SST-1 CRYOGENICS REQUIREMENTS AND THE WAY FORWARD

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Abstract

The SST-1 consists of sixteen toroidal (TF) and nine poloidal (PF) superconducting coils. To cool these coils, a 1350 W at 4.5 K helium cryogenic system is operational since 2003. The cryo system comprises of helium and liquid nitrogen distribution systems to facilitate the cooling requirements of SST-1. Several SST-1 campaigns, revealed that there are issues of higher heat loads and pressure drop of the PF coils system, which has led to limit the simultaneous cooling of the TF and PF coils. The results showed that the present cryo system is able to cool down only the TF coils, PF-3 (U/L) coils and a pair of TF current leads. It has been observed that an additional helium mass flow rate of 40 g-s^{-1} at 2.7 – 2.8 bar (a) at 4.5 K is required for the cooling of PF superconducting coils, which corresponds to the equivalent capacity of 900 W @ 4.5 K to meet the cooling requirements of PF coils and additional 600 W for the PF current leads. In order to resolve these issue, we have addressed few short term and long term plans as mentioned, (i) Cryo heat loads minimization and mitigation within the SST-1 to the best possible level. (ii) Introduction of efficient design of the current leads as "cold capacity saver" (iii) PF3 (U/L) current leads in SST-1 using NBI cryo plant of capacity 140 W at 4.5 K (equivalent to 45 l-h^{-1} liquid helium production rate) (short term). (iv) Full-fledged PF coils operation with the TF coils by additional similar capacity helium plant (1500 W at 4.5 K). The paper, a brief review of the installed cryo sub-systems as well as the plans of simultaneous cool down of the TF and PF coils of SST-1 will be discussed.

1. INTRODUCTION TO SST-1 CRYOGENICS SYSTEM

The SST-1 machine comprises of set of toroidal (TF) as well as poloidal field (PF) superconducting coils system and hence there is need of helium as well as liquid nitrogen cryo systems. We have helium cryo plant system of capacity 1350 W at 4.5 K operational since 2003 [1-2]. The helium cryo system was designed with customized requirements looking at the tokamak applications in mixed mode of operation i.e. Refrigeration (650 W at 4.5 K) and liquefaction rate of 7 g-s^{-1} simultaneously. A typical process flow diagram (PFD) of helium cryo system is shown in FIG 1. As this specific cryo plant is designed for fusion machine operational requirement, the basic cold process is as per modified Claudet cycle, where it can produce simultaneous refrigeration power as well as liquid yield during its operation. This cryo plant also can be operated either in pure refrigeration or pure liquefaction mode depending upon the needs at little lower efficiency level since it has been originally designed for mixed mode of operation. Additionally, we have wide spread of cryogenic installation at IPR, which includes helium cryo auxiliary systems (storage, transfer, distribution, control and monitoring systems as well as recovery systems). We also have secondary cryogen as liquid nitrogen with huge storage capacity of hundred thousand liters of inventory, distribution and control systems. Similar state of the art process for large cryogenics systems have been reported in EAST (China) [3], KSTAR (South Korea) [4] and ITER (France) [5] tokamaks as well as LHD (Japan) [6] and W-7X (Germany) [7] stellarators systems in the world. While sizing the large cryo system, lessons have been learnt to pay attention on cryogenic heat loads estimation, flow & hydraulic resistances balances and thermal shorting as well as direct room temperature view to the cold surfaces related issues to be critically monitored during the assembly of complex fusion devices. In this paper, we highlight the critical issues observed and some short term and long term technical resolutions have been prescribed for the future successful operation of SST-1 machine.

