Electron fishbones in Tore Supra and FTU tokamaks

Zwinglio Guimarães-Filho

S. Benkadda, N. Dubuit

Aix-Marseille Univ., PIIM, Marseille, France

J. Decker, D. Elbeze, X. Garbet, P. Maget, A. Merle , R. Sabot, J.-L. Ségui and Tore Supra team

CEA, IRFM, Saint-Paul-Lez-Durance, France.

P. Buratti, A. Botrugno, G. Calabrò, G. Pucella, F. Zonca, A.A. Tuccillo and FTU team

Associazione Euratom-ENEA sulla Fusione, Frascati, Italy.

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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

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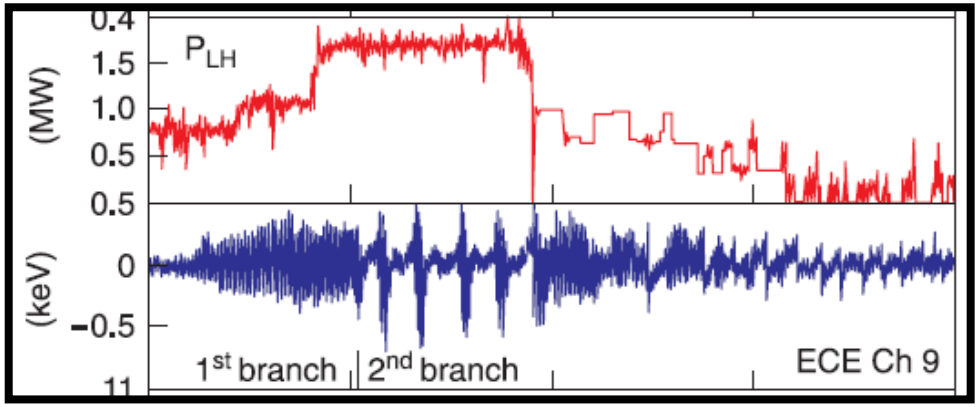
Nucl. Fusion 47 (2007) 1588–1597

Electron fishbones: theory and experimental evidence

F. Zonca[1], P. Buratti[1], A. Cardinali[1], L. Chen[2,3], J.-Q. Dong[4], Y.-X. Long[4], A.V. Milovanov[1,5,6], F. Romanelli[1], P. Smeulders[1], L. Wang[7], Z.-T. Wang[4], C. Castaldo[1], R. Cesario[1], E. Giovannozzi[1], M. Marinucci[1] and V. Pericoli Ridolfini[1]



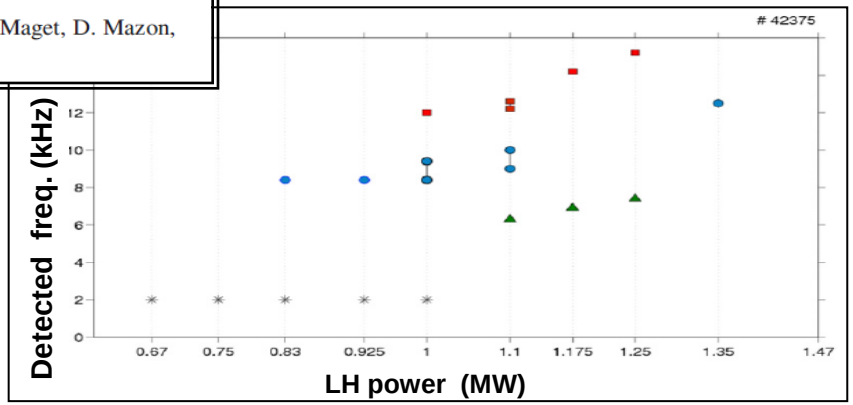
- In **FTU** two regimes of e-fishbones were observed according to the LH power
  - An almost **steady state** at low P_{LH} and periodic **bursting** when P_{LH}>1.5 MW

PRL 102, 155005 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

Redistribution of Suprathermal Electrons due to Fishbone Frequency Jumps

A. Macor,* M. Goniche, J. F. Artaud, J. Decker, D. Elbeze, X. Garbet, G. Giruzzi, G. T. Hoang, P. Maget, D. Mazon, D. Molina, C. Nguyen, Y. Peysson, R. Sabot, and J. L. Ségui

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



[R.Sabot, NF 2009]

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

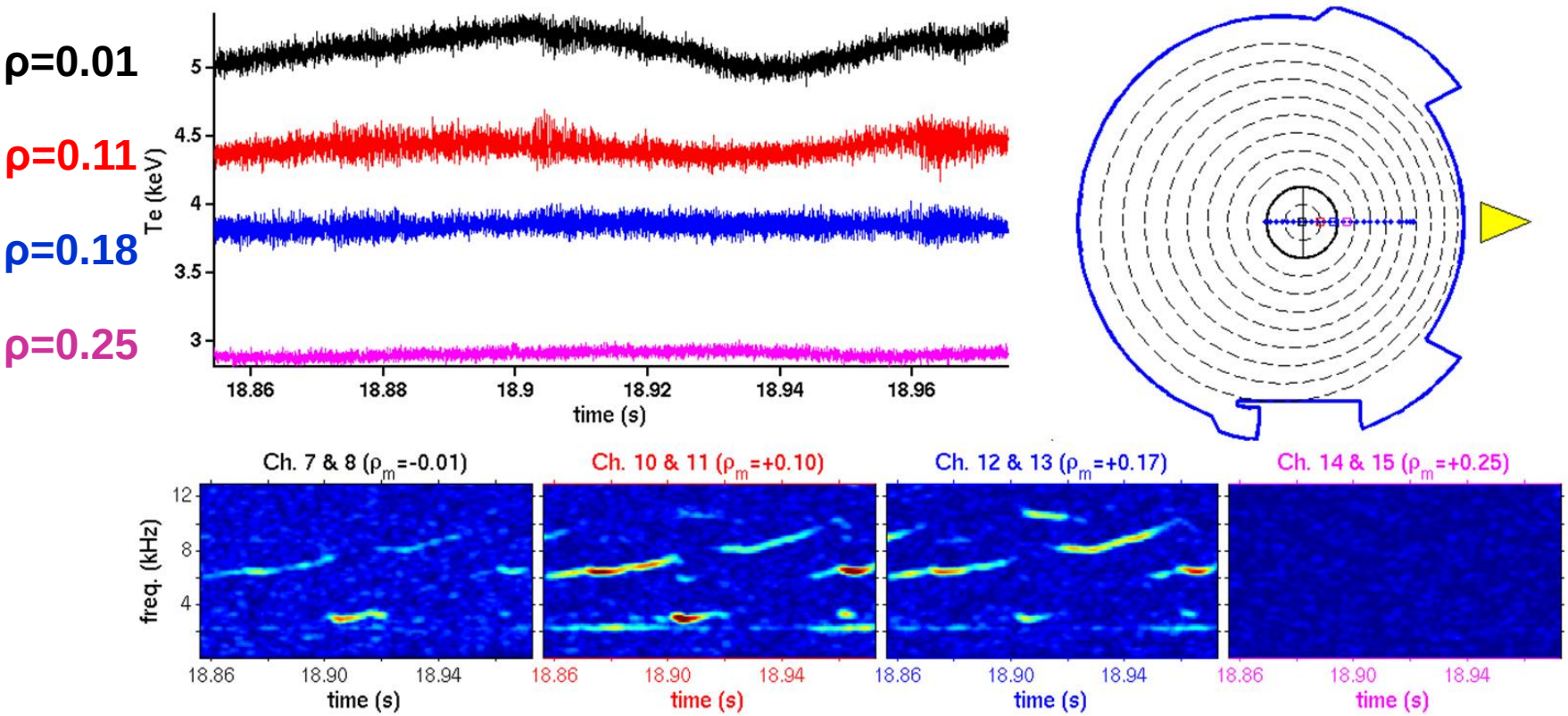
Radial displacement of the magnetic field lines induced by MHD modes can be describe as:

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

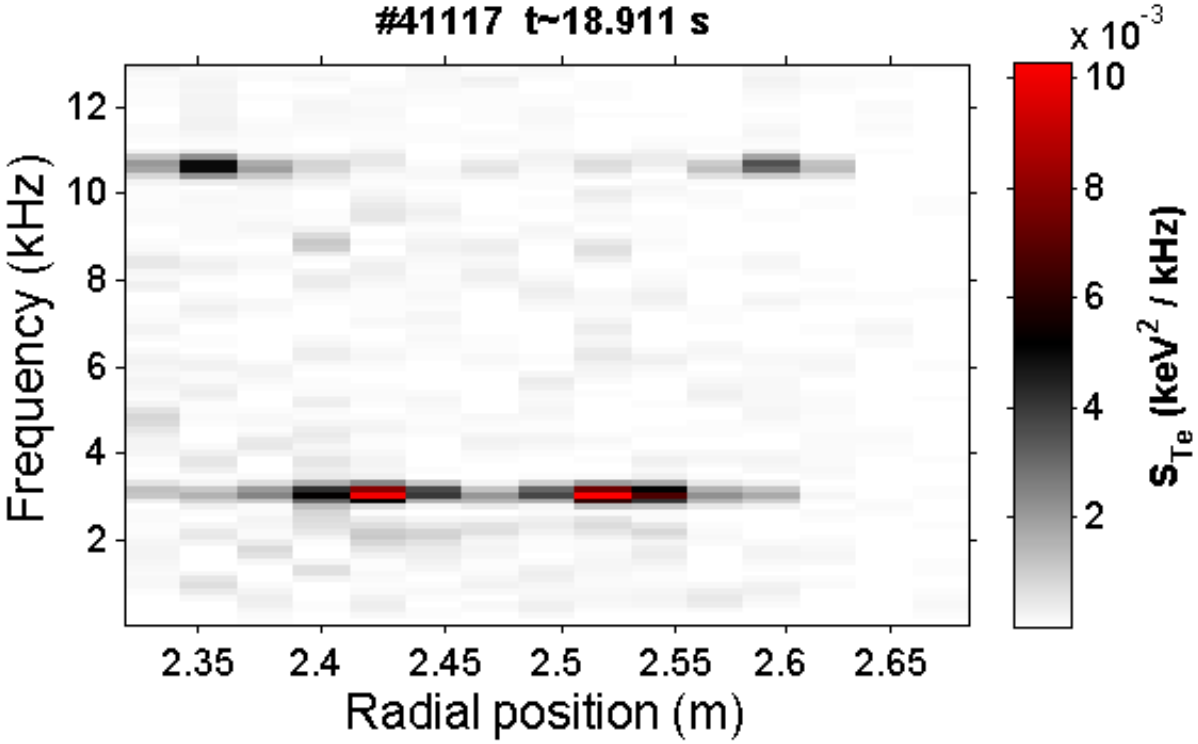
The mode-induced T_e oscillations are:

$$\tilde{T}_e \cong \xi . \nabla T_e$$

Example: e-fishbones with frequency jumps in Tore Supra



Radial spectral distribution of Te oscillations in a given time frame $S_T(f, \rho)$



