Characterization of Energetic Particles driven MHD modes by spectral analysis in Tore Supra and FTU tokamaks

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Outline

- Introduction
  - Remembering some basic ideas about experimental observation of the MHD modes
- Applications and some advanced methods

  e-fishbones with frequency jumps on Tore Supra

  e-fishbones without & with bursting behavior in FTU

  Beta-induced Alfvén Eigenmodes in Tore Supra
- Summary

fishbones and **BAEs** are important to understand the fast particle transport

T_e oscillations induced by MHD modes

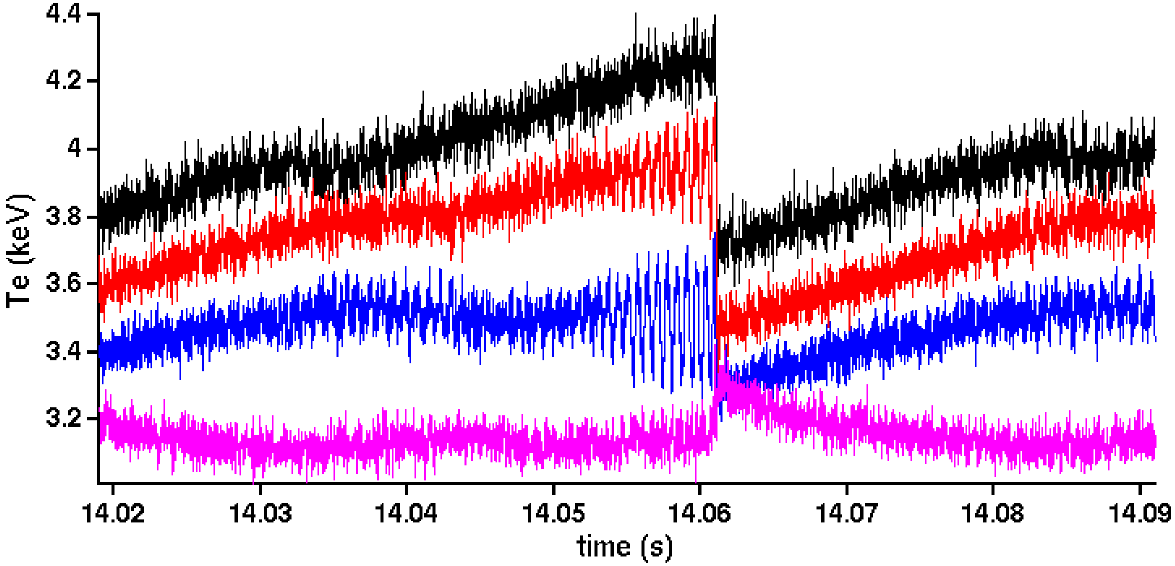
Radial displacement of the magnetic field lines induced by MHD modes:

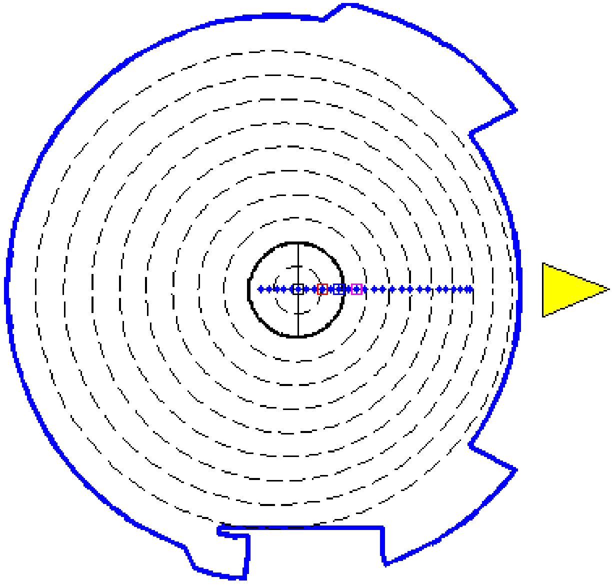
$$\xi = \xi_0 . e^{i(n.\varphi - m.\theta - \omega.t)}$$

The induced T_e oscillations:

$$\xi \cong \frac{\tilde{T}_e}{\nabla T_e} \cong \frac{\tilde{n}_e}{\nabla n_e}$$

Example: ECE measurements of a sawtooth precursor





ρ=0.01 **ρ=0.11** **ρ=0.18** **ρ=0.25**

Spectral analysis – Basic ideas

The spectral analysis is based on the representation of a signal $x(t)$ by its Fourier series $W_x(f)$:

$$x(t) = \sum_{f} W_x(f).e^{i.2\pi.f.t}$$

The Self Power Spectrum is:

$$P_{xx}(f) = W_x(f).W_x^*(f) = \left|W_x(f)\right|^2$$

$W_x(f)$ is a complex quantity, even when $x(t)$ is real:

$$x(t) = \sum_{f>0} a_x(f).\cos\left(2\pi.f.t + \Theta_x(f)\right) \quad \Rightarrow \quad W_x(f) = W_x^*(-f)$$

Interpretation of $W_x(f)$ and $P_{xx}(f)$ for $x(t)$ real:

$$W_x(f) = a_x(f).e^{i.\Theta_x(f)}$$

$$P_{xx}(f) = a_x(f)^2$$

Cross Spectral analysis

The Cross Spectrum is defined as:

$$C_{xy} = W_x(f).W_y^*(f)$$

The Cross **Power** Spectrum (or Correlation Power Spectrum) is:

$$S_{xy} = \left| \left\langle W_x(f).W_y^*(f) \right\rangle \right|$$

Interpretation of $C_{xy}(f)$ when both $x(t)$ and $y(t)$ are real:

$$C_{xy}(f) = a_x(f).a_y(f).e^{i.\left(\Theta_x(f) - \Theta_y(f)\right)}$$

The phase between the oscillations in x and y can be determined as:

$$\Delta\Theta_{xy}(f) = \tan^{-1}\left(\frac{imag\left(C_{xy}(f)\right)}{real\left(C_{xy}(f)\right)}\right)$$

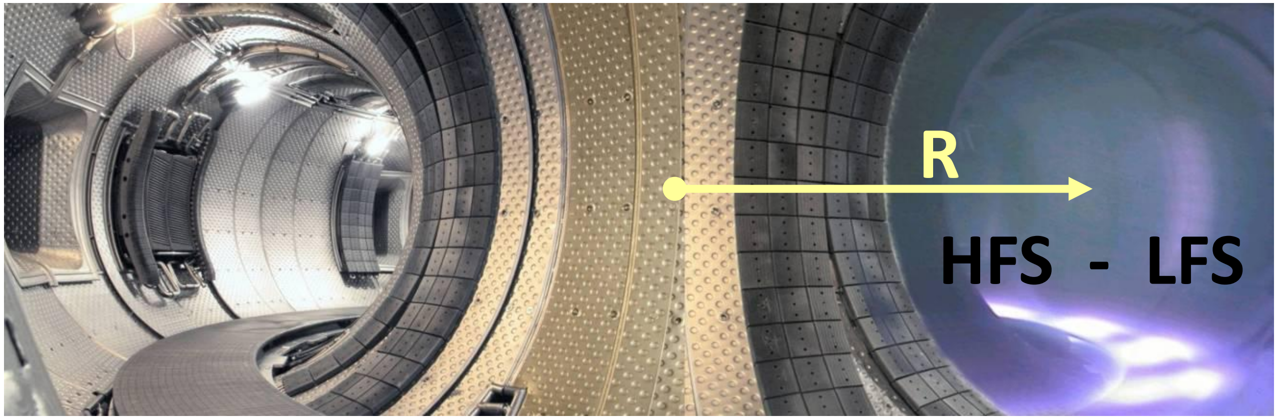
Tore Supra Tokamak

Largest tokamak with superconductor coils in operation

- R ≈ 2.4 m, a ≈ 0.7 m, $B_T < 4$ T
- Circular cross section
- Long pulse discharges (up to 6 min)
- **Lower Hybrid Current Drive (LHCD) for non-inductive discharges**
- **Ion Cyclotron Resonant Heating (ICRH)**
- Electron Cyclotron Resonant Heating (ECRH)

Diagnostics for high frequency MHD instabilities

- **Electron Cyclotron Emission (ECE) Radiometer (profiles of electron temperature, 32 channels)**
- **Reflectometer (localized measurements of density, 2 channels)**
- Interferometer (line-integrated density fluctuations, 10 chords, after 2011)



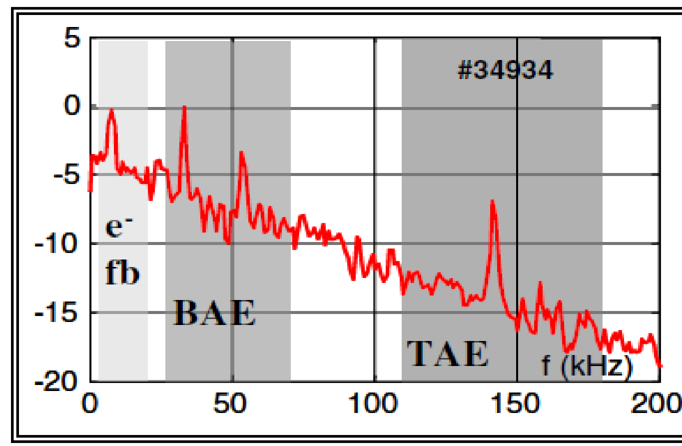
MHD instabilities driven by fast particles in TS

IOP PUBLISHING and INTERNATIONAL ATOMIC ENERGY AGENCY — NUCLEAR FUSION
Nucl. Fusion **49** (2009) 085033 (7pp) — doi:10.1088/0029-5515/49/8/085033

Observation of acoustic and subacoustic fast particles driven modes in Tore-Supra

R. Sabot, A. Macor, C. Nguyen, J. Decker, D. Elbeze,
L.-G. Eriksson, X. Garbet, M. Goniche, G. Huysmans,
Y. Ladroit, P. Maget and J.L. Segui

- **Electron fishbone-like modes**
  [A.Macor *et al.*, PRL 2009]
  - ✓ LHCD discharges (fast electrons)
  - ✓ Low frequency modes (< 15 kHz)
- **Beta Alfvén Eigenmodes**
  [C.Nguyen *et al.*, PPCF 2009]
  - ✓ ICRH discharges (fast ions)
  - ✓ Acoustic modes (Freq. ~ 50 kHz)
- **Toroidal Alfvén Eigenmodes**
  [VS. Udintsev *et al.*, PPCF 2006]
  - ✓ High frequency modes (~150 kHz)



[R.Sabot, NF 2009]

B_0=3.8T, I_p=0.6MA, n_0=4.4.$10^{19}$$m^{-3}$,

P_{LH}=3MW , P_{ICRH}=1.6MW

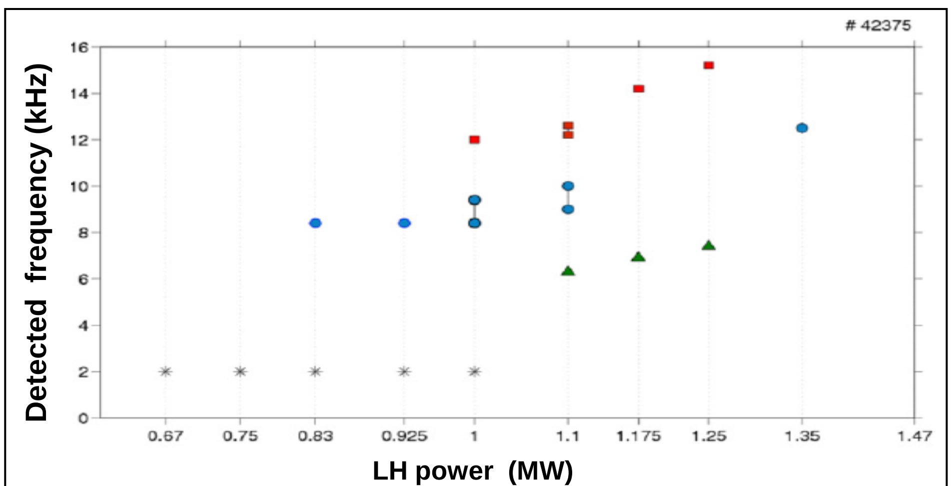
e-Fishbone-like modes in TS

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

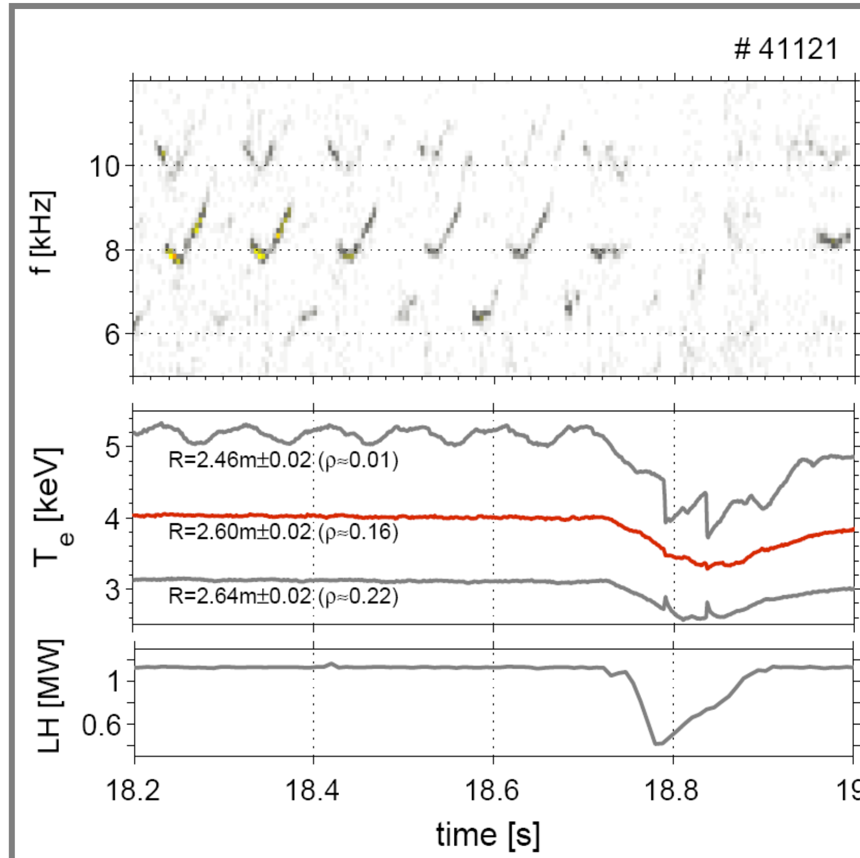
Redistribution of Suprathermal Electrons due to Fishbone Frequency Jumps

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

- At moderated Lower Hybrid power, P_{LH}~1MW, MHD modes identified as electron fishbones with frequencies between the diamagnetic and the acoustic ranges may be destabilized



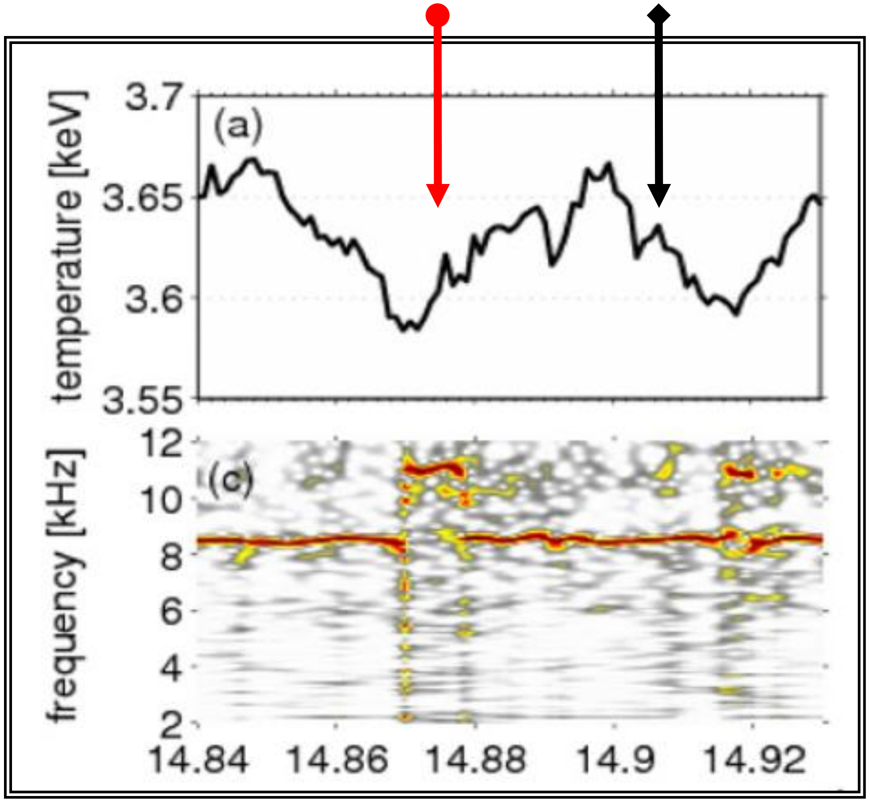
[R.Sabot, NF 2009]