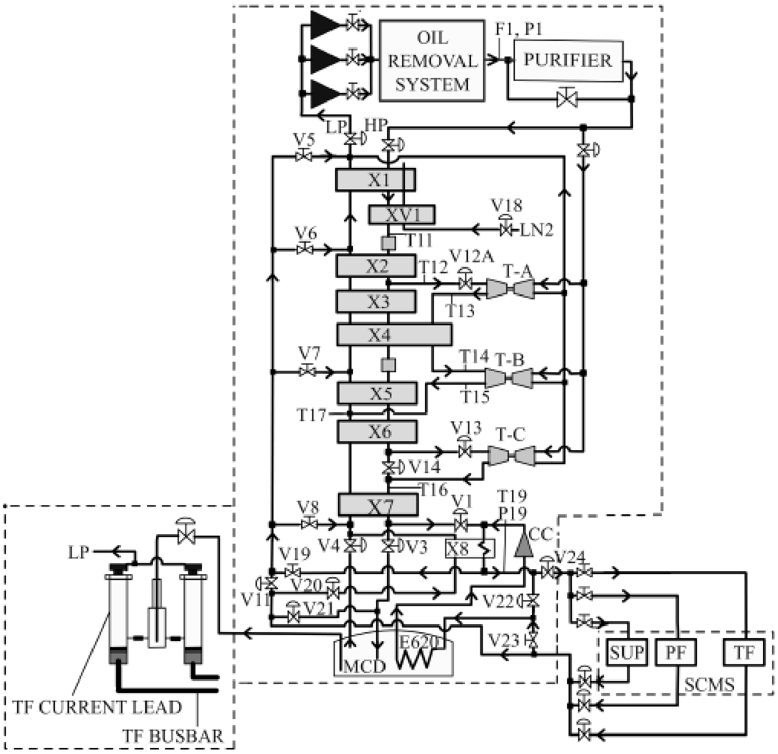

FIG. 1. Process Instrument Diagram of Helium Cryo Plant with Current leads and SCMS at IPR

2. COOLING REQUIREMENTS FOR SST-1

The cryogenic system of SST-1 facilitates the cooling requirements of superconducting magnets, feeder and current leads, which are described in details below [8],

2.1 Superconducting Magnets cooling

The SST-1 machine consists of sixteen TF and nine PF superconducting coils. To power the superconducting magnets, total ten pair of 10 kA rated vapour cooled current leads are installed. The SST-1 has typical cold mass of about 40 tons and is being cool-down from 300 K to 4.5 K in 13 - 14 days. From 300 K – 80 K range, the typical cool down rate of 1.0 K-h^{-1} and from 80 K – 4.5 K range, cooling down rate is 0.5 K-h^{-1}. During the operation, we maintain temperature difference of 50 K between the maximum temperature and minimum temperature on Magnets surface to prevent from any kind of undue thermal stress issues on to the magnets system. The recent measured cold capacity of HRL has shown 647 W (refrigeration at 4.5 K and 7 g-s^{-1}. This cryo plant is connected to cool and maintain the SST-1 superconducting magnets in superconductivity state. The cryo plant can offer both the two phase (low pressure mode) as well as single phase (supercritical helium at higher pressure) modes in Refrigeration mode (equivalent 650 W at 4.5 K) as mentioned below [8],

(a) Low pressure two-phase operation (1.2 – 1.6 bar (a) at 4.8 K (60-65 g-s^{-1}) (w/o sub-cooling)
(b) High pressure single phase helium operation (at 4 bar (a) / 4.5 K (under sub-cooling at flow rate of 300 g-s^{-1}, forced flow pressurized cold helium)

2.2 Current leads cooling

SST-1 has total ten pairs of current leads (CLs) rated for 10 kA, 9 pairs for PF CLs and 1 pair for TF CLs (based on VCCL concept) (VCCL: Vapour cooled current leads) similarly 9 pairs of SC feeders for the PF coils and 1 pair SC feeders for the TF coils have been installed. At present, only 1 pair of the TF current leads are installed in the current leads assembly chamber (CLAC). Other 9 pairs of CLs for PF coils are ready but not installed on to the CLAC. Each current leads is designed with same design architecture, each will consume about 35 W cooling power at 4.5 K. Based on the operation duty cycle of the machine, the liquefaction capacity from the average over a day consumption is sized as 200 l-h^{-1}, equivalent to 700 W (Refrigeration capacity). The current leads in SST-1 is major consumer of cryogen about 55% of the total capacity is just consumed by the current leads only. In future, better design concepts of the current leads are mandatory to save the precious cold power from the cryo plant. As the current leads are the major consumer of the total cold capacity of helium cryo system in a fusion reactor, now a days innovative concepts of “cold capacity saving current leads” design have been adopted worldwide, these include high temperature based superconductor current leads to be used in ITER (France), overloaded current leads used in (T-15, Russia) and KSTAR tokamak (South Korea) for PF current leads [9].

3. LIMITATIONS OBSERVED DURING COOL DOWN OF SST-1

During several SST-1 cool down campaigns, we have observed higher pressure drop within the PF coils system and excess cryo heat loads as compared to original design values. These aspects are discussed in detail in following sections.

