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Turbulent Transport Analysis of JET H-mode and Hybrid Plasmas using QuaLiKiz and TGLF

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ABSTRACT

The physical transport processes at the basis of JET typical inductive H-modes scenarios and advanced hybrid regimes, with higher thermal confinement, are analyzed by means of some of the newest and more sophisticated quasi-linear transport models: TGLF and QuaLiKiz. The temporal evolution of JET pulses is modeled by CRONOS where the turbulent transport is modeled by either QuaLiKiz or TGLF. Both are first principle models with a more comprehensive physics than the models previously developed, and therefore allow analyzing 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 also Trapped Electron Modes (TEM) are found to be important and different physical mechanisms for turbulence reduction play a decisive role. Whereas E×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 electromagnetic effects are taken into account. The TGLF transport model properly captures these mechanisms and correctly reproduces temperatures.

1. INTRODUCTION

In order to plan future tokamak devices, as ITER or DEMO, the availability of plasma models, 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 highly determine 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-modes core plasmas. However, the predictability of advanced tokamak regimes, as Hybrid [3] or Internal Transport Barrier [4], was more difficult and the models had to been retuned [5–7].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 of 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 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 selfconsistently reproduce JET core temperatures.

QuaLiKiz calculates the quasi-linear gyro-kinetic heat and particles fluxes. The linear response is calculated by an electrostatic eigenvalue gyro-kinetic dispersion relation. It includes two ion species and 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 5 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 then 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 give in addition some information about the linear instabilities predicted in the plasma core.

In this paper we focus on 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 hybrid ($\beta_N \sim 3$ [3], $\beta_p \geq 1$ [14] where $\beta_p = 2 <P> / <B_\theta^2>$, with $<P>$ the average pressure and $<B_\theta^2>$ 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 version. 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 H98(y,2) scaling [16]. The physical basis of this improved confinement are however not clear yet. 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 outer radii with respect 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 as E×B shear, electromagnetic instabilities and fast ions interplay, that 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 point out the effects that are more significant for hybrids 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 H98.

A first comparison between the two models has been carried out by an initial work of series of scans in transport relevant physical parameters using as basis the GA (General Atomics)standard case [1] (electrostatic, with s-α geometry, without ExB 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 Sec. II 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 behavior and their description of the dominant instabilities on standard regimes that are based on a well-known physics. In Sec III we present the results of heat transport simulations obtained for hybrid scenarios, carried out using TGLF, as above explained. Finally some conclusions are presented in Sec. IV. II

2. JET BASELINE PLASMAS

The self-consistent simulations presented in this paper have been carried out modelling the current and the ion and electron temperatures 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 temperatures evolution using the code HELENA [27]. No sawtooth model has been included. In addition the transport models here used 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 temperature pedestal has been taken fixed at the normalized toroidal flux coordinate $\rho = 0.93$, according to the experimental results. When we use the transport models in their stand-alone version we take all the profiles from the analyzed experimental discharge.

The carbon wall JET H-mode Pulse No's: 73344 and 73342 have been simulated. They have very similar parameters, as it is shown in table 1, except for the average density values: Pulse No: 73344 is a standard JET H-mode ($\langle n_e\rangle = 6.8\times10^{19}$ m^{-3}), 73342 has higher density ($\langle n_e\rangle= 9\times10^{19}$ 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 fig.1 the temperature profiles are shown for the Pulse No: 73344, together with the q and the ne profiles, typical of a standard JET H-mode. A reasonable good agreement has been found for Pulse No: 73342 as well, as illustrated in fig.2. Using the stand-alone version of QuaLiKiz and TGLF we have found that both the models predict the dominance of the ITG instabilities for the H-mode shots, as fig.3 shows for Pulse No: 73344. The agreement between the predicted temperature profiles and the drift modes analysis of TGLF and QuaLiKiz gives the indication that the physical effects as 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 low values of β and 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-modes discharges. In fig.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 Pulse No: 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 Pulse No: 73344, the values predicted by QuaLiKiz are very similar to the experimental ones outside $\rho = 0.4$, TGLF tends always to have a larger ratio in the external part of the plasma.

3. JET HYBRID PLASMAS

The self-consistent simulations of the hybrids have been carried out similarly to the H-modes study presented in Sec.II. The initial q profiles are taken from MSE-constrained equilibrium reconstruction and which are then evolved by the current diffusion equation, which coincides with experimental evolution as shown in [28].

The JET hybrid Pulse No: 77922 [29] have been first simulated with TGLF. It is a typical high triangularity improved confinement JET hybrid shot obtained using the 'overshoot technique' [30]. The main characteristics of this discharge are shown in table 1. 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. In fig.5 the temperature profiles together with the density and q profiles are shown. The agreement between TGLF and the experimental data is not as good as for the H-modes 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 dominant modes for $k_\theta\rho_s < 0.5$ inside $\rho = 0.6$ and the dominance of TEM outside $\rho = 0.65$, as the growth rates and the relative frequency for one of the most significant modes for the heat transport show in fig.6.

The temperature profiles of fig.5 have been obtained including the E×B shear effect, ElectroMagnetic (EM) instabilities and using the Miller geometry description. Because of the availability 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 fig.7a 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 [31] 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 [32]. From the agreement between GLF23 without the ExB 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 [7,32]. The study of the role of the geometry description is reported in fig.7b. The difference in the temperature profiles obtained using the s-α model and the Miller model is large, up to 14%. However, it is the particular description that is responsible of the different temperature profiles and not the high shape of the plasma of this shot. Carrying out the simulation using the Miller model with the same parameters as for the s-α geometry (that is $\kappa = 1$, $\delta = 0$ and both the shears of elongation and triangularity = 0), we found the same results as the case with Miller geometry with experimental elongation and triangularity. This is in agreement with previous investigations [33] that discovered a discrepancy in the fluxes obtained using the s-α geometry with respect to other more realistic models due to the overestimation of the linear thresholds by using the s-α geometry. This can explain the higher values of the temperature profiles in the case of s-α geometry founded in the inner region of the plasma. 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 [34], findings that are in disagreement with the results of the simulations here presented. The fig.7c 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 [35]) 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 βe lead the instabilities to decrease, however without achieving the complete stability. The reduction of very small fluxes, though relevant in percentage, turns out to β_e 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 Pulse No: 77922 by GYRO [36], 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 Kinetic Ballooning modes (KBM) regime. About 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 [21,37-39]. Very recent comprehensive gyro-kinetic simulations [40] 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 ITG and KBM regimes, the TGLF simulations predict to be very close to the KBM zone but 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 include such non-linear effects and does not predict KBM for this discharge.

The Pulse No: 77922 is characterized by a population of fast ions which contributes to the energy content for about the 15%. As it is shown in fig. 8 the ion and electron temperatures obtained including the fast ions in the TGLF simulation are slightly higher inside $\rho = 0.25$. For 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 Pulse No: 75225 [30] has been then simulated. Similarly to Pulse No: 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 fig.9, together with the density and the q profiles. Both ion and electron temperatures are under predicted 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 fig.10, 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 ($\rho > 0.7$) and in central region (close to $\rho = 0.2$), where the magnetic shear is equal to 0.

