OBSERVATIONS OF FAST IONS TRANSPORT INDUCED BY FISHBONE USING A FAST ION LOSS DETECTOR ON HL-3 TOKAMAK

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Fishbone mode was first observed to be excited by fast ions in PDX [1]. So far, it has been observed on many devices that fishbone can cause significant beam ion loss [2-6]. The mechanism of fast ions loss induced by fishbone is usually described by mode particle pumping process [7]. The frequency of fishbone is determined by the precessional frequency of resonant fast ions. After the fishbone is excited, the fast ion loses part of its energy and moves radially outward, while the precession frequency decreases. Then, these fast ions resonate with the low-frequency fishbone and lose some energy again, moving radially outward again. In the HL-3 experiment in 2024, the mode particle pumping process of fast ion loss induced by fishbone has been observed directly by a newly developed fast ion loss detector (FILD).

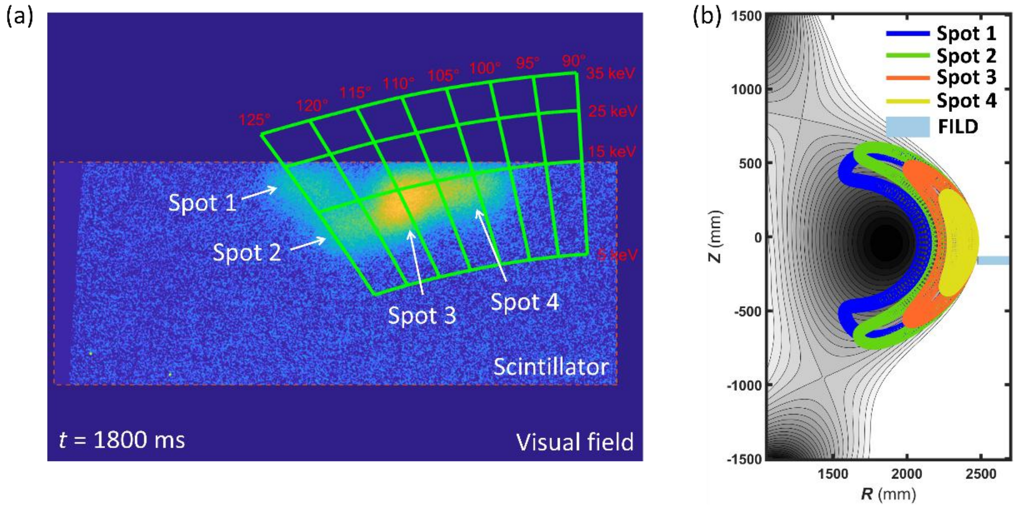

Fig. 1 A typical pattern image of the FILD during fishbone in shot 6011. The fluorescence pattern in the FILD vision (a). The unperturbed orbits of the spots in FILD vision (b).

The FILD in experiments of 2024 Q1 features a new dual collimator design that allows for a large pitch angle detection range while ensuring less self-shadowing. This paper focuses on lost fast ion signals with pitch angles greater than 90°. The FILD signals are calibrated by the FSC [8] to obtain the energy and pitch angle of the loss fast ions of each spot. The orbits of the loss fast ions can be calculated by the FSC inversion function. This work is a study of a typical NBI discharge 6011 of the HL-3 tokamak. The fishbone was coupled with sawtooth in this shot. As the sawtooth crash, the signal intensity of FILD changes dramatically. Fast ions loss induced by fishbone can be observed within a short period before sawtooth crash. During the fishbone, four spots with different energies and pitch angles were observed on the FILD vision, as shown in Fig.1 (a). The orbits of these spots are all banana orbits, but the inner side of them have different radial position (see Fig.1 (b)). The orbits of the lost ions are calculated in reverse based on the position of the spots on the scintillator. The alignment of the collimator as well as the installation position and angle of the detector head are also taken into account in the calculation. Therefore, these orbits can uniquely correspond to the spots in FILD vision.

