EUROfusion

EUROFUSION WPJET1-CP(16) 15066

P Mantica et al.

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Preprint of Paper to be submitted for publication in Proceedings of 26th IAEA Fusion Energy Conference

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Electron Heat Transport in JET from Ion to Electron scales: Experimental Investigation and Gyro-kinetic Simulations

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Abstract. Experimental studies and gyro-kinetic simulations of electron heat transport performed in JET C-wall L-mode plasmas with various combinations of NBI and ICRH heating have provided indications of a significant role of small-scale instabilities (ETGs, Electron Temperature Gradient). Comparison of the measured electron inverse critical gradient length with linear gyro-kinetic simulations using the GENE code is generally consistent with both TEM and ETG thresholds, but the rather high experimental electron stiffness level is not reproduced by non-linear gyro-kinetic simulations including only large-scale ITG/TEM instabilities. The fact that T_e peaking is very sensitive to the value of $\tau=Z_{eff}\,T_e/T_i$, which is a key player for ETG instabilities, suggests that ETG turbulence could account for the missing electron heat flux. A first study of the ETG contribution to the heat flux, using linear and non-linear local GENE simulations, was based on separate simulations of ion and electron scales. For the ETG saturation, either an ad hoc external flow shear or electron scale zonal flows were used. In both ICRH and ICRH+NBI cases it was found that a non-negligible electron heat flux can be carried by the ETG modes, explaining the observations. However, a high sensitivity of the results on multiple parameters was found. Following recent work showing that multi-scale simulations with real electron to ion mass ratio are needed for a proper ETG study, computationally heavy multi-scale simulations have then been started using GENE for these JET shots. First results indeed indicate a substantial fraction of ETG flux and a high stiffness level, consistent with experiment. These results are important in view of extrapolations to ITER scenarios, where the electron channel will be key for fusion performance, due to the dominance of electron heating.

1. Introduction

Electron heat transport in tokamak devices has been mostly ascribed to large (ion) scale ITG-TEM turbulence ($k_\theta\rho_i<1$). Several experiments were made on AUG [1,2], DIII-D [2,3,4], TCV[2,5], in plasmas with dominant ECRH and $T_e/T_i >> 1$, in which the observations and parametric dependences of the measured threshold were consistent with electron heat transport dominated by TEM instabilities, although we note that a quantitative comparison of heat fluxes with non-linear gyro-kinetic (GK) simulations was not available in those early studies. Past [2,6,7] and recent [8] experiments in JET L-mode plasmas with dominant ICRH electron heating were also initially interpreted along the same line, comparing the experimental threshold with linear TEM threshold and finding generally good agreement within experimental uncertainties, in particular with respect to the dependence of the electron

* See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)

threshold on the magnetic shear (s) [8]. In such study, a first attempt to compare also the experimental stiffness with non-linear GK simulations was made. This opened a series of questions, since the main finding on JET was that TEMs provide a level of electron stiffness significantly lower then the experimentally measured one, already in ICRH-dominated cases, but even more when large NBI power is applied in addition to ICRH. One hypothesis put forward to explain the missing electron heat flux was that electron-scale ($k_\theta\rho_i$>>1) instabilities such as ETGs could play a more significant role in these JET experiments. This is in line to having values of $\tau=Z_{eff}T_e/T_i$ (i.e. the main parameter that stabilizes ETGs) generally lower in JET than in ECRH dominated machines. In fact, expanding the database with respect to the one used in [8], one can see in Fig.1 that for most of the discharges analysed the TEM and ETG threshold are not too different, so a pure threshold comparison does not allow discriminating between the two instabilities, apart from the circled parameter corners in which one of the two is stabilized. It is then necessary to take into account stiffness and comparison with non-linear GK simulation to separate the relative contribution of the low and high electron scales. Therefore, a series of new experiments and massive GK simulations using the GENE code [9,10] was started to investigate in detail the role of ETGs in these JET plasmas. This paper will report the findings of such work, consisting of both experimental indications of a significant role played by ETGs in JET electron heat transport, and GENE GK simulations (linear, non-linear single-scale and multi-scale) showing that indeed a significant electron heat flux is foreseen to be carried by the high $k_\theta\rho_i$ part of the spectrum (ETG range). This result may have important implications for ITER scenarios and their modelling.

