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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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INTRODUCTION

ELM mitigation via pacing and plasma fuelling are the two main roles of pellet injection in ITER. ELM triggering by pellet injection provides a promising method for reducing the ELM size as demonstrated on ASDEX Upgrade (AUG). Thus, the ELM impact on plasma-facing components will be minimised. This should be achieved with the smallest possible impact on all other plasma parameters (besides ELM frequency). Hence, pellet injection for ELM pacing should use the smallest possible pellets and a shallow injection. An optimized use of pellets in ITER requires their integration in ITER plasma scenarios in an effective manner for both fuelling and ELM pacing. However, a successful scaling to ITER from results of present day tokamaks requires sound physics understanding. For this purpose, detailed investigations of the local impact of the pellet imposed perturbation are performed at both AUG and JET.

For fuelling purposes, pellet injection has to maintain the plasma density and allow high density operation with minimum detrimental effect on energy confinement. This requires pellet penetration as deep as possible into the core plasma. Investigations on JET are under way to identify the best approach to achieve this goal, e.g. by comparing injection from the torus inboard to outboard launch. While the first approach benefits - in hot plasmas - from strong drift effects, the latter has the potential for higher launch speed.

1. INVESTIGATION STRATEGY

To provide a better insight into the mechanism by which a pellet can trigger an ELM and on how it affects the evolution of the natural ELM cycle we have broadened previous investigations on the most relevant type-I ELMs towards other ELM type regimes (type III, ELM-free, radiatively cooled type-I). We also reconsidered the effect of pellets in high confinement regimes seemingly not prone to ELMs like the Quiescent H-mode (QH) and on core mode activity. Finally, we investigated also pellet injection under plasma conditions below the H-mode threshold where no pellet triggering of transient or persisting modes takes place. By this, we could study the purely pellet driven MHD activity lasting only as long as a local pellet perturbation is imposed.

For this purpose, we re-analysed results of previous experiments performed on JET and AUG with the scope of fuelling, but also new experiments performed on AUG. Currently, the new High Frequency Pellet Injector (HFPI) is put into operation at JET. This new launching system is potentially capable to inject pellets from three different poloidal positions (outboard mid plane, inboard mid plane and top) at high repetition rates (up to 60Hz) with size and speed optimized for pellet ELM pacing and corresponding physics investigations. Dedicated experiments are under way making use of the HFPI for ELM trigger physics investigations, for exploring ELM pacing at ITER relevant parameters and for establishing a fully integrated ITER reference scenario.

2. RESULTS

2.1. ELMY H-MODE REGIMES

The broadening of previous experimental investigations on the effect of pellet injection for the most relevant type-I ELMs towards other ELM type regimes (type III, ELM-free, radiatively cooled type-I) revealed more general features of the onset dynamics for spontaneous and triggered ELMs. Whereas in ELM-prone regimes frequency and growth time of spontaneous ELMs vary with changing plasma parameters, pellets can enforce the appearance of an ELM at any instant and always with the shortest observed growth time. This observation was made by comparing triggered and spontaneous ELMs in the above mentioned ELM regimes. In the low resistivity hot edge mode case spontaneous and triggered ELMs evolve equally fast. Obviously the growth rate of a spontaneous ELM is so large that even the finite-size seed pellet perturbation cannot accelerate the ELM dynamics any further. Increasing edge resistivity by Ar seeding for controlled edge and hence divertor cooling or strong D_2 gas puffing results in a reduction of the spontaneous ELM growth rate. However in all cases forcing of the ELM by a pellet restores the most rapid possible growth rate, giving rise to a different ELM onset dynamics. This indicates that - within the limits of pellet sizes and velocities explored - every pellet imposed perturbation in the above mentioned, intrinsically ELM-prone regimes can provoke a strong non-linear modes growth during any phase of the natural ELM cycle.

3. DIRECTLY PELLET DRIVEN MHD

This hypothesis is further supported by an analysis of the pellet driven magnetic perturbations in regimes below the H-mode threshold, and hence not subject to naturally occurring ELMs. As Ohmic and L-mode plasmas are not prone to the initiation and persistence of an intrinsic MHD mode, they allow to study the isolated effect stemming from the pellet induced impact. All local changes in plasma parameters are than directly driven by the ablated cold pellet particles. Pellets were found capable to create magnetic perturbations ultimately becoming significantly larger than those observed during an initial ELM phase (figure 2), but do not trigger ELMs. The directly pellet driven nature of the perturbation becomes obvious from the fast decay of the magnetic perturbation signal at pellet burn out, as the Mirnov signals drop back to noise level within about 50μs.

