Experimental helium exhaust studies in the full-W ASDEX Upgrade

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Understanding helium exhaust is critical for nuclear fusion research. In a fusion plasma the generation of helium ash in the core as a product of the D-T reaction will be unavoidable. Therefore, efficiently removing helium from a fusion plasma through active pumping will be mandatory in order to avoid fuel dilution and achieve stationary burning conditions [1]. Studying the processes involved in helium recycling and pumping in currently operating tokamaks is possible by applying He-seeding to deuterium plasma discharges. The desired outcome is a basic understanding of the dominant physics mechanisms, which can be used to predict and guide design and operation of future devices. Such experiments have been recently carried out at the ASDEX Upgrade (AUG) tokamak. ASDEX Upgrade features a full tungsten wall, an ITER-like plasma geometry and a very well diagnosed plasma edge and divertor, making it an ideal test environment for helium exhaust studies.

The dynamic behavior of helium in deuterium plasma discharges has been interpreted by means of a 0-D particle balance model, inspired by [2], which assumes inter-connected reservoirs for helium ions or atoms based on the AUG geometry (Fig. 1). The external injection of He atoms into the system (of which only a fraction f_{eff} enters the main plasma) is experimentally known. The He ion loss from the main plasma scales with a confinement time τ_{main}. SOL transport is neglected, as it occurs on timescales much smaller than the pumping ones. So the He ions lost from the main plasma are assumed to immediately enter the divertor chamber as recycled neutrals. The imperfect retention of He in the divertor volume (i.e. the backflow of recycled He atoms which are ionized again in the divertor volume) is taken into account through a retention time τ_{ret}.

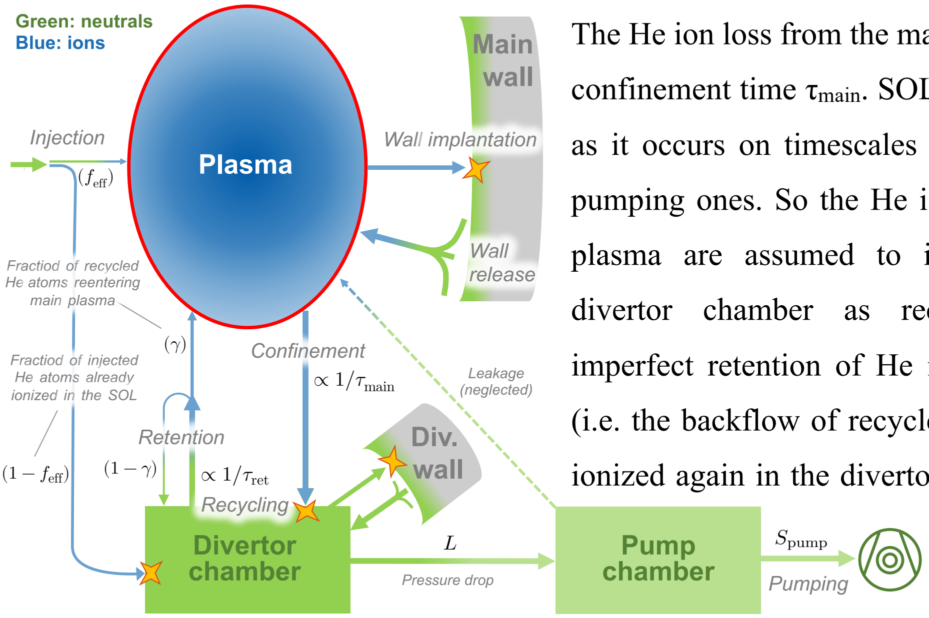

Figure 1: Schematic overview of the multi-reservoir particle balance model used for interpreting the experiments.

However, only a fraction γ of He ions escaping the divertor re-enters the confined region, so that the ‘effective’ retention time defined is τ_{ret}/γ. Those He atoms which are efficiently retained in the divertor can travel towards the pump chamber, with a flow described by a neutral conductance L. In the model the conductance effect is included by imposing an empirically assumed value of the pressure drop between the two chambers. Finally, He atoms are removed from the pump chamber as it is connected to a system of turbomolecular pumps, whose pumping speed S_{pump} has been measured to be 5-6 m^3/s [3]. A cryopump is also installed within the chamber but it is unable to remove helium. Additionally, helium has been experimentally shown to be efficiently retained in tungsten [4], making the effects of long-term He storage in the main chamber and divertor walls at AUG non negligible. In the model this is taken into account by assuming that all non-reflected He atoms impacting the walls are implanted. Conversely, He release from the wall is modelled as triggered by impurity ions (e.g. boron) sputtering. Realistic reflection and sputtering coefficients are employed [5], as well as the actual values of chamber volumes and plasma-wetted wall surface areas.

