Global gyrokinetic simulations of ASDEX Upgrade up to the transport time-scale with GENE-Tango

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Outlook

GENE-Tango: brief introduction and motivation

- Gyrokinetic simulations to confinement time - challenges and (possible) solutions
- Tango numerical scheme and coupling to GENE
- Possible speed-ups with GENE-Tango and extrapolations to ITER

Numerical simulations of ASDEX Upgrade #31555 at t = 1.45s

- Electrostatic simulations, with collisions, no (external) toroidal rotation
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- *Electromagnetic* simulations, with collisions, no (external) toroidal rotation
- *Electromagnetic* simulations, with collisions, with (external) toroidal rotation

Next steps with GENE-Tango:

- Profile prediction including fast particles and alphas
- Transport barrier analyses, profile prediction for W7-X (Alejandro B. Navarro)

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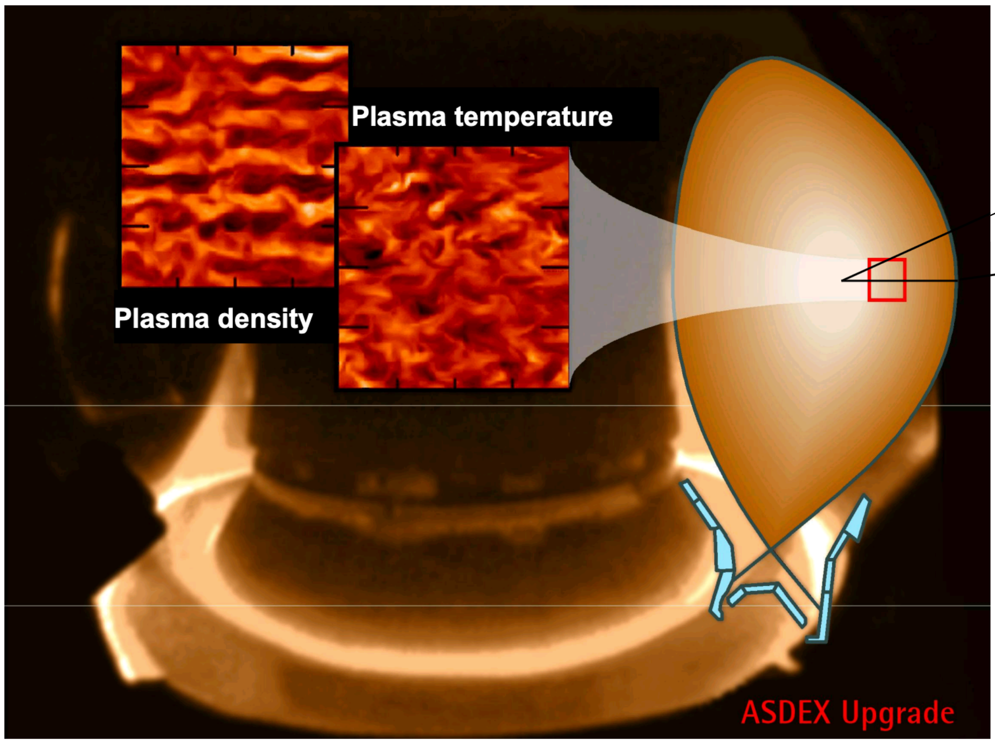
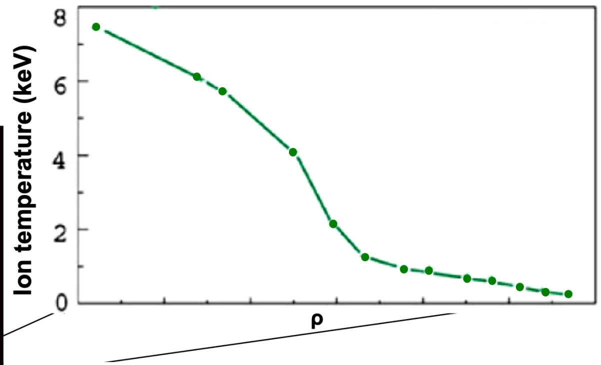
Goal: Predictive description of plasma evolution

