Assessing the impact of energetic particles and alphas on plasma confinement and performance in JET D-T plasmas and ASDEX Upgrade via Global GENE-Tango simulations

A. Di Siena[1]

with

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Outlook

Impact of fast particles on plasma performance at AUG

- GENE-Tango simulations with fast particles and electromagnetic effects reproduce the experimental measurements.
- Impact of energetic particle modes on the Ti peaking explained.
- Can flux-tube simulations reproduce the global results?

Assessing the role of alpha particles in JET D-T experiments

- Alpha particle effects at JET with GENE-Tango.
- Scan over alpha particle density - linear and nonlinear simulations up to ITER concentrations.

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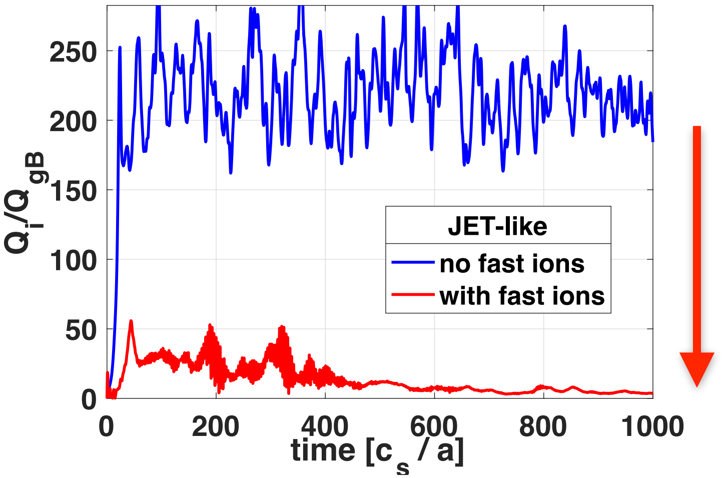
Theoretical background

Relevance

- Fast particles strongly suppress turbulent transport in experiments and simulations → **new pathways to scenario optimisation**.
- Heat flux decreases at fixed sources → pressure increase: **enhanced plasma performance**!
- Supra-thermal particle effects on turbulence not captured by reduced models, e.g., TGLF.



adapted from A. Di Siena et al. JPP 2021

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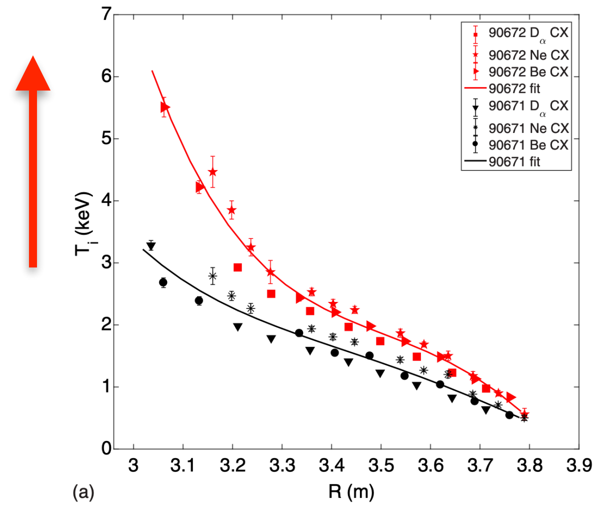

adapted from N. Bonanomi et al. NF 2019

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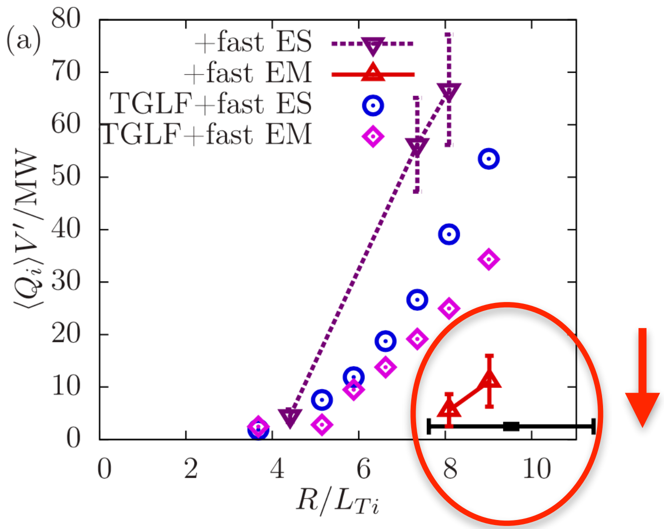

H. Doerk et al. NF 2018

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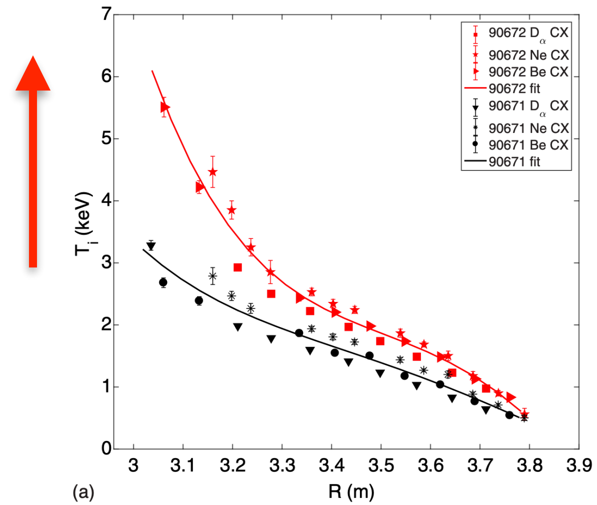

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Main goals

- Can we capture and explain the peaking of Ti observed in experiments?
- What is the role of fusion-born alpha particles on plasma performance?
- Can we predict their impact on future reactor performance?

Bringing gyrokinetic simulations to transport time scale

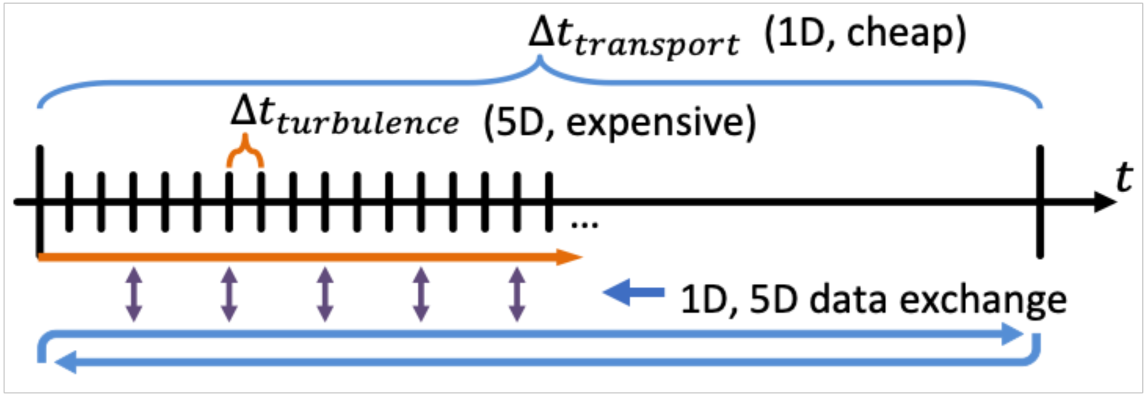
Current status

- Fast ion induced nonlinear stabilization effects on turbulence studied only on micro-turbulence time scales → plasma profiles and magnetic geometry fixed.

Technical limitations to study fast ion effects on confinement time

- Separation between transport ($\tilde{t}$) and turbulence (t) time scales is $\tilde{t}/t \sim (a/\rho)^2$.
- Simulations to confinement time are expensive: feasible for small machines (TCV: $a/\rho < 100$), prohibitive for large experiments (ITER: $a/\rho \sim 1000$).

Computational cost $> (a/\rho)^3 \rightarrow$



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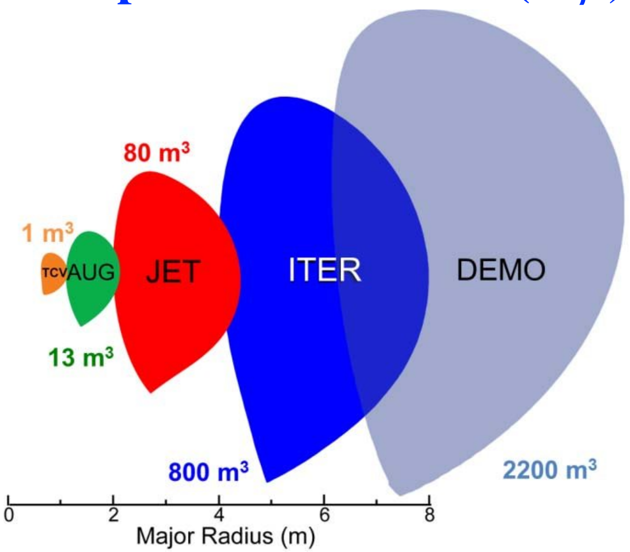


Bringing gyrokinetic simulations to transport time scale

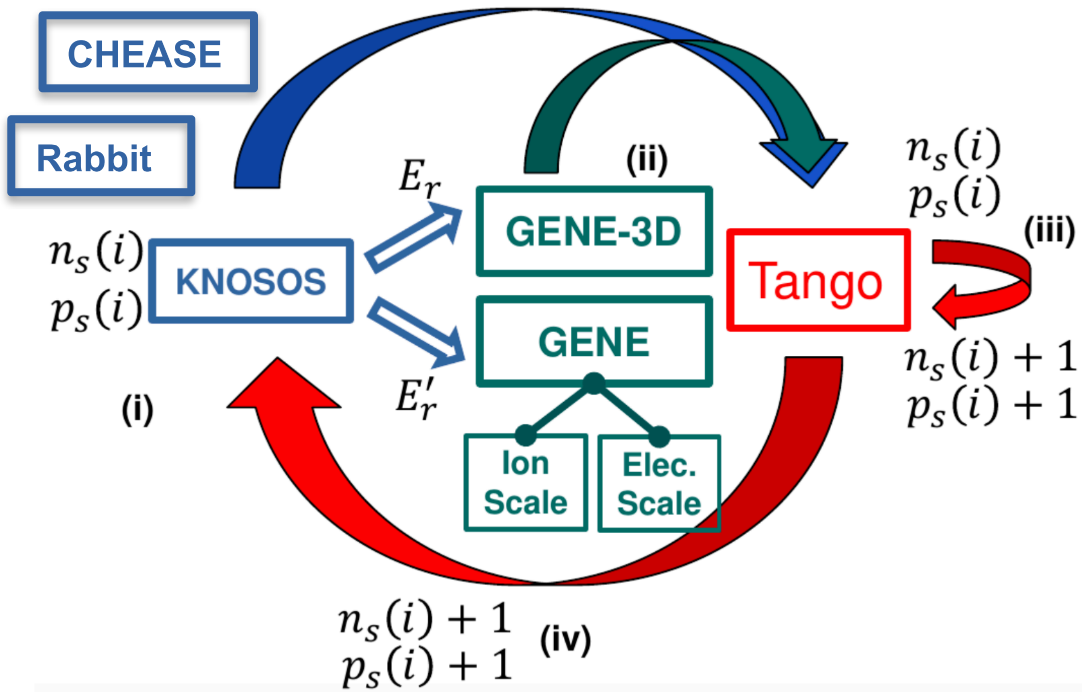
GENE-Tango coupling

(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.

