Abstract

The presence of fusion-produced helium is fundamentally connected to the performance of a fusion reactor. Not only will He ash dilute the fusion fuel if not removed promptly, but the presence of He in a D plasma is reported to negatively affect the plasma confinement. Furthermore, He plasmas are one of the options foreseen for the ITER non-nuclear phase, although, the energy confinement in such plasmas is consistently observed to be \( \sim 30\% \) lower than in D plasmas. These considerations strongly motivate the experimental characterization and theoretical understanding of the physics of He transport in tokamak plasmas, with He as main ion or impurity. The negative impact on the performance due to reactor relevant He concentrations in D plasmas is identified and compared in JET and ASDEX Upgrade (AUG) discharges. Moreover, the confinement of He plasmas in AUG is studied, experimentally identifying and theoretically explaining the plasma conditions where the confinement observed in He is the same as that in D plasmas.

1. INTRODUCTION

The confinement of helium plasmas is systematically lower than in deuterium plasmas, with \( \tau_{\text{He}} \sim 0.7 \tau_{\text{D}} \) [1, 2]. This is in contrast to the expectations based on the gyro-Bohm scaling of turbulent transport, which predicts that the turbulent diffusivities scale with the square root of the main ion mass. A deviation from the gyro-Bohm mass dependence is also observed in hydrogen isotope studies (see e.g. [3]). He plasmas are proposed for the initial, non-nuclear ITER operation stage, necessitating knowledge of the transport processes and the confinement of such plasmas. Furthermore, the experimental investigation and theoretical study of He plasmas can help in understanding the isotope effect, as the Larmor radius of He is equal to that of H. Moreover, He as a minority in D plasmas was identified to deteriorate plasma performance [4]. Low levels of He, even below 10% of the electron density, are sometimes observed to have a significant effect on plasma confinement. If levels of He as those expected in the nuclear ITER operation stage (up to \( \sim 10\% \)) are proven to be detrimental to confinement, understanding of the physics mechanisms behind this effect are essential in order to devise counteracting strategies. Experimental and theoretical work aiming to shed light on the effect of He on plasma performance, as a minority in JET (Sec. 2.1) and AUG (Sec. 2.2) and as a main ion in AUG (Sec. 3), is presented.
2. CONFINEMENT IN DEUTERIUM PLASMAS WITH A HELIUM MINORITY

2.1. Helium seeding experiments at JET

The effect of He as a minority impurity in deuterium plasmas was investigated in baseline H-mode scenario plasmas at JET (Bₚ≡2.1T, Ⅰₚ≡2MA, D-fuelling of unseeded pulse 1.6 ⋅ 10²² e⁻/s, βₜ≃1.5, qₚ≃3.1). Helium puffs were injected in three different experimental scenarios: with neutral beam injection (NBI) heating only, with combined neutral beam and H-minority ion cyclotron resonance heating (ICRH) and with NBI, ICRH and additional ELM frequency control. The He concentration was controlled in real time via divertor spectroscopy signals and scanned up to above 10% from pulse to pulse.

With the addition of He in NBI-only heated plasmas (Pₜ≃10 – 12 MW, core nₑ≃5.5 · 10¹⁹m⁻³), the stored energy and also energy confinement time and normalised confinement factor H₉₈ are strongly decreasing. The almost linear decrease of the plasma stored energy with increasing He concentration is shown in Fig. 1a (squares). Here, the He concentrations are estimated from divertor spectroscopy measurements and benchmarked against edge charge exchange spectroscopy (CXRS) measurements, using an approximate correction for the He plume emission and defined as nₜₑ = cₜₑ · nₑ. Furthermore, a significant reduction in measured neutron rates is observed. The contributions to the stored energy are plotted against the He concentration for the pulses with only NBI heating in Fig. 1b. The core contribution to the plasma stored energy (squares) is defined as

\[ W_{\text{core}} = \frac{3}{2} \int \left( P_e + P_i - P_{\text{ped}}^e - P_{\text{ped}}^i \right) dV, \]

where \( P_e \) and \( P_i \) are the electron and ion pressure, respectively, and \( P_{\text{ped}} \) is the plasma pressure at \( P_{\text{ped}} = 0.95 \). The pedestal stored energy \( W_{\text{ped}} \) (up-down triangles) is calculated as

\[ W_{\text{ped}} = \frac{3}{2} \left( P_{\text{ped}}^e + P_{\text{ped}}^i \right) V. \]

