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Helium transport and exhaust with an ITER-like divertor in ASDEX Upgrade

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Abstract

After modification of the ASDEX Upgrade divertor, i.e., installation of the 'LYRA'-divertor, extensive helium exhaust and transport studies have been performed to investigate two different aspects important for the development of a steady-state fusion device: (1) helium transport in the scrape-off layer (SOL) and divertor with a divertor geometry similar to the one foreseen for ITER, and (2) helium transport in the plasma core with internal transport barriers (ITBs). In ohmic and H-mode discharges larger compression ratios and enrichment factors as compared to divertor *I* have been found. With the new divertor configuration both quantities depend on the heating power and deteriorate with divertor detachment. In ITB-discharges with an H-mode edge, helium exhaust is rather slow – as expected for such low density scenarios – but not hindered by the transport barrier.

Keywords: ASDEX-Upgrade; B2/EIRENE; Divertor; Neutral particle; Transport

1. Introduction

The new LYRA-divertor which has been in operation since 1997, involves shaped, vertical divertor target plates and is considerably deeper, and more closed than the previous configuration, divertor *I* [1,2]. The neutrals produced at the vertical target plates are reflected towards the power-conducting sheath close to the separatrix, improving the power exhaust. Pumping is now done from the private flux region, i.e., the neutrals have to cross the divertor leg to reach the pumping chamber below the *X*-point. To prevent the back-flow to, and the immediate reionisation in the *X*-point region and to enhance the pumping efficiency, a dome baffle has been installed in this region between the target plates. First results on the particle exhaust and on the influence of the new divertor geometry on the divertor plasma behaviour, especially the target power load, have been described earlier in [2,3].

2. Helium exhaust diagnostics

Helium exhaust can be charaterised by the helium compression ratio, $C_{\mathrm{He}} = n^{\mathrm{div}}_{\mathrm{He},0}/n^{\mathrm{edge}}_{\mathrm{He},+}$ or, when normalised to the deuterium compression ratio, by the enrichment factor $\eta_{\mathrm{He}} = C_{\mathrm{He}}/C_{\mathrm{D_2}} = (n^{\mathrm{div}}_{\mathrm{He},0} \cdot n^{\mathrm{edge}}_{\mathrm{e}})/(n^{\mathrm{edge}}_{\mathrm{He},+} \cdot 2 \cdot n^{\mathrm{div}}_{\mathrm{D_2}})$ [4]. In previous investigations on ASDEX Upgrade, C_{He} has been determined from the global helium confinement time (determined from the decay rate of helium recycling signals in the divertor), using a simple 2-chamber model [4,5] because the local measurements used in the above definition were not available. For the new divertor, however, the volume below the dome baffle acts as an additional chamber and therefore a modified 3-chamber model was established [6]. In the meantime, the helium neutral density has been measured with a Penning gauge in the divertor pump duct [6], therefore allowing for local measurements of C_{He}. Fig. 1 compares the compression ratios determined

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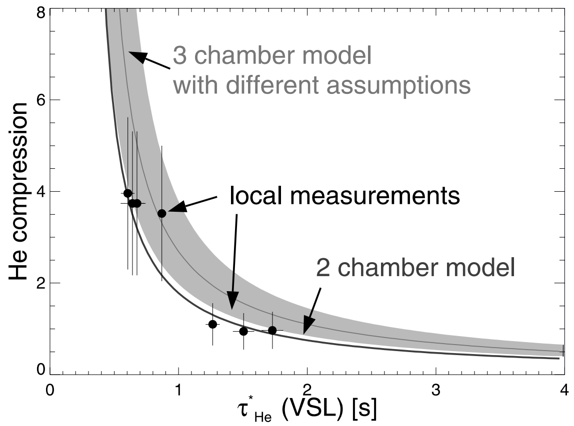

Fig. 1. Comparison of He compression factors determined from He-recycling signals in the divertor by means of a 2- or 3-chamber model (lines) or from local measurements (points).

from τ^*_{He} using the simple models (solid lines) with the values determined from the local measurements. For the 3-chamber model the conductance between the main chamber, the dome chamber and the pump chamber, and the leakage through the divertor assembly, all of which cannot be determined exactly, enter directly. The shaded band in Fig. 1 indicates the uncertainty in C_{He} resulting from these experimental uncertainties. Taking this into account, the results from local measurements agree rather well with the former evaluation method, thereby confirming the validity of these simple models.

