Fishbone-like internal kink instability driven by supra-thermal electrons on FTU generated by lower hybrid radiofrequency power

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Abstract. The fishbone-like internal kink instability driven by supra-thermal electrons generated by lower hybrid current drive (LHCD) is of strong interest for the burning plasma research, as the trapped particle averaged bounce characterising the interaction of trapped alpha particles with low frequency magnetohydrodinamic (MHD) modes in burning plasmas depends on energy, not on mass. The charged fusion product effects can be usefully modelled by the analogous effect induced by the fast electrons on the low frequency MHD modes. Fishbone-like internal kink instabilities driven by electrons were observed during experiment on FTU (Frascati Tokamak Upgrade) aimed at producing internal transport barrier by optimising the *q*-profile evolution by LHCD power (1.7 MW). By the available theory, the phenomenon was interpreted in terms of an oscillating "fixed point" activity followed by one of "limit cycle", produced by suprathermal electrons in presence of a *q*-profile with $q_{\min}\approx1$. More recent experiments of FTU have been performed for fully assessing the behaviour of the electron fishbone, by utilising a more controlled *q*-profile evolution obtained by: i) useful plasma-wall conditions and LHCD power waveforms, ii) robust *q*-profile evolution modelling, iii) high time resolution data of the fast electron Bremsstrahlung (FEB) camera, and MHD supported by soft X-ray tomography. The preliminary results are very interesting: during typical fixed-point oscillations, a spatial redistribution of the fast electron population occurs at the same radial position of fishbones, with the same characteristic time (0.1 ms).

Introduction

The interaction of trapped alpha particles with low frequency magnetohydrodinamic (MHD) modes in burning plasmas is characterised by small dimensionless orbits similar to electrons, so that the trapped particle averaged bounce depends on energy, not on mass. Consequently, the fishbone-like internal kink instabilities driven by supra-thermal electrons generated by lower hybrid current drive (LHCD) and electron cyclotron resonant heating (ECRH) is of strong interest for the burning plasma research. The charged fusion product effects can be usefully modelled by the analogous effect induced by the fast electrons on the low frequency MHD modes [1].

Fishbone-like internal kink instabilities driven by electrons were observed for the first time on Doublet III-D during ECRH experiments, and attributed to barely trapped supra-thermal electrons characterised by drift reversal [2]. The relevant physics of this instability is based on modes propagating in the ion diamagnetic direction that can be destabilized in presence of an inverted spatial gradient of the supra-thermal electrons. During experiment on FTU (Frascati Tokamak Upgrade) aimed at producing internal transport barrier by optimising the *q*-profile evolution by LHCD power (1.7 MW), a typical electron fishbone-like activity was observed, which was interpreted by theory by hypothesizing a spatial redistribution of the suprathermal population occurring in presence of a suitable evolution of the plasma current density profile [1]. The modelling indicated that the level of LH power input would control the transition from nearly steady state to bursting electron fishbone oscillations, i.e, quasi steady state non linear oscillations (fixed point) are followed by regular bursting (consistent with the limit cycle). During the electron fishbone activity, a significant redistribution of the fast electron population is expected to occur, analogous to the fast ion losses expected when ion fishbones are excited. In Toresupra, the data of hard-X ray diagnostic (60-80 keV range) provided some indication of some spatial redistribution of the suprathermal electron population [3]. However, the time behaviour of this phenomenon with respect to the MHD time scale (0.1 ms) could not be assessed due to the insufficient time resolution of the diagnostic (16 ms).

