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Cryogenic process optimization for simultaneous cool down of the TF and PF superconducting coils of SST-1 Tokamak

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Abstract. Recent experiments of SST-1 have shown that cryogenic heat loads are more than installed cold capacity. Due to this fact, the system cool down goes into the status-quo in temperatures at ~12K and further cool down is not possible. This issue can be resolved in three folds i.e. by grouping and distribution of the PF coils, optimization of the cryogenic plant process and heat loads reduction. First, we replaced common PF coils distribution to three groups having equal path lengths. Secondly, providing the best possible pressure heads to each PF groups during cool down and using turbine-C to get cold capacity with active cooling of all paths. Third is the heat loads reduction at some parts of SST-1. While adopting the same, it has been shown that the simultaneous cool down of the TF and PF coils are possible while achieving superconducting transition in all the coils except PF-5(lower).

1. Introduction

The steady state superconducting Tokamak (SST-1) consists of 16 D-shaped Toroidal Field (TF) and 9 circular Poloidal Field (PF) superconducting coils. A 1350W at 4.5K helium plant has been operational since 2004 to meet the static as well as pulsed heat loads of the SST-1. The helium plant runs in mixed mode with refrigeration capacity of 650W at 4.5K and liquefaction capacity of 200 l/h [1]. Integrated Flow Distribution & Control System (IFDCS) distributes cold helium from helium plant to different cold masses such as TF coils, PF coils and TF case with support structure. At present, one pair of vapour cooled conventional current lead rated at 10kA is used for the charging of TF Superconducting Magnet System (SCMS) [2].

Several circular plasma experimental campaigns have been carried out in SST-1 with TF SCMS [3]. Experiments have shown that the cryogenic heat loads are more than installed cold capacity of helium plant (1350W at 4.5K). During SST-1 cool down, at about 12K, the system goes into the status-quo in temperatures and further cool down is not possible. For plasma experiments, we have developed an operational protocol to stop cooling of the PF coils and TF case in order to get the cryo stable conditions within TF coils. This concept is in-house developed and known as hydraulic bypass of active paths. Due to hydraulic bypass phenomena, the temperatures of passive cold masses rise over days depending upon their heat capacities, hence plasma operation duration was limited to 8-10 days, so called “Experimental window”. The PF coils have non-uniform hydraulic path lengths in the range of 67 to 130 meter, while TF coils have uniform hydraulic path lengths of 48 meter. This demands higher pressure head for PF coils in comparison to TF coils and uniform distribution among PF coils.

During the recent SST-1 campaigns, we tried to resolve this issue by optimization of the process from helium cryogenic plant and distribution system as well as heat load reduction at some parts of SST-1. With these resolutions, we tried to cool all PF coils to 4.5K while TF SCMS and TF case were hydraulically bypassed in campaign - 20 to study hydraulic behaviour of PF coils. Further, we tried simultaneous cool down of all paths; making TF and some of PF coils superconductor simultaneously in campaign - 21. This paper describes various adopted solutions for simultaneous cool down of TF & PF coils and achieving superconducting transition in all coils except PF-5 (lower) for the first time.

2. Upgradation of IFDCS

The IFDCS consists of valve distribution box and vacuum jacketed transfer lines with 80K thermal shield [4]. Existing IFDCS has three different parallel paths for TF SCMS, PF SCMS and TF case with support structure. Each path has on/off valve at inlet and flow control valve at outlet equipped with process instrumentation for temperature, pressure & flow rate. As per original design, there was single flow control valve common to all the return paths of the PF coils, which has caused the difficulties to obtain uniform cool down within the PF coils due to their different path lengths. This caused undue thermal run away limiting the cool down of the PF coils to 23K - 27K at the outlet.

To facilitate uniform cooling in each PF coils, it was decided to redistribute the flow in PF as per their hydraulic path lengths. Hence, PF coils hydraulic distribution within the IFDC system and SST-1 machine were introduced for uniform hydraulic distribution and better control can be obtained for individual group of the PF coils. The group details are shown in table 1. The process flow diagram of upgraded IFDCS is shown in figure 1.