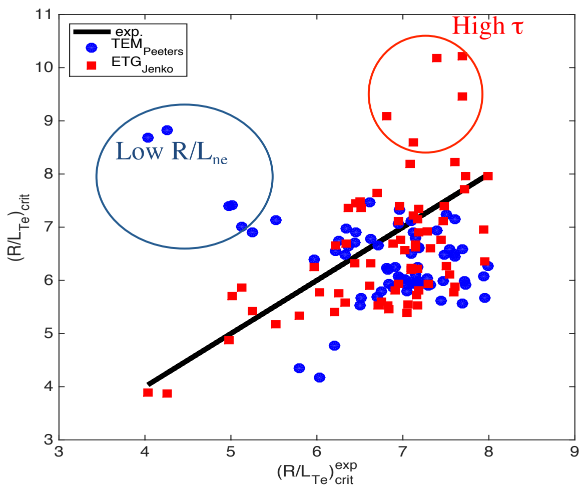

FIG.1. Critical R/L_{Te} calculated with analytical formulae for TEM (blue, from [11]) and ETG (red, from [12]) vs the experimentally derived value in an expanded dataset with respect to that used in [8].
The circled blue points are discharges with low R/L_{ne} where TEMs are expected to be stable, in which case ETGs alone seem to determine the experimental threshold, and the circled red points are discharges with high t values, with stable ETGs and TEMs regulating the threshold. In the other cases the two instabilities co-exist and have similar threshold values for the range of parameters of these discharges.

2. Experimental evidence for the role of ETGs in JET

The target discharge for JET electron heat transport experiments (both past and recent) is an L-mode plasma with B_T=3.45T/Ip=1.8-2 MA, n_{e0}~3 $10^{19}m^{-3}$, low triangularity, ICRH heating in (^{3}He)-D with concentrations from 6% (ion heating) to 18% (mode conversion, electron heating) and different levels of NBI power up to ~ 10 MW. Varying the ICRH frequency allows on- and off-axis deposition to perform heat flux scans, whilst ICRH modulation provides additional information on the electron stiffness.

Fig.2 shows over the full JET database of such discharges that whilst R/L_{Ti} can vary significantly, from 3 to 12 in the figure (which has been ascribed to non-linear e,m. stabilization [13]), R/L_{Te} unfortunately remains rather constant, in the range 5-8. Within such range, the parameter that orders best the R/L_{Te} values is clearly τ, as seen in Figs.3 and 4, although of course other dependencies are also in place, and causing the scatter in the plot, particularly the one on s. Fig.5 shows the normalized heat flux vs R/L_{Te} plot for the data of

Fig.4. Different colours indicate different τ ranges, pointing to an increase in threshold with increasing τ, as expected for ETGs. A striking observation shown in Fig.6a for 2 couples of shots at low and high ICRH power and different τ values but otherwise similar parameters (see Fig.6b) is that T_e peaking is more responsive to the τ value than even to the power level, since the same peaking is observed for the low and high ICRH power shots that have similar τ values, and only by increasing τ (which stabilizes ETGs) one can obtain significantly higher T_e peaking. This correlation of the T_e peaking with τ is a strong experimental indication that in these JET plasmas ETGs play a significant and possibly dominant role. Therefore the use of non-linear GK simulations is mandatory to quantitatively estimate their weight with respect to TEMs, although this task is far from simple, as we will discuss in the next sections.

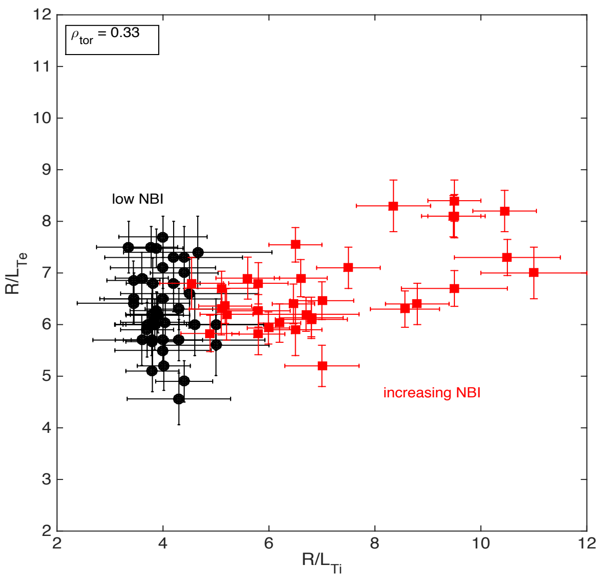

FIG.2. R/L_{Te} vs R/L_{Ti} at ρ_{tor}=0.33 for a series of JET L-mode plasmas with different types of heating.

