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Observation of Electron Fishbone-Like Instabilities in EAST Heavy Impurity Ohmic Plasma *

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The transient burst of an internal kink mode is first observed in EAST heavy impurity ohmic plasma. The features of the electron fishbone-like mode are presented, and the fishbone-like instabilities are found to be driven by the trapped supra-thermal electrons. The processional frequency of the trapped supra-thermal electrons is calculated with different discharge parameters. The results indicate that the calculated processional frequency is consistent with the experimental observations. Furthermore, we also find that the frequency chirping of the long-lived mode is related to the evolution of the safety factor profile.

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Ion fishbone instability was first discovered during neutral beam injection (NBI) almost perpendicular to the toroidal axis in the PDX tokamak.[1] The name fishbone comes from the characteristic shape of the magnetic signal from the edge Mirnov coils. It is widely accepted that a $(m, n) = (1, 1)$ internal kink mode is destabilized by energetic trapped ions via processional resonance.[2] Then, an internal kink instability, which is driven by the barely trapped superthermal electrons produced by high-field-side off-axis electron cyclotron resonance heating (ECRH), was observed in DIII-D and HL-2 A.[3,4] Soon afterwards, the theoretical interpretation of the destabilization of the electron fishbone was proposed by Sun *et al.*[5] They proposed that the internal kink mode can be excited by barely trapped supra-thermal electrons. An interesting property of fishbones is their nonlinear dynamics, which include (i) robust bursting behavior, and (ii) strong chirping and reduction of the mode frequency during a fishbone burst.[6] Frequency chirping is associated with energy losses and fast particle redistribution.[4] In this Letter, an impurity ion-related 1/1 electron fishbone-like instability is observed for the first time in EAST heavy impurity[7] ohmic plasma. The mode structures are located inside the $q = 1$ flux surface. The hot core of the 1/1 mode travels in the ion diamagnetism drift velocity direction in the poloidal cross section.[7] The internal mode appears in the soft x-ray emission in the plasma center when the intensity of the hard x-ray reaches a critical value. Because of the toroidal effect of the tokamak, the structures of the 2/1 mode are usually detected in the edge Mirnov signals. Furthermore, the processional frequency of the suprathermal trapped electrons is calculated with different discharge parameters. The results indicate that the calculated processional frequency is consistent with the experimental observations.

The electron fishbone-like modes are observed in soft x-ray signals (SXR) and Mirnov coil signals. In this study, the phenomenon is presented and analyzed mainly with the SXR signals. Three SXR cameras were installed in port C of EAST, with their arrangement as shown in Fig. 1. For the cameras, the thickness of the beryllium foil is 12.5 μm, and the spatial resolution is 2.5 cm in the central region. The maximum sampling rate is 100 kHz.[7]

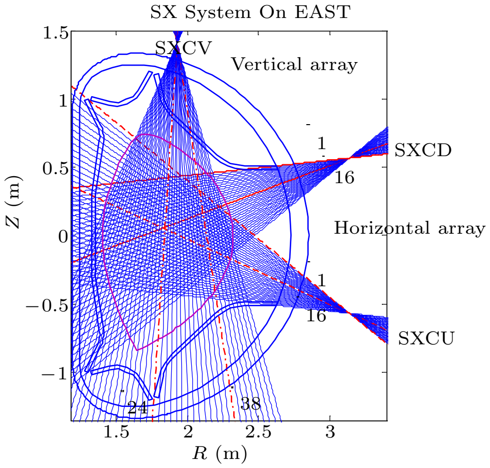

Fig. 1. The soft x-ray system in EAST. The red lines indicate the core region where the fishbones are generally found. Each U and D array has 35 chords that are numbered clockwise from 1 to 35. The V array has 46 chords named from SXC1V to SXC46V.

The poloidal number, m, is measured using a set of edge Mirnov probes (cmp1t–cmp26t) localized in the poloidal cross-section. The toroidal number, n, is determined by another set of 16 Mirnov probes (MITAB-MITPA) localized in the vessel.

