Actuator Development Step by Step: Pellet Particle Flux Control for Single- and Multiple-Source Systems

P. T. Lang, B. Ploeckl, R. Fischer, M. Griener, M. Kircher, O. Kudlacek, G. Phillips, B. Sieglin, S. Yamamoto, W. Treutterer, and AUG Team

Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
Fusion for Energy-F4E, Boltzmannstr. 2, 85748 Garching, Germany
National Institutes for Quantum and Radiological Technology, Naka Fusion Institute, 801-1 Mukoyama, Naka-shi, Ibaraki-ken, Japan 311-0193

Received April 26, 2021
Accepted for Publication May 28, 2021

Abstract — Fuel injection by means of solid cryogenic pellets is expected to provide a sound and efficient tool. Hence, the installation of a pellet launching system will be a necessity. Yet, pellets are considered as a serviceable actuator for integrated supplementary functions as, e.g., fast and efficient delivery of seeding gas, or in case needed, the pacing of edge-localized modes. Consequently, a control scheme has to be developed that is capable of mastering the simultaneous actuations covering different tasks. Our scheme relies on pellet launching by a centrifuge accelerator, providing the option for precisely predictable pellet injection sequences. In order to develop a suitable actuator control scheme, as a first step the central part was brought into service at ASDEX Upgrade. It proved operational for feedback particle flux control of a single pellet source. In a subsequent step, it is now upgraded to enable multitasked control of the JT-60SA multipellet source currently under construction. In its finally designated configuration, this control scheme provides a potential solution for a reactor-grade system.

Keywords — ASDEX Upgrade, JT-60SA, tokamak, pellet technology, plasma control.

Note — Some figures may be in color only in the electronic version.

I. INTRODUCTION

The preconceptual design elaborated for the matter injection of EU-DEMO attributes the core particle fueling task entirely to conventional pellet injection technology. In order to achieve this task with maximum efficiency, there is the need to establish the requested core density while keeping losses in the applied fueling particle flux at a minimum. Therefore, in a tokamak configuration, pellets must be launched from the torus vessel inboard side. A scheme relying solely on proven available technology has been elaborated for the pellet injection system and optimized by a detailed modeling approach. This analysis showed that the solution strived for is capable of covering the requested core fueling performance in a future fusion reactor. One decision yet pending is the selection of the accelerator unit. One choice considered is a mechanical centrifuge. This solution offers precise launch speed control, and thus, an exact prevision of pellet arrival at the plasma. Thus, it allows for timely measures necessary on other actuators like the notching of wave heating to avoid dangerous power reflection or correcting dropped diagnostic data that has been distorted by pellets. In addition, centrifugal acceleration is
not mass dependent. Hence, pellets of different configurations can be composed into a single pellet train.

Such different pellets can have an outlay with respect to size and consistency adapted to different tasks. As a consequence, the delivered single and precisely timed pellet train can serve simultaneously for multiple tasks. Such tasks beyond the basic fueling need could be, e.g., edge-localized mode (ELM) pacing or plasma seeding. The controlled triggering of ELMs by a sequence of pacing pellets is considered a candidate tool for plasma operational scenarios that are otherwise plagued by too strong ELMs (Ref. 4). Seeding the plasma with auxiliary gases applied for enhancing performance or needed to provide radiative power exhaust can be achieved highly efficiently and with low response time when the gases are hosted into a pellet produced from fuel.\(^5\) Hence, pellets can be regarded as potentially multitasking actuation tools provided their layout is made in an appropriate way. To achieve this goal, a concept is going to be developed based on the launch of a single pellet train by a centrifuge accelerator composed from differently produced and composed pellets. This way, a simultaneous coordinated actuation on different control parameters becomes possible. However, sound control has to take any kind of “cross talk” between those actuations into account. This approach poses the challenge of harmonizing the given set point values usually provided as analogue parameters for the respective actuators and their intrinsic discontinuous, i.e., digital nature of pellet injection. In this paper, we report on the full integration of a tool capable of pellet frequency control\(^6\) into the control system of the tokamak ASDEX Upgrade (AUG) and its commissioning for use in real-time, feedback-controlled plasma operation. There, this scheme demonstrated its capability to control the core plasma density by actuation with a single pellet source. To that effect, it has become now a part of the AUG control tool kit.

