Developing fuel sources for a steady-state multi-purpose pellet launching system

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Like for any power plant, refuelling will be one key issue in a future fusion reactor. It has to be safe and efficient; due to the operational principle, it also needs to occur in steady state. From previous investigations, it became clear that injection of pellets - mm-size solid bodies produced from frozen fuel – is the only possible and technically realistic solution for this task. Beyond their capability for fuelling, pellets have been found potentially useful as well for other purposes, e.g. to control edge localised modes. Therefore, efforts are required to develop a pellet launching system (PLS) capable to meet all basic reactor requirements.

To foster this kind of technology evolution and to enhance the PLS applied at ASDEX Upgrade (AUG), a collaborative investigation between IPP and ORNL has been initiated. This aims to replace the existing pellet source able to deliver to a centrifuge injector up to 130 stored pellets produced in a batch process with repetition rates up to 80 Hz by a steady state source. The new source is based on the ORNL extruder types and capable of delivering either in true steady state or at least from a reservoir with sufficient solid fuel to produce up to 2000 pellets. Experiments extruding ice with different square cross sections showed a maximum throughput of about 300 mm^3/s for Protium (H) and 215 mm^3/s for Deuterium (D) with a 1.9 mm square cross section. Ice temperatures of 9 K for H and 16 K for D were found to be optimum. For D, extrusion rates correspond to a 1.9 mm pellet delivery rate of about 25 Hz. Doping the ice with up to 2% Neon was achieved at the expense of moderately reduced extrusion speeds. A new scheme has been designed to inject pellets in parallel from multiple sources for further enhancing the delivery rate.

Keywords: Tokamak, Pellet fuelling, Launcher technology, ASDEX Upgrade

1. Introduction

The injection of pellets, mm-sized solid bodies produced from hydrogen isotopologues, is proven a suitable actuator in fusion research for a variety of tasks. Most prominent ones are the plasma particle fuelling and the mitigation of edge localised modes (ELMs). Pellet injection is an efficient way of fuel supply; studies asserted this as the only realistic option to establish the required densities in the core of a tokamak type fusion reactor. Recently, the doping of fuelling pellets with small amounts of elements employed for plasma performance enhancement of divertor radiative cooling has been considered to ease their burden on the fuel cycle. The pellet based ELM pacing scheme offers an option for taming the violent intermittent energy bursts potentially occurring under some reactor operating scenarios. Therefore, the pellet tool has the potential to serve several actuation needs simultaneously. It is understood that each task my need a specific set of pellet parameters like mass or composition. Nevertheless, any pellet applied for a distinct purpose can also show an unwanted side effect on any others. Consequently, simultaneous pellet parameter control has to take into account this potential crosstalk. Such a control approach relies on precise pellet launch timing and can likely be best achieved by a single accelerator system with pellets supplied from different sources. This way it becomes possible to establish and deliver a single self-consistent pellet train. It would consist of different pellets each tailored for its primary task. However, the sequence of pellets within the train is arranged in a way trying to cope with the corporate needs of all requested actuations. For example, such a pellet train composed from large fuelling and small pacing pellets is then assembled by taking into account the pacing born fuel influx and the ELMs released by fuelling pellets. To ensure pellets arrive at the plasma with the launch pattern desired, their speed scatter must be negligible. In addition, precise speed control avoids unsteady pellet transfer times between launcher and plasma. Hence, an accurate prediction of pellet arrival allows timely response of other actuators to synchronize with the pellet impact on the plasma. Due to its capability of launching pellets of different mass at a precise and congruent speed, a stop cylinder type centrifuge [1] would be the prime choice as accelerator unit.

For such a PLS design, suitable pellet sources are required. Any source has to provide pellet delivery with a sufficient ice quality and ample rate. Hence, the basic challenge is to provide sufficient ice with the required consistency to form the pellets on demand and deliver them into the stop cylinder with adequate spatial and temporal accuracy. In order to stay relevant for application in a reactor device, any reasonable technical solution has to also be capable for steady state or at least long pulse operation. Thus, a crucial accomplishment to be mastered by any fuel source is to steadily extrude enough mass throughput of any required ice at satisfactory

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quality through a nozzle that will likely employ a final bend for feeding the stop cylinder.

