Plasma Facing Components Technologies in SST-1

D. C. Raval, Z. Khan, Y. Paravastu, S. George, K. R. Dhanani, P. Semwal, A. Prakash A, G. R. Babu, M. S. Khan, P. Thankey, F. S. Pathan & S. Pradhan.

Institute for Plasma Research, Bhat, Gandhinagar 382428, Gujarat, India

E-mail: raval@ipr.res.in

Abstract. SST-1 Tokamak was successfully commissioned in 2012 and the first plasma was achieved in June 2013 with poloidal limiters having SS 304L as vessel wall material. Due to plasma wall interactions, high-Z impurities released from the vessel wall which in turn cools the plasma by radiation loss. In order to reduce this effect, in 2ndphase of SST-1 refurbishment PFC components were installed in the system. PFCs were integrated inside SST-1 vacuum vessel which is designed to withstand an input heat load of 1.0 MW/m^2. Graphite was chosen as Plasma facing material considering its good thermal properties, low atomic mass. Cu-Zr& Cu-Cr-Zr alloys plates embedded with SS 304L piping were used as back plate materials for proper heat conduction. Each and every component was tested at their functional conditions to verify its functionality and to ensure operation conformity. Approximately 3800 tiles were mounted on 132 numbers of copper alloys back-plates. The total surface area of the installed PFCs exposed to plasma is about 40 m^2 which is nearly 50% of the total surface area of stainless steel vacuum chamber (~75 m^2). The volume of the vessel with the PFCs is ~ 16 m^3. Gas-to-gas heat exchange method was adapted to heat nitrogen gas which is pressurized using dedicated gas blower system to bake the PFC components. All PFC components passed through temperature of 250 °C for 8 hours flat top and working pressure of 4 bar(a) under UHV conditions in validation testes. Strict metrology and QA/QC plans were structured and executed to integrate the PFC components inside the vacuum vessel. During pump down of SST-1 main vacuum vessel, PFCs were baked at 250 °C for nearly 10 days to remove the absorbed water vapours. At this condition, this main vacuum vessel was maintained at 150 °C. In addition, initially hydrogen discharge cleaning was carried out followed with subsequent helium discharge cleaning to removeother surface impurities. With all PFCs and diagnostic integrated to the system, a base pressure of 4.5×10^{-8} mbar was achieved.
This paper represents SST-1 post PFC Plasma-scenario, PFC requirement inciting factors, PFC architecture and lay-out details, PFC components experimental validations, metrology plan with QA/QC and final installation of PFC with the vacuum vessel.

1. Introduction

Plasma Facing Components (PFCs) of SST-1 Tokamak [1-4] consists of Inboard divertor plates (IDP), Outboard divertor plates (ODP), Inboard passive stabilizers (IPS), Outboard passive stabilizers (OPS) and main baffle (MBAF) along with their headers & sub-headers. Each IDP, ODP, IPS, OPS and MBAF has top and bottom modules completing SST-1 first wall structurally continuous in toroidal direction. Graphite was chosen as Plasma facing material considering its good thermal properties and low atomic mass. Copper Zirconium (Cu-Zr) & Copper Chromium Zirconium (Cu-Cr-Zr) alloys plates embedded with SS 304L piping were used as back plate materials for proper heat transfer during baking and cooling operations. Approximately 3800 tiles were mounted on 132 numbers of these copper alloys back-plates. Some of the major parameters of SST-1 Tokamak are tabulated in Table I while geometrical parameters of Cu-back plates are provided in Table II.

TABLE I: 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

TABLE II: GEOMETRICAL PARAMETERS OF Cu-BACK PLATES OF SST-1 PFC

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
Copper Alloy	CuCrZr	CuCrZr	CuZr	CuZr	CuCrZr	CuCrZr	CuCrZr

2. Metrology, Qualification and Engineering validationof PFC components

Before assembly of PFCs into SST-1 machine, the methodology of assembling was developed and implemented in SST-1 Prototype for feasibility study. Both Electronic Co-ordinate Determining System (ECDS) and Photogrammetric measurement were carried out during the prototype assembly. The reference co-ordinate was established by ECDS instrument for in-vessel measurements. Many coded and un-coded targets were mounted on the surfaces of vacuum vessel as shown in Fig. 1. The interested area is scanned using camera optimized to read targets and then 3-D models were generated using AUSTRALIS 7.0 software (Fig. 1). For referencing of measurements, some common points were marked and measured by both ECDS and Photogrammetry. An accuracy of 0.8 mm over 500 mm and 1.9 mm over 1600 mm was achieved in measurements using Photogrammetry relative to ECDS.