Further enhancement of this unit is under way in the context of a new pellet launching system (PLS) under development for the JT-60SA tokamak. The JT-60SA PLS is intended to start operation with two pellet sources acting for particle fueling and ELM pacing. It is designed to provide headroom to host up to three pellet sources as well as the application of pellets hosting auxiliary gases. Consequently, the control unit must be able to master several pellet sources in a well-coordinated manner. The design of this unit is under way, its central part to be provided by the already available AUG unit.

II. DEMONSTRATION OF THE SINGLE-SOURCE PELLET ACTUATOR: PARTICLE FLUX CONTROL AT THE AUG

II.A. Setup

A novel unit was developed to control the pellet particle flux launched by the AUG pellet system; details can be found in Ref. 6. The system was further advanced by its full integration into the discharge control system (DCS) supervising plasma operation at the AUG. Therefore, communication between the local programmable logic controller (PLC) supervising all actuations of the PLS and the DCS was extended. Now, the PLC makes all relevant set parameters of the PLS available to the DCS. These parameters are pellet material, pellet particle content (in electrons), and maximum available pellet rate. From these parameters, the DCS is able to calculate the maximum available pellet particle flux in the activated configuration. During an experiment with the applied pellet flux under DCS control, the actual request is communicated to the PLS as a fraction of this maximum flux. Hence, the request parameter is in the range [0 to 1]. The PLC unit then derives the best-suited launching pattern and assigns possible launching occasions (launching slots) as described in Ref. 6. Within the DCS this allows for the handling of the pellet actuator like a single gas valve, requesting a flux between nil and maximum flow. To be applied during a plasma discharge, the request is handled via the preprogrammed discharge program executed by the DCS. Requests can be employed by either feed-forward trajectories or driven by feedback control with the option to change between both modes within a discharge.

When including pellet injection to plasma operation, care must be taken to ensure safe operation. Pellets arriving in the plasma do cause strong instant perturbations resulting in misguidedness of several diagnostic systems. Some of these systems are used during standard operation for the sake of providing indispensable information for the safety interlock system. In particular, the real-time density measurements by the deuterium cyanide (DCN) laser interferometer are taken to inhibit, e.g., the neutral beam injection (NBI) in case the plasma density becomes too low to prevent wall damage. With the sudden pellet-induced jump in plasma particle inventory causing fringe losses in the interferometer record, this key signal becomes unreliable. As a pellet-resilient approximation, the DCS calculates a “validated density” signal derived from all available interferometer data and a suitable bremsstrahlung measurement. In order to enable density control in discharges with pellet fueling, an extended Kalman filter–based state observer RAPDENS (Refs. 7, 8, and 9) has been developed and implemented in the
real-time control system on AUG. RAPDENS uses a one-step-ahead, control-oriented transport model of plasma density profile evolution given the actuator inputs (gas valves, pellets, NBI fueling) and corrects the model-estimated density profile using available and valid real-time density diagnostics. After the pellets have been injected, the only reliable real-time measurement that provides information about plasma density is the bremsstrahlung. It has been shown that RAPDENS is sufficiently robust to provide the measurement of the volume-averaged density in the region enclosing 40% of the toroidal magnetic flux inside the last closed flux surface (separatrix), the $\rho_{\text{tor}}$ range [0 to 0.4] also in pellet discharges on AUG. This quantity is referred to as the RAPDENS density further in this paper.

For plasma experiments employing a significant pellet particle flux, simply adding the pellet actuator is not suitable since the strong additional particle flux easily pushes the edge density beyond a suitable level and causes degradation of the confinement. Hence, a compensating reduction of the initial gas puff rate is needed. As for all standard density measurements, measures for relevant locations close to the plasma edge are hampered by the pellets. RAPDENS offers an option to overcome this as well by deriving a control signal representing the edge density. However, since the algorithm needs some tuning in practice, for the commissioning a traditional method was used. Simpler yet, a reliable and robust approach is to employ the neutral gas pressure in the private flux region $n_0^{\text{Dec}}$ as the control parameter for monitoring the edge density.

