

Self-Sustained Divertor Plasma Oscillations in the JET Tokamak

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A bifurcative behavior of the divertor and edge plasma with self-sustained oscillations has been observed in the JET tokamak. Two plasma states are observed with high and low divertor densities. The oscillations between these two states are observed only within a certain core plasma density range and for input powers above a threshold. The change of divertor state has sizable effects on the main plasma leading to inverted density profiles and a clamping of the edge temperature which adversely influences the access to the *H*-mode regime.

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The simultaneous achievement of high density and high temperature plasmas is the main objective of controlled thermonuclear fusion research. Up to the present, the most successful scheme to approach this goal is the tokamak with a poloidal divertor, which separates the bulk plasma from the wall of the vacuum vessel by means of magnetic fields. Tokamaks operating with such a magnetic configuration can access regimes of improved energy and particle confinement (*H*-mode) [1], when the power used to heat the plasma exceeds a certain threshold. However, obtaining good plasma confinement in tokamaks at high densities and high levels of input power still remains a challenge [2]. In this paper, we describe new oscillatory phenomena observed in the Joint European Torus (JET) tokamak at medium/high densities and power levels close to those needed to achieve the transition to good confinement. We will first describe the experimental observation of this phenomenon and its comparison with other plasma processes observed at high densities, such as divertor detachment. Second, the effect of this oscillatory behavior on the main plasma and on the achievement of good confinement (*H*-mode) will be described. Finally, the experimental observations will be succinctly compared with theoretical predictions for the plasma edge [3,4]. From this comparison, it is postulated that the oscillatory behavior reported here constitutes a basic physical process at the edge plasma of fusion devices. This process is shown to influence the access to *H*-mode regimes and, thus, deserves more detailed experimental characterization and theoretical studies.

Oscillations at the plasma edge during *L*-mode discharges have been observed experimentally in several divertor tokamaks [5–9] and have been attributed to movements of the impurity radiation region and/or the formation of multifaceted asymmetric radiation from the edge (MARFEs). In this Letter, we present the experimental evidence from JET with the Mk I divertor showing such an interpretation to be invalid and, furthermore, demonstrates the existence of two plasma edge states between which the plasma oscillates. The conditions for

existence of these states and their physical characteristics are in good agreement with predictions from theoretical models based on the slow variation of the total particle content at the edge plasma of fusion devices [3,4].

The typical conditions for which these oscillations are observed are shown in Fig. 1. Starting at moderate core plasma densities ($\sim 2.5 \times 10^{19} \text{ m}^{-3}$) in the *L*-mode regime, the plasma density is increased by deuterium gas fueling. Once a sufficiently high density is achieved, the main plasma density and radiated power oscillate in a characteristic fashion, until the main plasma density increases further and the oscillations cease (at 17.7 sec). If the gas fueling rate is then decreased, the sequence of events is repeated in reverse order. Therefore, this phenomenon is not linked to high fueling rates but to the value of the plasma density itself. The oscillation cycle has two phases: one in which the main plasma density

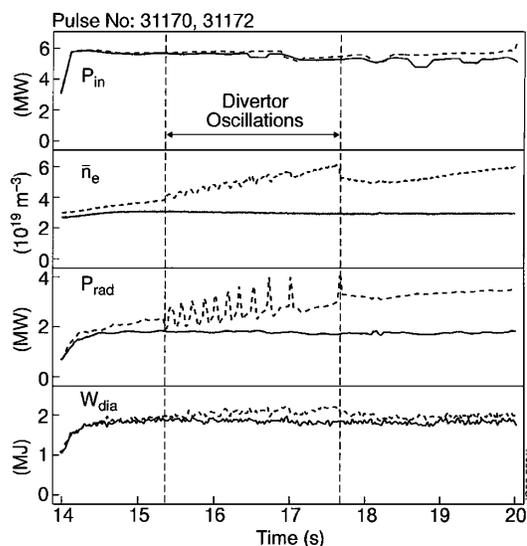


FIG. 1. Onset of divertor oscillations at high density for JET Mk I *L*-mode (2 MA/2.8 T) discharges (P_{in} is the input power, n_e the plasma line average density, P_{rad} is the total radiated power and W_{dia} is the plasma stored energy).

