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GENE-Tango simulations for the ITER 15MA baseline scenario

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ASDEX Upgrade

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Overview

Brief introduction to GENE-Tango

ITER baseline scenario:

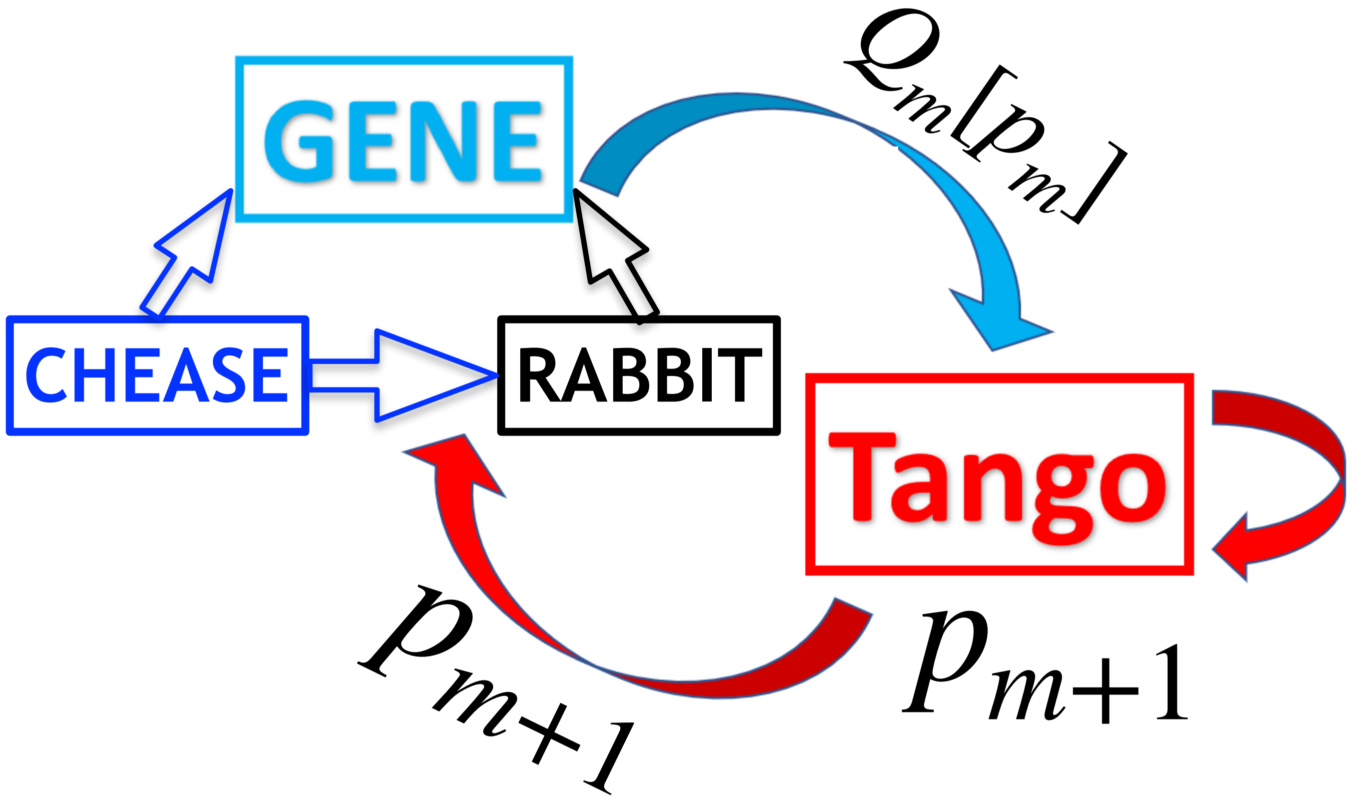
- Impact of electromagnetic effects on plasma peaking
- Comparison between local and global simulations
- Role of ETGs on turbulent fluxes
- Ongoing analyses with alpha particles

Summary and conclusions

Bringing gyrokinetic simulations to transport time scale

GENE-Tango coupling

(i) GENE evaluates turbulence levels for given pressure profile
(ii) Tango evaluates new plasma profiles consistent with given turbulence levels and experimental sources.
(iii) New profiles transferred back to GENE and the process is repeated.

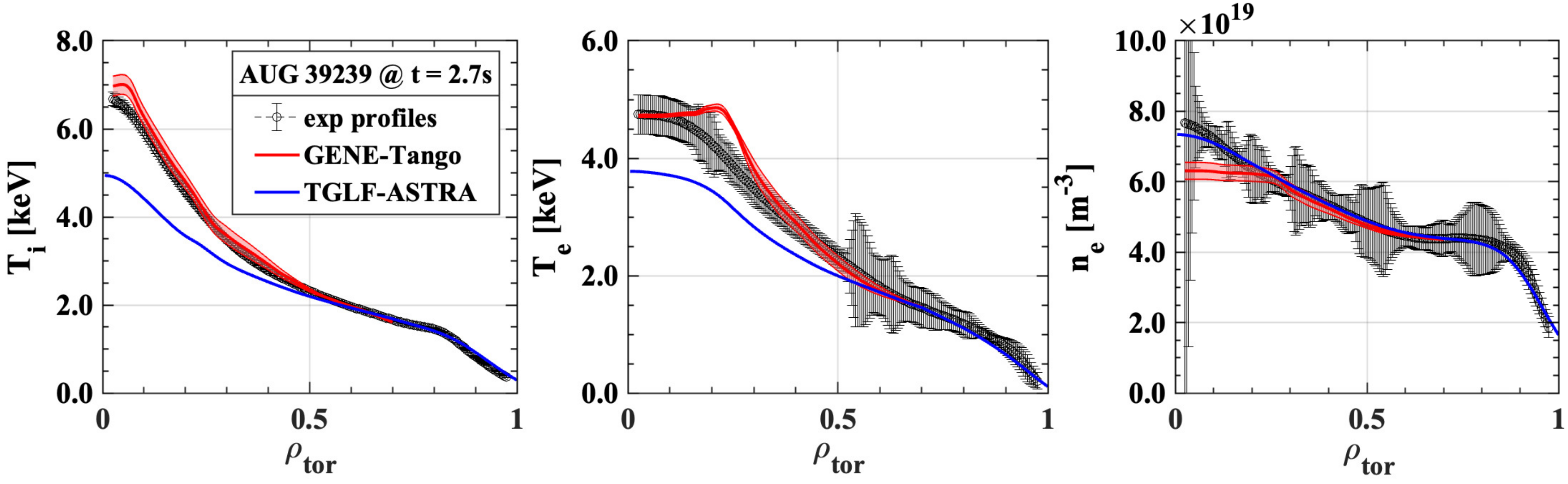


GENE-Tango validation: kinetic electrons high-beta with EPs

ASDEX Upgrade #39230: large fast ion content → good agreement.

- Poor matching of TGLF-ASTRA on the experimental pressure profiles → particularly evident for Ti.

- Ad-hoc models in TGLF to mimic fast ion stabilization do not help in improving the agreement with the experiment.



- Experimental T_i matched only when fast particles and electromagnetic effects are simultaneously retained in the modelling.

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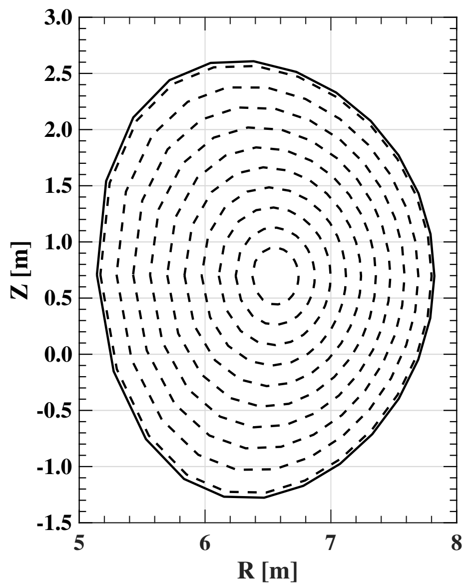
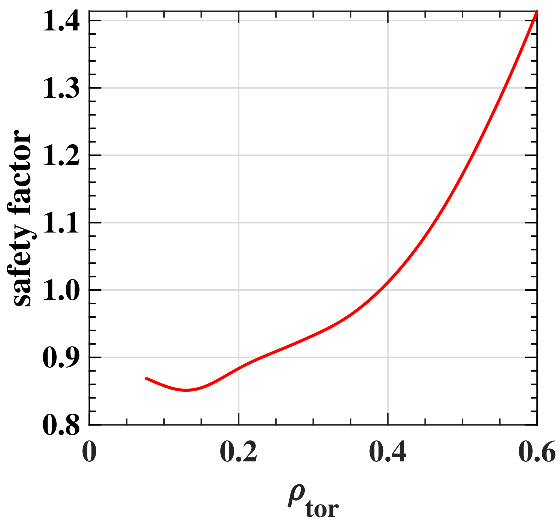
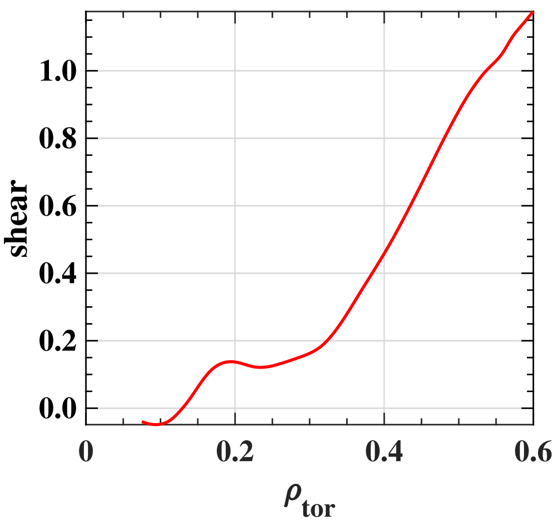
Summary and conclusions