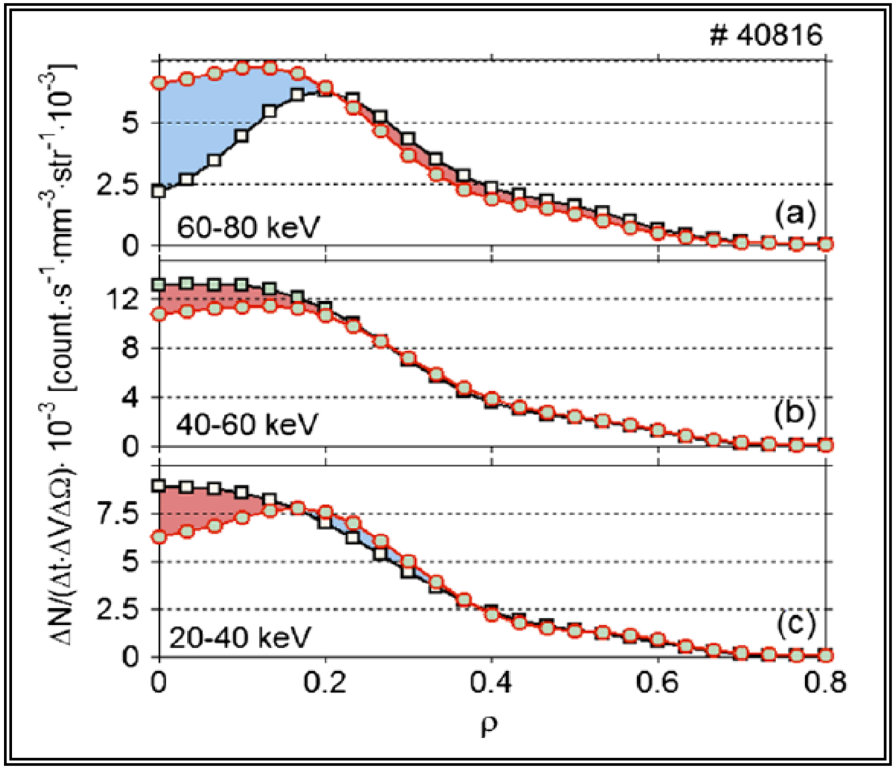


[A.Macor, PRL 2009]

Suprathermal electron redistribution

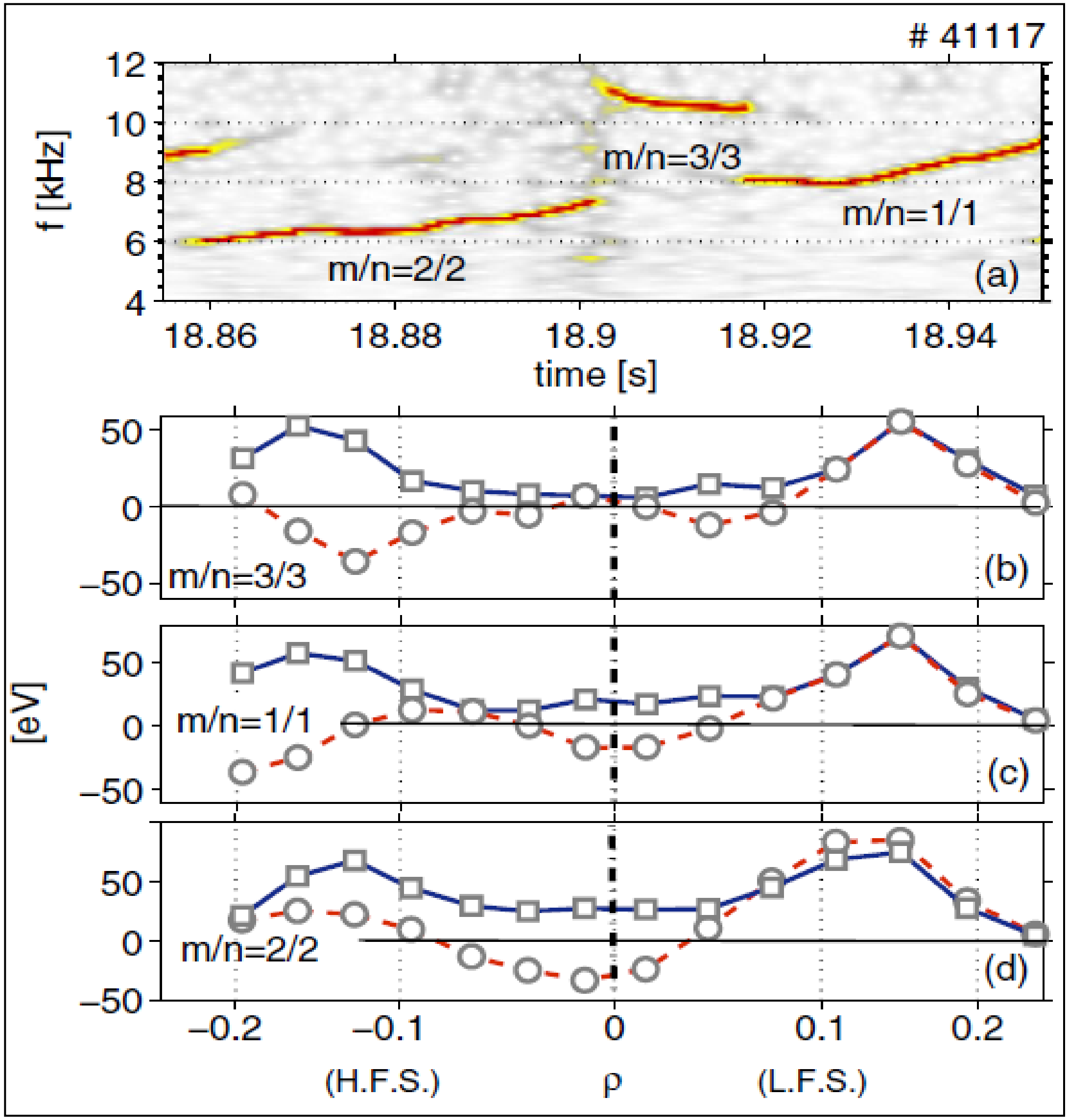
Differences in the radial profiles of hard X-ray emission during the 11 kHz and the 9 kHz modes





[A.Macor, PRL 2009]

EF – Jumps in frequency



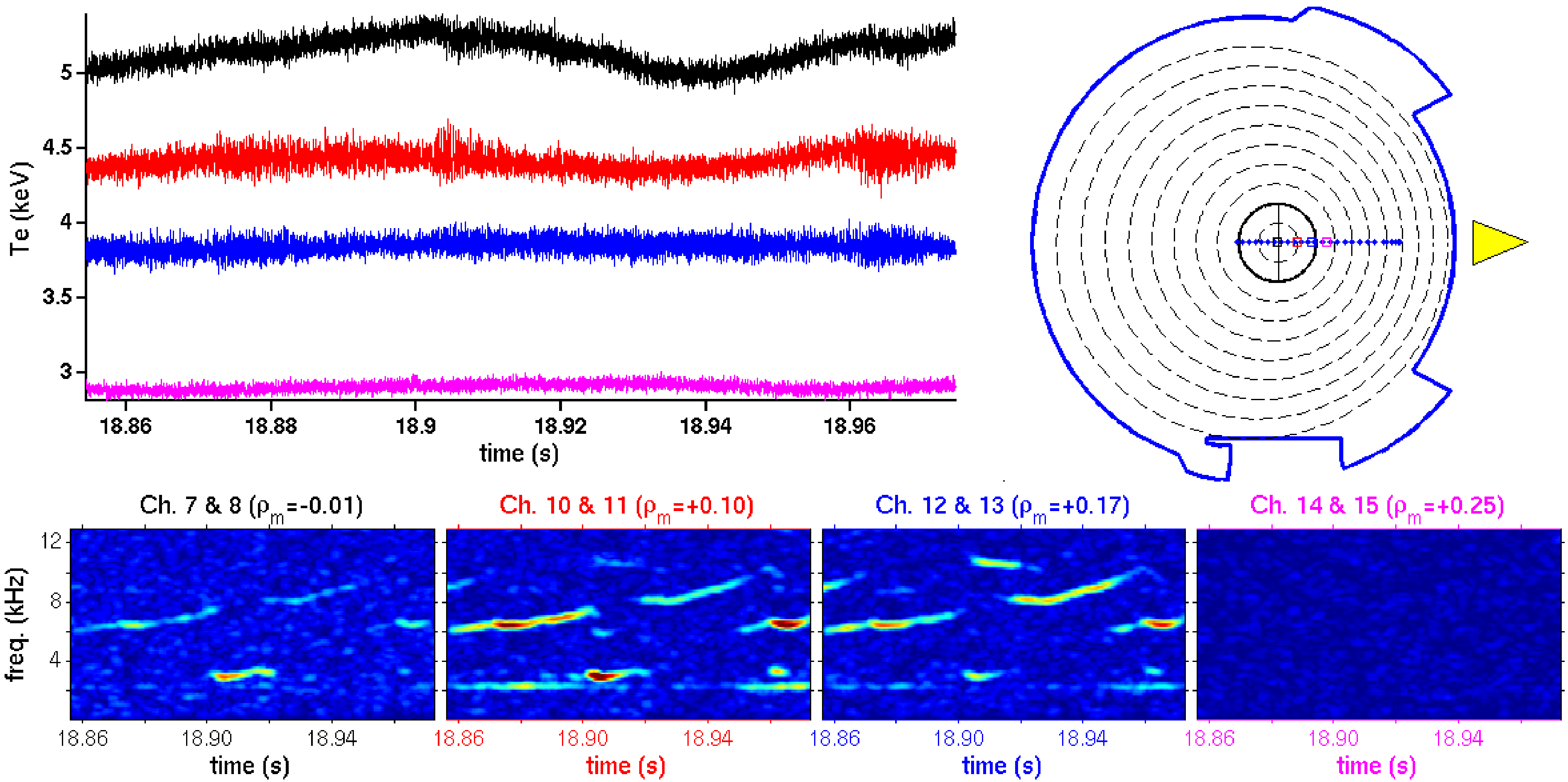
$$f_p = \frac{n.E}{r}\frac{q}{2\pi.R_0.B}$$

- ***n*** Toroidal mode number
- ***E*** Energy of the resonant particles
- ***q*** Safety factor at the mode position
- ***r*** Position of the mode
- ***R_0*** Major radius

[A.Macor, PRL 2009]

How does the energy of the resonant electrons evolve? $f(t)$ & $r(t) \rightarrow E(t)$

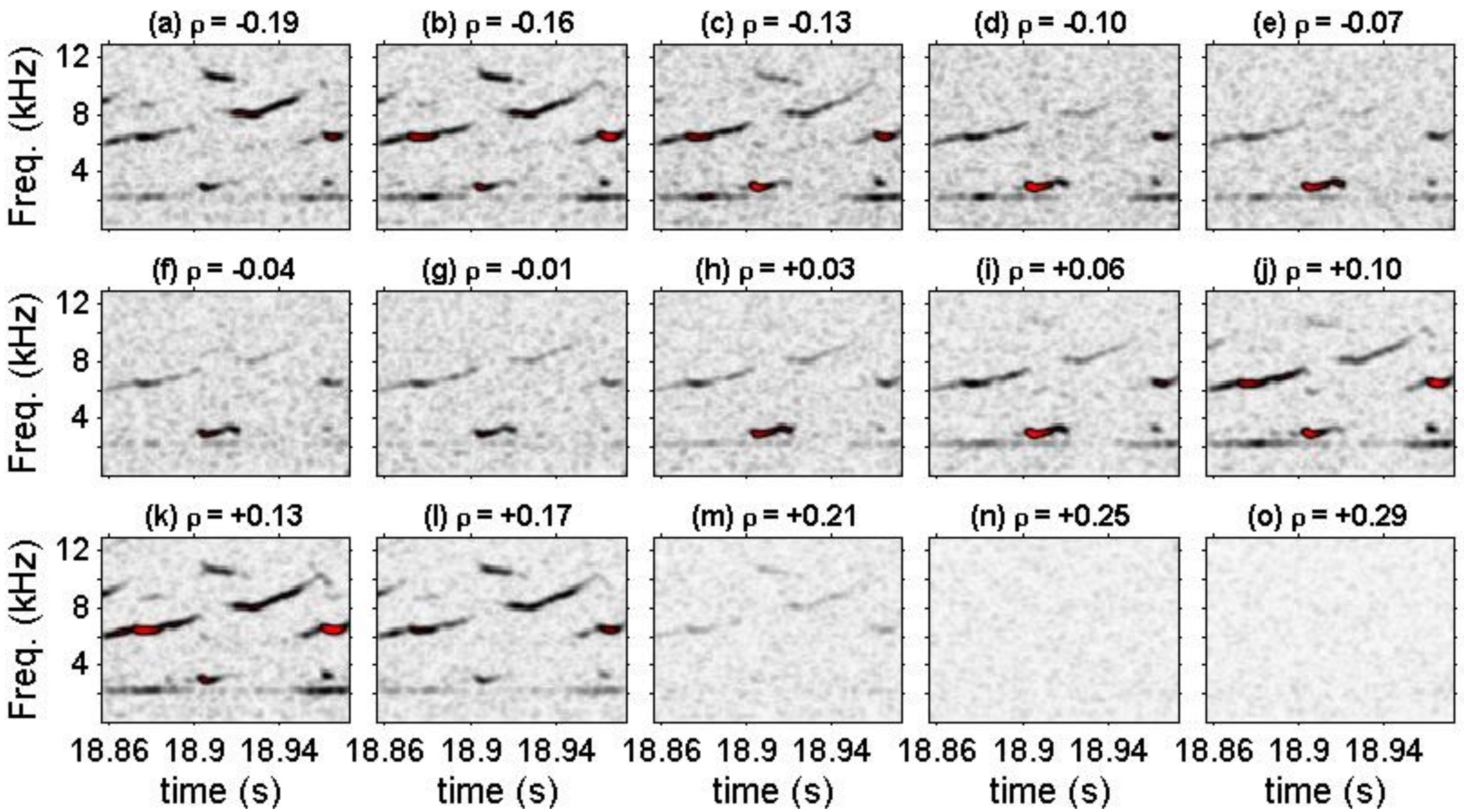
ECE measurements of the electron fishbones in oscillation regime



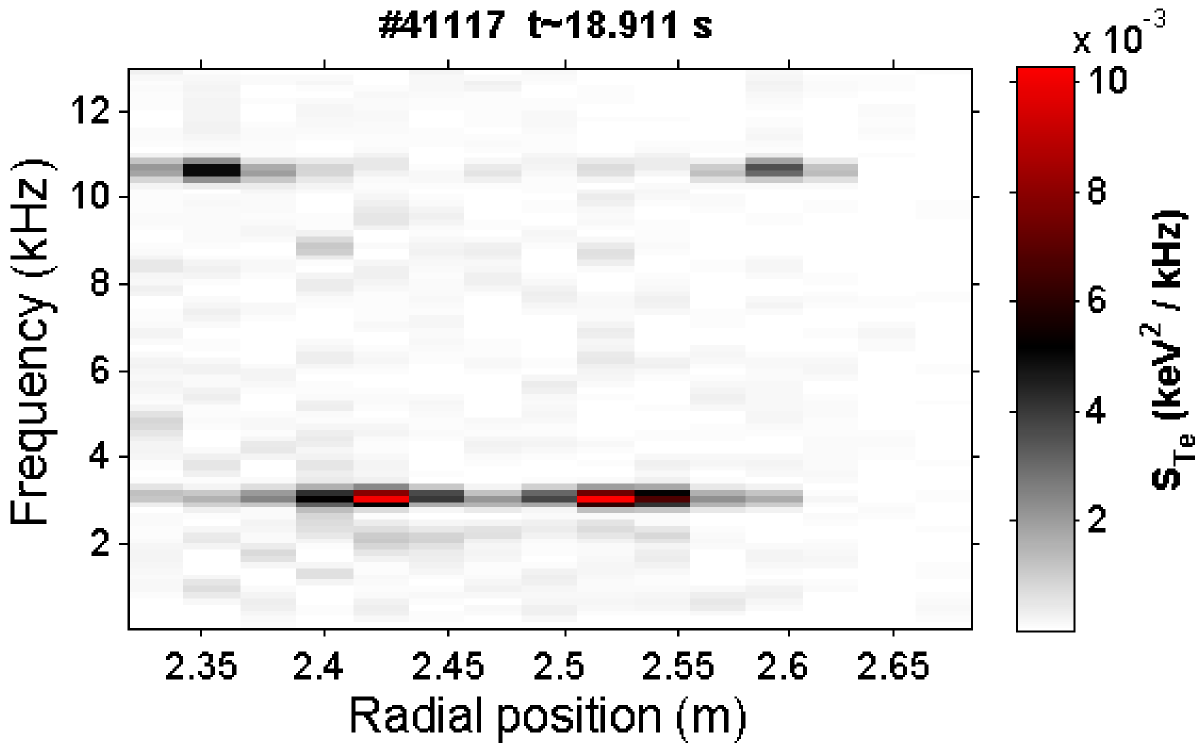
Radial dependence

The induced oscillations are not uniform: their characterization also demands spatial information

$$S(f, t, \rho)$$



For a given time frame $S_T(f, \rho)$



The mode structures can be described as a product of the dependence in frequency by the radial one

