

Confinement loss in JET ELMy H-modes

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1-Introduction A spontaneous transition of the plasma from the Type I ELM regime to a lower confinement mode is observed in JET ELMy H-modes with both the Mark II [1,2] and the Gas Box (GB) divertors. It was recognised already in Mark II that this transition is associated with operation too close to the L-H power threshold, and that it is possible to maintain the Type I ELM regime in steady state with input power in excess of twice the L-H threshold power. In Mark II, the occurrence of the loss of confinement constrained the effort to maximise the fusion power in JET deuterium plasmas by operating at high plasma current. New experiments with the GB divertor show that the loss of confinement is a transition of the H-mode from the Type I to the Type III ELM regime. In addition, GB results provide a description of the low density Type III regime in terms of pedestal parameters. This paper reports these recent results. The transition to lower confinement has similar behaviour with the two divertors, despite some significant differences which will also be described in the paper.

2-Loss of confinement: Type I to Type III transition - Power threshold for Type I ELMs

The GB results shows that the loss of confinement is a transition from the Type I to Type III ELM regime. In experiments aimed at the determination of the power threshold for Type I ELMs [3], the input power, P_{IN} , of NBI heated discharges with no external fuelling is increased in steps, starting from P_{IN} just above the L-H threshold power.

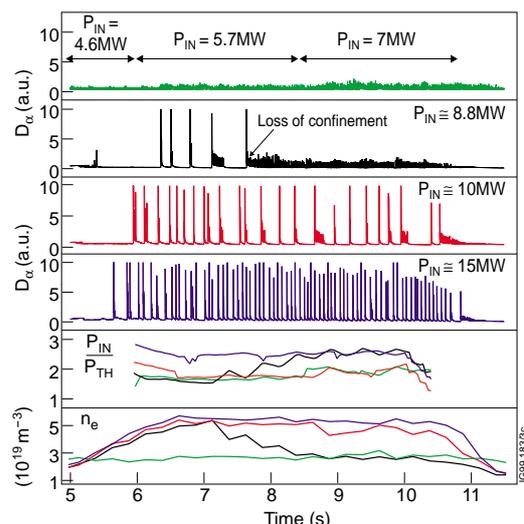


Fig. 1: Power scan at 2.5MA/2.4T showing the evolution of D_α , P_{IN}/P_{th} and n_e with increasing power. (#45526,46228,46227,47541).

Fig. 1 illustrates the typical features of such a power scan for a 2.5MA/2.4T plasma. In the first three power steps the H-mode has Type III ELMs (f_{ELM} decreases with power). At very high ELM frequency, the edge and core densities are low and they both increase as the ELM frequency decreases. The last two power levels (10 and 15 MW) of the scan show Type I ELM behaviour (f_{ELM} increases with power). The discharge at $P_{IN}=8.8$ MW, which is the highest power with steady state Type III ELMs, is in the Type I ELM regime before the spontaneous transition to lower confinement. Fig 2 shows the results from a dedicated scan in toroidal field (B_t - from 2 to 3T) and plasma current (I_p - from 2 to 3MA), with the GB divertor. In the figure, steady Type I ELMy H-modes are compared with the Type I ELM phase of plasmas which experience a transition to Type

III ELMs. The result shows that input powers greater than 1.8 times the predicted L-H threshold power, $P_{th(scaling)}=0.45 n_e^{0.75} B_t R^2$, are required to maintain a steady state H-mode