Plasma scenario post-SW crash

- GENE-Tango simulations for the ITER baseline scenario $Q = 10, I_p = 15MA$
- Plasma profiles initialized to the ones computed by QualiKiz-JETTO.
- Simulations: (i) without alpha particles in GENE EM, (ii) without alpha particles in GENE ES, (iii) with alpha particles in GENE.



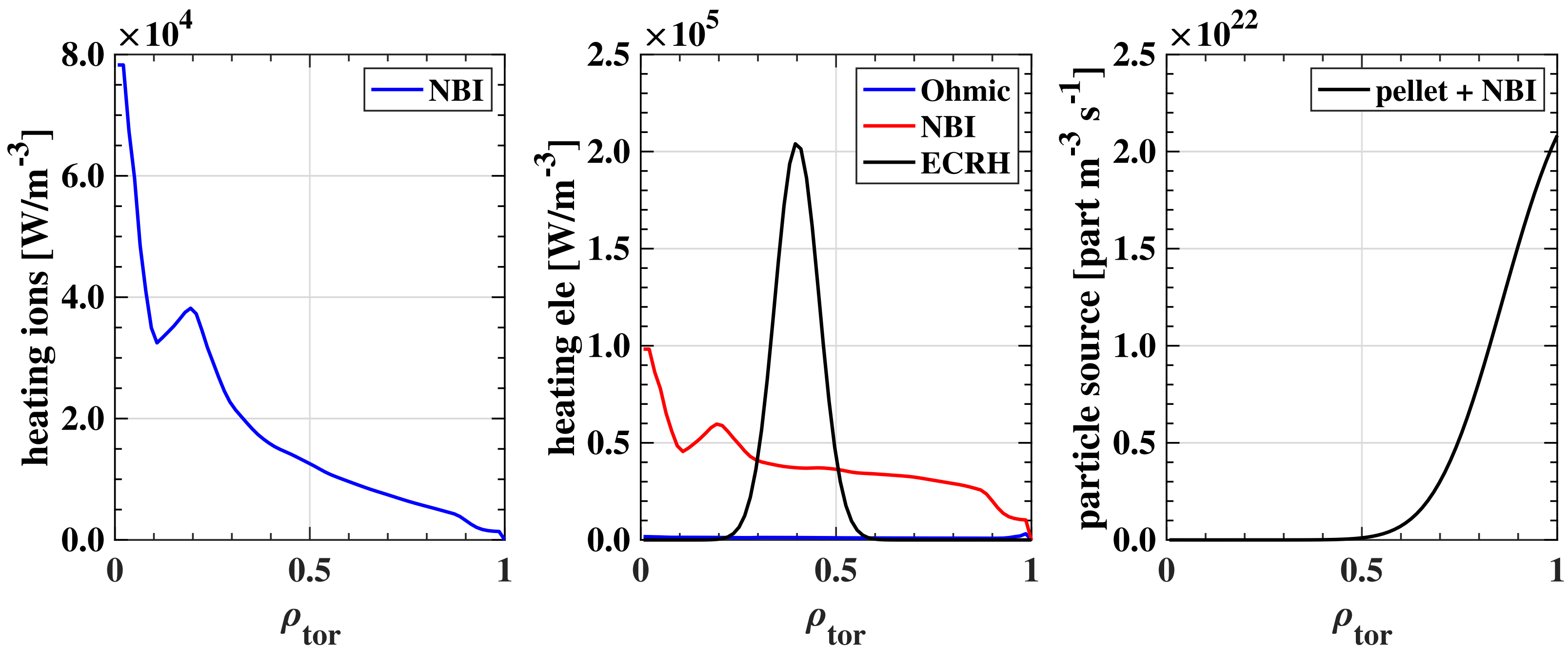




- A relaxed q-profile below q = 1 was chosen to mitigate strong KBM instability observed with a flat q-profile.

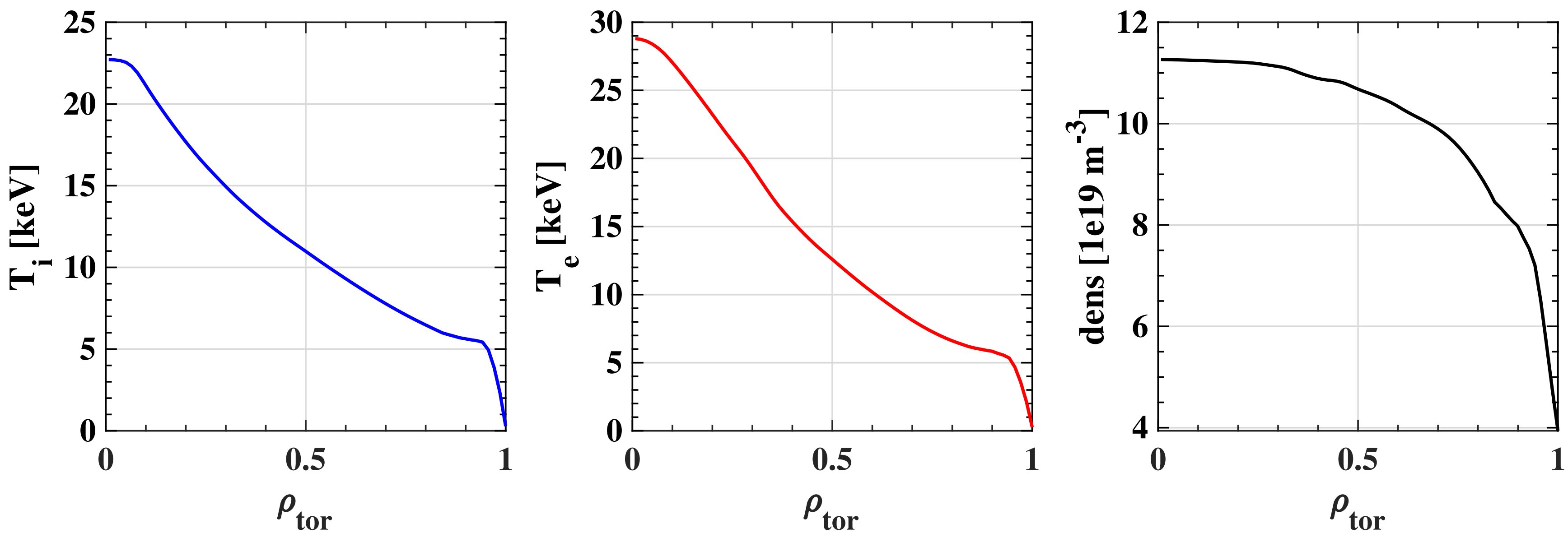
Initial setup

- GENE-Tango simulations are initialized using QLK-JETTO profiles.
- NBI, ECRH, Ohmic heating are taken from QLK-JETTO and kept fixed.
- Alpha heating, radiative losses (Bremsstrahlung, line radiation, synchrotron radiation), and energy exchange are computed dynamically by GENE-Tango at each iteration.
- Particle source is fixed to the one of QLK-JETTO (NBI+Pellett).
- Geometry evolves self-consistently with CHEASE and vtor kept constant.