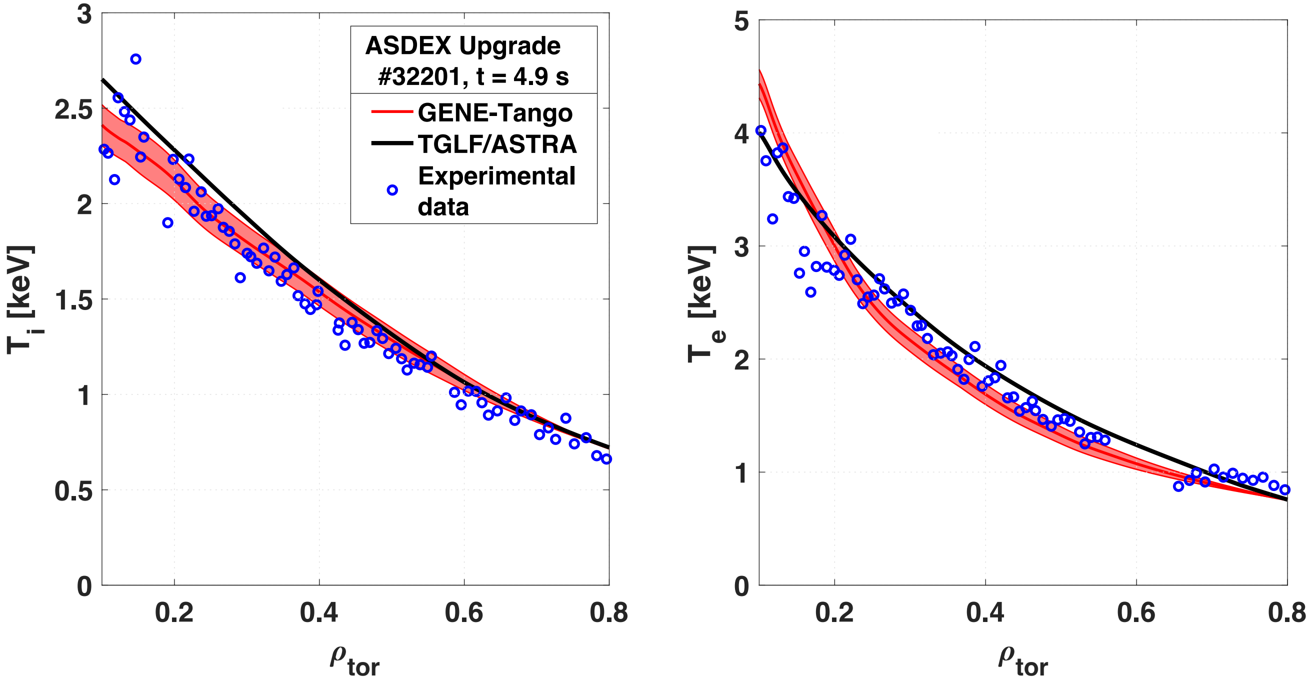
$$\Gamma_s(i) = \Gamma_s(i)^{\text{neo.}} + \Gamma_s(i)^{\text{turb.}}$$
$$Q_s(i) = Q_s(i)^{\text{neo.}} + Q_s(i)^{\text{turb.}}$$



GENE-Tango validation

- GENE-Tango can model kinetic electrons, fast ions with alpha heating, radiation (including bremsstrahlung, line radiation, synchrotron radiation), and energy exchange.
- Neoclassical fluxes and electron scale turbulence can be included.

ASDEX Upgrade #32201: negligible fast ion content → excellent agreement.



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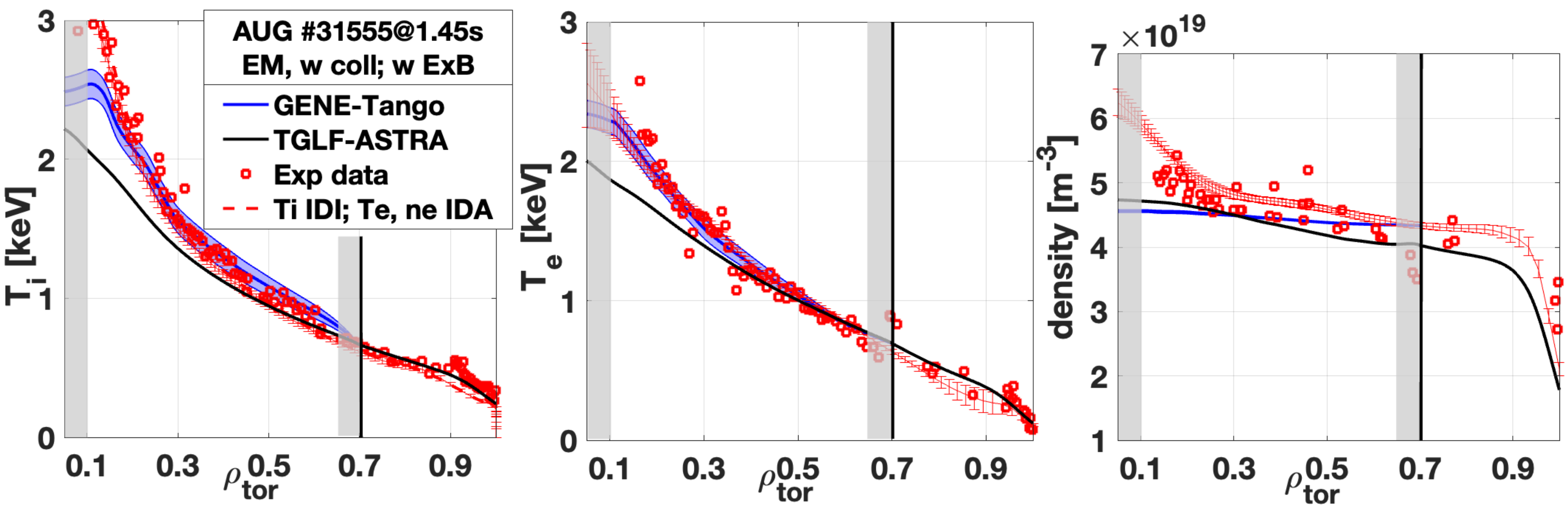
ASDEX Upgrade #31555: moderate plasma beta → good agreement.



A. Di Siena et al. NF 2022

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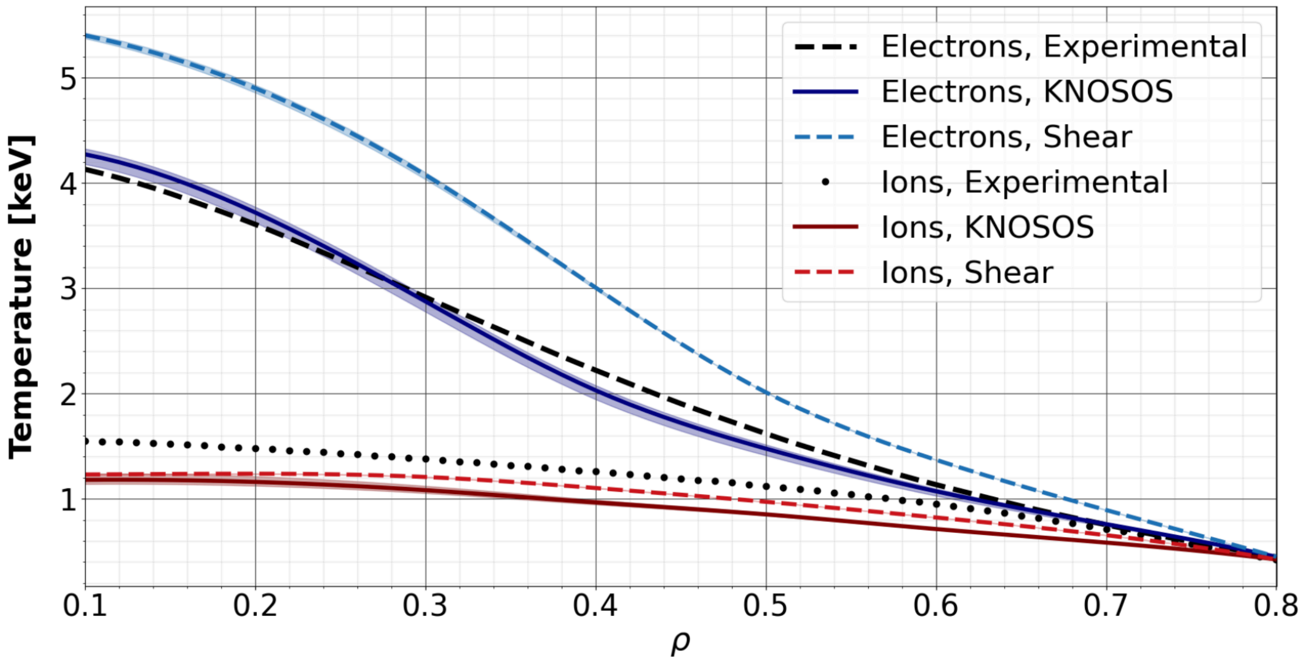
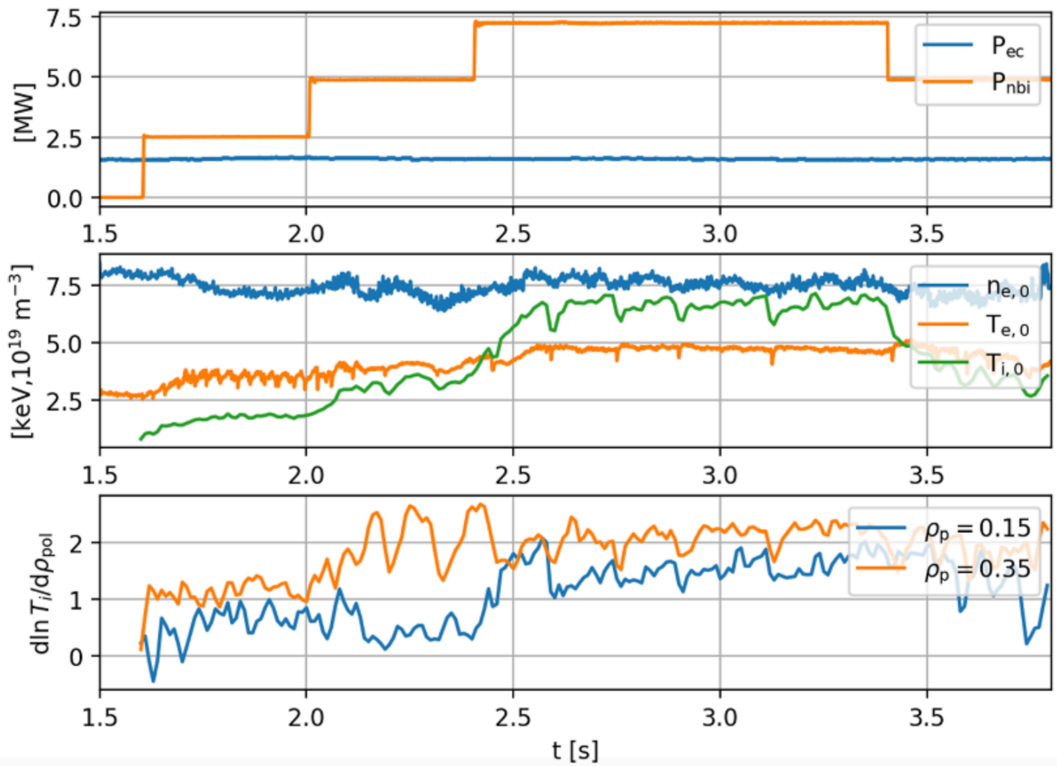
W7-X OP1.2b #180920.013: low density, ECRH → excellent agreement.



