

Upgradation plans of SST-1 Cryogenics system at IPR

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Abstract. Steady State Superconducting Tokamak (SST-1) is India's First Superconducting Tokamak and has Toroidal Field (TF) and Poloidal Field (PF) superconducting coils along with the cold mass support structure weighing about 38 ton of cold mass. A 1.3 kW Helium refrigeration and liquefaction (HRL) at 4.5 K along with its distribution network facilitates the cooling down of the cold mass and cryo-stable operation of SST-1TF magnets. SST-1 experimental campaigns have revealed that the existing HRL is just sufficient for the heat loads acting on it. Further, the SST-1 PF magnets require a higher pressure head and mass flow rate than the nominal values on account of the longer paths of some of the PF magnets. In order to make SST-1 being fully superconducting device, we are introducing superconducting central solenoid (CS). Detailed estimates have been made and it has been found that an additional ~ 900 W at 4.5 K of cryo power is required towards (i) cooling all the PF magnets (ii) the cooling down and the operation of a new Nb₃Sn based CS of SST-1. This paper will elaborate on (i) the experimental heat loads acting on the cryo system (ii) the 'thermal runaway amongst the PF magnets observed in the SST-1 campaign' (iii) the robust need of a higher operation pressure up to 2.1 bar (a) (iv) the need of the flow optimizations as per the hydraulic paths (v) the engineering solutions at each of these described (i)-(v) above.

1. Introduction

Several SST-1 cool-down experiments have been carried out for plasma campaigns. The SST-1 has sixteen toroidal field (TF) and nine poloidal field (PF) superconducting coils using NbTi superconductor. The PF coils have non-uniform hydraulic path lengths in the range of 67 m – 130 m. A 1.3 kW at 4.5 K helium refrigerator / liquefier (HRL) system is responsible to cool the TF, PF coils and cold mass support structure at 4.5 K [1]. Experimental data on magnets system have shown that the PF coils (Hydraulic path lengths of 67 m – 130 m) demand more than three times higher pressure head as compared to the TF coils (Hydraulic path length of 48 m) at lower temperature (15 K – 25 K). Till 2014, "Thermal run-away" situation observed amongst the PF coils, as there was only single common control valve for all the PF coils in the return path of distribution having non-uniform lengths. As a part of SST-1 up gradation activities, the PF hydraulic distribution system modified and branched into three groups having uniform path lengths for better control. To cool PF coils and to keep it in superconducting state, additional cold capacity of 450 W at 4.5 K is required [2]. In order to make SST-1 fully superconducting tokamak, Nb₃Sn based superconducting central solenoid (CS) is planned. The heat load for the CS is estimated based on physical sizing, distribution and a pair of current leads. This will demand cooling capacity of about 275 W at 4.5 K. To support the higher pressure head requirement on to the PF coils system, we need to provide the single phase sub-cooled helium at 2.7 bar (a) at 4.5 K. This has been deduced from the inlet and outlet conditions of the helium at rated flow rate of ~ 38 g/s in a single phase considering 100 mbar pressure drop across the heat-exchanger. An additional cold capacity of 175 W is needed to facilitate sub-cooled operation as shown in figure 1.



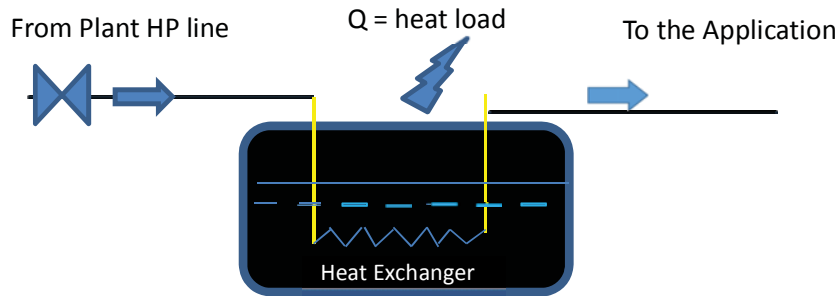


Figure 1. Schematic of a helium sub-cooler

In total, we proposed technical requirement of about 900 W at 4.5 K Helium Refrigeration (HR) system.