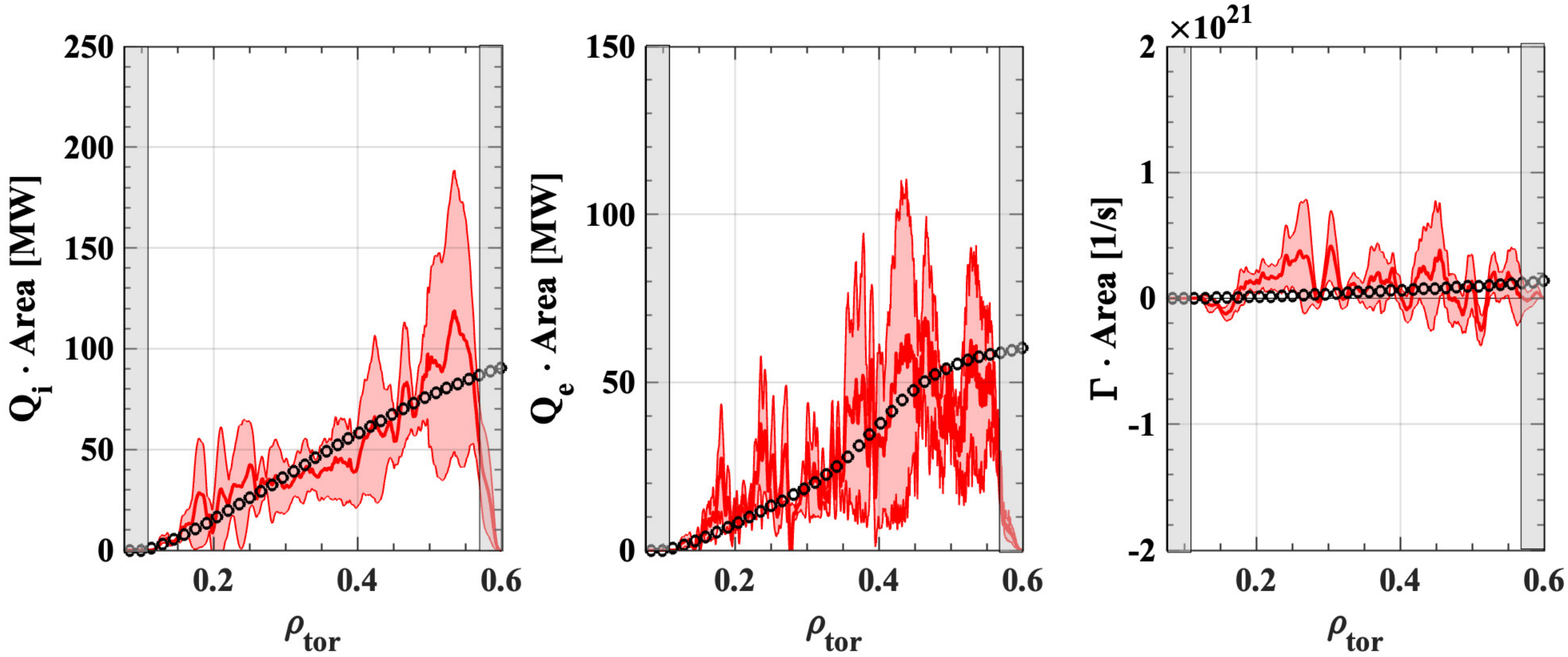
Numerical setup

- GENE resolutions: $(n_x, n_y, n_z, n_v, n_\mu) = (1024,96,48,48,32)$.
- Spectral range: toroidal mode numbers $n = 5$ to $n = 475$, corresponding to $k_y \rho_s (x = 0.34) = 0.02$ to ≈ 2 (covering ITG and TEM regimes).
- Includes toroidal rotation, collisions, electromagnetic effects, realistic geometry, and a realistic electron-to-ion mass ratio.
- Radial domain: $\rho_{tor} = [0.075,0.6]$.
- Each plasma species is modeled using a Maxwellian distribution function.



GENE-Tango without alphas EM

- GENE-Tango EM simulation at ITER for baseline $Q = 10$, $I_p = 15MA$ is converged after 28 iterations.
- Turbulent fluxes computed by GENE match the integral of the sources.



- ITER confinement time $\tau_E = 1s$, while the GENE run covered $9.5ms$ → overall speed-up $\times$ 110.

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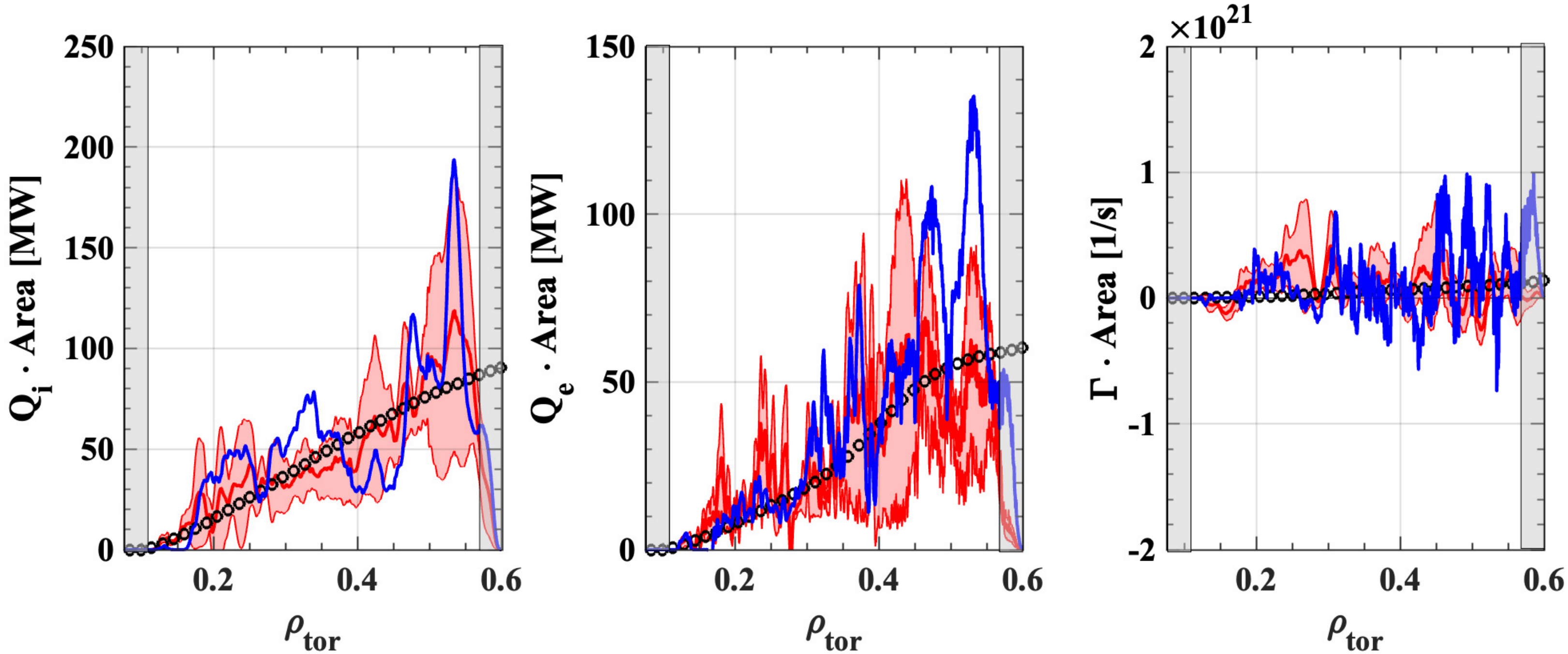
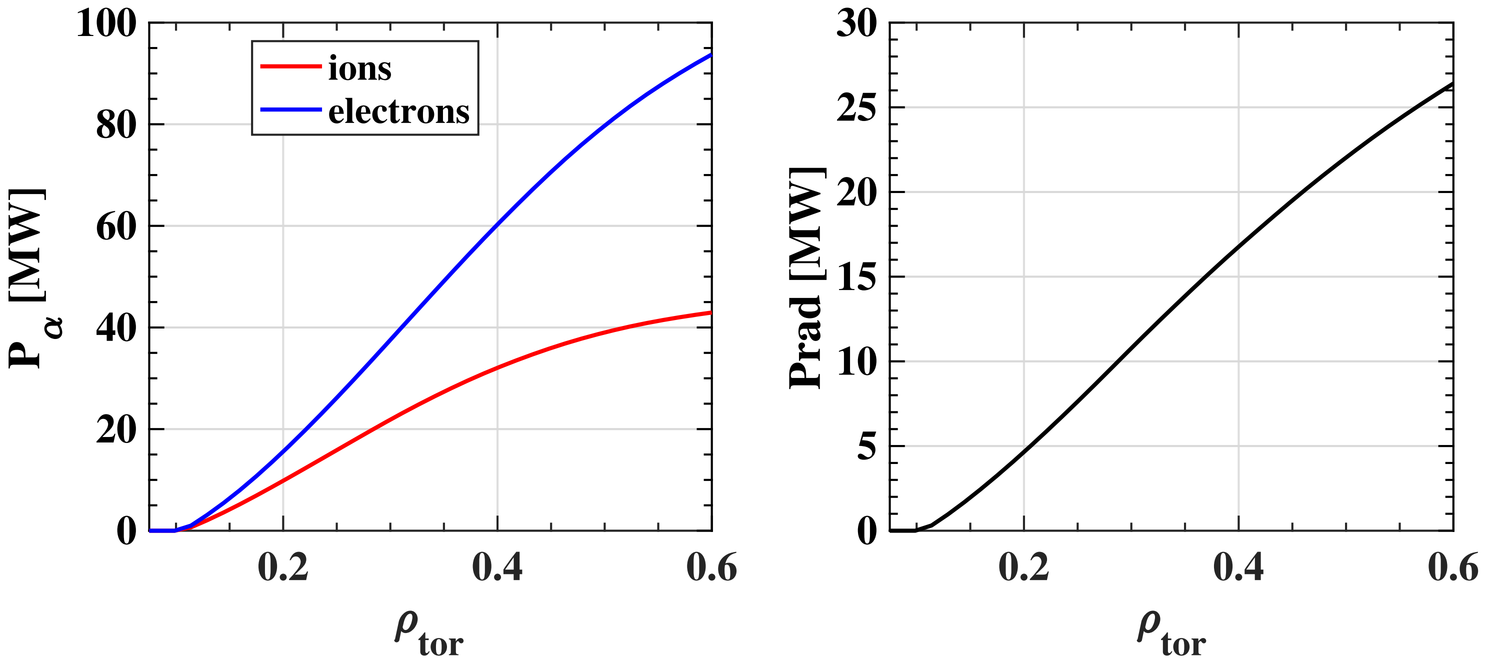


- Using the final GENE-Tango plasma profiles, a stand-alone GENE simulation produces fluxes that align with the power balance.

