ELM control at the L-H transition achieved by pellet pacing in the all-metal wall tokamaks ASDEX Upgrade and JET

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INTRODUCTION

Operating ITER in the reference inductive scenario at the design values of I_P = 15 MA and Q_{DT} = 10 needs to achieve good H-mode confinement relying on the presence of an edge transport barrier and the height of the plasma pedestal is a key to performance. Strong gradients evolving at the edge can drive MHD instabilities resulting in an Edge Localized Mode (ELM) producing rapid energy burst from the pedestal region. Without dedicated control ELM resulting impulsive heat loads on plasma facing materials in ITER becomes critical for operation at $I_P \approx 9.5$ MA [1], progressing beyond would result in an intolerable short life time of the divertor plates [2]. Currently, there are several options considered for this inevitable ELM actuation, but all of them need further validation for the ITER tasks. Evidently, the main task in this context is to achieve sufficient mitigation of the peak power flux to divertor in according scenarios, either by suppression or mitigation of ELMs. ELM control requirements in ITER have recently received focussed attention [1] in relation with the proposal to start ITER operation with a Tungsten (W) divertor, which was originally foreseen for the beginning of nuclear operations (DD and DT plasmas) and is now being considered also for the start of ITER operation in the non-nuclear phase (H and He plasmas) [3].

For the initial ITER operation the plasma current will be limited to $I_P \approx 7.5$ MA and hence ELMs are not likely to cause unacceptable divertor erosion or melting. However, W will be produced in between and by the ELMs. Hence, a minimum ELM frequency will be required to maintain an appropriate low W concentration in the main plasma [1]. Since ITER is expected to enter the H-mode already during the current ramp up phase, the mitigation technique must be compatible with a still changing plasma shape and edge magnetic configuration. Hence, for any considered control tool demonstration of successful actuation already immediately before and during the L to H transition is required. Crucial questions are further if the technique does have an impact on the L → H transition power threshold and if there is a residual influence on the final steady-state H-mode.

Injection of solid pellets formed from frozen fuel has been demonstrated a very well proven technique for the control of the ELM frequency in several tokamaks as e.g. ASDEX Upgrade (AUG) [4], JET [5] and DIII-D [6]. Consequently, a suitable system is under development for controlled ELM triggering at ITER by injection of pellets carrying at least 2.0×10^{21} particles [1] from the torus outboard [7].

Here, we report on corresponding experiments conducted at AUG and JET. Employing pellet injection for ELM control at the L → H transition, they aim to mimic initial ITER conditions (H pellets in H/He plasma during I_P ramp). Although a full coverage of all aspects in a single demonstration experiments could not be achieved, all critical issues were covered one by one.

FIRST DEMONSTRATION AT ASDEX UPGRADE

For investigations at ASDEX Upgrade the refurbished high speed launcher system basing on a centrifuge accelerator and a looping transfer system is used. The system is capable of delivering pellets covering a wide size and speed range at repetition rates up to 80 Hz from the torus inboard inclined by an angle of 72° with respect to the horizontal mid plane [8]. For operation with D ice, reliable and persistent operation is achieved for the entire parameter regime. Experiments employing H pellets were essentially performed using large pellets at low to moderate speed. Since the cryostat system is essentially laid out for operation with D ice, the lower triple point temperature of H compared to D resulted in a deficient cool down of the H ice rod. Hence, the lower yield strength of the pellets resulted in reduced delivery reliability, in particular too low for the task of ELM control when using small pellets. The pellet observation system was upgraded as well and it now allows fast individual pellet tracking.

