Observation of fishbone-like internal kink modes during LHCD operation in Alcator C-Mod

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I) Introduction and motivation.-

Understanding the formation and stability of three-dimensional (3D) helical modes in the core of an otherwise, axisymmetric toroidal configuration, is still one of the challenges of current fusion research [1-2]. A new set of (m,n)=(1,1) internal kink modes have recently been observed in the Alcator C-Mod tokamak during the operation of lower hybrid current drive (LHCD). The mode appears like periodic bursts in the soft x-ray (SXR) signals as shown in Fig. 1. The first scenario corresponds to a successive train of *m=1* fishbone-like bursts that appear during a sawtooth-free phase of the discharge. The other two cases occurred generally during the sawtooth ramp; the mode grows with a nearly constant frequency close to the frequency of bulk plasma rotation (no chirping), briefly saturates, and finally damps and disappears before the subsequent sawtooth crash [see Fig. 1-b)]; a hybrid sawtooth-mode is also possible [see Fig. 1-c)]. Detailed properties of their 3D structure and their effect on the background plasma are now measured using a full
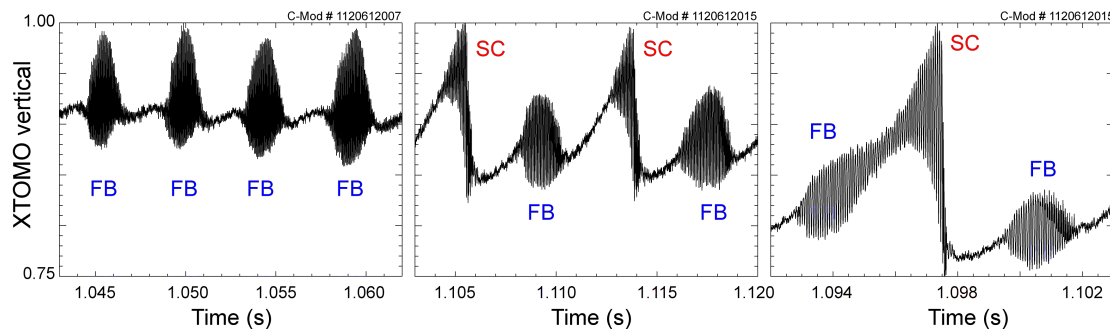

Fig. 1. SXR signatures of the (1,1) mode as well as sawtooth crashes.

suite of spectroscopic imaging diagnostics [2]. The temporal evolution of these modes resembles the so-called "electron fishbones" observed during electron cyclotron resonance heating (ECRH) and LHCD in DIII-D, FTU, Tore Supra, HT-7 and HL-1M (see [3,4] and references therein). The typical plasma discharge parameters were $I_p \sim 0.5$ MA, $B_{t,0} \sim 5.4$ T, $T_{e0} \sim 2.3$-2.9 keV and $n_{e0} = (1.3$-$1.7) \times 10^{20}$m^{-3}. The change in the loop voltage for a total $P_{LHCD} \sim 700$ kW at $n_{||,LHCD} \sim -1.6$ was $\Delta V_{loop} \sim -0.3$ V.

The conventional *fishbones* correspond to the so-called energetic (ion) particle driven instabilities and were observed first PDX during high-β experiments using near-perpendicular (v~ $v_{\perp}$) NBI [5]. The instability appeared in the plasma core and
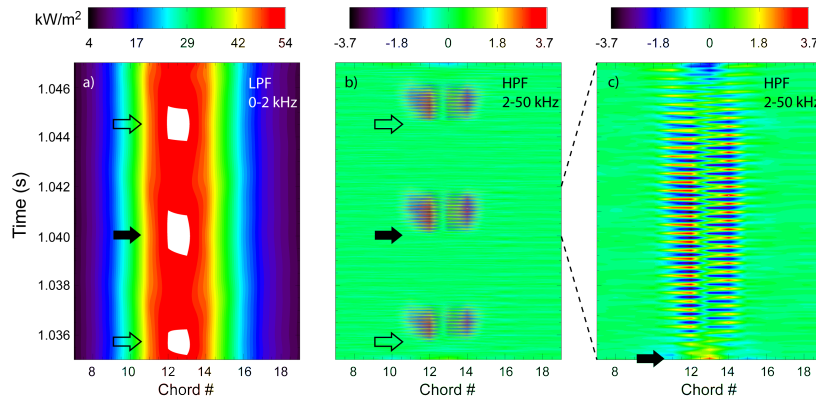
Fig. 2. Low-pass and high-pass filtered SXR brightness profiles indicating that mode is triggered when the background brightness reaches a maximum.