These values can be compared with the stored energy predicted based on the IPB98(y,2) scaling, denoted as \( \tau_{98} P_{\text{heat}} \). Information on the fast ion stored energy \( W_{\text{FI}} \) (triangles) is obtained from the PEN-CIL modelling code. For the calculation of the plasma pressure, HRTS profiles of the electron temperatures and densities are used, shifted so that \( T_e = 120 \text{ eV at the separatrix and it is assumed that } T_i = T_e \). The He concentration is now calculated on the shifted HRTS density profiles and the ion density is obtained assuming only He and Be as impurities in the plasma. It is observed that \( W_{\text{core}} \) is strongly reduced by \(~20\% \) with \(~14\% \) He, while \( W_{\text{ped}} \) is only very slightly affected by He concentrations of up to \(~10\% \). \( W_{\text{core}} \) assuming no impurities (\( n_i = n_e \), diamonds), is still strongly reduced (by \(~15\% \)), showing that only \(~5\% \) is due to the reduction of \( n_i \) due to dilution. In Fig 2, the impact of the He seeding on the plasma profiles is shown. The addition of He leads to a reduction of the electron and ion temperatures across the plasma radius and an increase of the electron density. The peaking of the profiles changes, albeit only slightly, except \( T_e \). The core \( T_e/T_i \) ratio reduces. The plasma rotation is also strongly reduced with increasing He concentration, but there is no strong reduction in its peaking. The addition of He in plasmas with pure NBI heating leads to an increase of the pedestal electron density and a corresponding decrease of the pedestal electron temperature (Fig. 2, black and red lines correspond to the unseeded and He-seeded pulses, respectively). As such, \( P_{\text{ped}}^e \) is constant and does not cause the loss in plasma confinement (pedestal \( T_i \) measurements were not available for these shots). The core pressure, however, does decrease.

FIG. 1. a) Reduction of the plasma stored energy with increasing helium concentration in JET pulses and b) Plasma stored energy and its components for a subset of cases with NBI heating only (definitions in the text).
The higher edge electron density induced by He in the NBI-only plasmas leads to a stronger attenuation of the NBI in the plasma, which results in a reduced core temperature, and to a significant reduction of beam-target neutrons. The TRANSP simulations assuming $T_e = T_i$ are shown on the lower right of Fig. 2 (the thermal DD neutron contribution is $< 15\%$ of the total neutrons). The simulations indicate also reduced NBI ion heating in the core (up to almost 20\%) and increased electron heating at the edge (up to 30\% at $\rho_{pol}$~0.9) with the first He level (not shown), relating to the observed profile changes. To counteract the pressure loss in the core, part of the NBI power was replaced with central H-minority ICRH heating ($P_{ICRH}$=2.5-3MW, core $n_e \sim 5 \cdot 10^{19}$m$^{-3}$). In these cases, represented by blue triangles in Fig. 1a, the plasma stored energy and the total neutron rates (not shown) are not as strongly reduced. The electron density increases more strongly with the addition of He in comparison to the NBI-only heated case (also seen at the pedestal in Fig. 2, blue and green solid lines), while the temperature is reduced less strongly in the core and almost not at all at the pedestal top. As a result, the electron pressure across the plasma radius reduces only slightly. The core ion pressure reduction is slightly stronger. In the pulses with He seeding, two bands of ELM frequencies appear, for example, 35 and 80Hz, with the first level of He in NBI-only heated plasmas, while only the lower ELM frequency is present in the unseeded case. The ELM frequency was controlled in pulses with combined ICRH and NBI heating to the frequency of the non He-seeded pulses ($\sim$60Hz), by reducing the D gas puff. The pedestal electron density could be kept at the levels of the unseeded pulse (Fig. 2, green dashed lines). While lowering the D-puff is expected to improve the confinement [5], the D gas was reduced much more than the added He gas (factor of 6 in $e^{-}$/s). In these cases (green triangles in Fig. 1), the electron pressure profile remains largely unchanged with increasing He concentration in comparison to the unseeded case. With the reduction of the D-fuelling, the NBI attenuation is no longer affected and the beam target neutrons are identical to the unseeded case with ICRH and NBI. The combined NBI and ICRH heating and ELM frequency control conditions indicate that both the changes in heat deposition and pedestal stability are responsible for the confinement loss.

