

High Temperature Pedestals in JET and confined current filaments

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High temperature pedestals can be obtained in JET, transiently, by reducing recycling and operating at initially low density in the hot ion H-mode regime [1]. The L-H transition occurs at low density, and after the transition the pedestal density, rotation and temperatures rise up until the occurrence of the first natural ELM. Recent examples at JET reach $T_{e,ped} = 2.8$ keV before the 1st ELM. Often the obstacle to reaching higher pedestal temperatures is MHD. Here we report on MHD observations in hot ion H-modes in high triangularity plasmas with 2.5 MA, 2.7T and 15 MW of Neutral Beam Injection heating.

During the ELM-free period of hot-ion H-mode plasmas MHD instabilities known as Outer Modes (OM) in JET are sometimes observed [2,3]. Time traces of an especially long OM are shown in Fig 1: D_α , electron density n_e , electron and ion temperature (T_e and T_i) and toroidal rotation frequency (f_{tor}). The profile quantities are taken at $R=3.78$ m, the top of the pedestal, inboard of the pedestal knee. Also shown is the spectrum (FFT) of a Mirnov coil. At the L to H transition, in this case marked by the initial D_α drop, pedestal values rise as usual. At the time $t = 13.98$ s, D_α rises, while the pedestal T_e begins to drop and the toroidal rotation frequency remains fairly constant. Density continues to rise, albeit slower than before. At the end of the OM the pedestal density has risen from $3.7 \times 10^{19} \text{ m}^{-3}$ to $4.5 \times 10^{19} \text{ m}^{-3}$. The D_α drop signals the end of the very high confinement phase of the ELM-free period, coinciding with the appearance of the OM. The H factor drops down from a maximum value of $H_{98}=1.4$ to a steady value of $H_{98}=1.1$ at the outset of the OM. A comparison of the profiles of rotation,

[†] See Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. FEC Geneva, 2008) IAEA, (2008)

density and temperatures is shown in Fig. 2. After the first ELM the pedestal density rises to $5.6 \cdot 10^{19} \text{ m}^{-3}$ due to impurity penetration [4] and thereafter $n_{e,\text{core}}$ rises slowly during the ELM phase. In this particular pulse the OM survives 2 sawtooth crashes, indicating that it is a robust feature of the plasma. There is a brief quiet interval between the end of the OM at 15.375s and the ELM at 15.430 s, indicating that the OM is not an ELM precursor, but a different instability. In this particular pulse the OM does not return after the first ELM. In other pulses it sometimes returns with ever decreasing duration some hundreds of ms after the first few ELMs. The OM often appears when recycling and fuelling are particularly low, and it can be reduced or eliminated by increased fuelling. The ELM-free period is prolonged by the presence of the OM: a pulse with the same conditions but more fuelling ($1.9 \cdot 10^{21}$ instead of $1.5 \cdot 10^{21}$ e/s, note both values are very low) had no long-lived OMs and the first ELM occurred 1s sooner, at 14.4 s.

The most clear signature of the OM is in the FFT of the Mirnov signals: its harmonic structure, shown in Fig 1.e. The fundamental harmonic has frequency $f=6$ kHz and toroidal mode number $n=1$, and every subsequent harmonic has n increased by 1. Typically harmonics are seen up to 45 kHz ($n=7$), but the mode is sometimes clearly recognisable up to 90 kHz ($n=15$). This rich harmonic structure is a clear indicator of strong localisation of the current source that produces the magnetic fluctuation. But the raw magnetic signals contain more information than their spectrum. Plotted in Fig. 3 are signals from a toroidal array of Mirnov coils, measuring the vertical field at different toroidal angles around the device. Plotted at the bottom of the same figure is an integrated signal: discrete blips can be clearly seen, propagating toroidally with $f=6$ kHz, due to a localised current structure. The sign of the blips indicate that this co-rotating current structure carries excess current relative to the axisymmetric equilibrium current profile. Since the current feature is long-lived, it must be located inside the separatrix, and must be aligned with the magnetic field at a rational surface. Analysis of the magnetic signals show that the current structure is best simulated as a current ribbon with excess current of 100-200 A, with $n=1$, $m=4$, rotating toroidally at 6 kHz, as illustrated in Fig. 4. Data in 1 inboard coil is substantially better fitted by $q=4$ than by $q=2$, but none of the other coils can distinguish these two cases.

