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 [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 discharges ($P_{\text{in}}$ is the input power, $n_e$ the plasma line average density, $P_{\text{rad}}$ is the total radiated power and $W_{\text{dia}}$ is the plasma stored energy).](image-url)
increases (mainly in the edge region $r/a \gtrsim 0.75$) 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 ($\sim 5$ 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 $D_α$ 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 $\sim 3$–$5$ 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 ($P_{DIV}^{neut}$) oscillates in phase with the $D_α$ emission from the inner divertor, while the neutral pressure in the private flux region of the divertor ($P_{PFR}^{neut}$) increases as $P_{neut}^{div}$ 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. 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).](image-url)

![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 $2.47 \leq R \leq 2.52$ m is saturated during state $A_{exp}$.](image-url)
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 $B_{\text{exp}}$ compared to $A_{\text{exp}}$ 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 phase 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 $B_{\text{exp}}$ (high edge $n_e$) has an improved energy confinement (by up to 20%) compared to state $A_{\text{exp}}$ (low edge $n_e$) and with a larger outer divertor $D_\alpha$ emission. This is in contrast to standard $L$-$H$ transition observations which link decreasing outer divertor $D_\alpha$ emission with the $H$-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 $B_{\text{exp}}$ 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 $A_{\text{exp}}$ to state $B_{\text{exp}}$, 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., $\sim 3$ cm from the separatrix) are plotted for two consecutive $2$ MA/$2.8$ T discharges: one at high power ($\sim 10$ MW), which undergoes a $L$-$H$ transition followed by type-I edge localized modes (ELMs), and the other at lower power ($\sim 5$ 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 $T_e$ ($\sim 550$ eV), which is much lower than that needed to achieve the $H$-mode regime in these conditions ($\sim 880$ 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
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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