

Real-time pellet ablation radiation monitoring for a refined plasma core density control in ASDEX Upgrade

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INTRODUCTION

Efficient and reliable core density control is a key requirement in a future fusion reactor. In e.g. EU-DEMO, the designated technical solution relies entirely on the injection of pellets; mm-sized bodies formed from solid hydrogen fuel. Fuelling pellets have to be injected at high speed from the torus inboard side and transferred through a curved guiding system. Thus, pellets undergo high mechanical stress during acceleration and transfer. Since hydrogen ice has low mechanical stability, pellets are fragile objects. This results in a size distribution of arriving pellets and in some cases a complete loss. Pellet-based core density control in a reactor can cause intolerable excursions of the burn power. For EU-DEMO, unrecognized missed-out pellets are a potential cause of disruptions and regarded even as safety importance class events.

At ASDEX Upgrade (AUG) efforts are under way to develop methods to recognize and counteract the effects of missed-out pellets and mass variations. They rely on pellet arrival recognition and monitoring of the arriving pellet mass in real-time. Several methods could potentially cover this task; in our approach we selected the intense radiation emitted during the ablation of the pellet in the plasma. AUG is equipped with a robust ablation monitor operated reliably for decades. Investigations performed during the AUG campaign 2024/25 of AUG aimed to develop and commission a reliable missed-out pellet detector: for any pellet launch request either successful arrival or a missed-out case is stated. As a first test for corrective action in case of a missed-out detection, an immediate substitution request was implemented. More sophisticated counteraction strategies are under development. Here, rather than characterising the pellet condition as binary result of ‘0’ (missed out) or 1 (confirmed), it is envisaged to commission an estimator for the arriving pellet mass, linking the total amount of emitted ablation radiation to the pellet size range 0 – 1, with 1 being the maximum size.

REAL TIME MONITORING OF PELLETS ARRIVAL

Indispensable for the fast actuation on a missed-out pellet is the recognition of such an event. The developed algorithm categorises every requested pellet either as “Confirmed” or “Missed-out” in real time, relying on the strong radiation emitted during the ablation process. This radiation is detected via a pellet monitor diagnostic providing a real time high temporal resolution signal. Since pellets are launched by a centrifuge accelerator with a known speed, their arrival at the plasma boundary can be precisely predicted [1]. This feature announces pellet arrival to the discharge control system (DCS) which handles plasma and actuator control in real-time. The rising edge of this “Announced” signal precedes pellet arrival at plasma edge by at least 3 ms, leaving sufficient response time for appropriate actuation. This is required to initiate notch-

ing of the electron cyclotron resonant heating (ECRH) in order to avoid unwanted stray radiation due to power reflection at the high-density cutoff layer of the ablating pellet [2]. Adaptation of the flight time calculation resulted in pellet arrival within 3.0 - 7.5 ms after the rising edge of the announcement signal for the vast majority of pellets, irrespective of size and speed setting. As the ECRH notching window was already timed accordingly, the pellet recognition algorithm is activated only during this time span as well. The algorithm analyses the ablation monitor signal and identifies an arriving pellet by the signal's magnitude and derivative. Once detected within the recognition time window, the "Confirmed" signal is generated and immediately sent to the DCS. In the case no pellet is detected until the recognition window ends, the "Missed-out signal" is generated and communicated.