GENE-Tango without alphas EM

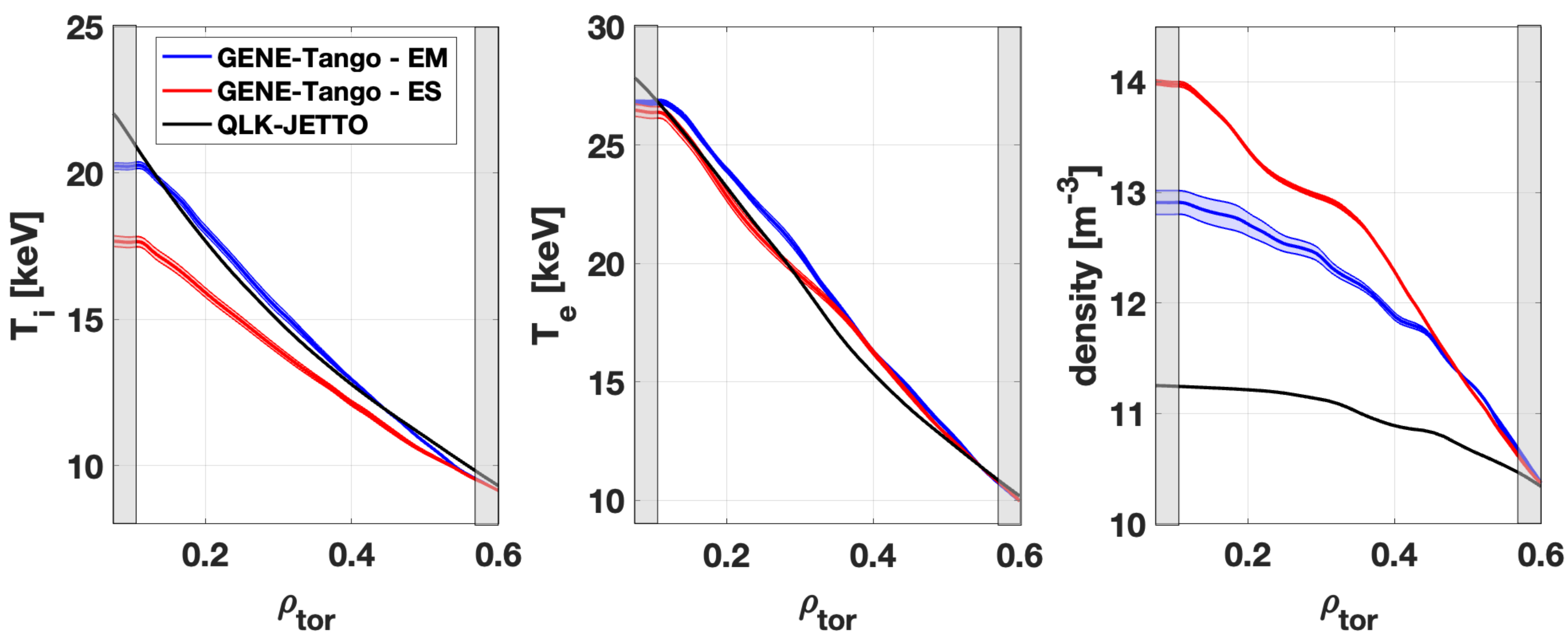
- GENE-Tango profiles exhibit minimal variation over the last five iterations.
- An inward particle flux within $\rho_{tor} = [0.4 - 0.6]$ results in large density peaking.



- According to GENE-Tango, total alpha heating power is $\approx$ 130MW with radiation of $\approx$ 25MW.

Impact of electromagnetic effects on plasma peaking

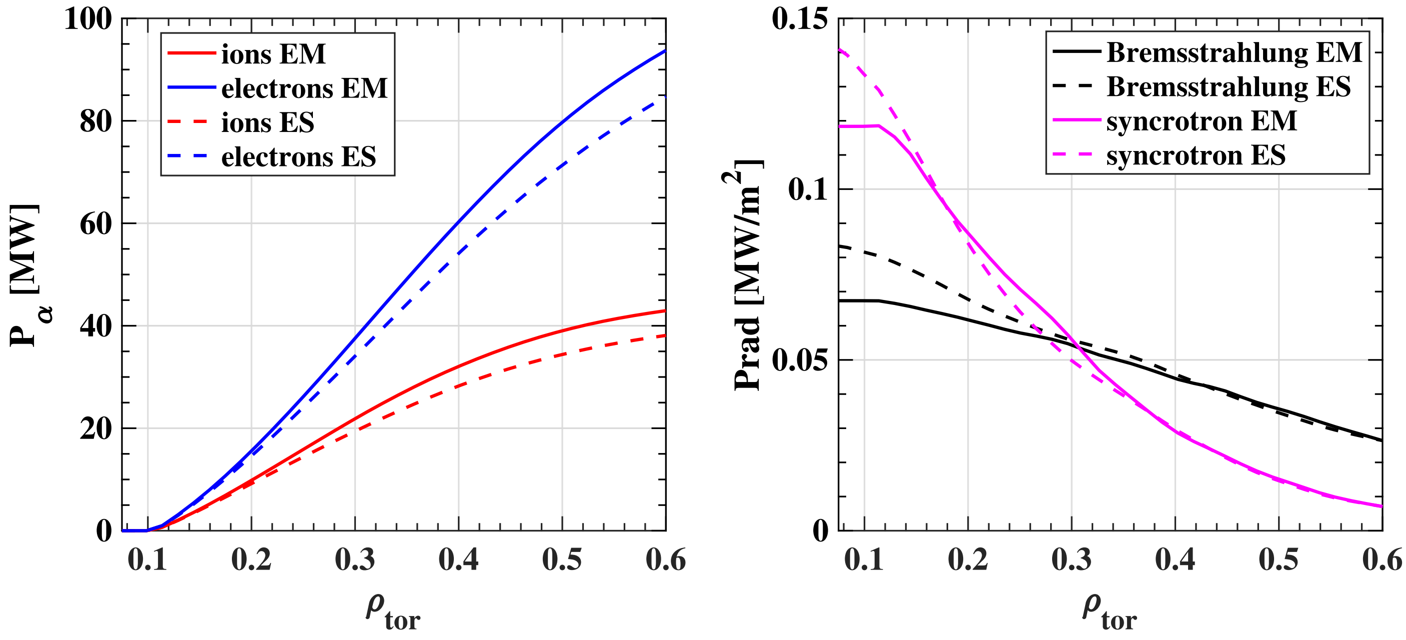
- Ion temperature profile is more peaked in the EM simulations due to β-stabilization of ITG turbulence.
- However, EM fluctuations result in increased outward particle flux, which reduces density peaking.



- Electron temperature profile is weakly affected by EM effects.

