Modelling and theoretical understanding of the isotope effect from JET experiments in view of reliable predictions for Deuterium-Tritium plasmas

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Abstract

This is an overview of the theoretical understanding of the so called isotope effect in JET Hydrogen versus Deuterium plasmas. Experimentally, weak to moderate deviations from naive GyroBohm scaling expectations are found for the core heat transport in L and H-modes. The physical mechanisms behind such deviations are analyzed in the framework of the Gyrokinetic theory. In the case of particle transport, divergence in edge transport is found to be on the origin of the strong difference on particle confinement. Comparison of such results to expectations for Deuterium-Tritium plasmas in ITER are discussed.

1 Introduction

One of the main theoretical challenges in plasma physics is the understanding of transport driven by turbulence, which is one of the main mechanisms leading to heat losses and loss of confinement in magnetically confined plasmas. Extensive theoretical and numerical studies have unveiled in the latest decades some of the characteristics of turbulence and transport. As an example, transport driven by Ion Temperature Gradient (ITG) [1][2], Electron temperature Gradient (ETG) [3] [4] and Trapped Electron Modes(TEM)[2] [5] has proven to explain heat and particle transport in numerous experiments. Saturation of ITG modes by a self-regulating system between turbulence and zonal flows has been also pointed out as an important mechanism to reduce transport [6].

Whereas the progress of turbulence understating has been impressive [7], notably in a context of increasing computational capabilities which allow extensive non-linear GyroKinetic (GK) simulations, there are still certain issues which remain unclear. One of the most important aspects still not understood is the dependence of heat and particle transport on the plasma main ion mass. Such issue is critical as the expected plasmas used to generate energy by fusion reactions are composed of Deuterium (D) and Tritium (T) ions rather than pure D as usually happens in present-day experiments. Understanding the inherent different between D and DT plasmas is essential in order to properly evaluate the fusion energy production in ITER and future tokamak reactors and as well as for extrapolating plasmas obtained in D to DT.

Special attention has been given to such topic since initial experimental results obtained in DT lead to significant differences with respect to D and even among different tokamaks. In TFTR, the so called supershots, L-mode with $T_i \gg T_e$ and strong input power by Neutral Beam injection (NBI), showed a strong positive dependence of the thermal energy confinement time, t_E^{th} on the effective mass, $M_{eff} = (n_H + 2n_D + 3n_T)/(n_H + n_D + n_T)$, $t_E^{th} \approx M_{eff}^{0.89 \pm 0.20}$ [8]. On the other hand, at JET, the comparison between DD and DT plasmas lead to drastically different results with $t_E^{th} \approx M_{eff}^{-0.25\pm0.22}$ for ELM free regimes while for ELMy H-modes t_E^{th} was nearly independent of M_{eff} [9]. Such contradictory results raised concerns about the extrapolations from smaller tokamak to reactor scale devices and in particular about what kind of fusion energy performance could be expected in ITER. This was particularly evident from the exponent of t_E^{th} in the power law obtained through regression in the Iter Physics Basis (IPB) scaling IPB98(y,2) [10] $t_E^{th} \approx M_{eff}^{0.2}$, quite different from some of the scaling found in dedicated DT experiments, which was used to evaluate the thermal energy confinement in ITER. Such exponent could mask strong non-linear physics and eventually lead to misleading results [11]. Therefore, the theoretical understanding of the physics mechanisms behind such surprising results has been a priority in the field, in particular, in view of future DT experiments.

From pure and simplified theoretical arguments, it has been considered that the turbulence which produces radial transport has a scale length of the order of the ion Larmor radius ρ_i with the decorrelation time of the ion diamagnetic drift time ω_*^{-1}. The resulting thermal diffusivity, i.e. the so called GyroBohm (GB) scaling, would then scale as $\chi \approx m_i^{1/2}$ [2][12]. Such dependence can be also obtained from the typical quasi-linear saturation rule $\chi \approx <\gamma/k_\perp^2>$ with γ the turbulence growth rate and $k_\perp \approx \rho_i^{-1}$ usually used in quasi-linear models for transport such as TGLF [13] and QuaLiKiz [14]. From these approximations, one should expect a degradation of energy confinement, at least in the plasma core where the thermal confinement is dominated by turbulent heat transport, and yet, a significant amount of experiments have shown strong deviations from such expectations both in Tokamaks [8][15][16][17][18][19][20] and Stellarators [21] [22] mostly in H vs D plasmas. On the other hand, scaling compatible with GB transport was obtained in JET DT plasmas [9]. A specific name, "Isotope effect", was created in order to highlight the challenge that such results raised both from the experimental and the theoretical/modelling point of view.

A strong experimental effort has been carried out at JET with the aim of clarifying the origin of the isotope effect. For such purpose, several campaigns have been performed in Hydrogen and Deuterium. Further campaigns in T and DT will provide more evidence on this topic. Results in H vs D plasmas have shown a dependence of the global energy confinement on the isotope used. For L-mode such dependence is $t_E^{th} \approx A^{0.15\pm0.02}$ with $A = m_i/m_p$ with m_p the proton mass. For H-mode plasmas it is found that, $t_E^{th} \approx A^{0.5}$. These results show that the isotope effect depends on plasma conditions and its origin may depend on the different transport physical mechanisms dominant in L or H-modes.

A theoretical and numerical effort has been carried out in parallel to JET isotope experiments with the aim of providing a clearer physics understanding behind the results obtained in the different campaigns. Such activity has been very useful in order to give a deeper insight on the mechanisms leading to the isotope effects but as well has been extremely valuable to prepare the upcoming JET DT campaign by proving the important guidelines. Furthermore, this activity has been accompanied by dedicated analyses of ITER DT extrapolated plasmas in order to study the relevance of JET results towards ITER but as well to guide JET experiments to ITER relevant conditions.

A summary of such results, with a focus on the comparison with recent experimental campaigns performed at JET, will be the focus of this paper. In section 2, a review of the isotope effect impact on the ion heat transport is given. In section 3 the isotope effect on particle transport is analyzed. In section 4, the validity of the quasi-linear approximation to deal with the isotope effect is discussed. Finally, the conclusions are given in section 5.

2 Ion heat transport isotope effect

The physical mechanisms behind the isotope effect on the ion heat transport have been widely analyzed since the first DT results obtained in TFTR. The theoretical challenge is actually double: understanding the conditions where GB transport applies and when deviations to lower transport levels with increasing mass can be expected. Current understanding provided by extensive experiments and associated theoretical analysis at JET will be clarified in the following sections.

2.1 GyroBohm scaling

Analyses about the validity of GB scaling have been undertaken in the framework of the GK theory since non-linear massive GK simulations have been widely possible. Such scaling has been found to be reproduced in the local, electrostatic, collisionless with adiabatic electrons limit, as shown in nonlinear GYRO simulations [23] performed for ITG scales. Very weak deviations were found in ITG-TEM scales in local, electrostatic, collisionless simulations performed with GENE [24]. Even in electrostatic DT simulations at very low collisionality, GB scaling was found with GENE in the case realistic ITER simulations [25].

