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Electron fishbones in FTU and Tore Supra tokamaks

Z.O. Guimarães-Filho¹, S. Benkadda¹, D. Elbeze², A. Botrugno³, P. Buratti³, G. Calabrò³, J. Decker², N. Dubuit¹, X. Garbet², P. Maget², A. Merle², G. Pucella³, R. Sabot², A.A. Tuccillo³ and F. Zonca³

¹ CNRS/Aix-Marseille Univ., IIFS-PIIM, UMR 7345, F-13397 Marseille, France
² CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
³ Associazione Euratom-ENEA sulla Fusione, I-00044 Frascati, Roma, Italy

E-mail: zwinglio-oliveira.guimaraesfilho@univ-amu.fr

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Abstract

This work presents a comparative study of the experimental observation of MHD instabilities identified as electron fishbone-like modes that appear in plasmas with lower hybrid current drive in FTU and Tore Supra tokamaks. Initially, the mode-induced electronic temperature oscillations measured by electron cyclotron emission were used to study the evolutions of the frequency and position of these modes. In FTU, where fishbones with and without bursting behaviour are observed, it was found that the evolutions of the mode position and frequency follow opposite trend in the two regimes. In Tore Supra, where abrupt changes between modes with different mode structures are often observed, it was found that the mode position evolves continuously and the wavenumbers follow an inverse cascade starting from an $m/n = 4/4$ mode and finishing in an $1/1$ mode. In a second step, the energy of resonant electrons was estimated from the resonant condition of the precession drift frequency. It was found that in Tore Supra the resonant condition does not change during the frequency jumps. The relevance of the correction due to the pitch angle of the resonant electrons and the possible role of the energetic passing particles in the drive of these modes are discussed from the results obtained in both machines.

(Some figures may appear in colour only in the online journal)

1. Introduction

The confinement of fast particles in the core region is an important issue for reaching the expected performance in the next-step fusion device ITER. The transport of energetic alpha particles produced by fusion reactions can be significantly influenced by the interaction with low-frequency MHD modes, such as precessional fishbones [1]. However, the number of energetic alpha particles produced in current fusion devices is too low to allow experimental studies of their transport properties and to benchmark theoretical models used to predict the behaviour of energetic alphas in ITER. Therefore, MHD modes excited by energetic particles produced by heating and current drive systems in current tokamaks are necessary to benchmark these models. A study of electron fishbone-like modes can provide useful information on the interaction between fast particles and internal kink modes [1].

Electron fishbones are usually observed in electron cyclotron resonant heating (ECRH) plasmas [2–4]. Fast electrons produced by lower hybrid current drive (LHCD) often help in destabilizing electron fishbones and these modes are sometimes observed using a combination of ECRH and LHCD [4]. However, in the tokamaks FTU [5] ($R = 0.91$ m, $a = 0.3$ m, $B_0 < 8$ T, circular cross section) and Tore Supra [6] ($R = 2.4$ m, $a = 0.7$ m, $B_0 < 4$ T, circular cross section) electron fishbones were observed in shots with LHCD only [1, 7–10].

This work reports a comparative study of fishbone observations in purely LH shots in FTU and Tore Supra, which show very different experimental behaviours, which are probably caused by the very different LH power density depositions in the two devices (the plasma volume is $\sim 15$ times bigger in Tore Supra than in FTU). In FTU, two regimes of e-fishbones were found and, by increasing the lower hybrid power, it is possible to switch from an almost stationary state to bursting behaviour [1]. On the other hand, in Tore Supra, only near-stationary evolutions are observed. Furthermore, in contrast with the FTU cases, where only the $m/n = 1/1$ mode is destabilized, frequency jumps between modes with different mode numbers are commonly obtained in Tore Supra [7, 8] during the operational regime called the oscillation-regime.
2. Mode evolution in FTU

In FTU, two regimes of e-fishbones according to the lower hybrid power were reported [1]. Figure 1 shows the LH power, the electronic temperature ($T_e$) measured by the ECE diagnostic at $\rho \approx 0$ and the spectrogram of $T_e$ in the central region, $|\rho| \leq 0.25$, for one shot where the two regimes are present. The main parameters of this shot are: central toroidal magnetic field $B_0 = 5.4$ T, line-averaged central electronic density $n_0 \approx 5.4 \times 10^{19} \text{ m}^{-3}$, plasma current $I_P \approx 0.51$ MA and loop voltage $V_L \approx 0.3$ V. The LHCD $N_{||}$ is 1.8 and the LH absorption peaks on $r/a \approx 0.34$ and $r/a \approx 0.30$, respectively, for the low and high LH phases, with a full-width at half-maximum (FWHM) of 0.10 (the profiles at $t = 220$ ms and 280 ms are presented in figures 2 and 3 of [1]).