D. Fernando et al. invited APS 2024, manuscript in preparation

ASDEX Upgrade 39230 @ t = 2.7 s

- GENE(global)-Tango simulations are performed with realistic electron-ion mass ratio, collisions, external ExB rotation.
- Magnetic equilibrium kept fixed to the one reconstructed via IDE.
- Cases analyzed: (i) no fast ions ES, (ii) no fast ions EM, (iii) with fast ions ES, (iv) with fast ions EM.



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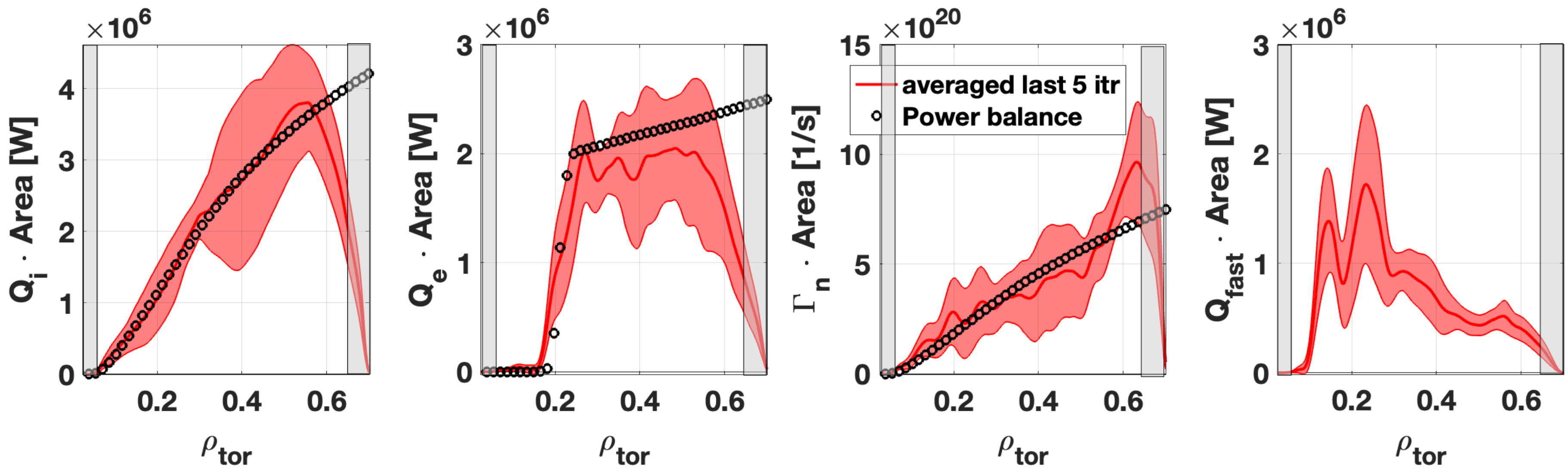
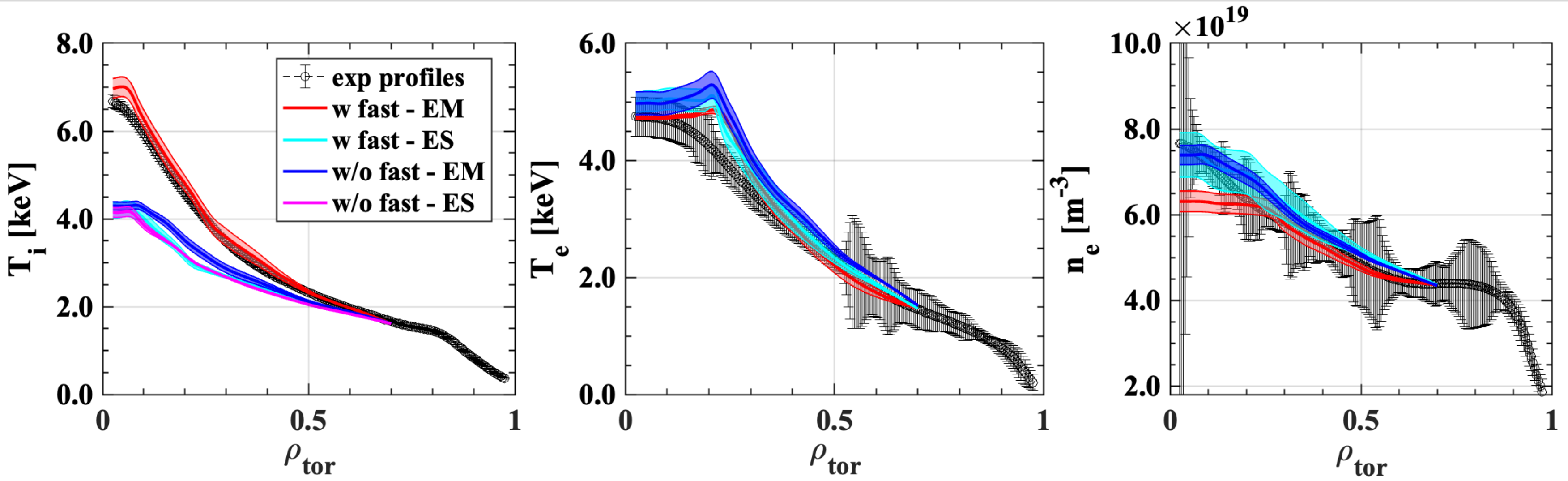
Case (iv): with fast ions EM



- Each case run until GENE turbulent fluxes match volume integral of injected heat and particle sources.

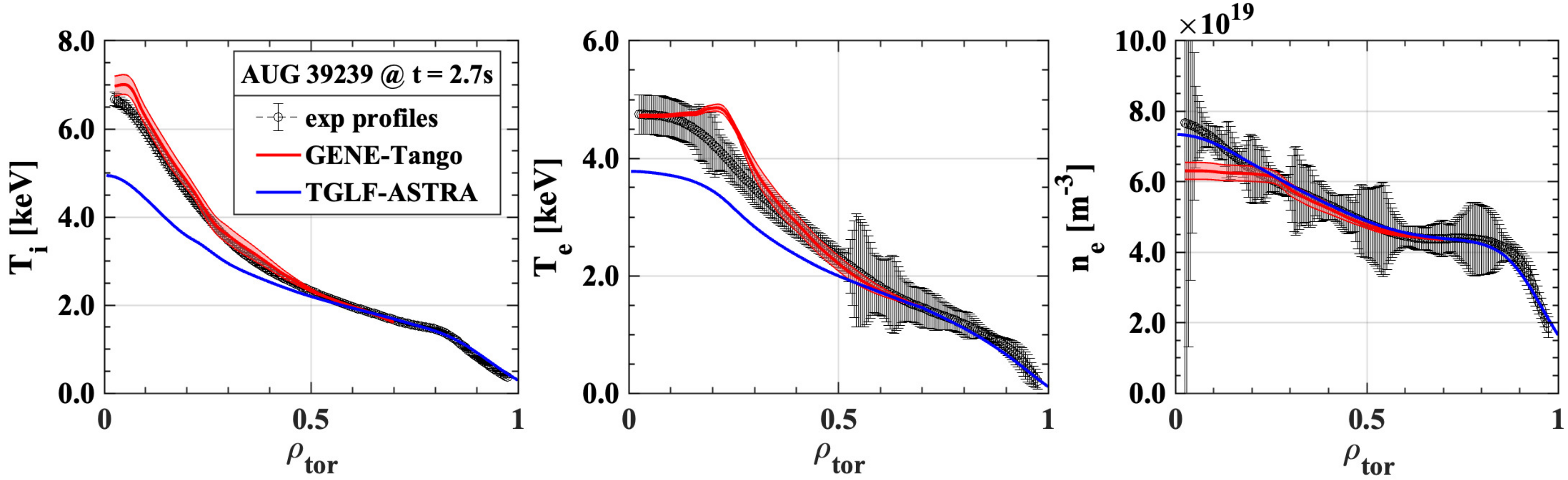
What is leading to the T_i peaking in the GENE-Tango simulations?