Realistic modelling of magnetic confinement experiments

- Our task: compute self-consistently plasma profiles → **performance predictions**!
- Experimental situation: heat/particle sources, steady-state characterised by flux equilibrium





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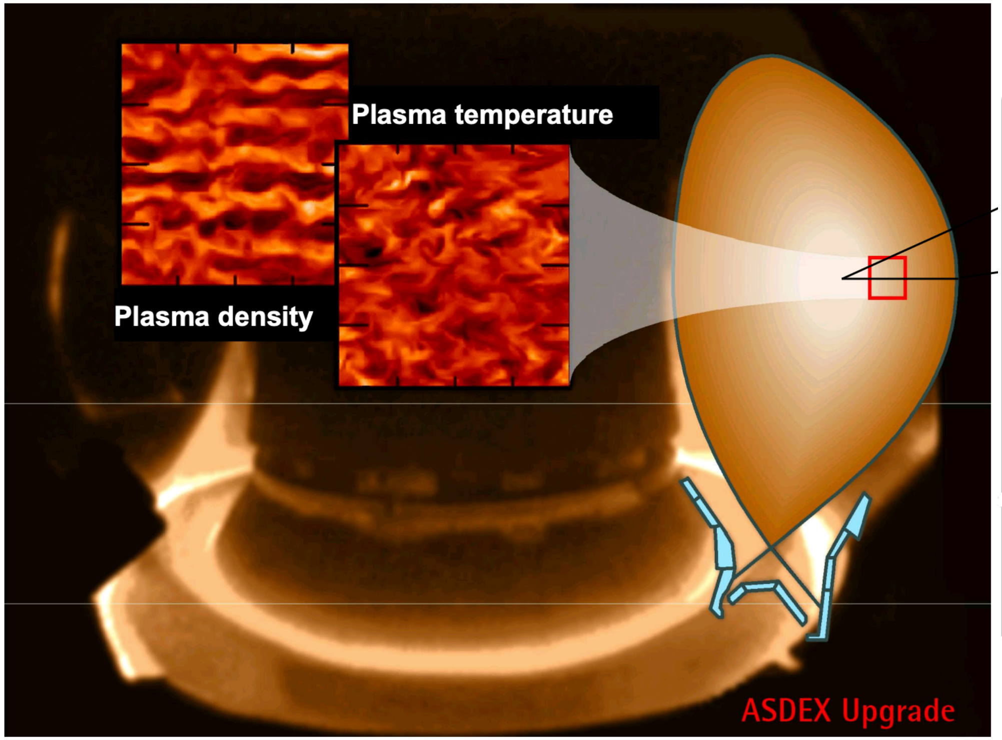
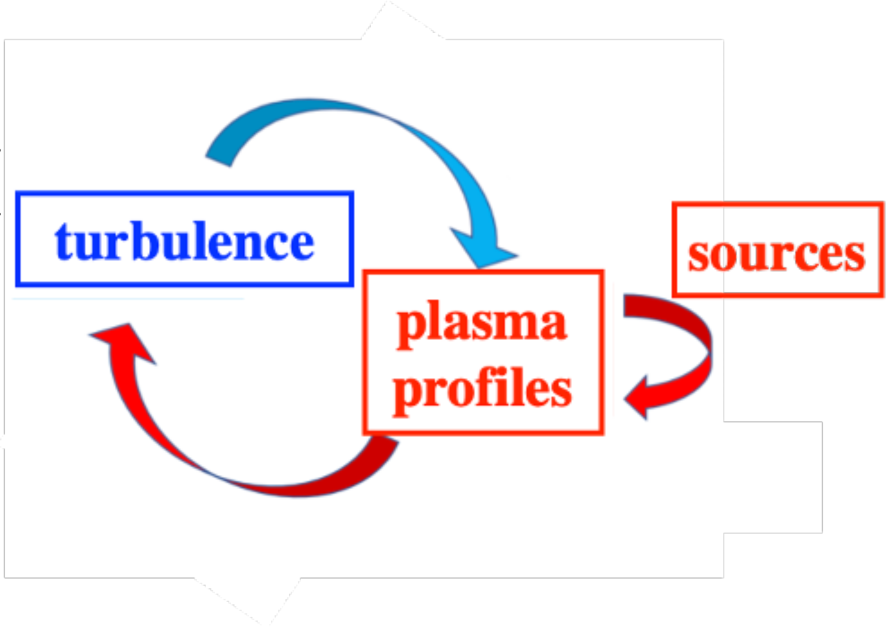




