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2.4 Control of Helium Accumulation by Fishbones

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Physics of Fishbone Oscillations

• It is well known that fishbone oscillations occur in the tokamak plasma at high $\varepsilon\beta_p$ and in the presence of large hot trapped particle population.[1,2,3]

• We adopt and extend the formalism of Chen et al. to analyze the trapped hot ion induced fishbones in the ITER-type plasma.

• Using the familiar assumptions like large aspect ratio and low beta, we consider the stability of the trapped-ion induced internal kink mode in the presence of alphas and one other species of hot ions.

Issues Under Consideration

- What is the effect of the multiple hot species on the stability of the trapped particle induced internal kink?
- In particular, how does the fishbone behave in the ignited ITER-type plasma?
- What are the possible mode frequencies?
- Can the fishbones be preferentially induced in the low energy range of the trapped particles?

Dispersion Relation

Toroidal Beta is given as

$$\beta_{th} = \frac{2^{9/2}\pi^2 m_h}{B^2 r_s^2} \int_0^{r_s} r dr d\alpha dE\, E^{3/2} K_b F$$

Noting that

$$E = \frac{v^2}{2} + \mu B$$

where v is the parallel velocity , B is the zeroth order magnetic field, μ is the magnetic moment(divided by m), we can extend the formalism of Chen et al.[1] to two hot particle species as follows:

Dispersion Relation:

$$0. = \frac{i\omega}{\omega_A} + \delta W_c +$$

$$\sum_{i=1}^{2} \frac{2^{7/2}\pi^2 m_{hi}}{B^2 r_s^2} \int r dr d\alpha \frac{K_2^2}{g_i(r,\alpha) K_b} \times$$

$$\{\sum_{n=0}^{\infty} \frac{(i\gamma)^n}{g_i^n(r,\alpha)} \frac{1}{n!} \{(\omega + i\gamma) c_{\beta i} c_i(r) [P \int dE \frac{(E^{5/2} p'(E))^{n+1}}{(E - \omega_r / g_i(r,\alpha))} + i\pi (E^{5/2} p'(E))^{n+1} \mid_{E_r}])$$

$$\frac{dc_i(r)}{dr} \frac{c_{\beta i}}{\omega_{ci} r} [P \int dE \frac{(E^{5/2} p(E))^{n+1}}{(E - \omega_r / g_i(r,\alpha))} + i\pi (E^{5/2} p(E))^{n+1} \mid_{E_r})]\}\}$$

$$- \sum_{i=1}^{2} \frac{2^{7/2}\pi^2 m_{hi}}{B^2 r_s^2} \int dr d\alpha dE E^{3/2} K_2 F c_{\beta i} c_i(r)$$

where

δW_c is the ideal MHD part of the potential energy;

$E_r = \omega_r / g_i(r,\alpha)$ is the energy at the pole of the integrated;

$\omega = \omega_r + i\gamma$ is the complex frequency;

$\omega_A = \frac{B}{\sqrt{3} R \hat{s} (4\pi p)^{1/2}}$ is the Alfven frequency;

m_{hi} is mass of the i'th species;
$\alpha = \mu B/E$; $(1-\varepsilon(r) \le \alpha \le 1+\varepsilon(r))$;
ω_{ci} is the cyclotron frequency of the i'th species;
E is energy (divided by m) of the hot particle;

$c\beta_i c_i(r)F(E)$ is the distribution function of the ith species; here for the sake of convenience we have retained the energy dependent part as independent of radius;

K_2, K_b are defined in terms of the elliptic integrals E and K of argument

$\kappa^2 = \frac{1}{2}(1+\varepsilon^{-1}(1-\frac{\mu B}{E})$ $(0 \le \kappa \le 1$ for the trapped particle),

as follows:

$$K_b = \frac{1}{\pi}\int_0^{\theta_b} \frac{d\theta}{\sqrt{1-\mu B/E}} = \left(\frac{2}{\varepsilon}\right)^{1/2} \frac{K(\kappa^2)}{\pi}$$

$$K_2 = \frac{1}{\pi}\int_0^{\theta_b} \frac{\cos\theta d\theta}{\sqrt{1-\mu B/E}} = \left(\frac{2}{\varepsilon}\right)^{1/2} \frac{2E(\kappa^2)-K(\kappa^2)}{\pi}$$

$g_i(r,\alpha)$ $= \omega_{di}/E$ is the space and pitch dependent part of the trapped ion precession frequency

$$= \frac{(2E(\kappa^2)-K(\kappa^2))q}{K(\kappa^2) r \omega_{ci} R}$$

The dispersion relation is written for all positive growth rates γ using the extended Dirac formula.