Table 1. Helium flow paths and flow rate details of PF coils hydraulics.

Group Name	Coils	Flow Paths per Coil	Total Parallel Paths per Group	Hydraulic Path Length (meter)
PF3	PF3 (Upper), PF3 (Lower)	8	16	67 – 84
	PF1	2		
PF124	PF2 (Upper), PF2 (Lower)	1	12	113
	PF4 (Upper), PF4 (Lower)	4		
PF5	PF5 (Upper), PF5 (Lower)	4	8	130

Therefore, IFDCS is upgraded with in-house developed 3-supply & 2-return (3S-2R) vacuum jacketed transfer line, process instrumentation (on/off & flow control valves, temperature, pressure, flow rate), hydraulics modification inside valve box & SST-1. The 3S-2R vacuum jacketed transfer line has two supply / return cryo lines for PF3 and PF5 group with DN20 schedule 5S and DN15 schedule 40S respectively. The 3S-2R transfer line is designed, fabricated in-house. Each cryo line is thermally shocked at 80K using liquid nitrogen (LN2) and thoroughly helium leak tested. The common cryo line for PF coils in existing 3-supply & 3-return (3S-3R) transfer line is utilized for PF124 group. New 3S-2R cryo line and modified hydraulic distribution for PF system inside valve box are shown in figure 2 & 3 respectively. The Graphical User Interface (GUI) of upgraded IFDCS scheme depicting all process instrumentation is shown in figure 4. It shows minimum achieved temperature for simultaneous TF and PF cool down with all active paths opened during campaign - 20. After IFDCS upgradation, hydraulic imbalance among PF coils during cool down is adjusted by control valve for each group and thermal run away is avoided.

3. Process optimization in the helium cryogenic plant

The helium plant has different modes for SCMS such as pre-commissioning, double phase, cold circulator, warm up and pure liquefier [5]. One of the changes in helium cryogenic plant process is opening of refrigeration stream cold end valve (FCV445) with SST-1 maximum temperature (T_{max}) for SCMC cool down during double phase mode. The initial logic is defined such that FCV445 remains 80% open till T_{max} reaches 200K from 300K during cool down. Then FCV445 operates linearly with T_{max} and maintains the compressor flow with its nominal value. So in original logic, the supply pressure reduces linearly from 200K of T_{max} [6]. This logic is modified such that helium cryogenic plant provides best possible supply pressure of helium to SCMS from room temperature to 125K of T_{max}. Then, the turbines A & B are authorised at T_{max} of 125K, the outlet pressure of the cryogenic plant varies as per the opening of FCV445. This logic change has reduced the temperature of PF coils much lower than original logic. Further change is made in this logic such that FCV445 opens 90% instead of 80% to provide best possible head to the PF coils. The maximum opening of FCV445 is kept 80% and 90% for campaign - 20 and 21 respectively. This change provided somewhat higher supply pressure to SCMS during cool down as shown in figure 5. Due to this change, helium plant allowed higher mass flow rate to SCMS during 200 to 50K of T_{max} with constraint of compressor flow rate of 150 g/s.

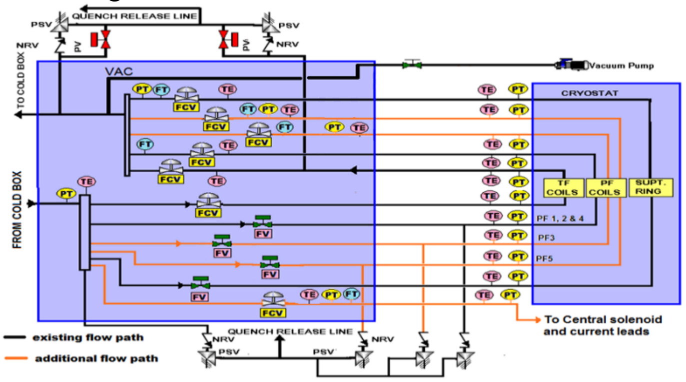

Figure 1. Process flow diagram of upgraded IFDCS.