In order to achieve a fully clear picture of the electron fishbone phenomenology, dedicated experiments have been recently planned and performed on FTU, by utilising a high performance hard-X ray diagnostic based on the fast electron Bremsstrahlung (FEB) camera, which has 4 microseconds of time resolution. It is useful for exploring with the necessary detail the linked behaviour of the suprathermal electrons produced by the LH power and the relevant MHD activity. The MHD signal has been analysed with the support of a new tool based on the soft X-ray tomography, which provides also information on the q-profile evolution [4]. In addition, a modelling of the q-profile evolution (described in the next paragraph) based on the kinetic and magnetic data of the experiment, has been produced for addressing the operations of experiment necessary for fishbone destabilisation, as indicated in the theory in Ref. 1. As preliminary condition, the fishbone-like modes should occur in presence of the q-profile approaching the condition $q_{\min} \approx 1$, and a sufficient population of fast electrons obtained by LHCD. For an accurate search of the fishbone features (e.g., threshold conditions, typical timing with respect to the q-profile evolution, etc.), a LH power (up to 0.5 MW) lower than that utilised in the aforementioned previous experiments of FTU has been performed. In order to produce the necessary q-profile in the experiment, the LH power is applied before the onset time of the sawtooth, so that the condition of $q_{\min} \approx 1$ is satisfied. The sawtooth onset time point is individuated by a companion discharge performed with same parameters but without LH. Standard FTU operating conditions (B_T=5.3 T, I_P=0.5MA, $<n_e> = 0.5\ 10^{20}\ m^{-3}$, R = 0.93 m, a = 0.33 m) have been considered. In order to detect with the necessary precision the radiofrequency power threshold and the relevant timing of the q-profile evolution, a relatively slow evolving q-profile should be produced. This condition is obtained, with the help of a modelling of the q-profile evolution, by applying a LH power waveform starting with a relatively low power (0.2 MW). In addition, in the very early phase of discharge, when the LH power cannot be applied due to the still too high loop voltage, the useful slow current relaxation is still guaranteed by utilising the low recycling/high peripheral electron temperature operation, which is provided by the Lithizated vessel facility available in FTU (see below) [8].

As new results of the FTU experiment, i) a q-profile evolution has been performed, useful for fishbone occurrence, as indicated by the available theory, ii) typical fishbone activity has been observed with 0.5 MW of LH power, consisting in quasi steady state non linear oscillations (fishbone fixed point phase), iii) a spatial redistribution of the fast electron population, occurring with the same characteristic time of the MHD signal (0.1 ms), and in phase with it, is obtained by the analysis based on the available FEB camera data.

Experiment parameters and *q*-profile evolution

The Figure 1 shows the time evolution of the main plasma parameters of the reference experiment. The LH power (Fig 1 d) switch-on is performed 0.14 seconds after the end of the plasma current ramp-up (Fig 1a). The LH power waveform consists of three steps (respectively of 0.2 MW at 0.30 s, the second of 0.5 MW from t = 0.36 s and t = 0.80 s, the third again of 0.2 MW from t = 0.80 s to t = 0.85 s) with the aim of maintaining the condition $q_{\min} \gtrsim 1$necessary for fishbone destabilisation.

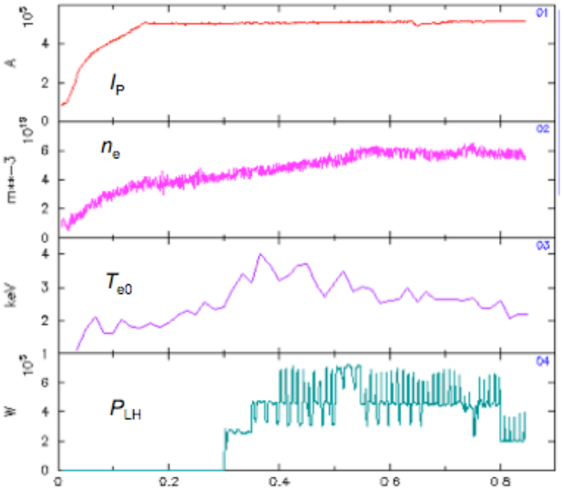


Fig. 1. Time evolution of the main plasma parameters of the reference experiment. a) Plasma current, b) line averaged plasma density, c) electron temperature, d) coupled LH power.

The modelling of the q-profile evolution utilised for the design of the experiment considers the realistic conditions of operation. This modelling has been produced by the JETTO code considering the whole plasma discharge, including the very early phase of the current ramp-up. As inputs, the measured kinetic profiles, the equilibrium data reconstructed by magnetic measurements, and the LH current density profile obtained by the LHstar code [5-7] have been utilised. As special features of the LH model utilised for individuating the deposition profile, the ray-tracing + Fokker-Planck analysis is simultaneously performed during propagation of each spectral component. The spectral broadening effect produced by ion-sound-quasimode-driven parametric instability at the edge is taken into account, as this phenomenon was recognised to be a general phenomenon accompanying the radiofrequency power coupling in experiments utilising externally launched LH waves in tokamak plasmas [5-7].