2. The task

For any PLS, restrictions of the pellet source will directly restrict the system performance. This can be seen in the PLS of the tokamak experiment AUG. Although constructed in a way found suitable for a large variety of investigations, the bottleneck turned out to be its initial design providing pellets at up to 20 Hz for up to 5 s. This was achieved by cutting pellets from an extruded ice rod stored in a cryostat, providing a reservoir for about 100 pellets. Meanwhile, AUG has extended its pulse duration to about 12 s while the PLS was revised to achieve rates up to 80 Hz [2] to cover experimental needs. Hence, considerations to overcome this situation were initiated. An expansion of the stored reservoir in the current PLS configuration [3] turned out to be rather complex due to hydrogen safety restrictions. Therefore, a different safety concept was developed capable of hosting a steady state extrusion system [4]. To achieve steady state operation, the ice rod has to be produced in time and extruded through a nozzle producing the required cross section. One major concern for this approach is whether the achievable extrusion speed $v_{ex.}$ can match the requirements for establishing the needed pellet frequency f_P since for a pellet length l it holds $f_P \leq v_{ex.}/l$. For AUG, f_P in the range 50 – 70 Hz is sufficient for most applications. For a pellet length l = 2mm, this requires $v_{ex.}$ in the range of 100 – 140 mm/s in case only a single source is employed. The aim of this study was thus to investigate the extrusion speed achievable under relevant conditions. For this purpose, a cooperation between IPP and ORNL was initiated, making use of the well-suited ORNL batch extrusion test stand. The prime task of this collaboration was determination of the maximum $v_{ex.}$ for a rod with quadratic cross section of 1.9 mm (as used for the AUG fuelling size pellets) using either pure Protium ($^1H_2 \rightarrow H$) or Deuterium ($^2H_2 \rightarrow D$). For the AUG PLS it appears inevitable because of geometric constraints to have the final section of the extruded solid ribbon with some bend rather than being straight to be able to cut and feed pellets into the stop cylinder. This geometry impact was investigated by comparing a curved channel after the nozzle to a simple straight nozzle and channel. To investigate the option to obtain a higher mass flow rate supply using bigger pellets with larger cross sections, a nozzle with a curved channel with 2.4 mm cross section was also investigated. Applying this configuration, the influence of doping the ice has also been examined by adding up to 2 mol % of neon (N) to the D_2 source gas. The use of a nozzle with a twin extrusion opening aiming to enhance the mass throughput with two identical ice rods is planned for the future.

3. Set up

Ice source

Initially, it was intended to make the investigations with a fully steady state capable twin-screw extruder [5]. However, this unit was not available on a short time scale. Thus, we made use of an existing fully equipped test stand hosting a large volume batch extruder providing 14000 mm^3 ice volume [6]. Since the extruder employed cannot be considered as a steady-state solution results presented in the following will need to be reassessed in the future with a truly steady-state extruder.

All gases with a purity of 99.999% used were supplied from cylinders. For obtaining the neon gas mixtures a 100 l reservoir outside the extruder was used. The premix neon % was determined by a Baratron pressure gauge when filling the reservoir.

The batch extruder used in these experiments [6] is cooled with liquid helium that flows to a liquefier, solidifier, and channel downstream of the nozzle in parallel. Temperature controllers with heaters are used to maintain constant operating temperatures. Gas enters the liquefier heat exchanger where it liquefies and flows from gravity into the solidifier section. A piston pushes the solid through a nozzle that has a channel attached to the exit of the nozzle to simulate the flow of solid into a centrifuge type pellet cutter system. The nozzle is directly bolted to the bottom face of the solidifier with a good thermal contact and thus is at the same temperature as the solidifier. The solidifier has a 14 mm diameter bore as does the entrance of the nozzle. The nozzle tapers from a 14 mm diameter round bore to the 1.9 mm or 2.4 mm square cross section exit over a 51 mm length.

