WPSA-CPR(18) 19805

PT Lang et al.

Final design of the JT-60SA pellet launching system for simultaneous density and ELM control

Preprint of Paper to be submitted for publication in Proceeding of
30th Symposium on Fusion Technology (SOFT)

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Final design of the JT-60SA pellet launching system for simultaneous density and ELM control

P. T. Lang[a], T. Nakano[b], S. Davis[c], G. Matsunaga[b], B. Pégourié[d], B. Ploeckl[a], W. Treuterer[a]

[a]*Max Planck Institute for Plasma Physics, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany*
[b]*National Institutes for Quantum and Radiological Technology, Naka Fusion Institute, 801-1 Mukoyama, Naka-shi, Ibaraki-ken, Japan 311-0193*
[c]*Fusion for Energy, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany*
[d]*CEA, IRFM, 13108 Saint-Paul-lez-Durance Cedex, France*

The key mission of the new tokamak JT-60SA is to conduct exploitations in view of ITER and to resolve key physics and engineering issues for DEMO. Its pellet launching system was designed to cover according requirements by providing a powerful and flexible tool for the control of density profile and ELM frequency. Modelling showed inboard launch is a must in order to achieve high fuelling efficiency; by analysing the potential pellet fuelling impact in all relevant plasma scenarios the optimized set of pellet parameters for fulfilling all the tasks requirements was elaborated. Accordingly, the systems lay has to be adapted for pellet injection via a guiding tube from the vessel inboard side. Currently, efforts are under way in order to elaborate the most appropriate solution yielding minimised pellet transfer losses and a maximum transfer speed yet compatible with boundary conditions imposed by the vessel already under construction. The feasibility of a mechanical centrifuge as pellet acceleration unit was studied. This approach would guarantee the precise pellet launch speed as needed to enable the best adaptation to the guiding tube transfer capabilities and accurate control of pellet frequency and particle flux as arriving in the plasma. While the appropriateness of the centrifuge principle has been already proven by several devices, the proposed version possesses a novel design employing several accelerator arms. Such, operation at heighten rates and with a more refined adjustment of pellet flux and frequency could be achieved. Moreover, it allows hosting several sources delivering different pellets and their simultaneous actuation. The appropriate control unit is designed to merge pellets from different sources and form a sequence for the simultaneous control of different basic plasma parameters as e.g. density and ELM frequency. This flexibility can also allow including additional applications like isotope fraction control or radiative power exhaust by the use of compound pellets. At present, the detailed engineering of all major components is in progress, aiming to provide specifications and get ready to prepare the procurement process.

Keywords: Tokamak, Pellet fuelling, Launcher technology, JT-60SA

1. Introduction

The task of this ongoing project is to provide a pellet launching system (PLS) for the new device JT-60SA in due time for the initial research phase II currently planned to start in early 2023. JT-60SA [1] is a tokamak using superconducting toroidal and poloidal field coils with a mission to contribute to early realization of fusion energy by supporting the exploitation of ITER and by resolving key physics and engineering issues for DEMO reactors. There are two main tasks assigned to the PLS: particle fuelling and ELM pacing. Fuelling has to enable access to the high density regime beyond the empirical Greenwald limit; technically a feedback control of the density gradient has to be facilitated. For the envisaged role for controlling the ELM activity, the physics task is to sound out the pellet potential for ELM triggering. In case pellets are found capable to initiate ELMs, the technical task is to optimize pellet parameters in order to minimize the fuelling impact and provide the pacing tool for the feedback control of the ELM frequency potentially applied for ELM mitigation.

Initial investigation taking into account the torus vacuum vessel is already under construction and hence any approach must comply with the according boundary conditions unveiled there are only few options still possible for pellet injection into the plasma. Modelling the fuelling impact of single pellets adopting the technical boundary conditions of every possible solution unveiled pellet launch from the torus inboard side is the best approach for any of the considered plasma operational scenarios [2]. This is despite the finally chosen inboard launch option requires pellet transfer through a multi-bend guiding system, for the pellet size range prescribed restricting the employable pellet speed to the range 200 – 500 m/s.