was observed as successive bursts of *m=1* activity on the SXR and Mirnov coils. The MHD activity was correlated with the measured neutron brightness indicating a loss of energetic ions. The two theoretical models [6,7] describing these observations relied on the modification of the ideal stability of the (m,n)=(1,1) internal kink by resonance with a population of energetic ions. A model introduced by Betti and Freidberg [8], postulated that the fishbone destabilization is due to fast ions injected parallel to the magnetic axis, explaining some of the experimental results obtained by Heindbrink [9] during tangential neutral beam injection ($v \sim v_{||}$); in such scenario, trapped particles in the magnetic axis were virtually absent and the destabilization, is parameterized by a poloidal ion $\beta_{hot,i}=p_{hot,i}/(B_\theta^2/2\mu_0)$. Modifications of the tails of the electron distribution function can be obtained similarly using ECRH and LHCD, providing therefore large sources of energetic electrons that can trigger these modes; while the cyclotron technique distorts the distribution function mainly in $v_\perp$ space, affecting the trapped electron population,

Fig. 3. Time history of the peaked SXR emissivities from the core to $\Delta r \sim 13$ cm on the low-field-side.

the LHCD in the core builds a plateau affecting mainly the parallel velocity ($v_{||}$) of the circulating electrons. The study of modes generated by energetic electrons remains a much less explored field than energetic ions.

II) Fishbone-like activity in C-Mod.-

The SXR features of the (1,1) kink-like mode are depicted in Fig. 2. Low-pass (LPF) and high-pass filtering (HPF) of such signals indicates that the mode onset coincides with the peaking or buildup of the background SXR brightness profiles. The time history of the reconstructed emissivity from the outboard side is shown in Fig.3, and confirms the core SXR build-up before the mode onset. These signals also suggest that a redistribution of particles and/or heat of the order of 20% in the core ($\Delta I_{SXR,0} \sim -100$ kW/m³) and just 10% outside the q~1 surface ($\Delta I_{SXR,1} \sim +20$ kW/m³) took place as a result of the fishbone-like mode; the redistribution started though, at the mode onset. The core radiated power measured by an AXUV diode array (not shown here) shows the same trend with $\Delta P_{rad,0} \sim 300$ kW/m³, while $P_{rad}(r>r_{q=1})$ is nearly constant.