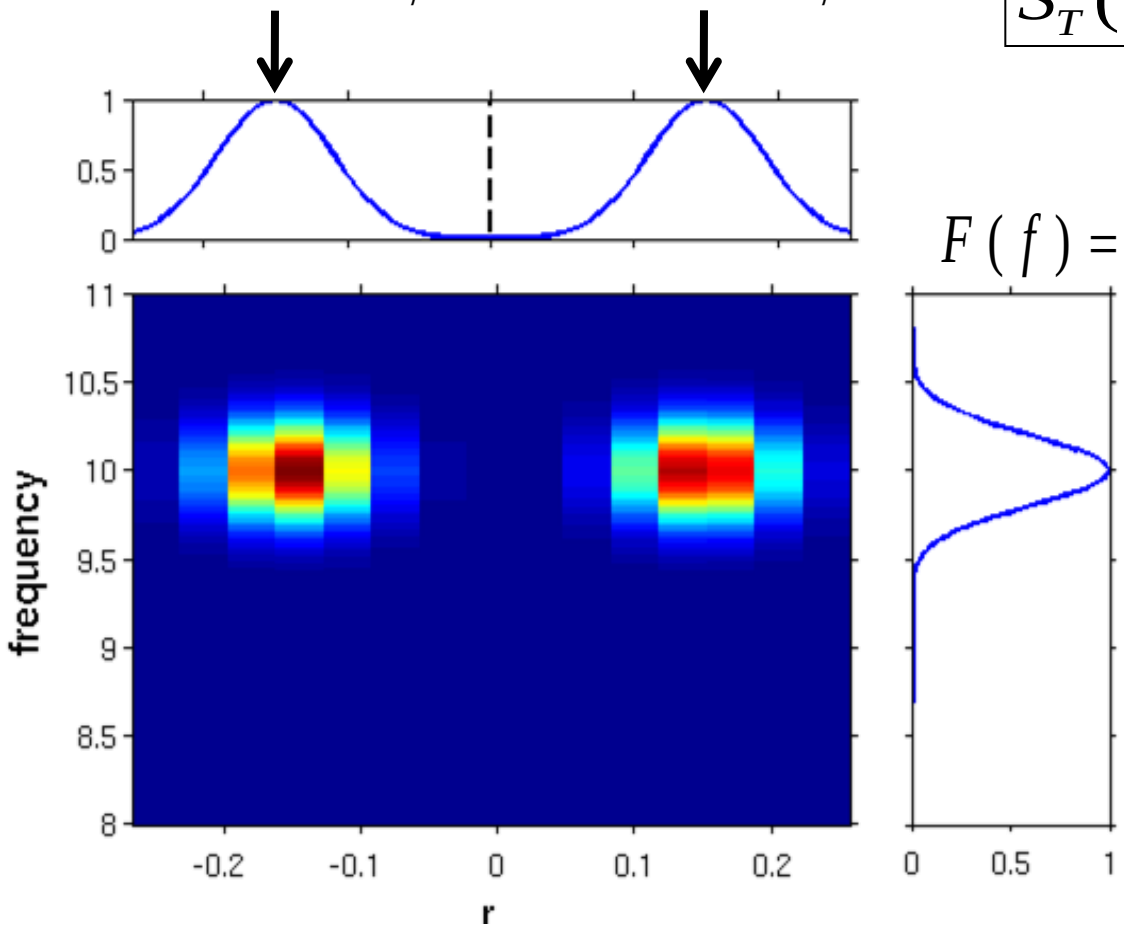
The radial spectral distribution can be described as a product of the dependence in frequency by the radial one

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

Method used to fit the data

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

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



$$F(f) = G(f, f_0, \sigma_f)$$

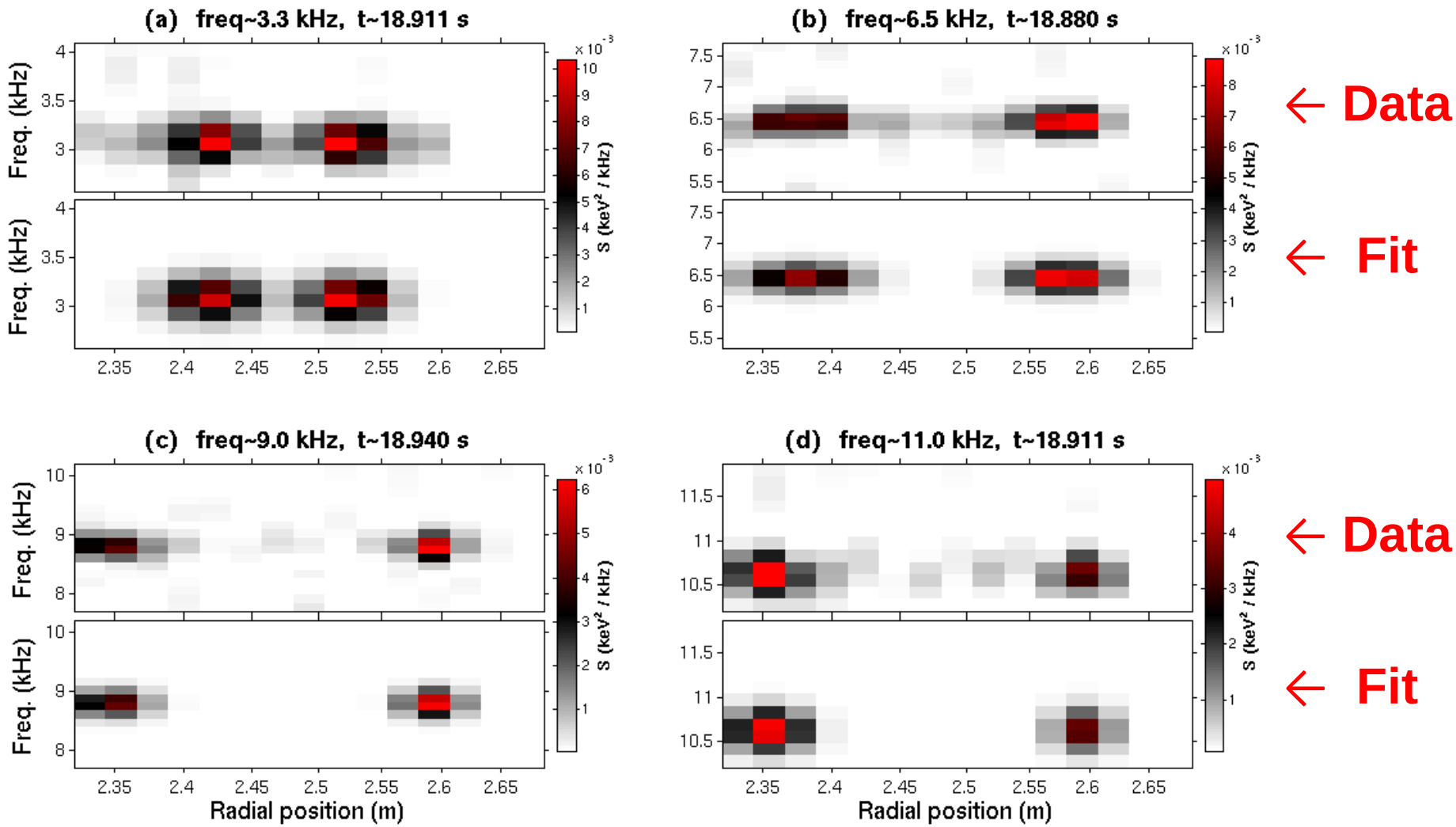
f_0

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, σ_f, ρ_0, σ_ρ 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