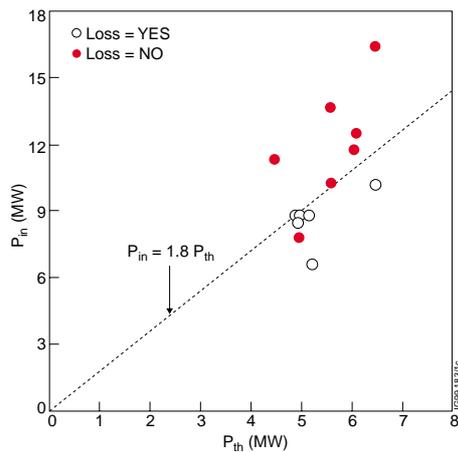


Fig.2: Power required to maintain Type I ELMs in steady state, derived from a P_{IN} , B_t and I_p scan in GB. Red points: steady H-modes with Type I ELMs, black points: H-modes with a transition from the Type I to the Type III ELMs regime

with Type I ELMs. This result is in agreement with the power dependence established in the Mark II high current experiment [1,2]. The GB results also confirm that the power threshold of Type I ELMs depends on I_p as well as on B_t . However, since the minimum density of NBI heated ELMy H-modes with Type I ELMs and without external gas fuelling increases almost linearly with I_p (the actual increase is less than linear), the observed I_p dependence of the power threshold for Type I ELMs might be a density dependence. The GB data have also confirmed that at 3.4T, the input power required for a deuterium H-mode with Type I ELMs at $I_p > 3.5$ MA exceeds the full capability of the JET NBI system.

The most significant difference between the Mark II and GB results is that in Mark II the plasma made a transition to the L-mode regime, sometimes preceded by a short period of Type III ELMs. Most probably, what

prevented the Mark II plasmas from maintaining a pressure pedestal was the presence, during the L-mode phase, of a $n=1$ MHD instability localised in the pedestal region [2]. The nature of this instability as well as the reason why it is not present in GB are not known. Clearly the mode was stable at the power levels required for a steady Type I ELM regime.

The power threshold for Type I ELMs exhibits some day to day variation ($\approx \pm 20\%$ in GB), indicating an effect of the vessel conditioning. Nevertheless, more power is necessary to maintain Type I ELMs in GB than in similar discharges in Mark II. This result, and the observed relation with $P_{th(\text{scaling})}$, are consistent with the observation that plasma magnetic configurations with the strike points on the vertical target (as used in GB) have higher P_{th} than horizontal target plasmas (where most of our Mark II data were taken) [3]. The difference in power threshold for Type I ELMs between the GB and the plugged Mark IIAP divertor ($P_{IN} \approx 1.3 P_{th(\text{scaling})}$ in Mark IIAP, [4]) is consistent with the measured increase in P_{th} [3]. On the other end, P_{th} also appears to decrease as the divertor is made more geometrically closed, so that the GB and the unplugged Mark IIA divertors have similar P_{th} . However, no difference was observed in the behaviour of the loss of confinement in Mark IIA and Mark IIAP plasmas.

3-Dependence of the Type I ELM transition on pedestal density

It is characteristic of the transition to lower confinement to be accompanied by a collapse in pedestal density (Fig. 3), followed by a large density reduction right across the plasma profile. The value of the pedestal T_e in the steady Type III phase depends on n_e , being higher for lower densities. The pedestal T_e in the Type III regime with lower confinement can be higher than the maximum T_e during Type I ELMs (Fig 3). At input powers just above the power required for the transition to Type I ELM, as well as in the Type I ELMy H-mode preceding a loss of confinement, ‘‘compound’’ ELMs are often observed (Fig.1 and Fig.3). ‘‘Compound’’ ELMs are the small frequent ELMs observed after a large ELM. As indicated by the continuous and dotted arrows in Fig.4, the drop in pedestal temperature at the ELM is followed by a trajectory towards lower n_e and higher T_e during the phase of compound ELMs. If the confinement is recovered, both density and temperature increase again in the ELM free period, otherwise n_e continues to decrease and T_e increases until the steady state values during the low density Type III phase (points labelled as ‘‘loss of confinement’’ in Fig.4) are reached. These points can be

