Dynamic of density profiles in JET during slow L-H transition

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I. Introduction

In tokamaks, the H-mode is characterized by density and temperature pedestals that build up at the L-H transition. During JET 2012 campaign, discharges were carried out with a smooth increase of heating power to compare the L-H transition threshold in JET-C and JET-ILW [1]. In these discharges, plasma passed through intermediate regimes between the L-mode and the H-mode: divertor oscillation [2] and M-mode [3]. The divertor oscillation (DO) is characterized by a periodic (typ. 10 ms) oscillation of plasma radiation with an opposition of phase between the inner and outer side D_α signal. Although reminiscent of the dithering L-H transitions [4], several features distinguish the divertor oscillations. The DO is an oscillation between two different plasma states: firstly the edge plasma density increases with low divertor radiation, secondly follows a sudden decrease of the plasma density with increased divertor radiation [2]. During the high plasma density phase, the plasma stored energy increases slightly whereas dithering cycles are periodic L-H-L transitions at frequency an order of magnitude higher [4].

Improvement of reflectometry [5] data processing to reduce noise and radial jitter allows to follow the dynamic of the density profile during the DO. This study is preliminary; a very limited number of shots were processed. The observations lead us to propose a simple model to explain the periodic density oscillations.

II. Oscillations of density profiles during the DO

In the discharge 83160 shown in this paper, the DO begins with an overshoot of the density profiles followed by periodic oscillations at ~110 Hz during 400 ms (fig 1a). Compared to the average DO profile, the L-mode profile, inside R=3.76m, is lower ($n_e - \langle n_e \rangle_{DO} < 0$, blue

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

on fig 1b). The H-mode (after 54.8s) pedestal profile is much steeper: the density inside R=3.76m is higher (red and yellow) while the density outside R~3.76 is lower (blue).

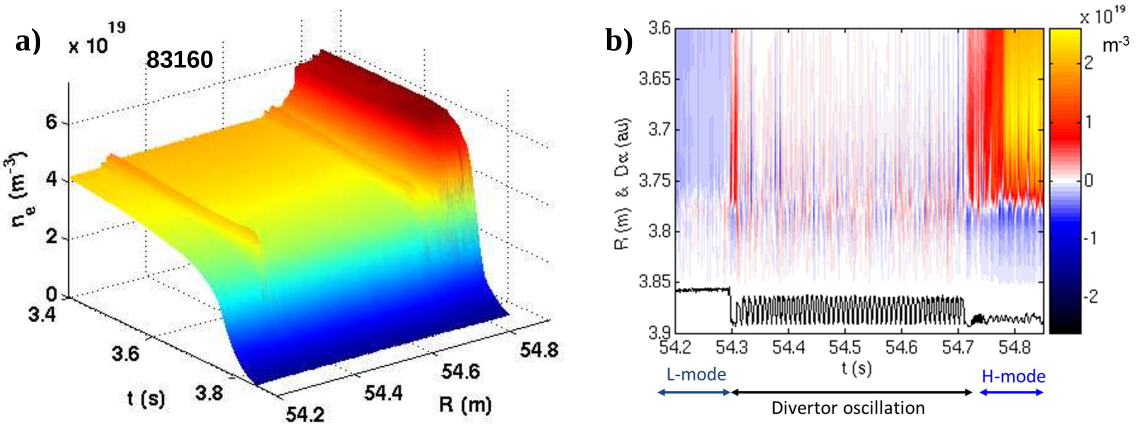

Figure 1a: evolution of density profiles measured by reflectometry every 15 µs (shot 83160). 1b: Density variation $n_e - \langle n_e(54.3 < t < 54.7)\rangle$ after subtracting the average density during the DO period. The H mode transition occurs around t~54.75s. Inner D_α is also shown (black line).

