Impact of electron scale modes on electron heat transport in the JET tokamak

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It is known that turbulent heat transport can be driven by instabilities such as ITG (Ion Temperature Gradient) modes, TEM (Trapped Electron Modes), and ETG (Electron Temperature Gradient) modes. Recent studies show that electron-scale (high-k) instabilities can contribute a significant amount of electron heat flux and can also significantly influence the ion scales instabilities, especially when low-k instabilities are near marginal stability [1, 2, 3]. This is the case in ITER. It is therefore very important to understand in present devices the complex interactions between different scales in determining electron and ion heat transport in order to be able to extrapolate to ITER conditions.

A few experimental observations reveal that in situation of high electron heating, or when NBI heating is used, an increase in the electron heat flux and in the electron stiffness can occour and that it could be related to high-k instabilities [4, 5]. In dedicated electron heat transport experiments in JET L-mode plasmas, higher values of electron stiffness have been observed in the presence of significant NBI (Neutral Beam Injection) power compared to discharges with pure ICRH (Ion Cyclotron Resonance Heating) power applied in mode conversion (MC) scheme yielding dominant electron heating. The main differences in NBI heated plasmas with respect to pure ICRH-MC plasmas are lower values of T_e/T_i, higher values of R/L_{Ti}, the presence of additional fast D ions and higher toroidal rotation. Due to the stabilization effects of fast ions on ITGs [6, 7], the effects of higher R/L_{Ti} are not expected to be significant. Possible effects of T_e/T_i on TEMs thresholds have been analyzed with linear gyro-kinetic simulations and the results suggest that they cannot explain the experimental observation [8]. However, one possible effect of lower values of T_e/T_i is an increase of the electron heat flux carried by ETGs, for which a stabilizing effect of $\tau = Z_{eff} \cdot T_e/T_i$ is expected [9]. Starting from the experimental data, a study with linear and nonlinear single-scale gyro-kinetic simulations using the GENE (Gyro-kinetic Electromagnetic Numerical Experiment) code [10] indicated that the impact of ETGs could explain the experimental observations and using a simple sum of the turbulent electron heat flux from ions-scale and from electron-scales it was possible to reproduce the experimental levels of electron heat flux and of the electron stiffness, at least in the pure ICRH-MC plasma case, that could not be reproduced using only ion-scales simulations [4] (see *figure* 4). A database of JET L-mode discharge data has been created in order to further clarify the role of ETGs. These plasmas were made with C-wall and with $q_{95} \sim 5, B_0 \sim 3.3-3.4T, T_{e,0} \sim 4-6keV, T_{i,0} \sim 2.5–5keV, n_{e,0} \sim (2–3.5)\cdot 10^{19}m^{-3}$ and $I_p \sim 2\ MA$. Within the database, a strong correlation between R/L_{Te} and τ has been found, especially at outer radii. Using the experimental data from discharges with different values of τ as input, linear and nonlinear simulations have been carried out in

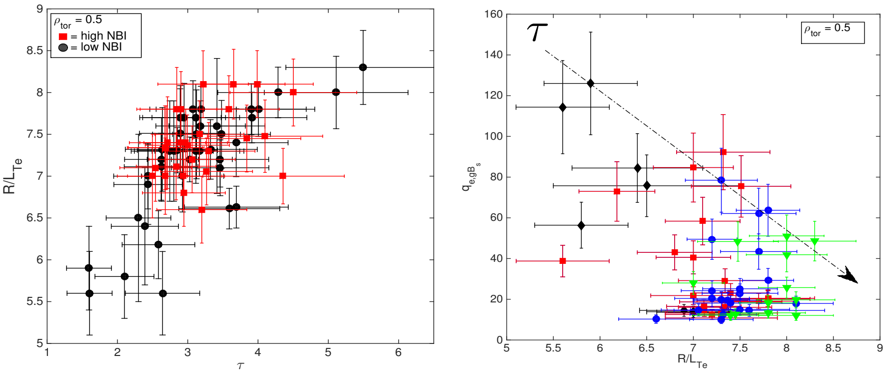

Figure 1: *R/L_{Te}vs τ (left) and $q_{e,gB}$ vs R/L_{te} for different τ (right) from a JET C-wall, L-mode plasmas database.*

