Observation of m/n=1/1 mode Behaviours during Molecular Beam Fuelling and ECRH discharges in HL-2A

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Abstract. *On the HL-2A tokamaks, a series of experiments have been conducted to study the m/n = 1/1 mode topology and its influence on transport properties in the plasma centre. Several new characteristics of central MHD activities during auxiliary fuelling and heating are observed, and some important information about the changes in local plasma parameters and how the plasma responds to the perturbation caused by molecular beam injection (MBI) or laser blow-off are provided. It was found that the m/n = 1/1ideal-fluid instability can be regarded as a possible cause for varieties of persistent m/n = 1/1 oscillations when there is a nonmonotonic q(r) profile in the central plasma region under different discharge conditions on HL-2A. During electron cyclotron heating (ECRH), a strong m=1/n=1 mode is excited when the heating power is high enough and the resonance position is located just around the core of the plasma. With the strong m=1 oscillation driven by ECRH, a sawtooth tends to saturate or decrease in its ramp phase and the shape of the sawtooth is usually changed, leading to formation of a saturated sawtooth, a hill, or a compound sawtooth. Furthermore, a strong effect of ECRH on sawtooth tailoring and plasma transport properties in the vicinity of the q=1 surface was found.*

1. Introduction

Magnetic islands with a poloidal mode number $m = 1$ are commonly observed in tokamaks. They either accompany sawtooth activity or are in the form of persistent oscillations. According to the reconnection picture, an $m=1$ magnetic island associated with the internal kink mode grows until it fills the whole plasma column, leading to the relaxation of the central value of q to be larger than unity everywhere in the central region. However, the m/n = 1/1 oscillation can behave in a steady-state, as observed in discharges after pellet injection or after sawtooth suppression by lower-hybrid current drive [1]. The formation of the persistent $m/n = 1/1$ mode reflects some important information about the changes in local plasma parameters and how the plasma responds to the perturbation caused by a molecular beam or pellet injection or ECR heating. These provide the motivation for a better understanding of the process and its relationship with plasma parameters.

On the HL-2A tokamaks, a series of experiments have been conducted to shed light on the persistent m/n = 1/1 mode topology and its influence on transport properties in the plasma centre. We study the evolution of central magnetohydrodynamic (MHD) modes experimentally using two-dimensional visualization achieved by a set of soft X-ray camera systems. Several important central MHD activities, for example, sawtooth suppression, monster sawtooth and, persistent m/n = 1/1 oscillations, have been observed.

This paper is organized as follows. At first the experimental apparatus and configuration are described in Sec. 2. The features of the persistent m/n = 1/1 modes caused by MBI and the information about the evolution of the central q profile revealed by a tracer during laser blow-off are presented respectively in Section 3 and 4. The influence of ECRH on sawtooth behaviour and plasma transport properties are illustrated in Sec. 5. Finally a summary will be given in Sec. 6

2. Experimental Configuration

HL-2A is a divertor tokamak device with a major radius of 1.65m and a minor radius of 0.4m. Most of the important issues of fusion physics, such as transport and confinement, auxiliary heating and current drive, wall conditioning，divertor and scrape-off layer physics, MHD instability, are being studied and explored on the HL-2A [2].

Electron cyclotron resonance heating (ECRH) is one of the main auxiliary heating schemes for the HL-2A plasma. The ECRH system consists of two 68GHz gyrotrons for fundamental resonance heating. The heating wave starts from the weak field side, and propagates along the equatorial plane nearly perpendicularly. In the present experiments, the input power is up to 0.56MW, and the pulse duration is about 1s. In addition to an 8 pellet injection system, a molecular beam injection system, which was first proposed on the HL-1M [3], has been further developed on the HL-2A for auxiliary fuelling. High Z impurities have been injected into ohmic hydrogen discharges by the laser blow-off for the studies of impurity transport. The experiments described here have utilized nearly circular discharges with a plasma current of 150kA and a toroidal field of 2.3T with auxiliary heating and fuelling. The typical parameters on the HL-2A of these experiments are: electron density, ne~$1.5\times10^{19}m^{-3}$, measured by a five-channel FIR HCN laser interferometer, central electron temperature, Te~1keV, measured by the soft x-ray spectra diagnostics. Electron temperature profiles are measured by electron cyclotron emission (ECE). In addition, the behavior of the injected impurity by laser blow-off is investigated by a VUV spectrometer, five soft X-ray cameras and three bolometric arrays.