The density oscillates in phase with the inner divertor D_α signal but in opposition with outer divertor D_α (fig. 2a) The oscillations peak inside the pedestal reaching δn~3.10^{18} m^{-3} at R=3.75 m ie δn/n > 10 % (fig. 2b). They are rapidly damped further inside decreasing below 3% or δn~1.10^{18} m^{-3} at R=3.65m and becoming difficult to detect in the core (δn<0.5 10^{18} m^{-3}). This figure shows also that the average reflectometry and High Resolution Thomson Scattering [6] density profiles are in good agreement. The ~2cm radial shift is within the expected global uncertainty on reflectometry position due to uncertainty on magnetic field value B.

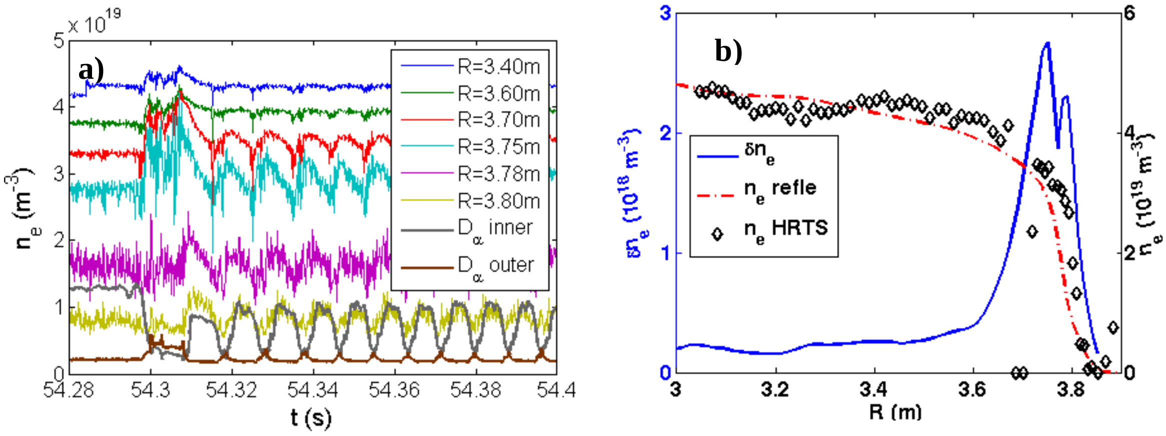

Figure 2 a): Density profile at different radii with inner and outer side D_α signal. 2b): The average oscillation amplitude profile (blue, right axis) peaks near the pedestal top. The density reflectometry (red, left axis) and HRTS (diamonds) profiles averaged over the DO period are also shown.

III. Dynamic of density profiles during the DO phase

The correlation time between the density at different radius and the density at R=3.75cm the position of the oscillation maximum shows that:

- The oscillations start in the region of the maximum amplitude since all delays are positive.
- Inside the pedestal, oscillations are almost synchronized within a small delay (δt<0.5 ms for R<2.76 m).
- The delay increases at the edge, the edge density lagging the pedestal density by 2.5 to 3 ms.

The inner divertor D_α signal is also delayed by 2.5 ms with respect to the density oscillations at R=2.75 m.

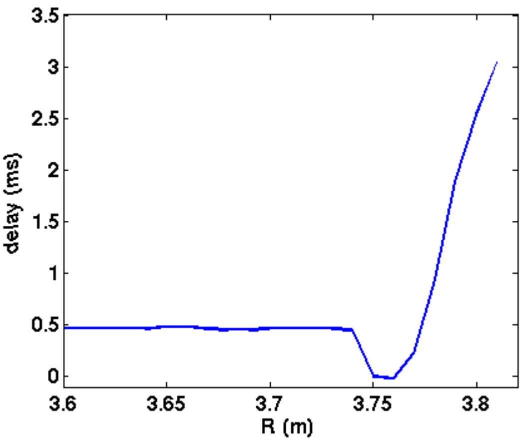

Figure 3: profile of the density oscillation correlation time over the DO period, the reference is at R=3.75m