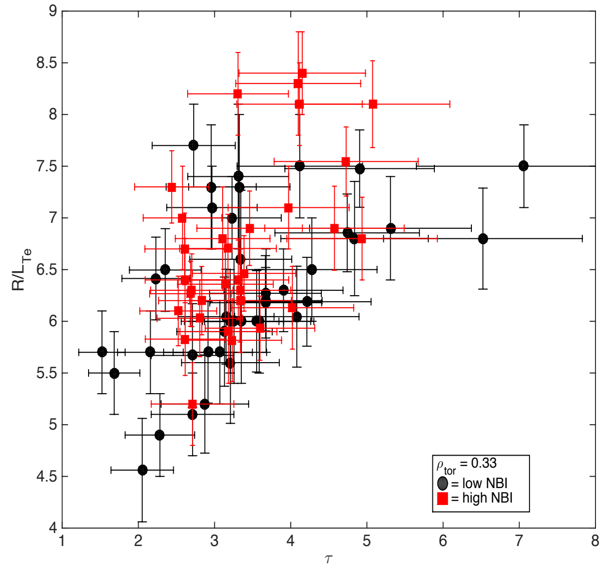

FIG.3. R/L_{Te} vs τ at ρ_{tor}=0.33 for the same data of Fig.2.

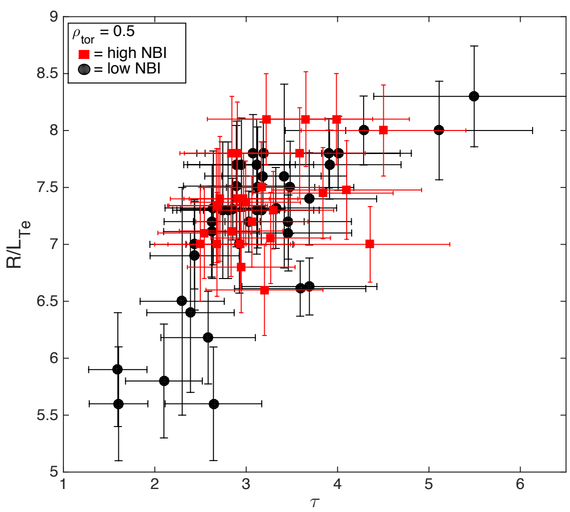

FIG.4. R/L_{Te} vs τ at ρ_{tor}=0.5 for the same data of Fig.2.

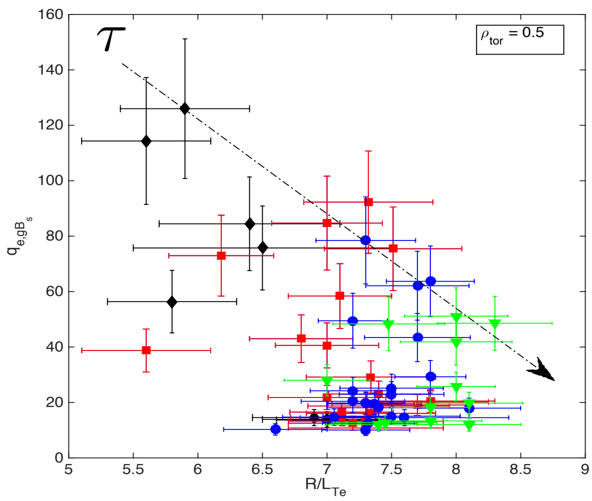

FIG.5. Normalized electron heat flux $q_{e,gB}$ vs R/L_{Te} at ρ_{tor}=0.5 for the same shots as in Fig. 4. Each colour marks a range of τ values.

