ELSEVIER

Journal of Nuclear Materials 241-243 (1997) 476-482

journal of nuclear materials

Influence of active pumping on density and confinement behaviour of JET plasmas

G. Saibene *, D.J. Campbell, L.D. Horton, A. Loarte, R.D. Monk, E. Righi, D. Stork

JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, UK

Abstract

This paper describes the confinement characteristics of high density Elmy H-modes obtained in the JET Mark I experimental campaign. Plasma pulses carried out with and without the in-vessel cryopump operational (≈ 240 m^3 s^{-1} pumping speed for deuterium) are compared. In all cases, it is found that the H-mode density limit is not disruptive, but manifests itself as a loss of confinement, accompanied by an increase of neutral pressure at the plasma edge. The interpretation of the H-mode density limit in terms of the Greenwald scaling is discussed. It is also shown that the loss of confinement correlates to the onset of detachment in the divertor, and that operation at high density in H-mode is compatible with partial detachment but not with full detachment.

Keywords: JET; Density limit; Active pumping; Detached plasmas; Improved confinement mode

---

1. Introduction

This paper studies the behaviour of the confinement for high density ELMy H-modes obtained in the 1994–95 Mark I campaign at JET. The motivation for this analysis is the observation of an apparent saturation of the plasma density in the H-mode regime, accompanied by a degradation in energy confinement when approaching the Greenwald density limit (GDL) [1]. This observation is in contrast with previous results found in JET before the installation of the pumped divertor, where densities 1.5 to 2 times the Greenwald limit were obtained up to plasma currents of 4 MA in L-mode, in a limiter configuration, and up to 1.5 MA in ELM-free H-modes, in an X-point configuration [2].

The GDL states that the density limit of a discharge is determined only by its plasma current and minor radius. Indeed, the analysis of the scaling of the 'natural' steady state density of neutral beam heated ELMy H-modes with no additional gas fuelling and in-vessel cryopump on [3] highlights a strong dependence of the density on the plasma current ($n_e \sim I_p^{1.0}$), while the dependence on the total power is much weaker ($n_e \sim P^{0.5}$). However, the analysis of the JET high density, high gas fuelling, ELMy H-modes shows that the response of the plasma density to gas fuelling does not follow this simple scaling. Moreover, the degree of the degradation of the energy confinement time τ_E at high density is not the same for all discharges, and it is found to depend in first order on whether the in-vessel cryopump is operational. For the pulses without active pumping, attempts to increase the main plasma density via gas fuelling always result in a strong deterioration of the H-mode, down to energy confinement times characteristic of L-mode. In contrast, with the cryopump on, plasma densities up to the Greenwald limit have been obtained, maintaining confinement enhancement factors at about 1.6 times the ITER89P L-mode scaling values ($H_{89} = \tau_E/\tau_{E\text{-}89P}$). It is also interesting to note that, while the density limit in L-mode is found to exceed the GDL and is disruptive, the density limit in H-mode discharges is associated with loss of confinement but is not disruptive. Similar observations are reported by Petrie for H-modes in DIII-D [4].

The effects of active pumping on JET plasma parameters are described in detail elsewhere [5], including the dependence of the global particle balance on the fuelling

---

* Corresponding author. Tel.: +44-1235 464 772; fax: +44-1235 465 385; e-mail: gabriella.saibene@jet.uk.

PII S0022-3115(96)00549-1

characteristics and duration of the ELMy phase of the H-mode.

2. Characterisation of high density ELMy H-modes

The analysis has been restricted to pulses with the following common characteristics:

1. long pulse H-modes (H-mode duration $\gg \tau_E$, τ_p [6]), with neutral beam heating;
2. divertor strike zones positioned on the horizontal target plates;
3. deuterium plasmas — most of the pulses had steady or slowly varying gas fuelling;
4. low radiated power: P_{rad}(bulk) ≈ 10–20% of P_{tot} and P_{rad}(total) up to 50% of P_{tot};
5. $q_{95} > 3$.

