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Turbulent transport analysis of JET H-mode and hybrid plasmas using QuaLiKiz and Trapped Gyro Landau Fluid

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Abstract

The physical transport processes at the basis of JET typical inductive H-mode scenarios and advanced hybrid regimes, with improved thermal confinement, are analyzed by means of some of the newest and more sophisticated quasi-linear transport models: trapped gyro Landau fluid (TGLF) and QuaLiKiz. The temporal evolution of JET pulses is modelled by CRONOS where the turbulent transport is modelled by either QuaLiKiz or TGLF. Both are first principle models with a more comprehensive physics than the models previously developed and therefore allow the analysis of the physics at the basis of the investigated scenarios. For H-modes, ion temperature gradient (ITG) modes are found to be dominant and the transport models are able to properly reproduce temperature profiles in self-consistent simulations. However, for hybrid regimes, in addition to ITG trapped electron modes (TEM) are also found to be important and different physical mechanisms for turbulence reduction play a decisive role. Whereas $E \times B$ flow shear and plasma geometry have a limited impact on turbulence, the presence of a large population of fast ions, quite important in low density regimes, can stabilize core turbulence mainly when the electromagnetic effects are taken into account. The TGLF transport model properly captures these mechanisms and correctly reproduces temperatures.

Keywords: plasma physics, tokamaks, transport

(Some figures may appear in colour only in the online journal)

1. Introduction

In order to plan for future tokamak devices, such as ITER or DEMO, the availability of plasma models that are able to predict the performance of the main operational scenarios, is an absolute requirement. Strong efforts have been made in order to obtain numerical instruments able to reproduce and predict heat and particle fluxes, which accurately determines the core plasma temperature and density. Several first-principle quasi-linear transport models like GLF23 [1] and Weiland [2] have been developed in the past and successfully used for simulating L-modes and inductive H-mode core plasmas. However, the predictability of advanced tokamak regimes, such as Hybrid [3] or Internal Transport Barriers [4], proved to be more difficult and the models had to be retuned [5–7].

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The disagreement of these existent transport models with the experimental results, together with the demonstration of the existence of new physical mechanisms at the basis of the improved scenarios given by the always more sophisticated gyro-kinetic simulations, have made clear the necessity for quasi-linear models which include a more comprehensive physics.

In this paper, two of the newest and more sophisticated quasi-linear transport models developed until now, QuaLiKiz [8] and trapped gyro Landau fluid (TGLF) [9], are applied in order to analyze the physics characteristics of JET inductive H-mode and Hybrid plasmas and, at the same time, to analyze their ability to self-consistently reproduce JET core temperatures.

QuaLiKiz calculates the quasi-linear gyro-kinetic heat and particle fluxes. The linear response is calculated by an electrostatic eigenvalue gyro-kinetic dispersion relation. It includes two ion species, both passing and trapped particles, collisions and assumes the shifted circle s-α geometry for equilibrium. The saturated electrostatic potential is given by a model based on a mixing length rule validated against both non-linear simulations and experimental observations [10]. Recently its validity has been extended to low scales of magnetic shear [11]. The E × B shear effect has been included in QuaLiKiz stand alone [12], however this version is not available in CRONOS yet. The version of QuaLiKiz used is, hence, the 2012 version. TGLF is the evolution of GLF23. It is based on a set of gyro-Landau fluid equations that include kinetic effects like gyro-averaging and Landau damping. TGLF includes the effects of trapped particles, up to five ion species, collisions, E × B shear, finite β (the ratio of the plasma pressure to the magnetic pressure) and both shifted circle s-α geometry and Miller shaped geometry. The quasi-linear fluxes are calculated from the fluid linear response of the equations and from a saturation rule for the turbulent intensity local in the wave number that was determined using a database of nonlinear GYRO simulations [13] carried out with Miller geometry and kinetic electrons.

TGLF and QuaLiKiz are two important instruments for reproducing and predicting the plasma profiles if self-consistently coupled with a transport code. If used in their stand-alone version, because of their theoretical bases, they can in addition give some information about the linear instabilities predicted in the plasma core.

In this paper we focus on the baseline ($\beta_N \sim 2$, with $\beta_N = \beta/(I_P/aB)$, where I_P is the plasma current, a the minor radius and B the magnetic field) and the hybrid ($\beta_N \sim 3$ [3], $\beta_p \geq 1$ [14] where $\beta_p = 2\langle P\rangle / \langle B_\theta^2\rangle$, with $\langle P\rangle$ the average pressure and $\langle B_\theta^2\rangle$ the poloidal magnetic field square average at the edge) regimes, presenting the results obtained using TGLF and QuaLiKiz coupled with the CRONOS suite of codes [15] and in their stand-alone versions. While for baseline scenarios the simulations have been carried out, compared and analyzed with both the transport models, for the hybrid regimes we report the results and the analysis using the TGLF transport model. In present day machines, the hybrid regime is frequently characterized by an improved confinement with respect to the standard $H_{98}(y, 2)$ scaling [16]. The physical basis of this improved confinement is however not yet clear. Many possible explanations have been proposed: a higher E × B given by strong gradients in high toroidal rotation [17], a higher pedestal pressure [18], a relative increase of the s/q at the outer radii with respect to the central broad region of low s that characterizes the hybrid plasmas [19, 20], the β-stabilization [21] and the fast ions stabilization mechanisms [22–25]. Because physical effects such as E × B shear, electromagnetic instabilities and fast ion interplay, which seem to play an important role in the hybrid scenario, are included in TGLF and not in QuaLiKiz, we have chosen TGLF to simulate and analyze these plasmas. In addition, for the investigated hybrid discharges, the Miller description of the geometry has been found to be relevant in order to achieve better results in reproducing experimental temperature profiles. The hybrid analysis itself presented in this paper has the scope of contributing to pointing out the effects that are more significant for the hybrid's improved confinement. That has been possible through the use of TGLF, which can include or not the investigated effects, isolating and then quantifying their influence on global confinement parameters as H_{98}.

A first comparison between the two models has been carried out by performing a series of scans in transport relevant physical parameters using as basis the GA (General Atomics) standard case [1] (electrostatic, with s-α geometry, without E × B shear effect) and comparing the obtained fluxes with the correspondent results of GYRO and GENE [26] non-linear simulations. A reasonable agreement has been found, as reported in the appendix of this paper. In section 2 JET H-mode heat transport simulations using QuaLiKiz and TGLF are compared with experimental data and with the resulting profiles obtained by the transport model GLF23, the first principle quasi-linear model that has given until now the best agreement with the experimental data for different plasma scenarios. These simulations have been done in order to validate the models, investigating their behaviour and their description of the dominant instabilities on standard regimes that are based on well-known physics. In section 3 we present the results of heat transport simulations obtained for hybrid scenarios, carried out using TGLF, as explained above. Finally some conclusions are presented in section 4.

2. JET baseline plasmas

The self-consistent simulations presented in this paper have been carried out modelling the current and the ion and electron temperature profiles. All the other quantities are taken from the experimental data.

The plasma equilibrium has been modelled self consistently with the current diffusion and the temperature evolution using the code HELENA [27]. No sawtooth model has been included. In addition the transport models used here are built and validated for the core plasma region, then the simulation results of the very central zone ($\rho < 0.2$) must be considered not trustable.

The kiauto model [28] is used for the pedestal: the temperature pedestal height and width at the normalized toroidal flux coordinate $\rho = 0.93$ are given as the input, according to the experimental results. When we use the transport models

Table 1. Values of the parameters which characterize the JET carbon H-modes and hybrid discharges modelled in this paper. The last column presents the times at which the calculated plasma temperature profiles are shown and analyzed.