2. Cryogenic Heat loads of PF coils system

As mentioned in preceding section 1, 1.3 kW at 4.5 K HRL system is responsible for cooling of the TF, PF coils and cold mass support structure. After several campaigns, it is concluded that the TF coils are cooling down to 4.5 K with existing 1.3 kW HRL for 10-12 days. At present, only 1 pair of vapor cooled current leads are connected. The PF coils are getting cool-down with inlet/outlet conditions of 15 K/24 K with the available pressure head from the HRL system. Estimated values of heat loads on the PF coils system are discussed in Table 1 and corresponding the mass flow rate requirements has been deduced from the actual experimental data on pressure drops and thermo-hydraulics. This has been also verified using established co-relation of H. Katheder [3] relation for CICC pressure drop estimation.

Table 1. Heat loads acting on to the PF magnets system in SST-1 (as installed conditions).

| Coils | Nos. | Each heat load from 80 K – 4.5 K (W) | Q_{total} (Watt) |
|---------------------------------------|------|---|---------------------------|
| PF-1 | 01 | 2.7 | 2.7 |
| PF-2 (U/L) | 02 | 3.1 | 6.2 |
| PF-3 (U/L) | 02 | 5.5 | 11.0 |
| PF-4 (U/L) | 02 | 3.5 | 7.0 |
| PF-5 (U/L) | 02 | 6.4 | 12.8 |
| Thermal conduction due to supports | | 10 | 25.0 |
| SC bus ducts | 18 | 3 W/bus | 54.0 |
| Cryo lines-I | 20 m | 1.5 W/m | 30.0 |
| Cryo-lines-II | 20 m | | 20.0 |
| Valve-Box | 01 | 20 | 20.0 |
| Total static heat load | | | 189 |
| Transient load | | | 11 |

| | |
|---|-----|
| Total Heat Load @4.5 K | 200 |
| Safety margin of uncertainty in heat load estimation (1.5 factor) | 300 |
| Cooling capacity sizing (1.5 factor) [6] | 450 |

3. Thermal Runaway in SST- 1 PF coils and its Mitigation

Existing 1.3 kW at 4.5 K HRL along with the IFDCS system used to cool down SCMS of SST-1. During SST-1 campaign, the sixteen TF coils are cooled down from 300K to 4.5K in a uniform and controlled manner. The behaviour of cool-down of individual PF coils is shown in figure 1 for one of the SST-1 campaign. As shown in figure 1, some of the PF coils show thermal runaway behaviour at temperature below ~ 90 K and pressure below ~ 6.5 bar (a). Due to thermal runaway the temperature distribution is not uniform in PF coils and the PF coils demands higher pressure heads to get cool-down further. The thermal run away problem is addressed by increasing the Helium pressure head from cold-box of the HRL by optimising the valves of refrigeration stream. The process optimization includes (i) maintaining constant source pressure to refrigeration stream till 125 K and (ii) reducing the source pressure by regulating the refrigeration Joule –Thomson (JT) valve of high pressure (HP) stream and maintaining compressor flow rate within nominal value [4]. This process optimization removed thermal run away as well as reduce the cool down time. The modification within existing helium integrated flow distribution and control (IFDC) system was implemented. In-house development of 3S-2R cryo line has made very important role in realizing the flow distribution upgradation [5]. Successful installation and commissioning of cryo control and on/off valves in IFDCS with process lines layout and provision of proper flexibility have been carried out. During recent SST-1 campaign, IFDC upgraded system was successfully operated. Appropriate precise control and valve adjustment provided in future SST-1 operation will be tried out to make PF coils superconducting as shown in figure 2.