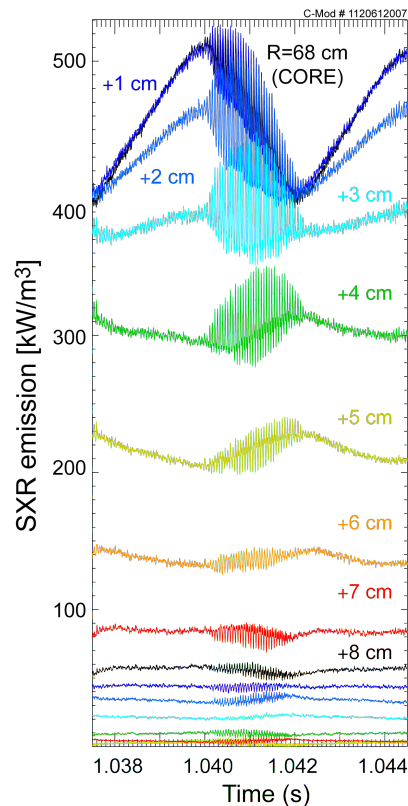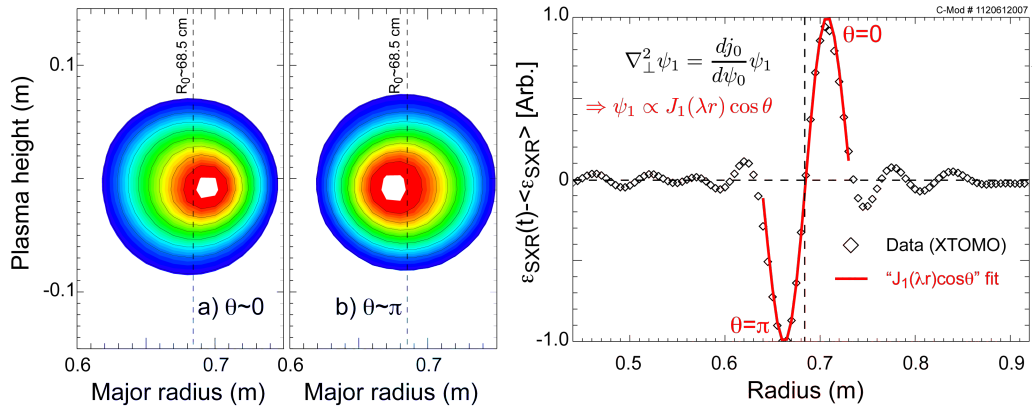Fig. 4 SXR emissivities of the kink-like perturbation in the a) LFS and b) HFS, respectively. c) The perturbation resembles an internal kink with a dependence of the form $J_1(\lambda r)\cos\theta$.
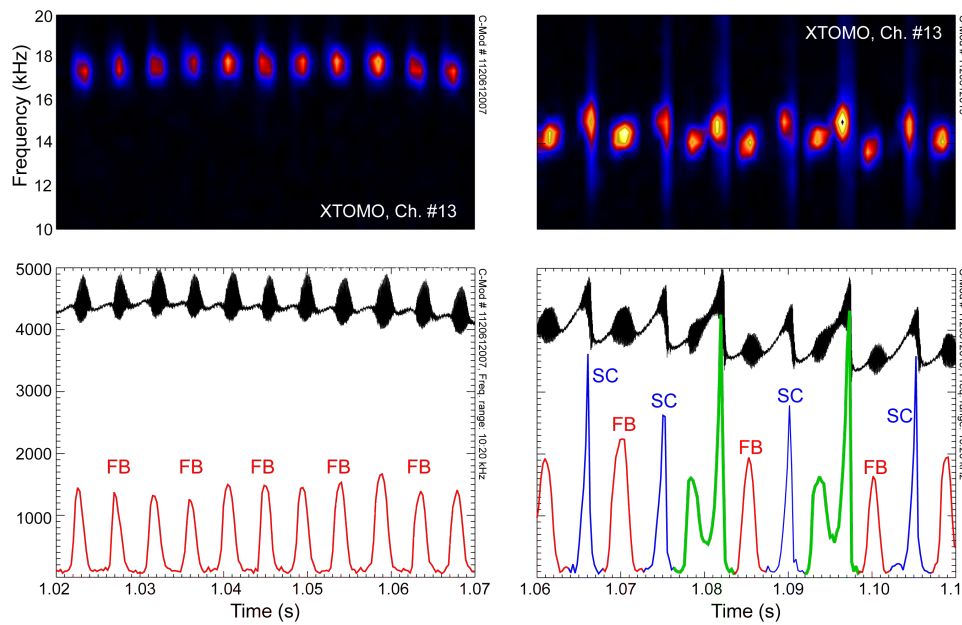

Fig. 5 FFTs and integrated power spectrum (10<f<20 kHz) of the SXR signals (in black).