increases (mainly in the edge region $r/a \geq 0.75$) with low divertor radiation, and, second, followed by a sudden decrease of the main plasma density with increased divertor radiation. During the high main plasma density phase, the plasma stored energy increases slightly, reaching values $\sim 20\%$ higher than similar L -mode discharges. After the oscillations cease, the divertor plasma evolves towards the detached state and the radiated power increases to higher values than those measured at the beginning of the oscillation phase. This oscillatory regime is achieved only when the input power is sufficiently high (~ 5 MW for 2 MA/2.8 T discharges in JET) and the plasma remains in the L -mode. When the power is increased further, the plasma finally enters the H -mode, and the divertor oscillations stop [10]. The fact that this regime is a L -mode regime throughout and not an incipient form of the H -mode state is demonstrated later in this Letter. The toroidal field for the experiments described in this Letter was directed clockwise (looking from the top of the torus) which corresponds to the favorable grad-B (forward) direction for access to H -mode. Some experiments were carried out with the opposite direction of the toroidal field with the JET-Mk I divertor. However, it proved difficult to obtain discharges with high plasma density at similar L -mode powers without disruptions. Therefore, no comparable dataset with the reversed field direction could be obtained.

The changes at the edge of the main plasma and in the divertor during these two oscillatory phases are shown in Fig. 2. We will concentrate upon the inner divertor, which we believe is driving the phenomena. During the low edge density phase (measured at $r/a = 0.97$), the ion flux and

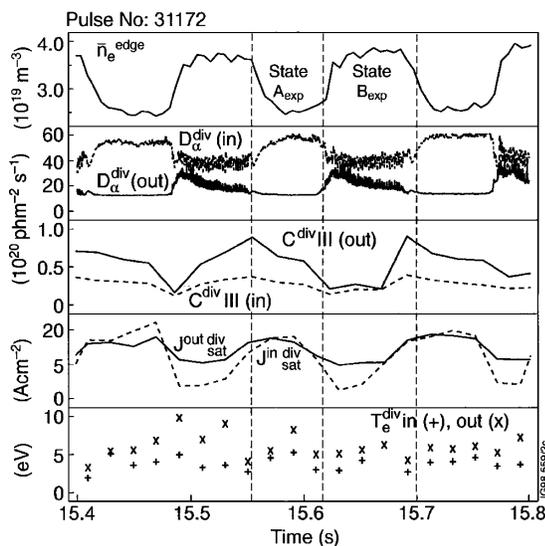


FIG. 2. Evolution of the line averaged plasma edge density (n_e) and the divertor parameters during the oscillations. D_α and CIII ($\lambda = 465$ nm) emissions are averaged for either divertor, J_{sat} is the measured ion flux at either divertor, and T_e is the electron temperature (the in and out sub/superscripts indicate the inner and the outer divertors, respectively).

D_α emission have large values typical of a high recycling divertor (state A_{exp}). As the edge density increases the ion flux and D_α emission decrease simultaneously (state B_{exp}) together with the divertor radiation (not shown). The inner divertor electron temperature remains at $\sim 3\text{--}5$ eV during the oscillations. Such experimental behavior is quite different from that seen at plasma detachment where the ion flux to the inner divertor decreases but the D_α emission increases [8]. In contrast, the processes occurring at the outer divertor indeed resemble those seen during plasma detachment since, as the edge density increases, the outer divertor ion flux decreases and the outer divertor D_α emission increases. The visible bremsstrahlung ($\lambda = 523.5$ nm) and divertor D_α emission for the oscillations are shown in Fig. 3. During detachment both the divertor D_α and bremsstrahlung emission have a third peak in the vicinity of the X point (MARFE) [8] not seen during the divertor oscillations (Fig. 3).