	B_T (T)	I_P (MA)	P_{NBI} (MW)	q_{95}	v_{t0} (rad s^{-1})	n_e/n_{GW}	δ/κ	β_N	$H_{98y,2}$	I_p flattop start time (s)	time (s)
73342	2.7	2.5	15	3.4	5 10^4	1	0.42/1.74	2	1	6.5	10.1
73344	2.7	2.5	15	3.4	5 10^4	0.75	0.39/1.74	1.5	0.95	6	8.8
75225	2	1.7	17	4.1	10^5	0.4	0.2/1.64	3	1.25	5	6
77922	2.3	1.7	17	4.3	10^5	0.7	0.38/1.7	2.7	1.2	6	7

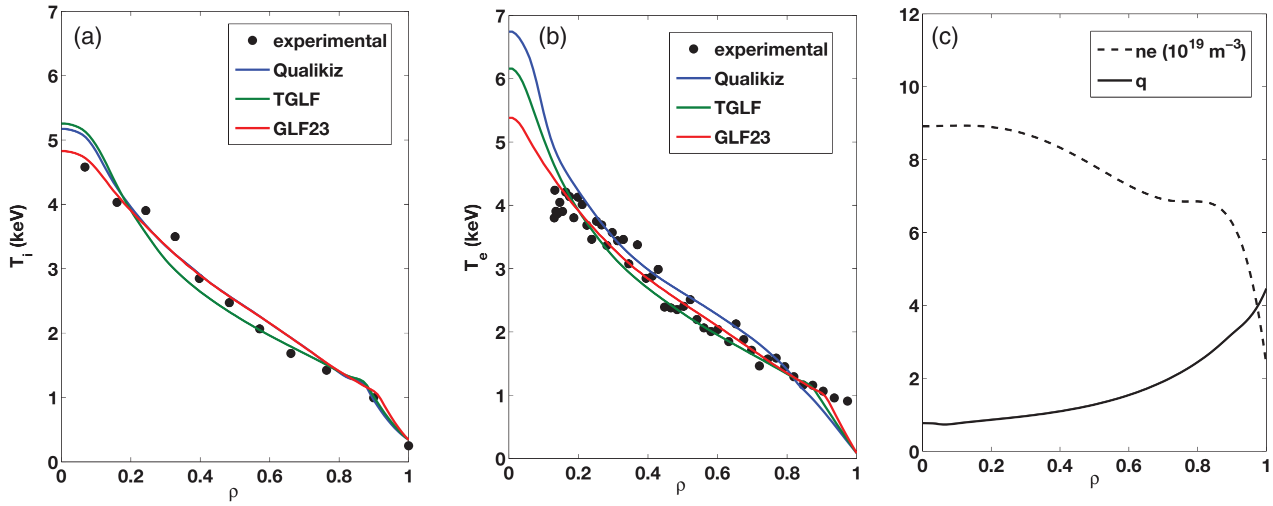

Figure 1. Ion (*a*), electron (*b*), n_e and q (*c*) profiles of the JET H-mode 73344 at t = 8.8 s, as functions of the normalized toroidal flux coordinate ρ. Circles represent the measurements from charge exchange diagnostic (*a*) and high resolution Thomson scattering (*b*). Lines represent the predictions using the QuaLiKiz (blue), TGLF (green) and GLF23 (red) models. The n_e profile is taken from the data, the q profile is evolving. The very high values of the central T_e are a consequence of the slightly inversed q profile in the very central region. No sawtooth model has been utilized in the simulations.

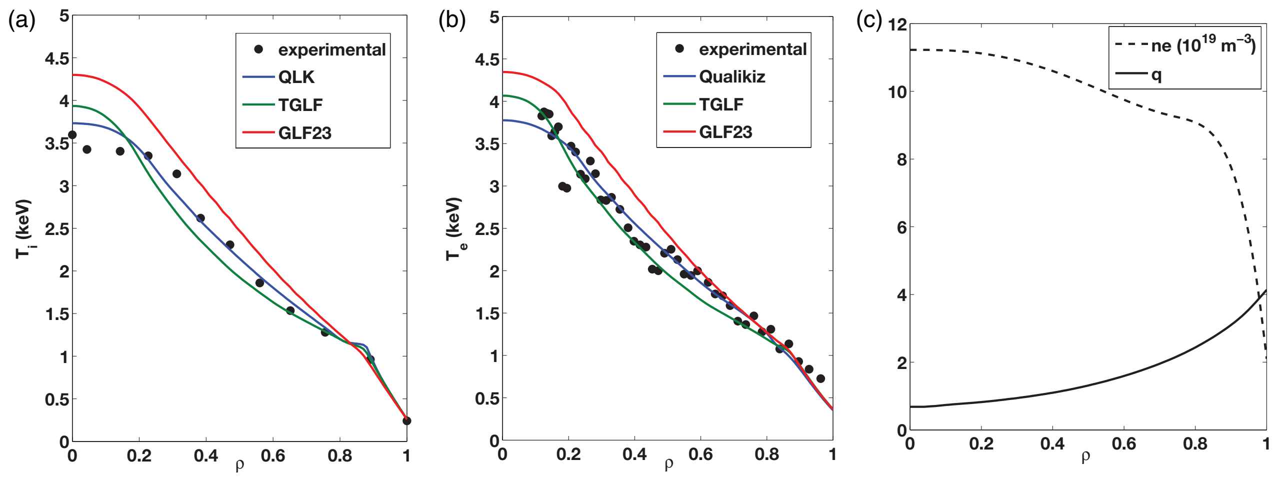

Figure 2. Ion (*a*), electron (*b*), n_e and q (*c*) profiles of the JET H-mode 73342 at t = 10.1 s. The n_e profile is taken from the data, the q profile is modelled. No sawtooth model has been utilized in the simulations.

in their stand-alone version we take all the profiles from the analyzed experimental discharge.

The carbon wall JET H-mode discharges 73344 and 73342 have been simulated. They have very similar parameters, as shown in table 1, except for the average density values: 73344 is a standard JET H-mode ($<n_e> = 6.8 \times 10^{19}\,m^{-3}$), 73342 has a higher density ($<n_e> = 9 \times 10^{19}\,m^{-3}$). Both ion and electron temperature profiles are well reproduced in the core region of the plasma by all the transport models that we have used (QuaLiKiz, TGLF and GLF23). In figure 1 the temperature profiles are shown for the shot 73344, together with the q and the n_e profiles, typical of a standard stationary JET H-mode. A reasonably good agreement has been found for 73342 as well, as illustrated in figure 2. Using the stand-alone versions of QuaLiKiz and TGLF we have found that both models predict the dominance of the ITG instabilities for the H-mode shots, as figure 3 shows for 73344. The agreement between the predicted temperature profiles and the drift mode

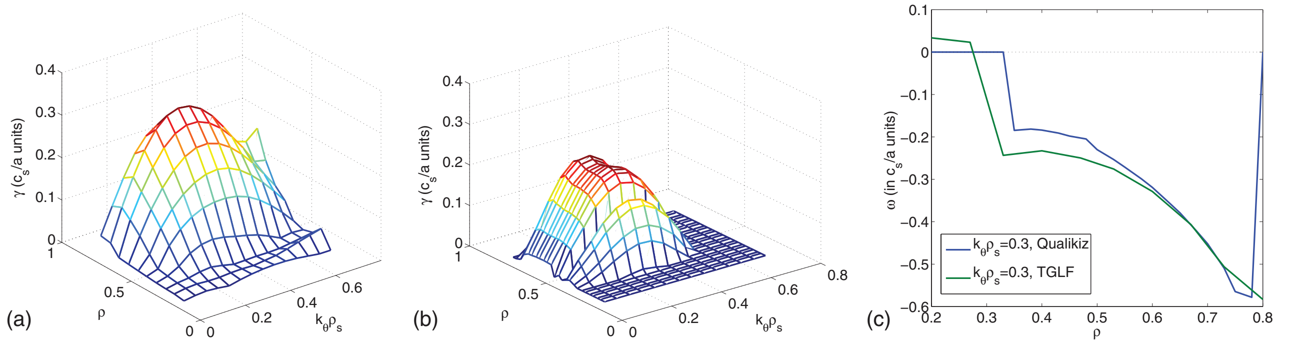

Figure 3. TGLF (*a*) and QuaLiKiz (*b*) normalized growth rates of the JET H-mode 73344 at t = 8.8 s as functions of the radial coordinate and $k_\theta\rho_s$. (*c*) normalized frequencies for $k_\theta\rho_s = 0.3$, around which the maximum growth rate is known to be achieved in the ITG regime, in the range of low $k_\theta\rho_s$, which are the most relevant in the calculation of the fluxes. In this paper the sign convention is as follows: negative ω for ion drift directed modes and positive ω for electron drift directed modes.

analysis of TGLF and QuaLiKiz gives the indication that the physical effects of E × B shear and electromagnetic instabilities, which are included in TGLF and not in QuaLiKiz, do not seem to play a large role for H-mode plasmas, as expected because of the low values of β and the low values of rotation. Even the different geometry description, that in the case of TGLF takes into account the effects of elongation and triangularity of the plasma, seems not to have any relevant impact on the core heat transport of H-mode discharges. In figure 4 the experimental T_i/T_e profiles of the two investigated JET baseline discharges are compared with the ratios obtained by the TGLF and QuaLiKiz simulations. For both the investigated discharges the core experimental T_i/T_e values are close to 1, as expected for typical JET baseline scenarios. That is well reproduced by the two models, which predict T_i/T_e between 0.95 and 1.05. For 73342, TGLF and QuaLiKiz predict a ratio lower than 1 for $\rho < 0.5$, like the experiment. For $\rho > 0.5$ the QuaLiKiz trend is in agreement with the experimental ratio, TGLF overestimates it. For the discharge 73344, the values predicted by QuaLiKiz are very similar to the experimental ones outside $\rho = 0.4$, TGLF always tends to have a larger ratio in the external part of the plasma.