As can be seen in figure 1, at lower values of LH an almost stationary non-linear saturated steady state is observed, and after increasing the LH power the e-fishbone starts displaying an almost regular bursting behaviour.

It is interesting to note in figure 1 that the LH power was increased at 0.24 s, but the frequency evolution remains slow for almost 10 ms after that, consistently with the characteristic time for the formation of the LH quasi-linear plateau in the supra-thermal electron distribution function at increased power. Moreover, the last burst is observed just after the reduction in the LH power at 0.295 s, which can be interpreted in a similar fashion.

In order to determine the evolution of the mode position the procedure presented in [13] was used. In this procedure, the radial distribution of the spectral power of $T_e$ oscillations in

(O-regime), in which cyclical and smooth evolutions of the equilibrium profiles are observed [11].

In the first step, the evolutions of the mode radial position and frequency in both tokamaks were determined from the induced electronic temperature fluctuations measured by electron cyclotron emission (ECE) diagnostic [12, 13]. Also, the mode wavenumbers in Tore Supra were identified using a new method based on the radial profile of the ECE measurements. Then, in the second step, the evolution of the energy of resonant electrons was estimated from the expression of the precession drift frequency. The importance of the correction due to the pinch angle of the resonant electrons and the possible role of the energetic passing particles are discussed from the results obtained in this analysis.

This paper is structured as follows: section 2 presents the analysis of fishbones in FTU, focusing on the effect of the LH power on the mode position and frequency evolutions. The same study for Tore Supra is shown in section 3, which also presents the reanalysis of the mode wavenumbers from the radial profile of the ECE measurements using the method described in section 3.1 and in the appendix. A discussion about the energy of the resonant electrons is presented in section 4. Conclusions are drawn in section 5.
short time intervals is considered in a least-squares fit whose parameters give the mode position and frequency with high precision and good temporal resolution.

The mode position is determined by the position of the peaks of the spectral power of ECE measurements at the frequency of the mode, which appears at the low-field side (LFS) and the high-field side (HFS). Gaussian shapes are used to fit the peaks in radial position and in mode frequency. It must be noted that the results are not sensitive to the considered shape of the peaks. In fact, the spectral noise is the most important source of error in the mode position determined by this method. Moreover, each peak is detected by a small number of channels (2–3 ECE channels in the case of FTU and 4–5 in Tore Supra) and details of the peak shape cannot be observed. More details about this method can be found in appendix A of [13], which presents some comparisons between data and fit for some fishbone modes measured in Tore Supra.

Figures 2(b) and (c) show the evolutions of the mode position and frequency. At low values of LH power, the mode drifts outwards while the frequency decreases; however, the tendency is opposite just after the increase in the LH power and during the bursts: the mode drifts inwards (when the frequency decreases (increases).

The slow continuous evolution shown in figures 2(b) and (c) occurs in a time scale of tens of milliseconds, which is consistent with the modifications in the equilibrium. In fact, the outward drift observed up to 0.25 s is probably just a consequence of the $q$-profile evolution, while the frequency increases between 0.24 and 0.25 s may be a consequence of the growth of the electronic temperature in the core region because of the enhancement of the LH power.

However, the bursts exhibit a much faster evolution as can be seen in figure 3, which shows a detailed view of the burst evolution. The mode grows for 0.4–0.5 ms, the saturated level is maintained for $\sim$1.5 ms (while the mode frequency decreases by $\sim$3 kHz) and finally the mode amplitude decreases for 0.5–0.7 ms. The overall duration of each burst is $\sim$2.5 ms and the time between successive bursts is $\sim$10 ms.

The order of magnitude of the temporal scales involved in the burst evolution agrees with the theoretical prediction that $\omega \sim \omega_{NL}$ for non-adiabatic downward frequency chirping produced by mode-particle pumping [14], with $\omega_{NL}$ the wave–particle trapping frequency for resonant supra-thermal electrons. In fact, the duration of the growth and the decay phases can be used to estimate the order of the non-linear time scale, $\tau_{NL} \sim \Delta f_{0} \sim 5 \times 10^{-4}$ s, and the wave–particle trapping frequency can be considered to be of the order of the non-linear growth rate, $\omega_{NL} \sim 1/\tau_{NL} \sim 2 \times 10^{7}$ s$^{-1}$, giving $\omega_{NL}^{2} \sim 4 \times 10^{6}$ s$^{-2}$. The experimental rate of the frequency chirping during the stationary phase of the burst is of the same order, $\omega \sim 2\pi (\Delta f_{Sat}/\Delta f_{Sat}) \sim 10^{6}$ s$^{-2}$.