It was also found that the magnitude of the pellet driven perturbation depends on the plasma but not on the pellet parameters. No relation was found between the amplitude of the pellet driven magnetic perturbation and the number of particles deposited either per unit time (= pellet ablation rate) or per unit length along the pellet path. In these experiments, pellets were injected into virtually identical 0.8MA OH discharges. Low repetition rates allowed for averaging over many identical pellets and hence better resolution and reliability. To vary the pellet parameters, the full accessible range of the AUG centrifuge injection system for torus inboard launch was applied, ranging from 1.6 (“small”) to 4.1×10^{20} (“large”) in nominal D-atom content and from 240 to 880m/s in velocity. The only correlation that could be identified was between the magnetic signal response and the pellet position along its injection path. As shown in figure 3, any pellet, independently of its size and velocity, causes the same response. Hence, in the accessible pellet parameter regime the mechanism driving the magnetic perturbation already saturates.

4. QUIESCENT H-MODE

The QH mode is an interesting regime with respect to edge instabilities as it displays no strong burst-like transport but an Edge Harmonic Oscillation (EHO), which is thought to keep the edge in a near-stable regime. Pellets injected during QH phases were observed to drive a direct magnetic perturbation like in the sub-H-threshold regimes, but - despite the large size used - did not trigger ELMs. This was concluded from the absence of a strong MHD response and a detectable global energy release as observed in the case of any triggered ELM. According to these experiments a pellet cannot trigger an ELM in the QH mode, a regime obviously not corresponding to conditions under which the pellet imposed perturbation can seed an instability that subsequently grows into a macroscopic MHD perturbation.

DISCUSSION AND OUTLOOK

The strong pellet perturbation can be applied to probe the edge stability against ELMs. Usual H-mode discharges remain permanently, at least non-linearly unstable while Ohmic, L-mode and quiescent H-mode plasmas have a stable edge. These results would indicate that ELM pacing in ITER could be achieved by injecting small high speed pellets from the LFS of the machine, causing only little impact on particle inventory and confinement. On the other hand pellet fuelling would appear to be also compatible with scenarios relying on ELM suppression or avoidance by e.g. edge ergodisation, since experimental evidence suggests that in such regimes (with stable pedestals) pellets no longer trigger ELMs.

It is clear that these findings require further substantiation. JET with its novel pellet injection system especially designed for ELM pacing experiments provides an unique opportunity for such investigations, as well as for the study of the physics of pellet/pedestal interaction at pedestal plasma parameters approaching those of ITER. Moreover, for the first time it will be possible to investigate steady state pellet pacing in an operational regime with an intrinsic natural ELM frequency low compared to the pellet injection frequency, and to test whether adequate pellet pacing can be achieved with a tolerably small perturbation of the total particle balance. The profile evolution towards a steady state and the impact of the residual fuelling induced convective losses on the confinement will be examined in detail. An encouraging result along this line is shown in figure 4. It shows a fuelling sized pellet in JET triggering an ELM, and, as reference, a spontaneous ELM.

The ELM is triggered with only about 4×10^{19} D (~1% of the injected pellet mass) ablated. Hence there is hope, that with the pellet parameter optimization possible in 2008, regular and reliable ELM triggering should be achievable with negligible plasma fuelling and density perturbation (and therefore less convective energy loss).

First results of spectral analysis of magnetic perturbations, based on wavelets, indicate that ELM triggered by pellets can be described as explosive instabilities, with a growth dynamics comparable to that of their spontaneous counterparts.

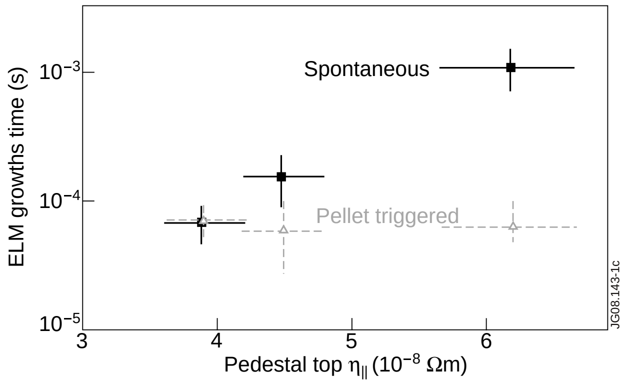

Figure 1: When creating a cooler edge at higher density, e.g. the pedestal top resistivity (parallel Spitzer) increases as the plasma undergoes a transition from type-I to type-III ELM regime. While the spontaneous ELM growth times rise significantly (note logarithmic scale), triggering maintains a fast ELM onset. Data from hot edge type-I, Ar seed cooled type-I and type-III ensembles (left to right); all discharges at I_P = 1 MA.