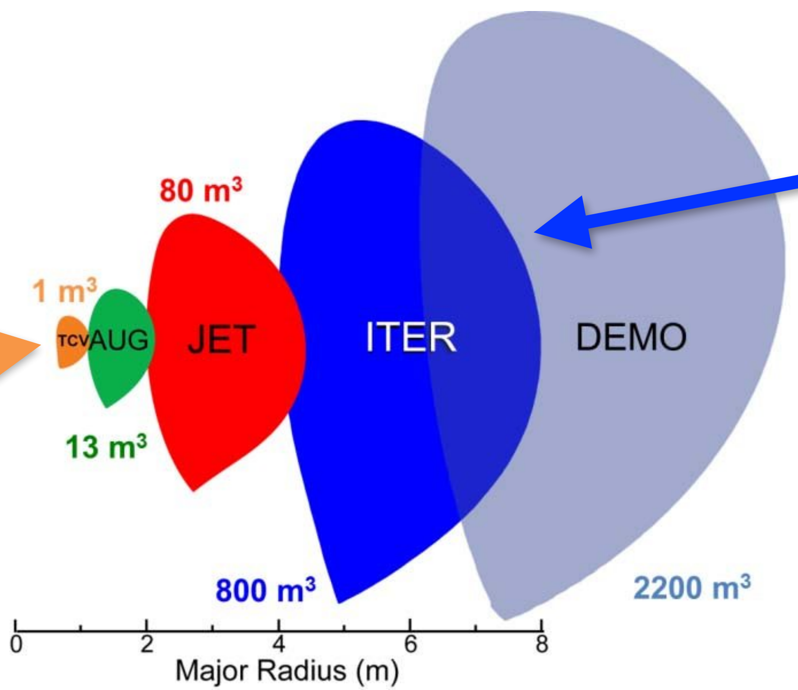
Goal: Predictive description of plasma evolution

Exploiting large time scale separation

- Separation between transport and turbulence 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**: $a/\rho \sim 1000$), e.g. x-resolution scales $\sim (a/\rho)^{1-2}$

Computational cost →

TCV:
$a/\rho < 100$



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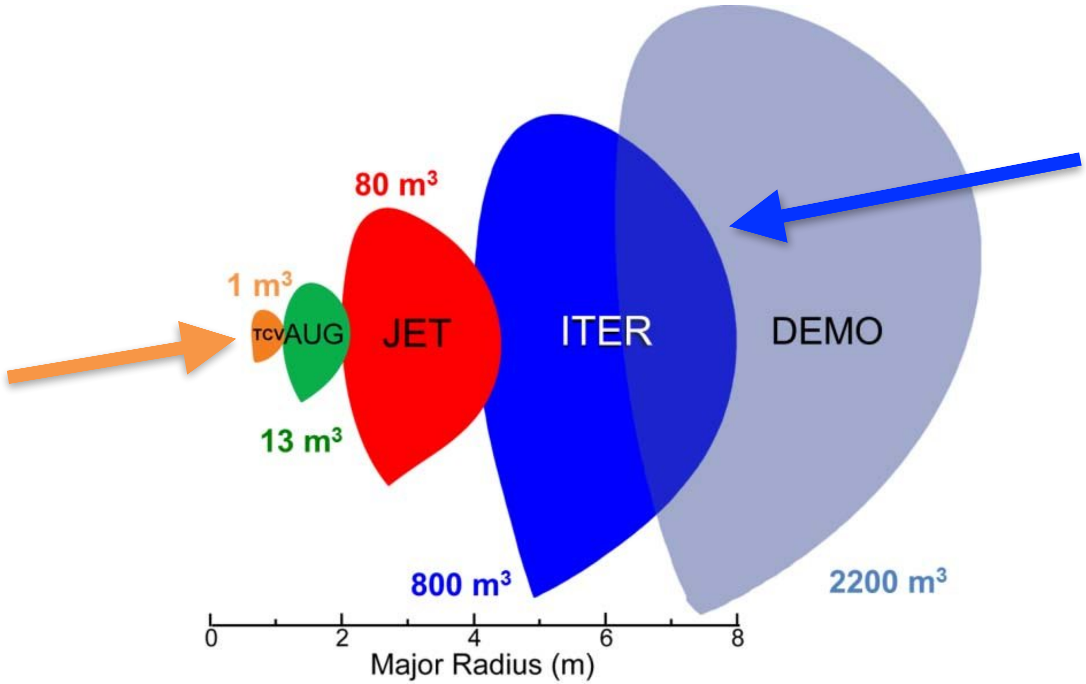