Impact of electromagnetic effects on plasma peaking

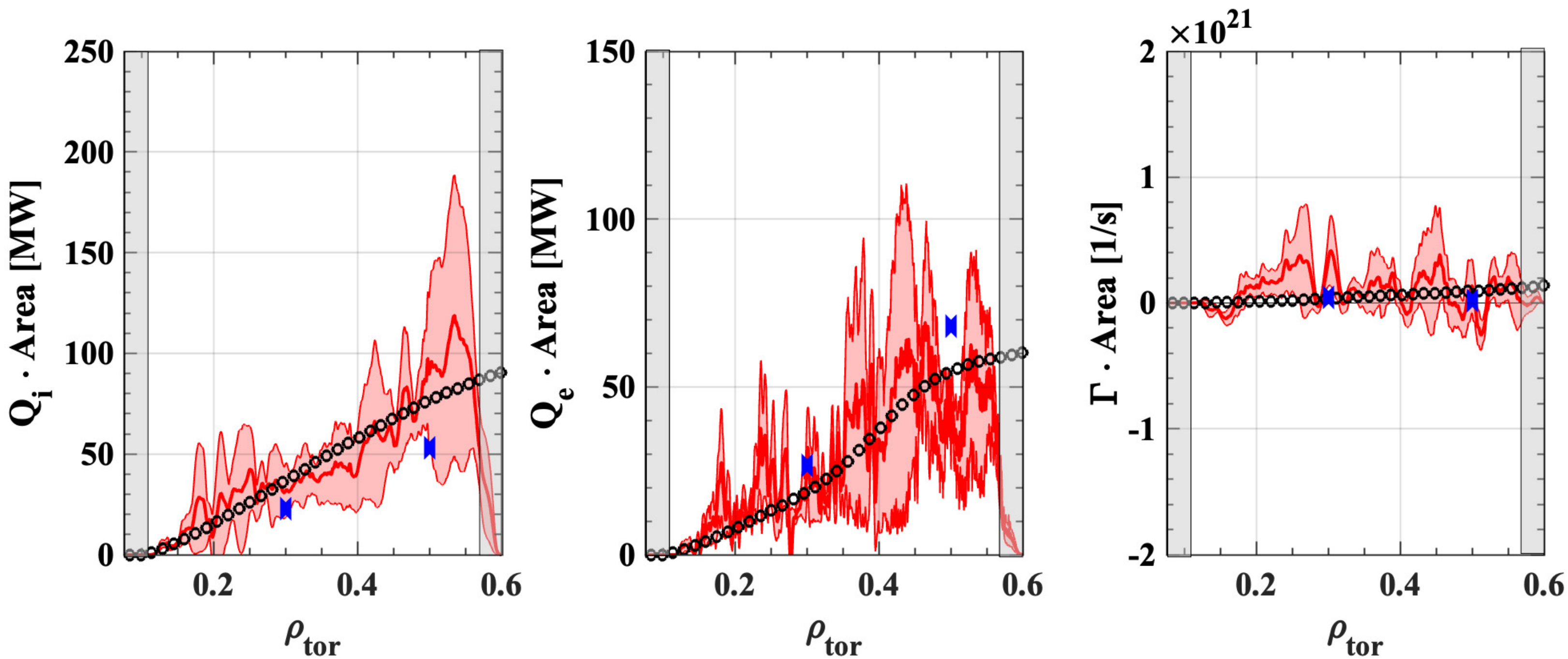
- Due to higher Ti in EM simulations, P_α is slightly larger compared to ES run.
- Radiation is higher in ES simulations due to the more peaked density profile.



- EM effects enhance fusion output by $\sim 11\,\%$.

Comparison between local and global simulations

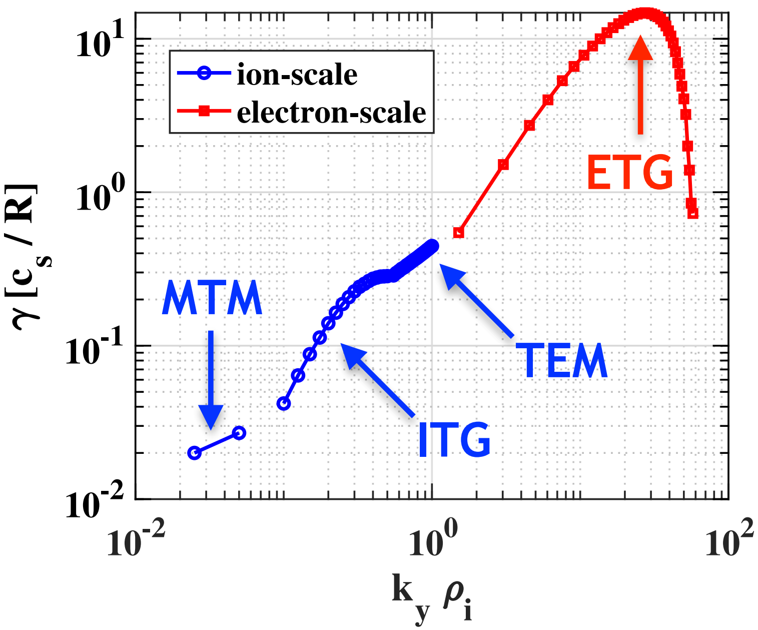
- Global simulations produce profiles with gradient corrugations → local simulations match global fluxes only when smoothed profiles are used.

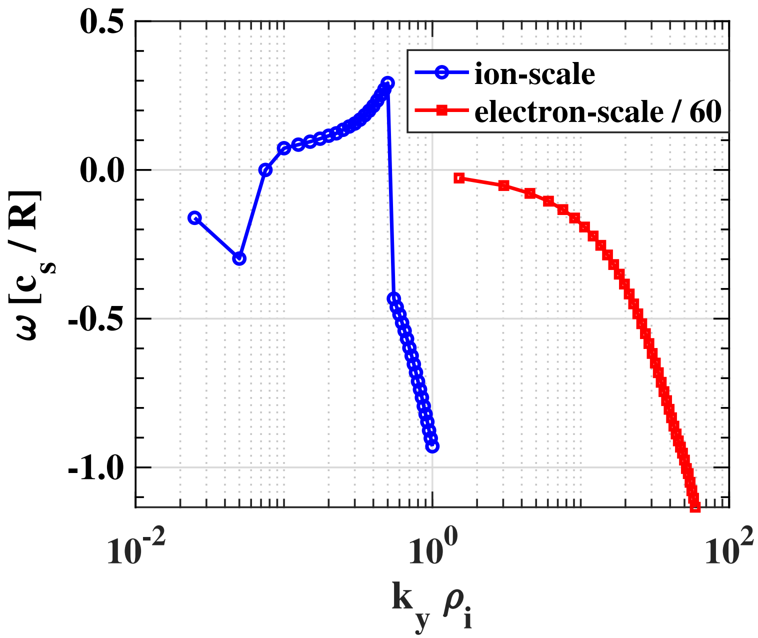


- Flux tube simulations require large resolution $(n_x, n_y, n_z, n_v, n_\mu) = (192,140,32,32,16)$.
- Linear simulations show unstable MTMs that survive in the nonlinear simulations.

Role of ETGs on turbulent fluxes - linear

- Linear flux-tube simulations in the outer plasma core indicate that ETG turbulence could significantly contribute to electron turbulent transport.
- These findings align with recent results obtained using the GKV code [S. Maeyama et al., Nature Comm., 2022].





- When computing the ratio $\dfrac{\gamma_{ETG}/k_{y|ETG}}{\gamma_{ITG}/k_{y|ITG}} \approx 0.87$ suggesting ETG could be important.

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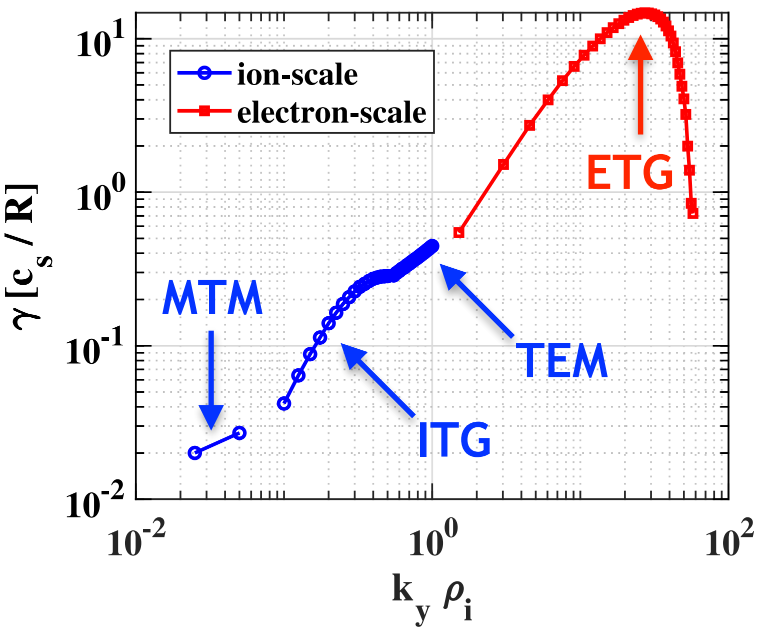
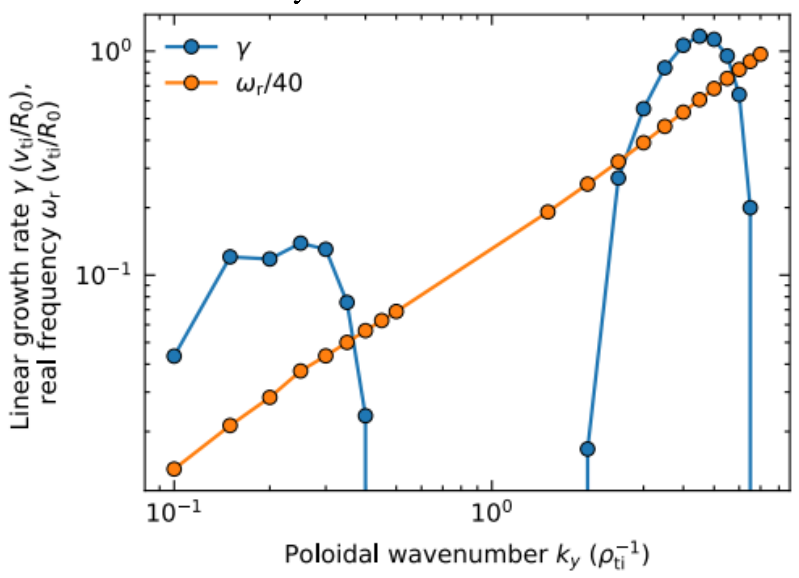


