Investigation on Low-Frequency MHD Instabilities during High Power Auxiliary Heating on HL-2A

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The transport and confinement of alphas and energetic ions are very important, which not only impact machine performance by affecting the fusion yield but also due to the large power carried by these energetic particles, even relatively small losses of alphas or energetic ions can damage the machine's first wall[1]. To understand the behavior of energetic electrons is also very important, because the alphas transfer their energy mostly to electrons firstly. Investigation on the low-frequency and macro-MHD waves, which are fishbone, beta-induced Alfvén Eigenmode (BAE)[2], long-lived mode (LLM) and tearing mode (TM), are significant, because (1) fishbone, BAE and LLM modes can lead to redistribution and loss of energetic particles; (2) LLM even can slow down the toroidal rotation in the core[3]; (3) TM is a very important MHD mode, which can lead to confinement degeneration, and will be the principal limit on performance in large tokamaks, like ITER; (4) fishbone can transit from/to LLM[4], and fishbone as magnetic seed island can even trigger TM/NTM[5]. It's important to investigate low-frequency MHD instabilities during high power NBI and ECRH on HL-2A.

The transition from fishbone to LLM modes has been observed on HL-2A, and the typical phenomenon is shown in Fig.1 in shot 21787 during t=620-630 ms. The discharge parameters are shown in Fig.1 (a), and toroidal magnetic field B_t=1.32 T. The fluctuations of Mirnov signals can be seen obviously from Fig.1 (b). The fishbone mode appears with the frequency about 30 kHz at 620 ms, and then its frequency decreases rapidly to 10 kHz during t=620-622 ms. The fishbone mode transits to LLM continuously at t=622 ms, and

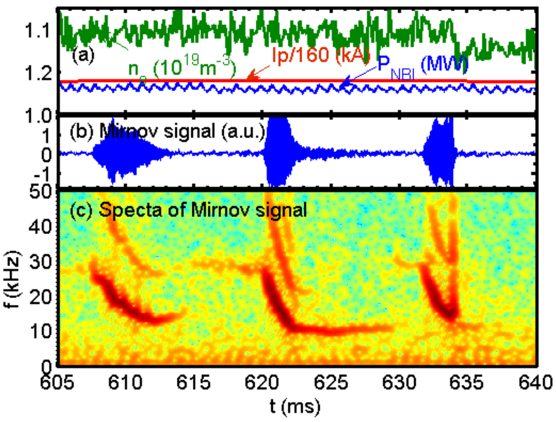

Fig.1 Transition from fishbone to LLM in shot 21787. (a) plasma current Ip=159 kA, line-averaged electron density n_e=1.2× 10^{19} m^{-3} and power of NBI P_{NBI}=0.95 MW, (b) fluctuations of Mirnov signal, (c) frequency spectra of Mirnov signal.

the frequency of the LLM (f_{LLM}) keeps as 10 kHz until the end of the LLM mode at 630 ms, as shown in Fig.1 (c).

Not only the transition from fishbone mode to LLM is observed, but also the inverse process is observed on HL-2A during high power NBI as shown in Fig.2. The discharge parameters in shot 19375 are shown in Fig.2 (a), (b) and (c), and B_t=1.42 T. The Mirnov signals during the LLM and fishbone period are shown in Fig.2 (d). The f_{LLM} increases from 15 to 18 kHz during t=480-548 ms slowly from the frequency spectra of Mirnov signals, as shown in Fig.2 (e). The LLM transits to fishbone at t=548 ms. The frequency of fishbone ($f_{fishbone}$) is in the range 18-29 kHz, and sweeps down rapidly.

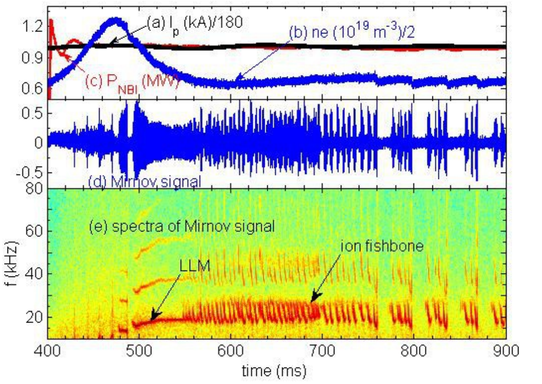

Fig.2 Transitions from LLM to fishbone mode during high-power NBI heating in shot 19375. (a) Ip=180 kA, (b) n_e=(2.4-1.3)× 10^{19} m^{-3}, (c) P_{NBI}=0.98 MW, (d) Mirnov signal and (e) frequency spectra of Mirnov signal.

