Real time monitoring of pellet delivery to facilitate burn control in EU-DEMO

P. T. Lang[1], M. van Berkel[2], W. Biel[3], T.O.S.J. Bosman[2], P. David[1], Ch. Day[4], E. Fable[1], L. Giannone[1], T. Giegerich[4], A. Kallenbach[1], M. Kircher[1], A. Krimmer[3], O. Kudlacek[1], M. Maraschek[1], B. Ploeckl[1], B. Sieglin[1], W. Treutterer[1], H. Zohm[1], ASDEX Upgrade Team
[1]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
[2]DIFFER, PO Box 6336, 5600HH Eindhoven, The Netherlands
[3]Institut für Energie und Klimaforschung, Forschungszentrum Jülich GmbH, Germany
[4]Karlsruhe Institute of Technology (KIT), 76021 Karlsruhe, Germany

INTRODUCTION

Efficient and reliable core particle fuelling, an essential task in EU-DEMO, relies on adequate pellet injection. These pellets, mm-sized bodies formed from solid hydrogen fuel, need to be launched via guiding tubes from the vessel inboard. However, pellets are fragile objects and their delivery efficiency can hardly be assumed to be unity. Thus, occasionally a requested pellet will be partially or fully lost. Exploring kinetic control of the EU-DEMO1 scenario by investigations coupling the ASTRA plasma model and a Simulink control system model indicates such missed-out pellets do cause a considerable problem for keeping a burning plasma sufficiently stable at a reactor grade level [1]. Missed-out pellets can cause a severe drop of plasma density which in turn results in a potential drastic loss of burn power. Hence, without an early detection of such missed-out events, the plasma control system will potentially struggle to keep the plasma parameters within the designated operational range. Consequently, this would require to detect “missed” pellets (e.g. that are not launched or arriving with insufficient size in the plasma) as early as possible and respond accordingly.

In order to gain more detailed insight, the recently updated code Fenix DEMO will be further applied to the issue. Also, efforts are under way at the ASDEX Upgrade (AUG) tokamak equipped with a pellet launching system in a configuration regarded suitable for EU-DEMO [2] aiming to provide real time monitoring of pellet arrival and announcement of missed-out cases to the control systems. In a previous effort [3] a Kalman filter based state observer has been integrated into the discharge control system (DCS) which is capable of estimating the density for real time control purposes, e.g. real time feedback control of the density profile with relevant actuators [4]. To further optimize the controllers, system identification experiments have been performed to identify the dynamic response of the system to the actuators.

PELLET ACTUATOR PRECISION ENHANCEMENTS

Since the AUG system launches pellets via a guiding system at high speed from the torus inboard it provides indeed a reactor relevant configuration. Pellets are accelerated by a centrifuge so their velocity is precisely defined. During the recent years, continuous efforts were made to set up the pellet launching system (PLS) in a way making it a valuable component in the controller toolbox of AUG. This allowed for its variable application for different research topics. However, with the control tasks at AUG also becoming more and more complex, requirements to the PLS actuator getting more demanding as well. One suggestion for improvement emerged when trying to include fast and efficient pellet fuelling into the path-oriented early reaction to pending disruptions [5]. There, the gyrotron power is controlled for adapted local heating and/or current drive (ECRH/ECCD). However, combining pellet and gyrotron operation requires additional safety measures. Injecting a pellet during gyrotron EC actuation can lead to power reflection at the high density cut-off layer of the ablating pellet and consequently, an emergency shut down of the gyrotrons. Hence, the gyrotron power is switched off during pellet ablation ("notching") and both actuators can be applied simultaneously [6]. Yet, this causes an unwanted cross talk between EC and pellet flux actuator – an increasing pellet flux resulting in decreasing gyrotron power. To minimize this, an approach was undertaken in order to shorten the notch duration as much as possible.

