Fusion Engineering and Design 185 (2022) 113333

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Concept for a multi-purpose EU-DEMO pellet launching system

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ARTICLE INFO

Keywords:
Tokamak
Pellet fuelling
Launcher technology
ASDEX Upgrade
JT-60SA
EU-DEMO

ABSTRACT

Pellets - mm-size solid bodies produced from frozen fuel – are mainly destined for fuelling purposes in the fusion reactor EU-DEMO. However, pellets have been proven capable tools for further tasks too, e.g. ELM frequency control and the efficient delivery of seeding gases have been already demonstrated. Here, a concept is presented for a single pellet launcher based on a stop-cylinder centrifuge accelerator equipped with multiple pellet sources. The sources can deliver pellets with different sizes and composition, finally combined into one single compound pellet train. Thus, the pellet launching system (PLS) is capable to control simultaneously different plasma parameters with a minimized cross talk between these different actuations. Currently, a new PLS is under development for the new large superconducting tokamak device JT-60SA which can be potentially regarded as a prototype for the envisaged EU-DEMO system. Its initial configuration will be capable to control plasma density and ELM pacing simultaneously; optionally a source for doped pellets can be added. Status and recent achievements of this systems are reported. At the full metal wall mid-size tokamak ASDEX Upgrade (AUG), work is ongoing developing a versatile control strategy and corresponding tools. Capable to inject pellets with high speed through a guiding tube from the torus inboard side, AUG represents a fully reactor relevant configuration. While all demonstrations have been performed with a single pellet source hence bound to actuation prioritizing one actuation parameter, all tools developed can be expanded straightforwardly to multi-purpose control. For example, one novel tool optimizes real-time feedback pellet flux control taking into account the discrete nature of the pellets. As well, a solution is worked to handle the issue of missed-out pellets. Such failed pellets are considered unavoidable due to the fragile nature of the solid fuel but identified as significant hazard for reactor burn control.

1. Introduction

The injection of pellets, mm-sized solid bodies produced from hydrogen isotopologues, has been proven a suitable and versatile actuator in fusion research for a variety of tasks. For a future fusion reactor, pellets will very likely also play a key role. In order to harvest a sufficient amount of fusion power, the reactor needs to operate at high core densities. Hence, efficient and reliable core particle fuelling will become a most essential task. The pre-conceptual design elaborated for the matter injection of EU-DEMO attributes this core particle fuelling task entirely to conventional pellet injection technology [1]. As optimised pellet fuelling scheme balancing advanced fuelling efficiency against related technical efforts a solution was identified aiming at pellet injection from the torus inboard side via a guiding system [2]. Beyond its capability to deliver pellets with an adequate fuelling performance, the EU-DEMO pellet system requires as well a sophisticated controller in order to allow for sustainable burn power control. For this it turned out inevitable to take into account as well imperfections in the pellet delivery and the impact pellets do have on standard diagnostic measurement. The latter calling for a pellet resilient diagnosing of essential plasma parameters.

Resonated by the relevant fuelling task, considerable efforts have

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https://doi.org/10.1016/j.fusengdes.2022.113333
Received 15 September 2022; Received in revised form 11 October 2022; Accepted 25 October 2022
Available online 31 October 2022

been invested in the development of suitable pellet systems. As a potential windfall it turned out that, once such a system is at hand, it can potentially serve for other tasks as well. It is understood that the layout the concept of a multi-purpose pellet system for EU-DEMO will result in some extra effort. However, it looks most likely this is more than outbalanced by the expected benefits.

One well know example of pellet actuation beyond fuelling is to control the frequency of edge localised modes (ELMs) causing periodic plasma losses [3,4] and mitigate their impact on wall components exposed [5]. Yet recently revalued this potential is currently regarded less reactor relevant, it proved the variability of pellet actuation – and might even regain this safety-relevant topic. An additional feature has been recently found when applying fuelling pellets doped with auxiliary components. The technique of plasma seeding by gases needed for either performance enhancement [6] and/or radiative power exhaust [7] has been found working better with pellet doping than with pure gas puffing [8].

Hence, we are aiming to develop a feasible concept for a pellet system acting simultaneously for multiple purposes. Development is intended step-by-step facing an increasing complexity making use of different tokamaks of different size - the already operating AUG, the superconducting JT-60SA currently entering its commissioning phase and the final design target EU-DEMO. All pellet systems share the same basic set-up relying on pellet injection via a guiding system from the torus inboard and are hence compatible with respect to the employed injection and control techniques. The essential concept of this stepladder approach to face all the challenges and tasks for the development of a reactor grade PLS is visualised in Fig. 1.