The peculiar in/out divertor D_α behavior is driven by the neutral pressure in the divertor region as shown in Fig. 4. The neutral pressure under the plasma at the inner divertor ($P_{\text{neut}}^{\text{div}}$) oscillates in phase with the D_α emission from the inner divertor, while the neutral pressure in the private flux region of the divertor ($P_{\text{neut}}^{\text{PFR}}$) increases as $P_{\text{neut}}^{\text{div}}$ decreases. Therefore, it is justified to describe state B_{exp} as a low inner divertor density state, since the ion flux and neutral pressure remain low during that phase, together with the divertor radiation, despite the increase of the edge density. This is in contrast to detachment processes, in which only the ion flux decreases but the neutral pressure and radiation remain high [8], and to the H -mode transition [1], in which the neutral pressure

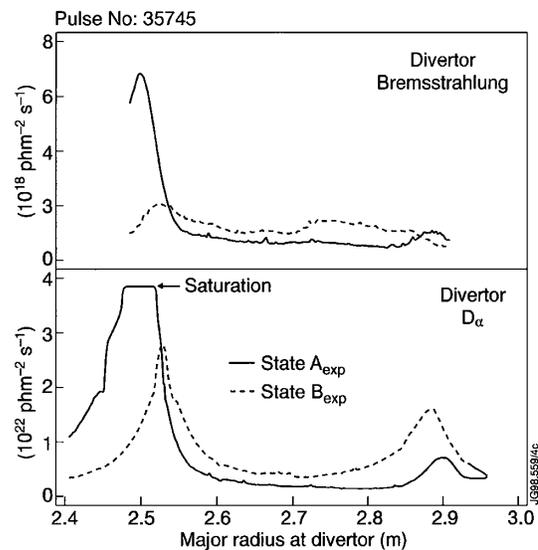


FIG. 3. Divertor D_α and bremsstrahlung emission ($\lambda = 523.5$ nm) for a L -mode discharge with divertor oscillations between states A_{exp} and B_{exp} . The D_α signal from the inner divertor in the region $2.47 \geq R \geq 2.52$ m is saturated during state A_{exp} .

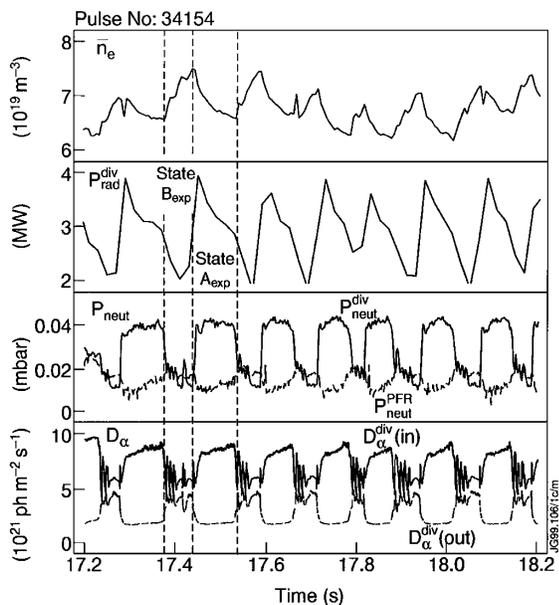


FIG. 4. Line average density (n_e), divertor radiation ($P_{\text{rad}}^{\text{div}}$), neutral pressure at the inner divertor ($P_{\text{neut}}^{\text{div}}$) and in the private flux region ($P_{\text{neut}}^{\text{PFR}}$), and inner/outer divertor D_α emission for a L -mode discharge with divertor oscillations. The oscillations seen in the D_α signal during the low $D_\alpha^{\text{div}}(\text{in})$ phase (state B_{exp}) are sub-oscillations similar to the main ones but at much higher frequency.

decreases everywhere (divertor and main chamber) due to the improvement of core particle confinement.

During divertor oscillations, the radiated power (measured by bolometers and VUV spectroscopy) oscillates in antiphase to that of the edge and main plasma density (see Fig. 4). Most of this oscillation in the divertor radiation is attributed to the radiation at the inner divertor. The atomic species that contribute to the radiation in JET can be determined by VUV spectroscopy [11] and are mainly hydrogen and carbon. Carbon radiation in the divertor is seen to affect the value of the density at which the oscillations are observed but it is, however, not the driving mechanism behind these phenomena. The inner divertor radiation is typically dominated by hydrogen emission throughout both phases of the oscillation.

