M-mode: axi-symmetric magnetic oscillation and ELM-less H-mode in JET

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Recent experimental studies of H-mode plasmas in JET [1, 2] have revealed an n=0 m=1 magnetic oscillation starting immediately at the L to H transition (called M-mode for brevity). While the oscillation is present a weak ELM-less H-mode regime is obtained (medium confinement), with a clear increase of pedestal density ($n_{e,ped}$) and a weak temperature pedestal ($T_{e,ped}$). In ICRH heated plasmas or low power, low density NBI plasmas the mode and the pedestal pressure can remain steady for the duration of the heating phase, of order 10 s or more. The observed axisymmetric MHD oscillation has period ~ 1-2 ms, and odd parity across the mid-plane: m=1 with $\sin(\theta)$ dependency. Electron Cyclotron Emission, interferometry, reflectometry, SXR and fast Li beam measurements locate the mode in the pedestal region. D_α, fast infrared camera and Langmuir probe measurements show that the mode modulates heat and particle flux to the target. Similar phenomena are described elsewhere [3-8], lately described as an “I-phase”. From a physics point of view, our fundamental observation is that the M-mode is magnetic, not electrostatic, and its frequency scales with pedestal poloidal Alfvén velocity.

Shown in Figs. 1 and 2 are some of the most salient characteristics of the M-mode: the L-H transition is marked by the drop in D_α and rise in line integrated pedestal density. We see that simultaneously a mode appears in the FFT of a Mirnov coil located in the plasma HFS, half-way above the midplane. Further, the FFT of a fast electron cyclotron emission channel in the plasma pedestal indicates pedestal mode-localisation, corroborated by reflectometry

*See Appendix of F. Romanelli et al, Proc. of 24th IAEA Fusion Energy Conference 2012, San Diego, USA

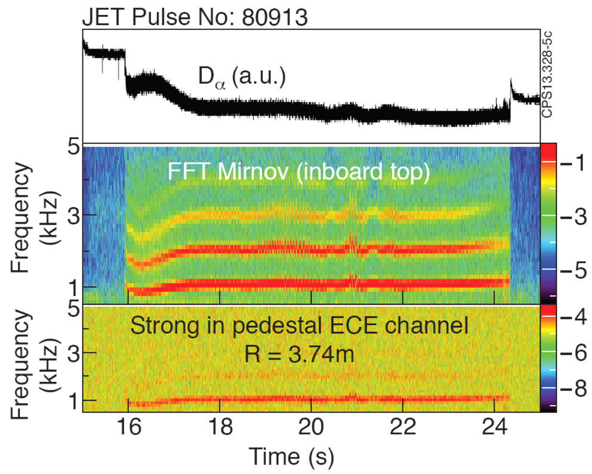

Fig. 1: a) D_α, showing L-H transition;
b) FFT o Mirnov signal at top inboard;
c) FFT of pedestal top ECE signal (R=3.74 m)

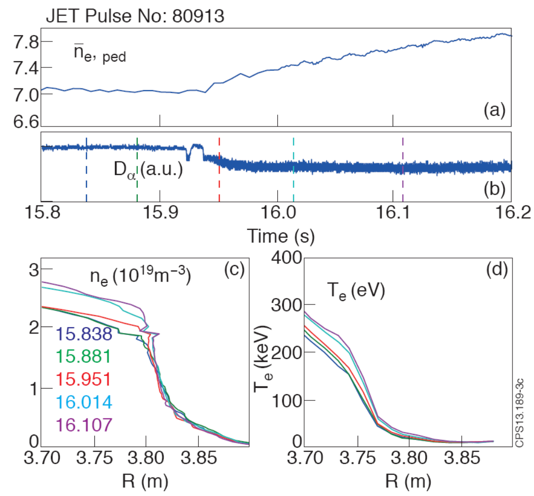

Fig. 2: a) line averaged pedestal density;
b) D_α; c) n_e and d) T_e profile.
Note: radial position of n_e, T_e profiles is uncertain, but steepness and height are well described in c,d).

and Beam Emission Spectroscopy (BES, not shown in figure). Figure 2 illustrates profile evolution, showing an increase in the pedestal density and formation of an electron temperature pedestal. Confinement is "medium": better than L-mode, not as good as in ELM-free or ELMy H-mode. BES (near top of plasma) shows in one pulse that $n_{e,ped}$ changes correspond to a combination of plasma motion and a periodic change in the density gradient.

