The enhanced pellet centrifuge launcher at ASDEX Upgrade: advanced operation and application as technology test facility for ITER and DEMO

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The pellet centrifuge at ASDEX Upgrade has served for more than 20 years as a powerful tool for plasma control. Its recently enhanced control system provides more thorough control over parameters and a detailed view of all measured values. A study has recently been initiated on the conceptual design of an optimized DEMO core particle fuelling system. For this approach, first technical tests aimed on an optimized pellet transfer with respect to the preparation of the solid fuel and the transfer systems have been performed.
An investigation of the temperature dependence of transfer efficiency (mass loss due to erosion and broken pellets) has revealed a weak dependence. For ITER, in which it is intended to operate a heating scheme with ICRF minority heating of He-3, test injections are performed using D_2 –pellets as carriers for He-4. Admixing of N_2 was investigated as well.
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Keywords: Tokamak, Pellet fuelling, Centrifuge launcher, DEMO

1 Introduction

Pellet injection is a key technology to fuel fusion plasmas to the desired particle density and is well established at many fusion devices [1, 2, 3, 4, 5] or under construction [6]. Serving for more than 20 years, the ASDEX Upgrade pellet centrifuge launcher provides excellent options for fuelling and ELM pacing studies as well as technology investigation [7], see Figure 1.

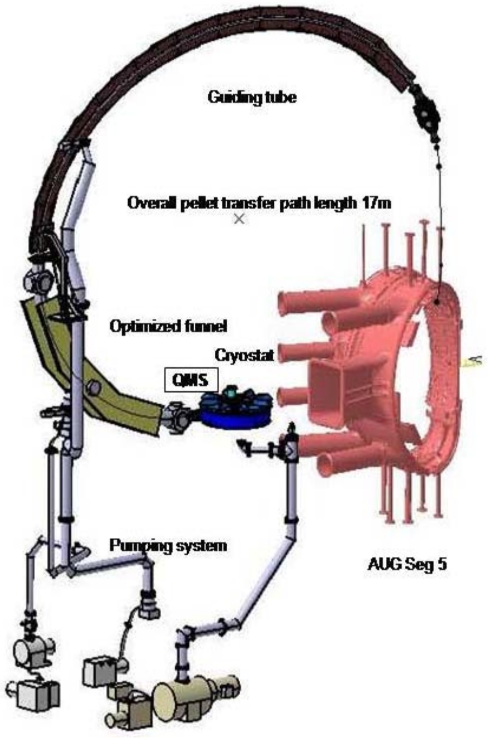

Fig.1: High Speed inboard pellet injection system at ASDEX Upgrade composed of cryostat, centrifuge, transfer looping and vacuum system in AUG Seg.5

The centrifuge and its control system were enhanced during the last years [8]. This enhancement opens a pathway towards technology investigations. A Quadrupole Mass Spectrometer (QMS) was installed to analyse the residual gases during ice production and pellet production processes. The gas manifold was modified to enable the ice production from gases with admixed substances.

2 Test facility for ITER and DEMO

In the "Workplan for the roadmap to fusion energy 2014-2018" eight different missions are articulated [9]. One of these missions is devoted to produce an integrated DEMO design supported by targeted R&D activities. As a part of this mission, a work package "tritium, fuelling & vacuum systems" (WPTFV) was defined. This project was started recently and will last until 2018. One goal in this work package is to provide a relationship between the plasma physics and the material injection technology data. In this context the fuel cycle and its technical components have to be investigated. The technical components of the material injection system are the fuelling system, the vacuum system and the tritium plant together with the breeding blanket systems. These parts are strongly coupled with regard to their specifications and performance. In this respect, the efficiency of the fuelling system is crucial for the dimensioning of the vacuum system and tritium plant. The fuelling mass flux is defined by the necessary D-T flux to achieve the desired plasma density for a given scenario. As a first step to get a clear view, the relevant sections of the system are identified and highlighted by their efficiency with respect to the contribution to the required plasma density.