### 2.2. Helium seeding experiments at ASDEX Upgrade

At AUG, the effect of He as a minority in D plasmas was investigated by injecting 0.5s long He puffs into high confinement D plasmas $P_{NBI} = 10$MW, $P_{ICRH} = 1.3$MW, $B_T = 2.5T$, $I_p = 1MA$, $\beta_N \sim 1.9 - 2.3$, $q_{95} \sim 4.3$) with two different levels of D fuelling ($5 \cdot 10^{21}$ and $7.5 \cdot 10^{21} e^{-}$/s), as well as into N-seeded D plasmas, leading to He concentrations of up to $\sim 14\%$. The He density profile was measured with CXRS, taking into account the plume effect [6].

A clear reduction of the plasma stored energy, shown in Fig. 3a, was observed when He was puffed. As in JET, the reduction is almost linear with the He concentration in all different plasma scenarios. The addition of He does not
have such an effect in low confinement plasmas. In Fig. 3b, the different contributions to the plasma stored energy for a low D-fuelling rate pulse without N-seeding are plotted. Here, the He concentration corresponds to the value at about mid-radius and the fast ion stored energy is obtained from TRANSP simulations. Dilution due to He (and N, not shown) alone cannot explain the reduction in plasma stored energy, as indicated by the reduction in $W_{\text{core}}$ assuming $n_i = n_e$. Rather, the reduction is mainly due to the kinetic profiles changes induced by the He puff.

In the plasmas with the higher level of D-fuelling and in the absence of N-seeding, two distinct ELM frequencies are present and a high field side high density front is observed in the SOL (HFSHD [7]). The He puff affects neither the ELMs nor the HFSHD. In the low D-fuelling cases, without N-seeding, two ELM frequencies are observed, and the upper ELM frequency band is populated more with the He-puff. With N-seeding, the HFSHD is reduced, leading to an increase of the plasma stored energy and the confinement [8, 9]. However, when He is added, the ELM frequency increases, which leads to flushing of W and N from the plasma core. The reduced radiation losses in the core result in an increased power deposition to the scrape-off layer, which causes the reappearance of the HFSHD. It is, therefore, not straightforward to decouple the effect of He on the confinement of N-seeded plasmas when the ELM frequency is increasing. Further attempts to avoid the increase of the ELM frequency are planned.