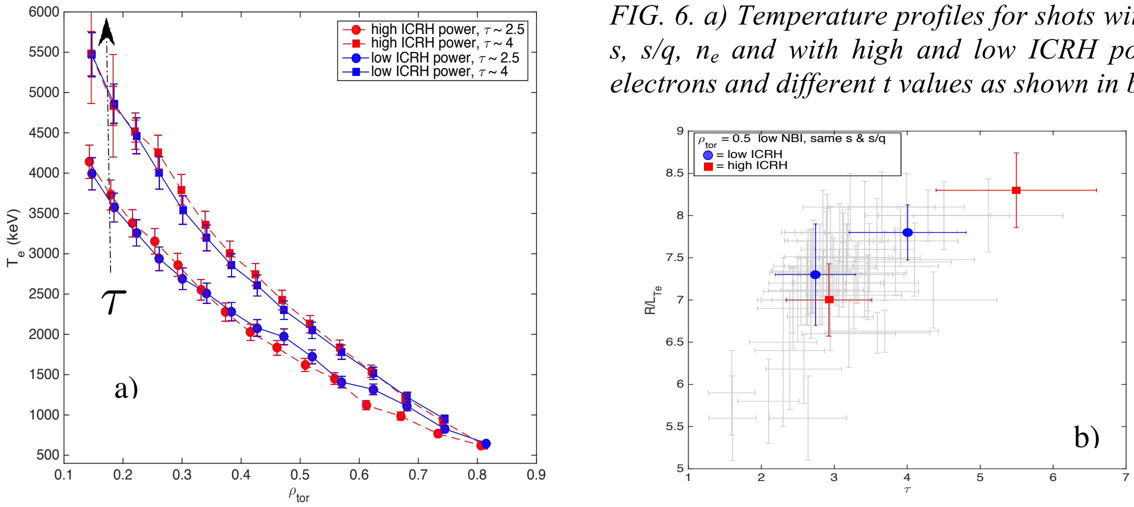

FIG. 6. a) Temperature profiles for shots with fixed s, s/q, n_e and with high and low ICRH power to electrons and different t values as shown in b)

3. Single-scale non-linear gyro-kinetic simulations

To study properly the impact of ETG modes on transport, multi-scale gyro-kinetic simulations including both electron and ions scales are necessary. Ion scale zonal flows can provide a mechanism for ETG streamer saturation and conversely ETG modes can affect the ion scales through non-linear coupling mechanisms, increasing the level of heat transport carried by TEM/ITG modes [14-18]. However, such simulations demand enormous computational resources (10^6–10^7 CPUh per run) and for this work they could be afforded only for two sets of plasma parameters, one of which not yet stable, as will be discussed in the next section. It is therefore useful to explore the parameter space first, using linear and non-linear separate scale simulations. In all these simulations, Miller geometry, collisions, kinetic ions and 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 high NBI case. In the ETG simulations, we used adiabatic ions and we included Debye length shield and a higher level of external flow shear than the measured one (~4 times the experimental value). 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. Of course, this is a strong assumption to allow us to gain a quicker feeling on the possible role of ETGs in different plasma conditions, and proper multi-scale simulations will be the object of the next section. Extensive convergence tests were made for linear and non-linear cases.

Linear GK simulations were carried out with scans in $0.1 < \rho_s k_y < 42$ (where $\rho_s^* = c_s m_i/eB$ and $c_s = \sqrt{T_e/m_i}$) at different radii and for various sets of the main parameters to see the effects on the ITG/TEM/ETG thresholds. They indicated that:

- In the low k_y range, ITGs are dominant at higher τ, while at lower τ ITGs tend to be less unstable and TEMs are dominant for $\rho_s k_y > 0.5$.
- In the high k_y range, ETGs are unstable in the studied region $0.33 < \rho_{tor} < 0.6$ in both ICRH and ICRH+NBI cases. The strong effect of τ on the ETG threshold is shown in Fig.7 (for ρ_{tor}=0.5) and the simulations generally confirm the correlation between the ETG threshold and other plasma parameters (such as s, q, R/L_n, α_{MHD}) found in [12].