For the pacing task, required pellet sizes are most likely much smaller than those of fuelling pellets. To ensure reliable delivery, however a minimum residual size of about 10% fuelling pellet mass is necessary and envisaged. Foreseen pellet pacing rates are likely to exceed the injection rate of the fuelling pellets by a factor of up to 5 – 10. In turn, for scenarios where pacing pellets cause sufficient impact to trigger an ELM fuelling pellets for sure will do so as well. It is thus obvious there will be a strong interference between fuelling and pacing actuation. However, by controlling both parameters simultaneously it is possible to take advantage of this "cross-talk". The system layout and the suggested approach for the launch control have been made accordingly.

author's email: peter.lang@ipp.mpg.de

Finally, experience with existing pellet systems have shown some headroom in the operational features beyond the initially prescribes scope can be of great benefit. Consequently, the design proposed comprises several options for upgrades. These would the system enable to cover additions points of interest as e.g. the efficient handling of plasma enhancement gases or isotopic mixtures for burn control simulation.

2. System design

2.1. Adaptation to the boundary conditions

As already noted previously, the major boundary condition to be coped with is the fact JT-60SA's vacuum vessel is already under construction and thus guiding tubes required for pellet transfer have been subject to significant constructional restrictions. Currently, extensive efforts are made investigating several options for the guiding tube routing enabling the pellet inboard launch. Possible solutions are evaluated employing a model calculating an effective average curvature radius for a given track and finally calculating the critical transfer speed applying the empirical AUG calibrated relation [2]. Reasoning for this is the pellet speed found advantageous for the performance of pellet fuelling in the sense that fast pellets can achieve the same density increase with less particle flux. Due to the necessity of inserting a multi bend guiding tube the maximum possible pellet transfer speed will be considerably constricted; estimations yield a critical transfer speed of 470 m/s. Consequently, the acceleration system had to be adapted in order to deliver pellets in the accessible transfer speed range. In order to match at the optimum speed, it is even unavoidable to provide for pellet launch with precise speed control and small speed scatter. Beyond its need for adaptation purposed, the precise control of the pellet launching speed at the exit of the acceleration system is a must for the requested control performance. Due to a significant distance between accelerator exit and plasma entrance position, significant speed scatter would result in significant flight time scatter causing distortions of pellet arrival times and hence the applied frequency. Mainly for these reasons, a centrifuge accelerator was chosen. This type of acceleration units have already proven a high precision in pellet speed control in combination with very low speed scatter while providing reliable pellet delivery [3]. Furthermore, our design takes advantage of the centrifuge features enabling it to establish pellet trains combined from both fuelling and pacing pellets. Equipped with an according controlling unit, it thus will be able to provide an integrated solution for simultaneous actuation on fuelling and pacing taking into account the fuelling impact of pacing pellets and the pacing impact of fuelling pellets as well. It is understood the pellet sources has to be designed to cope with the arising boundary conditions. And for the pellet sources as well a design has been derived covering all basic needs but also rendering the possibility of an upgrade in order to allow for more sophisticated applications as well.

2.2. Layout of the major components

Pellet sources

Separate sources are needed for the fuelling and the pacing task due to the significantly different mass. Since JT-60SA envisages steady state operation, any source has to be capable to deliver sufficiently long pellet trains. Consequently, continuously working screw extruders have to be employed. For this type of pellet production units, delivery of mass fluxes, pellet sizes and rates already approaching reactor grade needs has been already demonstrated [4]. As well, the handling of any required hydrogen isotope is possible producing ice with a consistency well suitable for pellet production. Since operation with deuterium (D) will have highest priority, the lay out is optimised for this isotope while operation with protium (H) is kept as an option.