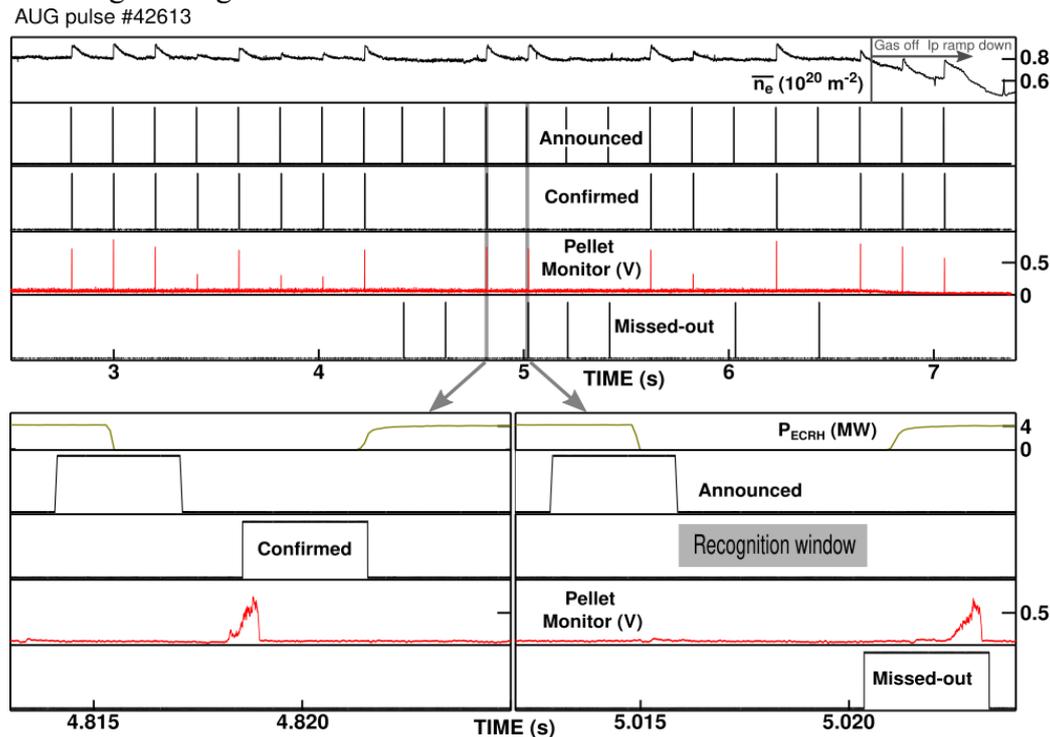


Figure 1: Pellet recognition demonstrated in real time during an experiment performed to characterise the ablation monitor. Pellets injected during the steady heating phase and the initial part of the ramp-down can be identified by their impact on plasma density and monitor signal. A full test of this algorithm was performed during AUG pulse #42613 in deuterium (D) with sound H-mode conditions established and maintained by (almost) steady auxiliary heating applying 9.9 MW neutral beam injection (NBI), 2.7 MW ion cyclotron resonance heating (ICRH) and 4.2 MW pellet-notched ECRH. Pellets containing initially 3.6×10^{20} D atoms, launched at a speed of 236.4 m/s, were injected at rate of 4.9 Hz during the steady state and early plasma ramp down phase. The low pellet rate was chosen in order to allow for proper analysis of pellet density impact required for the pellet mass correlation analysis. The outcome of this test is displayed in the upper part of figure 1, showing top to bottom: the corrected line averaged density measured by the central chord of the laser interferometer; the announcement, confirmation, monitor and missed-out signals. Obviously, all pellets are correctly categorised with the sole exception of the pellet arriving shortly after 5.0 s. The reason for this misinterpretation becomes apparent (lower part of figure) when comparing this pellet erroneously categorised "Missed-out" (right part) to the previous, correctly categorised "Confirmed" pellet (left part). For the correct case the pellet arrives in the designated recognition window. For the erroneous case the pellet represents a late outlier in the arrival time distribution. The algorithm categorises

it “Missed-out” the very moment its recognition time window has elapsed. Consequently, the recognition time window duration should be optimised with a compromise between the sufficiently fast recognition of missed-out pellets and an acceptable number of outliers.