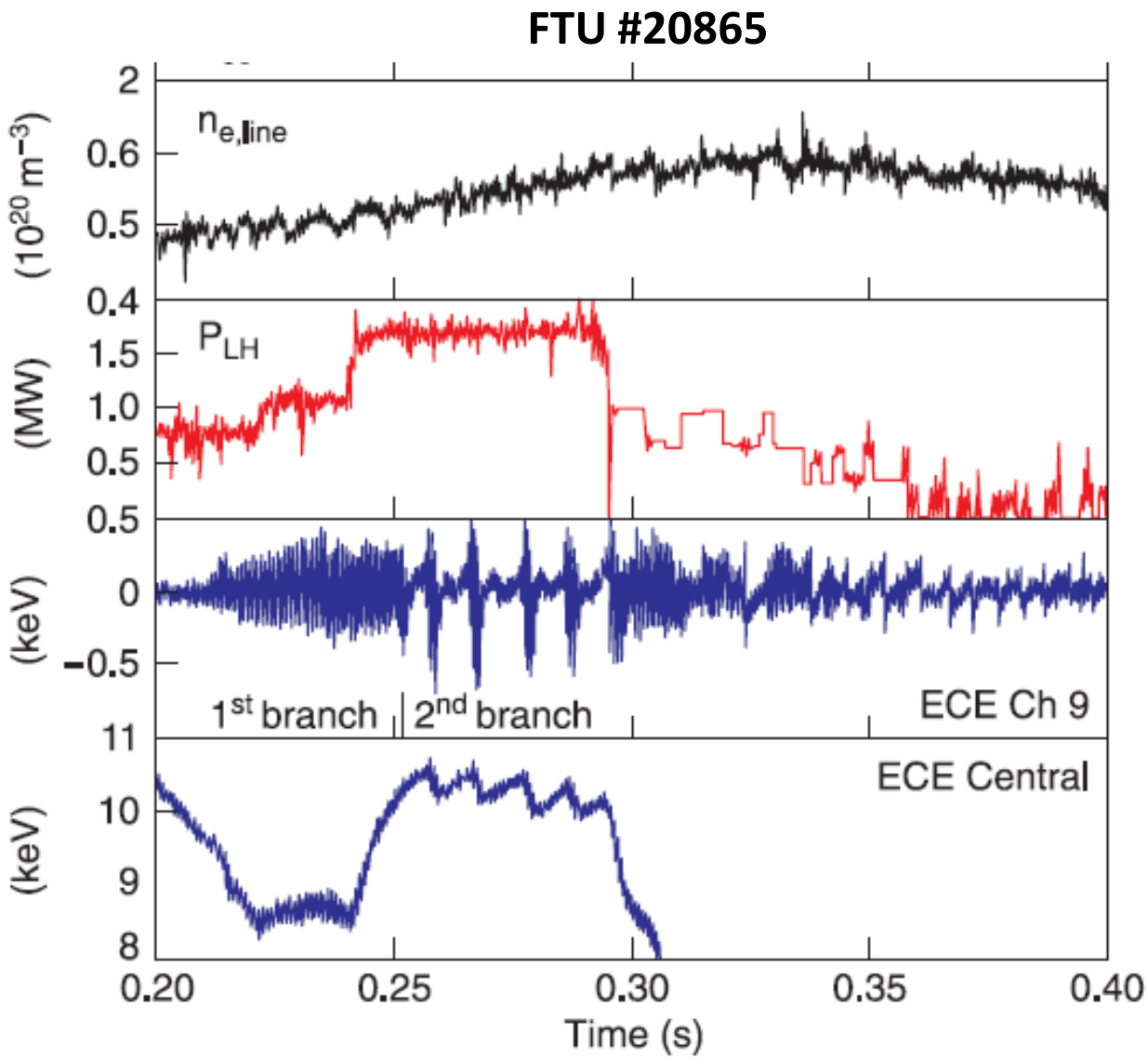
Evolutions of e-fishbones in FTU

e-fishbones without and with periodic bursts

e-fishbones in FTU tokamak

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 (1st branch)
- A regular bursting behavior (limit cycle) at high LH power (2nd branch)



[F.Zonca, Nucl. Fusion 2007]

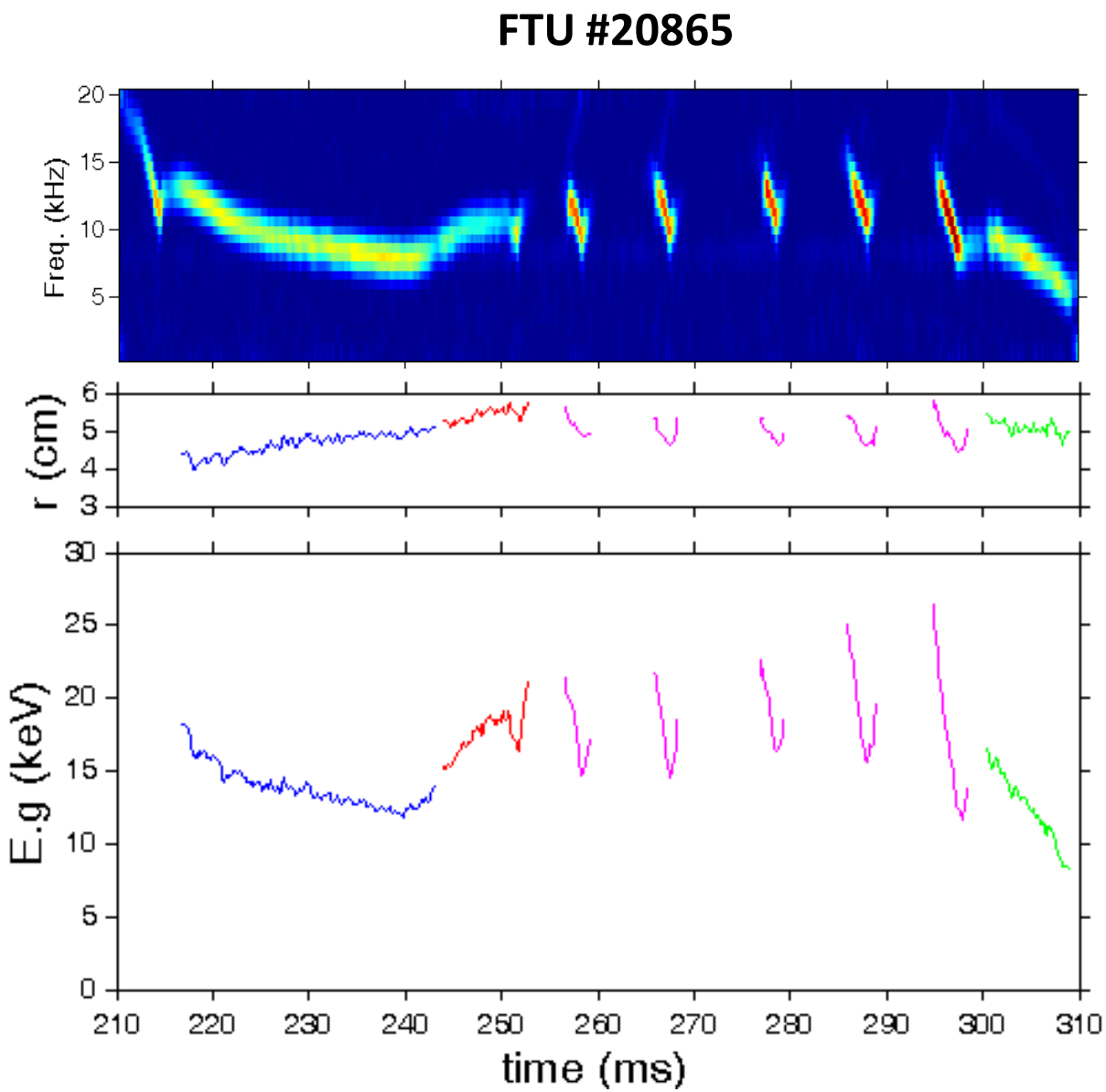
e-fishbone radial position evolution in FTU

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

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

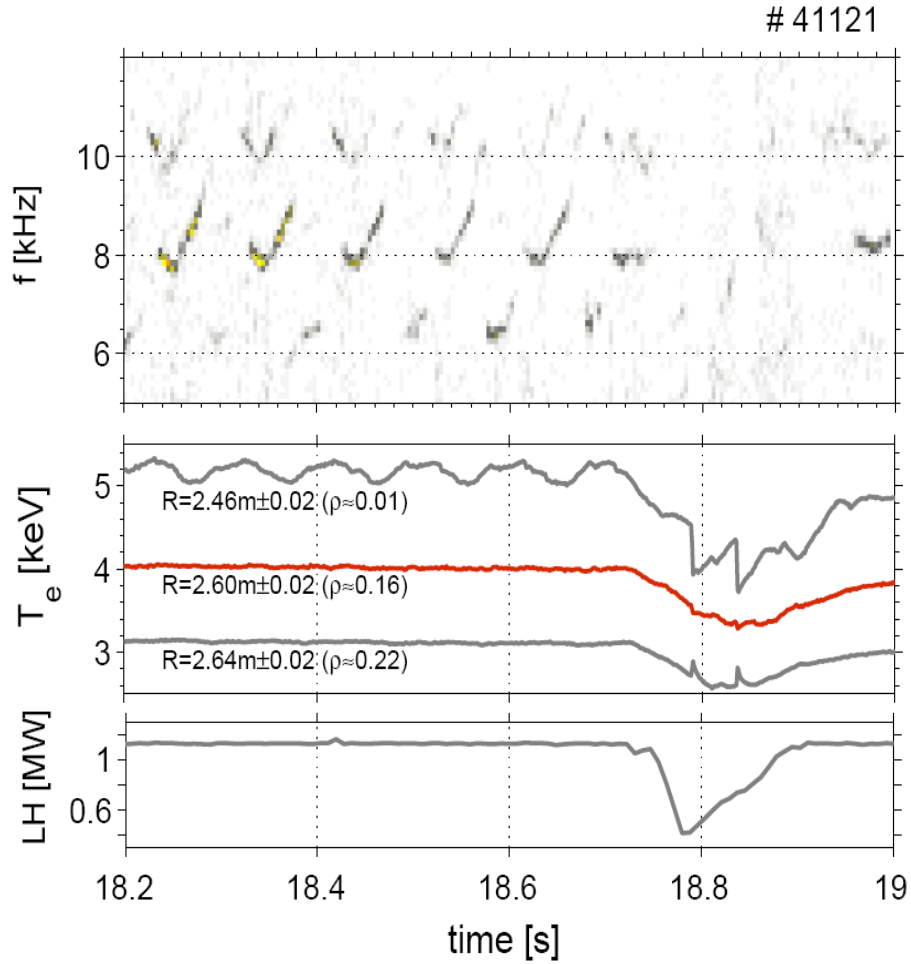


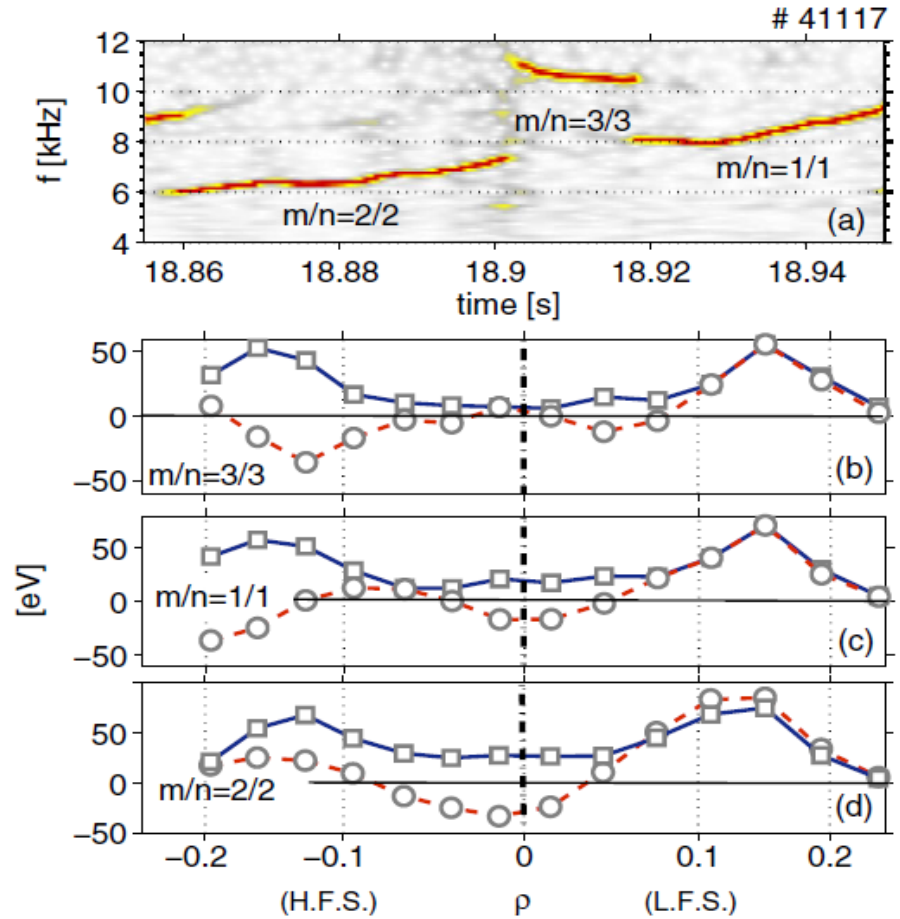
Evolutions of the e-fishbones in Tore Supra