2. The AUG solution

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) [9] 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 for the needed plasma analysis and characterization.

The AUG PLS is already in operation for more than 3 decades and thus be considered a truly sustainable workhorse. During this period, it had been employed for a wide range of investigations on pellet physics and technology. It covered a wide range of operational parameters with respect to pellet speed, size and composition. In particular, it served for fuelling, ELM pacing or seeding experiments using doped pellets [10]. However, it is equipped with a single pellet source only with limited reservoir.

Recently, corresponding to its role as initial step, a new control tool has been developed for the pellet flux suitable to be upgraded along the stepladder. The tool shown in the upper part of Fig. 4, takes into account that in the case of a centrifuge launcher injection events can take place only on a discrete time grid determined by the centrifuge revolution time and the maximum delivery rate of the pellet source. Any of these possible “launching slots” can then be potentially occupied by a single pellet on request [11]. The algorithm derives then the most suited pattern for the population of the launching slots in order to match the quasi-continuous flux request. A demonstration example is shown in Fig. 2 where a continuous linear flux ramp with a final steady part at the maximum possible pellet flux was requested. This request is handled by the discrete pellet events by appropriate timing. The set of possible flux levels is indicated in the lowermost box of Fig. 2 (<1> levels) as well as the requested flux referring to the flux averaged over a single (red dots) or 4 pellet sequences (purple dots) – a detailed description can be found elsewhere [12].

Calculated flux data refer to the requested pellet launch events with accordingly predicted pellet arrival in the plasma. However, in reality – due to the fragile nature of the pellets – some pellets do not make it to the plasma. Such missed-out pellets can be recognized from the absent monitoring signal derived from the pellet ablation radiation and the evolution of the plasma electron contend. Since such missed-out pellets have been identified as a potentially serious hazard for the burn control in EU-DEMO, additional efforts are taken at AUG in order to provide their recognition in real-time and take according steps for a sufficiently fast response as discussed in more detail elsewhere [13]. In addition, the Kalman filter based state observer RAPDENS has been developed and integrated into the discharge control system of AUG enabling real time feedback control of the density profile [14]. When applying pellet fueling in this framework, access to the high density regime can be achieved with core densities at a level like suggested in EU-DEMO [12]. The next step envisaged is to embed the pellet tool into the actuator sharing concept for multiple control tasks. This way, solutions are going to be elaborated applicable as well in the more complex environments of JT-60SA and EU-DEMO.

3. The JT-60SA concept

JT-60SA is a new superconducting tokamak (major radius R about 2.95 m, minor radius a_0 about 1.15 m) currently approaching its initial commissioning phase. It had been built under the Broader Approach Satellite Tokamak Programme run jointly by Europe and Japan, and under the Japanese national program. It will then be at the forefront of the international fusion program and is expected to provide key

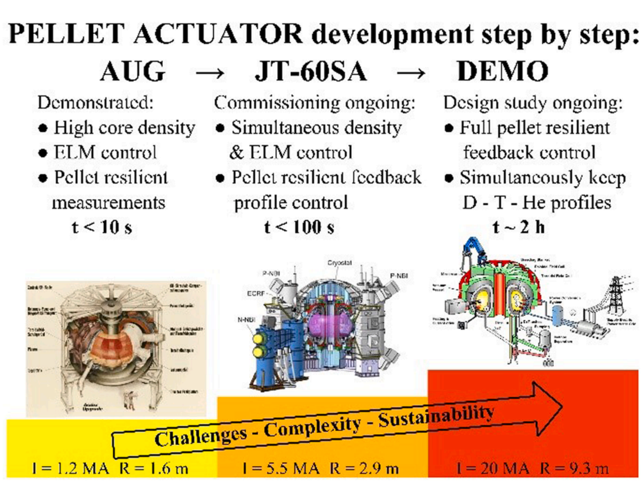

Fig. 1. Step-by-step approach for the pellet actuator development for tokamaks with increasing size. Experience gained from an existing system at AUG is introduced for the design and construction of the JT-60SA system. The JT-60SA solution can be regarded a potential prototype solution for a future reactor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

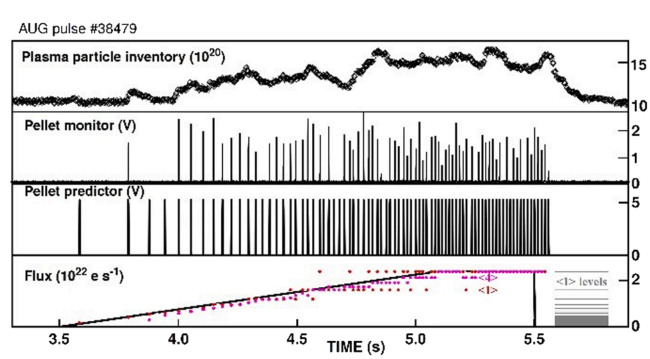

Fig. 2. Pellet flux ramp boosting the (electron) plasma particle inventory. The flux controller approximates the requested continuous flux by discrete pellet injection events at an adapted averaged rate. More details to be found in [12].