- Magnetic equilibrium itself (e.g., reversed shear, rational surfaces) cannot explain the increase on T_i on-axis.
- Electrostatic simulations (with or without fast ions) predict too much ITG transport $\rightarrow T_i$ stays at $\sim$ 4keV with negligible effects on T_e and density.
- Electromagnetic effects without fast ions lead to a mild peaking of T_i with minor impact on the on-axis value.
- Electromagnetic effects and fast particles are essential to reproduce experimental profiles.

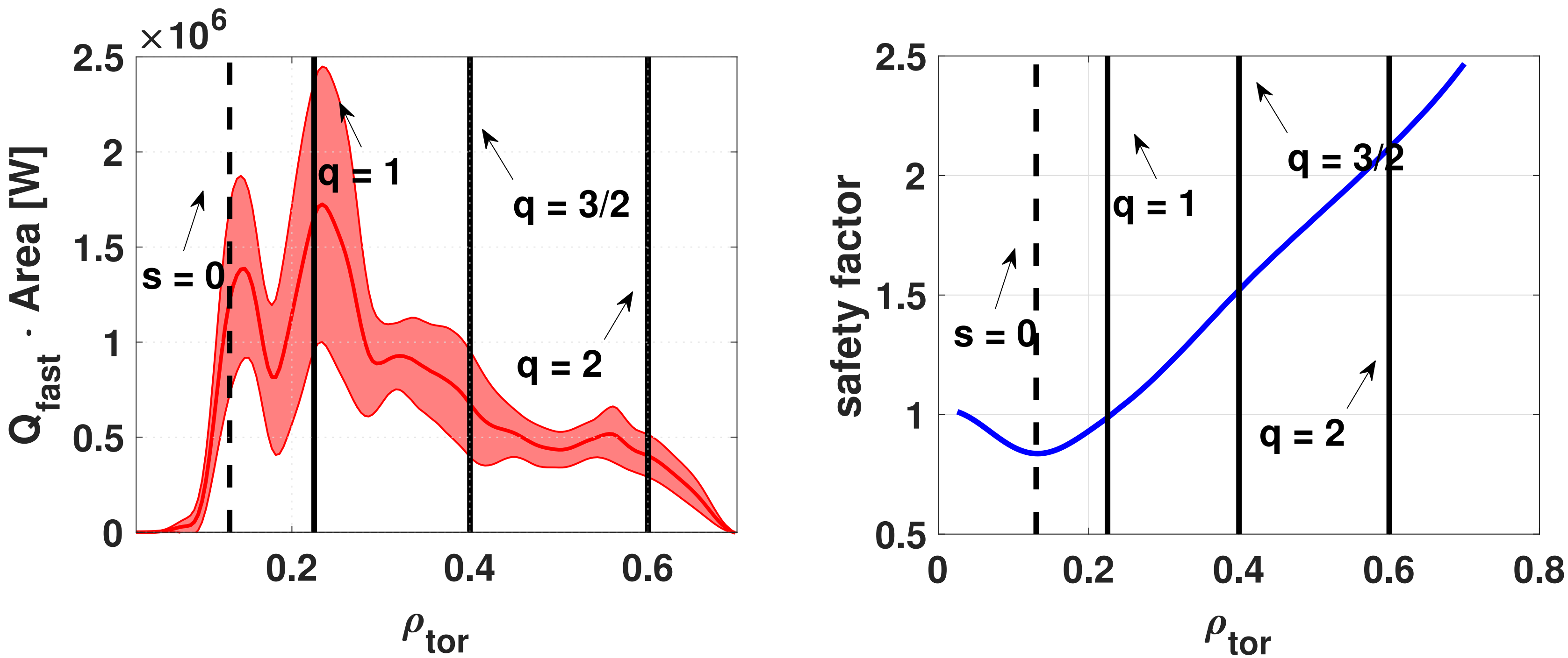
Comparison with TGLF-ASTRA

- TGLF-ASTRA strongly underpredicts T_i in this particular plasma discharge.
- Supra-thermal particle effects on turbulence not captured by reduced models, e.g., TGLF.



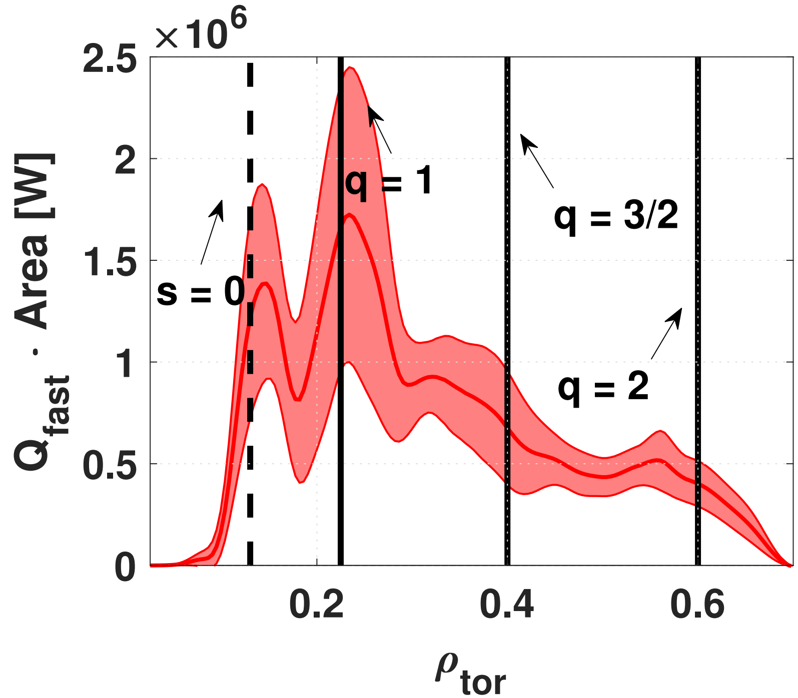
- Experimental T_i matched only when fast particles and electromagnetic effects are simultaneously retained in the GENE modelling.

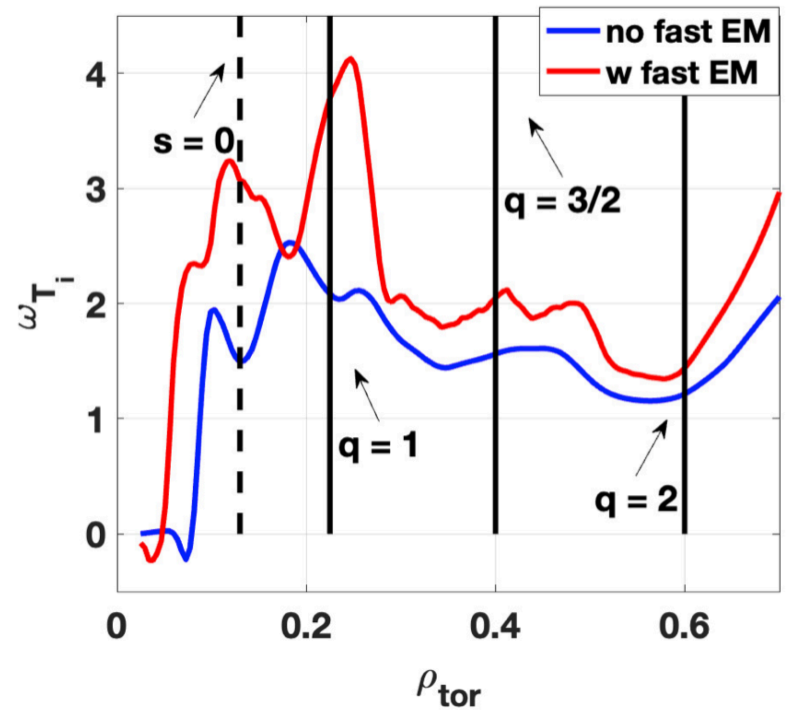
Fast ion heat flux and rational surfaces



- Fast ion heat flux peaks at the rational surface $q = 1$ and $s = 0$.
- Other rational surfaces do not affect fast ion heat flux significantly - low fast ion density and temperature at $\rho_{tor} > 0.3$.

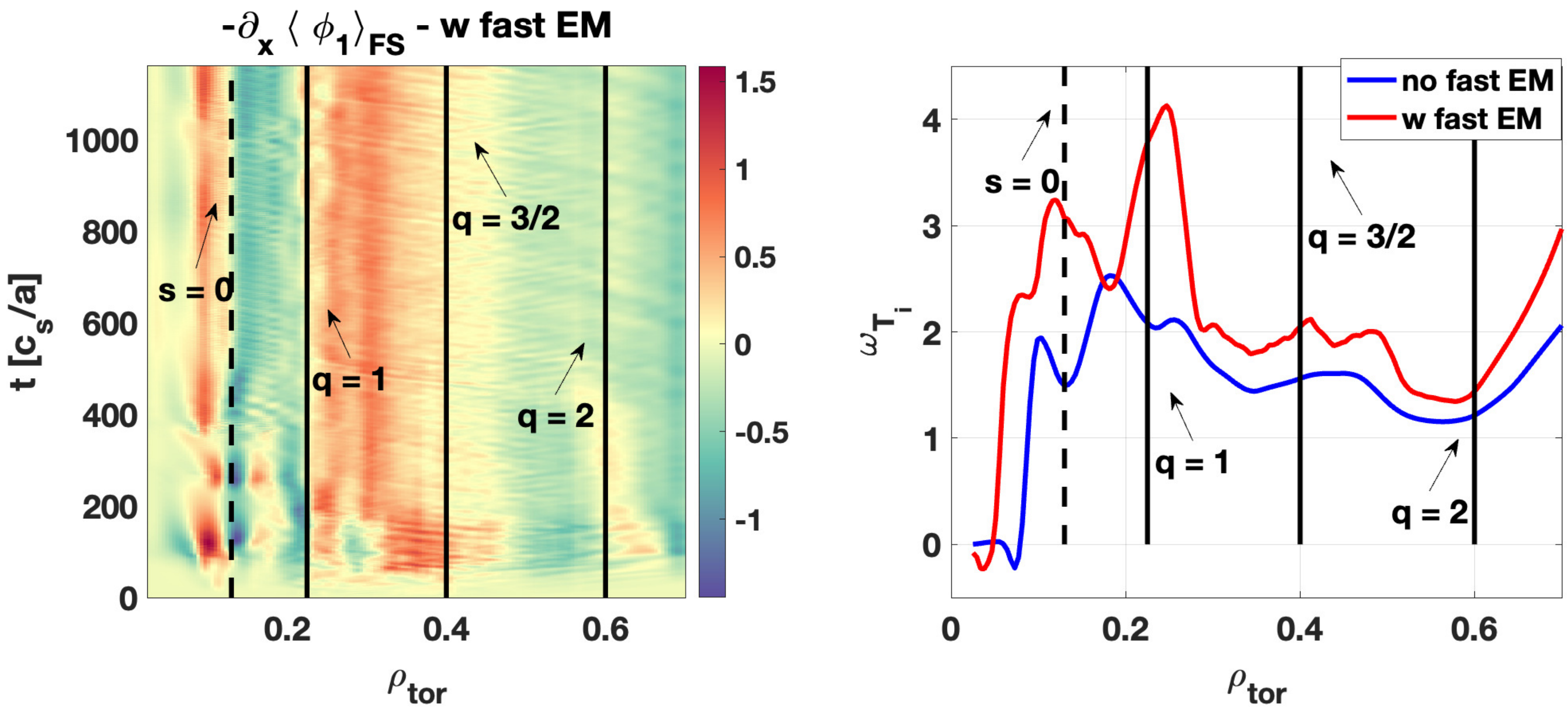
Fast ion heat flux and rational surfaces





- The peaks of the energetic particle heat flux are strongly linked to the regions where the logarithmic temperature gradient increase.
- Simulation without fast ions - despite having same geometry - do not show clear improvements at $q = 1$ and $s = 0$.