3. Feature of steady m=1/n=1 Phenomena Triggered by MBI

The molecular beam injection is a promising fuelling tool on a tokamak. Many advantages such as peaked density profiles and confinement improvement have been found in the MBI experiments on several devices. On HL-2A, high-pressure multi-pulse MBI has been applied to the plasma for effective refuelling. Stair-shaped density increments were obtained. Each MBI pulse produces a fast rise in plasma density, and a tempreture drop even in the central ECE channel which indicates that the injected particles can penetrate into the core region of the plasma.
A persistent m/n=1/1 perturbation with a rotating frequency of 4kHz has newly been

observed in the core region after injection of MBI into the HL-2A plasma. This usually happens in the decay phase after a stair-shaped density increment, as shown in Fig.1. The discharge experienced a sudden onset of a large oscillation, and a concurrent fast decrease of central SX intensity. The oscillations grew rapidly at the beginning, then saturated for a long time. It can survive the subsequent sawtooth crash, though it is perturbed at the crash time, as shown in Fig.2.

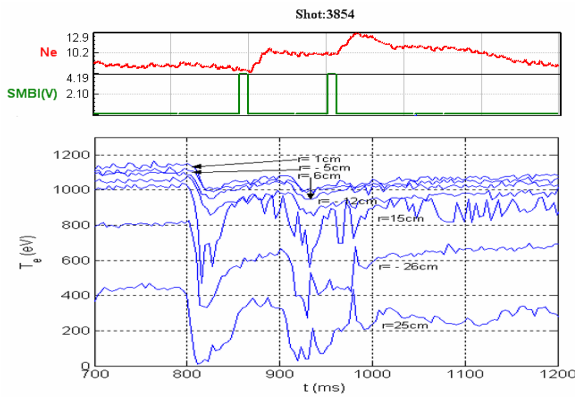

Fig.1 The plasma density increases 2.2 × $10^{19}m^{-3}$ after MBI, while a tempreture drop was observed in the central ECE channel.

The persistent m/n=1/1 perturbation is quite similar to the snake phenomenon observed in pellet injection (PI) expriments as shown in Fig.3, in which a long-lived and sawtooth absent m=1 perturbation in plasma core was observed. Due to the high injection speed, the pellets can penetrated to and beyond the q = 1 surface leading to the formation of snake phenomenon.

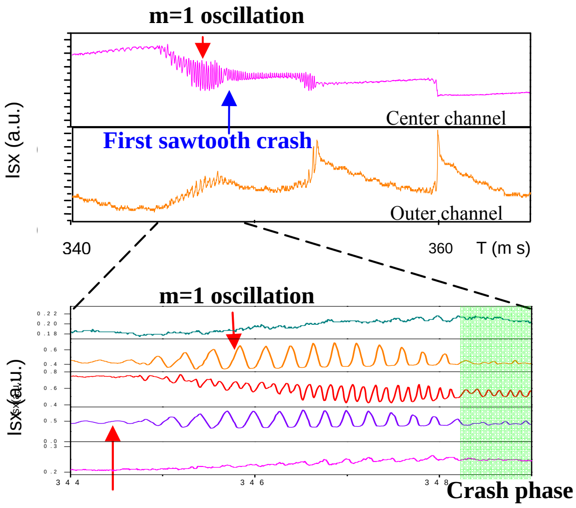

Fig.2 A persistent m/n=1/1 perturbation observed after MBI.

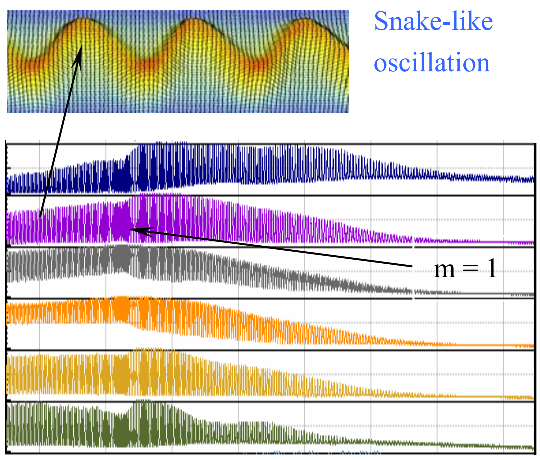

Fig.3 A long- lived thermal Oscillation in plasma core after PI.

