Suppression and destabilization of ion fishbone activities on HL-2A

W. Chen¹, L. M. Yu¹, X. L. Zhu², M. Jiang¹, P. W. Shi¹, X. Q. Ji¹, Z. B. Shi¹, B. S. Yuan¹, D. L. Yu¹, Y. G. Li¹, Z. C. Yang¹, Y. R. Yang¹, X. T. Ding¹, M. Xu¹, Q. W. Yang¹, Yi. Liu¹, L. W. Yan¹ and X. R. Duan¹

¹Southwestern Institute of Physics, P.O. Box 432 Chengdu 610041, China
²School of Physics, DLUT, Dalian 116024, China

Corresponding Author: chenw@swip.ac.cn

Abstract:
In the present paper the recent progress of ion fishbone activities will be present on HL-2A. Firstly, it will be reported the stabilization of m/n=1/1 fishbone by the ECRH. The stabilization of m/n=1/1 fishbone depends not only on the injected power but also on the radial deposition location of ECRH, and the instability can be completely suppressed when the injected ECRH power exceeds certain threshold. Analysis by the fishbone dispersion relation, including the resistive effect, suggests that the magnetic Reynolds number plays a key role in the mode stabilization. Secondly, it is found for the first time in tokamaks that an unstable tearing mode with slowly rotating m/n=2/1 helicity interacts with energetic-ions and results in amplitude-bursting/frequency-chirping fishbone-like activities. Nonlinear hybrid kinetic-MHD simulations with M3D-K code prove that the co-passing energetic-ions are responsible for the drive of tearing modes, and the wave-particle resonance condition is satisfied at \( \omega_\phi - 2\omega_\theta - \omega = 0 \).

Introduction.–Magneto-hydrodynamic (MHD) instabilities in a hot plasma can strongly limit the operational parameter space of a fusion reactor. Their stabilization, suppression and active control have therefore attracted much attention, in particular with regard to expansion of the operational space, enhancing the fusion performance and decreasing the energetic particle losses in both present-day fusion devices and future devices with burning plasmas. Control of multiple instabilities including sawtooth, neoclassical tearing mode (NTM), resistive wall mode (RWM), edge localized mode (ELM), Alfvén eigenmode as well as energetic-particle mode (EPM), has been successfully achieved, to various degrees, by different means such as the radio frequency wave heating/drive, the three-dimensional magnetic perturbations, and so on, in many fusion devices [¹]. On the other hand, understanding of both the control and physics of these instabilities, in many cases, is still far from complete, and remains area of active research. The fishbone mode is one of these key instabilities, destabilized by a population of energetic particles [²]. In burning plasmas, energetic alpha particles, though being a minority species, carry a large fraction of the plasma kinetic energy, and can potentially drive the fishbone instability. The fishbone has also been proposed as a possible scheme for ash removal and burn control [³, ⁴], as well as tungsten-impurities removing from the plasma core on ITER [⁵]. In this paper, we present two experimental results: (I) controlling and suppressing the ion fishbone activities, by applying the electron cyclotron resonant heating (ECRH); (II) tearing mode driven by energetic-ions, resulting in fishbone activities.
FIG. 1: Typical discharge (Shot 1) parameters with the stabilization of ion fishbone activities by ECRH. From top to bottom, line-averaged plasma density \( n_e \), electron temperature \( T_e \) near \( q=1 \) rational surface, poloidal Mirnov signal \( dB/dt \) at the midplane, and soft X-ray signal in the core. \( B_t = 1.34T \), \( I_p = 150kA \), and \( P_{NB} \approx 1MW \). The ECRH power is deposited at \( \rho_d \approx 0.42 \).

Suppression of \( m/n=1/1 \) ion fishbone.---The full suppression of ion fishbone activities by ECRH has been observed on HL-2A. This experimental phenomenon is perfectly reproducible. Figure 1 shows a typical experimental result. During NBI the injected beam-ions stabilize the sawtooth and drive the fishbone unstable. However after the high-power ECRH is switched on at \( t \approx 704ms \), the core electron temperature substantially increased, accompanied by a slight density drop. More crucially, the fishbone was completely stabilized. When the ECRH was switched off at \( t \approx 804ms \), the temperature and density began to change in the opposite direction, and the mode suppression lasted for another \( t_d \approx 30ms \), which is close to the energy confinement time \( (\tau_E) \). In fact, this experiment suggests that the high-power ECRH induces a sawtooth-free and fishbone-free operation regime during the NBI.