The SXR emissivities of the fishbone-like perturbation are shown in Figs. 4-a) and b), respectively. The core displacements suggest that mode forms and grows as an ideal (1,1) kink with a nearly circular cross section when the central safety factor q<1 region is small. The fishbone-like perturbation resembles the internal kink solution in a cylinder with a dependence of the form $J_1(\lambda r)\cos\theta$. An electron density perturbation of the order of $\delta n_e \sim 1$-2% was measured using a 10-channel two-color interferometer (TCI) with a chord spacing of $\Delta r \sim 1.1$ cm (not shown here). The mode propagates toroidally in the counter current direction, or alternatively a poloidal motion in the electron diamagnetic drift direction. The frequency of the mode is comparable to the core toroidal rotation and that of the sawtooth precursors (in scenarios when the fishbone-like mode coexist with sawteeth).

As shown in Fig. 5-a), the fishbone-like perturbation has a frequency and amplitude that is nearly "constant" when sawteeth is suppressed, while the properties of sawtooth precursors, fishbones and hybrid modes can be slightly different when all coexist in the same discharge [see Fig. 5-b)]. The time-history traces of the integrated-
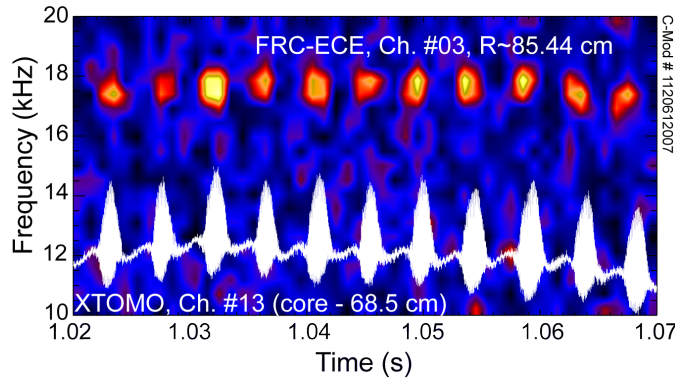
Fig. 6 Core fishbone-like MHD is also detected in edge channels of high resolution FRC-ECE radiometer

power-spectrum also reveal, in the first case, that the fishbone-like MHD occurs every 4-5 ms which is consistent with the rebuilding of the central fast electron population. However, for the second case, it is clear that the (1,1) fishbone-like activity and sawteeth can coexist, suggesting that these bursty-modes have an independent driving mechanism (δW_{hot}) from that of the sawtooth crash ($\delta W_{thermal}$). The mechanism by which this (1,1) coexists with sawteeth is also different than that of the (1,1) impurity snakes observed recently in C-Mod [1-2]. In addition, the crash amplitude of hybrid mode is also greater than individual fishbones and sawteeth.

III) Direct measurements of electron energies and estimates of $\beta_{hot,e}$.-

The time-history of the core signals from the slow ECE grating polychromator (not shown here), suggests that the growth of the mode coincides with a maximum of the density and energy of the non-thermal fast-electrons [11]. A direct estimate of the energy of the fast electrons driving the fishbone-like mode has been obtained though measuring the ECE emission shown for instance in Fig. 6. The core fishbone-like MHD is detected in the <u>edge</u> channels ($2\Omega_{ce}$ is~ 20 cm away from the magnetic axis) of the high resolution FRC-ECE radiometer [10]. A possible explanation of this observation is the well-know downshift of electron gyrofrequency due to relativistic effects given by, $\Omega_{e,rel}=leB/\gamma m_e$, where l is the ECE harmonic, $\gamma=(1-\beta^2)^{-1/2}$ and $\beta=v/c$. With the assumption of a 1/R dependence for the toroidal field it is possible to calculate that $\gamma=1.24$ and the electron energy is of the order of 122 keV. A first estimate of $\beta_{hot,e}$ at the q=1 surface, constrained by the density of fast electrons and an average electron energy between $3v_{th,e}$ and $n_{||}=c/v$, is of the order of 5%. Better estimates of $\beta_{hot,e}$ will be computed using the moments of the electron distribution functions obtained using CQL3D [11].

In summary, the (1,1) internal kink appears to be destabilized by the fast-electron pressure carried by the suprathermal electrons, which explains its independence from the sawtooth cycle. This is a new explanation for the so-called electron fishbones [11]. This work was performed under US DoE contracts including DE-FC02-99ER54512 and others at MIT and DE-AC02-09CH11466 at PPPL.

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