In the MBI case, due to the large number of neutrals in a high-pressure supersonic gas jet, and the low parameters of the incident electrons which are determined by the relatively low parameters of the HL-2A plasma (especilly the density and tempertur), the ionization degree and temperature in the whole jet volume are quite low. This helps the MBI to penetrate into the core region of the plasma. In experiment, electron density pulse perturbations can be observed in the plasma center from the ECE 3rd harmonic measurements. The results from microwave reflectometer show that the particle source injected by pulsed MBI is located at about r/a = 0.5 ~ 0.75. This provide the necessary condition for the formation of a persistent m/n=1/1 oscillation.

To identify the properties of such a persistent perturbation, we performed an SVD on the soft x-ray chord integrated measurements. The SVD analysis gives the temporal evolution and profile structure of the first three components of the perturbation as shown in Fig. 4， indicating that the dominate poloidal mode number of the mode is m=1. In Figure 5, tomographic reconstructed soft x-ray images show a picture of a hot core displaced inside the q=1 surface. The radial dimension of the perturbation was determined from the reconstructed soft x-ray emission as 7.5cm, while the q=1 surface is located near r_s=12cm, indicating the oscillation is limited to the q=1 surface.

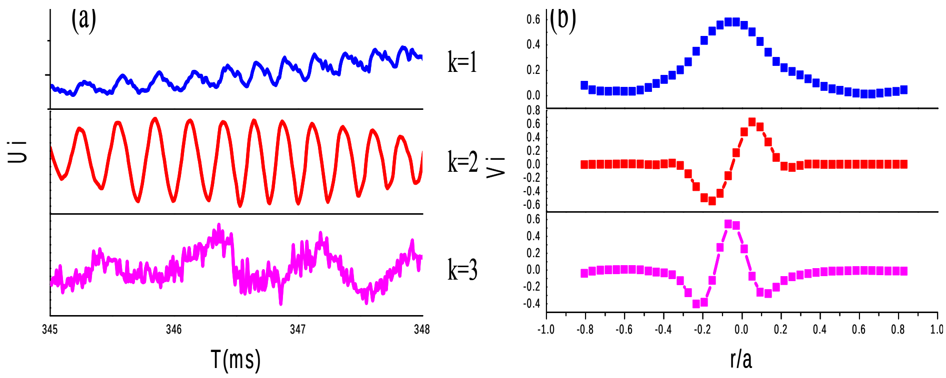

Fig.4 SVD analysis of signals: (a) time evolution of SVD principal components; (b) three corresponding spatial eigenfunctions. The k=2 component describes a m=1 perturbation, while the k=3 component corresponds to a variation due to sawtoothing.

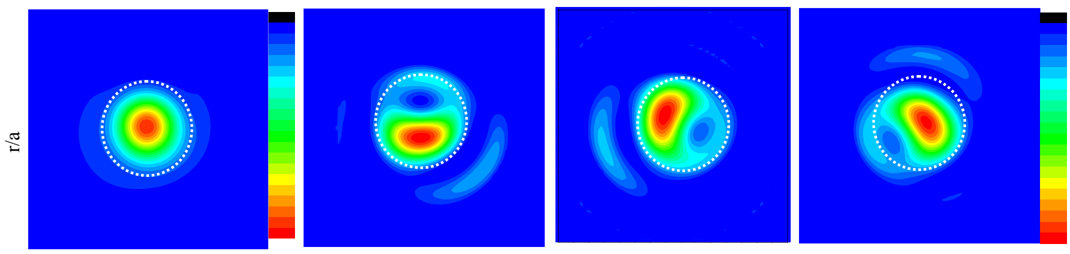

Fig.5 Four successive contour plots of the tomographically reconstructed soft x-ray emission measured every 0.01s after MBI. The white circle indicates the q=1 surface.

