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Commissioning and experimental validation of SST-1 plasma facing components

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Abstract. Plasma facing components of SST-1 are designed to withstand an input heat load of 1.0 MW/m^2. They protect vacuum vessel, auxiliary heating source i.e. RF antennas, NBI and other in-vessel diagnostic from the plasma particles and high radiative heat loads. PFC's are positioned symmetric to mid-plane to accommodate with circular, single and double null configuration. Graphite is used as plasma facing material, back made of copper alloy and SS cooling/baking tubes are brazed on copper alloy back plates for efficient heat removal of incident heat flux. Benchmarking of PFC assembly was first carried out in prototype vacuum vessel of SST-1 to develop understanding and methodology of co-ordinate measurements. Based on such hands-on-experience, the final assembly of PFC's in vacuum vessel of SST-1 was carried out. Initially, PFC's are to be baked at 250 °C for wall conditioning followed with cooling for heat removal of incident heat flux during long pulse plasma operation. For this purpose, the supply and return headers are designed and installed inside the vacuum vessel in such a way that it will cater water as well as hot nitrogen gas depending up on the cycle. This paper will discuss the successful installation of PFC's and its plasma operation respecting all design criteria.

1. Introduction

SST-1 Tokamak was successfully commissioned in 2012 [1-3] and the first plasma was achieved in June 2013 with poloidal limiters having SS 304Las a vessel wall material. Due to plasma wall interactions, high-Z impurities released from the vessel walls which in turn cools the plasma by radiation loss. In order to reduce this effect, PFC components were installed insideSST-1 main vacuum vessel (VV) in 2nd phase of SST-1 up-gradation.

Plasma facing components (PFCs) of SST-1 Tokamak [4] (figure 1 and figure 2) consist of Inboard divertor plates (IDP), Outboard divertor plates (ODP), Inboard passive stabilizers (IPS), Outboard passive Stabilizers (OPS), Main baffle (MBAF), Inboard limiters (I-Lim) and Outboard limiters (O-Lim).Each IDP, ODP, IPS, OPS and MBAF has top and bottom modules which enable SST-1 to produce elongated D-shaped double null divertor plasma. Divertors are specially designed for steady-state removal of heat energy escaping out of the plasma core region and placed to intercept the magnetic flux surfaces immediately outside the last closed flux surface of the plasma core region. Thus most of the plasma particles escaping out of the last closed flux surface are diverted so as to dump their energy on to the divertors. Pair of inboard and outboard divertor are installed in SST-1 to extract dumped energy of particle escaping out of the plasma. Main baffle is positioned in between inboard and outboard divertor structure to provide closed divertor geometry which ensures high neutral pressure in the divertor region for effective pumping and reduction in electron temperature due to high recycling. Set of inboard and outboard poloidal limiters are installed diagonally opposite in SST-1 which assists plasma breakdown, current ramp-up and ramp-down during steady state operation. Outboard limiter is designed to move which provides effective protection to RF antenna and other in-vessel components during steady state operation and events like VDEs and disruption. The elongated plasma column in tokamak is intrinsically unstable to vertical displacements which leads to plasma disruption and also causes large halo currents to flow in nearby structures. It is very necessary to stabilize this instability in plasma by active or passive feedback control. Having a conducting structure in inboard side and outboard side surrounding the plasma like Inboard and outboard passive stabilizers suffice the requirement of passive feedback control to stabilize vertical displacements in plasma. Some of the major parameters of SST-1 tokamak are listed in table 1.