An example of electron fishbone-like oscillations appearing in the end of the current ramp-up phase is shown in Fig. 2. The main parameters of this discharge (#12007) are: plasma current $I_{\rm p} \approx 300\,{\rm kA}$, central chord-averaged electron density $n_{e0} \approx 2 \times 10^{19}\,{\rm m}^{-3}$, and toroidal field $B_{\rm t} = 2.0\,{\rm T}$. The transient burst electron fishbone-like mode, as shown in Fig. 3,

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is found in ohmic discharge. These internal kink instabilities have an $m/n = 1/1$ structure. The poloidal harmonic with $m = 2$ is also visible in this shot. Due to the toroidal effect of the tokamak configuration, the $m = 2$ sideband mode is commonly detected in the edge Mirnov probes. The 2/1 mode in the Mirnov signals correspond to the strong 2/2 mode of the internal kink mode. It is natural that the Mirnov signals are usually dominated by the $m = 2$ sideband mode, since the $m = 1$ internal kink modes have very small amplitudes on the edge where the magnetic coils are located. From Fig. 4, it is clear that the impurity content is high in this discharge. Moreover, the long-lived modes (LLMs) destabilized by heavy carbon impurities are also observed. It is unsurprising that the interaction between the plasma and the first wall (the graphite wall) is intensive during the current ramp-up phase and can generate a large amount of impurity.

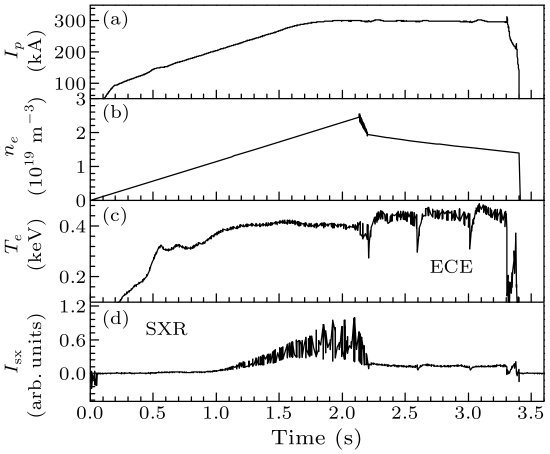

Fig. 2. The time evolution of the main plasma parameters of ohmic shot 12007. $I_{\rm p}$ is the plasma current, n_{e0} is the central chord-averaged electron density, ECE is the electron temperature T_e of the central region, and SXR is the chord-integrated SXR intensity $I_{\rm sx}$ 2.7 cm away from the plasma center.

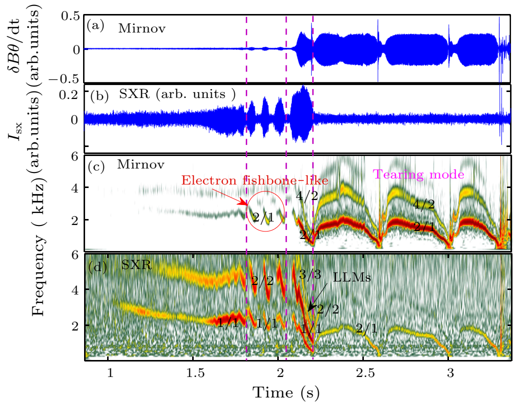

Fig. 3. The transient burst of electron fishbone-like instability in 12007: (a) the SXR signal, and (b) the edge Mirnov signal. The continuous wavelet transform (CWT) scalogram of (a) and (b) is in (c) and (d), respectively.