The data set includes pulses with the cryopump on and off, plasma current from 1 to 3 MA, toroidal field from 1 to 2.7 T and input power from 8 to 15 MW. The experiments reported were carried out well into the Mark I campaign, with the vessel fully conditioned. Moreover, JET operates at an average wall temperature of 300°C, and no inter-pulse conditioning is required due to the thermal outgassing from the walls. Overnight glow discharge cleaning and/or Be evaporation are typically carried out twice a week or less.

A common feature of all the discharges without active pumping is the gradual deterioration of the confinement while deuterium gas fuelling is applied. As the confinement degrades, the rate of increase of the plasma density slows down; in some cases the loss of confinement is such that the plasma density even decreases. In contrast, with the pump on, steady increase of the density can be obtained, while maintaining good confinement. The time evolution of some characteristic parameters of two discharges showing this typical behaviour of the confinement, is shown in Figs. 1 and 2 (#35726 pump off, #34903 pump on). For the same bulk plasma density, the D_α emission in the divertor and in the main chamber are higher for the pump off pulse #35726. The H-mode termination and the loss of density correspond to large oscillations in the D_α emission; the main chamber pressure and divertor neutral pressure (the latter not shown in the figures) are higher for the pump off pulse (a factor of 5 in the main chamber pressure), in spite of the external gas fuelling rate being approximately 10 times higher for the pump on case. The fraction of radiated power from the X-point region is between 20 and 30% at the maximum density; Z_{eff} is ≈ 1 (pump on) and 1.3 (pump off).

For all the discharges analyzed, the ratio between the neutral pressure in the main chamber and in the divertor is similar with and without pumping. Moreover, the neutral compression factor (defined as the ratio of the neutral pressure in the divertor to the neutral pressure in the main chamber) is low and decreases for increasing main plasma density, in contrast to the predictions from simple models [7], and to the observations for ohmic and L-mode plasmas in JET [8] and elsewhere [9]. The low compression obtained in JET indicates that the neutral distribution and the recycling both in the divertor and in the main SOL are strongly influenced by the leaks connecting the Mark I

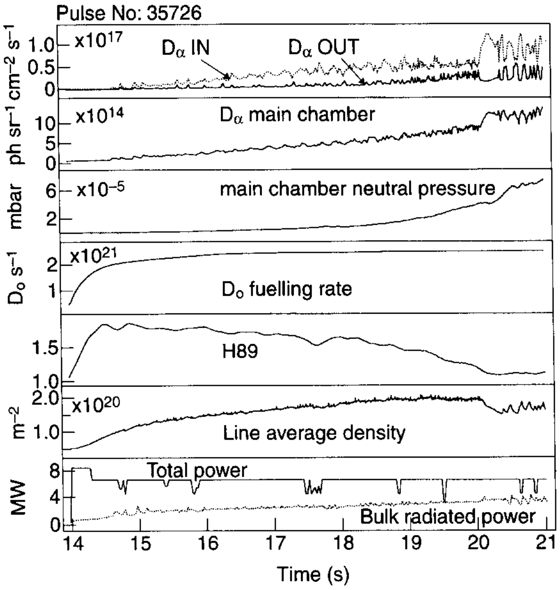

Fig. 1. Time evolution of D_α emission (inner and outer divertor targets, main chamber), main chamber neutral pressure, gas fuelling rate, confinement enhancement factor H_{89}, line average density, total power and bulk radiated power for the plasma discharges #35726 (2.0 MA/2.1 T, pump off).

