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Experimental characterization of *M-Mode* in JET tokamak

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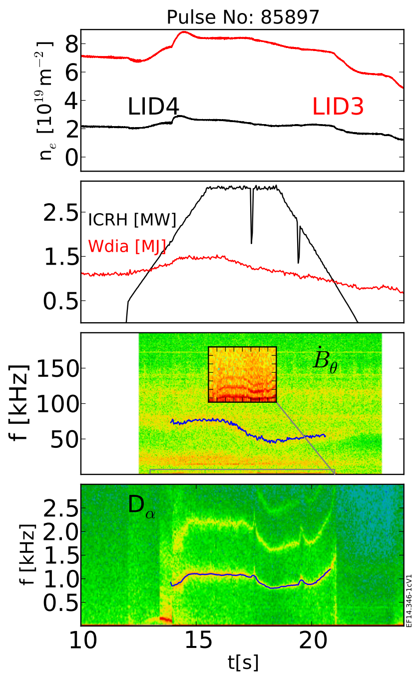

Figure 1: From top to bottom: Core(red) and edge(black) line integrated density, ICRH power (black) and W_{dia} (red), spectrogram of $\dot{B}_\theta$ and spectrogram of D_α

In recent years detailed investigations on the L-H transition in tokamaks have revealed that at power close to the L-H power threshold an intermediate oscillatory phase between the L and H phases exists [1]. This phase, generally appearing prior to a final transition to a proper H-Mode, is characterized by *dithering cycles* with periodic oscillations between high and low confinement regime and it has been confirmed in a variety of devices [2–5]. In all these devices the temporal dynamics has been often association to limit cycle oscillations (LCO) describing the interaction between turbulence (generally electrostatic turbulence is considered) and $\mathbf{E} \times \mathbf{B}$ flow, although some of the machines have been observing also a magnetic oscillation during these phases [2, 6, 7]. It is in any case accompanied by periodic oscillations of the pedestal profiles. A weak ELM-free H-Mode regimes, dubbed *M-Mode* has been observed at JET [8], with a clear increase of pedestal density and a weak temperature pedestal. A peculiarity of the M-Mode is the presence of a clear low-frequency coherent magnetic oscillation, with periodicity $(n,m) = (0,1)$ around 1-2 kHz. It has been observed in the pedestal region, as confirmed by ECE, Reflectometer and Li-Beam diagnostic, but it also modulates particle and heat flux at the target as confirmed by D_α, Langmuir probes and fast infrared cameras.

The present contribution will continue the description of the experimental observation associated to this state, highlighting the existence of an associated high frequency magnetic oscillations and the observed modulation of edge and SOL density gradient. In Figure 1 a typical ICRH heated pulse with the appearance of the M-Mode is shown. The M-mode oscillation is clearly visible in the spectrogram of the D_α in the bottom panel where the dominant frequency around 1 kHz and the second harmonic are shown. The mode appears whenever the ICRH power is increased and it is accompanied by a modest increase in the energy content and in the edge and core density. In the same plot the third panel shows the spectrogram of a magnetic pick-up coil located in the HFS. The inset amplify the evolution of the spectrogram in the lower frequency branch where the M-Mode appears but also a second branch at higher frequency (50-80 kHz) is clearly evident. This high frequency branch (HFB) exhibits similar spectral properties with respect to the dominant low frequency oscillation as shown in Figure 2. The HFB has a clear $n = 0$ toroidal periodicity and it is worth noting that these broad-band oscillation is present even before the appearance of the M-mode, marked with a vertical white line. At the appearance of the M-Mode the HFB branch starts pulsating at the characteristic frequency of the M-mode as shown in the bottom panel, where the band-pass filtered $\dot{b}$ signal obtained from two poloidally separated probes are shown. We have marked the typical periodicity of the M-Mode with an arrow and in the smaller inset we provide a zoom on the two signal to highlight that also the HFB maintain the $m = 1$ periodicity. As stated at the beginning the M-Mode is generally observable in different diagnostic apart from the magnetic, both in the pedestal and in the Divertor region. In the top panel of figure 3 the Power Spectral Density (PSD) of the magnetic field (in the HFS of the tokamak, above the equator), is shown together with the same quantity calculated for a fast ECE channel located at the top of the pedestal the reflected phase of the correlation reflectometry Φ_{rfl}. The dominant frequency of the M-Mode, located near 1.5 kHz for this pulse, is clearly visible in all signals together with higher harmonics. The proper phase between magnetic and kinetic fluctuations

