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

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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 GENES code [1]. Quasi-linear (QL) simulations with TGLF [2].
• Results indicate that only cases with a proper balance of electron and ion heat transport are compatible with an ETGs role. The effect of fast ions (FI) produced by NBI and ECH 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_Ti = −R/N_Vi r/T_i;
• Linear threshold: R/L_Ti ≈ (+Z_{eff}/T_i)Ω [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_{iso} vs R/L_i slope (ETG ‘wall’), where q_{iso} = −ω/(eB_i N^2 T_i) is the electron heat flux 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=1.41T, l_e=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;
• AUG [8, 9]: H-modes, B=2.67T, l_e=0.8MA; ECH power (∼2.5MW, steady and modulated) on- vs off-axis; NBI (∼5MW) to have T_e;
• JET [10]: L-modes and H-modes, B=3.3T, l_e=2MA; ICH power (∼6MW, H minority to mainly heat electrons, only steady) on- vs off-axis; NBI (∼20MW) to vary T_e.

Experimental results

• Same radial position p_r=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_{iso} ECH modulation;
  - JET (c): no RF modulation, but exp. points with largest q_{iso} and T_e,T_i ETG ‘wall’?
• Comparison: ETGs possible role: balanced electron/ion-heating: T_e,T_i and large R/L_i.

Linear multi-scale gyrokinetic simulations

• Linear frequency spectra: ion scales: ITG dominant (except TCV with ECH: TEM dominant), electron scales: ETGs; γ_yk spectra;
  - 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_{iso} ECH modulation;
  - JET (c): no RF modulation, but exp. points with largest q_{iso} and T_e,T_i ETG ‘wall’?
  - Comparison: ETGs possible role: balanced electron/ion-heating: T_e,T_i and large R/L_i.

• Simple criterion: ETGs could impact q_{iso} if γ_yk is large at electron scales (ETGs) [11];
• TCV (a): ETGs impact: mixed NBI-ECH case (T_e,T_i) F1 stabilising TEMs at ion scales;
• AUG (see [8]): ETGs role for R/L_i=6 (lower boundary, since Z_{eff}=1.4=exp. in the runs);
• JET (b): ETGs role: R/L_i=11 when R/L_i<5.7, R/L_i=9 when R/L_i=5.17.

Linear multi-scale gyrokinetic simulations

• TCV (a): ETG-on-axis cases (and NBI only);
• AUG and JET: exp. point with highest q_{iso}: R/L_i scan (also varying R/L_i for JET matching q_{iso} within error bar);
• Varying R/L_i, AUG and JET: ETG wall?
• Comparison: ETGs possible role: balanced electron/ion-heating: T_e,T_i and large R/L_i.

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 exp. (GK MS).
• JET: strong impact on ETG ‘wall’; ETG wall for realistic Z_{eff} is much higher than R/L_i=6, only for Z_{eff}=1, nearer to the exp. points;

CONCLUSIONS

• ETGs could impact q_{iso} for cases with T_e,T_i and high R/L_i: (conjunction of electron and ion heating): in line with the actual theoretical understanding of ETGs;
• TCV mixed ECH case: a synergy of fast ions and ECH shearing, stabilising 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_i, 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.

REFERENCES

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