The observed moderate increase of the stored energy (shown in Fig. 1) for state B_{exp} compared to A_{exp} is associated with the formation of hollow density profiles in the main plasma. A comparison of the main plasma n_e and T_e profiles for a discharge which enters the H -mode after the oscillatory phase (due to the increase of the input power), is shown in Fig. 5.

Several features distinguish the divertor oscillations from dithering L - H transitions. For instance, state B_{exp} (high edge n_e) has an improved energy confinement (by up to 20%) compared to state A_{exp} (low edge n_e) and with a larger outer divertor D_α emission. This is in contrast to standard L - H transition observations which link decreasing outer divertor D_α emission with the

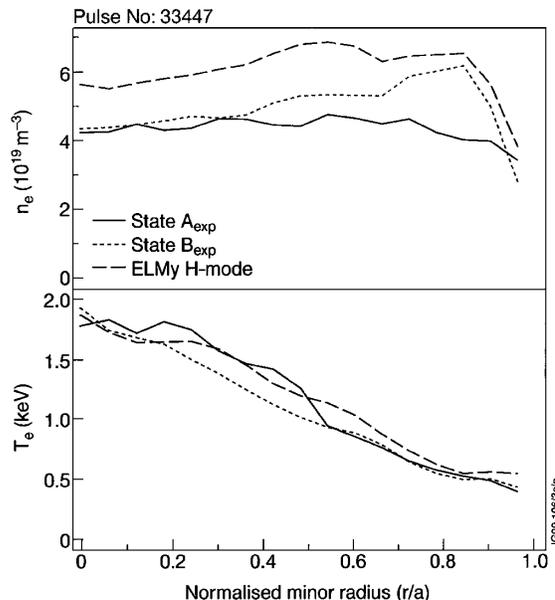


FIG. 5. Main plasma electron density and temperature profiles during divertor oscillations. A reference H -mode profile obtained later in the discharge is shown for comparison. The hollow density profiles during state B_{exp} are clearly seen.

H -mode transition and improved confinement [12,13]. Furthermore, the electron temperature at the plasma edge remains constant during the oscillations. The larger stored energy of state B_{exp} is due entirely to the increase in edge density, as the T_e profiles do not show the formation of a pedestal at the plasma edge in the transition from state A_{exp} to state B_{exp} , typical of H -mode transitions. An illustration of the differences between conventional L - H transitions and that of an oscillatory L -mode is shown in Fig. 6, by means of the edge operational space diagram [14]. In this diagram, the measurements of the edge T_e and line averaged edge n_e (both at $r/a = 0.97$, i.e., ~ 3 cm from the separatrix) are plotted for two consecutive 2 MA/2.8 T discharges: one at high power (~ 10 MW), which undergoes a L - H transition followed by type-I edge localized modes (ELMs), and the other at lower power (~ 5 MW), which remains in the L -mode and exhibits divertor oscillations. In both cases, the edge T_e increases with the additional heating (Ohmic to L -mode) and then remains constant during the L -mode oscillatory phase. In the H -mode case, both n_e and T_e increase after the L - H transition until the ELM pressure limit is reached (type-I ELMs). For the oscillatory L -mode instead, there are large increases in the edge n_e (2.4 – $3.5 \times 10^{19} \text{ m}^{-3}$) at an approximately constant T_e (~ 550 eV), which is much lower than that needed to achieve the H -mode regime in these conditions (~ 880 eV) [10].

The effect of the oscillations to maintain a low edge T_e has sizable effects on the power required to achieve the H -mode. An example of this is shown in Fig. 7, where two discharges with similar densities at the beginning of the L -mode phase are compared. The discharge with slightly

