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Application of the Soft X-Ray Tomography Analyses in Heliotron-E Plasmas

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Abstract

Soft X-ray tomography analysis is used to understand physical mechanisms during the internal disruption. An interrelation between the amplitude and growth rate of the coherent mode, and the driving term is derived. The observed non-linear behavior is quite different from the physical picture based on the linear stability analysis. This technique is also applied to clarify the sawtooth stabilization effects by ECRH. Shafranov shift and power deposition profile are derived.

Keywords:

soft X-ray tomography, growth rate, hysteresis relation, sawtooth, internal disruption, ECRH

1. Introduction

Stabilization of MHD activities and deep understanding for the physical mechanisms have been one of the important subjects to the fusion plasma[1]. It has been reported in JET that at an internal disruption a helical instability is abruptly triggered[2]. Although observation of these trigger phenomena stimulated us, only the time evolution of the instability is shown and no relation between the mode growth and the driving term is given. In currentless heliotron plasmas, pressure driven instabilities have been investigated so far[3-5]. In this paper, using tomography we investigate the nonlinear dynamics of a coherent mode during the disruption phase. The another application of the tomography analysis is performed to study the Shafranov shift and the rf deposition profile for plasmas stabilized by ECRH.

2. Experimental Condition

Four sets of SX array with each 20 detectors are used for tomography. From the energy sensitivity (0.1 ~ 1 keV) of the detector the signals reflect the dynamics in density. This system allows us to reconstruct an image by the expansion up to m = 3 component[6]. Here, m is the poloidal mode number used in Fourier-Bessel expansion. The vacuum magnetic configuration is characterized by magnetic hill, the q = 2 surface near the magnetic axis, weak magnetic shear near the q = 2 surface and the inward shift (2–4 cm) of the axis. The range of plasma parameters are as follows: $B = 1.9$ T, $P_{ECH} < 0.5$ MW, $P_{NBI} = 3$ MW, 0.5 keV < $T_e(0) < 2$ keV, and $\beta(0) < 1$ %.

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3. Explosive Growth of the Coherent Mode and a Hysteresis Relation

We use the reconstructed emissivity $\varepsilon(r, t)$ to analyze the dynamics at the disruption. Especially, an interrelation between following quantities, $\tilde{\varepsilon}_{m=2}$, $\gamma_{m=2}$, and $\nabla\varepsilon$ is analyzed. Here we consider that $\tilde{\varepsilon}_{m=2}$ is the $m=2$ mode amplitude, $\gamma_{m=2}$ the growth rate derived from the time derivative of ln $(\tilde{\varepsilon}_{m=2}(t))$, and $\nabla\varepsilon$ the local gradient as the driving term. The growing process of the $m=2$ mode during the sawtooth oscillations is shown in Fig. 1. The non-rotating $m=2$ mode is abruptly enhanced just before the sawtooth crash. The $m=2/n=1$ mode associated with the $q=2$ surface is considered destabilized by the increased in the local pressure gradient at the $q=2$ surface. Thus both $\tilde{\varepsilon}_{m=2}$ and $\gamma_{m=2}$ are investigated as a function of $\nabla\varepsilon|_{r=r_s}$ at the disruption, as shown in Fig. 2. Since the peak position of $\tilde{\varepsilon}_{m=2}$ is shifted outward during the crash, we trace the peak value of $\tilde{\varepsilon}_{m=2}$. $\nabla\varepsilon|_{r=r_s}$ is taken at the fixed position. The $m=2$ mode is abruptly triggered, when $\nabla\varepsilon$ is $\nabla\varepsilon^*$ (a critical value). The $m=2$ mode amplitude reaches its maximum, and then decays as $\nabla\varepsilon$ decreases during the crash phase. Finally the amplitude becomes noise level. As $\nabla\varepsilon$ increases again, the amplitude does not increase below $\nabla\varepsilon^*$. That is, a hysteresis relation exists in the mode growth and drive term. Another aspect is that $\nabla\varepsilon$ is almost constant in the interesting time period. That is, even if $\nabla\varepsilon$ reaches $\nabla\varepsilon^*$ several ms before the crash, the occurrence of the jump in the growth rate seems to be random. In this sense this trigger event is quite probabilistic[7]. Finally we also studied a relation between $\gamma_{m=2}$ and $\tilde{\varepsilon}_{m=2}$ in this non-linear phase. The result is given in Fig. 3. When the mode is triggered abruptly, $\gamma_{m=2}$ increases with $\tilde{\varepsilon}_{m=2}$, and then it stops to increase and turns over, However, $\tilde{\varepsilon}_{m=2}$ continues to increase and reaches to the maximum. This observation is quite different from the physical picture based on the linear stability analysis.