S. Maeyama et al. Nature Comm. 2022



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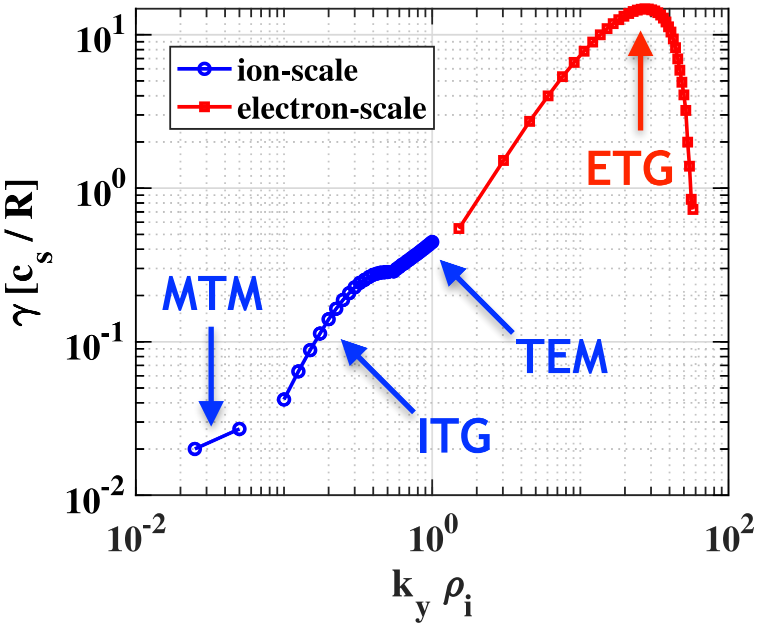

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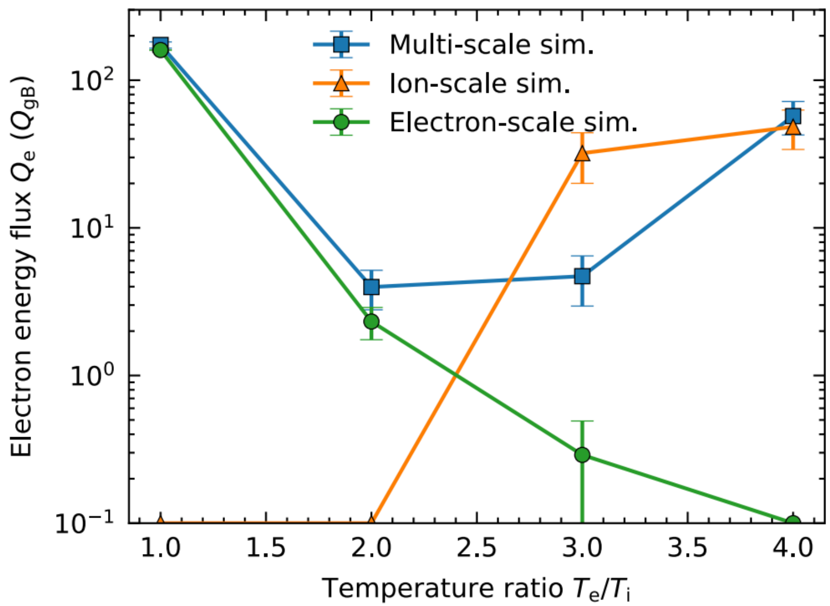

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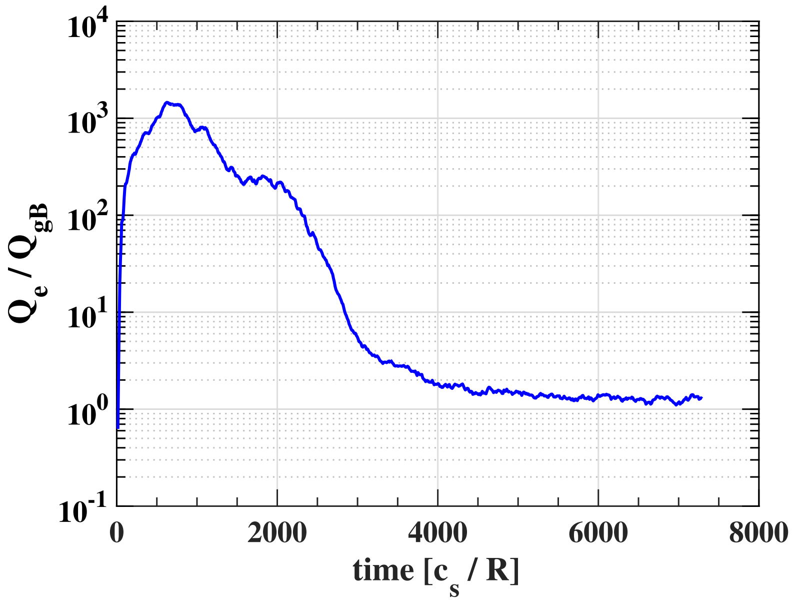
Role of ETGs on turbulent fluxes - nonlinear

- The heat flux "quasi-saturates" at large turbulence levels $Q_e \approx 100MW$.
- However, the zonal fluctuation component continues to grow gradually over time, eventually reaching a new saturated state dominated by zonal modes.



- At long time scales heat flux is proportional to the collision rate due to collisional damping of zonal flows [similar to G. J. Colyer et al PPCF 2017].
- Multi-scale effects may still play a role via modifications of the zonal structures.

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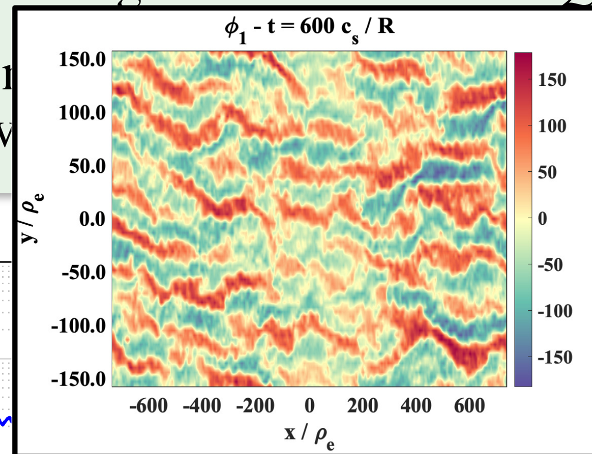