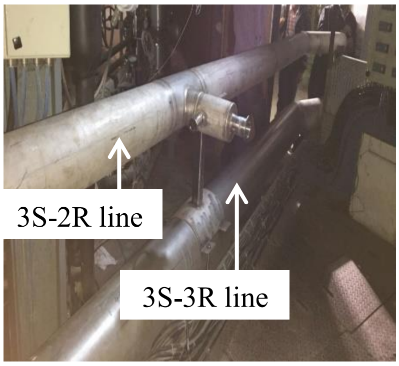

Figure 2. New 3S-2R cryo line with existing 3S-3R cryo line.

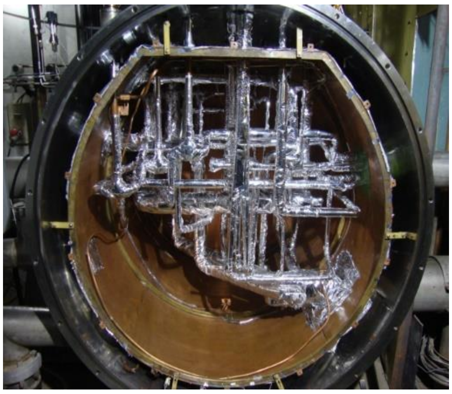

Figure 3. Internal view of upgraded IFDCS.

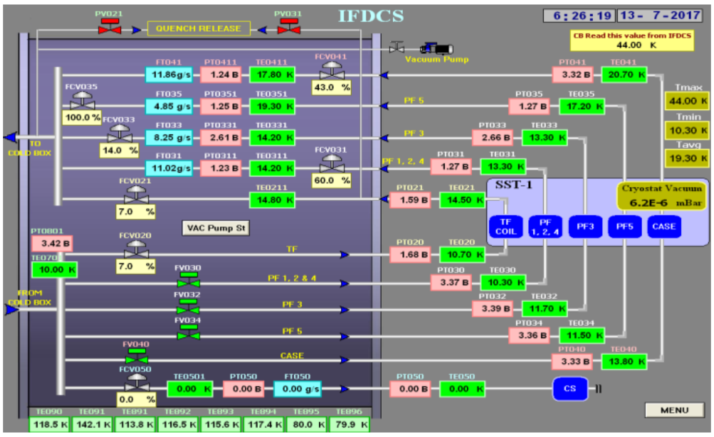

Figure 4. GUI of upgraded IFDCS during campaign - 20.

Second change in helium process is authorisation of turbine - C to provide extra cooling power during cool down. We stopped the cooling of active paths of TF SCMS and TF case, and diverted all cold capacity of helium plant to cool the PF coils together to study hydraulic behaviour of PF coils in campaign - 20 and cooled all PF coils to 4.5K. In campaign - 21, we cooled all the active paths of TF, PF coils and TF case to low temperature (~10.9K) and ensure that the turbine - C (TC) inlet and outlet temperature were at the verge of starting condition irrespective of helium supply temperature to SCMS and return temperature from SCMS. As shown in figure 6, supply temperature to SCMS and return temperature from SCMS are higher by 2 - 3K than previous campaign - 20, turbine - C is authorised successfully and reduced supply temperature to SCMS faster. Though turbine - C is running with less efficiency due to operation at little bit higher temperature than its nominal values, it provided extra cooling power and reduced supply temperature to SCMS fast with all active paths open.

Due to the mixed mode design of helium plant, there is better possibility to adjust the thermodynamic process of the cryogenic plant in terms of distribution of refrigeration capacity vs liquefaction capacity. So, after turbine - C authorisation, maximum weightage is given to refrigeration to the SCMS through its cold end valve at the cost of liquefaction capacity and required quantity of liquid helium (LHe) is produced in Main Control Dewar (MCD) for one pair of TF current leads.