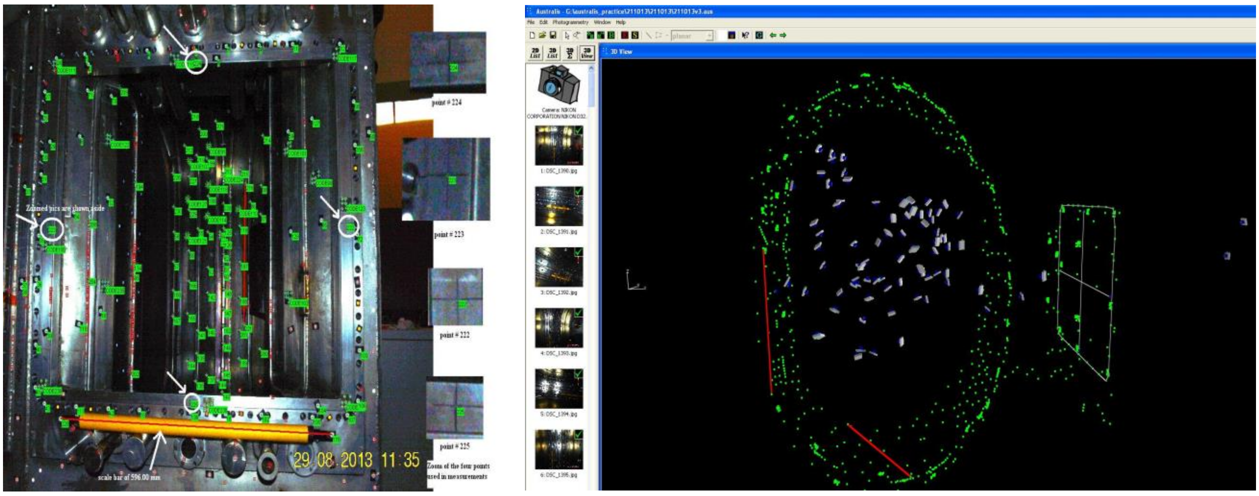

FIG. 1. Coded and un-coded targets mounted on prototype vacuum vessel and co-ordinate generation in AUSTRALIS 7.0 software.

During fabrication of PFCs, since bending, annealing and vacuum brazing were carried out, these processes may have induced deformation in copper alloy back plates. In order to get accurate deformed shape, PFC modules were scanned under Co-ordinate measuring machine (CMM) which generates co-ordinates of modules. These co-ordinates were transferred to CATIA software where scanned one was superimposed to reference model tomeasure the deviation. Figure 2 shows the superimposing of scanned and reference model of main baffle with the bar showing deviation in dimension.

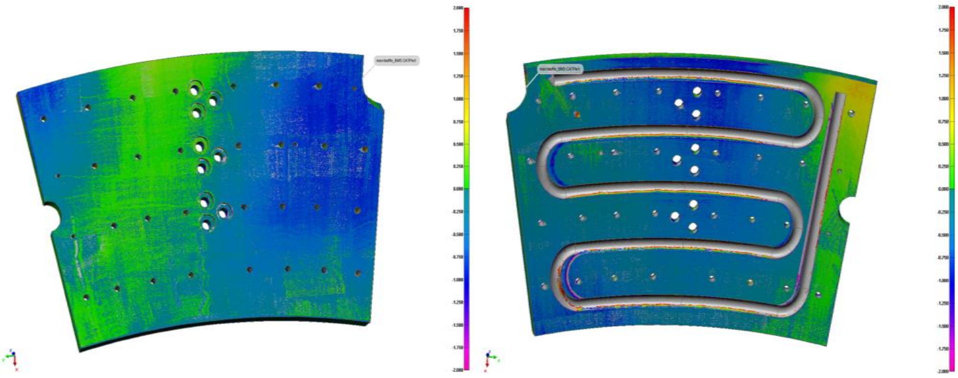

FIG. 2. Superimposed image of reference model and scanned model of Main baffle.