Diagnosing

The temperatures of the liquefier, solidifier, and channel downstream of the nozzle are all measured with calibrated DT470 silicon diode temperature sensors from Lakeshore. The piston speed is determined by a rotary potentiometer attached to the screw actuator that drives the piston and measures the position of the piston along its entire travel length. The piston force is measured by a button load cell (strain gauge type Futek FTH300) mounted between the piston shaft and the screw actuator and measured with a Futek IPM650 monitor. The extruder has a maximum limit based on the piston shaft buckling strength, which is estimated to be 3500 N. However, this is not always the limiting factor for the extrusion. The top of the ice column is subjected to work done on it by the piston. This causes softening of the ice which can cause backflow of material around the piston head. This effect is a function of the temperature of extrusion and force applied, so at warmer temperatures, the throughput is limited by this backflow. From the piston motion, a direct estimation of the extrusion speed was obtained assuming there is no ice compression or loss during the extrusion. Video recordings were taken with a 60 Hz framing rate at the nozzle exit with a scale within the viewing area (left part of figure 1). Consecutive video frames analysed applying the optical flow (OF) method [7] provided additional information on $v_{ex.}$. While $v_{ex.}$is estimated only indirectly from the speed motion, the OF method provides a direct measurement and is therefore attributed higher confidence. As can be recognized in the data from figures 2 – 4, for most settings the results from both methods are in fair agreement.

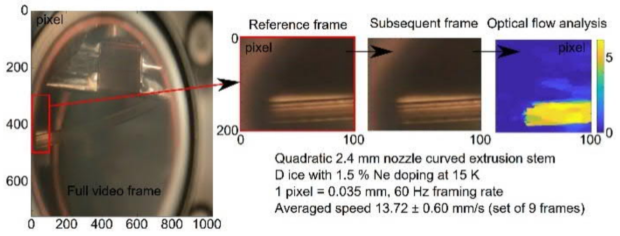

Figure 1: Example of an extrusion speed analysis by the optical flow method [7]. From the original full video (left), a region of interest frame (red box) is selected. From two consecutive frames, the displacement pattern is determined (right). From this displacement pattern, the actual extrusion speed is calculated. For the case shown, eight speed measurements were derived from nine consecutive frames. The speed value provided refers to this full data set.

4. Results

AUG reference case: 1.9 mm nozzles

For any configuration, the aim was to find the maximum achievable $v_{ex.}$ for a chosen ice temperature and thus determine the accessible and best operational conditions. The control of ice temperature is achieved by controlling the solidifier and thus the nozzle temperature. The channel downstream of the nozzle has a slightly larger cross sectional area than the nozzle output and was kept at temperatures above that of the solidifier but not too high to affect the extrusion. For the envisaged delivery into a stop cylinder, minimizing the repulsion force from sublimating gas at a low ice temperature is necessary. In the experiment, first the nozzle temperature was set to a pre-selected value. Then, a certain speed for the piston motion was selected as well. For each setting, it was tested whether sound ice quality can be achieved in the extrusion. The extrusion has to be stable and last for at least 10 s while keeping within the force limit. Stepping up the piston speed in subsequent extrusions allowed the operational limits to be determined. In order to demonstrate the real long pulse capability, for some cases stable extrusions lasting for 100 s were generated. However, due to the restricted reservoir, this could be achieved only in cases with sufficiently low flow rates. The first extrusion tests were through a straight square opening 1.9 mm nozzle using either pure H or D.

The results achieved are shown in the upper part of figure 2. For H (blue) the operational temperature range spans from 7 to 12 K. However, below 8 K the extrusion tends to stall while for 11 K and above there is a tendency to get unstable due to the backflow issue mentioned above. In order to obtain stable extrusion, a temperature near 9 K is considered optimal. A similar stability behaviour is found for D. Here, extrusion is possible between 13 and 17 K but for stable operational the temperature needs to be kept in the 15 – 16 K range. There is a significant difference in achievable speed for H and D, the latter mainly required for AUG applications. Taking the AUG fuelling pellet length of 2 mm, this ice delivery flow rate was sufficient for a pellet rate of about 25 Hz. Changing to a curved extrusion channel attached to the nozzle, as is needed for the envisaged stop cylinder feed in, essentially reproduced the behaviour for the straight channel as can be seen from the lower part of figure 2. No indication was found the specific channel geometry causes a major impact on its extrusion capabilities since its cross section is slightly larger (0.1 mm) than that of the nozzle opening.