ITER:
$a/\rho \sim 1000$

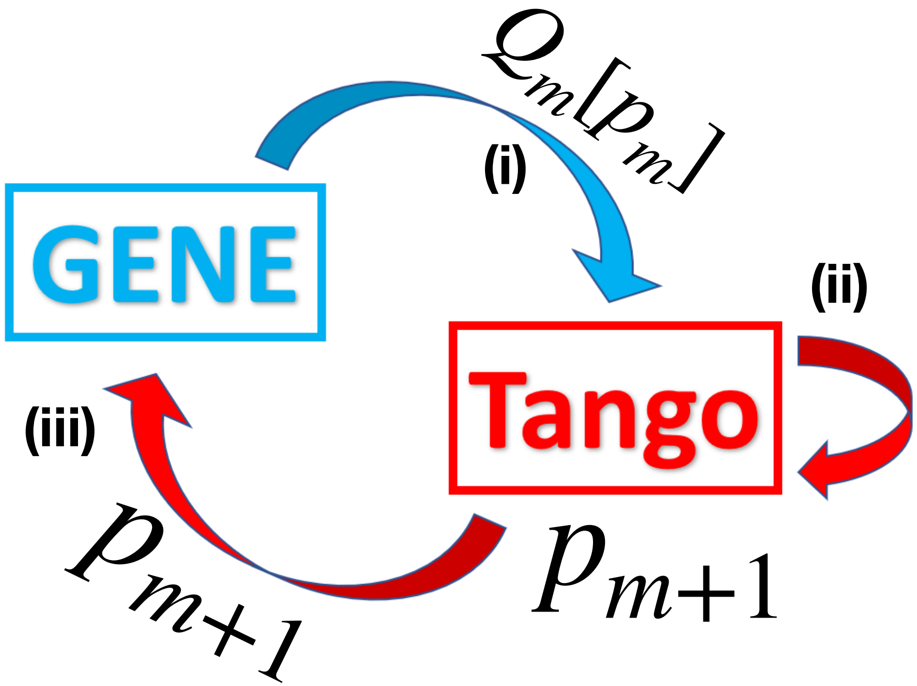
Possible way around

- Coupling a core turbulence code (e.g. GENE) with a **global** transport code (e.g. Tango) → steady-state profiles can be obtained even for large devices

Bringing gyrokinetic simulations to transport time scale

GENE-Tango coupling

(i) GENE evaluates turbulence levels for given pressure profile over several microscopic time steps.
(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.



