SST-1) is a large aspect ratio tokamak, configured to run double null diverted plasmas with significant elongation (κ) and triangularity Superconducting (SC) magnets are deployed for both the toroidal and poloidal field coils in SST-1. A NbTi based cable-in-conduit conductor (CICC) has been fabricated by M/S Hitachi Cables Ltd., Japan under specification and supervision of IPR. The suitability of this CICC for the SST-1 magnets has been validated through test carried out on a model coil (MC) wound from this CICC. Toroidal and poloidal SC magnets have been fabricated and factory acceptance tests have been performed. SC magnets require liquid helium (LHe) cooled current leads, electrical isolators at LHe temperature, superconducting bus bars and LHe transfer lines. Full scale prototypes of these have been developed and tested successfully. SC magnets will be cooled to 4.5K by forced flow of supercritical Helium through the CICC. A 1 kW grade liquefier/refrigerator has been installed and is in final stages of commissioning at IPR. SST-1 deploys a fully welded ultra high vacuum vessel, made up of 16 vessel sectors having ports and 16 rings with D-shaped cross-section. To establish the fabrication methodology for this, a fullscale proto-type of the vessel with two vessel sectors and three rings has been fabricated and tested successfully. Based on this the fabrication of the vessel sectors and rings is in final stage of fabrication. 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. SST-1 will have three different high power radio frequency (RF) systems to additionally heat and non-inductively drive plasma current to sustain the plasma in steady state for a duration of up to 1000 sec. Ion cyclotron resonance frequency (ICRF) and electron cyclotron resonance frequency (ECRF) systems will primarily be used for heating the plasma while lower hybrid waves will be used for non inductive current drive (LHCD). A Neutral Beam Injection (NBI) with peak power of 0.8 MW with variable beam energy in range of 10-80 keV will be used as additional auxiliary heating system. A number of proto-types for various critical components have confirmed the fabrication methodology. The fabrication of most of the subsystems is nearing completion and many components have already been accepted at site. Erection and installation of the base of the mechanical structure has already been initiated in the SST hall. This paper reports on the results of the tests on various prototypes and actual components to be used on SST-1 for various subsystems.

1. Introduction

A steady state superconducting tokamak SST-1 [1] is being fabricated at the Institute for Plasma Research (IPR), with the objectives of studying physics of plasma processes in tokamak under steady state conditions and to learn technologies related to the steady state operation of the tokamak. SST-1 is a large aspect ratio tokamak, configured to run double null diverted plasmas with significant elongation (κ) and triangularity (δ). The machine has a major radius of 1.1 m, minor radius of 0.20 m, a toroidal field of 3.0 T at plasma center and a plasma current of 220 kA. Elongated plasma with elongation in the range of 1.7 to 1.9 and triangularity in the range of 0.4 to 0.7 will be produced. Hydrogen gas will be used and plasma discharge duration will be 1000 s.

2. SST-1 Machine

2.1 Superconducting coils

Superconducting (SC) magnets are deployed for both the toroidal and poloidal field coils in SST-1. A NbTi based cable-in-conduit conductor (CICC) has been fabricated by M/S Hitachi

Cables Ltd., Japan and the suitability of this CICC for the SST-1 magnets has been validated [2] through tests carried out on a model coil (MC) wound from this CICC. With Supercritical Helium mass flow rate of 1 g/s through the CICC, the MC coil is successfully charged up to 12 kA. A ramp rate of 2 T/s up to current of 6 kA is also achieved.

The MC is designed [3] for a maximum flux density to current ratio similar to that in TF winding pack of SST-1 (10 kA @ 5 T). The MC consists of double pancakes with total number of Ampere-turn close to the SST-1 PF-3 magnet and hydraulic length close to that in SST-1 windings (i.e. to 47 m). It has been observed that the CICC in MC can be charged without any quench at least up to 12 kA even at minimum mass flow rate (0.5 g/s). The magnetic flux density exceeds 6.2 T along at least 1.2 m length of CICC in the MC, as against 10 kA (5.1 T over 0.7 m length) operation of TF magnets at 1.4 g/s in SST-1.