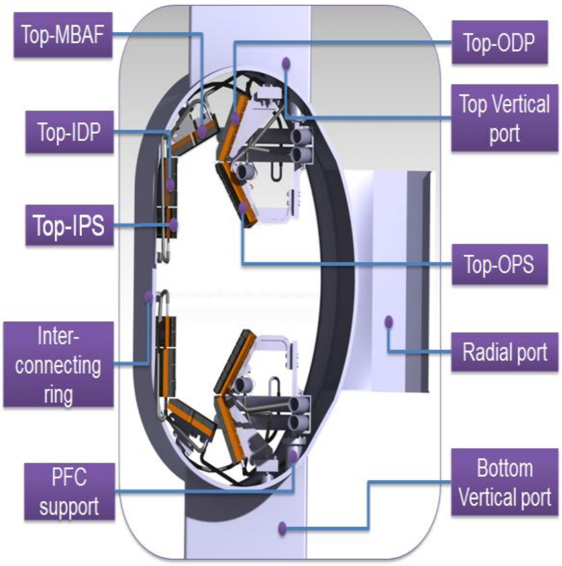

Figure 1. Elevation view of PFC inside vacuum vessel of SST-1

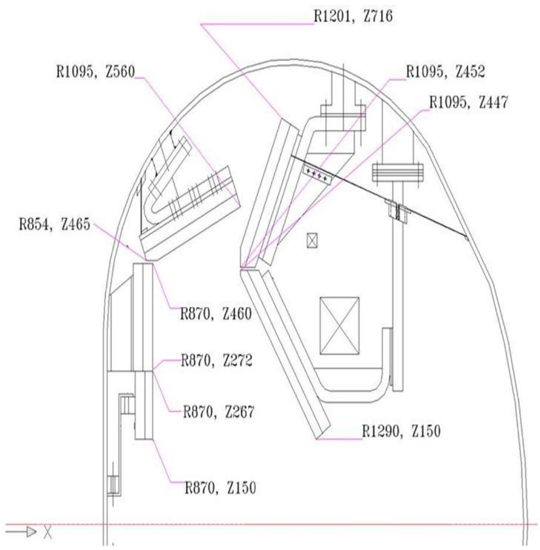

Figure 2. Elevation view showing coordinate of PFC with respect to machine axis.

Table 1. Major SST-1 machine parameters.

Parameters	**Values**
Major radius	1.1 m
Minor radius	0.2 m
SS surface area of VV	75 m^2
Exposed surface area of PFC	40 m^2
Plasma species	Hydrogen
Volume enclosed by PFC	16 m^3
Steady State Heat Flux	
Main Baffle	0.25 MW/m^2
In / Outboard Passive Stabilizer	0.25 MW/m^2
In / Outboard Divertor Plate	0.6 MW/m^2
In / Outboard Poloidal Limiter	1.0 MW/m^2

Each PFC module was fabricated from copper alloys (CuCrZr and CuZr) back plates on which graphite tiles were mechanically attached using graphoil in between so that the incident heat flux could be removed very fast. Passive stabilizers require high electrical conductivity in order to reduce the growth of vertical instability which has taken care by using CuZr back plate. This alloy gives good electrical conductivity without suffering degradation in mechanical properties at higher temperature ~350 °C. The normal incident peak heat flux on each PFCs is different due to provided angle/inclination to each of them. The components like ODP, OPS, IDP and IPS were mounted parallel to VV due to space constraints which still have average incident heat flux in tolerable limits.

SS pipe of 10.0 mm internal diameter (ID) and 1.0 mm thickness was brazed at the backside of these modules through which water will be flown to remove such incident heat flux. The layout of one of the module is shown in figure 3. Since SST-1 Tokamak is designed to operate for 1000 s in double-null configuration, the temperature of PFC modules may rise from room temperature (RT) to beyond the copper alloy melting point. CuCrZr and CuZr copper alloys degrade at 400 ^{o}C while the electrical property of CuZr degrades at 150 ^{o}C. Therefore, it is necessary to maintain the temperature of these components well below these limits.PFCs of SST-1 machine have 139 numbers of copper alloy back plates.The geometrical parameters for each PFCs is listed in table 2.

Table 2. Geometrical parameters of Plasma facing components of SST-1.

