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Experimental investigation and gyrokinetic simulations of multi-scale electron heat transport in JET, AUG and TCV

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 and 2019-2020 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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ABSTRACT

- Tokamaks dominated by electron heating (ITER): electron temperature gradient (ETG) modes could limit the fusion performance by limiting T_e;
- Dedicated pulses from TCV, AUG and JET are compared, studying the electron heat transport for cases compatible with ETGs presence;
- Experimental analysis: steady state heat flux scans and perturbative analysis by radio frequency (RF) modulation.
- Numerical analysis: linear and nonlinear (NL) gyrokinetic (GK) ion-scale (IS) and multi-scale (MS) simulations with the GENE code [1], Quasi-linear (QL) simulations with TGLF [2].
- Results indicate that only cases with a proper balance of electron and ion heating are compatible with an ETGs role. The effect of fast ions (FI) produced by NBI and ExB shearing is evidenced in TCV, while the sensitivity of the results to the ion temperature gradient and impurity content is investigated for AUG and JET cases.

ETGs: properties and their experimental investigation

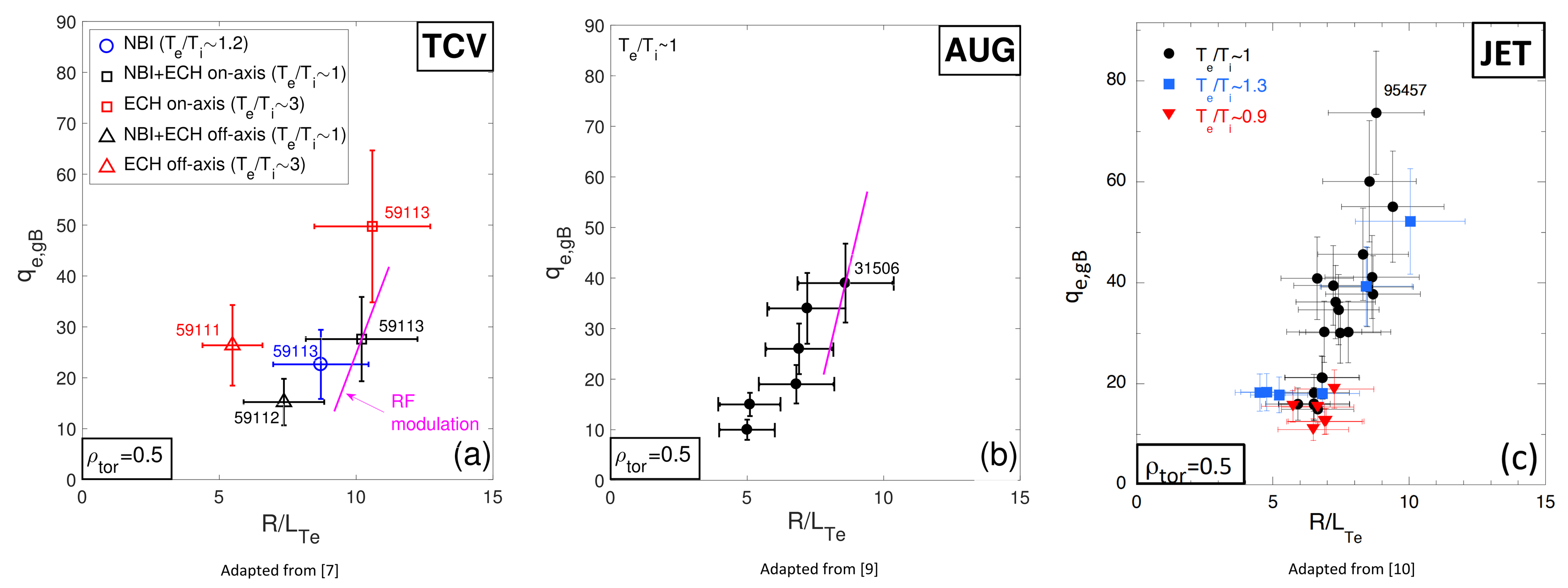
- Linearly destabilised by increasing $R/L_{Te} = -R\nabla T_e \cdot \hat{r}/T_e$
- Linear threshold: $R/L_{Te,crit.} \sim (1+Z_{eff}\, T_e/T_i)$ [3];
- Nonlinear behaviour: destabilised if ion-scale modes are marginally stable (reduced nonlinear zonal flows damping of ETGs) [4-6];
- Experimental evidence: high electron stiffness, i.e. large $q_{e,gB}$ vs R/L_{Te} slope (ETG 'wall'), where $q_{e,gB} = q_e(e^2R^2B_0^2/\sqrt{m_i}n_eT_e^{5/2})$ is the electron heat flux q_e in gyro-Bohm (gB) units.
- Experimental strategies: change heating power deposition: heat flux scan at fixed radius; heating power (RF) modulation: measure local stiffness.