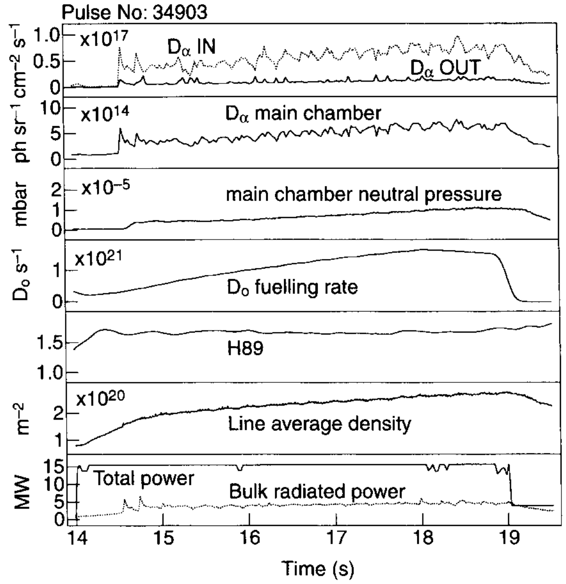

Fig. 2. Same set of signals as in Fig. 1, for pulse #34903 (3 MA/2.7 T, pump on).

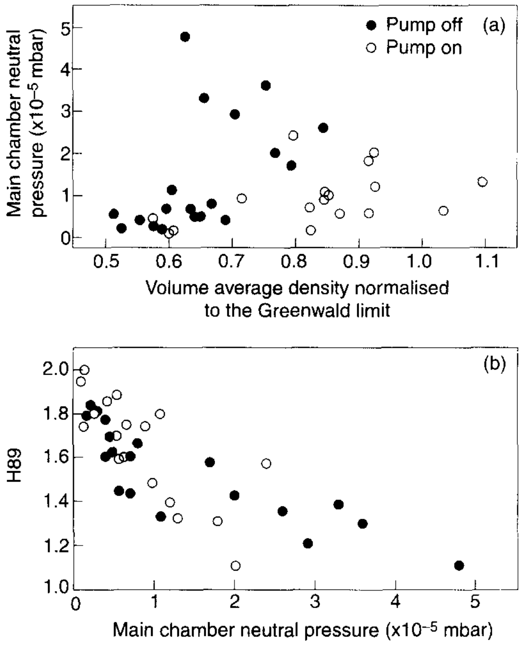

Fig. 3. (a) Main chamber neutral pressure as a function of the main plasma density (normalised to the GDL). (b) Variation of H_{89} as a function of the main chamber pressure.

divertor volume to the rest of the main chamber. The unexpected decrease of the compression factor with increasing plasma density during ELMy H-modes is possibly related to the ELM frequency and could be related to the ergodization of the magnetic surfaces near the X-point [10] that in turn enhance the neutral leakage. The principal effect of active pumping is therefore to reduce the absolute levels of neutral density and recycling flux in the whole vessel, in addition to changing the local divertor recycling.

The analysis of the deuterium consumption during the limiter phase of the discharges studied in this paper (from 0 to 10 s) provides an indication of the wall saturation levels and allows one to compare the wall status between pump on and pump off pulses. The average gas consumption per unit line average density ($\int_0^{10}\Phi(t)\mathrm{d}t/\langle n_{\mathrm{el}}\rangle_{t=10}$, [$\mathrm{D}_0 \times 10^{19}/10^{18}$ m^{-2}]), was calculated for the pulses 34900–34911 (pump on) and 35721–35730 (pump off). It is found that the amount of fuelling required to obtain the required density is similar for the two series of pulses, 5.5 compared to 5.2 for the pump on and off cases, respectively. Therefore, the average mobile deuterium wall loading is similar for the two series of pulses, and wall saturation is not the main candidate to justify the observed differences in the main chamber recycling and neutral pressure with the pump on and off.

The correlation between plasma density, confinement and neutral pressure is illustrated in Fig. 3a and b. We observe that the edge neutral pressure increases with main plasma density (normalised to the GDL, Fig. 3a) more steeply for the discharges without active pumping, compared to the pump on cases. This large increase may be due to the high wall particle release and to the higher absolute value of the leakage neutral flux from the divertor. Note that the density of the discharges without active pumping is limited to below 85% of the GDL. Fig. 3b shows that the energy confinement degrades with increasing edge neutral pressure. A similar result was reported from ASDEX-U [11], although the degradation of confinement seems to be less severe than in JET. The loss of confinement is correlated to the absolute value of the pressure, with similar trends for pump on and pump off discharges. As illustrated by the example of the plasma discharge #35726 (Fig. 1), the degradation of confinement precludes the access to high density H-mode regimes.