3.1 Higher Pressure drop within the Magnets system

Cold helium at 4.5 K within the distribution to main SST-1 application is controlled and monitored using Integrated Flow Distribution and Control (IFDC) system. It has cryo compatible vacuum and 80 K thermal shields. It consists of supply and return cryo lines communications, vacuum barrier, many essential instrumentation and cryo valves [2]. As per 2004 design, a common single flow control valve was provided to control the hydraulic resistances of the return paths of the all PF coils, which has caused non-uniform hydraulic resistances within individual PF coils as their hydraulic path lengths are different. Therefore, it introduced the thermal run away (non-uniform temperature distribution) within the PF coils system, which in turn limiting the cool down of the PF coils to 23K - 27K at the outlet. Estimated pressure drop within the largest PF5 (U/L) coils is about 520 mbar at 5 K whereas experimental observation shown the pressure drop of more than 1000 mbar at 11.8 K at the outlet.

In 2015, the efforts were made to upgrade the IFDC system for better cool down and flow controls within the PF coils. The basic philosophy was adopted to group the similar path lengths PF coils using the combination of on/off and flow control cryo valves. Therefore, we have realized the flow distribution scheme for the PF coils in broadly three groups in Table 1 below,

TABLE 1. PF COILS HYDRAULICS GROUPING SCHEME

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

The present upgraded IFDC system connects in-house developed (3 supply / 2 return) vacuum and super insulation wrapped cryo lines, essential instrumentation Viz. pressure, temperature, flow and differential pressure transducers. It also facilitates the on-line control, monitoring and archiving the trends and database of process parameters using Graphical User Interface (GUI) with support of SCADA based data acquisition system as shown in FIG 2. It has been reported the minimum achieved temperature for simultaneous TF and PF cool down with all active paths opened during recent campaign. 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.

3.2 Higher Cryogenic Heat Loads

During 1998, while carrying out the conceptual design of SST-1 cryo system the typical estimated cryo heat load from 80 K – 4.5 K as about 180 W. By introducing uncertainty in the calculation, the factor of safety was taken as 1.5. It gave total static heat load on cryo system of 270 W at 4.5 K inclusive of all possible sources within the SST-1 machine infrastructure. Looking at the cool down efficiency, the refrigeration capacity of 400 W at 4.5 K was fixed. The superconducting magnets of SST-1 envisaged to cool them using forced-flow single phase sub-cooled helium at 4.0 bar (a) and 4.5 K at flow rate of about 300 g-s^{-1}. The mass flow rate boosting from 60 g-s^{-1} to 300 g-s^{-1} has been provided by a helium cold circulator, an additional 250 W of heat load is expected from the helium cold circulator. Therefore, the requirement on the net refrigeration capacity was about 650 W at 4.5 K.

Based on duty cycle of VCCLs (current leads), the cooling requirements of VCCLs was about 7 g-s^{-1} liquid yield equivalent to 200 lh^{-1} (~ 700 W /4.5 K of refrigeration). Finally, the procured total cold capacity of the helium cryo system was about 1350 W at 4.5 K in mixed mode where the same cryo plant can give simultaneously refrigeration capacity of 650 W / 4.5 K and about 7 g-s^{-1} of liquid helium yield. Since 2012, after SST-1 refurbishment, there were many additional sub-systems introduced undue heat load sources have been found e.g. unshielded PF feeders leads, cryostat 80 K panel's baffles, direct view in current leads assembly chamber etc. The present situation in cryo plant is able to cool the TF coils and a pair of TF CLs and PF3 coils. As built system cryogenic heat loads have been estimated in two category as summarized below in Table 2 and Table 3 respectively,

