Investigation of fishbone instabilities excited by trapped energetic electrons on the HL-2A tokamak

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Abstract

A generalized dispersion relation for fishbone modes is obtained by considering density and pitch angle profiles of energetic electrons (EEs). The fishbone modes excited by trapped energetic electrons are investigated based on HL-2A ECRH experiment. Numerical results show that the calculated time evolution of fishbone mode real frequency reasonably agrees with the observation during ECRH. The fishbone mode is excited at the position of maximum density gradient of EEs. High frequency fishbone mode can be induced in the case of on-axis heating and the background plasma is a favorable factor to retard fishbone mode to be excited.

1. Dispersion relation

Auxiliary heating by employing ECRH is one of the effective methods to heat plasma at present-day tokamak. Electron fishbone modes during ECRH have been observed on HL-2A and the corresponding theoretical studies have been done [1-2]. The fishbone instabilities usually result in loss of energetic particles and degrade the heating efficiency, even bring about the corruption of plasma column. So, it is the main task to avoid fishbone-like instabilities. In this work, we will find out the influence of background plasma on fishbone instability and the excitation position of fishbone modes. Following the minimizing procedure described in Refs.[3-4], the dispersion equation is obtained as following,

$$-i\omega/\omega_A+\delta\hat{W}_c-\frac{\beta_h}{\varepsilon a}\int_{\alpha_1}^{\alpha_2}\frac{f(\alpha)d\alpha}{\sqrt{\alpha}}\int_{\hat{r}_1}^{1}n_{0h}(\hat{r})\hat{r}d\hat{r}KK_2'(1-\frac{K_2'}{qK_c})\sigma^2(\hat{r}-\hat{r}_0)-\frac{2\beta_h}{3\varepsilon a}\int_{\alpha_1}^{\alpha_2}\frac{f(\alpha)d\alpha}{\sqrt{\alpha}}\int_{\hat{r}_1}^{1}n_{0h}(\hat{r})\hat{r}d\hat{r}\times$$

$$\frac{KK_2'^2}{qK_c}\Omega\hat{r}[-\frac{3}{4}\varepsilon+(\varepsilon\frac{\alpha^2(\alpha^2-\alpha_0)}{\Delta_\alpha^2}+\frac{\sigma^2(\hat{r}-\hat{r}_0)}{qK_c}+\frac{\varepsilon\Omega\hat{r}}{2qK_c})H(\Omega)]=0 \qquad (1)$$

Where, $a=\int_{\hat{r}_1}^{1}n_{0h}(\hat{r})\hat{r}d\hat{r}\int_{\alpha_1}^{\alpha_2}\frac{f(\alpha)d\alpha}{\sqrt{\alpha}}K$, $H(\Omega)=1-\frac{2\Omega\hat{r}}{qK_c}-2i(\frac{\Omega\hat{r}}{qK_c})^{3/2}Z(i\sqrt{\frac{\Omega\hat{r}}{qK_c}})$, $K_2'=\frac{2\mathrm{E}}{\mathrm{K}}-1$, $\alpha_1<\alpha\le\alpha_2$,

$\hat{r}_1\le\hat{r}\le1$, with $\alpha_1=\frac{1}{1+\varepsilon}$, $\alpha_2=1+\varepsilon$, $\hat{r}_1=\left|\frac{1}{\alpha}-1\right|/\varepsilon$, $\Omega=\frac{\omega}{\omega_{ds}}$, $\omega_{ds}=\frac{T_h}{r_s\omega_0 R}$, $\omega_A=B_t/(R\sqrt{\mu_0 n_i m_i})$

and $\omega_0 = \frac{|e|B}{mc}$ is the cyclotron frequency of EEs.. $Z(y) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{+\infty} \frac{\exp(-x^2)}{x-y} dx$ is plasma dispersion function. $\delta \hat{W}_c = 3\pi \Delta q \varepsilon^2 (13/144 - \beta_{ps}^2)$ is given in Ref. [19] with $\Delta q = 1 - q_0$, $\beta_{ps} = -(\frac{R_0}{r_s^2})^2 \int_0^{r_s} r^2 \frac{d\beta}{dr} dr$, and $\beta = 8\pi P / B^2$ is the beta value of the core component. K_c is a function of the first and second kind of complete elliptic functions with the argument $k = \sqrt{\frac{1/\alpha - 1 + \varepsilon \hat{r}}{2\varepsilon \hat{r}}}$,

$$K_c = \frac{2\mathrm{E}(k)}{\mathrm{K}(k)} - 1 + 4s[\frac{\mathrm{E}(k)}{\mathrm{K}(k)} - 1 + k^2], \qquad (2)$$

Here, k<1, $\varepsilon = \frac{r_s}{R}$, $\hat{r} = \frac{r}{r_s}$, $s = \frac{rdq}{qdr}$ is magnetic shear and r_s is the magnetic flux surface of q=1.

