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

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1. INTRODUCTION

This paper studies the behaviour of the confinement for high density ELMy H-modes obtained in the 1994-95 MarkI 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 4MA in L-mode, in a limiter configuration, and up to 1.5MA 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 [3], highlights a strong dependence of the density on the plasma current ($n_e \sim (I_p)^{1.5}$), while the dependence on the total power is much weaker ($n_e \sim P^{0.5}$). Analysis of the JET high density, high gas fuelling, ELMy H-modes shows that 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 in steady state, 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 general effects of active pumping on JET plasma parameters are described in detail elsewhere [5]. In the case of steady state ELMy H-modes, the deuterium particle removal rate is in general greater than the external fuelling, resulting in the reduction of the wall particle inventory. Moreover, active pumping decreases the neutral pressure in the main chamber and divertor. The excellent reproducibility of plasma discharges and the improved plasma performance obtained with active pumping can be correlated to the control of the wall particle load and to the reduction of the recycling levels and neutral pressures.

2. CHARACTERISATION OF HIGH DENSITY ELMY H-MODES

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

- Long pulse H-modes (H-mode duration >> τ_E, τ_p [6], with neutral beam heating.
- Divertor strike zones positioned on the horizontal target plates
- Deuterium plasmas - Most of the pulses had steady or slowly varying gas fuelling.
- Low radiated power : P_{rad} (bulk) ≈ 10-20% of P_{tot} and P_{rad}(total) up to ≈ 50% of P_{tot}
- $q_{95} > 3$.

The data set includes pulses with the cryopump on and off, plasma current from 1 to 3MA, toroidal field from 1 to 2.7 T and input power from 8 to 15 MW.

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, are reproduced in figures 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.

For all the discharges analysed, 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 compressions obtained in JET indicate that the neutral distribution and the recycling both in the divertor and in the main SOL are strongly influenced by the leaks connecting the MarkI 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, rather than changing only the local divertor recycling.

The correlation between plasma density, confinement and neutral pressure is illustrated in figures 3a and 3b. We observe that the edge neutral pressure increases with main plasma density (normalised to the GDL, figure 3a) more steeply for the discharges without active pumping, compared to the pump on cases. This large increase may be due to the high (uncontrolled) 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. Figure 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 (figure 1), the degradation of confinement appears to preclude the access to high density H-mode regimes.

The pressure and the recycling levels in the divertor show a similar behaviour to the main chamber neutral pressure. For the same plasma density and external fuelling, the D_α emission is larger and increases more steeply for the pump off cases than for the actively pumped discharges.

3. ANALYSIS OF THE CONFINEMENT BEHAVIOUR

In comparison to reference discharges without gas fuelling ($H_{89}\approx1.8$ 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>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_{tot}-P_{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 discharges with active pumping reached 90 to 100% of the GDL, maintaining a confinement enhancement of 1.6, and at low current (1 MA), 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} $D_0 s^{-1}$) [13].

The D_0 external fuelling rate per MW of injected power is used as a "figure of merit" to further analyse 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 MarkI L-mode density limit [14], 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 (figure 4a). Figure 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 the 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 figure 2). Nonetheless, the dependence of the density on the fuelling per MW is not univocal, 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 figure 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 analysed 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 (figure 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 around 15eV 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. figures 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.

#35726 (pump off) - figure 6:

(a) t=17s: 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 [15]. H_{89} is around 1.7, and n_e is <60% of the GDL.

(b) t=20s: 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=21.5s: the ion flux still shows infrequent ELMs reaching the target, but the D_α signature is now typical of an divertor instability [16]. The temperature at the separatrix is near or below 5eV, and the plasma is detaching on both sides. The confinement is back to L-mode values.

#34903 (pump on) - figure 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 5eV 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 is limited by the length of the heating/fuelling phase.

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 figure 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 analysed 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 5eV 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.

The neutral pressure increase and the progressive divertor detachment happen simultaneously. Due to the large neutral leakage from the divertor region into the main chamber via the structural by-pass leaks of the MarkI divertor, it is difficult to understand if it is either the high edge neutral pressure or the divertor instability causing the degradation of the energy confinement.