As shown in Fig. 3 the mode is axisymmetric (n=0), and magnetically similar to very small up-down displacement of the plasma (m=1, sin(θ)). The mode frequency can be as high as 1-2 kHz, too fast to be attributed to global plasma up-down motion, or to be produced by the plasma position control system (its maximum switching frequency is typically set to 600 Hz). This is illustrated in Fig. 4(g), showing a proxy for the "plasma velocity", ~ $I_p dZ_p/dt$, used by the position control system, the corresponding "plasma position" Fig. 4(b) and the current Fig. 4(h) in the vertical position control system. In this case the position control system detects the M-mode pulsation, but only reacts to it some of the time.

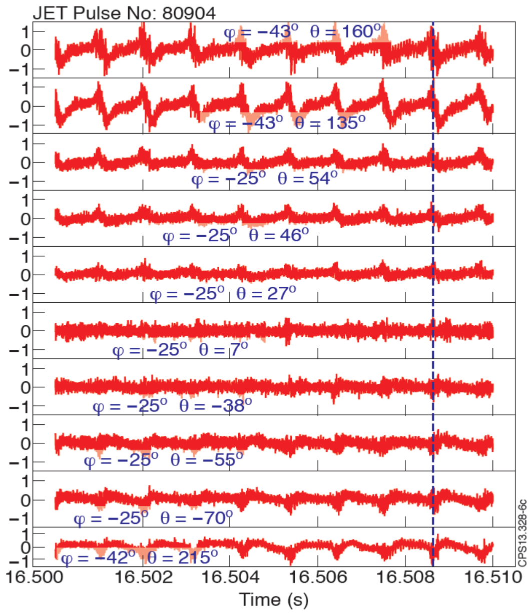

Fig. 3: Mirnov signals from poloidal array, showing mode is m=1, sin(θ). Toroidal array identifies n=0 (not shown).

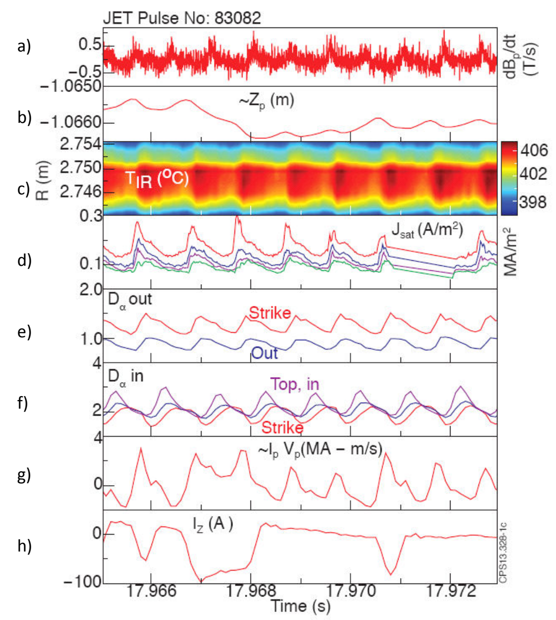

Fig. 4: a) dB_θ/dt from inner Mirnov; b) Proxy of plasma vertical position; c) Temperature profile at outer strike (IR); d) Ion saturation current at outer strike (red), and further out (by 1-2 cm); e) D_α at outer strike (red); f) D_α inner strike (red), others further out; g) Plasma velocity proxy, used for position control; h) current in position control power supply.

Further, in Fig 4 we show that the mode could be considered as a periodic series of L-H-L transitions in phase with the magnetic oscillations: when the plasma is "up" (a) the outer strike temperature (measured with IR) (b), ion saturation current $j_{sat,ion}$ (c) and D_α at the outer strike (d) have a minimum followed by a pulse of heat and particles to the outer strike, without displacement of the strike point. Differently from typical L-H transitions, outer (d) and inner (e) D_a light signals are out of phase during M-mode pulsations.

Albeit the mode was first noticed in ICRH heated plasmas with the ITER-like wall (ILW: Be wall, W divertor target), it is also present in ILW NBI heated plasmas [2]. In both C wall and ILW NBI-heated plasmas the M-mode can be present early in the H-mode, but is usually replaced by oscillations commonly described as type III ELMs.

