Gyrokinetic modeling of ion transport anomalies on electron-heated ASDEX Upgrade L-modes

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Introduction

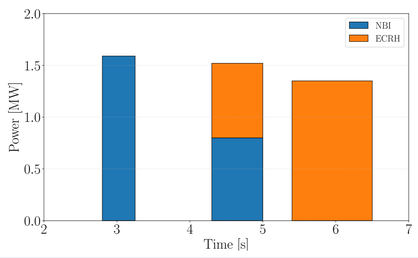
- Microinstability-driven turbulence dominates confinement degradation. High-fidelity gyrokinetic simulations are computationally expensive and contain the full physics, driving reliance on faster integrated models.
- In electron-heated regimes, TGLF-SAT2 overpredicts ion heat transport and underpredicts ion stored energy [1]. This discrepancy highlights the existence of room for improvement in current saturation rule physics.

Mission & Strategy

This work investigates ASDEX-Upgrade L-mode discharge #35475, utilizing time-varying heating schemes to explore how different regimes alter plasma physics. By tracking the temperature ratio (τ) as a proxy, we examine its profound impact on the turbulence spectrum [2-4]. We employ linear and nonlinear gyrokinetic simulations across multiple radii and heating stages to analyze turbulence evolution. Ultimately, this allows us to map turbulence responses to core plasma parameters and evaluate the implications of linear spectra on nonlinear saturation, with one case analyzed in detail.

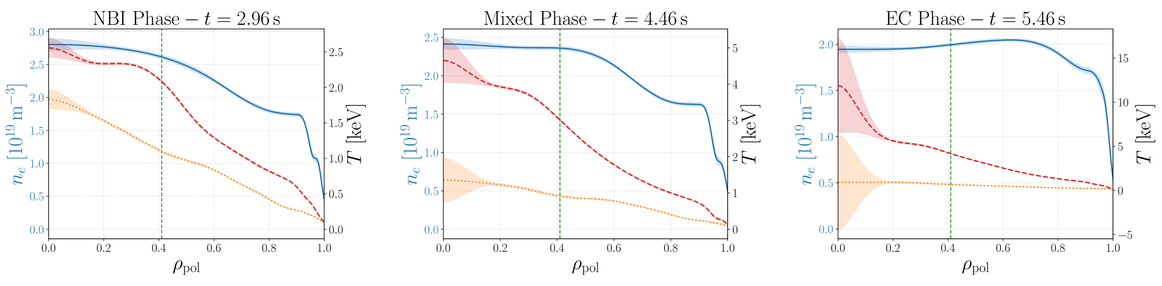
The heating phases in AUG#35475

- $t \in [2.80, 3.25]$ s: 1.59 MW - NBI.
- $t \in [4.30, 5.00]$ s: 0.80/0.72 MW - NBI/ECRH.
- $t \in [5.4, 6.50]$ s: 1.35 MW - ECRH.



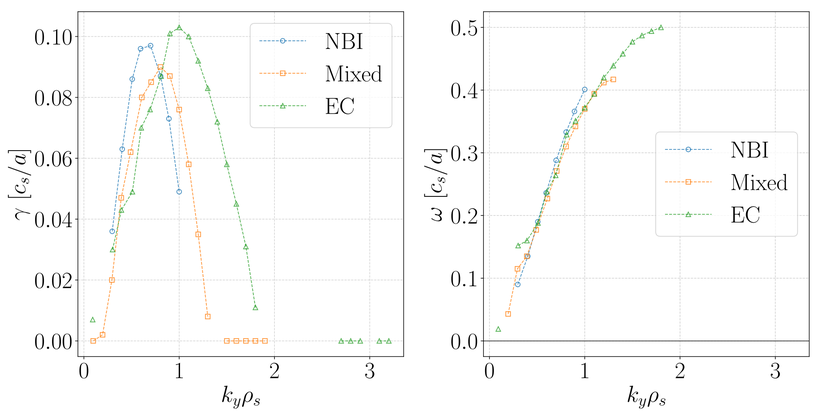
Simulation setup

- We employ the Eulerian δf gyrokinetic code GENE which solves the nonlinear gyrokinetic equation on a fixed grid in 5D phase space [5].
- The experimental data was accessed through IMAS and converted to GENE input.
- $\rho = \rho_{\text{tor}}^{\text{norm}} = 0.3$ & $t_{\text{sim}} = 2.96,\ 4.46,\ 5.46$ s
- Typical grid for linear runs: $N_x \times N_{k_y} \times N_z \times N_{v_\parallel} \times N_\mu = 32 \times 32 \times 64 \times 32 \times 8$
- Typical grid for nonlinear runs: $N_x \times N_{k_y} \times N_z \times N_{v_\parallel} \times N_\mu = 256 \times 64 \times 64 \times 48 \times 16$