e-fishbones with frequency jumps between modes with different mode structures

e-fishbones in Tore Supra

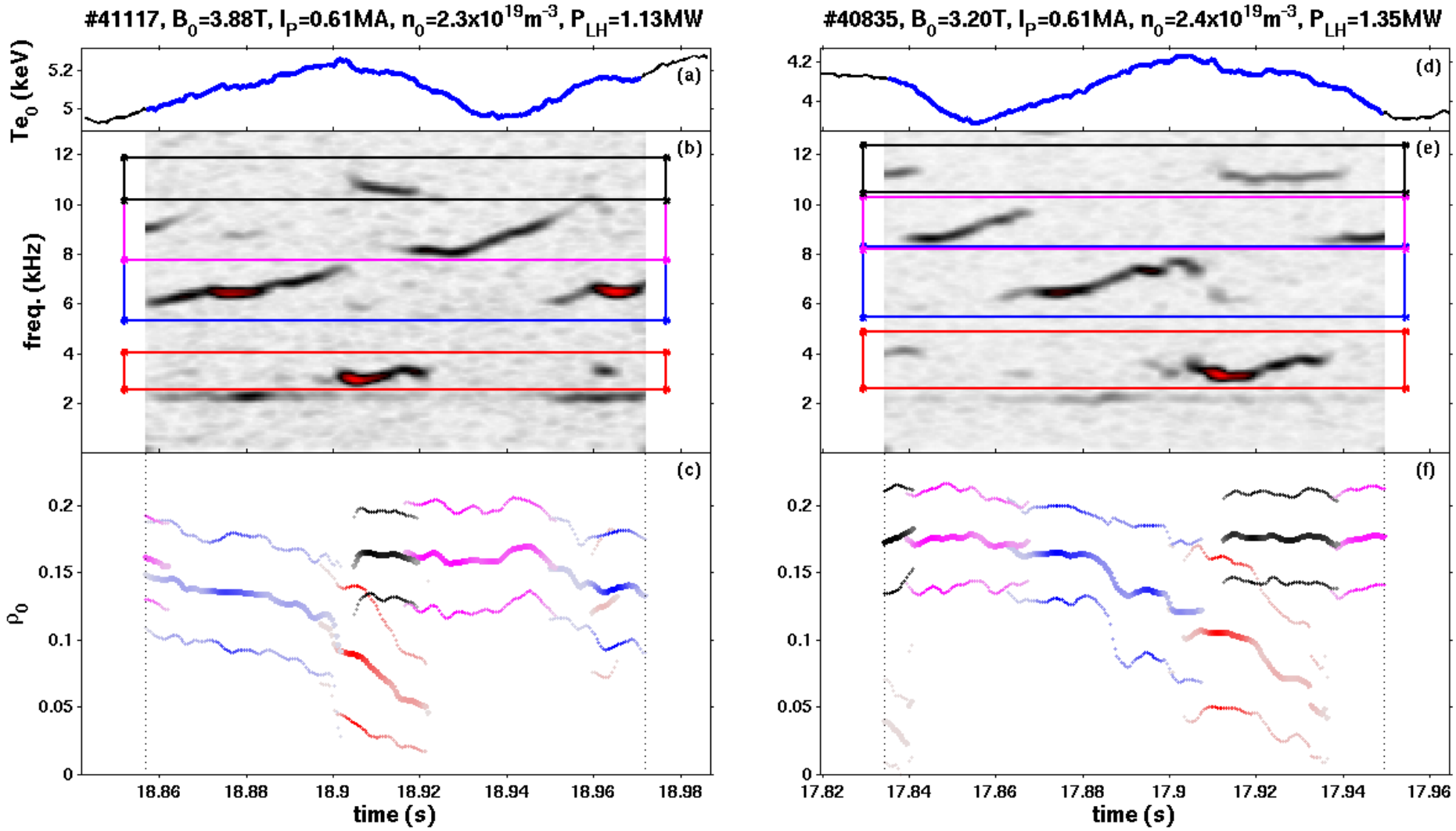
- **At moderated Lower Hybrid power, 1MW, and low density, n_0~2.5x10^{19}m^{-3}, MHD modes identified as precessional e-fishbones may be destabilized**
- **Frequency jumps between modes with different structures are observed**





[A.Macor, PRL 2009]

Evolution of the mode position in Tore Supra

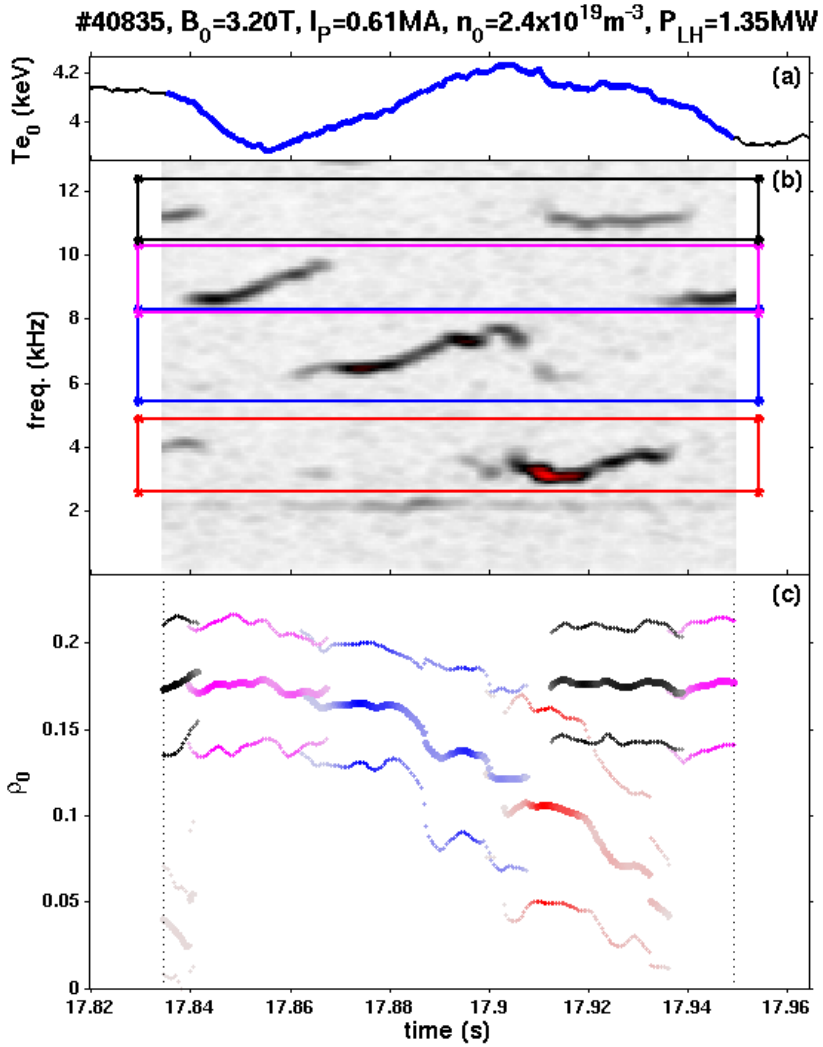


- **Frequency jumps are not linked with abrupt changes on the mode position**
- **The evolution in the mode position follows the q-profile evolution in O-regime**

E-fishbone evolutions

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

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

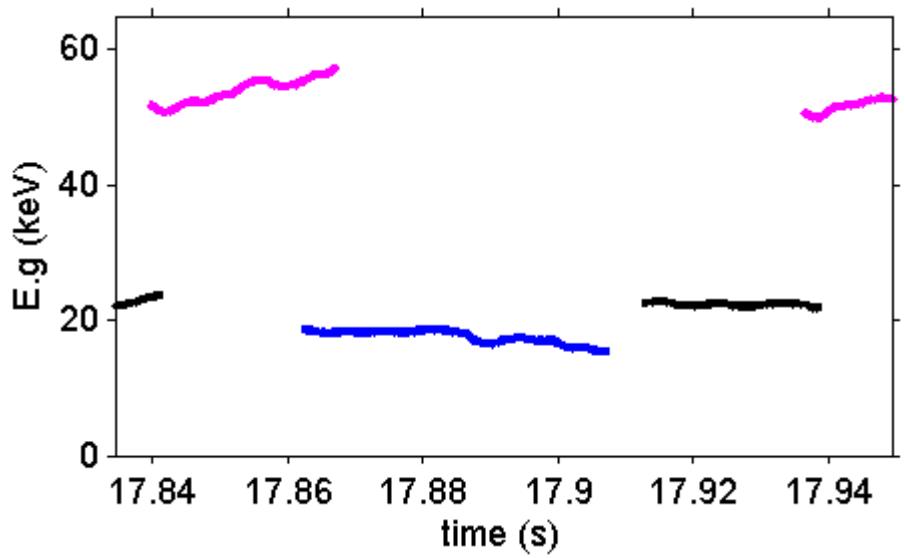


- The continuity in the mode position suggests the following evolution:

11 kHz → 9 kHz → 6 kHz → 3 kHz

From the proposed mode numbers:

3/3 → 1/1 → 2/2 → odd

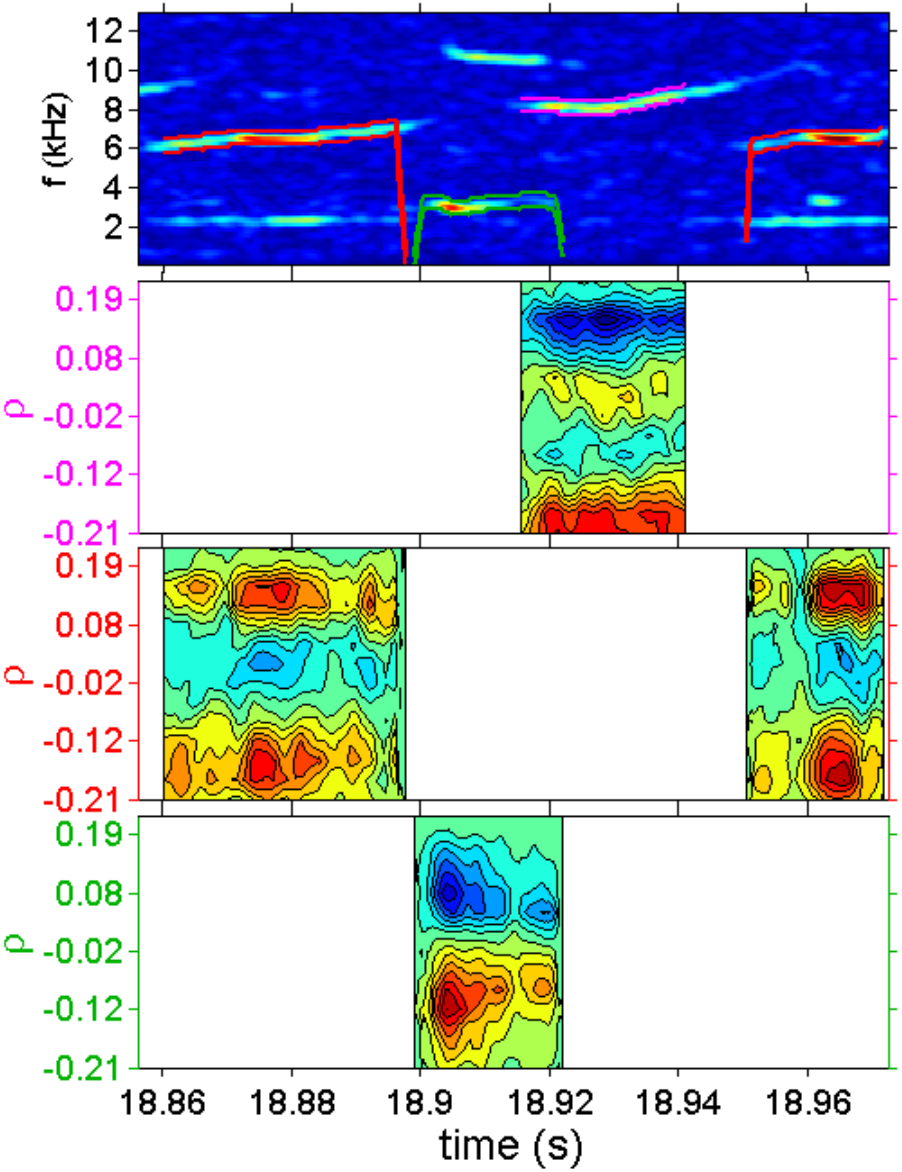


Detailed study of the ECE measurements

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

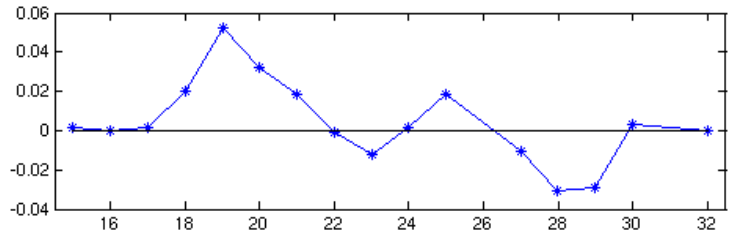
1) The finite size of the ECE antenna
2) The effect of vertical displacements of the ECE LoS

Complex radial profiles of ECE measurements

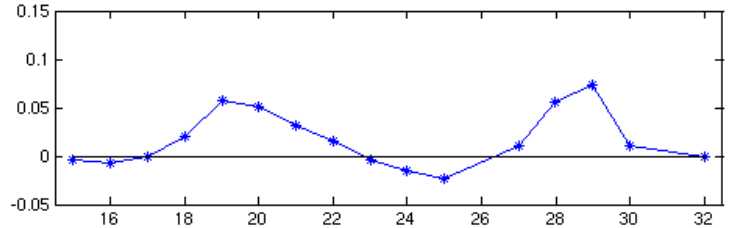


$$|W_x|.\cos(\alpha_{xR})$$

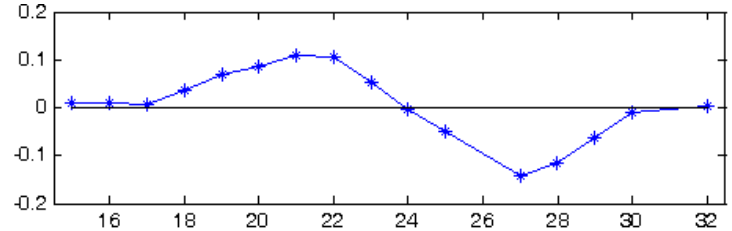
9 kHz 1/1 (?)



6 kHz 2/2



3 kHz 1/1



ECE channel

The numerical ECE

- Simplified model for the ECE signals
  - The “real” Te oscillations induced by these modes are simulated by

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

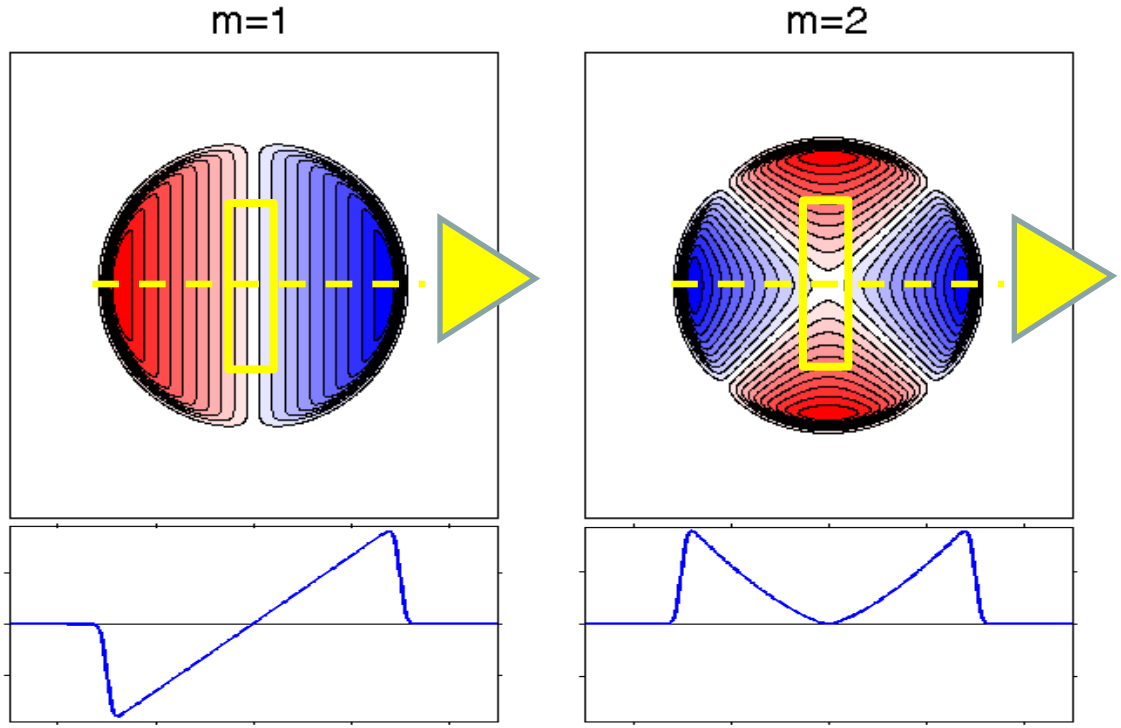
where ξ is the MHD displacement

  - The measured signal is simulated by averaging the real Te oscillations inside the probed region (δ_R~2.5 cm and δ_Z~10 cm)