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

Phenomenological model for $S_T(f, \rho)$

- The dependency in frequency can be fitted as a Gaussian in the mode frequency, f_0, with dispersion σ_f

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

- The radial dependence can be fitted by a sum of two Gaussians at $-\rho_0$ and $+\rho_0$ with dispersions σ_ρ

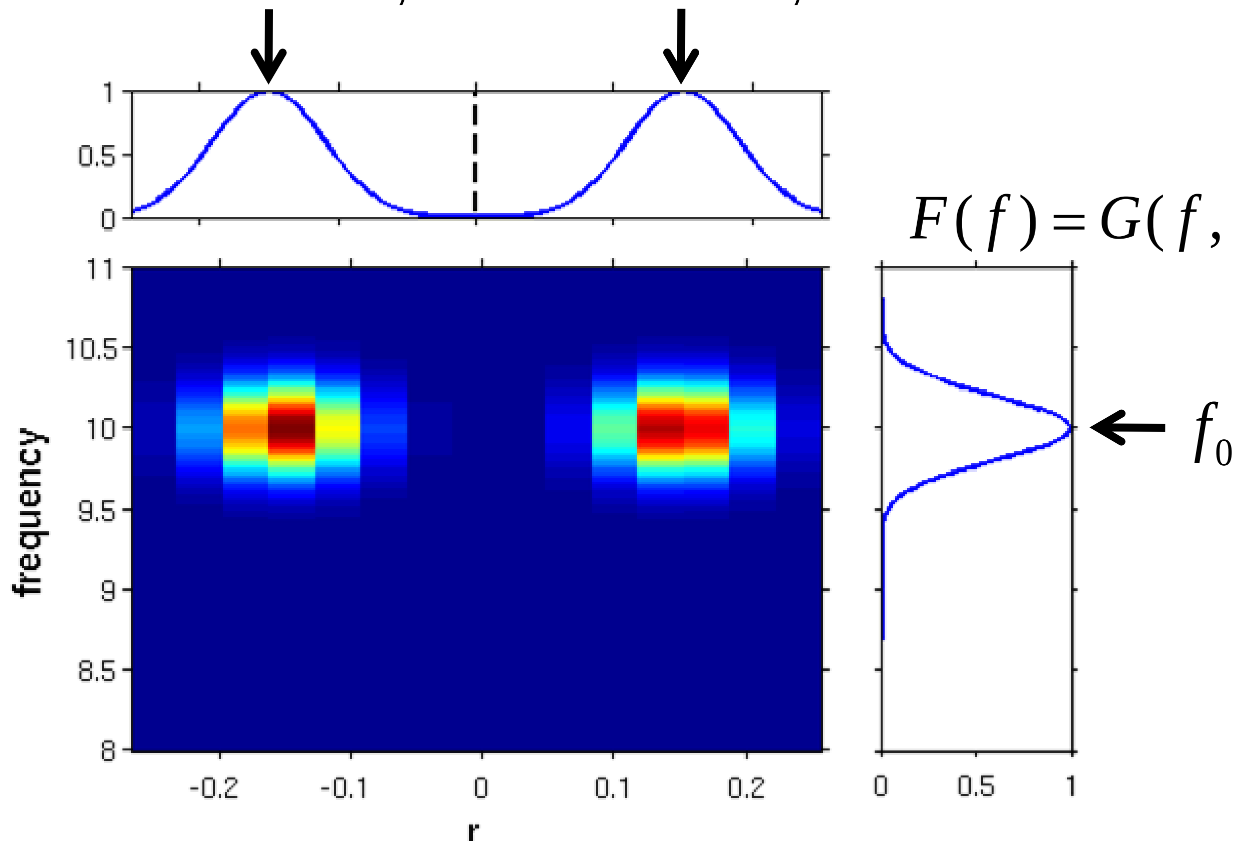
$$R(\rho) = G(\rho, -\rho_0, \sigma_\rho) + G(\rho, +\rho_0, \sigma_\rho)$$

- Where:

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

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

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



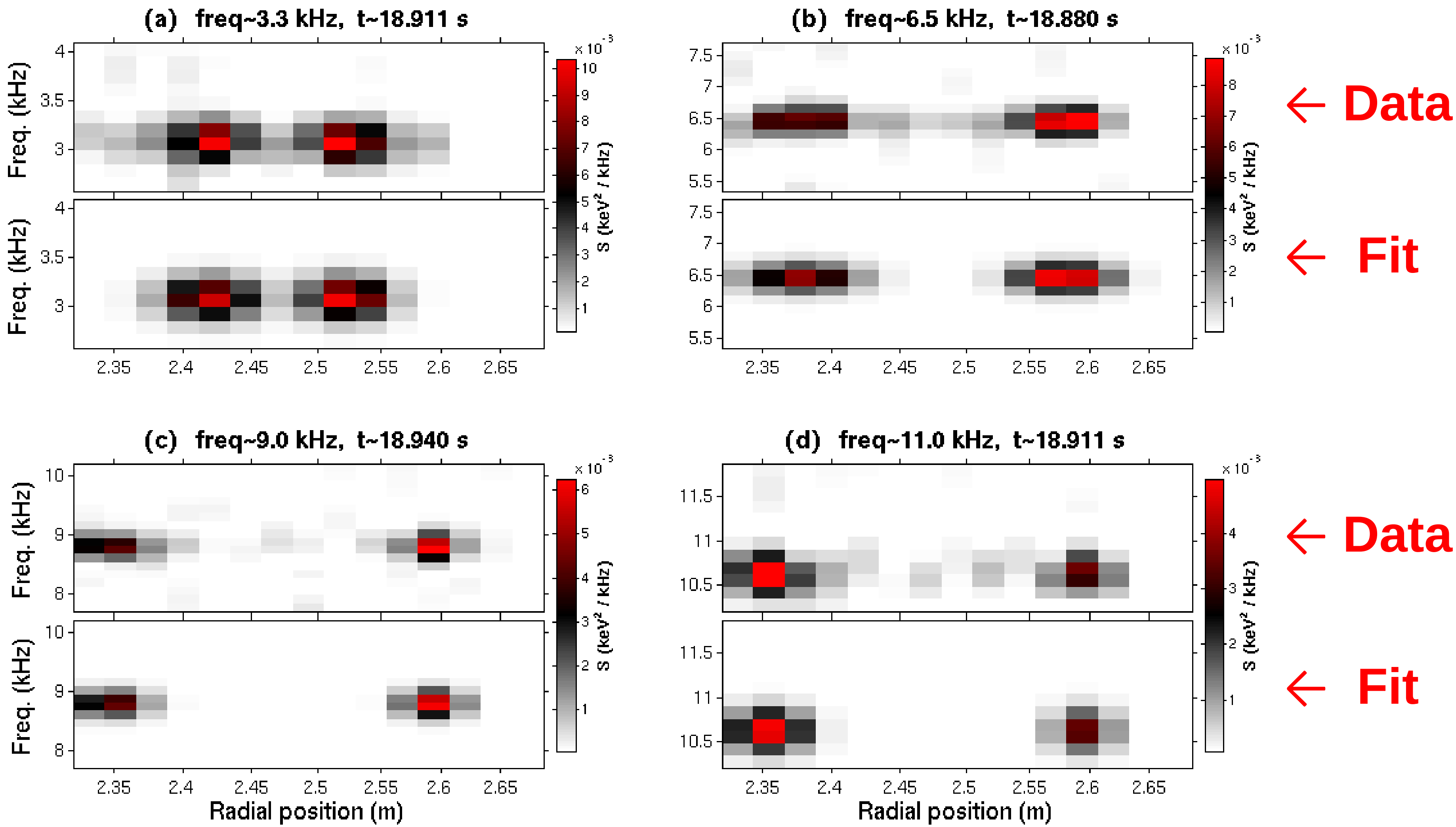
Where:

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

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

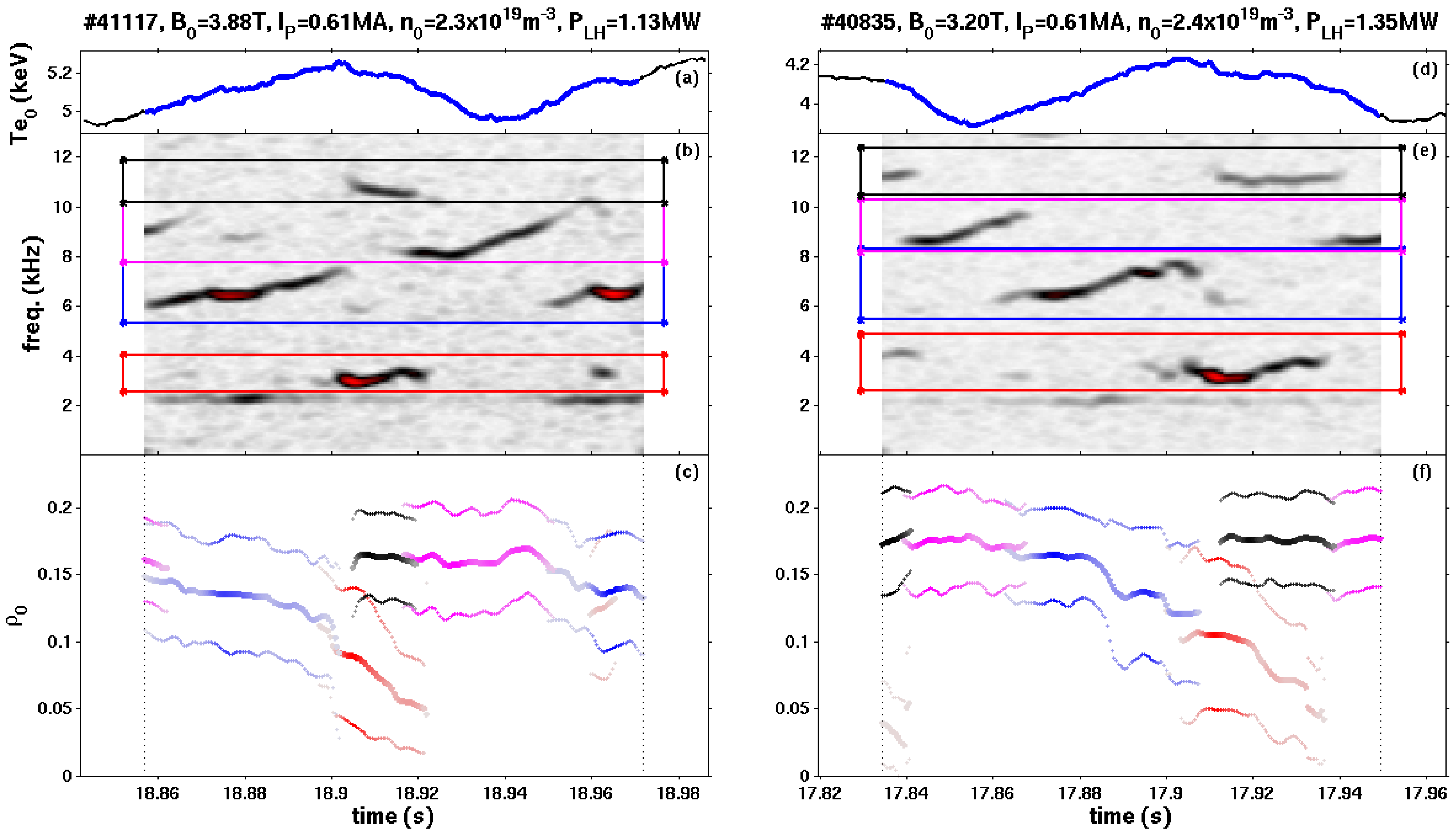
The unknown parameters f_0 , σ_f , ρ_0 , σ_ρ and A can be determined by using Least Square Fits

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

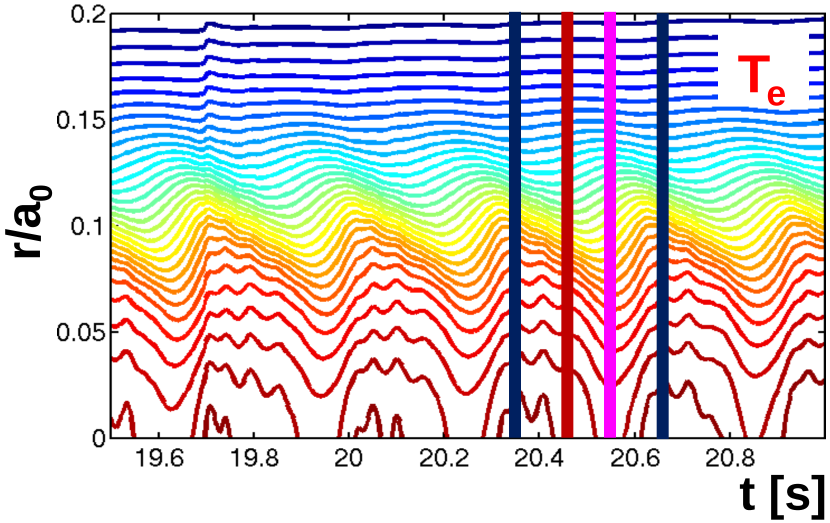
Evolution of the modes radial localization

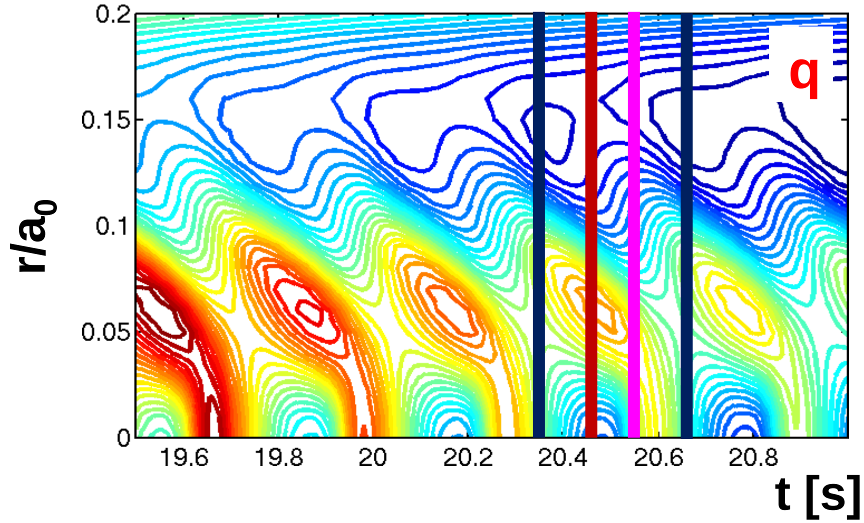


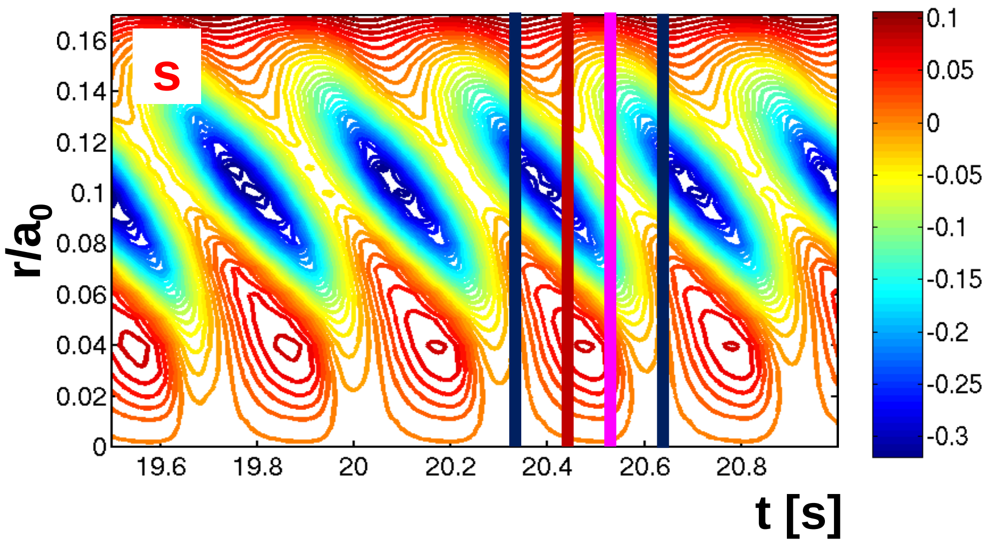
- **Frequency jumps are not linked with abrupt changes on the radial position of the modes**

q-profile evolution during O cycles

[G. Giruzi PRL 2003]