The modelled q-profile evolution, in presence of the LH power waveform, is shown in Figure 2.

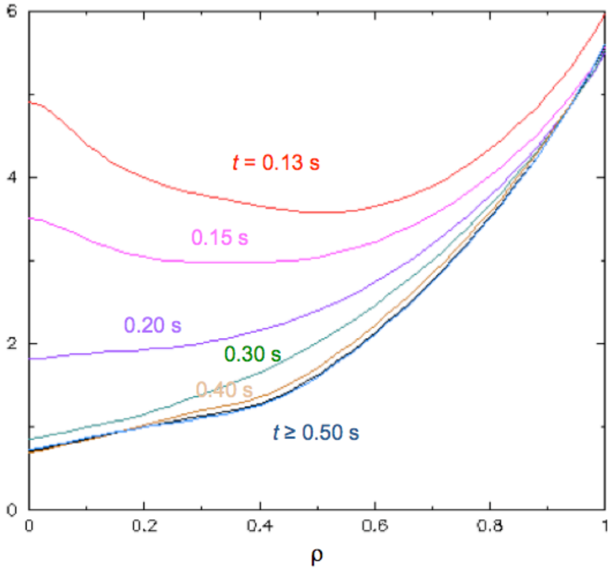


Figure 2. Modelling of the q-profile evolution obtained by inputting the available data of kinetic profiles, magnetic equilibrium and LH driven current density profile (by the JETTO and LH star codes). The q-profile remains practically unchanged during the whole LH phase (t ≤ 0.9s).

It indicates that the q-profile at normalised flux coordinate $\rho \approx 0.3$ has a nearly flat shape, and satisfies the request: $q_{\min} \approx 1$ for $t \geq 0.40$s. In this condition, during the experiment, the LH power was switched to the highest power step (0.5 MW, see Fig. 1) with the aim of maintaining unchanged the q-profile as effect of the non-inductive current driven by the LH waves. This goal was actually obtained, as shown in the Figure 2: the q-profile remains practically unchanged during the high power LH phase (t = 0.4s - 0.9s), in which no significant changes in the kinetic profiles as well as in the LH deposition profile occur. The modelling indicates that the utilised LH power waveform satisfies the conditions requested by the fishbone-like mode destabilisation. As result of a broad experience obtained in experiments performed also in other devices, such a model approach for determining the evolution of the q-profile appears robust enough, as a general consistency of the q-profile evolution and the characteristic onset timing of relevant MHD activities was generally found. This modelling is thus useful for designing the operating parameters as well as for interpreting outcomes strongly dependent on the q-profile evolution.

The experiment considered in the present work was performed with Lithizated vessel, as it provides a radially broader T_e profile than in the standard boronised vessel, as well as a lower Z_{eff}. As consequence, a slower current diffusion is produced with respect to the first experiment in which fishbones were observed on FTU [1] that operated in boronised vessel. The present slower current diffusion is useful for the goal of accurate search of the fishbone-like mode destabilisation conditions, as a more controllable evolution of the plasma current density profile is achieved by LHCD. Due to the relatively slow current diffusion obtained during the experiment, this search could be extended to fishbone like instability expected to occur also for $q_{\min} \gtrsim 2$. In this latter case, it would be sufficient to perform the LH power coupling by properly advancing the radiofrequency power waveform, as the modelling indicates ($t \gtrsim 0.15$ s). This study will be performed in the next experiments.

MHD Fishbone activity by MHD and soft X-ray data

The signals collected by the Mirnov coils and the data of the soft X-ray tomography have allowed the present MHD analysis to be performed. The results are summarized in the Figure 3 showing the time evolution of the soft X ray (Fig 3a) and the MHD spectrogram (Fig 3b).