Both with and without N-seeding, the He-puff leads to small increase of the electron density (<5%) and a reduction of the electron and ion temperatures, as well as of the core plasma rotation. These changes are stronger in pulses with lower D-gas fuelling. The effect of the added He on the profiles is shown in Fig. 4, before the He-puff ($c_{\text{He}}$~2%) and immediately after ($c_{\text{He}}$~6%). Reduced NBI ion heating (<10%) is found with TRANSP (not shown) inside $\rho_{\text{tor}}$~0.6 and increased NBI electron heating across the plasma radius up to 15%. Also here, the core $T_e/T_i$ ratio is reduced. The gradients of the ion temperature and plasma rotation are reduced, while the ion heat diffusivity and momentum diffusivity increase, indicating increased transport with the addition of He. Despite the flattening of the rotation profile, the $E \times B$ shearing rate is anyway small in comparison to the Ion Temperature Gradient (ITG) growth rate (estimated as $\gamma_{E\times B}/\gamma_{\text{ITG}} = (e/q) \cdot (R/R_{\text{ioh}}) \cdot d\Omega/dr$), making possible $E \times B$ shearing effects unimportant. In contrast to JET, the electron pedestal pressure is slightly reduced. The effect is larger for the ions, due to the stronger reduction of $T_i$ and the reduction of ion density with added He. Alongside this erosion of the ion pedestal, also reported in [4], loss of core ion pressure is observed, which can be attributed to increased transport with the addition of He.

3. CONFINEMENT OF HELIUM PLASMAS AT ASDEX UPGRADE

To investigate the confinement of helium plasmas at AUG, these were compared with D plasmas matching the heating power (NBI and ECRH) and line averaged core electron densities. Both H-mode plasmas ($I_p = 0.6$ MA, $q_{95} = 7.2$, $B_T = 2.5$ T, with $P_{\text{ECRH}} = 0.7 - 2.7$ MW, $P_{\text{NBI}} = 1.4 - 6$ MW and $n_e = 4.0 - 6.2 \cdot 10^{19}$ m$^{-3}$) and L-mode plasmas ($I_p = 1$ MA, $q_{95} = 4$, $B_T = 2.5$ T, with $P_{\text{ECRH}} = 0.7$ MW, at two levels of $n_e = 2.1 \cdot 10^{19}$ m$^{-3}$ and $4.5 \cdot 10^{19}$ m$^{-3}$) were investigated. In these pulses, $n_{\text{He}}/n_e$ was in the order of 40-45%.
The plasma stored energy in these discharges, normalised with \((n/n_G)^{0.11-0.22\log(n/n_G)}\) [10] to account for not exactly identical plasma densities, where \(n_G\) is the Greenwald density, is plotted against the total input heating power \(P_{TOT}\) in Fig. 5a. The stored energy of the He plasmas with low levels of \(P_{ECRH}\) and various levels of \(P_{NBI}\) (red crosses) follows a less favourable scaling with the heating power in comparison to the D plasmas (triangles). However, when \(P_{ECRH}\) is increased on top of constant \(P_{NBI} = 3\) MW (blue crosses), the scaling becomes more favorable, and with \(P_{ECRH} = 2.6\) MW and \(P_{NBI} = 1.6\) MW (green cross), the stored energy in He reaches that of D plasmas. As shown in Fig. 5b, the stored energy in He compared to that in the corresponding D plasmas improves with higher fractions of ECRH, for both H- and L-mode plasmas. The core stored energy \(W_{core}\), assuming a pure plasma up to the pedestal top for the H-mode plasmas, chosen at \(r/a=0.85\), and up to \(r/a=0.77\) for the L-mode plasmas (chosen to match the same ratio of \(W_{core}/W_{TOT}\) of the H-mode plasmas) increases with increasing ECRH fraction from \(~80\%\) with dominant NBI heating to \(~120\%\) with dominant ECRH heating in low density plasmas (Fig. 5c). The edge stored energy in He is, however, consistently lower than that in D plasmas, with a very weak correlation with the ECRH fraction (Fig. 5d). Both large type I and small ELMs are observed in these cases, indicating that they have limited role in defining edge confinement. Only the low density H-mode case and the lower density L-mode case, which also correspond to the highest ECRH fraction, approach the edge stored energy of the D plasmas. As such, the core confinement can compensate the lower edge confinement observed in He plasmas.

