Isotope mixture control in the high density regime by pellet injection at ASDEX Upgrade

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INTRODUCTION

To produce economic net electricity in a demonstration fusion power plant like the EU-DEMO [1] operation at a sufficiently high core density with a D/T fuel mixture of close to 1:1 will be required in order to harvest sufficient fusion power. Simultaneously, the energy confinement has to be kept high; hence the edge density must stay below a critical level. Apparently one major control task will thus be to establish and keep an appropriately peaked density profile with the required isotope mixture in the centre.

For operational reasons it is likely in a fusion device additional gases have to be inserted into the reactor vessel. As a consequence, the pumped exhaust gas will be a multi species composite, subject to be handled in the fuel cycle. Also, for the engineering design of the H removal system in the EU-DEMO fuel cycle a low percentage contribution of H to the plasma particles has been mooted as acceptable. For the purity of the fuel returned to the matter injection systems still the best solution has to be elaborated, covering all operational requirements at reasonable efforts. For the matter injection systems thus it will be likely necessary to handle fuel composed by different hydrogen isotopologues.

The task of core particle fuelling in a fusion reactor will be virtually entirely attributed to pellets, the injection of mm size bodies of solid fuel at high speed into the plasma column. Integrated into the plasma feedback control system, thus the pellet launching system must be capable to establish and keep the desired core density with the correct isotope mixture.

INVESTIGATION STRATEGY

Multi-faceted and complex problems must still be solved to master challenges of a fusion reactor. In particular, density control has to comply simultaneously with many demands. Our investigations at ASDEX Upgrade (AUG) aimed to mimic this task, commencing from a well-established base of operational experience [2] adding stepwise additional requirements. Tools and a reliable scenario have been already developed for a feedback controlled high density operation keeping the initial confinement [3], however yet with sole D representing the fuel. Here, we present first results on our efforts to proceed by including the target of isotopic mixture control. It is understood the situation involving D and T is mimicked by the combination of H and D.

TOOLS & TECHNOLOGY

AUG is a mid-size divertor tokamak (major radius $R_{maj.} = 1.65$ m, minor radius $a_0 = 0.5$ m) with a reactor-relevant all-metal-wall configuration. It is equipped with a versatile auxiliary heating system, a broad set of diagnostics enabling sophisticated investigations and an elaborated discharge control system (DCS); however the device is not designed for T handling. The pellet launching system allows for reactor relevant and efficient pellet injection from the torus inboard side at repetition rates up to 83 Hz providing pellets of different available particle contend m_P and speed v_P. Applied pellet parameters m_P and v_P are pre-selected and fixed for every discharge; the pellet frequency f_P and hence the delivered pellet particle fluxes $\Gamma_P = m_P \cdot f_P$ can be controlled by the DCS. Since pellet acceleration takes place

in a stop-cylinder type centrifuge [4] rotating at a preselected revolution rate f_C, $f_P = f_C/n$ with n integer. Thus, only a discrete spectrum of f_P and Γ_P values is available for the DCS.
Pellet production takes place in a batch process. Ice rods with a preselected cross section are extruded from a reservoir into a storage cryostat where they are kept until pellets are cut on request, accelerated and guided into the torus. Due to the finite length of the stored ice rod, the amount of available pellets per discharge is limited, in the case of large size fuelling pellets to 96. Initially the system was designed to handle either high purity H_2 or D_2 for the ice formation, recently gas handling and extrusion control capabilities have been improved in order to create and handle gas mixtures [5]. In this study, we made use of this feature to produce ice from a mixture of H_2 and D_2 gas, which was taken from a high pressure bottle initially filled with H_2 and D_2 gas at ratio 1:1. Due to isotope exchange reactions, in such a gas mixture gradually HD molecules are formed finally approaching a composite of three isotopologues with a H_2:HD:D_2 ratio of 1:2:1 [6]. For the predominant conditions reaction rates are rather low, hence only slowly increasing the amount of HD molecules. Mass spectrometric analysis showed in our initial gas mixture the fraction of HD molecules was only 1.2 %. For freezing and extrusion, process parameters temperature and pressure had to be adapted for this mixture. It turned out their progression is more similar to those elaborated for pure H_2 but the parameter range is smaller, hence their handling requires higher precision. Nevertheless, finally reliable and reproducible formation of intact and stable HD pellets is well suitable for fuelling purposes.