The notching is handled by the DCS and in order to enable all such kinds of interaction, a predictor signal is generated by the PLS and communicated for every attempt to launch a pellet. This predictor signal announces a pellet is expected to arrive at the separatrix, in order to ensure proper processing within a DCS cycle with a lead time of at least 3 ms [6]. The precision of the underlying predictor algorithm was improved now by installing a measurement of the instantaneous centrifuge revolution frequency to calculate the speed of every individual pellet. This means, the pellet arrival at the separatrix can be predicted with less than 1 ms uncertainty – i.e. pellet ablation sets in between 3 – 4 ms after the predictor pulse. Under normal operational conditions the following pellet ablation lasts less than 1 ms. Hence, the entire pellet ablation process is taking place within a 2 ms time window precise predictable. Consequently the notching gap was shortened to 2 DCS cycles, since pellet launching times are not yet correlated to the DCS cycles this is the minimum possible notch duration anyway.

REAL TIME MONITORING OF PELLET DELIVERY

In order to provide the information of a missed-out pellet in real time, a new diagnostics has been developed. It relies on the already existing pellet monitor, recording the intense radiation emitted during pellet ablation inside the hot plasma with a μs temporal resolution. Thought this monitoring approach is likely not the most suited one relevant in EU-DEMO, it was chosen for its simplicity and reliability at AUG and in order to allow for a straightforward proof-of-principle demonstration. In principle, any suitable pellet monitor signal or even several confirmation techniques can be applied following the same ansatz.

In a first step, a confirmation monitor signal was generated. For cases showing up in the pellet monitor with a radiation level sufficient intensity and duration (the latter to eliminate electronic noise spikes) a DCS compatible square pulse "confirmed" is released. In the second step, a dedicated unit in the PLS local control unit compares the pellet predictor and the confirmation signals. In cases the confirmation signal does not arrive within the predicted time slot, the requested pellet is regarded as missed out and the according TTL pulse is generated. While already generated in real time and communicated to the DCS, the incorporation of this signal into the control algorithm is still pending.

A first successful demonstration of the novel unit is shown in figure 1. The discharge displayed was run with plasma current I_P = 1.0 MA, toroidal magnetic field B_t = -2.5 T, edge safety factor q_{95} = 4.5; H-Mode conditions were established and maintained by steady auxiliary heating applying 7.3 MW neutral beam and 2.3 MW ion cyclotron resonance heating. The aim of this experiment was to identify the dynamic response of the divertor pressure under strong pellet fuelling. To do so, the gas flux was modulated using a multi-sine perturbation signal containing 1, 5 and 11 Hz frequency components (box f). Simultaneously, a strong steady pellet flux was applied, consisting of pellets each containing 3.6×10^{20} D atoms and injected at a speed of 550 m/s. To deliver the requested flux, the recently installed pellet flux controller [4] toggles between 35 and 47 Hz injection frequency. Trying to consume the entire pellet reservoir, 91 launch attempts took place, each with its accordingly predicted pellet arrival (box b). 87 pellets arrive, as indicated by the monitor signal (box c), in the plasma and are correctly confirmed (box d). While processing predictor and confirmation signals, all missed-out pellets are recognized. Two of them originate from the ice rod end tips and their losses were likely caused by the waiting time for the discharge run after the ice rod formation. Two pellets were missed-out during the high flux fuelling phase. The effect of such failed pellet delivery can be clearly recognised in the evolution of the plasma density (box a). Displayed are the line averaged density as obtained by a real time calibrated measurement of the Bremsstrahlung (black, "validated" line averaged), a local core measurement by the Thomson scattering diagnostics (red crosses) and the density calculated for the plasma core region by RAPDENS (blue). Although available in real time, the latter was not applied for control purposes in this discharge. Due to the significant flux, core densities beyond the Greenwald density (green) are established and maintained during the pellet phase.

