

Instability Analysis in Aditya Tokamak Discharges with the help of Soft X-ray

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Sawtooth oscillations (internal disruptions) and major disruptions are routinely observed in ohmically heated Aditya tokamak discharges. Soft x-ray (SXR) tomography has been used as the main tool to analyse the instabilities in the tokamak discharges along with other supportive diagnostics. SXR tomography is done with the help of a single array of detectors assuming rigid rotation of the modes to analyse the mode structure of internal disruption. The dominant frequencies obtained by the fast Fourier transform (FFT) analysis of the signal at the time of internal disruption are the harmonics of the same mode which are common in toroidal system. The presence of such harmonics makes the signal non-sinusoidal and could easily couple in resonance with the mode oscillations at higher q -surfaces to accelerate the major disruption. The growing $m/n=1/1$ oscillation at the time of internal disruption and the tomographic images indicate that the sawtooth instabilities seem to be due to the total reconnection model by Kadomtsev, but the crash time according to Kadomtsev model does not obey the observed experimental value. The $m/n=1/1$ mode rotation is also clear at the time of internal disruption from the tomographic images. After analysis of all other probable possibilities coupling of $m/n=2/1$ and $m/n=1/1$ modes appears to be the main mechanism for the major disruption. Singular value decomposition (SVD) method has been used to analyse the time series of tomographic reconstructions to identify the dominant magnetohydrodynamic modes and to show different features of the spatio temporal evolution of the emissivity distribution.

Keywords: Internal disruption, total disruption, SVD analysis, magnetohydrodynamic modes, SXR tomography, tokamak.

1. Introduction

The understanding of sawtooth instability (internal disruption) in tokamak plasma which consists of a slow increase in the central temperature and density followed by a sudden collapse is still incomplete, though a lot of explanations have been given to elucidate the phenomenon. Early explanation in terms of single magnetic reconnection model given by Kadomtsev [1] is believed to explain sawtooth oscillation in small tokamaks [2-4]. But this model can not explain the fast sawtooth crash, large precursors and presence of large slowly decaying successive oscillations, the presence of giant and monster sawtooth [5] and recently the evidence that q -factor at the center remains below unity throughout the sawtooth phenomenon [6] which is generally observed in large tokamaks. Though Wesson's quasi interchange model [7] out of many attempts to explain the phenomena is successful to predict many aspects of soft x-ray (SXR) emission reconstructions on the Joint European Torus (JET) [8,9], still it can not properly explain very rapid collapse of the core density and temperature. The precise nature of

this event remains unclear, though some explanations have been presented by Bussac et al [10], Merceir [11], Lichtenberg et al [12].

The major disruption which completely destroys the plasma confinement deserves more attention than the internal disruption which is not so dangerous. To know the causes of major disruptions are very important for the reliable functioning of future fusion reactor and to develop the mechanism to control it. Several explanations have been given for the degradation of confinement and subsequent disruption e.g. radiation losses, magnetic field line ergodization, multifaceted asymmetric radiation from edges (MARFES), microturbulence, touching of $m=2$ mode with the limiters [13], coupling of $m=2$ mode with different other modes (of either higher or lower m -values) [14, 15]. Though a lot of experimental evidences and measurements have been reported to explain the major disruption phenomenon, still the final stage of disruption is quite complex and is not fully understood.

Many groups around the world are working till now to explain the inconclusive portion of the disruption phenomena and newer

ideas are presented. Considering this point of view we report here the plasma disruptions in the medium size, low β tokamak, Aditya [16]. The soft x-ray (SXR) diagnostic technique has been used to elucidate the disruption phenomena combined with some other supportive diagnostic results. Singular value decomposition (SVD) method has been used to identify different magnetohydrodynamic (MHD) modes and different features of the spatio temporal evolution of emissivity distribution analyzing the time series of tomographic reconstructions.

2. Experimental Details

The basic parameters of Aditya tokamak are: major radius $R_0=75$ cm, minor radius $a=25$ cm, toroidal magnetic field $B_T \approx 0.75$ T, central temperature $T_0 \approx 400$ eV, plasma current lies between 65 and 85 kA and discharge duration upto 100 ms. We have analyzed a number of disruptive shots in Ohmically heated plasma with current, I_p , in the range $75 \text{ kA} \leq I_p \leq 85 \text{ kA}$ and safety factor, $q(a)$ range $3 \leq q(a) \leq 3.3$. The main two diagnostics which are used to analyze the data are SXR diagnostic system with an array of 12 surface barrier detectors (ORTEC, active area 50 sq. mm, thickness 100 μm) placed inside an imaging camera [16] and a garland of 36 Mirnov coils [17]. The SXR tomography was done with the help of analytical method [18] assuming rigid rotation [19-21] of the mode.