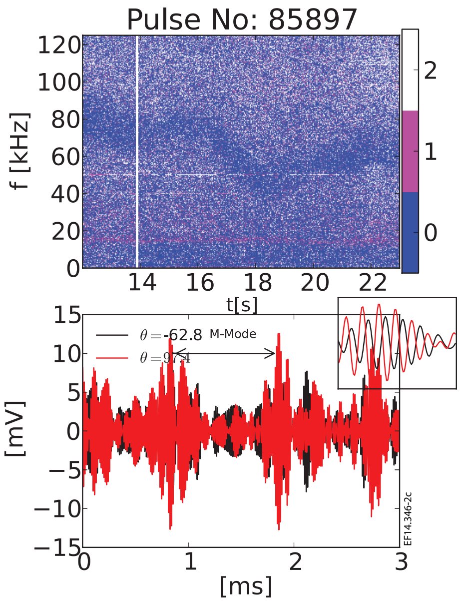

Figure 2: Top:Toroidal mode spectrum. Bottom: zoom on two $\dot{b}$ probe, located at different poloidal position, pass-band filtered between 60 and 80 kHz. The inset magnify the two signals to highlight the poloidal periodicity

(i.e density and temperature) has been analyzed in the frequency domain and shown in the same figure 3.

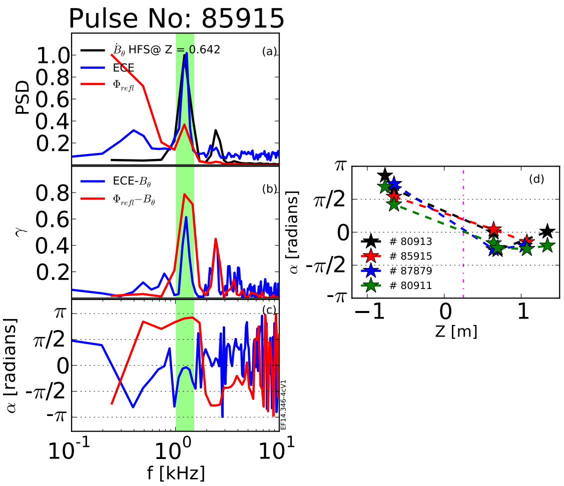

Figure 3: (a) PSD of $\dot{B}_\theta$ (black), ECE Channel (blue), Φ_{refl}(red). Coherence (b) and Phase (c) between integrated magnetic and ECE (blue) and magnetic Reflectometer (red). (d) Phase between ECE and Magnetic field at different Z computed at the M-Mode frequency

The magnetic signal has been integrated with a proper high-pass filtering above 50 Hz and coherence and phase with the ECE and Reflectometer have been computed. The observed high coherence at the mode frequency between magnetic and kinetic signals, ensures that the phase estimate is reliable in this frequency range. Actually, consistently with the idea that the M-Mode is associated to a small up-down motion of pedestal plasma surface [8], the phase is found to depend on the Z value of the chosen probe. In the same Fig. 3 panel (c) we show the phase, between ECE and magnetic field, computed at the M-Mode frequency as a function of the vertical position for a series of pulses. Considering the ECE LOS is located at $Z = 0.248$ we can conclude that, within the uncertainty due to the poloidal resolution, the phase between T_e and b_p is close to zero. We have checked that the same consideration holds for the density oscillations suggesting we have a pressure perturbation in phase with B_θ.