The cases with the highest and lowest stored energy ratios shown in Fig. 5, with dominant ECRH and NBI heating, respectively, are now compared in detail. The changes in the temperature profiles are considered, as the density profiles are similar among the He and D pairs. With dominant NBI heating (Fig. 6, ‘NBI’, top row), lower core ion temperatures are observed in He in comparison to D. The normalised ion temperature gradient \(R/L_T\) is also lower in He in the region \(r/a = 0.2 - 0.65\), while the ion heat diffusivity is higher, by a factor of 2 inside \(r/a = 0.5\). Similar to the observations made in He-seeding scenarios (Fig. 4), this is characteristic for increased turbulent transport in the core of He plasmas, in contradiction to the expectations of the gyro-Bohm scaling. With dominant ECRH heating (Fig. 6, ‘ECRH’, bottom row), both the ion and electron temperatures are higher in helium. This increase of \(T_i\) and \(T_e\) in He compensates the loss of confinement linked to the reduced ion density. Additionally, the ion heat diffusivity is lower in He, with similar \(R/L_T\), as in the corresponding D case, suggesting reduced core turbulent transport, unlike the observations in the NBI dominated case and in agreement with the expectations of the gyro-Bohm scaling. In contrast to this low density case, where the ion and electron temperatures in He are higher than those in D across the plasma radius and up to the pedestal top, at higher density (intermediate cases in Fig. 5), only the core temperatures are higher, resulting in a systematic loss of confinement as the edge ion kinetic pressure reduces. The loss of confinement from the edge ion kinetic pressure is also observed in the L-mode cases, implying that the mechanisms at play are not related to pedestal physics but to the plasma density.
The two transport regimes in the plasma core identified in the cases of dominant NBI and dominant ECRH heating are investigated with electromagnetic and electrostatic flux-tube nonlinear gyrokinetic simulations using the GKW code [11], at $r/a = 0.3$ and $r/a = 0.5$, respectively. The He case is simulated by changing only the main ion species to He in the D simulations. While this is limiting the capabilities for comparison to the experiment, it facilitates the identification of the fundamental mechanisms breaking the gyro-Bohm scaling. The contours of the normalised perturbed electrostatic potential are shown in Fig. 7 for D plasmas on the left and for He plasmas on the right. The 'NBI' case shown in the top plots is found to be dominated by Ion Temperature Gradient (ITG) turbulence. The zonal flow strength is particularly stronger in D compared to He plasmas, where the turbulent convective cells are more pronounced ($\langle |\phi_{ZF}|^2 / |\phi_{turb}|^2 \rangle$ equal to 6 in D and 1.23 in He). In complete opposition to the gyro-Bohm expectation, it is found that $\chi_{He}/\chi_{D} = 2.64$. This is not the case in the electrostatic regime, where the zonal flows are weaker in D and lower levels of turbulent transport are found in He in comparison to D plasmas. The 'ECRH' case shown in the bottom plots shows increased $T_e/T_i$ in the core and is Trapped Electron Mode (TEM) turbulence dominated. Here, the zonal flows are less dominant in D ($\langle |\phi_{ZF}|^2 / |\phi_{turb}|^2 \rangle = 1.7$ in electromagnetic simulations) consistent with previous works examining cases with high $T_e/T_i$ and low magnetic shear TEM turbulence [12, 13]. Smaller convective cells are observed in He with $\chi_{He}/\chi_{D} = 0.56$, in qualitative agreement with the gyro-Bohm scaling. Therefore, it is the coupling of zonal flows...
and electromagnetic effects that breaks the gyro-Bohm scaling of turbulent transport, supporting the experimental evidence of increased transport in He in the ITG regime (NBI heated plasmas) only, as seen in Fig. 6. This relates with previous works on the turbulent transport and confinement in H isotope plasmas [13, 14, 15], which connect the isotope effect with the zonal flow activity and electromagnetic effects. $E \times B$ shearing is, however, negligible in these He plasmas, indicating a more fundamental aspect of the electromagnetic stabilisation.