3. Aditya Disruptions

The plasma pulse shown in Fig. 1 is a typical of how disruptions are occurred in Aditya Ohmic discharges. It corresponds to a plasma discharge of maximum current, $I_p \approx 83.7$ kA (Fig. 1a) which disrupts at $t \approx 81$ ms. The SXR emission (Fig. 1b) goes below zero at 72.5 ms, far below the total current disruption time which means rapid cooling of the plasma center and already on set of plasma disruption phenomena. Growing amplitude in poloidal magnetic field derivative (Mirnov oscillation) (Fig. 1c), Spikes in H_α line (Fig. 1d) and in hard x-ray (HXR) (Fig. 1f) are strongly correlated with the cessation of SXR emission. It is note worthy that loop voltage, V_{loop} (Fig. 1e) does not show any negative loop voltage at this time.

3.1 Internal Disruption

The presence of sawtooth event was observed in Aditya tokamak in many

experimental situations and under different machine conditions. The periods and amplitudes of the sawteeth (Fig. 1b) are seen to slightly vary with time with an average frequency of 0.98 KHz and no transients were observed in loop voltage (Fig. 1e). The HXR time evolution shown in Fig. 1f indicates good confinement and low density of runaway electrons. Plotting some of these experimental data on an expanded scale in sawtooth region (Fig. 2), it can be observed that the growing amplitude of the poloidal magnetic field derivative (Fig. 2c) strongly correlated with the drop in SXR emission (Fig. 2b). This indicates that MHD perturbation plays a role in triggering

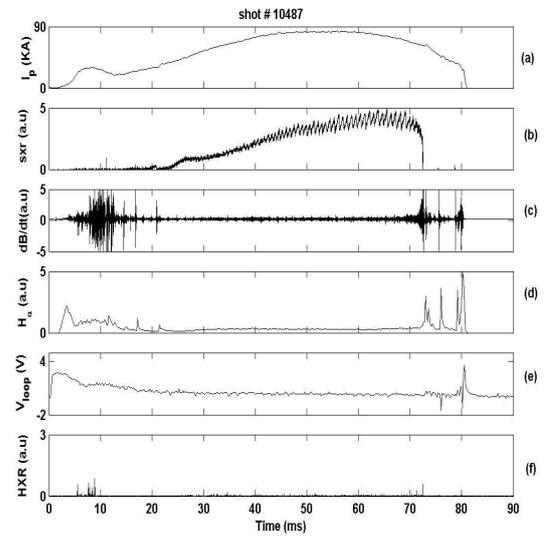


Fig. 1 Time evolution of plasma current (a), Soft x-ray signal of central chord (b), Mirnov oscillation (c), H_α spectrum (d), loop voltage (e) and hard x-ray spectrum (f) in Aditya discharge.

this disruption. Loop voltage signal (Fig. 2d) has no negative value in sawtooth region which indicates no minor disruption in this region. Figure 2a and Fig. 2b are the SXR signals at tangent chord radius at $r = 6.38$ cm and $r = 4.70$ cm respectively. An inverted sawtooth (Fig. 2a) is observed for each sawtooth crash (Fig. 2a). This implies that there is obviously a node in between 4.70 cm and 6.38 cm. Because after that a phase reversal in SXR radial mode structure occurs. This radius is called *inversion radius*, r_{inv} , and is related to the location of $q=1$ surface. Calculating from the empirical law [22], $r_{inv} = 0.5a / \sqrt{q(a)}$, we get inversion radius as 6.3 cm for $q(a)=3.3$ and $a=23$ cm which

approximately conform with experimental observation.

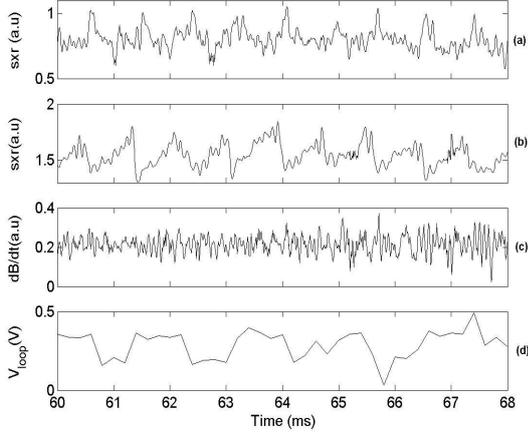


Fig. 2 SXR signals of the detectors at tangent chord radii (a) $r=6.38$ cm (b) $r=4.70$ cm. Figures (c) and (d) are Mirnov oscillation and loop voltage respectively