Experiments described here were performed at the beginning of the campaign 2020/21 at AUG. AUG is a mid-size divertor tokamak (major radius $R = 1.65$ m, minor radius $a_0 = 0.5$ m) where plasma-facing components are mainly tungsten ($W$), while the walls are repeatedly conditioned by boronization. Operating in a reactor-relevant, all-metal-wall configuration, AUG is equipped with powerful auxiliary heating systems and a versatile set of diagnostics enabling the needed plasma analysis and characterization.

The PLS combines a centrifuge launcher with a “looping” guiding system capable of injecting cubic pellets from the torus inboard in the speed range $\nu_p$ of 240 to 1050 m/s (Ref. 12), yielding response times for pellet request to pellet arrival in the plasma of 170 to 40 ms. Pellets are prepared prior to the plasma discharge and stored in a cryostat containing a reservoir sufficient to deliver about 100 pellets for one discharge. Pellets can have different volumes and can be composed for different gas samples, their mass $m_p$ accounting for their content of electrons. As pellets can only be launched at the rotating accelerator arm reaching the exit position, pellet repetition rates $f_p$ have to be integer fractions of the centrifuge revolution rate $f_C$. $f_p = f_C/n$, with $n$ integer. In addition, a further limitation occurs by the maximum 80-Hz delivery rate of the pellet source; obviously $f_p$ can never be higher than this frequency. For the centrifuge layout, the relation $\nu_p$ (m/s) = $4 \times f_C$ (Hz) holds. Thus, for any chosen pellet speed only a discrete spectrum of $f_p$ and hence, flux values $\Gamma_p = m_p \times f_p$ values are possible.

**II.B. Demonstration in Feed-Forward Control: Constant Particle Flux with Increasing Pellet Fraction**

For the first full application of the new pellet flux control feature, an experiment was performed with a preprogrammed feed-forward trajectory. The aim was to start with a steady gas puffing rate $\Gamma_G$ at a rather high level but yet below a magnitude compromising plasma performance. Then, a large fraction of the total particle influx $\Gamma = \Gamma_G + \Gamma_p$ is swapped from gas to pellet fueling while keeping $\Gamma = \text{const.}$ Notably, investigations of such kind replacing gas by pellet fueling have been made on several occasions, though to our knowledge, however, never as smooth as this way.

The plasma scenario chosen is one suitable for robust and reliable operation in the high-confinement mode (H-mode) even when approaching the high-density regime in the region beyond the Greenwald density $n_{GW}$ (Ref. 13), hardly to be accessed in AUG without pellet fueling. Although showing a plasma confinement on a moderate level only during the initial phase prior to the pellet-enforced density ramp up, this performance can almost be kept as the discharge progresses into the pellet-enforced, high-density regime revealing the scenario as particularly suitable under such conditions. The discharge #38479 was run at a plasma current $I_p = 1.0$ MA, toroidal magnetic field $B_t = 2.5$ T, edge safety factor $q_{95} = 4.5$, plasma volume $V_p = 13.3$ m$^3$, elongation $\kappa = 1.70$, and upper and lower triangularities $\delta^u = 0.09$ and $\delta^l = 0.39$, respectively. The H-mode conditions were established and maintained by steady auxiliary heating comprising NBI with $P_{NI} = 5.0$ MW and ion cyclotron resonance heating at 36.5 MHz with $P_{IC} = 3.5$ MW, adding up with the Ohmic heating to total heating power $P_{\text{tot}} = 9.0$ MW. The initially applied $\Gamma_G$, and hence the total particle flux throughout, was $2.9 \times 10^{22}$ electrons/s (e/s) (fluxes in AUG usually calibrated to e/s). Here, where both the gas species chosen for gas puffing and pellet production were pure deuterium, it equals the flux in D atoms/s. Entering the pellet phase, first a linear $\Gamma_p$ flux ramp was requested from 0 to $2.4 \times 10^{22}$ e/s lasting
1.5 s followed by a 0.5-s plateau, keeping this final value. This maximum flux request corresponds to the utmost capacity of the PLS only achievable for a parameter setting making use of the system’s full technical potential. The layout of the feed-forward trajectory, requested values, and duration was tailored in order to consume almost the entire reservoir of pellets. After the pellet sequence, an instant switch back to the initial pure gas puff approach took place allowing for study of the relaxation of the pellet-induced, high-density plasma state. During the pellet phase, as already mentioned, $\Gamma_G = 2.9 \times 10^{22} \text{ e/s} - \Gamma_P$ was requested. Both the applied gas (solid blue line) and request pellet flux (solid red line) are shown in Fig. 1f. The actuated response of the PLS, represented by the electronically generated pellet predictor signal, is shown in Fig. 1e. This signal is released when a pellet launch is started. The announcing predictor pulse, however, is delayed, taking into account the pellet acceleration and flight time to announce an expected pellet arrival at the separatrix in 4 ms, such that the DCS can still take necessary measures in case needed.