Before installation into SST-1 machine, all copper alloys back plates along with their brazed piping were baked at 250°C for engineering validation at operating condition.Also, fluid isolators and bellows which are most important part of hydraulic design to ensure the electrical isolation between IPS and OPS modules were integrated to hydraulic lines for validation at working condition.Copper modules, bellows, fluid isolators along with their hydraulic circuits were kept inside a high vacuum chamber for baking purpose as shown in Fig. 3. Hot nitrogen gas at 2.5 bar(a) and 300 °C was passed through these back plates and a temperature flat-up of eight (08) hours was maintained. A few numbers of temperature sensors were mounted at different places of entire circuitry to monitor and maintain the temperature of the modules. Figure 4 shows the temperature of copper modules and fluid isolators reaching in excess of 250°C during baking ensuring the validation of hydraulic design [5]. After baking for few hours, the entire circuit was cooled to room temperature (RT) and the leak testing of copper modules, bellows and fluid isolators were carried out in vacuum mode as well as in sniffer mode. All these components were found to be leak tight at the order of 1.0×10^{-8} mbar l/safter baking in vacuum mode.

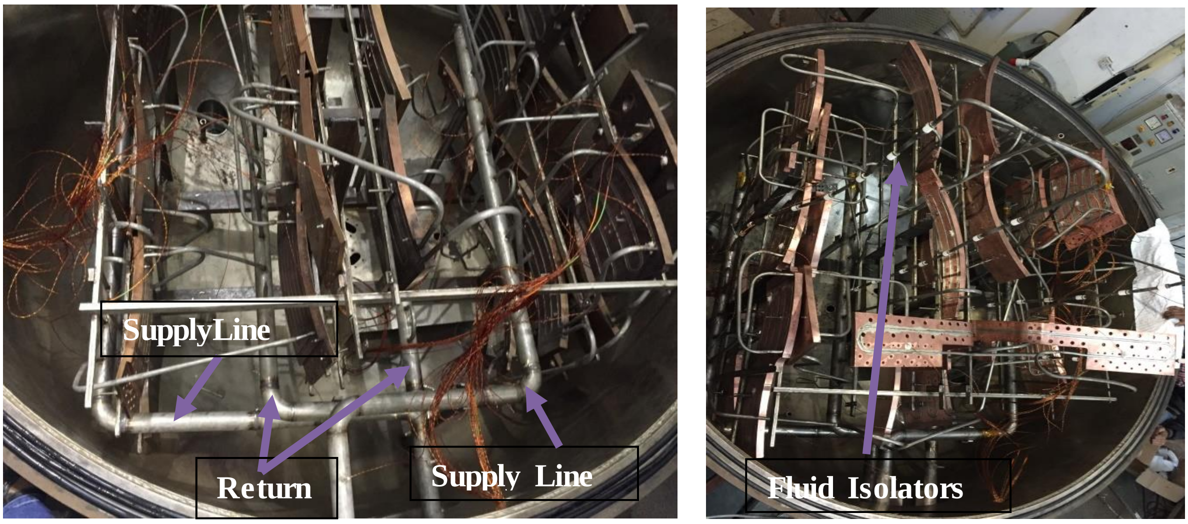

FIG. 3. Baking qualification of copper modules and fluid isolators.