REAL TIME COMPENSATION OF MISSED-OUT PELLETS

With the missed-out pellet recognition in place, a first attempt was made to demonstrate the real time replacement of missing pellet flux. Performed in AUG pulse #42613, the outcome is displayed in figure 2. The plasma scenario of AUG pulse #42613 was applied with only 10.0 MW NBI auxiliary heating. Also, the same number of pellets were launched at 237.6 m/s but run out at 4.67 s due to an only partially filled ice reservoir. At 3.0 s, about half of the initial gas puff (blue line) was replaced by an initial steady feed forward pellet flux request (red line) precisely equivalent to 50% of the maximum available pellet flux. This initiates a regular pellet train at 29.7 Hz with a pellet launch attempt every second revolution of the centrifuge acceleration arm. The first pellet arrives in the plasma after the system response time of 133 ms. Once a missed-out pellet is detected, the initial request is either increased to a maximum flux request for a time span of which a duration is calculated to cover the missing pellet flux or this duration is added to an already ongoing full flux request time window. This compensated flux request (shaded region) deviates from the initial 50% request during such full flux request windows, initiating a 59.4 Hz train request taking every possible pellet launch option. By comparing the pellet monitor and the “Announced” signal it becomes obvious here the detection of missed-out pellets worked as expected. As well, the required compensation actuation was initiated immediately. However, subsequent analysis showed the calculation of compensation time window resulted in a duration resulting in a flux compensation about twice the correct value. Accordingly, and missed-out pellet was replaced by two attempts to launch a pellet for compensation, following recognition of the “Announced” signal. Apart from this initially incorrect (and afterwards corrected) calculation of the window duration, the compensation actuation on missed-out pellets in real time as such was demonstrated for the first time.

AUG pulse #42891

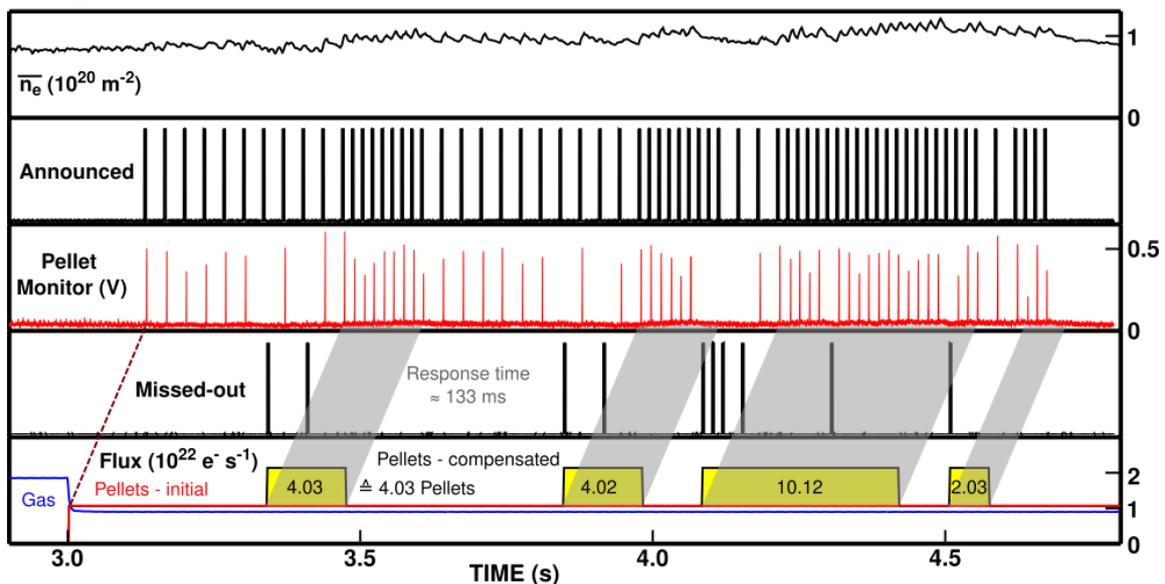


Figure 2: Pellet compensation in real time. At 3.0 s, half of the gas fuelling (lowest box) is replaced by pellets. While the initial feed forward pellet fuelling is steady (red), the applied compensated request replaces all missed-out pellet. Due to an initially incorrect calculation, every missed-out pellet is compensated by two requested ones.