FIG. 2: Effects of ECRH on the stability of ion fishbone activities. Same ECRH power \( P_{ECRH} \approx 1MW \), but different deposited location (Left col.); Same deposited location \( \rho_d \approx 0.42 \), but different ECRH power (Right col.). \( P_{NB} \approx 1MW \) and \( I_p = 150kA \) in all cases.

By scanning the ECRH configuration parameters, we found that the fishbone stability
depends not only on the injected power, but also on the radial deposition location of ECRH. The fishbone can be completely suppressed, when the injected ECRH power level exceeds certain threshold. As shown in figure 2, at the same power level \((P_{\text{ECRH}} \approx 1\,\text{MW})\), when the ECRH power is deposited on-axis \((\rho \sim 0)\), the observed mode frequency obviously decreases, but the mode amplitude is only weakly reduced. When the power is deposited outside of the \(q=1\) rational surface \((\rho \sim 0.38)\), the mode is fully stabilized. When the power is deposited off-axis \((\rho \sim 0.66)\), the mode is partially stabilized. On the other hand, with the same deposition position \((\rho_d \approx 0.42)\), ECRH at low power \((P_{\text{ECRH}} = 0.37\,\text{MW})\) has hardly any stabilizing effect on the mode, whilst with increasing the power level, the mode is progressively suppressed, with the full stabilization achieved at about \(P_{\text{ECRH}} \approx 0.60\,\text{MW}\).

**FIG. 3:** Profiles of density \((n_e)\), safety factor \((q)\), ion temperature \((T_i)\) and toroidal rotation frequency \((f_{\phi})\) during the existence and full suppression of ion fishbone (FB) activities for Shot I.

There is no any experimental evidence which suggests that the ECRH can enhance ion fishbone activities on HL-2A. What does induce the mode stabilization? Figure 3 shows the radial profiles of the thermal electron density, the safety factor, the ion temperature and the toroidal rotation frequency, for two cases: with fishbone in the absence of ECRH, and without fishbone in the presence of ECRH. It is found that the \(q\)-profile does not obviously change between these two cases. The profiles of the ion temperature and the toroidal rotation frequency both become flat after application of ECRH. This suggests that ECRH weakens the toroidal flow shear and the ion diamagnetic drift frequency \(\omega_{si}\) at the \(q=1\) rational surface. From Figure 1, it is also found that the slowing-down time \(\tau_s \propto T_i^{3/2}/n_e[6]\) increases during the ECRH phase. The weakened flow shear \[7\] and the prolonged slowing-down time should both improve the mode growth-rate. But on the contrary, the mode stabilization was observed in all experiments, indicating a hidden piece of physics which plays a dominant role in the mode stabilization.

Figure 4 shows the detail of the mode-frequency chirping, and the comparison of the observed mode frequency with the averaged precession frequency \((f_d)\) of trapped energetic ions. It clearly suggests that the mode frequency presents a hook shape, and the maximum and the minimum of the mode real frequency satisfy \(f_{\text{max}} \sim f_d\) and \(f_{\text{min}} \sim 0\), respectively. These features indicate that the observed fishbone activity asserts itself a resistive mode at the last stage of chirping \[8\], and the mode stability is marginal due to the cyclic burst feature of the mode amplitude.

It is well known that the growth-rate \((\gamma/\omega_A)\) of the resistive internal kink in toroidal
FIG. 4: Comparison of observed mode frequency with averaged precession frequency ($f_d$) of trapped energetic-ions after considering the toroidal rotation frequency ($f_{rot}$) near $q = 1$ rational surface (a). Typical 2D mode structure of fishbone activity from ECEI (b).

