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

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In dedicated electron heat transport experiments in JET L-mode plasmas [1], lower values of R/L_{Te} are observed, at the same level of gyro-Bohm normalized electron heat flux, in the presence of significant NBI (Neutral Beam Injection) power with respect to discharges with pure ICRH (Ion Cyclotron Resonance Heating) applied in mode conversion (MC) scheme yielding dominant electron heating. The discharges studied in this paper were made with C-wall and with B_0~3.45 $T_{e,0}$~5 keV, $T_{i,0}$~2.5 – 5 keV, $n_{e,0}$~(2 – 3)10^{19} m^{-3} and I_p~(1.8 – 3) MA with I_p overshoot, ramp-up and ramp-down.
As seen in Fig.1, the R/L_{Te} decrease is due to both a decrease in inverse critical gradient length and an increase in stiffness. This is in contrast with the strong reduction of ion stiffness observed in presence of NBI (Fig.1a, [2]), which was interpreted as due to non-linear electromagnetic stabilization of ITG modes by fast ion pressure gradient [3].

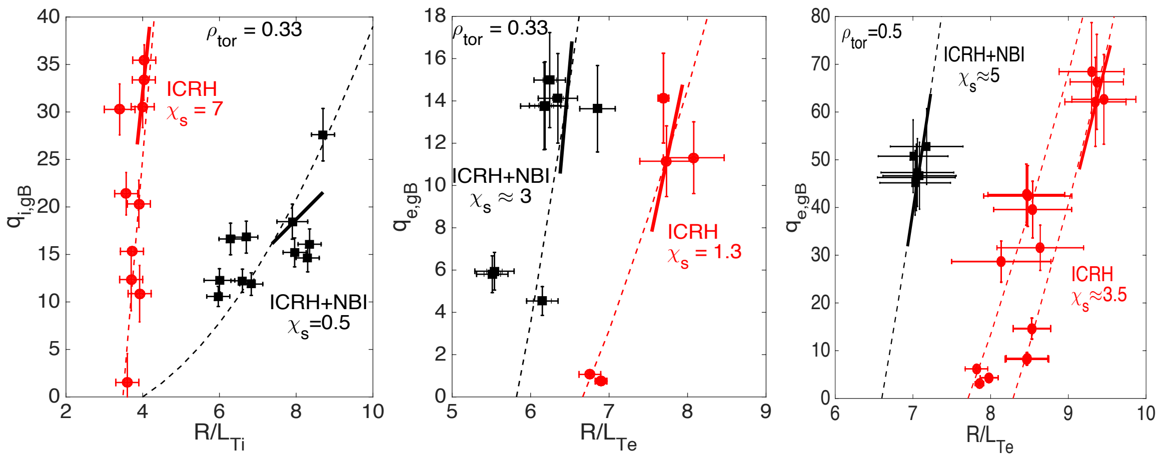

Figure 1: Effect of the presence of NBI heating on ions in L-mode JET discharges at ρ_{tor}=0.33 (left panel, reproduced from [2]) and on electrons at ρ_{tor}=0.33 (centre panel) and ρ_{tor}=0.5 (right panel) [1].

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 ions and higher toroidal rotation. Due to the stabilization effects of fast ions on ITG, the effects of higher R/L_{Ti} are not expected to be significant. Possible effects of T_e/T_i on TEM modes thresholds have been analysed with linear gyrokinetic simulations and the results suggest that it can't explain the experimental observation [1]. However, one possible effect of lower values of T_e/T_i is an increase of the electron heat flux carried by ETG modes, for which a stabilizing effect of $\tau=Z_{eff}T_e/T_i$ is expected [4].

In this work we investigate the presence of ETG modes in these JET discharges and their effects on the electron heat flux using linear and nonlinear gyro-kinetic simulations with the gyro-kinetic code GENE in the local limit [5].
To study properly the impact of ETG modes on transport, multiscale gyro-kinetic simulations including both electron and ions scales are necessary: ion scale zonal flows can provide a mechanism for ETG streamer saturation; ETG modes can affect the ion scales through non-linear coupling mechanisms, increasing the level of heat transport carried by TEM/ITG modes [6,7,8,9]. However, such simulations demand exceeding computational resources (10^6 – 10^7 CPUh per run) and could not be afforded for this work. Instead, we carried out separate scale simulations. In all simulations, Miller geometry, collisions, kinetic electrons and experimental input parameters varying within their error range were used. In all ion-scale simulations, a carbon impurity was included, at a level consistent with the experimental values of $Z_{eff.}$ Fast ions and electromagnetic effects were retained in the NBI case. In the ETG simulations, we used adiabatic ions and included the measured external flow shear. This leads to ETG streamer saturation. We assume here that the external flow shear leads to a similar ETG saturation level as the ion scale zonal flows would have done in a multi-scale simulation. However, validating this assumption is out of the scope of this work. Extensive convergence tests were made for both linear and non-linear cases.
Linear gyro-kinetic simulations were carried out to establish the effect of τ on ETG linear threshold within the experimental parameters range. The results obtained at ϱ_{tor}=0.5 are shown in Fig. 2.

