The Determination of Plasma Radial Shafranov Shift ($\Delta R$) and Vertical Shift ($\Delta Z$) experimentally using Magnetic probe and Flux loop Method for SST-1 Tokamak

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Abstract. The radial Shafranov shift ($\Delta R$) and vertical shift ($\Delta Z$) has been calculated for steady state superconducting tokamak (SST-1) experimentally using magnetic probes and flux loops. The SST-1 plasma at the present phases of operations is circular in shape and leans against the limiters. The radial and vertical shift formulated from Shafranov equation have been used for computation. We have selected best possible pairs of flux loops and magnetic probes location for the measurements. The comparison of results obtained from these two methods also has been performed for numerous numbers of shots for repeatability and reliability purpose. We have observed that the results of both the methods are in good agreement for almost all SST-1 experiment campaigns. Since the control of plasma position plays an important role in plasma confinement and optimizing tokamak operations, the computed $\Delta R$ and $\Delta Z$ could later on be used as a control parameter for feedback control of plasma position in SST-1.

1. Introduction

Steady state superconducting tokamak (SST-1) [1, 2] has been commissioned since June 2013 and is in operations since then. SST-1 produces circular ohmic plasmas having maximum currents of $\sim 100$ kA in a central field of $1.5$ T for a maximum duration of $\sim 400$ ms. Experimental efforts are presently underway for extending the duration of SST-1 plasma beyond 1 second. SST-1 being a highly complex and multivariate device, it necessarily requires inputs from several sensor signals that will be computed upon using suitable algorithms for generating feedback signals for actuators. The study carried out would be helpful in incorporating robust and precise feedback control system and in turn obtaining long duration confined plasma in SST-1.

In ohmically heated low beta ($\beta < 1$) tokamaks, the plasma equilibrium is achieved by the controlled vertical field for radial force balance of outward hoop force. In force balance problem, the opposite force may not be equal and therefore plasma intends to shift inward or outward and experiences a radial Shafranov shift ($\Delta R$) and vertical shift ($\Delta Z$). It is considered as one of the critical problem for tokamak plasma control and equilibrium studies. The Grad-Shafranov analytical solution and different experimental methods [3-7] are available to measure the plasma horizontal shifts. This paper describes calculation of radial Shafranov shift ($\Delta R$) and vertical shift ($\Delta Z$) in section 2 and 3 followed by result, analysis and conclusion.
Table 1. Parameters of SST-1 Tokamak.

| Parameters       | Values       |
|------------------|--------------|
| Major radius ($R_0$) | 1.1 m       |
| Minor radius ($a_0$) | 0.2 m       |
| Toroidal Field        | 1.5 T       |
| Plasma current ($I_p$) | $\sim$ 100 kA |
| Plasma Duration       | $\sim$400 ms |
| surface area of VV    | 75 m$^2$    |
| Plasma species        | Hydrogen    |
| Operating pressure range | $5.0 \times 10^{-6}$ mbar |

Figure 1. 3D cut view of SST-1 Machine.

Figure 2. (LEFT) Plasma current ($I_p$), Central solenoid current ($I_{OT}$) and Vessel pressure  
(RIGHT) ECRH Power, Internal loop voltage and External loop voltage for SST-1 shot # 7712

SST-1 plasma formation is dependent on synchronization of its different systems and sub systems. The primary magnetic configuration is provided by Super- Conducting Magnet Systems (SCMS) comprising of sixteen superconducting D-shaped Toroidal Field (TF) magnets and nine superconducting Poloidal Field (PF) magnets. An air core Ohmic Transformer (OT) with ECRH system is used for the pre-ionization, break-down and initial current start-up. A pair of resistive vertical field magnets outside the cryostat are placed symmetrically around the mid plane to provide the initial equilibrium. The particle environment within the plasma chamber is maintained using gas puffing. Figure.1 shows various components of SST-1 machine shell. In figure 2, plasma current ($I_p$), central solenoid current ($I_{OT}$), vessel pressure, ECRH Power, internal loop voltage and external loop voltage for specimen shot # 7712 has been shown.
2. Radial Shift and Vertical shift Methods

2.1. Radial Shafranov shifts Calculation

For determination of the radial plasma position, we have considered both installed magnetic flux loop and magnetic probes. The positions of the flux loops and probes [8] in SST-1 machine used for this method has been presented in figure 3 and figure 4 in a cross sectional view.