Since this steady-state m/n=1/1 perturbation manifests itself with a feature of hot core displacement instead of an m=1,n=1 island, it is more likely related to a nonlinear saturated state of the m=1,n=1 ideal MHD instability rather than a resistive tearing mode which causes the reconnection of field lines and a sawtooth crash. Furthermore, this phenomenon happens at the decay phase after MBI refuelling, at which the central q(r) profile may be nonmonotonic with q_{min} above but close to 1 because of the flattening of the electron temperature profile along with enhanced electron density over the core region. Such a q profile may lead to a nonlinear displacement[4], as $\frac{\xi^2 q''}{\Delta q} = \frac{8}{71}\left[\frac{8\pi}{3}\right]^2\left[(\frac{\Delta q_c}{\Delta q})^{3/2} - 1\right]$, where the $\Delta q_c \approx \varepsilon^{4/3}$ is the critical value at which the mode is marginally stable. This secondary equilibrium state can be stable against further deformation and may account for the observation of persistent m/n=1/1 perturbation after

MBI. This may also account for the appearance of m=1 mode throughout the sawtooth crash which indicates that the reconnection is not complete. It is very likely that if there is already a kinked equilibrium inside the q=1 surface($r<r_1$) the influence of localized reconnection starting from the q=1 surface will limited to the region just around the resonant q=1 surface and lead to a partial reconnection.

4. Features of sawtooth and m=1/n=1 mode after Laser blow-off

Impurities have been injected into ohmic hydrogen discharges by laser blow-off for transport studies. In order to improve the understanding of the transport of trace impurities injected into plasma, especially during the sawtooth crash phase, a fast soft X- ray camera system has been applied to supplement the standard VUV line spectroscopy for visualizing the evolution of impurity radiation. Figures 6 displays time evolutions of plasma parameters in a discharge with Aluminum injected at 800ms. The injection does not disturb the plasma current, loop voltage and electron density in any noticeable way, but it can be clearly detected as a short pulse on the line emission of Al XI, soft X-ray, and bolometric signals.

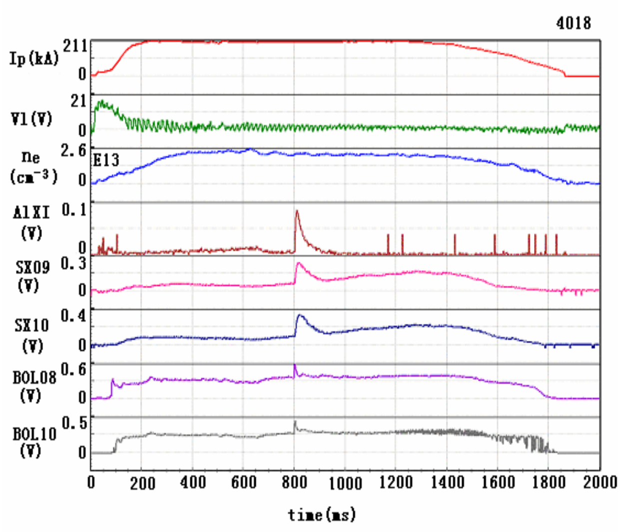

Fig.6. Time evolution of the plasma current, loop voltage and electron density, Al line brightness from VUV, the soft X-ray and bolometer signals.

Usually, there are several sawteeth being suppressed or inverted on the central Soft-X ray chord signals during the rising phase of the pulse after impurity injection, as shown in figure 7(a). A jump is clearly seen during the inverted sawtooth crash within 200 μs while the usual feature of the sawtooth crash is a rapid decrease, indicating a rapid inwards flux of impurity particles during the crash. Figure 7(b) shows the tomographic reconstructed soft X-ray profiles before and after such a crash, it suggests that the impurity transport is greatly enhanced (up to 10-15 times) over the central region during the sawtooth crash phase. The most conspicuous feature of an inverted sawtooth is the appearance of a post-cursor oscillation after the internal crash, shown in figure 7(c), which is not the case before impurity injection where only a precursor oscillation is found. The post disruptive oscillations observed after impurity injection can be attributed to a nonmonotonic q profile with q_{min} slightly above unity after a complete reconnection which leads to the relaxation of the central value of q to be larger than unity everywhere in the central region. As analyzed in a linear calculation [5], such a profile is unstable to an ideal m=1 perturbations and the perturbation is a rigid displacement for $r<r_1$. This is an indication that perhaps such a post disruptive oscillations could not be distinguished experimentally from the flat distribution

after a normal sawtooth crash, although it may have been present. With the illumination effect of the impurity radiation, the post-collapse helical core deformation due to m/n=1/1 ideal MHD instability can be clearly identified.

