High density H-mode operation by pellet injection and ELM mitigation with the new active in-vessel saddle coils in ASDEX Upgrade

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INTRODUCTION

The power load deposited by type-I ELMs onto the first wall and divertor forms a severe threat for ITER. Currently, there are several options for ELM mitigation: (i) operating with plasma scenarios developing no or only benign ELMs, (ii) ELM pacing to enhance the ELM frequency at least by a factor of 15 – 30, and (iii) ELM control with non-axisymmetric magnetic perturbations. Pacing tries to reduce the ELM size by triggering the instability through an external perturbation, e.g. by pellet injection with a rate higher than the natural ELM frequency. Suppression of type-I ELMs is preferred over ELM pace-making if it can be achieved without significant deleterious impact on the plasma performance. A key issue for H-mode operation with suppressed or mitigated ELM activity is whether core pellet fueling, a requirement in ITER, will trigger strong ELMs and thereby re-introduce excessive peak power loads. Full suppression, respectively significant mitigation of ELMs, has been achieved with in-vessel coil induced edge magnetic perturbation in DIII-D [1] covering a wide operational range. Pellet fueling, applied to compensate for the observed density pump out, however, caused recurring of the ELMs [2]. The all tungsten wall tokamak ASDEX Upgrade has been enhanced with a set of in-vessel coils in order to support ELM amelioration investigations in support of ITER. For fueling studies in this operational regime, also the pellet fueling system has been refurbished and upgraded.

STATUS OF COIL AND PELLET INJECTION SYSTEM

ASDEX Upgrade is currently equipped with a set of in-vessel saddle coils for magnetic perturbations that consists of two arrays of 4 coils each, toroidally spaced at the low field side (one row above and one below mid-plane) as a first step of a staged enhancement with ultimately 24 in-vessel saddle coils. The presently installed coils have five turns each and create a mainly radial field with toroidal mode numbers up to $n = 2$. For the present experiments, $n = 2$ perturbations are applied with either even or odd parity of the upper and lower coil currents. Positive coil current corresponds to a radial outward directed perturbation field. All B-coils are connected in series and are supplied with a single DC power converter. Mitigation of large type-I ELMs was achieved in the $n = 2$ configuration with heating power significantly above the H-mode threshold [3]. Strong divertor peak power loads associated with type-I ELMs disappear during the ELM-mitigation phases. The most apparent feature for successful ELM amelioration seems to be the existence of a critical minimum edge density. ELM mitigation is only observed above a peripheral line density of about 5×10^{19} m^{-2} for I_P = 0.8 MA and about 6.5×10^{19} m^{-2} for I_P = 1.0 MA. Achieving an edge density beyond the threshold level at an approximately constant fraction 0.65 of the Greenwald density opens a wide operational range for ELM mitigation while keeping about the same confinement than in unmitigated reference plasmas. A wide range of edge safety factor profiles is covered including cases with both magnetic perturbations resonant and not resonant. A detailed description of the coils system and its application for magnetic perturbation (MP) ELM mitigation can be found in [3].

To perform pellet fueling studies, the refurbished high speed launcher system based on a centrifuge accelerator and a looping transfer system is used. The system is currently capable of delivering pellets with a nominal particle content ranging from 1.5 – 3.7 x 10^{20} D in the velocity range 240 – 560 m/s from the high field side with repetition rates of up to 50 Hz. Within a pellet train launched into a discharge both pellet speed and size are fixed; repetition rates can be changed to a fixed fraction of the centrifuge revolution frequency. The pellet observation system was refurbished and upgraded by two ultra fast CMOS cameras and it now allows fast individual pellet tracking. The camera system, called EDICAM, can be operated by recording a full 1024 ×1024 pixel image with 450 frames/s or at a higher rate up to 100 kframes/s with an accordingly reduced image size. The PHOTRON SA5 camera records 1024 × 1024 pixels at 7500 frames/s or up to 1 Mframe/s.