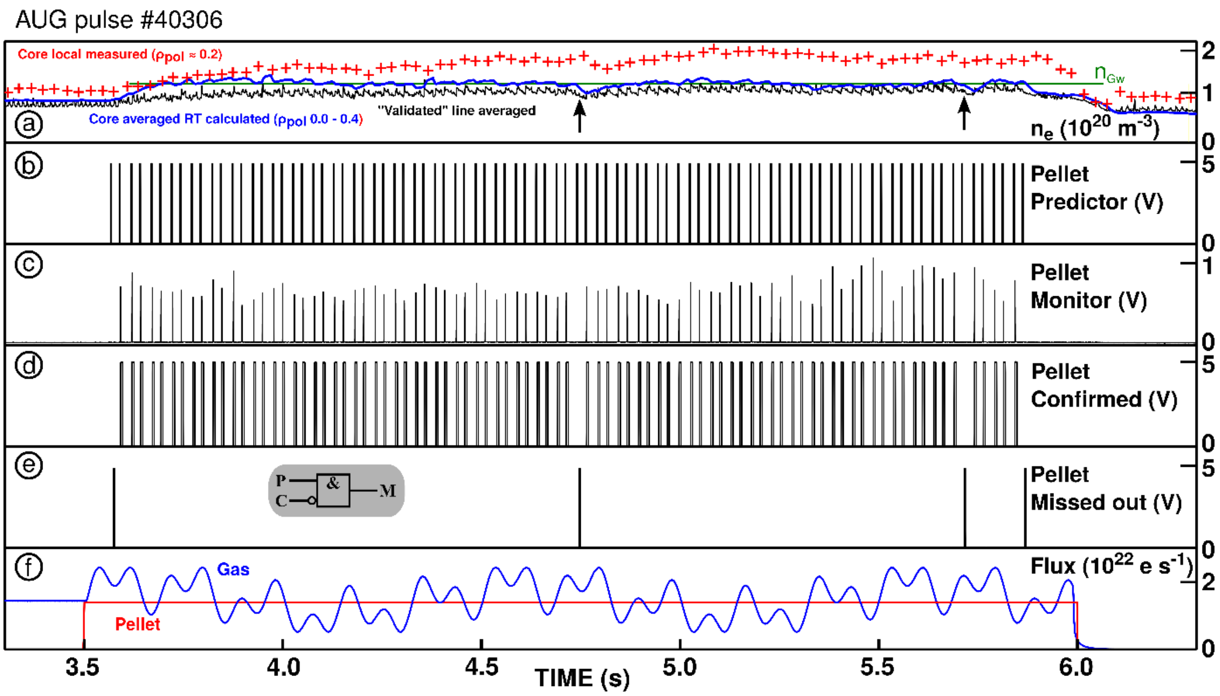

Figure 1: Demonstration of detecting missed-out pellets in real time during a system identification experiment. The gas flux is modulated in the presence of strong pellet fuelling ramping up the core density to a reactor grade. For every launch attempt, the pellet is announced by the "Predictor" prior to its expected arrival at the plasma edge. Analysing the ablation monitor signal in real time, either successful pellet delivery is monitored as "Confirmed" or identified as "Missed out". Unwanted drop in density is clearly correlated to failed pellet delivery (arrows in box a).

ALTERNATIVE PELLET MONITORING TECHNIQUES

Providing an adequate monitor is considered challenging within a reactor environment. In our first proof-of-principle demonstration at AUG shown previously, pellet arrival or loss is detected in real time by the ablation radiation. Once this information is integrated in the control algorithm, losses can be compensated by either fast instant substitutions or an adaptation of the pellet flux requested by the control system. Yet, the currently used method requires observation of a considerable fraction of the designated ablation region. However, analysis showed that a sufficiently large field of view cannot be covered with reasonable effort in EU-DEMO under current assumptions (pellet flight path, penetration depth and diagnostic lifetime) and is thus anticipated as being unsuitable. Consequently, alternative methods need to be investigated in parallel. As one option, magnetic pickup coils mounted in a DEMO-like configuration at the vessel exterior of AUG were successfully tested. Despite their moderate sensitivity and temporal resolution, missed-out pellets were well identified, even in plasmas with strong ELM activity.