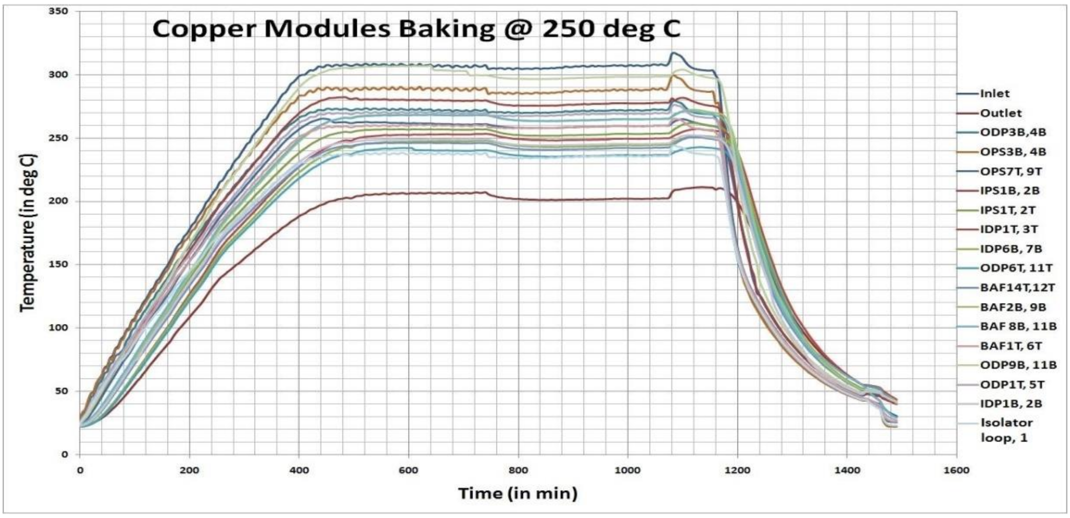

FIG. 4. Temperature profile of PFC copper back plates and fluid isolators.

3. Methodology of Assembly of PFC in SST-1 Machine

After establishing the metrology, a model for assembly sequence (Fig. 5) was developed to assemble all 132 numbers of copper back plate including hydraulics piping layout in SST-1. During assembly in SST-1 machine, 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. Graphite tiles were mechanically bolted on copper alloy back plates. During assembly, the baking/cooling headers were also installed back-to-back prior to final assembly of PFC. Assembly of IPS ring in Vacuum vessel and the complete first wall assembly is shown in Fig. 6. Vacuum leak test for the leak tightness of ~ 1.0×10^{-8} mbar l/s was ensured while the leak tightness of ~ 1.0×10^{-6} mbar l/s at 7.6 bar(g) pressure was ensured for Sniffer mode for assembly into SST-1 machine vacuum vessel.

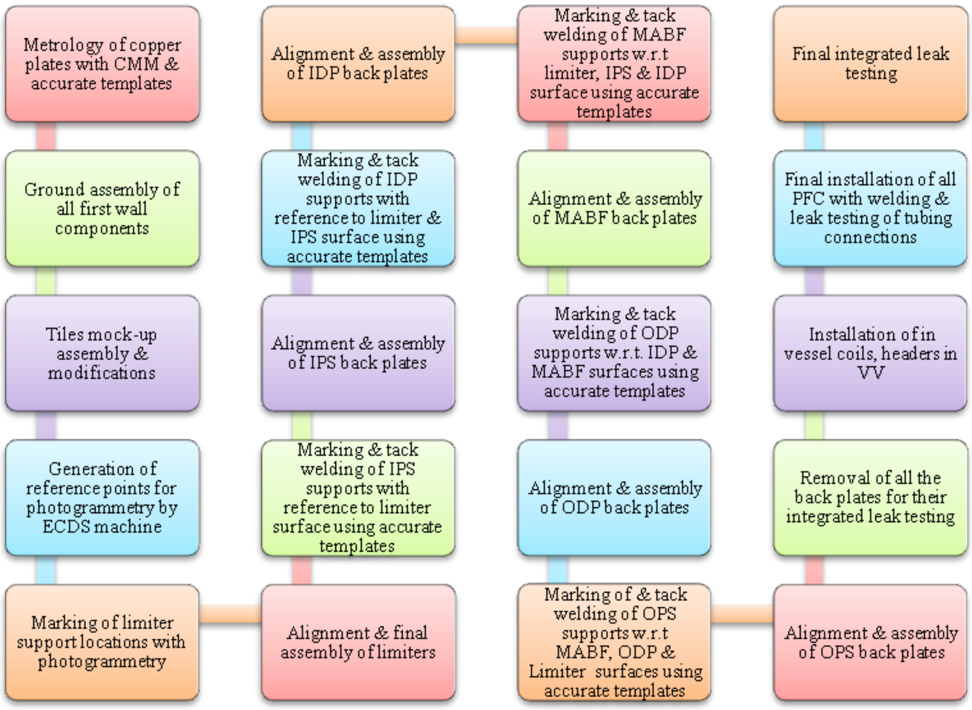

FIG. 5. sequence of activity carried out for assembly of PFC in SST-1 machine.

