

Pellet as tool for high density operation and ELM control in ASDEX Upgrade

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INTRODUCTION

Injection of cryogenic solid hydrogen isotope pellets provides a powerful tool for the development of enhanced plasma scenarios. The main tasks assigned to this tool are efficient particle fuelling to achieve high density operation with high confinement and ELM control.

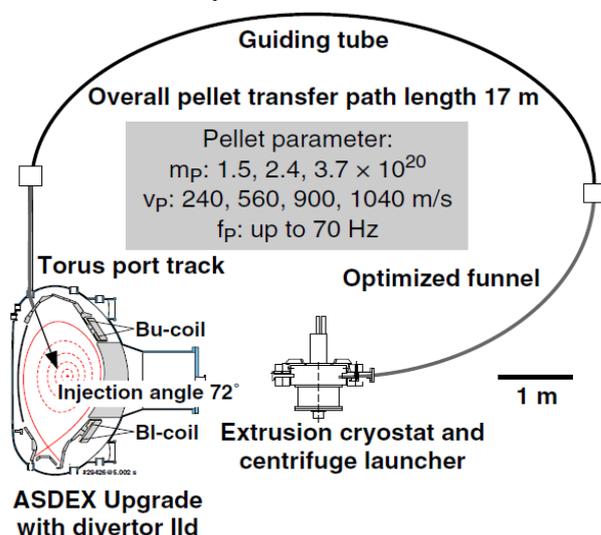
Studies for future fusion power plants based on the tokamak principle recommend operation at core densities above the empirical Greenwald density limit n_{GW} to avoid temperatures in excess of the optimum for D-T fusion at high central pressure and ease the exhaust issue. Since in present day tokamaks, density profiles become flat and are restricted to values below n_{GW} when using gas puff fuelling, a more advanced efficient fuelling method is required.

The power load deposited by type-I ELMs onto the first wall and divertor forms a severe threat for ITER. ELM pacing tries to reduce the ELM size by triggering the instability through an external perturbation with a rate higher than the natural ELM frequency. Pellets are considered as an appropriate actuator applicable in almost all operational scenarios requiring ELM pacing including the very first one in the non-nuclear phase when entering H-mode during the current ramp up phase.

The all metal wall tokamak ASDEX Upgrade is now equipped with a modernized and upgraded centrifuge type launcher covering a wide range of pellet parameters and capable of inboard pellet injection. Thus, this configuration is most suitable to perform investigations of the physics underlying pellet fuelling and ELM pacing in order to allow for a reliable extrapolation towards ITER.

SET UP: ASDEX UPGRADE AND THE IMPROVED PELLET LAUNCHER

ASDEX Upgrade is a divertor tokamak with all plasma facing components completely covered with tungsten (W). Recently, in-vessel saddle coils that can produce non-axisymmetric magnetic perturbations were installed. Presently the set-up is yet composed of 16 B-coils (each 8 upper and lower ones, referred to as Bu- and Bl-coils, respectively) which can create a mainly radial field with toroidal mode numbers up to $n = 4$ [1]. Investigations



reported here where performed in the campaign 2012/13 concluding operation in the divertor IId configuration. The high speed inboard launching system, based on a centrifuge accelerator and a looping transfer system, was recommissioned

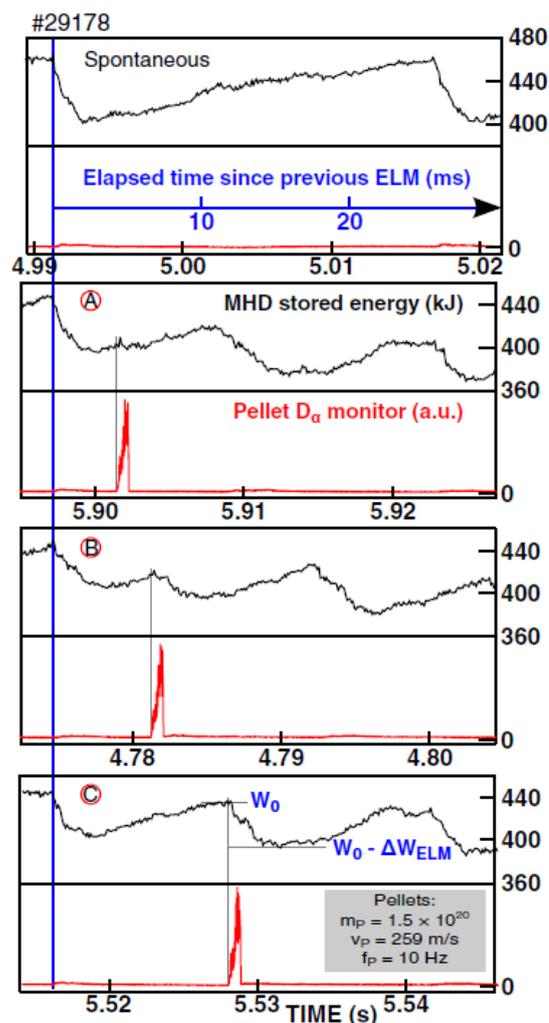
Figure 1: Set up as operated in the campaign 2012/13: AUG with an all W clad wall still with divertor IId and the full set of B coils. The revitalized pellet launching system is now capable to cover a wide range of pellet parameters for both fuelling and ELM pacing applications.