Zonal structure generation by fast ion modes

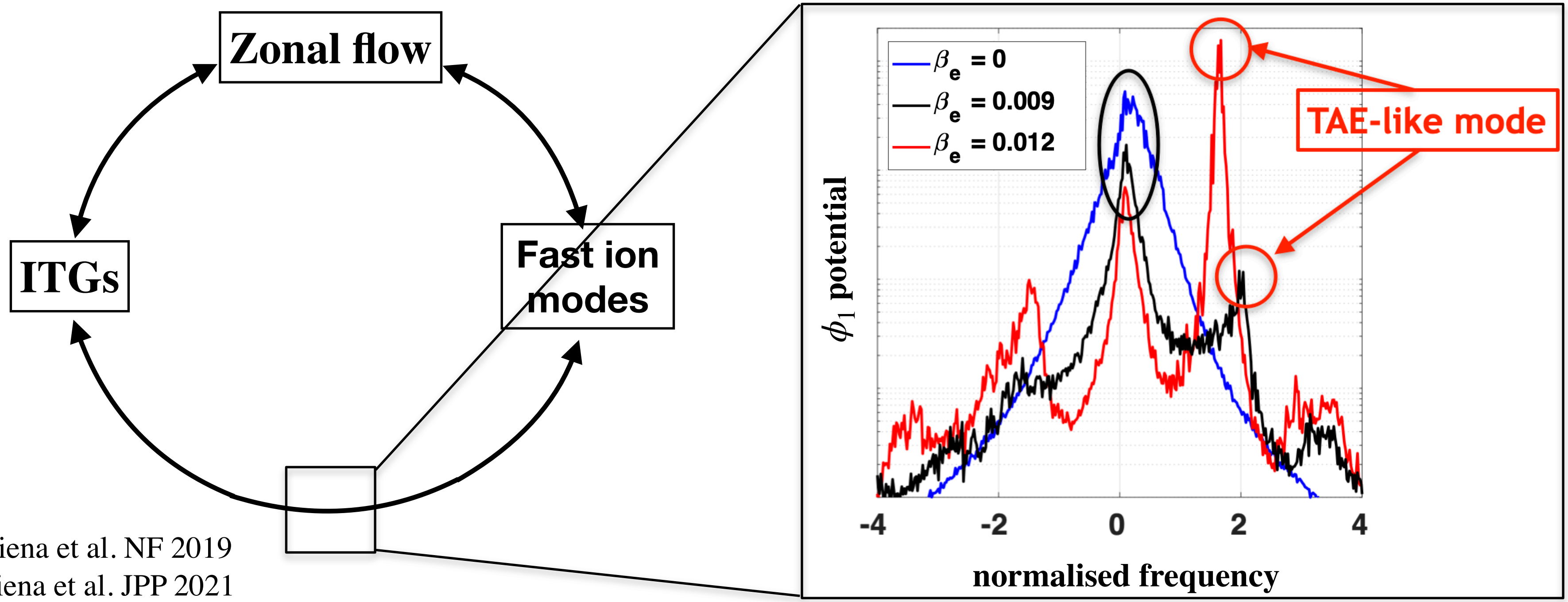


- Generation of flux-surface averaged radial electric field in proximity of $q = 1$ and $s = 0$.
- Simulation without fast ions - despite having same geometry - do not show clear improvements at $q = 1$ and $s = 0$ in ω_{T_i}.

Supra-thermal ion effects on core plasma turbulence

Coupling to marginally-stable fast ion modes

- Fast particles can destabilise high-frequency modes.
- Energy redistribution from thermal to fast ion-driven modes → depleting the energy content of the turbulence.
- Fast particle modes interact with zonal flow.
- Direct impact of zonal flows on ITGs, strongly suppressing heat/particle fluxes.



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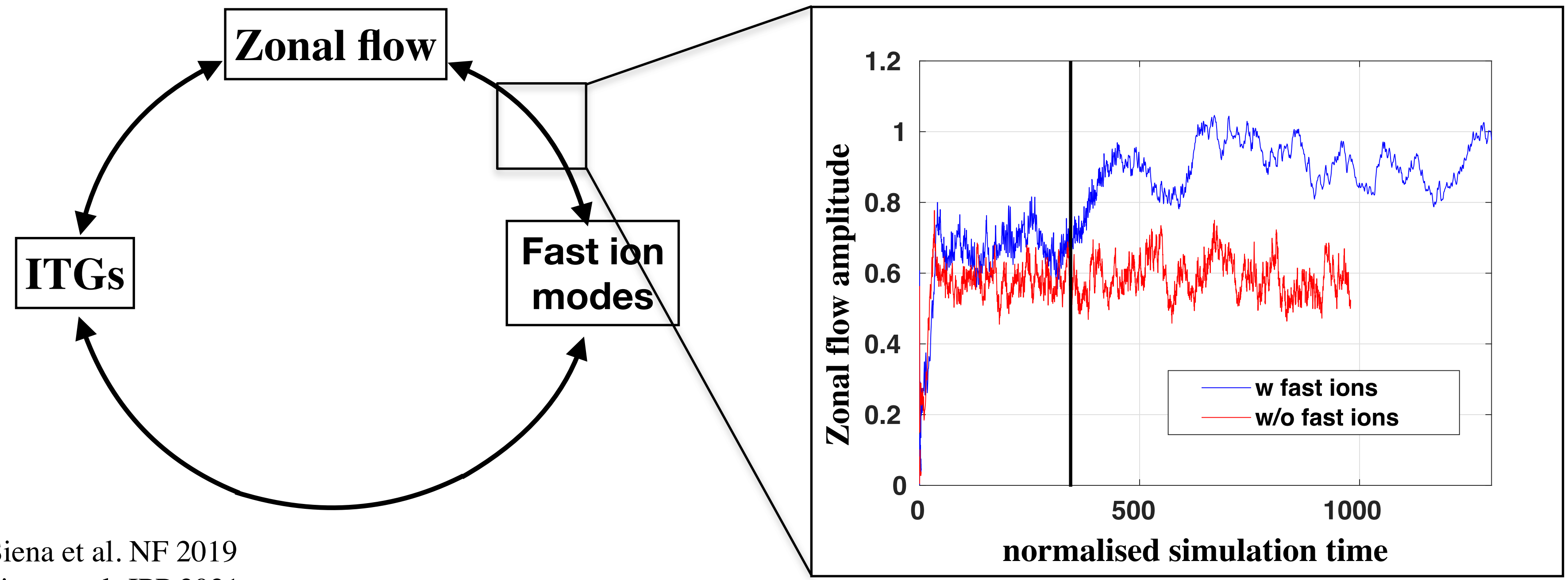

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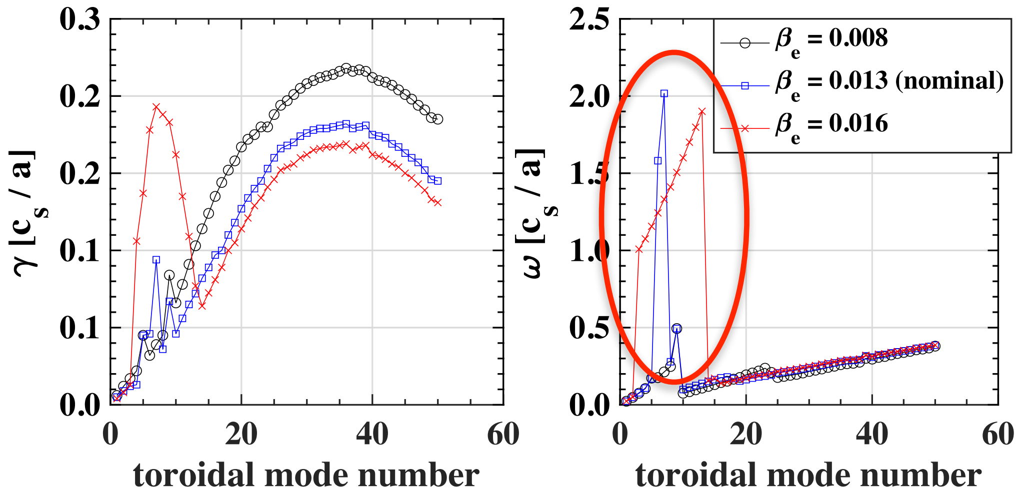
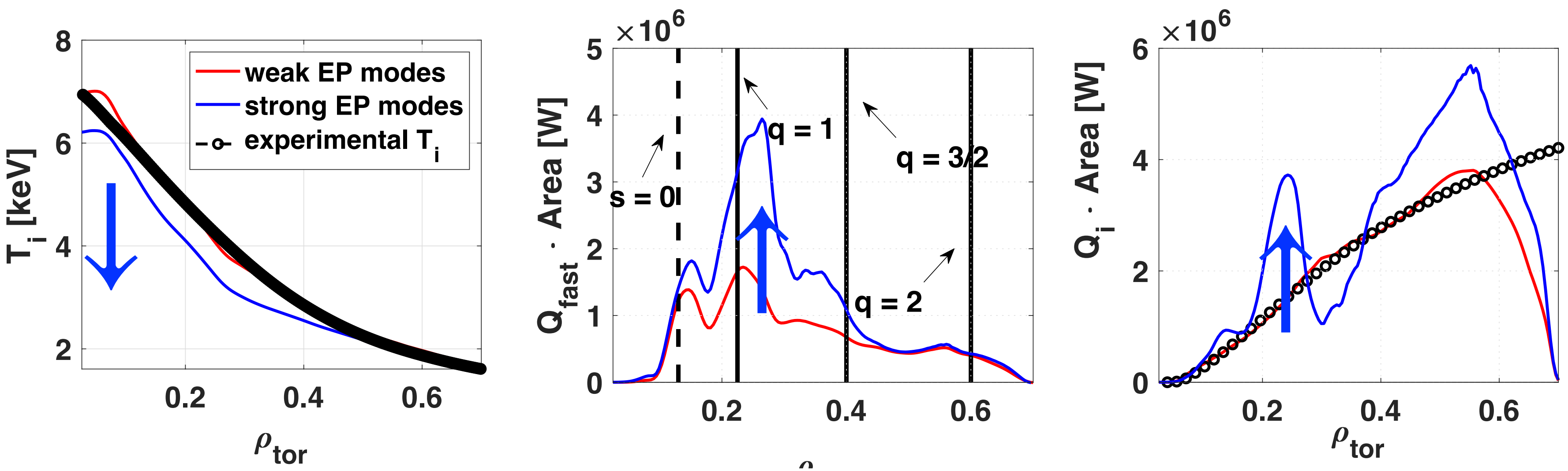
Linear global stability analyses