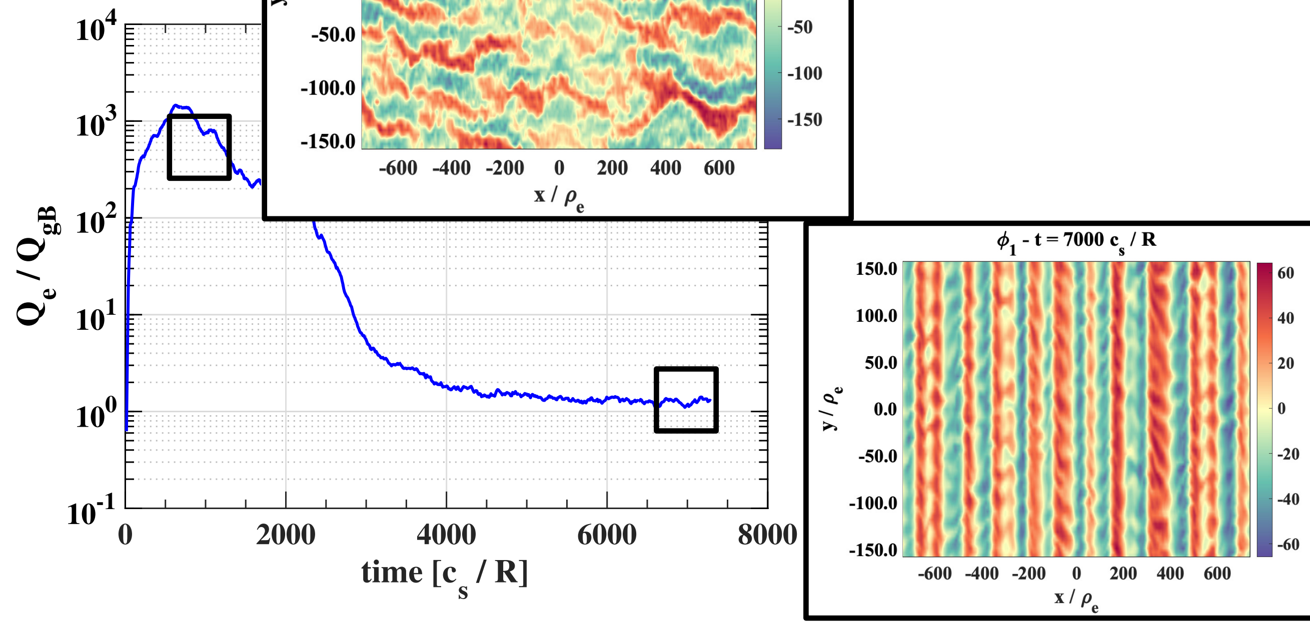

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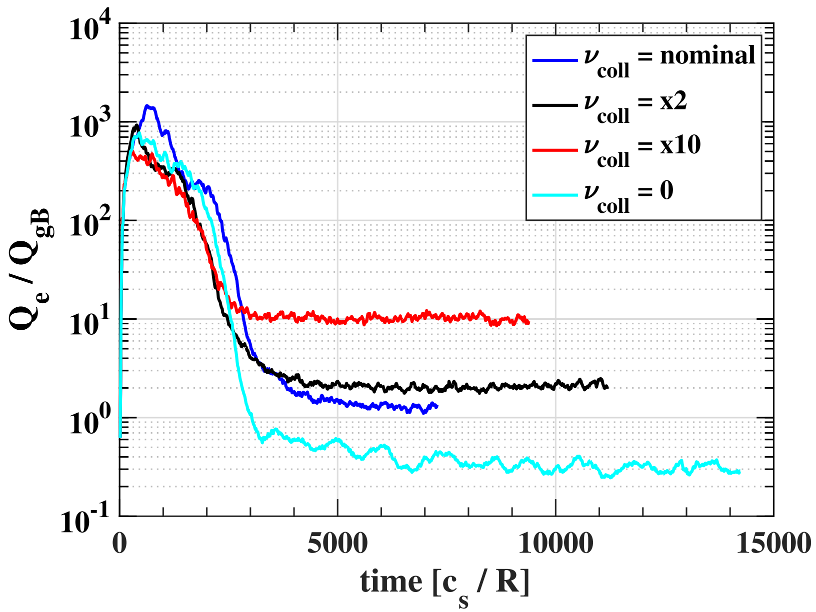

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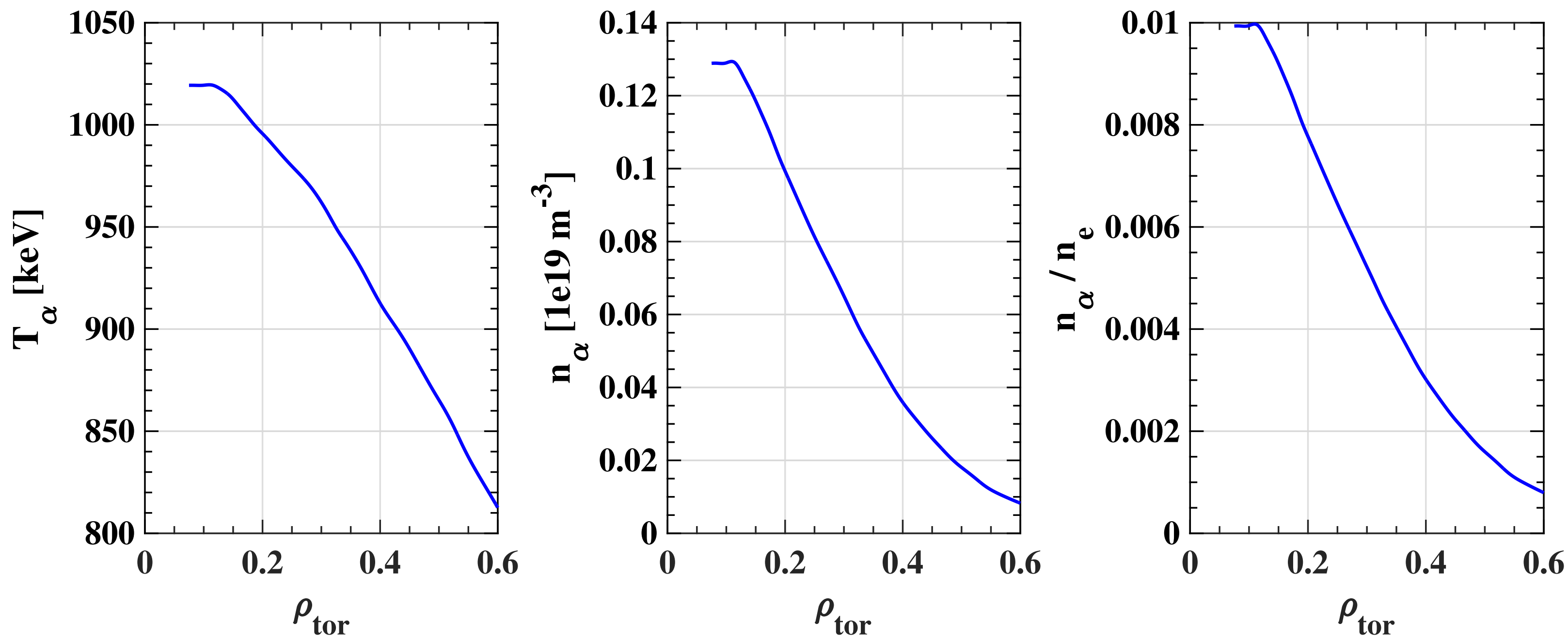
Ongoing analyses with alpha particles

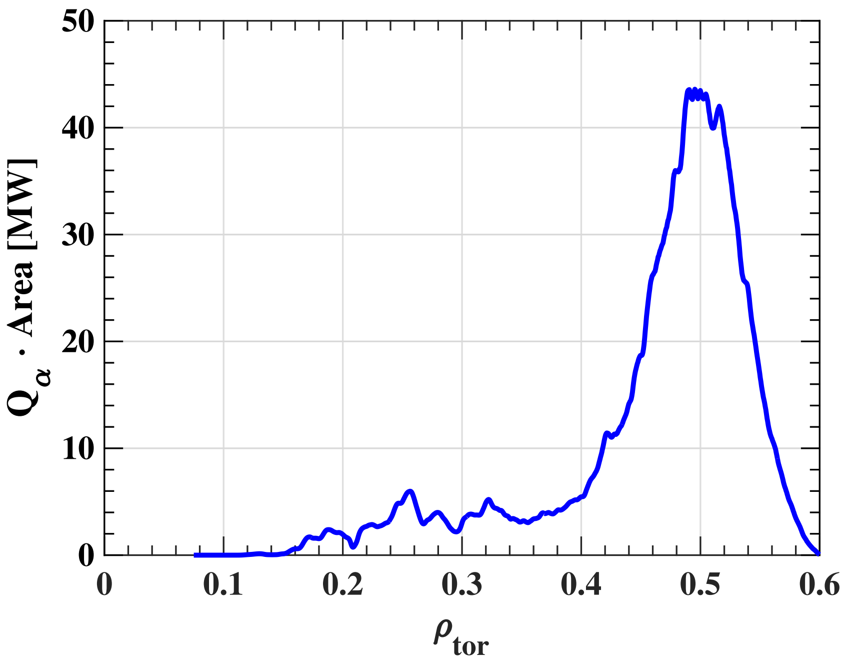
- GENE stand-alone simulations including alpha particles are still running.
- Tango will self-consistently compute the alpha particle density and temperature for each updated thermal profile, adjusting these values at every iteration

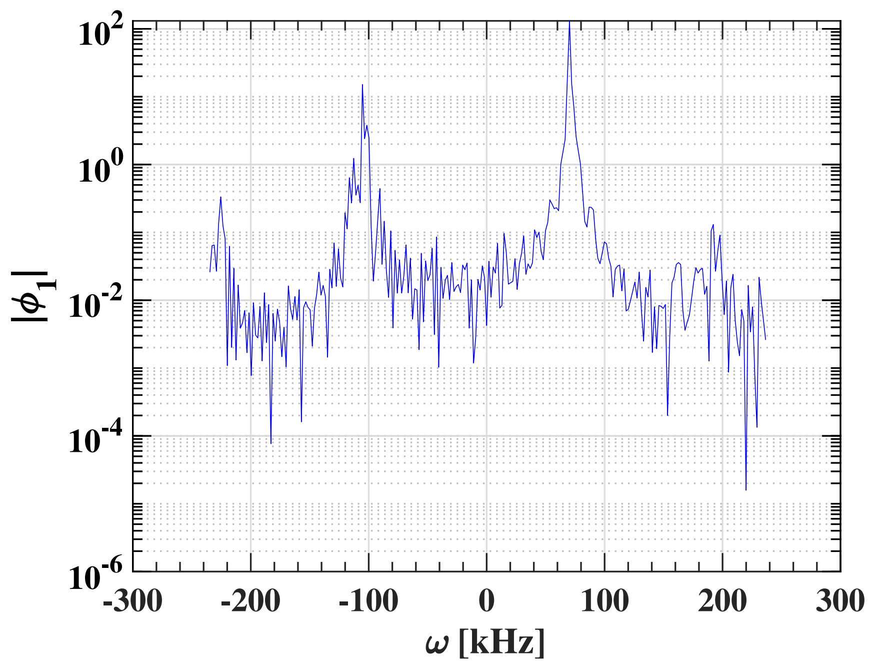


- Geometry includes alpha particle pressure and it evolves self-consistently at each iterations with CHEASE.