Figure 2 shows a poloidal view of AUG, as well as the main diagnostics used in this study. He ion density profiles in the main plasma are routinely measured via charge-exchange recombination spectroscopy [6,7]. Such profiles are used to compute the average helium ion content in the main plasma. He partial pressure in the neutral exhaust gas is measured by a recently installed in-vessel Penning-type cold cathode gauge [8] and is converted to neutral He density assuming room temperature for the gas.

The main experimental input into the model is the helium compression C_{He}, defined as the ratio of neutral helium density in the divertor chamber and the average helium ion density in the confined plasma. This parameter describes the physical efficiency of helium transport towards the divertor and the retention in the divertor volume. Since S_{pump} is roughly constant in the investigated divertor pressures range, C_{He} is the most important parameter describing the overall helium exhaust efficiency.

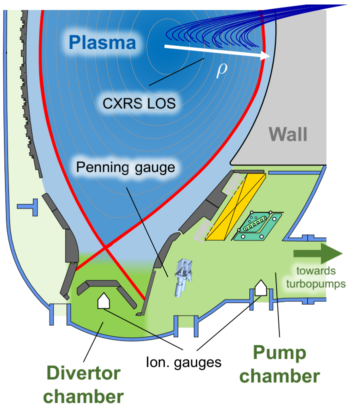

Figure 2: Poloidal cross section of the AUG geometry showing the various ‘chambers’ employed in the model and the location of the most relevant diagnostics for this work.

We performed 3 type-I ELMy H-mode deuterium discharges with constant feedback-controlled divertor neutral pressure, featuring one single He puff (Fig. 3). A reliable experimental measurement of C_{He} was possible for the first time at AUG thanks to the measurement of He partial pressure in the exhaust gas. C_{He} was found to increase with divertor neutral pressure (Fig. 4), in agreement with previous estimates made with the full-C AUG presented in [9].

The model described here was applied to these discharges aiming to reproduce the experimentally measured C_{He} and to match the experimental trends for the He content in the plasma/neutral gas. A realistic confinement time τ_{main} of 80 ms and a pumping speed S_{pump} of 6 m^3/s were assumed. Figure 4 shows the τ_{ret}/γ values used to reproduce the experimentally measured C_{He}, thereby showing that, in the model, larger values of C_{He} result in a more efficient divertor retention of the recycled He.

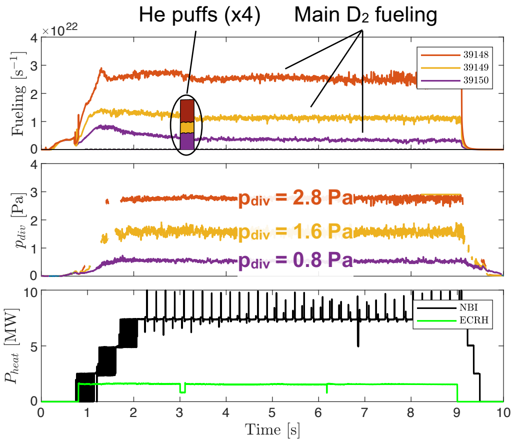

Figure 3: Fueling, divertor neutral pressure and heating power time traces of the executed He-seeded deuterium discharges.

Once τ_{ret}/γ is imposed and the experimental C_{He} has been reproduced, the model is well enough constrained to allow to match the experimental trends solving for the remaining free parameters. Figure 5 shows the results of the model applied to the discharge #39149. A very good agreement between the experimental and the modelled dynamics (boxes a,b) is found. The initial conditions for the He content in the main chamber and divertor walls are chosen to be consistent with the experimental ones in the plasma and divertor. In this way, the dynamic He wall content (boxes c,d) is self-consistently modelled together with the He ion and neutral densities. As a result we observe the modelled He wall storage to decay very slowly throughout the discharge, especially in the main chamber wall. The subsequent continuous release of He from the wall can be then seen to play a key role for the long tail of the decay curve of the He content in the plasma and, ultimately, for the inefficient He removal at AUG. Additionally, the experimental decay is reproduced when using a pressure drop of 2-3 between divertor and pump chambers. This is less than the drop experimentally observed for deuterium in the same range of pressures (about 4-6). This is consistent with the fact that He is not pumped by the cryopump, resulting in different flow

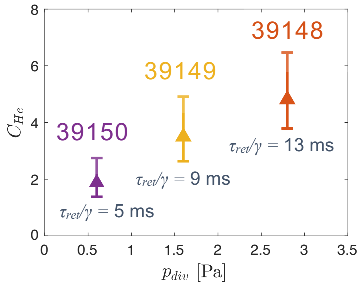

Figure 4: Experimental helium compression measurements from the executed discharges.