These issues should be clarified in the forthcoming 1996 JET MarkII campaign, since the MarkII divertor is more geometrically closed compared to MarkI. Moreover, deuterium shallow pellet injection should be available for the coming experimental campaign, as alternative to gas fuelling. These two changes should enable us to separate the effects of high pressure/recycling in the main chamber and detachment in the divertor on the confinement and density of ELMy H-modes.

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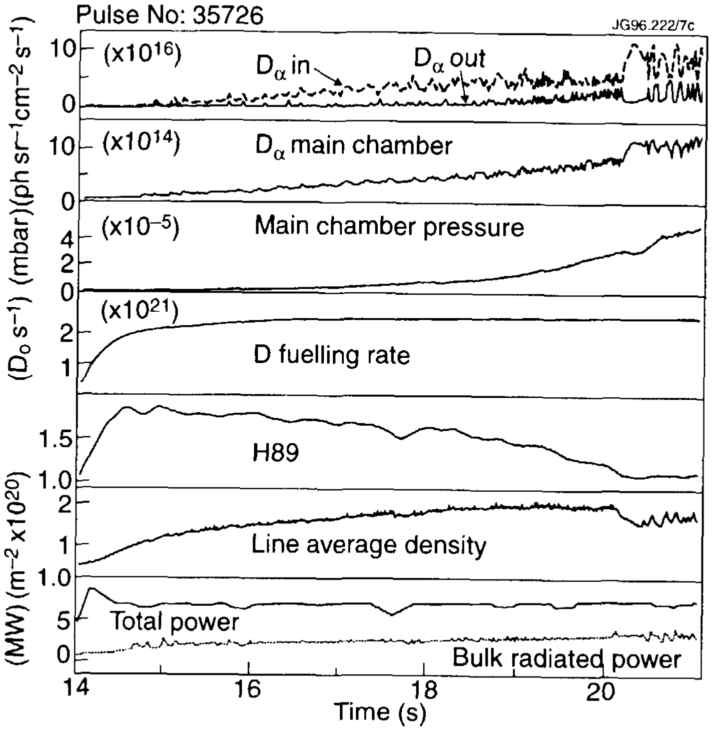

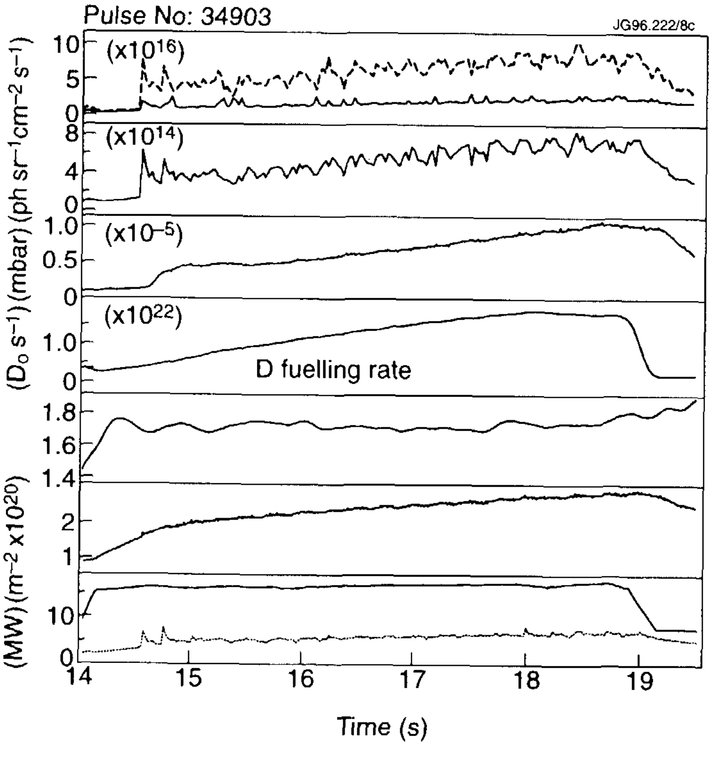

Figures 1 and 2: Time evolution of D_α emission (inner and outer divertor targets, main chamber), main chamber neutral pressure, gas fuelling rate, confinement enhancement factor H_{89}, line average density, total power and bulk radiated power for the plasma discharges #35726 (2.0MA/2.1T, pump off) and 34903 (3MA/2.7T, pump on).