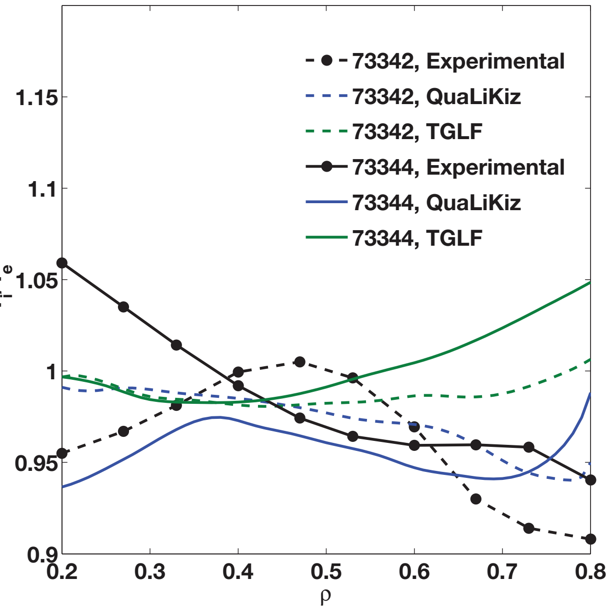

Figure 4. T_i/T_e ratio as a function of the radial coordinate ρ for the investigated JET baseline discharges.

3. JET hybrid plasmas

The self-consistent simulations of the hybrids have been carried out similarly to the H-modes study presented in section 2. The initial q profiles are taken from MSE-constrained equilibrium reconstruction and are then evolved by the current diffusion equation, which coincides with the experimental evolution as shown in [29].

The JET hybrid discharge 77922 [30] was first simulated with TGLF. It is a typical high triangularity improved confinement JET hybrid shot obtained using the 'overshoot technique' [31]. The main characteristics of this discharge are shown in table 1 and in figure 5. It has a high β_N and high toroidal rotation, which are the candidate physical effects for explaining the improved core confinement and they are included in TGLF. Unlike the baseline discharges, for which the middle of the steady state has been chosen for the analysis, the time interval after the start of the current flat-top has been considered for hybrids simulations (see table 1 and figure 5). At 1 s after the start of the flat-top, the plasma has reached the steady state and it is characterized by a broad flat q profile in the inner region, typical of the hybrid plasmas [7]. In figure 6 the temperature profiles together with the density and q profiles are shown at this time. The agreement between TGLF and the experimental data is not as good as for the H-mode simulations: the ion temperature is overestimated in the core region ($0.2 < \rho < 0.8$), the electron temperature profile is well reproduced for $\rho > 0.2$. Inside $\rho = 0.2$, the model predicts no unstable modes. A fixed *ad-hoc* value of the turbulent heat transport diffusivity for ions and electrons has been used because of numerical instabilities due to very low neoclassical transport in that very central zone of the plasma.

From the stand alone analysis we find that TGLF describes the presence of ITG as the dominant modes for $k_\theta\rho_s < 0.5$ inside $\rho = 0.6$ and the dominance of TEM outside $\rho = 0.65$. This is shown in figure 7 by the growth rates and the relative frequency for one of the most significant modes for the heat transport.

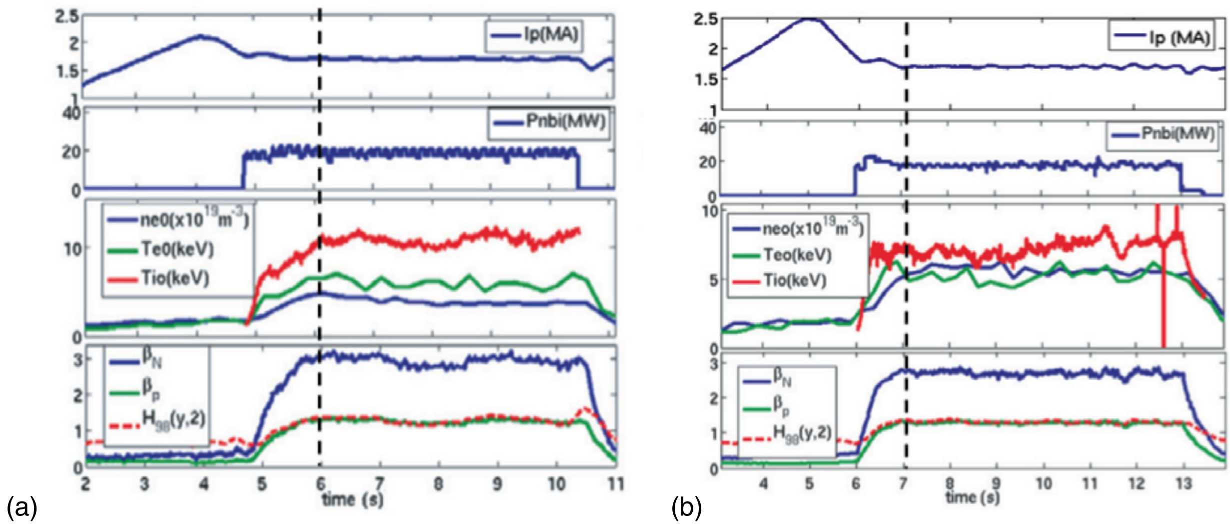

Figure 5. From the top: I_p, P_{NBI}, n_{e0}, T_{e0} and T_{i0}, β_N, β_p and H_{98} time traces of the JET hybrids 75225 (*a*) and 77922 (*b*). The vertical dashed lines correspond to the times of the analysis.

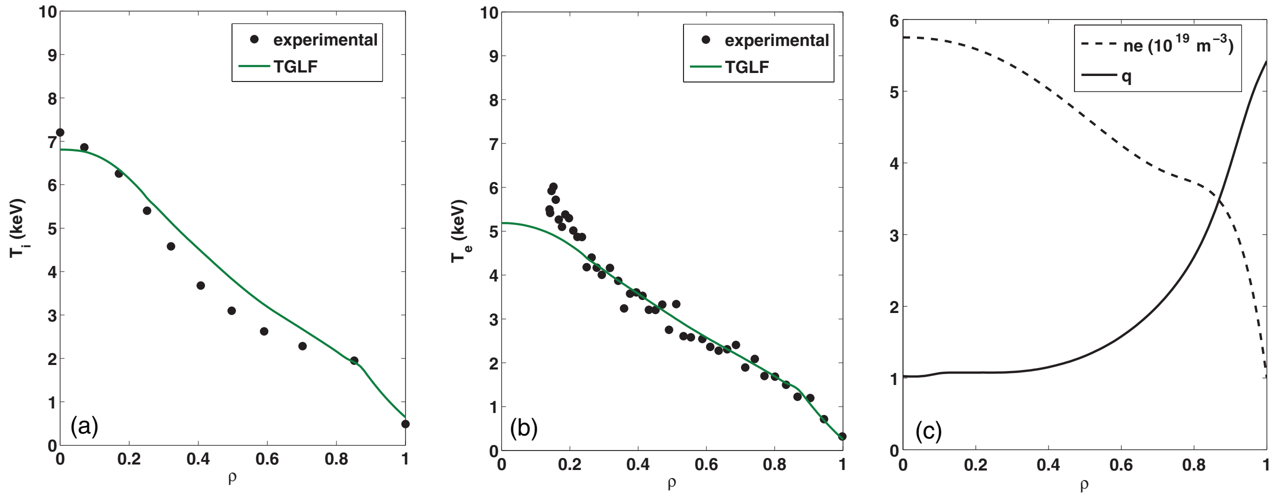

Figure 6. Ion (*a*), electron (*b*), n_e and *q* (*c*) profiles of the JET hybrid 77922 at t = 7 s. The n_e profile is taken from the data, the *q* profile is modelled.

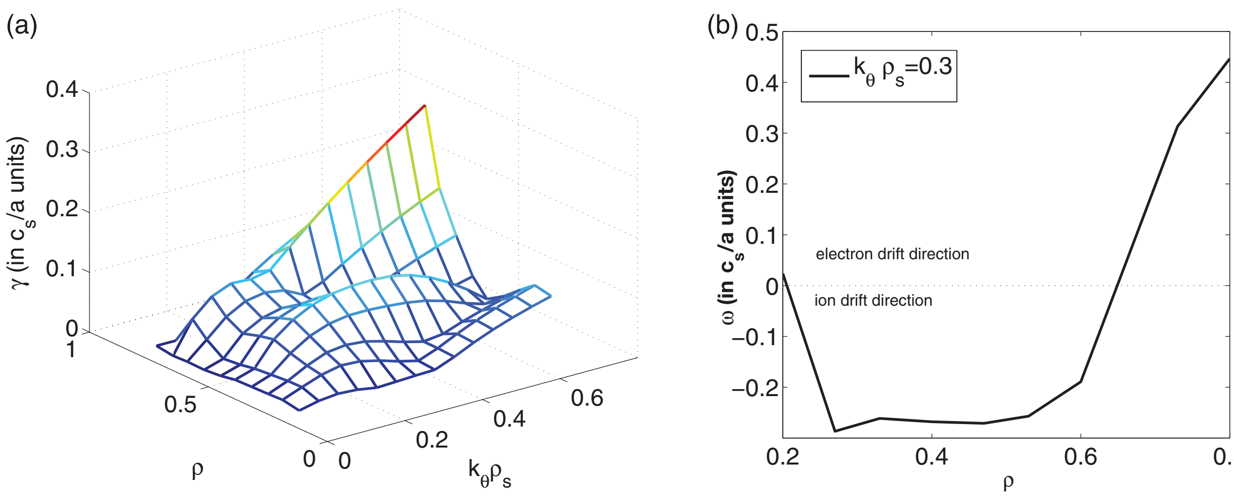

Figure 7. TGLF maxima normalized growth rates (*a*) of the JET hybrid 77922 at 7 s as functions of the radial coordinate and $k_\theta\rho_s$; (*b*) normalized frequency profile for $k_\theta\rho_s = 0.3$.