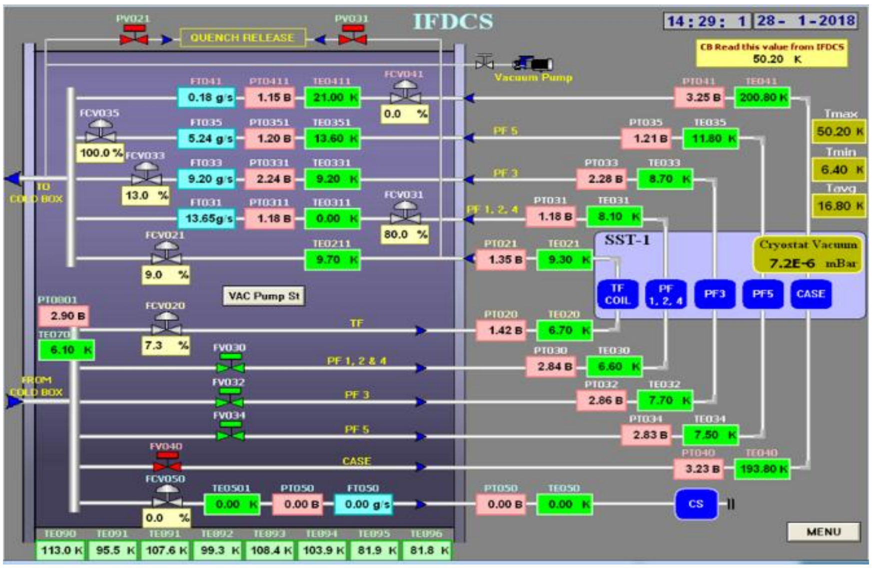

FIG 2: GUI Mimic for upgraded IFDC system

TABLE 2: INSIDE THE SST-1 MACHINE PART: A

Sr. No.	Panel Type	Average Temp. (K)	No. of Panels	Total Cold Surface Area (m^2)	Total Warm Surface Area (m^2)	Q_{rad} (Watt)	Q_{rgc} (Watt)
1	Thermal shields	80 K	138	144	121	38	4.2
2	Baffles	115	32	9.08	7.68	10.27	0.39
3	RT Baffles	300	12	2.83	2.4	148	0.325
4	Unshielded PF leads (Top)	300	10	1.18	1.0	61.88	0.135
5	Unshielded PF leads (Bottom)	300	08	0.708	0.8	49.0	0.081
6	Uncooled side plates	130		0.805	0.7	1.5	0.04
7	Conduction Loss due to supports	1 W / support	8 supports			8.0	
8	TF BB supports on PF5	0.5 W/support	32 nos.			16	
9	Other PF supports	0.5 W / support	144 nos.			72	5.17
10	Joint Heat loss		220 Joints			22	
						426.6	10.34
					NET TOTAL	437 W (Approx.)	

TABLE 3: OUTSIDE THE SST-1 MACHINE PART: B

Sr. No.	Systems	Remarks	Heat load at 4.5 K
1	Cryo + Magnets Instrumentation	300 Sensors	30
2	IFDC	Instruments / Valves / Thermal shields at 140 K	75
3	VB of SC Bus ducts	3 W (20 nos.)	60
4	# 3 nos. of Bus ducts	1.0 W/m (16 m)	48
5	Cryo Lines - 3S-3R (6 lines) (15 m) - 3S-2R (5 lines) (15 m) - 1S (1 line) (7 m) - 1S-1R (2 lines) (10 m)	 0.5 W/m per line 0.75 W/m per line 0.75 W/m 0.75 W/m	 45 56 5 15
			334 W

Therefore, the net total heat load on the cryo system is about 771 W at 4.5 K and for the sizing of the HRL plant capacity, the capacity is defined as 1.5 times of the total net heat loads on the system = 1.5 x 771 W at 4.5 K = 1157 W at 4.5 K.

4. EFFORTS TO MITIGATE THE CRYOGENIC HEAT LOADS

Radiation and thermal conduction heat transfers are kind of the severe static heat loads in cryo system. While carefully looking at the machine assembly, we have found several locations within the machine from where unexpected heat loads are observed. Few of example are depicted as mentioned in FIG 3.

FIG 3. Some of the examples of identified unknown heat loads sources in SST-1

There are twelve man-hole ports, which see direct room temperature view from the SST-1 cryostat to the cold surfaces at 4.5 K. The direct room temperature view is seen by the SCMS of SST-1. Estimation has shown that the radiation heat-in leak through such man-hole ports is significant has revealed that radiation heat load can be reduced with minor modification in the system. By lowering the temperature of baffles with application of passive conduction cooling along with wrapping of optimum layers of superinsulation. Proper layout of instrumentation wiring and thermal anchoring to active liquid nitrogen path would also be helpful.

In recent SST-1 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 shield.

Significant reduction on direct radiation heat transfer was observed. The typical heat load due to radiation from a man-hole was about 50 W at 4.5 K whereas after superinsulation wrapping, we have onset measured the temperature on baffle and shown the heat load of only 5.2 W at 4.5 K. Out of twelve man-holes, only three ports are accessible to carry out radiation protection but still there is ample possibility to minimize these heat loads and further heat loads mitigation is under progress.

5. CRYO PERSPECTIVES: THE WAY FORWARD

In this section, we have tried to convey the facts that how to take the complete SST-1 magnets system to its cold temperature of 4.5 K. Different short-term and long-term plans have been discussed with innovative and cost saving concept of current leads to be adopted for the SST-1 machine.