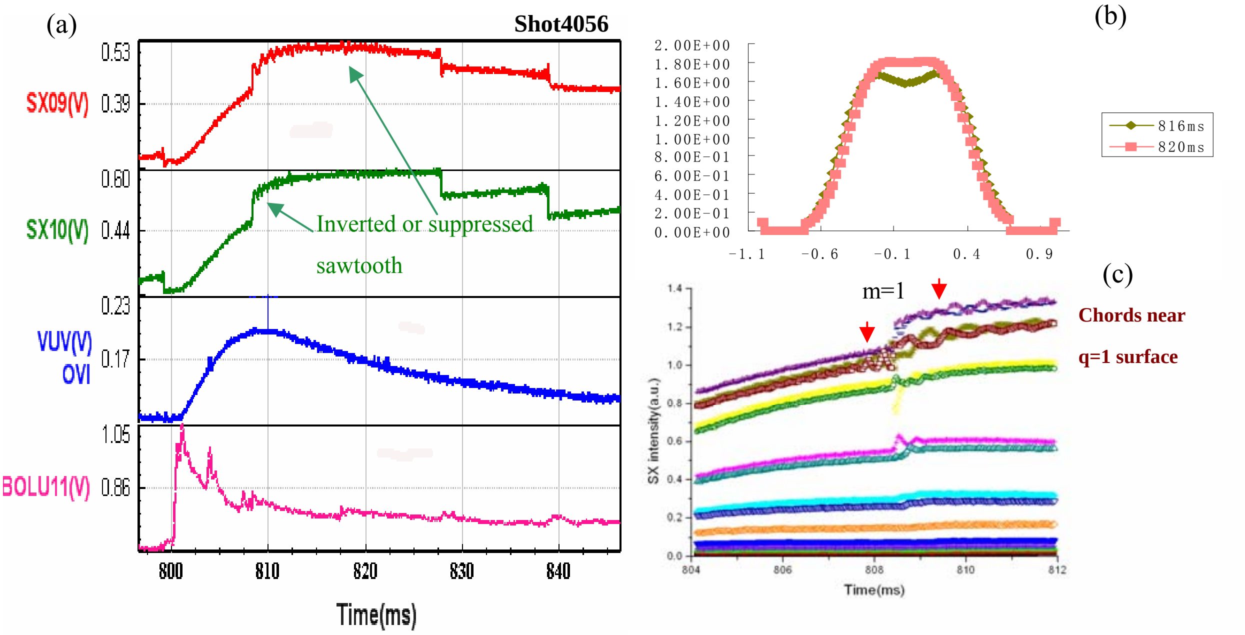

Fig.7. (a) Inverted sawteeth on the central Soft-X ray chords after impurity injection. (b) Profiles before and after the last inverted sawtooth crash. (c) The m=1 oscillations on several central SX channels before and after the crash of an inverted sawtooth.

5. MHD mode activity and Sawtooth behaviour during ECH

In the ECRH experiment, the direct responses of plasma are electron temperature rise, and the enhancement of soft X-ray radiation with an order of magnitude. Figure 8 shows time evolutions of the basic plasma parameters (I_p, B_T, central T_e, average n_e, central soft-X-ray intensity) in an on-axis ECRH discharge (Shot 4339, P=465kW, t=700 ～ 950ms). The decrease in electron density may be related to the so-called density pump-out, which refers to the thermo-diffusive pinch in the particle flux at the application of ECRH to low density plasma [6].