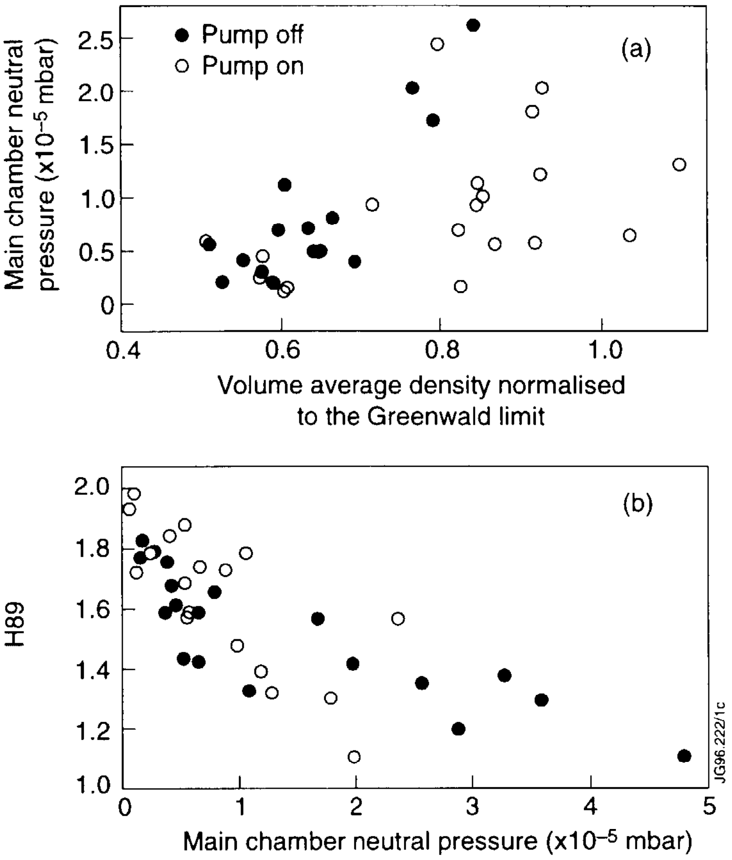

Figure 3a: Main chamber neutral pressure as function of the main plasma density (normalised to the GDL).
Figure 3b: Variation of H_{89} as function of the main chamber pressure.

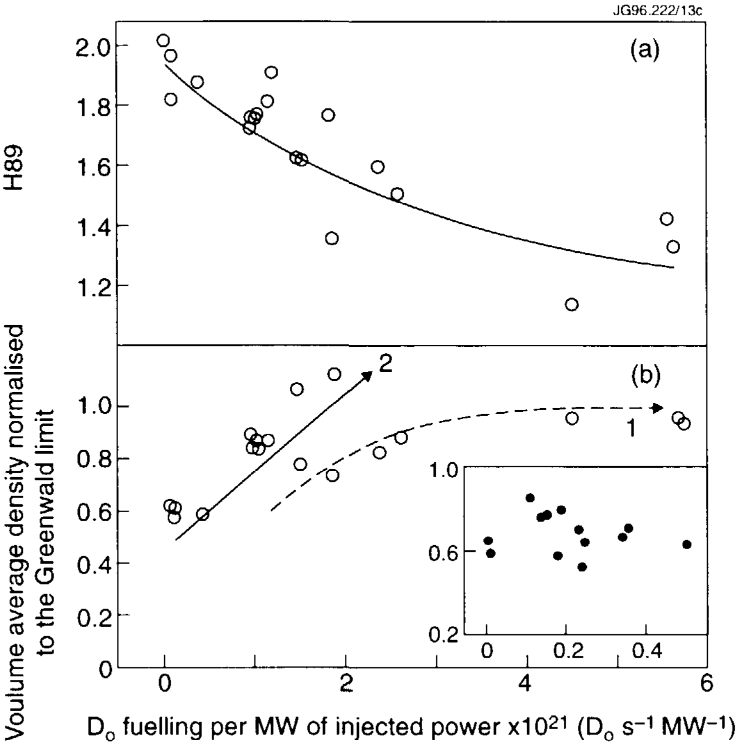

Figure 4: H_{89} and normalised plasma density as function of D_o fuelling per MW of injected power (a and b), for ELMy H-modes with active pumping. The inset in figure 4b shows the behaviour of the pump off pulses, on the same scale as figure 4b.