Simulation by CRONOS

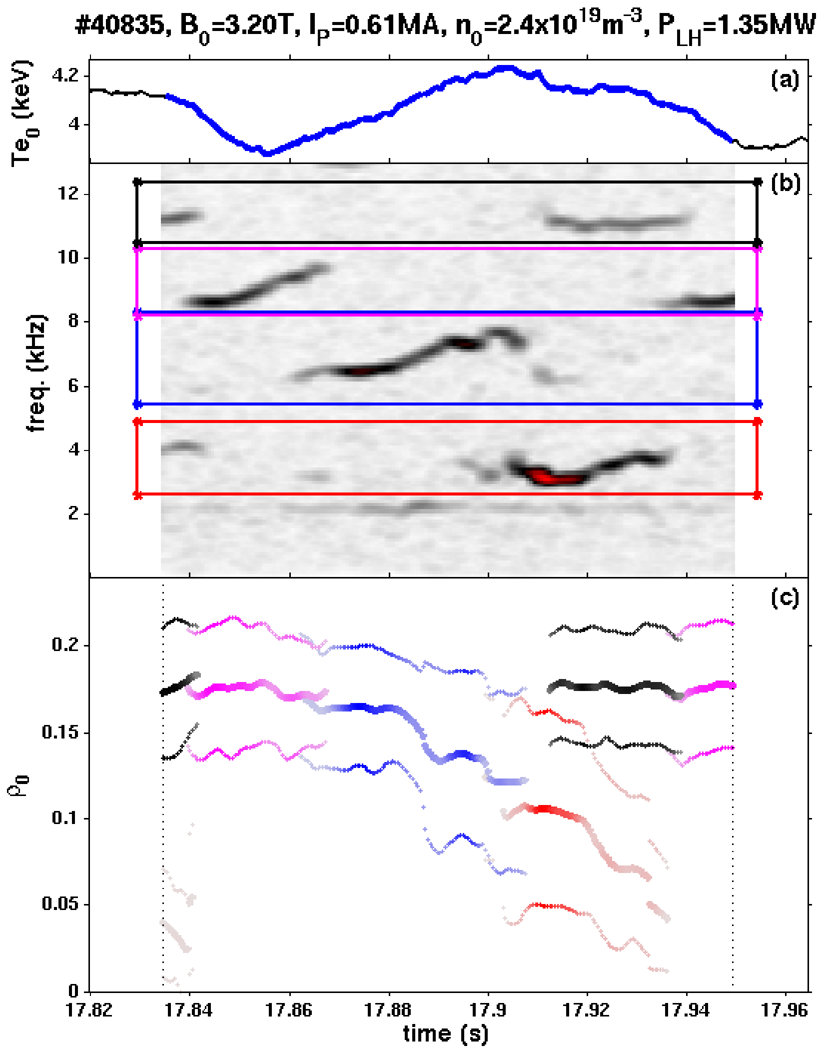
With $j_{LH}(r) \propto j(r)T_e(r)$:

- T_e is the prey
- j is the predator

E-fishbone evolutions

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

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

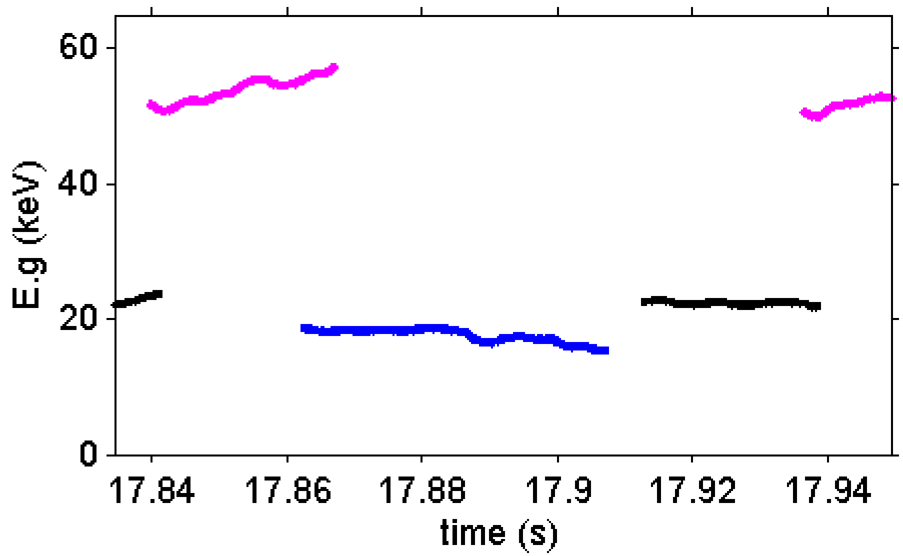


- The continuity in the mode position suggests the following evolution:

11 kHz → 9 kHz → 6 kHz → 3 kHz

From the proposed mode numbers:

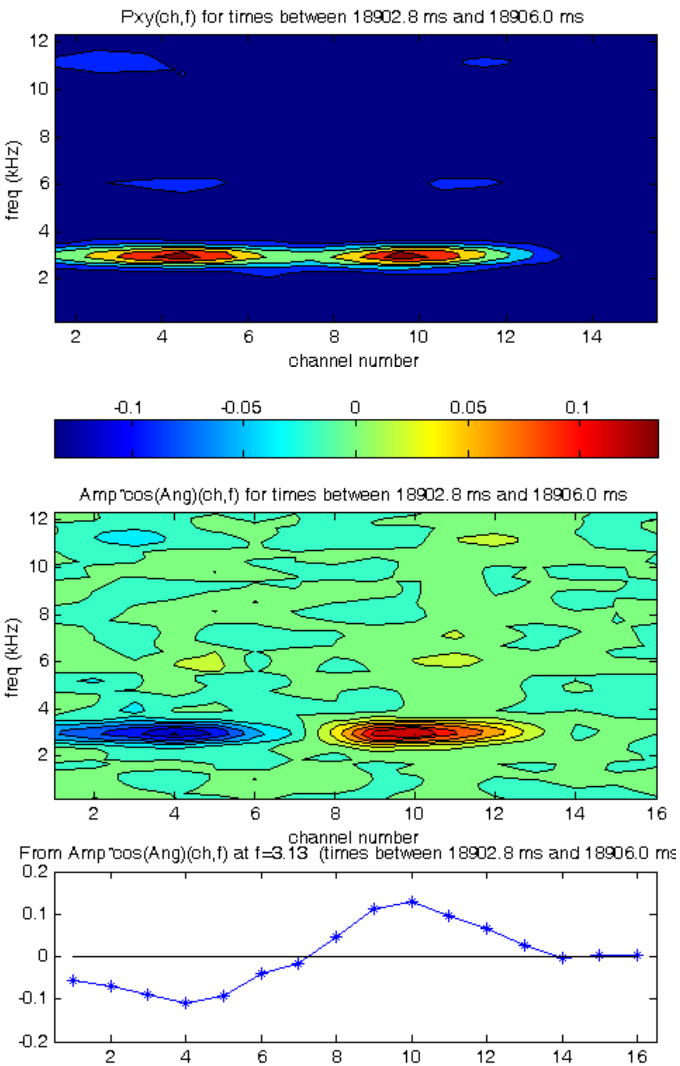
3/3 → 1/1 → 2/2 → ? .



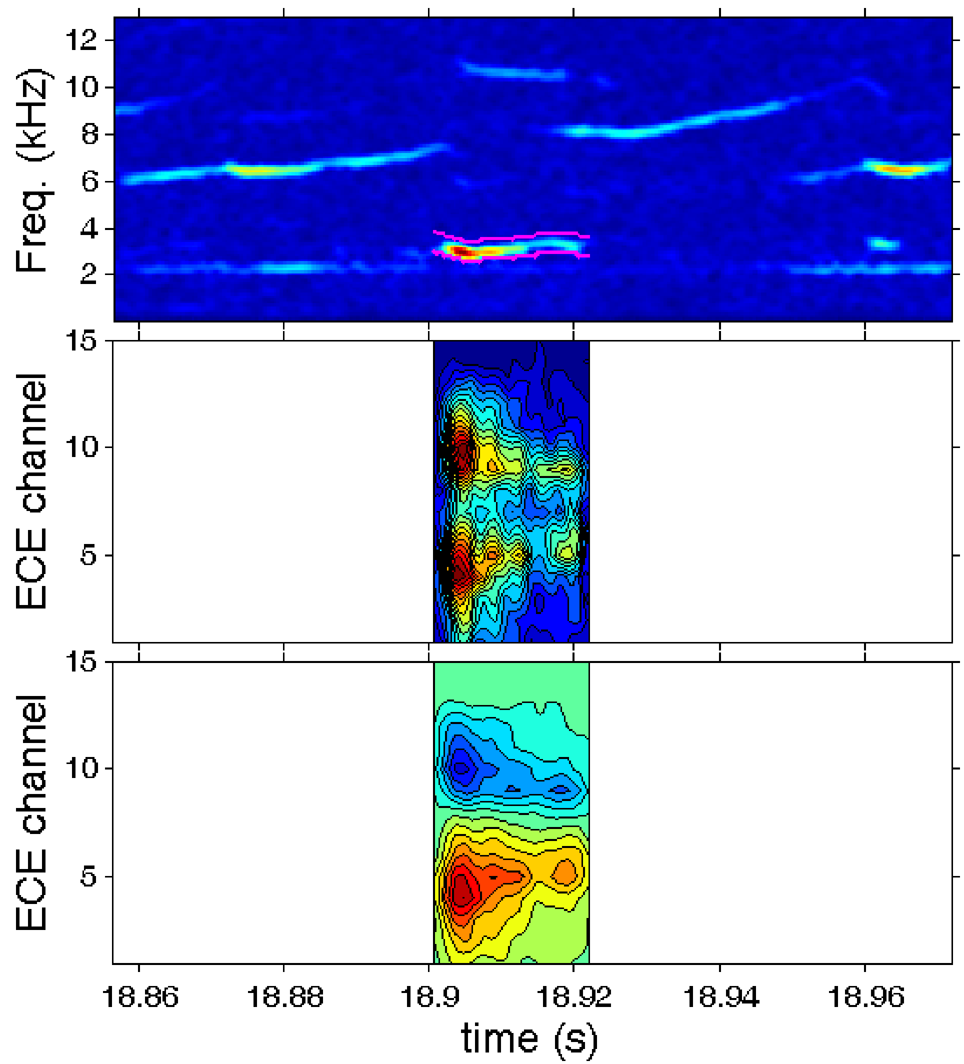
- **Who are the m,n of the 3 kHz mode ?**

Poloidal parity

$$\Delta\Theta_{xy}(f) = \tan^{-1}\left(\frac{imag\left(C_{xy}(f)\right)}{real\left(C_{xy}(f)\right)}\right)$$

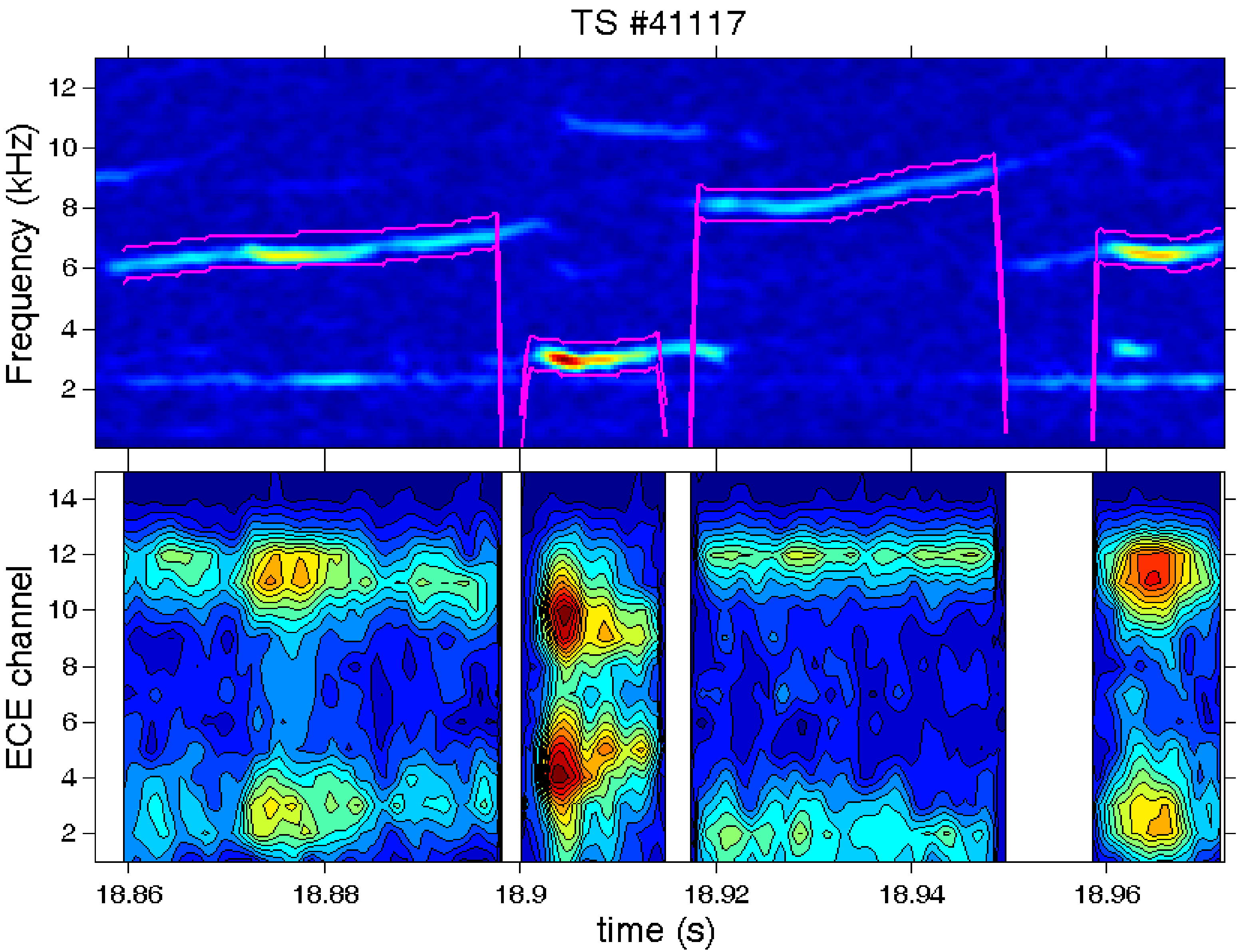


The poloidal parity can be found by the phase between the oscillations in the LFS and LFS



- **Oscillations are out of phase**
  - ➢ **The poloidal parity is odd**

Radial structure of the Te oscillations



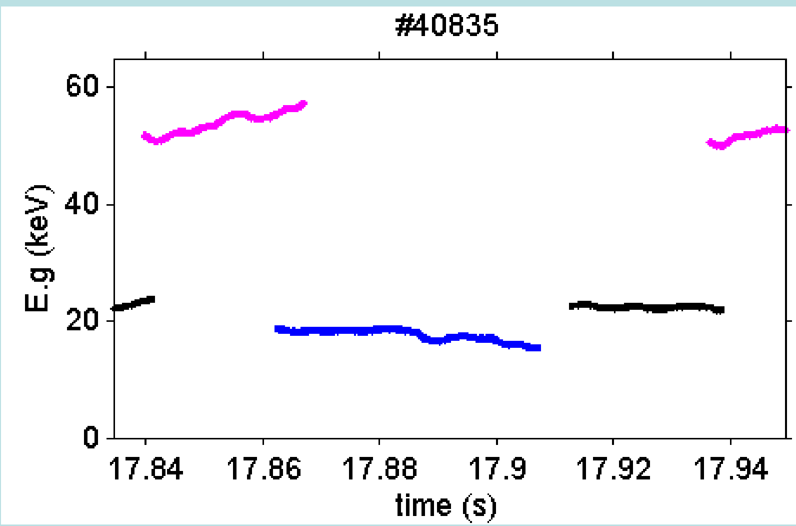
6 kHz (2/2) **3 kHz (odd)** **9 kHz (1/1 ?)** **6 kHz (2/2)**