RESULTS

The first topic of the investigation was the characterisation of the pellet actuator. This was done by injecting the HD pellets into the pre-evacuated torus, surveying the released gas with the residual gas analyser (RGA). Results achieved for fuelling size pellets consuming two entire 192 mm long ice rods are shown in figure 1. In fact arriving pellets show a H:D ratio very close to 1:1; obviously neither ice production nor pellet transfer did alter the initial ratio. However, compared to the initial gas analysis, a significantly higher fraction of HD molecules was found by the RGA. This is attributed to reactions on the wall of the plasma vessel.

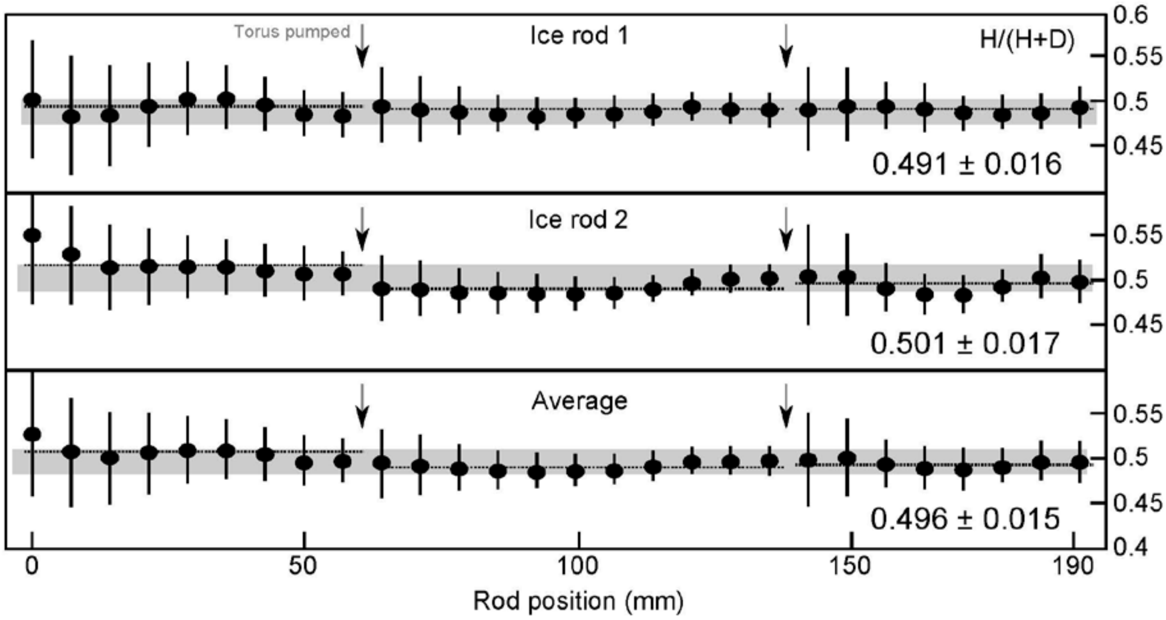

Figure 1: Analysis of the H/(H+D) composition of an ice rod produced from an initially 1:1 H_2/D_2 gas mixture. Consecutive sequences of 3 pellets were launched into the torus, after each sequence the residual gas was analyzed. After several sequences, the torus had to be re-evacuated, thus 3 rod sections are analyzed separately. Dashed lines represent the average isotope composition of the three sections.

The next step was to sound out the efficacy of the HD pellets for isotope mixture control. For this we selected a reference scenario known from previous investigations to be suitable for the application of strong pellet fluxes. H-Mode conditions were established and maintained by steady auxiliary heating by typically 6 MW neutral beam injection (NBI) and 1 MW electron cyclotron resonance heating (ECRH). With respect to the pure D reference discharges (D pellets into D plasma) the NBI was injecting H instead of D; ion cyclotron resonance heating (ICRH) of the core preventing impurity accumulation was replaced by ECRH. To cope with the resulting high densities, the ECRH was changed from X2 mode into O2 mode shortly before pellet injection for the sake of its higher cut-off density.