order to study the impact of this parameter in our plasmas. The results at $\rho_{tor} = 0.5$ indicate that in discharges with higher τ values the ITGs are more unstable compared to discharges with lower values of τ. ETGs are predicted to be unstable in all the studied cases, but at lower τ there is a smooth transition in the linear growth rate between ion-scale and electron-scale instabilities, with the linear growth rate never going to 0, while at high τ a gap in the linear growth rate is visible between ions and electrons scale. Also the ratio between the maximum growth rate on electron-scale and on ion-scale, $\gamma_{ETG}/\gamma_{ITG}$, is lower for higher values of τ (see *figure* 2).

In order to properly study the role of multi-scale interactions and ETGs, a first gyrokinetic multi-scale simulation of a JET L-mode plasma has been carried out using the parameters from shot n. 78834 at $\rho_{tor} \sim 0.53$ and $t \sim 7\,s$. The simulation features Miller geometry, collisions, kinetic D ions and electrons, plasma rotation and is electrostatic. In order to cover both ions and electrons scale toroidal mode numbers up to the electron-scales have been coupled using $0.1 \lesssim k_y\rho_s \lesssim 48$. Perpendicular box sizes were $[L_x, L_y] \sim [64, 64]\rho_s$. Grid points $[n_x, n_y, n_z, n_{v\|}, n_w] \sim [1200, 448, 36, 32, 12]$ ($\sim 7 \cdot 10^9$ points in the phase space, x = radial, y=binormal, z=parallel (to B_0), $v \parallel$ = parallel velocity, w= magnetic momentum). The ions and electrons heat flux time evolutions from the simulation are shown in *figure* 3. The simulation indicates that multi-scale interactions and high-k instabilities can play an important role for the electron heat flux in a JET L-mode discharge. Compared to the ion scale simulations, the electron heat flux increases of ~50% at $R/L_{Te} = 10$ and of ~80% at $R/L_{Te} = 11$, with a considerable amount of heat flux brought by ETGs. As can bee seen in *figure* 3, where the plots of the electron flux density (as a function of $k_y\rho_s$) are shown, the strong increase of the flux is due to a strong increase of the contribution from the high-k part of the spectrum. Also the low-k part of the spectrum is increasing, but this cannot explain the differences with the ion-scale simulations as can be seen in the plot for the $R/L_{Te} = 10$ case. The simulation indicates that multi-scale interactions and high-k instabilities can play an important role for the electron heat flux in a JET L-mode discharge. Considering multi-scale interactions and high-k instabilities in the simulation helps also to obtain a better comparison with the experiment as can be seen in *figure* 4: the electron heat flux is closer to the experimental level for experimental values of R/L_{Te} and the predicted electron stiffness, even if still lower than in the experiment, is more than doubled with respect to the one predicted by single-scale simulations. The ion heat flux is within the experimental error bars and is not observed to change considerably between single and multi-scale simulations even when the ETG drive is increased.