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The main components of a pellet system are: the pellet source (source), the transfer system (trans), the passage through the vacuum vessel (VV) and the flight path from the end of the guiding tube to the plasma core (fuel). Each component has its own efficiency η. The overall efficiency is the product of the efficiencies of the components:

$\eta_{tot} = \eta_{source} \times \eta_{trans} \times \eta_{VV} \times \eta_{fuel}$.

Thus each stage has to meet minimum requirements. The technical system has to be designed for the overall mass flow, which can be estimated: $\Gamma_{tot} = \frac{\Gamma_{eff}}{\eta_{tot}}$.

Γ_{eff} is the required effective particle flux to fuel the plasma core. All losses along the path from the D-T source to the plasma core burden the vacuum system as well as the tritium plant and limit the overall efficiency of the fusion reactor.

2.1 Test facility for fuel cycle investigations

The efficiency of fuel cycle in fusion devices is important. The pellet injection system has a large influence of this efficiency as all mass loss paths are related to its performance. The analysis of existing systems helps to find answers for the system layout of a DEMO fuelling system.

The enhanced ASDEX Upgrade centrifuge launcher was modified to enable such investigations. In view of this, basic advantage of the ASDEX Upgrade pellet source is that it consists of two cryostats: one with a piston extruder for ice production and one for the storage of the extruded ice rod. The temperatures of the cryostats can be adjusted independently (within some limitations). Therefore, the temperature of the launched pellet can be adjusted to a temperature different to that of the extrusion process thereby allowing both temperatures to be optimised. The extrusion temperature has to be optimised to get good ice quality. The storage cryostat temperature has to be adjusted to minimize the mass loss during acceleration and transfer process, in which mass loss may be dependent of pellet temperature.

Indeed, mass loss during the acceleration and transfer process may be influenced by the admixture of some elements to the carrier gas. For example, pellets made from mixture containing a few percent of nitrogen in deuterium are significantly harder than those made from pure deuterium. This may lead to a higher survival probability [10].

2.2 ITER Helium injection

In addition, the ITER organisation has raised the point of exploring pellet injection as a means of injecting He-3 into plasmas. helium could be trapped in the deuterium ice so that it could be injected with a higher efficiency compared to a conventional gas puff into the plasma. The aim is to optimize the use of He-3, which is required at concentrations ~2% in the plasma core for some ICRF heating schemes (minority heating of He-3 at its fundamental cyclotron frequency). Tests at ASDEX Upgrade will be performed with He-4.

3 Pellet Temperature Studies

3.1 Introduction

The design of the transfer system is essential for the overall efficiency of the fuelling system. The transfer system connects the pellet source with the plasma, passing through the vacuum vessel interface. The geometrical shape of the transfer system (radii and cross section design) determines the performance for a given pellet size and velocity.

In addition, the yield strength of the pellet, and therefore its resistance to abrasion, may be dependent on its temperature.

The pellet temperature is characteristic for the methods of extrusion and acceleration. Continuous extruders operate usually at higher temperatures than piston extruders due to the mechanical forces needed for this process. [11]

3.2 System / experiment description

The recent upgrading of the ASDEX Upgrade centrifuge launcher has provided new features for its control and data acquisition systems [6]. This has permitted the pellet temperature to be controled via measurement of ice temperature close to where pellets are cut from the ice rod. In the experiment described here, pure D_2-pellets are injected along curved guide tubes to the inboard side of plasmas in the ASDEX Upgrade tokamak, see Figure 1. For this, target plasmas are reproducible, as is reasonably possible, with their main parameters almost identical: (H-mode, I_P=1 MA, B_t=2.5 T, q_{95}=4.4, typically P_{NBI}=5 MW, P_{ICRF}=2 MW, pre-injection with gas puffing, line averaged density $7.5x10^{19}$ m^{-2}). By analyzing the results, the main parameters of interest are the density increase per pellet. See Figure 2. The fuelling efficiency per pellet in this target plasma is supposed to be close to one, thus the density step per pellet represents the size of the ablated pellet. The results of these first experiments show a weak dependence of the inceased density per pellet on pellet temperature over the pellet temperature range studied. This study should be continued

