Observation of MHD phenomenon for SST-1 superconducting tokamak

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Abstract. Steady State Superconducting Tokamak (SST-1) is a medium size Tokamak (major radius $R = 1.1$ m, minor radius $r = 0.2$ m) and is operational at the Institute for Plasma Research (IPR), India. In the last few experimental campaigns SST-1 has successfully achieved plasma current in order of 60-70kA and plasma duration in excess of $~500$ ms at a central magnetic field of $1.5$T. An attempt has made to study the behavior of the magneto-hydrodynamic (MHD) activity during different phases of plasma pulse which leads to major/minor disruptions, its present modes (poloidal/toroidal mode number i.e. $m = 2$, $n = 1$) impact on plasma confinement and signature of lock mode and its frequency in the SST-1 plasma using experimental data from Mirnov signals. Observed MHD phenomenon has also been correlated with other diagnostics (i.e. ECE, Density, Soft X-Ray etc.) and heating system (ECRH) for the recent campaigns of SST-1.

1. Introduction
Steady State Superconducting Tokamak (SST-1) is a medium size Tokamak (major radius $R = 1.1$ m, minor radius $r = 0.2$ m, toroidal magnetic field $B_t = ~1.5$ T) in operation after successful refurbishment since June 2013. [1] During last few campaigns, experiments at SST-1 has successfully produced circular ohmic plasmas having current $~102$ kA and plasma duration in excess of $~400$ ms at the central toroidal magnetic field (TF) of $1.5$ T. The plasma is generated by a resistive central solenoid (ohmic transformer) with the pre-ionization being provided by a 42 GHz Electron Cyclotron source.

Analysis of the experimental data from prior/post plasma facing components (PFC) campaigns shows that major disruptions in the plasmas are always connected with MHD phenomenon. MHD instability is limiting factor for improving plasma. Many tokamaks use Mirnov coils for the detection of plasma instability (e.g. mode locking activity, saw teeth activity etc.) during the discharges. SST-1 has Mirnov Diagnostic consists of an array of Mirnov coils to measure the fluctuations in magnetic field at the plasma edge. Structurally Mirnov coil arrays are distributed in both Toroidal and Poloidal directions to gather the information on mode structure, mode number and mode frequency during disruption. In SST-1, there are arrays of eight in-vessel poloidal Mirnov coils and four in-vessel toroidal Mirnov coils are installed to gather the information regarding MHD activities.

At SST-1, MHD activity has been observed during different phases (Ramp-Up, Flat-Top and Ramp-down) of plasma pulse which leads to major/minor disruptions. The analysis includes multiple Mirnov bursts with increasing amplitude and locked modes (phase locking between modes) which leads to degradation of confinement and discharge terminates permanently [5].
analysis also includes to study its present mode (poloidal/toroidal mode number i.e. m = 2, n = 1) and its impact on plasma confinement. Fast Fourier Transform (FFT) for understanding dominant frequency component, Wavelet spectrogram for time resolved frequency for cross confirm with dominant mode frequency, Singular Value Decomposition (SVD) analysis for spatial structure of mode number, magnetic island width (W) and rate of island growth (dW/dt) during lock mode duration [3,8].

In this paper, the major disruption caused by mode lock instability has been studied. It has observed that during mode locking, the frequencies of the mode rotation gradually slow down while the MHD instabilities grow up, and then mode lock appears when the rotation stops suddenly. Due to the mode locking, as the plasma cannot flow through a large island at any significant rate, it is leads to a stopping of the plasma rotation at the resonant surface and an appreciable slowing down of the plasma as a whole due to viscous coupling [2,7]. The modes do not lock at every crash, but when they do, this sequence is extremely reproducible and obviously harmful to the plasma confinement. [5] Some times after a minor disruption the plasma pressure and rotation recovers, but MHD activity may reappear and slowing-down process starts again. This may sometimes leads to a series of minor disruptions. [6]

2. Lock mode observation at SST-1 plasma

Observation started with analyzing mode locking duration for different plasma pulses, found out its present mode (poloidal/toroidal mode number i.e. m = 2, n = 1) using SVD [8] and its co-relation with drift frequencies.

For ohmic heated plasmas, the rotation frequency of magnetic perturbation is about the
electron drift frequency \( f_{De} \) [2, 4].

\[
\hat{f} \approx f_{De} \propto \frac{kT_{e0}}{eB_a\alpha^2}
\]

where \( k \) is the Boltzmann constant and \( T_{e0} \) is the central electron temperature.

At SST-1, mode lock instability has been observed at different phases of the plasma pulse (ramp-up, flat-top and ramp-down), which leads to degradation of confinement or majorly terminates the discharges abruptly. In particularly, it has observed that they more dominant to appear in low density discharges [2, 4].

Statistical observation on mode lock instabilities encourages studying the characteristics of field errors influencing the mode rotations and its co-relation with drift frequencies [2,3] for the plasma at SST-1. Rotational frequencies have been calculated before and during mode lock occurrence to find out its drift frequency.