Fourier analysis (Fig. 3) of the signal in the sawtooth region shows the existence of two prominent modes, one at 4.98 KHz and another at 9.96 KHz besides the other modes of low intensities. Fourier analysis of other SXR signals, performed on the whole or part of the sawtooth like relaxation also yielded these two prominent modes. The mode with frequency 4.98 KHz is associated with $m=1$ mode and another at 9.96 KHz matches with the frequency of $m/n=2/1$ mode in the disruption region identified with magnetic coils experiment [17]. These two prominent frequencies of the precursor mode to sawtooth crashes might be the harmonics of $m=1$ mode.

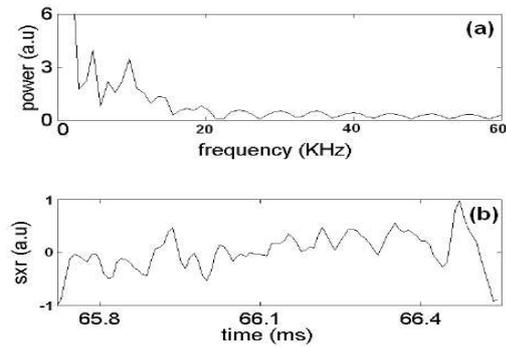


Fig. 3 Frequency spectra of the soft x-ray signal (a). Figure (b) is a sawtooth region (subtracting mean signal) of SXR signal. 128 data points are considered. The sampling time is $8 \mu\text{s}$.

This proves that the precursor mode is not 100% sinusoidal which is not uncommon in toroidal

system. This mode having the structure of $m/n=1/1$ but frequency of $m/n=2/1$ mode helps couple $m/n=1/1$ mode with normal $m/n=2/1$ mode generated at the time of disruption. Full explanation with strong experimental support of this phenomenon is not possible at this stage.

Figure 4 shows the SVD analysis of SXR emissivities in the time windows 50-65 ms. The singular values (SVs) has gentle slope in the spectrum (Fig. 4) as drawn singular value, S_k vs. SV number, k which is typical for SXR data. The distribution of SVs reveal that first five topo/chrono pairs contain more than 99.75% of the total energy. It is to be noted that as SVD is done averaging the data to zero, so the SXR perturbation emission can be negative as well as positive. The negative perturbation is shown by dotted curve here. The first topo/chrono pair (Fig. 4) represents the evolution of the average SXR emission. It corresponds to the largest singular value. The second topo/chrono pair is associated with sawtooth ($m=0$ mode). Topo is poloidally symmetric but somewhat shifted (Figs. 4).

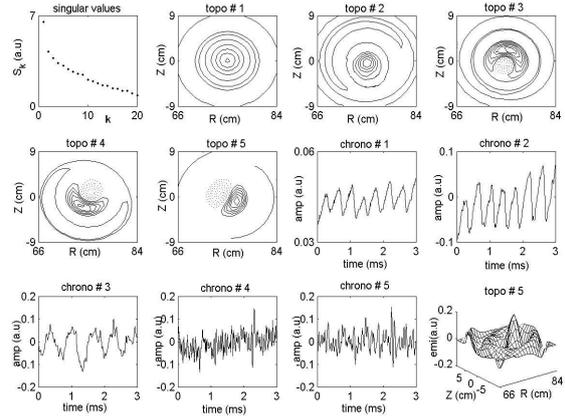


Fig. 4 SVD analysis of the reconstructed SXR emissivities in Ohmically heated Aditya Tokamak of shot # 10487 in time interval 50-65 ms. Top row first figure is the distribution of singular values. Only 20 largest singular values are shown. Five spatial eigen modes (topos) and their temporal eigen values (chronos) corresponding to first five singular values have been shown. Extreme right figure of the last row shows the dipole nature of the mode $m=1$ corresponding to topo # 5.

Chrono 2 shows the typical temporal evolution of sawtooth. The presence of oscillating topo/chrono pairs for $k=3, 4, 5$ show the rotating MHD mode (Fig. 4). Dipole structure of topo numbers 3, 4 and 5 indicates the poloidal mode number, $m=1$ as shown in Fig. 4 where only 3D view of topo 5 has been shown.. Some distortion in structures in

topos may be due to the presence of higher harmonics of $m=1$ mode. The toroidal mode number is $n=1$ as found from toroidal magnetic coils [17] with a frequency of ≈ 5 KHz. The mode rotates in diamagnetic drift direction. In our case no $m=2$ mode with two maxima and two minima along poloidal direction in topo structure was observed in this time interval.