5.1 Using additional small capacity helium cryo plant for current leads cooling

In the vicinity of 1.3 kW at 4.5 K Helium cryogenic system, we have another smaller capacity about 100 W at 3.8 K (which is equivalent to 140 W at 4.5 K) helium cryogenic system for neutral beam injector (NBI) system for their cryo pump applications [10]. This system can produce about 40 lh-1 liquid helium yield. Therefore, we would propose to use this smaller cryo plant specific for the cooling of PF-3 (U/L) coils current leads. Using the combination of vertical field and PF-3 (U/L) coils, in one of the SST-1 plasma reference scenario, one can elongate plasma with kappa (□) of 1.17. Therefore, there is possibility to study the shaped / elongated plasma in SST-1. This will be the short time solution. By next winter 2019, we have planned to realize the operation using NBI cryo plant for the PF-3 current leads cooling, where both the cryo plants will run simultaneously to support SST-1 experimental campaign.

5.2 Realization of efficient current leads

The superconducting magnets system (SCMS) of the fusion devices consist of complex superconducting magnetics along with auxiliaries. In order to supply such high currents from the power supplies to the SCMS, many numbers of current leads (CLs) are required in the range of 4.5 K – 300 K. As the studies revealed that based on the duty cycle of operation of fusion device, almost 25% - 30% of the total operation cost of a fusion reactor is just consumed by the CLs only. Therefore, an optimum, reliable and low loss CLs are essential for fusion devices. Several literature studies include such CLs development using unitary (conventional heat exchanger) and binary (HTS or other superconductors module with metal or alloys heat exchanger) concepts. It would be possible if replacing the conventional CLs by innovative and techno-economically viable solution using MgB2 and Brass based overloaded CLs. The overall efficiency, exergy flow and cryogen consumption based on operation duty cycle, operation cost of the device can be compared with the conventional current leads and savings by providing innovative solution. This proposal has three folds benefits, the capital cost of the MgB2 materials is cheaper compared to HTS materials. The critical temperature of MgB2 is ~ 39 K, where the thermodynamic efficiency of the helium cryo plant is maximum. The last but not least, significant cost can be reduced by designing the CLs in overloaded mode using Brass. This type of engineering solution is quite unique and suitable for pulsed magnets of the fusion devices and till now not tried out. The preliminary estimation shows that the cooling power required for the conventional CLs is 3 – 4 times higher than that of MgB2 and Brass based overloaded CLs, this design concept can be easily adopted in case of the pulsed current leads of SST-1.

5.3 Possibility of procurement of similar capacity Helium Plant

As discussed earlier in section 3(b), looking at the estimation on the cryogenic heat load exists as on today with the present infrastructure, we need about 900 W at 4.5 K (refrigeration capacity) plus 6 g-s^{-1} (liquefaction yield) for cooling of the PF coils current leads. The cryo plant will provide sub-cooled single phase liquid helium at 2.75 bar (a) / 4.5 K with best possible pressure head to cool the PF superconducting coils of SST-1. This will be the long term technical solution but it will ensure the simultaneous cool down requirements of complete SST-1 machine. This solution will call for additional space requirements, utilities, capital as well as operational costs along with the round the clock basis manpower for operation. We believe, at least 24 months will be taken to deliver the system after procurement procedure will be completed. Additionally, there would be at least 6 months' time for site installation, commissioning and site acceptance.

6. SUMMARY

In order to cool the TF and PF coils simultaneously, we have addressed few short-term and long -term solutions by which we will be able to cool the superconducting coils of SST-1 as mentioned below,

(i) Cryo heat loads minimization within the SST-1 Machine by identifying the possible sources of heat loads and its feasibility to minimize them. We have already identified few critical areas within SST-1 Machine, where there are ample opportunities to minimize the direct heat-in-leak on to the 4.5 K surfaces Viz. uncovered man-hole ports of cryostat, providing additional 80 K thermal shields and having thermal anchoring post at 80 K in instrumentation wires /cables etc.

(ii) PF3 (U/L) coils operation with the VF coils to get elongated plasma in SST-1. In this scheme, we will be utilizing 1350 W at 4.5 K helium cryo plant just dedicated to TF and PF coils cooling in pure refrigeration mode. The liquid helium required for the current leads operation for the PF 3 coils can be met using other cryo plant within the institute of capacity 140 W at 4.5 K (short-term).

(iii) Introduction of efficient design of the current leads as “cold capacity saver” focused to the duty cycle of operation as well as steady and pulsed operation scenario. As original design concept of current leads was based on vapour cooled conventional concept (same design for all current leads), which consumes huge cold capacity as compared to hybrid or overloaded current leads, the innovative design of the current leads is possible by which one can save the cold capacity by a factor of 3 – 4. Parallel, indigenous development and test program is going on at institute.

(iv) Full-fledged all the PF coils operation along with the TF coils can be done using additional similar capacity helium plant (1500 W at 4.5 K). We are also working on this plan as parallel plan for future operation.

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