COMPATIBILITY OF MP ELM MITIGATION AND PELLET FUELING

First checks for the compatibility of injection by fueling-size pellets with ELM mitigation by coil induced magnetic perturbations were performed piggy back at the tail-end of a phase where stable ELM mitigation was established. Pellet trains covered the ending of the coil current steady-state phase (usually at the maximum of 1 kA), the fast coil current ramp down (100 ms) and also the immediate phase afterwards, which showed sustained ELM mitigation. After termination of the coil current a slow gradual increase of the pedestal top pressure sets in, lasting up to several hundred ms. Finally, the level of type-I activity (typically about 5% above the mitigated phase) is approached and type-I ELMs reappear. As shown in figure 1, neither in the ELM mitigated phase with activated coils nor in the following sustained phase pellets do trigger strong type-I ELMs. The example in figure 1 displays a pellet sequence consisting of 8 pellets (the second one is very small) where the 7 regular pellets impose the strongest local perturbation attainable with the available launching system. Pellets do exhibit remarkable good fueling behaviour. Since no initial ELM is triggered, high fueling efficiency is obtained for the pellet particle deposition followed by a smooth density evolution. Little impact is observed on confinement, which quickly recovers after every pellet.

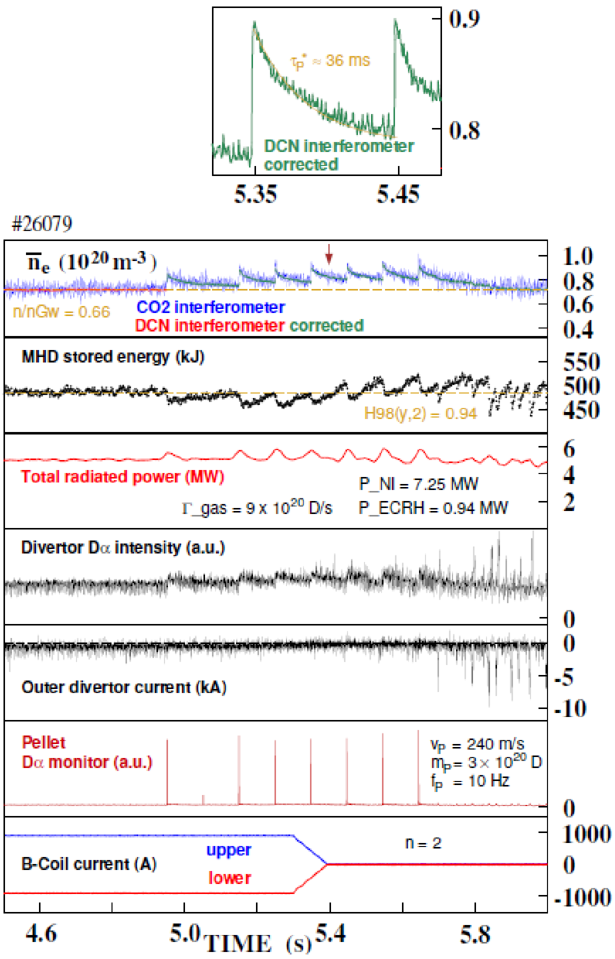

Figure 1: Slow fueling size pellets (largest achievable perturbation magnitude) at the tail-end of a MP generated ELM mitigated phase. Pellets do not trigger ELMs, neither during phases with full or ramped down coil current nor in the following phase with still sustained ELM mitigation. Instead, they show high fueling efficiency and a smooth density relaxation after each pellet induced density jump (see top insert on expanded time scale).

Hence, it is concluded that in the operational regime found for coil MP ELM mitigation, which is characterized by a sufficiently high peripheral density, pellet fueling is a suitable fueling approach since reappearance of large type-I ELMs does not take place even for the strongest pellet perturbations to be expected. Rather, excellent fueling behaviour was found as major benefit of the complete absence of large ELMs. Consequently, dedicated attempts to fuel by pellets were envisaged.