Regarding the 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] ρ_i , with a numerical resolution of [128,24,48,48,12] points in [x,y,z,$v_{/\!/}$, μ] and $0.05 \le k_y\rho_i \le 1.2$. In the ETG case,

we used a box size of $[L_x,L_y]=[195,125]\ \rho_e$, with a numerical resolution of [256,24,48,48,12] points in [x,y,z,v//, μ] and $0.05\leq k_y\rho_e\leq 1.2$. x, y, z, v//, μ indicate respectively the radial direction, the binormal direction, the parallel direction, the parallel velocity space and the magnetic momentum space. k_y is the binormal mode number and $\rho_{i/e}$ 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}=0.53 for the electron heat flux are shown in Fig. 8 a) and b). In Fig.8c the results obtained at ρ_{tor}=0.53 for ions are compared with the experimental values. All the fluxes are normalized to gyro-Bohm units using $q_{e(i),gB} = q_{e(i)}/(T_e n_e \rho_s^{*2} c_s)$.
The experimental normalized ion heat flux remains almost 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 work [13]. 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 carried by low k_y modes, namely R/L_{ne} and R/L_{Te} driven TEM modes and especially ITG modes (for a total of ~40% of the experimental flux in the ICRH case and ~60% of the experimental flux in the NBI case). Still, it is not possible to account for the whole flux with TEM/ITG only. In addition, the scan in R/L_{Te} allows also a comparison with the experimental slope of the flux, i.e. the stiffness level. It is clear from Fig.8 a-b that TEMs show very low dependence on R/L_{Te}, i.e. extremely low stiffness, at variance with experiment. In the NBI case, the experimental values of R/L_{Te} are also very close to the nonlinear threshold of R/L_{Te} driven TEM modes, so their contribution is minimal. These findings suggest that another kind of instability besides ITG/TEM is carrying the remaining part of the flux and is responsible for the high electron stiffness. In both cases ETG modes are unstable and adding the ETG heat flux calculated with the single-scale simulations allows to approach the experimental flux values. As mentioned, the amount of ETG flux calculated is just indicative with single scale simulations, but it is a fact that 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 in our experimental range of parameters and can help to explain the higher electron stiffness and/or the lower threshold values found experimentally in the NBI case, which has lower τ values.

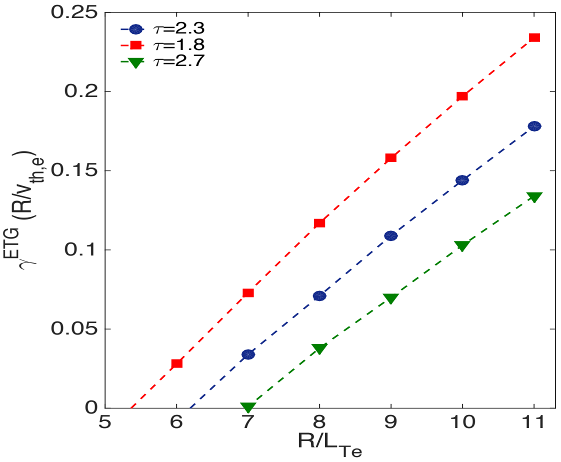

FIG.7: ETG linear growth rates vs R/L_{Te} for different values of τ.

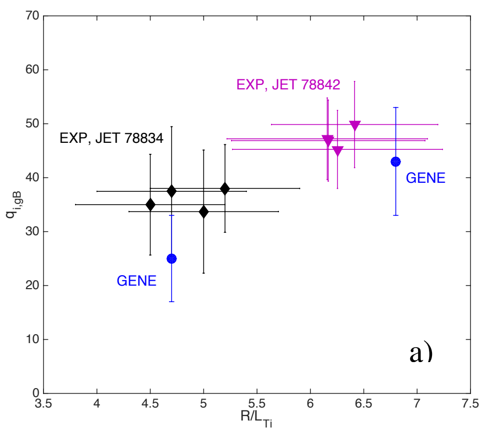

FIG.8 (a) $q_{i,gB}$ vs R/L_{Ti}. Experimental flux of the ICRH case (black) and of the ICRH+NBI case (purple) and GENE TEM/ITG flux for both cases (blue).