IV. Delayed plasma fuelling: a model for divertor oscillation?

Observation of this delay between edge and pedestal density leads us to propose a simple model to explain density oscillations. Let us consider the edge (pedestal) plasma particle content $\mathcal{N}$. A single reservoir is introduced assuming that the core particle evolves on slower time. The particle balance for this reservoir is governed by fuelling by ionisation of incoming neutrals and transport losses either to the core plasma or to the SOL and the divertor. Let ϕ_{inj} be the incoming neutral flux with characteristic velocity v_N and let τ_p^e be the particle confinement time in the edge plasma. The particle balance then takes the form:

$$\frac{d}{d\tau}\mathcal{N} = \frac{\mathcal{N}}{\tau_p^e} + \mathcal{N}\frac{\phi_{inj}}{v_N}\langle\sigma v\rangle_i = \frac{\mathcal{N}}{\tau_f}$$

where τ stands for the time, $\langle\sigma v\rangle_i$ is the ionisation rate and τ_f is the effective edge plasma characteristic time $\tau_f = \tau_p^e \frac{1}{1-\tau_p^e\phi_{inj}\langle\sigma v\rangle_i/v_N}$. τ_f is positive during density ramp-up.

In this equation, all the wall out flux as well as the gas injection reach the edge plasma and contribute to the incoming neutral flux ϕ_{inj} as typically in the high temperature divertor regime, the so-called sheath-limited regime. If a fraction of the incoming neutral flux n_N^s is ionised in the SOL and does not reach the edge plasma, the balance equation becomes:

$$\frac{d}{d\tau}\mathcal{N} = \frac{\mathcal{N}}{\tau_f} - \mathcal{N} n_N^s \langle\sigma v\rangle_i$$

Assuming that the divertor screening of the incoming neutrals is typically exponential one then obtains after linearization:

$$n_N^s = \frac{\phi_{inj}}{v_N}\frac{n_{div}\Delta_{div}}{\bar{n}\bar{\lambda}_i}$$

Δ_{div} is the characteristic length of the line of flight along which neutrals can be ionised prior to reaching the edge plasma volume V, $\bar{\lambda}_i$ is the neutral ionisation mean free path at the reference plasma density $\bar{n}$, and, most important for the present model, n_{div} is the characteristic density in the divertor volume. From the previous observations, we suppose that the SOL hence the divertor density is proportional with a delay τ_d (typ. 2.5 ms) to the edge particle content: $n_{div}(\tau) = \alpha\mathcal{N}(\tau - \tau_d)$. The evolution equation is then:

$$\frac{d}{d\tau}\mathcal{N} = \frac{\mathcal{N}}{\tau_f} - \alpha\frac{\phi_{inj}\langle\sigma v\rangle_i}{v_N}\mathcal{N}(t)\mathcal{N}(t - \tau_d)$$

Introducing the time normalisation $t^* = \tau_d/\tau_f$, $T^* = \tau_d/\tau_f$ and the normalized density N^* this system is recast in a generic delayed equation with a single parameter:

$$\frac{d}{dt}N^* = N^*(t^*)\big(1 - N^*(t^* - T^*)\big)$$

This equation is a typical equation for population [7]. For $0 < T^* < \frac{\pi}{2}$, it has stable solutions. Above the threshold $T \geq \frac{\pi}{2}$ oscillatory solutions are obtained, the period being approximately 4 times the delay. The delay of 2.5 to 3 ms between the edge and the SOL density deduced from the edge density profile dynamic would reproduce the 10 ms oscillation period of the pedestal density. Existence of a threshold might also explain the transition from stable (L-mode) to oscillatory densities.

V. Conclusion

Pedestal density profiles steepen and flatten periodically during DO preceding the SOL and Dα oscillations by few milliseconds. A model based on this delay is proposed to explain the oscillations. Although this model gives the right range for the oscillation period, more elements (Zonal Flows, turbulence) are probably required to explain other DO characteristics like the light confinement increase, the phase opposition between inner and outer divertor D signal.

Acknowledgment

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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