PELLET FUELING DURING MP ELM MITIGATED PHASES

In a first step, pellets were employed for assisting access to the ELM mitigated regime when operating with freshly boronized walls. Under such conditions, due to the high wall pumping capability, the plasma density and the gas puff rate were essentially decoupled. Requested peripheral densities therefore could be hardly established, even with massive gas bleeding resulting in unwanted deconditioning of the first wall. Pellets were found well capable to establish required conditions. For appropriate initial plasma parameters the sudden pellet initiated density step was able to kick the edge into the ELM mitigation regime. Hence, it was observed that pellets switched off strong type-I ELM activity. For low repetition rates the pellet-induced density enhancement decays and drops back below the critical density level, while type-I ELMs recur until arrival of the next pellet. Persistent mitigation was achieved using pellet rates sufficiently high to keep the edge density above the threshold level.

The primary aim of the fueling experiments was to achieve high densities in order to expand the operational space of the MP mitigated regime. For an overall optimized performance of the scenario the gas puffing required to achieve suitable operational conditions was replaced, as far as possible, by the more efficient pellet fueling. Furthermore, the approach aimed at the largest possible density enhancement with the least deleterious impact on confinement. As a reference, a scenario with MP ELM mitigation at Ip = 1.0 MA plasma current and strong auxiliary heating (mix of neutral beam and central electron and ion cyclotron resonance heating) with strong gas puffing was chosen. Pellet fueling was employed in order to replace the gas puff partially. The pellet particle flux was adjusted by the pellet frequency and doubled for the second part of the pellet train. For control purposes the neutral gas density in the private flux region was chosen, because density measurements show strong perturbations by the pellets.

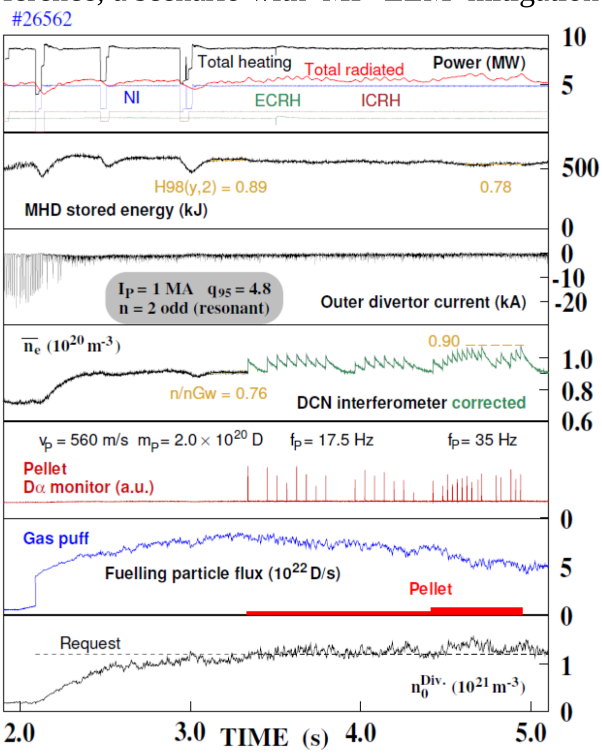

Figure 2: Density ramp up by fueling pellets with increasing frequency. To ensure stable MP ELM mitigation a minimum divertor neutral gas pressure is kept – the required gas puff is reduced by an amount more than 5 times the applied pellet particle flux.

The requested value of $n_0^{Div} = 1.2 \times 10^{21}$ m^{-3} was found to guarantee operation well above the critical edge density. Feedback actuation was entirely assigned to the gas valves. Pellet fueling resulted in the expected increase of the density. In the case shown here maximum electron densities of about 1.07 x 10^{20} m^{-2} were achieved, corresponding to a Greenwald factor of about 0.9. Simultaneously, a significant reduction of the gas puff can be afforded. Only a weak (about 5 %) reduction of the plasma energy is observed, most likely due to pellet driven convective losses. No indication is found, however, at such high densities for a confinement increase with density as predicted by the ITERH98P(y,2) scaling (~ $n_e^{0.41}$) [4].

Applying still higher pellet particle fluxes (by using larger pellets and higher frequencies) already densities up to about 1.5 times the Greenwald density were achieved, however at the expense of a mild confinement reduction. Further investigations in this high-flux regime aiming to improve both the scenario and the control capabilities are in progress.

