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1. INTRODUCTION

Type I Edge Localized Modes (ELMs) remain a serious concern in ITER because of the high transient heat and particle flux that can be deposited on the plasma-facing components of the divertor. This has stimulated worldwide research on experimental methods to mitigate the ELM energy losses without significant degrading the confinement. Among various mitigation techniques, magnetic triggering based on a fast vertical movement of the plasma column has demonstrated that the ELM frequency (f_{ELM}) can be locked to the frequency of the externally imposed magnetic perturbation, enabling the production of more frequent, smaller ELMs. The method, first developed in TCV [1], has also been successfully applied in ASDEX-U [2] and JET [3]. In JET the plasma vertical movement relied on the vertical stabilization controller that has been modified to allow the application of a user defined voltage pulse (so called kick) at an adjustable frequency which is presently limited to a maximum value of ~60 Hz due to technical constraints. This paper summarizes recent experiments on the JET tokamak devoted to study the nature of the magnetic ELM triggering mechanism and its effects on plasma performance. The experiments reported here have been carried out in high triangularity plasmas (2.2-4T/2MA, $q_{95} = 3.6\text{-}3.9$, $\delta_{ave} = 0.43$) with the outer strike position optimized for high resolution infrared measurements and additional heating dominated by NBI ($P_{NBI} = 7-12$MW, $P_{ICRH} = 1-2$MW).

2. MAGNETIC TRIGGERING OF ELMS IN JET

In the experiments reported here, a reference Type I ELMy H-mode (2MA/2.2T, q_{95}~3.6) and low ELM frequency (f_{ELM}~5-10Hz) is established for approximately 2.5 sec before the switching on of the kicks (fast radial field variations). These conditions are achieved by keeping the heating power close above the L-H transition and no or very small levels of gas fuelling. The plasma response to the kicks is illustrated in Fig.1. It appears that the ELM frequency adapts almost immediately to the frequency of the externally controlled vertical plasma movement (f_{ELM} increases by a factor of 3) and dropped back to its initial value after the perturbation is switched off. The increase in f_{ELM} is accompanied by a decrease in the fast energy losses caused by the ELMs. In this example, both ΔT_e and ΔW_{ELM}, as well as the peak divertor heat load, are reduced by a factor of 2. During this phase particle transport changes, which reduces both core and pedestal density (so called density pump-out effect, similar to that observed when resonant magnetic perturbations are applied for ELM control [4]), and electron and ion temperature increases, leaving the pedestal pressure almost constant. As a result, the plasma exhibits only a minor, 10% reduction of the thermal stored energy.

In JET, as in ASDEX-U, ELMs are preferentially triggered when the plasma is moving down, contrary what it is observed in TCV, and a minimum kick size is necessary for the trigger to occur. Successful ELM triggering is obtained in JET with displacements of the current centroid (Δz_{cc}) ~0.5-1.5cm and velocities ($v \cong dz_{cc}/dt$) in the order of 5−10ms/s. Those values remain less than double that caused by intrinsic ELMs. However the fast plasma movement is not the only requirement for the ELM to be triggered. For similar pre-programmed kicks the plasma response depends also on the local plasma parameters. It has been found that, for a fixed frequency, the threshold in kick size is reduced either by increasing gas fuelling (decreasing T_e) or increasing the heating power (increasing T_e). In both cases the ELM frequency measured before the kicks are applied increases, which suggest that the proximity to the ‘natural’ stability limits might play a positive role in the triggering mechanism. Typically 2−3ms delays are observed between the start of the kick and the ELM and the delays are slightly higher for plasmas with higher pedestal T_e (for similar density). An increase in the edge T_e will increase the current penetration time. While this observation might suggest a possible role for the ELM trigger of the modification of edge currents by the induced field and/or change in the plasma equilibrium, the precise physics is still unknown.