Taking the predictor signal, the pellet flux really intended to be delivered by the PLS can be obtained, according to values taking into account the granular nature of this flux, as illustrated by the dots in Fig. 1f. The red dots represent values calculated as

$$\Gamma_P(t_n) = m_P(t_{n+1} - t_n),$$

with $t_n$ the time when arrival of the $n$’th pellet is predicted. Purple dots are calculated by

$$\Gamma_P(t_n) < 4 > = 4m_P(t_{n+2} - t_{n-2}).$$

The first option averages over a single sequence composed from two neighboring pellets as indicated by the denotation $<1>$. Obviously, only such values can be realized relating to the discrete repetition rates fixed by $f_C$ and the maximum pellet source delivery rate. In this experiment, with $f_C = 136.6$ Hz and a maximum pellet source rate of about 80 Hz, possible delivery rates are $f_P = 136.6 \text{ Hz/N}$ with

\[\text{Fig. 1. Gradual replacement of gas puff by pellet fueling while keeping the total flux fixed. This results in a considerable increase of core density, particle inventory, and particle confinement. Despite the intrinsic granular structure of the pellet fueling, the averaged intended pellet flux responds well to the changing flux request.}\]
the integer $N \geq 2$. According to $<1>$, flux levels are displayed by the solid gray bars in Fig. 1f. To approach the requested flux, the PLS controller toggles between these levels. The resulting smoothened flux evolution can be recognized by, e.g., the four sequence average (indicated by $<4>$).

However, not every requested pellet did make it into the plasma. This becomes obvious from the pellet monitor signal shown in Fig. 1d. The monitor displays the intense radiation emitted when the pellet ablates in the hot plasma and indicates for positive arrival. For the case shown, 69 arrived while 82 pellets had been requested. As a consequence, there is a difference between the intended and real pellet particle flux. Since the loss of some pellets, practically inevitable due to their fragile nature, is unpredictable, this will finally result in some deviation between requested and achieved density. Obviously, this is a challenge for the control system to master. For our experiments, the DCS and the RAPDENS observer have been prepared accordingly.

The impact on the plasma performance when replacing gas fueling with the more efficient pellet injection is well known$^{16}$ and can be observed here also very clearly and cleanly. As expected for this scenario, keeping the total particle influx constant sustains the densities of neutrals in the divertor almost stable, as plotted in Fig. 1g. This avoids significant confinement degradation, which could be the result of an overdue increase in edge density. Local density measurements of the Thomson scattering (TS) system$^{17}$ gained from post-pulse data analysis (blue dots in Fig. 1c) show no indication of any significant slipping away of the edge density. In striking contrast, the TS measurement representing the core density (red dots) shows a steady and strong increase under pellet actuation, finally rising quite far beyond the Greenwald density (solid green line in Fig. 1c). This pattern is the typical one observed when the density profile undergoes the sought after favorable peaking created by the deeper and more efficient pellet fueling.$^{16}$ Also plotted in Fig. 1c are the validated density (black solid line) and the according real-time signal from the DCN interferometer (gray solid line), the latter one heavily affected during the pellet phase. The peaking of the density profile results in a pronounced increase of the plasma particle inventory. This can be seen clearly from the (electron) particle inventory $N_e$ of the confined plasma region. Calculated by an integrated data analysis of all the available valid profile diagnostics,$^{18}$ the evolution of $N_e$ is displayed in Fig. 1b. Unquestionably this shows the advanced efficiency of pellet fueling when compared to gas puffing. For a fixed particle flux, the achieved plasma particle content strongly increases with increased pellet fraction. Disregarding details of the underlying physics, a technical particle confinement time can be defined as