2. Simulation and experimental results

We consider the ECRH experiment with temperature T_h ranges from 10 to 70 KeV on HL-2A. The toroidal magnetic field is B_t=1~2T, the major/minor radius R/a=165/40cm. The results from the top to bottom shown in figure 1 are respectively temporal evolution of the hard x-ray photon numbers for different energy (*a-c*), the background electron density (*d*), the power of soft x-ray (*e*) and the measured electron fishbone mode frequencies (the spots) (*f*) for shot 10338. Meanwhile, the dash-dotted line with circles in figure 1 (*f*) is the calculated temporal evolution of fishbone mode real frequencies near the critical β_h. Here, $f = \omega / 2\pi$. The results in figure 1 (*f*) indicate that the calculated real frequencies of the fishbone mode excited by trapped electrons are in reasonable agreement with those of the experimental measurements.

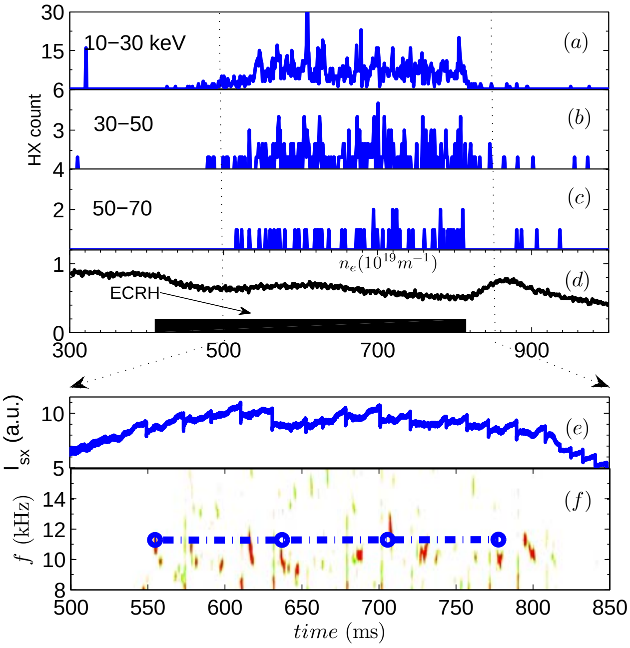

Figure 1. Temporal evolution of hard x-ray photon number for different energy (*a-c*), of the background electron density (*d*), of the power of soft x-ray (*e*), of the measured real frequencies (*f:* the spots) and the calculated temporal evolution of fishbone real frequency (the broken lines with circles (*f*) at critical β_h point with $\sigma = 2$, $\hat{r}_0 = 0.6$, $\alpha_0 = 0.99$, $\Delta_\alpha = 0.5$.

The lines in figure 2 are the real frequency and growth rate as function of background plasma density. The results indicate that the real frequencies slightly depend on background plasma density whereas the growth rates are on the contrary. There exists a cut-off plasma density which depends on the energy of energetic electrons and sharply decreases with increasing energy. The cross lines in figure 2 represent the case for $\beta_h = 0.005$ which indicates the cut-off plasma density still exists for high β_h. Therefore, high- β tokamak plasmas are favorable to avoid fishbone instabilities. The stable effect of background plasma on fishbone mode is maybe due to the perturbation energy is changed via Alfven frequency.