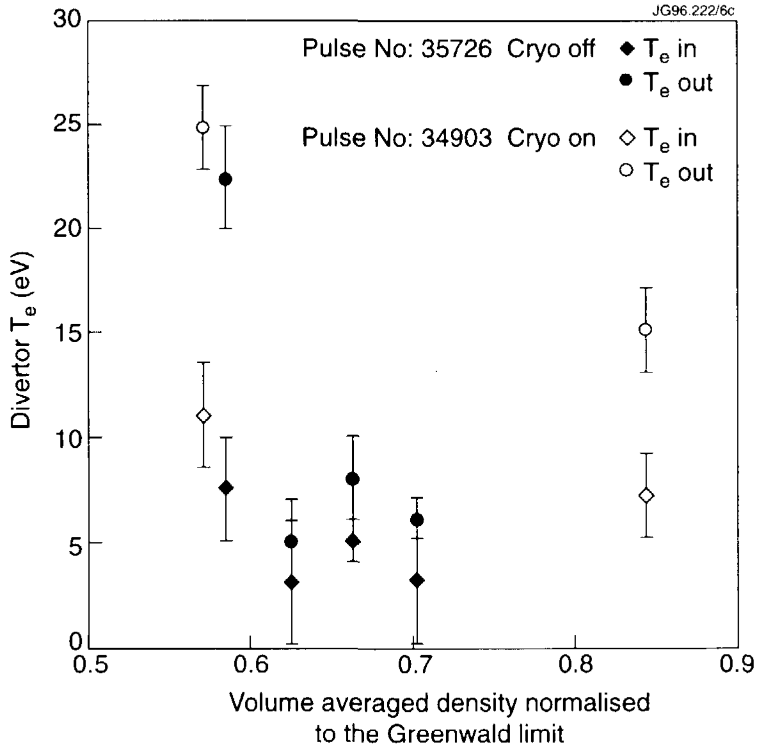

Figure 5: Evolution of the peak target electron temperatures at the inner and outer strike zones of pulses #35726 and #34903.