$$\tau_{tech}^{p} \equiv \frac{N_e}{\Gamma_{tech}}.$$  

where $\Gamma_{tech}$ is the technically applied gross particle flux (constant at $2.9 \times 10^{22}$ e/s here). While the pellet fraction of $\Gamma = \Gamma_{tech}$ is increased from 0 to 0.83, $\tau_{tech}^{p}$ raises from 32 to about 55 ms. Concurrently, the confined energy represented by the magnetohydrodynamic stored energy (displayed in Fig. 1a) keeps almost stable as does the energy confinement time:

$$\tau_e \equiv \frac{W}{P_{net}},$$

where $W$ is the plasma energy, and $P_{net}$ is the absorbed heating power. The initial phase shows a reasonable performance, as indicated by the ratio H98 = 0.9 with respect to the scaling law expression IPB98(y,2) employed usually as a reference to evaluate the global thermal energy confinement in tokamaks.$^{19}$ Yet while widely used, this scaling is no longer reasonable in the high-density regime.$^{15}$

II.C. Demonstration in Real Feedback Control: Core Density Ramp up to DEMO Level

Having achieved the positive commissioning result with feed-forward control, the next and concluding commissioning step was employing pellet flux control also for density profile control. In this context also, the full capability of the DCS came into action. The approach aimed to combine the two feedback loops to gain the ability to form a peaked density profile by increasing the core density while effectively keeping the edge density as low as desired. For the latter, the neutral gas pressure in the divertor was taken as control parameter. Actuation was on the gas puff rate, expecting the controller to force an accordingly compensatory reduction during pellet actuation. Evidently, core density control was assigned to the pellet actuator. As mentioned before, as control parameter, the $\rho_{tor}$ [0 to 0.4] volume-averaged density as calculated by RAPDENS was adopted. For conditioning the algorithm, it was trained off line taking data from relevant previous experiments. Finally, very few setup plasma shots had to be conducted for a final adjustment of control parameters. At last, the discharge presented in Fig. 2 was performed.
This demonstration aimed to ramp up the core density to about 1.25 times $n_{\text{Gd}}$, the value envisaged for the EU-DEMO 1 scenario.\textsuperscript{20} For this, the request preprogrammed was a 1.5-s-long linear ramp from 1.3 up to $1.55 \times 10^{20}$ cm$^{-3}$, which was then kept steady for another 0.5 s. The final value hence was mimicking a reactor-grade target, with the duration and magnitude of the request once again tailored to make almost full use of the available pellet reservoir. As well, the same plasma scenario as used for the feed-forward demonstration was employed again. In the initial phase, after plasma startup, stable and steady conditions were established with the controller setting the gas puff to achieve the $n_0^{\text{Div}} = 3.5 \times 10^{20}$ m$^{-3}$ target. At 3.5 s, the pellet actuator request kicks in resulting in an immediate pellet request and the arrival of the first pellet after 75 ms. All relevant data showing the controller managing the requested tasks well in discharge #38760 are displayed in Fig. 2. Figure 2e shows the requested (solid gray line) and measured (solid black line) neutral gas pressure in the divertor. As the pellet flux sets in, the pressure starts rising until this is counteracted by a gradual reduction of the gas puff. Kept well all along the pellet phase, it starts to drop after the abrupt end of the pellet train, once again it is recovering gradually now by the rising gas flux. With a response time of several 100 ms, the control loop “$n_0^{\text{Div}} \leftrightarrow \Gamma_G$” seemingly works reliably. Both controller-driven fluxes can be found in Fig. 2d, which shows the gas (blue solid line) and the requested pellet (red solid line) flux. Shown also in Fig. 2d are the single- and four-sequence-averaged requested pellet flux (red and purple dots, respectively) and the possible flux levels (here for $f_p = 137.1$ Hz/N with integer $N \geq 2$). Like in Fig. 1, the expected (Fig. 2c) and indeed arriving (Fig. 2b) pellets are displayed. This time, 91 pellets were requested with 83 arriving. The resulting delivery efficiency of 83/91 = 0.91 is a typical value for the AUG PLS (Ref. 21). The same density signals as explained before in Fig. 1 are displayed in Fig. 2a. Via $n_0^{\text{Div}}$ control, the edge density is kept reasonably stable while the core density is increased as anticipated. This can be realized by comparing the targeted (solid gray line) and achieved (solid purple line) core density shown in Fig. 2a. The latter one represents the averaged core density as calculated by the RAPDENS tool. Seemingly, the request for ramping up and keeping the core density steady is carried out very well, taking into account the system response time and the unavoidable coarseness of the real pellet flux. The control loop “core density $\leftrightarrow \Gamma_G$" copes well with missed out pellets and the inherent 75-ms delayed pellet delivery. The delayed pellet delivery is well visible at onset and termination of the pellet flux request.