- Linear stability analyses were performed on the steady-state profiles to identify the most unstable modes.
- A mode transition to an electromagnetic high-frequency mode for $n = [6,7]$ was found for the steady-state profiles.
- No unstable electromagnetic high-frequency mode found in the linear simulations at $n = 1$.

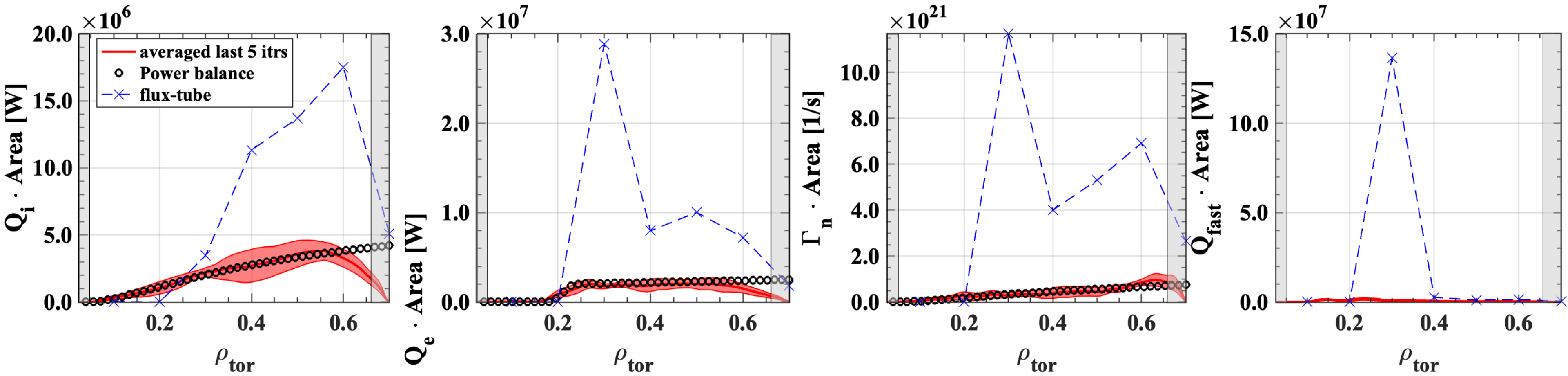
Further destabilization of the high-frequency modes

- If the high-frequency modes get strongly unstable during the GENE-Tango iterations, thermal fluxes strongly increase → all profiles relax.



- Strongly unstable high-frequency modes cannot be sustained → turbulent fluxes increase.
- Tango reacts to the increases transport reducing the pressure gradients until stabilizing or reducing the drive of the high-frequency modes.

Comparison with GENE flux-tube simulations



- Flux-tube GENE simulations are performed at seven radial locations.
- Large turbulent fluxes observed in the flux-tube simulations which are not compatible with power balance.
- Unstable high-frequency modes cannot be sustained in flux-tube simulations → profile will likely flatten until reducing plasma beta to stabilize these high-frequency modes.

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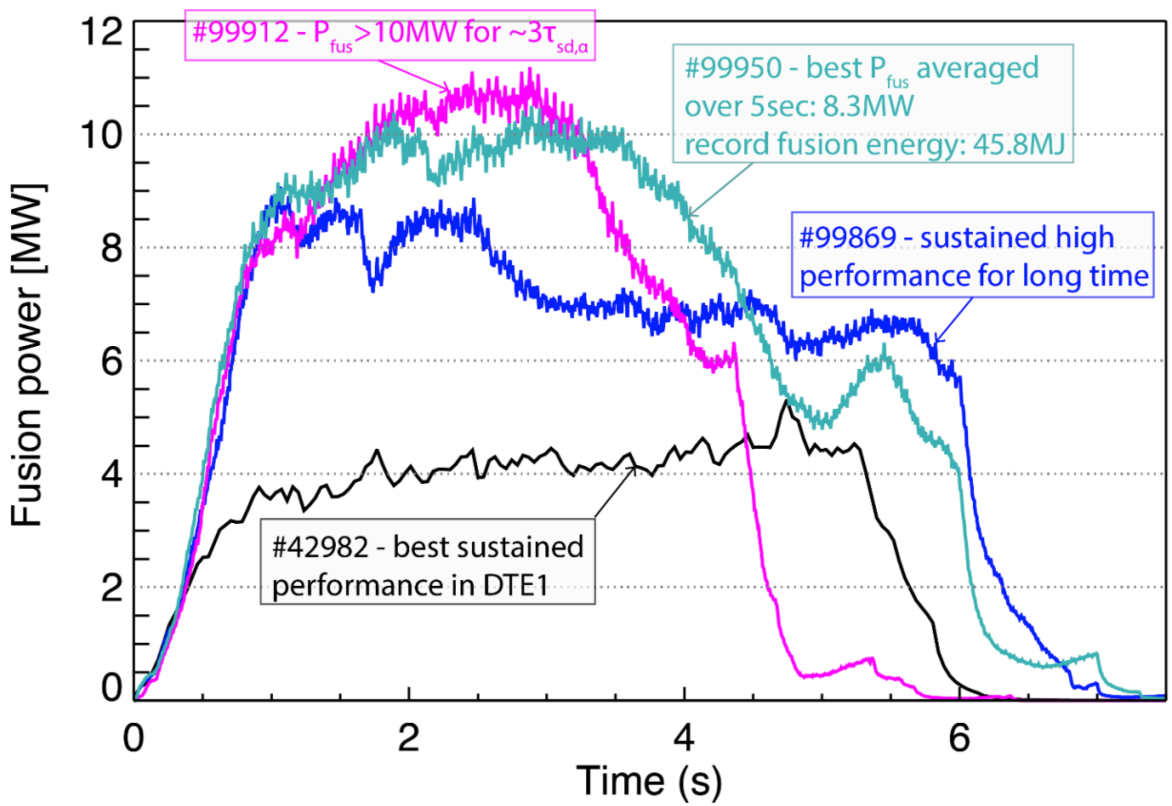
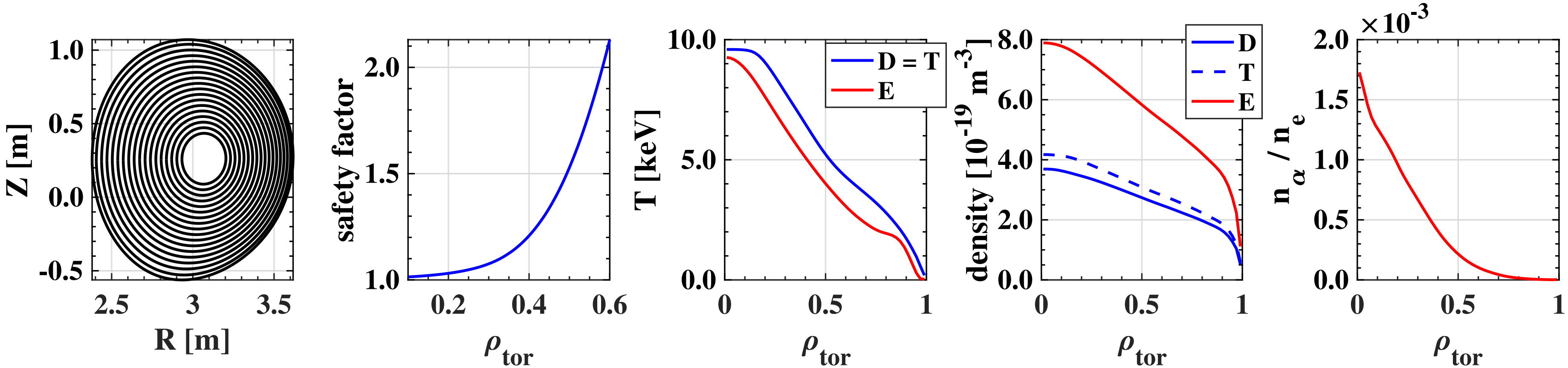
Alpha particle studies at JET with GENE-Tango

- JET 50-50 D-T hybrid scenario #99912 achieved record sustained $P_{fus} > 10MW$ for ~ 3 α-particle slowing down time.
- $I_p = 2.3$MA, $B_0 = 3.45$T, $q_{95} \sim 4.8$, $\beta_{pol} = 1.4$, gas injection only, lower density, $T_i > T_e$.