The spectra of various fluctuation measurements show multiple harmonics of the mode near the gradient region. Interferometry indicates that the mode is strongest at the iso-density layer with $n_e=2.5 \cdot 10^{19} \text{ m}^{-3}$ early on. Towards the end of the OM the pedestal density has risen and the mode becomes visible at $n_e=5 \cdot 10^{19} \text{ m}^{-3}$, inboard of the density pedestal. Fluctuations of

D_{α} , Electron Cyclotron Emission in the T_e gradient region and edge channels of Soft X-Rays, all show at least 3 harmonics of the OM. Fluctuations of n_e and T_e are localised by $|B|$ and are particularly sensitive to gradients: it is not possible to establish from these measurements if the current ribbon is located at the top of the pedestal, where their sensitivity is much reduced. Data from high field side ECE channels show that the OM is not a tearing mode [5].

Characteristic profiles at the onset and at the end of the OM were shown in Fig. 2a and 2b. From the charge-exchange measurements of the toroidal ion rotation frequency and in the usual assumption that the fluid velocity is dominated by the ion velocity, we can identify the radial position of the current ribbon. Early in the OM it appears that the location of the mode is as the top of the density pedestal, at the edge of the ion rotation gradient region, inboard of the maximum pressure gradient. At the end of the OM the toroidal rotation shear is greatly eroded and the mode is located in the toroidal rotation gradient region, albeit still inboard of the density and temperature high gradient regions.

The heat flux to the outer divertor target was measured with a fast Infra-Red (IR) camera, with a frame rate especially set to $1/38\mu\text{s}$, and an integration time of $27\mu\text{s}$. Soon after the mode onset the average heat flux to the outer target rises from $10\text{-}15\text{ MW/m}^2$ to 25 MW/m^2 . Periodically ($1/6\text{ kHz}$), bursts of heat arrive away from the maximum deposition location, as shown in Fig. 5. Both, overall transport, and a time-localised “hose-pipe” contribute to target heat flux during the OM. This is most easily explained by a mixture of confinement deterioration and homoclinic tangles [6]. A rotating even mode at the top of the pedestal could produce partial ergodisation of field lines in the pedestal region, increasing overall heat flux. At a specific toroidal location a particular flux tube can escape through the broken X-point and deliver intermittent heat flux away from the main strike position.

A linearized ideal MHD analysis (Mishka-1 [7]) before the OM shows the plasma is far from the $n=1$ instability boundary. Earlier understanding of the OM as an external kink [3] may need to be revisited. A vortex solution of ideal MHD is a non-linear effect driven by $j \times B$ and it is unlikely to be picked up by linear codes. We speculate that either the high $T_{e,\text{ped}}$ and/or the high rotation velocities present in the plasma before the mode onset leads to the circumstances necessary for current filaments (MHD vortices) to form and survive.

Note that the OM is very similar to the Edge Harmonic Oscillation of Quiescent H-modes of DIII-D and AUG, as described in [8,9]. Further studies of this phenomenon in JET may enable us to design OMs and QH phases for ITER operation.

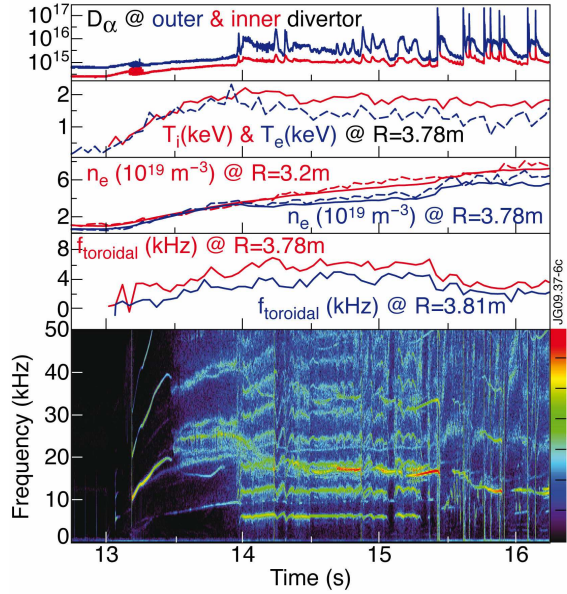


Fig. 1: time traces of a hot ion H-mode interrupted by an Outer mode, see text.