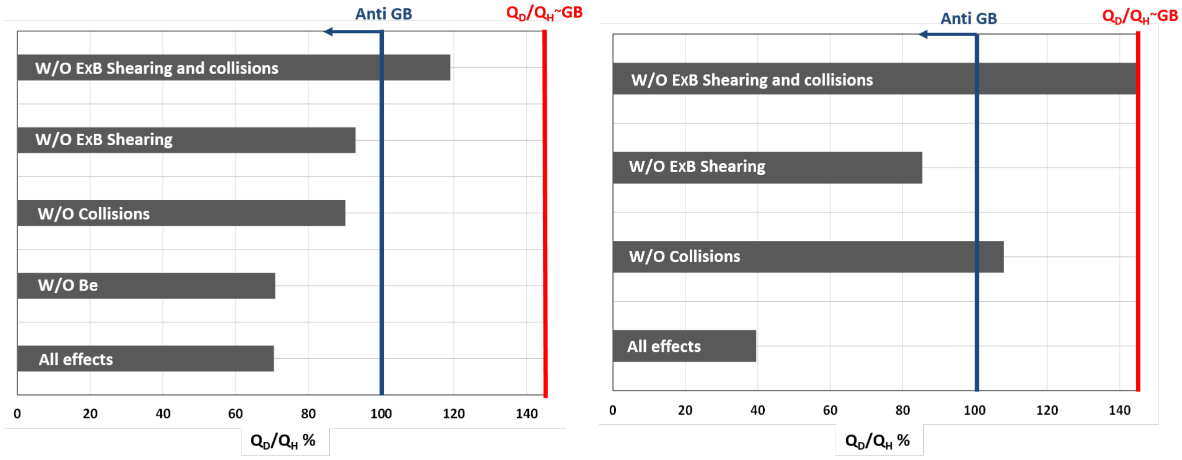

Figure 1: Dependence of the ratio Q_D/Q_H on different physical mechanisms which are removed one by one in non-linear GK simulations for the JET H-mode discharges 91554 in H (left) and 84796 in D (right) when the main ion mass is artificially changed.

Such theoretical results have been confirmed at JET when analyzing experimental core transport in H versus D experiments carried out both in L and H modes [19]. Whereas, a weak core isotope effect was experimentally found in such plasmas, non-linear gyrokinetic simulations performed with the GENE code [4] revealed that GB transport should be expected in electrostatic, collisionless, rotationless with adiabatic electrons limit conditions for L-mode plasmas [26].

All these results suggest that the flux scaling $Q/Q_{GB} \approx m_i^{-1/2}$ is a solid basis for the dependence of transport with m_i and therefore has been used as a fundamental underlying scaling for both quasi-linear and nonlinear GK physics. Extra physical mechanisms are therefore required to explain the reversal of heat flux with mass found in particular experiments.

2.2 $E \times B$ shearing

One of the first physical mechanisms invoked to explain heat fluxes deviations from GB scaling with increasing mass was the existence of radial electric fields leading to $E \times B$ shearing effects on turbulence [27]. Such mechanism was invoked to explain the high thermal energy confinement obtained in L-mode DT plasmas at TFTR and assumes that the ion heat difussivity is of the form $\chi_i = \chi_{i0}(1 - |\omega_{E\times B}|/\gamma_{lin}^{max})H(1 - |\omega_{E\times B}|/\gamma_{lin}^{max})$ where H is the unit step function, γ_{lin}^{max} is the maximum linear growth rate of the dominant instability and the $E\times B$ shearing rate is

$$\omega_{E\times B} = \frac{RB_\theta}{B}\frac{d}{dr}\left(\frac{E_r}{RB_\theta}\right) (1)$$

with R the major radius, B the total magnetic field, B_θ the poloidal magnetic field and E_r the radial electric field. In high NBI power plasmas, such as the ones used in the DT campaign at TFTR, E_r was mainly determined by the toroidal rotation caused by the injected torque. Such mechanism can lead to an inherent isotope effect if the main turbulent instability is assumed to be ITG, with a growth rate which scales as $\gamma_{lin}^{max} \approx v_{thi}/L$ with $v_{thi} = \sqrt{T_i/m_i}$ and L a suitable macroscopic length scale. Therefore, also assuming that $\omega_{E\times B}$ does not depend on the mass as $\omega_{E\times B} \approx E_r/L$ then the ratio $|\omega_{E\times B}|/\gamma_{lin}^{max} \approx m_i^{1/2}$ holds, indicating that the effectiveness of the $E \times B$ flow shear for quenching ITG transport increases with the mass at constant $\omega_{E\times B}$. Such isotope effect has been confirmed in non-linear gyrokinetic simulations involving DD vs DT projected plasmas in ITER [25]. When including $E \times B$ effects from the expected weak ITER rotation, a weak reversal of the ion heat fluxes from DD to DT was obtained.

GK analyses performed for recent JET experiments both in H and L-mode [20] in H and D have indicated that such effects have also played a role for explaining core confinement deviations from GB scaling [12][26]. This is shown in Figure 1 where two H-mode discharges #91554 in H and #84796 in D are analyzed by artificially changing the main ion mass to D and H respectively. In particular, the $E \times B$ shearing approaches the ratio Q_D/Q_H, which

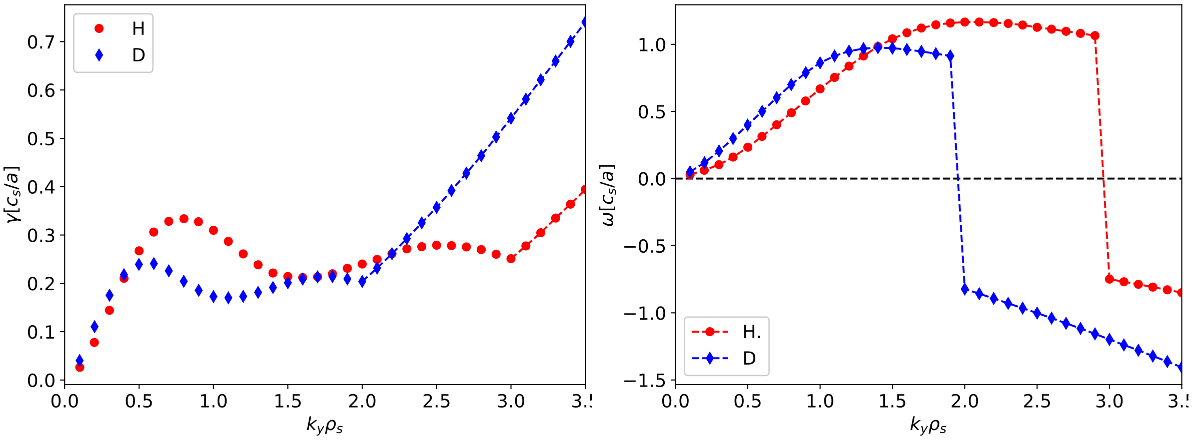

Figure 2: Turbulent linear growth rate γ (left) and frequency ω (right) for the discharges 91450 in H and 89723 in D

is used as a measure about how close the fluxes are to GB scaling, from $Q_D/Q_H \approx 0.5$ up to $Q_D/Q_H \approx 1$ which is closer to the expected value for GB, $Q_D/Q_H = 1.44$.