In EAST, the CdTe detector array is used to measure the fast electron thermal bremsstrahlung (FEB) emission in the energy range 20–300 keV. The FEB emissions resulting from the collisions between the fast electrons and the bulk plasma ions provide considerable information on the dynamics of fast electrons. On the other hand, the hard x-ray (HX) emission provides information on the generation, loss and energy content of supra-thermal trapped electrons. The peaking of the HX signal before the formation of an electron fishbone is clear, as shown in Fig. 5(a). The sudden decrease in HX signal reflects the loss of supra-thermal electrons after the burst of electron fishbone-like instability. The typical frequency chirping of the electron fishbone-like instability is shown in Figs. 5(b) and 5(c). However, there is no HX peak just before the formation of carbon-induced LLMs. The surprisingly longer timescale of LLMs is significantly different from the typical fishbone. Again, the LLMs are related to the higher impurity density.[9]

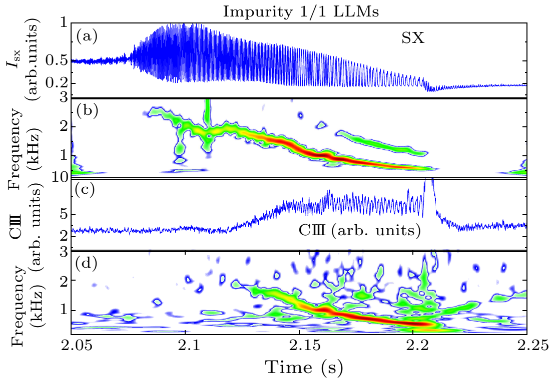

Fig. 4. The good agreement between LLMs and carbon emissions (CIII): (a) SXR signal, and (c) carbon emissions (CIII). Here, (b) and (d) are the time-frequency plots of (a) and (c).

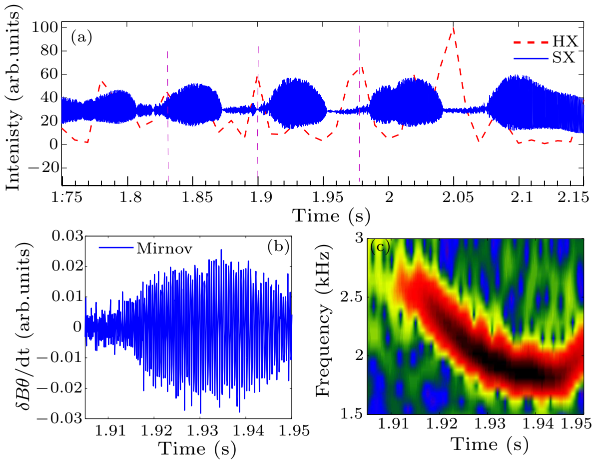

Fig. 5. (a) The intensity of the HX signal reaches a critical value just before the formation of the e-fishbone. (b) The edge Mirnov signal, and (c) the frequency chirping of the e-fishbone.

To study the interaction between the energetic electrons and fishbone modes, the processional frequency[10] is estimated by the equation

$$\omega_d = \frac{Eq}{eB_{\rm t}R_0a}H(k,s) + o(\varepsilon), \tag{1}$$

where E is the electron energy, e the electron charge, a the minor radius, s the magnetic shear, and $H(k, s)$

is defined as

$$k = \sqrt{\frac{1+\varepsilon}{\varepsilon}\cos(\theta_0)},\ \varepsilon = \frac{a}{R_0},\ \theta_0 = \arccos(\frac{\vartheta_{ll}}{\vartheta}),$$
$$H(k,s) = 4s(k^2-1) - 1 + 2(1+2s)\frac{E(k^2)}{K(k^2)}, \qquad (2)$$

where ϑ_{ll} and ϑ are the parallel and total velocities of energetic electrons, respectively; and $E(k^2)$ and $K(k^2)$ are the complete elliptic integral of the second kind and first kind, respectively. The q-profile is obtained by the EFIT code in $t = 1.80$ s, as shown in Fig. 6.

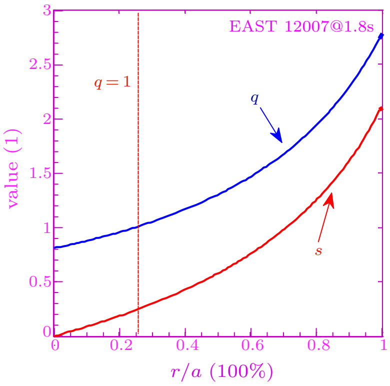

Fig. 6. The safety factor q profile and magnetic shear s profile in the $t = 1.8$ s of shot 12007 from the EFIT code. The vertical red line indicates the position of the $q = 1$ surface.