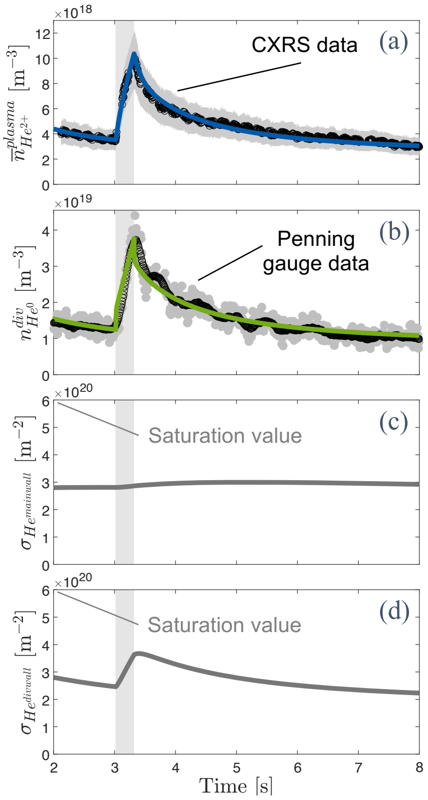

Figure 5: Average He ion density in the main plasma (a), neutral He density in the divertor (b) and He stored in the main chamber (c) and divertor (d) walls modelled from the discharge #39149 (colored solid lines) and comparison with the experimental data (black scatter points).

characteristics with respect to D, and indicates that the He flow itself might be not greatly entrained into the background D flow. This supports the assumption of D-He collisions not having a relevant effect on He exhaust, at least at the investigated pressures.

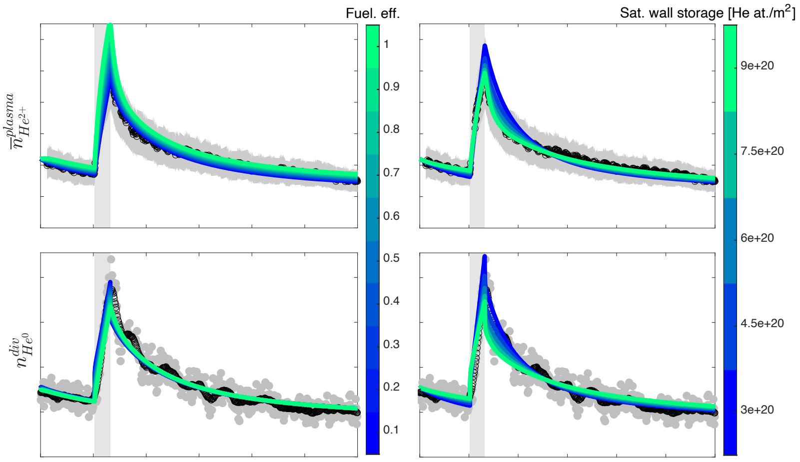

Figure 6: Sensitivity analysis on the modelled He exhaust dynamics for discharge 39149 varying fueling efficiency (left) and saturation value of He stored in the wall (right).

Because of the many free parameters contained in the model a sensitivity analysis was performed. Some examples of the investigated parameters are shown in Fig. 6. f_{eff} was varied between 0 and 1, and surprisingly the model solutions were seen to be not much affected, but only weakly during the active injection phase. The wall saturation storage for He, which is thought to be of the order of 10^{20} atoms/m^2 [4] but whose exact value is uncertain, was also varied. This variation was seen instead to have a major effect on the shape of the first part the decay curve. For the investigated discharges, the best match was achieved using a value of $6 \cdot 10^{20}$ atoms/m^2.

To conclude, experiments have shown that divertor retention for He improves with increasing divertor pressure, in line with previous estimates. In all scenarios the poor pumping capability and the long-term He storage in the W-wall have been identified as strong bottlenecks for an efficient exhaust. All such aspects can be succesfully captured by a simple model which, in addition to being useful for intepreting the performed experiments, might be also used for predictive purposes. A numerical modelling the performed discharges through the SOLPS-ITER code package is underway, in order to reproduce and interpret the physical mechanisms leading to the experimentally observed helium compression values.

References

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