High-vacuum compatibility tests of SST-1 superconducting magnets

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Abstract. SST-1 Tokamak is under commissioning at Institute for Plasma Research in mission mode. It comprises of a toroidal doughnut shaped plasma chamber, surrounded by liquid helium cooled superconducting magnets and LN$_2$ thermal shields, housed inside the cryostat chamber. The superconducting magnet system of SST-1 consists of toroidal field (TF) magnets and poloidal field (PF) magnets and will be operated at internal supercritical helium pressure of 4.5 bar (a) under very low temperature of 4.5 K and carrying a DC current of 10 kA. High-vacuum compatibility up to low-pressure $\leq 1 \times 10^{-5}$ mbar is one of the most essential features of these superconducting magnets in order to avoid the heat losses due to conduction and convection. This paper describes the extensive tests carried out under representative conditions to ensure the high-vacuum compatibility of the SST-1 magnets before assembly to the main system.

1. Introduction

Steady state Superconducting (SST-1) Tokamak [1, 2] is in refurbishment state at Institute for Plasma Research (IPR) for Double Null configuration plasma discharge. This double null configuration is provided by the magnet system. Magnet system is one of the main subsystems of SST-1 and it consists of sixteen (16) superconducting D-shaped Toroidal Field (TF) coils and nine (09) superconducting Poloidal Field (PF) coils [3] together with a pair (02) of resistive PF coils. The TF magnets are designed to generate 3.0 T field at the major radius of 1.1 m while the PF magnets are meant for the plasma equilibria with wide range of elongation and triangularity. The base conductor for these magnets is an NbTi based cable-in-conduit conductor (CICC) [4, 5]. The CICC consists of 135 NbTi/Cu strands of 0.86 mm diameter each, with a high copper to superconductor ratio of $\geq 4.9$: 1. These strands are twisted in four stages before being jacketed inside a conduit made of stainless steel having a cross-section of 14.8 mm $\times$ 14.8 mm and a void fraction of 40 % inside the cable space for liquid helium to flow. The entire magnet systems are cooled with supercritical helium at 4 bar (a) and 4.5 K, which is fed at the high field region in the middle of each of the double pancake over a hydraulic path length of 47 m.

Each TF coil is made up of six (06) double pancakes, each pancake having nine turns. The complete double pancakes winding pack is shrunk fitted into a stainless steel (SS 316L) casing, which supports most of the electromagnetic loads. For cool down of casing, each TF coil is also fitted with 5 K bubble type thermal shield. Figure 1 shows a 3D model of a pair of TF coils along with some associated components and hydraulics. Due to such pancake configuration, six numbers of low
resistance lap inter-pancake joints within and inter-coil joints between the coils are made for current transportation. These joints are fabricated by inserting unconduited cable of each double pancake into a hollow copper block and by filling silver solder (95Sn-05Ag) in the voids between inserted cable and copper termination block. Two adjacent such prepared cable terminations are joined by 0.1 mm thick soft solder (60Sn-40Pb) layer to form a joint. This coil joint is jacketed using especially joint boxes made of SS 304 L. The schematic of these joint boxes along with weld joint locations is shown in the figure 2.

**Figure 1.** 3D model of a pair of TF coils along with some associated components and hydraulics

**Figure 2.** Schematic of the CICC joint boxes along with weld joint locations
The entire SST-1 TF coils system has such 96 numbers of such joint boxes enclosing the superconducting transition joints. These transition joints with such a large numbers of SS to SS welding are forced flow cooled and are exposed to thermal stresses during cool down to 4.5 K and electromagnetic stresses during 10 kA current charging. Hence these weld joints have to be rigorously tested and qualified for the leak tightness both at RT and cold conditions before taken for assembly into the tokamak as there is almost zero accessibility after assembly.

Since these TF coils are connected electrically in series and each of them are fed separately for cool down, their inlets and outlets are electrically isolated from liquid helium supply and return headers using isolator manifolds. Each TF coil has 02 numbers of isolator manifolds containing 06 numbers of isolators each as shown figure 3. There are 32 pairs of isolator manifolds. Isolators used here are fabricated using specially grade G-10 materials, SS 304 L tube and epoxy. During cool down of TF coils and operation at 10 kA, each manifold assembly, figure 3 and joint boxes will be subjected to very high thermal as well as electrical stresses. Due to dissimilar materials presence in isolators, these are more prone towards the leak development. Here also these manifolds joints along with isolators have to be rigorously tested and qualified for the leak tightness both at RT and cold conditions before taken for assembly into TF coils.

