Experimental separation of core transport and edge pedestal isotope dependencies by variation of the plasma shape

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The mass dependence of energy confinement in fusion plasmas is still not fully understood. One of the main reasons is the difficulty of making direct comparison studies. Often the cause for this difficulty is multiple different mechanisms influencing confinement. A variety of these mechanisms depending on the hydrogen isotope mass have been reported on in the past [1–4]. If not separated properly, understanding one of these mechanisms always relies on accurate knowledge of the others. In this contribution we present a possibility to separate the influence of the core transport and the edge pedestal on confinement.

In H-mode plasmas there are two major contributions which determine the energy confinement. The heat and particle transport in the core and the stability of the edge transport barrier. Both are largely independent, such that for core transport studies the pedestal top can be regarded as an important boundary condition for the profiles. However, in experiments with different isotopes, here hydrogen and deuterium, it is difficult to match the boundary conditions. The reason for this is a strong degradation of the pedestal in hydrogen compared to deuterium for similar heat and particle fluxes. If the core and edge scale differently with the input heating power, as suggested in [5], it even becomes impossible to match the boundary condition at the same time as the stored energy by only varying the sources. However, to study the impact of the isotope mass on core transport it is beneficial to minimise the impact of the boundary condition.

In this contribution we show how to utilize the plasma triangularity δ to match the pedestal top and the total stored energy with constant source for a hydrogen and deuterium plasma.

Experimental setup

Two plasma discharges with different hydrogen isotopes as main gas have been run in the ASDEX Upgrade tokamak. The discharges have the same plasma current $I_\mathrm{p} = 0.8$ MA and magnetic field $B_\mathrm{t} = -2.5$ T. To compensate the degradation of the pedestal top the triangularity of the hydrogen plasma is varied as shown in figure 1. In the high triangularity $\delta = 0.37$ phase the plasma stored energy rises to the level of the deuterium reference $\delta = 0.25$ (right panel). For the first time in H-mode the same stored energy is achieved for different hydrogen isotopes with the same input heating power as well as with comparable gas puff levels. The heating power was chosen to match the heat fluxes of electrons q_e and ions q_i for the two gases. As shown in figure 2, q_e is matched for

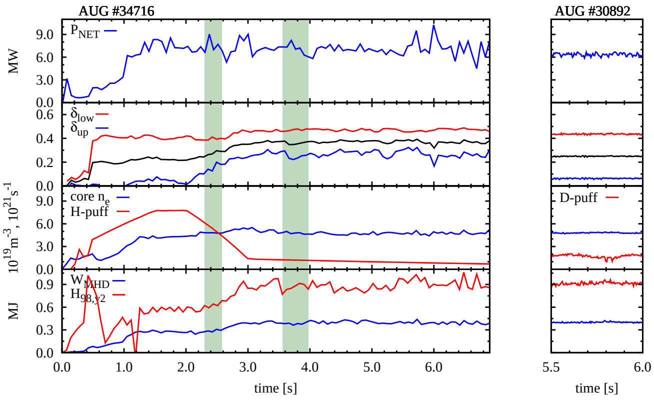

FIG. 1: Time traces of the net heating power P_{net}, triangularity δ, core line averaged density, gas puff, stored energy W_{MHD} and confinement factor $H_{98,\mathrm{y2}}$, for the hydrogen plasma #34716 (left) and the deuterium plasma #30892 (right).

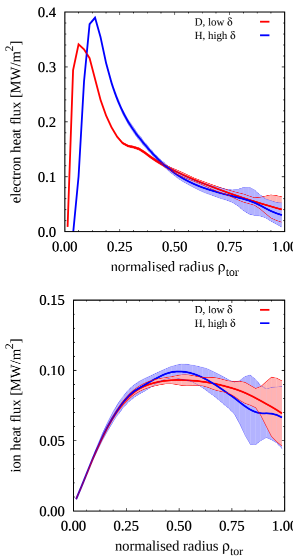

FIG. 2: Heat fluxes of electrons (left) and ions (right) as computed with TRANSP .

$\rho_{\mathrm{tor}} > 0.3$ and q_{i} over the whole radius.

