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The dependence of confinement on the isotope mass in the core and the edge of AUG and JET H-mode plasmas

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The dependence of particle and energy confinement in fusion plasmas on the main ion mass still challenges the current theoretical understanding of tokamak physics, although it represents one of the aspects of paramount relevance for the extrapolation to a fusion reactor. Moreover, knowledge is required in order to allow the experience developed in hydrogen (H) operation to be directly transferred into a successful operation in deuterium (D), an essential step from the pre-nuclear phase to the nuclear phase in ITER and in any future nuclear fusion reactor.

Many effects, which are connected to different physical mechanisms $[1-6]$, can concur in determining the mass dependence. However, as these mechanisms are often interdependent and can result in non-linear coupling of the edge and the core of the plasma, clear comparisons with the theoretical predictions are hindered by the difficulty of separating their roles. This also prevents a solid progress in the physical understanding.
In this contribution a new method is demonstrated, which allows us for the first time to experimentally separate the effects of core transport and edge pedestal with respect to the mass dependence. This enables unprecedented analyses on the separate properties of these two plasma regions. The resulting knowledge is then applied to mitigate the degradation of confinement in H and investigate previously inaccessible parameter regimes.

In experiments with hydrogen isotopes in the ASDEX Upgrade (AUG) and JET tokamaks a strong degradation of the pedestal is observed in H compared to D plasmas for similar heat and particle fluxes $[4,5]$.
In consequence, a strong interconnection between the core and edge plasma arises in these isotope studies. We demonstrate experimentally that an increase of the plasma triangularity δ for H plasmas results in a matched pedestal top with low δ D plasmas without affecting the core transport properties.
This breaking of the core and edge plasma interconnection allows an independent analysis of both regions.

A data set of H and D H-mode plasmas on AUG (0.8 MA and -2.5 T) and low density hybrid plasmas on JET (1.4 MA and 1.7 T) shows a strong correlation of the core confinement with the fast-ion content.
The fast-ion energy in D plasmas with D-NBI is 2-3 times higher than for H plasmas heated with the same power by H-NBI (FIG. 1(c)).
Therefore, for standard operational conditions the fast-ion content is directly correlated with the isotope mass.
The reason for this is partly the reduced voltage typically used for H-NBI, but also the fast-ion slowing down time which is mass dependent.

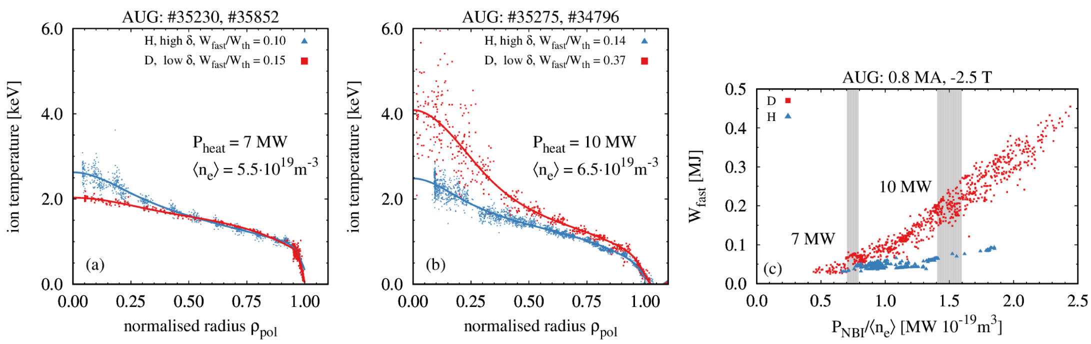

Figure 1: Ion temperatures for low W_{fast} and different isotopes (a). Ion temperatures for high W_{fast} with $W_{\mathrm{fast,H}} < W_{\mathrm{fast,D}}$ and different isotopes (b). Heating power dependence of classical W_{fast} from RABBIT (c).

It is known that ITG turbulence can be stabilised by fast ions in L-mode $[6,7]$ and H-mode $[8,9]$.
For a discharge pair with different isotopes and matched pedestal in AUG non-linear GENE simulations quantify the fast-ion ITG stabilisation. While collisions and EM effects show differences with ion mass, the dom-

inant contribution which allows steeper gradients with D main ions for the same heat fluxes is due to fast ions in AUG (FIG. 1(b)). This explains the possibility for improved core confinement with higher isotope mass when a significant fraction of fast ions is present - typically, $W_{\mathrm{fast}}/W_{\mathrm{th}} > 1/3$.

The comparison of simulations for AUG and JET plasmas allows to assess the relative importance of the different contributions to ITG turbulence stabilisation - collisions, EM effects, $E \times B$ shearing and fast ions. The similarities and differences found between the two tokamaks help to understand how each contribution scales.
E.g. the isotope dependence introduced via fast ions should vary with NBI heating power and will be mitigated with increasing density at constant heating power. This is indeed observed for AUG (FIG. 1) and JET.
The NBI power dependence enters because $W_{\mathrm{fast}}/W_{\mathrm{th}}$ is not constant with power, since $W_{\mathrm{fast}} \propto P_{\mathrm{NBI}}^{\alpha}$ with $\alpha > 1$ while $W_{\mathrm{th}} \propto P_{\mathrm{heat}}^{\beta}$ with $\beta < 1$.

The H-mode pedestal is degraded with lower isotope mass independently of the fast-ion content in the plasma. The reasons for this are the ELM losses/stability or the heat/particle transport or a combination of both.
Linear GENE simulations at the edge of these plasmas reveal drift-wave turbulence to be dominant. Drift waves already exhibited an isotope dependence in L-modes on AUG and JET [10]. While decreasing the isotope mass enhances the linear growth rates of drift waves, stronger plasma shaping will reduce them again. While important for drift waves, little impact of δ on stability is found as expected, because, for the analysed collisionality range the pedestal is mainly ballooning limited.
Drift waves provide a theoretical explanation for the experimental observations of a matched pedestal between differently shaped H and D plasmas. This explanation is supported by measurements with Doppler reflectometers which show a strong reduction of the edge density fluctuation amplitude when increasing δ in H.

Understanding mechanisms that reduce confinement in hydrogen H-modes allows us to counteract them. For the first time H discharges will be run with β_{N} approaching the maximum values achieved in D. Thereby, the β dependence of $\chi_{\mathrm{H}}/\chi_{\mathrm{D}}$ as predicted by theory [3] is tested.
Altogether, this will improve the accuracy of predictions towards fusion plasmas with higher M_{eff} and more dominant fast-ion population and will increase the confidence for transferring to D, the ITER results obtained in H.

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