3. Analysis of the confinement behaviour

In comparison to reference discharges without gas fuelling ($H_{89} \approx 1.8$ to 2), the energy confinement of steady state ELMy H-modes deteriorates when the main plasma average density increases approaching the GDL, both for pumped and unpumped cases. Nevertheless, we can identify differences between the two types of discharges.

The maximum density achieved for H-mode pump-off discharges is below 85% of the GDL and good confinement ($H_{89} > 1.6$) is maintained only up to about 80% of the limit. The subsequent degradation of confinement and decrease of density correspond to the loss of the edge pedestal, visible in the 'erosion' of the edge density profiles down to typical L-mode characteristics. In JET, it has been established that the net power to achieve the L to H transition increases with plasma density [12]. The analysis of the time evolution of the net power ($P_{\mathrm{tot}} - P_{\mathrm{rad}}$(bulk)) for these pulses, against the density dependent scaling for the L to H transition, excludes that the loss of confinement can be due to the net power falling below the H-mode threshold.

In contrast to the pump off cases, some of the discharges with active pumping reached 90 to 100% of the GDL, maintaining a confinement enhancement H_{89} of 1.6, and at low current (1 MA, 10 MW additional heating), the GDL was exceeded by 10%, with an H_{89} factor of approximately 1.4. Although these discharges have a reduced confinement, they may be relevant as a possible operating scenario for ITER, because of their very low impurity content (Z_{eff} is near 1). The loss of confinement and density observed for the pump off pulses, can also occur in discharges with the pump on, when very high gas fuelling rates are applied (typically above 4×10^{22} D_0 s^{-1}, or $\approx 3 \times 10^{21}$ D_0 s^{-1} MW^{-1}, see Fig. 4a).

The D_0 external fuelling rate per MW of injected power is used as a 'figure of merit' to further analyze the pump on data. The choice of this indicator is guided by the observation, valid both for the old JET data [2] and for the

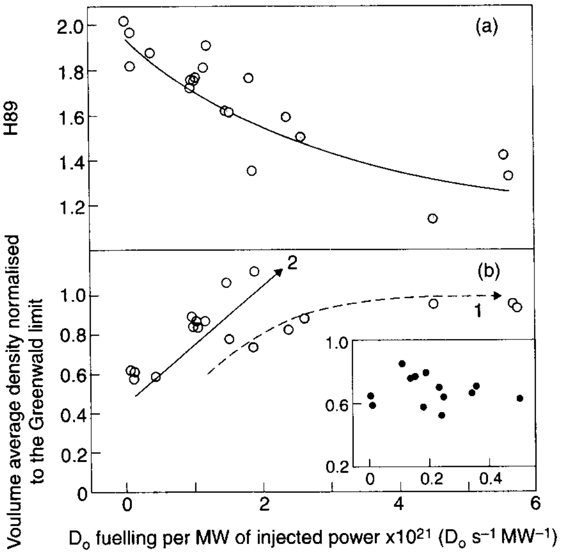

Fig. 4. H_{89} and normalised plasma density as function of D_0 fuelling per MW of injected power (a and b), for ELMy H-modes with active pumping. The inset in b shows the behaviour of the pump off pulses, on the same scale as b. The points on trajectory 1 are shaded gray to identify them in graph a.

Mark I L-mode density limit [13] of the power dependence of the maximum achieved density, in contrast with the pure plasma current dependence invoked by the Greenwald limit.