Experimantal scenario

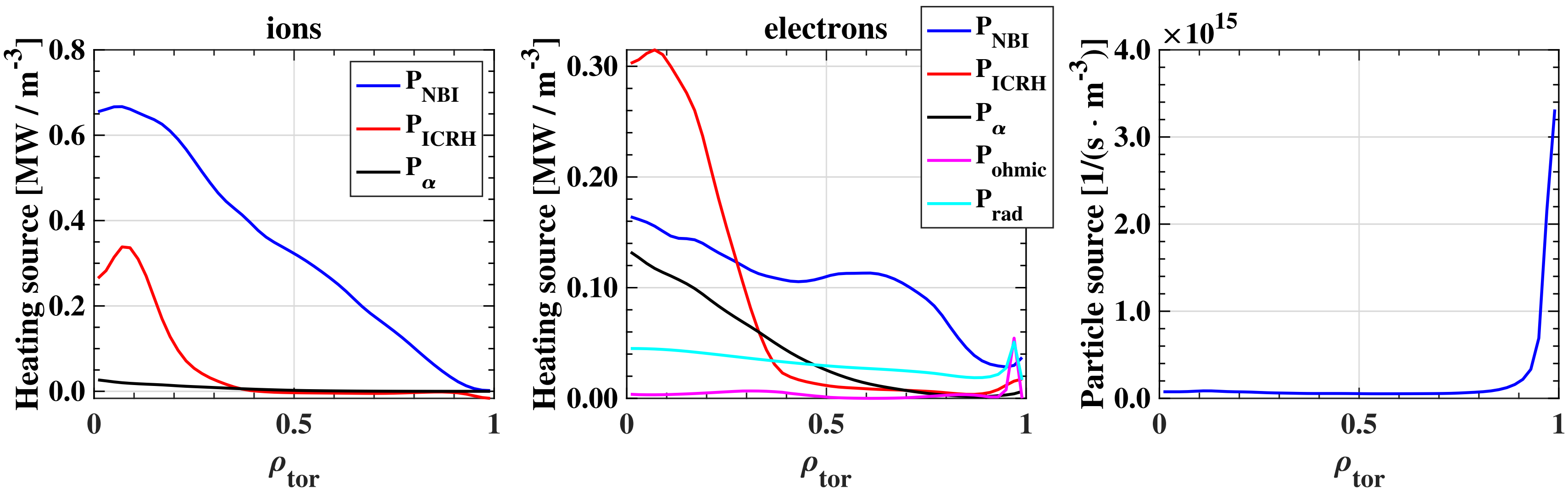
- GENE (global)-Tango simulations are performed with realistic electron-ion mass ratio, collisions and finite β.
- Magnetic equilibrium reconstructed via pressure contrained EFIT.
- Equivalent Maxwellian used for each plasma species.
- Fishbones present in this discharge.



- Negligible alpha particle density for the nominal profiles.

Experimantal scenario

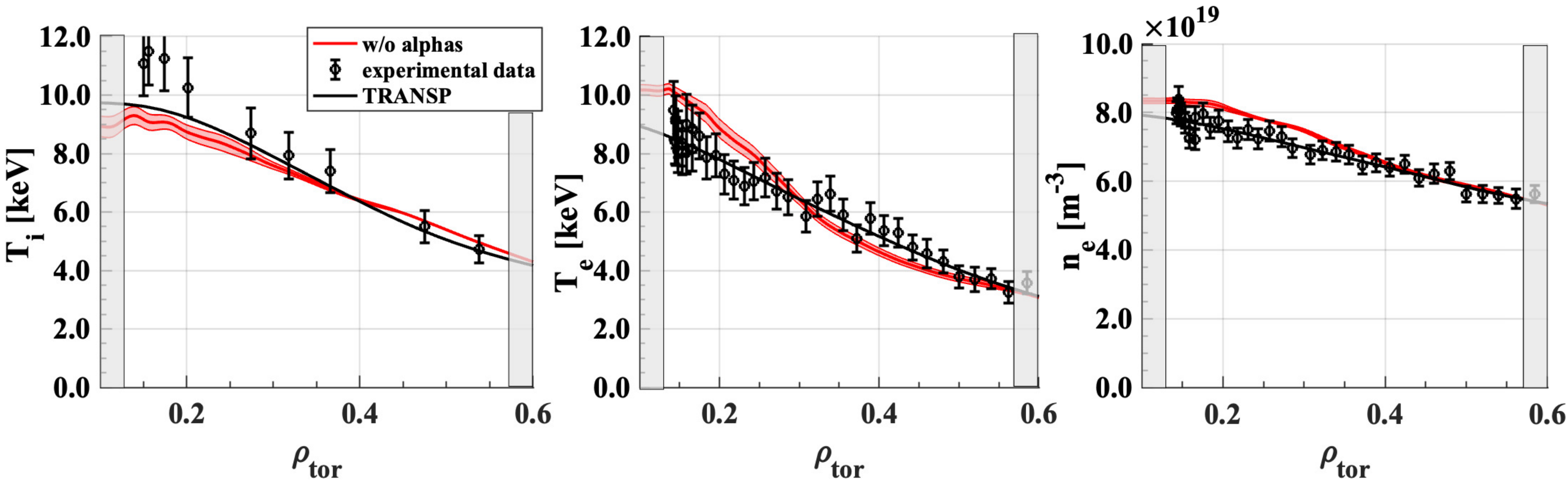
- Heat, particle sources and initial guess for plasma profiles computed by TRANSP interpretative runs.



- Negligible alpha particle heating on thermal ions; considerable contribution to electrons.
- Cases analyzed: (i) without alpha particles in GENE, (ii) with alpha particles in GENE, (iii) without alpha particles in GENE and alpha heating in Tango.

GENE-Tango simulations: w/o alpha particles in GENE

- GENE-Tango simulations performed until reaching steady-state → turbulent fluxes match volume integral of injected sources at each location.
- Alpha particles are neglected from GENE, but alpha heating contribution is retained in Tango.



- Excellent agreement between GENE-Tango and experimental measurements!

GENE-Tango simulations: w alpha particles in GENE

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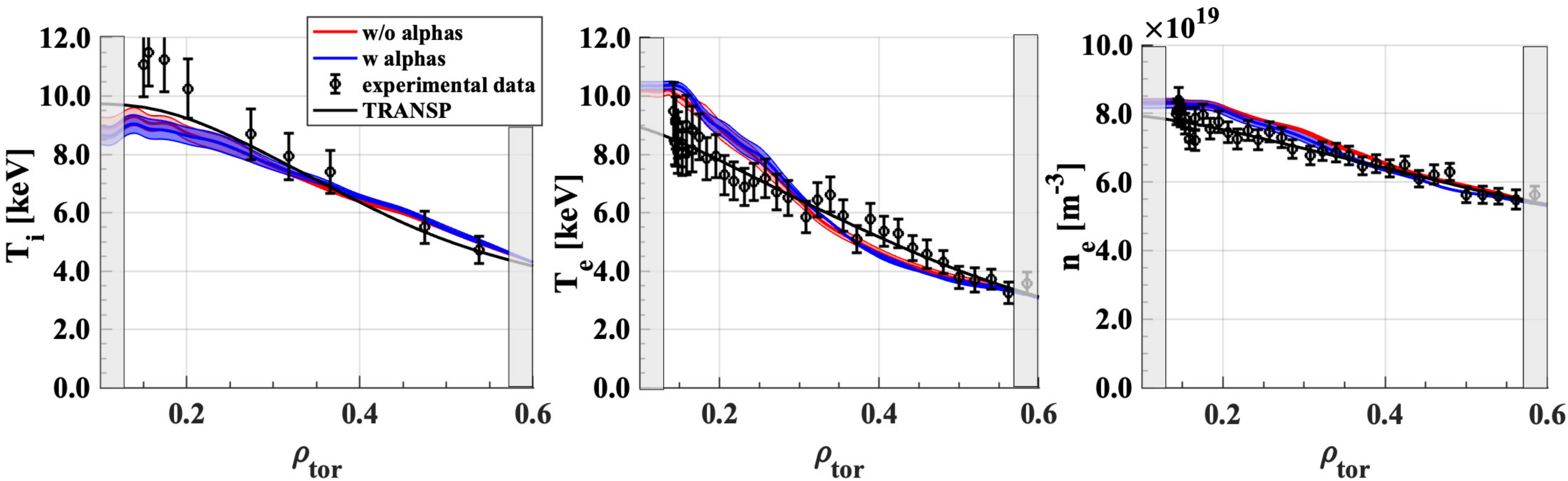
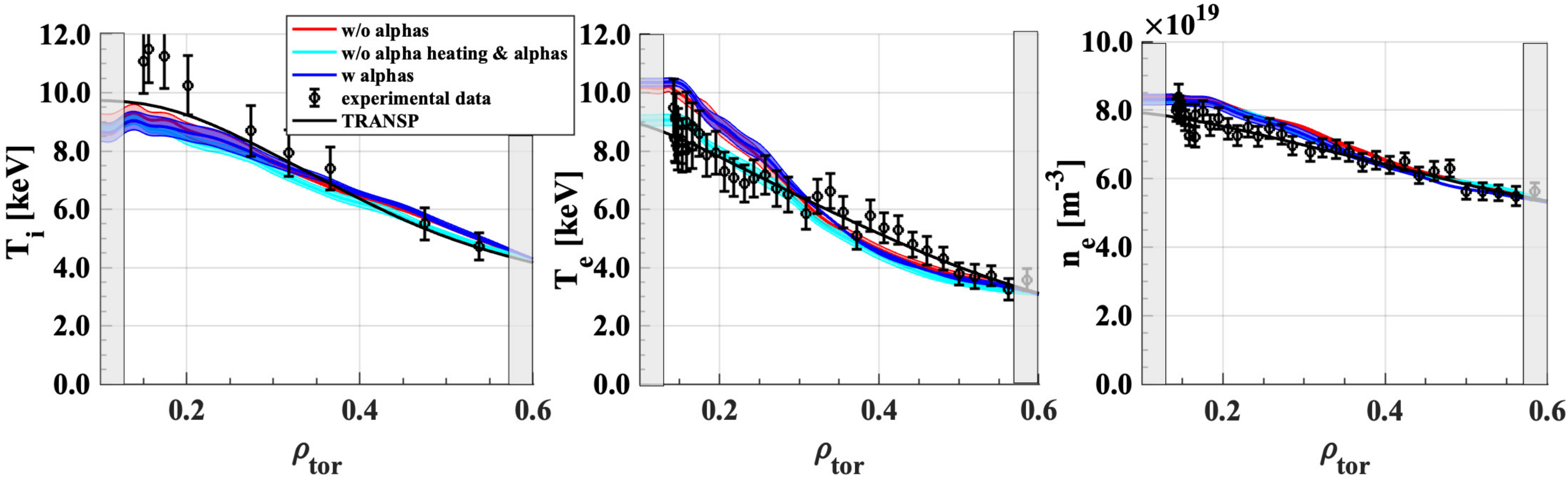


- GENE-Tango recovers the same plasma profiles obtained without alpha particles → alpha particle density is too low to make a significant contribution.