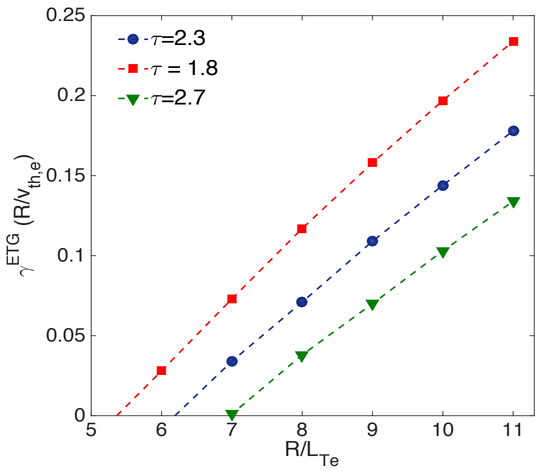

Figure 2: ETG linear growth rates vs R/LT$_e$ for different values of τ.

The linear threshold of ETG modes decreases for lower values of τ, i. e. for lower values of T_e/T_i. The values found are below the experimental values of R/L_{Te}, indicating that ETG modes are unstable for the experimental set of parameters in both ICRH and ICRH+NBI cases.
Regarding non-linear simulations, we used the parameters of JET discharge n. 78834 for the pure ICRH heating case and of JET discharge n. 78842 for the ICRH+NBI heating case. In the TEM/ITG nonlinear runs, we used a box size of $[L_x,L_y]=[100,125]\varrho_i$, with a numerical resolution of [128,24,48,48,12] points in [x,y,z,$v_{/\!/}$, μ] and $0.05\leq k_y\varrho_i \leq 1.2$. In the ETG case, we used a box size of $[L_x,L_y]=[195,125]\varrho_e$, with a numerical resolution of [256,24,48,48,12] points in [x,y,z,$v_{/\!/}$, μ] and $0.05\leq k_y\varrho_e \leq 1.2$. x, y, z, $v_{/\!/}$, μ indicate respectively the radial direction, the binormal direction, the parallel direction, parallel velocity and magnetic moments. k_y is the binormal mode number and $\varrho_{i/e}$ is the ion/electron Larmor radius.
We made a scan in R/L_{Te} of the electron heat flux in order to compare the levels of the heat flux and of the electron stiffness with the experimental values. The results obtained at ϱ_{tor}=0.5 for the electron heat flux are shown in Fig. 3. In Fig. 4 the results obtained at ϱ_{tor}=0.5 for ions

are compared with the experimental values. All the fluxes are normalized to gyro-Bohm units using $q_{e(i),gB} = q_{e(i)}/(T_e n_e \rho_s^{*2} c_s)$, where $c_s = \sqrt{T_e/m_i}$ and $\rho_s^* = c_s m_i/ReB$.