It is found that the confinement decreases with increasing fuelling per MW (Fig. 4a). Fig. 4b shows the maximum density achieved in the actively pumped H-modes (expressed as a fraction of the GDL) as function of the fuelling per MW. This figure suggests that two trends may be identified in the data: trajectory No. 1 groups discharges where low rates of the density rise and eventually saturation of the density are observed, in correspondence with a progressive degradation of the H_{89} factor, down to L-mode values. Trajectory No. 2 groups plasma discharges where the density increase was achieved without strong degradation of the confinement (H_{89} is between 1.5 and 1.7). This was obtained only at low fuelling rate per MW, and in most of the cases it corresponds to higher power used for a given fuelling rate than for the discharges on trajectory No. 1. The analysis of the time evolution of the plasma density for these high power pulses (15 MW) shows that the density increase does not saturate, and therefore the maximum density achieved seems to be limited by the length of the power pulse and not by loss of confinement (as shown by the example of #34903 in Fig. 2). Nonetheless, the dependence of the density on the fuelling per MW is not unambiguous, indicating that other factors, not included in this study, affect the maximum density achieved.

For the discharges without active pumping, the maximum density and the confinement show no strong dependency on the external fuelling (inset in Fig. 4b). It will be shown for these discharges that the onset of detachment in the divertor determines the maximum achieved density and confinement.

4. Divertor SOL behaviour

Divertor Langmuir probe data were analyzed in detail for two similar ELMy H-modes (neutral beam fuelling only) with and without active pumping [5]. It was found that the pump affects the divertor ion fluxes, the electron densities and temperatures. In particular, the integrated ion fluxes and the peak density decrease by a factor of 2 with the pump on, while the peak electron temperature T_e goes up by approximately a factor of two.

For high density ELMy H-modes, the detailed analysis of the divertor parameters is complicated by the increased ELM frequency and by the onset of instabilities and/or detachment. Therefore, the analysis of the peak electron temperature T_e as derived from the divertor target probes at the inner and outer strike zones, has been carried out for the representative pulses #35726 and #34903, only at selected time slices (Fig. 5).

At medium plasma density ($n_e < 60\%$ of the GDL), the temperatures at the outer strike zones are very similar for the two pulses, around 20 to 25 eV. At the inner strike zone, T_e of #35726 (pump off) is already low, between 5 and 10 eV; when the main plasma density further increases to 70% of the GDL, both the inner and outer strike zone separatrix temperatures fall at or below 5 eV. In contrast, the outer strike zone T_e of #34903 decreases only to

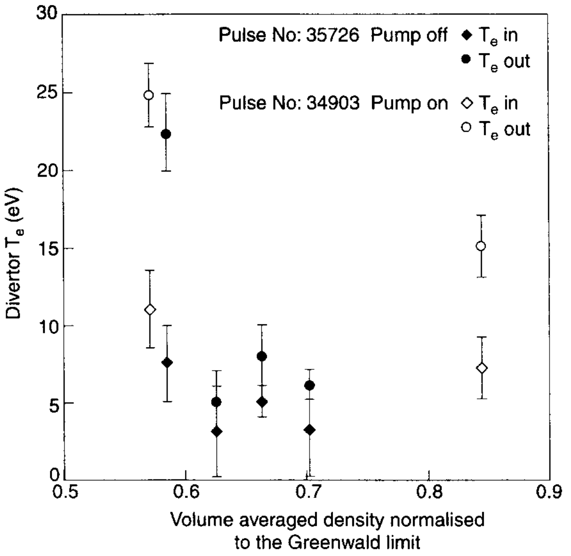

Fig. 5. Evolution of the peak target electron temperatures at the inner and outer strike zones of pulses #35726 and #34903.

around 15 eV at the maximum density (85% of the GDL), while the inner strike zone temperature goes to about 7 eV.

More insight may be gained on the relationship between divertor parameters and the changes in the confinement by analysing the time evolution of the target ion flux and D_α emission. Figs. 6 and 7 show the time traces of the ion fluxes and fast D_α signal at the inner and outer strike zones for the two pulses #35726 and #34903.