3. Mode evolution in Tore Supra

In Tore Supra, modes with frequencies up to 20 kHz are observed in plasmas with moderate values of LH power ($\sim$1 MW) and low density ($n_{0} \sim 2.5 \times 10^{19}$ m$^{-3}$) [7, 8]. The frequency evolution of these modes often displays discontinuities (frequency jumps), which are related to abrupt changes between modes with different structures (poloidal and toroidal wavenumbers) [7, 8]. The influence of the LH power on the stability of these modes was studied in [8], which presents an experimental bifurcation diagram describing the observed modes according to the LH power.

Figure 4 shows one case of frequency jumps among several modes in a shot with toroidal magnetic field $B_{0} = 3.8$ T, line-integrated central electron density $n_{e} = 2.3 \times 10^{19}$ m$^{-3}$, plasma current $I_{p} = 0.6$ MA and loop voltage $V_{L} = 0.18$ V. The LHCD $N_{||} = 1.74$, and the coupled LH power was 1.13 MW. The LH absorption, estimated from the hard x-ray measurements, peaks on $r/a \sim 0.15$ with a FWHM of $\sim 0.35$. In this shot, it is possible to observe frequency jumps among modes with frequencies around 3, 6, 9 and 11 kHz.

The central electronic temperature (figure 4(a)) describes an almost periodic sinusoidal oscillation with a repetition rate of the order of a few tens of hertz, the so-called O-regime of Tore Supra [11]. In this regime, the phase of the temperature oscillation depends on the radial position and the oscillatory behaviour is attributed to the interplay between the position where the LH waves are absorbed and the local temperature, which forms a predator–prey system [11, 15, 16].

The evolutions of the mode position and frequency in Tore Supra were obtained using the same procedure as for FTU shots (see also appendix A of [13]). The discontinuities in the mode frequency that can be seen in figure 5(b) are not observed in the mode position (figure 5(c)). In fact, the mode position evolution suggests a cycle starting by the mode with frequency around 11 kHz, which appears during the peak of the central temperature, followed by a sequence of frequency jumps to modes with frequencies around 9, 6 and 3 kHz. It is important to note that a new cycle starts before the end of the previous one and that the same sequence is also observed in other shots (see figure 2 in [13]).
The evolution of the mode position during the cycles of the central temperature oscillations agrees with the expected $q$-profile evolution during the O-regime obtained in CRONOS simulations [15, 16] when considering the non-linear coupling of the temperature and current density profiles [11, 15]. Moreover, the position of the modes agrees with the expected position of the $q = 1$ surface.

The observed sequence of mode appearance during the cycle ($11\,\text{kHz} \rightarrow 9\,\text{kHz} \rightarrow 6\,\text{kHz} \rightarrow 3\,\text{kHz}$) includes the $3\,\text{kHz}$ mode which was not considered in previous analyses [7, 8]. An analysis of the phase of the induced $T_e$ oscillations measured by ECE clearly shows that the poloidal parity of the $3\,\text{kHz}$ mode is odd (figure 6(d)), the $m/n = 1/1$ mode being a natural candidate. However, as in the previous analysis [7, 8], the $9\,\text{kHz}$ mode was identified as $1/1$, and a reanalysis of the wavenumbers was performed.

The mode numbers are necessary to compute the resonant energy of the driving electrons which can help one to understand the role of supra-thermal electrons in the mode evolution. However, the usual diagnostics to determine the mode wavenumbers, Mirnov coils and soft x-ray, cannot be used to analyse these experiments: the Mirnov coils in Tore Supra are unable to detect modes above a few kHz and the fast acquisition of the soft x-ray measurements in LH shots is very noisy. In order to overpass these limitations, the poloidal mode numbers were determined from the ECE measurements using the method described in the following subsection and in the appendix.

### 3.1. Reanalysis of the wavenumbers in Tore Supra

Figures 6(b)–(d) presents the time evolutions of the radial profiles of the 9, 6 and $3\,\text{kHz}$ modes. The radial profile is
obtained from the $T_e$ oscillations at the mode frequency $f$ as
\[ \delta T_e = \phi_{k,k} \cos(\delta_k \cdot \mathbf{B}) \], where $\delta T_e$ is the amplitude of the electron temperature fluctuation measured at the ECE channel $k$, and $\phi_{k,k}$ is the phase difference between the $T_e$ oscillations at the ECE channels $k$ and $k_0$, with $k_0$ being an arbitrarily chosen reference channel. In figures 6(b)–(d) the reference channels were chosen in the HFS.