Radial shafranov shift ($\Delta R_p$) can be written as equation (1) and have been computed from magnetic probes [6, 9].

$$\Delta R_p = \frac{a_0^2}{a} \left( \left( \frac{a^2}{a_0^2} - 1 \right) - 2 \ln \frac{a_0}{a} \right) + \frac{\pi a^2}{2 \mu_0 J_p} \left\{ \Delta B_\theta \left( 1 - \frac{a_0^2}{a^2} \right) + \Delta B_r \left( 1 + \frac{a_0^2}{a^2} \right) \right\}$$

where, $a_0$, $a$, $R_0$, $\Delta R_p$ are the plasma minor radius (0.2m), chamber minor radius(0.35m), major radius, shift using magnetic probes and $\Delta R_l$ is measured using magnetic probes.

$$\Delta R_l = \frac{a_0}{R_0 \mu_0 J_p \cos \theta} \Delta \psi$$

where, $\Delta \psi = \psi_{P_{out}} - \psi_{P_{in}}$ and $\psi_{P_{out}} = \psi_{out} + B_o \Delta S_o$ and $\psi_{P_{in}} = \psi_{in} + B_i \Delta S_i$.

Figure 3. (Left) Schematic diagram of flux loop orientation and (Right) orientation of flux loops in SST-1 machine (marked in red dotted circle is used for measurement).

The $\psi_{P_{out}}$ and $\psi_{P_{in}}$ have been measured using outer and inner flux loop respectively. The $B_o$ and $B_i$ are the average magnetic field between outer and inner flux loops and plasma surface (LCFS)
respectively obtained from magnetic probes, $\Delta S_i$ is the intervening area for internal loop and $\Delta S_o$ is the intervening area for external loop as per figure 3 (Left) and experimental result have been observed as per figure 5. We have used two set of flux loops (upper and lower) for radial shafranov shift measurement in SST-1. The lower flux loop (G, K) and upper flux loop (F, B) used are located as shown in figure 3 (Right) schematic diagram. According to Faraday’s law, outputs of all magnetic diagnostics are proportional to the derivatives of the magnetic flux that pass through them. Therefore, the output of flux loops and magnetic probes signals are integrated after some compensation. A compensation technique is used to compensate central solenoid and VF current field contributions on probe and flux loop diagnostics signals. Necessarily, the compensation signals are the vacuum shot signals for the given ohmic and vertical field coil current profiles.

2.2. Vertical shifts Calculation

For determination of the vertical plasma position, we have used magnetic probes, their location and orientation is described in figure 4.

The vertical shift ($\Delta Z$) can be measured from the below formulation [6]

$$\Delta Z = \frac{\pi a_o^2}{\mu_0 P} \Delta B_{2\theta}$$

where $a_o$, $a$, $R_0$, $\Delta Z$ are the plasma minor radius (0.2 m), chamber minor radius (0.35 m), major radius, vertical shift using magnetic probes and $\Delta B_{2\theta} = B_{\theta}(\theta = 3\pi/2) - B_{\theta}(\theta = \pi/2)$. The experimental result observed for specimen shot no 7712 is shown in figure 5.

3. Results and Analysis

In figure 5, the plasma current ($I_P$) and applied vertical field current ($I_{VF}$) is shown plotted on top and bottom of the figure respectively. The radial Shafranov shift ($\Delta R$) has been measured using the described flux loops and magnetic probe method. The vertical shift ($\Delta Z$) is computed using magnetic probe method. For the shot under discussion, a pre-profiled vertical field has been applied (without using any feedback control method). It was observed that the plasma gets formed initially inboard side and maintains a stable position for some time before moving towards outboard side due to the inadequate availability of vertical field at the end. The pre-profiled VF ($I_{VF}$) reference signals take care of the vacuum vessel penetration time that is ~12 to 13 ms.

Figure 4. The Schematic orientation of Magnetic Probe (marked in red dotted circle is used for measurement).
4. Observations and Conclusions
The Radial Shafranov shift measured using the flux loops method and magnetic probes methods are in good agreement, the results obtained are consistently repeatable in most of the shots and hence said to be reliable. To verify the results, the comparison and repeatability test with other diagnostics such as imaging was also carried out. The same trends of plasma movement were found between magnetic and imaging diagnostics, more details can be found in reference [10]. The studies carried out here on $\Delta R$ and $\Delta Z$ computations, later will be used as one of the vital input parameter in plasma position feedback control system to achieve long duration plasma discharges in SST-1.

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References
[1] Pradhan S and Team SST-1 mission 2010 J. Fusion Res. Series 9 650
[2] Pradhan S et al. 2015 Nuclear Fusion 55 104009
[3] Rahimirad A et al. 2010 Journal of Fusion Energy 29(1) 73
[4] Salar Elahi A and Ghoranneviss M 2012 Journal of Nuclear and Particle Physics 2(6) 142
[5] Shafranov V D 1963 Journal of Nuclear energy 5 251
[6] Salar Elahi A and Ghoranneviss M 2010 Brazilian journal of physics 40(3) 323
[7] Zheng S B, Wootton A J and Solano E R 1996 Physics of plasmas 3 1176
[8] Raju D et al. 1997 Fusion Engineering and design 34-35 717
[9] Ninomiya H and Suzuki N 1982 Japanese journal of applied physics 21(9) 1323
[10] Jana S et al. 2016 Accepted in Fusion Engineering and Design with title “Magnetic flux surfaces and radial Shafranov shifts($\Delta R$) in SST-1 Tokamak Plasma”