Module	IDP	ODP	IPS	OPS	MBAF	ILIM	OLIM
Poloidal Length (m)	0.187	0.267	0.117	0.330	0.264	0.290	0.290
Toroidal Length (m)	0.644	0.460	0.648	0.415	0.375	0.180	0.310
No. of Modules (Top + Bottom)	16	32	20	32	32	02	02
Area of each module (m^2)	0.126	0.128	0.073	0.143	0.092	0.052	0.090
Length of brazed Tube (m)	2.62	3.09	1.70	2.90	1.85	1.45	1.16
Copper Alloy	CuCrZr	CuCrZr	CuZr	CuZr	CuCrZr	CuCrZr	CuCrZr
Nos. of Graphite tile	480	1024	256	960	1024	48	72

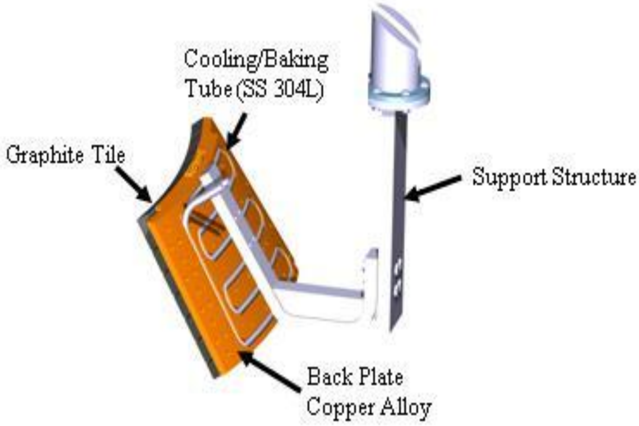

Figure 3. Typical PFC module

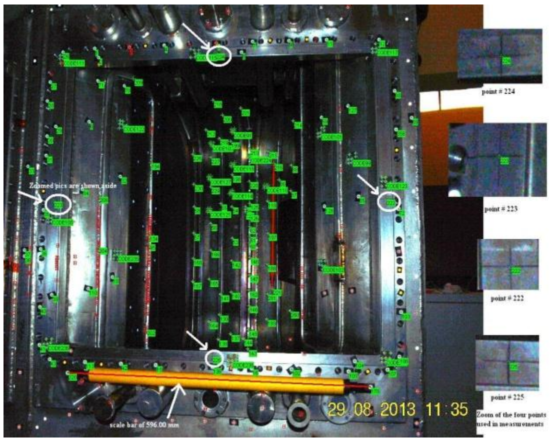

Figure 4. Typical PFC module

2. Metrology and assembly of PFC on SST-1 prototype vacuum vessel

For accurate assembly of PFCs into SST-1 machine, the methodology of assembling was developed and implemented in SST-1 Prototype for feasibility study. Electronic co-ordinate determining system (ECDS) and Photogrammetric measurement were carried out during the prototype assembly. The initial measurement of XYZ co-ordinate was carried out by ECDS instrument to establish the reference point for in-vessel measurements. Many coded and un-coded targets were mounted on the surfaces of VV as shown in figure 4.The interested area is scanned using DSLR camera and then 3-D models were generated using AUSTRALIS 7.0 software. For comparison of measurements, some common points were marked and measured by both ECDS and Photogrammetry. An accuracy of 0.8 mm over 500mm and 1.9 mm over 1600 mm was achieved in measurements using Photogrammetry relative to ECDS. A plot depicting the error in measurements between ECDS and Photogrammetry is shown in figure 5. Mock up assembly of back plate and support structure of PFC in prototype vacuum vessel is shown in figure 6.

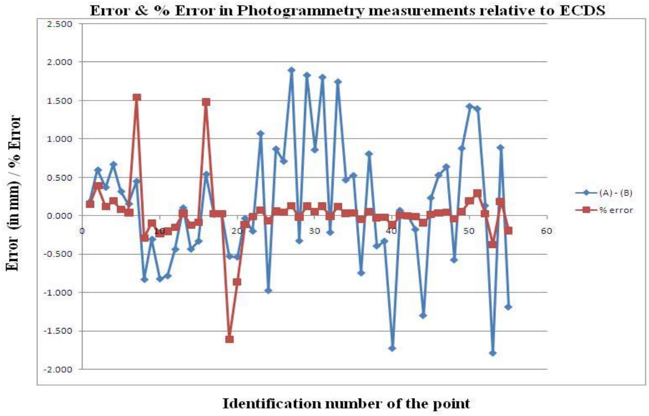

Figure 5. Error and % error in Photogrammetry measurements relative to ECDS

Figure 6. Back plate and support structures are installed in prototype Vessel.