Proceeding with the same analysis done for Pulse No: 77922 about the investigation of the weight of E×B shear, geometry description and electromagnetic effects, we can see in fig. 11a that the E×B shear effect as described by TGLF has a stabilizing role not negligible for Pulse No: 75225 inside $\rho = 0.5$. It has however a very weak impact, giving a variation in the temperature profile up to 3%. On the contrary GLF23 always overestimates the impact of this factor. In the TGLF simulations it is included even the effect of the parallel velocity gradient (PVG), which is known to be destabilizing [41]. 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 compensates then the E×B shear, otherwise important in the central part of the plasma. In fig.11b the impact of the geometry description is shown. Even for this shot, the difference in the temperature profiles is due to the different description, and not for the parameters that describes the geometry. The Miller simulation with triangularity = 0 and elongation = 1 in fact gives the same results of the Miller simulation with the experimental parameters. For Pulse No: 75225 the difference of the temperature profiles obtained using the s-α and the Miller model is about 3%, smaller than for Pulse No: 77922. The Pulse No: 75225 has a lower shape with respect the Pulse No: 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 of the differences in the diffusivities obtained using s-α and Miller descriptions has not been identified yet. The electromagnetic effects seem not to have a large impact even for this discharge (fig.11c), slightly stabilizing the temperature profile inside $\rho = 0.4$, with the effect of growing the ion temperature of nearly 4%.

The discharge75225 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 electromagnetic effects [24,40], together through the mechanisms of the dilution of thermal ions [22] and the enhancement of the Shafranov shift [23]. The fast ions interplay has been included in the TGLF simulation through the dilution effect, i.e. introducing a new specie in the quasi-neutrality equation, and through the effect of the fast ions pressure on the Shafranov shift. The TGLF heat transport simulation with included fast ions, E×B shear and electromagnetic effects gives the temperature profiles shown in fig.12. There is a very good agreement between the simulation results and the experimental data, both for electron and ion temperatures. Looking at fig.13, where β_e scans with the inclusion/exclusion of the fast ions mechanisms of stabilization are shown, TGLF predicts for Pulse No: 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 important role, in a mechanism of interaction between these two factors that lead to the plasma stabilization of the Pulse No: 75225, as is possible to see in fig.12, 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 Pulse No: 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 plasma core and edge has been demonstrated. The comparison of the predictions carried out by TGLF simulations for the two investigated hybrid discharges is shown in fig.14, where the core Ti vs Te ratios, as given by the experimental data, are represented together with the ones resulting from the simulations. In both the cases TGLF gives a ratio well above one, and overestimates it. For the Pulse No: 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 Pulse No: 75225 discharge is due to the underestimation of the T_e profile, which is a consequence of a slight underestimation of the pedestal.

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 well describe the known ITG dominance physics typical of JET standard H-modes and to well reproduce 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 ExB 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 above listed. 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 β_N~3and Mach number M~0.2 here reported 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 that overestimates 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 to8% for the Pulse No: 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 [33]. 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 accord with the impact of β found from TGLF simulations of DIII-D hybrids [42].
- The inclusion of fast ions effects in the Pulse No: 75225, with a high presence of fast ions, gives the best prediction for ion and electron temperatures, improving the ion temperatures by15%. Isolating the contribution of the electromagnetic effects, they have been found to increase the ion temperature of 8% and to have even a 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 physical based, however without effects as electromagnetic instabilities that this analysis has pointed out to be fundamental in order to reproduce JET hybrid discharges.

It also gives some important indication about the possible mechanisms underlying the improved confinement of the hybrids with respect the baseline scenario. The role of the ExB shear effect is properly re-dimensioned, and the mechanism of interaction between electromagnetic and fast ions effects seems to be dominant in stabilizing the core heat transport for Pulse No: 75225. From the analysis here carried out, where the temperature pedestal is always kept fixed, we find $H_{98}(y,2) = 1.25$ for the simulation of Pulse No: 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 removing also 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 due to the pedestal (not modelled in the self-consistent simulations here reported but taken from the experimental data), and the difference between $H_{98} = 1.25$ and $H_{98} = 1.15$ as caused by the core mechanism of the interaction between fast ions stabilization and EM effects. That confirms the gyrokinetic analysis of this discharge reported in [25], in which this mechanism, together with the mutual beneficial interaction core-pedestal, are suggested as the main player of the enhancement of the energy confinement in the core and even in the pedestal regions. For Pulse No: 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 the baseline scenario is due almost totally to the pedestal region.

Finally, an increase in the temperatures of the 15% because of this mechanism, as it has been found for the JET Pulse No: 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 instead in which 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 version 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 [10,11,43]. In this work we have used as 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 the regions of values typical for H-modes and hybrids, in order to obtain some first indication about the behavior of TGLF and QuaLiKiz for these two scenarios. The TGLF version 2013 is used.

Most of the figures presented here are based on previous works where non linear gyrokinetic codes (GENE or/and 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 QuaLiKiz version 2012 is used.

In fig. A1 the scan of R/LT (for both electrons and ions) is shown. The parametric dependence is well described by both TGLF and QuaLiKiz. TGLF underestimates up to 15%the ion heat transport, QuaLiKiz gives better results, agreeing with GYRO simulation within 6%. Figure A2 represents the scan of R/L_{Ti} , keeping fixed R/L_{Te} to 9. For values of R/L_{Ti} close to R/L_{Te}, then in ITG regime, characteristic of H-modes, there is good agreement between 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 better reproduced by TGLF, while QuaLiKiz underestimates it. This region, where TEM start to become dominant, can be relevant for the outer radial zone of hybrid plasmas. The scan of the collisionality is shown in fig.A3. The qualitative behavior described by 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 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, overestimated by QuaLiKiz. Both the models well reproduce the electron heat flux values and the direction reverse of the particle flux with increasing collisionality. Figure A4 shows the scan for T_i/T_e. QuaLiKiz matches well the GYRO fluxes in the H-modes typical region where $T_i \sim T_e$, and tends to slightly overestimate the ion heat fluxes for 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 [44]. The q factor dependence of the fluxes has been then investigated, as it is shown in fig.A5. Qualikiz reproduces well both qualitatively and quantitatively the GYRO results, 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 the H-modes in the outer part of the plasma. Figure A6 shows the scan of the magnetic shear s. The qualitative trend is well described by both the 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 are one of the characteristics of hybrid plasmas inside $\rho = 0.5$, both the models matches with the GYRO and GENE simulations. Around values of $s = 1$, close to s typical of H-modes for $\rho < 0.5$, QuaLiKiz gives very good agreement with the non linear results, TGLF always underestimates the ion heat flux. Figure A7 present the R/L_n scan. Both R/L_{ne} and R/Lni have been varied. QuaLiKiz matches well the GYRO results, TGLF slightly underestimates the ion heat flux for $R/L_n<3$. Finally a dilution scan is shown in fig.A8 and A9 with electrons, D main ions and He impurity. QuaLiKiz predicts a rather good agreement for both heat and particle fluxes until $Z_{eff} = 1.2$. For higher Zeff some discrepancies are visible. TGLF underestimates ions heat transport and He particle transport.