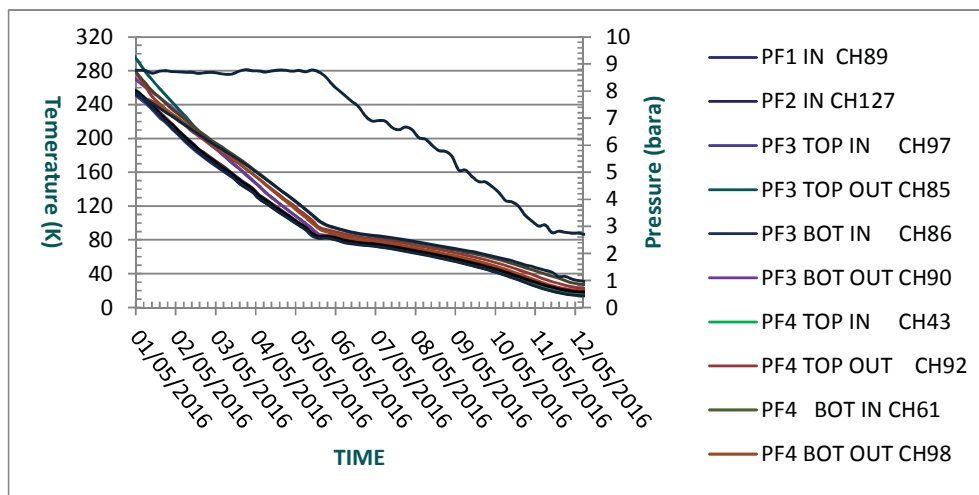


Figure 2. Temperature trend of PF coils for SST-1 Campaign

4. Heat loads of the SST-1 Central Solenoid (CS)

In order to make SST-1 as fully superconducting device, as a part of upgradation activities, new central solenoid has been planned using Nb₃Sn superconductors. Therefore, we need an additional cooling power for making the CS to be in a superconducting state. The total heat loads acting on the CS system has been estimated and summarize in Table 2.

Table 2. Heat loads estimation for the CS system.

| Sr. No. | Sources of heat load from 80 K – 4.5 K (W) | Quantity | Each heat load estimation (W) | Total heat loads estimation (W) |
|--|--|----------|-------------------------------|---------------------------------|
| 1 | Radiation | 01 | 3.0 | 3.0 |
| 2 | Residual gas conduction | 01 | 0.5 | 0.5 |
| 3 | Thermal conduction | 03 | 1 W/no | 3.0 |
| 4 | Cryolines | 20 m | 0.5 W/m | 10.0 |
| 5 | SC feeders + Vacuum Barriers (VB) | 5 m | 1.6 W/m | 8.0 |
| 6 | Instrumentation losses | | 9.0 | 9.0 |
| Static losses (Total) | | | | 33.5 |
| Pulsed / AC losses (During operation) | | | | |
| 7 | Joint Joule heating loss | 02 | 0.5 W/joint | 1.0 |
| 8 | AC losses (inclusive of Eddy, Coupling and Hysteresis) | | | 20.8 |
| 9 | Transient heat load | | | 21.8 |
| Total heat load | | | | 55.0 |

5. Overall cooling capacity sizing as upgradation

In order to size the cooling capacity of helium cryo system, should be determined from the required capacity in both the steady state operation and the cool-down operation. In general, the steady state refrigeration capacity of the cryo system is defined to be 1.5 times of the steady state heat loads of a system. On the other hand, the required refrigeration capacity during the cool-down of a system is used to be estimated from the specified cool-down time and the total mass to be cooled under the conditions of cool-down efficiency of 50% [6]. With reference to above heat load estimation, IPR requires $(300 + 83) \times 1.5W = 575W$ at 4.5 K refrigeration capacity for the cooling of PF and CS systems. There is a pair of MgB₂ based CLs to power the CS at 14 kA. This will have additional cooling capacity demand of 150 W or equivalent to 1.5 g/s at 4.5 K. IPR also needs the high pressure (2.7 bar (a)) cold helium looking at the PF coils pressure head demands with sub-cooled temperature of 4.5 K at the inlet of the PF and CS using heat exchanger bath cooled in a sub-cooled Dewar (SBD). The requirement of cold capacity for sub-cool Dewar is estimated as 175 W equivalent cooling power

at 4.5 K for 38 g/s single phase flow at 4.5 K and 2.7 bar (a) (inlet). Therefore, in total, there is a clear need of helium refrigeration plant of 900W at 4.5 K.