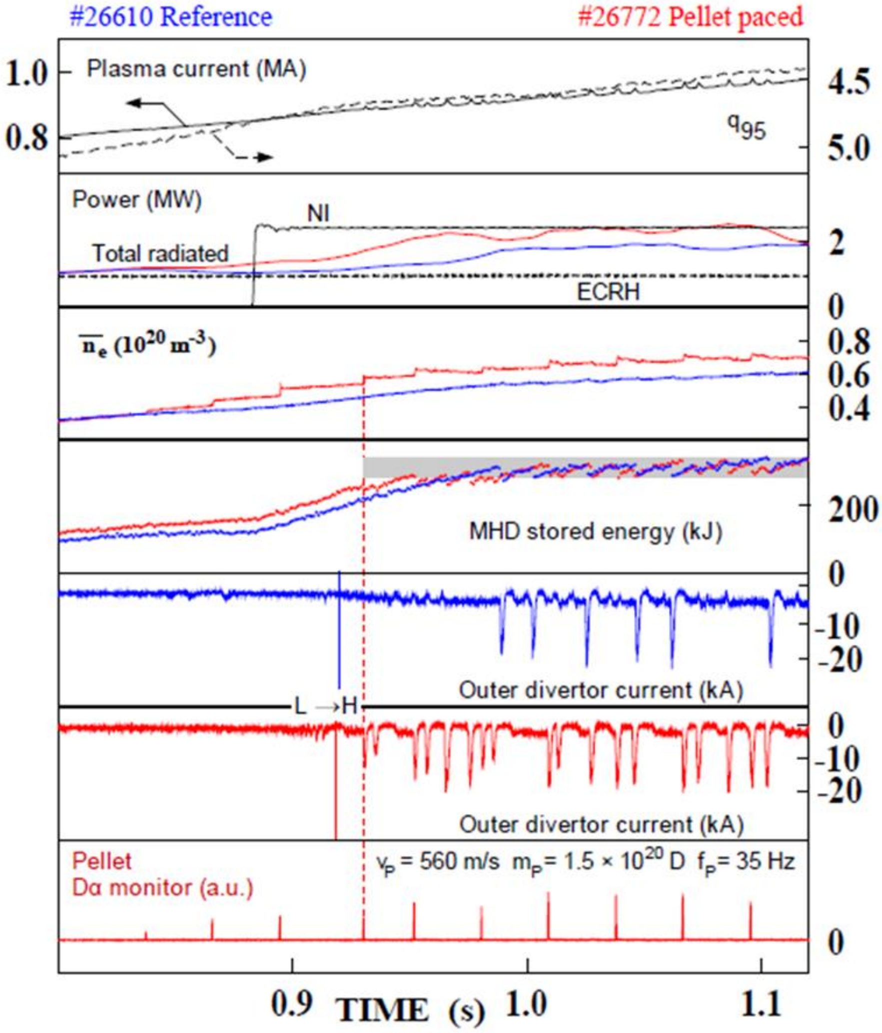

Figure 1: Demonstration of ELM control by pellet pacing at ASDEX Upgrade while the plasma undergoes the L → H transition during current ramp up with changing shape. The reference discharge (#26610, blue traces) shows a delay of about 70 ms between entering the H-mode and the first ELM in the absence of active ELM control. Sustained pellet pacing (#26772, red traces) enforces ELM activity already virtually immediately after the L → H transition. Every pellet triggers an ELM but fuelling induced ELMs appear as well. The first ELM is triggered at a plasma energy level even below the regime spanned by the spontaneous ELM cycle.

As a first step, a full demonstration of the scenario, however yet using D pellets in a D plasma, was attempted and achieved at AUG. The pellet controlled shot (#26772, red traces) is shown together with an uncontrolled reference discharge (#26610, blue traces) in figure 1. The injection of pellets already during an early heating phase forcing the L → H transition during current ramp up with still changing shape and q_{95} did not show a significant impact, neither on transition power threshold nor on the confinement finally reached. Pellets arriving a few ms before the transition clearly do not trigger ELM like events. Pellets reaching the plasma immediately after the transition do trigger ELMs despite an edge pedestal just starting to evolve but still far from its final magnitude. Hence, it can be concluded an ELM can be triggered by a strong local 3D perturbation already significantly before the pedestal is fully established reaching its linear stability limit.

For the sake of a closer match to the ITER requirements for the initial phase, the technically more challenging launch of H pellets into H and He plasma was mastered as well. For operational restrictions already mentioned, this had to come with a strong fuelling impact, even more pronounced than in the case shown in figure 1. A plasma scenario similar to the presented one became available operating with He as main ion species. Again, early heating triggered the L → H transition already during the current ramp up. However, only a very short (less than 10 ms) phase without ELMs was observed before a dithering H – mode evolved [9]. A pellet arriving in this phase caused an MHD event composed from a pure pellet component as observed for the previously injected pellet during the L – Mode, and the pure dithering ELM signature. As this was identified as typical fingerprint of a triggered ELM [10], also for this scenario the pellet trigger potential was confirmed. Pellet ELM triggering clearly truncated the initial ELM free phase in an H plasma. Here, the L → H transition was initiated by pure wave heating, applied however during a current steady state phase.

ELIMINATION OF THE FUELING IMPACT AND CONFIRMATION AT JET

Due to the much larger plasma volume of JET, the density build-up using the same pellet size as on ASDEX Upgrade is not objectionable. Pellets at JET are produced by the high frequency pellet injector (HFPI), installed at the end of 2007 undergoing several modifications since then [11]. The HFPI system was designed to launch pellets from three different injection locations for fuelling and ELM pacing purposes with variable size and speed. In operation it turned out reliable pellet delivery can only be achieved when launching the pellets from the torus outboard. While the full designated repetition rate of 15 Hz was achieved for large pellets, for the small pacing size pellets only one of the two installed extruders worked properly restricting operation to 25 Hz rather than the nominal 50 Hz for pacing. A further revision planned for late 2014 aims to optimize the system for inboard launch, restricting to this singly launch location but allowing operation with full performance with respect to variability and reliability.