Consequences of the new mode numbers

- The analysis based on the radial structure of Te oscillations suggests that the **3 kHz** is **1/1**, and the **9 kHz** may be **3/3**. Then, probably the **11 kHz** is **4/4.**

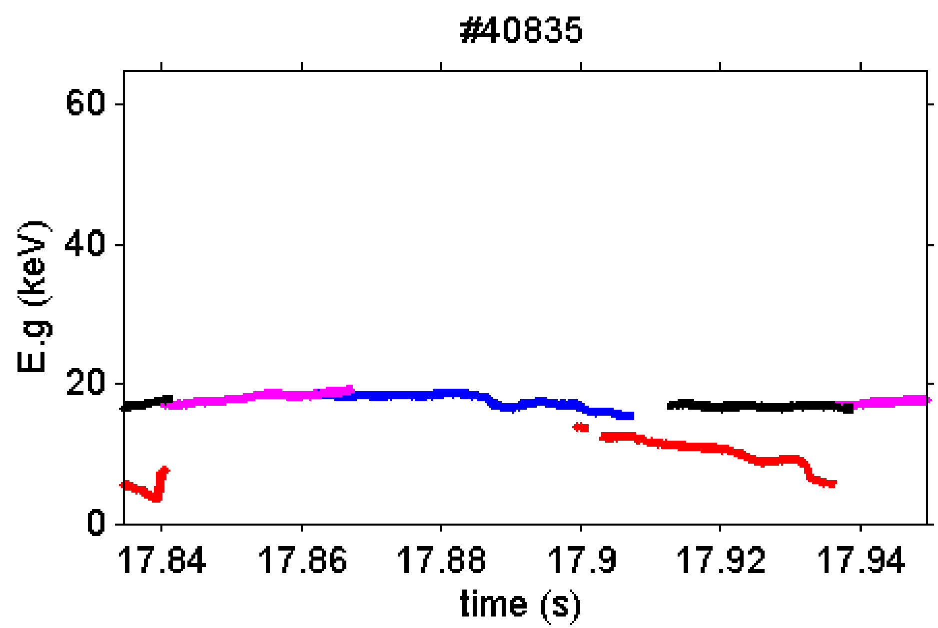
11 kHz → 9 kHz → 6 kHz → 3 kHz

3/3 → 1/1 → 2/2 → ?



11 kHz → 9 kHz → 6 kHz → 3 kHz

4/4 → 3/3 → 2/2 → 1/1



- **Additional experimental data are necessary to check the identification**

e-fishbones in FTU tokamak

IOP Publishing and International Atomic Energy Agency — Nuclear Fusion
Nucl. Fusion **47** (2007) 1588–1597 — doi:10.1088/0029-5515/47/11/022

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 LHCD discharges two behaviors of e-fishbones evolutions were observed according to the LH power**
  - **Almost stead state → Periodic bursting**
- **Evolutions in the energy of the resonant particles were determined by using the LS fit**

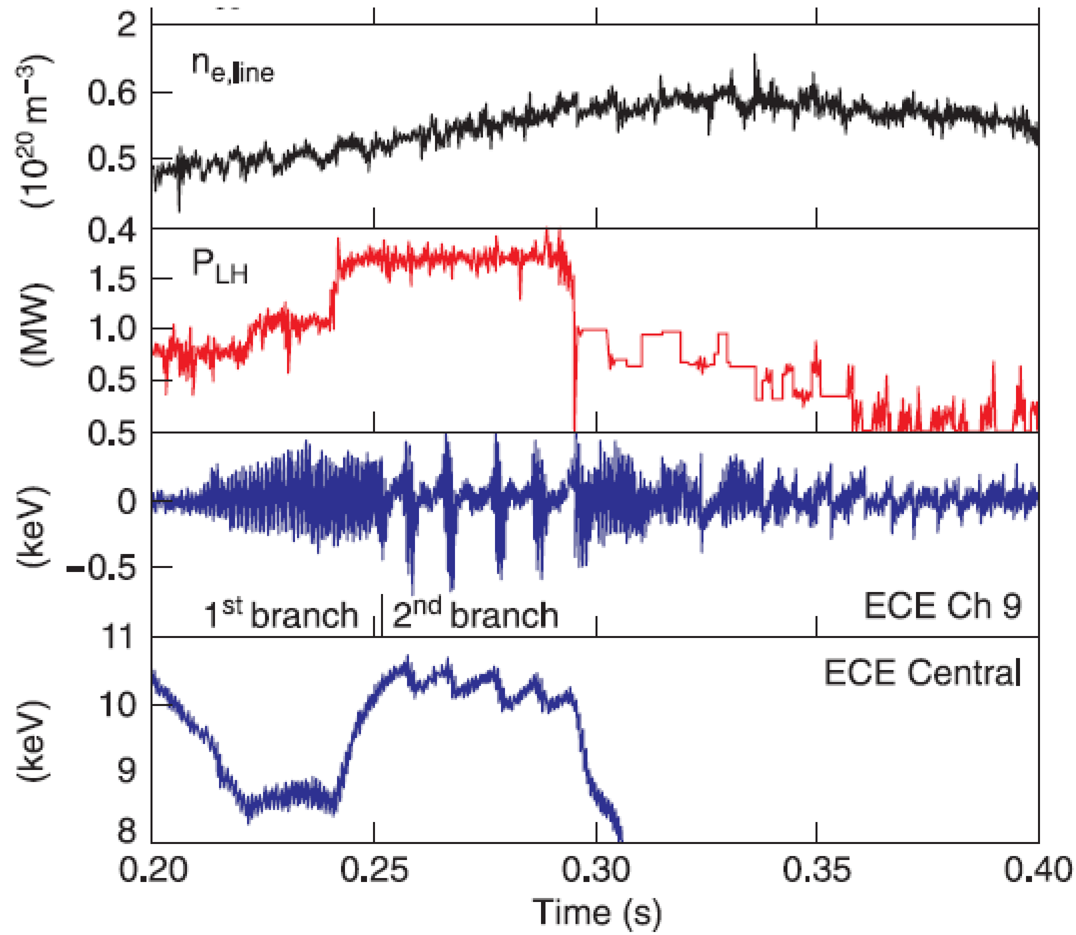
The FTU tokamak (Frascati Tokamak Upgrade):
- Medium size tokamak (R=0.935m, a=0.31m) with circular cross section
- High toroidal magnetic field (B_0 up to 8T)

e-fishbones in FTU tokamak

In LHCD discharges two behaviors were observed according to the LH power:

- An almost steady state (fixed point) at moderated values of LH power (1st branch)
- Regular bursting behavior (limit cycle) at high LH power (2nd branch)

FTU #20865



[F.Zonca, NF 2007]

e-fishbone radial position evolution in FTU

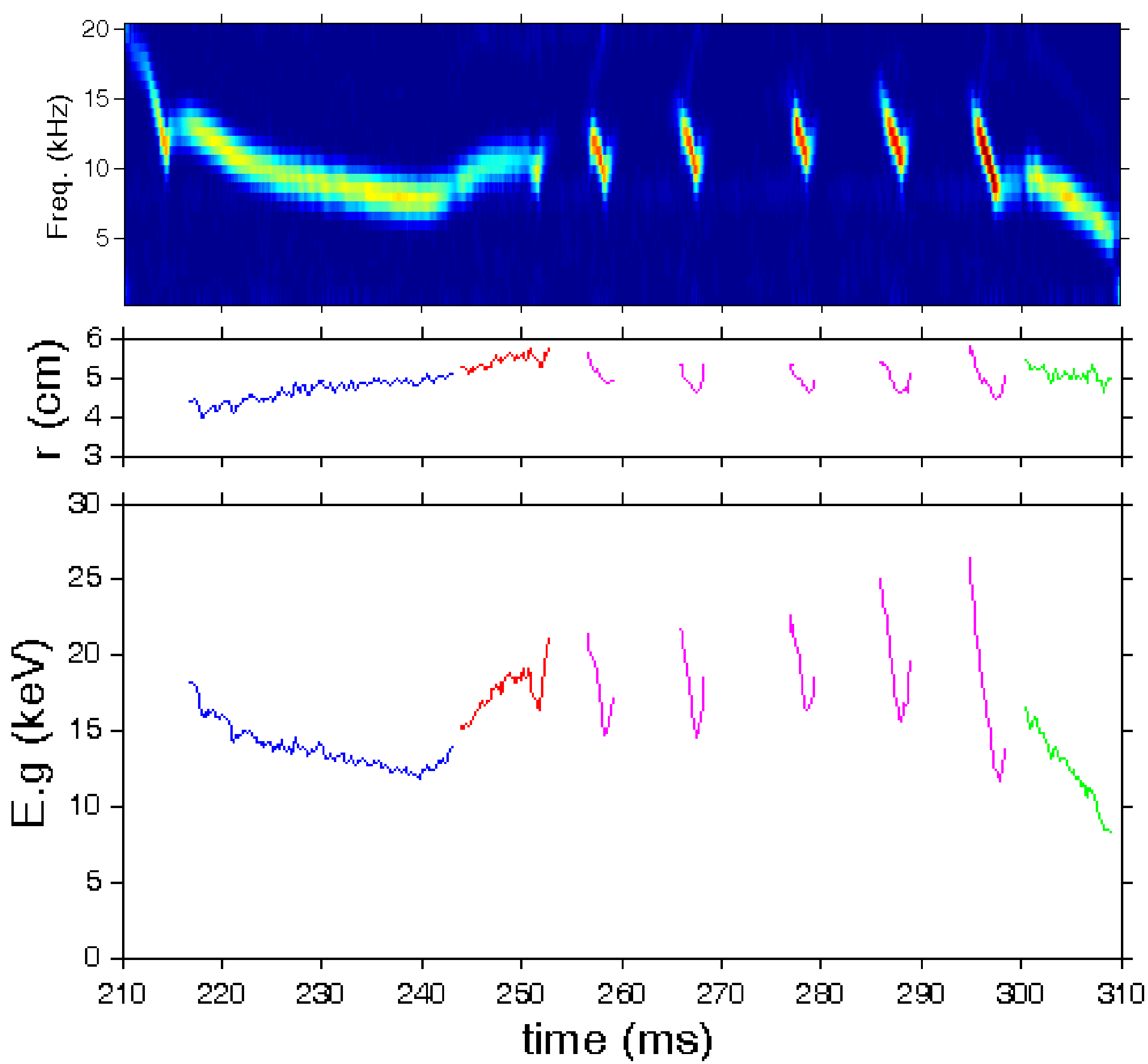
The radial position evolution shows opposite drifts for the two branches

Energy of resonant particles during the regular burst phase varies quickly

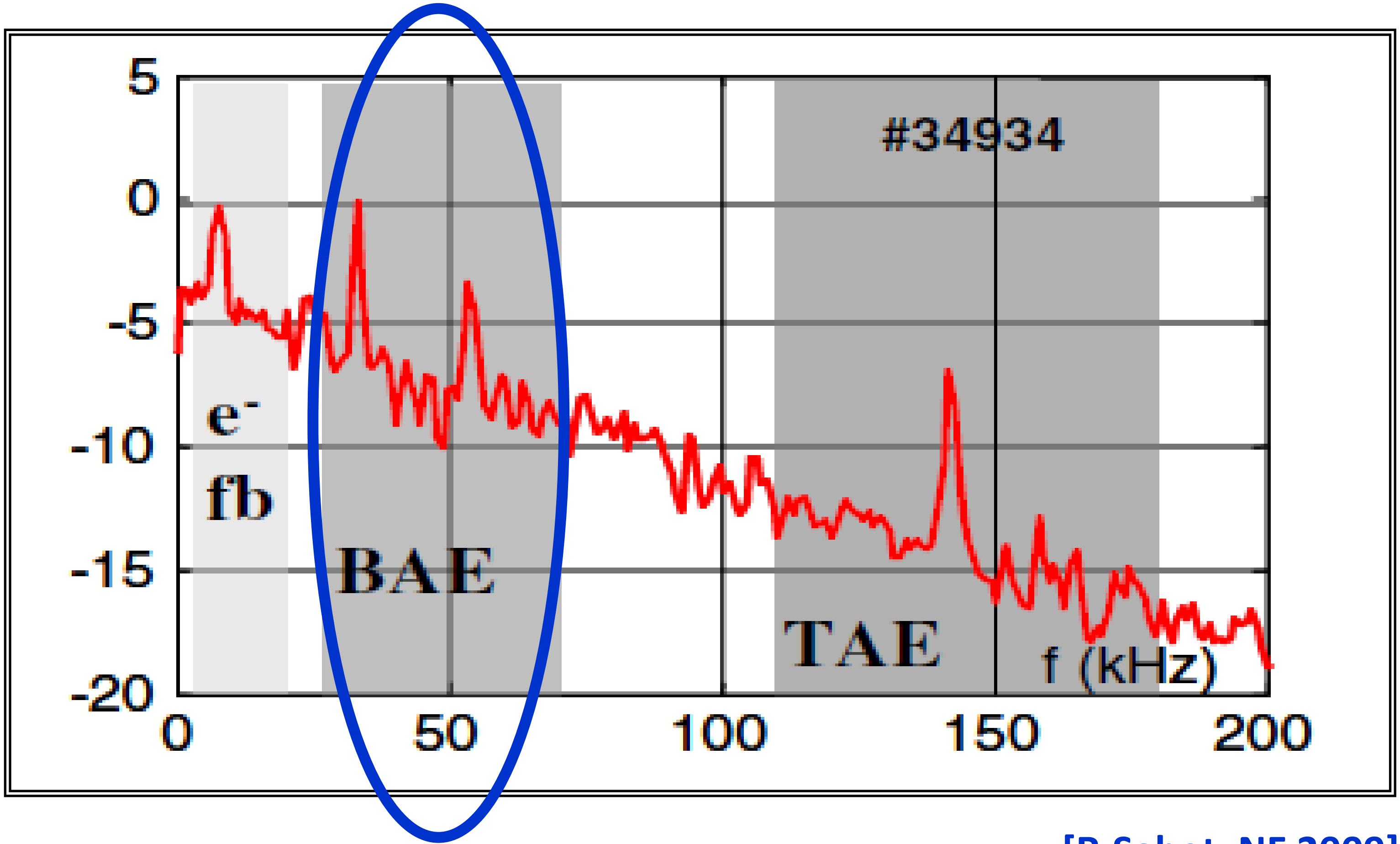
$$E.g_{\lambda} = \frac{f.r}{n.\frac{q}{2.\pi.R_0.B}}$$

Induced fast particle loses may affect the q-profile

FTU #20865



Beta-induced Alfvén Eigenmodes in Tore Supra



[R.Sabot, NF 2009]

IOP PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION
Plasma Phys. Control. Fusion **51** (2009) 095002 (24pp) doi:10.1088/0741-3335/51/9/095002

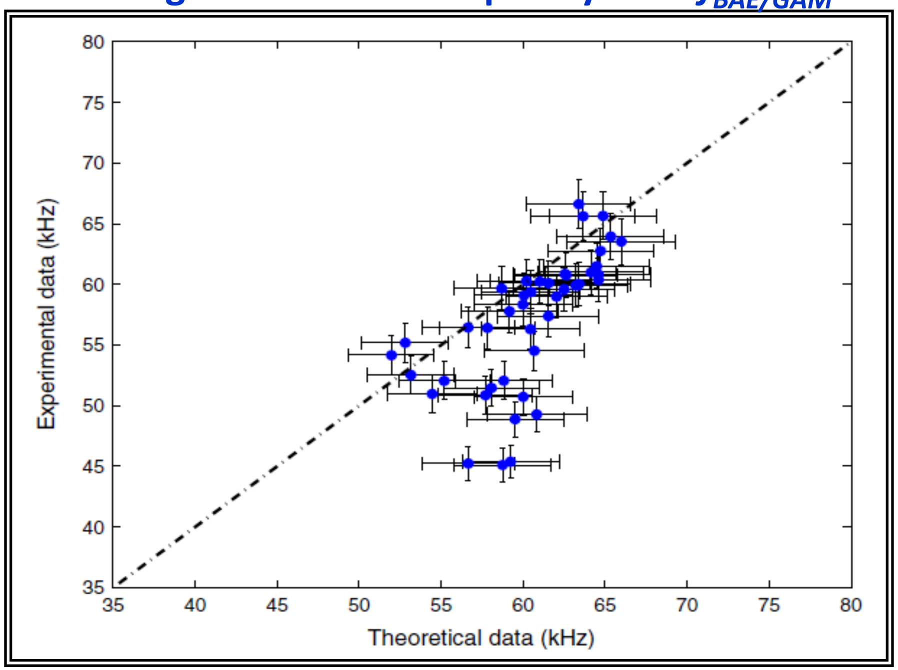
Excitation of beta Alfvén eigenmodes in Tore-Supra