As can be seen in figures 6(b)–(d), the profiles of the 9 and 6 kHz modes contain unexpected complex structures in the central regions that are produced by an instrumental effect of the ECE diagnostic which affects modes with poloidal mode numbers bigger than 1, as explained below.

The main instrumental contribution that must be considered in order to understand the origin of the complex structures presented in figure 6 is the finite size of the region probed by the ECE antenna. A simplified model of the ECE measurements can be used in order to illustrate this effect. Considering a kink mode with poloidal mode number $m$ and frequency $\omega_0 = 2\pi \cdot f$, the induced $T_e$ oscillation in the poloidal plane view by the ECE antenna, $\tilde{T}_e(\rho, \theta, t)$, is simulated by

\[ \tilde{T}_e(\rho, \theta, t) = \varepsilon_0(\rho) \cdot \nabla T_e \cdot \cos(m \cdot \theta - \omega_0 \cdot t), \tag{1} \]

where $\varepsilon_0(\rho)$ is the MHD displacement at the radial position $\rho$.

The measured ECE signal of each channel is then simulated by considering the average of the induced $T_e$ oscillations in the region probed by the ECE antenna. In Tore Supra the estimated resolution in the direction of the major radius is $\sim 2.5$ cm, while in the vertical/toroidal direction the resolution is $\sim 8$ cm. Therefore, the probed regions are much wider in the vertical direction than in the radial one.

The right panel of figure 6 illustrates the effect of the finite size of the ECE beam on the measured radial profiles. Figures 6(e)–(f) show the mode-induced $T_e$ oscillations of $m = 2$ and $m = 3$ modes simulated using equation (1). The rectangle in figure 6(e) indicates the region probed by the central channel of the ECE when measuring an $m = 2$ mode. The average induced $T_e$ oscillations in the central channel are in opposite phases with respect to the closest peak. The rectangle in figure 6(f) indicates the region probed by an ECE channel in the HFS close to the magnetic axis: it is possible to see that the averaged $T_e$ oscillations in this channel are in opposite phases with respect to the closest peak. The rectangles in figure 6 indicate the size of the region probed by an ECE channel in channels close to the magnetic axis. (bottom right panel) Simulated profiles of the ECE measurements when considering the finite size of the ECE beam for $m = 3 (g)$, $m = 2 (h)$ and $m = 1 (i)$ modes.

**Figure 6.** (left panel) Experimental profiles of the $T_e$ oscillation detected by ECE for the same shot presented in figure 4: spectrogram of the $T_e$ oscillation (a) and radial profiles of the 9 kHz $m/n = 3/3$ mode (b), the 6 kHz 2/2 mode (c) and the 3 kHz 1/1 mode (d). (upper right panel) Simulated real $T_e$ oscillations induced by $m = 2$ (e) and $m = 3$ (f) modes. The rectangles indicate the size of the region probed by the ECE antenna in channels close to the magnetic axis. (bottom right panel) Simulated profiles of the ECE measurements when considering the finite size of the ECE beam for $m = 3 (g)$, $m = 2 (h)$ and $m = 1 (i)$ modes.
that this is an 1/1 mode. Also, the profile of the mode at 6 kHz (figure 6(c)) agrees with the simulated structure of the mode $m = 2$ modes (figure 6(h)), which agrees with the previous identification of this mode as $m/n = 2/2$ [7, 8]. However, the 9 kHz mode (figure 6(b)) clearly exhibits the profile of an $m = 3$ mode (figure 6(g)), but previously this mode was identified as 1/1 [7, 8].

It must be noted that these complex structures can also be observed on the measured $T_e$ oscillations induced by core magnetic islands with $m > 1$, as the $m/n = 2/1$ and 3/2 islands, which are often observed in Tore Supra during the final stage of the ohmic ramp-up of the plasma current (before the start of the sawtooth regime).

More details about the determination of the poloidal wavenumbers from the ECE measurements are presented in the appendix. The analyses presented in the appendix confirmed the identification of the 9 kHz mode as $m = 3$. These analyses also showed that the 11 kHz mode, which was previously identified as 3/3 [7, 8], in fact has an even poloidal parity and it is an $m = 4$ mode.