It is worth pointing out that since the confinement in H is low, the NBI power used in D was relatively low in order to match the kinetic profiles, which means that both the input torque and the toroidal rotation are low, specially for L-mode plasmas. Whereas strong rotating plasmas will show a stronger impact of the $E \times B$ shearing on the isotope effect will be corroborated in future T and DT campaigns.

Furthermore, experimental confirmation of the role of $E \times B$ shearing on the isotope effect is difficult as in practice the toroidal rotation significantly changes for different isotopes due to differences in torque when NBI is used [20]. Furthermore, an intrinsic isotope effect on momentum transport could possibly play a role too.

2.3 Collisionality

The plasma collisionality, in particular the ion-ion collision, can play a role on the isotope effect through the dependence on the ion mass as shown in equation 2 for the ion-ion collision frequency,

$$\nu_{ii} \approx \frac{Z^4 e^4 ln\Lambda}{8\sqrt{2}\pi\epsilon_0^2 m_i^2 v_i^3}(2)$$

with $ln\Lambda$ the Coulomb logarithm, ϵ_0 the vacuum permitivity and v_i the ion thermal speed.

In the case of JET, the impact of collisionality on core transport has been extensively analyzed for both H-mode [12] and L-mode [26] in plasmas that are in a mixed ITG-TEM regime as shown in Figure 2 for the L-mode discharges 91450 in H and 89723 in D. The linear analyses show that the growth rates in the ITG range for both discharges peak at a different wave-number ($k_y^{\max}\rho_s \approx 0.52$ for D and $k_y^{\max}\rho_s \approx 0.75$ for H). This difference is, however, due to the different mass that enters in the definition of ρ_s. Indeed, we see that they approximately satisfy $(k_y^{\max}\rho_s)_H \approx (k_y^{\max}\rho_s)_D * \sqrt{m_H/m_D}$, thus following the Gyro-Bohm (GB) scaling. We also find that the maximum growth rate for ITG modes $\gamma_{\max}$ is lower for D, $\gamma_{\max,\mathrm{D}} = 0.24\, c_s/a$, than for H, $\gamma_{\max,\mathrm{H}} = 0.33\, c_s/a$. This trend also closely follows the Gyro-Bohm scaling as $\gamma_{\max,\mathrm{D}} \approx \gamma_{\max,\mathrm{H}} * \sqrt{m_H/m_D}$. Therefore, from the pure ITG scale analyses no deviations from GB expectations is obtained in linear simulations. In order to highlight deviations from GB transport non-linear simulations are needed.

The non-linear impact of collisonality is shown in Figure 1 for H-mode pulses where removing collisions can even reverse Q_D/Q_H from anti GB scaling to weak GB scaling. It is also found that collisionality is essential to recover the experimental fluxes and that it suppresses TEM modes and the ITG fluctuation amplitude while increasing the zonal flow shearing. All these combined effects lead to a reduced transport for both H and D but the effect is stronger in D. A similar trend, although weaker, was found in the core of L-mode plasmas where it was found that TEM are essential to explain deviations from GB scaling as they are strongly stabilized by collisionality [26]. In fact, assuming pure TEM simulations, the deviation of GB scaling with collisonality is stronger than in mixed ITG-TEM.

These JET results are in agreement with TEM dominated plasmas developed in helical plasmas [28]. Nonlinear gyrokinetic simulations performed with the GKV code [29] have identified a strong isotope effect through the collisional TEM stabilization, stronger with increasing mass, which is non-linearly enhanced by an increased impact of zonal zonal flows which is particularly enhanced in the near-marginal TEM stability.

The role of collisionality has been found to be significantly stabilizing in ITER hybrid extrapolated plasmas [26], however, no heat flux reversal from DD to DT was found in dedicated collisonality scans. Indications that in such case, close to threshold, Trapped Ion Modes (TIM) play a role may explain the difference with respect to isotope effects in plasmas with TEM. TIMs are a prototype of kinetic mode since they are driven through the resonant interaction between a wave and trapped ions through their precession motion. Although TIMs have been theoretically studied [30][31], their relevance in present days plasmas is not well understood as they are usually not found in turbulence studies. This indicates that extrapolation of isotope studies from present day plasmas to ITER could encounter difficulties as different turbulent regimes might play a role in ITER transport.

2.4 Adiabatic vs kinetic electrons

Kinetic electrons were originally found to play a role on the isotope effect when TEM were destabilized even in collisionless plasma conditions [24]. Such results have been confirmed for the core transport of L-mode JET plasmas by means of GENE simulations were kinetic electrons allow for a deviation of 20% from GB scaling when the plasma mass is artificially changed from H to D [26]. A similar trend has been found in the edge region for the same plasmas [32] by performing linear simulations with the GENE code. Indeed as pointed out in the previous section, collisionality has been found to play an important role on this physical mechanism by damping the parallel electron dynamics allowing the ion mass to have a stronger effect on the instability. It is important to notice that this effect is not related to a change of the effective collisionality but it is related to the change of the isotope mass itself, pointing to a role of m_e/m_i when the electron parallel dynamics is strongly damped by collisions. Actually, in non-linear simulations for the edge region, higher heat fluxes are found in H with respect to D simulations at high collisionality while, at low collisionality, consistency with the GB expectations is found for the fluxes.

Such results are in agreement with non-linear simulations performed with the CGYRO code [33] for a L-mode DIII-D plasma. Whereas for the plasma inner core, non-adiabatic electrons play a minor role (similar to the one found for JET) at the plasma edge it strongly regulates the turbulence levels and plays a key role in altering and in the case of the DIII-D L-mode edge, reversing naive GB scaling [34][35]. Such results are important as they point out a key element which could play a significant role of the isotope effect on the L-H transition [19].

2.5 Zonal flows

Zonal flows are important mechanisms that regulate turbulence and transport [6]. Basically, zonal flows are electrostatic potential fluctuations with m=n=0 and finite radial structure. They are self-generated by turbulence and it is an essential ingredient on the saturation of ITG turbulence through the energy transfer from drift-waves to m=n=0 modes [36][37].

An isotopic dependence of residual zonal flows was first found for finer scale zonal flows, narrower than the ion banana width [38]. In general, the influence of zonal flows on the isotope effects has been extensively analyzed in dedicated GK simulations. Zonal flows play a role on weak deviations from GB scaling even in collisionless plasmas in ITG-TEM and TEM regimes as found with GENE [24] however such effect was weak and did not lead to a heat flux reversal for the conditions analyzed.

The experiments performed at JET did not lead to conclusive results regarding the impact of zonal flows in the core or edge regions [32]. However, zonal flows have been found to play a much stronger role in plasma conditions where this phenomenon is boosted. Such is the case, for instance, of plasmas close to threshold [39][40]. This was found on DT vs DD plasmas for ITER that naturally are close to threshold [25]. In particular, when electromagnetic effects were considered, a weak reversal of the ion heat flux from DD to DT was obtained as a consequence of a boost of zonal flow activity at high beta in ITG dominated plasmas. Interestingly, it is found that the radial correlation length follows GB scaling while longer correlation scales do not. This points out to a mechanism that could be validated in experiments. Closeness to threshold is also found to play a role in TEM dominated plasmas in the 3D stellarator geometry, for which zonal flows are mostly responsible for strong deviations from GB scaling [28]. Further evidence about the coupling of electromagnetic effects, zonal flows and mass was also found in ${}^3H_e$ plasmas at Asdex-U [41].