3. Helium exhaust in ELMy H-mode plasmas

Fig. 2 shows an overview of the helium compression ratios in ohmic and H-mode discharges in ASDEX Upgrade. Again, as previously seen in divertor *I*, there is a strong trend of C_{He} increasing with the divertor neutral gas flux density, but a much larger scatter which reveals a dependency on P_{sol}, the power flux into the scarpe-off layer (P_{sol} is the heating power minus the power radiated in the plasma core). A systematic density variation, as in the ohmic heating scan, however, shows very nicely not only the increasing helium compression, but also a rollover at high density. A similar rollover is seen for the data with $5\ \mathrm{MW} < P_{sol} < 7\ \mathrm{MW}$, but since these data have been taken over a variety of discharges during a longer time interval, we find a larger scatter in the data which is due to the differences in plasma parameters which could not be identified.

The corresponding enrichment factors are shown in Fig. 3, indicating that the enrichment factor for a given range of power fluxes over the separatrix is mostly constant (except for the detached plasmas, indicated with an arrow), but the enrichment factor decreases with

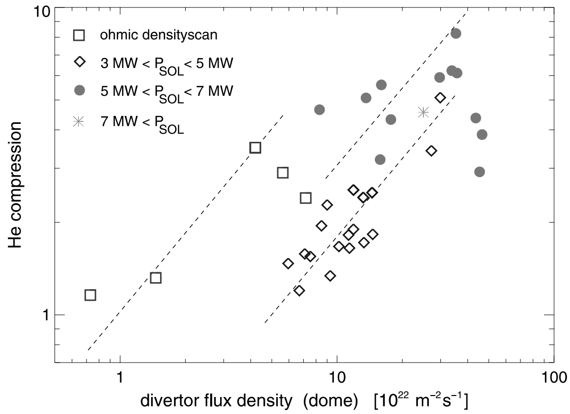

Fig. 2. Overview of the helium compression ratios for ohmic discharges and H-mode plasmas in ASDEX Upgrade.

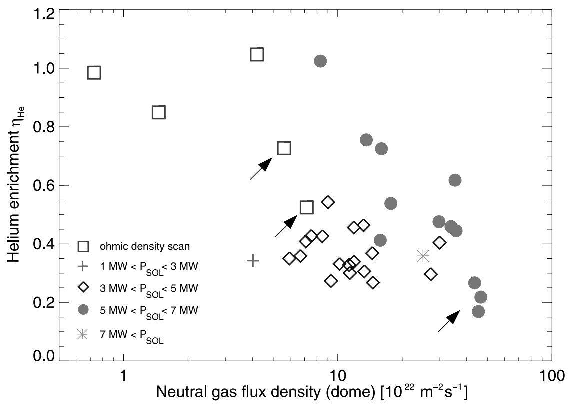

Fig. 3. Overview of the helium enrichment factors in ohmic discharges and H-mode plasmas in ASDEX Upgrade.

P_{sol}. For most of the plasma conditions, however, η_{He} is still above 0.2 which has been considered the lower limit for the ITER design.

4. Helium compression in detached plasmas

To study the helium compression at high plasma density in more detail, Fig. 4 shows divertor plasma parameters for the above-mentioned ohmic density scan. The neutral flux density in the divertor chamber (below the dome baffle) increases monotonically with density and it is roughly proportional to the third power of the line-averaged density, as one would expect for a divertor in the high-recycling regime [7]. Above a line-averaged density of $4 \times 10^{19}\ \mathrm{m}^{-3}$, however, the ion flux to both of the target plates starts to drop and simultaneously the H_β intensity in the divertor increases, indicating a detachment of the divertor plasma. At the same time, the