ELM TRIGGER INVESTIGATIONS

The potential of the coil induced MP for the suppression of edge instabilities eventually evolving into an ELM event becomes obvious when considering the pellet-induced perturbation as a probe for edge stability. While even the strongest pellet-imposed perturbation does not trigger an ELM under appropriate suppression conditions, much weaker perturbations trigger type-I ELMs under plasma conditions with less pedestal pressure without coil activation. The latter is shown in figure 3 displaying results from an ELM pacing approach in the absence of coil induced MP. Pellet injection was sustained during an early heating phase, while the plasma undergoes the L-H transition during a current ramp up with still changing shape and q_{95}. Pellets did not show an obvious impact on the transition threshold. Also the finally achieved confinement was not different. Since the first ELM is often larger than the following ELMs it poses a significant threat to the ITER divertor. Pellets arriving a few ms before the transition do drive MHD activity but do not trigger ELMs, despite a heating power applied beyond the threshold level. Pellets reaching the plasma immediately after the transition do trigger ELMs despite an edge pedestal just starting to evolve being still far from its final magnitude.

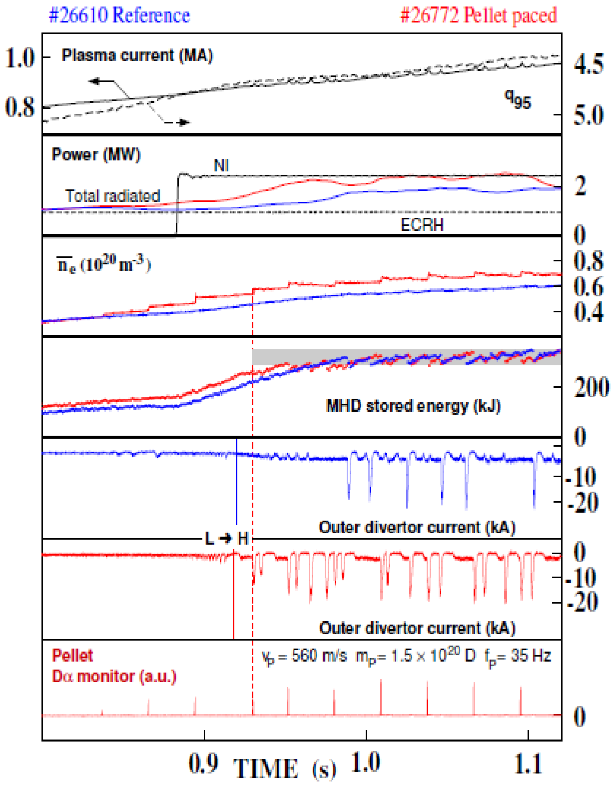

Figure 3: Pellet pacing controls the ELM activity already upon entering the H-mode. In the absence of MP coil activation pellets do trigger ELMs immediately after H-mode is reached.

CONCLUSIONS

Our experiments suggest that pellet fueling is compatible with the ELM mitigation technique that relies on magnetic perturbations. Moreover, they indicate that such a scenario is even the most appropriate one for pellet particle fueling: inboard launch takes advantage of the drift forces that accelerate the pellet-ablated material towards the low field side while prompt losses due to pellet-triggered large ELMs are avoided by successful ELM mitigation. Pellet fueling can be employed to ensure reliable access into the operational regime, characterized at ASDEX Upgrade essentially by a threshold in the peripheral density. Pellets can extend the MP ELM mitigated domain towards high densities, even far beyond the Greenwald density. For scenario optimization the gas-puff rate can be replaced resulting in high density operation with minor impact on the confinement. However, as with strong gas puff, no indication was found for a confinement improvement with density beyond about 0.8 times the Greenwald density. There is a remarkable potential of the coil induced MP on the suppression of the pellet ELM trigger capability. Even strongest achievable pellet perturbations during MP phases did not trigger ELMs, while much weaker perturbations without coil activation did trigger type-I ELMs under plasma conditions with less pedestal pressure. This observation may be useful in order to understand the impact of coil perturbations on the plasma edge.

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