Regarding the poloidal parity of the 11 kHz mode, the detailed analysis of the phase of the ECE measurements presented in the appendix shows that in these experiments there was an unknown vertical shift of the ECE line of sight (LoS) of $\sim 3$ cm, which affects the determination of the poloidal parity of core MHD modes with high $m$ numbers.

Finally, regarding the new identification of the 9 kHz and 11 kHz modes as $m_0/n_0 = 3/3$ and $m_{11}/n_{11} = 4/4$, respectively, it is interesting to note that the ratio of the frequencies of the 9 kHz and 11 kHz modes during the time windows in which these modes coexist is $\sim 0.77$ (while $n_0/n_{11} = 3/4$), and the ratio between the frequencies of the 6 kHz and 9 kHz modes is 0.67 (while $n_0/n_0 = 2/3$). Good reproducibility of the frequency ratios (within 0.03) is obtained when considering several observations of the sequence (11 $\rightarrow$ 9 $\rightarrow$ 6 $\rightarrow$ 3) kHz.

From these results, we conclude that the sequence suggested by the radial position evolution (figure 5) corresponds to an inverse cascade (a decreasing sequence) of mode numbers: 4/4 $\rightarrow$ 3/3 $\rightarrow$ 2/2 $\rightarrow$ 1/1. Moreover, the analysis presented in the appendix also gives information about the direction of the mode rotation which allows the estimation of the effect of the Doppler shift on the mode frequency. To correct the Doppler shift, the measured frequencies in Tore Supra must be decreased by $n \cdot f_{\text{ROT}}$, with $f_{\text{ROT}} \sim 2$ kHz.

4. Energy of the resonant electrons

In order to elucidate the drive mechanism, it is interesting to identify the energy of the resonant electrons. The resonance condition for trapped electrons is reached when the frequency matches the precession drift frequency, i.e. [1, 9]

$$f \approx \frac{E \cdot n \cdot q}{2\pi \cdot R_0 \cdot B \cdot |g_\lambda|},$$

(2)

where $E$ is the energy of the resonant electrons, $n$ is the toroidal mode number, $q$ is the safety factor associated with the resonant surface localized at the small radius $r$, $R_0$ is the tokamak major radius, $B$ is the magnetic field and $g_\lambda$ is a correction factor (typically between −1 and +1) that accounts for the dependence on the pitch angle [1, $\lambda$]. The evolutions of the $E \cdot g_\lambda$ product ($E \cdot g_\lambda = 2\pi \cdot R_0 \cdot B \cdot |g_\lambda| \cdot f/|n \cdot q|$) are presented in figure 7.

For the ($m/n = 1/1$) e-fishbones in FTU (left panel of figure 7), a fast evolution of the $E \cdot g_\lambda$ product is observed in the bursting regime, while only a small variation occurs in the almost steady state at low LH power. However, given the fast frequency variation in the bursting phase, discussed in section 2, at least the fast changes in $E \cdot g_\lambda$, shown in figure 7(b), are likely to be attributed to the change in the wave–particle resonance condition with supra-thermal electrons [1]. For the Tore Supra observations we got for the $E \cdot g_\lambda$ product a continuous evolution with values that are close to the thermal energy (right panel of figure 7).

It must be noted that a quantitative use of the resonant condition requires the correction of the Doppler shift due to the plasma rotation, which was performed only for the Tore Supra case (due to the lack of experimental diagnostics for plasma rotation in FTU). Even so, from the phase of the oscillations detected by the soft x-ray diagnostic it was found that in FTU the modes and the plasma rotate in the same direction. Therefore, the Doppler shift correction in FTU will decrease the observed frequency, and the estimated $E \cdot g_\lambda$ product will decrease as well.

A rough estimate of this correction can be obtained using the diamagnetic velocity presented in [1].
\( \omega_{a,p} \sim 23 \text{krad s}^{-1} \sim 2 \cdot \pi \cdot f_{\text{ROF}}, \) which leads to a reduction in the estimated \( E \cdot g_i \) product in FTU to \( \sim 60\% \) of the value presented in figure 7(b). Just for comparison, in Tore Supra the Doppler shift correction reduced the estimated \( E \cdot g_i \) product to \( \sim 40\% \) of its uncorrected value (figure 7(d) presents the Doppler shift corrected values).

Although surprising at first sight, the low values obtained for the \( E \cdot g_i \) product (figures 7(b) and (d)) in both machines are not inconsistent with a drive due to energetic electrons. In fact, as discussed in section 4.2, there are two factors that must be considered: the variation of the function \( g_i \) within the trapped domain and the possible contribution of barely passing electrons to the drive when \( q \) is close to one.