Experiments at TCV, AUG and JET

- TCV [7]: L-modes, B_0=1.41T, I_p=170kA; heat flux scan: vary ECH power (~0.4-0.7MW) deposition on- vs off-axis; perturbative analysis: ECH steady and modulated; each pulse: different phases with different proportion of NBI(~1MW) /ECH power to vary T_e/T_i;
- AUG [8, 9]: H-modes, B_0=2.6T, I_p=0.8MA; ECH power (~2.5MW, steady and modulated) on- vs off-axis; NBI(~5MW) to have T_e~T_i.
- JET [10]: L-modes and H-modes, B_0=3.3T, I_p=2MA; ICH power (<6MW, H minority to mainly heat electrons, only steady) on- vs off-axis; NBI(<20MW) to vary T_e/T_i.

Experimental results

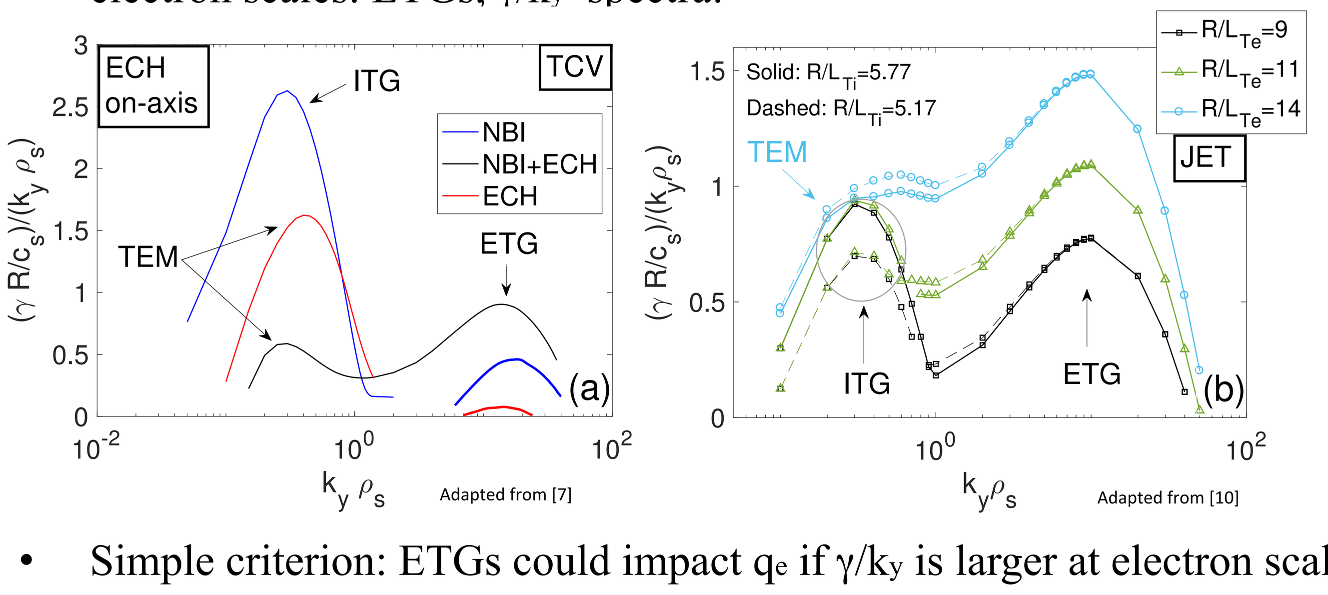
- Same radial position ρ_{tor}=0.5: steady state scan and ECH modulation (TCV and AUG, not possible in JET due to H minority heating):



- TCV (a): ETG-like stiffness for mixed NBI-ECH case (T_e~T_i) ⟵ ECH modulation;
- AUG (b): ETG-like stiffness for the exp. case with largest $q_{e,gB}$ ⟵ ECH modulation;
- JET (c): no RF modulation, but: exp. points with largest $q_{e,gB}$ and T_e~T_i ⟶ ETG 'wall'?
- Comparison: ETGs possible role: balanced electron/ion-heating: T_e~T_i and large R/L_{Te} .

