Helium Exhaust and Transport in ASDEX Upgrade

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1. Introduction

One of the important requirements for steady state operation of a fusion reactor is sufficient exhaust of the fusion-produced helium from the core plasma. This, however, involves two separate but linked processes, namely radial transport on closed flux surfaces in the core plasma and scrape-off layer (sol) transport into the divertor, including high divertor retention to optimize the pumping efficieny by increasing the helium density in front of the pump duct.

2. Core helium transport

The global helium exhaust time in ASDEX Upgrade has been shown to decrease strongly with increasing divertor neutral gas density[1], and this is attributed to improved divertor retention due to neutrals recirculating from the divertor chamber. Figure 1 compares the helium transport coefficients as deduced from CXRS-measurements for two CDH-mode discharges (with neon cooling and detached divertor plasma) with different values of the neutral gas flux density (as a measure of the neutral density) in the divertor chamber. In the discharge with the higher neutral flux density (#6131, $\phi_0 = 5.4 \times 10^{22}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$), the global helium confinement time, normalised to the energy confinement time ($\rho^*_{He} = \tau^*_{He}/\tau_E$) is 25 % smaller than in the discharge with lower neutral gas flux density (#6136, $\phi_0 = 4.0 \times 10^{22}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$), namely 6.4 compared with 8.4.

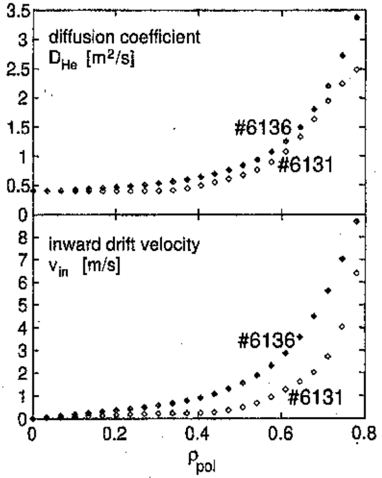

Figure 1: Helium transport coefficients for two CDH-mode discharges with different divertor neutral flux densities.

The core transport coefficients, however, are practically identical, as shown in figure 1, as the slightly higher D$_{He}$ in #6136 is in principle offset by the v$_{in}$ also being larger. The quantitative similiarity of core transport in these discharges was shown with the STRAHL code, including a simple scrape-off layer and divertor model [2]. To reproduce the experimentally measured decay times of the helium density, different sol and pumping time constants have to be used for both discharges, expressing the better sol transport in #6131, when using the transport coefficients from figure 1 for the core. Using these core coefficients, and identical time constants for sol and divertor, both discharges show identical helium decay times. This proves that the improvement in helium exhaust is solely determined by the physics in the scrape-off layer and divertor.

3. Scrape-off layer transport and divertor retention

It has been shown previously in ASDEX Upgrade, that the improvement in divertor compression with increased neutral gas density in the divertor chamber is due to this gas density, or the corresponding particle flux out of the divertor onto the divertor leg (internal recirculation), and not due to the externally fed deuterium flux in the main chamber [3]. That means, it is not the particle flux in the scrape-off layer that flushes the impurities into the divertor, but the internally recirculating fluxes in the lower part of the scrape-off layer, namely below the divertor baffle ring which is installed in ASDEX Upgrade at about the height of the X-point.

This physics picture was confirmed by 2d-modelling of the scrape-off layer and divertor plasma with the SOLPS-code package [1,4]. Not only do these simulations show the behaviour seen in experiment, namely the divertor compression increasing with divertor neutral flux density, and the compression of neon being higher than that of helium, but they also show that in higher density plasmas the helium (and neon) neutrals from the divertor plate are quickly ionised, and in ASDEX Upgrade they are transported radially by an almost "diffusive" process towards the outer edge of the scrape-off layer and into the divertor chamber. In this outer edge the impurity compression is determined by the deuterium flux towards the target plate, which is built up by the neutrals streaming towards the divertor plasma, as was shown with the modelling [1].

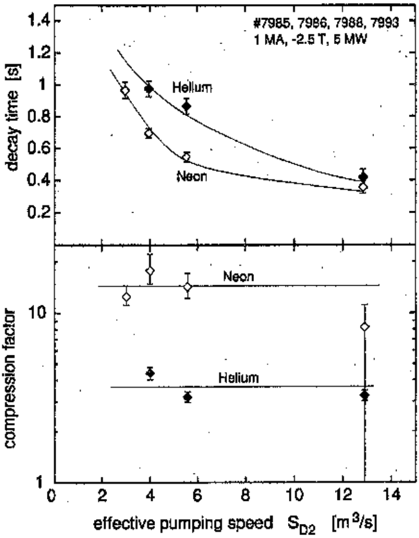

Figure 2: Exhaust rates (top) and compression factors (bottom) for He and Ne as a function of the pumping speed. The external deuterium flux into the main chamber was varied to keep the divertor neutral flux density in all discharges constant. While the exhaust rates decrease with increasing pumping speed, and net particle throughput, the divertor compression is independent of these two correlated parameters.

These results which have been observed in CDH-mode plasmas [3], are different from similiar experiments in DIII-D H-mode plasmas [5], where an improvement in divertor compression was found with increasing net particle throughput in the scrape-off layer. The influence of ELMs has been discussed as a possible reason for the difference, and figure 2 shows the results of experiments in ASDEX Upgrade with type-I ELM H-mode plasmas (I_p = 1 MA, B_t = 2.5 T, P_{NBI} = 5 MW). For a fixed divertor neutral flux density $\phi_{0,div}$, the pumping speed was varied (by closing valves to the turbomolecular pumps on a shot to shot basis), and the external gas flux was varied accordingly to keep $\phi_{0,div}$ constant (feedback-controlled).