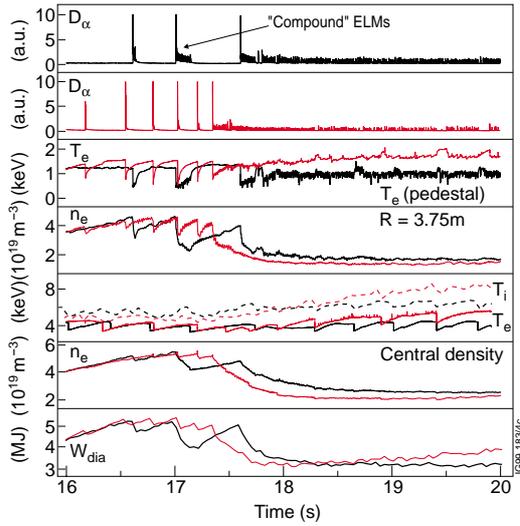


Fig.3: Evolution of the pedestal and core n and T at the transition from the Type I to the Type III ELMs regime. 2.5MA/2.4T, $P_{IN}=9\text{MW}$ (#46246:strike points on the vertical target,#46241:strike points on the corner).

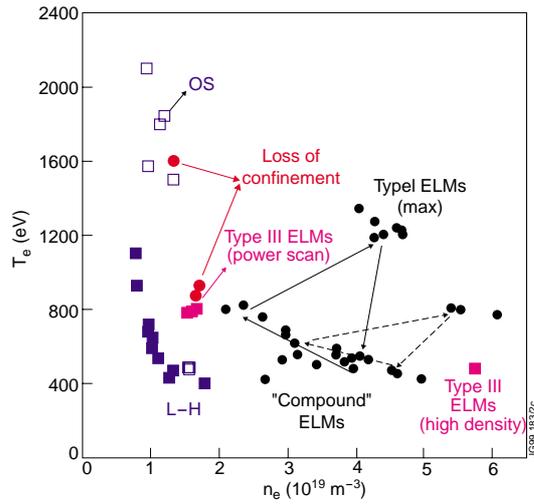


Fig.4: 2.5MA/2.4T, pedestal n_e - T_e diagram. n_e from the FIR interferometer outermost channel, T_e from the ECE heterodyne radiometer. The OS discharges have $B_i=2.5$ - 2.6T and higher triangularity

seen to describe the T_e evolution of the Type III ELM boundary as a function of n_e . In other words, the compound ELMs are transitions to the Type III regime from which the confinement is recovered. Fig 4 also shows the pedestal n_e and T_e values for the low power - low density Type III ELMs of the power scan of Fig 1 and for high density Type III ELMs, achieved with strong gas fuelling [5]. At the lowest densities, Fig 4 includes data from discharges with an internal transport barrier and an H-mode edge with small frequent ELMs (OS). The Type III n_e - T_e data of Fig 4 are consistent with the model described in [6]. According to this model, the resistive interchange instability accompanied by magnetic flutter (RI-F) is responsible for the onset of Type III ELMs.

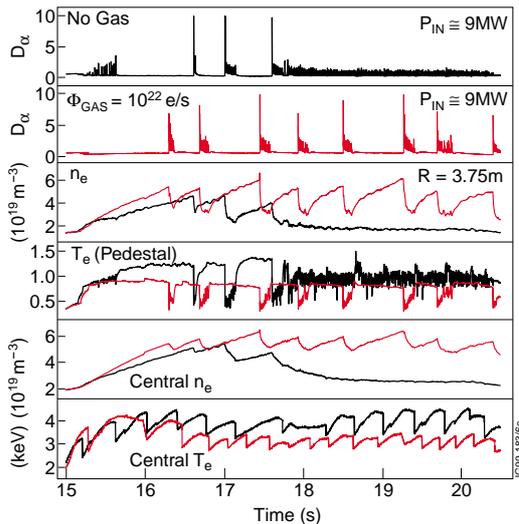


Fig.5: Effect of gas fuelling on the Type III to Type I ELM transition. 2.5MA/2.4T - $P_{IN}=9\text{MW}$, #46246: no fuelling, 46248: with fuelling. 46246 is a "loss of confinement" point in Fig.4, 46248: dotted line ELMs trajectory in Fig.4.

