Linear and nonlinear dynamics of electron fishbones

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Introduction

• Internal kink instabilities exhibiting fishbone like behaviours have been observed in a variety of experiments, where a high-energy electron population was present, due to, e.g., ECRI and/or LH/LHCD
• These e-fishbones have linear dispersion relation and excitation mechanisms that are similar to those of energetic ion driven fishbones
• They are characterized by a very small ratio between the resonant particle orbit width and the the characteristic fishbone length scale (~δzc, the rigid radial kink-type displacement)
• This feature is also expected to characterize ion fishbones in burning plasmas of fusion interest due to the large plasma current, while it is not realized for the energetic ions in present-day experiments
• Moreover, fluctuation induced transport of magnetically trapped resonant particles, due to precession resonance, is expected to depend on energy and not mass because of the bounce averaged dynamic response
• These analogies between e-fishbones in present-day devices and fishbones in burning plasmas make the investigation of the former a good basis to study and predict the effects of the latter

Outline

• The results of global, self-consistent, non-linear hybrid MHD-Gyrokinetic simulations will be presented, using the code XHMGC
• Linear dynamics analysis will enlighten the effect of kinetic thermal ion compressibility and diamagnetic response, and kinetic thermal electrons compressibility, in addition to the energetic electron contribution
• Non-linear saturation and energetic electron transport will be addressed, making use of Hamiltonian mapping techniques, discussing both centrally peaked and off-axis peaked energetic electron profiles
• Centrally peaked energetic electron profiles are characterized by resonant excitation and non-linear response of deeply trapped energetic electrons
• Off-axis peaked energetic electron profiles are characterized by resonant excitation and non-linear response of barely circulating energetic electrons which experience toroidal precession reversal of their motion.

What can we expect from linear theory?

• Stability of the fishbone mode given by |\( \delta W \)| (see Chen et al., 1984 PRL 52, 1122)
• Condition for instability: \( \Delta \omega_{\text{elas}}/\omega_0 > 0 \)
• Real frequency given by the resonant denominator of \( \delta W \)
• Note: the ratio \( \omega_{\text{elas}}/\omega_0 \) does not depend on the sign of the electric charge \( e \)

Linear dynamics: \( \omega = \omega_{\text{elas}} = \omega_0 R/Q_A \) (trapped particles)

\[ \sigma_{\text{elas}} = k \cdot v_{\text{elas}} = k \cdot \frac{\mu_0}{\omega_0^2} \cdot c \cdot \omega_0 \]

(\( \rho = 10^6 \text{ m} \))

- Normalized parallel velocity
- Normalized magnetic moment

Energetic electrons density profile peaked on-axis

FTU-like Equilibrium

Linear dynamics: \( \omega = \omega_{\text{elas}} = \omega_0 R/Q_A \) (trapped particles)

- Power exchange between energetic (deeply trapped) and circulating particles and wave

\[ \frac{\rho_0}{\rho} \approx \frac{1}{2} \cdot \frac{1}{\omega_0^2} \cdot \frac{1}{\omega^2} \cdot \frac{1}{Q_A^2} \]

- Relative importance of the different contributions treated kinetically in XHMGC

- Energetic electron pressure tensor: drives the mode
- Diamagnetic bulk term: negligible contribution
- Thermal ion pressure tensor: Landau damping and generalized inertia
- Thermal electron pressure tensor: can contribute to the drive in presence of the energetic particles

Linear equations: non-linear saturation characterized by frequency chirping and phase locking: radial transport of energetic electrons ends when \( \omega_{\text{elas}} \) is approached (radial decoupling)

Test particle Hamiltonian mapping, kinetic Poincaré plots

XHMGC

• Thermal (core) plasma:
  - Described by reduced \( \mathrm{O}(e) \) visco-resistive MHD equations in the limit of \( \beta = 0 \) \( (\chi = e/R_0) \) — equilibrium shifted circular surfaces only can be investigated
  - MHD fields: \( \phi, \psi \) (poloidal magnetic flux function and electrostatic potential)
• Kinetically treated populations
  - (here: energetic electrons, thermal ions, thermal electrons):
    - Described by the nonlinear gyrokinetic Vlasov equation, expanded up to order \( \mathrm{O}(e) \) and \( \mathrm{O}(e^2) \), with \( \gamma = \gamma_0, \lambda_0 \) the gyrokinetic ordering parameter and \( \tau_0 = \gamma_0, \lambda_0 \) in the \( k \cdot \mu_0 > \ll 1 \) guiding-center approximation
    - Energetic particle pressure: \( P_{\text{H},1/2} \)
    - Fully retaining magnetic drift orbit widths
    - Solved by particle-in-cell (PIC) techniques.
    - \( \gamma_0, \lambda_0 \) energetic particle Larmor radius
    - \( \lambda_{\text{e},\lambda_{\text{i}}} \): the equilibrium density and magnetic field scale lengths
    - Toroidal coordinates system (\( \tau, \theta, \phi \))

Kinetically treated energetic electrons

• Energetic electrons treated kinetically to describe resonant excitation
• Strongly anisotropic Maxwellian (as, e.g., produced by ECRI or Lower Hybrid heating)

\[ f_{\text{ee}} \propto \frac{n_{\text{ee}}(\psi)}{T_{\text{ee}}(\psi)^{3/2}} \Delta \omega_{\psi} \text{erf} \left( \frac{1 - \cos \alpha_\psi}{\Delta} \right) + \text{erf} \left( \frac{1 + \cos \alpha_\psi}{\Delta} \right) e^{-E/T_{\text{ee}}(\psi)} \]

\[ E = \frac{1}{2} m_{\text{ee}} v^2 + \mu_\text{ee} \cdot \chi, \quad \cos \alpha_\psi \equiv \frac{v_i}{\sqrt{2 E/m_{\text{ee}}}}, \quad \sin^2 \alpha_\psi \equiv \frac{\mu_\text{ee}}{E} \]

Kinetically treated bulk ions and bulk electrons

• Magnetic effects and thermal ion compressibility retained in the extended momentum equation of the bulk plasma through \( \sqrt{\psi} \cdot \nabla \psi \) obtained by solving the non linear Vlasov equation for that population, in order to account for enhanced inertia response (mostly due to trapped particles) and ion Landau damping: isotropic Maxwellian
• Thermal electron compressibility retained in the same way: isotropic Maxwellian

Non linear dynamics: weak drive: \( \omega_{\text{elas}} \cdot \omega_I \) strong drive: \( \omega_{\text{elas}} - e\nabla_{\text{elas}} \)
This kind of equilibria is closely related to the experimental configuration in which electron fishbones have been observed in current devices. In these experiments, high field side (HFS) off-axis heating is applied close to the $q_{min}$ flux surface in the equatorial plane, using ECRH; thus, an inverted (positive) gradient of the energetic electron density profile is generated in the radial region of the discharge which is internal to the $q_{min}$ flux surface and in which the internal kink can develop. Moreover, because of the HFS deposition, a selective heating on barely trapped/barely circulating particles will be obtained. Because of the stability condition, $q_{min} > R_{i}$ instability can occur only by resonance with energetic electrons characterized by precession reversal.

### References:

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