Pellet actuator development step-by-step: from AUG to JT-60SA and EU-DEMO

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INTRODUCTION

Operation in a future fusion reactor will aim to establish a high plasma core density in order to harvest a maximum output power. This requires an efficient core fuelling actuator, capable to establish the required target value with a minimum of applied particle flux. Inefficient core fuelling will result in reduced plasma performance and/or intolerable high fuel cycle throughputs of tritium (T). Injecting pellets - mm-size solid bodies produced from frozen fuel – from the torus inboard side is currently regarded as the only realistic option for the core fuelling task. Moreover, pellets have proven their potential to serve for other tasks as well – e.g. for ELM frequency control. If handled properly, the pellet actuator can be applied for simultaneous control of different plasma parameters. For the development of a potentially multi-tasking pellet launching hard- and software appropriate for reactor requirements, we have chosen a step-by-step approach along the route ASDEX Upgrade (AUG), JT-60SA and EU-DEMO. This strategy is visualised in figure 1, indicating as well the underlying tasks. Due to the increasing machine size and the growing pulse duration, the pellet particle flux has to be increased correspondingly and produced after all in a quasi-continuous mode.

The AUG pellet launching system (PLS) is operating on plasma since already almost 30 years. During these three decades, it has been continuously developed further and adapted to the enhanced capabilities of the tokamak devices. Furthermore, it had to be revised considerably in order to make use of physics findings like the advanced fuelling efficiency for injection schemes that launch pellets from the magnetic high field side of the torus or the capability of pellets to trigger edge localised modes (ELMs). Hence, the AUG PLS has been optimised for high-speed inboard injection lasting a few seconds for either fuelling or ELM pacing. Techniques have been developed for density measurements which are robust against strong short-term perturbations by the injected pellets and thereby allow for feed-back on performance parameters on a confinement time scale. Using the pellet tool within a multi-parameter control scheme, we established a reactor-relevant high-density high-confinement plasma regime [1].

Currently, a novel and state-of-the-art pellet system is being built for the new large superconducting tokamak JT-60SA. The advanced PLS design is based on the experience gained at AUG and will aim to extend the potential of a pellet system for extended high-performance operation lasting up to 100 s and enable simultaneous density profile and ELM control. This requires to manage both actuators simultaneously with one system. Finally, a conceptual design for EU-DEMO's core fuelling actuator is under way. For this task, true steady state operation and an adequate actuation capability is required in order to keep all relevant plasma parameters with their designated operating range.