C Nguyen[1], X Garbet[1], R Sabot[1], L-G Eriksson[2], M Goniche[1], P Maget[1], V Basiuk[1], J Decker[1], D Elbèze[1], G T A Huysmans[1], A Macor[1], J-L Ségui[1] and M Schneider[1]

$$f=\frac{1}{2\pi R}\sqrt{\frac{T_i}{m_i}\left(\frac{7}{2}+2\frac{T_e}{T_i}\right)}$$

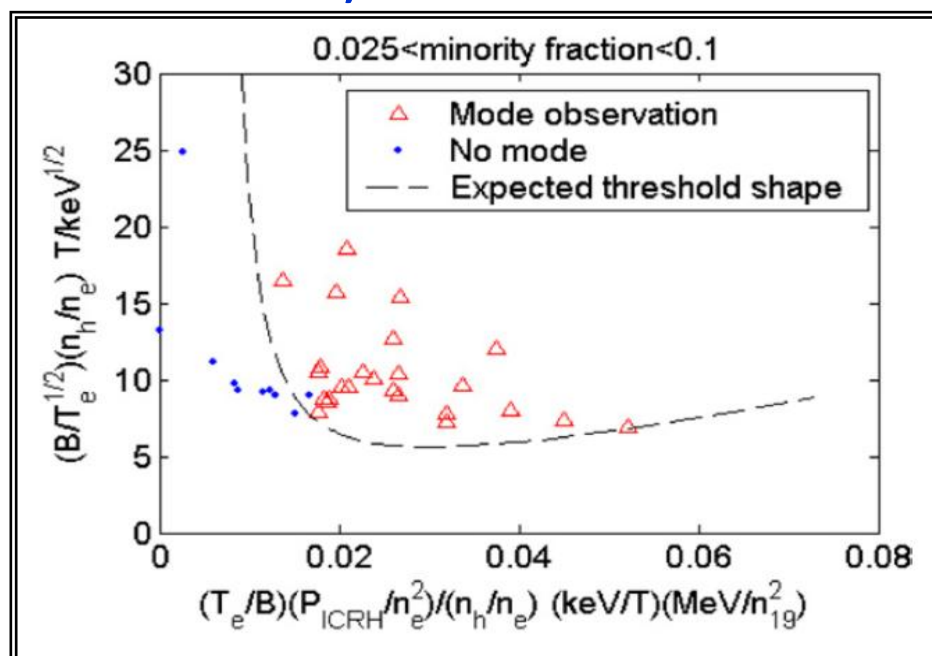
- R Major radius
- m_i main ion mass
- T_i ion temperature
- T_e electron temperature

Scaling of the mode frequency with $f_{BAE/GAM}$



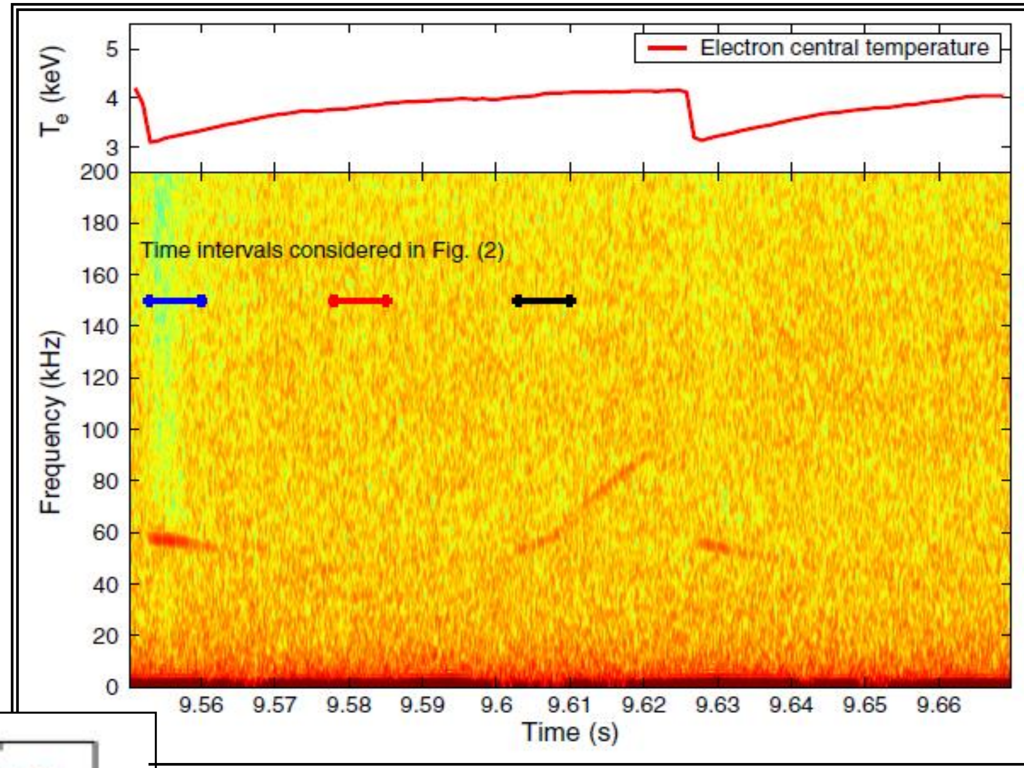
[C.Nguyen, PPCF 2009]

Parametric analysis of the excitation threshold

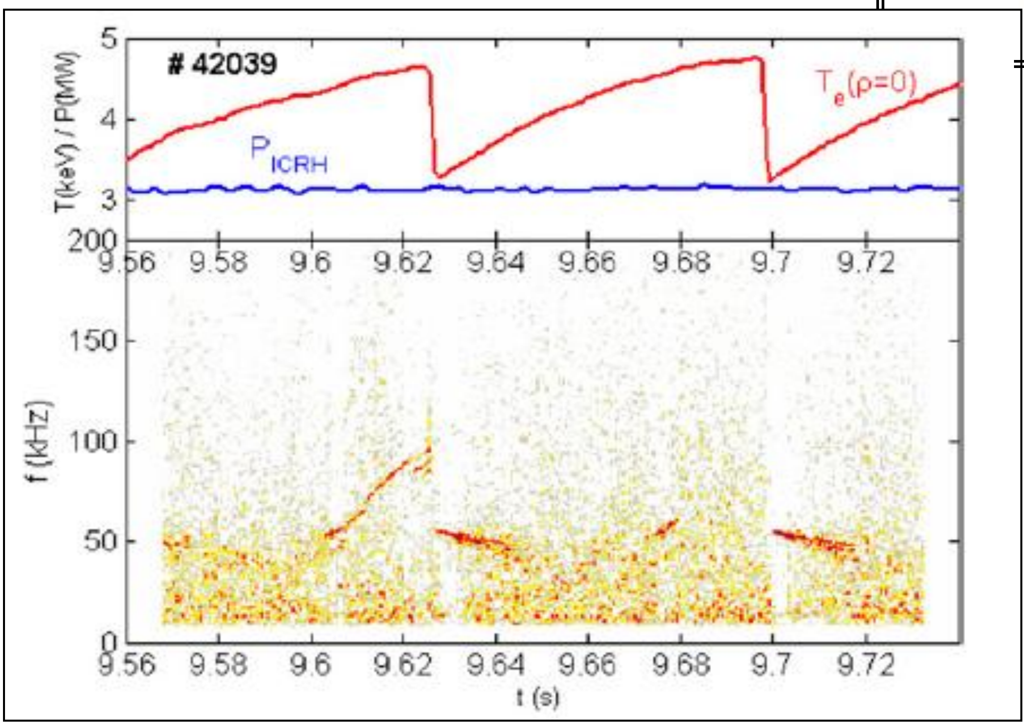


[R.Sabot, NF 2009]

Evidences that the BAE frequency evolves



[C.Nguyen, PPCF 2009]

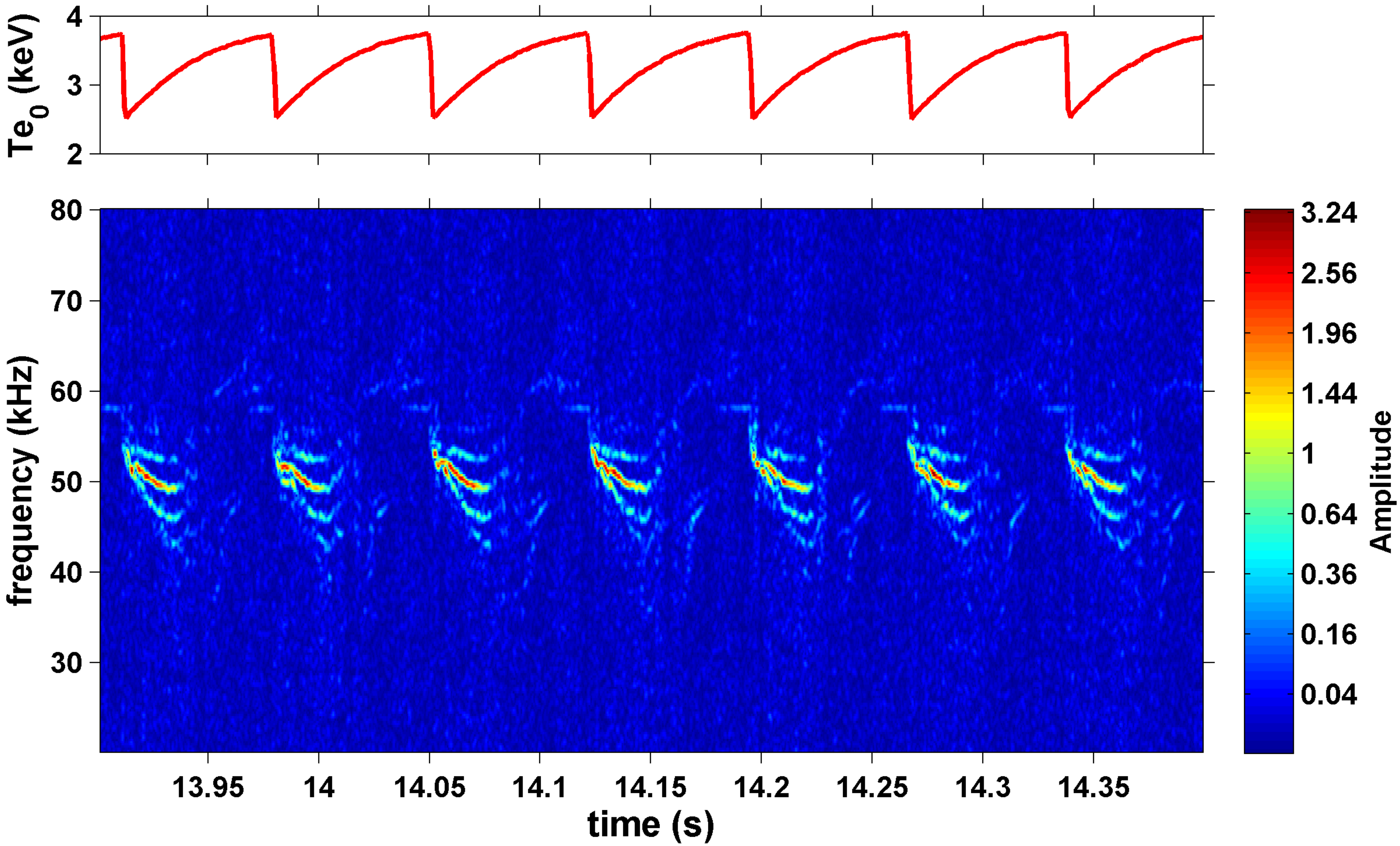


[R.Sabot, NF 2009]

BAEs evolution from correlation spectrogam

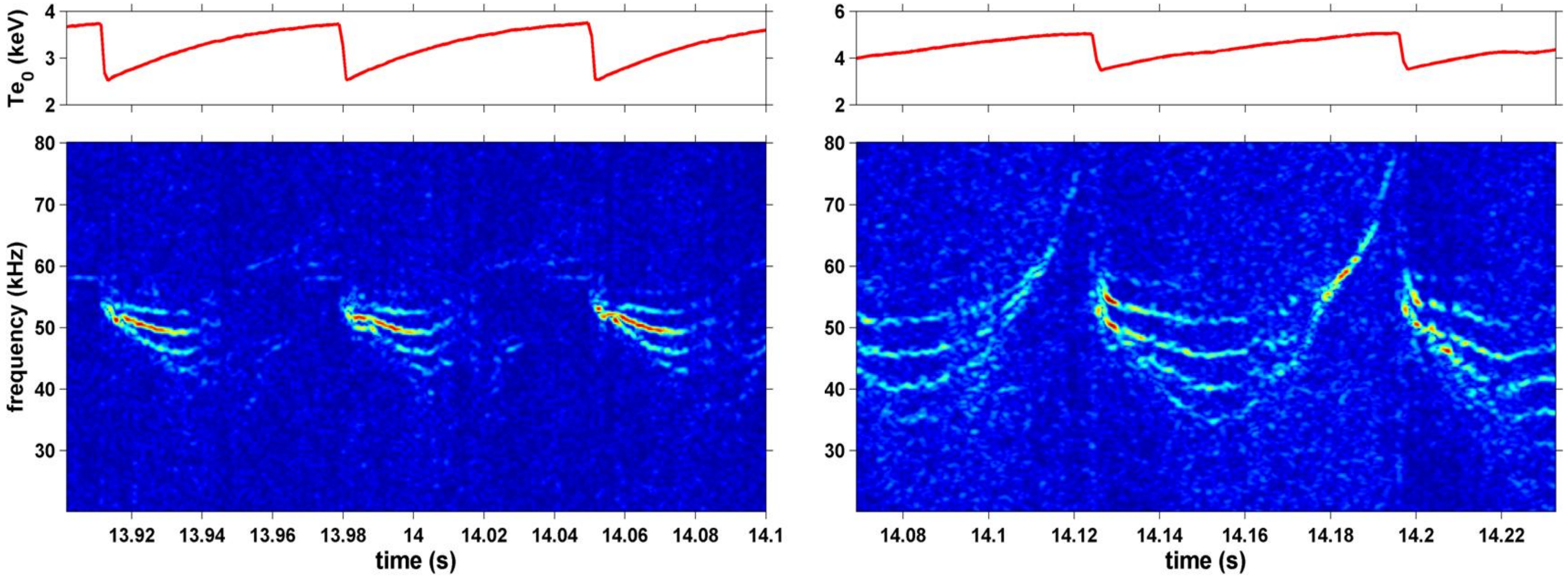
$$S_{xy} = \left| \left\langle W_x(f).W_y^*(f) \right\rangle \right|$$

TS # 41926 $P_{ICRH} = 3.4$ **MW**

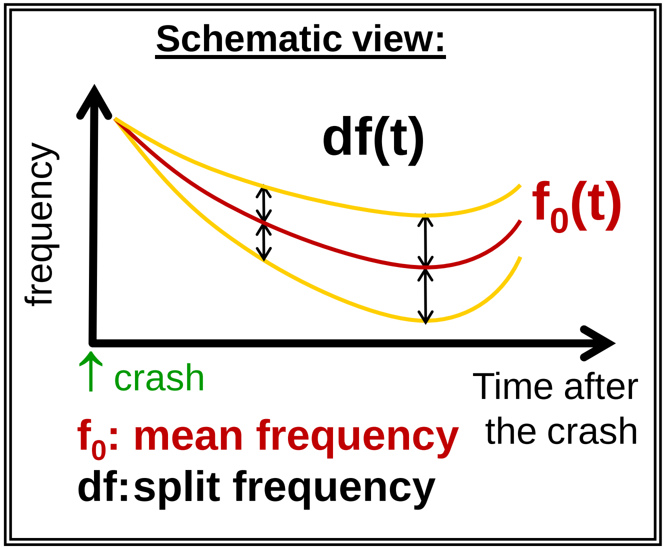


Frequency evolution during sawteeth

#41926 $P_{ICRH} \approx 3.4MW$ #42039 $P_{ICRH} \approx 4.6MW$



- Several modes are present at the same time
- Both the mean frequency and the split frequency are not constant in time
- Evolutions are well correlated with the phase of the sawtooth cycle