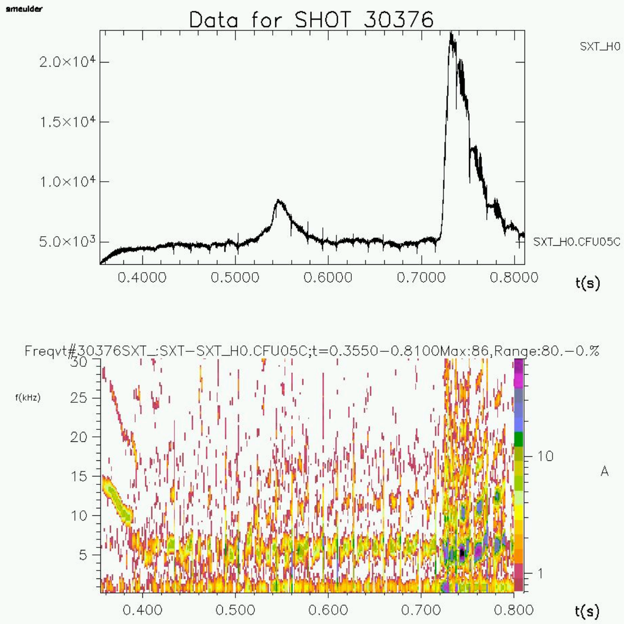


Figure 3. Time evolution of the soft X ray (Fig 3a) at minor radius of 5 cm, and the Fourier spectrum of the MHD signal (Fig 3b).

The MHD activity consists in sawtooth precursors and fishbone-like structures as well, with varying mode amplitude. The onset of 1,1 modes starts (at t=0.38 s) just after the highest LH power step (0.5 MW at 0.36 s, see Fig. 1d), and is consistent with the q-profile evolution of Figure 2: it presents indeed the intersection of the $q_{\min} \approx 1$ at around the t = 0.4s. A steep increase of SXR emission occurs at t

=0.72 s, concomitant with a transient increase of the Molybdenum spectroscopic level (from t = 0.72 s and t = 0.78 s), attributable to unwanted ingress of impurity. The phenomenology of the fishbone activity appears more clearly in the Figure 4, which magnifies the time window of Figure 3 in the region with a more marked increase of the fishbone signal amplitude (from t =0.65 s and t = 0.82 s).

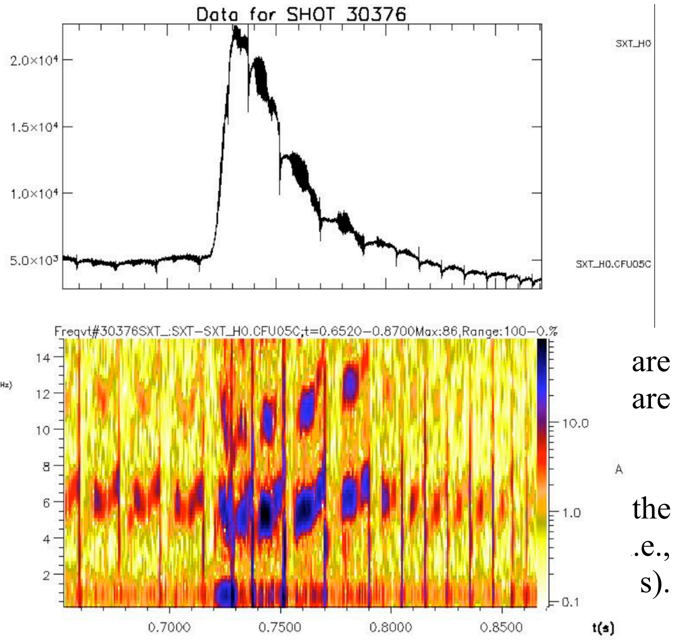


Figure 4. Same data of Figure 3 with magnified time window around t=0.75s: time evolution of the soft X ray (Fig 4a) and the MHD spectrogram (Fig 4b) of the reference FTU shot.

The occurrence of the fishbone signatures are independent of the Mo ingress, as they are present before as well as later in time wi respect to the Mo ingress. The fishbo activity is in particular strong enough wh the standard level of Molybdenum is restor .e., the same level occurring for t = 0.40s – 0. s). After the LH power switch-off, the fishb activity ceases, while only the sawtooth is present. We retain that the impurity influx would produce only minor changes in the q-profile evolution, as it does not produce detectable changes in the kinetic profiles. Such perturbation of the q-profile evolution would possibly result in some increase of the rapidity of the current relaxation, not determinant for the fishbone behaviour.