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

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	B_T (T)	I_P (MA)	P_{NBI} (MW)	q_{95}	v_{t0} (rad/s)	n_e/n_{GW}	/	$_N$	$H_{98y,2}$
73342	2.7	2.5	15	3.4	$5\ 10^4$	1	0.42/1.74	2	1
73344	2.7	2.5	15	3.4	$5\ 10^4$	0.75	0.39/1.74	1.5	0.95
75225	2	1.7	17	4.1	10^5	0.4	0.2/1.64	3	1.25
77922	2.3	1.7	17	4.3	10^5	0.7	0.38/1.7	2.7	1.2

Table 1: JET carbon H-modes and hybrid discharges modelled and analyzed in this paper.

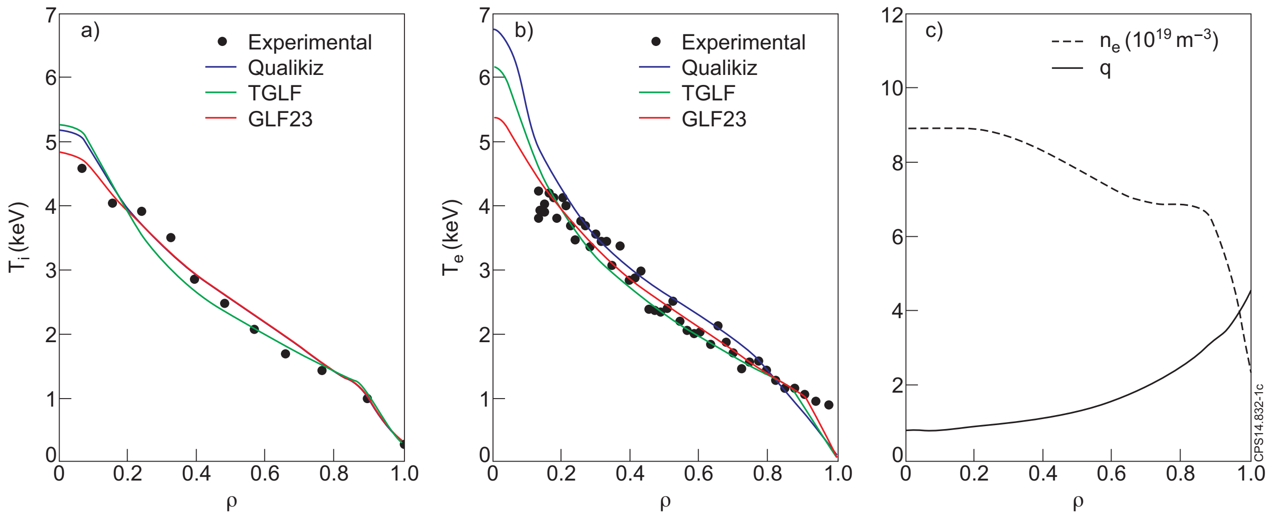

Figure 1: Ion (a), electron (b), n_e and q (c) profiles of the JET H-mode Pulse No: 73344 at t = 8.8s, as a function of the normalized toroidal flux coordinate ρ. Circles represent the measurements from charge exchange diagnostic (a) and high resolution Thomson scattering (b). Lines represent the predictions 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.

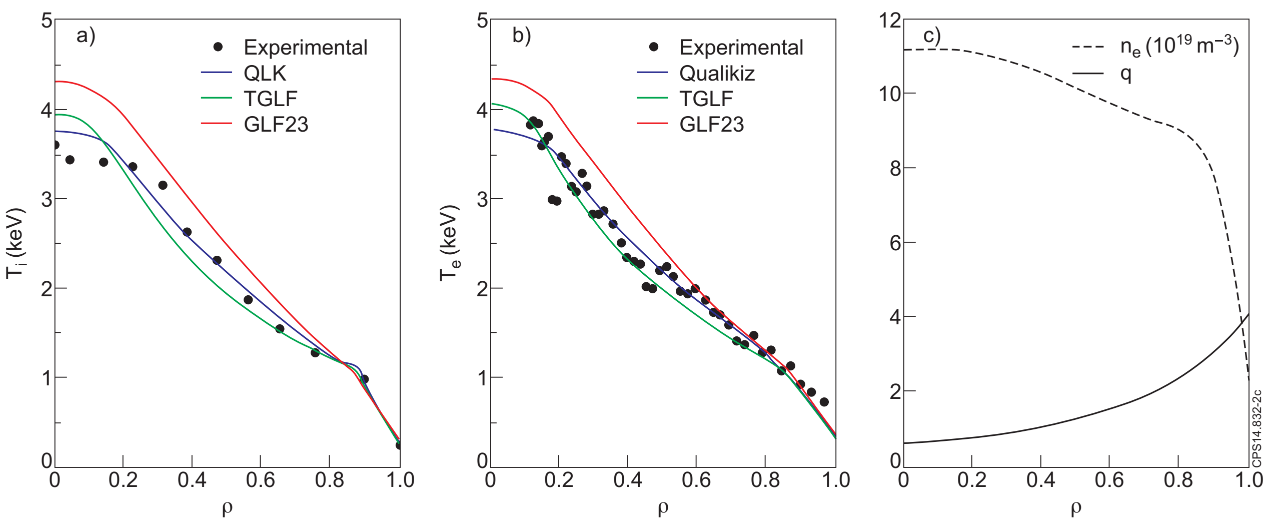

Figure 2: Ion (a), electron (b), n_e and q (c) profiles of the JET H-mode Pulse No: 73342 at t = 10.1s. The n_e profile is taken from the data, the q profile is evolving. No sawtooth model has been utilized in the simulations.

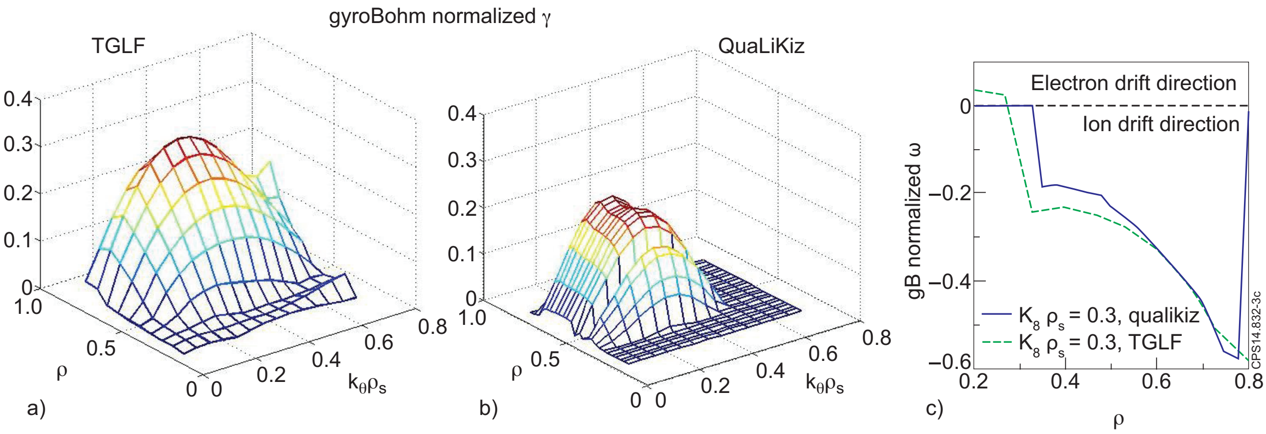

Figure 3: TGLF (a) and QuaLiKiz (b) gyroBohm normalized growth rates of the JET H-mode Pulse No: 73344at t = 8.8s as functions of the radial coordinate and $k_\theta\rho_s$. (c) gyroBohm normalized frequencies relatives to the growth rates shown in (a) and (b) for $k_\theta\rho_s$ =0.3, around which the maximum growth rate is known to be achieved in ITG regime, in the range of low $k_\theta\rho_s$, that are the most relevant in the calculation of the fluxes. In this paper the signs convention is the following: negative ω for ion drift directed modes and positive ω for electron drift directed modes.