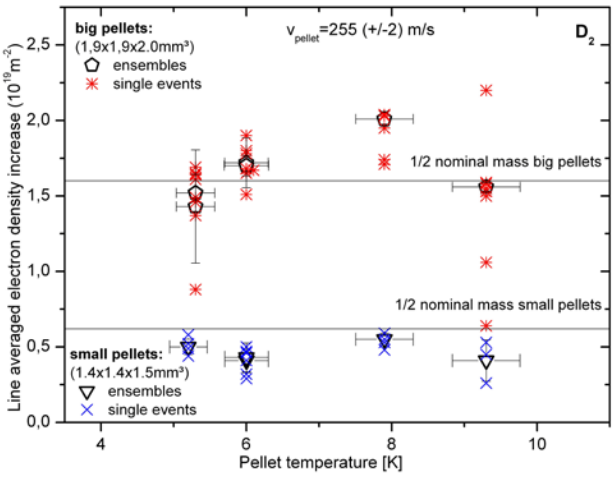

Fig. 2: Line-averaged density increase after pellet injection into reproducible H-mode discharges in ASDEX Upgrade as a function of the pellet temperature. The pellet velocity (v_P) is 255 m/s. Values for single pellet events are plotted; longer pellet trains into a plasma discharge are combined (ensemble) with the average value plotted. The density increase calculated for pellets with 50 % of their design mass (m_p) is indicated by horizontal lines. The temperature sensor is not calibrated, there is an unknown offset to the given values.

4 Pellets with admixed elements

4.1 Introduction

The ITER organisation expressed an interest to check whether Helium could be injected into the plasma core using D_2-Pellets as a carrier. The intention is to establish a heating scheme with ICRF minority heating of He-3. For economic reasons, it was proposed, as a proof of concept to trap He-4 in a D_2 pellet. Thus helium has to be trapped as gas in the D_2-ice.
The admixing of nitrogen to deuterium hardens the ice and consecutively the pellet made from this ice. This leads to lower mass losses due to abrasion along the guide pathways in the transfer system. The hardening of pellets by slight admixing of nitrogen is feasible for scenarios with divertor cooling by nitrogen, as long as the resultant perturbation of the plasma core by the nitrogen content is minimal.

4.2 System enhancements

The gas manifold was extended to admix gas in the range of 0.5-5% to the pellet carrier gas. Pre-mixed gas bottles can be used as well. In the present investigation, the admixing of He and N_2 is of interest. Pellets can be produced by this gas mixture and accelerated. A small amount of N_2 admixed in a deuterium pellet hardens the pellet. This property is basically advantageous for the survival probability, but due to the actual design of one part of the acceleration system (the stop cylinder in Ref. [9]) the nitrogen content has to be limited to a few percent. In order to obtain more details of the situation in the gas phase, a QMS system was installed in the cryostat vessel. This enables the analysis of outgassing of the ice rod. The new options have to be integrated into the AUG operational regime.

4.3 Experimental set up

The working principle is to pre-fill two volumes with the subsequent injection of the small fraction with high pressure into the larger volume (Fig.3). It is essential, that the smaller volume has the higher pressure to ensure mixing of different gases.
For analysis of residual gas coming out of the ice rod in the storage cryostat a quadrupole mass spectrometer (QMS) was installed in the centrifuge vessel. The existing ones in the ASDEX Upgrade vacuum vessel were used as well. Investigating the chronological sequence of mass species, a statement about the status of the ice rod can be made. The QMS in the centrifuge vessel allows identification and quantification of the outgassing elements as well as the analysis of pellets which were evaporated intentionally in-situ.
. The analysis of pellets injected into the vacuum vessel of ASDEX Upgrade is done by the QMS installed there. For this, the gate valves of the torus pumps were closed and the cryo pump, which is installed in the vacuum vessel, was warmed up.