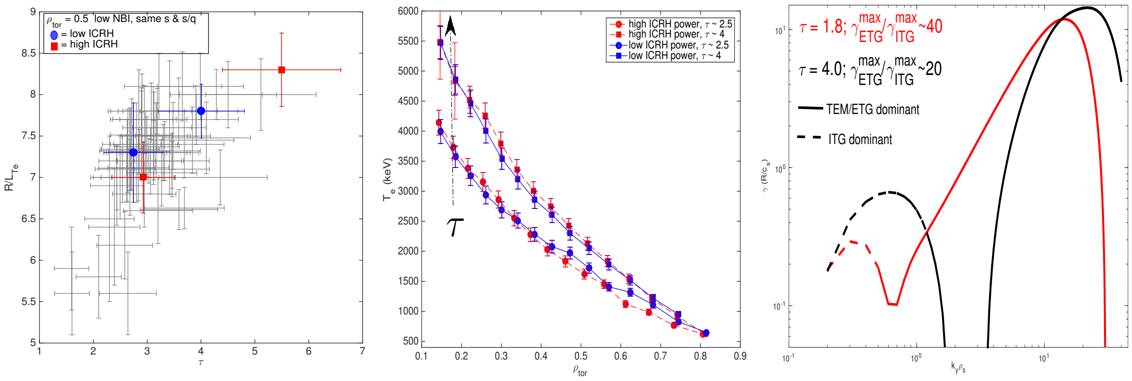

Figure 2: *R/L_{Te}vs τ (left), T_e profiles for shots with fixed $s, s/q, n_e$ and with high and low ICRH power directed to electrons (center) and linear growth rate of the main instability from GENE linear simulations for two different values of τ. The correlation between τ and the T_e peaking is independent from the power applied to the electrons.*

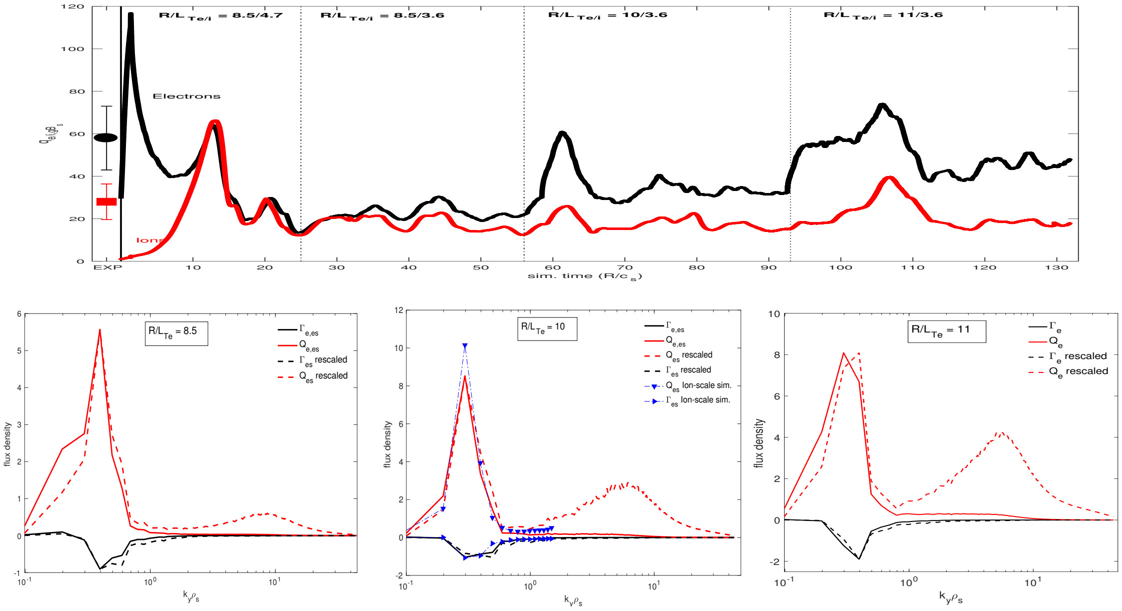

Figure 3: *Time evolution of the heat fluxes from the multi-scale simulation (up) and electron flux density as a function of $k_y\rho_s$ for $R/L_{Te} = 8.5, 10, 11$ (bottom).*

Furthermore, a comparison between the multi-scale simulation, the experimental results and the new version of TGLF using the new saturation rule (sat 1) [11, 12, 13] has been done. In TGLF simulations the same input parameters as in GENE multi-scale simulation have been used, considering just main D ions and electrons and using Miller geometry. In *figure* 4 some scans in R/L_{Te} of the electron heat flux using different values of R/L_{Ti} are shown. When the ion heat flux is matched between TGLF and GENE, TGLF predictions are in good agreement with the multi-scale ones (red triangles in *figure* 4). A strong increase of the electron heat flux due to ETGs is predicted by TGLF, reaching the experimental level of electron stiffness. The main discrepancy between the predictions of TGLF and GENE is the value of R/L_{Ti} at which the ion heat flux reaches