### 4.1. Continuous evolution of the resonant conditions during frequency jumps on Tore Supra

Also unexpected, the continuous evolution for the \( E \cdot g_i \) product during the frequency jumps obtained in the case of Tore Supra (figure 7(d)) is substantially different from the values presented in [7, 8]: the \( E \cdot g_i \) of the 9 kHz mode was estimated as \( \sim 70 \text{keV} \), while for the 11 and 6 kHz modes, \( E \cdot g_i \sim 30 \text{keV} \) was obtained (the 3 kHz mode was not considered in [7, 8]).

There are two main factors that explain the difference between the analysis presented here and the previous estimate of \( E \cdot g_i \) in Tore Supra: the first one is the correction of the mode wavenumbers (discussed in section 3.1 and the appendix), which leads to a continuous evolution of \( E \cdot g_i \) during the frequency jumps; and the second factor is the Doppler shift correction, which substantially reduces the \( E \cdot g_i \) of all modes.

As a consequence of the continuous evolution of \( E \cdot g_i \) during the frequency jumps, the experimental correlation between the frequency jumps and the radial profile of the supra-thermal electron distribution cannot be attributed to different resonant conditions on the \( E \cdot g_i \) product, as claimed in [7, 8]. In fact, there is an indirect relationship between these two quantities, once the evolutions of the stability condition of the modes (which are likely determined by the equilibrium profiles) and of the position of the LH absorption (which affects the radial distribution of the supra-thermal electron population) are both related to the phase of the central temperature oscillation [11, 15].

### 4.2. On the pitch-angle correction and the role of passing electrons

The process underlying electron fishbone excitation is rather complex. In fact, electron fishbones result from the resonant interaction of the internal kink mode with the slow toroidal precessional motion of electrons. As internal kink modes usually rotate in the ion diamagnetic direction, resonant electrons must have a reversed toroidal precession frequency, which is the case only for barely trapped or for passing electrons. Moreover, the mode will only be driven by fast electrons if the radial gradient of the distribution function is positive (for example in the case of off-axis electron heating or current drive).

When trapped electrons are considered, the resonant condition is given by

\[ f = n \cdot f_d, \]  

where \( f \) is the Doppler shift corrected frequency, \( n \) is the toroidal mode number and \( f_d \) is the toroidal precession frequency of trapped electrons:

\[ f_d = \frac{-E \cdot q}{2\pi \cdot R_0 \cdot B \cdot r \cdot g_i}, \]  

which leads to equation (2) when the modulus of the frequency is considered. The multiplicative factor \( (g_i) \) varies between 1 and \(-1\) over the whole pitch-angle range (see figure 8(a)), allowing solutions resonating with supra-thermal electrons if \(|g_i|\) is small (which is the case for trapped electrons with pitch angles slightly higher than the trapped condition).

Moreover, barely passing electrons also can contribute to the drive when \( q \) is close to one [17, 18]. In fact, the resonance condition for passing electrons is of the form

\[ f = (n \cdot q - m) f_b + f_d, \]  

where \( f_b \) is the poloidal transit frequency, proportional to \( E^{1/2} \), and it also depends on \( \lambda \). This condition can be fulfilled for fast passing electrons even if \( f \ll f_d \), due to the transit frequency offset in (5).

By considering resonances with both trapped and passing electrons, the energy of the resonant electrons according to the pitch-angle value was estimated for the Tore Supra case (figure 8(b)). It clearly appears that the resonant energy of electrons falls in the typical range of fast electrons produced by LHCD for a wide range of pitch-angle values. In fact, it is interesting to note that for \( q \sim 1 \) this range is wider in the passing region than in the trapped one.

### 5. Conclusions

This work presents a comparative study of the MHD modes identified as electron fishbones in lower hybrid current drive shots in FTU and Tore Supra. Initially, the evolutions of the mode position and frequency were determined through the radial distribution of the mode-induced electronic temperature fluctuations measured by ECE and the identification of the mode wavenumbers in Tore Supra was revised using a new method based on the radial profile of the ECE signals in standard and vertically shifted plasmas.

In FTU, where by increasing the lower hybrid power it is possible to switch from a regime with continuous evolutions to bursting behaviour [1], the relative trend of the mode frequency and position evolutions depends on the regime and the LH power. The evolutions in the continuous regime are much slower than those in the burst regime and probably only reflect the modifications of the equilibrium parameters, such as the \( q \)-profile and plasma rotation. On the other hand, the frequency evolution during the saturated stage of the bursts is consistent with a non-adiabatic downward frequency chirping produced by mode-particle pumping [14].