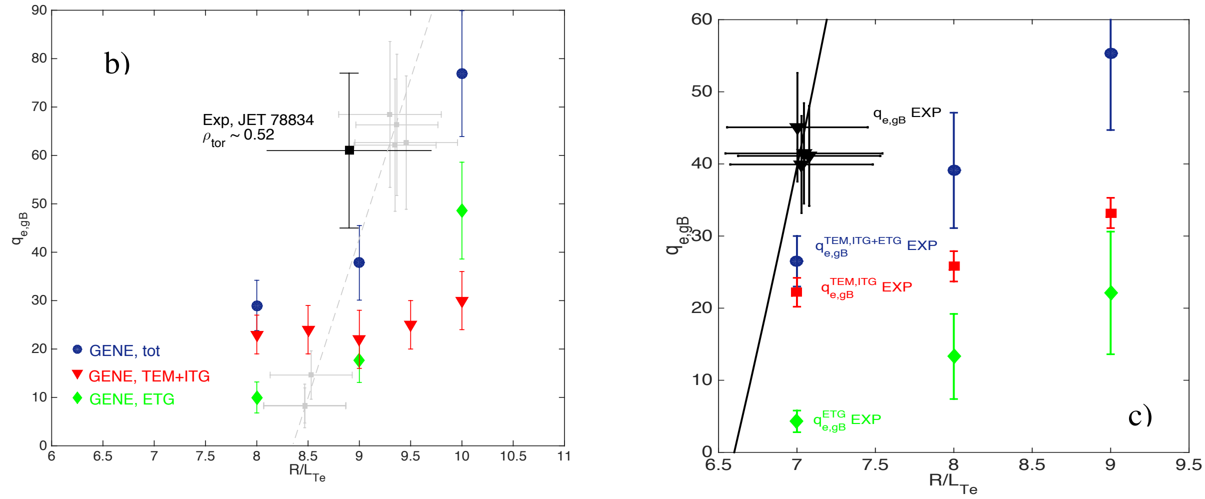

FIG. 8 (b) and (c). $q_{e,gB}$ vs R/L_{Te}. Experimental flux (black/grey), GENE TEM/ITG flux (red), GENE single scale ETG flux (green) and GENE TEM/ITG+ETG flux (blue) for discharges with pure ICRH heating (b) and for discharges with ICRH+NBI heating (c). The black/grey lines indicate the experimental slope (stiffness) of the electron heat flux.

Further tests of single-scale ETG simulations were also made using electron scale zonal flows to saturate the ETG streamers. However this mechanism showed high sensitivity to factors like kinetic vs adiabatic ions, L_x/L_y, e.m. effects, collisionality. Therefore, it was deemed necessary to run proper multi-scale simulations for a few selected sets of parameters.

4. Multi-scale non-linear gyro-kinetic simulations

For the multi-scale GK GENE simulation the experimental parameters of JET shot 78834 (high ICRH, low NBI) at ϱ_{tor} ~ 0.52 and t ~ 7 s are used. The simulation features Miller geometry, collisions, kinetic ions and electrons, $0.1 < \varrho_s k_y < 48$. Perpendicular box sizes were $[L_x, L_y] \sim [64, 64]\ \varrho_s$. Grid points $[n_x, n_y, n_z, n_v, n_w] = [1200, 448, 32, 32, 12]$ (~ 7 10^9 points in the phase space, x = radial, y=binormal, z=parallel (to B_0), v = parallel velocity, w= magnetic momentum). Fig.9a shows ion and electron normalized heat flux vs simulation time, obtained using ~9 10^6 CPUh. During this time, some adjustments of the plasma parameters were made within the error bars of the experiments to help matching the experimental flux, which is marked by the dots on the left side. The contour-plots of the electrostatic potential are shown for a few significant times. The heat and particle flux spectra are shown in (Fig.9 b-c) for two different phases of the simulation. Also, the density fluctuation spectra are shown at two different times (Fig.9 d). One can see the initial phase when ion zonal flows are not yet established and ETG streamers are well developed, carrying a huge electron heat flux. This decays away whilst ITG zonal flows are established, until a rather stable condition is reached in which ETGs carry ~15% of the flux, with similar total electron and ion heat flux, which does not match the experimental observation of electron heat flux twice the ion one. This simulation phase yields us a flux point at $q_{e,GB}$~ 25 for R/L_{Te}=8.5 (the nominal experimental value is 9). Then R/L_{Te} is increased to 10, which is at the high side of the experimental error bar, and we see a sharp increase of the electron heat flux at high k_y, clearly decoupling electron from ion flux, and approaching the experimental levels. The streamers are now observed in the potential contour plot, and a large peak develops in the density fluctuations. The simulation is still not stationary, so we cannot anticipate the final level, but it appears that this second phase of the simulation is representative of the experimental conditions. It indicates a relevant fraction of electron heat flux carried by ETGs, with a sharp dependence on the R/L_{Te} value, i.e. high stiffness, in agreement with experiment and at variance with the low stiffness of TEMs, which was the first indication that motivated all this work. One can also note that the increase in high k_y electron flux is accompanied by a (smaller) increase of the low k_y ion heat flux, which was also observed in [14]. The different slopes in the density fluctuations seen in Fig.9d could be a signature to look for in turbulence measurements using the newly installed Doppler backscattering reflectometer, which is left for future work.