The original hypothesis behind the TCV experiments [1] was that, as a consequence of the plasma movement (away from the X-point), the edge current increased, which might destabilize MHD activity, causing the ELM to be triggered. In contrast, in JET and ASDEX-U the ELMs are triggered when the plasma is moving towards the X-point. In the case of ASDEX-U, it has been shown [6] that the current density in the edge region increases when the plasma is moving away from the X-point and decreases when moving downwards. Complete calculations of the edge current in JET, including 3 dimensional effects caused by non-axisymmetric eddy currents in the vessel, has not been undertaken yet and therefore it is not clear whether the simple interpretation about the sign of the induced edge current perturbation can be applied. It is worth mentioning that the induced edge current is only one of the effects of the fast vertical movement in the plasma equilibrium. While moving down, the plasma also shrinks which produces a deformation of the plasma shape. This leads to a perturbation of the local edge pressure and reduced lower triangularity and q95. Recent detailed analysis of the ASDEX-U and TCV results has shown that the overall effect of the plasma shape deformation on the stability can be significantly stronger than that of the edge current perturbation [6].

4. EFFECT OF KICKS ON ELMS AND CONFINEMENT

The possibility to control the size of the ELMs by controlling its frequency has been further explored by varying the kick frequency in a series of unfuelled pulses with otherwise similar plasma parameters (2.4T, 2MA, q_{95} = 3.9, d_{av} = 0.43, $n_{e,ped}/n_{Greenwald}$ ~ 60%, P_{NBI} = 8MW). Figure 2 shows the evolution of some chosen parameters for 3 discharges with different ELM frequency. This includes one reference pulse without kicks (f_{ELM} ~ 5Hz) and two other pulses with f_{ELM} = 20 and 40Hz (controlled by the kicks). The initial phase of the pulses features low frequency Type I ELMs (f_{ELM} ~ 5Hz) with good confinement (H_{98} ~ 1.1). Changes in the pedestal parameters are seen immediately after the ELM frequency is locked to the kick frequency (f_{kick}). Typically within 1 or 2 kick cycles the ELM frequency is locked to the fkick. The increase in ELM frequency immediately reduced the crash in T_e and WMHD caused by the ELMs and caused a noticeable drop in the edge density as well as the edge rotation (from charge exchange spectroscopy measurements). The core density decreases in a slightly longer time scale (~2sec), saturating at a level that depends on the ELM frequency. The reduction in density is accompanied by an increase in temperature (both for electrons and ions) which in turns results in a reduction of electron and ion edge pressure of less than 15%. In all the pulses with kicks the relative decrease in thermal store energy with respect to the plasma phase with natural ELMs is $\leq$ 10%. The increases in the scan shown in Fig. 2 due to the density dependence in the 1998 H-mode scaling law. It is worth mentioning that, in conditions where the fELM is completely governed by the kicks (for a sufficiently large kick size), the reduction in density is only observed when the frequency of the triggered ELMs is at least a factor of 2 higher than that of the spontaneous ELMs.

The performance of ELMy H-mode with kicks has been compared to that of gas fuelled plasmas. With gas fuelling the frequency of the ELMs is relatively higher (~55Hz) than the maximum fkick used in the experiments and the drop in edge pressure (mainly due to a decrease in temperature) and in the stored energy is stronger (a reduction of ~30% compared to the unfuelled phase) than that obtained with kicks (in unfuelled plasmas). The degradation in confinement is apparent in the decrease in the H98 factor shown in Fig.3. Figure 3 also illustrates that the pedestal density loss caused by the kicks can be restored by gas fuelling but the global confinement decreases to those of the similar fuelled H-mode plasmas.

The relative losses associated with the ELMs for an extended database that includes natural and triggered ELMs are shown in Fig.4. This analysis is restricted to the relative temperature and energy losses ($\Delta T_e/T_{e,ped}$, $\Delta W_{ELM}/W_{ped}$) due to the lack of reliable density information (due to difficulties in the operation of the Thomson Scattering and interferometer diagnostics during the kicks experiments). We find that for triggered ELMs, $\Delta T_e/T_{e,ped}$, $\Delta W_{ELM}/W_{ped}$ (averaged values over 3-5 ELM cycles) decrease with increasing ELM frequency, following the trend observed in fuelled H-mode plasmas. With gas fuelling the frequency of the ELMs is relatively higher and îTe and îWELM become smaller. îWELM/Wped for triggered ELMs in unfuelled plasmas deviates clearly from the trend of ELM energy losses to increase with decreasing pedestal collisionality (decreasing density) [7]. As shown in Fig.4, the amplitude of the triggered ELMs can be up to 3 times smaller than spontaneous ELMs at the same pedestal collisionality. The reason for this difference is the difference T_e perturbation caused by the ELMs in the case of spontaneous and triggered ELMs. For spontaneous ELMs ΔT_e is larger at low density and decreases strongly with increasing density while for triggered ELMs the T_e perturbation is smaller and decreases with decreasing density. The reduction on energy loss is not accompanied with a reduction on the plasma volume affected by the T_e crash following the ELM (from ECE). The ELM affected region is ~20-25% of the plasma radius for spontaneous and triggered ELMs of similar pedestal plasma parameters.