3. Engineering validation of hydraulic scheme and PFC modules.

Hydraulic scheme for PFC baking / cooling was designed [5] considering the constrains like (a) the space available inside the VV, (b) the reduction of number of weld joints & their accessibility for repair and (c) the uniform flow distribution. The entire hydraulic scheme was distributed through two supply headers at the top and other two supply headers at the bottom. Each top and bottom configuration has a return header. Top / bottom MBAF, IDP and IPS were in series and fed through top two supply headers each having 11 parallel sub-connections while top / bottom ODP and OPS were in parallel and fed through the bottom two supply headers each having 16 parallel sub-connections as shown in figure 7. Prior to assembly of PFCs inside SST-1 VV, all copper alloy back plates along with their header piping, bellows and isolators were qualified for leak tightness at the operating temperature of 250 °C. A dedicated test facility was developed in which a number PFCs, their headers along with associated components as per design scheme were baked under high vacuum condition and qualified for final assembly into SST-1 VV as shown in figure 8.For baking the high temperature nitrogen gas at 250 °C 2.5 bar(a) pressure was flown through the circuit. A number of K-type thermocouples were mounted at different places of the entire scheme so that the temperature distributions though out the system could be monitored and maintained accordingly.

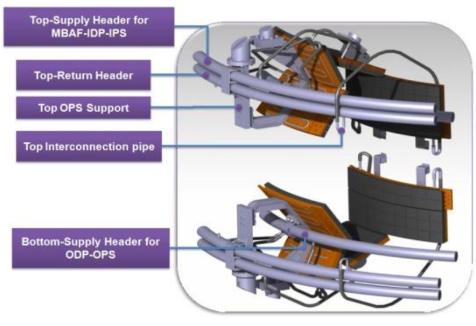

Figure 7. Hydraulic scheme for baking cooling of PFC modules.

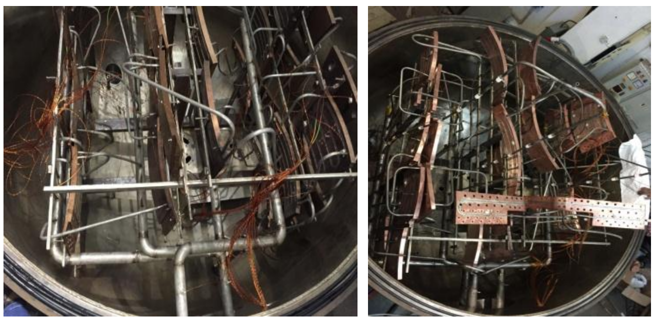

Figure 8. Baking facility for PFC modules, and and Header pipe, isolators and bellows.

Figure 9 shows the temperature profile during baking of copper alloy back plates. It shows that PFCs were baked in excess to 250 °C for few hours as per designed configuration. After baking for few hours, the entire circuit was cooled to RT and the leak testing of copper modules, bellows, isolators were carried out and found to leak tight after baking.

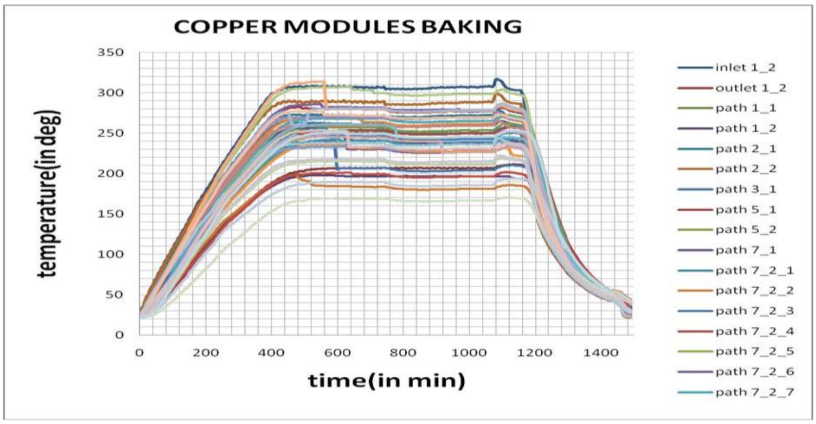

Figure 9. Temperature plot of PFC copper alloy back plates.