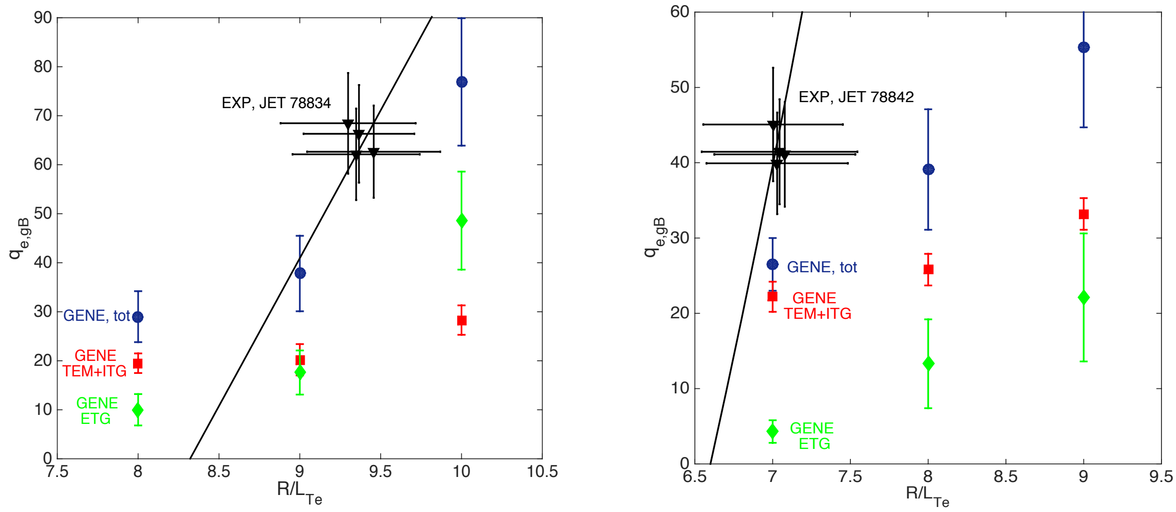

Figure 3: Normalized electron heat flux vs R/L$_{Te}$. Experimental flux (black triangles), GENE TEM/ITG flux (red squares), GENE ETG flux (green diamonds) and GENE TEM/ITG+ETG flux (blue circles) for discharges with pure ICRH heating (left) and for discharges with ICRH+NBI heating (right). The black lines indicate the experimental slope (stiffness) of the electron heat flux.

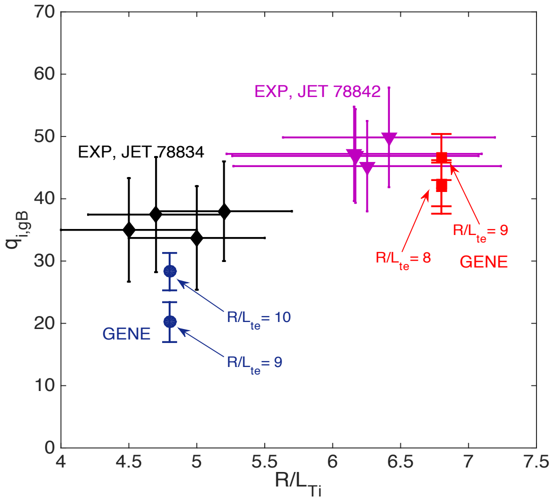

Figure 4: Normalized ion heat flux vs R/L$_{Ti}$. Experimental flux of the ICRH case (black diamonds) and of the ICRH+NBI case (purple triangles); GENE TEM/ITG flux for the ICRH case (blue circles) and GENE TEM/ITG flux for the ICRH+NBI case (red squares).

The experimental normalized ion heat flux remains unchanged in the two cases despite the differences in R/L$_{Ti}$ and this is reproduced quite well in the simulations using fast ions and electromagnetic effects, confirming what found in previous works [3]. The fact that the ion heat flux is reproduced is an indication of the consistency of our simulations.

Regarding the electron heat flux, the simulations indicate that a considerable amount of flux is independent of R/L$_{Te}$ and is carried by non-diagonal terms such as R/L$_n$ TEM modes and especially ITG modes (~25% of the experimental flux in the ICRH case and ~40% of the experimental flux in the NBI case). The flux carried by ion scale modes is in both cases too low to reproduce the experimental flux: in both cases we can reproduce the ~50% of the experimental flux with TEM-ITG modes. The scan in R/L$_{Te}$ allows also a comparison with the experimental slope of the flux and also in this case the TEM/ITG contribution to the flux cannot alone reproduce the experimental slope. In the NBI case, the experimental values of R/L$_{Te}$ are also very close to the nonlinear threshold of ∇T_e TEM modes: this could indicate that an other kind of instability, such as ETG, is carrying the remaining part of the flux. In both cases ETG modes are unstable: as mentioned, the amount of ETG flux calculated is just indicative as multiscale scale simulations would be needed, but in both cases we can't reproduce the experimental values and especially the experimental slope of the electron heat flux without retaining the ETG flux. This suggests that ETG modes could play an important role for electron heat flux for our experimental range of parameters and can help to explain the higher electron stiffness and the lower threshold values found experimentally in the NBI case. Also, a small reduction of the TEM modes threshold due to lower collisionality in the NBI case can contribute to explain the experimental observations.

Conclusions

This work provides a comparison between experiments and gyrokinetic simulations for JET L-mode discharges with and without substantial ion heating provided by NBI. It indicates that a significant amount of electron heat flux (~25%) can be carried by non-diagonal terms such as ITG modes. Using ion scale modes alone it's difficult to reproduce the experimental slope and the experimental electron heat flux, reaching only the ~50% of the experimental values. Electron scale modes can help to reproduce the experimental fluxes in both ICRH and ICRH+NBI cases. Furthermore, being more unstable in presence of substantial ion heating due to lower values of T_e/T_i, ETG modes can help to explain why, in presence of NBI heating, we observe lower values of R/L_{Te}: the electron heat flux carried by ions scale modes doesn't increase significantly in the NBI case, but in this case there is almost the same amount of electron heat flux carried by ETG modes at lower values of R/L_{Te}. It is important to underline again that these results are only indicative. Complete scale simulations should be done in order to properly consider the nonlinear interactions between different scales modes.

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