information for the operational scenario of future DEMO fusion reactors, in particular for a steady state, advanced performance design option. This holds as well for the new PLS under development construction which can be potentially regarded as a prototype for the envisaged EU-DEMO system.

The JT-60SA research plan [15] calls for a PLS capable to achieve high-density operation via pellet fuelling and ELM control via pellet pacing. Hence, this requires a system able to control in real time simultaneously the plasma density profile and the pacing rate. The PLS design was hence decided to follow the AUG centrifuge launcher concept yet upgraded employing at least two pellet sources with both capable for steady operation lasting up to 100 s. Modelling showed that with the projected pellet parameters as detailed in the following both assigned control tasks can be achieved; however the cross-talk (in particular the contribution of pacing pellets to fuelling) has to be taken into account [16]. An example design of the PLS is presented in Fig. 3. It shows the case with already 3 pellet sources installed while the initial start-up configuration foresees 2 sources - leaving access for an optional diagnostic unit through the spare port.

The fuelling pellet source is a screw type ice extruder, cylindrical pellets with length l = diameter ∅ = 2.4 mm are cut from the continuously delivered ice rod. Pellets can be delivered up to a maximum rate of 20 Hz. Indeed, due to the high mass throughput needed, the ice is provided via 2 parallel extrusion channels with two cutter systems both able to operate up to 10 Hz. The source can operate with pure Protium $^1H_2$, pure Deuterium $^2H_2 \equiv D_2$, isotopologues mixture from both isotopes and Protium doped with either up to 1.0 mol% Nitrogen N_2 or 2.0 mol% Neon Ne.

The same extruder design is used for the pacing pellet source, delivering l = ∅ = 1.2 mm at up to 50 Hz. It can be operated with either pure $^1H_2$ or D_2.

Both sources are mounted on top of the centrifuge, supplying the pellets into the stop cylinder where they are caught and transferred to the acceleration arm. There, they are accelerated to the designated speed controlled via the centrifuge revolution rate within the envisaged operational range of 100 – 500 m/s. At the centrifuge exit, pellets will be collimated by a funnel into the guiding system transferring them towards the torus vessel. The guiding system outside the vessel comprises a diagnostic section checking pellet integrity and speed before their arrival at the torus gate valve. There, the pellet can enter via a short free flight section the in-vessel guiding tube to be installed under QST responsibility, finally yielding pellet transfer to the vessel inboard for their designated injection location from the magnetic high-field side.

For the combined control of fuelling flux and pacing rate, it is required to compose one single pellet train from pellets delivered from the two sources. Applying the concept of filling available launching slots, the train will consist of pellets all arriving at the same speed but potentially different masses and/or composition on the time grid settled by the launching slot pattern. Yet one demand has to be strictly obeyed – only a single pellet can be put in any available launching slot. Otherwise, pellet collision and damage would result. To cover this, the AUG controller was expanded accordingly. The upper part of Fig. 4 shows the proven AUG solution for single fuelling source [1]; the lower part its expansion for the two sources. For this start up configuration it has been decided to give priority to the fuelling pellet in case of both kinds are requested via their loop for the next time slot. This is based on the assumption that under all plasma conditions where a pacing pellet triggers an ELM, the fuelling pellet will do as well.

Self-evidently, pacing pellets contribute as well to the pellet particle flux and hence to fuelling. Consequently, the pacing pellet flux will be taken into account by accordingly reducing the fuelling flux. In case the pacing related flux exceeds the requested fuelling rate, an alarm will be communicated to the tokamak controller indicating its request for pacing and fuelling are contradicting. Of course, the initial version can be still upgraded into a version capable for a potentially unlimited number of pellet sources with flexile prioritisation. This is realised in the suggested solution for DEMO discussed in the following section.

4. The EU-DEMO concept

The matter injection concept for EU-DEMO assigns the core particle fuelling task to the pellet tool [1]. When launching them from the torus inboard, the required fuelling performance can be achieved [2]. The JT-60SA PLS fosters the EU-DEMO needs by enhancing most key capabilities as e.g. high fuel throughput by steady state extrusion when operating with different hydrogen isotopologues. This leaves just the tritium handling capability as a remaining issue.