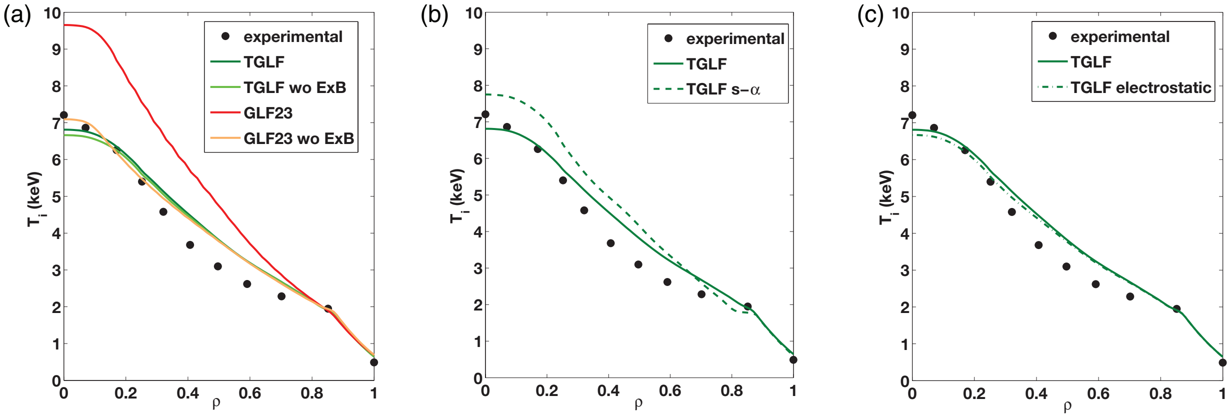

Figure 8. Ti profiles: (*a*) E × B shear effect, (*b*) geometry description, (*c*) em effects analysis for the JET hybrid 77922 at 7 s.

The temperature profiles of figure 6 have been obtained including the E × B shear effect, ElectroMagnetic (EM) instabilities and using the Miller geometry description. Because of the possibility in TGLF of using different geometry descriptions and of including/excluding the E × B shear effect and the electromagnetic instabilities, it has been possible to isolate the impact of these factors on the heat transport as described by TGLF in hybrid discharges with different characteristics.

In figure 8(*a*) the role of E × B shear is analyzed using TGLF and GLF23. In this shot the E × B shear stabilization as predicted by TGLF by the spectral shift paradigm [32] seems to be nearly negligible and very similar temperature profiles are given for the cases with and without this factor. The same weak impact of E × B shear has been found by linear gyro-kinetic simulations with GYRO [33]. From the agreement between GLF23 without the E × B shear effect and TGLF, and the larger values of the temperatures obtained by GLF23 with the inclusion of this factor (through the quench rule used with the standard coefficient $\alpha_E = 1.35$) it is clear that the effect of the rotation shear as predicted by GLF23 is largely overestimated, confirming previous hybrid simulations works [7, 33].

The study of the role of the geometry description is reported in figure 8(*b*). The difference in the temperature profiles obtained using the s-α model and the Miller model is large, up to 14%. In order to decouple the effect of the geometry and the impact of the different approximations in the models, we carried out the same simulation using the Miller model with the same geometrical parameters as for the s-α geometry (that is $\kappa = 1$, $\delta = 0$ and both the shears of elongation and triangularity = 0). We obtained the same results as the case with Miller geometry with experimental elongation and triangularity. The discrepancy in the profiles of figure 8(*b*) is then due to the different models and not to the different geometrical parameters. These findings are in agreement with previous investigations [34], which discovered a discrepancy among the fluxes obtained using the s-α model and other more realistic models, due to the overestimation of the linear thresholds by using the s-α geometry. This explains the higher values of the temperature profiles in the case of the s-α model found in the inner region of the plasma (see figure 8(*b*)). Some relevant effects due to the geometry are in fact expected almost only in the outer region, where elongation, triangularity and their shear are significantly different from the circular geometry values. In addition, non-linear gyrokinetic simulations foresee a stabilizing effect of the elongation and a weak dependence of the transport on the triangularity [35], findings that are in disagreement with the results of the simulations presented here. The approximation made in the models and not the high shape of the plasma of this shot, is then responsible for the different temperature profiles.

Figure 8(*c*) shows that the electromagnetic effects as described by TGLF are nearly negligible for this discharge, despite the high value of β_N, from which some important electromagnetic effects are expected, at least inside $\rho = 0.4$, where β_e (defined as $8\pi n_e T_e/B_{unit}$, where B_{unit} is the effective field strength [36]) has quite high values ($\beta_e(\rho = 0.33) = 0.01$). From a scan in this parameter using the stand-alone version of TGLF with the simulated profiles as input, we obtain already in the electrostatic case very low ITG growth rates, close to the stability. Finite values of β_e lead the instabilities to decrease, however without achieving complete stability. The reduction of very small fluxes, though relevant in percentage, turns out to be nearly negligible in the perspective of a variation in the temperature profiles. The results of this β_e scan are in agreement with the linear gyro-kinetic β_e scan carried out for 77922 by GYRO [37], which foresees that the ITG instabilities' strength is reduced with increasing β_e and that the experimental value of β_e is positioned in the boundary region between ITG dominance and the Kinetic Ballooning mode (KBM) regime. With regard to the the kind of dominant instability in this particular zone, the existence of hybrid ITG/KBM modes has been predicted by gyro-kinetic simulations and studies about the failure of ITG turbulence saturation at typical transport values because of critically weakened zonal flows are in progress [21, 38–40]. Very recent comprehensive gyro-kinetic simulations [41] describe the core plasma of this discharge to be in the KBM regime. It is even possible that because of numerical reasons, or because of the importance of the non-linear contribution to the transition between the ITG and KBM regimes, the TGLF simulations turn out to be very close to the KBM zone but are still in the reduced ITG region. The presence of one of these modes could explain the overestimation of the temperature profiles of TGLF, that does not

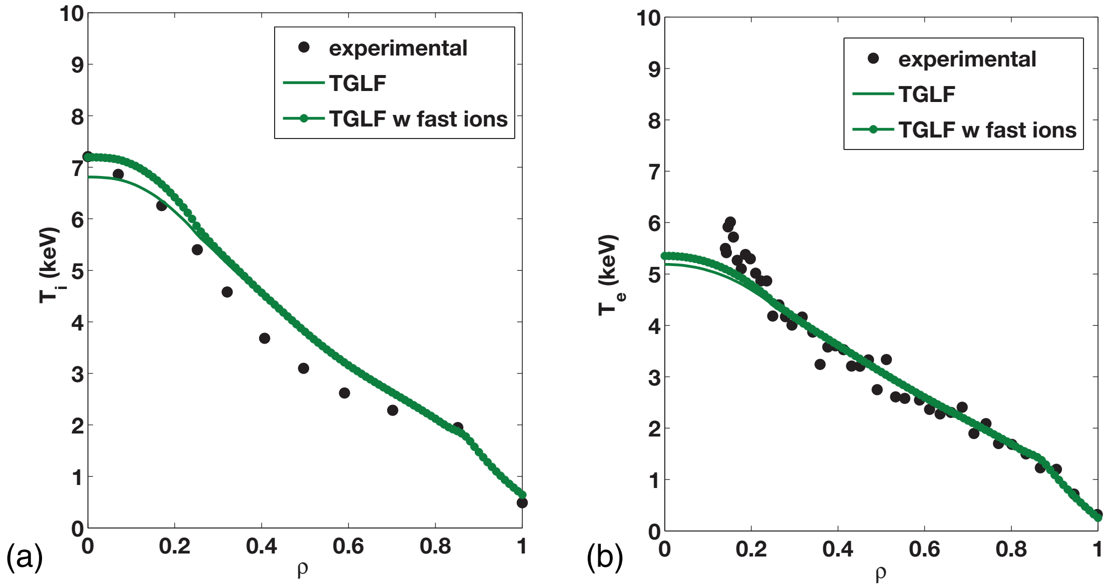

Figure 9. Ion (*a*) and electron (*b*) temperature profiles without fast ions and with fast ions for the JET hybrid 77922 at 7 s.