FIG. 5: Relative changes of Magnetic Reynolds number ($S_M \propto n_e^{-1/2}T_e^{3/2}$) and resistive layer width ($\rho_R \propto n_e^{-1/4}T_e^{-3/4}$) near $q = 1$ rational surface (Shot I).

geometry, being similar to that of the tearing mode, depends strongly on the magnetic Reynolds number ($S_M = \tau_R/\tau_A$), with $\gamma/\omega_A \propto S_M^{\alpha}$ ($1/3 < \alpha < 3/5$) [9,10]. Here $\tau_R = \mu_0 r_c^2/\eta$ and $\tau_A = R_0/v_A$ are resistive diffusion time and the Alfvén time, respectively. $\eta = 1.65 \times 10^{-9} Z_{eff} \ln \Lambda/\Lambda e$ is the Spitzer resistivity, and $v_A = B/(\mu_0 n_i m_i)^{1/2}$ is the Alfvén velocity. The resistive layer width is given by $\rho_R \sim (\tau_A/\tau_R)^{1/2} r_1$ [11]. Figure 5 shows the relative changes of the Magnetic Reynolds number ($S_M \propto n_e^{-1/2}T_e^{3/2}$) and the resistive layer width ($\rho_R \propto n_e^{-1/4}T_e^{-3/4}$) near the $q = 1$ rational surface, during ECRH. The Magnetic Reynolds number and the resistive layer width experiences substantial increase and decrease, respectively. In these cases, the typical value of $S_M$ is in the range of $10^5 - 10^6$. In the presence of trapped energetic-ions and the resistive effect, this instability is described by the dispersion relation [12,13]

$$\delta W_e + \delta W_k + \frac{8\Gamma[(\Lambda^{3/2} + 5)/4]}{S_M^{1/3} \Lambda^{9/4} \Gamma[(\Lambda^{3/2} - 1)/4]} \times [\Omega(\Omega + i\omega_{di})]^{1/2} = 0$$

(1)

where $\Omega = -i\omega/\omega_R$, $\Lambda = [\Omega(\Omega + i\omega_{te}/\omega_R)(\Omega + i\omega_{si}/\omega_R)]^{1/3}$, $\omega_R = S_M^{1/3} \omega_A$ is the resistive frequency, $\omega_A$ is the Alfvén frequency. The $\omega_{di,te}$ terms are the ion and electron diamagnetic drift frequencies respectively, and $\omega_{te} = \omega_{de} + 0.71(c/eBr)(dT_e/dr)$. By use of a slowing-down distribution of trapped energetic-ions, the kinetic contribution becomes

$$\delta W_k = i(\beta_h/\varepsilon_1)\Omega A \ln[1 + i/(A\Omega)]$$

(2)
where $\beta_h$ is the energetic-ion beta, $\varepsilon_1 = r_1/R_0$, $A = \omega_R/\omega_{dm}$, $\omega_{dm} = E_m q/(r_1 R_0 B)$ is the maximum precessional frequency, and $\omega_d = \omega_{dm}/2$.

\[
\gamma / \omega_A \sim 0.5, \quad \omega / \omega_{dm} \sim 0.5,
\]

which is consistent with the general fishbone theory prediction.

\[
\delta W_c = -0.01.
\]

**FIG. 6:** Mode growth-rate ($\gamma/\omega_A$) and real frequency ($\omega_r/\omega_{dm}$) versus energetic-ion beta ($\beta_h$) (a-b) and Magnetic Reynolds number ($S_M$) (c-d). $\delta W_c = -0.01$.

**FIG. 7:** Typical discharge (Shot I) parameters with TM's and fishbone-like activities during NBI heating on HL-2A. From top to bottom, (a) plasma current $I_p$, line-average electron density $n_e$ and NBI power $P_{NBI}$, (b) soft X-ray signal, (c) magnetic probe signal, (d) enlarged Mirnov signal with a burst, and (e-f) poloidal/toroidal mode-numbers.

Figure 6 shows solutions of Eq.(1), according to characteristic frequencies on HL-2A, i.e., $\omega_{el} = 3 \times 10^4 \text{rad/s}$, $\omega_{ce} = 4 \times 10^4 \text{rad/s}$, $\omega_A = 3.7 \times 10^6 \text{rad/s}$ and $\omega_{dm} = 2 \times 10^5 \text{rad/s}$. Figures 6(a-b) show large growth-rate at high $\beta_h$, with the real frequency satisfying $\omega/\omega_{dm} \sim 0.5$, which is consistent with the general fishbone theory prediction. With
decreasing $\beta_h$, the growth-rate and the real frequency both decrease, indicating that the resistivity becomes more important, as the mode gradually reveals its resistive nature. We should point out here, that the fishbone is not noticeably modified by the resistivity in the high $\beta_h$ regime. The resistive effect is prominent near the marginal stability point of the mode. Figures 6(c-d) show that the growth-rate falls, and the real frequency raises, with increasing the Magnetic Reynolds number.