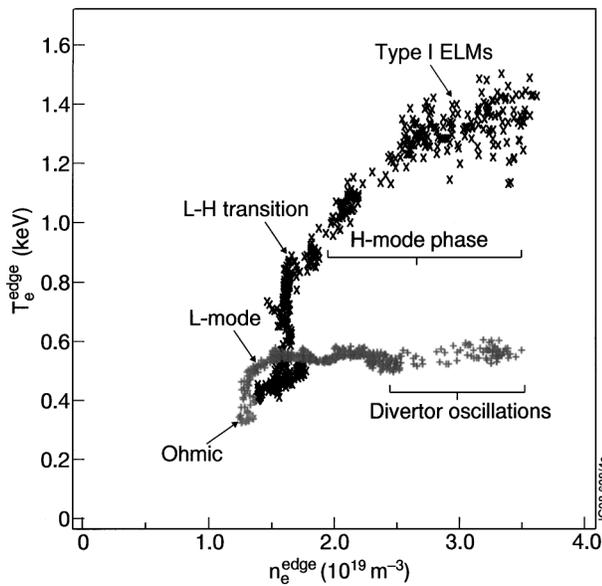


FIG. 6. Evolution of the edge density and temperature (at $r/a = 0.97$) for two similar discharges (2 MA/2.8 T): one with $P_{input} \sim 10$ MW undergoes a $L-H$ transition and reaches a type-I ELMy H -mode regime; the other with $P_{input} \sim 5$ MW exhibits a L -mode oscillatory regime when the edge density increases above $2.4 \times 10^{19} \text{ m}^{-3}$.

higher density/power develops into an oscillatory L -mode at 15.5 sec, which lasts until 19.4 sec, in which the plasma enters the H -mode, as seen by the ELM spikes in the divertor D_α , for an input power of 9 MW. The D_α spikes

in between major oscillations (clearer from 18 to 19.4 sec) are associated with sub-oscillations similar to the main ones but at higher frequency. Such sub-oscillations are shown in detail in Fig. 4. The reference discharge enters the H -mode at 17.4 sec and with an input power of 7 MW. The deleterious effect of the L -mode oscillatory behavior is evident from such a comparison and even has an influence in the quality of the subsequent H -mode phase, which has a 20% lower stored energy despite the larger input power.

A detailed comparison of the experimental observations with the theoretical predictions for such oscillations [3,4] is beyond the scope of this Letter. However, it is important to mention that the following experimental features shown in this Letter are in agreement with such predictions: the need for a minimum input power to achieve the oscillatory regime; the existence of oscillations within a density window; the increase of the edge plasma density and of the private flux region neutral pressure when the divertor neutral pressure, density, ion flux, and radiation decrease; and, finally, the temperature range [$T_e \sim (3-5 \text{ eV})$] at which oscillations are seen. The effects of such oscillations on the bulk plasma and on the H -mode transition are not predicted by the models [3,4], which concentrate only on the physics of the scrape-off layer and edge plasma without considering the bulk plasma. While the identification of these self-sustained divertor oscillations is interesting in its own right, their deleterious effect on the achievement of good confinement at high density, crucial for nuclear fusion, warrants a more detailed experimental and theoretical characterization of this phenomenon.

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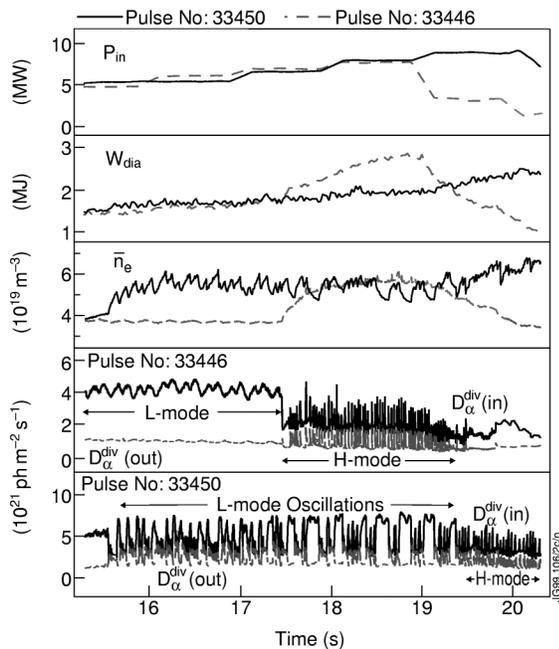


FIG. 7. Total input power (P_{in}), plasma stored energy (W_{dia}), line average density (n_e), and inner and outer divertor D_α emission for two discharges, one reaching the H -mode after a L -mode oscillatory phase and another going directly from L -mode into H -mode.

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