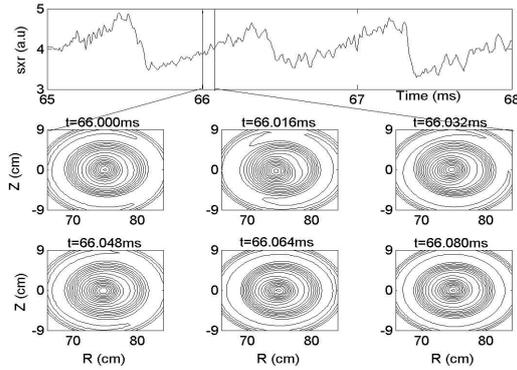


Fig. 5 Contour plots of SXR emissivity before sawtooth crash. Shifting of central region towards sawtooth inversion radius is not prominent.

Figures 5 and 6 show the sequence of tomographic images depicting the time evolution of SXR emissivity contours. Figure 5 is the contour plots of SXR emissivity before sawtooth crash and Fig. 6 are those at the time of crash. No prominent shift of the central region is noticed before internal disruption as shown in Fig. 5. Some distortion in the structure may be due to the presence of other harmonics of mode besides the prominent $m=1$ mode and/or small artifacts.

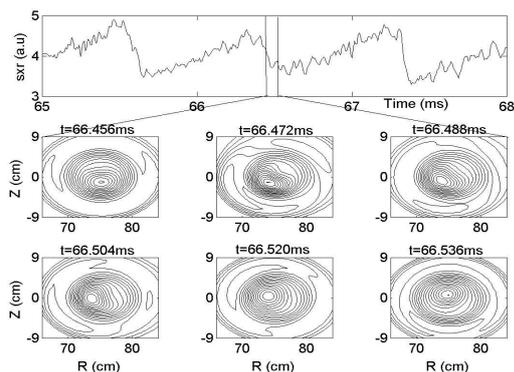


Fig. 6 Contour plots of SXR emissivity at sawtooth crash, showing prominent $m=1$ mode rotation and shifting of central region towards sawtooth inversion radius.

Figure 6 shows a prominent $m=1$ mode rotation at the time of internal disruption. Pushing of the

central region towards $m=1$ inversion radius is also obvious and indicates Kadomtsev like disruption. The rotation of mode and corresponding flat region are obvious from the figures. The cause of island rotation might be due to ω_* diamagnetic effect (the so called drift tearing mode [23]) or to radial electric field, \vec{E}_r , giving rise to $\vec{E}_r \times \vec{B}$ drift, where \vec{B} is the toroidal magnetic field.

3.2 Major Disruption

The major disruption in Ohmically heated Aditya tokamak is characterized by a lot

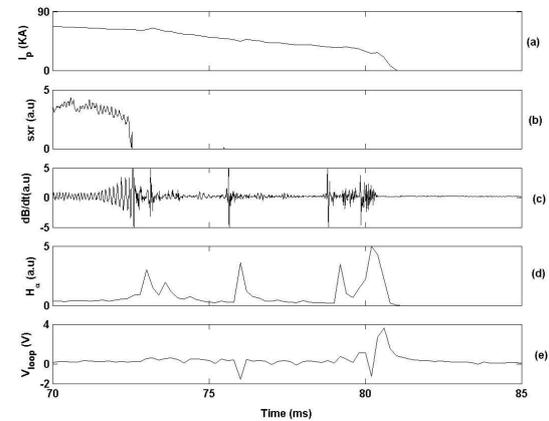


Fig. 7 Time evolution of plasma current (a), SXR emission (b), Mirnov oscillation (c), H_α spectra (d) and loop voltage (e) at disruptive period. Disruption starts at ~ 72 ms and ends with total current loss at ~ 81 ms. Cessation of SXR emission occurs at ~ 72.5 ms.

of phenomena viz., sudden disappearance of SXR signals much before the total current disruption, burst of Mirnov oscillations, negative spikes in the loop voltage and spikes in H_α spectrum. The duration of major disruption event and cessation of SXR emission much before the disruption only indicate the sudden drop in core temperature due to some MHD phenomena already started. The duration of major disruption events of several number of shots have been observed to lie in the range 3.3- 19.2 ms and that of cessation of SXR emission before the total current disruption lies in the range of 1.9- 18.5 ms. Such large duration disruption is not uncommon and has also been observed by Vannucci et al in TEXT-U tokamak [24]. Figure 7 shows that the disruption starts around the time 72 ms with a current fall of $\sim 35\%$

(Fig. 7a) and stopping of SXR emission at ~ 72.5 ms (Fig. 7b).