(1) - 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

$$\xi.\nabla T_e.\cos(m.\theta + w.t)$$

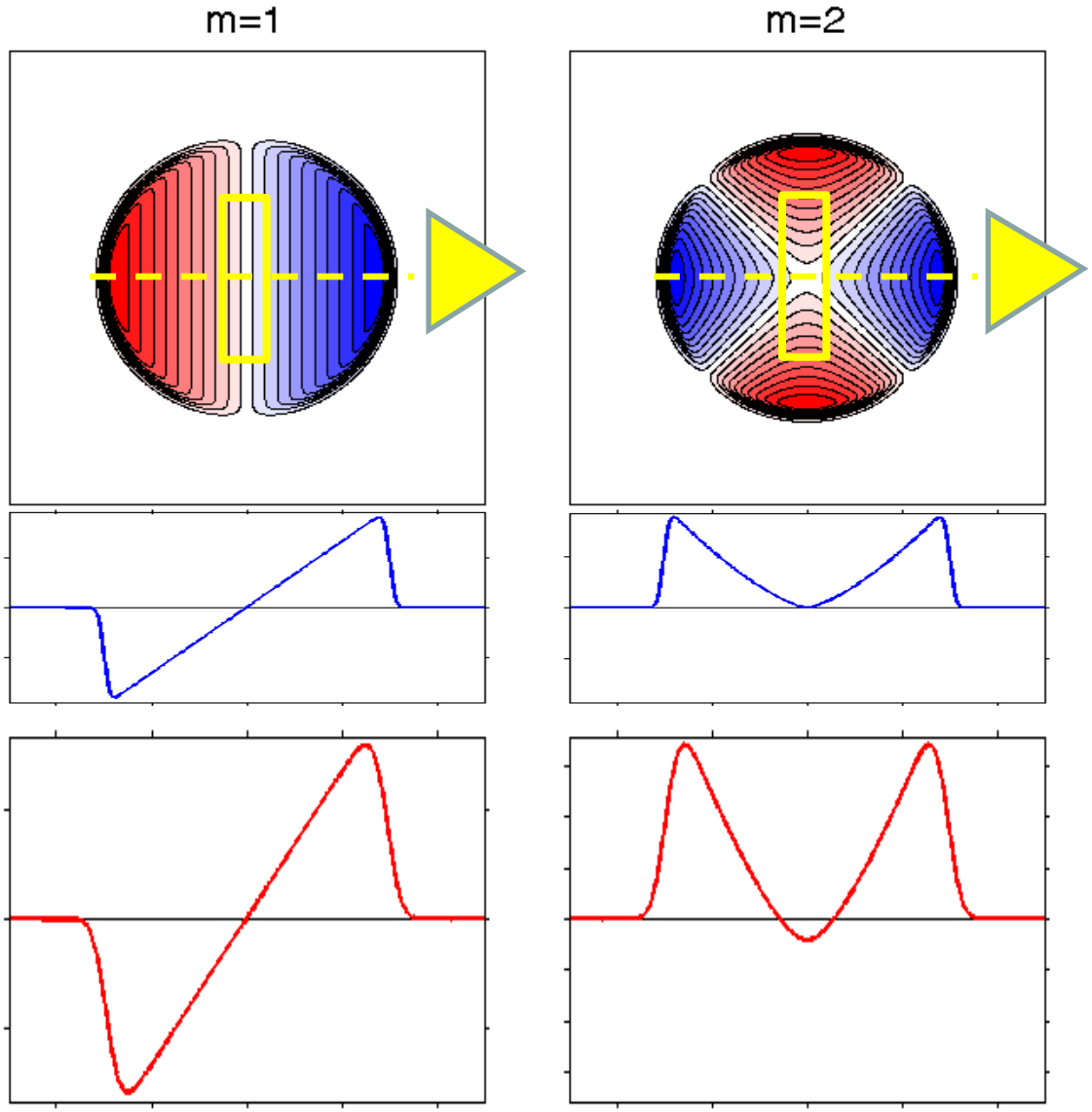


(1) - The effect of the finite size of the probed region on the experimental profiles

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

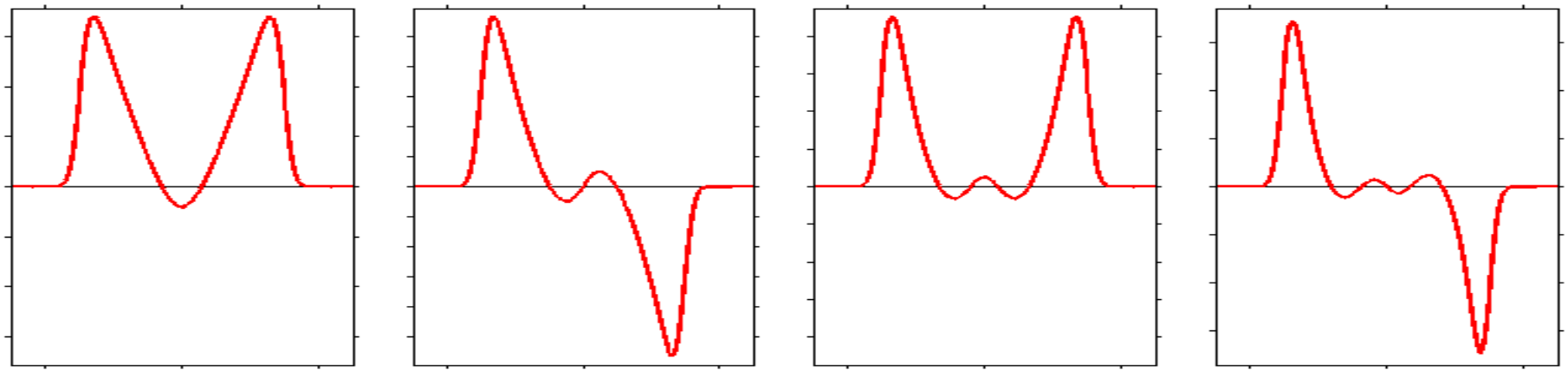
$$\xi.\nabla T_e.\cos(m.\theta + w.t)$$

Observed Te oscillations when the vertical size of the probed region is considered