The impact of zonal flows on the isotope effects can be understood in a similar way to the main flow $E \times B$ shearing, however in this case, the $E \times B$ shearing has a zonal origin and it is generated by the turbulence itself [6]. This indicates that multi scale effects could play a role on the isotope effect as different scales are affected in a different way by the $E \times B$ shearing.

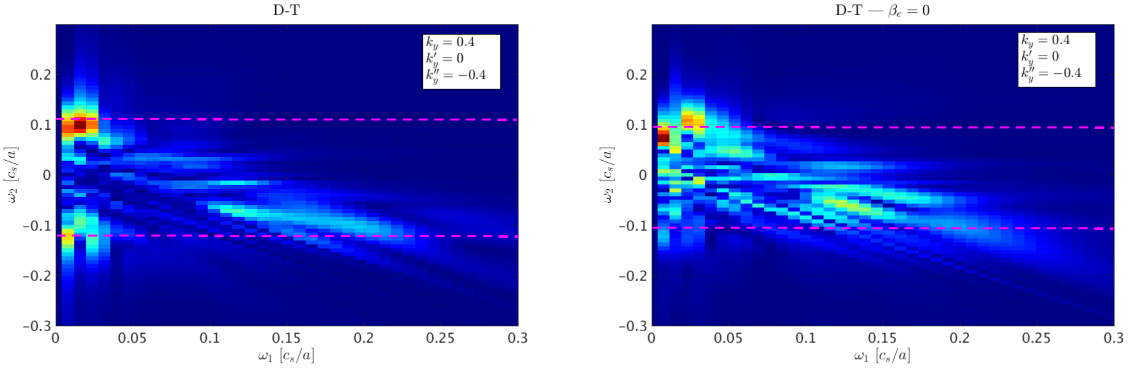

Figure 3: Bispectral analysis performed for $k_y = 0.4$ and $k_y = 0$ for the ITER hybrid DT case including electromagnetic effects (left) and excluding it (right). The pink dashed line indicates the frequency of the ITG mode at $k_y = 0.4$

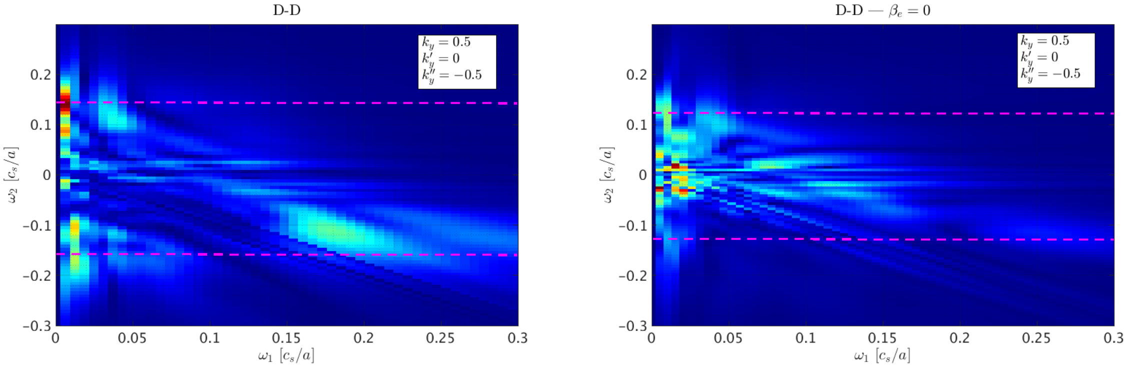

Figure 4: Bispectral analysis performed for $k_y = 0.5$ and $k_y = 0$ for the ITER hybrid DD case including electromagnetic effects (left) and excluding it (right). The pink dashed line indicates the frequency of the ITG mode at $k_y = 0.5$

Whereas the direct impact of zonal flows on the isotope effect is poorly understood experimentally, numerical results point out that the isotope behaviour could be quite different in future devices compared to the results obtained in present day devices due to the different behaviour of turbulence. In particular, in larger devices, the expected dependence of thermal energy confinement on ρ_* in H-mode, $\Omega_i \tau_{th} \approx \rho_*^{-3\pm0.2}$ [42], with Ω_i the ion cyclotron frequency, suggests that turbulence levels might be quite low and changes of isotope could lead to significant turbulence stabilization.

2.6 Electromagnetic effects

Electromagnetic effects have been shown to play a significant role on turbulence. Whereas linear GK simulations have shown that ITG turbulence can be reduced at increasing beta [43][44], it was found at JET that such effect is stronger non-linearly [45][46] due to the boosted correlation time of the triplet interaction of the unstable mode, stable mode, and zonal flow [47]. Due to the bad confinement obtained in H, no high core beta comparisons were obtained in H vs D at JET [20]. This will change when performing T and DT plasmas as the expect good confinement will allow to reach high beta regimes. This is important as there are indications that electromagnetic effects at high beta might play a role on the isotope effect. As pointed out in the previous section, electromagnetic effects have been found to lead to isotope effects via zonal flow enhancing at high beta [25]. This is shown in Figure 5 for an ITER case in DD vs DT where only β_e, with $\beta_e = 2\mu_0 p_e/B^2$ and μ_0 the vacuum permeability, p_e the pressure and B the magnetic field, is changed and all the other parameters are kept constant. At $\beta_e = 0$, i.e. the simulation is electrostatic, the ratio Q_{DT}/Q_{DD} closely follows GB scaling $Q_{DT}/Q_{DD} \approx 1.11$ whereas at $\beta_e = 2.52\%$ there is a weak reversal of fluxes with $Q_{DT}/Q_{DD} \approx 0.77$.

In order to evaluate the nonlinear coupling bewteen ITG unstable modes and zonal flows, a bispectral analysis of the binormal, k_y and radial k_x Fourier modes has been carried out for the electrostatic potential in the cases of DD vs DT including and excluding electromagnetic effects. The technique used here is based on the decomposition

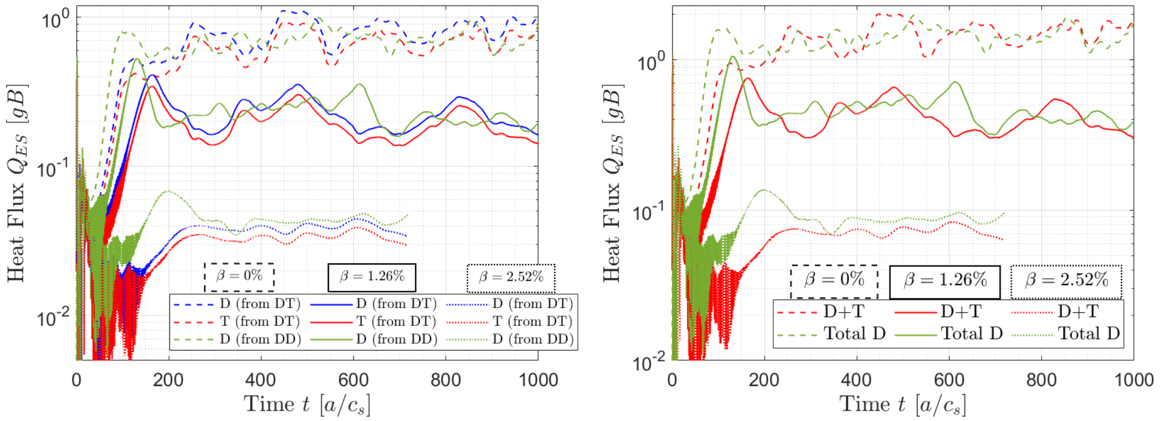

Figure 5: Time evolution of the ion heat flux for D (from DD) and D and T (from DT) from non-linear GK simulations for ITER. Several values for β_e are considered whereas all teh other parameters are identical. (left) Time evolution of the total ion heat flux for DD and DT from non-linear GK simulations for ITER. (right)