Achieving its final commissioning goal with this demonstration, the pellet flux control feature was fully validated and approved for getting incorporated into the DCS tool kit. In the following, it was applied for several different tasks as, e.g., for event-driven flux control in experiments aimed at the development of the control
schemes for avoiding the H-mode density limit at AUG (Ref. 22).

III. EXTENSION TO A MULTISOURCE PELLET ACTUATOR: PROJECTED CONTROL SCHEME FOR JT-60SA

The JT-60SA is a large superconducting tokamak device in its commissioning phase. It will be at the forefront of the international fusion program, supporting the ITER experimental program as a satellite machine. In addition, it is expected to provide key physics and technology information for the operational scenario of future DEMO fusion reactors, in particular for a steady-state, advanced-performance design option. With respect to this, it requests a powerful and versatile pellet injection system that at least is expected to serve simultaneously for its particle fueling and ELM pacing experiments. Following this request, a conceptual design was worked out for a suitable PLS (Ref. 23), which is now under construction. It is based on the stop cylinder centrifuge principle of the AUG PLS (Ref. 12), but is going to extend it further. For the pellet sources, it will apply an advanced and more reactor-relevant technology using quasi-steady-state extruders capable of delivering pellets continuously for the entire plasma duration of up to 100 s. The extruder layout offers the option to operate with both stable hydrogen isotopes but also with admixed gases. Hence, they can be operated as a seeding source on demand. Furthermore, these multiple pellet sources have to be controlled in parallel. In the startup configuration, the PLS will incorporate two extruders (one for fueling, one for pacing); the layout made can host three extruders, so their control system has to be construed accordingly. For the controlling of the pellet launch, in order to avoid pellets colliding and damaging each other, it must take into account that only a single pellet can be put into any launching slot. This enforces a priority ordering of all tasks, determining which one gets accepted in case of simultaneous requests. Too, possible cross talk between different actuations has to be taken into account. For example, modeling showed ELM pacing pellets can increase the density considerably and thus result in an unwanted density overshoot. Hence, the ultimate control task is to decide which launching slot has to be occupied and by which pellet. As a result, it will compose a single train of different pellets most suitable for all activated tasks.

Consequently, the controller has to be capable of mastering all tasks simultaneously while taking into account prioritization and cross talk. The detailed layout is still a work in progress, but the approach is as described briefly in the following. Up to three pellet sources are controlled by local PLC synchronizing pellet delivery and centrifuge revolution to recognize any launching slot. Any source will own its own flux controller based on the AUG unit. However, activation will be under the provision of a priority supervisor taking care for exclusive launch slot occupation. Priorities can either be set locally by the PLC or externally by the tokamak control system SCSDAS (Ref. 25). The latter potentially adapts and revises the priority order during a discharge as required. In addition, actuation on any source has to be taken into account for the other sources in case it matters. This is indicated on the example assuming three extruders are active on the tasks fueling, ELM pacing, and seeding in Table I. Any pellet contributes with its particle content for fueling, any pellet potentially triggers an ELM irrespective to its size, but only the seeding pellet hosts admixed gases and hence remains unaffected in its actuation.