![Isolator manifold consisting of 6 numbers of isolators](image)

Since the vacuum < $1.0 \times 10^{-5}$ mbar inside the cryostat is basic criterion in order to prevent any shot of discharge occurring during charging of TF coils at 10 kA apart from other concerns, so each and every weld joints has to be qualified for the leak tightness individually as well as at their operational conditions below certain defined values.

## 2. Experimental set-up and procedure

A dedicated ultra-high-vacuum (HV) chamber of 2.4 meter diameter and 3.5 meter height is fabricated from SS 304 L material for testing all 16 numbers of TF coils. Due to very larger dimension, double O-ring configuration is utilized along with inter-space pumping in order to ensure the better leak tightness. Since these TF coils are cool down to 4.5 K, copper thermal shields are used in between TF coil and test chamber inner surface. Also a proper fixture arrangement is done in order to sustain the forces due to charging of TF coils at 10 KA current.

For roughing, two numbers of rotary pumps are connected, each having a pumping speed of 120 m$^3$/hr. For high vacuum, one turbo-molecular pump of 5000 l/s pumping speed ($N_2$ equivalent) is connected to the chamber with effective pumping speed of 2300 l/s. Due to very high magnetic field...
produced during the charging, the pumping system is mounted at far location where the magnetic field value was < 5 mT as per pump specification in order to avoid the pump failure. To measure the vacuum inside the chamber, two numbers of BA gauges were mounted. One is mounted at the bottom port of the test chamber while other is mounted nearer to pump so that during charging of TF coil this gauge could be used for vacuum measurement. Also one MKS RGA is mounted at the bottom port of the chamber. The entire pumping system and vacuum DATA acquisition is remotely operated using PXI based system which has both the software and hardware interlocks for any un-eventual failures. The schematic of the test facility is shown in the figure 4.

At the component level, 5 K panels, individual isolators and isolator manifolds are leak tested before and after thermal shock at the background < 5.0 \times 10^{-9} \text{ mbar l/s} for their initial qualifications. Then these components are mounted to the TF coils followed with other diagnostics. TF coil as an assembly then leak tested in the vacuum mode at the background < 5.0 \times 10^{-9} \text{ mbar l/s} and then leak tested in sniffer mode at the background < 1.0 \times 10^{-6} \text{ mbar l/s} with internal helium pressure of 12.5 bar (g). Then TF coil assembly was inserted into the test chamber as shown in the figure 5. Pumping of the test chamber was carried out and after achieving the vacuum < 1.0 \times 10^{-4} \text{ mbar}, cool down of TF coil assembly was started at the rate of 5-6 K/hr. The vacuum inside chamber during the entire cool down and during the charging of one of the TC coil is shown in the figure 6. During cool down, it is observed that as soon TF coil reaches below 273.15 K, water vapor gets condensed and at \leq 63 \text{ K}, a sudden vacuum improvement is observed indicating the cryo-condensation of nitrogen gas. Also the test chamber vacuum along with TF coil temperature status during the magnet charging is shown in the figure 7 where the magnetic field effects on the vacuum gauge is clearly seen.
3. Results

After achieving a pressure $< 1.0 \times 10^{-4}$ mbar in the chamber, RGA scan is taken to see the status of leak tightness of the TF coil by pressurizing it with helium at an internal pressure of 12.5 bar (g) at room temperature. Then, after the leak tightness is ensured, the cool down of the TF coil is started by passing liquid helium. RGA scans are taken time to time throughout the cool down up to 4.5 K, to ensure the leak tightness of the TF coil. The scans are also taken after the charging of the TF coil and during warm up of the TF coil. After warm up, the TF coil is tested for its leak integrity.

Figure 8 shows the RGA scans before and after the passing of current in a leak-tight TF coil, both showing negligible $(\sim 1.3 \times 10^{-10}$ mbar) partial pressure of helium (yellow graph).
Figure 8. RGA scans before and after passing of current in a leak-tight TF Coil

Figure 9 shows the RGA scans before and after the passing of current in a TF coil in which a leak developed in the helium circuit during the passing of current through it. The scans show a rise in the partial pressure of helium (yellow graph) from ~ $1.0 \times 10^{-11}$ mbar to up to ~ $5.0 \times 10^{-9}$ mbar.

Figure 9. RGA scans before and after passing of current in a TF Coil in which a leak developed during passing of current

In this particular coil, the helium leak testing by sniffer method at room temperature and 12.5 bar (g) internal helium pressure revealed that a leak of $1.0 \times 10^{-4}$ mbar l/ sec had developed in the edge of the CICC of a winding pack.

4. Conclusion
The probability of leak development in the weld joints of TF coils and 5 K thermal shields are eliminated ensuring leak tightness of the system at RT and at their operating conditions. Also the helium isolators which are the most venerable to leaks in cold are ensured for leak tightness.

References
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