For the fuelling extruder, according to the request expressed in the research plan and confirmed by detailed modelling, a pellet mass of $m_P = 6.5 \times 10^{20}$ D atoms is envisaged. This is due to cylindrical pellets with diameter Ø and length L each 2.4 mm. In order to provide some flexibility but still keeping a robust pellet shape, adjustment of L within the range Ø/2 to 2Ø is foreseen, allowing varying m_P by a factor of 4. The maximum extruder throughput is set to $\Gamma = 1.3 \times 10^{22}$ D/s, corresponding to a pellet rate of $f_P = 20$ Hz for the reference Ø = L pellets.

The major request for pellet pacing refers to the repetition rate; in order to provide a tool for ELM control at a sufficiently high frequency here $f_P = 50$ Hz is asked for. Here, in order to minimize the fuelling side effect, a pellet size as small as possible is preferred. Yet, reliable pellet delivery to the plasma has to be granted. A pellet size of Ø = L = 1.2 mm was chosen, regarded sufficient for yielding reliable transfer through the entire guiding system. Again, mass adaption to actual requirements is possible. In addition to a fast response via L variation here the exchange of extrusion nozzle for altering Ø is foreseen. Notably, in this start-up configuration full pellet ELM pacing would cause a particle flux of about $\Gamma = 0.4 \times 10^{22}$ D/s, unlikely to be negligible when density control is requested simultaneously.

Centrifuge pellet acceleration unit

As pellet acceleration unit, a stop cylinder centrifuge known for its capability of precise speed and frequency control [3] will be employed. In order to allow pellet delivery by several extruders simultaneously, a stop cylinder radius r_0 of 0.4 m is foreseen. Thus, up to 6 pellet sources could be equipped to a single centrifuge unit. To ideally adapt the launch speed of this centrifuge to the accessible transfer speed range, a straight double acceleration arm with a radius R of 0.23 m has been chosen. Yielding a relation of about $v_P = 2\ \mathrm{m} \times f_C$ between pellet speed and centrifuge revolution frequency f_C, this optimizes the accessible f_P range as well. Employing the double arm, thus a maximum $f_P = 500$ Hz is possible, potentially enabling the access to pacing rates up to 200 – 300 Hz in case. Possibly some advanced plasma scenarios calling for higher pellet flux could be covered by extending the system adding further fuelling pellet extruders. And finally, the option of running several pellet sources in parallel provides the amenity to add a device processing an alternative pellet composition as e.g. hydrogen isotope mixtures or admixture of other gases.

With the chosen layout, a fine tuning of the pellet rate is possible; due to the centrifuge principle only discrete values satisfying the relation $f_P = 2\ f_C/n$ with n integer can be realised. Due to the low pellet speed, mechanical stability demands to the acceleration units remain quite relaxed. To note, since acceleration takes place mass independent, fuelling and pacing pellets will achieve identical speed. Consequently, a pellet train launched can be composed by any arbitrary sequence of fuelling and pacing pellets.

Pellet guiding system

For the chosen inboard launch solution it is necessary to transfer the pellets through guiding tubes. The possible layout for this route is constrained by the need to insert it into a vessel design already prefixed. Details and resulting pellet speed restrictions have been already discussed and estimated [2]; currently efforts to find the optimum possible routing are under way. According to the actual planning, the installation of the in-vessel guiding tubes will take place during the first maintenance and enhancement phase. Yet, the final route and hence the according maximum pellet transfer speed needs to be found. However, a fine tuning of the pellet speed to the finally require value is possible with the centrifuge accelerator.

Pellet sources :
2 steady state extruders
Operation in D, alternatively in H
Fuelling:
Ø = 2.4mm, l = 1.2 – 4.8 mm
m_P = 3.3 – 13.0 x 10^{20} atoms (for D)
f_P: up to 20 Hz (at l = 2.4 mm)
Γ_P: up to 1.3 x 10^{22} /s (for D)
Pacing:
Ø = l = 1.2 mm
m_P = 0. 8 x 10^{20} atoms (for D)
f_P: up to 50 Hz
Pellet acceleration:
Stop cylinder double arm centrifuge
f_C = 100 - 250 Hz
v_P = 200 – 500 m/s
f_P: up to 2 x f_C = 200 - 500 Hz
Pellet guiding:
Guiding tubes – two variants
Inboard (tilted by 70°)

Table I: Main parameters of the itemized JT-60SA pellet system order for the envisaged start-up configuration.