TAB. I: SST-1 DISRUPTION VALIDATION ON MODEL COIL

	L_{dist}(m)	Δt_{dist}(ms)	$\dot{m}_{path}$ (g/s)	$(\Delta B_{\|\|})_{peak}$(T)	$\langle \Delta B_{\|\|} \rangle_{L_{dist}}$ (T)
SST-1 TF	0.7	10	1.4	0.27	0.23
MC	1.2	10	0.85-1.2	> 0.29	> 0.29

It is evident from TAB. I that the SST-1 CICC, in wound condition can comfortably withstand the SST-1 plasma disruption induced transients in excess of I_p = 330 kA ($\Delta B_{||}$ =0.27 T) (*FIG. 1*).

MC withstands sinusoidal (125 ms period) disturbances of any orientation (i.e either longitudinally applied or transverse applied) with amplitude larger than 25 mT. The Model Coil could withstand a total deposited energy of 200 kJ without quenching as against the expected energy deposit of 50 kJ during the 1000 s plasma event due to feedback coil induced disturbances.

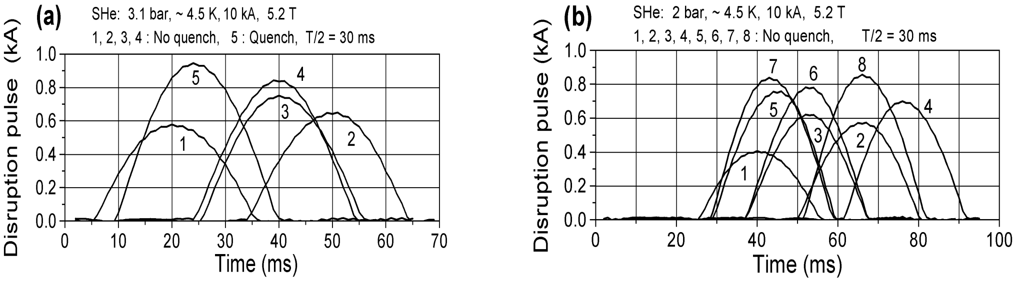

FIG. 1. Transient Stability against disruption (a): for dm/dt = 0.85 g/s (b): for dm/dt=1.2 g/s.

The possibility of 2 T/s (5 kA/s) ramp rate in MC is demonstrated at helium mass flow rates larger than 0.8-0.9 g/s. Further increase of the mass flow rate does not result in the critical ramp rate increase. The SST-1 CICC is thus found suitable for SST-1 start-up scenarios. All the field coils have been fabricated and the inter pancake joints are being finalized at site for the TF coils already received at site.

2.2 Vacuum Vessel

SST-1 has two vacuum chambers, (i) Vacuum vessel for plasma production and confinement and (ii) Cryostat to provide operational environment to all superconducting magnets. Vacuum vessel is made of sixteen modules to maintain modularity with sixteen Toroidal magnetic

Field (TF) coils. Poloidal cross-section of the vessel is close to 'D' shape. Vacuum vessel is fabricated from SS 304 L material due to its obvious advantages for UHV systems and high mechanical strength to withstand large forces acting on it. Vacuum vessel will be baked up to 525 K by passing hot nitrogen gas at mass flow rate of 0.712 Kg/s at 5 bar through the U - channels welded on its inner surface. Cryostat is toroidally continuous sixteen sided polygonal vacuum chamber which encloses vacuum vessel and all superconducting magnets. It was essential to establish all fabrication techniques, manufacturing of appropriate tools and fixtures, detail inspection / testing stages and procedures etc.; before commencing the fabrication of main vacuum vessel and cryostat. For this 45° toroidally continuous full scale prototype vacuum vessel and cryostat have been successfully fabricated and tested for its functional parameters.

D - Shaped poloidal cross-section of vessel sector is formed by rolling the plate with different radii and pressing at straight sections. Final angle of 22.5° is machined between two faces of vessel sector using CNC machined angle fixture. Each vessel sector has one radial port and two vertical (top/bottom) ports. The radial port is a rectangular box in construction. 3-D curvature is required on side plates to match with (a) poloidal curvature of vessel sector and inter connecting ring and (b) changing radial port opening. Side plates are hot pressed using a special die and punch tool to meet these requirements.