The last term in the dispersion relation is the ideal MHD contribution of the hot particle pressure.

When growth rate is zero we obtain the condition for the marginal stability; the real and imaginary parts at marginal stability are:

$$0 = \delta W_c + \sum_{i=1}^{2} \frac{2^{7/2}\pi^2 m_{hi}}{B^2 r_s^2} \int r dr d\alpha \frac{K_2^2}{g_i(r,\alpha) K_b} \times$$

$$\left\{ \omega_r c\beta_i c_i(r) [P \int dE \frac{(E^{5/2} p'(E))}{(E - \omega_r / g_i(r,\alpha))}] - \frac{dc_i(r)}{dr} \frac{c\beta_i}{\omega_{ci} r} [P \int dE \frac{(E^{5/2} p(E))}{(E - \omega_r / g_i(r,\alpha))}] \right\}$$

$$- \sum_{i=1}^{2} \frac{2^{9/2}\pi^2 m_{hi}}{B^2 r_s^2} \int dr d\alpha dE E^{3/2} K_2 F c\beta_i c_i(r)$$

$$0 = \frac{\omega_r}{\omega_A} + \sum_{i=1}^{2} \frac{2^{7/2}\pi^2 m_{hi}}{B^2 r_s^2} \int r dr d\alpha \frac{K_2^2}{g_i(r,\alpha) K_b} \times$$

$$\left\{ \omega_r c\beta_i c_i(r) \pi (E^{5/2} p'(E)) |_{E_r} - \frac{dc_i(r)}{dr} \frac{c\beta_i}{\omega_{ci} r} \pi (E^{5/2} p(E)) |_{E_r} \right\}$$

We have three variables ω_r, $c\beta_1$, $c\beta_2$ and only two equations. We solve for the mode frequency and the second trapped species coefficient $c\beta_2$ for fixed values of $c\beta_1$.

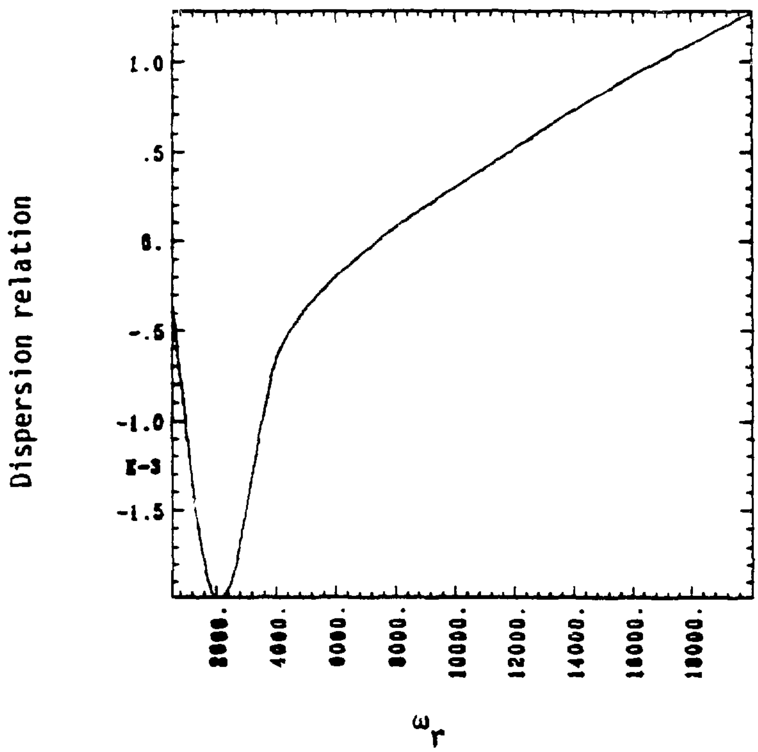

Fig. 1 The dispersion relation at marginal stability obtained by eliminating $c\beta_1$ from Eq. 1. The values are shown as a function of ω_r. [Minor rad. =2.3m; Major rad. = 5.8m; B = 5 T; r_s = 1.4m; E_{max} of second species= 400 keV; δW_c= 0.; critical beta at marginal stability: $\beta_{t1}= 0.85\times10^{-2}$; $\beta_{t2}= 0.1\times10^{-2}$]