Experiments were performed right after a phase of D plasma operation during the transition towards H plasma operation. Therefore, conditions with respect to the wall loading by H and D have been transient and not fully consistent with the aim of this approach. For the test, we replaced a strong gas puff in several steps by HD pellets, keeping the total particle flux approximately the same. Three consecutive shots have been made. In the first one, the gas puff was purely D_2. Pure H_2 gas was puffed in the second shot; here the pellet sequence was concluded by a short phase applying the maximum f_P to probe access to very high densities. In the concluding shot, aiming to a establish plasma with the desired isotope mixture, both H_2 and D_2 gas was puffed at a ratio of 1:1. Results are shown in figure 2, displaying the temporal evolution of the three cases. Upper boxes show the particle fluxes from the gas valves (blue D_2, green H_2) and from the pellet launcher (red, calculated from set parameter). In the lower boxes the H/(H+D) fraction as calculated for the total particle flux from gas and pellets is plotted as solid grey line. This same parameter is displayed as measured by spectroscopy observing the divertor region (red crosses). To note, spectroscopy results are found in very good agreement to RGA data, the latter however providing less temporal resolution.

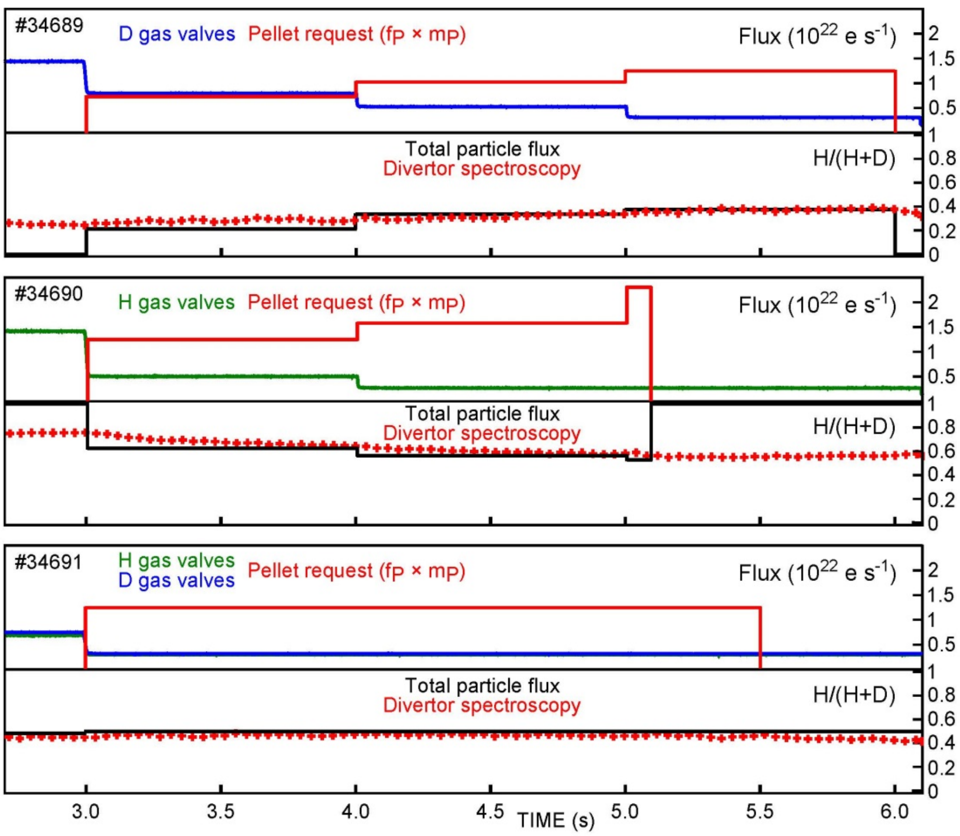

Figure 2: Adjusting the H/(H+D) isotope fraction by injection of H/D pellets replacing the initial strong gas puff. In case a pure D gas puff is replaced, the H content is increased; H gas puff replacement reduces the H content. For sufficiently strong particle fuelling, the isotopic fraction measure by divertor spectroscopy approaches quickly the total flux fraction.