An example is given in figure 2. There, a sequence of three pellet launch attempts into an ELMing H-mode is shown. The two arriving pellets show a clear impact on density, ELM monitor and different magnetic coil monitor signal including one installed in a reactor relevant configuration outside the vacuum vessel. The missed-out pellet can be recognised from the absence of an according impact within the expected time window.

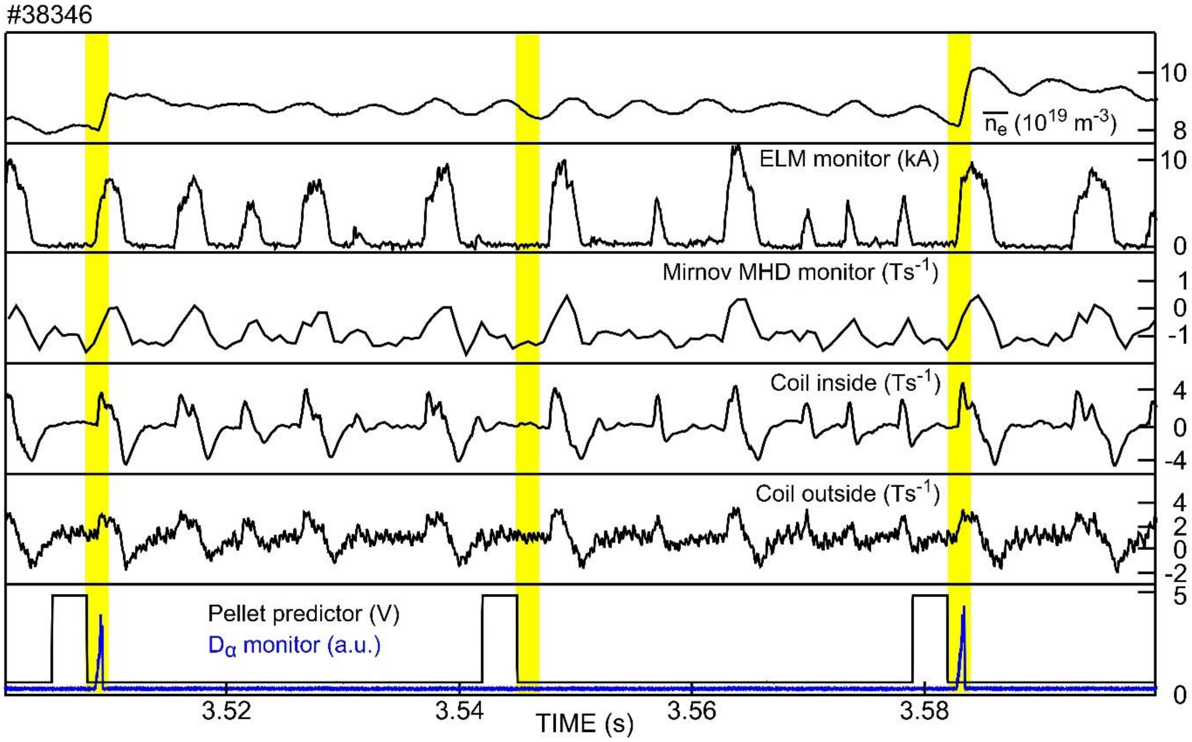

Figure 2: Alternative approach for missed-out pellet detection. Even under H-mode with strong ELM activity, with some likelihood such events can be recognized. Relying on pellet arrival is only expected within a short phase – visualised by the yellow bars – absence of the typical pellet related impact indicates a missed-out event.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

REFERENCES:

[1] F. Janky et al., "Kinetic control", 5th IAEA DEMO programme workshop, May 2018, Daejeon.

[2] P.T. Lang et al., Fusion Eng. Des., **156**, 111591 (2020).

[3] T. Blanken et al, Fusion Eng. Des., 147, 111211 (2019).

[4] P.T. Lang et al., Fusion Sci. Techn., **78**, 1 (2022).

[5] M. Maraschek et al., Plasma Phys. Control. Fusion, **60**, 01447 (2018).

[6] B. Ploeckl et al., Fusion Eng. Des., **88**, 1059 (2013).