Electron fishbones in Tore Supra and FTU tokamaks

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Outline

• Introduction
  – E-fishbones in LH shots in FTU in Tore Supra

• Study of the spatial-temporal evolutions from ECE
  – Method
  – Results
    • FTU
    • Tore Supra

• Instrumental effects on ECE measurements in TS
  – New methods to characterize internal kink modes
  – New interpretation for the Tore Supra observations

• Conclusions
Previous observations of e-fishbones in FTU & TS

- Usually electron-driven fishbone modes are observed in ECRH shots

- In FTU and Tore Supra e-fishbones were observed in Lower Hybrid Current Drive shots
In FTU two regimes of e-fishbones were observed according to the LH power:

- An almost steady state at low $P_{\text{LH}}$ and periodic bursting when $P_{\text{LH}}>1.5$ MW

In Tore Supra, frequency jumps between MHD modes identified as electron fishbones were observed.

How do these modes evolve? $f(t) \& r(t) \rightarrow E(t)$
Study of the e-fishbone evolution

Method to determine the evolutions of the mode position and frequency from ECE measurements [Z. Guimarães-Filho, PPCF 2011]
$T_e$ oscillations induced by MHD modes

Radial displacement of the magnetic field lines induced by MHD modes can be described as:

$$\xi = \xi_0 e^{i(n.\varphi - m.\theta - \omega t)}$$

The mode-induced $T_e$ oscillations are:

$$\tilde{T}_e \approx \xi \nabla T_e$$

Example: e-fishbones with frequency jumps in Tore Supra

<table>
<thead>
<tr>
<th>$\rho$</th>
<th>$T_e$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>5.0</td>
</tr>
<tr>
<td>0.11</td>
<td>4.5</td>
</tr>
<tr>
<td>0.18</td>
<td>4.0</td>
</tr>
<tr>
<td>0.25</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Radial spectral distribution of $T_e$ oscillations in a given time frame $S_T(f, \rho)$

The radial spectral distribution can be described as a product of the dependence in frequency by the radial one

$$S_T(f, \rho) = A.F(f).R(\rho)$$
Method used to fit the data

\[ R(\rho) = G(\rho, -\rho_0, \sigma_\rho) + G(\rho, +\rho_0, \sigma_\rho) \]

\[ S_T(f, \rho) = A.F(f).R(\rho) \]

\[ F(f) = G(f, f_0, \sigma_f) \]

Where:

\[ G(x, x_0, \sigma_x) = \frac{1}{\sqrt{2\pi \sigma_x}} e^{-\frac{1}{2} \left( \frac{x-x_0}{\sigma_x} \right)^2} \]

The unknown parameters \( f_0, \sigma_f, \rho_0, \sigma_\rho \) and \( A \) are determined by Least Square Fits.
Comparison between data and fit

- Proposed function fits well the experimental data
- Parameters of the fit give the frequency and the position of each mode
Evolutions of e-fishbones in FTU

e-fishbones without and with periodic bursts
In LHCD discharges two regimes of e-fishbones were observed according to the LH power:

- An almost steady state (fixed point) at moderated values of LH power (1\textsuperscript{st} branch)
- A regular bursting behavior (limit cycle) at high LH power (2\textsuperscript{nd} branch)

[FTU #20865]

[F. Zonca, Nucl. Fusion 2007]
The evolutions of the mode frequency and radial position are opposite in the two regimes.

A fast increase in the mode frequency and an outward drift are also observed in the final part of each burst.

The condition of the resonant electrons varies quickly in the regular burst regime.

\[ E.g_\lambda = \frac{f.r}{n \cdot \frac{q}{2\pi R_0 B}} \]
Evolutions of the e-fishbones in Tore Supra

e-fishbones with frequency jumps between modes with different mode structures
e-fishbones in Tore Supra

- At moderated Lower Hybrid power, 1MW, and low density, $n_0 \sim 2.5 \times 10^{19} \text{m}^{-3}$, MHD modes identified as precessional e-fishbones may be destabilized.
- Frequency jumps between modes with different structures are observed.
• Frequency jumps are not linked with abrupt changes on the mode position
• The evolution in the mode position follows the q-profile evolution in O-regime
E-fishbone evolutions

- The energy of the resonant particles depends on the frequency, position and mode numbers.