In Tore Supra, where smooth cyclical evolutions of the equilibrium conditions are observed in the so-called oscillation-regime [11], frequency jumps between modes with different mode numbers are commonly observed, but the mode position evolves continuously even during the frequency jumps. Moreover, in the regime with frequency jumps among several modes, the reanalysis of the mode numbers shows that
the continuous evolution of the mode position corresponds to a decreasing sequence (an inverse cascade) in mode numbers starting by an \( m/n = 4/4 \) mode and finishing in a 1/1 mode. The inward drift of the mode position evolution agrees with the expected \( q \)-profile evolution during the O-regime; however, the origin of the frequency jumps remains unclear. The suprathermal electrons are expected to play a role in the stability of these modes and it may help one to explain how modes with high wavenumbers (e.g. \( m/n = 4/4 \)) can be the most unstable one.

In the second step, the energy of the resonant electrons was estimated from the precession drift frequency using the evolutions of the frequency and position of the modes determined in the first step. For the Tore Supra case, these results contrast from those estimated before [7, 8], basically because of the reanalysis of the mode numbers and the Doppler shift corrections. The continuous evolution of the energy of the resonant electrons during the frequency jumps indicates that consecutive modes resonate with the same kind of electrons. It may help one to understand why during the frequency jumps the growth of a new mode is followed by the suppression of the previous one (the coexistent 4/4 and 1/1 modes are in different radial positions).

Finally, it was showed that the interpretation of the estimated energy of the resonant electrons in both tokamaks depends on the consideration of the pitch-angle effect. Moreover, the results are also consistent with a drive by energetic passing particles [17, 19], which are abundantly produced in LHCD shots. Further studies are necessary in order to quantify the relative effect of the contributions due to the barely trapped and barely passing energetic electrons on the drive of these modes.

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Appendix. Determination of poloidal wavenumbers of core MHD modes by ECE using slightly vertically shifted plasmas

As presented in section 3.1, the radial profile of core MHD modes with poloidal mode numbers \( m > 1 \) in Tore Supra contains complex structures, which appears because the region measured by each ECE channel is wider in the vertical direction than in the radial one. However, it must be noted that due to the small number of ECE channels in the central region and to the presence of noise, the determination of these profiles can be a difficult task in the case of weak modes or modes with high poloidal wavenumbers (\( m > 4 \)).

This appendix describes a complementary method to analyse the ECE profiles based on the use of plasmas slightly displaced in the vertical direction, which is carried out in order to shift the vertical position of the ECE LoS, once in Tore Supra the ECE antenna is fixed to see the equatorial plane of the vacuum vessel. This method can be used to confirm the identification obtained by the analyses of the radial profile of the \( T_e \) oscillations in non-shifted plasmas, and to determine the poloidal direction of the mode rotation within the laboratory frame.

This method is based on the analysis of the integrated (and unwrapped) phase shift of the ECE oscillations at the mode frequency, \( \Phi_{\lambda,k} = \sum_{\lambda=1}^{\lambda=1+1} \Phi(\lambda+1) \), in slightly vertically shifted plasmas. In Tore Supra, it requires plasmas shifted by only \( \Delta z \sim 2 \text{ cm} \) in the vertical direction (~1.5% of the minor radius).

The basis of this method is the following: when the ECE LoS is exactly at the midplane (that is, aligned with the magnetic axis), the mode-induced \( T_e \) oscillations in adjacent channels are expected to be either totally in phase or totally in opposite phases (phase shift 0 or \( \pi \)) due to the vertical symmetry. Therefore, the phase shift cannot be unwrapped. However, when the ECE LoS is slightly shifted, the symmetry is lost and the phase transitions are not abrupt anymore, allowing unwrapping of the phase shift between the oscillations in adjacent channels.
In slightly shifted plasmas, the modulus of the integrated phase shift $\Phi_{k_{1z},k_{2r}}$ between the peaks at the HFS and LFS is close to $m \cdot \pi$. The signal of $\Phi_{k_{1z},k_{2r}}$ depends on the poloidal direction of the mode rotation in the laboratory frame and on the vertical direction of the vertical shift of the plasma. In fact, for a mode rotating in the clockwise direction, the integrated phase shift will be $\Phi_{k_{1z},k_{2r}} \cong +m \cdot \pi$ when the plasma is shifted up (because the ECE LoS in this case is below the midplane and the $T_e$ oscillations will be seen as coming from the LFS to the HFS). If the mode rotates in the counter-clockwise direction, the opposite signal of the shift ($\Phi_{k_{1z},k_{2r}} \cong -m \cdot \pi$) is obtained. The signal changes if the plasma is shifted down, instead of up.