4.1. #35726 (pump off) – Fig. 6

(a) $t = 17$ s: initially, the outer strike zone D_α and ion flux show the normal signature of an ELMy H-mode, while negative ELMs in the D_α signal are observed in the inner strike zone, indicating that the plasma may be close to detachment between ELMs [14]. H_{89} is around 1.7, and n_e is $< 60\%$ of the GDL.

(b) $t = 20$ s: although normal ELMs are still visible in the ion flux, the D_α signal shows an oscillatory behaviour in both strike zones. This coincides with the drop of the separatrix electron temperature to around 5 eV. At this time the plasma density has reached 70% of the GDL. This phase is immediately followed by a large scale instability in the divertor, the collapse of the main plasma density and a decrease of H_{89} to 1.2.

(c) $t = 21.5$ s: the ion flux still shows infrequent ELMs reaching the target, but the D_α signature is now typical of a divertor instability [15]. The temperature at the separatrix is near or below 5 eV, and the plasma is detaching on both sides. The confinement is back to L-mode values.

4.2. #34903 (pump on) – Fig. 7

In contrast to #35726, large scale instabilities in the divertor region are not observed. Negative ELMs are visible at the inner strike zone only, indicating that the plasma may be partially detached there. The separatrix electron temperature remains above the critical level of 5 eV in both strike zones, for the whole discharge duration. H_{89} stays above 1.75 during the density increase, up to 85% of the GDL. The analysis of the divertor parameters supports the statement that the maximum density achieved in this pulse is limited by the length of the heating/fuelling phase.