4. Assembly and integration of PFC in SST-1 vacuum vessel

Support structures of all the modules as shown in figure 1 were marked in SST-1 main vacuum vessel and installed sequentially. Mechanical templates and Go and Not-go gauges were used to ensure the alignment and the space between each module during assembly. During assembly, combined ECDS and Photogrammetric measurements were carried out for confirming the coordinates. Appropriate mechanical spacers and shims were used wherever required to correct alignment of the components with respect to other modules and machine axis. Figure 10 and figure 11 shows assembled PFCs in SST-1 machine.

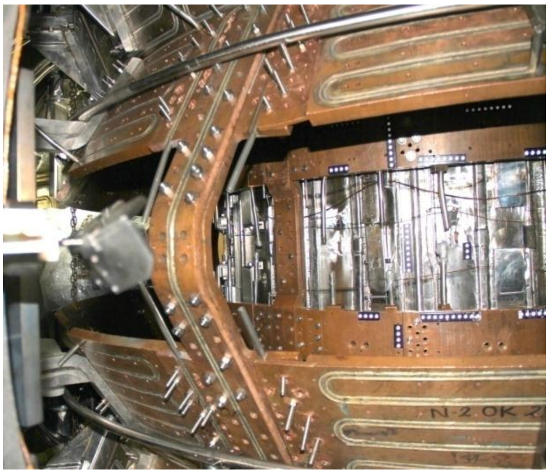

Figure 10. Full assembly of copper module in SST-1 main vessel.

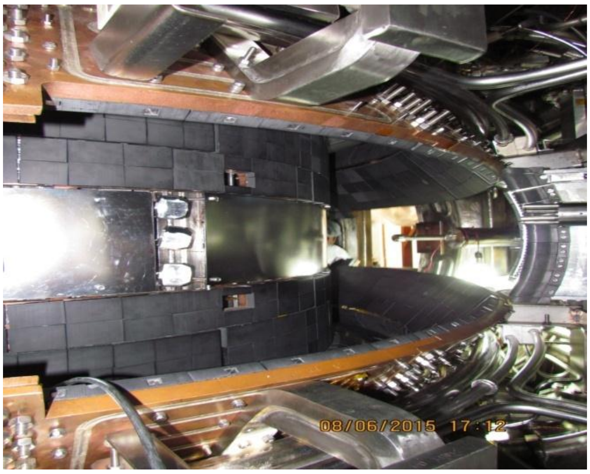

Figure 11. Final assembly of PFC modules in SST-1 main vessel.

Graphite tiles were mechanically bolted on copper alloy back plates. Graphoil sheet is sandwiched between the back plate and graphite tile to increase the thermal contact between them. Ultra-high vacuum (UHV)compatible mineral insulated thermocouples were mounted on each copper module and on graphite tiles to maintain and monitor the temperature. During assembly, the baking/cooling headers were also installed back-to-back prior to final assembly of PFC. Also the interconnecting piping were laid and connected from modules to respective supply and return headers. Each and every weld joints were leak tested in both vacuum and sniffer modes using helium gas. Vacuum leak test for the leak tightness of ~ 1.0×10^{-8} mbar l/s was ensured while the leak tightness ~ 1.0×10^{-6} mbar l/s at 7.6 bar(g) pressure was ensured for Sniffer mode. During the first attempt of PFCs baking at 250 °C, the VV temperature [6] started rising beyond 160 °C due to radiation. In order to avoid the VV from additional thermal stress, the VV temperature was restricted below 150 °C. Nitrogen gas baking system is than modified, in which a bypass line from condenser is separately laid and connected to vessel supply line. During baking, room temperature nitrogen gas will be supplied to vacuum vessel simultaneously high temperature gas for PFC. In order to bake PFC to 250 °C hot nitrogen gas is passed at 2.5 bar(a) having supply temperature of 385 °C and mass flow rate of 0.95 kg/s. Figure 12 shows assembled Plasma Facing Components in SST-1 tokamak were successfully baked to 250 °C for a duration of 170 hours.