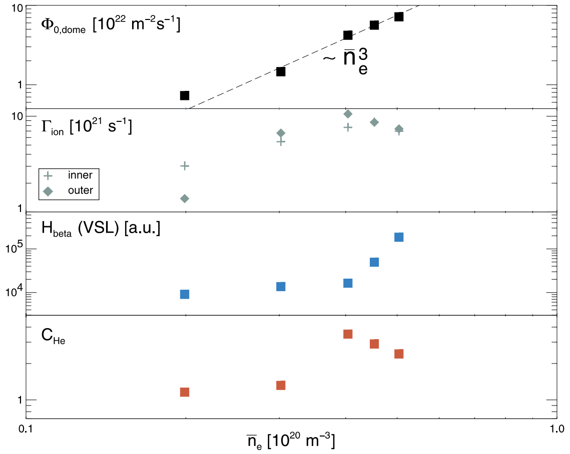

Fig. 4. Density variation in ohmic discharges in ASDEX Upgrade with $I_p = 1.0$ MA, $B_t = -2.5$ T.

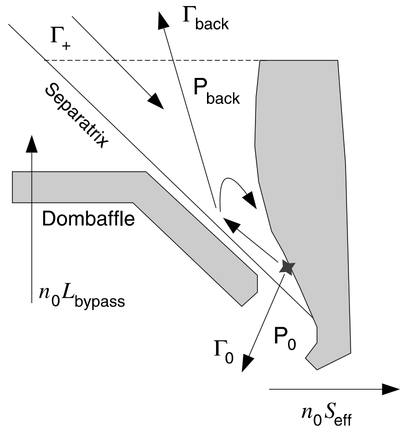

Fig. 5. Simplified model of the outer divertor for analytical modelling of the influence of the separatrix position on helium compression.

helium compression starts to drop. Because $\phi_{0,\mathrm{dome}}$ and $n_{e,\mathrm{sep}}$ (not shown here) still increase with $\bar{n}_e$, the deuterium compression still increases with the detached divertor plasma. Therefore, the helium enrichment factor decreases strongly with plasma detachment, as was seen in Fig. 3. This is in contrast to divertor *I* where the best compression ratios had been achieved with the highest plasma densities, and no influence of the plasma detachment had been seen.

This behaviour of helium compression is supported by 2d-modelling with the B2-EIRENE code package [8]. Systematic scans of the separatrix density show a rollover of the helium compression at a density which increases with the power flow over the separatrix. The reason for the drop in detachment is related to the fact that with increasing detachment the ionisation front (and in parallel also the source of helium neutrals) moves upward, and therefore, the acceptance angle of the baffle chamber for helium neutrals decreases, while the helium ionisation probability in the main plasma increases. Such a 'ballistic' behaviour of the helium neutrals, as predicted in earlier B2-Eirene modelling [9], is due to the long mean free path of helium.

5. Vertical shift of the separatrix

Similar conditions as in the evolution of detachment can be set up externally by shifting the plasma vertically, as was shown already in [2]. Moving the plasma upward by only 3 cm, reduces the compression ratio by more than a factor of 2 (see Fig. 6).

The geometrical model discussed before can also be quantified in an analytical model, as sketched in Fig. 5 [6]. The position of the source of helium neutrals (indicated by the star), which is also linked to the separatrix

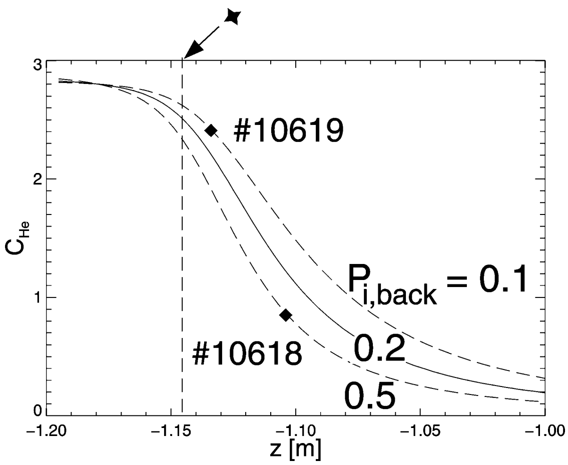

Fig. 6. Influence of the vertical separatrix position on the outer target plate on the helium compression. The lines show the result of the analytical model, where P_{back} also depends on the divertor plasma, the diamonds indicate experimental data.