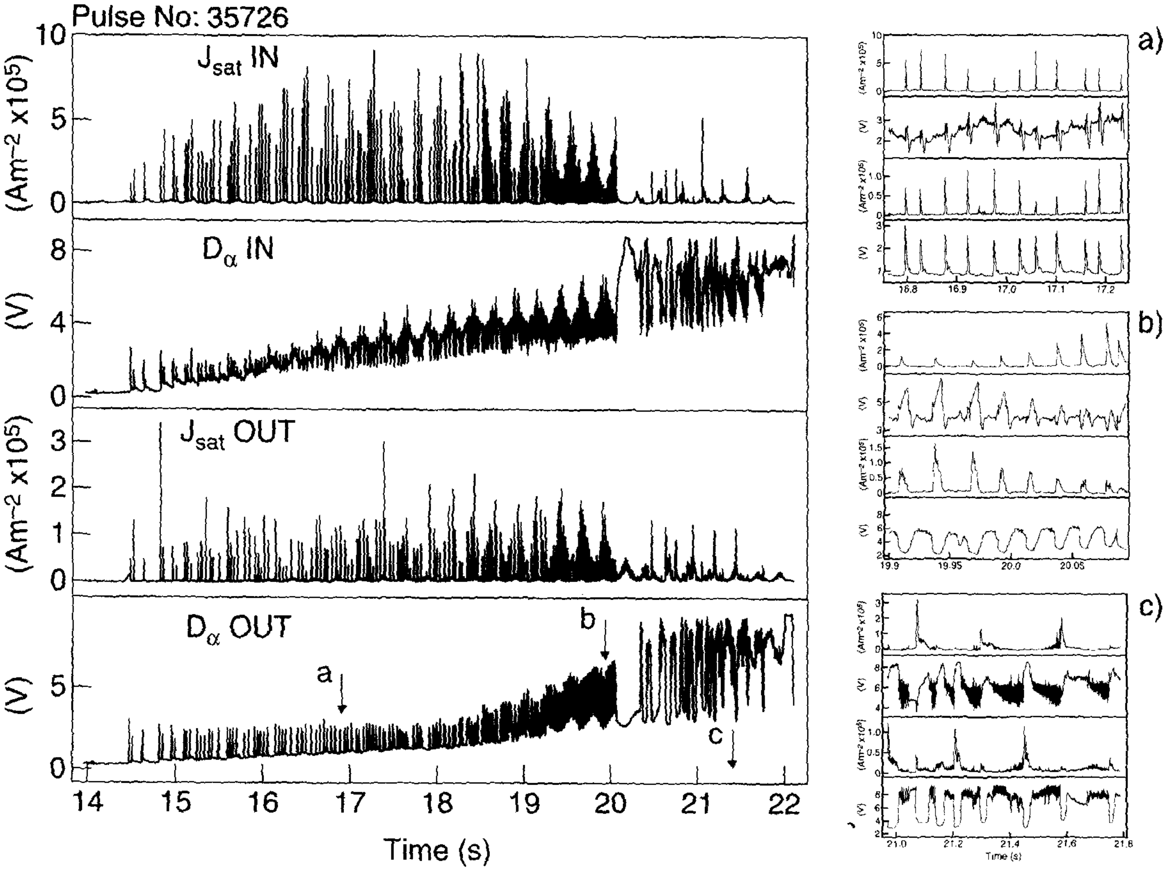

Fig. 6. Ion saturation current and fast D_α signals from the inner and outer divertor strike zones, for pulse #35726 (pump off). The 4 Hz oscillations in the base level of the signals is due to the sweeping of the strike points across the target.

The active pumping delays the onset of detachment of both strike zones. The effect is twofold: first the divertor is stable; second the loss of compression observed at plasma detachment [8] and the associated large increase of the edge neutral pressure do not occur, limiting the extent of the confinement degradation (refer also to Fig. 3b).

5. Summary and conclusions

To date, only with active pumping has it been possible to obtain ELMy H-modes with plasma density near or at the GDL and acceptable energy confinement time in JET. Degradation of the energy confinement time is observed at the highest densities.

The analysis of actively pumped ELMy H-modes indicates that, to achieve high density and high confinement at the same time, the fuelling per MW of injected power should be kept below some critical level (in the case of JET discharges analyzed in this paper, the maximum is between 1 and 2×10^{21} deuterons s^{-1} MW^{-1}) In other words, this indicates that given a sufficient power per particle, good confinement can be maintained at high plasma density, and therefore densities above the Greenwald density limits may be achieved in ELMy H-mode regimes.

The degradation of the confinement is clearly correlated to the increase of neutral pressure in the main chamber, for discharges with and without active pumping. On the other hand, the analysis of the divertor SOL parameters highlights a correlation between the loss of confinement and detachment. In fact, for the pump off discharges, the drop of the separatrix temperature at both strike zones near or below 5 eV coincides with the loss of the H-mode and the onset of divertor instabilities. In contrast, the partial detachment observed for pump on pulses seems to be compatible with maintaining H-mode confinement. The Z_{eff} of these pulses is near 1, possibly making the performance of these type of discharges attractive for ITER.

It is observed that the increase of the edge neutral pressure and the progressive divertor detachment occur simultaneously. Given the large neutral leakage from the divertor region into the main chamber via the structure of the Mark I divertor, it is difficult to assess if it is either the high edge neutral pressure or the divertor instability that degrades the energy confinement.