![Contour plots showing the normalised perturbed electrostatic potential](image1)

**FIG. 7.** Contours of the normalised perturbed electrostatic potential in the plane perpendicular to the magnetic field at the low field side, computed from local nonlinear gyrokinetic simulations of the deuterium plasmas (left) with dominant NBI (top) and dominant ECRH heating (bottom). The helium plasma cases are simulated (right), by changing the main ion species to He.

![Graph showing the ratio of normalised most unstable mode](image2)

**FIG. 8.** The ratio of the normalised most unstable mode in the electron scales $\gamma_{etg}$ over that in the ion scales $\gamma_{ITG}$ at $r/a = 0.85$, obtained from linear gyrokinetic simulations for H- (squares) and L-mode (triangles) He plasmas with low (open) and medium to high densities (filled symbols), plotted against the normalised collisional thermal exchange strength. Note, the linear ITG growth rate in He is larger than in D (not shown) for the same parameters [16].

Linear gyrokinetic simulations with GKW are performed to assess the confinement loss observed at the edge of He plasmas. The highest normalised linear growth rates of the ETG turbulence, known to increase electron heat transport, are compared to the ITG growth rates in Fig. 8, in H- and L-mode He plasmas. Their ratio is plotted against the normalised collisional thermal exchange strength $n_e^2(T_e - T_i)/T_e^{3/2}$. For all medium to high electron densities (filled symbols), the collisional thermal exchange in He goes unfavourably from the ions to the electrons. The current understanding is the following: any increase of the turbulent drive ($R/L_T$) is met with a strong increase of the turbulent transport through destabilised ETG modes, resulting in stiff $T_e$ profiles and preventing the increase of $T_e$. At low densities (open symbols), the collisional thermal exchange is reversed and the ETG are less destabilised, allowing an increase of both $T_e$ and $T_i$ (‘ECRH’ case). The loss of edge confinement in both L- and H-mode He plasmas is, therefore, attributed to thermal coupling and ETG destabilisation. Computationally
demanding multi-scale nonlinear simulations are underway to confirm this conclusion. Beyond this explanation, pedestal stability effects contributing to the confinement loss at the edge cannot be excluded.

4. SUMMARY AND DISCUSSION

The degrading effect of He on plasma performance was demonstrated at JET and AUG. Despite the fact that the AUG and JET experiments are not directly comparable, among others due to the different approaches to the He puffing and the lower power flux in the JET case, the effect of the He-seeding on the kinetic profiles has a phenomenological similarity: an increase in the electron density (small at AUG), accompanied by a reduction of the electron and ion temperatures. However, in AUG, a constant electron pedestal pressure is not sustained and the reduction of the produced neutrons is stronger in the JET plasmas. In both ASDEX Upgrade and JET, the stored energy recovers after a He gas puff on the same time scale as the He concentration decays, which is defined by wall recycling and pumping and is different for the two experiments.

Helium plasmas at ASDEX Upgrade with confinement comparable to counterpart D plasmas were created. The confinement of He plasmas is shown to increase with increasing fraction of electron heating. As a result, regimes with large fraction of electron heating and low collisionality, as expected in the initial ITER non-nuclear operation, are found to be beneficial in terms of He plasma confinement and similar to D. It was shown that the variations of confinement in He plasmas are a combination of core and edge effects. The observed impact of nonlinear electromagnetic effects on the gyro-Bohm scaling of turbulent transport in ITG turbulence between He and D can also provide input for understanding the ion mass dependence of confinement.

Further modelling and experimental work is planned to link the observations in He-seeded D plasmas and He plasmas at AUG and to connect the observations of increased transport with the addition of He to D plasmas with the increased transport observed in ITG dominated, NBI heated He plasmas. Plasmas with increasing electron heating fraction can provide a valuable link in the understanding of the transport processes involved.

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