Wire seal made of soft UHV compatible metals like aluminium and copper will be used in SST-1 leak rate 1×10^{-9} mbarl/s after baking at 250° C as shown vacuum vessel. Detailed test experiments have been carried out to find out required force per unit length to achieve in *FIG. 2*.

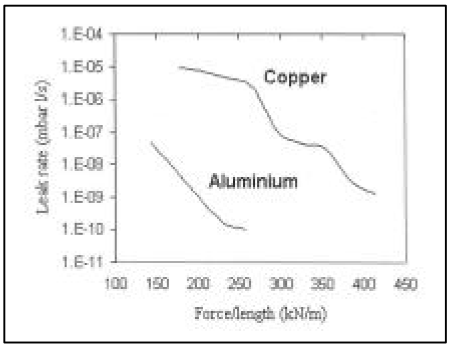

FIG. 2: Average helium leak rate against per unit length for triangular wire seal

Superconducting coils operating at 4.5 K will be protected against thermal radiation from hot surfaces using liquid nitrogen cooled panels. These panels will be maintained by passing liquid nitrogen at a rate of 1200 liters/hour. A technique to braze SS 304L flattened tube with 2.0 mm thick SS 304 sheet has been established by fabricating one triangular panel of about 1.2 meter height and 0.4 meter base for cryostat bottom plate.

Cryostat along with the vacuum vessel components is being fabricated. Assembly and integration of the machine would begin soon on the support structure that has been already erected at site.

2.3 First Wall

Plasma Facing Components (PFC), one of the sub-systems of SST-1, are under various stages of fabrication. PFC consisting of divertors, passive stabilisers, baffles and limiters are designed for long pulse operation. The immediate consequence of long pulse operation on PFC is the problem of heat removal Considering the technologies and resources at our command, we designed the PFC with a steady state heat removal capability of 1.0 MW/m^2. This corresponds to a maximum input power of about 1.0 MW. A design based on the mechanical attachment of the graphite tiles to the copper alloy heat sink back-plates is adopted for the PFC.

Heat removal capability of such plasma facing components is studied on a test mock-up using a 8 KW CO_2 laser beam as heat source. The test mock-up consists of graphite tiles having 100 w/mk thermal conductivity. Different samples of graphite tiles of appropriate size are mechanically attached to copper alloy back plate using stainless steel fasteners. One k-type thermocouple is used to measure tile temperature 5 mm below its heat receiving surface. Two immersion thermometers, one each at inlet and outlet are used for calorimetric measurements.

TAB. II: DETAILS OF PROTO-TYPE EXPERIMENT

	Parameter	Experiment-1	Experiment-2
1	Graphite Tile Size (mm^3)	50×50×25mm^3 (#A)	50×50×25mm^3 (#B)
2	Graphite Thermal Conductivity ($k_{@R.T.}$)	100 W/mK @R.T.	100 W/mK @R.T.
3	Torque on M6 size SS-Bolt (N.m)	4.0 N.m	4.0 N.m
4	Flexible Graphite Thickness (mm)	0.7mm (#C)	0.2mm (#D)
5	Flow rate of water @R.T.(≈22^{o}C) through rectangular (8×6 mm^2) groove in copper back-plate on which graphite tiles are mounted.	700 LPH	700 LPH
6	Incident heat energy measured by Calorimetry (CO_2 Laser Power Meter)	4.3kW (4.6 kW)	4.3kW (4.6 kW)
7	*Heat Flux on 50mm diameter area*	*2.2 MW/m^2*	*2.2 MW/m^2*
8	Temp. measured by K-type thermocouple at *5mm below* graphite surface.	500^{o}C	500^{o}C
9	Calculated temperature at graphite surface [Assume $k_{@1000C} = 0.5\times k_{@R.T.}$]	715^{o}C	715^{o}C
NOTE: #A & #B : CGW grade graphite tiles from *UCAR Carbon*, USA. #C : 0.7mm tick GRAFOIL grade flexible graphite from *UCAR Carbon*, USA. #D : 0.2mm thick flexible graphite from *Graphite India Limited*, INDIA.			

