The confinement of helium tokamak plasmas, impact of electron heating, turbulent transport and zonal flows

P. Manas[1], C. Angioni[1], A. Kappatou[1], F. Ryter[1], P. A. Schneider[1]
and the ASDEX Upgrade Team
[1] *Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany*

Helium plasmas in tokamaks are regularly observed to have a reduced confinement with respect to deuterium plasmas [1, 2], which is inconsistent with the gyro-Bohm scaling of turbulent transport. A theoretical explanation of this confinement reduction is required to reliably predict the plasma confinement in the initial non-nuclear phases of ITER operation and also extend the understanding of the isotope effect, hydrogen and helium having the same Larmor radius.

Pairs of D and He steady state phases (for about 4 confinement times) have been performed at the ASDEX Upgrade (AUG) tokamak with identical (among pairs) heating powers (neutral beam and electron cyclotron resonance), plasma current I_p, toroidal magnetic field B_T, $q_{95} = 7.2$ and line averaged core electron densities n_e. H-mode plasmas were produced at $I_p = 0.6$ MA, $B_T = 2.5$ T with the ECRH power (P_{ECRH}) ranging from 0.7 to 2.7 MW, the NBI power from 1.4 to 6 MW and n_e from 4 $\times 10^{19}$ m^{-3} to 6.2 $\times 10^{19}$ m^{-3}. Two pairs of L-mode plasmas have also been performed, one at $n_e = 2.1$ $\times 10^{19}$ m^{-3} and the other at $n_e = 4.5$ $\times 10^{19}$ m^{-3} with $I_p = 1$ MA, $q_{95} = 4$, $B_T = 2.5$ T and $P_{\mathrm{ECRH}} = 0.7$ MW.

The ratio of total stored energies for the companions D and He steady state phases are shown in Fig. 1 where W_{MHD} is computed from a function parametrisation algorithm based on magnetic signal measurements. Additionally, core and edge contributions to the kinetic stored energy are also plotted and are deduced from the measured electron and main ion kinetic profiles assuming a pure plasma ($n_e = n_i$). Comparing all cases, a general trend is observed: the stored energy, or equivalently the confinement time, in helium improves with higher fractions of ECRH. The core and edge components of the stored energies identify two distinct behaviours. In the core, the stored energy in He increases throughout the scan in $P_{\mathrm{ECRH}}/P_{\mathrm{TOT}}$ from $\sim 80\%$ of that in D with strong NBI heating to $\sim 120\%$ with strong ECRH and low density. In contrast, the edge stored energy in He is systematically lower compared to D (with a much lower variation compared to the core) except in the low-

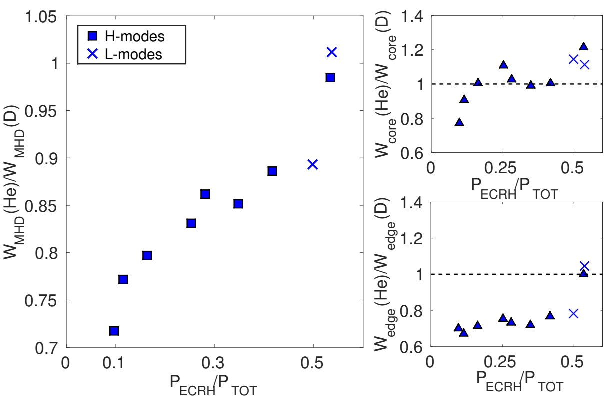

Figure 1: Ratio of the helium to deuterium measured total plasma stored energy against the ratio of ECRH over the total heating power (left panel). Core and edge contributions to the stored energies (right panels).

est density case (which also corresponds to the highest $P_{\mathrm{ECRH}}/P_{\mathrm{TOT}}$) where it becomes similar. The lower density L-mode is also found to have a better He edge confinement compared to the higher density one.

Fig. 2 showcases the time averaged temperature profiles, normalised gradients ($R/L_T = -(R/T)(\partial T/\partial r)$ with R the major radius) and power balance heat diffusivities χ for the highest and lowest stored energy ratios shown in Fig. 1 and denoted by 'ECRH' and 'NBI', respectively. These plasmas have identical (within error bars) electron density profiles between D and He pairs which makes the temperature profile comparison equivalent to the kinetic stored energy comparison.