\[ E.g_\lambda = \frac{f.r}{n.\frac{q}{2.\pi.R_0.B}} \]

- The continuity in the mode position suggests the following evolution:

  \[ 11 \text{ kHz} \rightarrow 9 \text{ kHz} \rightarrow 6 \text{ kHz} \rightarrow 3 \text{ kHz} \]

  From the proposed mode numbers:

  \[ 3/3 \rightarrow 1/1 \rightarrow 2/2 \rightarrow \text{odd} \]
Detailed study of the ECE measurements

Simulation of the mode-induced Te oscillations and their detection by ECE

1) The finite size of the ECE antenna
2) The effect of vertical displacements of the ECE LoS
Complex radial profiles of ECE measurements

\[ |W_x| \cdot \cos(\alpha_{xR}) \]

- 9 kHz 1/1 (?)
- 6 kHz 2/2
- 3 kHz 1/1
The numerical ECE

• Simplified model for the ECE signals
  • The “real” $T_e$ oscillations induced by these modes are simulated by

$$\tilde{T}_e = -\xi_0 \nabla T_e \cos(m\theta + \omega t)$$

where $\xi$ is the MHD displacement

• The measured signal is simulated by averaging the real $T_e$ oscillations inside the probed region ($\delta_R \sim 2.5\,\text{cm}$ and $\delta_Z \sim 10\,\text{cm}$)
The effect of the finite size of the probed region on the experimental profiles

Te oscillations induced by m=1 and m=2 kink modes

\[ \xi \nabla T_e \cdot \cos(m \theta + w t) \]
The effect of the finite size of the probed region on the experimental profiles

Te oscillations induced by \( m=1 \) and \( m=2 \) kink modes

\[ \xi \nabla T_e \cdot \cos(m \theta + w t) \]

Observed Te oscillations when the vertical size of the probed region is considered
Comparison between simulated and experimental profiles

Simulated profiles from Numerical ECE

m=2
m=3
m=4
m=5

Experimental ECE profiles (2011 experiment)
ECE profiles give the poloidal wavenumbers

9 kHz  
1/1 -> 3/3

6 kHz  
2/2

3 kHz  
1/1

\( \frac{m}{N} \)
(2) – The effect of vertical displacements of the ECE Line of Sight

Vertical displacements of the ECE LoS can lead to misidentification of the poloidal parity.

Modes with high m are more sensitive.
The effect of vertical displacements of the ECE Line of Sight

Vertical displacements of the ECE LoS can lead to misidentification of the poloidal parity. Modes with high $m$ are more sensitive.

11 kHz mode (2008 experiment)

Simulation of $m=4$ with $\Delta z=3\text{cm}$
(3) – Vertical displacements of the ECE Line of Sight and the mode rotation

Ex: sawtooth precursor with $\Delta z = +7$ cm
(3) – Vertical displacements of the ECE Line of Sight and the mode rotation

Ex: sawtooth precursor with $\Delta z = +7\text{cm}$

2011 shots with slightly vertically shifted plasmas:

$\Delta z = +2\text{ cm}$

The modes and the plasma rotate in the same direction (the observed frequencies are bigger than the real ones)

> The correction of the Doppler Shift will reduce the energy of the resonant electrons

$m=5$
New interpretation for the Tore Supra observations

- The detailed study of ECE signals shows that the 3 kHz is $1/1$, the 9 kHz is $3/3$ (instead of $1/1$) and the 11 kHz is $4/4$ (instead of $3/3$)
- Data from 2011 experiment allow to correct the Doppler shift

The energy of the resonant electrons evolves continuously

Modes are resonant with thermal electrons
Conclusions

• In FTU, it was found significant differences between the evolutions of the e-fishbones in the regimes with and without bursting behavior

• In Tore Supra, the detailed analysis of the ECE measurements pointed out instrumental effects which were not considered in the previous works
  – The energy of the resonant electrons falls in the thermal range and evolves continuously (even during the frequency jumps)
  – The explanation of the frequency jumps are still unclear
  – Observation of modes with high modenumbers suggests that the energetic particles may play a role on the stability of the modes

• The developed methods are powerful tools to characterize core MHD instabilities and to determine their evolutions

• The size of ECE antenna must be considered when performing tomographic reconstructions or computing phase shift with other diagnostics