The CO_2 laser beam is focused so as to occupy maximum area on a single graphite tile and its power is gradually increased till temperature measured by the thermocouple reaches 500^0 C. It is observed that graphite tiles of test mock-up could withstand several cycles of 2 MW/m^2 heat flux with time period of each cycle greater than ten minutes. The time period is limited by the laser source. Table II gives experimental details and results obtained. The study indicates that the plasma facing components of SST-1 could withstand the expected steady state heat flux.

One of the important aspects of the fabrication of the PFC is the process of brazing the SS tube on the copper alloy heat sink and regaining the mechanical and physical properties after the brazing. Vacuum leak tests (out-gassing tests) have been carried out at room temperature and at 250^o C on some brazed samples of CuCrZr and SS304L. The out-gassing rates obtained were 1.06×10^{-9} mbar.l/sec.cm^2 and 6.94×10^{-11} mbar.l/sec.cm^2 respectively and samples have been approved from the out-gassing point of view. Base plates and graphite tiles are being fabricated along with the support structure for the PFC. Movable poloidal limiter, its support with accessories etc., has already been fabricated and tested.

2.4 Cryogenic system

SC magnets will be cooled to 4.5K by forced flow of supercritical Helium through the CICC. The magnets require liquid helium (LHe) cooled current leads, electrical isolators at LHe temperature, superconducting bus bars and LHe transfer lines. Full scale prototypes of these have been developed and tested successfully.

Isolators have been designed and tested for the operating temperatures in the range of 300 K to 4.2 K, operating pressure of 4.0 bar (Normal) and to withstand quench pressure of 40 bar. They are designed to have a leak rate of $\leq 10^{-8}$ torr.lt/sec and to provide electrical isolation of 5 KV.

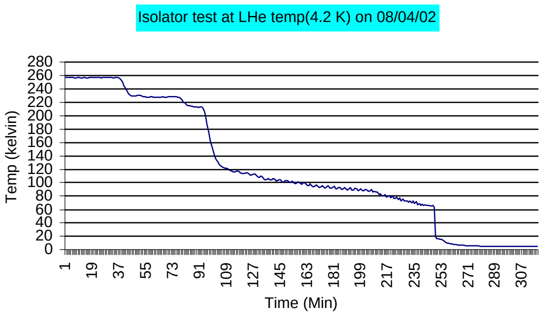

FIG. 3. Cool down curve for the electrical isolator/liquid helium feed through

Typical cool down curve during one of the test is represented in *FIG. 3*. Helium vapor cooled current leads have also been designed and developed for interfacing the power supply at room temperature. The basic design involves parallel plate heat exchanger consisting of 11 nos. of Zr – Cu plates for each current lead. One pair of current leads has been assembled inside a specially designed cryostat with liquid nitrogen shield. No abnormal distortions have been observed during cool down. The result shows that there is an agreement on the numerically calculated data at the low temperature end for 30 % of the length. The evaporation rate at zero, 1 KA and 2 KA current has been measured as 55 lpm, 78 lpm and 120 lpm respectively. A 3-m long CICC based bus bar having straight configuration has been designed and developed to carry out required performance tests.

A fully automatic closed cycle 1 KW class He refrigerator/liquefier, with a capacity of 400 W refrigeration at 4.5K and 200 l/hr liquefaction equipped with a cold circulation pump has been manufactured and erected at site by M/S Air Liquide, DTA, France. All the three compressors along with the oil removal system have been commissioned. Tests have been conducted on the compressors with 100 % load on the slide valve at high pressure set point of 14 bar and low pressure set point of 1.05 bar. The suction and discharge temperatures have been 30^o C and 78-80^o C respectively. The flow achieved for each compressor are 76 g/s, 74 g/s and 66 g/s respectively. The full flow on–line purifier has also been commissioned in the on-line mode. The first test with 60g/s of Helium gas with 70 ppm of N_2 impurity at the inlet has resulted in a 0 ppm impurity level at the outlet. 1200 l of liquid helium has been produced as part of the commissioning tests. The full load tests on the plant will be carried out in near future.