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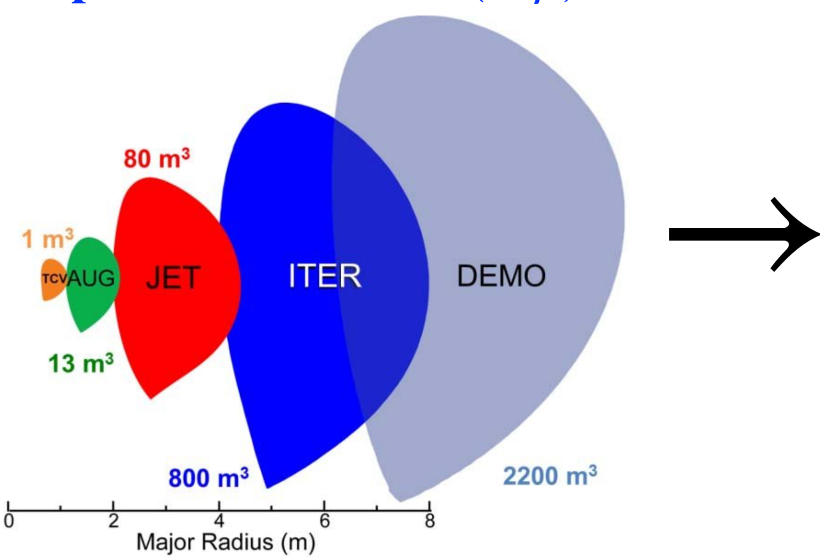
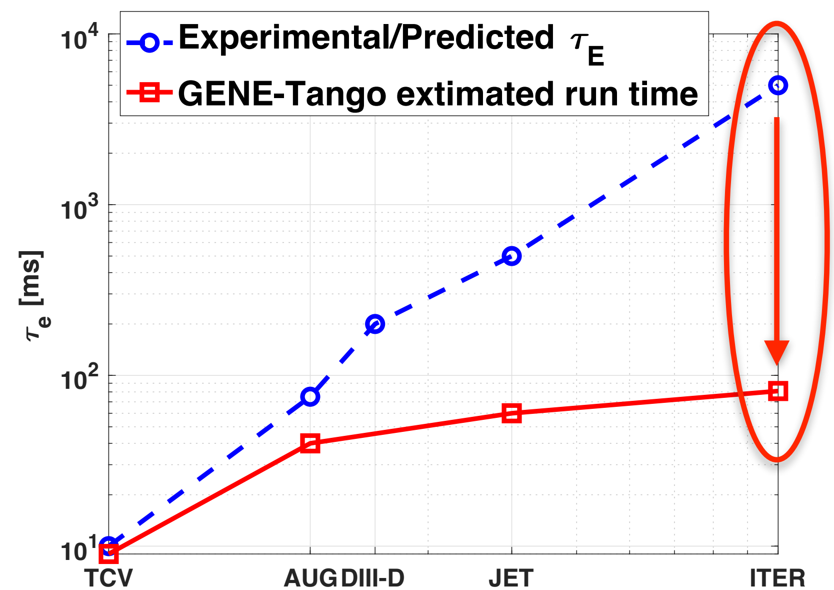
Computational cost $> (a/\rho)^3 \rightarrow$





Transport solver Tango: basic equations

1D transport equation

- Macroscopic profiles are constant on magnetic flux surfaces

$$\frac{3}{2}A\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}AQ = AS$$

J. Parker et al. NF 2018
A. Shestakov et al. JCP 2003

A: Area flux-surface

Q = $\langle Q \cdot \nabla x \rangle$: Turbulent fluxes

S: Sources

- subscript ***m***: transport time step index; ***l***: iteration index within a time step

$$\frac{3}{2}A\frac{p_{m,l} - p_{m-1}}{\Delta t} = \frac{\partial}{\partial x}(AQ_{m,l}[p_{m,l}]) + AS_m$$

- Turbulent fluxes taken as **time-average quantities** over many turbulent time steps (in the saturated phase) $\Delta\tilde{t}$ and the pressure profile is evolved by the macroscopic time step Δt

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$$\frac{3}{2}A\frac{p_{m,l} - p_{m-1}}{\Delta t} = \frac{\partial}{\partial x}(AQ_{m,l}[p_{m,l}]) + AS_m$$

- Q is the sum of diffusive and convective contributions

$$Q_{m,l} = -D_{m,l-1}\frac{\partial p_{m,l}}{\partial x} + c_{m,l-1}p_{m,l}$$

Transport solver Tango: basic equations

- There is freedom in the splitting of the turbulent flux Q between D and c

$$D_{m,l-1} = -\frac{\theta_{l-1} Q[p_{m,l-1}]}{\frac{\partial p_{m,l-1}}{\partial x}} \qquad c_{m,l-1} = \frac{(1-\theta_{l-1}) Q[p_{m,l-1}]}{p_{m,l-1}}$$