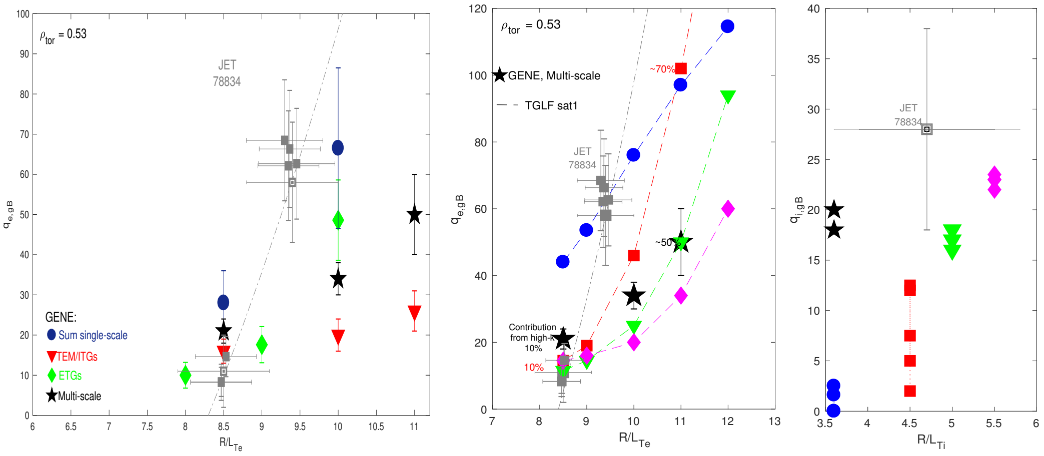

Figure 4: *Experimental, GENE multi-scale and GENE single-scale $q_{e,gB}$ vs R/L_{Te} (left). Experimental, GENE multi-scale and TGLF $q_{e,gB}$ vs R/L_{Te} and $q_{i,gB}$ vs R/L_{Ti} (center and right). Different colors indicate different values of R/L_{Ti} in TGLF.*

the experimental level, TGLF under-predicting the ion heat flux respect to GENE for the same value of R/L_{Ti}. Both codes predict a very strong impact of ion scale zonal flows on ETGs. In the multi-scale simulation the ITG drive had to be reduced to the lowest value within experimental error bar in order to have appreciable contribution from high-k instabilities. In TGLF, a slight increase of the ITG drive can bring to a strong suppression of ETGs.

In conclusion, there are strong experimental indications that ETGs are important, in certain experimental conditions, to explain the experimental electron heat flux and stiffness. Linear, quasi-linear, non-linear single-scale and non-linear multi-scale simulations support these indications and predict a fundamental contribution from high-k instabilities to the electron heat flux and a big importance of multi-scale interactions for the turbulent dynamics in the studied plasma core. New resources have been requested in order to study the effects of finite beta and especially of impurities in the multi-scale simulation (adding impurities has a stabilizing effect both on ion-scale and on electron-scale instabilities).

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[1] T. Görler and F. Jenko, Phys. Rev. Lett. 100, 2008
[2] N. T. Howard et al., Phys. Plasmas 21, 2014
[3] S. Maeyama and Y. Idomura, Phys. Rev. Lett. 114, 2015
[4] N. Bonanomi et al., EPS 2015
[5] T. L. Rhodes et al., Phys. Plasmas 14, 2007
[6] P. Mantica et al., Phys. Rev.Lett. 107, 2011
[7] J. Citrin et al., Phys. Rev. Lett. 111, 2013
[8] N. Bonanomi et al., Nucl. Fusion 55, 2015
[9] F. Jenko et al., Phys. Plasmas 8, 2001
[10] F. Jenko, et al., Phys. Plasmas 7, 2000
[11] G. M. Staebler et al., Phys. Plasmas 12, 2005
[12] G. M. Staebler et al., Phys. Plasmas 14, 2007
[13] G. M. Staebler et al., Phys. Plasmas 23, 2016