3. High power RF Systems

3.1 Ion Cyclotron Resonance Frequency (ICRF) System

ICRF system would operate at 1.5 MW for 1000 sec operation in a range between 22.0 to 91.0 MHz to accommodate various heating schemes, Fast Wave current drive at 1.5 T and at 3.0 T operation of SST-1 as well as for initial breakdown and wall conditioning experiments. Two high power generators are being developed in house. Frequency is tunable from 20 MHz to 45.6 MHz for the first one while the second is a fixed frequency generator at 91.2 MHz.

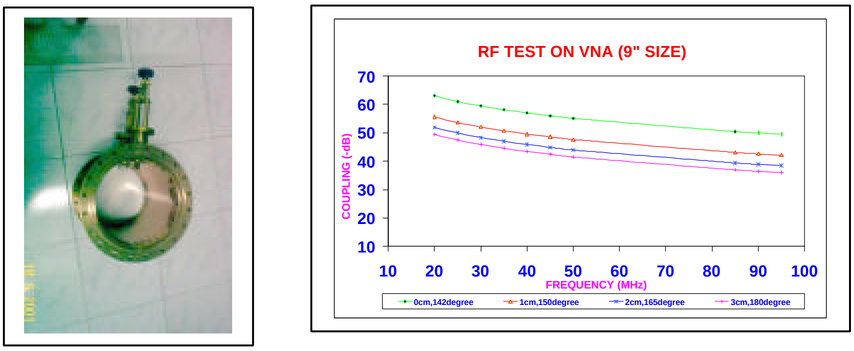

FIG. 4. Directional coupler and its RF characteristics

High power transmission line components have been designed, fabricated and tested for high power CW operation on a test stand before integration to SST-1 ICRF system. The inner conductor for the transmission line and all other coaxial components are water cooled by DM water with required flow and pressure. The interface components in UHV environment are cooled by introducing DM water in an annular region between the inner conductor and the tube carrying the inlet water placed inside it. Indigenously built CW high power (200 kW stage) RF generator with all required controls has been successfully tested on a 50 Ohm dummy load. Output of 200 kW stage is connected to 1.5 MW dummy load through SPDT switch, directional coupler, gas barrier, 90^0 Mitre type bend and 9 inch to 6 inch reducer. Reflection coefficient for all the above cases is measured as less than 1%. Gas barrier made of teflon interfacing has been developed for 3 bar gauge pressure and tested successfully. High power directional coupler with its RF characteristics at different frequencies is shown in *FIG. 4*. RF characteristics have been successfully measured for the first water cooled antenna. All main components for transmission line section are tested for high power continuous wave and integration to the main system has been initiated.

3.2 Lower Hybrid Current Drive (LHCD) System

LHCD system is being prepared at 3.7 GHz [4]. The system is based on two 500 kW, CW Klystrons with four outputs. Power at these arms are further divided successively to sixty four channels which then finally delivers the power to a grill type window positioned at the equatorial plane on a radial port at the low field side of SST-1. High power CW tests of the indigenously designed and fabricated components along with other high power components are conducted in a test bench built around one of the klystrons.

It consists of DC-Break, Isolator, Directional couplers, Device under test followed by a water cooled dummy load. All the components have been actively cooled and pressurised to 3 bar. Components have been tested at a power level of *50kW*. Apart from other components, the indigenously developed components like *dummy-loads*, *waveguide-transformers*, *waveguide-bends*, *narrow-waveguides*, *radiation tight conducting seals* have been tested at the above power level. S11 parameter of the dummy load is measured at –44 dB. The electrical field profiles have been optimized using *Ansoft Software* by appropriately positioning the inductive post in the dummy load.

The antenna of the LHCD system consists of 64 non-standard narrow waveguide (7 mm x 76 mm) channels, requiring a same number of waveguide transformers to couple from the standard WR 284 transmission line. These transformers have been designed and tested at high power. The thickness of each step has been optimized using *Ansoft Software* for best performance. The S11 parameter is measured as –23dB while S12 is measured as –0.07 dB.
In order to prevent radiation leak and any possible arcing, conducting gaskets have been developed and tested for radiation leak.

High power components have been fabricated and tested for compatibility. Erection of the support structure has been initiated.

3.3 Electron Cyclotron Resonance Frequency (ECRF) System

ECRF system is based on a 200 kW, CW gyrotron at 82.6 GHz. Beam launching systems have been designed, fabricated and tested for microwave compatibility for radial and top launch. The launchers (low field side and high field side) have one focusing mirror and one plane mirror. The focal length of LFS launch mirror is 575mm while the focal length of the HFS launch mirror is 563mm.