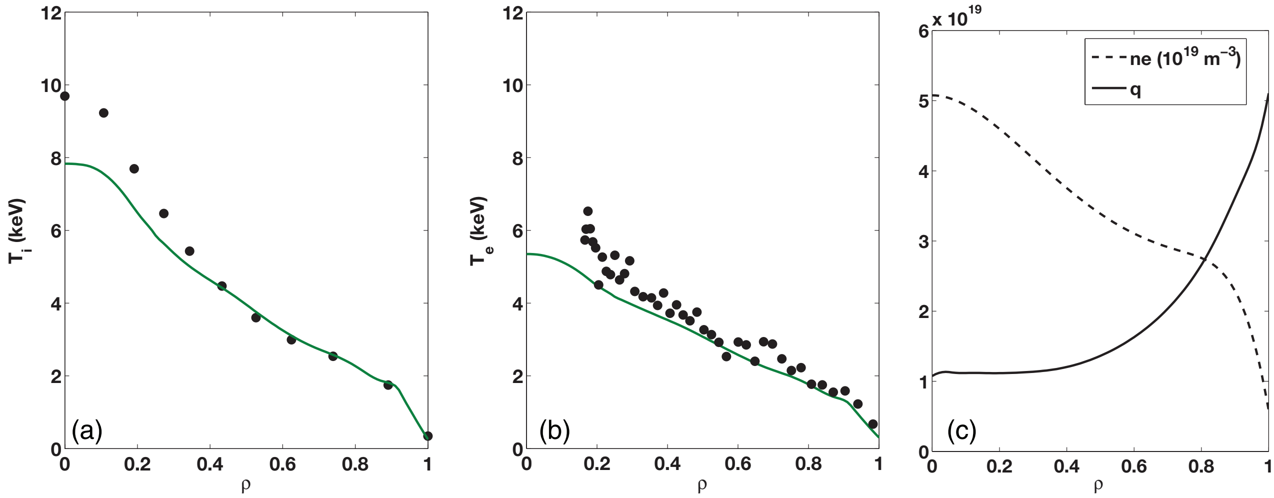

Figure 10. Ion (*a*), electron (*b*), n_e and q (*c*) profiles of the JET hybrid 75225 at 6 s. The n_e profile is taken from the data, the q profile is modelled.

include such non-linear effects and does not predict KBM for this discharge.

The discharge 77922 is characterized by a population of fast ions which contributes to the energy content for about the 15%. As shown in figure 9, the ion and electron temperatures obtained including the fast ions in the TGLF simulation are slightly higher inside $\rho = 0.25$. For a fixed heating power, the amount of fast ions in the plasma is lower in the case of higher density discharges. Then we can expect that, for this discharge, the known stabilizing effect of the fast particles plays a weak role.

The hybrid JET discharge 75225 [31] was then simulated. Similar to 77922 it is an improved confinement shot obtained using the same technique but with lower triangularity and lower density, as shown in table 1. The temperature profiles obtained by the TGLF simulation including the E × B shear, the electromagnetic effects and the Miller geometry are shown in figure 10, together with the density and the q profiles. Both the ion and electron temperatures are underestimated inside $\rho = 0.5$. In the outer region we find a good agreement between TGLF and the experimental data.

From the study of the instabilities growth rates and the relative frequencies, shown in figure 11, TGLF predicts the dominance of ITG for low $k_\theta \rho_s$ and the existence of modes drifting in the electron direction, TEM dominated, in the outer radial part of the plasma ($\rho > 0.7$).

Proceeding with the same analysis that was done for 77922 regarding the investigation of the weight of E × B shear, geometry description and electromagnetic effects, we can see in figure 12(*a*) that the E × B shear effect as described by TGLF has a stabilizing role not negligible for 75225 inside $\rho = 0.5$. It has however a very weak impact, giving a variation in the temperature profile up to 3%. In contrast, GLF23 always overestimates the impact of this factor. In the TGLF simulations even the effect of the parallel velocity gradient (PVG) is included, which is known to be destabilizing [42].

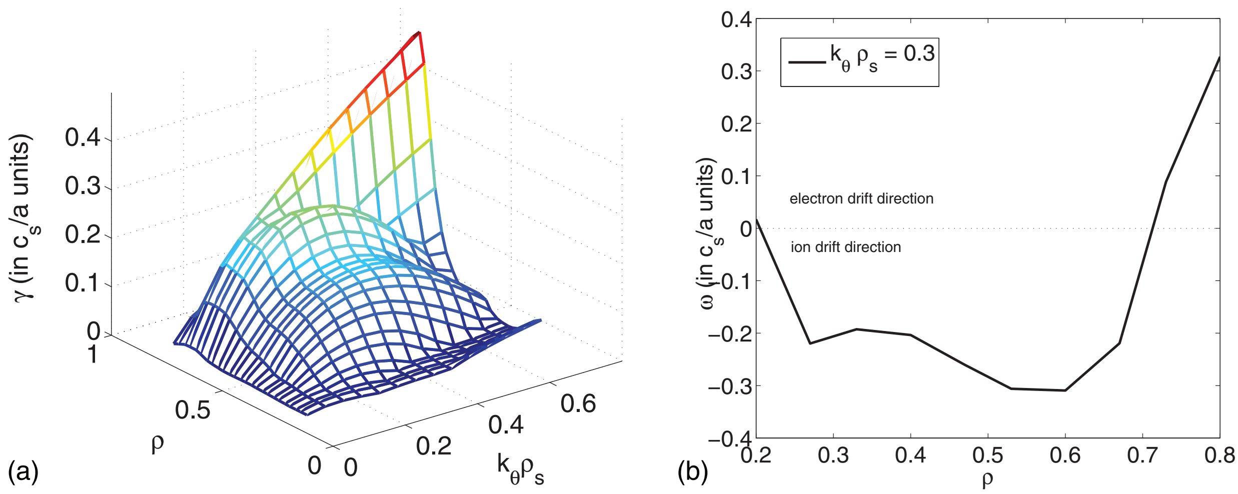

Figure 11. TGLF maxima normalized growth rates (*a*) of the JET hybrid 75225 at 6 s as functions of the radial coordinate and $k_\theta\rho_s$; (*b*) normalized frequency profile relative to the maxima growth rates for $k_\theta\rho_s = 0.3$.

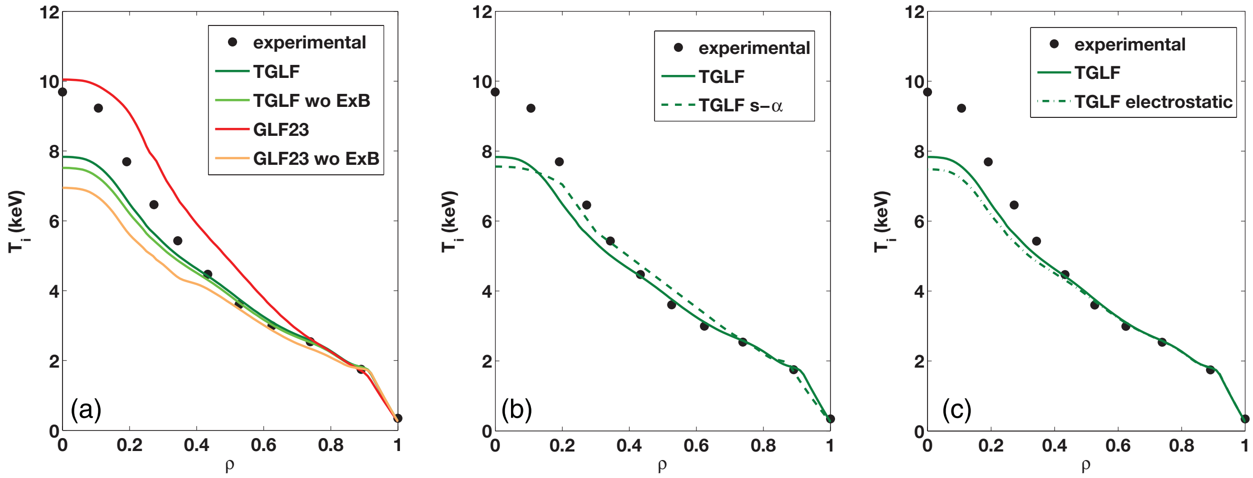

Figure 12. Ti profiles: (*a*) E × B shear effect, (*b*) geometry description, (*c*) em effects analysis for the JET hybrid 75225 at 6 s.