During the first two shots the pellet actuator definitely provides its key feature by changing the isotopic ratio in the requested manner. In the third case, the isotopic ratio established during the initial gas phase is virtually unaffected by the switch to pellet fuelling. In the initial phases and also during phases with a low particle flux there are cases where the isotope mixture of plasma and applied flux deviate significantly. This is attributed to a wall reservoir not yet fully equilibrated. However, once a sufficiently high flux is applied – either by gas, pellets or combining both – the plasma H/(H+D) fraction approaches the set point value within about 1 s. For the discharges performed here, even the 1:1 hit-or-miss choice made for the isotopic ratio in this first test turned out suitable to establish the requested plasma consistence. However, it might turn out a different fuel ratio is needed for differing circumstances and once a more sophisticated analysis of the isotope ratio in the plasma center becomes available.

As expected, pellet actuation proved again most suitable for operation at high density. Due to its higher fuelling efficiency with respect to gas puffing, replacing gas on par with pellet fuelling results in a significantly higher density. This can be seen from figure 3, showing the second discharge of the series. It is obvious both line averaged and central densities increase the more the higher the pellet contribution gets. Comparing phases of same particle flux, the confinement is kept. Just the final part of the discharge with reduced fuelling showed higher confinement, but this situation is very prone to core impurity accumulation and hence not suitable for steady operation. During the short concluding pellet sequence applying maximum flux the density profiles is even peaking with the central density reaching already the Greenwald density. Next steps envisaged now aim to apply feedback core density control and a careful analysis of the isotope mixture in the plasma core.

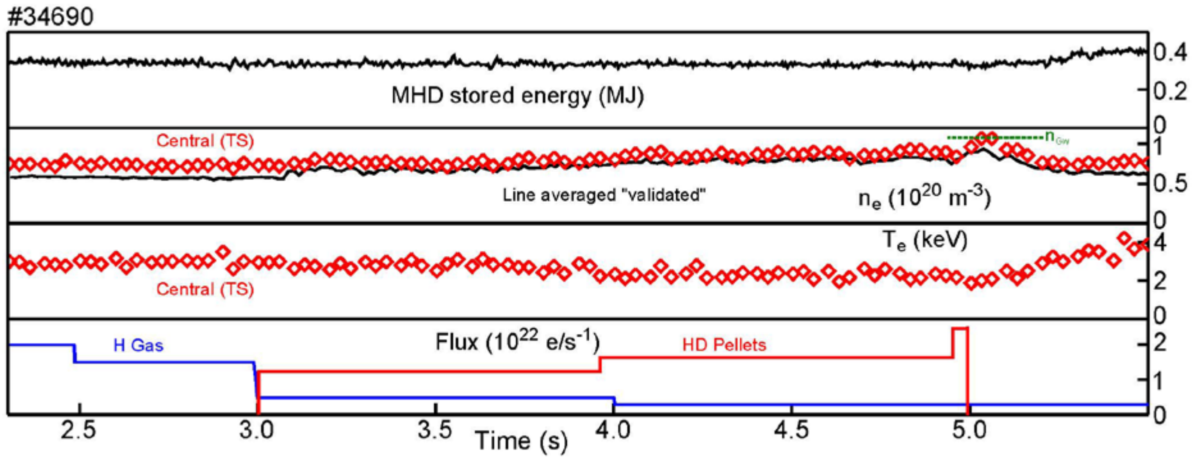

Figure 3: Due to the higher fuelling efficiency, both line-averaged and core density are increased by the pellets. The plasma stored energy remains unaffected while the temperature is decreased. The pellet sequence is concluded by a short phase with maximum pellet flux generating a short high-density phase reaching the Greenwald density in the plasma center.

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