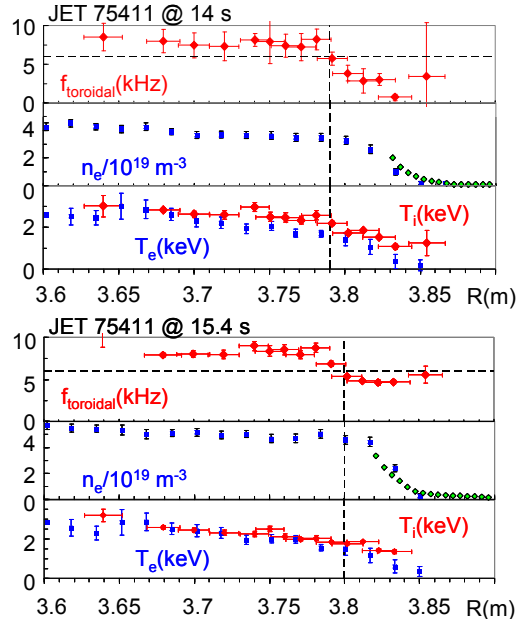


Fig. 2: profiles of toroidal rotation frequency, n_e , T_e , T_i start (top) and end of OM.

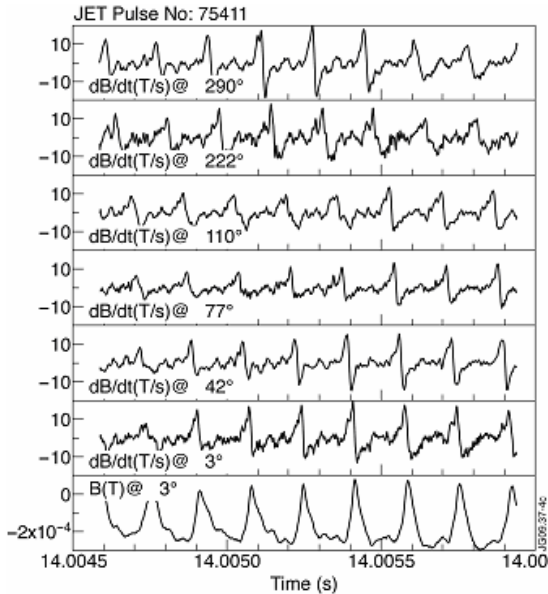


Fig. 3(left): Mirnov coil signals from toroidal array, showing toroidal propagation of current feature in co-current direction. The lowest plot is the integrated signal from coil at 3°

References

[1] JET Team, presented by P.J. Lomas, Plas. Phys. & Contr. Nucl. Fus. Res. 1994 (Proc. 15th Int. Conf. Seville, 1994), Vol. 1, IAEA, Vienna 211 (1995).
 [2] M.F.F. Nave et al [Nucl. Fusion 35 409](#) (1995)
 [3] G.T.A. Huysmans et al, [Nucl. Fusion 38, 179](#) (1998)
 [4] P. Belo, this conference, P2.165.
 [5] L. Barrera, this conference, P5.171.
 [6] T. E. Evans et al [J. Phys.: Conf. Ser. 7 174](#) (2005)
 [7] A.B. Mikhailovskii et al, Plas. Phys. Rep. 23, 844 (1997)

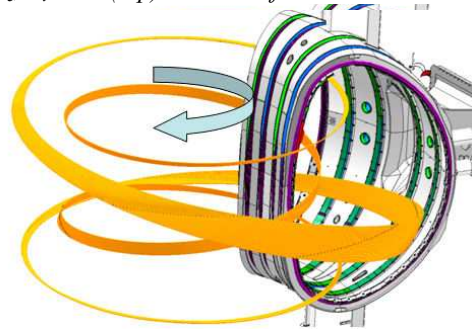


Fig.4: $q=4$ current ribbon that provides best fit to magnetic signals from Mirnov coil set, with current 100-200 A.

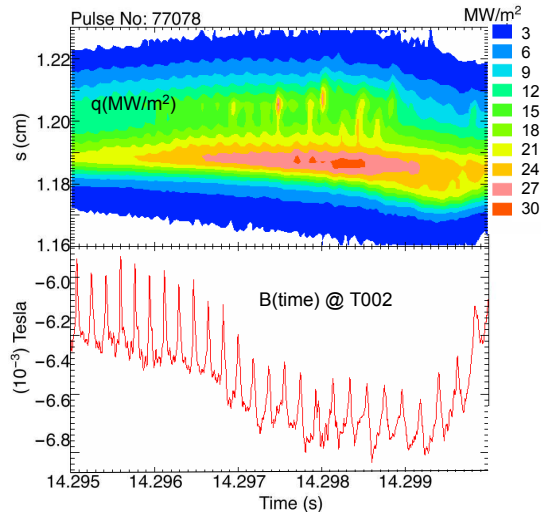


Fig. 5: heat flux contours at outer strike are, measured with IR, and integrated magnetic signal showing synchronisation of heat pulses with OM.

[8] K.H. Burrell et al, Phys. Plas., 12, 056121 (2005)
 [9] W. Suttrop et al, Nucl. Fus. 45, 721 (2005)