Energetic ion excited long-lasting internal modes in HL-2A tokamak with low magnetic shear

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1. Introduction

Steady state operation and burning plasma physics are fundamental challenges not only to International Thermonuclear Experiment Reactor (ITER) Project, but also to future fusion reactors as well. Control of magnetohydrodynamics (MHD) activities and interaction between energetic particles and MHD modes are therefore essential issues in advanced scenarios of ITER operation [1]. After negative magnetic shear distribution of a non-monotonous q-profile, another advanced operation scenario called hybrid scenario with a flat q(r) ~ 1 profile in the core plasma is then also recommended recently for high performance tokamak operations. The low magnetic shear feature of the flat q-profile can substantially eliminate the free-energy due to current driven, and consequently circumvent sawtooth crashes. Nonetheless, pressure gradient driven instabilities such as interchange and/or infernal modes may be generated due to the low magnetic shear [2]. Different from the fast growth of current driven instabilities, such pressure driven modes usually have a continuously slow growth feature and are therefore called long lived (or long lasted) modes (LLMs), observed on NSTX [3] and MAST [4], and often causes rotation flattening in core plasmas and degraded fast-ion confinement and operation performance. Considering the high plasma beta of MAST and NSTX, the LLMs were found ideal MHD interchange (q=1) /infernal (q>=1) modes driven by pressure gradient.

Recently the long-lasting internal modes were observed in HL-2A plasmas with a low magnetic shear during NBI (Neutral beam injection). When those modes occurred, a reduction in the electron density and the plasma stored energy, and a fast ion loss were frequently observed. Moreover, it was observed that the electron cyclotron resonant heating (ECRH), and supersonic molecular beam injection (SMBI) induced strong influence on the behavior of the mode, or even suppressed it on HL-2A. The control of the mode in HL-2A experiments was found to be related to the magnetic shear change or the pressure gradient variation due to the local heating or fuelling. The mechanism of the phenomenon is also explored.

2. Characteristics of the mode on HL-2A

Experimental results shown in this subsection were obtained in HL-2A plasmas with Bt ~ 1.2-2.33T, Ip ~ 160-320kA, PNBI ~ 320- 1000kW, and the line-average density ne ~ (1.7-3.3)×$10^{19}m^{-3}$, the edge safety factor q_a ~ 3.5-4.5.

Unlike LLMs observed in NSTX [3] and MAST [4], the mode propagated along the diamagnetic direction and its frequency was on the order of the procession of trapped fast ions in the toroidal rotation frame, a typical property of fast ion driven modes. A toroidal rotation frequency of the central plasma (~7kHz) calculated from the carbon charge exchange recombination spectroscopy (CHERS) data was found lower than the frequency of the mode (~14kHz) in Shot16074 discharge (Fig 1). This is different form the case in MAST [4], where the mode rotates at a frequency corresponding to bulk plasma rotation. Thus, taking account of contribution form fast ion makes the frequency range consistent with the n=1 frequency observed experimentally.

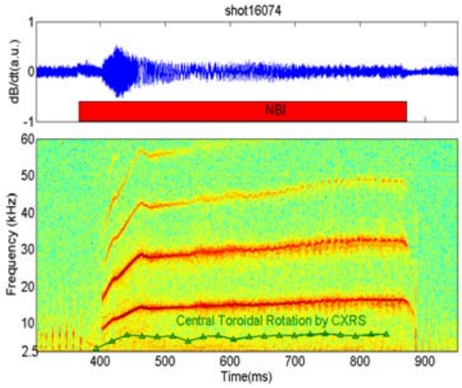

Figure 1: The magnetic perturbation signal (upper) and SXR frequency signals of the m/n=1/1 mode (lower) and its higher frequency 2/2, 3/3/, 4/4, … harmonics of Shot 16074 during NBI in HL-2A.

As we know, a population of fast ions induced by the NBI can affect the kink mode stability. It is appropriate to assume that a fast ion driven mechanism may also play a role in determining the onset of the sword. If we take the frequency of trapped ions $\omega_d \cong \frac{nEq}{erR_0B} \approx 8kHz$, where n is the toroidal mode number, e is the charge of the ion, E the energy of resonant ions(~35keV), q is the safety factor associated to the plasma surface of minor radius r, and R0 is the tokamak major radius while B is the magnetic field(~1.3T). The difference between the measured sword frequency and plasma rotation can be made up with including the rotational effects through a Doppler shift in the form of $\omega_d + n\Omega \approx 16kHz$. Thus, taking into account the contribution of fast ions makes the frequency range being consistent with the n=1 frequency observed experimentally. Hence, it verifies that the energetic particles play an important role in determining the behavior of the sword.

Dissimilar to fishbone either, magnetic perturbation signals of the mode were not fishbone-looking bursts but in a long sword type envelope lasting for hundreds of milliseconds (Fig.1). Correspondingly, the mode frequency didn’t chirp but approximately a constant as seen in Fig. 1. Thus, to distinguish the mode from fishbone and underline the difference in magnetic perturbation signals, we call it the sword mode instead. Measured q-profiles with a low shear for the sword mode (Shot 16074) and a higher shear for the fishbone mode (Shot 19072) were shown in Fig. 2.