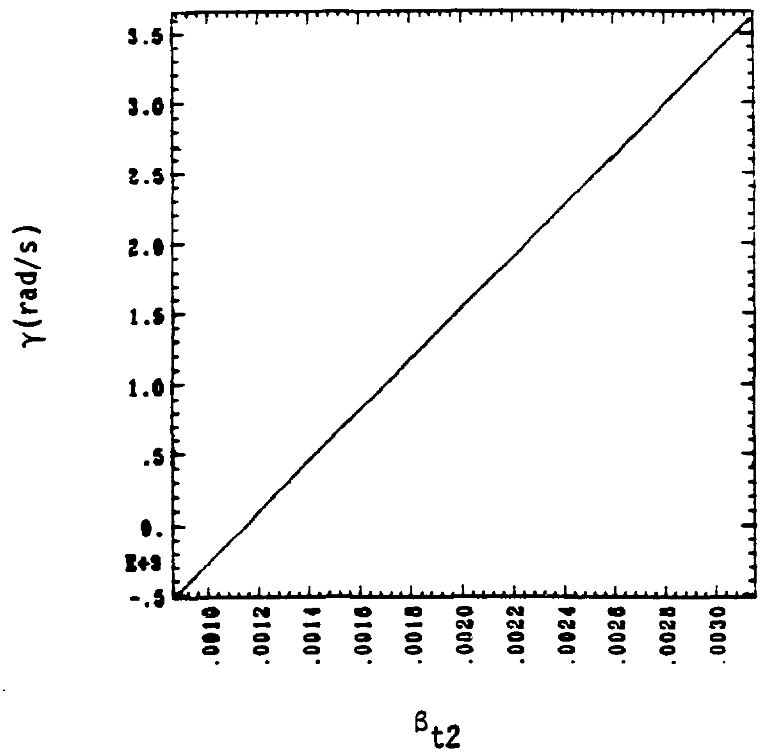

Fig. 2 Growth rate vs. toroidal beta of the second species, β_{t2}, of an unstable mode; $\beta_{t1} = 0.85\times10^{-2}$

Results

- Mode frequencies are found in the moderate frequency range (~8000 rad/s) for ITER like conditions.

- The mode is stable for wide range of δW_c in the presence of alphas alone.

- The fishbone mode can be made marginally stable and, further, unstable when the second hot species is increasingly introduced.

- The large aspect ratio analysis as described here shows that even small toroidal beta of the second hot species is enough to drive the mode unstable.

- This fact suggests that the light species which is considered as the second hot species here behaves in a fashion opposite to the heavier alphas in the frequency range of interest.

Wall Loading

- Total production rate of hot particles is about 35×10^{19} and about 10×10^{19}/s in the center.

- The fishbones can achieve a good control over the continued heating of the plasma by reducing the hot ion density, thereby adding a strong negative source for the burn stability.

- Trapped particle removal rate should be around 10^{20}/s.

- If we reduce the background density as well by fishbones by about 10%, we will remove about 2.5×10^{21} trapped hot particles with average energy about a few hundred keV.

- The heat load on the wall due to these particles, at an average energy of about 400 keV, is about $\sim 2.5\times10^{21} \times.4\times10^{6}\times1.610^{-19}/t$ $s^{-1} \sim 160 MJ/(t\ s)$

where t is the time of duration of the fishbone mode resulting in a deposition of 160 MJ on the first wall.

- If the time of removal is about 1 s, wall heat load is about 160MW.

- Using a surface area of about 300 m^2, we see that the additional heat load will be .5MW/m^2.

- Additional divertor plate heat load may be around 3 MW/m^2.

- By increasing the time of fishbone activity to about 2 seconds, we can cut the excess heat load on the divertor plates to about 1.5 MW/m^2.

- The additional heat load on the wall when all the energy is deposited on the outboard side is about .8 MW/m^2.

- Intermittent hot ion removal amounts to only about a few percent of the normal particle flux.

- Sputtering at high energies by light ions and/or neutrals remains to be investigated.