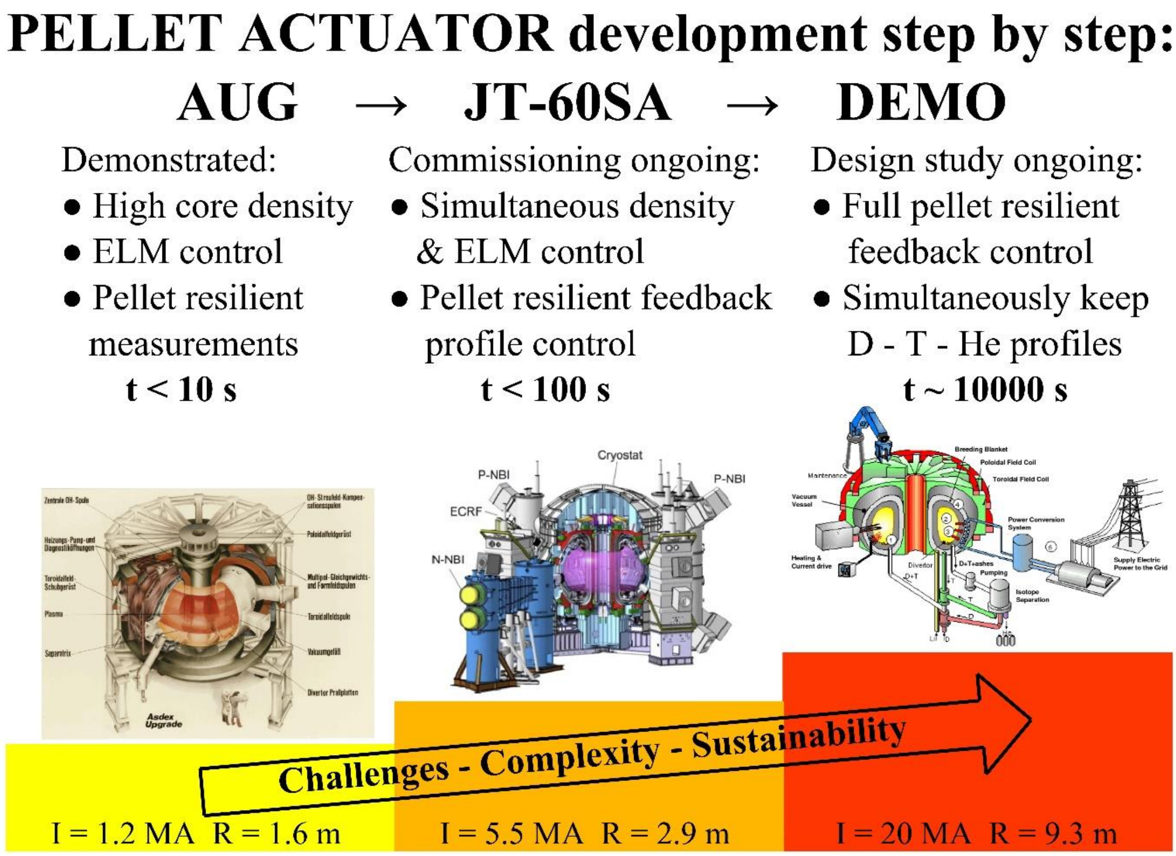

Figure 1: Step-by-step approach for the pellet actuator development for tokamaks with increasing size. Experience gained from an existing system at AUG is introduced for the design and construction of the JT-60SA system. The JT-60SA solution can be regarded as a potential prototype solution for a future reactor like EU-DEMO.

The pre-conceptual design elaborated relies only on pellet technology already proven and reliable, yet it is concluded from modelling to be capable for granting the required operational plasma core density. Ongoing optimisation takes care of keeping the fuel cycle throughput low while staying still compatible with the detailed EU-DEMO design. In this context, integration of the pellet guiding system into the breeding blanket has turned out to be most crucial [2].

SINGLE-SOURCE PARTICLE FLUX CONTROL AT AUG

In order to prepare the control scheme for a multi-tasking JT-60SA PLS, hosting several pellet sources, a control scheme for the single source AUG PLS was developed. It is based on a novel local control unit within the PLS able to compose rather smooth flux trajectories despite the granularity of initial flux caused by the centrifuge accelerator unit [3]. The local control unit is integrated into the discharge control system (DCS) supervising plasma operation at AUG. Thus, real time feed-back control of pellet actuator in order to achieve e.g. density profile control becomes possible. Employing pellets, two essential elements are the availability of pellet resilient measurements [1] and the extended Kalman filter based state observer RAPDENS [4]. The entire necessary tool kit has been developed at AUG to full maturity and applied for a successful demonstration of its technical capabilities. An according example is shown in figure 2, displaying an experiment where the core density is ramped up and kept at a reactor grade level while avoiding a degradation of the plasma energy confinement.