Linear stability results at $\rho = 0.3/\rho_{\text{pol}} = 0.41$

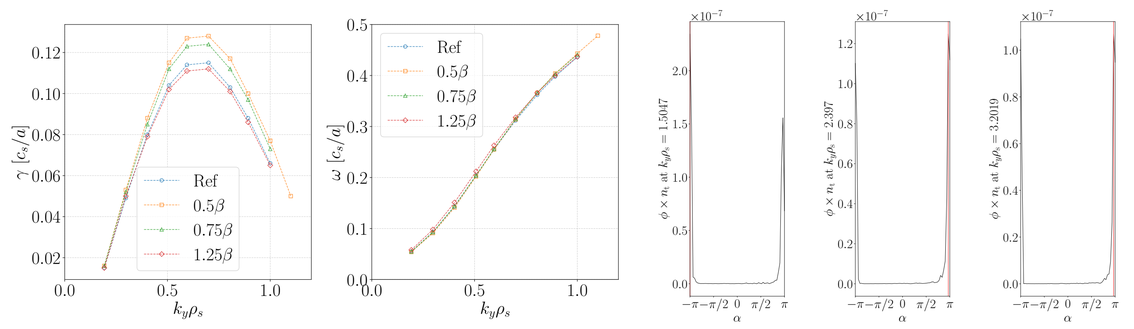
- **Dominant ion modes**: Initial value GENE simulations reveal ion-directed modes ($k_y\rho_s \leq 1.5$) in every heating phase, peaking around $k_y\rho_s \approx 0.7 - 0.8$.
- **Heating impact**: The electron scale remains stable initially, but EC heating triggers instabilities at higher wavenumbers.
- **Subdominant electron modes**: Eigenvalue simulations found electron-directed modes at shorter wavelengths, but their growth rates are negligible (not shown).



Mode identification

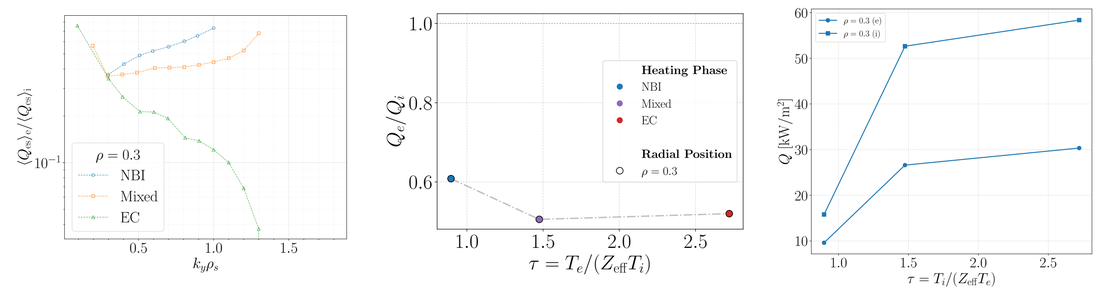
- **Identification**: Modes with $\omega > 0$ are classified as ITG modes via their β dependence.
- **β-driven stabilization**: Higher β values trigger electromagnetic perturbations that cause field-line bending which then linearly stabilizes the ITG modes.
- ∇T-TEM and ETG modes are hard to distinguish at shorter wavelengths.
- **Key difference**: TEMs drive particle flux, whereas ETGs do not.
- The electrostatic potential and trapped density perturbation cross-phases exhibit no peaks near $\pi/2$ confirming no particle flux, indicating that those are ETG modes.

Mode identification: β-scans (ITG) $\alpha_{n_t \times \phi}$ Cross phases (ETG)



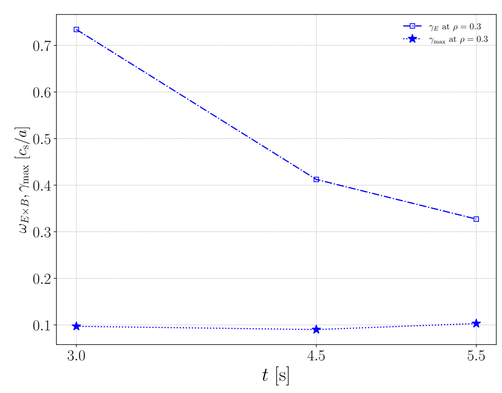
Flux ratios

- The quasilinear heat flux ratio estimates from linear simulations emulate the ion transport overprediction observed by TGLF-SAT2 during the EC phase, where the electron-to-ion heat flux ratio reduces to values below 0.1.
- Nonlinearly, the interplay of the ITG and TEM is more apparent by the more balanced contributions from each channel to the total transport [6].



Zonal flow generation

- **ZF Dominance**: Nonlinear $\mathbf{E} \times \mathbf{B}$ shear exceeds $\gamma_{\max}$ verifying zonal flows as the main turbulence saturation mechanism [7].
- **Gap**: Quasilinear models (TGLF-SAT2, etc.) may overpredict the ion heat transport in electron-heated regimes due to changes in the saturation physics or strength of the zonal flow that are not encoded in their estimate.



Summary

- The ASDEX Upgrade discharge #35475 was modeled within the gyrokinetic framework using the GENE code.
- A case study was presented in detail to study the overprediction of the ion heat transport in electron heated regimes by TGLF-SAT2.
- The ITG-dominated linear picture appears to match the exaggerated contribution of the ion channel to the total heat transport.
- Nonlinearly, the ITG/TEM mixing along with the zonal flow generation results in more moderate electron-to-ion heat flux ratios as well as overall heat fluxes.
- The combination of those nonlinear effects, and their absence from quasilinear models, could bridge the gap between the gyrokinetic simulations and the anomaly as it was reported originally.

Outlook

- Additional linear and nonlinear gyrokinetic simulations across the radius and time to establish a similar trend to the one presented in this case study.
- Comparison of output growth rate, heat and particle flux spectra against ETS/TGLF (joint work B. Brandström) to examine how the experimental profile evolution can affect the predictions.
- Power balance studies for the nonlinear simulations to investigate whether the heat flux levels as predicted by GENE, match the experimental power input.

References

[1] C. Angioni *et al.* NF **62**: 066015 (2022)
[2] H. Doerk *et al.* PPCF **58**: 115005 (2026)
[3] Z. Lin *et al.* PPCF **49**: B163 (2007)
[4] G. A. Peeters PoP **12**: 072515 (2005)
[5] F. Jenko *et al.* PoP **7**: 1904 (2000)
[6] F. Merz, F. Jenko NF **50**: 054005 (2010)
[7] J. Chowdhury *et al.* PoP **19**:102508 (2012)

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