and modernized. Presently the system is capable of delivering pellets with a nominal particle content ranging from $1.5 - 3.7 \times 10^{20}$ D in the velocity range 240 – 1040 m/s from the magnetic high field side of the torus with repetition rates of up to 70 Hz. Within a given pellet train launched into a discharge both pellet speed and size are fixed. However, repetition rates can be changed to a fixed fraction of the centrifuge revolution frequency. The pellet observation system was also upgraded to include two ultra-fast CMOS cameras and is now capable of fast individual pellet tracking up to 1 Mframe/s.

ELM TRIGGERING AND PACING EXPERIMENTS

In tokamaks like AUG, JET and DIII-D, when operated with an at least partial carbon (C) wall, in H-mode plasmas pellets trigger ELMs usually within less than about 0.5 ms. Triggered ELMs showed all the basic features of their spontaneous counterparts in the same plasma regime. Pellet pacing applied e.g. to sustain of a minimum ELM frequency in order to prevent impurity accumulation worked reliably in the presence of C as wall material. When C is completely eliminated as wall material, not only the ELM behaviour was found to change significantly; also the capability to trigger ELMs by external perturbations (like fast vertical plasma movements or pellets) was altered. After the change from a C to an all-metal ITER like wall at JET, a study comparing pellet ELM triggering and pacing was performed [2]. With the ILW the type-I ELM duration has become much longer for both, spontaneous and pellet triggered ELMs. Also, a reduced capability of the pellets to trigger ELMs was observed. Whereas an ELM could be triggered immediately in a C wall environment, now with the ILW an ELM can be triggered only after a lag time of about 20 ms. This finding was confirmed at ASDEX Upgrade and investigated in more detail. The scenario developed for this investigation is a stable type-I ELMy H-mode with a sufficiently low spontaneous ELM frequency of about 40 Hz. Launching probing pellets at a rate of 10 Hz did not alter the target plasma significantly. Hence, every pellet created a local edge perturbation of the same magnitude within a spontaneous ELM cycle. Since the spontaneous ELM frequency and pellets are not synchronized, this experiment probed the pedestal stability against the external pellet perturbation with statistically changing elapsed time since the previous spontaneous ELM. Typical response results obtained within a single discharge (fixed plasma and pellet parameters) are shown in figure 2. The uppermost box displays a reference spontaneous ELM. The boxes beneath show pellet events ordered (top to bottom) with respect to the elapsed times since the previous ELM at pellet arrival. There are many indicators for an on-going ELM like e.g.

Figure 2: Pellets probing their ELM trigger capability at different times of the ELM cycle. The plasma energy loss induced by the pellet turned out as useful monitor. Early in the cycle no ELM is triggered (A), later ELMs are triggered first smaller (B) and finally (C) as large as the spontaneous reference ELM.



strong MHD activity or thermal load at the divertor strike points. In this study, it turned out that the most appropriate monitor is the pellet-induced normalized loss of plasma energy, $\Delta W_{\text{ELM}}/W_0$, calculated as indicated in figure 2. For the shortest time elapsed (case A) the recovery after the ELM is not affected by the pellet ablation and obviously no ELM is triggered. A few ms later in the ELM cycle but still at a point where no spontaneous event is yet likely pellets become capable to trigger an ELM; however this triggered ELM drops the plasma energy less than the spontaneous reference (case B). Finally virtually full sizes ELMs are triggered (case C) but still at an elapsed time significantly shorter than the typical spontaneous cycle time. From the pellet cases shown in figure 2 it is obvious that the spontaneous ELM cycle time is shortened after every pellet, no matter if it triggers an ELM instantaneously (while the ablation is still on-going) or not. This is due to the strong edge fuelling significantly altering plasma edge parameters and hence the spontaneous ELM frequency. However, this transient secondary fuelling impact is sufficiently short lived such that the plasma recovers its initial state before the next pellet arrives.