IV. SUMMARY AND OUTLOOK

A new control scheme has been developed for the PLS at the mid-size tokamak AUG. It is capable of mastering pellet flux control in a stop cylinder centrifuge accelerator device equipped with a single pellet source. During dedicated plasma experiments performed at the beginning of the campaign 2020/21 it has proven to be fully operational. In feed-forward operation, on average

| TABLE I |
| Cross-Talk Considerations for an Example with Three Extruders Dedicated to Fueling, Pacing, and Seeding via Host Pellets | |
| **Actuation** | **Fueling** | **Pacing** | **Seeding** |
| Fueling pellet | Fueling size | Pacing size | Nil |
| Pacing pellet | Pacing size | Pacing size | Nil |
| Seeding pellet | Seeding size | | Seeding size |
a smooth flux ramp was achieved despite the granular nature of the pellet injection technique. Embedded in the environment of the DCS system, taking care for the entire plasma operation and in interplay with the dedicated real-time control algorithm RAPDENS, it can be used for plasma density profile control. Here, stable controlled operation at a reactor-grade core density level was achieved. Yet, it was one move forward on a step-ladder approach, with the next one now under way with the PLS for the large tokamak JT-60SA.

The main goal of this ongoing project is to develop a pellet actuator with an according control system capable of multitasked operation. The JT-60SA PLS system is under construction for a layout that could be a prototype for a later reactor-grade solution. It has to master several pellet quasi-steady-state sources in combination with a single centrifuge accelerator unit in order to compile a single train of precisely timed pellets. This train is collated from pellets of potentially different sizes and compositions in order to fulfill all tasks simultaneously in an optimized way. Due to the nature of the acceleration process, any potential position in this train, relating to a launching slot, can only be occupied by at most one single pellet. The schedule of such a multitasking control system is currently under development. Its central part will be formed by the validated controller of a single pellet source.

There are also already lessons to be learned for DEMO from these actual investigations. The plasma control system has to cope with the requested but not arriving pellets. For a device like AUG with rather short response times, this was found to be a task that is quite manageable. For EU-DEMO, missing pellets could result in unacceptably high variations of core density, and as a consequence, fusion burn power. Therefore, a prewarning approach is desirable that spots lost pellets as early as possible in the delivery chain to allow for timely counter action. According to this, strategies and detection techniques are now also taken into consideration.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under grant agreement no. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Raw data for the experiments presented in this paper were generated at the AUG facility. Derived data supporting all the findings of this study are available from the corresponding author upon reasonable request.

ORCID

P. T. Lang http://orcid.org/0000-0003-1586-8518
B. Ploeckl http://orcid.org/0000-0001-6057-5402

References

1. B. PLOECKL et al., “Matter Injection in EU-DEMO: The Pre-Conceptual Design,” Fusion Sci. Technol., 77, 4, 266 (2021); https://doi.org/10.1080/15361055.2021.1903784.
2. B. PEGOURIE et al., “Physical Constraints on the Design of the DEMO Pellet Fueling System,” Proc. 43th EPS Conf. Controlled Fusion and Plasma Physics, Leuven, Belgium, July 4–8, 2016 (2016), P4.076.
3. P. T. LANG et al., “Optimizing the EU-DEMO Pellet Fuelling Scheme,” Fusion Eng. Des., 156, 111591 (2020); https://doi.org/10.1016/j.fusengdes.2020.111591.
4. M. LENNHOLM et al., “Statistical Assessment of ELM Triggering by Pellets on JET,” Nucl. Fusion, 61, 3, 36035 (2021); https://iopscience.iop.org/article/10.1088.
5. P. T. LANG et al., “Targeting a Versatile Actuator for EU-DEMO: Xenon Doping of Fueling Pellets,” Fusion Sci. Technol., 77, 1, 42 (2021); https://doi.org/10.1080/15361055.2020.1842713.
6. B. PLOECKL et al., “Targeting a Versatile Actuator for EU-DEMO: Novel Control Scheme for Multisource Pellet Injector,” Fusion Sci. Technol., 77, 3, 199 (2021); https://doi.org/10.1080/15361055.2020.1864172.
7. T. BLANKEN et al., “Control-Oriented Modeling of the Plasma Particle Density in Tokamaks and Application to Real-Time Density Profile Reconstruction,” Fusion Eng. Des., 126, 87 (2018); https://doi.org/10.1016/j.fusengdes.2017.11.006.
8. T. BLANKEN et al., “Model-Based Real-Time Plasma Electron Density Profile Estimation and Control on ASDEX Upgrade and TCV,” Fusion Eng. Des., 147, 111211 (2019); https://doi.org/10.1016/j.fusengdes.2019.05.030.
9. T. BOSMAN et al., “Kalman Filter Density Reconstruction in ICRH Discharges on ASDEX Upgrade,” Fusion Eng. Des., 170, 112510 (2021); https://doi.org/10.1016/j.fusengdes.2021.112510.
10. P. T. LANG et al., “Feedback Controlled, Reactor Relevant, High-Density, High-Confinement Scenarios at ASDEX Upgrade,” Nucl. Fusion, 58, 3, 36001 (2018); https://doi.org/10.1088/1741-4326/aaa339.
11. A. KALLENBACH for the ASDEX Upgrade Team and the EUROfusion MST1 Team, “Overview of ASDEX Upgrade Results,” Nucl. Fusion, 57, 10, 102015 (2017); https://doi.org/10.1088/1741-4326/aa64f6.