Edge stability

The edge profile measurements (figure 3) illustrate that the pedestal gradients and top values are nicely matched between the high δ H and low δ D plasma. The influence of the plasma triangularity on the ELM stability is assessed in a series of linear stability calculations. While in general one expects a more stable plasma with increasing triangularity [6] this is not the case for triangularity scan in hydrogen. As illustrated in figure 4 the triangularity has no influence on the stability boundary which is dominated by the steep gradients of the kinetic profiles. This is to be expected when the plasma is close to the ballooning boundary which is typically the case for higher collisionalities.

The H and D cases with different δ, where the profiles are matched, are both close to the linear stability boundary. However, the low δ hydrogen plasma with overall reduced confinement is found deep in the peeling-ballooning stable region. This indicates that as soon as the pedestal characteristics (top value, gradient, width) are similar in H and D, the plasmas are consistent with the well established peeling-ballooning theory. However, the pedestal is more easily degraded in H compared to D. The periodic ELM like events in the peeling-ballooning stable region might be H-L back transitions. Although, the heating with over 7 MW is well above the L-H power threshold, the plasma is close to the critical E_{r} necessary for H-mode [7]. The causality behind this observation continues to be under investigation.

Core transport

As discussed in the previous sections the pedestal top can be the same for different isotopes with a match of the sources. This again allows a straight forward treatment of the core transport since the boundary condition at the pedestal is matched. The impact of the triangularity on the flux surfaces vanishes in equilibrium reconstructions for radii $\rho_{\mathrm{pol}} < 0.85$. In the outer region the higher δ also elevates the magnetic shear by $\sim 10\%$ - as calculated without taking different kinetic profiles into account. However, this change is negligible compared to the change in shear caused by the difference in bootstrap current locally at the edge. Due to the steeper gradients the boostrap current is significantly

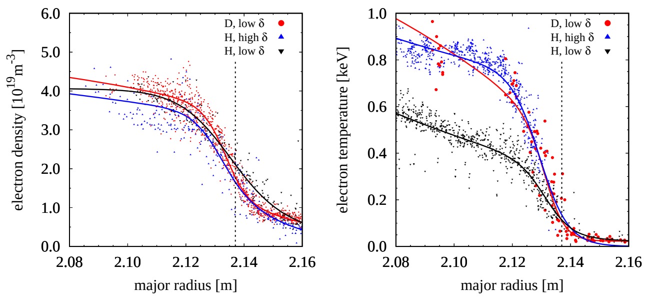

FIG. 3: Electron density and temperature at the plasma edge, the separatrix is indicated by the vertical dashed line.

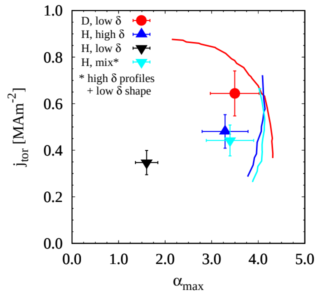

FIG. 4: Linear stability analysis with MISHKA *code (lines).*

larger in the high δ case.

The resulting profiles are shown in figure 5 with the temperatures on logarithmic scale to highlight the gradient lengths. In the ions for $\rho_{\text{tor}} > 0.60$ and up to the pedestal top the temperature gradient lengths is fairly similar at the same time T_{i} is slightly elevated in H (H: blue, D: red). In fact this difference is exactly as big as expected by the gyro-Bohm mass scaling $q_{\text{gB}} \sim M^{0.5}T^{2.5}/B_{\text{t}}^2$. This is illustrated in figure 6 where the ion heat flux is plotted in gyro-Bohm units. The low δ phase in H has a much higher normalised heat flux due to the lower pedestal top temperatures. However, for most of the radius the normalized gradient R/L_T is also larger, which is consistent with the higher normalized flux. Only around mid-radius the ion temperature gradient lengths are comparable which corresponds to a deviation from the gyro-Bohm scaling at this position.

In the inner half of the plasma $\rho_{\text{tor}} < 0.50$ the transport is dominated by MHD mode activity (H: 3/2, D: 4/3). This prevents reliable conclusions about the background heat flux. Although, most of the reduced confinement in the low δ H plasma originates from the edge, linear simulations with the gyro-kinetic code GKW suggest that the growth rates of ITG modes can be enhanced in the core. This is the case when the gradient lengths are reduced because of a lower pedestal height.