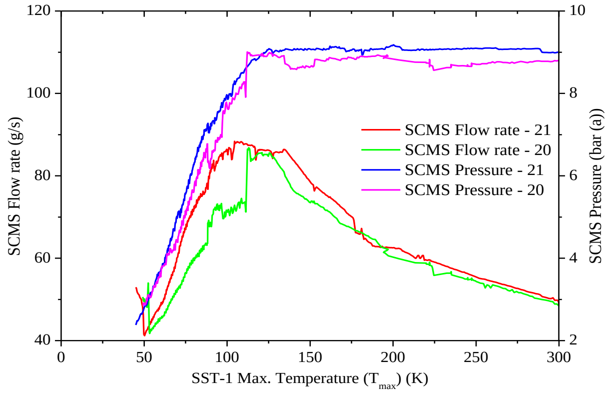

Figure 5. SCMS supply pressure and flow rate.

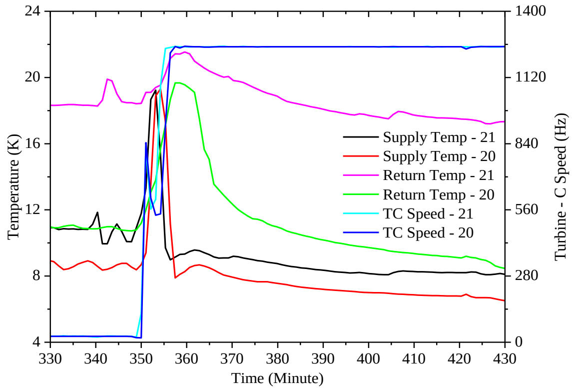

Figure 6. Authorisation of turbine - C.

4. Heat load reduction at some parts of SST-1 machine

Analysis of cryogenic heat loads has revealed that radiation heat load can be reduced with minor modification in the system. One candidate is radiation heat load due to Room Temperature (RT) view from man-hole ports of SST-1 machine. This can be reduced by wrapping multi-layer insulation (MLI) or providing passive cooling on baffles. In recent campaign, one copper baffle of man-hole was covered with 20 layers of MLI using double aluminized Mylar with single nylon-net spacers and passive conduction with neighbour 80K thermal panel. It is equipped with two PT-102 temperature sensors with proper mounting technique, namely T1 and T2, equally spaced on baffle, as shown in figure 7.

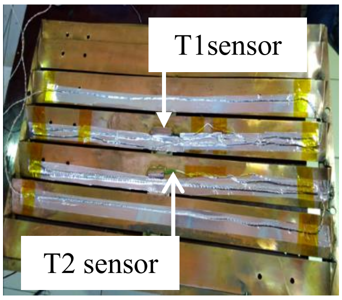

Figure 7. Direct RT view from Man-hole Ports

Figure 8. Direct RT view from Man-hole Ports with MLI.

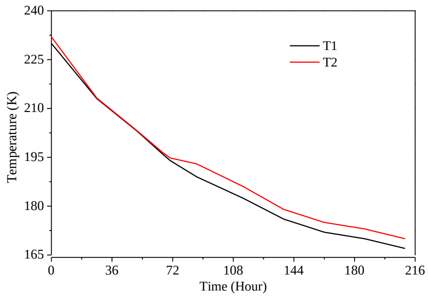

Figure 9. Baffle temperature trend during campaign - 21.

The temperature of baffle with MLI (figure 8) was ~230K initially, as cool down of 80K bubble panel started before cool down of SCMS. As the SCMS cool down progressed, the temperature of baffle reduced and saturated at ~170K as shown in figure 9. The radiation heat load from a man-hole with a cross section area of 0.35 m^2, emissivity of 0.32 at 300K to a cold surface of SCMS having cross section area of 2 m^2, emissivity of 0.16 at 4.5K is ~50W. By applying MLI on a copper baffle at one man-hole and passive conduction cooling, the radiation heat load is reduced to ~5.2W from 50W. There are 12 nos. of man-hole port in SST-1, where active liquid nitrogen cooling is not provided. Radiation heat load can be reduced at some parts of machine by reducing temperature of such surfaces with application of passive conduction cooling along with MLI wrapping. Thermal anchoring of some instrumentation and control cable was routed with thermal shield in the machine. During campaign - 21, it was ensured that uniform 80 - 85K is maintained in all active thermal shields using LN2.