It's interesting to find that fishbone mode and its second harmonic as magnetic seed islands can trigger TMs. The typical phenomena are shown in Fig.3 in shot 21789. The discharge parameters are shown in Fig.3 (a), and B_t=1.32 T. The fluctuations of Mirnov signal are shown in Fig.3 (b). There is the detail process of the transition from fishbone mode to TMs in Fig.3 (c). The frequencies of fishbone mode and its harmonic decreases from 30-10 kHz and 60-20 kHz during t=577.0-578.5 ms, respectively. Then two TMs, with starting frequencies about 10 kHz and 20 kHz, follows the fishbone modes and its harmonic tightly and continuously at t=578.5 ms. Two TMs exists during t=578.5-586ms. It's found that the poloidal and toroidal mode numbers of TMs are m/n=2/1 and 3/2 for the low- and high-frequency TMs, respectively. Except that, it's identified that there is a LLM mode, and its frequency and evolution are just the same as the m/n=2/1 TM period. The mode number of the LLM is likely m/n=1/1. By further investigation, it’s found that the high frequency 3/2 TM is likely coupled between the 1/1 LLM and the low-frequency 2/1 TM. Because the frequency and mode number of 3/2 TM are

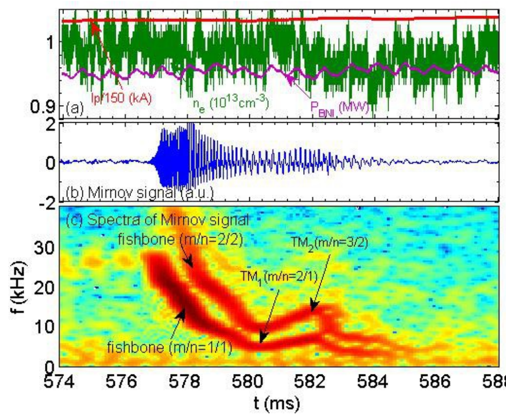

Fig.3 Fishbone mode and its second harmonic as seed magnetic islands triggering TMs in shot 21789. (a) Ip=159 kA, n_e=1.0× 10^{13} cm^{-3} and P_{NBI}=0.95 MW, (b) Mirnov signal and (c) frequency spectra of Mirnov signal.

agree with the sums of 1/1 LLM and 2/1 TM, for example, $f_{TM_1} + f_{LLM} = f_{TM_2}$ (5+5=10) and $n_{TM_1} + n_{LLM} = n_{TM_2}$ (1+1=2) near t=580 ms.

Periodic frequency jump phenomena of fishbone have been detected by a soft x-ray array during high power ECRH on HL-2A [6]. The frequency jump can be observed, when P_{ECRH} increases to about 0.9 MW the frequency jumps between 8 kHz and 14 kHz within about 25ms periodically, when P_{ECRH} is 1.2 MW, as shown in Fig.4 (d). The poloidal and toroidal mode numbers for low- and high-frequency branch e-fishbone are m/n=1/1 and 2/2, respectively. According to statistics, it is found that the threshold ECRH power for the appearance of low- and high-frequency branch e-fishbone are about 0.6 MW and 0.9 MW, and not only the frequency of low-frequency branch but also that of the high-frequency branch increases with ECRH power. The trapped electrons with energy 20-30 keV and 40-60 keV are approved to be related with low- and high-frequency branches of fishbone by hard X-ray measurement.

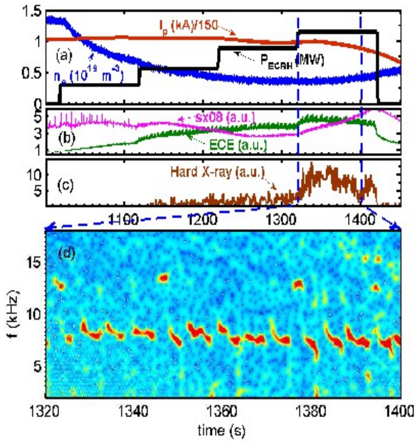

Fig.4. Typical temporal evolution of (a) Ip=155 kA, (b) n_e=(1.3-0.4)× 10^{13} cm^{-3}, (c) P_{ECRH}=0.3/0.6/0.9/1.2 MW, (d) electron temperature from ECE, (e) soft X-ray intensity, (f) hard X-ray with the energy of 10-20 keV and (g) soft X-ray's frequency spectra in shot 17892.

