Active Control of Fast-Ion-Stabilized Sawteeth by Electron-Cyclotron Current Drive on HL-2A

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The effects of localized heating on the sawtooth period have been explored in HL-2A ECRH discharges and the simulations study. This set of results suggests the presence of a heating location, just inside the q = 1 surface, which is the most effective to destabilize sawteeth. Moreover, the dedicated experiments on HL-2A clearly demonstrate that ECCD can shorten sawteeth lengthened by the fast ions which produced by neutrol beam injection heating (NBI). The response of the sawtooth instability to ECCD seems to be largely, and the shortening proved to be very reliable despite the modest amounts of ECCD power applied.

1. Introduction

In a tokamak plasma, sawtooth oscillations in the central temperature, caused by a magnetohydrodynamic instability, can be partially stabilized by fast ions [1]. The resulting long sawtooth periods have been observed to result in triggering NTMs at lower plasma β, which in turn can significantly degrade plasma confinement. This has led to great interest in the control of sawtooth, and in particular to destabilize long sawtooth. According to the model proposed by Porcelli et al[2], a sawtooth crash occurs when $s_1 > s_{1crit}$, the shear s_1 and the critical shears s_{1crit} at the q = 1 surface, which can be in creased by the presence of fast ions. Thus, it should be possible to modify the fast-ion-stabilized sawteeth by varying s_1 through localized current drive. Another factor to take into account is that the heating itself influences the evolution of s_1, and thereby the sawtooth period[3]. Earlier measurements of sawtooth period variation with the radial position of localized Electron-Cyclotron Current Drive(ECCD) in plasmas heated by electron-cyclotron waves on TCV have shown good agreement with the theory [2]. Recently, experiments on TORE SUPRA showed that ECCD can destabilise long sawteeth induced by core ICRH [4]. The HL-2A device, equipped with a very flexible and

powerful ECCD system, is specifically suited for this kind of investigation. In this paper we report a set of new experimental results about active control of fast-ion-stabilized sawteeth during NBI by ECCD in HL-2A and a set of related simulations obtained applying a sawtooth period model[2].

2. Effects of localized heating on the sawtooth period

Experiments performed on HL-2A have shown the effect of localized heating on the sawtooth period during a magnetic field scan. Such scan of the average sawteeth periods, was performed with variation of the power deposition radius(r_{dep}) by changing the toroidal magnetic field B_t in the range of 1.21-1.39T for the different ECRH discharges (I_p=152kA, q_a ~ 5, $\bar{n}_e$ ~ 1.3×10^{19} m^{-3}). A total of 600kW of ECRH power absorbed by the plasma, within a width of ~0.1a, computed with the transport code CRONOS [5].

In figure 1(I) squares show the evolution of the sawtooth period as a function of the power deposition. With circles we have plotted the corresponding simulated sawtooth period. The sawtooth period is simulated by the MHD code MISHKA-ST, in which sawtooth crash triggering conditions have been implemented as determined by linear stability thresholds of the ideal and resistive internal kink computed by MISHKA[6] and included in the Porcelli's sawtooth period model. The simulation reproduces the variation of the sawtooth period, but exhibits a location maximizing the sawtooth period which is slightly shifted as compared to the experimental trace, however, that is below the errorbars. In the same figure we have plotted the average q = 1 radius computed by CRONOS, and the average experimental inversion radius, determined from two-dimensional reconstructions of SXR emissivity profiles [7]. We observe that when the deposition is close to the q = 1 radius, or close to the measured sawtooth inversion radius, the sawtooth period is small, which is less than the Ohmic sawtooth period(τ_{ST}(OH)). In contrast, at the time of maximum sawtooth period, which is more than a factor of 3 longer than τ_{ST}(OH), r_{dep} is clearly outside the inversion radius, and the q = 1 surface, that Δr is more than 3cm. It allows us to conclude that the heating location maximizing the sawtooth period is outside the q = 1surface. In figure 1(II) we have plotted the time evolution of the s_1 and s_{1crit}, as computed by MISHKA-ST, where s_{1crit} is

given by the expression in the resistive regime. The key role in determining the sawtooth period is played by the speed at which s_1 grows up during the sawtooth ramp. The shear s_1 is affected due to changes in the plasma conductivity caused by localized electron heating. This set of results suggests the presence of a heating location, just inside the $q = 1$ surface, which is the most effective to destabilize sawteeth.
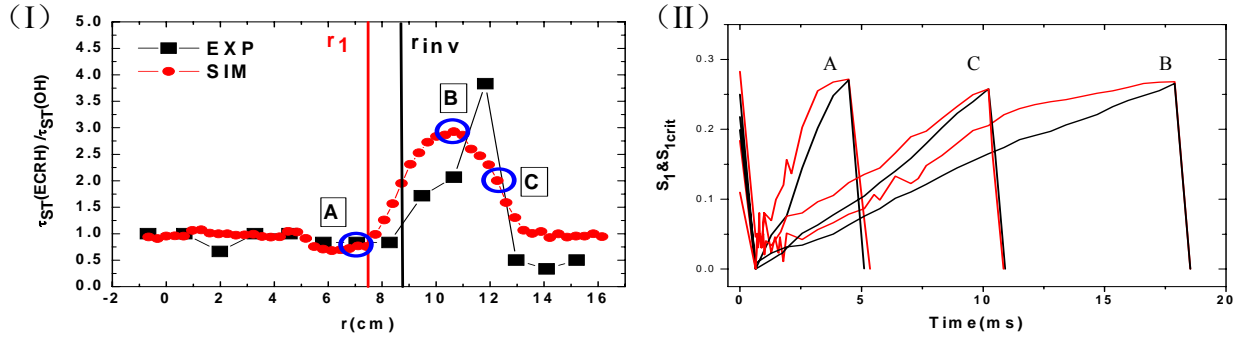

