Initial results in SST-1 after up-gradation

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Abstract. SST-1 Tokamak has recently completed the 1st phase of up-gradation with successful installation and integration of all of its First Wall components. The First Wall of SST-1 comprises of ~ 3800 high heat flux compatible graphite tiles being assembled and installed on 132 CuCrZr heat sink back plates engraved with ~ 4 km of leak tight baking and cooling channels in five major sub groups equipped with ~ 400 sensors and weighing ~ 6000 kg in total in thirteen isolated galvanic and six isolated hydraulic circuits. The phase-1 up-gradation spectrum also includes addition of Supersonic Molecular Beam Injection (SMBI) both on the in-board and out-board side, installation of fast reciprocating probes, adding some edge plasma probe diagnostics in the SOL region, installation and integration of segmented and up-down symmetric radial coils aiding/controlling plasma rotations, introduction of plasma position feedback and density controls etc. Post phase-I up-gradation spanning from Nov 2014 till June 2016, initial plasma experiments in up-graded SST-1 have begun since Aug 2016 after a brief engineering validation period in SST-1. The first experiments in SST-1 have revealed interesting aspects on the ‘eddy currents in the First Wall support structures’ influencing the ‘magnetic Null evolution dynamics’ and the subsequent plasma start-up characteristics after the ECH pre-ionization, the influence of the first walls on the ‘field errors’ and the resulting locked modes observed, the magnetic index influencing the evolution of the equilibrium of the plasma column, low density supra-thermal electron induced discharges and normal ohmic discharges etc. Presently; repeatable ohmic discharges regimes in SST-1 having plasma currents in excess of 65 KA (q a ~ 3.8, BT = 1.5 T) with a current ramp rates ~ 1.2 MA/s over a duration of ~ 300 ms with line averaged densities ~ 0.8 × 10 19 and temperatures ~ 200 eV with copious MHD signatures have been experimentally established. Further elongation of the plasma duration up to one second or more with position and density feedback as well as
coupling of Lower Hybrid waves are currently being persuaded in SST-1 apart from increasing the core plasma parameters with further optimizations and with wall conditioning.

1. Introduction

The Steady State Superconducting Tokamak (SST-1) is a ‘working’ experimental superconducting device since late 2013. In the long term, SST-1 envisages steady state operation in both the single null and double null configurations in large aspect ratio configurations [1]. The primary magnetic configurations and plasma shaping magnetic requirements are provided by Superconducting Magnet Systems (SCMS) comprising of sixteen superconducting D-shaped Toroidal Field (TF) magnets and nine superconducting Poloidal Field (PF) magnets together with a pair of resistive PF coils inside the vacuum vessel. An air-core Ohmic transformer together with three pairs of resistive compensating coils along with a 500 kW, 500 ms Gyrotron are used for the pre-ionization, initial break-down and initial current start-up. A pair of resistive vertical field magnets outside the cryostat placed symmetrically around the mid plane provides the initial equilibrium. Figure 1 shows the various components of SST-1 machine shell.

![Figure 1. 3D cut view of SST-1 Machine](image)

Table 1. Major SST-1 machine parameters (PFC related)

| Parameters                  | Values          |
|-----------------------------|-----------------|
| Major radius                | 1.1 m           |
| Minor radius                | 0.2 m           |
| SS surface area of VV        | 75 m²           |
| Exposed surface area of PFC | 40 m²           |
| Plasma species              | Hydrogen        |
| Volume enclosed by PFC      | 16 m³           |

2. SST-1 Up-gradation (Phase-1)

During 2014-15, the major up-gradations in SST-1 has been carried out involving PFC integration, cryogenic flow distribution and control (IFDC) system and SMBI system for gas fuelling.
2.1. PFC Up-gradation
SST-1 Tokamak was successfully commissioned in 2012 and the first plasma was obtained in June 2013 with poloidal limiters having SS 304L as vessel wall material. In the phase-1 up-gradation [2], Graphite based PFCs designed to withstand an input heat load of 1.0 MW/m² have been mounted on a back plate made of Cu-Zr & Cu-Cr-Zr alloys embedded with SS 304L piping to carry the heat away. Approximately 3800 tiles have been mounted on 132 numbers of copper alloys back-plates on a surface area of 40 m² on a vacuum vessel volume of ~ 16 m³. PFC components are baked up to 250 °C for twenty four hours under UHV conditions using hot nitrogen baking system while keeping the vacuum vessel at 150 °C.