These issues will be studied further in the forthcoming

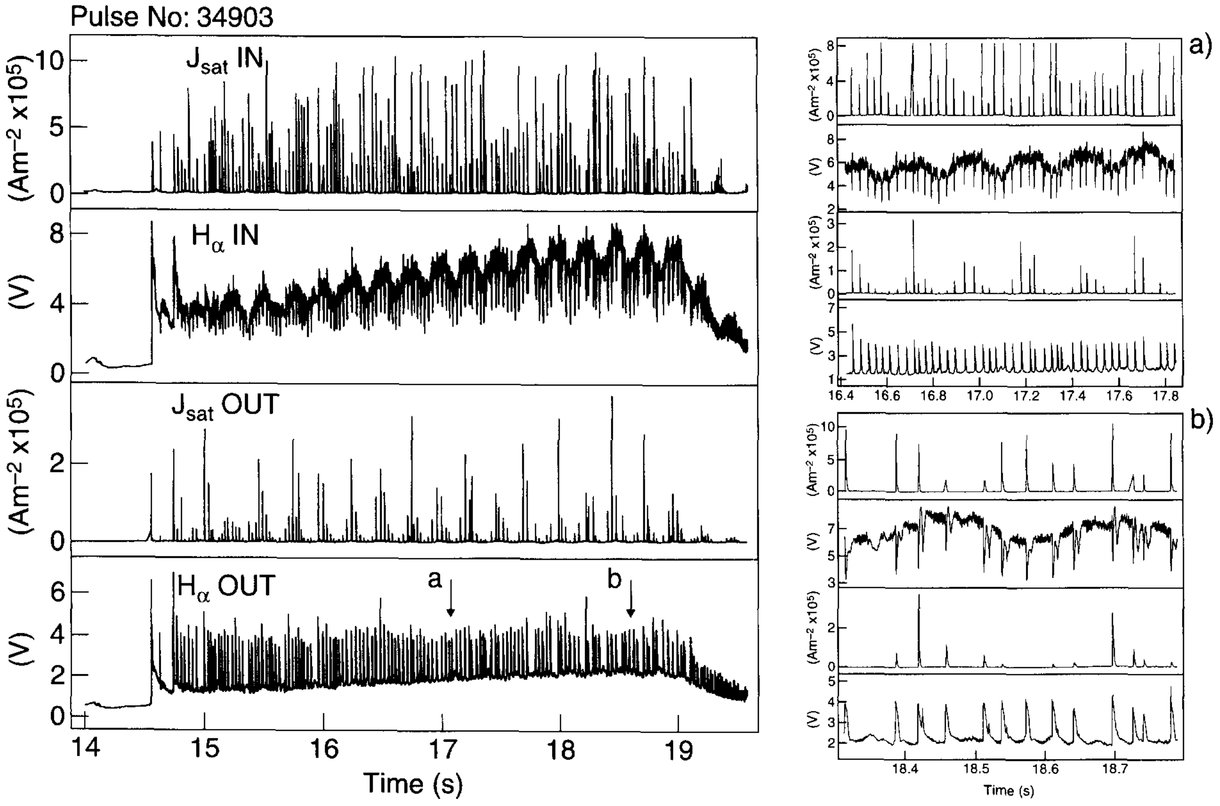

Fig. 7. Same set of signals as in Fig. 6, for the pulse #34903 (pump on).

1996 JET campaign with the new and more geometrically closed Mark II divertor.

References

[1] M. Greenwald et al., Nucl. Fusion 28(12) (1988) 2199.

[2] D.J. Campbell et al., Europhys. Conf. Abstr. 18B(I) (1994) 2.

[3] L.D. Horton, the Divertor Task Force and the JET Team, Plasma Phys. Controlled Fusion, to be published.

[4] T.W. Petrie et al., Nucl. Fusion 33(6) (1993) 929.

[5] G. Saibene et al., Europhys. Conf. Abstr. 19C(II) (1995) 121.

[6] D. Stork et al., Europhys. Conf. Abstr. 19C(II) (1995) 125.

[7] M. Keilhaker et al., Phys. Scr. T 2 (1982) 443.

[8] J. Ehrenberg et al., these Proceedings, p. 420.

[9] A. Niemczewski et al., MIT Rep. PFC/JA-96-12.

[10] J. Lingertat et al., these Proceedings, p. 402.

[11] J. Neuhauser et al., Plasma Phys. Controlled Fusion 37(11A) (1995) A37.

[12] E. Righi et al., Europhys. Conf. Abstr. 19C(II) (1995) 73.

[13] A. Loarte, Divertor Physics and Divertor Modelling and Database ITER Expert Group Meeting, Naka, Japan, 1995.

[14] J. Lingertat, JET Joint Undertaking, private communication.

[15] R.D. Monk, Ph.D. thesis, University of London (1996).