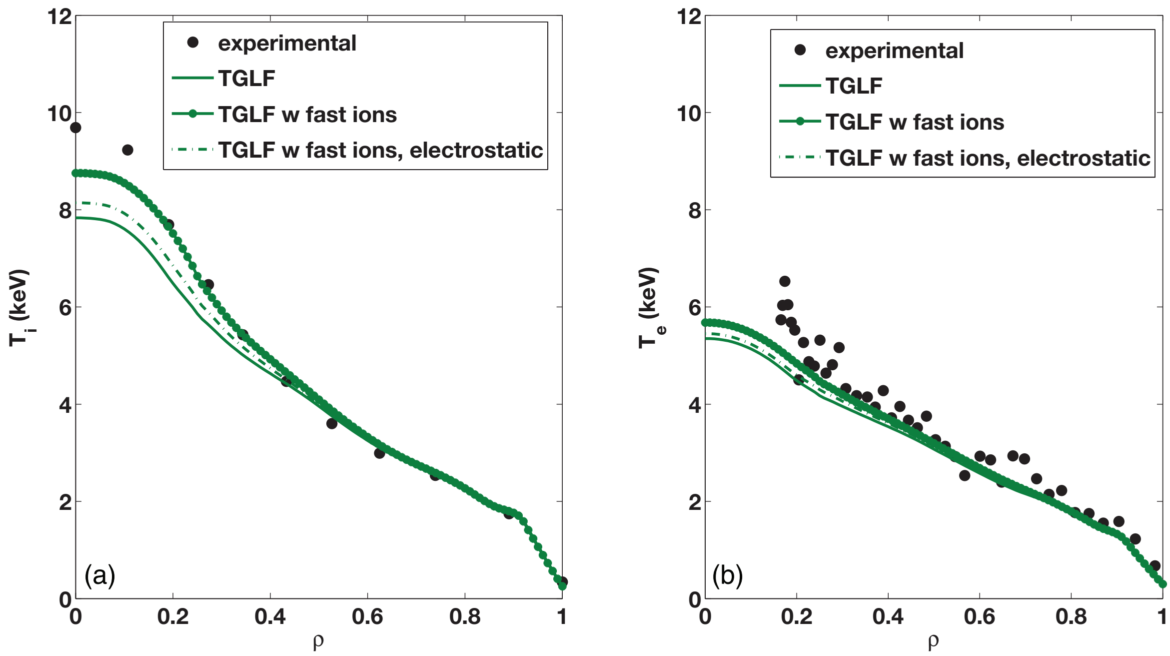

Figure 13. Ion (*a*) and electron (*b*) temperature profiles without fast ions and with em effects, with fast ions and em effects, with fast ions and electrostatic for the JET hybrid 75225 at 6 s.

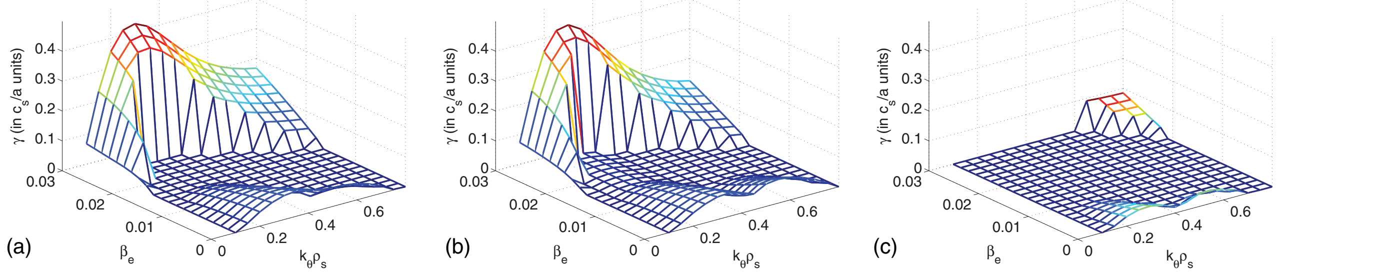

Figure 14. Normalized maxima growth rates as a function of β_e and $k_\theta\rho_s$ for the JET hybrid 75225 at 6 s: (*a*) without fast ions (*b*) with fast ion equilibrium (*c*) with fast ion equilibrium and fast ion dilution.

Isolating the E × B shear effect from it, we have found an increase of the ion temperature up to 13% inside $\rho = 0.3$. The PVG then compensates the E × B shear, otherwise important in the central part of the plasma. In figure 12(*b*) the impact of the geometry description is shown. Even for this shot, the difference in the temperature profiles is due to the different approximations in the models and not to the different geometrical parameters. The Miller simulation with triangularity = 0 and elongation = 1 in fact gives the same results as the Miller simulation with the experimental parameters. For 75225 the difference of the temperature profiles obtained using the s-α and the Miller model is about 3%, smaller than for 77922. The discharge 75225 has a lower shape with respect to the 77922, however we have seen that the pure geometric factors do not seem to play any role in the self consistent simulations. The different impact of the geometry description on the two investigated discharges may depend on several other factors, like, for example, the presence of other modes beyond ITG. For this case a clear trend in the differences between the diffusivities obtained using s-α and Miller descriptions has not been identified yet. The electromagnetic effects seem to not have a large impact even for this discharge (figure 12(*c*)), slightly stabilizing the temperature profile inside $\rho = 0.4$, with the effect of growing the ion temperature by nearly 4%.

The discharge 75225 is characterized by a high percentage of fast ions (nearly 28% of the plasma total energy content), which are known to have the effect of stabilizing the ITG instabilities with increasing β_e linearly and non-linearly through the electromagnetic effects [24, 41], together through the mechanisms of the dilution of thermal ions [22] and the enhancement of the Shafranov shift [23]. The fast ion interplay has been included in the TGLF simulation through the dilution effect, i.e. introducing a new species in the quasi-neutrality equation and through the effect of the fast ions pressure on the Shafranov shift. The TGLF heat transport simulation including fast ions, E × B shear and electromagnetic effects gives the temperature profiles shown in figure 13. There is a very good agreement between the simulation results and the experimental data, both for electron and ion temperatures.

Looking at figure 14, where β_e scans with the inclusion/exclusion of the fast ions mechanisms of stabilization are shown, TGLF predicts for 75225 that the dilution has the most important role. With the inclusion of the fast ions the electromagnetic effects are described by TGLF to play an

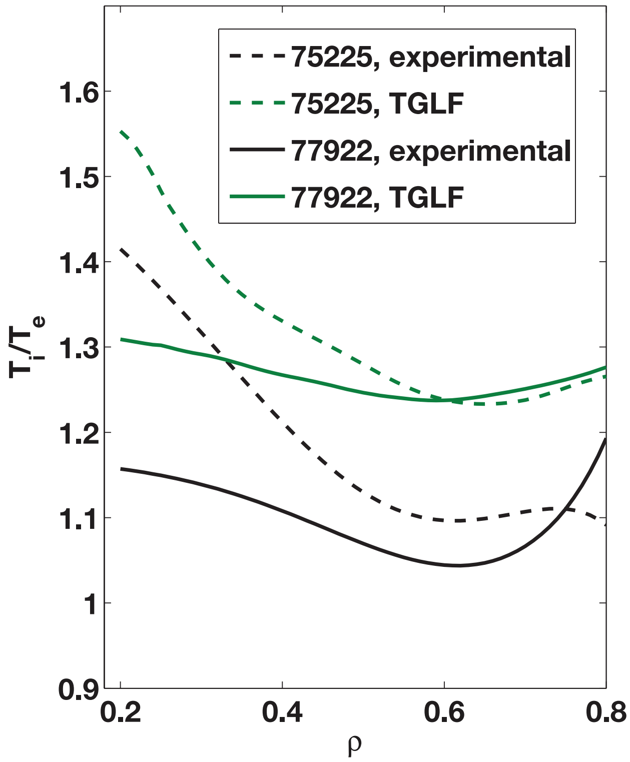

Figure 15. T_i/T_e ratio as a function of the radial coordinate ρ for the investigated JET hybrid discharges.

important role, in a mechanism of interaction between these two factors that leads to the plasma stabilization of the shot 75225, as can be seen in figure 13, where electromagnetic and electrostatic simulations including the effect of the fast ions are compared. The weight of the electromagnetic stabilization is now relevant in order to achieve the experimental results and seems to have a slightly higher impact (8%) with respect to the introduction of the fast ions effect (7%). These good predictions are in agreement with the results of [25], where the role of fast ions on the core of the 75225 plasma has been investigated using non-linear electromagnetic gyro-kinetic simulations and the key role of fast ions for the sustainment of hybrid scenarios through a positive feedback between the plasma core and the edge has been demonstrated.

The comparison of the predictions carried out by TGLF simulations for the two investigated hybrid discharges is shown in figure 15, where the core T_i versus T_e ratios, as given by the experimental data, are represented together with the ones resulting from the simulations. In both cases TGLF gives a ratio well above one and overestimates it. For the 77922 discharge this is caused by the T_i overestimation. We find a difference of about 0.15 between the experimental and the simulated T_i/T_e for the whole core region of the plasma. The T_i/T_e overestimation of the 75225 discharge is due to the underestimation of the T_e profile, a consequence of a slight underestimation of the pedestal, which is caused by the kiauto model used for the pedestal.