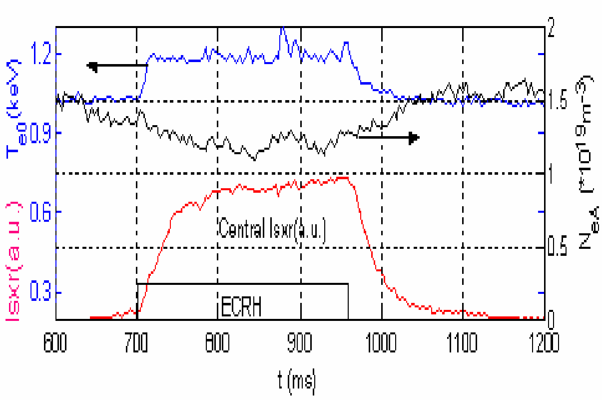

Fig.8. Basic parameters of on-axis ECRH experiment (central Te, average Ne, central soft-X-ray).

Evidence that ECRH modifies the plasma temperature profile and affects the plasma MHD behaviour has been obtained in low density ($\bar{n}_e \le 1.8 \times 10^{13}\ cm^{-3}$) discharges. Figure 9 shows the time evolution of Te profiles during on-axis and off-axis ECRH. For shot 4343，450kW ECRH power is deposited on-axis with a temperature rise of about

200eV. For shot 4163, the deposit position is at the low field side at the minor radius r=16cm. The off-axis nature with the center nearly unaffected is clearly visible. In this case, the temperature rise at the deposit position is about 110eV with the ECRH power of 340kW, resulting in a flat T_e profile. A strong m=1/n=1 mode is excited when the heating power is high enough and the resonance position is located just around the plasma core. With the strong m=1 oscillation driven by ECRH, a sawtooth tends to saturate or decrease in its ramp phase and the sawtooth shape is usually changed, leading to formation of a saturated sawtooth, a hill, or a compound sawtooth.

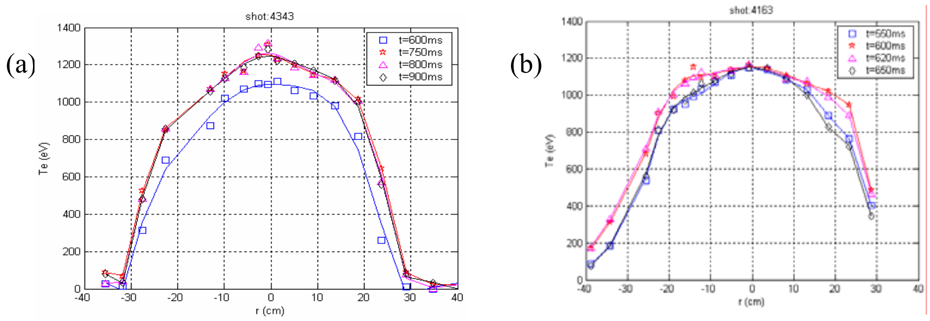

Fig.9. (a) on-axis ECH (P_{ECH}=450kW);(b) off-axis ECH (P_{ECH}=340kW)

Sawtooth tailoring by ECRH has also been observed. As shown in Fig 10, on-axis ECRH results in a shorter sawtooth period than in the Ohmic regime. It suggests that the centrally localized electron cyclotron heating increases the central plasma temperature and hence shorten the current penetration time over the central region in the sawtooth ramp phase, leading to sawteeth with smaller periods. Such a destabilization of sawtooth activity has been observed on other tokamak devices, and the control of sawteeth is expected to be important in a next step device. On the other hand, only a slight influence of ECRH power on the sawtooth activity is observed in the off-axis ECRH discharges, the reason may relate to the lower RF power level.