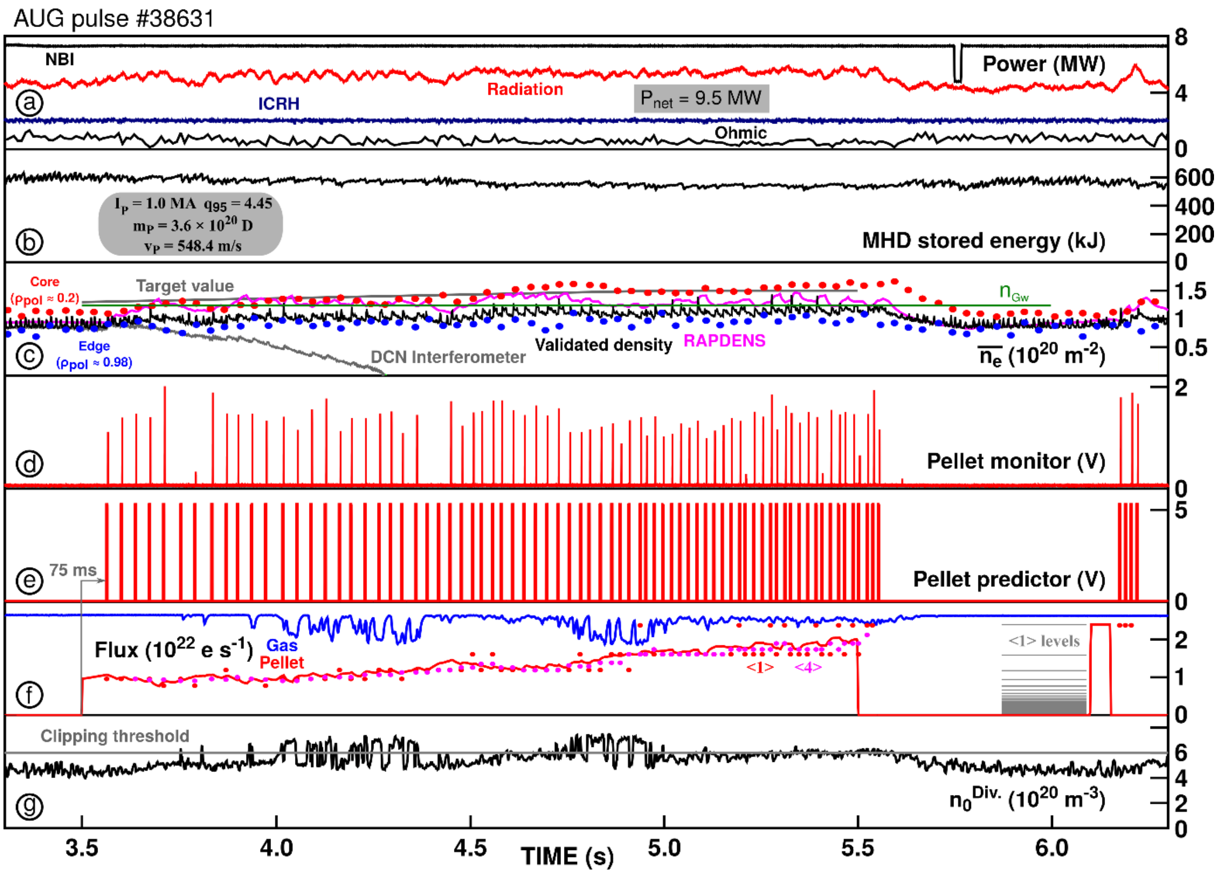

Figure 2: Ramping up the core density to a reactor grade level of 1.2× n_{Gw} while restricting the edge density. Core density control is achieved by pellet actuation, gas actuation on edge density via surrogate divertor density control. Pellet delivery delay by 75 ms response time and missed out pellets are well compensated for by the RAPDENS algorithm.

All relevant data traces as well as plasma and pellet parameters (m_P pellet particle content, v_P pellet speed) are displayed in the boxes a - g. Steady heating (a) results in stable access to a high density regime while keeping almost the initial energy content (b) despite the intermittent pellet fuelling. Box c displays all relevant density data: the validated line-averaged density (black line), the averaged density calculated by RAPDENS for the core region $\rho_{tor} = 0 - 0.4$ (purple line), local density at the edge and in the core (blue and red dots, respectively), the perturbed measurement by the standard DCN interferometer diagnostics. The targeted density trajectory (grey line) aims at operation beyond the Greenwald density (green line) which is achieved in AUG only by pellet fuelling [5]. The corresponding requested pellet flux (f, red line) results in the requested pellet flux (e) yet fewer pellets arrive in the plasma (d). Taking the requested pellet sequence, the according flux is calculated - averaged either over a single or four pellet cycles (f, red/purple dots). The single cycle averaged flux values obviously correspond to the values settled by the intrinsic granular launch frequencies of the centrifuge type accelerator [3] (f, grey lines). On average the requested flux follows the controller request more closely by toggling between these flux levels. Finally, the applied pellet flux results in a reasonable evolution of the core density since RAPDENS executes the request well by anticipating the 75 ms system response time and by compensating for missed out pellets. In order to monitor the system response, after 6.1 s a short feed forward flux request at the maximum level took place. Finally, in order to avoid confinement degradation by an overshooting edge density, the gas flux (f, blue line) was reduced accordingly. Since standard real-time measurements for the edge density are heavily perturbed, the neutral gas density in the divertor (g, black line) is taken for pellet resilient monitoring [1]. Keeping this quantity below a critical threshold value (g, grey line) turned out to be an effective measure.

MULTI-SOURCE CONTROL AT JT-60SA

The design of the JT-60SA PLS is based on the same stop cylinder centrifuge principle as the AUG PLS system [6]. This choice has been made for its ability to grant precise and predictable pellet arrival times on plasma, an essential feature for its application as an adequately manageable actuator. In contrast to the AUG system, the JT-60SA PLS will be built to host up to three pellet sources. Hence, the control scheme has to be upgraded accordingly. The local PLS control unit under development envisages application of a unit very similar to that one developed at AUG for every single source with any source dedicated to its own prime use as an actuator. However, it must be taken into account that the actuator actions of these systems mutually interfere. For example, small size pacing pellets will still contribute to fuelling while large size fuelling pellets will provide at least the same ELM trigger potential as pacing pellets. Consequently, there arises the need for task prioritisation in order of conflicting requests for the different actuations. This necessary prioritisation can be set e.g. locally in advance and fixed or communicated by the tokamak control system for a dynamic event driven adaptation even during a plasma discharge.

DEMO ISSUES

EU-DEMO in its pre-conceptual design foresees pellet actuation mainly for the fuelling purpose. Yet, assigning other tasks like the supply of seeding gas for performance enhancement or radiative cooling is found very appealing due to the pellet proven ability for efficient and fast actuation [7]. Hence, a multi-tasking PLS presumably is an adequate solution for any fusion reactor. Consequently, the JT-60SA PLS layout can be regarded as a suitable prototype option for any DEMO reactor – with the only exception of lacking tritium handling. Yet another issue discovered in the consideration for reactor grade PLS is the need for an early pre-warning of missed out pellets. Investigations for a proper approach on this topic has just started, again envisaging a step-by-step route with first tests at AUG and validated solution to be considered for JT-60SA and finally for DEMO.

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