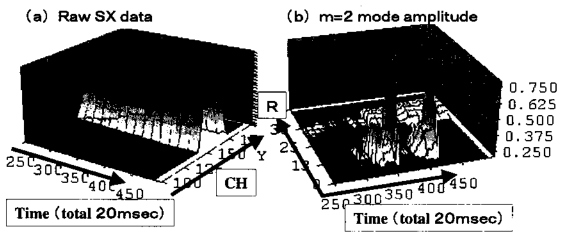

Fig. 1 Time evolution of the line integrated raw signals and the reconstructed $m=2$ mode.

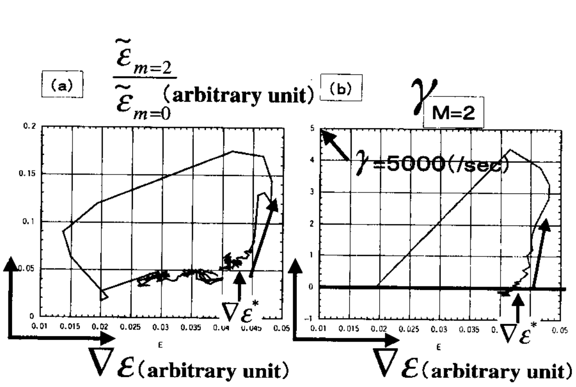

Fig. 2 Hysteresis relation during a crash: the ratio of $\tilde{\varepsilon}_{m=2}/\varepsilon_{m=0}$ *vs.* $\nabla\varepsilon$ (a) and $\gamma_{m=2}$ *vs.* $\nabla\varepsilon$(b).

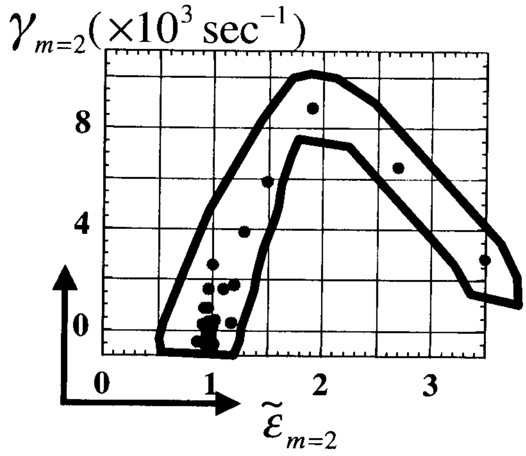

Fig. 3 Functional dependence of $\gamma_{m=2}$ on the mode amplitude.

4. Stabilization by ECRH

In particular case, mainly −3.5 cm shift case, it has been observed that unstable plasmas are stabilized by ECRH[7]. The second harmonic off-axis heating was performed with a 106 GHz gyratron. During the pulse, the sawtooth oscillations are suppressed, but they appear again ~ 20 ms after ECRH turned-off. Within this time-scale $T_e(0)$ is reduced to a previous level before ECRH. The Te and ne profiles are shown in Fig. 4. Although $\beta(0)$ is increased from 0.8 % to 1.1 %, and $-\nabla p_e|_{r=r_s}$ is also increased by a factor of 2, the observed plasma becomes stable. Although $-\nabla p_e|_{r=r_s}$ is increased, ε(r) becomes hollow during the pulse. This is ascribed to that the SX signal is more sensitive to the density (impurity ions) change because of its energy window (0.1−1 keV). The change in $\varepsilon(r)$ reflects that the both density and impurities are pumped-out [8] from the heating zone except the very early phase of the pulse.