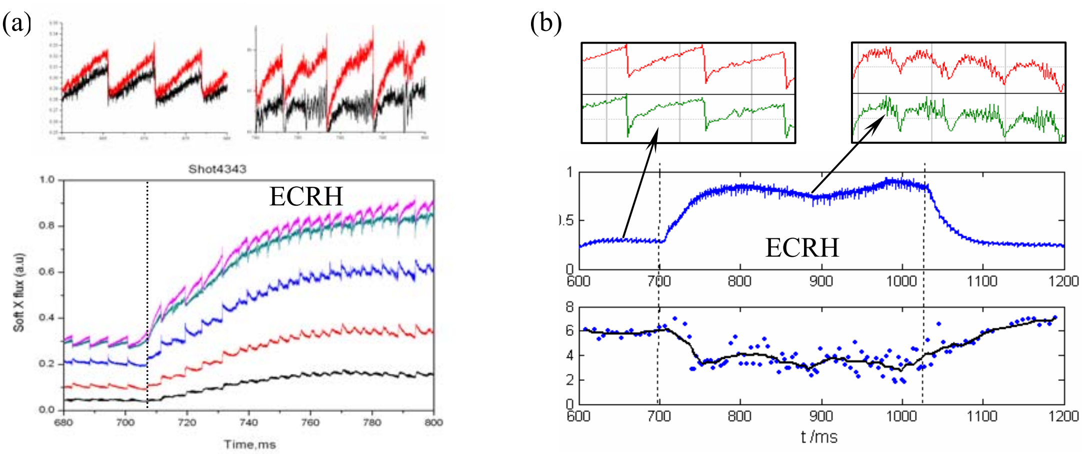

Fig.10 Destabilization of sawtooth by on-axis ECRH. A normal sawtooth becomes a compound sawtooth (a) or a saturated sawtooth (b).

The localized ECH not only has the effect of creating a local perturbation in the current and electron temperature profiles which leads to changes in MHD behaviour, but also has an effect on plasma transport properties in the vicinity of the q=1 surface especially during a compound sawtooth. In the Figure 11(a), a sudden change in the profile gradient happens from 814.5ms to 816ms, forming a steep profile residing near the q=1 surface. Such a barrier-like feature can be sustained for several milliseconds before the main compound crash. Furthermore, Figure 11(b) displays the heat pulse propagation after the partial crash and main crash in a compound sawtooth cycle. The smaller value in the electron heat diffusivity χ_e after the partial crash (typically 3.2 and 4.1 m^2s^{-1}, respectively) indicates a better confinement even outside the q=1 surface before the main crash.

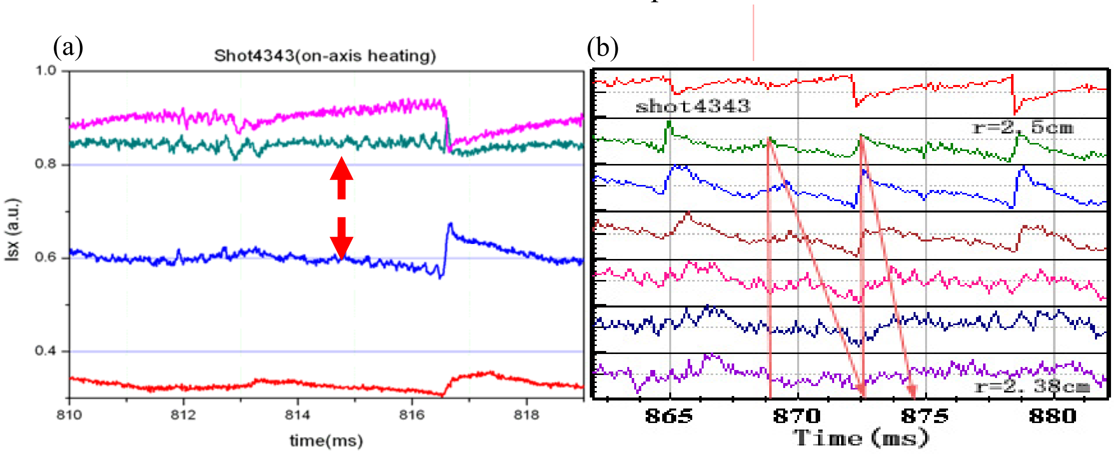

Fig.11 (a) A steep profile near the q=1 surface before the compound crash; (b) the heat pulse propagation after the partial crash and main crash in a compound sawtooth cycle.

6. Summary of results

We have investigated the structure of the persistent *m/n* = 1/1 mode observed in the experiments of MBI and laser blow-off on the HL-2A tokamak. The results show that the persistent *m/n* = 1/1 mode seen during these experiments can be related to an ideal-fluid instability in the plasma with a nonmonotonic q(r) profile caused by MBI injection or sawtooth crash. Furthermore, we analyze the changes in the sawtooth activity during electron cyclotron heating, finding the strong effect of ECRH on sawtooth tailoring and plasma transport properties in the vicinity of the q=1 surface.

Acknowledgments

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