**Destabilization of m/n=2/1 ion fishbone.**—Another new experimental result, which is an unstable TM interacts with energetic-ions and results in the amplitude-bursting and frequency-chirping fishbone-like activity, has been observed on HL-2A, and it is perfectly reproducible. Figure 1 shows a typical experimental result. In high NBI heating power $P_{NBI} \sim 1$ MW and relatively low density plasmas of the line averaged density $n_e \sim 1 \times 10^{19} \text{m}^{-3}$, the sawtooth is absent. During the auxiliary heating the m/n=2/1 is unstable, has a slow rotation frequency ($f < 2 \text{kHz}$) and propagates in the electron diamagnetic drift direction. The TM induces the large temperature oscillation, but the Mirnov signal has the small amplitude ($|dB_\theta/dt| < 0.5$) due to the slow rotation of magnetic islands. Specifically, it is found that an intense bursting mode is unstable in the presence of the slow rotation TM (Fig.7 (b-d)). The mode-numbers of this new mode are m/n=2/1 (Fig.7 (e-f)), its frequency fast chirps downward within $\Delta t = 1\text{ms}$, propagates in the ion diamagnetic drift direction, and it is similar to the conventional fishbone instability on HL-2A. This phenomenon only occurs while the TM rotation direction changes from electron to ion diamagnetic drift, otherwise, not appears. All experimental results indicate that the TM resonantly interacts with energetic-ions.

**FIG. 8:** Time-frequency characteristics and growth-rate of the fishbone-like activity (Shot II). (a) temporal evolution of the amplitude $dB_\theta/dt$, (b) spectrogram corresponding to sub-graph (a), (c) $d|B_\theta|/dt$ versus $|B_\theta|$, (d) amplitude dependence of the growth rate estimated as $\gamma_{\text{exp}} = (d|B_\theta|/dt)/|B_\theta|$. Colorbar denotes time.

Fig.8 shows the experimental results of another discharge. The mode frequency is around $f=2-10\text{kHz}$ (Fig.8(b)), which is obtained using the Choi-Williams distribution\[14\], and the maximum of the mode growth rate estimated as $\gamma_{\text{exp}} = (d|B_\theta|/dt)/|B_\theta|$ is about 1kHz(Fig.8(c-d)). The resistivity $\eta = 1.65 \times 10^{-9} Z_{\text{eff}} \ln \Lambda / T_3^{3/2}$ is high due to low electron temperature at $q=2$ rational surface. All of experimental evidences suggest that $1 < q_{\text{min}} < 2$ in these discharges. Compared with the classical m/n=1/1 fishbone, generally the new mode has larger amplitude, shorter chirping time, lower frequency and longer
FIG. 9: $\delta f$ structures in $\Lambda$ (a) and $\mu$ (b) spaces. Plasma resistivity $\eta = 2 \times 10^{-4}$ and energetic-ion beta $\beta_f = 0.65\%$. The back solid curve denotes the resonance line.

To identify resonant effects of energetic-ions on TM, we examine the resonance condition of wave-particle in tokamaks. Generally it has the form $\omega - n\omega_\phi - p\omega_\theta = 0$ [10]. $\omega_\phi$ and $\omega_\theta$ are the toroidal transit and poloidal transit angular frequencies for passing particles. $\omega$ is the mode frequency, $n$ is the toroidal mode number, and $p$ is an integer. The $\delta f$ is shown in Fig.9 using the M3D-K simulation. In $\Lambda$ and $\mu$ spaces, the $\delta f$ structures are both perfect. The test particle method gives that the precise resonance-line is $\omega_\phi - 2\omega_\theta - \omega = 0$, and co-passing energetic-ions are responsible for the mode drive. The effects of counter-passing and trapped energetic-ions on the TM have also explored, and it is found that the TM is influenced by them, but the corresponding resonance conditions are both unfound.

Summary.—An experimental result on the stabilization of the energetic-ion driven internal kink mode by ECRH, observed for the first time on HL-2A. Analysis by the fishbone dispersion relation, including the resistive effect, suggests that the magnetic Reynolds number plays a key role in the mode stabilization. Another experimental result suggests the tearing mode can be driven by energetic-ions, resulting in fishbone activities. Numerical simulations from M3D-K code suggest the co-passing energetic-ions driven TM unstable by the resonance of $\omega_\phi - 2\omega_\theta - \omega = 0$.

References