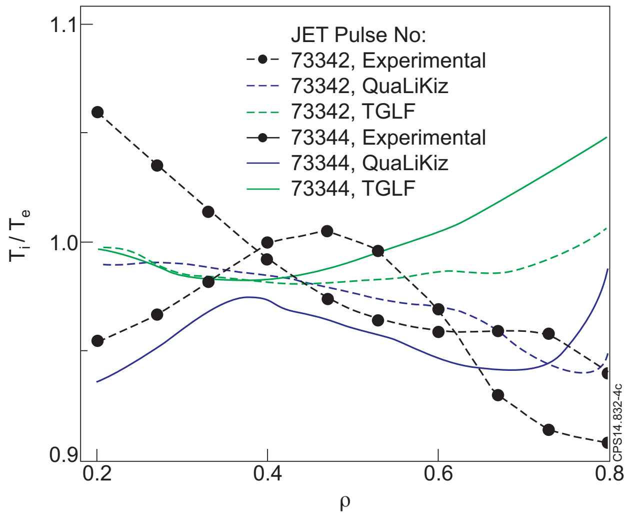

Figure 4: T_i/T_e ratio as a function of the radial coordinate ρ for the investigated JET baseline discharges.

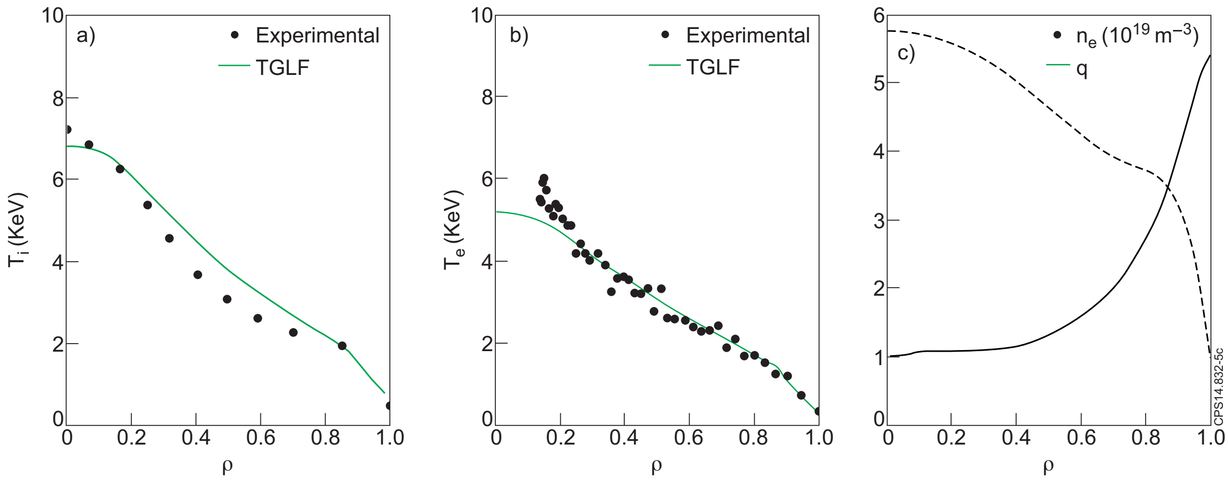

Figure 5: Ion (a), electron (b), ne and q (c) profiles of the JET hybrid Pulse No: 77922 at t = 7s. The n_e profile is taken from the data, the q profile is evolving.

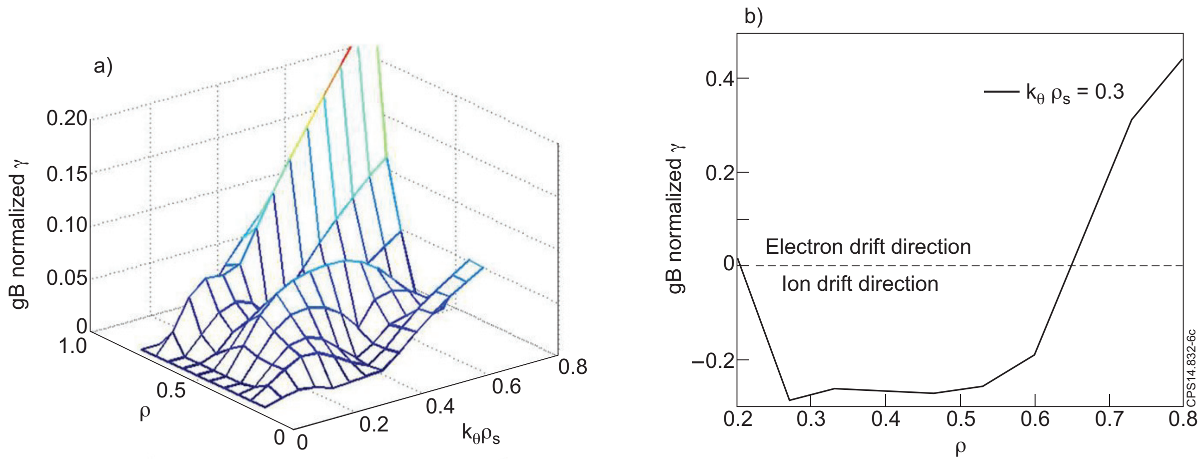

Figure 6: TGLF maxima gyroBohm normalized growth rates (a) of the JET hybrid Pulse No: 77922 at 7s as functions of the radial coordinate and $k_\theta\rho_s$; (b) gyroBohm normalized frequency profile relative to the maxima growth rates for $k_\theta\rho_s = 0.3$.