in time of the wavelet transformed field fluctuation [48] [49]. The k_y analyzed for each case involves one mode close to the maximum growth rate and $k_y = 0$ corresponding to the zonal flow. The results are shown in Figure 3 and Figure 4. In both DT and DD cases, the inclusion of electromagnetic effects clearly enhances the coupling between the ITG mode and the zonal component (at $\omega_2 \approx 0$). Furthermore, at $\beta_e = 0$, the coupling is stronger in the DT case compared to the DD case, confirming that in general the impact of zonal flows should be stronger in increasing mass plasmas.This behaviour is also clear at $\beta_e > 0$, where the intensity of the coupling is stronger.

Whereas the trend found with β_e is weak, it is worth to point out that high beta is usually obtained at JET in plasmas with high torque (and hence rotation and $E \times B$ shearing) and fast ion content, which can lead to a favourable situation where concomitant weak isotope effects can lead to strong deviations from GB scaling. This will be tested at JET during the T and DT campaigns.

Surprisingly, as beta is low, electromagnetic effects have also been found to play a critical role at the edge of JET L-mode plasmas although beta is relatively low in that plasma region, $\beta_e = 2.2 \times 10^{-2}\%$ [32]. Comparisons between H and D show that including electromagnetic effects both in linear and non-linear simulations have strong effects in both isotopes however it is found a strong enhancement of the fluxes, specially for H, at values of β_e much lower than those predicted from linear simulation. These strong electromagnetic effects in non-linear simulations can be related to the fact that larger structures in the electrostatic potential, with more MHD-like properties, become dominant when increasing β_e at values well below the linear MHD limit. The parameter $\hat{\beta} = \beta_e(qR/L_\perp)^2$ with $L_\perp$ a suitable normalized perpendicular scale length is identified for the importance of electromagnetic effects in non-linear simulations, i.e. when $\hat{\beta} \approx 1$ such effects should be considered. The fact that electromagnetic effects play a role at the edge and that it is different for different isotopes points out to inherent limitations in L-mode confinement which could disappear at increasing isotope mass, in particular in T and DT.

2.7 Impurities and mixed plasmas

The expectations of an increase of heat transport with increasing ion mass following GB scaling were based on the assumption of the existence of a single ion specie in the plasma. However it is well known that plasmas are usually polluted at some degree by impurities generated by the plasma wall interaction [**?**] as it became evident at JET after the installation of the Iter Like Wall (ILW). Furthermore, the plasmas expected to generate fusion energy are a mixture of D and T and in such conditions, a clear isotope effect was also found in the first DT campaign performed at TFTR [8]. Therefore it is essential to clarify the impact of multi ion plasmas on the isotope effect.

The presence of impurities has been identified as a source of deviations from the intrinsic mass scaling for the linear growth rate [50] in both ITG [51] and TEM [52] dominated plasmas, suggesting that mixed plasmas can lead to a different behaviour than single ion plasmas. This is of particular importance for tokamak devices with a metallic wall for which pollution by impurities is a usual feature. This is the case of JET, where the presence of Berylium, Nickel or Tungsten in the plasma core is common even for plasmas with no strong impurity core accumulation [53].

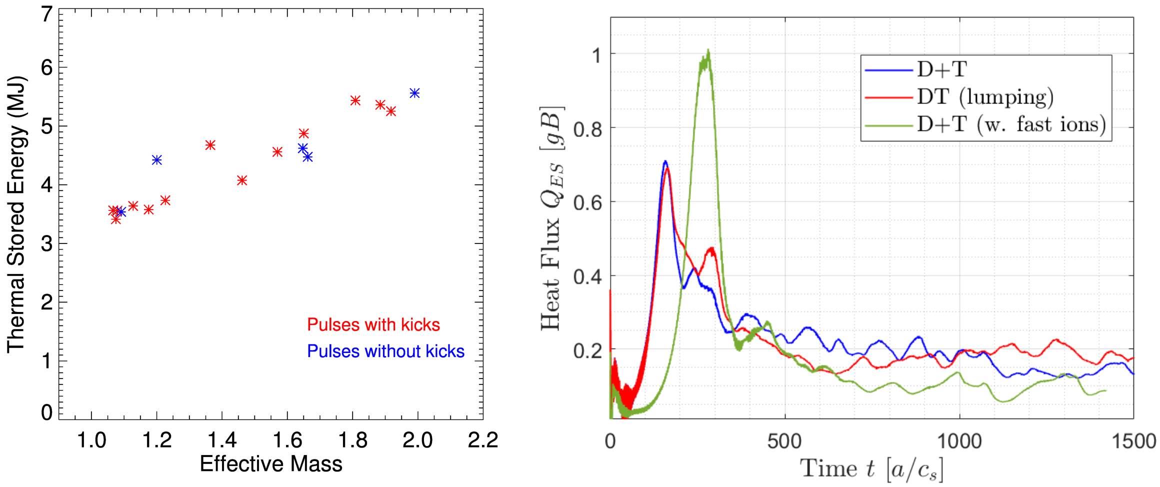

Figure 6: Thermal stored energy dependence on the effective mass at JET.(left) Time evolution of the total heat flux from non-linear GK simulations for ITER including DT as separate species, DT as a single specie with $M_{eff} = 2.5$, and finally including the fast ion species from NBI and fusion reactions in the DT case. (right)

Such possibility has been analyzed in dedicated JET plasmas by performing non-linear simulations with GENE including beryllium as an impurity. As shown in Figure 1 beryllium definitely contributes weakly to deviations from GB scaling in JET in H-modes. However, further studies are being performed in other plasma conditions with stronger impurity content.

If multi ion plasmas can behave in a different way than single ion plasmas, this can have a significant impact on fusion energy generation which will use DT mixtures. Therefore, understanding mixed plasmas is essential. Experiments with mixtures in H and D at different concentration levels have been performed recently at JET showing that mixed plasmas can deviate from naive expectations from pure H and D plasmas. Experiments with 8-10 MW of NBI were performed by scanning the effective mass, M_{eff} [54]. The thermal stored energy in these discharges did not rise linearly with M_{eff}, instead exhibited a plateau with near constant stored energy for $1.2 < M_{eff} < 1.8$. However, since such experiment was performed at constant power, type-III ELMs, rather than type-I, were obtained at low M_{eff}. Recently, further experiments were performed by increasing the power injected to 13MW and by keeping constant as well the ELM frequency, which in type-I ELMs regimes increases with power, by using the so-called kicks [55]. The kicks is a technique inducing fast vertical plasma motion which allows ELM frequency control. The thermal stored energy, W_{th} dependence on M_{eff} is shown in 6. Unlike previous results, a linear dependence of W_{th} on M_{eff} is obtained with little influence of the ELM frequency. From such results, it would be tempting to assume that transport in mixed plasmas has a linear dependence on M_{eff}. In particular, in 50% DT mixtures, deviations from that dependence could indicate alpha particle effects. However extended analyses, beyond the scope of this paper, are required to confirm such hypothesis.