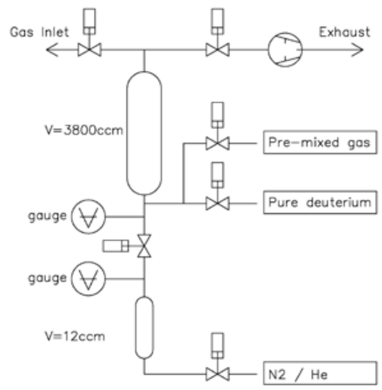

Fig. 3: Schematic view of the modified gas manifold (see text)

4.4 Results

The mixture D_2/1% He-4 can hardly be analysed by standard mass spectrometry in the gaseous phase due to the very small mass difference of the species. Thus, the total pressure in the centrifuge vessel is the only indicator for outgassing processes during ice production or storage.
The total pressure during the ice extrusion process was slightly higher when compared to the total pressure during ice production under similar conditions with pure D_2. The ice is extruded at a temperature of about 15 K. This higher background pressure level is assumed to be generated by the outgassing of He, which is still in the gaseous phase at this temperature. The pumping speed of the cold surfaces of the cryostat for helium is rather low. After its extrusion , the ice rod is stored in the storage cryostat at a lower temperature i.e. at about 5 K. When at this temperature, the background pressure returns to the reference value. The detection of injection of pellets

made from this ice into a standard H-mode plasma in ASDEX Upgrade suffers from the detection limit for helium in ASDEX Upgrade, which is higher than the nominal helium content of the pellets. Further investigations are necessary.

Pellets from a mixture of D_2 with 1%N_2 were produced. The optimal extrusion temperature is slightly higher than with pure deuterium. It is assumed that this is a result of the higher melting point of nitrogen (~63 K). The QMS analysis of a pellet train of 20 pellets that were fired into the torus with no plasma present, is shown in Fig. 4. The torus was not being pumped out at that moment (the gate valves to the pumps were closed). Pellets with 1% nitrogen were injected, as well as pellets with pure deuterium, in a second experiment as reference. The signal of mass 28 (N_2) increases in both cases due to the leak rate of the machine almost at an identical rate. After injecting pellets with 1%N_2, the signal of mass 28 increases significantly. After subtracting the background, an value of 0.8% N_2 was determined.