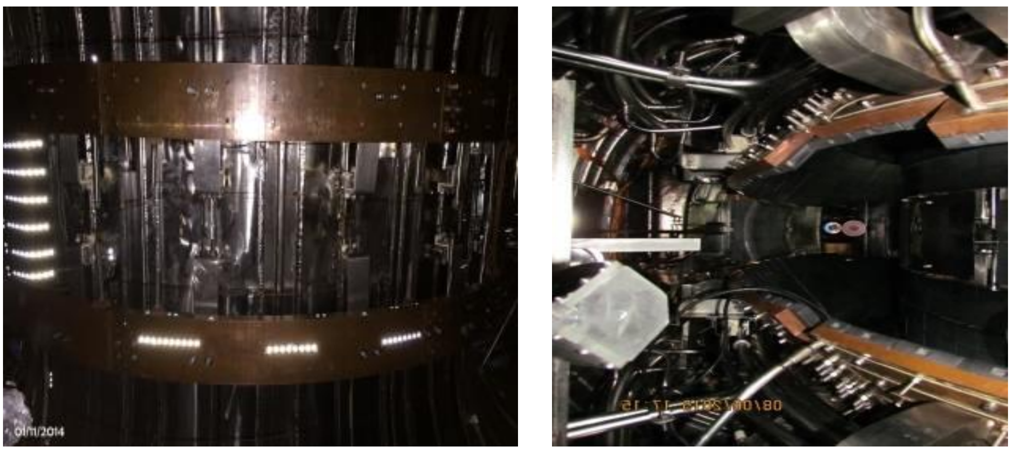

FIG. 6. Assembly of IPS ring in Vacuum vessel, complete first wall assembly.

4. Pumping and Bakingeffects in SST-1 vacuum vessel assembled with PFC

The vacuum vessel (VV) was initially pumped down from atmosphere to 1.0×10^{-3} mbar using a single roots pumping station of 1800 m^3/h pumping speed. Two turbo-molecular pumps (TMPs) with a net pumping speed of 3250 l/s (N_2 gas) were mounted at diagonally opposite radial ports (R-3 & R-11) of VV [6], each having an electro-pneumatic gate valve. Eight numbers of TMPs were also installed at the top diverter while another eight numbers of

TMPs were at the bottom divertors for diverter pumping during long pulse plasma operation. Each divertor TMP set has a net pumping speed of 1750 l/s (N_2 gas). All these eighteen sets of TMPs were situated at a place where the transverse magnetic field is less than 30 gauss. A residual gas analyzer (RGA) and some vacuum gauges were mounted in one of the pumping lines. RGA was operated time to time for measuring the partial pressures of different gases as well as the leak tightness of the vacuum vessel. Also a cryopump with a net pumping speed of 1400 l/s (water vapour) was installed at the radial port R-7. Only four TMPs and the cryopump were under operation for pumping purpose.After achieving a base pressure of 1.5×10^{-5} mbar inside the VV, baking of VV and PFCs was carried out in a controlled manner by flowing hot nitrogen gas at required temperature through the respective baking channels in a closed loop.Ultra-high vacuum (UHV) compatible mineral insulated K-type thermocouples were mounted on each copper module and on graphite tiles to maintain and monitor the temperature. During baking of VV and PFCs, the pumping lines were maintained at 100°C using heating pads. During the first attempt of PFCs baking at 250°C, the VV temperature [7] 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 was than modified, in which a bypass line from condenser was separately laid and connected to vessel supply line. In order to bake the PFCsat 250 °C, hot nitrogen gas was passed at 2.5 bar(a) having supply temperature of 385°C and mass flow rate of 0.4 kg/s. During this PFC baking, room temperature nitrogen gas was also flown simultaneouslyto vacuum vessel. Fig. 7 shows the assembled Plasma Facing Components in SST-1 tokamak successfully baked to 250°C for duration in excess of 250 hours.