CORRELATION ABLATION RADIATION TO ARRIVING PELLET MASS

As ablation radiation turned out to be suitable for reliable detection of pellet arrival, it was considered plausible to employ the available monitor signal for an estimation of the arriving pellet mass. It was observed that arriving pellets showed some variation of the resulting density impact. This is likely related to scatter in the pellet mass due to various losses during pellet production and transfer and correlated to the magnitude of ablation radiation. To investigate this approach, data is analysed from a set of 8 discharges, covering pellet size/speed scans and comparing low and high heating power H-modes. The magnitude of ablation radiation is calculated by simple numerical integration of the base line corrected monitor signal. As an approximate measure of the arriving pellet mass, the related sudden increase of plasma electron particle inventory (ΔN_e) was adopted. As shown in figure 3, there is a clear correlation between the magnitude of ablation radiation and ΔN_e . Seemingly, the pellet speed shows no significant impact, under otherwise same conditions faster pellets shine shorter but accordingly brighter. Contrarily, a clear impact of the applied heating is found: more power results in less radiation. Hence, employing ablation radiation appears constructive for a mass estimator by following a predetermined relation as supported by the simple power fit functions represented by the solid lines. Evidently, some parameters like the pellet speed are ignorable while others, e.g. the heating power, must be considered. Considered too has to be a potential change (degradation) in the radiation detection systems sensitivity. Currently, the implementation of a real time algorithm is in progress. Additionally, modelling activity is under way to gain understanding of these correlations, aiming to establish a sound model-based prediction.

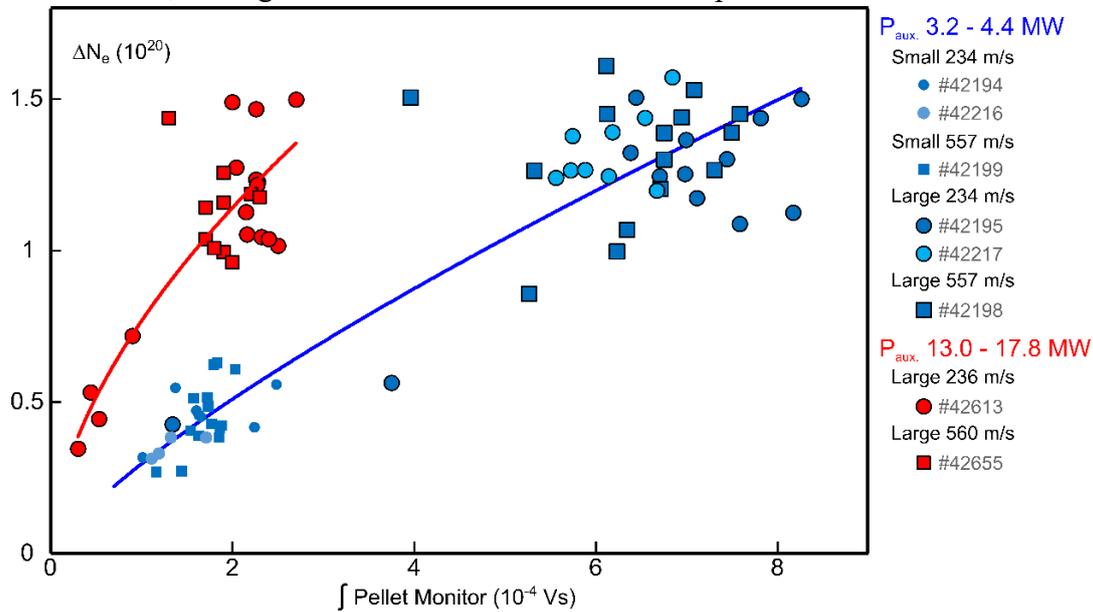


Figure 3: Pellet induced plasma electron inventory enhancement versus radiation magnitude. While different pellet speed does not show a significant impact, a variation of the heating power results in an altered correlation. Solid lines represent simple power fits.

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