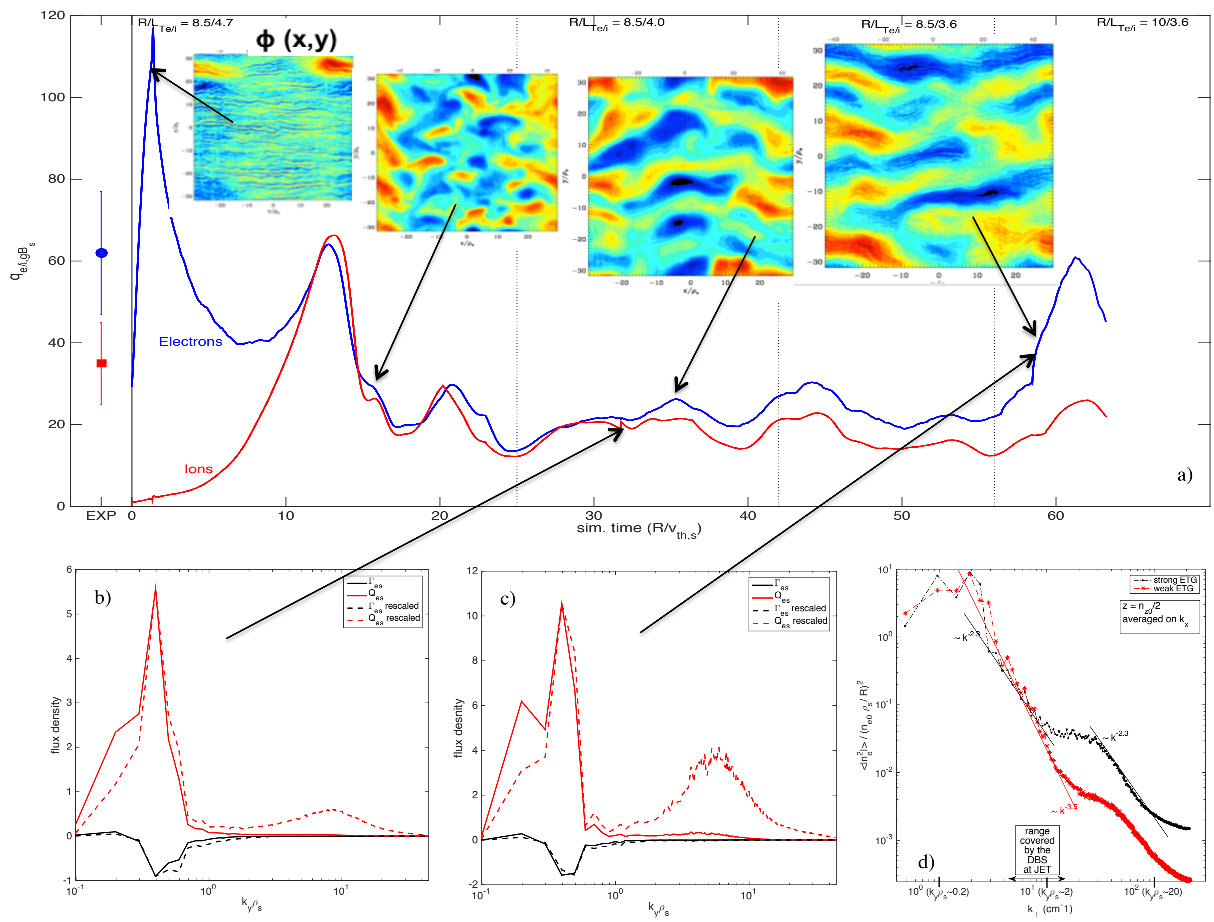

FIG. 9. a) q_{gB} vs simulation time from the multi-scale simulation. The contour-plots of the electrostatic potential is shown for different times. b) & c) Heat and particle flux spectra at two different times: the contribution of ETGs is visible at high k_y. d) Density fluctuation spectra at two different times: when ETGs become more strong the slope at low k_y tend to become lower and a second maximum appears at the ETG peak.