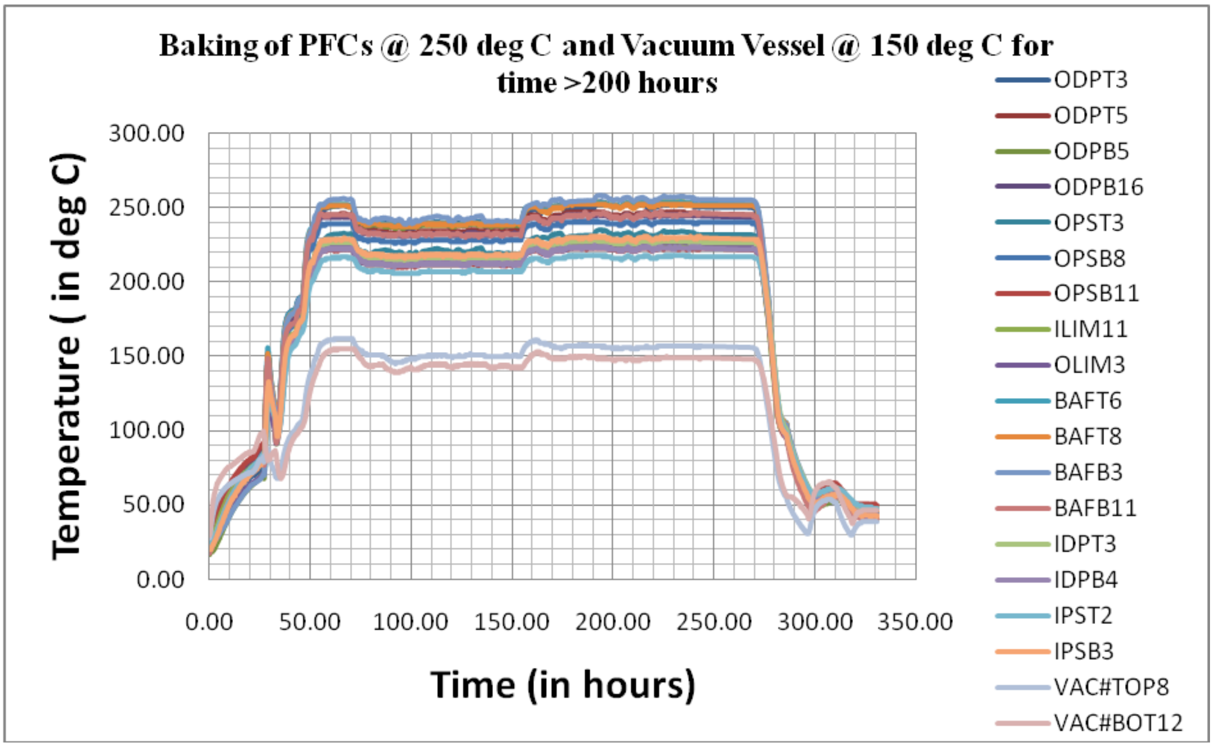

FIG. 7. Temperature profile of PFC and vacuum vessel during PFC baking.

RGA scan of VV before bake out at a total pressure of 6.17×10^{-7} mbar is shown in Fig. 8(a). Most dominant peak is observed at mass no18 which indicates the presence of large amount of water vapour inside the vessel. In order to remove it, the VV and PFCs were baked at an average temperature of 120°C and 230°C respectively for about 20 hrs. After baking, the ultimate vacuum achieved at room temperature (RT) inside VV was 1.07×10^{-7} with six (06) numbers of turbo-molecular pumps (TMP) having a total effective pumping speed of 10,140 l/s (for N_2). RGA spectra of the vessel acquired after baking is shown in Fig. 8(b). It can be seen that there is a decrease in the partial pressure of mass no. 18 by a factor of ~ 10 after bake out.