Further evidence supporting a linear dependence of transport on isotope mixtures, at least in the ITG regime, was obtained in the analyses of DT plasmas for ITER with GK non-linear simulations with the GENE code [25]. As shown in Figure 6, the ion heat fluxes obtained considering 50%/50% D and T as separate species and lumping into a single one with $M_{eff} = 2.5$ lead to very similar results, $Q_i(D+T)/Q_i(M_{eff} = 2.5) \approx 1.14$.

A possible link between residual zonal flows in DT plasmas and impurity content has been shown to exist [56]. Depending on the gyroradius of impurities, larger or smaller than that of main ions, the intermediate scale (radial wavelength between trapped ion radial width and trapped electron radial width) residual ZF level can significantly change. Evidence of such behaviour is expected to be obtained in the upcoming JET DT plasmas.

2.8 Fast ions

Pure isotope effects can be masked in experiments by changes in operational conditions when changing the main ion mass. Changes in input torque and input power characteristics or deposition can lead to differences in confinement which are not directly related to an inherent change of the transport characteristics. Such effects are not covered in this paper, however, due to its special relevance for DT plasmas, the role of energetic ions on the isotope effect is going to be covered in this section.

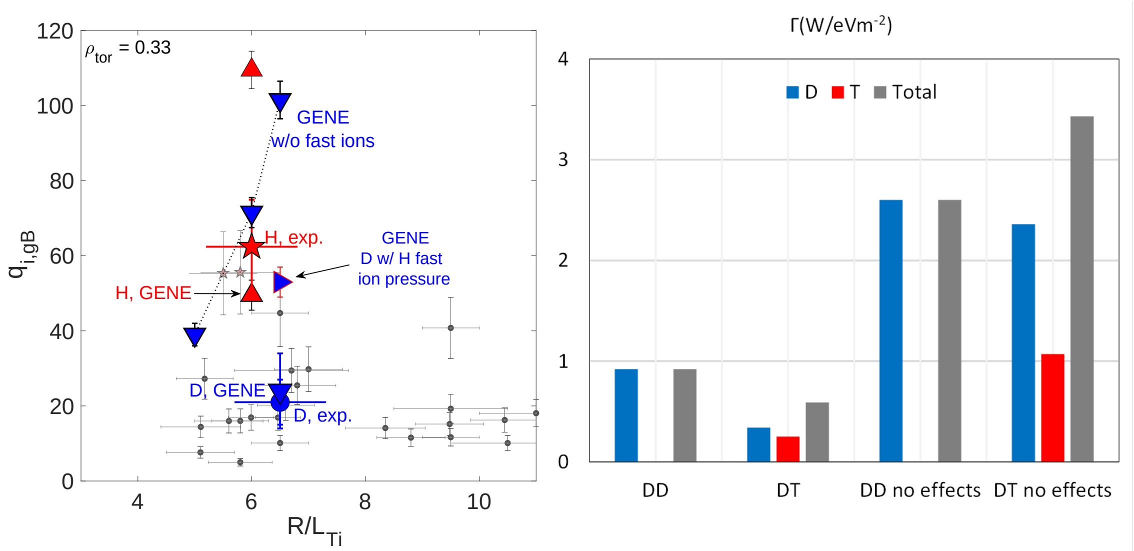

Figure 7: Ion heat flux obtained from GENE for a couple of JET L-mode discharge in H and D. The values of the heat flux for the D case are well reproduced when the fast ion content is taken into account, while without fast ion the stiffness is too high. By artificially replacing the level of fast ions in D by the one obtained in H, the heat flux is very similar to the H levels (left) D and T particle fluxes in DD vs DT simulations for ITER hybrid scenario including external $E \times B$ shearing and electromagnetic effects or removing such effects (Right)

Fast ions generated by heating systems were discovered to significantly reduce turbulent transport in both L-mode [57][58][59] and H-mode [45][46][60] plasmas at JET as well as in other devices such as Asdex-U [61][59]. Such strong impact is mostly seen with a combination of high fast ion pressure gradient, obtained at high input power, in electromagnetic simulations. The characteristics and amount of fast ions depend on the main ion plasma through collisions as in particular the slowing down time depends on the main ion mass, $\tau \approx m_i T_e^{3/2}/Z^2 n_e ln\Lambda$ with T_e the electron temperature and n_e the electron density. Therefore, it is expected that inherent differences appear when changing the main ion mass if the input power remains the same. Such changes could lead to an overall different confinement for different isotopes. This is specially important for DT plasmas through the generation of energetic alpha particles at 3.5MeV. Although such effect could have at least partially explained the strong isotope effect found in TFTR L-mode high power plasmas in DT [8], it was not identified at that time.

In order to validate the hypotheses that differences in fast ion generation can mask an isotope effect, dedicated experiments and GK analyses were performed in H vs D plasmas at JET in L-mode [62]. As shown in Figure 7, indeed the different fast ion characteristics in such plasmas, notably in terms of fast ion pressure gradient, can explain the better core thermal energy confinement found in D with respect to H. This is shown by including/excluding the fast ion content for H and D. Whereas the fast ion content significantly stabilizes ion heat transport in both species, the effect is stronger in D due to the higher fast ion content. An extra simulation was performed by exchanging the fast ion content for the D plasma with the fast ion content from the H plasma. Clearly, the heat fluxes obtained are similar to the H plasma with fast ions.

The fact that the presence of fast ions can significantly change the transport characteristics between different isotopes is a key point to understand how to extrapolate DT plasmas from DD. This has been analyzed for the case of DT vs DD plasmas in ITER by means of non-linear GK simulations with the GENE code when considering both the fast ions from NBI and also the alpha particles [63]. As shown in Figure 7, such particles can have a strong stabilization effect on the ITG dominated plasmas in ITER, an effect stronger than the inherent isotope effect also found from DD to DT. It is worth to point out that considering the inherent isotope effect from DD to DT plus the impact of fast ions, the heat fluxes obtained for the core of ITER is quite low, $Q_i \approx 0.1[gB]$, which means that turbulence is nearly fully stabilized.

2.9 Summary

In previous sections, different physical mechanisms have been shown to play a role on deviations from GB expectations for the ion heat transport. It is clear that pure GB scaling cannot be expected in realistic experimental conditions in present day plasmas as it would require rotationless collisonless, electrostatic, single ion pure ITG plasmas. However, this does not mean that strong deviations from GB scaling could be expected either at least from the plasma core. In contrast to TEM dominated plasmas, GK simulations have shown that the different physical mechanisms leading to isotope effects are weak in the core of ITG regimes and they can be likely masked by operational differences when working at different isotope gases. Since ITG dominated plasmas are prevalent in JET and likely to be the case for ITER, it remains open the question whether strong isotope effects can be observed in the plasma core of such tokamak devices. This is an important aspect in view of potential strong differences between DD and DT plasmas in ITER which could lead to operational issues when starting the fusion ITER phase.