However, our concept aims beyond a pure fuelling task by taking advantage of the existing PLS as a tool for other tasks. A schematic design of a potential solution for the according control system is shown in Fig. 5. It can be used in principle for any number of pellet sources

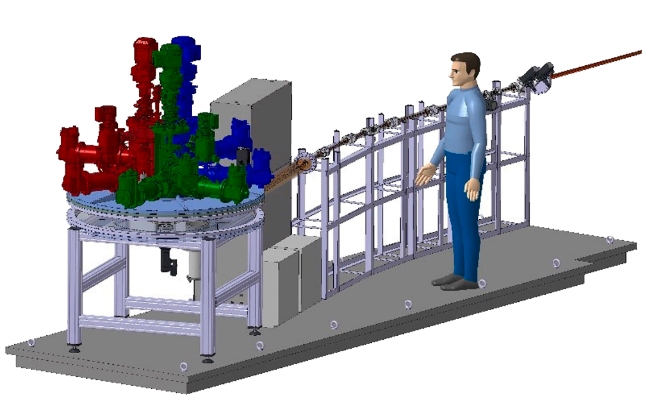

Fig. 3. Example design of the JT-60SA centrifuge with 3 pellet sources mounted on top and the initial part of the ex-vessel guiding system.

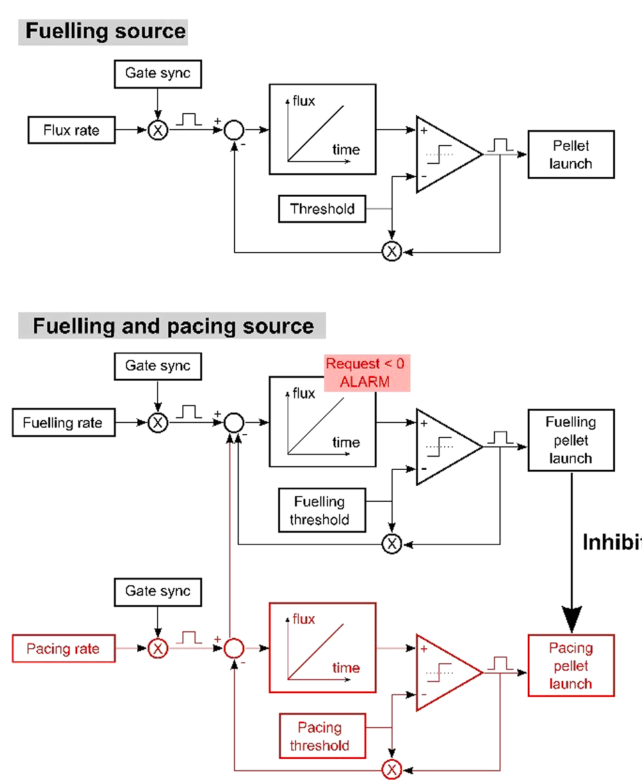

Fig. 4. Flux controller applied at AUG for actuation on a single pellet source [1] (upper) and projected extension for the initial configuration at JT-60SA for simultaneous control of flux and pacing rate (lower). In this configuration, priority is admitted to the requested launch of fuelling pellets.