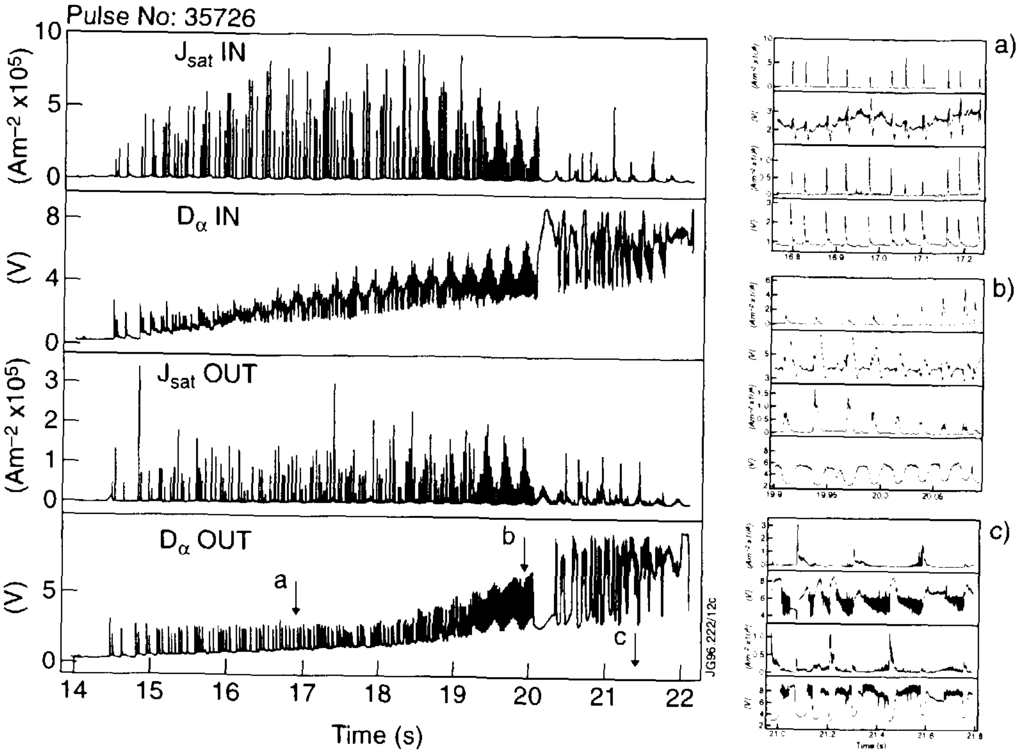

Figure 6: Ion saturation current and fast D_α signals from the inner and outer strike zones, for pulse #35726 (pump off). The 4Hz oscillations in the base level of the signals is due to the sweeping of the strike points across the target.

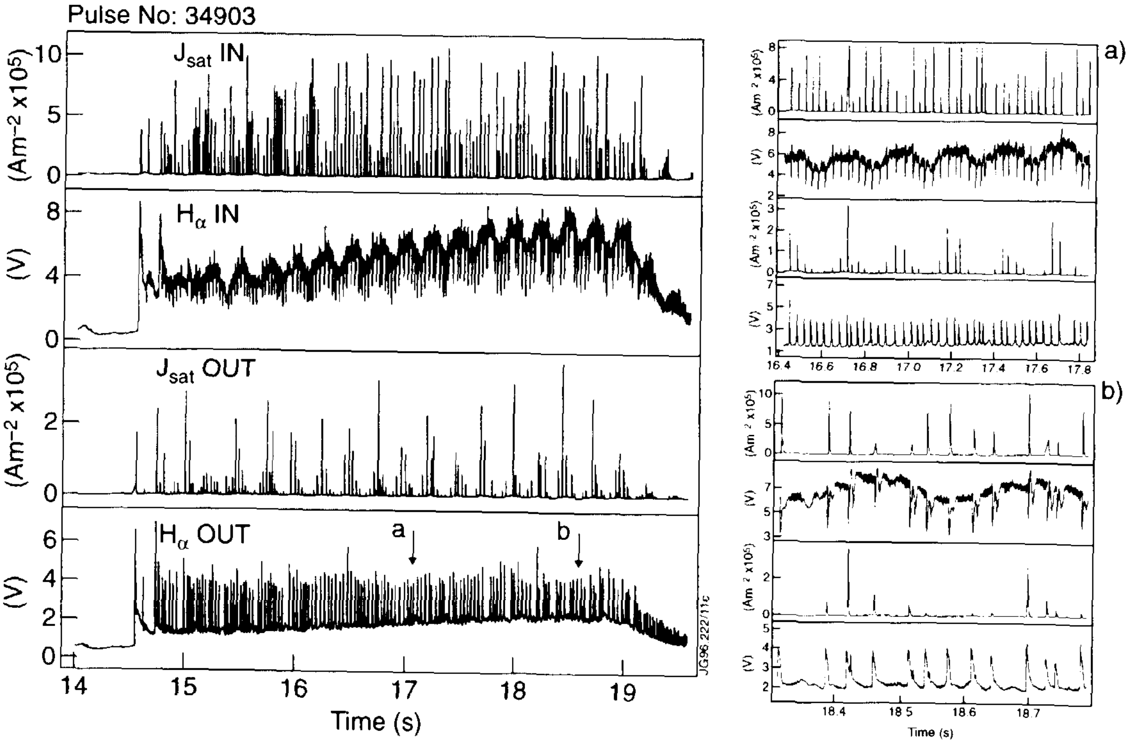

Figure 7: Same set of signals as figure 6, for the pulse #34903 (pump on).