Pellet sources :
Up to 6 sources
Any combination of fuelling, pacing and test extruders or batch sources
Fuelling:
Γ_P: up to 5 x 10^{22} /s (for D)
Pacing:
Exchangeable nozzel with different Ø
f_P: up to 250 Hz
Test:
Operation with HD mixtures or with ice doped with gases for plasma enhancement or radiative power exhaust

Table II: Possible upgrade making full use of source bearing capacity. Parameters for acceleration and transfer units remain.

2.3. System layout overview

Combined and interacting together, all the major components form a pellet launching system fully capable to serve both for fuelling and pacing requests as formulated in the research plan. An overview is presented, distinguishing between the basic start up configuration shown in table I and the possible maximum extension displayed in table II. The approach bases on the installation of a single centrifuge acceleration unit. In case a further unit is installed, potentially possible due to the two available inboard guiding tubes, even higher fuelling fluxes and ELM pacing rates up to about 500 Hz would become possible.

3. Combined fuelling and pacing control

Any feedback control approach employing a centrifuge acceleration unit must take into account the according specific feature. This is on the one hand the fact only a discrete spectrum of f_P values is possible and the resultant, delivered particle fluxes, $\Gamma_P = m_P \times f_P$, also take on discrete values. On the other hand, already at the time a pellet request is made a precise prediction of the expected pellet arrival time is at hand. Thus, the control system can initiate appropriate actuation already before the pellet impact takes place; this response time is typically in the order of 100 ms! Typical related actions are e.g. the notching of wave heating to avoid strong reflections from the ablation region or corrective actions in measurements disturbed by the pellet.

Algorithms mastering the discrete nature of the pellet particle flux while taking advantage of the precise prediction of pellet arrival have been developed and successfully applied in the tokamak experiment ASDEX Upgrade [5]. There yet used for sole fuelling purposes employing a single acceleration arm with a single pellet source, the approach is now extended for controlling two acceleration arms and multiple pellet sources. Therefore, obviously the centrifuge has to be equipped with at least pellet sources; in case of combined fuelling and pacing control with each of the two types.

A sketch of the control scheme is shown in figure 1, the example incorporating 4 different pellet sources. Their type is not specified, but any could represent a source for fuelling or pacing pellets – or a source delivering pellets for another task like e.g. mixture pellets for radiative power exhaust control [6]. For every source pellet material and size are preselected before the pellet tool can be applied within a plasma discharge. These parameters have to be communicated prior to the experiment to the plasma control system together with the source characteristic like e.g. the maximum available repetition rate. A continuing synchronization signal sent indicating the revolving centrifuge passing the reference zero position enables the control system to calculate the actual pellet speed and the achievable pellet rates.

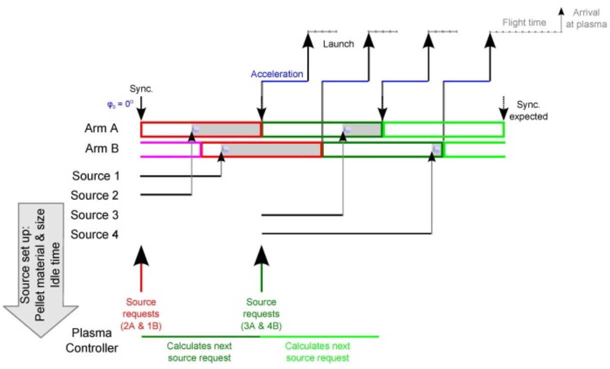

Figure 1: Control scheme sketch for double arm centrifuge equipped with four different pellet sources. Per revolution, two "launching slots" can be filled with a single pellet. Provided by all relevant pellet data including a sync clock, the controller can occupy these slots as requested by the various control requirements.