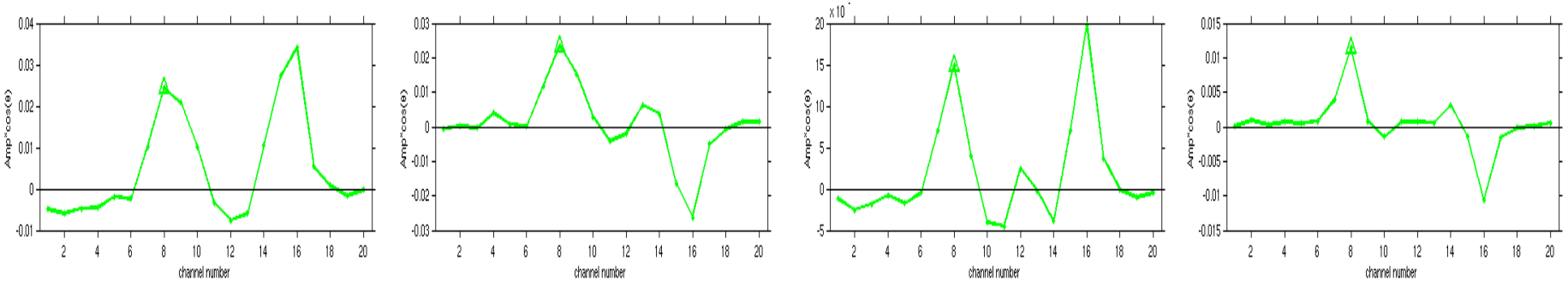


Comparison between simulated and experimental profiles

Simulated profiles from Numerical ECE

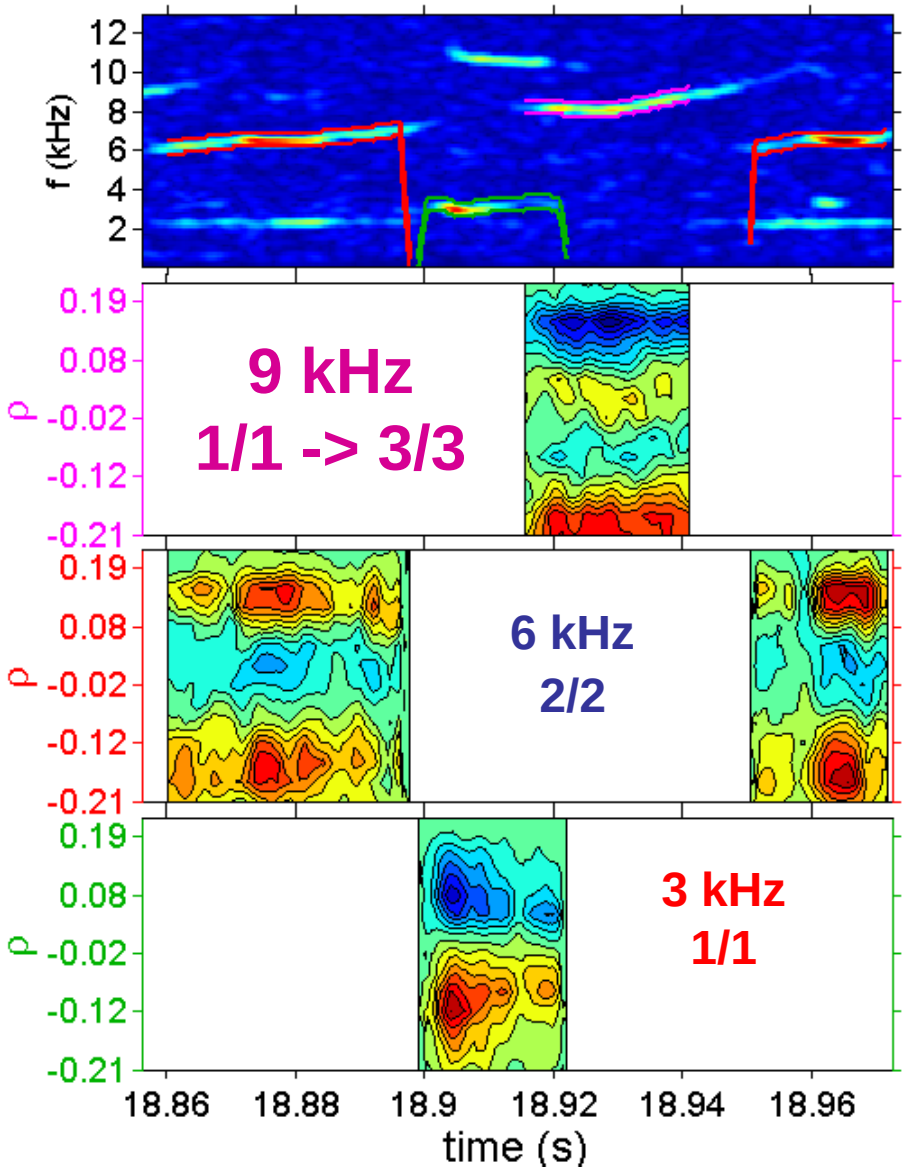


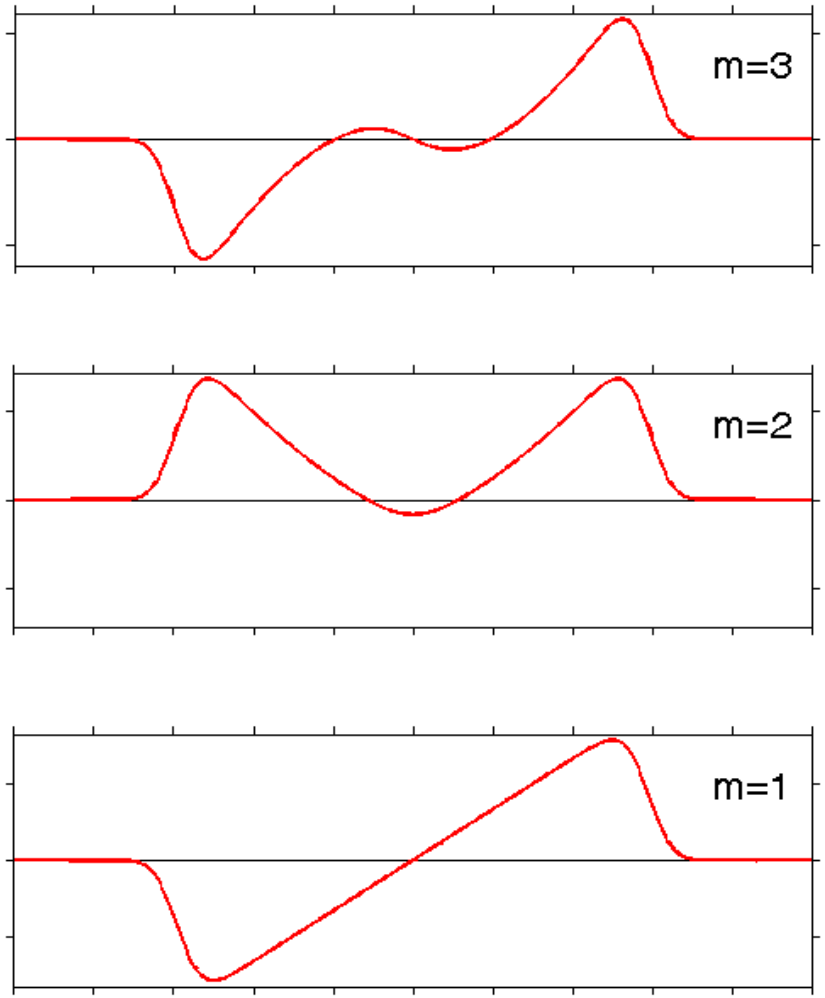
m=2 **m=3** **m=4** **m=5**



Experimental ECE profiles (2011 experiment)

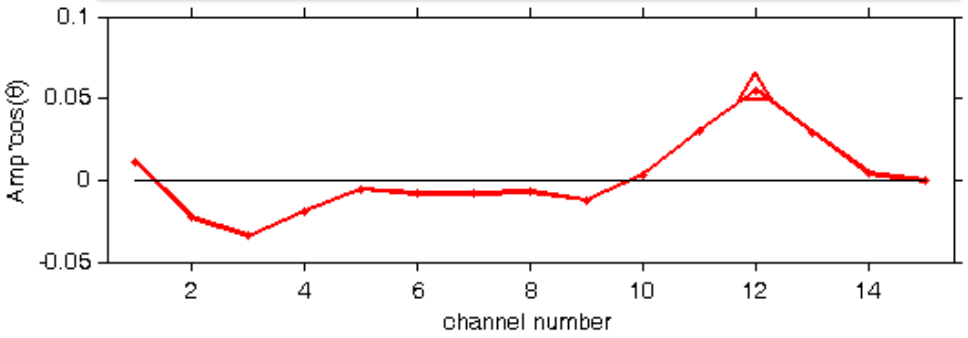
ECE profiles give the poloidal wavenumbers





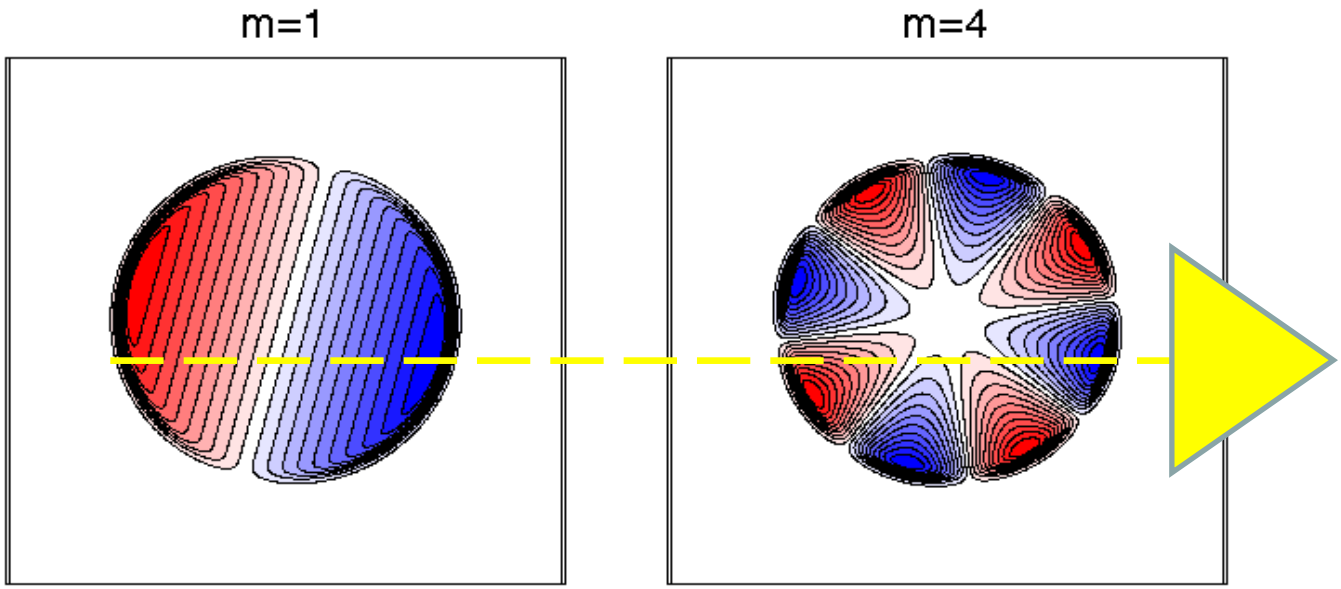
(2) – The effect of vertical displacements of the ECE Line of Sight

11 kHz mode (2008 experiment)



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

Modes with high m are more sensitive



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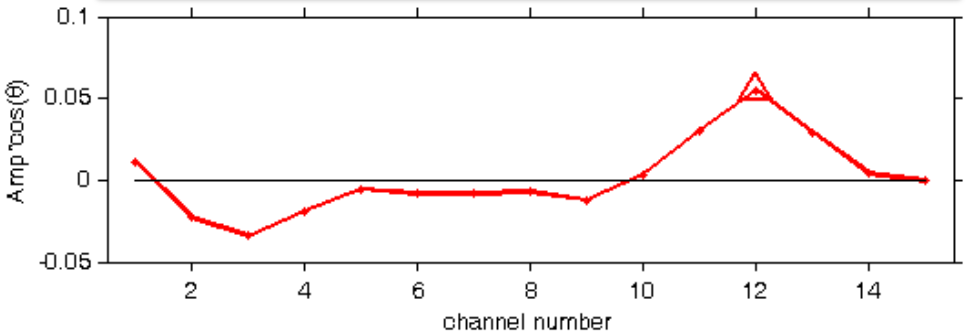
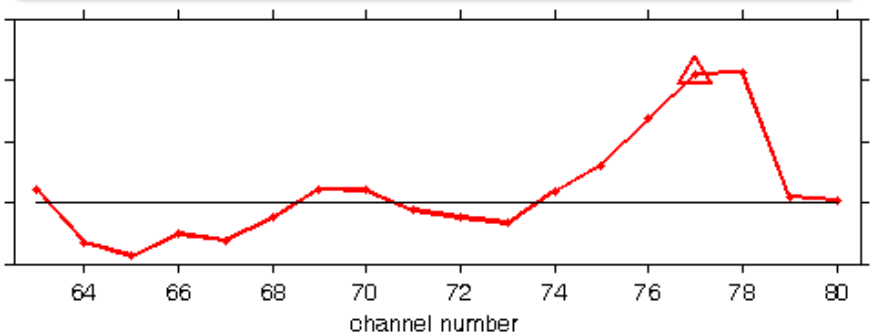
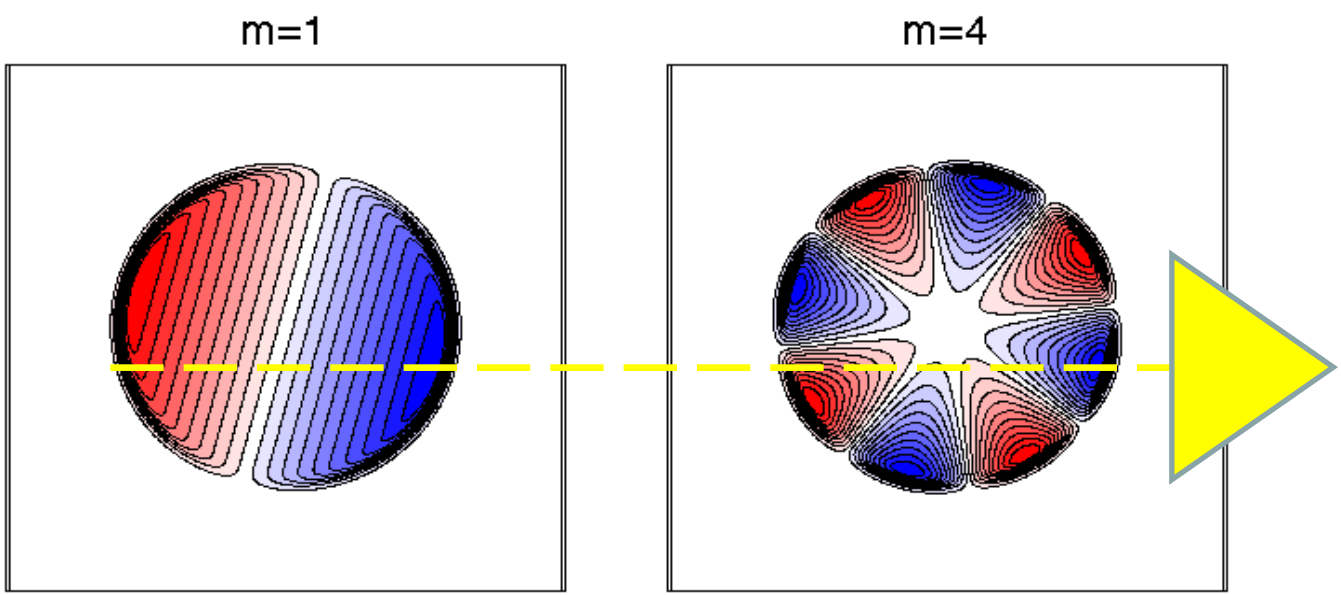