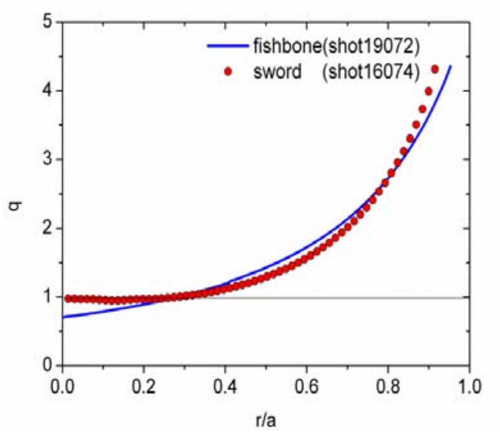

Figure 2: Measured q-profiles with a low shear for the sword mode (Shot 16074) and a higher shear for the fishbone mode

When the sword occurs, a reduction in the electron density, and the plasma stored energy, are usually observed. The neutron rate following the mode onset remains lower than that before the onset for the rest discharge period, indicating an enhanced level of fast ion losses which would reduce the effective NBI heating power.

Besides, in HL-2A plasmas the sword often transfers to fishbone or chirping modes, as depicted in Figure 6. Such a feature is opposite to those observed in other machines where typically a transition from fishbone or chirping modes to the sword was recorded [3, 4]. The transformation from the sword to chirping modes or the back transition to the sword suggests that the role of energetic ions remains important in the sword development.

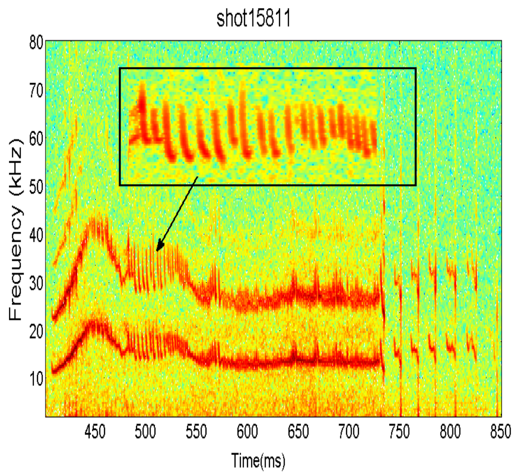

Figure 3. Fourier spectrogram of SXR measurements in the HL-2A discharge (shot 15811). Typically the sword transits into a chirping mode in the NBI-heated plasmas at

Additionally, it can be found that the oscillation in the low field side (LFS) was stronger than that in the high field side (HFS), exhibiting a clear pressure gradient driven characteristic. This is understandable, because in the low shear region the magnetic shear stabilization is minimized, but the pressure drive is enhanced due to the steep pressure gradient established by NBI heating. To further demonstrate the interchange features of the modes, figure 4 is given to show the evolution of central pressure gradient during the sword mode. Form this figure one can find that as the steepened pressure gradient at the q=1 surface reached a critical value at about 403ms, the sword was triggered. The largest pressure gradient at the position approximately r/a ~ 0.36 (near the q=1 surface), and the pressure gradient in LFS was bigger than that in HFS, again it shows a pressure-driven characteristic.

Then, at about 470ms the pressure gradient start to decrease but the sword continues. It indicates that the thermal pressure gradient is not the only possible energy sources, the fast particles pressure gradient might also play a considerable role as in these experiments the suprathermal pressure fraction (related to energetic ions) typically was of 20%.

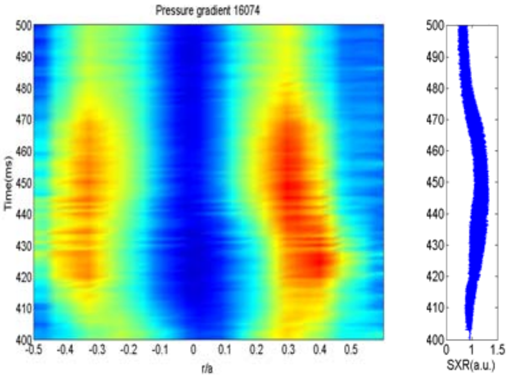

Figure 4. Spatial-temporal plot of the pressure gradient during the sword in discharge 16074.

3. Summary

In conclusion, the newly observed long-lasting m/n=1 mode in low shear plasmas is studied based on experiment results and theoretical investigations. Unlike the LLM in MAST[4], the mode is driven by trapped fast ions with a frequency on the order of the processional. On the other hand, the mode has a slowly varied radial structure differing evidently from that of the fishbone. Particularly, the long lasting (for hundreds of milliseconds) and no frequency chirping features of the mode are easily identified and significantly distinguishable from the fishbone. The sword mode, due to its pressure-driven feature, is destabilized by large pressure gradients and by strong interaction with fast ions in the low shear region during the NBI.

To prevent the deleterious impact on fusion relevant plasmas in advanced tokamak scenarios, an effective control of the sword mode is also studied. The mode is destabilized by large pressure gradient in the low magnetic shear region. To avoid this instability, it is thus necessary to maintain finite magnetic shear in the interior of the plasma or to broaden the pressure profile so that the pressure gradients are reduced in regions of low shear. Successful suppression has been obtained in HL-2A experiments with ECRH or SMBI. The control of sword is primarily attributed to the change of the magnetic shear and the pressure profile through the local heating or fuelling.

Acknowledgement

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