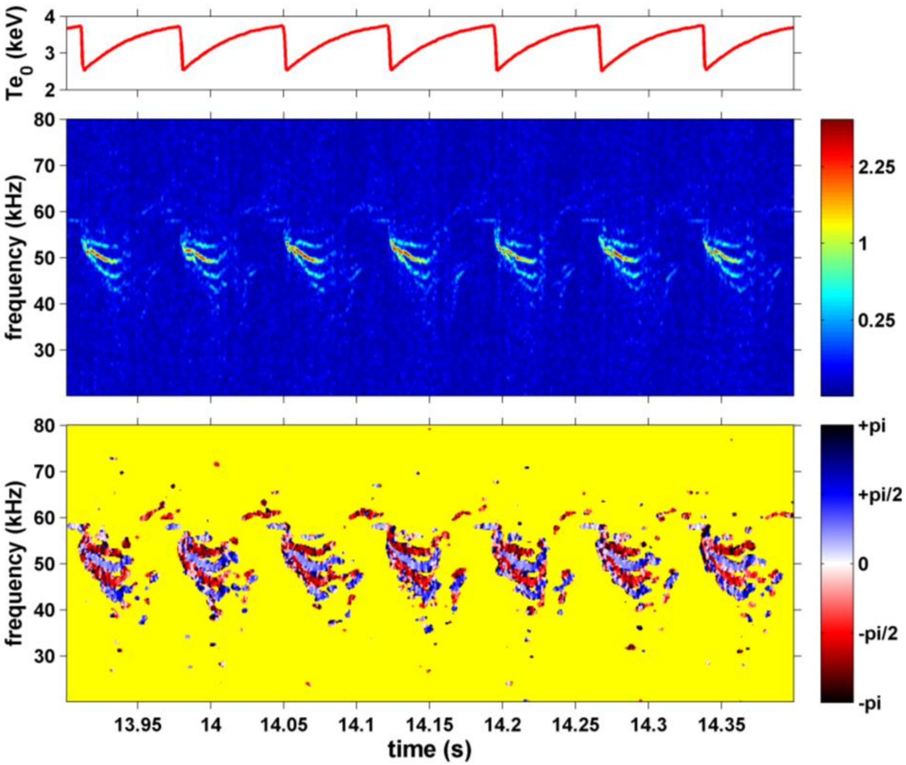


Phase between oscillations in two radial positions

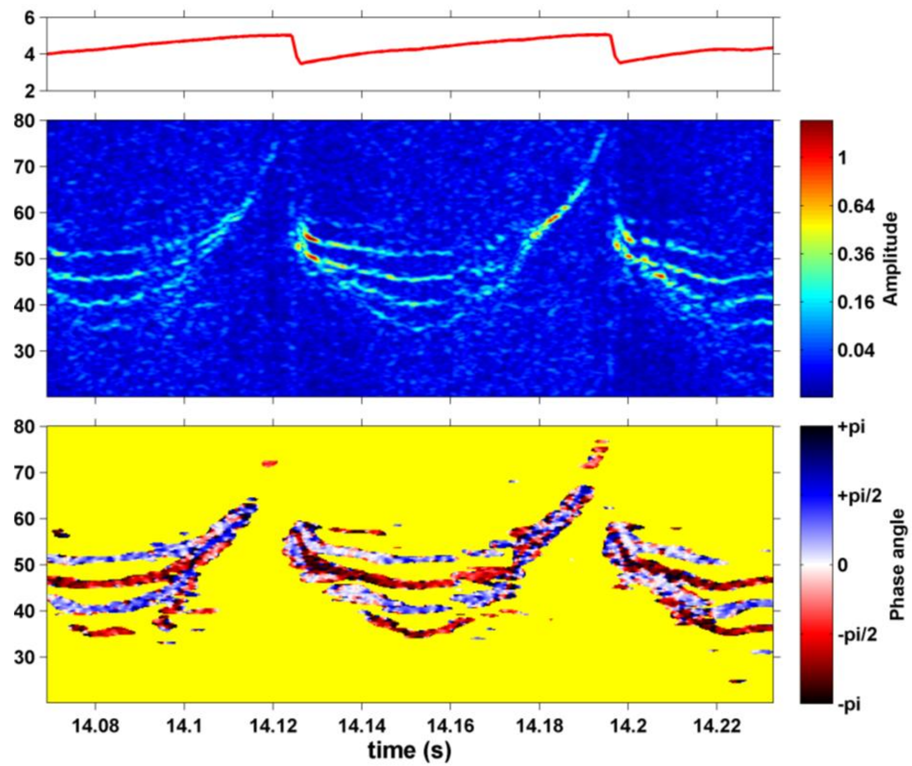
Phase between x and y:

$$\Delta\Theta_{xy}(f) = \tan^{-1}\left(\frac{\mathrm{Im}(S_{xy})}{\mathrm{Re}(S_{xy})}\right)$$

#41926 $P_{ICRH} \approx 3.4MW$



#42039 $P_{ICRH} \approx 4.6MW$

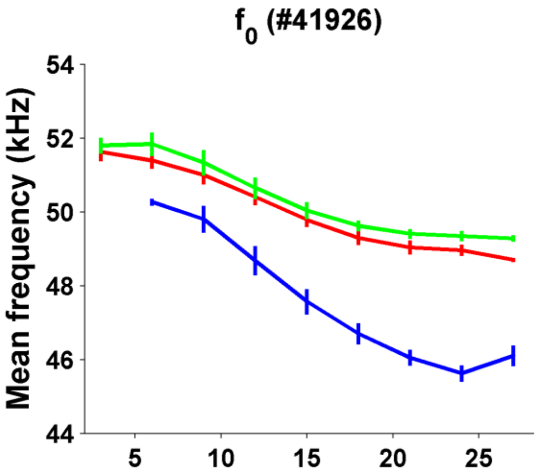


- Phase between adjacent frequencies suggests an alternation of the poloidal parities

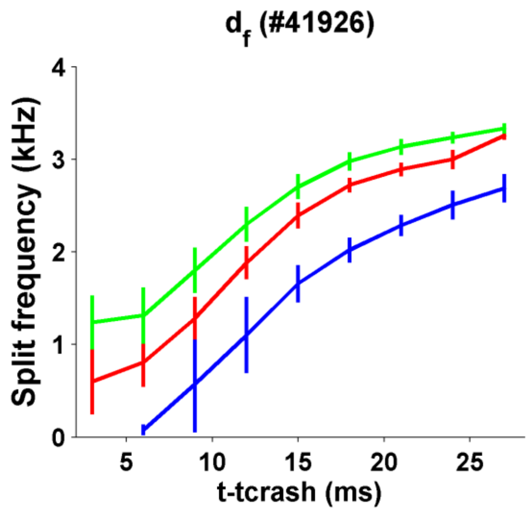
Effect of ICRH power on the mode evolution during the initial phase of the sawteeth cycles

 # 41926:

- **P_{ICRH} = 3.4 MW**
- **P_{ICRH} = 2.8 MW**
- **P_{ICRH} = 2.1 MW**



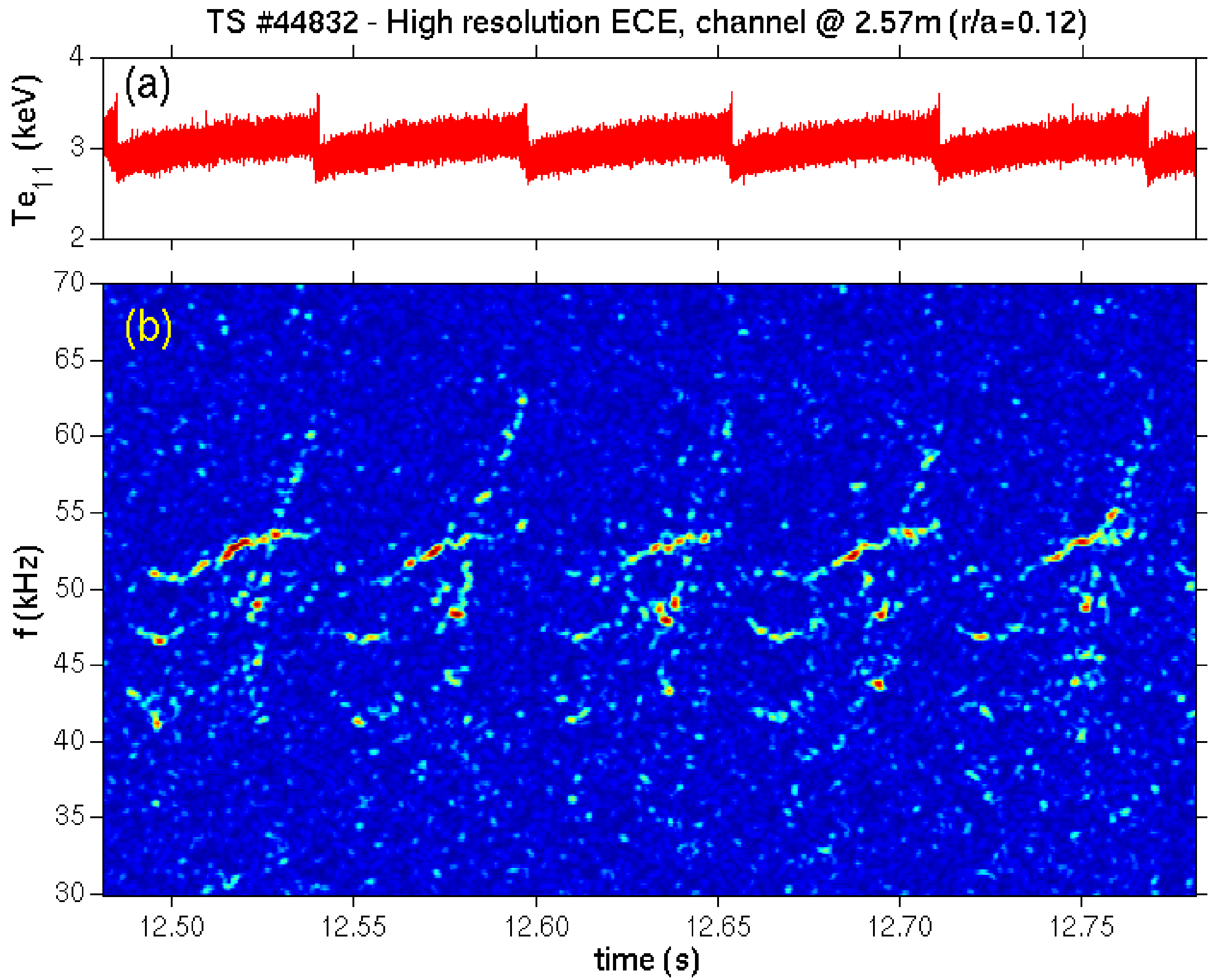
- Both the mean frequency and the split frequency increase with the ICRH power
    - Modes are not harmonics of a basic frequency
- The mean frequency decreases while the acoustic and the plasma rotation frequencies increase ($T_{e,i}$ inside q=1 increase after the crash)



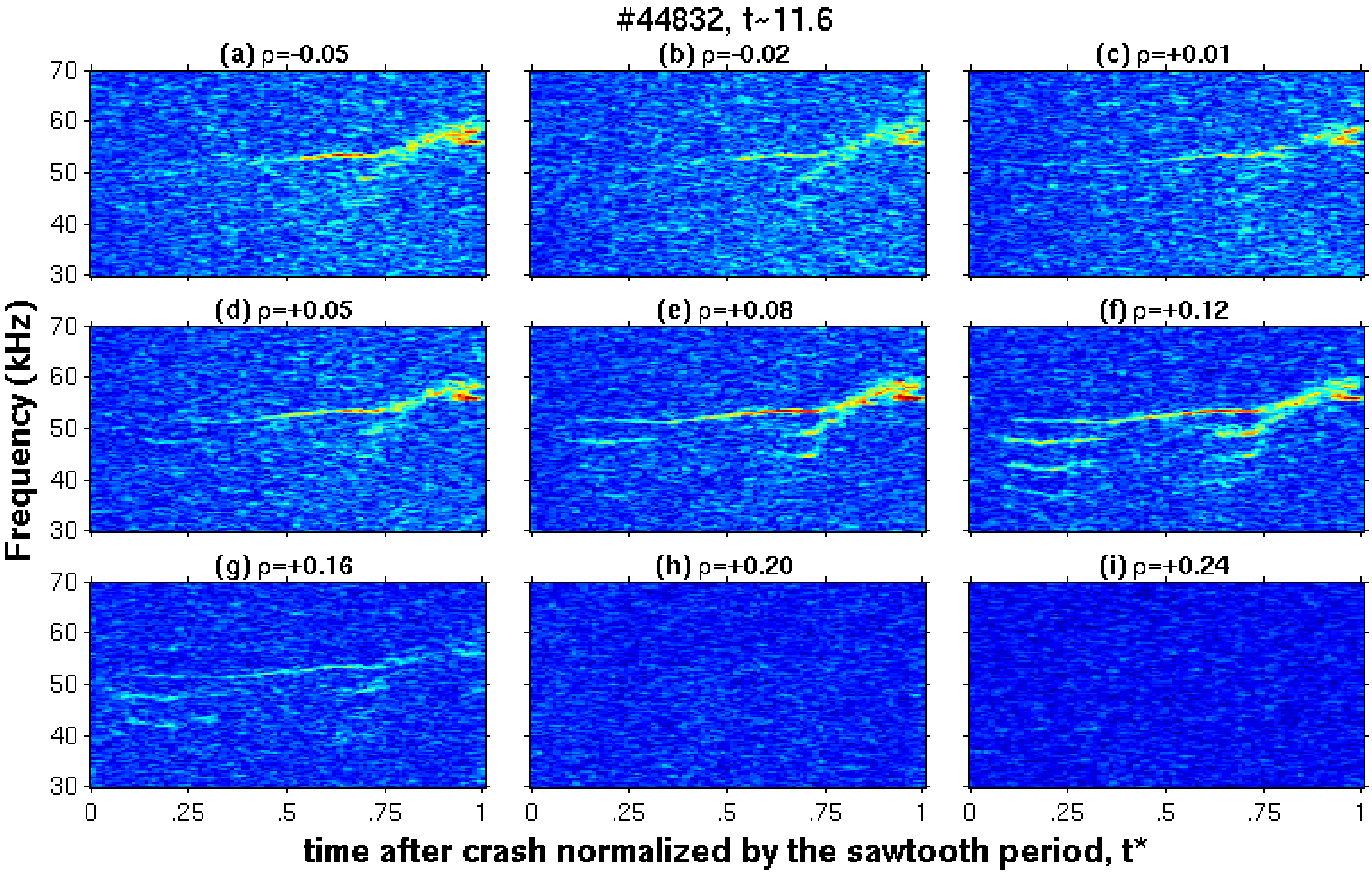
BAE – Mode localization

- The mode localization must be determined by profile measurements: **ECE** diagnostic
- However, ECE is much less sensitive than the reflectometer
- Use of **coherent addition** during several sawteeth to improve the signal to the noise ratio