Investigation with a Li-Beam reveals that the entire pedestal gradient is oscillating at the frequency of the M-Mode. The time evolution of the entire pedestal and SOL density profile has been computed using Li-Beam data and a combination of hyperbolic tangent and linear fit (corresponding to the pedestal and SOL region respectively). It has been observed that there is no modulation of the pedestal position neither of the pedestal height, whereas the gradient is found to oscillate at the M-Mode frequency, as confirmed by the figure 4 where phase and coherence between ∇n_e and the integrated magnetic field computed at different vertical position are shown. As done

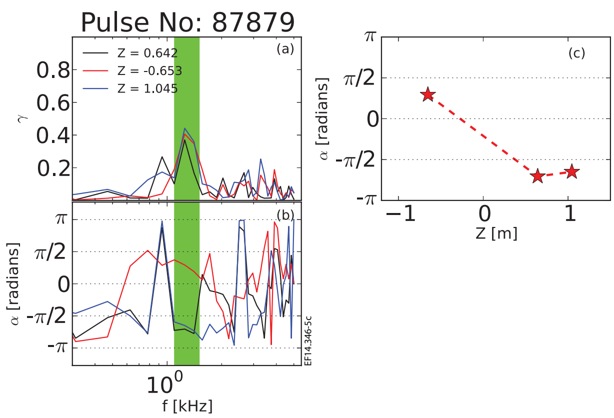

Figure 4: Coherence (a) and Phase (b) between density gradient and magnetic field computed at different poloidal position. (c) Phase computed at the M-Mode frequency as a function of vertical position

for the temperature and density we have also computed the phase at the M-Mode frequency, and 4 (c) shows this phase as a function of the vertical position of the probes. We can conclude that the density gradient is almost in quadrature with the magnetic field.

Finally, hints of the scaling of the Mode frequency with the poloidal Alfvén speed have already been provided [8]. A further consistent observation has been obtained by comparing similar discharges obtained during L-H threshold investigation in Hydrogen and Deuterium plasmas [9]. The two sets have been obtained comparing similar discharges with $I_p = 1.7$MA and B_T=1.8T. The mode frequency has been tracked in time and the scaling with the time evolution of the poloidal alfven speed as computed at $\rho = 0.97$ is shown in the bottom panel of figure 5. Apart from a slight deviation at lower frequency, where we should take into account the feedback system reacting to vertical oscillation at JET, a linear trend is visible, consistent with the poloidal Alfvén speed scaling with an appropriate isotope dependence.

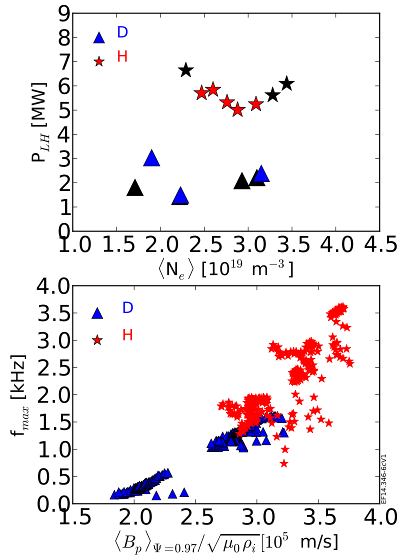

Figure 5: Top: L-H Power threshold vs density for Hydrogen and Deuterium discharges. Bottom: scaling of the M-Mode frequency vs Poloidal alfven speed. The color code is consistent with the top panel

Concluding further investigation of the M-Mode on JET tokamak is reported. The oscillation of the poloidal magnetic field is in phase with density and temperature. An higher frequency broadband fluctuation is observed with the same symmetry of the M-Mode. At the appearance of the M-Mode this HFB starts pulsating. The pedestal gradient is found to oscillate at the mode frequency, resembling similar observation in the dithering or I-phase. The dynamical interplay with the density gradient is presently under investigation. Finally by considering an isotope scaling the dependence of the M-Mode on the poloidal alfven speed has been confirmed.

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