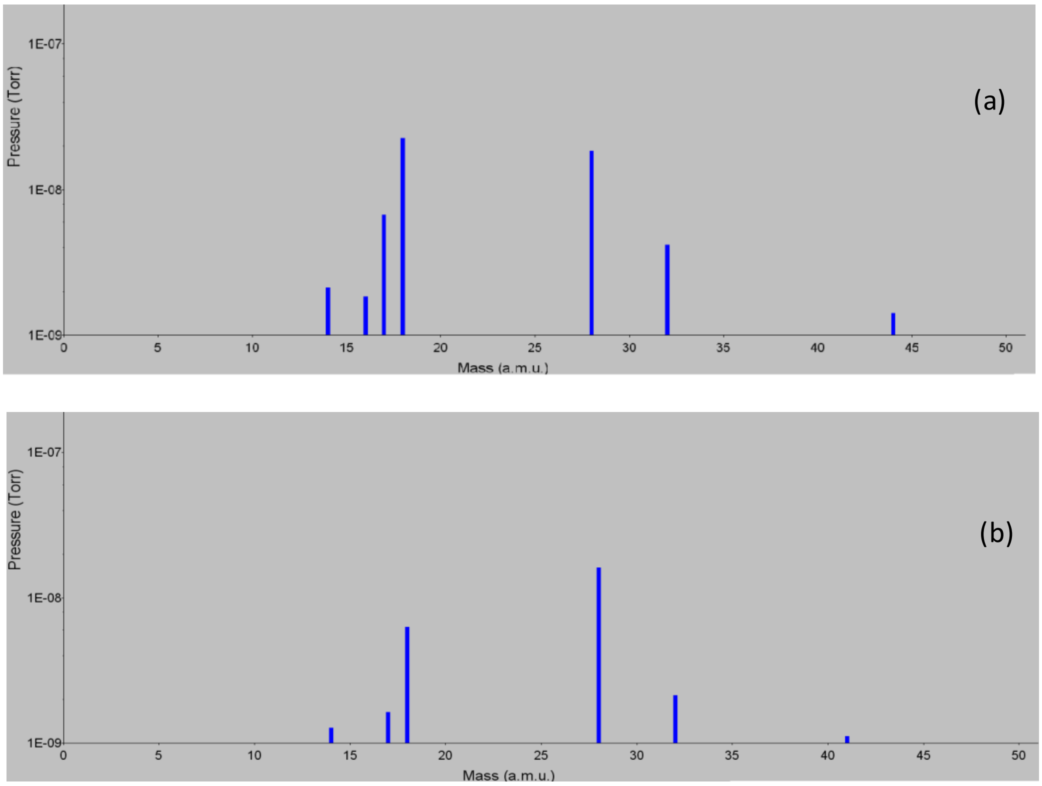

FIG. 8. (a) RGA scan of unbaked VV, (b) RGA scan of VV at RT after bake out.

5. Conclusion

Assembly of complete PFCs system was successfully carried out in SST-1 tokamak with an accuracy of ±3.6 mm. SST-1 vacuum vessel and graphite based PFCs were baked successfully at temperatures of 150°C and 250°C respectively for few days and 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. This baking has been found effective in removing the water vapour absorbed in the bulk of graphite of PFCs. The experimental campaign of October 2015, the circular plasma breakdown of 65 kA current for 250 ms was demonstrated. The pumping system, baking system, gas feed system and GDC have been successfully and continuously operated for months without any fault. No major problems or serious deviation were observed which could affect the plasma operation indicating satisfactory performance of PFCs under Ultra-High Vacuum condition.

Acknowledgement
We acknowledge Mr. Tejas Parekh, Mr. Hitesh Patel, Mr. Prabal Biswas and Mr. Prosonjit Santra for extending valuable support in Qualification and Assembly aspects of PFC installation in SST-1 Tokamak.

References

[1] S. Pradhan, Z. Khan, V.L. Tanna, et. al, Nuclear Fusion (2015) 55 104009.
[2] Pradhan S and Team SST-1 mission 2010 *J. Fusion Res. Series* **9** 650.
[3] Pradhan S, Sharma A N, Tanna V L, Khan Z, Prasad U et al. 2012 *IEEE Trans. Plasma Sci.* **40** 614
[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, Pathan F, Gorge S, Dhanani K R, Yuvakiran P et al. 2014 *IEEE Trans. Plasma Sci.* **42** 1006
[7] Khan Z, Paravastu Y and Pradhan S 2014 *Procedia Materials Science* **6** 216