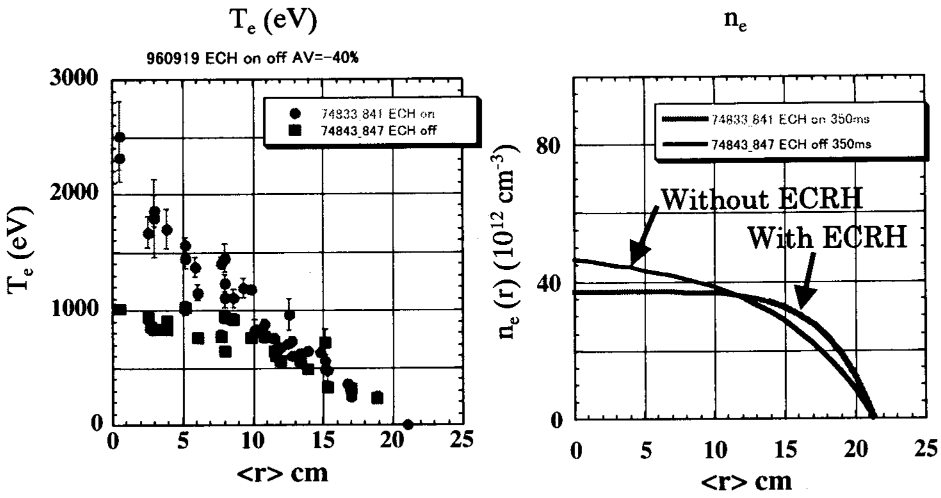

Fig. 4 The profiles of T_e(Thomson data) and n_e(inverted from the FIR interferometer profile) with and without ECRH.

In order to understand this stabilization effect the tomography technique is used from a different point of view. It has been reported in Ref. [7] that a reduction of MHD activities is seen by decreasing resistivity, η, at the $q=2$ surface by ECRH. Although the reduced η is favorable to stabilization, η^{α}-dependence ($\alpha < 3/2$) of $\gamma_{m=2}$ is considered too weak to explain the observed complete stabilization during the ECRH pulse. Thus Shafranov shift is studied by this tomography technique. Concretely, the shift is checked by following the location of the peak emissivity. Figure 5 shows the trajectories of the peak and the time evolution of the horizontal displacement with respect to the axis in vacuum for cases with and without ECRH. It is clear that the peak position is shifted outward compared with the case without ECRH. Although this suggests that the $q=2$ surface disappear due to additional shift, that is, the minimum value of rotation transform is expected above 0.5, the change of ΔR with ECRH is small. Preliminary calculations with a peaked profile at $\beta(0)=$ 1 % support this observation. Qualitative comparison with the theoretical prediction is under study.

It is an important issue to study how close the heating zone is the rational surface. The rf deposition profile is simultaneously derived from the signals offset at just ECRH turn-on time. Reconstructed profiles at $\Delta t < 1$ ms are shown in Fig. 6. The results suggest that the deposition profile is hollow and generation of energetic electrons seems to be non-uniform within the reconstruction accuracy. The heating zone is just outside the $q=2$ surface in vacuum. Systematic analysis is under study to clarify the effective location of the de-

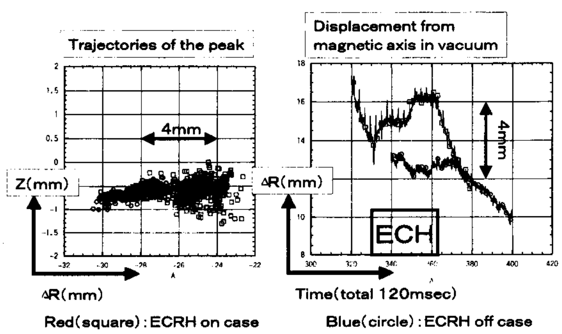

Fig. 5 Trajectories of the peak emissivity and the time evolution of the horizontal displacement from the magnetic axis in vacuum.

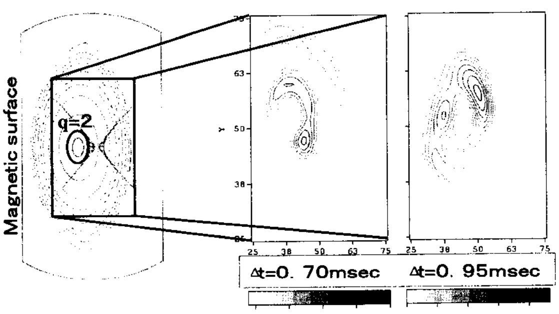

Fig. 6 ECRH power deposition profiles at very beginning of the ECRH pulse ($\Delta t < 1$ ms). For comparison the magnetic surfaces including the $q=2$ surface are shown.

position zone with respect to the rational surface.

5. Summary

Application of soft X-ray tomography method to MHD phenomena is described. The nature of explosive growth of the coherent mode is investigated. It is found that there exists a hysteresis relation between the mode amplitude and the local gradient. From this tomography technique, both Shafranov shift and rf power profile are simultaneously deduced for the plasma stabilized by ECRH.

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