5. Conclusions

The strong dependence of T_e peaking on $\tau=Z_{eff}T_e/T_i$ observed in JET L-mode plasmas, together with the finding that the rather high experimental electron stiffness cannot be matched by gyro-kinetic non-linear simulations using GENE when only ITG/TEM instabilities are included, suggest that high-k ETG modes play a role in electron heat transport in these JET plasmas. In all the conditions examined ETGs are found linearly unstable, and single-scale non-linear simulations using the external flow shear to saturate the ETGs provide a non-negligible electron heat transport at high k_y. This is further confirmed by GK non-linear multi-scale simulations, which show a strong sensitivity of the ETG-driven electron heat flux on R/L_{Te}, i.e. high stiffness, in agreement with experiment. The total experimental electron heat flux can be matched only when ETGs are taken into account. These results provide evidence of the importance of high-k_y instabilities in JET scenarios and suggest that they should be properly taken into account in ITER scenario simulations.

Acknowledgement This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors are grateful to D. R. Mikkelsen for assistance. This research used resources of the National Energy Research Scientific Computing Centre, a DOE Office of Science Use Facility supported by the Office of Science of the U.S. Department of Energy under contract No.DE-AC02-05CH11231. A part of this work was carried out using the HELIOS supercomputer system at Computational Simulation Centre of International Fusion Energy Research Centre (IFERC-CSC), Aomori, Japan, under the Broader Approach collaboration between Euratom and Japan, implemented by Fusion for Energy and JAEA. We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support.

References

[1] RYTER, F., et al., “Experimental Study of Trapped-Electron-Mode Properties in Tokamaks: Threshold and Stabilization by Collisions”, Phys. Rev. Lett. **95** (2005) 085001.

[2] RYTER, F., et al., “Electron heat transport studies”, Plasma Phys. Control. Fusion **48** (2006) B-453

[3] DE BOO, J. C., et al., “Electron profile stiffness and critical gradient studies”, Phys. Plasmas **19** (2012) 082518.

[4] SMITH, S.P., et al., “Electron temperature critical gradient and transport stiffness in DIII-D”, Nucl. Fusion **55** (2015) 083011.

[5] CAMENEN ,Y., et al., “Impact of plasma triangularity and collisionality on electron heat transport in TCV L-mode plasmas”, Nucl. Fusion **47** (2007) 510.

[6] MANTICA, P., et al., “Core transport studies in JET”, Fusion Science and Technology **53** (2008) 1152

[7] MANTICA, P. and RYTER, F., “Perturbative studies of turbulent transport in fusion plasmas”, C. R. Physique **7** (2006) 634

[8] BONANOMI, N., et al., “Trapped electron mode driven electron heat transport in JET: experimental investigation and gyro-kinetic theory validation”, Nucl. Fusion **55** (2015) 113016

[9] JENKO, F., et al., “Electron temperature gradient driven turbulence”, Phys. Plasmas **7** (2000) 1904

[10] GÖRLER, T., et al., “the global version of the gyrokinetic turbulence code GENE”, J. Comput. Phys. **230** (2011) 7053

[11] PEETERS, A. G., et al., “Linear gyrokinetic calculations of electron heat dominated plasmas in ASDEX Upgrade”, Phys. Plasmas **12** (2005) 022505

[12] JENKO, F., et al., “Critical gradient formula for toroidal electron temperature gradient modes”, Phys. Plasmas **8** (2001) 4096

[13] CITRIN, J., et al., Phys. Rev.Lett. **111**, (2013) 155001

[14] HOWARD, N. T. et al., Phys. Plasmas **21**, (2014) 112510

[15] CANDY, J. et al., JPCS **78**, (2007) 012008

[16] GORLER, T. and JENKO, F.,, Phys. Rev.Lett. **100**, (2008) 185002

[17] WALTZ, R. E. et al., Phys. Plasmas **14**, (2007) 056116

[18] MAYEAMA, S. and IDOMURA, Y., “Cross-Scale Interactions between Electron and Ion Scale Turbulence in a Tokamak Plasma”, Phys. Rev. Lett. **114** (2015) 255002