CONCLUSIONS

Magnetic triggering has been successfully demonstrated in JET. We have shown that plasma kicks (fast radial field variations) moving the plasma towards the X-point can generate high frequency, synchronous ELMs in standard Type I ELMy H-modes, although the precise physics of the ELM triggering is still unknown (modification of edge current and/or changes in plasma equilibrium). With the application of the kicks the edge pressure gradient reduces, and this reduction is mainly due to a decrease in the plasma particle content (density pump-out). Density 'pump-out' and drop in edge rotation increase with increasing ELM frequency. ELM size reduces with the increase in f_{ELM}, however in the case of the triggered ELMs, the link between the ELM size and the pedestal plasma parameters (pedestal collisionality) is lost and small ELMs can be sustained even at low pedestal collisionality (in unfuelled plasmas). Reduction in the ELM size is due to a reduction on the DT_e at the crash and not to a smaller ELM affected volume. The interpretation of these results requires detailed stability analysis, still in progress for the experiments reported here. The fact that these small ELMs can be maintained without significant deterioration of the energy confinement (<10% in unfuelled plasmas) is a very favourable result in view of mitigation of ELMs in ITER

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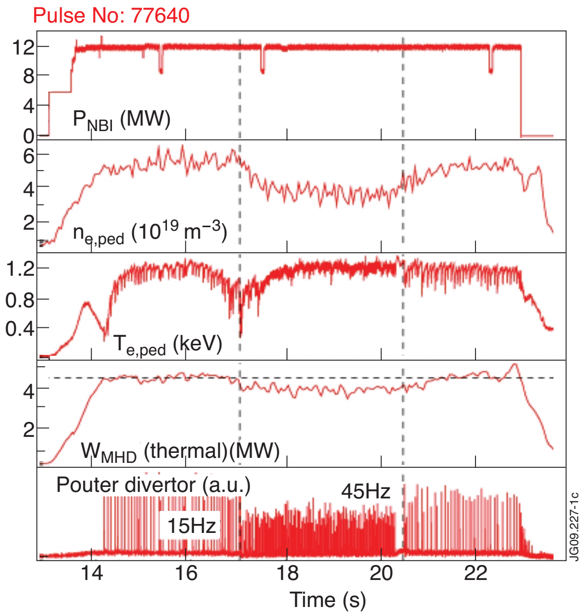

Figure 1: Temporal evolution of the pedestal top electron density and temperature, thermal W_{MHD} and heat flux from fast IR measurements. Kicks at45Hz are applied between 17 and 20 sec.

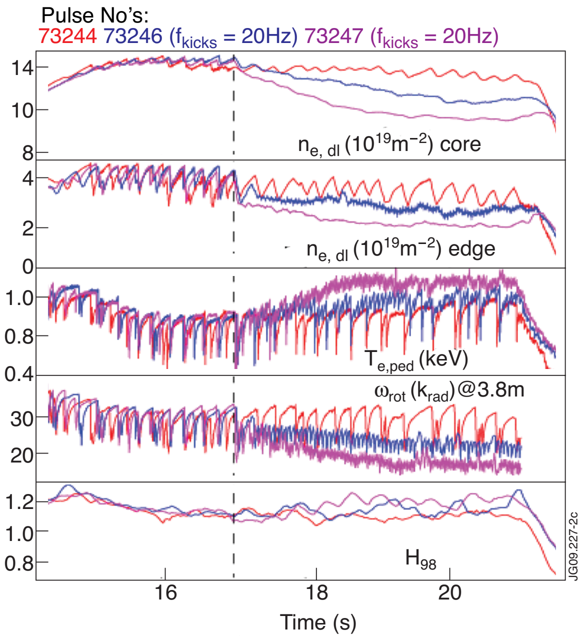

Figure 2: Comparison of some chosen plasma parameters for Pulse No's: 73244 (no kicks), 73246 (18 Hzkicks) and 73247 (40Hz kicks). Kicks starts at 17sec.