position determines the probability of neutrals to enter the dome baffle (P_0) and their probability to be reionised in the plasma core, P_{back}. The latter one depends on geometry, but also on assumptions on the plasma parameters. As mentioned before, a higher position of the source reduces P_0 and increases P_{back}. Using the ASDEX Upgrade geometry data, one can derive an analytical formula for the compression ratio as a function of the *z*-position of the separatrix, as is shown by the curves in Fig. 6. The parameter on these lines describes the plasma parameter dependency of P_{back}. The diamonds show experimental data for two discharges, indicating good agreement with this simple model.

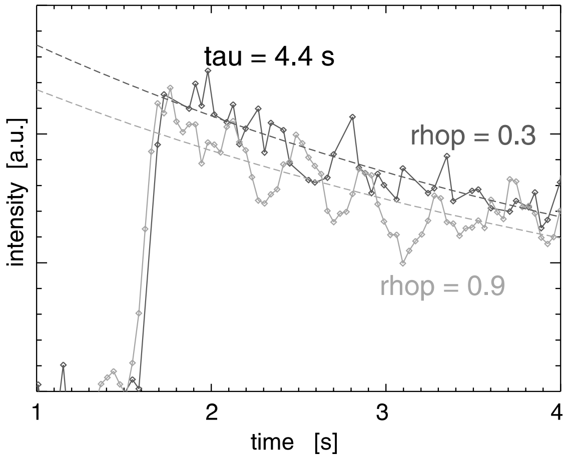

Fig. 7. Time traces of the core helium density at two normalised radii in an ASDEX Upgrade discharge with ITB and H-mode edge (#13543). At 1.6 s a short helium gas puff is introduced which penetrates quickly into the plasma core. At both radii, a fit to the helium density decay yields the same time constant of 4.4 s.

6. Helium exhaust with advanced tokamak scenarios

Recently, scenarios with improved core confinement or internal transport barriers have been investigated extensively in ASDEX Upgrade [10,11]. In a scenario with improved core confinement and an H-mode edge, which has been shown to be stationary for more than 40 energy confinement times, helium exhaust has been studied. The enhanced confinement properties are associated to a current profile with zero shear in the central region of the plasma core, with $q_{\min} \geqslant 1$.

Previous investigations of medium-Z impurity transport show a peaking of C- and Ar-profiles, consistent with neoclassical predictions considering the balance between temperature screening and density peaking [12]. Nevertheless, due to the length of the discharge, steady-state conditions could be reached in all cases.

Helium transport and exhaust in this scenario using short helium gas puffs indicate a rather slow helium density decay, as can be seen in Fig. 7 for an H-mode discharge with improved core confinement as described in [10] ($I_p = 1$ MA, $B_t = -2.5$ T, $P_{NI} = 5$ MW). However, with regard to the rather low separatrix density (and consequently also very low divertor neutral gas flux density) these data fit rather well into the behaviour shown in Fig. 2. While one might argue, that helium from the gas puff does not penetrate into the plasma core under theses conditions, Fig. 7 reveals that the helium influx into the core is not prevented by the transport reduction, as the helium density (which is proportional to the light intensity shown here) increases simultaneously and equally fast for both plasma radii. Also, the helium density decay shows the same time constant for both radii, i.e., inside and outside the transport barrier. The transport barrier does not influence the helium exhaust in either direction. This result is similar to JT-60U, where helium exhaust with a ‘weak ITB’ is not hindered by the ITB [13].

7. Conclusions

The new LYRA-divertor in ASDEX Upgrade shows enhanced helium compression as compared with the old, rather open divertor *I*. Again, helium compression in general increases with density, but now at divertor detachment the compression ratio starts to deteriorate, and for the enrichment factor, this decrease is even larger. Such a behaviour is in good agreement with B2-Eirene modelling and can be understood in terms of the divertor geometry and the long mean free path of helium.

In H-mode ITB scenarios in ASDEX Upgrade, helium exhaust is rather low, but this is fully in agreement with the low divertor neutral density, and does not seem to be limited by the core plasma transport. More detailed investigations in these scenarios are planned.

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