The beam launching systems for the radial and top launch have been fabricated and tested for ultra high vacuum compatibility. Both the launchers are tested for leak rate better than $1x10^{-9}$ mbar.lt/s. The hydrostatic pressure test of the system is done for more than 3bar in vacuum condition. Profiles of the mirrors are checked on curvature coordinate measurement machine.

Microwave characterization is done for both the ECRH launchers. The profiles of the beam pattern at locations equal to plasma center are shown in *FIG. 5* and *6*. The 1/eth of the beam pattern for the LFS launch is experimentally measured as ~25mm at these locations.

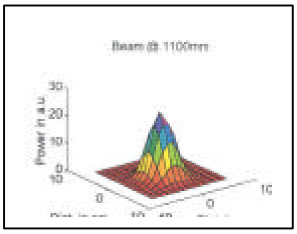

FIG. 5. Beam Pattern for LFS launcher

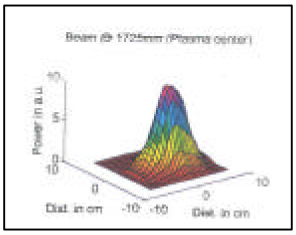

FIG.6. Beam Pattern for HFS launcher

4. Neutral Beam Injection (NBI) System

A Neutral Beam Injection (NBI) with peak power of 0.8 MW with variable beam energy in range of 10-80 keV [5] will be used as additional auxiliary heating system. The engineering designs have been completed and a number of proto-types for various critical components are under development to establish the fabrication methodology. Quantified results have been obtained in many of the prototyping activities.

Notable among them is the successful performance demonstration of the country's first indigenously designed, engineered and fabricated cryocondensation pump for a pumping efficiency of 10^5 l/s for D_2 at 4.2 K LHe temperature yielding a specific pumping speed of ~ 7 l/s/cm^2. Results from other prototypes have been equally encouraging; these include successful testing of electroforming of OFHC copper on a similar base; development, manufacture and tests of 80kV compact post insulator; dis-similar material jointing between the heat Cu-Cr-Zr and SS 316 l by explosive bonding and vacuum brazing for the fabrication of heat transfer elements (H T E).

Similar achievements have been registered in the larger systems that include the design, fabrication and installation of the country's largest rectangular (~ 20 m^3) vacuum vessel (*FIG. 7*); design, development and testing of 26 units of 160 V / 100 A discharge power supplies with fast turn On and turn Off AC-DC converters; development of VXI based data acquisition system; development of 16 channel multiplexer cards for the 700 channels of data acquisition; fabrication and testing of a computer controlled movement system for the neutral beam power dump.

FIG.7. Rectangular Vacuum Vessel

5.Conclusion

In conclusion, most of the components of SST-1,namely, the cryostat and the vacuum vessel have been successfully prototyped and tested. Various other subsystems like different magnetic field coils, PFC have been, fabricated and in the process of erection and commissioning at site. Support structure for the cryostat and vacuum vessel has been commissioned. Different components of the auxiliary heating and current drive systems have also been fabricated and tested. The systems would be integrated to the machine after the machine shell commissioning is over.

6. References

[1] SAXENA, Y.C., SST-1 Team, Present Status of the SST-1 project, Nucl. Fusion, **40**, (2000), 1069.

[2] HOSONO, F., et al, Performance of Cable-in-Conduit Conductors for SST-1 at IPR, Hitachi Cable Review, **20** (Aug 2001), 101.

[3] PRADHAN, S., et al, `Cable-in-Conduit Conductor for SST-1 Superconducting Magnets', 2nd IAEA Technical Committee Meeting on Steady State operation of Magnetic Fusion Devices,_ Fukuoka, Japan, **2**, (1999), 482.

[4] BORA. D., et al., Fusion Engineering and Design, **56-57** (2001) 575.

[5] CHAKRABORTY., A. K., et al., in Fusion Technology (Proc. 19th Symp. Lisbon, 1996), Elsevier, Amsterdam and New York, (1996), 657.