SST-1 Prototype is used for first installation of plasma facing components along with supports using combination of ECDS (Electronic co-ordinate determining system) and Photogrammetric measurements. Mechanical templates and Go and No-go gauge were made to ensure the alignment and space between each module during assembly. Then after, full assembly of copper modules was carried out in SST-1 main vessel. Appropriate mechanical spacers and shims were used to correct alignment of the components with respect to other modules and machine axis.

Graphite tiles are mechanically bolted on the back plate with a graphoil sheet in between to ensure good thermal contact whereas the temperature of the back plate is monitored with thermocouples. In continuation to PFC assembly, the interconnecting pipes are also laid to connect different modules with supply and return headers for baking and cooling. As a part of PFC conditioning, baking of components is carried out at 250 °C for extended duration (figure 5). Afterwards, prior to plasma experiments hydrogen discharge cleaning followed by extended helium discharge cleaning are usually carried out.
2.2. IFDC Up-gradation
Hydraulic imbalances and thermal run way had been observed amongst the different hydraulic path lengths of PF coils systems. The original PF distribution scheme had a single control valve for the entire PF magnets. The flow distribution scheme has been subsequently modified (figure 6 and figure 7) balancing the hydraulic impedances to various unequal PF flow paths. With these modifications and up-gradations, the cooling down in PF magnets has now been devoid of thermal run away.

2.3. SMBI system for SST-1 Tokamak
The currently adopted fueling techniques in Tokamak devices include conventional gas puffing (GP), supersonic molecular beam injection (SMBI) and pellet injection (PI) etc. Among these methods, SMBI is found to be better as compared to GP and is technically simpler in comparison to PI. The fueling efficiency of SMBI is around 30 – 60 %, about three to four times higher than the conventional gas puffing (GP). SMBI can also enhance the penetration depth and the fueling
efficiency. A higher fueling efficiency, reduced gas-wall interaction and therefore a lower wall saturation limit have been observed in L-mode plasma experiments in limiter tokamaks. In divertor tokamak experiments with the supersonic gas jet, a fueling efficiency of 10 – 30% has been reported. In SST-1 machine, two Laval nozzles made up of SS 304L with throat diameters of 0.5 mm and 1.0 mm are installed at high field side (HFS) at the port locations 7 and 10 respectively. The taper angle is 12° – 15° for these two nozzles having the exit diameters of 5.0 mm & 10.0 mm with lengths of 12.6 mm and 30 mm respectively.

The initial characterization of the nozzle for flow rate and injection rate was carried out in the laboratory using a chamber of 50 mm diameter and 400 mm length (figure 8). The cylinder is connected to a turbo-molecular pump having an effective pumping speed of 150 l/s. The pressure inside the chamber was maintained at ~ 1.0 × 10⁻² Pa. A laser source (405 nm, 5 mW) was mounted horizontally with a fast imaging camera mounted perpendicular to the line of sight of laser as shown in figure 9.

Figure 8. Schematic of experimental set-up

Figure 9. Fast imaging data.

3. Initial validations of PFC equipped SST-1 circular plasma

3.1. Eddy current Aspects and Equilibrium Re-construction

Eddy currents temporal and spatial characteristics have altered in PFC equipped SST-1 compared to earlier limiter equipped SST-1 and thereby was influencing the transient field errors and subsequently the magnetic NULL and break-down characteristics. A detailed quantitative distribution of the eddy current in the electrically continuous SST-1 vacuum vessel have been computed employing the array of internal voltage loops (flux loop) and with the help of simple circuit model [3-4]. The computed results from this model have been benchmarked against experimental measured integrated eddy current. The computed values and the experimentally measured values are in good agreement. The calculated eddy current based on flux loop signal and circuit equation model have been extended towards the reconstruction of the vessel magnetic field line (B-field) for SST-1. Comparison between the field line of plasma and vacuum shot explains the plasma current contribution from all other sources also.
The eddy current (figure 10) and magnetic field (figure 11) for eddy has been computed through a MATLAB code using simulated data calculated from each vessel sectional current and location of the segment and cryostat position. The inductance and resistive effect of vessel segments have also been included here. Results show under representative conditions, the maximum Eddy current has been computed to be ~ 15 kA. The rate of change of current in the central solenoid \((dI_{OT}/dt)\) and the sudden disappearance of plasma current during the disruptions are the primary sources of eddy currents apart from sudden plasma movements. The computed eddy current distributions including their temporal behaviour shall be extended to plasma equilibrium and electromagnetic modelling \([5]\) as well as plasma discharge process in future.