- θ denotes the nature of the turbulent fluxes, i.e. diffusive and/or convective, assuming plasma turbulence mainly diffusive $\rightarrow \theta \sim 1$
- Diffusion coefficients depending on $\partial p_{m,l-1}/\partial x$ makes the iteration numerically unstable. It is stabilised by adding the relaxation coefficient α to D and c

$$\bar{Q}_{m,l-1} = \alpha Q[\hat{p}_{m,l-1}] + (1-\alpha)\bar{Q}_{m,l-2}$$

$$\bar{p}_{m,l-1} = \alpha p_{m,l-1} + (1-\alpha)\bar{p}_{m,l-2}$$

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Transport solver Tango: basic equations

- Tango solves iteration equation within an implicit timestep advance of a transport equation: nonlinear equation for the time-advanced (backward Euler step)

$$\frac{3}{2}A\frac{p_{m,l}-p_{m-1}}{\Delta t}=\frac{\partial}{\partial x}\left(AD_{m,l-1}\frac{\partial p_{m,l}}{\partial x}-Ac_{m,l-1}p_{m,l}\right)+AS$$

- Each coefficient is evaluated at the previous iterate ***l*-1** and the transport equation is linear in the unknown $p_{m,l}$

$$M_{m,l-1}p_{m,l}=g$$

***l*-1 terms**

Sources + terms p_{m-1}

- When the iteration in ***l*** converges, the representation for the flux (right-hand side) is equal to the actual turbulent flux Q (left-hand side)

$$Q_{m,l}=\int dV(P_{ICRH}+P_{NBI}+\ldots)$$

Outlook

Numerical simulations of ASDEX Upgrade #31555 at t = 1.45s

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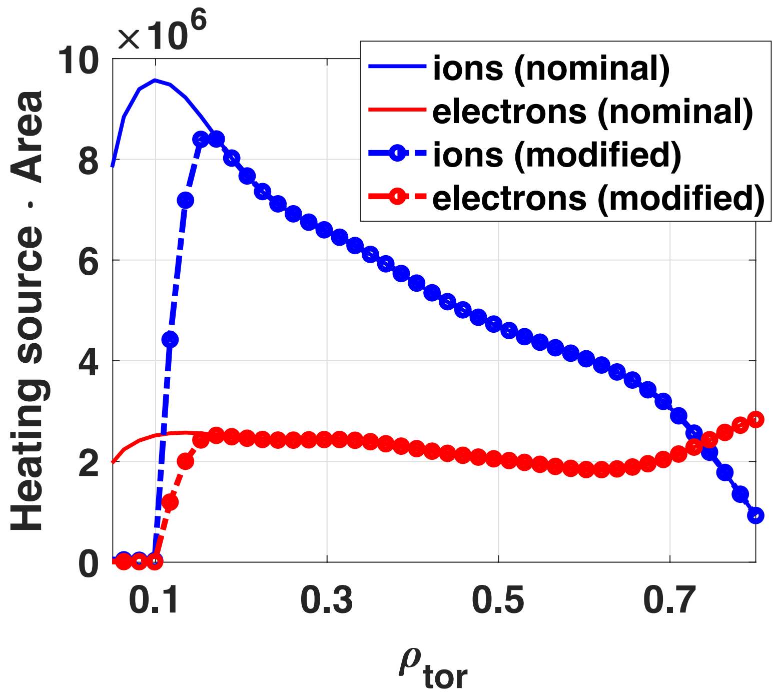
Gene-Tango applications with kinetic electrons