Temperature evolution and spectrogram from fast ECE



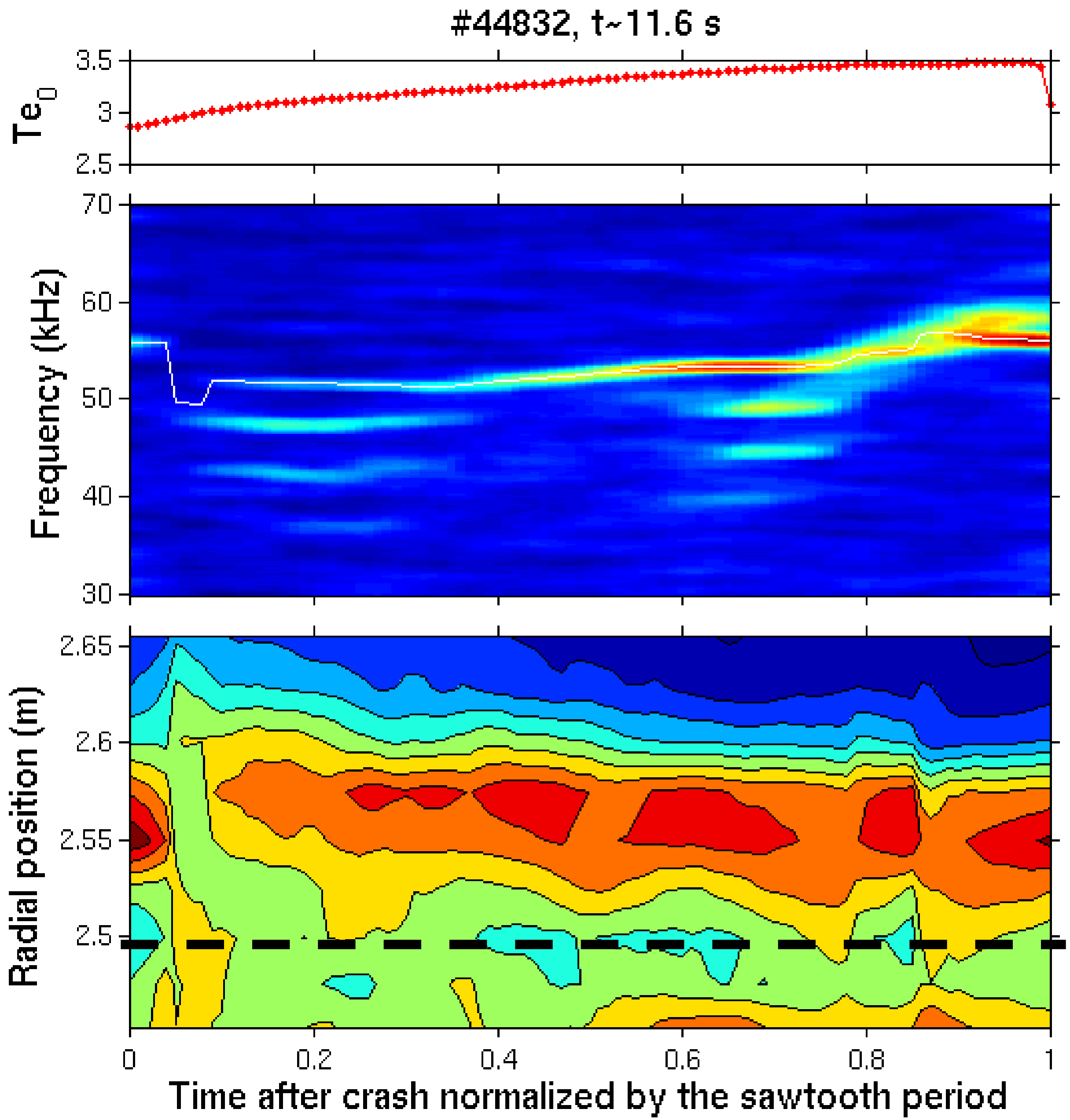
BAE – Spectrograms of Te fluctuations
(after coherent addition)



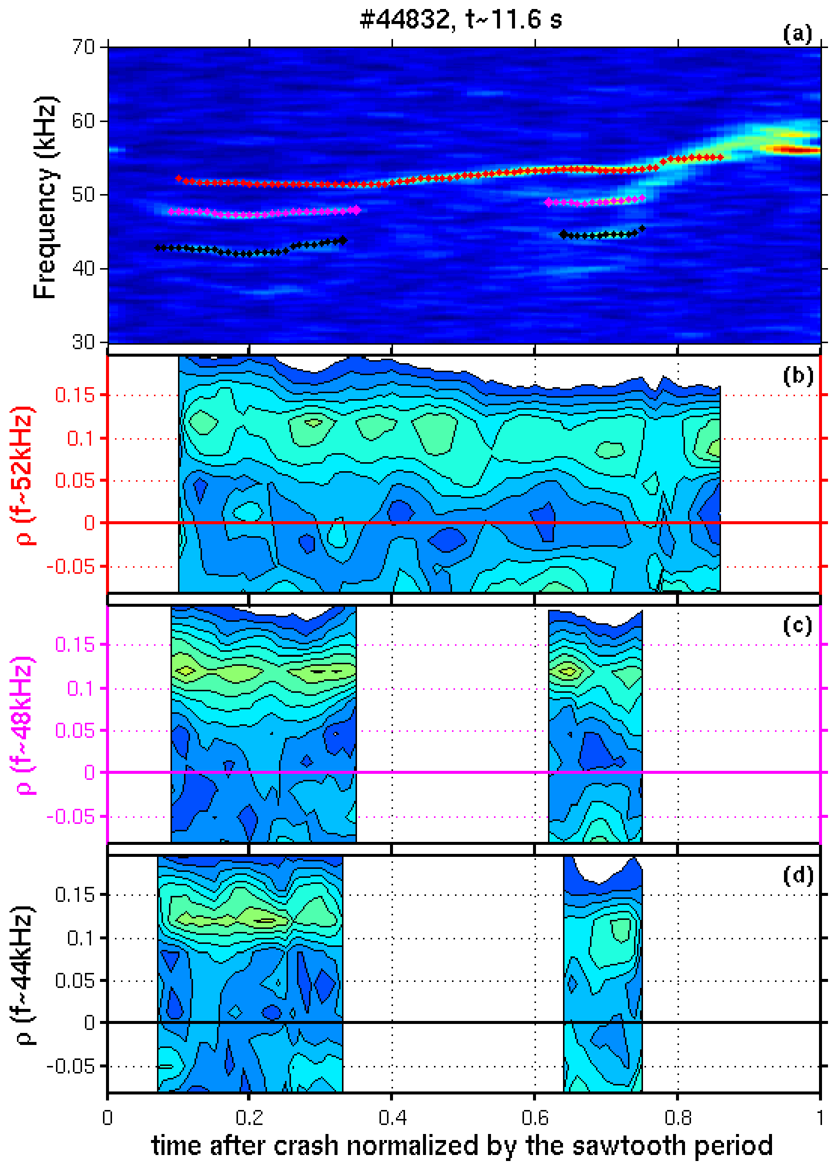
#44832: B_0=3.9T, I_P=0.6MA, n_0=4.5.$10^{19}$$m^{-3}$, P_{ICRH}=6MW

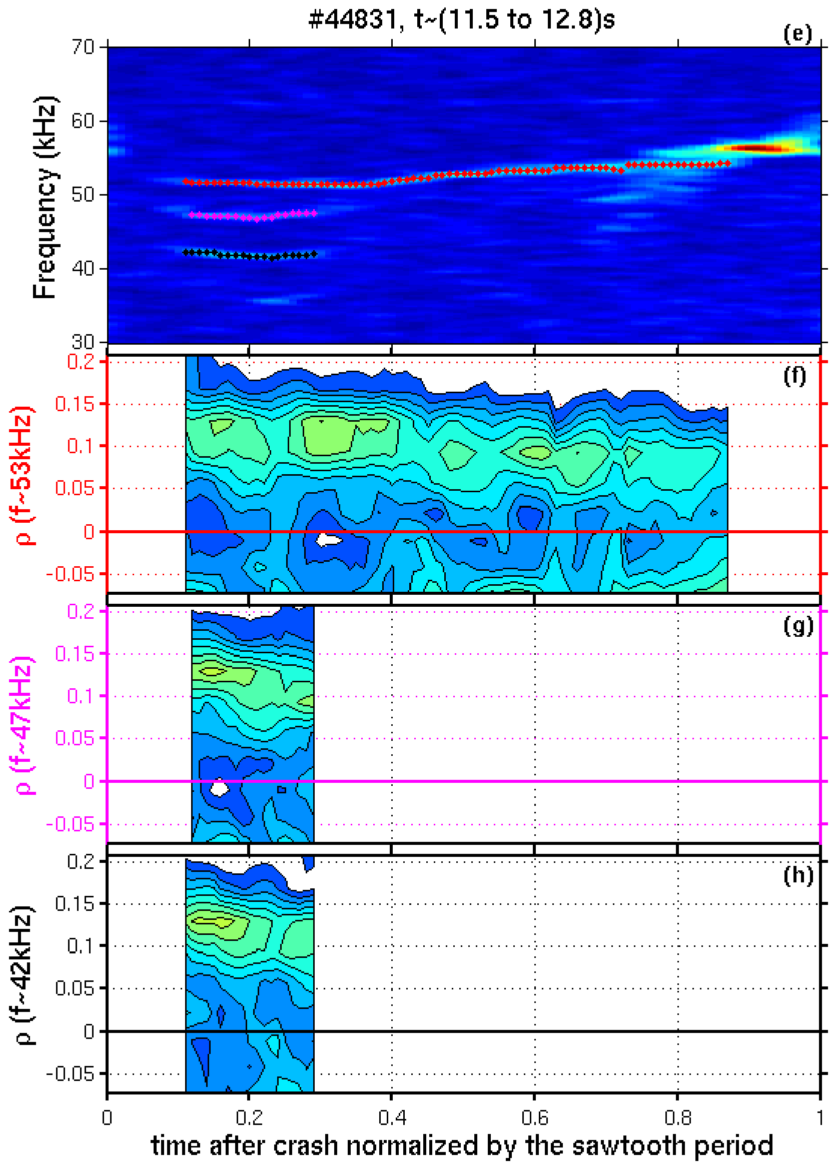
BAE – Evolution of the radial profile

- Oscillations slowly drift toward to the center during the sawtooth cycle



Evolution of the radial position of the modes



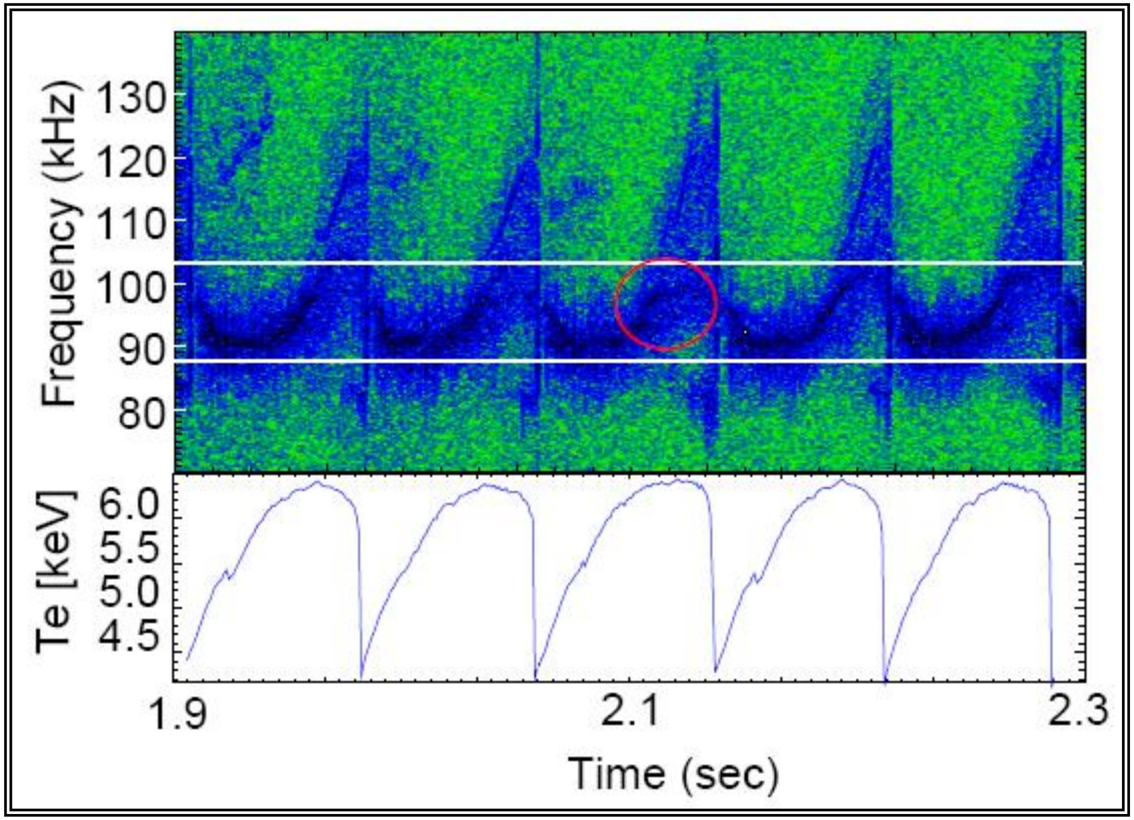


#44832: B_0=3.9T, I_P=0.6MA, P_{ICRH}=6.0MW

#44831: B_0=3.9T, I_P=0.6MA, P_{ICRH}=5.5MW

BAEs - Relationship with results obtained in other tokamaks – ASDEX-Up

- The evolution of the main frequency correlated with the sawtooth cycle was also observed in **ASDEX-Up**
- This evolution was explained by diamagnetic effects on the BAE dispersion relation
- The fast increase at the final part of the cycle was identified as RSAE

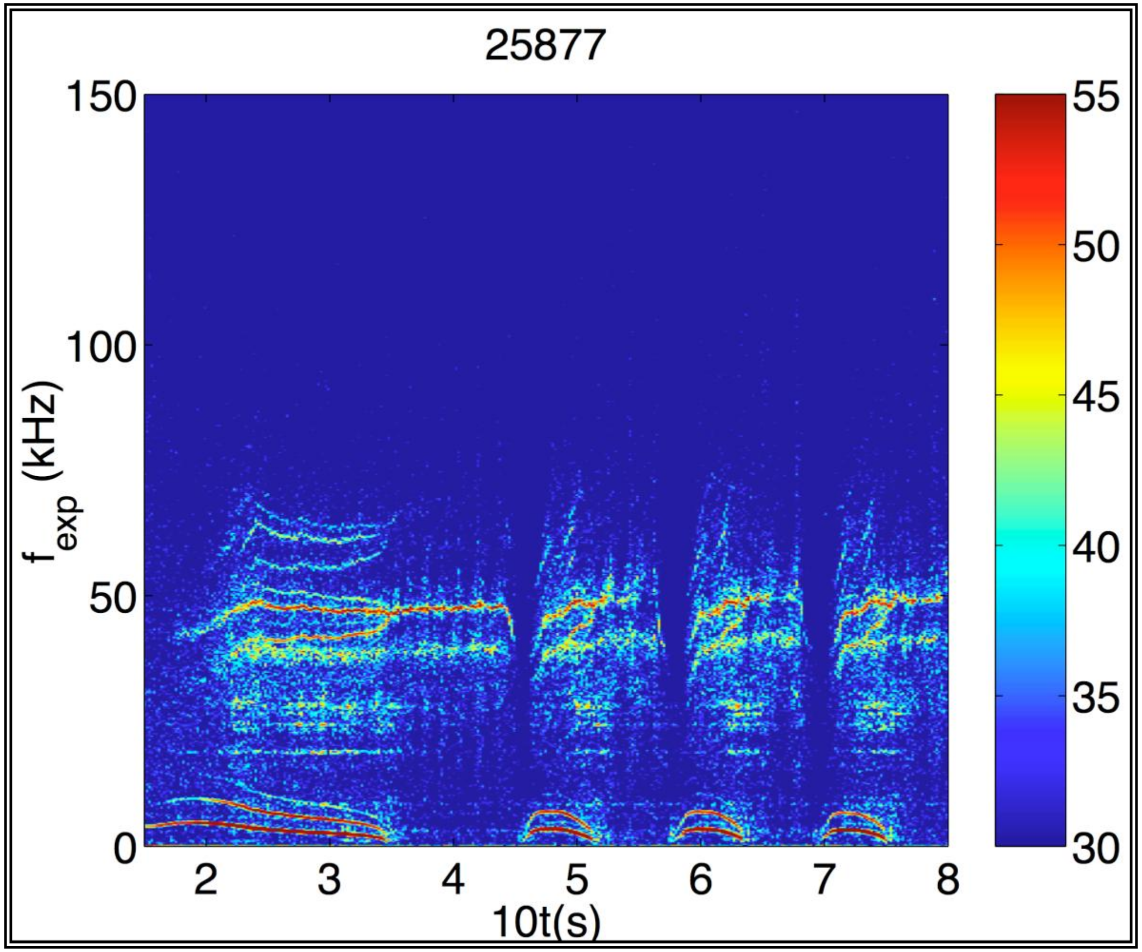


[P.Lauber, PPCF 2009]

BAEs - Relationship with results obtained in other tokamaks – FTU

- In FTU Ohmic discharges with large Magnetic Islands BAE modes were observed in pairs whose split is correlated with the island rotation frequency
- The split frequency is twice the island rotation frequency

A.Botrugno poster (P.4)



[A.A.Tuccillo, IAEA-FEC 2008]

Summary

- Spectral methods are an useful tool to characterize MHD instabilities and to determine their evolution
- The e-fishbones and BAEs examples illustrate how properties of the modes can be pointed out by using advanced spectral methods
  [Z.Guimarães-Filho, PPCF 2011]
- Detailed experimental characterizations can be used to benchmark theoretical models, helping to improve the reliability to make predictions for ITER

Thank you for your attention