Linear multi-scale gyrokinetic simulations

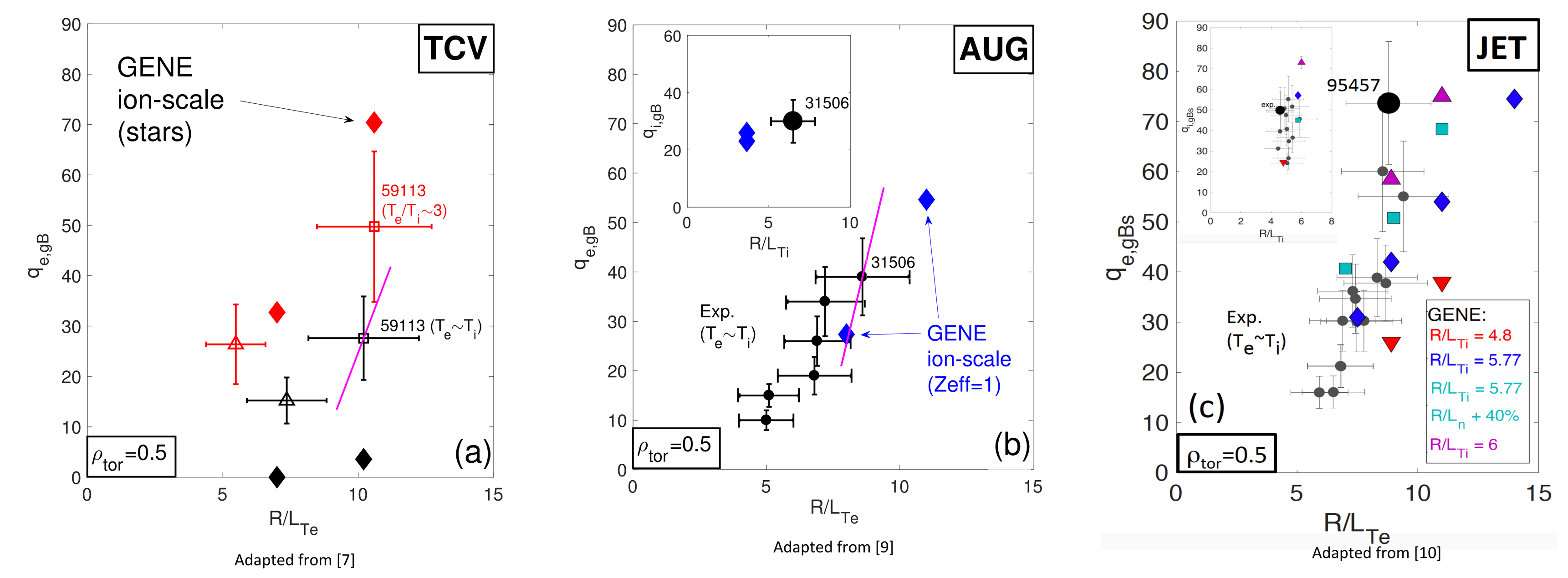
- Linear frequency spectra: ion scales: ITG-dominant (except TCV with ECH: TEM-dominant), electron scales: ETGs; γ/k_y spectra:



- TCV: ECH on-axis cases (and NBI only);
- AUG and JET: exp. point with highest $q_{e,gB}$: R/L_{Te} scan (also varying R/L_{Ti} for JET matching q_i within error bar);