6. Cooling Philosophy

As a part of SST-1 up gradation activities, the cryo-distribution of PF system will be modified such that uniform path lengths of PF coils are grouped together with combination of more or less equal path lengths. These modifications have been already made in existing IFDCS. These three groups of PF coils will be cooled with new helium refrigeration (HR) system. The PF coils require much higher pressure head of 2.7 bar(a). The new HR system must supply cold power at 4.5 K, 2.7 bar(a) in sub-cooled single phase form. The return from PF system is at 1.1 bar (a) or equal to suction pressure of new HR system. In distribution system, 3 – supply, 2 – return (3S-2R lines) cryo lines are fabricated to provide cold power from IFDCS system to SST-1. Intended new HR plant will be completely separate from the existing 1.3 kW at 4.5 K HRL system. However, they will use common buffer as well as recovery systems. They will be interfaced at IFDC and SST-1 systems as shown in figure 3.

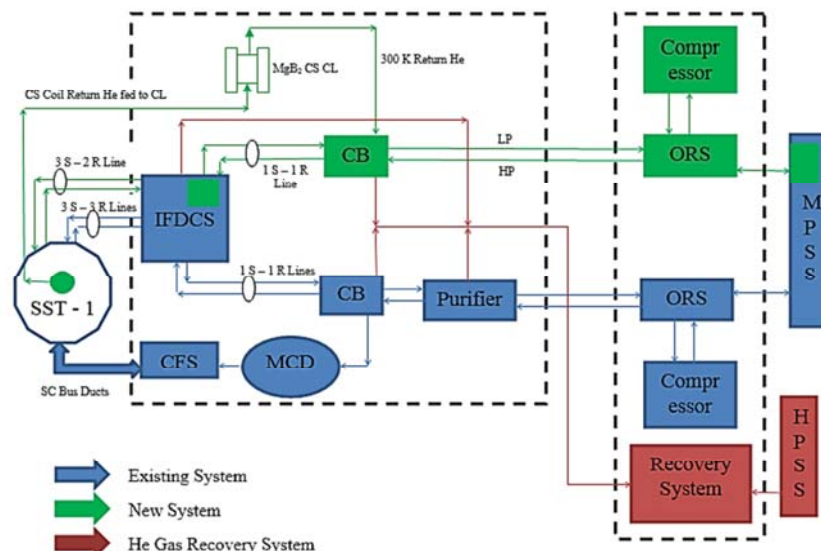


Figure 3. Cooling Philosophy of existing and upgraded helium cryo system at IPR

The CS will be made from Nb_3Sn and have a pair of MgB_2 based current leads (CL) rated at 14 kA. It will be cooled by new HR system with sub-cooled single phase helium at 4.5 K, 2.7 bar (a) as shown in figure 3. Similar to the PF system, the CS will have CICC path lengths of 200 m approximately, which require higher pressure head of 1.2 bar in comparison to PF & TF system. To take the advantage of MgB_2 based CL, the return cold helium from the CS, the helium flow will be fed to the bottom of individual CL equally. The helium gas is warmed up to 300 K along the MgB_2 CL heat exchangers and fed back to the suction of compressor of HR plant at room temperature. Considering this aspect, as this return enthalpy is not used in cold-box, equivalent cold flow taken as liquefaction load in calculation of plant capacity. For this purpose 1.5 g/s at 4.5 K, 2.7 bar(a) single phase flow is considered to remove static and dynamic (transient) heat load of CS. The equivalent additional refrigeration power for CL is 150 W at 4.5 K needs to be considered while sizing of HR capacity. A sub-cool Dewar (SBD) with heat exchanger in bath is required to mitigate the longer path lengths with inlet of 2.7 bar(a), 4.5 K and mass flow rate of ~ 38 g/s. The plant outlet must offer stable 4.5 K after SBD.

7. Conclusions

As a part of SST-1 cryo system upgradation, we have made the estimation of cryo heat loads and which was compared with the actual SST-1 experimental data from the recent campaigns. It is clear that we need an additional cold capacity of about 900 W at 4.5 K for facilitating the PF coils and central solenoid to be in a superconducting state at higher pressure head requirements as part of SST-1 upgradation plans. In-house efforts such as increasing the pressure head from existing HRL by optimising the process of refrigeration stream of cold-box of HRL and IFDC upgradation has facilitated the uniform cool-down of PF coils system without any thermal run away situation.

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