4. Conclusions

The core heat transport in JET baseline discharges has been modelled and investigated in this paper using the quasi-linear transport models TGLF and QuaLiKiz. They have been found to describe well the known ITG dominance physics that is typical of JET standard H-modes and to reproduce well the experimental temperature profiles of these discharges. These results have been obtained despite the differences between QuaLiKiz and TGLF in the geometry description, the inclusion of the E × B shear and of the electromagnetic effects, then confirming the weak effect of these factors on the H-mode regime. On the contrary they are known to play a non-negligible role in the hybrid scenarios. Then we have investigated and modelled the heat transport in JET hybrid discharges using the transport model TGLF, which includes the effects listed above. A general good agreement with the experimental data has been found, except for some discrepancies in the resulting ion temperature profiles. From the analysis of the factors included in TGLF that are known to give a contribution to the plasma stabilization, we can summarize the results for the improved core confinement JET hybrids with $\beta_N \sim 3$ and Mach number M ~ 0.2 reported here in this paper as follows:

- A weak dependence of the temperature profiles on the E × B shear effect has been found, in contrast with the predictions of GLF23 which overestimate this effect, confirming [7]. TGLF predicts this effect to be negligible in high density shots, weak (about 3%) in low density discharges, for which the parallel velocity gradient has the impact of compensating the stabilizing E × B shear effect inside $\rho = 0.3$, otherwise relevant in that region.
- The description of the geometry has a non-negligible effect: the profiles obtained with the Miller description are closer to experimental points, improving the simulated results. The s-α model underestimates the fluxes, leading to temperature profiles higher than the experimental data up to 8% for the discharge 77922, characterized by a high shape. However the inclusion of the effects of the elongation and the triangularity in the Miller model does not lead to any relevant difference in the resulting temperatures. Then, for the single discharge, the difference in the profiles found by changing the geometry description has to be ascribed to the approximation made in the implementation of the s-α model, in agreement with [34]. In order to understand the discrepancy of the impact of varying the geometry description in different hybrid discharges further investigations are needed.
- The inclusion of the electromagnetic effects leads to a weak stabilization (about 1–4%), trend in agreement with the ITG stabilization expected for finite β, in accordance with the impact of β found from TGLF simulations of DIII-D hybrids [43].
- The inclusion of the fast ions effects in the discharge 75225, with a high presence of fast ions, gives the best prediction for ion and electron temperatures, improving the ion temperatures by 15%. Isolating the contribution of the electromagnetic effects, they have been found to increase the ion temperature by 8% and to have an even more important role than the fast ions stabilization, which lead to 7% higher ion temperatures.

TGLF then leads to improved predictions about the heat transport in JET hybrid plasmas with respect to the models previously developed and gives some indication for the improvement of transport models such as QuaLiKiz, which is very sophisticated and physically based, however without effects such as electromagnetic instabilities which this analysis has pointed out to be fundamental in order to reproduce JET hybrid discharges.

It also gives some important indications about the possible mechanisms underlying the improved confinement of the hybrids with respect to the baseline scenario. The role of the E × B shear effect is properly re-dimensioned and the mechanism of interaction between the electromagnetic and fast ion effects seems to be dominant in stabilizing the core heat transport for the 75225. From the analysis carried out here, where the temperature pedestal is always kept fixed, we find $H_{98}(y, 2) = 1.25$ for the simulation of the 75225 including the fast ions effect. Without the contribution of the fast ions we have $H_{98} = 1.15$ and $H_{98} = 1.11$ is obtained by also removing the electromagnetic and the E × B shear effects. We can interpret the improvement of 0.11 with respect to the value 1 that characterizes the baseline discharges as being due to the pedestal (not modelled in the self-consistent simulations reported here but taken from the experimental data) and the difference between $H_{98} = 1.25$ and $H_{98} = 1.15$ as having been caused by the core mechanism of the interaction between the fast ions stabilization and the EM effects. That confirms the gyrokinetic analysis of this discharge reported in [25], in which this mechanism, together with the mutually beneficial interaction core-pedestal, are suggested as the main players in the enhancement of the energy confinement in the core and even in the pedestal regions. For the 77922 discharge this mechanism seems not to play such an important role, which allows us to conclude that the improvement of the confinement with respect to the baseline scenario is almost totally due to the pedestal region.

We have to point out that the modelling and the analysis reported here refer to plasmas characterized by low magnetic shear in the inner region and then high s/q at outer radii. This characteristic, which has been found to improve the core confinement in the hybrids [6, 7], is however lost with the time during the steady state of the considered discharges, which are characterized by the same confinement improvement for the whole main heating period. Future analyses and simulations are needed to investigate the dependences of the results of this paper on the q profile variation, in order to clarify which are the main players and how they interact to sustain the improved confinement.

The presence of an amount of fast ions at the end of the flat-top phase, being as important as at the beginning, together with the relevance of the mechanism of the combined electromagnetic and fast ions effects (shown here for 75225 and demonstrated in [42] where the non-linear contribution is investigated) could suggest this mechanism as a key factor in the confinement improvement, even in the presence of a different q profile.

An increase in the temperatures of the 15% because of the mechanism of interaction between the electromagnetic and fast ions effects, as has been found for the JET shot 75225, is an important and encouraging result if extrapolated to ITER, which will be characterized by a significant amount of α particles from fusion reactions and in which instead the foreseen low rotation will not be able to play a big role in the plasma stabilization.

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Appendix

TGLF and QuaLiKiz have been used in their stand-alone versions to carry out a series of scans for the plasma transport relevant parameters. The computed quasi-linear fluxes have been compared with the results of the gyrokinetic non linear simulations previously obtained from GYRO and GENE [10, 11, 44]. In this work we have used as a basis the GA standard case, characterized by the following parameters: r/a = 0.5, $R/LT_{i,e} = 9$, $R/L_n = 3$, $q = 2$, $T_i/T_e = 1$, s = 1, $\beta = 0$, $\nu_e = 0$.

The GA standard case consists of a very narrow window of quantities and the scans have been done using s-α geometry, without any rotation effect and in the electrostatic case. However in the scans the investigated parameters have been varied in intervals wide enough to cover both regions of values typical for H-modes and hybrids, in order to obtain some first indication about the behaviour of TGLF and QuaLiKiz for these two scenarios. The TGLF version 2013 has been used.

Most of the figures presented here are based on previous works where non linear gyrokinetic codes (GENE and/or GYRO) fluxes were compared to QuaLiKiz. Here TGLF fluxes are added and in some parametric cases the range is extended. For information on non linear runs the reader is referred to [10, 11]. Now in all cases the QuaLiKiz version 2012 has been used.

All the presented scans have been carried out varying only one parameter and taking the GA standard case values for the other quantities. In figure A.1(*a*) the scan of R/L_T (for both electrons and ions) is shown. The parametric dependence is well described by both TGLF and QuaLiKiz. TGLF underestimates by up to 15% the ion heat transport, QuaLiKiz gives better results, agreeing with the GYRO simulation within 6%. Figure A.1(*b*) represents the scan of R/LTi, keeping fixed R/L_{Te} to 9. For values of R/L_{Ti} close to R/L_{Te}, then in the ITG regime, characteristic of H-modes, there is good agreement between the QuaLiKiz and GYRO simulations. TGLF slightly underestimates the ion heat flux. For lower R/L_{Ti} QualiKiz describes well the electron heat flux, which is overestimated by TGLF. The ion heat flux is reproduced better by TGLF, while QuaLiKiz underestimates it. This region, where TEM starts to become dominant, can be relevant for the outer radial zone of hybrid plasmas. The scan of the collisionality is shown in figure A.1(*c*). The qualitative behaviour described by the GYRO results is recovered by both QuaLiKiz and TGLF for all the transport channels. The QuaLiKiz and TGLF ion heat fluxes are less sensitive to the collisionality with respect to GYRO simulations, leading us to conclude that the linear collisional TEM damping, which is the dominant mechanism because of the reduction of the flux with the collisionality, is too weakly reproduced by the quasi-linear models. The values of the ion fluxes are slightly underestimated by TGLF and overestimated by QuaLiKiz. Both models reproduce the electron heat flux values well and the direction inversion of the particle flux with increasing collisionality. Figure A.1(*d*) shows the scan for T_i/T_e. QuaLiKiz matches the GYRO fluxes well in the H-modes typical region where $T_i \sim T_e$, and tends to slightly overestimate the ion heat fluxes for the increasing T_i/T_e, hybrid plasmas zone. TGLF underestimates the ion heat flux for all the values of T_i/T_e. The QuaLikiz discrepancy about the particle flux in $T_i/T_e = 0.5$ has been investigated in [45]. The q factor dependence of the fluxes was then investigated, as shown in figure A.1(*e*). Qualikiz reproduces the GYRO results well both qualitatively and quantitatively, even for large q values, for which TGLF underestimates the ion heat flux. This region becomes important in the case of hybrid shots, characterized by higher q values with respect to the H-modes in the outer part of the plasma. Figure A.1(*f*) shows the scan of the magnetic shear s. The qualitative trend is well described by both models. However the peaks of the heat transport as calculated by TGLF are shifted from s = 0.5 to s = 0.25. For low values of s, which is one of the characteristics of hybrid plasmas inside $\rho = 0.5$, both models match with the GYRO and GENE simulations. Around values of s = 1, close to the s typical of H-modes for $\rho < 0.5$, QuaLiKiz gives very good agreement with the non linear results and TGLF always underestimates the ion heat flux. Figure A.1(*g*) presents the R/L_n scan. Both R/L_{ne} and R/L_{ni} have been varied. QuaLiKiz matches the GYRO results well and TGLF slightly underestimates the ion heat flux for $R/L_n < 3$. Finally a dilution scan is shown in figures A.2(*a*) and (*b*) with electrons, D main ions and He impurity. QuaLiKiz predicts a rather good agreement