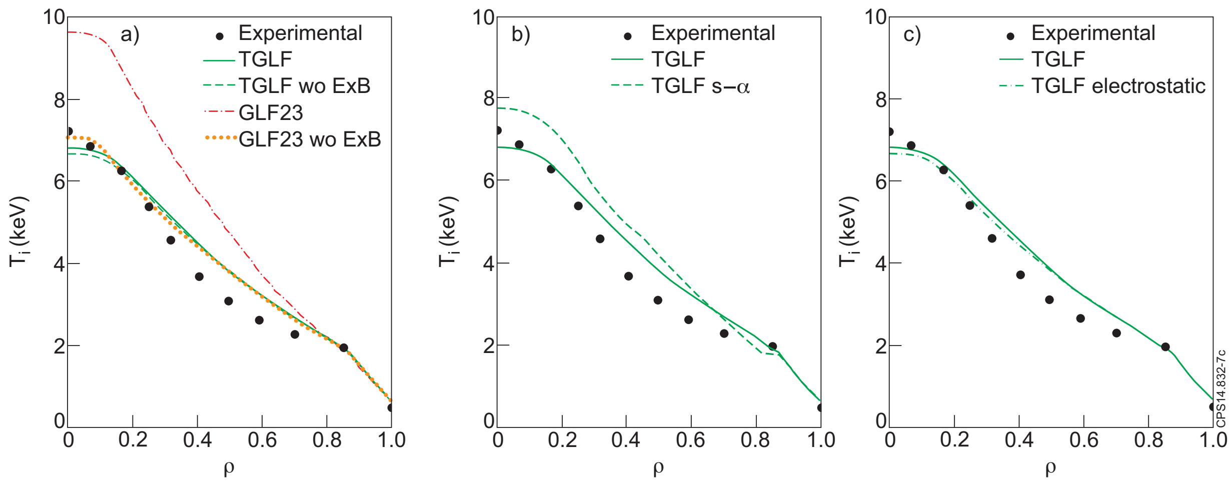

Figure 7: T_i profiles: (a) ExB shear effect, (b) geometry description, (c) em effects analysis for the JET hybrid Pulse No: 77922 at 7s.

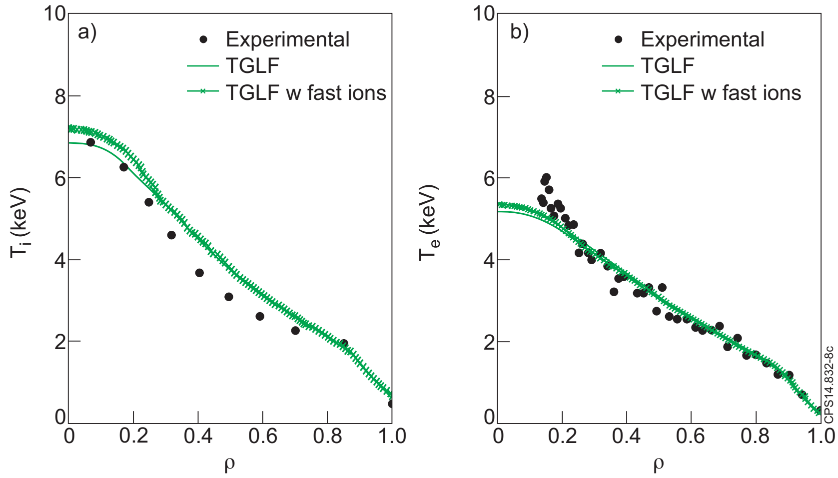

Figure 8: ion (a) and electron (b) temperatures profiles without fast ions and with fast ions for the JET hybrid Pulse No: 77922 at 7s.

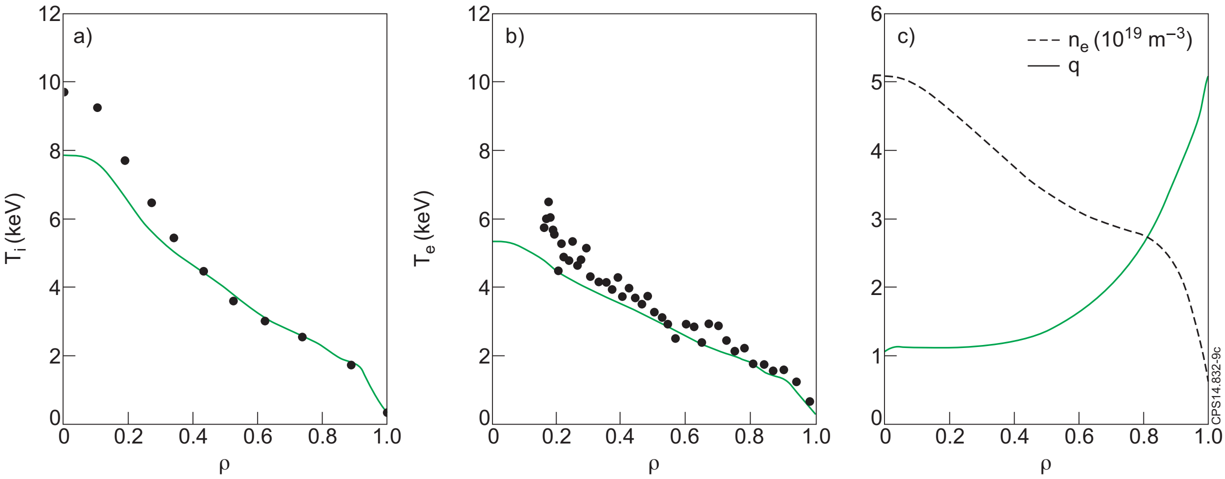

Figure 9: Ion (a), electron (b), n_e and q (c) profiles of the JET hybrid Pulse No: 75225 at 6s. The n_e profile is taken from the data, the q profile is evolving.

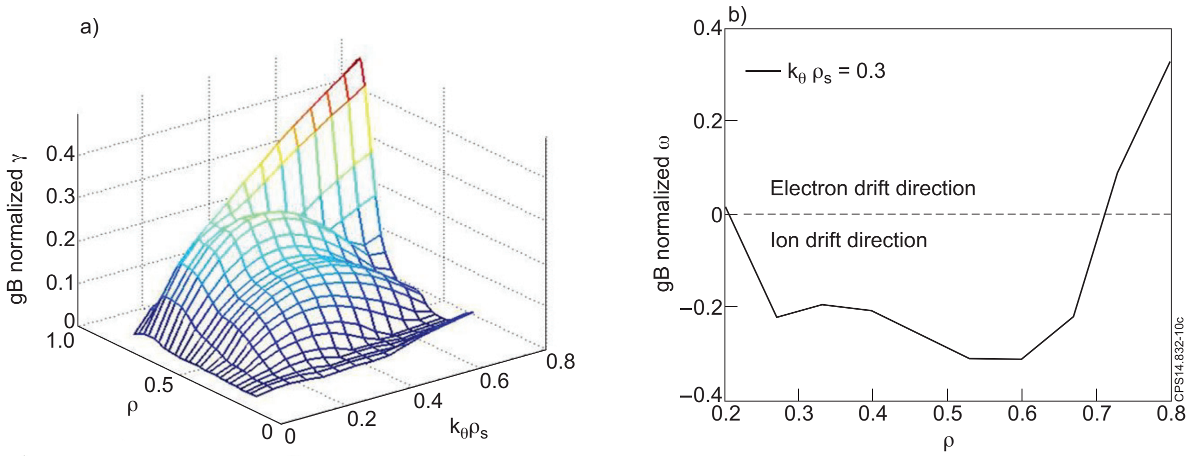

Figure 10: TGLF maxima gyroBohm normalized growth rates (a) of the JET hybrid Pulse No: 75225 at 6s as functions of the radial coordinate and $k_\theta\rho_s$; (b) gyroBohm normalized frequency profile relative to the maxima growth rates for $k_\theta\rho_s$ =0.3.