These experiments again show, that in ASDEX Upgrade the internal recirculation of neutrals from the divertor region is responsible for the divertor compression of neon and helium. This is understandable from the above mentioned 2d modelling which shows that this internal flux in the region below the X-point is much stronger than the net particle influx, and therefore one can expect it to be the leading force. It also shows, however, that the geometry of the ASDEX Upgrade divertor plays an important role. The baffle ring is located about 14 cm above the outer divertor plate, i.e. the length of the divertor leg where the neutrals can again be ionised and where they can enhance the plasma flow, is rather large, and covers the whole region below the X-point.

In DIII-D the baffle ring is very close to the divertor plate, and the particle fluxes into the divertor chamber as well as the reflux of neutrals are strongly reduced. Therefore the scrape-off layer transport of impurities as discussed above for ASDEX Upgrade will not work, and the smaller effect of friction driven flow might become the leading force. This has to be confirmed by 2d modelling, but could easily explain the differences between the two experiments.

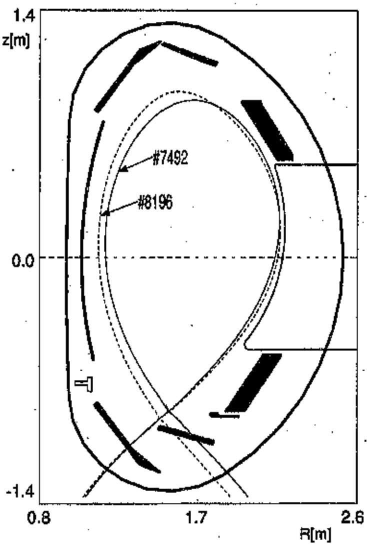

Figure 3: Magnetic configurations for the standard case in ASDEX Upgrade (#7492, solid line) and a higher triangularity plasma (#8196, dotted line).

As discussed above, the divertor geometry in ASDEX Upgrade plays an important role for divertor compression of impurities. This also becomes evident when the magnetic configuration is varied, as seen in figure 3. Very similiar plasmas have been performed with different plasma shape. The separatrix of the standard equilibrium with a low triangularity is shown as solid line in figure 3, the separatrix of the medium triangularity plasma as a dotted line. These higher triangularity plasmas show generally better energy and particle confinement, but the two discharges shown here are almost identical in global parameters, as shown in figure 4. The separatrix density and the average sol density in #8197 are only slightly smaller than in #7492, as it is the case for the main chamber neutral gas flux density $\phi_{0,midplane}$. Also the plasma parameters at the target plates are similiar, but there is a large change in the divertor neutral flux density $\phi_{o,div}$, and in the deuterium compression C=$\phi_{o,div}/\phi_{0,midplane}$. Modelling of short Ne puffs in both discharges with STRAHL [6] shows that the Ne-compression in #8197 is almost negligible, and the reduction compared with #7492 is much larger than expected for the lower $\phi_{0,div}$ [7]. The shift of the X-point to smaller radii opens a gap between the scrape-off layer and the baffle ring, and thereby destroys the compression of deuterium as well as of the impurities.

4. Conclusions

It has been shown that exhaust of noble gas impurities (helium as well as neon) in ASDEX Upgrade is determined by transport in the sol and by the divertor compression. This can be influenced by the neutral gas in the rather open divertor chamber (in divertor I). Variations of the magnetic configuration, where the X-point is shifted to smaller radii and the region between sol and baffle ring is opened, deteriorate strongly the divertor compression of neon as well as of deuterium.

From B2-EIRENE modelling of the divertor compression of helium and neon, it is clear that the geometry of divertor I played an important role for this mechanism, where internally recirculating deuterium fluxes determine the divertor compression.

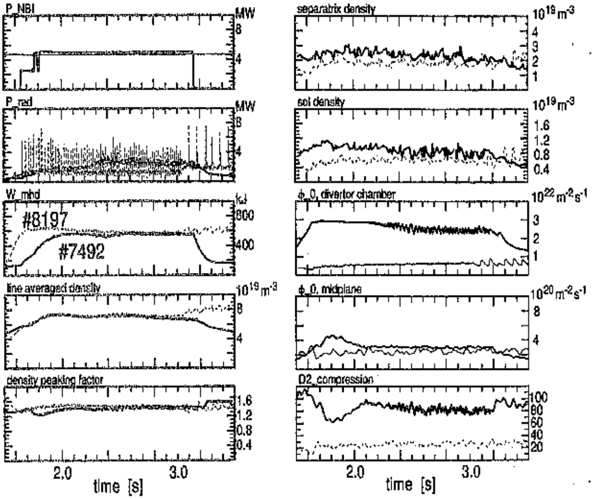

Figure 3: Plasma parameters for the discharges shown in figure 3 .

Therefore differences in He transport are expected for the modified divertor II of ASDEX Upgrade which will start operation soon. The new divertor will have vertical target plates which are LYRA-shaped to distribute the heat fluxes more homogeneously. Additionally, the private flux region is equipped with a dome-shaped baffle to prevent large influxes of neutrals to the main plasma through the X-point and to increase the neutral density in the divertor chamber for a given plasma flow towards the divertor. 2d-modelling of this divertor geometry predicts a better He compression compared with divertor I, mainly due to the vertical orientation of the target plates.

References

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