12. B. PLOECKL and P. T. LANG, “The Enhanced ASDEX Upgrade Pellet Centrifuge Launcher,” Rev. Sci. Instrum., 84, 10, 103509 (2013); https://doi.org/10.1063/1.4824429.

13. M. GREENWALD et al., “A New Look at Density Limits in Tokamaks,” Nucl. Fusion, 28, 12, 2199 (1988); https://doi.org/10.1088/0029-5515/28/12/009.

14. M. BERNERT et al., “The H-mode Density Limit in the Full Tungsten ASDEX Upgrade Tokamak,” Plasma Phys. Control. Fusion, 57, 1, 14038 (2015); https://doi.org/10.1088/0741-3335/57/1/014038.

15. P. T. LANG et al., “H-mode Confinement in the Pellet-Enforced High-Density Regime of the All-Metal-Wall Tokamak ASDEX Upgrade,” Nucl. Fusion, 60, 9, 92003 (2020); https://doi.org/10.1088/1741-4326/ab6ea9.

16. P. T. LANG et al., “High-Density H-mode Operation by Pellet Injection and ELM Mitigation with the New Active In-Vessel Saddle Coils in ASDEX Upgrade,” Nucl. Fusion, 52, 2, 23017 (2012); https://doi.org/10.1088/0029-5515/52/2/023017.

17. B. KURZAN and H. D. MURMANN, “Edge and Core Thomson Scattering Systems and Their Calibration on the ASDEX Upgrade Tokamak,” Rev. Sci. Instrum., 82, 10, 103501 (2011); https://doi.org/10.1063/1.3643771.

18. R. FISCHER et al., “Integrated Data Analysis of Profile Diagnostics at ASDEX Upgrade,” Fusion Sci. Technol., 58, 2, 675 (2010); https://doi.org/10.13182/FST10-110.

19. ITER PHYSICS EXPERT GROUP ON CONFERENCE AND TRANSPORT et al., “Chapter 2: Plasma Confinement and Transport,” Nucl. Fusion, 39, 2175 (1999); https://doi.org/10.1088/0029-5515/39/12/302.

20. R. WENNINGER et al., “The DEMO Wall Load Challenge,” Nucl. Fusion, 57, 4, 46002 (2017); https://doi.org/10.1088/1741-4326/aa4fb4.

21. B. PLOECKL et al., “Advanced ASDEX Upgrade Pellet Guiding System Design,” Rev. Sci. Instrum., 91, 8, 83502 (2020); https://doi.org/10.1063/5.0012145.

22. M. MARASCHEK, Max Planck Institute for Plasma Physics, AUG monday morning operations meeting, Personal Communication (2021).

23. P. T. LANG et al., “A Flexible Pellet Injection System for the Tokamak JT-60SA: The Final Conceptual Design,” Fusion Sci. Technol., 75, 3, 178 (2019); https://doi.org/10.1080/15361055.2018.1471960.

24. G. GIRUZZI et al., “Advances in the Physics Studies for the JT-60SA Tokamak Exploitation and Research Plan,” Plasma Phys. Control. Fusion, 62, 1, 14009 (2020); https://doi.org/10.1088/1361-6587/ab4771.

25. “Version 4.0, 2018, September, JT-60SA Research Unit,” JT-60SA (Sep. 2018) http://www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf (current as of Apr. 26, 2021).