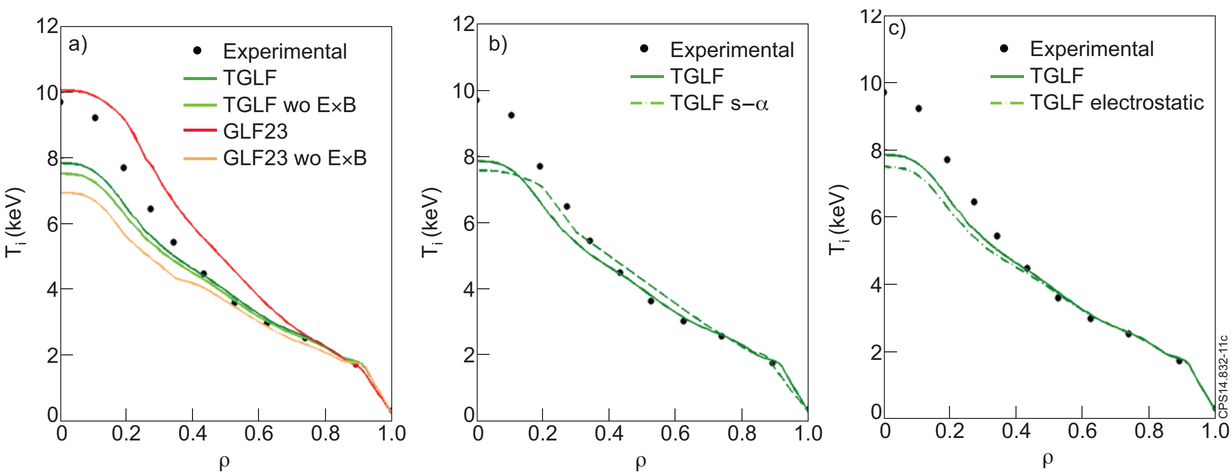

Figure 11: T_i profiles: (a) ExB shear effect, (b) geometry description, (c) em effects analysis for the JET hybrid Pulse No: 75225 at 6s.

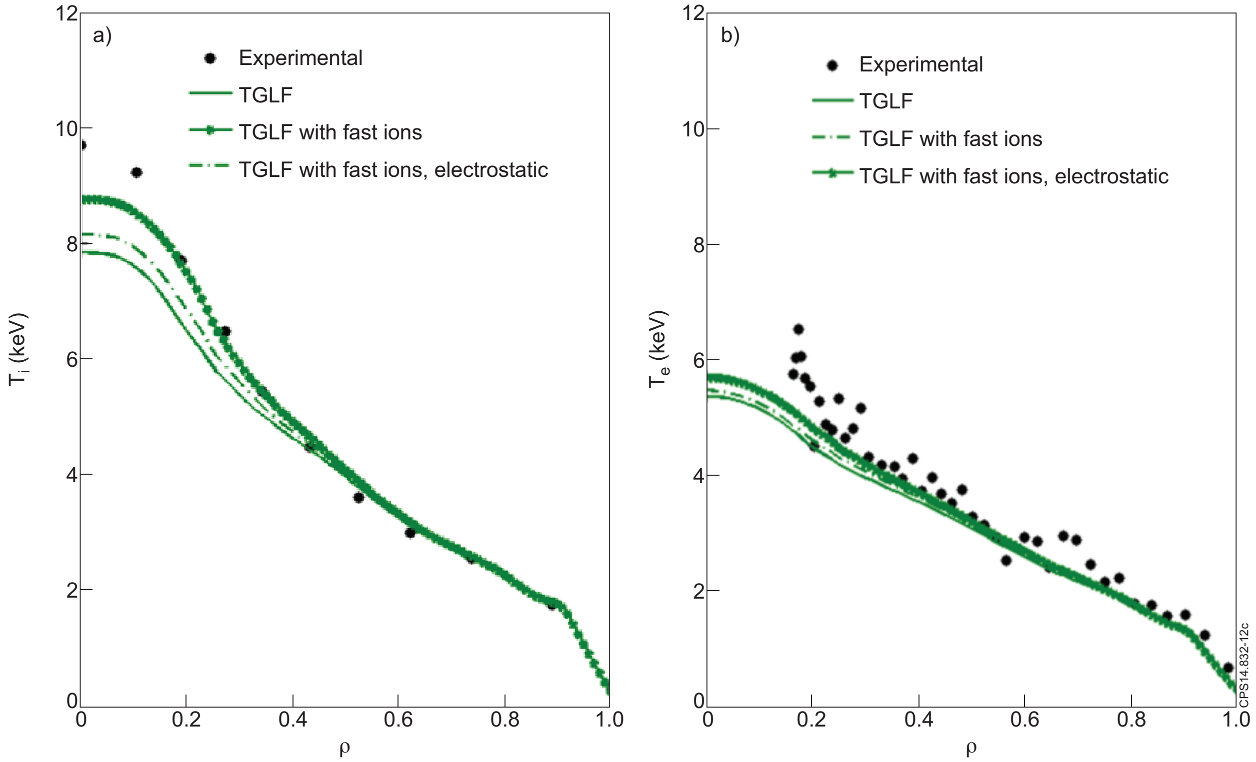

Figure 12: Ion (a) and electron (b) temperatures profiles without fast ions and with em effects, with fast ions and em effects, with fast ions and electrostatic for the JET hybrid Pulse No: 75225 at 6s.

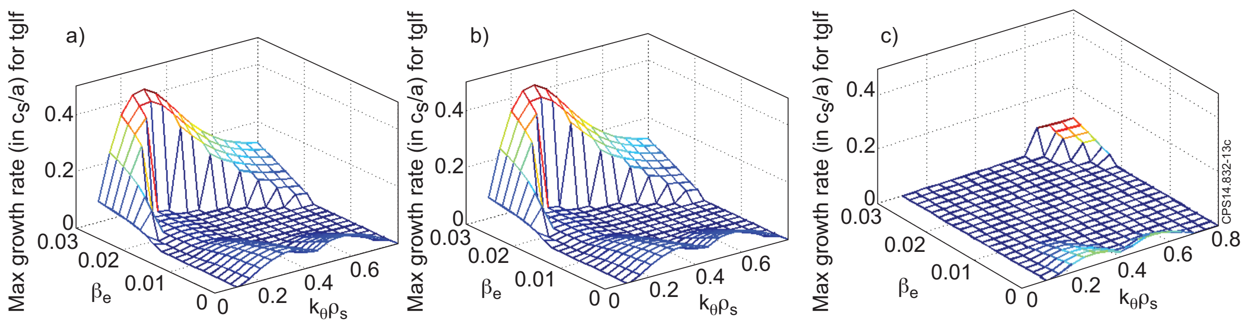

Figure 13: GyroBohm normalized maxima growth rates as function of βe and $k_\theta\rho_s$ for the JET hybrid Pulse No: 75225 at 6s: (a) without fast ions (b) with fast ion equilibrium (c) with fast ion equilibrium and fast ion dilution.