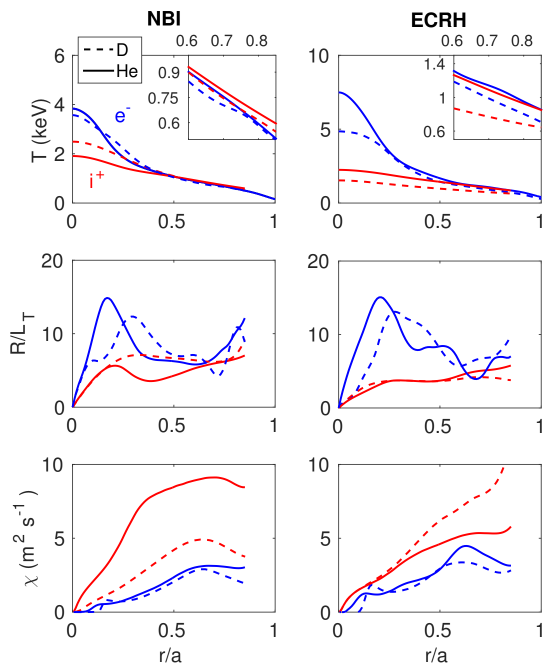

Figure 2: Electron and ion temperature profiles for the highest NBI (left)/ECRH (right) heated plasmas. The normalised temperature gradients R/L_T and power balance heat diffusivities χ are also shown against r/a.

In the high NBI heated case, the core ion temperature profile is lower in He compared to D. The ion normalised temperature gradient R/L_{T_i} which acts as a drive for turbulent heat transport is also lower in the range $r/a = 0.2 - 0.65$ and the ion heat diffusivity is larger (more than a factor 2 for $r/a \leq 0.5$). This is a signature of increased core turbulent transport in He, which is opposite to the expectations of the gyro-Bohm scaling.

For the high ECRH heated case, while one would expect that for identical deposited power on the ions and identical stored energies in He and D, T_i would be 2 times larger in He to exactly compensate the reduced ion density compared to D, it is observed that, not only the ion temperature in He is higher but also the electron temperature T_e. This can be explained by considering the dominant electron heating and collisional energy exchange between ions and electrons, coupling the evolution of T_i and T_e. Furthermore, the ion heat diffusivity is lower in He with similar R/L_{Ti} as in D which suggests reduced core turbulent transport, this time in agreement with the gyro-Bohm scaling. Additionally, in this case, which is also the lowest density case, the ion and electron temperature profiles in He increase on the whole radial domain up to the pedestal top. In contrast, for higher densities but still significant ECRH heating (as the intermediate cases of Fig. 1), only the core temperature profiles in He increase compared to D yielding a systematic loss of confinement from the edge ion kinetic pressure. This feature is also observed for the L-modes pointing toward mechanisms linked to the density rather than pedestal physics.

The two distinct regimes identified in the core of He plasmas in Fig. 2 and the reduced edge confinement are explored by flux-tube nonlinear and linear gyrokinetic simulations of the turbulent transport. First, electromagnetic and electrostatic nonlinear simulations are performed for the core of the 'NBI' and 'ECRH' cases, at $r/a = 0.3$ and $r/a = 0.5$ respectively, using the gyrokinetic code GKW [3]. Input parameters of the D cases are used and a companion simulation is done by changing only the main ion species to He, thus allowing the identification of fundamental mechanisms breaking the gyro-Bohm scaling.

The contours of the normalised perturbed electrostatic potentials are compared in Fig. 3. The turbulence in the 'NBI' case is Ion Temperature Gradient (ITG) dominated whereas in the 'ECRH' case it is Trapped Electron Mode (TEM) dominated and related to the increased T_e/T_i in the core. For the ITG turbulence regime, the zonal flow strength, characterised by $|\phi_{ZF}|^2/|\phi_{turb}|^2 = |\phi_{k_y=0}|^2/\sum_{k_y\neq 0}|\phi_{k_y}|^2$, is particularly stronger in D compared to He plasmas. This yields the opposite result to the gyro-Bohm expectation $\chi_{i,He}/\chi_{i,D} = 2.64$. In the electrostatic limit, zonal flows are weaker in D, resulting in $\chi_{i,He}/\chi_{i,D} = 0.64$. In the TEM regime, zonal flows are less dominant, as also observed in previous works for high T_e/T_i and low magnetic shear TEM turbulence [4,5]. In this case convective cells are smaller in He with $\chi_{i,He}/\chi_{i,D} = 0.56$, which is now in qualitative agreement with the gyro-Bohm scaling. Thereby, the coupling of zonal flows and electromagnetic effects breaks the gyro-Bohm scaling of turbulent transport which is consistent with the current experimental observations of increased transport in He in the ITG regime only. Interestingly, this is also consistent with several previous works on turbulent transport and confinement times for H isotopes [5,6,7].