With ICRH heating and pumped divertor (the majority of the dataset) the mode frequency is proportional to the poloidal Alfvén speed, as shown in Fig. 5 for one pulse in which the density is deliberately increased and decreased. In Fig. 6 we show the estimated $V_{Alfvén,poloidal}$

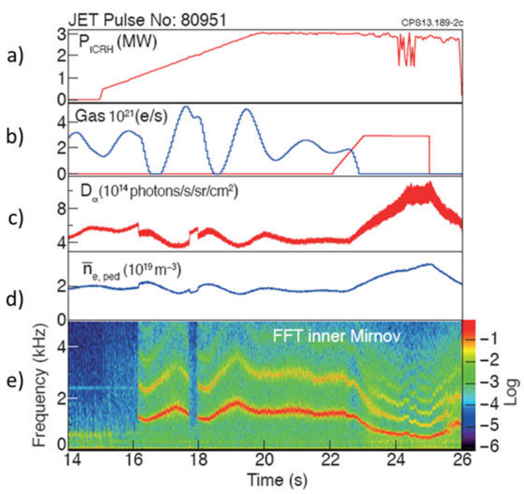

Fig. 5: a) ICRH heating power; b) fuelling from divertor and equator (blue) and from plasma top (magenta); c) D_α; d) line integrated pedestal density; e) FFT of Mirnov coil.

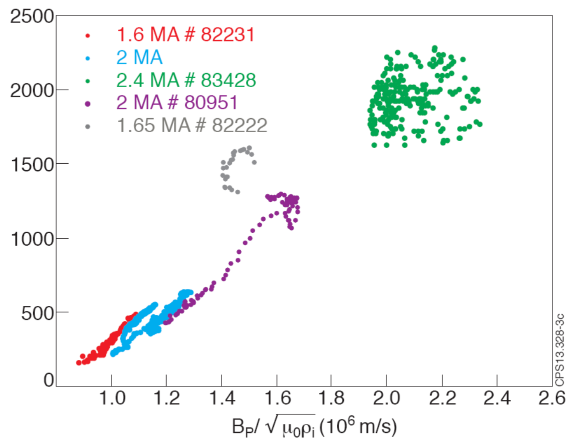

Fig. 6: Relationship between M-mode frequency (kHz) and poloidal Alfvén velocity. Pulse 80951 was shown in Fig. 5, illustrating density dependence at constant current.

vs. mode frequency for various plasma currents. The large scatter in the 2.4 MA pulse is due to sawtooth crashes, which affect mode frequency and both pedestal density and poloidal field in ways unaccounted for by our estimation. In the present dataset mode frequency does not scale with Alfvén velocity (total magnetic field), nor with plasma rotation.Neither is there correlation between mode frequency and ion sound speed, implying that the M-mode is not a Geodesic Acoustic Mode.

Is this an I-phase? I-phases are often explained as Limit Cycle Oscillations: a complex interaction between zonal flows, turbulence, GAMs and mean flows [8-11]. To our knowledge none of those electrostatic turbulence and transport-related views of the oscillations would lead to a scaling of frequency with $I_p/\sqrt{(m_i\ n_e)}$. Nevertheless, magnetic modes with n=1 and frequencies of order 10 kHz are sometimes associated with M-modes at JET, they could be magnetic consequences of GAMs, we do not discuss them here.

We are not aware of any theoretical model that relates poloidal Alfvén frequency with the L-H transition, nor with any n=0, m=1 MHD wave. We consider it likely that the frequency of an axi-symmetric Alfvén mode would scale with the poloidal field. But this is not just a conventional surface Alfvén wave, which would be parallel to the poloidal field. We propose that it is actually similar to a hydrodynamic internal wave, as described in textbooks [13]. In those waves the relation between wave frequency and velocity in a cylindrical model would be given by $\nu = \left(k_\theta^2/k\right)V \simeq \left(\lambda_r/\lambda_\theta^2\right)V_{Alfven,pol}$, which would match the plots in Fig. 6 if the radial scale length was of order a few cm and the poloidal scale length the perimeter of a flux surface in the pedestal. The density scale length in the pedestal region in M-mode is of order 3- 6 cm, so this formula may actually match the observations. But we do not have a proper MHD derivation for it yet, nor can we analyse the complete dataset of pedestal widths.

In summary: we find that the M-mode is an n=0, m=1 magnetic pulsation intimately correlated with a series of periodic L-H transitions. Its frequency is proportional to the Alfvén poloidal velocity and it could be related to an internal wave, localised in the pedestal.

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