the discharge with no fuelling collapses to

the low confinement, Type III regime. In a similar

Experiments with the GB divertor [3] have shown that, below a critical density, the critical temperature for the L-H transition increases with density (L-H points in Fig.4). At the critical density P_{th} has a minimum. As the critical temperature for the transition to Type I ELMs also increases at low density, one could conceive that a similar minimum of the power threshold for Type I ELMs might be expected. Experimentally, one indeed finds that increasing the density of a low density Type III discharge reduces the power threshold for Type I ELMs. In fact, in the Mark II experiment we observed that with reduced divertor pumping, which resulted in higher pedestal n_e and lower T_e , it was possible to maintain Type I ELMs at lower power. Fig 5 shows the result of a similar experiment carried out in the GB. With identical P_{IN} , the discharge with a constant external fuelling of 10^{22} atoms/s is in the Type I ELM regime while the discharge with no fuelling collapses to

manner to the reduced divertor pumping, the effect of the external fuelling is to increase both the edge and core n_e and reduce edge and core T_e . These results explain the apparent contradiction of an increased $P_{IN}/P_{th(\text{scaling})}$ during the low density Type III phase not leading to the plasma recovering the Type I ELM behaviour (see time evolution of Fig 1). Moreover, they show that the global description of the second paragraph, were the power threshold for Type I ELMs is given in terms of the present scaling for P_{th} , is only valid at relatively high density.

4-Confinement As for the Type III ELMs at high density [5], the reduction in energy confinement with Type III ELMs is not entirely due to the lower pedestal pressure. TRANSP analysis of discharges which experience a transition from the Type I to Type III regime shows an increase in the transport also in the plasma core. In fact, the effective heat diffusivity doubles over the whole profile. The lower plasma pressure is mostly due to the lower density across the profile. The central fuelling at low edge n_e produces slightly more peaked density profiles with Type III ELMs than with Type I ELMs. The central T_e is either unchanged or increased with Type III ELMs, and $T_i > T_e$. Both T_e and T_i profiles are more peaked during the Type III ELMs.

5- Current ramp down In both GB and Mark II, an I_p ramp down during the low confinement phase which follows a loss of confinement produces a transition back to the Type I ELM regime. The immediate response of the edge and core confinement to the I_p ramp, as seen in the time evolution of the core χ_{eff} , suggests that the modification of the edge current profile and not the lower I_p is responsible for the transition to good confinement.

6-Conclusions The results of the GB divertor experiments confirm that input power in excess of twice the L-H threshold power are required to maintain in steady state an ELMy H-mode with Type I ELMs. At marginal powers, the plasma can access the Type I ELM regime and sometimes maintain it for several energy confinement times, but cyclic or permanent transitions to lower confinement are then observed. Such transitions are accompanied by a large decrease in pedestal (and core) density. The pedestal T_e in the Type III ELM regime increases at low density, as does the critical temperature for the L-H transition. In a similar manner to the low density L-H threshold, it is possible, by increasing the edge density, to reduce the power required to maintain the type I ELM regime. The power necessary to maintain Type I ELMs is found to depend on either plasma current or plasma density, which varied together in our experiments. Separate experiments, which show that P_{th} depends on n_e and not I_p [3], suggest that the observed dependence may be on density. Nevertheless, experiments aimed at separating the n_e and I_p dependence of the Type I threshold power are required.

The different character of the transition to lower confinement in Mark II and GB (L-mode in Mark II, Type III ELMs in GB) is most probably to be attributed to the presence of an additional edge instability in the Mark II plasmas, and not to higher P_{th} for Mark II. Somewhat higher threshold power for Type I ELMs is required in GB, probably as a result of the higher P_{th} for plasma configurations with the strike points on the vertical target.

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