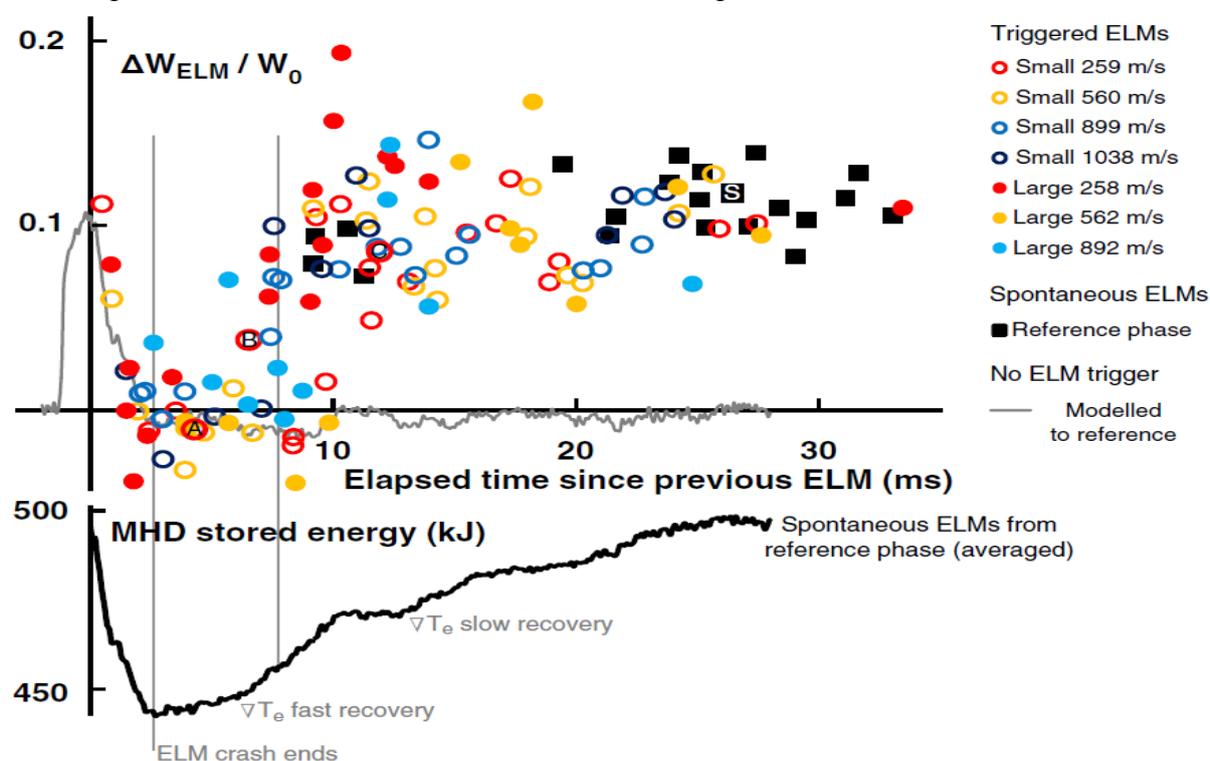


Figure 3: Upper: Relative loss of plasma energy versus time elapsed since onset of the previous ELM. Data obtained for different pellets and from spontaneous ELMs. The modelled response a pellet causing no impact on the ELM cycle is displayed a solid grey line. Lower: Averaged plasma energy evolution during a spontaneous ELM cycle.

Data from different discharges, all with the same plasma configuration but varying pellet parameters speed and mass are show in figure 3. The upper part displays $\Delta W_{\text{ELM}}/W_0$ versus the elapsed time since the last ELM; it reveals a clear transition at about 7-10 ms during the ELM recovery from a state where no triggering can be achieved by the pellets to conditions where pellets reliably trigger. No indication is found for the magnitude of the pellet perturbation in the covered parameter range playing a role for the resulting trigger lag time. In this plasma scenario the crossover from a stable edge to conditions where at least a strong local perturbation can trigger an ELM correlates well with the phase where the fast recovery of the edge temperature gradient [3] comes to an end. Performing the same analysis for a variety of plasma conditions with different separatrix power flux causing changes of the ELM

recovery dynamics resulted in quite a diversity of trigger lag times. Cases found range from failed attempts to provide ELM sustainment and avoid impurity accumulation in weakly heated scenarios by pellet pacing; here lag times in excess of 36 ms were found. On the other hand strongly heated plasmas requiring already radiative power exhaust employing N₂ seeding [4] showed lag time shorter than 3 ms. Under appropriate conditions (sufficiently high heating power and low gas flux) successful ELM pacing was demonstrated. However, no longer pronounced ELM mitigation could be achieved. In a case where the spontaneous ELM frequency was raised 1.6 times by pacing at 70 Hz, ΔW_{ELM} was only reduced by about 1.2 times while virtually no reduction of the peak heat flux on the divertor took place. A detailed description will follow in the extended paper.