3.2. Magnetic flux surfaces and Radial Shafranov shifts in SST-1 Tokamak Plasma

Magnetic flux surface contours of SST-1 tokamak plasma have been computed from the magnetic probes, flux loops experimental data and from the analytical solution \([6]\) of Grad-Shafranov equation (GSE). SST-1 plasma, at the present phases of operations is circular in shape and leans against the limiters. The radial Shafranov shift \((\Delta R)\) \([7]\) from the above formulations has been calculated from experimental measurements.

Figure 10. Total vessel eddy current profile and \(I_p\), \(I_{OT}\), \(I_{VF}\) (red) for plasma shot no 7161

Figure 11. The eddy B-field contours of plasma shot 7161

Figure 12. Plasma current \((I_p)\), Plasma Radial shift \((\Delta R)\) & Vertical Field current \((I_{VF})\) for SST-1 Shot No: 7161.

Figure 13. Magnetic flux surface for SST-1 shot no 7161 at time instant 100ms at maximum plasma current \((I_p)\).
Since the control of plasma position plays an important role in plasma confinement and optimized
tokamak operations, this \( \Delta R \) would be used as a plasma position feedback control parameter in long
duration SST-1 plasma experiments later. The plasma flux surface contours computed (figure 13) as
above have also been approximately compared with the time synchronized fast imaging signals of the
SST-1 plasma. These comparisons shows a good agreement between the real time trends of plasma
position shift at the equilibrium regions with those seen with fast imaging.
The plasma current and applied vertical field current (\( I_{VF} \)) have been plotted at top and bottom of
figure 12.
The Radial Shafranov shift (\( \Delta R \)) has been measured [8-9] using the described flux loops and
magnetic probes.
The flux surface contours computed following these prescriptions have been in good agreement
with the experimental data from a large number of SST-1 plasma shots. The radial Shafranov shift
measured using the flux loops and magnetic probes are also in good agreement, repeatable and
reliable. Plasma currents up to 65kA have been obtained repeatedly at a central field of 1.5 T as
shown in figure 14.

4. Future Plans
SST-1 presently aims at improving the plasma current up to 110 kA at a central field of 1.5 T,
improve the plasma density and temperature characteristics, implementing several controls in the
current profile through an in-house developed control system within the prevailing hardware
constraints. The near future plans include plasma current flat-top elongation, extending the plasma
duration assisted with LHCD as well as integrating a MW level Neutral Beam Injection system to
SST-1.
5. Summary

SST-1 has been upgraded with graphite first wall and is now a compatible Tokamak towards long pulse plasma in both circular and elongated cross sections. Initial experiments have begun in SST-1 and plasma currents in excess of 65 kA with typical core density ~ 0.8 × 10^{19} m^{-3} and core electron temperatures ~ 200 eV having duration in excess of 250 ms corresponding to q_{edge} ~ 3.8 have been obtained. The pre-ionization induced break down, eddy current induced NULL dynamics, subsequent plasma start-up, copious MHD activities, mode locking and other signatures of standard Tokamak plasma have been obtained. The circular equilibrium has been reconstructed from experimental signals and has been validated with imaging measurements.

SST-1 experiments observe the MHD instabilities such as saw teeth, m/n = 1/1 and m/n = 2/1 tearing modes, similar to the observations reported by other Tokamaks. Study of such MHD instabilities and disruption characteristics will be useful for the subsequent disruption mitigation and avoidance strategies in long pulses of SST-1.

References
[1] Pradhan S, Khan Z, Tanna V L et. al. 2015, Nuclear Fusion 55 104009
[2] Jacob S et al. 1996, Journal of Nuclear Materials vol. 233-237 pp. 655-659
[3] Jana S , Pradhan S et. al (accepted 2016), Fusion engineering and design
[4] Gates D A, Menard J E et. al 2004 , Review of scientific instruments 75(12) 5090.
[5] Leuer J A et al., 2010 Fusion science and technology 38(3) 333
[6] Solovev L S et al., 1968 Soviet Physics JETP 26(3) 333
[7] Mukhovatav V S and Shafranov V D, 1971 Nuclear Fusion 11 605.
[8] SalarElahi A and Ghoranneviss M, 2012 Journal of Nuclear and Particle Physics 2(6)142.
[9] Rahimirad A, Emami M et al 2010, Journal of Fusion Energy 29 73.