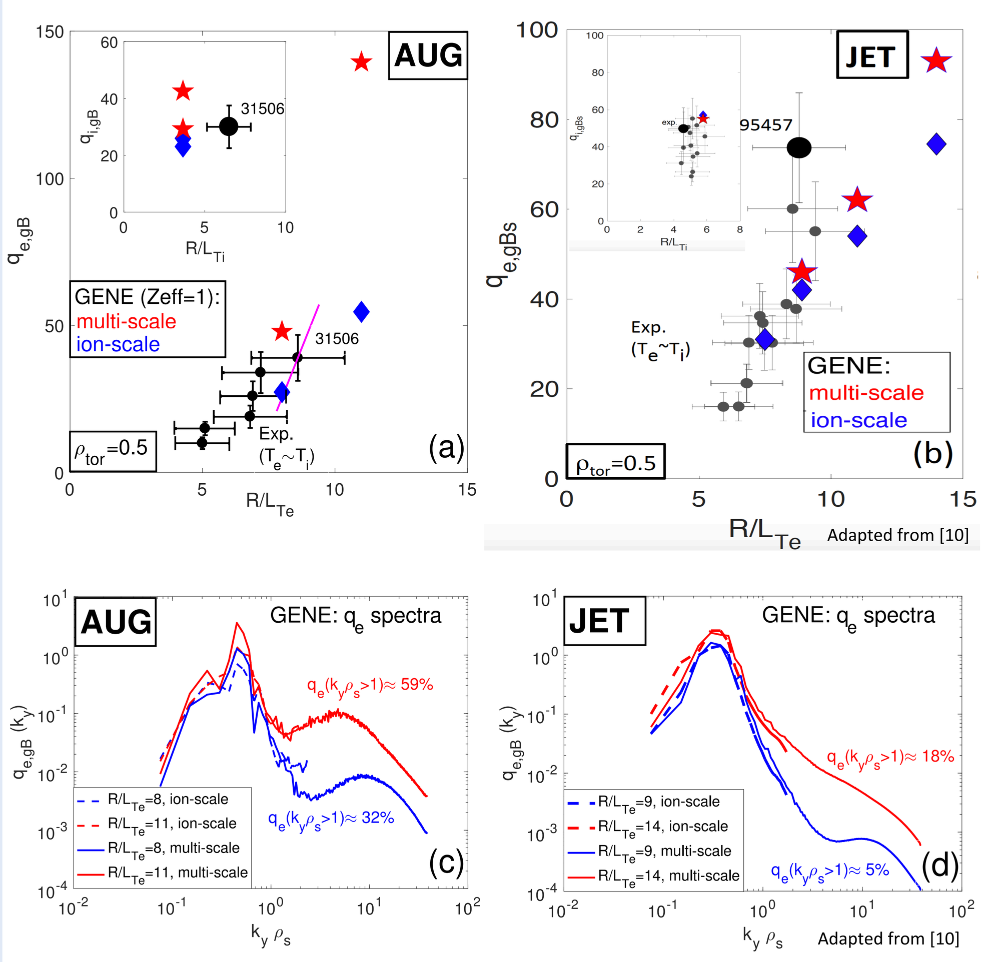
- Simple criterion: ETGs could impact q_e if γ/k_y is larger at electron scales (ETGs) [11]:
- TCV (a): ETGs impact: mixed NBI-ECH case (T_e~T_i) FI stabilising TEMs at ion scales;
- AUG (see [8]): ETGs role for R/L_{Te}>6 (lower boundary, since Z_{eff}=1<1.4=$Z_{eff,exp.}$ in the runs);
- JET (b): ETGs role: R/L_{Te}>11 when R/L_{Ti}=5.77, R/L_{Te}>9 when R/L_{Ti}=5.17.