To better understand the effect of the vertical shift on the ECE LoS, the ECE measurements were simulated by taking the weighted average of the $T_e$ oscillations given by equation (1) in a LoS vertically shifted by $\Delta z$. This corresponds to vertical displacements of the rectangles presented in figures 6(e) and (f). Figure 9(a) shows the simulated phase angle of the ECE signal in the case of modes with different poloidal wavenumbers ($m = 1$ to $3$) for $\Delta z = 2$ cm. It is possible to see in figures 9(a)–(c) that a smooth transition of the ECE phase angle is obtained when going from the HFS to the LFS with a total phase shift that is close to (but slightly smaller than) $m \cdot \pi$.

To confirm the mode identification, a new e-fishbone experiment was conducted in the Tore Supra 2011 experimental campaign. In order to better see these modes by ECE a lower central magnetic field, $B_0 = 3.66$ T, was used and the vertical shift of the plasma was changed on a shot-by-shot basis. However, the condition of frequency jumps among several modes was not obtained in this experiment (only cases without frequency jumps or with frequency jumps between only two modes were observed).

The experimental phase shift analysis of the modes labelled 3, 6 and 9 kHz obtained in one of the vertically shifted shots of the 2011 campaign is presented in figures 9(b)–(d). From the ECE phase angles we can clearly see that the 9 kHz mode (figure 9(d)) has $m = 3$, being a $3/3$ mode (instead of $1/1$, as considered in [7, 8]).

More details about this method will be presented elsewhere. By now, it must be observed that it can be used on core MHD modes (that is, modes which are close to the magnetic axis) and that it was tested for both kink modes and magnetic islands. Also, the application of this method is limited in the case of modes with high $m$ numbers, once due to the limited number of ECE channels the phase angle jumps between some of the adjacent channels can be closer or bigger than $\pi/2$, compromising the automatic unwrap of the phase shifts.

Finally, it must be noted that by increasing the vertical shift the phase transitions are smoothed out among a bigger number of channels (which helps in unwrapping the phase shifts), but on the other hand, the modulus of the total integrated phase shift gradually becomes lower and far from $m \cdot \pi$. In fact, by using a simplified geometrical model, it is possible to derive an approximated expression for the integrated phase shift between the peaks at the HFS and LFS of a mode at position $r$ in a ECE LoS shifted by $\Delta z$ in the vertical direction as $|\Phi_{k_{1z},k_{2r}}| \cong m \cdot \pi - (2 \cdot m \cdot \Delta z/r)$. The reduction in the total phase shift can induce a misidentification of the poloidal parity because the total phase shift can eventually become closer to $(m - 1) \cdot \pi$ than $m \cdot \pi$, which leads to an inversion of the relative phase between the oscillations of HFS and LFS peaks (which is expected to occur if $(2 \cdot m \cdot \Delta z/r) > (\pi/2)$).

The effect of the vertical shift on the relative phase of the peaks explains why the poloidal parity of the 11 kHz mode was previously identified as odd, instead of even [7, 8] when analysing the shots of the e-fishbone 2008 experiments (like the TS #41117, analysed in this work). An unknown vertical shift of the ECE LoS of $\sim 3$ cm with respect to the magnetic
axis exists in these experiments (which for an $m = 4$ mode at $r = 13\text{ cm}$ implies $2 \cdot m \cdot \Delta z/r = 1.9 > (\pi/2)$).

This effect is explained in figures 10(a)–(b), which show that the average radial profile of the 11 kHz mode in the TS #41117 shot (figure 10(a)) agrees well with the simulated profile of an $m = 4$ mode with a vertical shift of 3 cm (figure 10(b)). In fact, there are several other experimental proofs (even for sawteeth precursors) that support the conclusion that there was an unknown shift of 2–4 cm on the vertical position of the ECE LoS in these experiments.

The same effect was observed in the new experiments in which the vertical position of the plasma was changed on a shot-by-shot basis. Figures 10(c)–(d) present the radial profile of an $m = 5$ mode in the 2011 experiment in a standard (non-shifted) plasma (figure 10(c)) and in a plasma shifted by 2 cm (figure 10(d)). The poloidal parity which is clearly identified as odd in the non-shifted plasma (figure 10(c)) appears as if it was even in the shifted one (figure 10(d)).