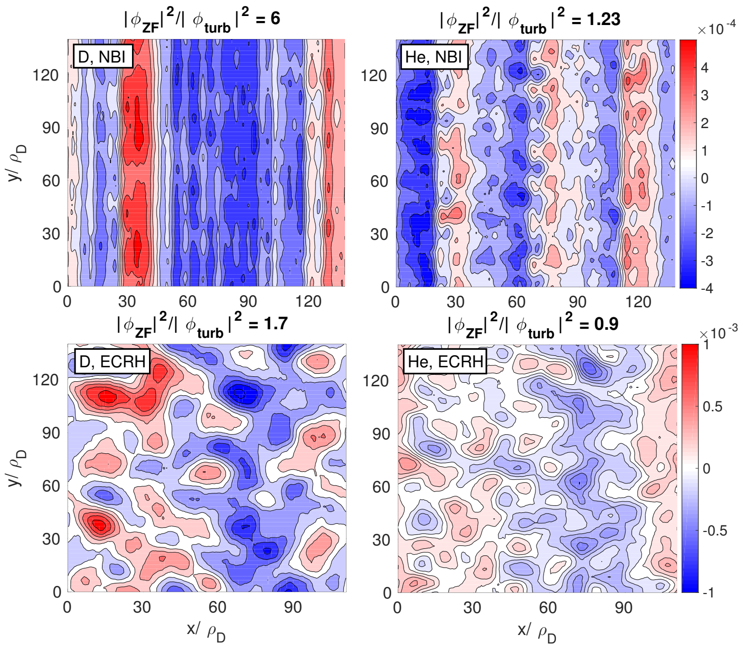

Figure 3: Contours of the perturbed electrostatic potential in the plane perpendicular to the magnetic field at the low field side, computed from local non-linear gyrokinetic simulations of the deuterium NBI and ECRH cases (left panels) at $r/a = 0.3$ and $r/a = 0.5$ respectively. The same simulations have been carried out by changing only the main ion species to He (right panels).

Finally, to account for confinement losses at the edge of He plasmas, the role of Electron Temperature Gradient (ETG) driven turbulence is investigated by linear gyrokinetic simulations.

These electron scales instabilities are known to increase the electron heat transport, in particular via complicated multi-scale interactions (e.g. [8]). The ratio of the normalised most unstable mode in the electron scales denoted by γ_{etg} over the ion scales γ_{itg} is shown in Fig. 4 for the He discharges at $r/a = 0.85$ versus the normalised collisional thermal exchange strength. We note that with the normalisation used, the linear ITG growth rate in He is larger than in D for the same parameters. It is shown that for all medium to high density cases, collisional thermal exchange in He goes unfavourably from the ions to the electrons. Indeed, any increase of the turbulent drive R/L_{T_e} is met with a strong increase of the turbulent transport through destabilised ETG, thus preventing T_e from increasing (profile stiffness). At low densities collisional thermal exchange is reversed and the ETG are less destabilised allowing an increase of both T_e and T_i. Thermal coupling and ETG destabilisation at the edge of He plasmas can thus explain the loss of edge confinement in both L- and H-modes. This result awaits a confirmation by computationally demanding multi-scale nonlinear simulations. Additional effects due to a change in pedestal stability cannot be excluded in more general conditions.

In conclusion, for the first time, in the ASDEX Upgrade tokamak the confinement of helium plasmas is experimentally demonstrated to increase with increasing fraction of electron heating, reaching values comparable to those of the D plasmas. These observations have been identified to be a combination of core and edge effects. Nonlinear electromagnetic gyrokinetic simulations show that the different impact of zonal flows in regulating the core turbulence in the limit of low electron heating in D and He plasmas breaks the gyro-Bohm scaling of transport, leading to higher levels of transport in He. Additionally, the thermal coupling between electrons and ions and stronger destabilization of electron temperature gradient modes lead to reduced confinement at the edge of He plasmas. As a result, regimes with large fraction of electron heating and low collisionality, as expected in the initial ITER pre-fusion power phase of operation, are found to be beneficial in terms of He plasma confinement.

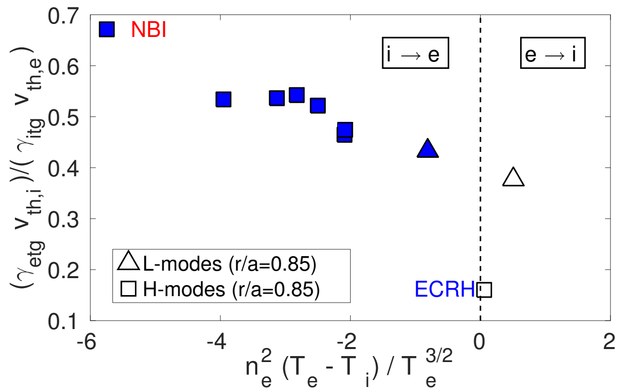

Figure 4: Normalised ratios of the highest linear growth rates of the ETG and ITG instabilities versus the electron to ion collisional thermal coupling strength for He plasmas. Low density cases are represented by open symbols.

References

[1] D. C. McDonald *et al*, PPCF **46**, 519 (2004)
[2] F. Ryter *et al*, NF **49**, 062003 (2009)
[3] A. G. Peeters *et al*, CPC **180**, 2650 (2009)
[4] J. Lang *et al*, PoP **15**, 055907 (2008)
[5] A. Bustos *et al*, PoP **22**, 012305 (2015)
[6] J. Garcia *et al*, NF **57**, 014007 (2017)
[7] Y. Xu *et al*, PRL **110**, 265005 (2013)
[8] N.T. Howard *et al*, NF **56**, 014004 (2016)