Simulation of m=4 with Δz=3cm



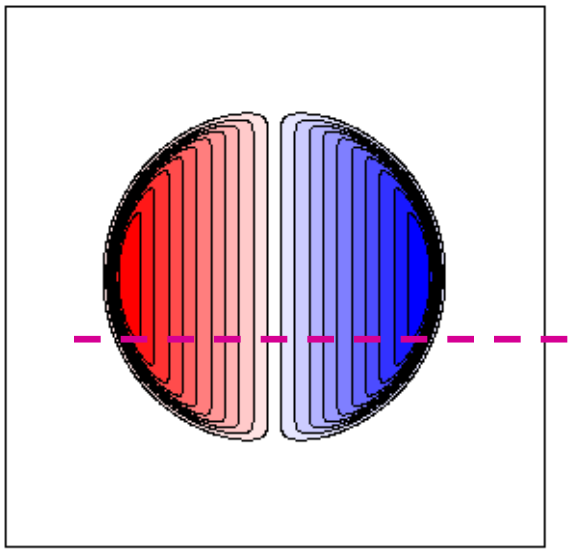
Vertical displacements of the ECE LoS can lead to misidentification of the poloidal parity

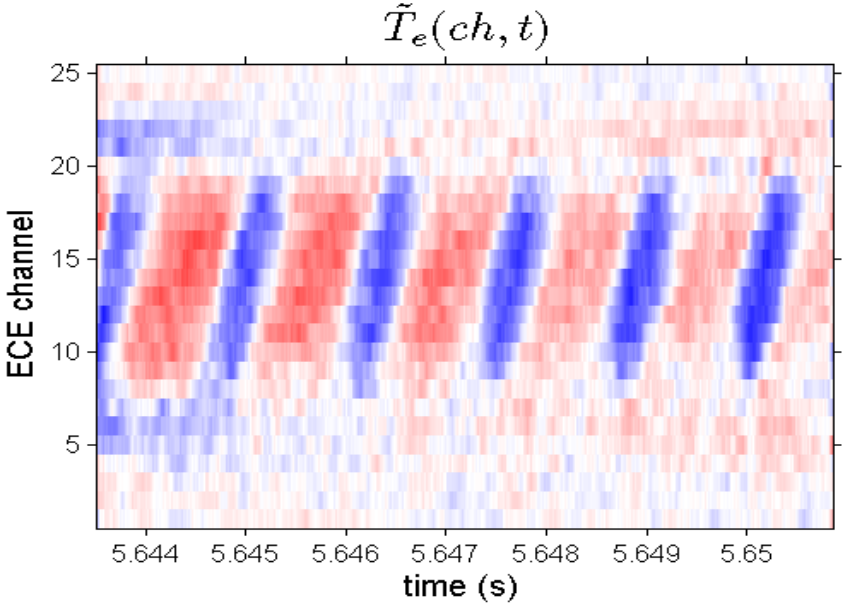
Modes with high m are more sensitive



(3) – Vertical displacements of the ECE Line of Sight and the mode rotation

Ex: sawtooth precursor with Δz = + 7cm





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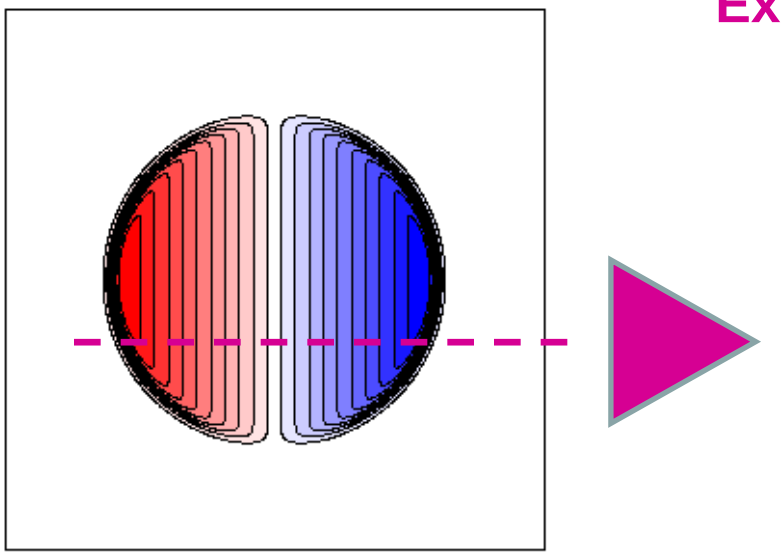
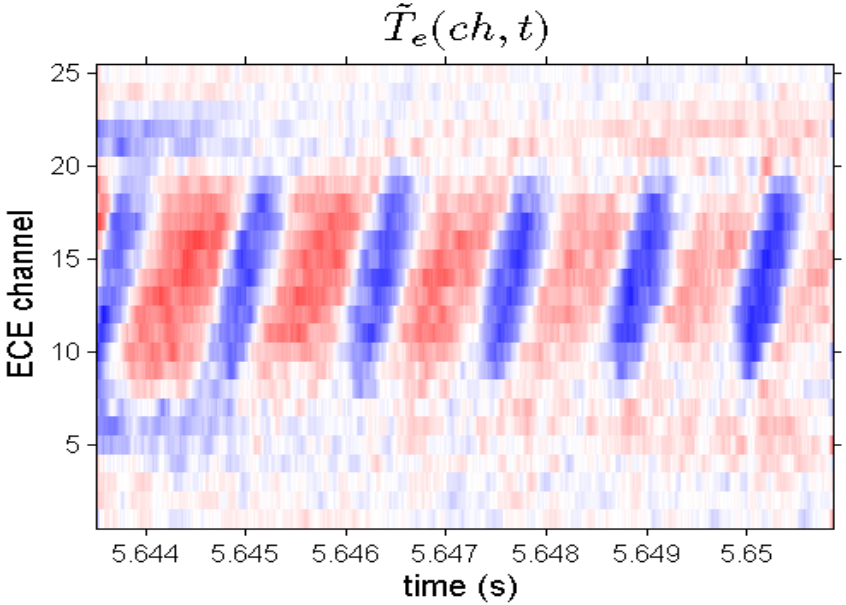


Ex: sawtooth precursor with Δz = + 7cm

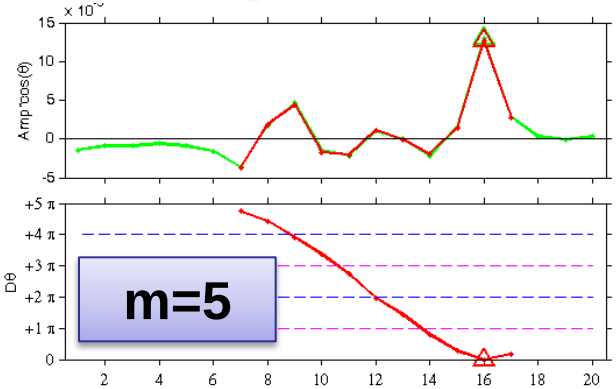


2011 shots with slightly vertically shifted plasmas: Δz=+2 cm

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

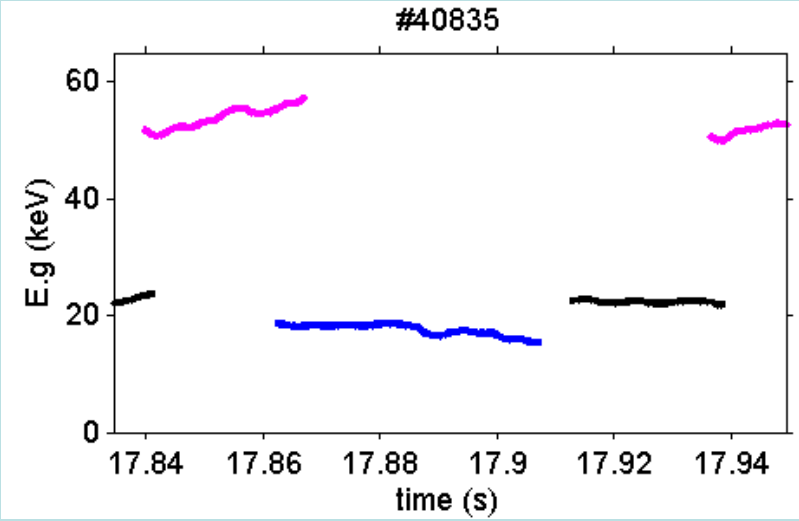


New interpretation for the Tore Supra observations

- 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

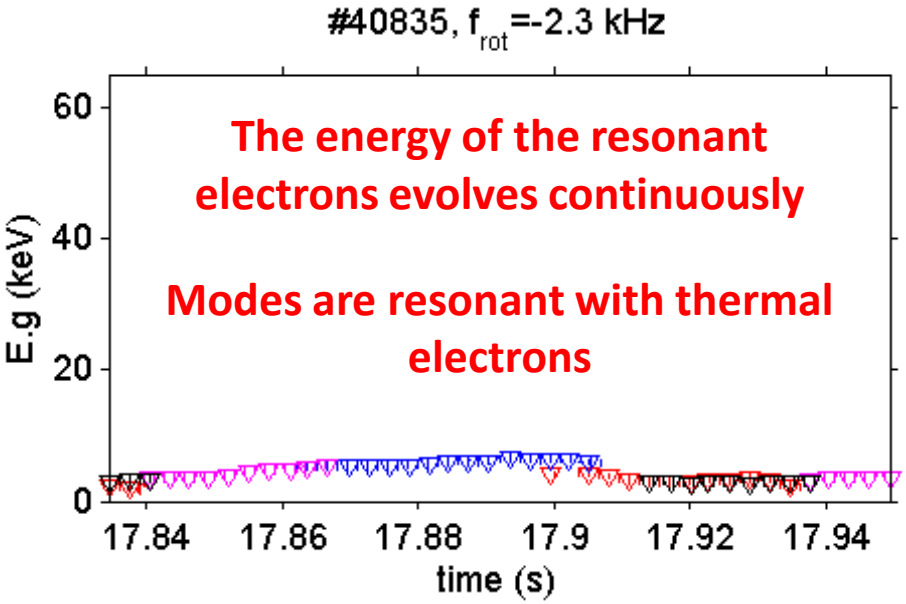
11 kHz → 9 kHz → 6 kHz → 3 kHz

3/3 → 1/1 → 2/2 → odd



11 kHz → 9 kHz → 6 kHz → 3 kHz

4/4 → 3/3 → 2/2 → 1/1



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