Nonlinear ion-scale gyrokinetic simulations



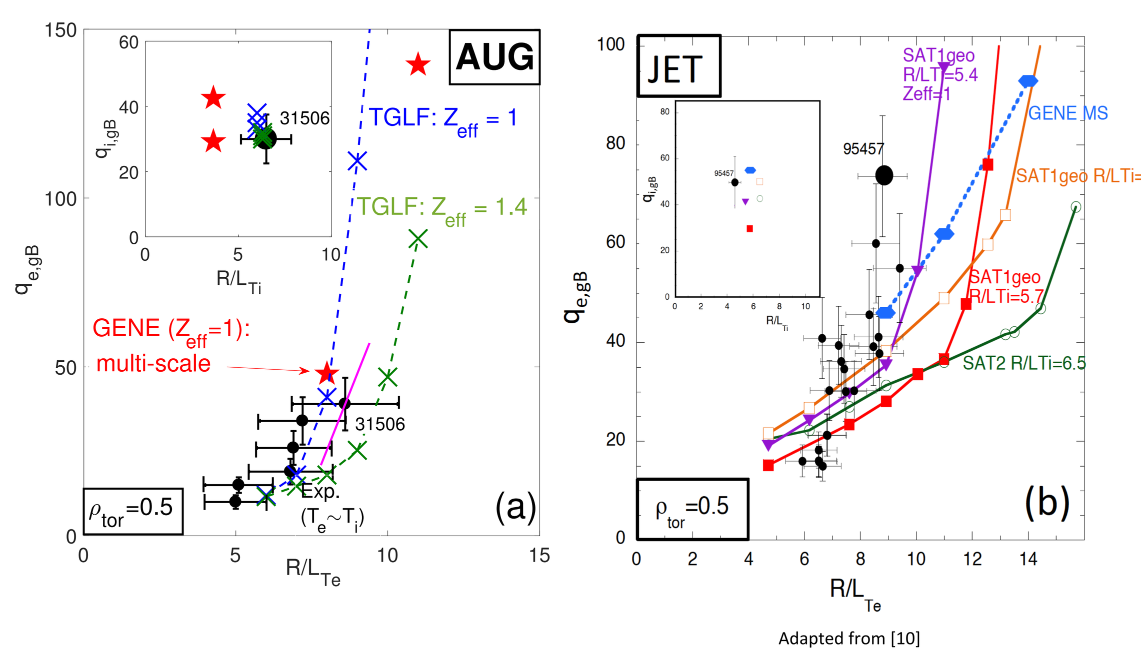
- TCV (a): NBI-ECH case (black): $q_{e,gB}$ and stiffness (perturbative) under-estimated: ETGs?
- AUG (b): $q_{e,gB}$ slightly under-predicted, stiffness (perturbative) under-predicted: ETGs?
- JET (c): possible to match $q_{e,gB}$ but not the stiffness varying R/L_{Ti} and R/L_{ne}: ETGs?

Nonlinear multi-scale gyrokinetic simulations



- NL multi-scale runs: quantify ETGs impact: made for AUG (Z_{eff}=1) and JET (kinetic eff. C impurity with Z_{eff}=1.5=exp.). TCV: 'global' effects could play a role (global multi-scale run: not affordable);
- Collisions, electromagnetic effects and real electron/ion mass ratio;
- AUG (a)/(c): ETGs role: moderate/ large (~32%) at exp. R/L_{Te}=8,large (~59%) at R/L_{Te}=11; multi-scale stiffness: high and well aligned with the ECH modulation result;
- JET (b)/(d): ETGs role: negligible (~5%) at exp. R/L_{Te}=9, moderate (~18%) at R/L_{Te}=14; multi-scale stiffness: moderate, does not explain exp.; run at R/L_{Te}=11 (reduced R/L_{Ti}): ongoing.

Quasi-linear multi-scale simulations (TGLF SAT1geo, SAT2)



- AUG: Z_{eff}: impact on ETG 'wall'; both Z_{eff}=1 and Z_{eff}=1.4=exp. scans agree with exp.; stiffness: good agreement with exp. (perturbative) and GK MS.
- JET: Z_{eff}: strong impact on ETG 'wall'; ETG wall for realistic Z_{eff} is much higher than $R/L_{Te,exp.}$=9; Only for Z_{eff}=1: nearer to the exp. points;

CONCLUSIONS

- ETGs could impact q_e for cases with T_e~T_i and high R/L_{Te}, (conjunction of electron and ion heating): in line with the actual theoretical understanding of ETGs;
- TCV, mixed NBI-ECH case: a synergy of fast ions and ExB shearing, stabilizing the TEM-dominant ion scales, allows ETGs to possibly play a role;
- AUG and JET: ITG-dominant ion scales cause high ion stiffness which allows a possible ETGs role varying R/L_{Ti} within error bar; need of sensitivity scans (MS GK runs);
- High impact of impurities for JET case: more results are needed (need of more MS GK runs with impurity species: one simulation is ongoing for the JET case);
- Need of exp. measurements of density and temperature fluctuations at electron scales.

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We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support. Part of the simulations presented in this work were performed at the COBRA HPC system at the Max Planck Computing and Data Facility (MPCDF), Germany. This work was also conducted under the auspices of the ITPA Topical Group on Transport & Confinement.