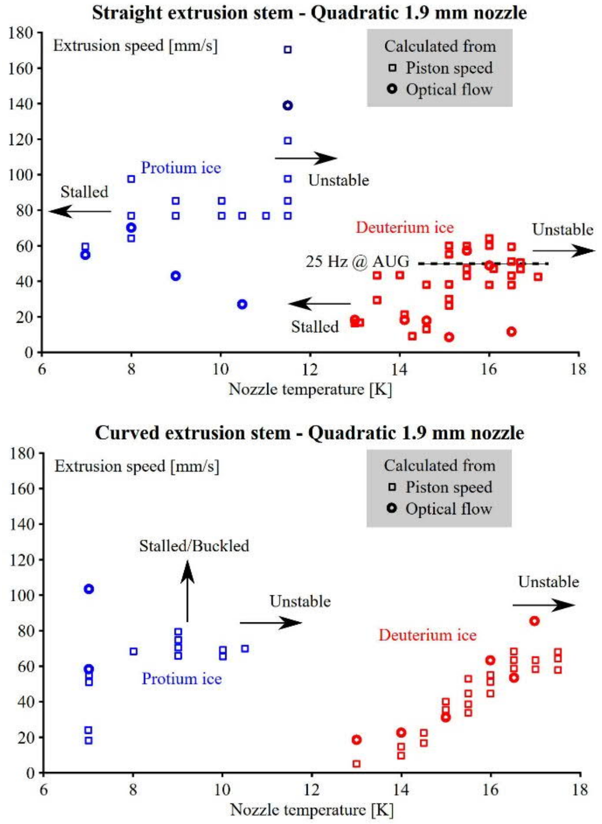

Figure 2: Extrusion speed achieved in different runs as taken from the piston speed (squares) and from the optical flow analysis (circles) for pure H (blue) and D (red) versus nozzle temperature. For the AUG reference size, two different configurations are tested: straight (upper) and 90 degree bend (lower) channel.

Enhanced size: 2.4 mm nozzle

Since one option for enhancing the pellet mass throughput could be to increase the pellet size, it was investigated how a larger cross section of the extrusion nozzle and channel affects the extrusion speed. The chosen alternate value was 2.4 mm, again with a square cross section. The size was selected deliberately since such large pellets are considered still suitable for fueling applications in AUG and refers as well to the designated fuelling pellet dimensions of the JT-60SA PLS under construction [8]. Due to the channel geometry effect already clarified as essentially insignificant, here only the curved extrusion channel variant was manufactured and tested. Taking the same colours and symbols as in figure 2, the results are displayed in figure 3. From these results it is clear that the large nozzle cross section leads to slightly slower extrusion speeds. Again, the typical behavior for H and D is similar with respect to nozzle temperature. With this extrusion speed capability only a 20 Hz pellet cutting rate could be achieved. Notably, the mass flux achievable would nevertheless significantly increase by about a factor $(2.4/1.9)^2 \approx 1.6$.

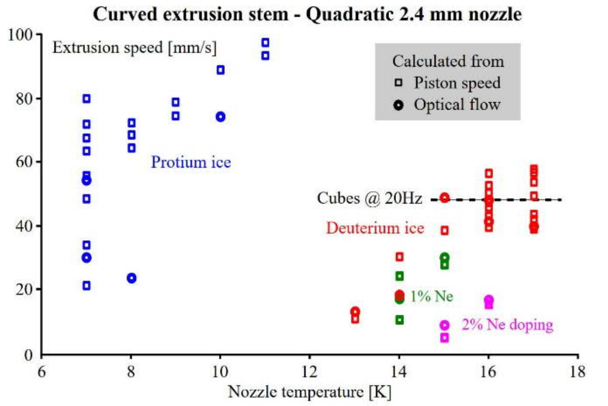

Figure 3: Extrusion speed achieved for a 90 degreed bend 2.4 mm nozzle, color and symbols as in figure 2. Here, in addition data from ice produced by freezing D gas with Ne admixed are provided.

For different potential applications, doping the pellets with suitable additives is considered as helpful or even necessary. To investigate the impact of such an additive, the noble gas neon (Ne) was added to the D host gas. Four different doping grades have been used, increasing the content added to the filling gas in steps of 0.5 mol % up to a maximum of 2 mol %. It should be noted that the composition of the ice was not analyzed in detail; hence, the amount of Ne trapped in the ice could differ from these values. Nonetheless, the chosen approach to produce admixed ice by direct freezing of a gas mixture flowing from a reservoir may be a suitable technique, worth further investigations. Is has already been demonstrated previously with nitrogen, where the arrival of the additive was detected with doped pellets launched into a target plasma [9]. In addition, the visual appearance of the ice becoming less transparent with more neon and an observed altered extrusion force behavior provide a qualitative indication for the presence of the admixed Ne. As can be seen also from figure 3, for the Ne doped ice the temperature trend of $v_{ex.}$ reproduces that of pure D; however, increasing the doping dose (green and purple symbols) results in a progressive overall slowing down. Under similar conditions increasing the doping requires higher extrusion forces. Remarkably, for all runs a very stable durable extrusion was still achieved. There was no indication of a deteriorating ice quality at all. Hence, it can be clearly concluded that applying this simple and straightforward ice production with moderate admixing of auxiliary gases to the host pellets is possible. However, this comes at the expense of the maximum achievable pellet rate. Such applications as tracer deposition deep inside the confined plasma for particle transport studies can well be served. Otherwise, for controlled co-fuelling of additives as e.g. considered for radiation control or plasma seeding there is a considerable impact on the basic fuelling potential.