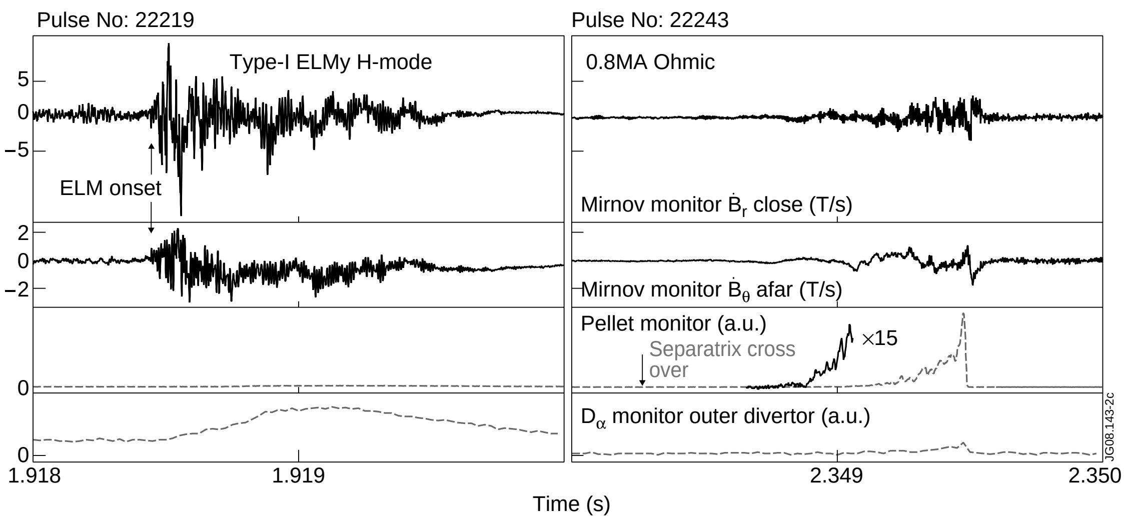

Figure 2: MHD perturbation during spontaneous type-I ELM and pellet injection into OH plasma (identical scales). This pellet driven magnetic perturbation in OH represents the weakest observed impact of all available pellet parameters; it exceeds the magnitude of the MHD activity observed at the very onset of the ELM (indicated by the arrows).

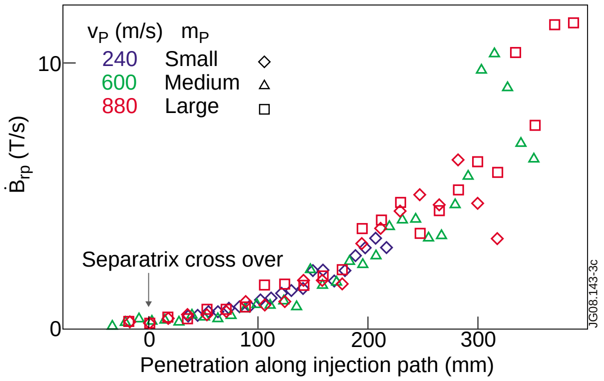

Figure 3: Pellet induced magnetic perturbation versus pellet position along the injection path, separatrix position defines 0. At the given plasma position, the same magnitude for the pellet driven magnetic response is observed for any pellet speed and/or mass applied (inserted legend show different pellet velocities and sizes used during the study).

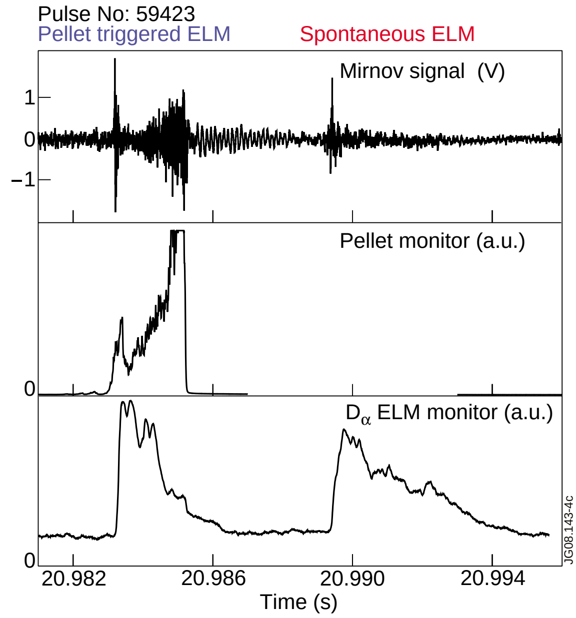

Figure 4: Mirnov coil response, pellet ablation and divertor D_{α} ELM monitor (top to bottom) for a fuelling size (4×10^{21} D) pellet triggered (left) and a spontaneous (right) ELM.