5. Results

In recent campaign - 21, we have adopted above three fold solution to cool the TF and PF coils simultaneously. Process optimization of helium plant provides best possible pressure head to PF coils.

In addition to this grouping of the PF coils helps to regulate flow in each PF groups and results in faster cool down. Condition to authorise turbine - C has been achieved on 11th day. Operation of turbine - C to get cold capacity with active cooling of all paths enabled plant to reduce supply temperature to SCMS at faster rate. All active paths have been kept open for ~ 42 hours with turbine – C to get cryo stable condition. The cool down trend is shown in figure 10. Superconducting transition of PF coils has been observed for each coil and found that all coils except PF5 (lower) become superconductor. The PF5 (lower) coil could not become superconductor and its return temperature is ~14.5K. The inlet temperature to all TF and PF path is below 9K before bypassing active paths as shown in figure 11. After cryo stability of 42 hours with turbine - C, the TF case was bypassed hydraulically and PF SCMS cooled down further. This time simultaneous cool down is observed in TF and PF-3 coils with liquid helium production in main control Dewar at the rate of 50 l/h with hydraulic bypass of TF case, PF5 and PF124 groups.

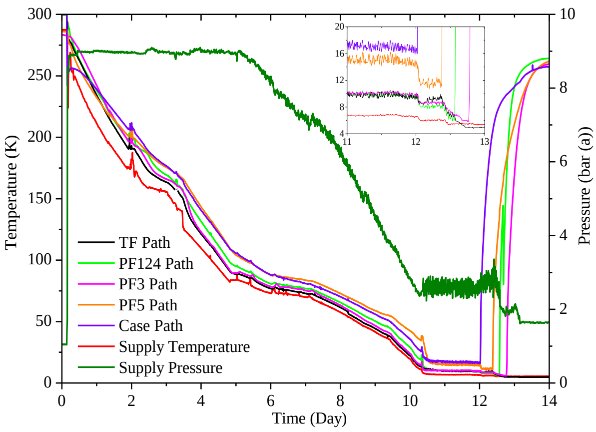

Figure 10. Cool down trend of campaign - 21.

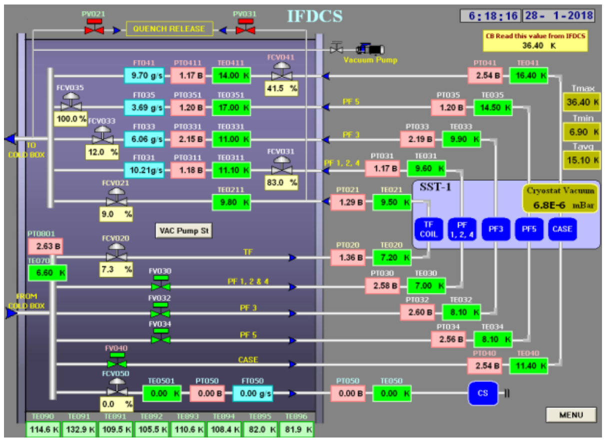

Figure 11. Demonstration of simultaneous cool down of the TF and PF coils during campaign-21.

6. Conclusion

The SST-1 TF and PF coils were simultaneously cooled down and superconducting transition has been achieved in all coils except PF5 (lower) by adopting three fold solutions. Balancing of hydraulic path of PF coils has been met with upgradation of IFDCS through individual flow control valves in each group. The higher pressure head requirement for PF coils has been met with logic change in helium plant. Radiation heat load reduction at one man-hole port is established with passive conduction cooling and MLI wrapping. With minor modification to other parts in machine, radiation heat load can be reduced to a certain extent. In future, simultaneous operation of TF and PF3 coils with current leads for shaped plasma experiments will be possible with above optimization methods and providing additional LHe for current leads, if required from an additional 140 W at 4.5K helium cryogenic plant.

Acknowledgements

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