Ongoing analyses with alpha particles - frequency spectra

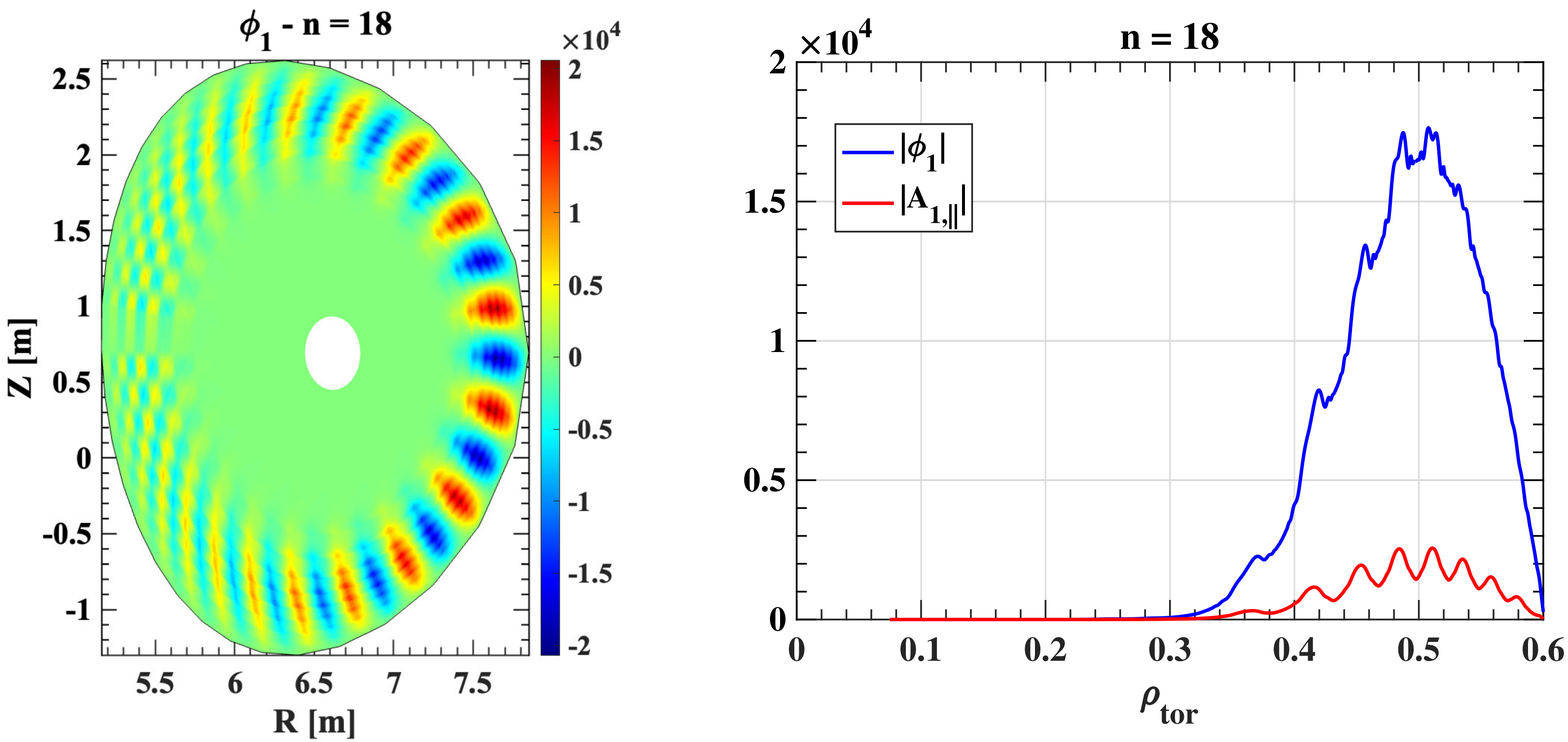
- Alpha particle flux is mostly localized around $\rho_{tor} = 0.5$.
- At this location, two high-frequency modes are observed in the spectrograms with frequency $\omega[kHz] \approx 75$ and $\omega[kHz] \approx -100$.
- Possible nonlinear interaction with thermal ion-scale turbulence.





Ongoing analyses with alpha particles - linear simulations

- Linear global simulations reveal that alpha particles can linearly destabilize a mode with characteristics of a TAE mode.
- Impact of boundary conditions is currently under-investigation.



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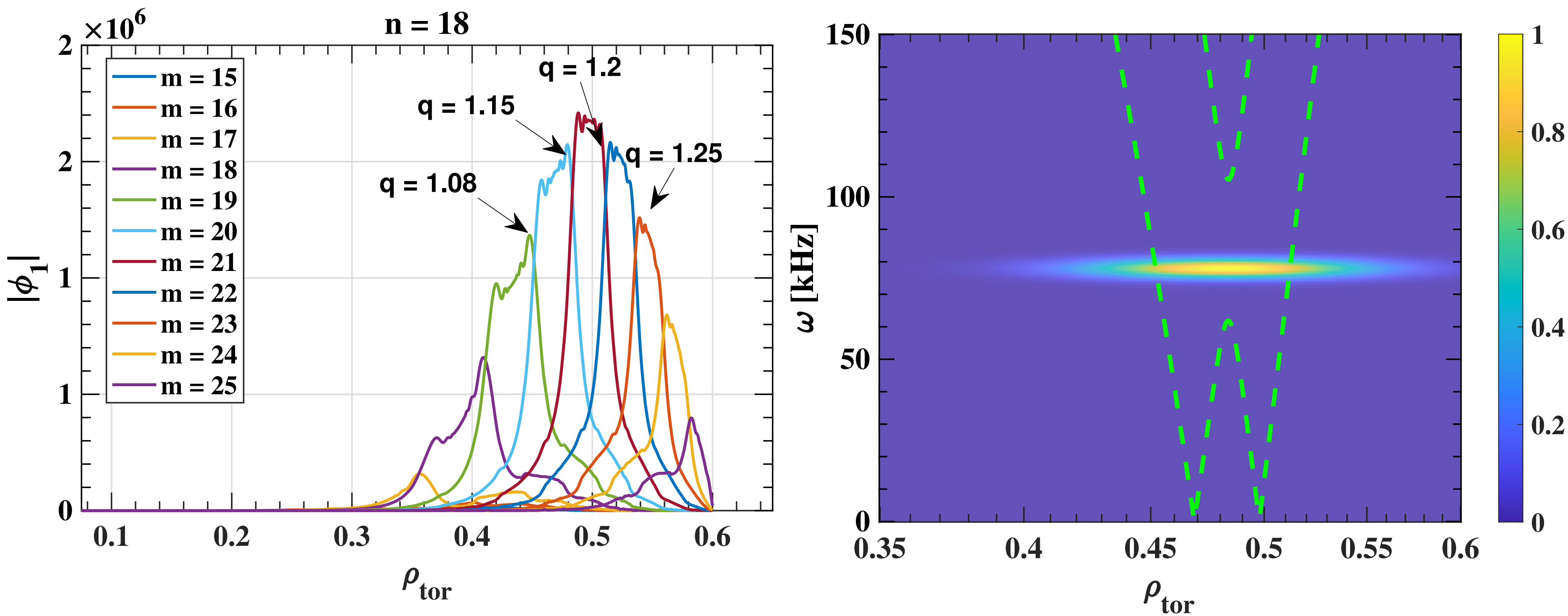

- This mode lies at the center of the TAE gap.

Summary and conclusions

- GENE-Tango EM simulation of ITER baseline scenario is converged → EM effects lead to an increased ion temperature but reduced density peaking.
- While linear simulations suggest ETG might be relevant for ITER, nonlinear results show a long time evolution of zonal flows, that eventually lead to negligible ETG transport.
- Nonlinear flux-tube simulations at different radial positions show good qualitative agreement with global results.
- Alpha particles trigger TAE modes over long time scales, gradually influencing thermal fluxes.

- GENE-Tango simulations retaining alpha particles are still running → preliminary results suggest possible interaction with underlying turbulence.
- Comparison between GENE-Tango and TGLF-ASTRA and QLK-JETTO are on-going.
- We have started a benchmarking activity between local GENE and GKW simulations at several radial locations.