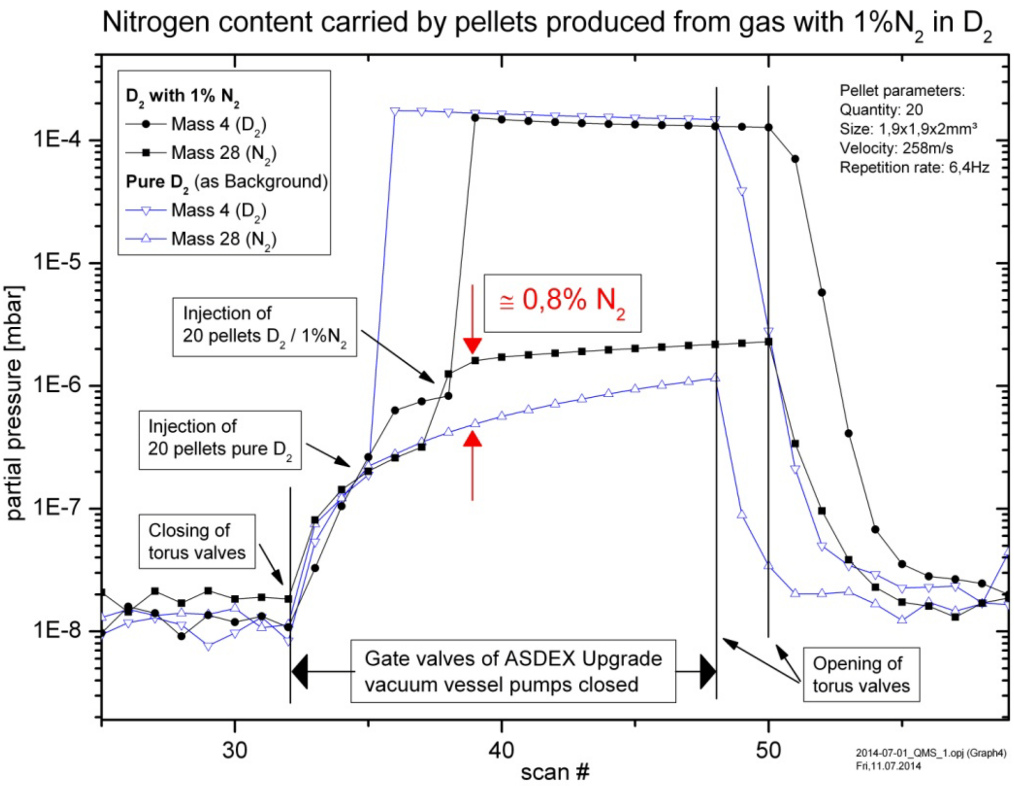

Fig. 4: Signals from the quadrupole mass spectrometer (QMS) for two experiments. In each case a pellet train was injected into the torus vessel of ASDEX Upgrade. (scan# counts the number of mass scans and is proportional to the time scale). After the torus valves were closed, the pressure rises due to leaks in the vessel which is no longer being pumped out.. The partial pressures of D_2 and N_2 increase as well. At the indicated moments, the pellet train is injected and the partial pressures increase by at least one order of magnitude. One pellet train consists of pure D_2- pellets, the other contains 1% N_2. In the first case, the signal at Mass 28 rises in agreement with the leak rate of the vessel. However, in the case of the nitrogen admixed pellets, this signal shows a clear increase. As the signal on mass 4 (D_2) is almost identical in both cases for both cases, the background can be subtracted from the rising N_2 signal. Doing this, a 0.8% nitrogen content is found for the pellet reaching the torus. The nominal content is 1%N_2 in D_2.

5 Conclusions

The ASDEX Upgrade centrifuge was originally designed and optimized to meet the requirements of ASDEX Upgrade. Following some enhancements, the centrifuge launcher can be used as a technology test bed facility for future fusion devices due to its integration in this operational and relevant tokamak device. However it cannot be regarded as a full mock up for future fusion devices. Nonetheless, due to form of its construction, it offers some flexibility concerning pellet material and pellet temperature. Finally, in combination with relevant plasma scenarios, which can act as reference, relevant technological research is possible.

The technical efficiencies regarding the mass flow into the plasma and the paths for the mass loss can be studied in detail on this system. Interfaces can be defined and values for the mass loss can be given for relevant components of the system. Data obtained have to be implemented into a currently ongoing study about the material injection system for DEMO (WPTFV: work package tritium fuelling and vacuum).

Using the pellet temperature as an optimization parameter, its influence on mass loss shall be investigated further. Admixing of elements may help to mitigate mass losses and inject elements of interest into plasmas. Further efforts will be necessary.

6 References

[1] S.K. Combs, et al. Proc. 18th IEEE/NPSS SOFE, (Albuquerque, 1999) 202–205.

[2] K. Kizu et al. Fusion Eng. and Des. 58–59 (2001) 331–335

[3] Al. Geraud et al., Fusion Eng. and Des. 88 (2013) 1064-1068

[4] H. Yamada et al, Fusion Eng. and Des. 49-50 (2000) 915-920

[5] D.J. Wilson, et. al. Proc. 20th IEEE/NPSS SOFE, (San Diego, 2003) 86-91.

[6] S.K. Combs et al. Fusion Eng. and Des. 87 (2012) 634–640

[7] C. Andelfinger, et al.; Rev.of Sci. Instrum., 64 (1993) 983-989

[8] B. Plöckl and P. T. Lang., Rev. of Sci. Instrum. 84, 103509 (2013); doi: 10.1063/1.4824429

[9] F. Romanelli et al., A roadmap to the realisation of fusion energy, EFDA Garching, Germany, 2012 (ISBN 978-3-00-040720-8)

[10] A. Lorenz, et al. Fusion Eng. and Des. 69 (2003) 15-20

[11] P.T. Lang et al, Rev. of Sci. Instrum. 71 (2000) 3744-3746

7 Disclaimer / acknowledgement

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