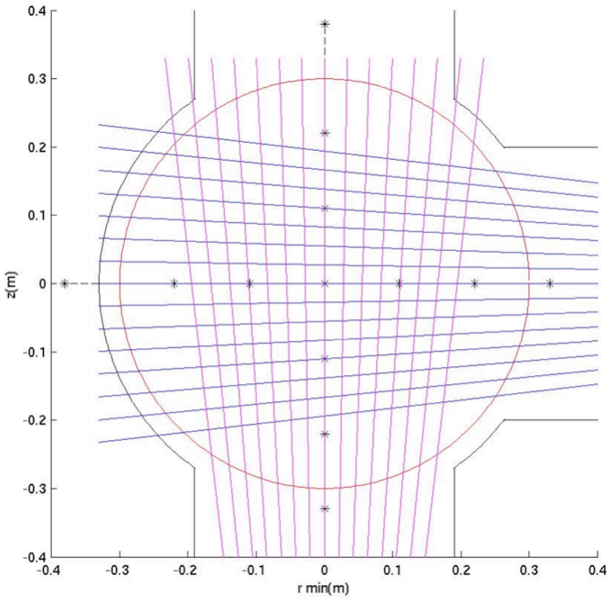
It should be noted that the observed fishbone phenomenology would be reasonably attributed to quasi steady state non linear oscillations (fixed point), not followed by the typical regular bursting phenomenology (consistent with the limit cycle), as observed instead in the aforementioned experiments of FTU at higher LH power (1.7 MW) [1]. These present results are thus consistent with the hypothesis that a higher LH power is necessary in FTU for detecting the fishbone limit cycle bursting (it is planned to be performed in the coming experiments).

The contour plot of the soft X ray emission provides preliminary information of the spatial localization of the fishbone activity. The fishbone activity appears quite localized around r=0.06 m. During the stronger phase of MHD activity, they are more around 0.09 m and much stronger (the signal level is height times higher). In similar discharges produced operating with same parameters, but without LH power the MHD signal shows no fishbone activity at all, but only sawtooth activity. Therefore, it is the LH power the important condition for the appearance of the fishbones.

Re-distribution of the fast electron population during fishbone activity

The assessment of the space and energy distribution of the fast tails produced by the LH power in the distribution of the plasma electrons can be obtained measuring the hard X-ray Bremsstrahlung emission. In FTU, two independent pinhole cameras with 15 lines of sight each, as shown in Figure 5, carry out the measurement.

Figure 5. FEB camera lines of sight in a poloidal cross-section of the FTU tokamak. Lines of horizontal camera are starting from right side. Lines of vertical camera are starting from bottom side. Geometrical centre of torus is to the left.



All lines of sight lie on a plasma poloidal cross-section. The horizontal camera is centred on an angle of 0 degree, and the vertical one is centred on an angle of -90 degree. The cameras are identical each other, including the viewing angles. For each line of sight there is a CdTe detector with a thickness of 2 mm and a square surface of 25 mm^2. The used absorbers and screens allow an energy range from 20keV to 200keV. The detector is closely connected to a proper pre-amplifier. The output signals is sent far enough from the torus through a transmitter–line-receiver-shaper system. Up to the shaper included, this diagnostics is very similar to equivalent diagnostics of TORE SUPRA [9]. After the shaper component, the system is very different and it is peculiar of FTU. In fact the shaper output signal is sent to ADC(analogic-digital converter) modules with 10 MHz of acquisition frequency. At the input of ADC the time duration of the pulse is equal to 4 μs (all inclusive), so we can assume this time as minimum time interval useful for analysis. After the shot, software modules properly perform, inside the local PC, the elaboration aimed at performing energy discrimination, pile up cleaning and event counting. The results of this standard elaboration are stored into the general archive of FTU tokamak, so it is possible to retrieve them to operate specific and accurate elaborations, when necessary. The energy discrimination and time integration computations performed by software are a special feature of the FEB diagnostic system of FTU, which has allowed the original work presented here.