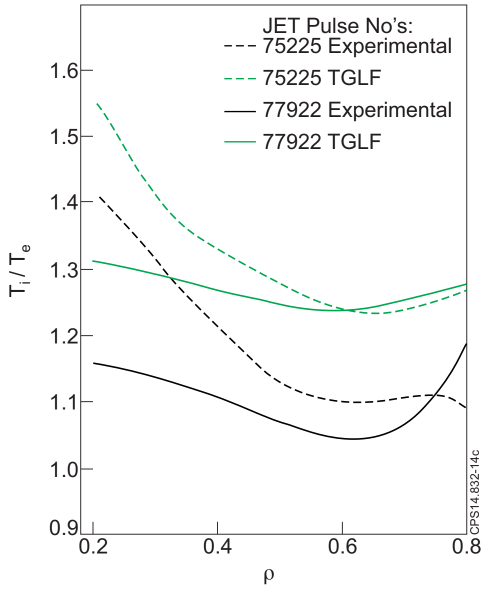

Figure 14: T_i/T_e ratio as a function of the radial coordinate ρ for the investigated JET hybrid discharges.

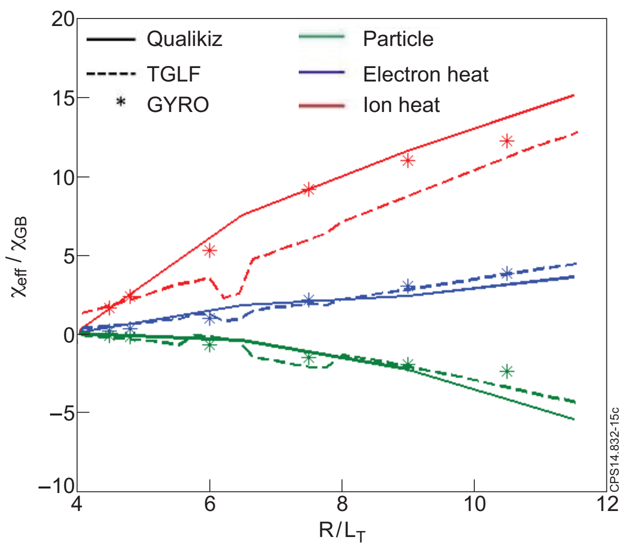

Figure A1: GyroBohm normalized effective diffusivities as function of R/L_T. The non-linear GYRO data have been taken from the GYRO database [15].

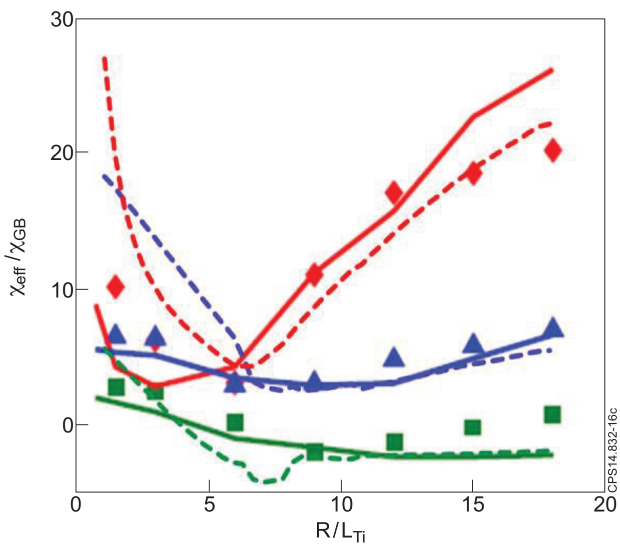

Figure A2: GyroBohm normalized effective diffusivities as function of R/L_{Ti}. Based on fig. 9 of [10]. For GYRO non linear simulations particle diffusivities are represented as squares, electron heat diffusivities as triangles and ion heat diffusivities as diamonds. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Green color represents particle diffusivity, blue is for electron heat diffusivity, red is for ion heat diffusivity.

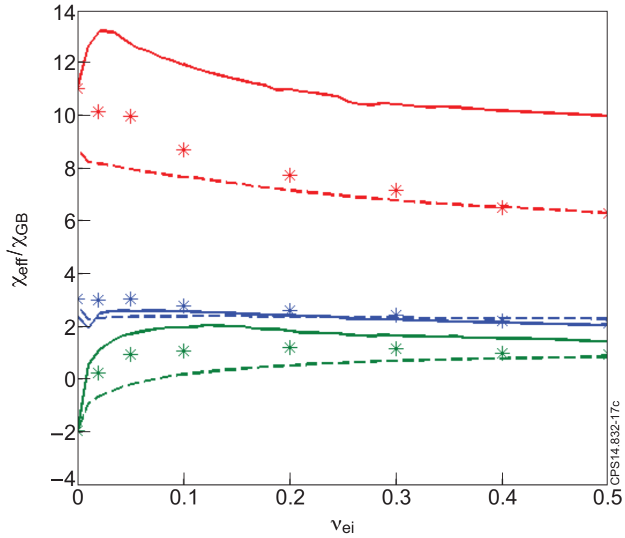

Figure A3: GyroBohm normalized diffusivities as function of the collsionality. The non-linear GYRO data have been taken from the GYRO database [15]. GYRO non linear simulations diffusivities are represented as asterisks. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Green color represents particle diffusivity, blue is for electron heat diffusivity, red is for ion heat diffusivity.

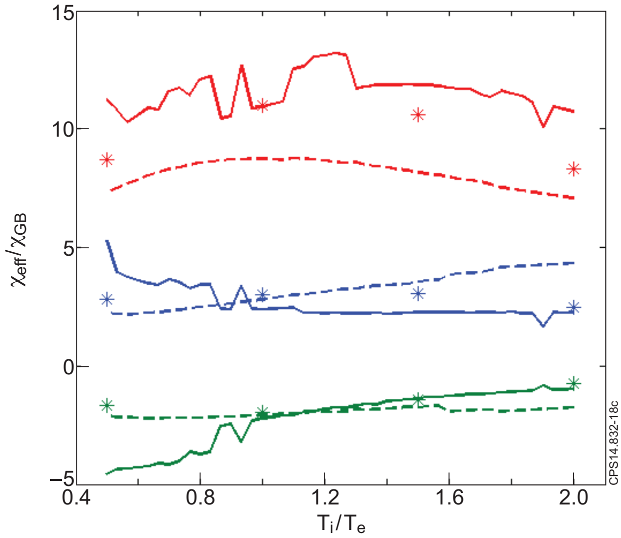

Figure A4: GyroBohm normalized diffusivities as function of T_i/T_e. The non-linear GYRO data have been taken from the GYRO database [15]. For GYRO non linear simulations particle diffusivities are represented as asterisks. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Green color represents particle diffusivity, blueis for electron heat diffusivity, red is for ion heat diffusivity.