GENE-Tango simulations: w/o alpha particles and alpha heating

- GENE-Tango simulations performed until reaching steady-state → turbulent fluxes match volume integral of injected sources at each location.
- Both alpha particles and alpha heating neglected in the modelling.



- Alpha heating has a negligible effect on ion temperature and plasma density, but a visible effect on electron temperature → T_e relaxes on axis by ∼ 1keV.

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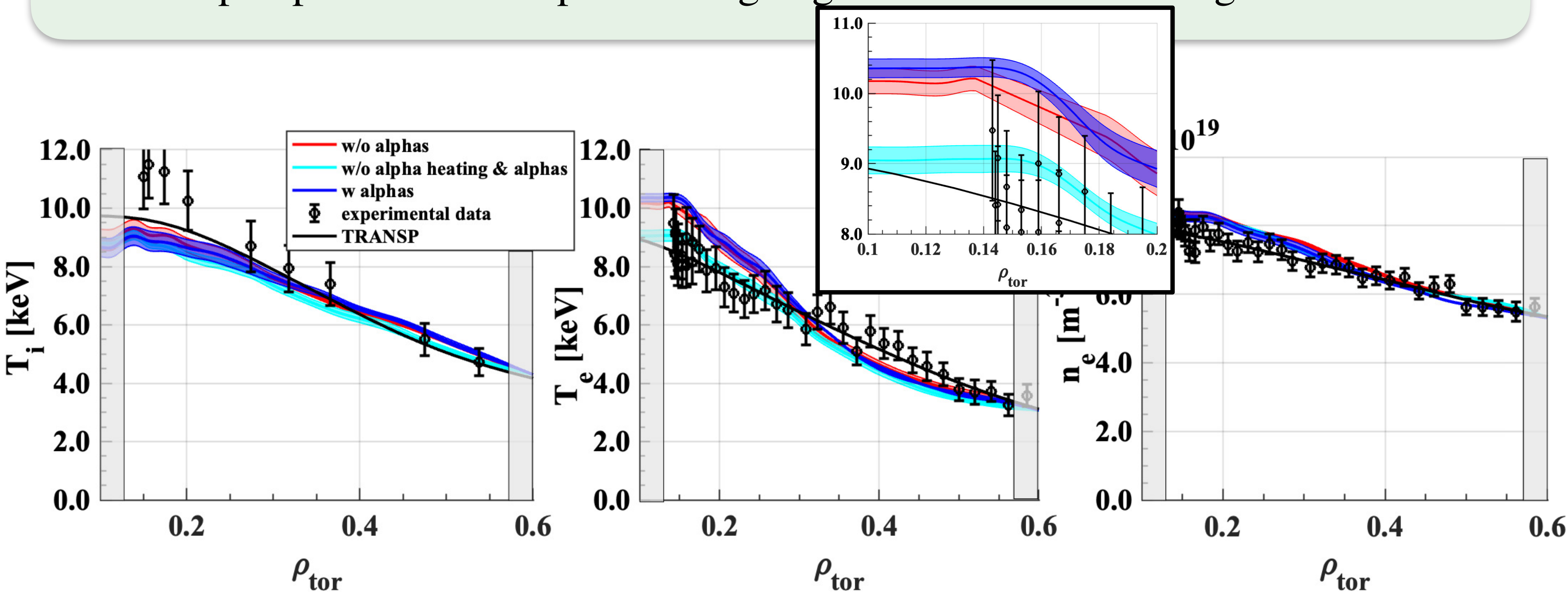
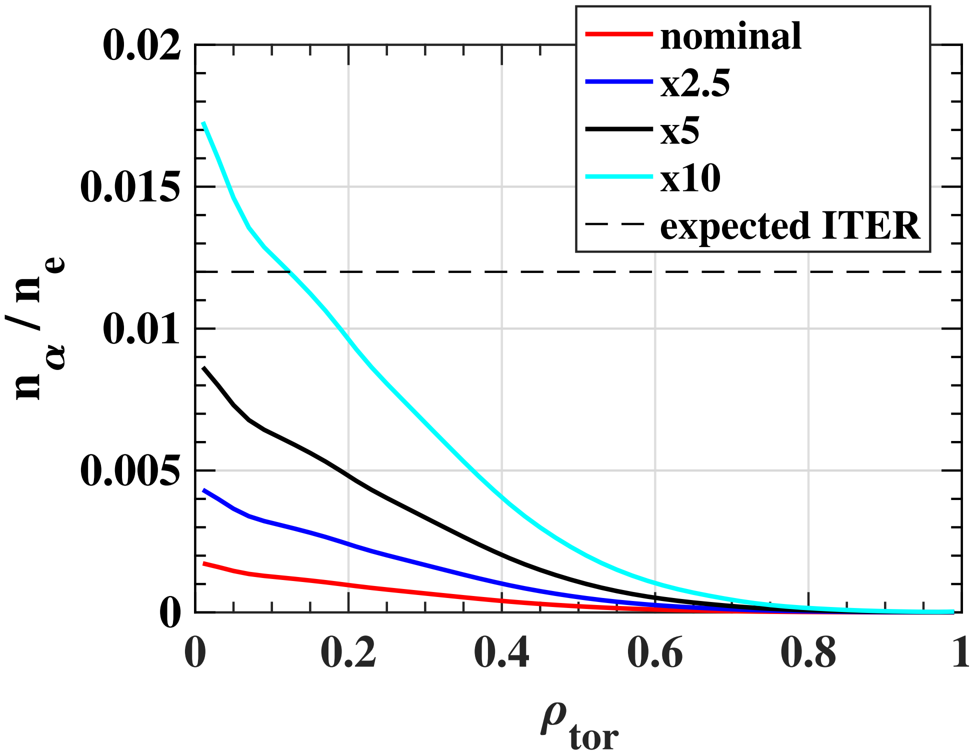


- Alpha heating has a negligible effect on ion temperature and plasma density, but a visible effect on electron temperature → T_e relaxes on axis by ~ 1keV.

Scans over alpha particle density with GENE

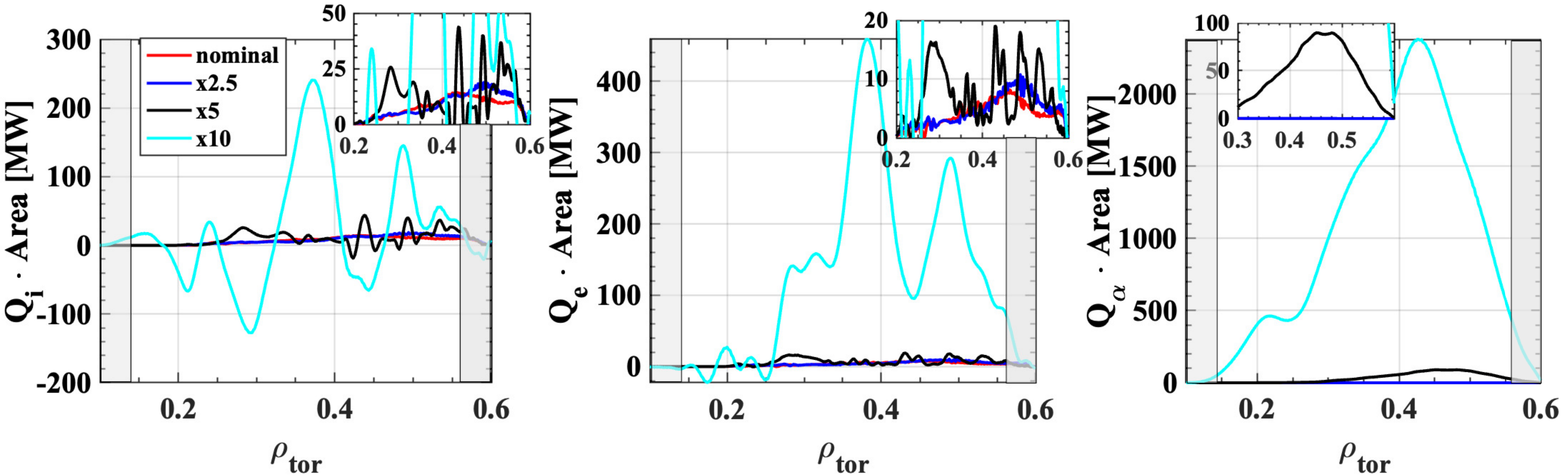
- Alpha particle density is artificially increased respect to the nominal density to increase alpha particle effects on core turbulence.
- We consider four cases spanning from $n_\alpha / n_e \sim 0.15\,\%$ to $n_\alpha / n_e \sim 1.5\,\%$ (ITER like density).



- Thermal profiles are not self-consistent and cannot sustain $n_\alpha / n_e \sim 0.15\,\%$.

Scans over alpha particle density with GENE

- Negligible differences observed for the case x2.5 compared to the nominal case.
- Oscillatory pattern develops for ion and electron turbulent fluxes corresponding to the different poloidal harmonics of the unstable TAE for the case x5 → alpha particle heat flux increase up to large fluxes reaching Q = 90 MW.



- Alpha particle heat flux experiences a substantial four-order-of-magnitude increase, leading to a significant rise in the electron heat flux for x10.
- Oscillatory pattern of the thermal ion heat flux becomes more pronounced with increasing alpha particle density.

Conclusions

Impact of fast particles on plasma performance at AUG

- GENE-Tango simulations with fast ions reproduce experimental profiles of AUG #39230 @ t = 2.7s.
- Enhanced radial electric field observed in the electromagnetic GENE-Tango simulation with fast ions at the location of EP-driven modes.
- When these modes are strongly destabilized all turbulent fluxes increase → profiles relax.

Assessing the role of alpha particles in JET D-T experiments

- GENE-Tango simulations at JET D-T show minimal alpha particle effects on plasma confinement → alpha particle density too small.
- Removing alpha heating from the GENE-Tango loop leads to a mild relaxation of the on-axis electron density in line with other works at JET VG. Kiptily et al. PRL 2023.
- When the alpha particle density is artificially increased at JET, strong confinement degradation observed in the GENE stand-alone simulations. However, it is difficult to extrapolate this result to ITER.

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