The measurements of the charge exchange diagnostics show the importance of the pedestal region on the toroidal rotation. The torque input by the neutral beams is the same for the two different triangularities in hydrogen. The deuterium neutral beam torque calculated with TRANSP is about twice the hydrogen value, therefore, exactly compensating the higher inertia of the deuterium plasma. So the match of the rotation velocity between D, low δ and H, high δ is what can be expected if the momentum transport is comparable in both cases.

Conclusion

It was shown how, with the same heat fluxes and similar gas puffing, matching pedestal top values are achieved despite different hydrogen isotopes as main gas. This is true for electron and ion temperature and electron density as well as toroidal plasma rotation. Already in previous isotope studies the impact of the edge pedestal in H-mode was often highlighted [4, 8, 9]. The presented results strongly support the dominant role of the pedestal in confinement variations due to different hydrogen isotopes.

The interpretation of the observations in the pedestal region is ongoing. Peeling-ballooning theory can explain the observed confinement in the high δ hydrogen plasma. The strong confinement degradation in the hydrogen plasma with low shaping is not explained by linear edge stability. Most likely the inter ELM transport physics governing the build up of the profiles will be crucial in understanding the observed differences.

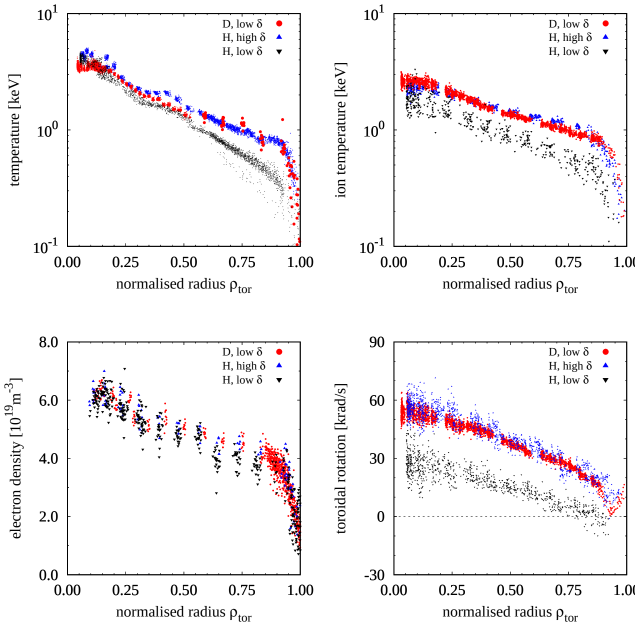

FIG. 5: Electron density, electron and ion temperature as well as toroidal rotation.

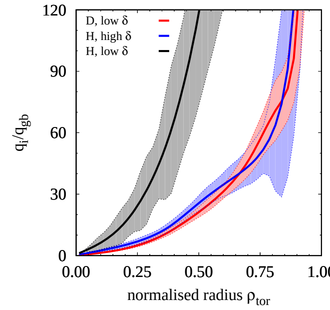

FIG. 6: Ion heat fluxes in gyro-Bohm units for two different isotopes and plasma triangularities.

The different distances to the ELM stability boundary also provide a possible explanation for the different impact of triangularity in H vs. D plasmas: when in hydrogen the transport in the edge is reduced with higher δ, the pedestal can build up until it hits the peeling-ballooning stability - thereby, the energy confinement is improved significantly. In deuterium when the operational point is already close to the boundary, little room is left for improvement, only the impact of δ on the boundary itself will play a role. The latter is very small in the collisionality regime analysed here.

With the match of the pedestal top values via different triangularity the boundary condition does not impact the core isotope studies. Then parts of the core plasma are found to scale with the mass as in the gyro-Bohm scaling. This is observed for the first time in H-mode for different hydrogen isotopes. The very accurate T_i measurements available for these plasmas support this. Still, disentangling the two governing terms in the gyro-Bohm scaling, $T^{2.5}$ and $M^{0.5}$, to a satisfying certainty requires a broader set of data. In particular, a β_N variation is necessary to test theoretical expectations [3], but also the impact of $\nu_\star$ and $T_\mathrm{i}/T_\mathrm{e}$ on transport with different isotopes needs to be investigated. To continue this effort experiments are planned at AUG and JET.

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