In this configuration, two pellets can be launcher per revolution cycle. Both "slots" can be attributed to their related arm (A or B). Definitely a single pellet only can be filled into a slot. Available slots can be filled as needed for the control requirements. All requirements have to be handled by the control algorithm, in case to be prioritised and taking into account inhibit times for recharging a source (since the maximum source rate is usually much smaller than f_C). As for any slot the arrival time on plasma can be calculated, anticipatory controlling can be achieved. This includes the accounting of pacing pellets for fuelling and vice versa of fuelling pellets on pacing. Due to the fact sources past by the arms first after the exit slot dominates over the later ones – once they filled a slot this one is blocked for any further access – these positions should be filled by those with the highest priority. It is assumed this preference will be assigned to the fuelling source(s) since every fuelling pellet facilitates the full potential of a pacing pellet while the reverse does not hold.

4. Project plan for the manufacturing

With the conceptual design finished in time, now preparations are ongoing in order to work out a detailed design and initiate the manufacturing of all major components. A project plan, shown in figure 2, has been worked out for a 3 years term aiming to provide finally the pellet launching ready for shipping to JT-60SA. It covers the development and testing of all required major components with the exception of the major part of the transfer system, the guiding tubes installed inside the torus vessel. Foreseen is the initial installation of two steady state extruders, one each dedicated for fuelling and pacing needs. Both will be equipped with the corresponding gas supply, cooling and vacuum system. At present, it is assumed both extruders will employ the proven twin-screw technology developed at ORNL [4].

Yet, it is envisaged to build a single centrifuge accelerator, embedded in his vacuum system and equipped with all the accordingly required control capacity. Here, still the decision is pending if the basic centrifuge will be manufactured re-apply a well proven and reliable but already somewhat outmoded technology [3] or following a proposed novel approach yielding more flexibility [6]. To allow for a proper testing and pre-commissioning of the entire system, the required diagnostics equipment for pellet quality and performance analysis will be supplied as well. And finally, the connection of the launching system to the guiding tubes will be tested. Here, eventually a funnelling section has to be provided in order to bridge a potential gap.

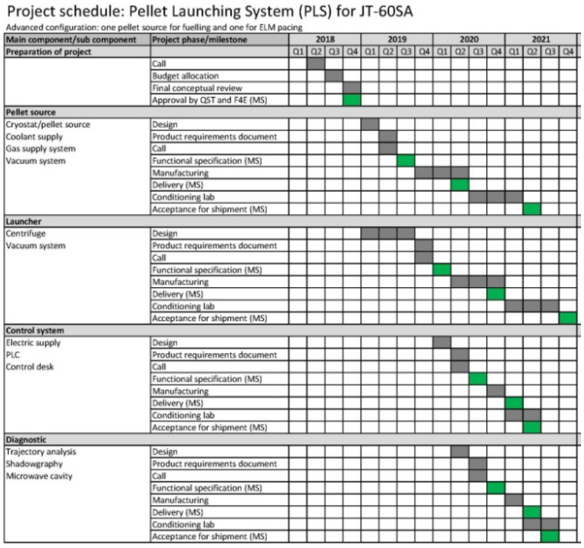

Figure 2: Project schedule proposed for the development of the pellet launching system excluding the in vessel transfer system. Due to this plan, the system would be available for shipping at the end of a 3 years term.

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] JT-60SA Research Unit, JT-60SA Research Plan "Research Objectives and Strategy", Version 3.3, March 2016 http://www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf
[2] P.T. Lang et al., Fusion Eng. Design, 123 (2017) 167
[3] B. Ploeckl et al., Fusion Eng. Design, 86 (2011), 1022
[4] S.J. Meitner et al. Fusion Sci. and Tech. 56 (2009) 52
[5] P.T. Lang et al., Nuclear Fusion, 58 (2018) 036001
[6] A. Kallenbach et al., Nuclear Fusion, 57 (2017) 102015
[7] B. Ploeckl et al., this conference