OPERATION IN THE HIGH DENSITY REGIME

The reduced impact of pellets on the ELMs in an all metal wall tokamak resulting in less ELM losses even for large pellets turned out to be very favourable for fuelling purposes. An operational scenario for core densities far beyond n_{GW} was established, showing no confinement degradation and benign ELMs also without B coil actuation. This regime is reliable and reproducible; the density increase is fully reversible and returning to the initial conditions after termination of the pellet sequence the discharge can be safely ramped down. An example is shown in figure 4, displaying the evolution of a plasma with $I_{\text{p}} = 1.0$ MA, $B_{\text{t}} = 2.55$ T, $q_{95} = 4.65$; $\kappa = 1.70$, $\delta^{\text{l}} = 0.39$ and $\delta^{\text{u}} = 0.11$. The entire pellet reservoir was consumed in one go at 70 Hz rate. To avoid impurity accumulation core heating was essential, at high densities solely contributed by ICR heating; as well as a minimum gas puff of about 10^{22} D/s. Densities beyond n_{GW} are achieved by peaked profiles with high core densities but the edge density always staying below. Hence, the ‘‘Greenwald limit’’ can be regarded as edge limit easily overcome by pellet injection. Typically profiles with a density gradient at the edge extending into the core to the pellet burn out point. Finally, indications are found for an enhanced particle confinement at the highest densities, where sustainment times of pellet deposited particles are increasing by a factor up to about 3 with respect to the initial values.

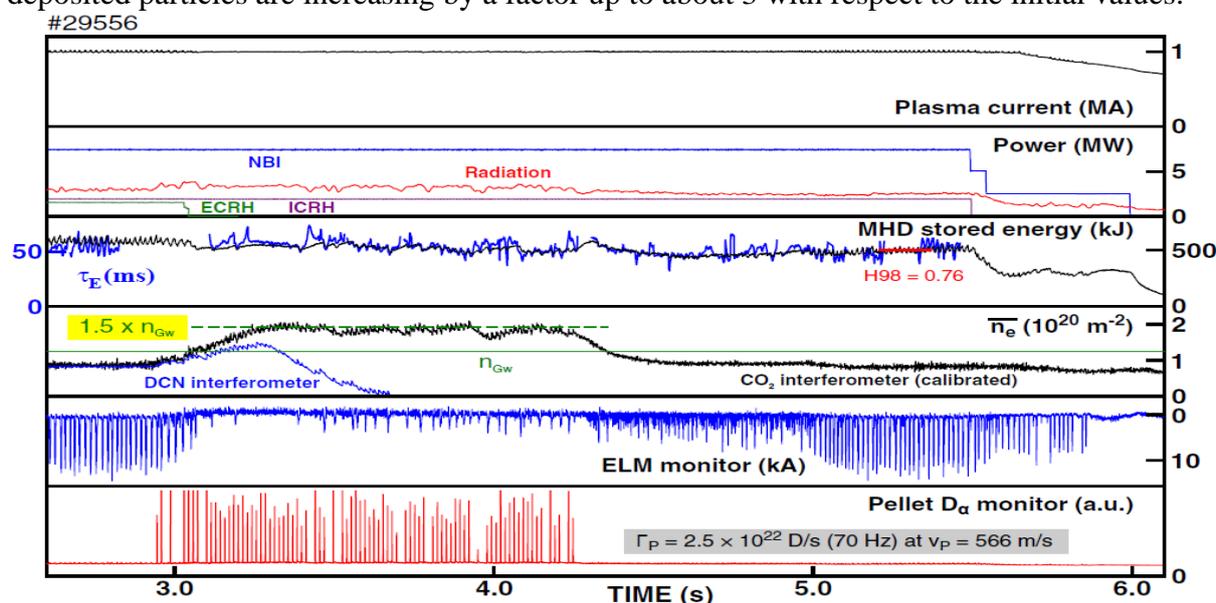


Figure 4: High density operation without confinement degradation achieved by pellet fuelling. Densities beyond the Greenwald values with benign ELM behaviour were achieved.

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