The multi-mode structure of BAEs is observed for the first time on Tokamaks [7]. To observe the features of the mode in the different heating power, P_{ECRH} is increased step by step, as shown in Fig.5 (f). The ECRH power deposits at the minor radius of r=15cm in the lower field side mainly with the toroidal magnetic field of 1.33 T in this shot. The discharge parameters and diagnostic signals are shown in Fig.5 (a)-(e). The evolution of the frequency spectrum of the magnetic fluctuation measured by Mirnov probes is shown in Fig.1 (g). It has been found that in the ohmic or low power ECRH plasma, only one peak can be seen clearly in the frequency spectrum. When the

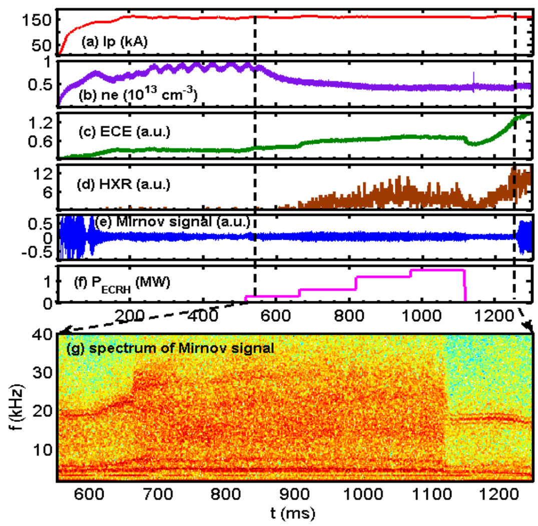

Fig.5. Evolution of (a) Ip=157 kA, (b) n_e=(0.9-0.4)× 10^{13} cm^{-3}; (c) electron temperature from ECE, (d) hard X-ray (HXR) in the energy range of 10-20keV (e) signal of Mirnov probe; (f) P_{ECRH}=0.3/0.6/1.2/1.5MW and (g) frequency spectrum of Mirnov signal in shot 17461.

power is over about 0.6 MW, two peaks or three peaks appear and it is broadening with the heating power. After ECRH switch-off, the spectrum comes back to previous one with only one frequency peak. The three modes with frequencies in the range f_3~28-32 kHz, f_2~20-22 kHz and f_1~13-15 kHz, which are proportional to Alfven speed and in agreement with the accumulated point frequencies of the BAE. And their corresponding mode numbers are m/n=2/1, 5/2 and 3/1, respectively. The multi-mode of BAEs cover almost half of the cross section, so is important for the confinement of plasma and loss of energetic particles. The energetic trapped electrons with energy of 10-15 keV, 15-20 keV and 20-30 keV are proved to be related with the three BAEs, with frequencies f_1, f_2 and f_3, respectively.

The transition and interaction processes between the low-frequency MHD modes are illustrated in Fig.6. Fishbone modes excited by energetic ions and electrons have been observed during NBI and ECRH on HL-2A. The ion fishbone mode can transit to/from LLM. It's interesting to find that fishbone modes and its harmonic as seed magnetic islands can trigger TMs, simultaneously. The mode numbers of high- and low-frequency TMs are m/n=3/2 and 2/1, respectively. The nonlinear interaction between m/n=2/1 TM and 1/1 LLM are found.

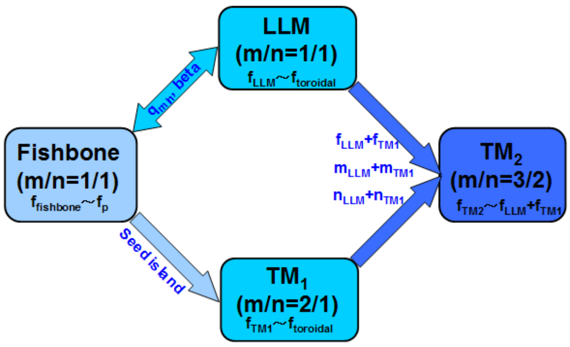

Fig.6 Transition and interaction processes between the low-frequency MHD modes.

Acknowledgement

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