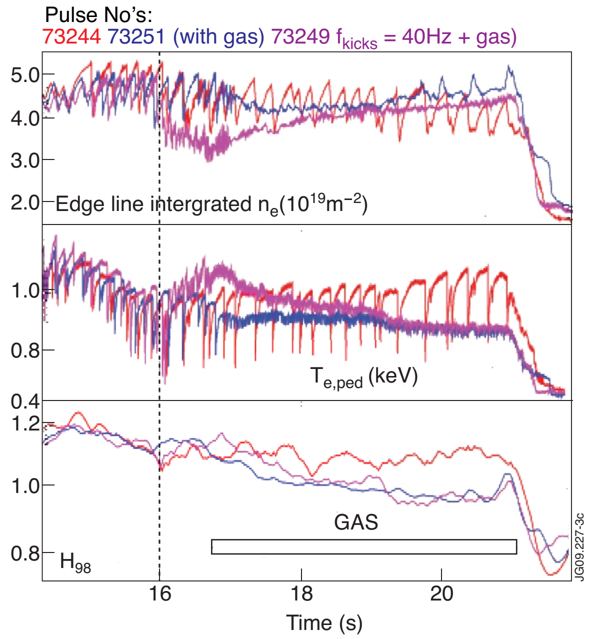

Figure 3: Temporal evolution of pedestal T_e and n_e(line integrated) and H_{98} factor for three Pulse No: 73244 (unfuelled), 73251 (with gas fuelling), 73249 (with gas fuelling and 40Hz kick startingat 16 sec); showing the plasma response to gas.

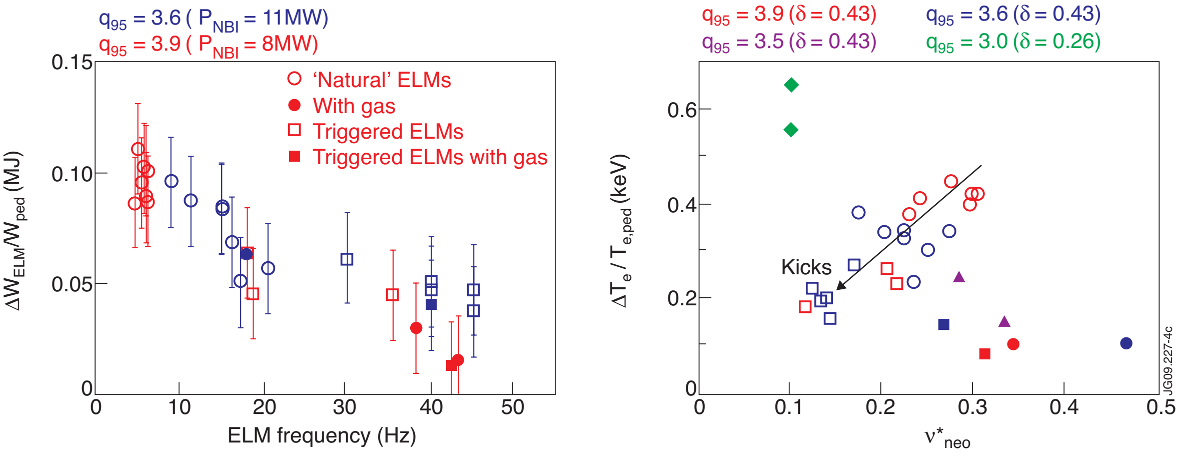

Figure 4:a) Normalized ELM energy loss (to the pedestal energy) versus ELM frequency, b) Normalized electron temperature perturbation caused by the ELMs versus pedestal plasma collisionality showing that, with kicks, small ELMs can be sustained even at low pedestal collisionality.