The answer to that question might come from the TFTR results in L-mode in the presence of strong NBI input power [8] and the non-linear GK results obtained for ITER [25][63]. In both cases, there are indications that concomitant physical mechanisms, which individually could lead to weak isotope effects, might lead to strong deviations from GB scaling even in ITG plasmas. This would be the case for plasmas with a strong torque and rotation, high beta (favouring the impact of zonal flows) and high fast ion fraction as expected for some ITER DT scenarios, in particular the hybrid [64][65][66].

It is therefore important to investigate such possibility before ITER reaches its DT phase. For such purpose, JET is going to explore those plasma regimes in a new DT campaign.

3 Particle transport isotope effect

Compared to the extended studies about the role of isotope effect on the ion turbulent heat transport, particle transport has been much less studied. However, JET results have shown that particle transport, both in the electron and ion channels, is strongly impacted by the isotope effect. At JET, the electron particle confinement is found to closely follow that of the thermal energy confinement, both in L-mode, $N_e \approx A_{eff}^{0.12}$, and H-mode, $N_e \approx A_{eff}^{0.57}$. The strong dependence in H-mode type-I ELMs plasmas has its origin mainly from the significant increase of the pedestal density with increasing mass [19].

Analytical and numerical studies with the GK code GKW [67] have shown that differences in the electron particle flux with different isotopes can provide from the trapped particle convection induced by collisions [68]. This convective contribution is directed outward in ion temperature gradient turbulence, increases with increasing collisionality, and is proportional to the square root of the ion mass, keeping all other parameters the same. Nonlinear gyrokinetic simulations have shown that this effect can produce measurable differences, particularly when comparing H and T, leading to the expectation that the peaking of the density profiles of H plasmas be slightly higher than those of D. However, in the particular case of JET L-mode H and D plasmas with a maximum of one positive ion neutral injector of the NBI system shows an overall clear trend of decreasing density peaking with increasing collisionality, but provides weak evidence only of different density peaking between H and D plasmas. Data from T plasmas will be used to compare to H plasmas in order to further validate such expectations.

Ion particle transport in JET isotope experiments has shown surprising results. In mixed H/D plasmas, it has been shown that there is a clear asymmetry between electron and ion transport [69]. This could be surprising taking into account that electron and ion particle transport must fulfill radial ambipolarity. However such is the case in single ion plasmas, in multi ion plasmas, transport can be different if the particle diffusivity and pinch for electrons and ions are clearly different.

The evidence for asymmetrical electron and ion transport in mixed H/D plasmas was obtained at JET in dedicated experiments where scan on the H/D composition with different gas fuelling and using D NBI to heat the plasma. The central isotope composition was indirectly inferred from the neutron rate. TRANSP analyses showed that ion diffusivities are much higher than electron diffusivities, $D_i >> D_e$, however that also means that the ions convective pinch is strongly inward $V_i << 0$. In such conditions, the plasma is characterized by the uniform isotope ratio profile regardless of the location of the particle source of each species.

Theoretical and numerical studies for these JET plasmas have been performed with QuaLiKiz and GKW [70][71]. Results show that in ITG turbulence regimes,as the ones usually obtained in JET H-mode plasmas, ratios of the ion to electron diffusive and convective terms up to 5 are obtained. Such values lead to the concept of fast ion mixing, i.e. ion transport much faster than electron transport. On the other hand, in cases with TEM dominated turbulence, both the ion diffusivity and pinch would be lower than those for the electrons, allowing for similar time scales. Since ITER and fusion reactors are expected to work with palsmas dominated by ITG turbulence, fast ion mixing can definitely provide good core D and T mix for optimal fusion power generation.

The GK analysis of D and T particle flux is essential to understand differences between present day plasmas and DT.Some effort has been carried out towards such goal. Initial results obtained with the GYRO code pointed out to an asymmetry, in terms of fluxes, between D and T particles fluxes in 50%-50% mixtures [72]. Further analyses

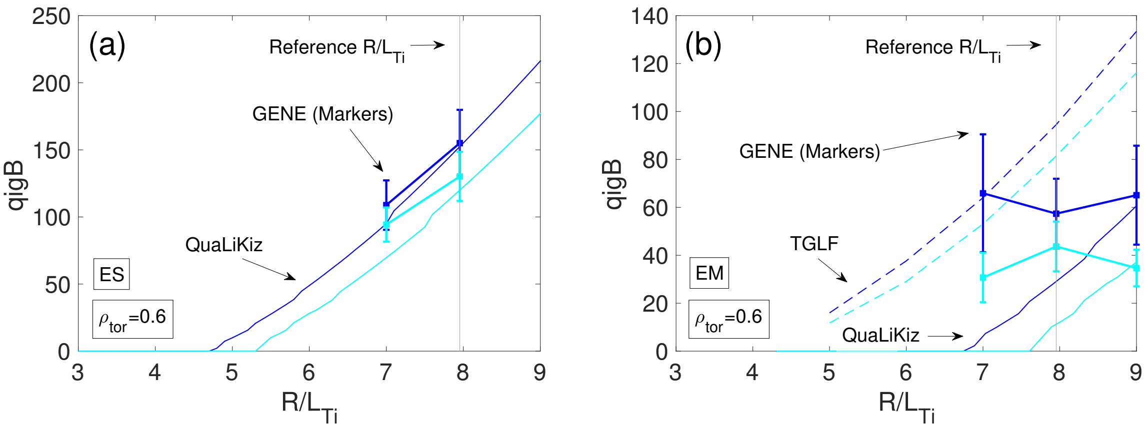

Figure 8: Comparison between the ion heat flux in D (dark blue) for the discharge #94875 and the one obtained by artificially changing the main ion mass to T (light blue). The GENE fluxes are compared to the ones obtained from Qualikiz and TGLF in electrostatic (left) and electromagnetic (right) conditions.

showed that such results strongly depends on the assumption about perfect 50% mixture and the fact that the normalized density gradient for both species was assumed to be equal.

These results were confirmed in GK simulations performed with the GENE code for the ITER hybrid scenario. As shown in 7, T fluxes are systematically lower than D fluxes regardless $E \times B$ shearing and electromagnetic effects are taken into account or they are suppressed. However the level of asymmetry strongly depends on the simulation conditions. When taken into account $E \times B$ shearing and electromagnetic effects, $\Gamma_T/\Gamma_D \approx 0.73$ whereas when the effects are removed, $\Gamma_T/\Gamma_D \approx 0.45$. Actually, such difference in the asymmetry plays a role in the global isotope effect in the ion particle transport which is slightly different to the heat transport isotope effect. In terms of total particle ion fluxes, $\Gamma_{DT}/\Gamma_{DD} \approx 0.64$ for the full case whereas $\Gamma_{DT}/\Gamma_{DD} \approx 1.32$ for the case without $E \times B$ shearing and electromagnetic effects, which is super GB transport and higher than the ion heat flux ratio. Particle transport in H and D JET plasmas has been also analyzed in the pedestal region [73]. In general, it was found experimentally that the pedestal pressure is typically reduced in H compared to D at the same input power and gas rate, primarily due to lower pedestal density in H. Extended studies with the code EDGE2D-EIRENE [74] have shown that inter/intra ELMs changes on transport characteristics rather than neutral penetration differences are responsible for the lower confinement in H. Furthermore, linear stability MHD analyses have pointed out that Peeling-Ballooning modes are more stable in D than in H, but the effect is small and alone does not explain the higher pedestal pressure observed in D. The previous results demonstrate that the isotope effect on particle transport deserves further experimental and theoretical attention in view of addressing some of the issues arise when dealing with DT plasmas, such as the fuelling necessary to sustain an optimum mixture of D and T to generate high fusion power.