To quantify this impact, detailed information on the cost-benefit ratio is needed. More precisely, to which extent the fuelling flux will be reduced for a given magnitude of an additive. This can be derived from the correlation between maximum achievable $v_{ex.}$ and doping percentage. The data on this are displayed in figure 4. Apparently, higher Ne concentrations do result in a clear speed reduction and thus less D fuel flux. Yet, assuming the Ne amount in the ice correlates linearly with that one in the supply gas, the total Ne flux modestly increases.

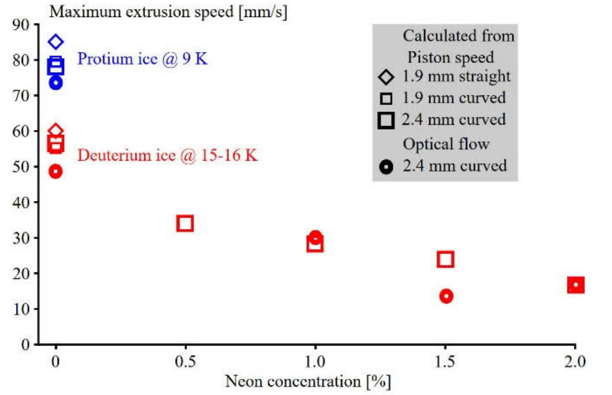

Figure 4: Extrusion speed achieved for a 90 degreed bend 2.4 mm nozzle for ice produced by freezing D gas with different amounts of Ne admixed. As well, maximum values achieved for cases only showing steady and stable extrusions are plotted for all three different channels.

Also shown in figure 4 are all maximum $v_{ex.}$ values achieved under stable and steady extrusion conditions.

For pure D, about 50 – 60 mm/s is attainable while operation in H allows for a somewhat higher speed of approximately 80 mm/s. Within the arrangement variations carried out in this study, nozzle cross section and geometry apparently showed no significant impact on these values.

5. Outlook

Our results so far indicate that replacing the storage cryostat of the AUG PLS by a steady or at least long pulse extruder of the type investigated in this study would likely result in a significant reduction of the maximum pellet rate. For most of the experimental investigations, this would clearly not be sufficient anymore. One option already mentioned here is to use larger sized pellets. Thereby, the reduction in fuelling particle flux can be recovered at least partially. However, it would come at the expense of more coarseness when controlling the plasma density and the larger pellet size would cause stronger perturbations that can more easily trigger plasma instabilities. Another option now under consideration is the installation of a double extrusion nozzle. The aim is to double or at least significantly increase the total pellet rate. Design and manufacturing of such a nozzle are already in progress. The layout chosen is a curved channel with both nozzle openings having an identical square 1.9 mm cross section.

Finally, a more fundamental redesign of the entire stop cylinder and pellet feed in configuration could be considered. The current set up of the AUG PLS is capable of having pellets delivered only by a single source. However, a more advanced layout concept has been developed for the JT60-SA PLS raising the potential to supply pellets in parallel from multiple sources [8].

Applying this novel design, it would become possible to tailor pellet trains composed from pellets of different size and/or consistency. This could, in turn, open the option of acting simultaneously on different control parameters making the PLS a powerful multi-faceted plasma control tool.

Such an approach could as well be considered for a device like DEMO. Certainly, for application at a reactor grade level further important issues remain to be considered as well. Any DEMO solution requires a truly steady state capability, most likely only achievable by screw type extruders. In addition, application for a fusion reactor requires PLS operation with ice containing at least a significant share of tritium. Thus, ice handling will be clearly much more complicated, e.g. due to the associated radiological safety needs. A more detailed discussion of such issues and ongoing dedicated research efforts can be found elsewhere [10].

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. Work supported in part by the US DOE under contract DE-AC05-00OR22725.

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