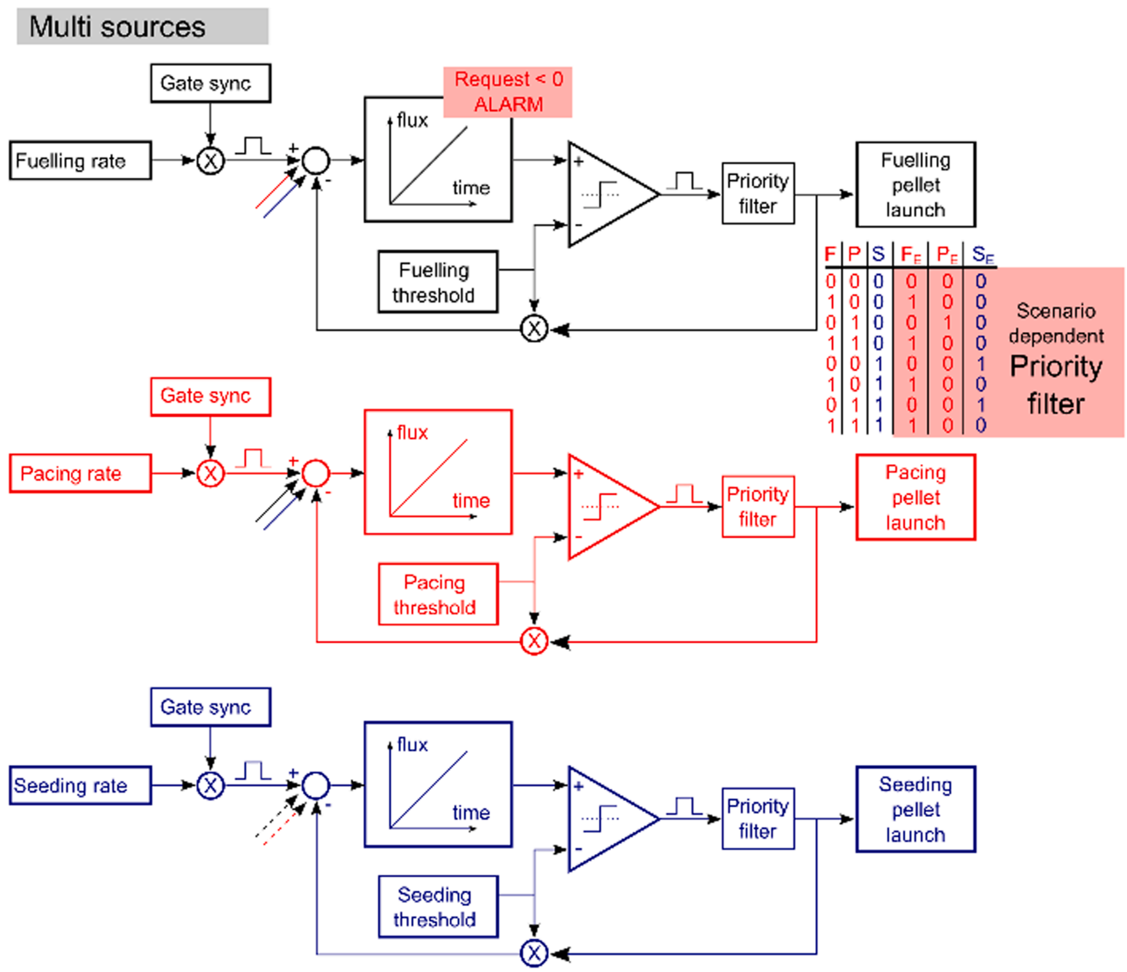

Fig. 5. Schematic design of a controller for multi-actuator pellet controller. Example shows version for 3 different tasks (fuelling, pacing, seeding). Potential cross-talk effects as shown in table I have to be accounted for. In addition, prioritisation is indispensable to avoid pellet interferences in the launcher.

mounted on a single centrifuge accelerator. The example shows three sources for three different tasks – fuelling, pacing, seeding. Again, a single pellet train is composed from different kinds of pellets but only one pellet can occupy a launching slot. Thus, flexible priority ordering is applied – allowing its dynamical adaptation during a plasma discharge.

It is understood the cross-talk between the different actuations has to be taken into account. For the example given, as indicated in Table 1. For fuelling, any pellet launched contributes with the amount of fuel carried. For pacing, any pellet injection can trigger an ELM. Assumed fuelling and pacing pellets are formed from pure hydrogen isotopologues, they do not matter for seeding. Yet, due to their potentially small size pacing pellets likely will not penetrate deep into the EU-DEMO plasma and thus create a significant fuelling contribution. The resulting “pacing size” flux will however end up finally in the divertor and has to be taken into account. For the seeding with admixed pellets first encouraging results have been obtained for batch extrusion [8]; however further investigation are needed in order to clarify which gases at which amount can be admixed during a steady extrusion process.

5. Conclusion and outlook

Our concept aims to develop the PLS for EU-DEMO step-by-step, making use of the devices AUG and JT-60SA. Dedicated analysis showed the fueling scheme applied or developed there has the potential to meet the required targets. However, care has to be taken to adapt the envisaged pellet mass and for a proper handling of missed-out pellets. Ongoing work shows pellets can grant core fuelling, but the PLS tool provides valuable actuator options.

Table 1
Cross talk considerations for the example with 3 extruders dedicated to fuelling, pacing and seeding via host pellets.

Accounted as for	Fuelling rate	Pacing rate	Seeding rate
Actuator			
Fuelling pellet	Fuelling size	Pacing size	Nil
Pacing pellet	“Pacing size”	Pacing size	Nil
Seeding pellet	Seeding size	Pacing size	Seeding size

Efforts to develop this concept with clear focus on EU-DEMO needs are currently under way at the tokamaks AUG and JT-60SA. While the new JT-60SA PLS under construction is the main technology driver, advances on the control system are the contribution from AUG.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

Acknowledgments

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.

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