During the experiment in object, the data of the FEB camera have been collected. The raw data sampling time is of 100 nanoseconds, but the minimum time scale to be used is of 4 microseconds, because of pulse shaping. This is short enough with respect to the typical half period of fishbone oscillation (about 50 microseconds). The time interval of one fishbone burst is short enough with respect to other phenomena, but it is long enough for allowing an accurate FEB data analysis within the time scale of the MHD signal. In this time interval, proper integrations over all positive and, separately, all negative half periods have been performed, and the resulting data have been submitted to suitable inversion operation. As preliminary conclusion of the analysis utilising the FEB and the Soft X data, the fast electron population redistribution occurs, during the single fishbone event, in phase with the oscillation and with the same time scale. In addition, as the fishbone activity seen by the soft X rays has the same radial position as the peak emission seen by the FEB, the fast electrons and the fishbones are connected in time and space.

As preliminary result of the analysis utilising the FEB camera data, the profiles shown in figure 6 exhibit a spatial redistribution of fast electron population across layers centred at $r/a \approx 0.33 - 0.40$. Such redistribution extends to the inner and the outer half of plasma, up to $r/a \approx 0.13$ and $r/a \approx 0.60$, respectively.

The comparison of the preliminary FEB and Soft X data analyses indicates that, during the single fishbone event, the fast electron population redistribution occurs with the same time scale of the MHD high frequency oscillation. In addition, as the fishbone activity seen by the soft X rays has the same radial position as the peak emission seen by the FEB, the fast electrons and the fishbones should be connected in time and space. Analysis of FEB profiles for longer time scale (with 3 ms of time integration) before, during and after fishbone event has been begun. At this regard, in a very preliminary way, it is possible to guess some agreement between theory and experimental data of Ref 1 about the characteristic time behaviour of the observed fishbone activity.

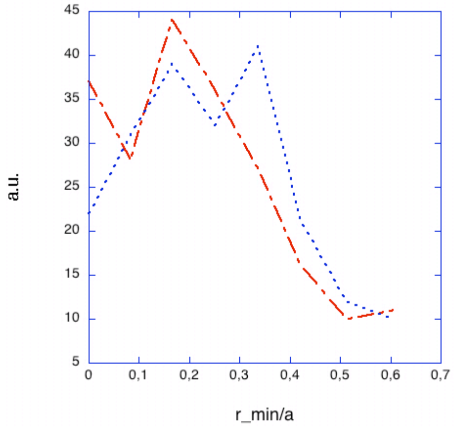


Figure 6 - Line integrated radial profiles (normalised minor radius in abscissa) of the fast electron data by FEB camera, obtained at different time points of fishbone oscillation: during positive half period (red curve), negative half period (blue curve). Energy range 40÷60 keV

Comment and conclusions

The available modelling tools and the FTU facilities, consisting in the Lithizated vessel and the LH current drive system, have been revealed useful for performing an accurate search of the electron fishbone like instability, which is expected to occur for $q_{\min} \approx 1$.

Due to the relatively slow current diffusion obtained during the experiment, this search could be extended to fishbone like instability expected to occur also for $q_{\min} \gtrsim 2$. In this latter case, it would be sufficient to perform the LH power coupling by properly advancing the radiofrequency power waveform, as the modelling indicates ($t \gtrsim 0.15$ s). This study will be performed in the next experiments. In the utilised operating conditions, the electron fishbone like instability appears quite well developed only in discharges in which a sufficient LH power (0.5 MW) is coupled. The observed phenomenology should be reasonably attributed to quasi steady state non linear oscillation (fixed point), not followed by the typical regular bursting phenomenology (consistent with the limit cycle), which was instead observed in previous experiments of FTU at higher LH power (1.7 MW) and in boronised vessel [1]. The present results indicate that the possible threshold in power for the observed activity is lower than 0.5 MW.

The preliminary analysis of the fast electron Bremsstrahlung (FEB) data show an interesting behaviour of the fast electron population produced by the LH power when the q-profile meets the condition $q_{\min} \approx 1$: a marked redistribution in space occurs across layers centred at $r/a \approx 0.33 - 0.40$. Such redistribution extends to the inner and the outer half of plasma, up to $r/a \approx 0.13$ and $r/a \approx 0.60$, respectively.

In the next experiments planned in FTU, the electron fishbone behaviour will be fully assessed, by exploring the limit cycle phenomenology by means of a higher LH power. In addition, higher electron temperatures will be produced by means of the ECRH power, as useful for further reducing the plasma current relaxation, as well as for enhancing the available FEB camera level useful for improving the precision of the fast electron population modelling.

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