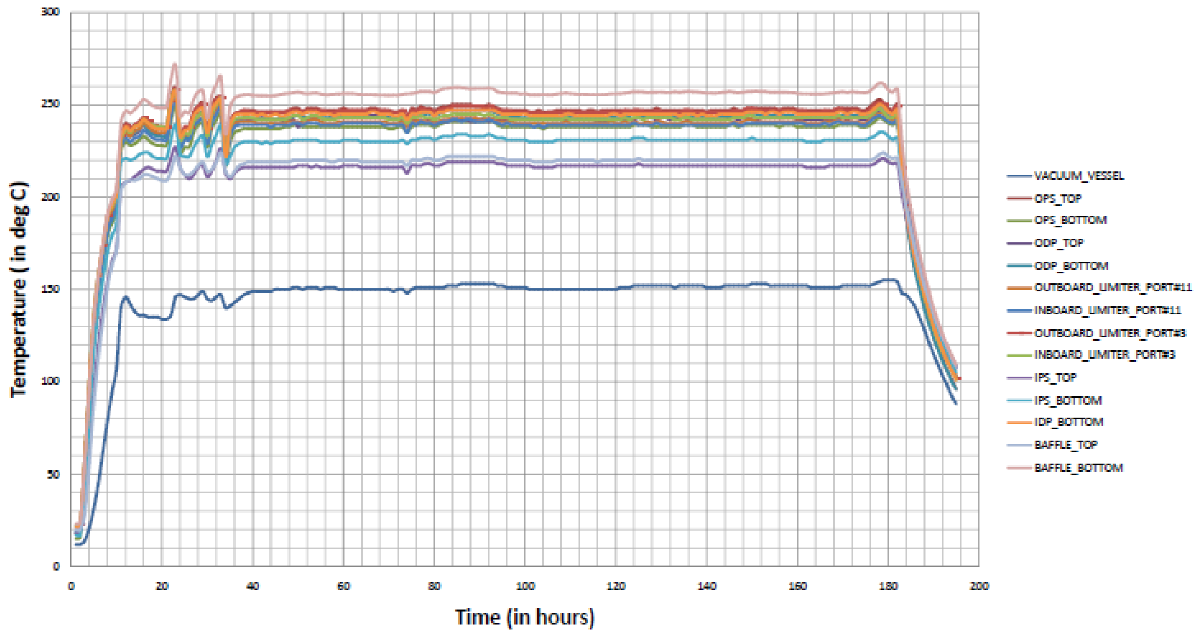

Figure 12. Temperature profile of various PFC modules during baking.

5. Conclusion

Assembly of complete PFCs system was successfully carried out in SST-1 tokamak with an accuracy of ± 3.6 mm. Also the performance of PFCs was satisfactorily demonstrated under Ultra High Vacuum conditions. The temperature distribution among PFCs was found to be within the limit of ± 12 °C. During and after baking, all the weld joints, isolators and flexible bellows were found to the leak tight as per design requirements. With integrated PFCs, we have demonstrated a plasma break down of 65 kA plasma current for 250 ms duration.

Acknowledgement

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References

[1] Pradhan S and Team SST-1 mission 2010 *J. Fusion Res. Series* **9** 650.
[2] Pradhan S, Sharma A N, Tanna V L, Khan Z, Prasad U et al. 2012 *IEEE Trans. Plasma Sci.* **40** 614
[3] Khan Z, Pathan F, Gorge S, Dhanani K R, Yuvakiran P et al. 2014 *IEEE Transaction on Plasma Science* **42** 1006
[4] Jacob S et al. 1996 *Journal of Nuclear Materials* **233-237** 655
[5] Paravastu Y, Khan Z and Pradhan S 2015 *Fusion Engineering and Design* **98-99** 1375
[6] Khan Z, Paravastu Y and Pradhan S 2014 *Procedia Materials Science* **6** 216