4 Isotope effect in quasi linear modelling

Whereas deep transport and turbulence analyses of the isotope effect are necessary, the prediction of its full impact on plasmas cannot be obtained from such studies. For instance, one key point point, the impact of the isotope on the transport stiffness, cannot be fully addressed with the local GK approximation used in the studies showed in previous sections. Furthermore, the impact of different heating characteristics in plasmas with different isotopes, e.g. different NBI deposition, requires the interplay with transport, which is not possible to obtain in an integrated way with GK codes due to the significant computational times required.

Therefore, simplified transport models have become an essential tool in integrated modelling activities. Several of such models have been used in the past to predict DT operation in JET, ITER and DEMO [75][26][76][64][77][65][78][66][79][80][81]. Of particular importance are the models using the so called quasi-linear approach as they are the closest ones to first-principle physics. Therefore, verification and validation of quasi-linear models with GK codes and experiments is an essential step to be performed before extrapolating present day plasmas toward DT predictions.

Such activity has been performed recently in the framework of isotope studies for JET. The quasi-linear models

QuaLiKiz and TGLF have been used in plasmas in H and D. Specifically, in the case of TGLF, initial integrated modelling simulations for the discharges #89723 in D and the #91450 in H both in L-mode showed mixed results. The simulations are in reasonable agreement for the discharge in D however the confinement for the H discharge is overestimated. This is particularly the case of the electron density, which is very similar for both shots but it is significantly overestimated in H with TGLF [26].

These initial results made evident that deeper analyses about the validity of the quasi-linear approach, and in particular, of the models TGLF and QuaLiKiz was necessary. This has been carried out by performing systematic comparisons between linear simulations but as well with the heat fluxes obtained with TGLF and QuaLiKiz and those obtained from non-linear simulations performed with GENE. One important point, as clarified in section is the role of electromagnetic effects, which can play a role in the isotope effect. Whereas TGLF is a full electromagnetic model, QuaLiKiz is electrostatic. A mock-up has been introduced to obtain approximate QuaLiKiz fluxes in the electromagnetic regime based on electrostatic results. This consists in running a R/L_{Ti} scan of QuaLiKiz simulations in the electrostatic regime and then re-scaling R/L_{Ti} multiplying it by the radially local ratio $\beta_{thermal}/\beta_{total}$ of the thermal and total(including the fast ion contribution) $\beta = 2\mu_0 p/B^2$ values, with p the pressure.

As an example, this has been done for a comparison between D and T for an original hybrid D plasma, #94875 for which the mass has been artificially changed to T. As shown in Figure 8, at $\rho = 0.6$, a weak isotope effect is found with GENE assuming electrostatic simulations as the T heat flux is lower than the D one by 20%. Such isotope effect is also found in QuaLiKiz with a quite good match in terms of fluxes. However, when adding the electromagnetic effects, the situation is quite different. As previously pointed out in section 3, electromagnetic effects enhance the isotope effect and now the difference between D and T is about 50%. The fluxes obtained from both TGLF and QuaLiKiz match non-linear simulations for some particular R/L_{Ti} cases but the stiffness obtained from GENE, almost negligible, is not reproduced by both models, which show a strong stiffness.

5 Summary and conclusions

Heat and particle transport deviations with respect to naive expectations from GB scaling have been analyzed in H vs D plasmas obtained in JET campaigns. For such purpose, extensive linear and non-linear GK simulations have been performed with the GENE code. Further studies about the validity of the quasi-linear approach to reproduce some of the effects found have been also carried out.

In general, GK simulations have shown that GB scaling can be expected in collisonless, electrostatic, adiabatic electrons and single ion ITG regimes with no rotation effects. As a matter of fact, these ideal conditions are not matched in JET plasmas both in L and H-modes and deviations from GB scaling are systematically found in GK simulations for the ion heat transport when such physical mechanisms are added one by one. When the analyses are done considering realistic plasma conditions, weak to moderate decreasing fluxes with increasing mass are obtained for the type of plasmas obtained in the JET experimental campaigns. These results show that rather than expecting a systematic ”isotope effect” when changing the mass of the main ion, a full set of broad conditions, from close to GB scaling to significant deviations, can be expected depending on the plasma conditions or the radial point analyzed.

Although a set of clear physics mechanisms have been identified to lead to an isotope effect, their true impact in realistic experimental conditions is far from clear. As an example, operational changes on the plasma configuration can be expected when changing the isotope and hence masking or altering possible inherent isotope effects on transport. Such is the case of the fast ions generated by the heating systems, which has been shown to have an impact on the transport levels, and can significantly change dependent on the heating characteristics.

Furthermore, non-linear local GK simulations cannot be used for analyzing the full impact of the change of isotope as they cannot address some effects that can be also impacted. For instance, the full impact of transport stiffness, turbulence spreading or core-edge interplay (including the Scrape-off layer) would require global flux driven simulations which were not performed, in particular, because of the high computational requirements. Self-consistent simulations using simplified models for core transport could provide some clarification however it has been shown that quasi-linear models have some difficulties on capturing the essential difference on turbulence characteristics when changing the mass.

The issues previously pointed out may be on the origin of the apparent contradiction between the moderate isotope effects found in some JET plasmas when performing GK simulations and the very weak core thermal energy confinement dependence found in experiments, where most of the difference between H and D plasmas has the origin at the edge, and in particular in H-mode, from the particle transport at the pedestal.

At this point, it is essential to stress that due to the limitations of the operation in H at JET, which prevents to work in conditions of high input torque, beta, T_i/T_e and fast ion fraction, it was not possible to explore a broad operational space. Therefore, some of the results obtained in GK simulations could not be properly validated in optimum experimental conditions. For such purpose, further experiments, which are expected to cover a broader operational space in pure T plasmas, are expected.

Precisely, simulations performed for extrapolated ITER DT plasmas are in fair agreement with the mechanisms leading to isotope effects found for JET. In particular, weak ion heat transport reversals are expected when including the $E \times B$ shearing or electromagnetic effects. Also in this case, the presence of a significant amount of fast ions, in particular alpha particles, can enhance the difference between DD and DT plasmas in conditions close to turbulence threshold where stronger impact of zonal flows with mass is found.

Whereas the isotope effect starts to be better understood, there is not a complete understanding of the full impact of the change of isotope hydrogen mass on heat and particle transport. Such understanding is essential to properly evaluate potential changes from DD to DT in ITER and the future tokamak reactor. A DT campaign at JET will further help to this end.

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