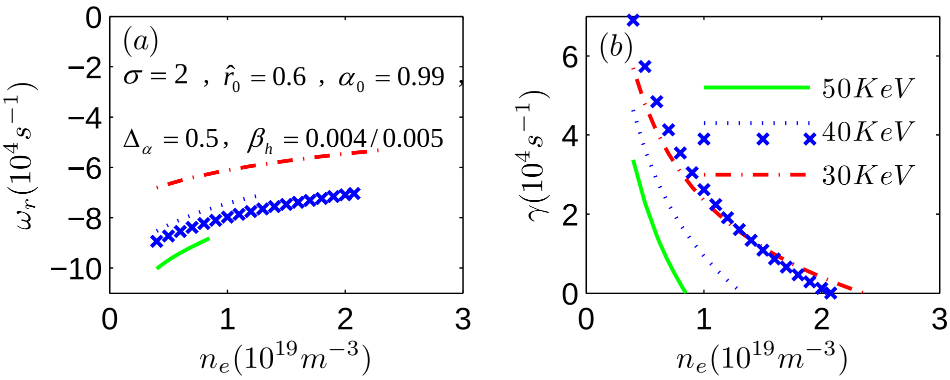

Figure 2. Real frequency (a) and growth rate (b) of electron fishbone mode as functions of background plasma density for different energy with q_0=0. 99.

The toroidal precession frequency at the position of maximum density gradient of EEs is $\omega_{d,g} \propto \sqrt{2}\sigma/(1+\sqrt{2}r_0\sigma)$. So the real frequency of fishbone mode is $\omega_r \sim \omega_{d,g}$. The lines in figure 3 (a) are real frequencies (solid/cross lines) and growth rates (dash-dotted/point lines) as functions of σ. Here the cross/point lines represent high frequency mode. These lines show the fishbone mode can be excited when density profile of EEs is peaked enough and the real frequency agrees with $\omega_{d,g}$. The lines shown in figure 3 (b) are real frequencies (solid/circle/point lines) and growth rates (dash-dotted line) as functions of r_0, which indicate the high frequency fishbone mode can be induced in the case of near-axis heating. Moreover, there exists a cut-off r_0 for excitation of fishbone mode due to negative density gradient being necessary. The circle line is real frequency of fishbone with $\sigma = 30$. The point line is the result by using $\omega_{d,g}$ to fit the circle line, which indicates the real frequency of fishbone mode for very peaked density profile can be well fitted by $\omega_{d,g}$. The lines representing real frequencies in figure 3 show that the resonant interaction happens at the position of maximum density gradient when the fishbone mode is induced.

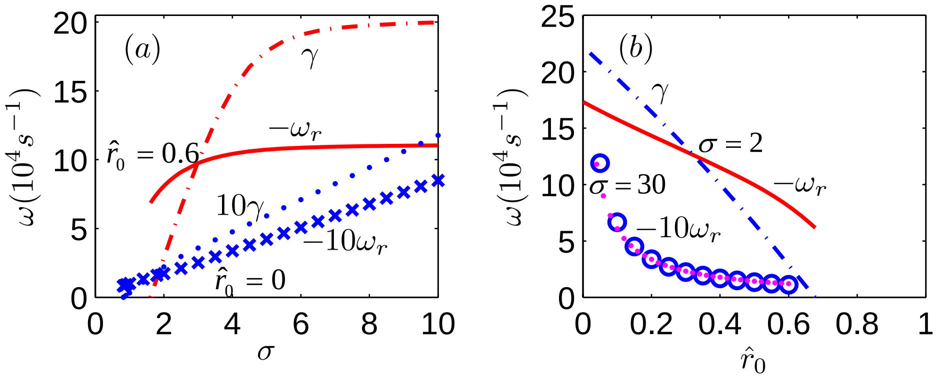

Figure 3. (a) real frequency (solid and cross lines) and growth rate (dash-dotted and point lines) as functions of σ, (b) real frequency (solid, circle and point lines) and growth rate (dash-dotted line) as functions of $\hat{r}_0$, the other parameters: T_h=40KeV, n_e=0.6×$10^{19}$$m^{-3}$, $\alpha_0 = 0.99$, $\Delta_\alpha = 0.5$, $\beta_h = 0.004$ and q_0=0.99.

3. Conclusions

The fishbone mode induced by trapped energetic electrons is investigated based on HL-2A ECRH experiment. The dispersion relation for fishbone mode is derived when the profiles of both spatial density and pitch angle of energetic electrons are considered. Numerical results show that the calculated time evolution of fishbone real frequency is in reasonable agreement with observation during ECRH. High density background plasma is benefit to prohibit fishbone mode from being excited. Fishbone modes are excited at the positions of maximum density gradient of EEs and high frequency fishbone mode can be induced in the case of on-axis heating.

Acknowledgments

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