After ~ 8.5 ms of the cessation of SXR emission, total disruption occurs at ~ 81 ms. A lot of phenomena occur in this time interval in other spectra e.g. small spikes in current (Fig. 7a), burst in Mirnov oscillation (Fig. 7c), spikes in H_α emission (Fig. 7d) and negative loop voltages (Fig. 7e). These are all common physical phenomena in tokamak plasma disruption. Figure 8 shows that the frequency of SXR and Mirnov oscillation match well at the time of disruption events. Mirnov oscillation was detected at the time of disruption events as the oscillation of $m/n=2/1$ mode from magnetic coil experiment

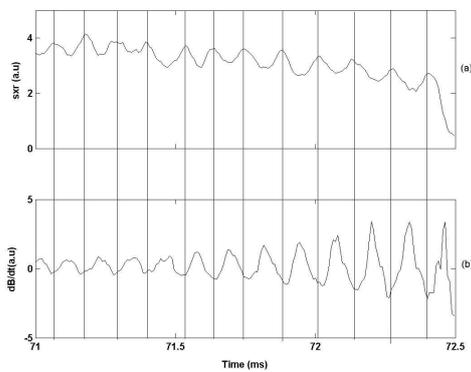


Fig. 8 The $m/n=1/1$ oscillation in SXR signal (a) and $m/n=2/1$ oscillation in Mirnov signal (b) have the same frequency at disruptive period indicating the mode coupling

[17]. This indicates the presence of $m/n=2/1$ frequency in SXR signal also at the time of disruption events. Calculation of $q=2$ resonant magnetic surface and its width with the help of empirical relation given by K Toi et al [25] and F Salzedas et al [26] showed that the $q=2$ resonant surface is well inside the plasma surface and there may be less chances of island interaction with the limiter. Also the presence of negative spikes in the loop voltage and the burst of Mirnov oscillation prior to the disruptions rule out the interaction between the plasma column and the wall (limiter) of the vessel as the probable cause of disruption. Disruption due to touching of limiter, in general, does not show these phenomena. Impurities and/or transportation of H-atoms are not the main factor for disruption as indicated by Z_{eff} value and H_α spectra. Contraction of the current channel and consequently plasma detachment as a result of edge cooling is not the main disruption triggering

mechanism as in this case radiation power stayed well below the input power (figure not shown).

Judging all aspects, it appears that coupling between the $m/n=2/1$ and $m/n=1/1$ modes could be the realistic mechanism for the cause of disruption. The presence of the harmonic of $m=1$ mode having frequency of $m/n=2/1$ mode at the time of sawtooth oscillation favours the coupling of $m/n=1/1$ mode at $q=1$ surface with normal $m/n=2/1$ mode at $q=2$ surface very easily to trigger disruption.

4. Conclusion

The internal disruption (sawtooth relaxation) mentioned presently is a very interesting phenomenon. The $m/n=1/1$ mode is responsible for internal disruption. In sawtooth region harmonics of $m/n=1/1$ mode are evolved which are not uncommon in toroidal system. The prominent one is the 1st harmonic of $m=1$ mode having the frequency of $m/n=2/1$ mode. This mode helps couple with real $m/n=2/1$ mode at $q=2$ surface at the time of disruption.

The presence of oscillating topo/chrono pairs for $k=3, 4, 5$ reveals the rotating MHD mode with poloidal mode number $m=1$ as shown by the dipole structure of the topologies 3, 4, 5. The toroidal mode number as obtained from the toroidal magnetic coils is $n=1$. The mode rotates in diamagnetic drift direction with a frequency of ~ 5 KHz.

The observation of the internal disruption with growing $m/n=1/1$ oscillation and the tomographic images indicate that the sawtooth instabilities could be due to the total reconnection model of Kadomtsev, though the crash time according to Kadomtsev model does not conform with the experimental value $\sim 68 \mu s$. This discrepancy is not clear and may be due to the presence of other modes and/or triggering of other mhd phenomena at the time of sawtooth crash. Tomographic images clearly show the $m=1$ mode rotation.

The observed plasma decays due to disruption in Ohmically heated tokamak, Aditya is not fast. Certainly, the faster the plasma decay, the higher are the risk to operate tokamak due to induced voltages and stress on electromechanical components of the tokamak. Therefore, if the mechanism of plasma current decay is understood and controlled we can operate the machine safely due to the reduction of stress. Finally, it appears that the coupling of $m/n=1/1$ mode with $m/n=2/1$ mode could be the possible cause for major disruption.

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