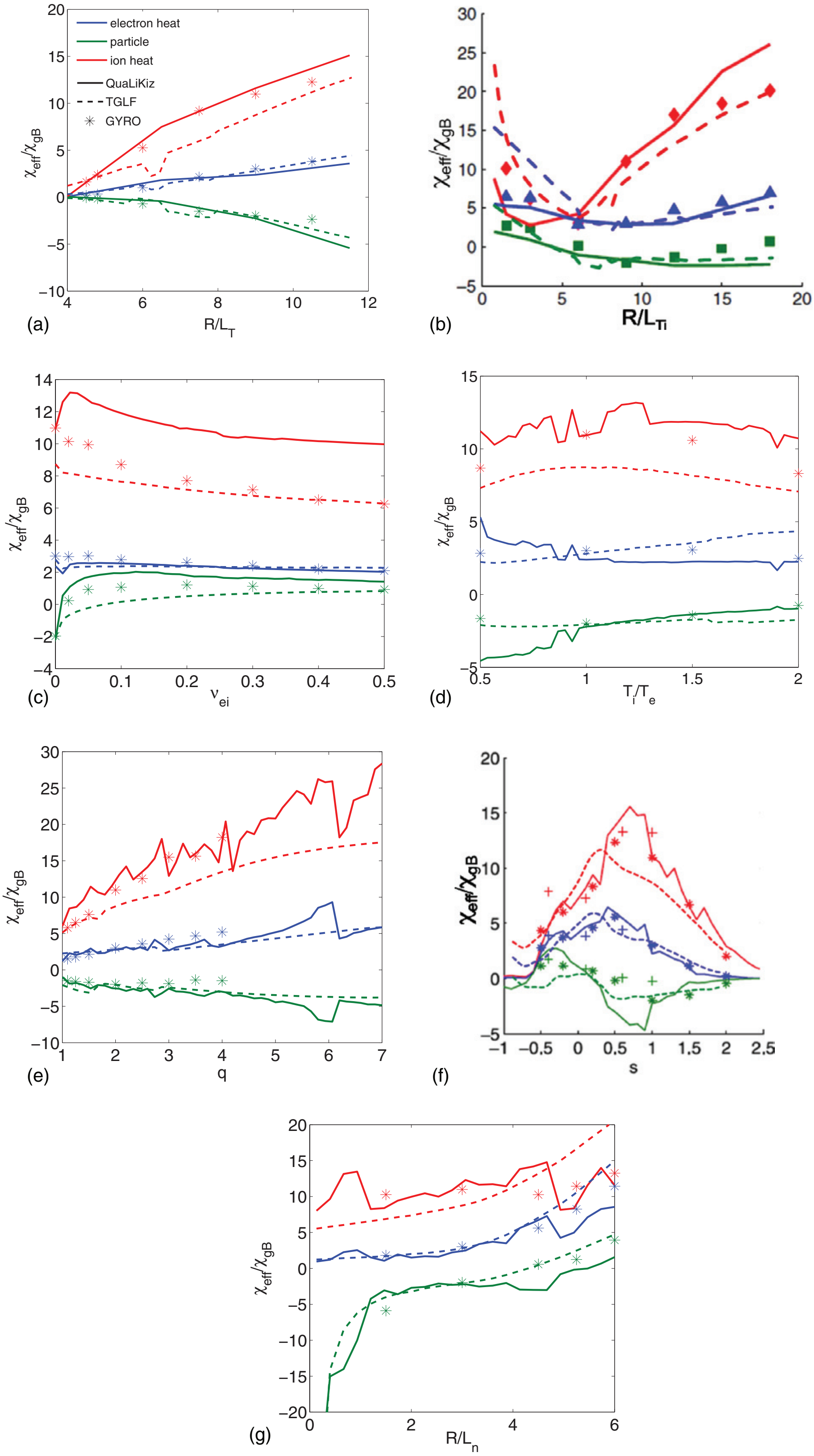

Figure A.1. GyroBohm normalized diffusivities as a function of (*a*) R/L_{T}, (*b*) R/L_{Ti}, (*c*) collisionality, (*d*) $T_{\mathrm{i}}/T_{\mathrm{e}}$, (*e*) q, (*f*) s and (*g*) R/L_{n}. The non linear GYRO data, shown with asterisks (*a*) (*c*)–(*e*) (*g*) have been taken from the GYRO database [15]. (*b*) is based on figure 9 of [10]: for GYRO non linear simulations particle diffusivities are represented as squares, electron heat diffusivities as triangles and ion heat diffusivities as diamonds. (*f*) is based on figure 15 of [11]. GYRO non linear simulation diffusivities are represented as asterisks, GENE non linear simulation diffusivities as crosses. For quasi-linear simulations the solid lines are for Qualikiz, the dashed lines for TGLF. The green colour represents particle diffusivity, blue is for electron heat diffusivity, red is for ion heat diffusivity.

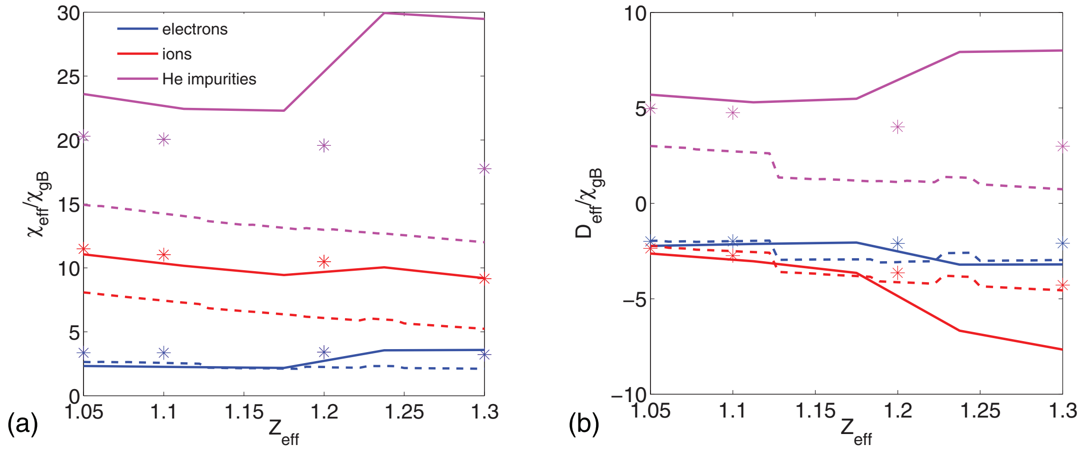

Figure A.2. GyroBohm normalized heat (*a*) and particle (*b*) diffusivities as a function of Z_{eff}, considering D ions and electrons' plasma with He impurity, as carried out in [10]. The non-linear GYRO data have been taken from the GYRO database [15]. GYRO non linear simulation diffusivities are represented as asterisks. For quasi-linear simulations the solid lines are for Qualikiz, the dashed lines for TGLF. The purple colour represents impurity heat (*a*) and particle (*b*) diffusivity, blue is for electron heat (*a*) and particle (*b*) diffusivity, red is for ion heat (*a*) and particle (*b*) diffusivity.

for both heat and particle fluxes until Z_{eff} = 1.2. For higher Z_{eff} some discrepancies are visible. TGLF underestimates the ions' heat transport and the He particle transport.

These series of scans presented here have shown a general qualitative and quantitative agreement for the GA std case among TGLF, QualiKiz and the non linear simulations results. The more relevant discrepancies have been found regarding the TGLF underestimation of the ion heat flux, which however is slight, except for some marginal cases and regarding the TEM dominated regions prediction given by both TGLF and QuaLiKiz. We can then conclude that in the case of ITG dominated regimes both codes have a solid base of agreement with the non linear simulations. When the ITG starts to no longer be the dominant instability some disagreement has been found. This point should be taken into account when the models are used to self consistently simulate the discharges of present and future machines.

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