Figure 1. (I) Sawteeth periods, measured (■) and simulated (●), versus the ECRH power deposition location for HL-2A shots. (II) Time behaviour of the shear at $q = 1$ (black) and the critical shear (red) for three sawteeth periods, marked with A, B, C.

3. Active control of fast-ion-stabilized sawteeth by current drive

For the further study of the effect of localized electron-cyclotron waves on sawtooth period, we carried out a set of experiments in HL-2A to control the fast-ion-stabilized sawteeth in NBI heated plasma by utilizing ECCD. The ECCD in these experiments (Ip = 330kA, qa ~ 4, $\bar{n}_e$ ~ 2.1×10^{19} m^{-3}, P_{NBI} = 610kW) was depositied from outside the $q = 1$ surface to the plasma center. P_{EC} was in the range of 600kW-1MW, and small toroidal ECCD injection angles (10°) was used within a width of ~ 0.15a. Such discharge with co-ECCD is shown in Fig.2(a). For reference, the traces of a similar discharge without ECCD is also shown. As can be seen, the sawtooth period increases from about 5 ms in the Ohmic phase to around 17 ms due to the presence of fast ions when NBI is applied[1]. Then when the ECCD deposition moves inside the $q = 1$ surface, there is a sudden drop in sawtooth period, reduced by 1.7**,** almost to the level in the Ohmic phase. This result is particularly remarkable in two respects: the modest amount of ECCD power applied and the abruptness with which the sawtooth period drops. Figure 2(b) shows the sawtooth period, normalized by the sawteeth period during NBI only, for a number of similar discharges with co-ECCD as a function of

the distance between the measured sawtooth inversion radius and the peak of the ECCD driven current computed by CRONOS. The sawtooth period shortenings are achieved with the ECCD current driven inside the q = 1 surface. The statistics of the normalized sawtooth period as a function of the P_{EC} normalised by P_{NBI} is shown in Fig. 2(c). It is seen that the efficient normalized P_{EC} required to destabilise sawteeth is 0.6-1.3. The efficiency of ECCD as a tool for sawtooth destabilization in the presence of fast ions has been demonstrated. More works will be carry out on experimental and simulation study, in order to make contributions for increasing confidence that ECCD can be relied upon for this purpose on ITER.
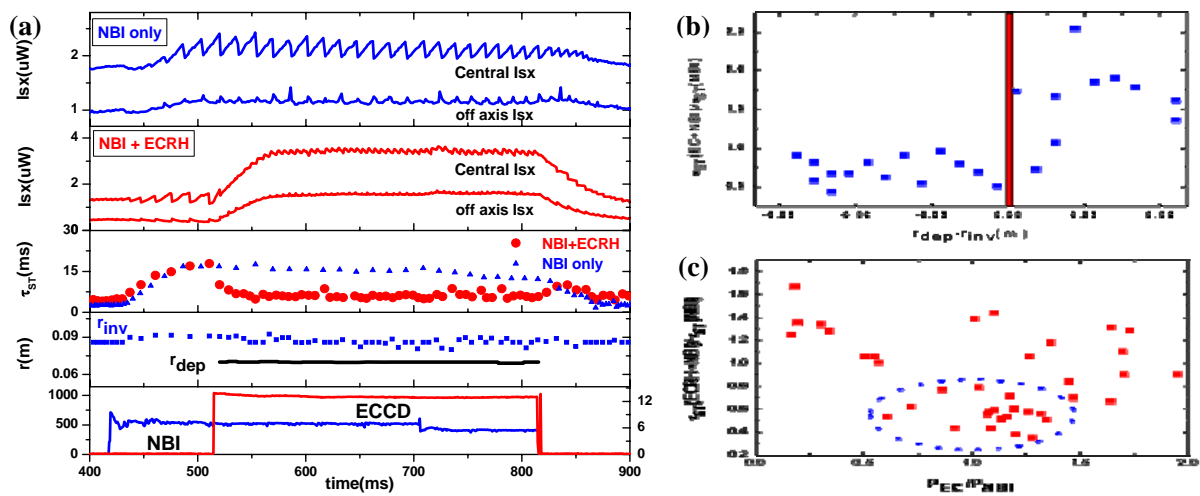

Figure 2. （a）Two shots with NBI with and without ECCD, plotting Soft x-ray emission, sawtooth period, sawtooth inversion radius rinv and cyclotron resonance layer r_{dep} and heating power. (b) The normalized sawtooth period versus distance between ECCD location and inversion radius. (c) The statistics of the normalized sawtooth period as a function of the P_{EC} normalised by P_{NBI}.

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