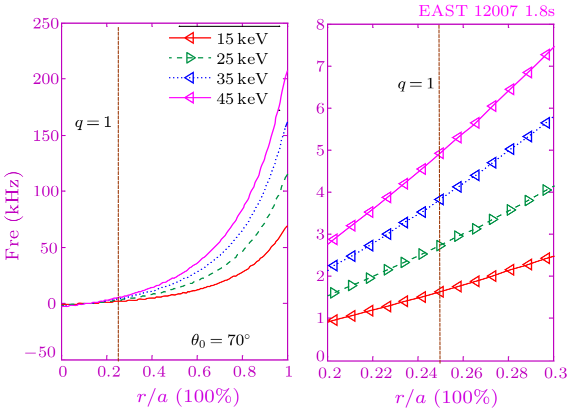

Fig. 7. Calculation of the processional frequency: trapped electrons with toroidal magnetic field $B_{\rm t} = 2.0$ T and pitch angle 70° at different energies.

Taking $a = 0.43$ m, and $B_{\rm t} = 2.0$ T for the EAST shot 12007, according to Eq. (1), the calculated results are shown in Figs. 7 and 8. The frequency range of the electron fishbone in 12007 is less than 5 kHz. From Figs. 7 and 8, the processional frequency increases with the increase in energy and the pitch angle of electrons. Taking $\theta_0 = 70°$ in the hypothesis, therefore, the 5 kHz frequency of e-fishbone instabilities is probably excited by the energetic electrons with $E_\gamma = 35$ keV, with which the calculated processional frequency is 3.74 kHz. Furthermore, the frequency chirping of LLMs is related to the evolution of the q-profile, as shown in Fig. 9.

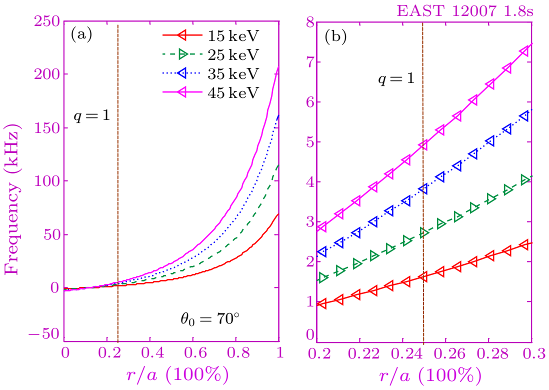

Fig. 8. The processional frequency of trapped electrons with toroidal magnetic field $B_{\rm t} = 2.0$ T and $E_\gamma = 35$ keV with different pitch angles.

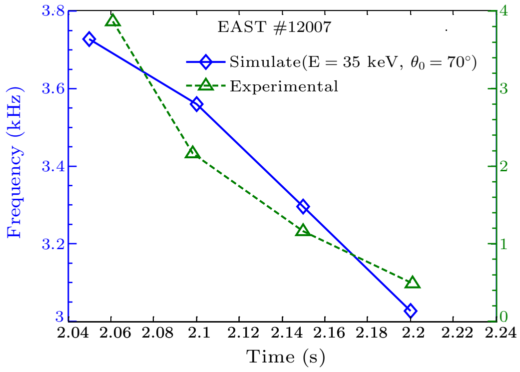

Fig. 9. The calculated processional frequency under different q-profiles is comparable with the time evolution of the detected experimental frequency of LLMs.

In summary, the internal kink mode is destabilized by the supra-thermal electrons in EAST impurity ohmic plasma. The mode structures are located at the $q = 1$ flux surface. It is proved that the energetic electrons with an energy of 35 keV play a dominant role in the excitation mechanism, and the calculation analysis shows that the mode frequency is close to the precession frequency. The frequency chirping of LLMs is related to the evolution of the q profile. However, the role of impurity in the excitation of LLMs, as well as the electron fishbone-like mode, is still unclear. The existence of the magnetic reconnection during the electron fishbone-like mode process is also unknown.

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