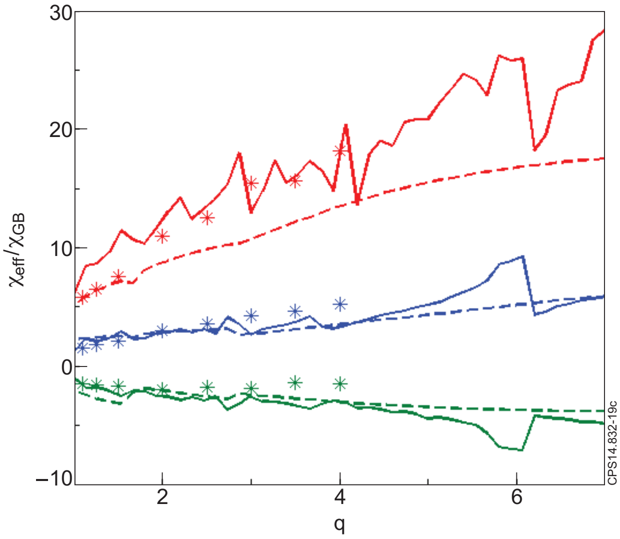

Figure A5: GyroBohm normalized diffusivities as function of q. The non-linear GYRO data have been taken from the GYRO database [15]. GYRO non linear simulations diffusivities are represented as asterisks. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Green color represents particle diffusivity, blue is for electron heat diffusivity, red is for ion heat diffusivity.

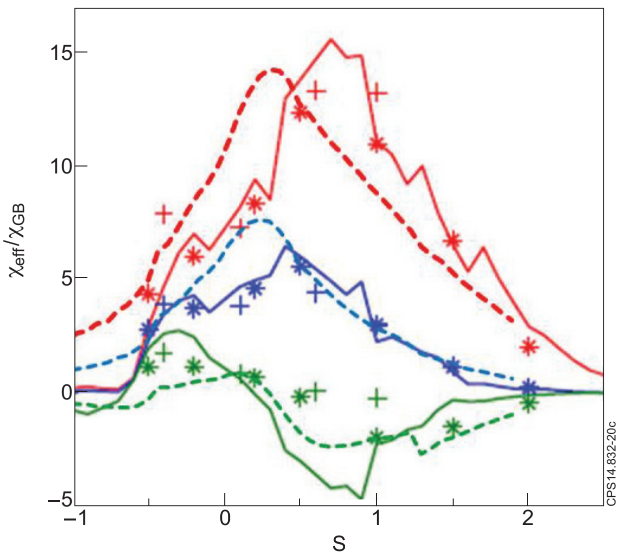

Figure A4: GyroBohm normalized diffusivities as function of T_i/T_e. The non-linear GYRO data have been taken from the GYRO database [15]. For GYRO non linear simulations particle diffusivities are represented as asterisks. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Green color represents particle diffusivity, blueis for electron heat diffusivity, red is for ion heat diffusivity.

Figure A6: gyroBohm normalized diffusivities as function of s. Based on fig. 15 of [11]. GYRO non linear simulations diffusivities are represented as asterisks, GENE non linear simulations diffusivities as crosses. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Green color represents particle diffusivity, blue is for electron heat diffusivity, redis for ion heat diffusivity.

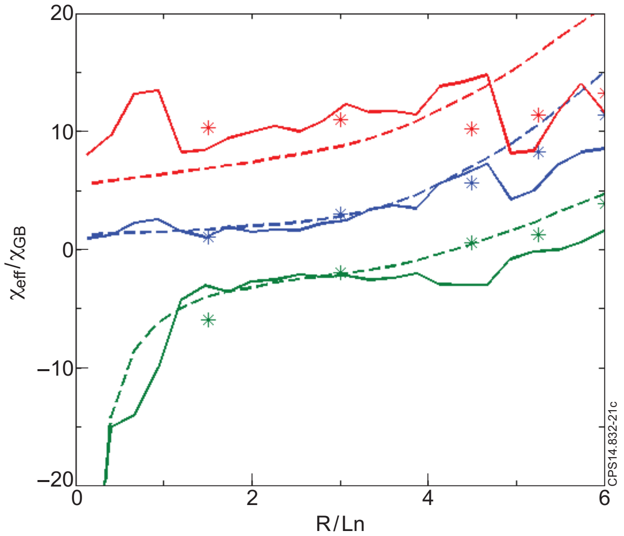

Figure A7: GyroBohm normalized diffusivities as function of R/L_n. The non-linear GYRO data have been taken from the GYRO database [15]. GYRO non linear simulations diffusivities are represented as asterisks. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Green color represents particle diffusivity, blue is for electron heat diffusivity, redis for ion heat diffusivity.

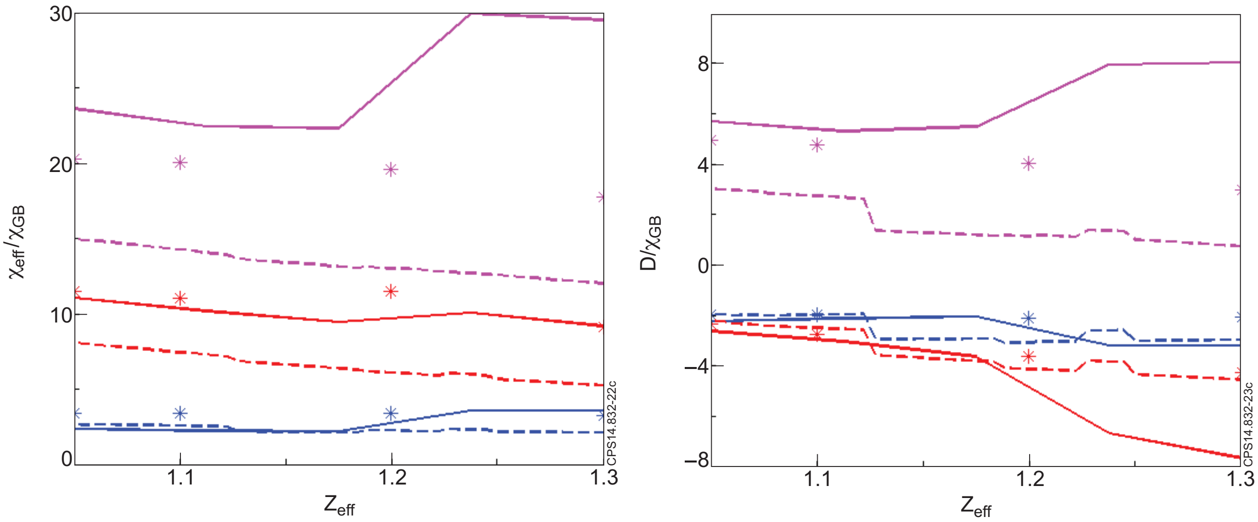

Figure A8: GyroBohm normalized heat (a) and particle (b) diffusivities as function of Z_{eff}., considering D ions and electrons plasma with He impurity, as carried out in [10]. The non-linear GYRO data have been taken from the GYRO database [15]. GYRO non linear simulations diffusivities are represented as asterisks. For quasi-linear simulations solid lines are for Qualikiz, dashed lines for TGLF. Purple color 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.