Experiments reported here were embedded in studies of the L → H transitions investigating the power threshold [12]. These investigations assess the impact of the fuelling method and location on the threshold value. Replacing the gas puff partially by pellets (again D pellets in D plasmas) showed that pellets do have higher fuelling efficiency but do not alter the transition parameters with respect to density and heating power [12]. The experiment where a train of pacing size pellets was launched at a rate of 25 Hz (JPN84730) is shown in the left part of figure 2, the reference discharge with pure gas fuelling (JPN84726) in the right part. Pellet injection resulted in ELM control after the L → H transition. Due to the moderate density rise per injected pellet a density evolution almost matching the gas fuelled reference discharge was obtained. This was demonstrated for a pulse type displaying a pronounced ELM-free phase just after the L → H transition with gas fuelling. In such a discharge, every single pellet arriving after the L → H transition enforced an ELM accordingly, thus avoiding the ELM-free phase observed in the reference case. Notably, the density evolution was essentially influenced by the changed confinement regime rather than the pellets.

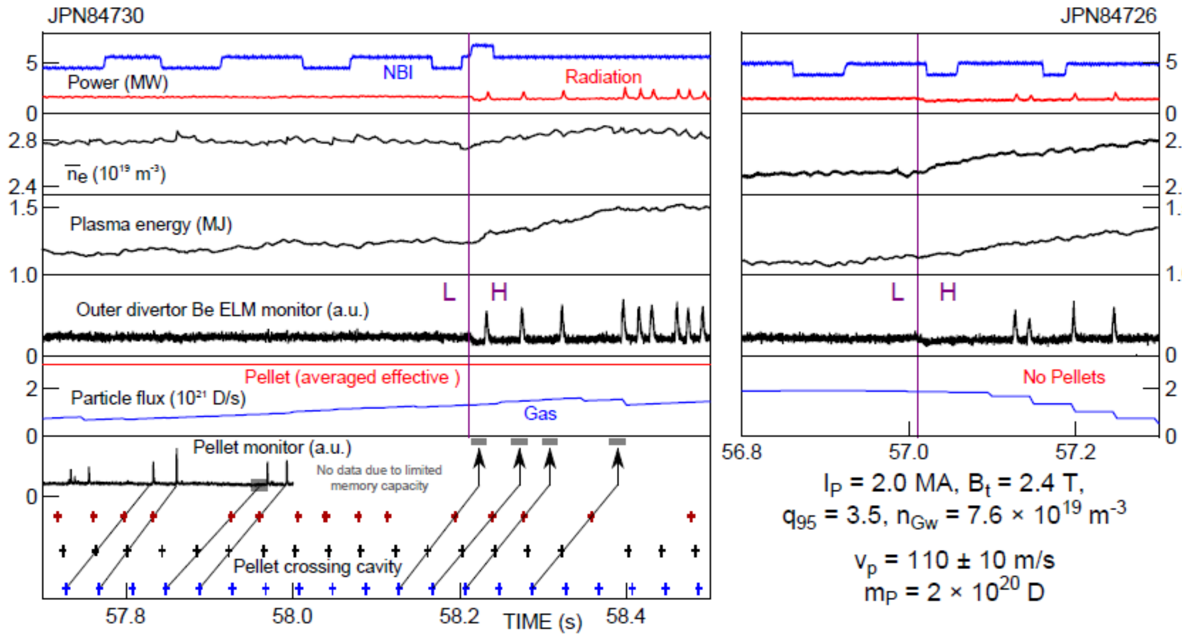

Figure 2: Demonstration of ELM control at JET by pellet pacing while the plasma undergoes the L → H transition. The reference discharge (JPN84726, right) with pure gas fuelling shows a delay of about 110 ms between entering the H-mode and the first ELM. Applying partial pellet fuelling (JPN84730, left) results in a slightly higher density in the L - Mode phase due to better fuelling efficiency. In the H-mode phase a similar fuelling efficiency as in the gas reference is found but now every pellet triggers an ELM and the ELM free phases is avoided. The first ELM is triggered in a still almost L - Mode like pedestal. Due to the higher density in the pellet case, the L → H transition occurs later and the pre-set timed pellet monitor run out of data memory. Pellet arrival in the plasma is estimated (uncertainty represented by the grey bars) from a time-of-flight analysis of the pellets passing through several cavities installed along the flight tubes, as shown in the lower box. Note the speed scatter resulting in a distorted pellet train frequency and the gap due to a pellet obviously destroyed in flight.

CONCLUSION

The study presented shows a control of the ELM frequency by pellet pacing can be established while the plasma undergoes the L → H transition. Even all aspects of an application during the initial operational phase of ITER were demonstrated one by one. It is stunning how easily pellets can trigger ELMs although the edge is still far from the peeling-ballooning stability boundary. This result was obtained by a detailed stability analysis of the JET case, details to follow in the extended paper. The question arises for the underlying physics explaining the easiness of ELM control in both presented cases although AUG and JET have been operated already with all metal walls while under such conditions steady state pacing was found much more intricate [13].

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