To understand the conditions leading to locked mode instabilities, onsets of disruptions are also correlated with other SST-1 diagnostics. (e.g ECE Radiometer, Density from Homodyne diagnostic, Soft-Xray etc.).
Figure 1. Shot#6440 (1) Plasma Current kA (Ip), (2) ECRH power (kW), (3) Soft X-ray signal (4) Density measurement from Homodyne(1e12) diagnostic (5) ECE Signal (6) Mirnov signal shows lock mode bursts during ramp-down phase of Plasma Current (Ip)

Figure 2. Zoomed time range of Mirnov signal during lock mode duration at ramp-down phase: Lock mode bursts during the 205-215ms duration for poloidal Mirnov coils

In figure 1, Mirnov signal observes the lock mode bursts at ramp-down phase during 205-215 ms. From many experimental data at SST-1, it has observed that sometimes minor disruption
occurs at ramp-up phase but plasma pressure and rotation recovers and plasma current sustains. In this typical shot # 6440, major MHD activity has appears during ramp-down phase (during 205-215 ms), which have resulted in degration of confinement followed by major disruption.

It has observed that during major disruption, multiple Mirnov bursts are observed with increasing amplitude (figure 2), which leads to frequencies of the mode rotation gradually slows down and results in degration of confinement. As shown in figure 1, during mode locking duration (205-215 ms), major disruption occurs and it has co-related with the reduction/degration of temperature/density (from Homodyme diagnostics)/ECE signals with plasma current.

3. Analysis
In typical shot # 6440, from the lock mode duration (205-215 ms), found out its present mode using Singular Value Decomposition (SVD)[8] shows $m = 2$ (figure 4), predominantly mode (poloidal). As shown in figure 3, dominant frequency component is $\sim 1$-15 kHz; in the same figure Wavelet spectrogram also shows the same for time for the resolved frequency.

![Figure 3. FFT & spectrogram of Mirnov (m6)](image1)

![Figure 4. Shot # 6440-SVD shows m = 2](image2)

Figure 5 shows the rotational frequencies before and during the mode lock duration and found out its drift frequency. For the representative shot # 6440, it has observed that rotational frequency has reduced to $\sim 37\%$ during lock mode duration (205-215 ms).

In figure 5, in 1st phase (Before lock mode), the Mirnov signal representing the magnetic perturbations are rather a harmonic, indicating a gradual slowing down of the plasma. In 2nd phase (or during island growth), the frequency drops an harmonic, indicating that the mode no longer rotates with constant angular velocity. This behaviour can be due to the combination of two different forces acting on a rotating magnetic perturbation (1) due to the interaction with the external error field or (2) due to the eddy currents induced in the resistive wall [7]. As shown in figure 5, reduction of rotational frequencies during lock mode event is $\sim 37\%$ for typical shot # 6440.
Figure 5. Shot # 6440 Rotational frequency reduction before/ during mode locking period

From experimental data of SST-1, statistically it has observed that the rotational frequency has reduced ~ 32-48 % during lock mode duration. Table 1 shows \( f_{de} \) (kHz) calculated is in the range with what had achieved during \( f_{experimental} \) kHz in many shots, shows the theoretic predications is very consistent with the experimental results, which are in range with other similar contemporary devices (e.g. COMPASS-C, DIII-D, HL-1M) [2,4].

Table 1. SST-1’s \( f_{de} \) calculated & \( f_{experimental} \) is matching with other contemporary devices.

| Tokamak       | \( T_{e0} \) (eV) | \( B_{t} \) (T) | \( R_{0} \) (m) | \( a \) (m) | \( f_{De} \) (kHz) | \( f_{experimental} \) (kHz) |
|---------------|-------------------|-----------------|----------------|-----------|-------------------|-----------------------------|
| COMPASS-C*    | ~ 600             | 1.1             | 0.56           | 0.18      | ~ 15              | ~ 13                        |
| DIII-D*       | ~ 920             | 1.3             | 1.67           | 0.67      | ~ 1.7             | ~ 1.6                       |
| HL-1M*        | ~ 700             | 2.1             | 1.02           | 0.26      | ~ 3.2             | ~ 3.1                       |
| SST-1#        | ~ 280             | 1.5             | 1.1            | 0.2       | ~ 4.7#            | ~ 4.61                      |

* [2, 4]  
# for representative shot#6440, Campaign 12.

4. Summary and conclusion
The lock modes in the SST-1 have obvious similarities with other devices. It occurs at any phase (ramp-up, flat-top or ramp-down) during the discharge and lead to degrade the confinement. In major disruption it remains locked until termination. The analyzed results shows major disruptions were observed within a few milliseconds after the occurrences of the mode lock instabilities. Generally it appears with low density discharges. The rotational frequency has reduced to ~ 32-48 % during mode lock. The study is going on to suppress the mode locking instability, inherence error field and to increase the plasma density.
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References
[1] Pradhan S et al. 2015 *Nuclear fusion* **55** 104009 (10pp)
[2] Qingwei Y et al. 2002 *Brazilian Journal of Physics* **32** 160
[3] Asif M et al. 2005 *Physics Letters A* **342** 175
[4] La Haye R J, Fitzpatrick R et al. 1992 *Physics of Fluids B: Plasma Physics* **4** 2098
[5] Almagri A F, Assadi S, Prager S C et al. 1992 *Phys. Fluids B* **4** 4080
[6] Vries P C de et al. 1996 *Plasma Phys. Control. Fusion* **38** 467
[7] Zohm H 2014 *Magnetohydrodynamic Stability of Tokamaks* (Wiley-VCH: Garching, Germany) p 146-152
[8] Dhongde J, Bhandarkar M, and Pradhan S 2016 *Fusion Engineering and Design* **108** 77