Fig.2 shows the brightness changes of the four spots during the fishbone period. The frequency of fishbone sweeps down during 1836 ms ~ 1840 ms. Meanwhile, the peak of intensity gradually shifts from spot 1 to spot 2.

As shown in Fig.2 (a), the two spots have been mapped to the energy space, it can be seen that the energy of lost fast ions is gradually decreases from 16 keV to 13 keV during the process. This may correspond to the energy loss of fast ions after the excitation of fishbone. As a comparison, there is no significant change in the mode frequency between 1876 ms and 1880 ms. During this process, the energy of the lost fast ions is always concentrated at 13.5 keV without significant change. Therefore, the change in the energy of lost fast ions is primarily attributed to the fishbone with frequency chirping rather than the sawtooth crash.

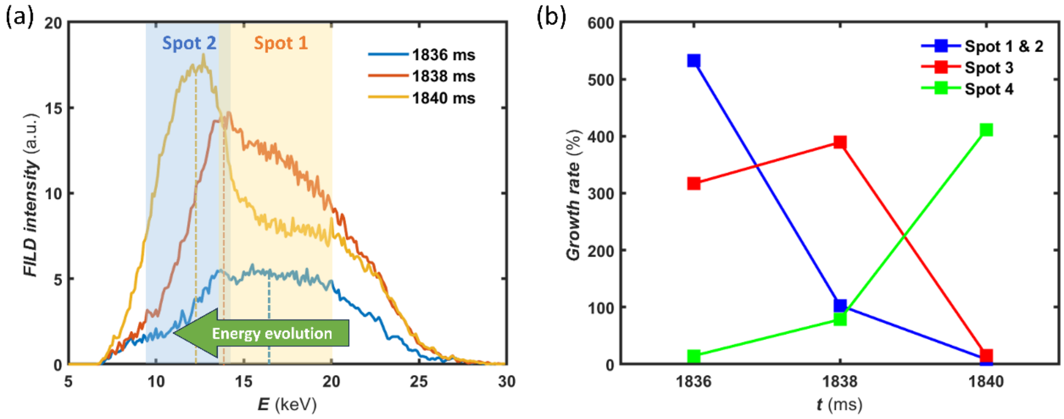

Fig. 2 Evolution of the energy and pitch angle of lost fast ions during fishbone. Evolution of the energy of lost fast ions during 1836ms-1840ms (a). Evolution of the Pitch angle of lost fast ions during 1836ms-1840ms (b).

Fig.2 (b) shows the brightness variation of the four spots during the fishbone period, and they have been mapped to the pitch angle space. The rate of change of spots brightness is demonstrated here. Between 1836 ms and 1840 ms, the spots with the strongest rate of change in brightness shifted from spots 1 and 2 to spot 3 and finally to spot 4. This implies that as the frequency of the fishbone decreases, spots 1 and 2 are the first to respond, followed by spot 3, and lastly by spot 4. Comparison with the orbits of the spots reveals that the orbits that show a strong response are gradually shifted outwards in the radial direction, which corresponds to the process of fast ions being expelled outwards by fishbone. The SXR signals indicate that an m/n=1/1 mode is excited firstly in the process, which is thought to be responsible for the loss of fast ions closer to the core area, and an m/n=2/1 mode is excited latterly with a radial position more outward compared to the former one, and is thought to be responsible for the loss of fast ions further away from the core area. A similar phenomenon occurred between 1906 ms and 1908 ms, but spot 4 never showed a response. This may be due to the fact that the fishbone ends its frequency sweep at a too high frequency. The frequency of the fishbone in 1908 ms is about 8.2 kHz, higher than the 7 kHz in 1840 ms. This may mean that the fishbone at 1908ms is located in a region closer to the core area than at 1840ms and therefore cannot directly expel fast ions to the plasma boundary corresponding to the orbits of the spots 4.

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