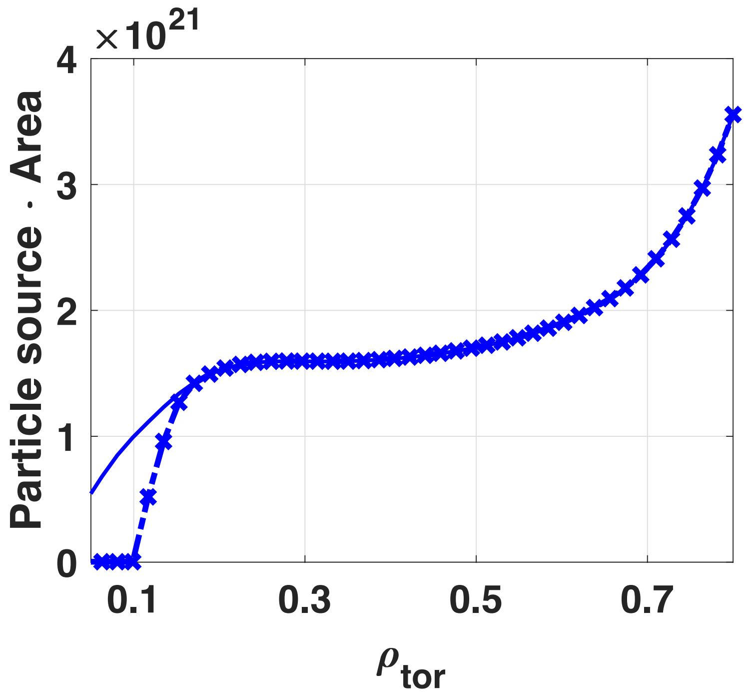
Development and current status

- GENE-Tango coupling originally developed for adiabatic electrons and recently extended to kinetic electrons and coupled to CHEASE.
- Kinetic electron extension validated agains TGLF/ASTRA and experiments for three different H-mode ASDEX Upgrade discharges.

ASDEX Upgrade #31555 @ t = 1.45s

- Heating and particle sources extracted from ASTRA

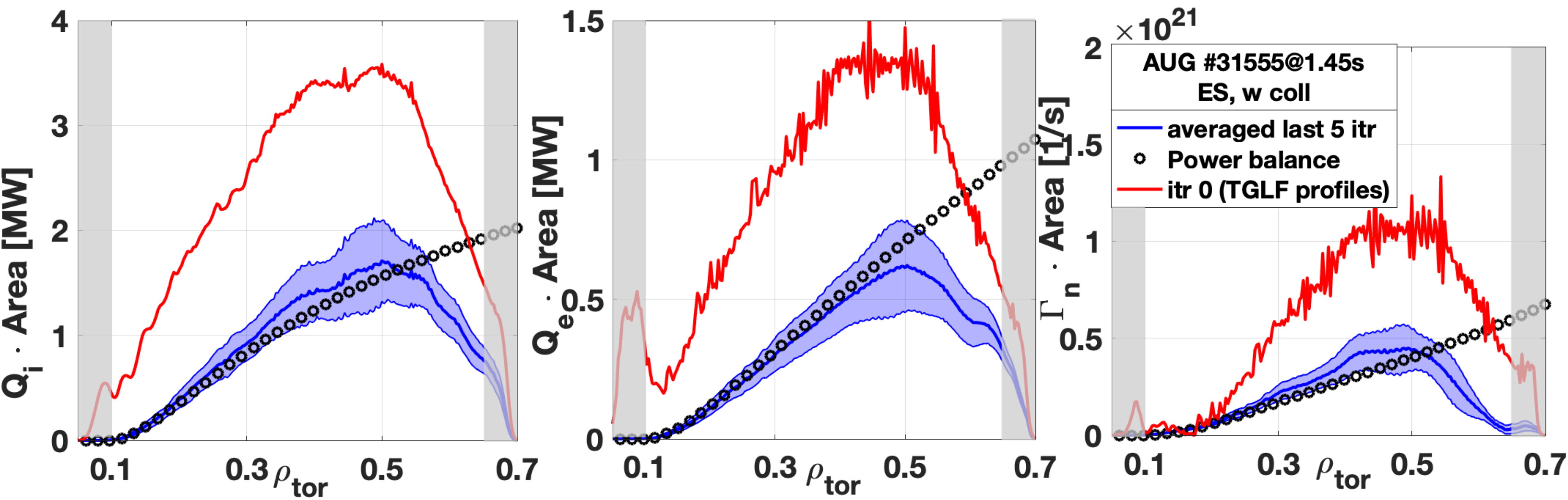




- GENE buffer regions do not allow turbulent fluxes to match power balance → Tango will progressively increase profile gradients on axis.
- Sources modified close to the GENE left boundary to ensure zero flux condition between $\rho_{tor} = [0 - 0.1]$ in Tango

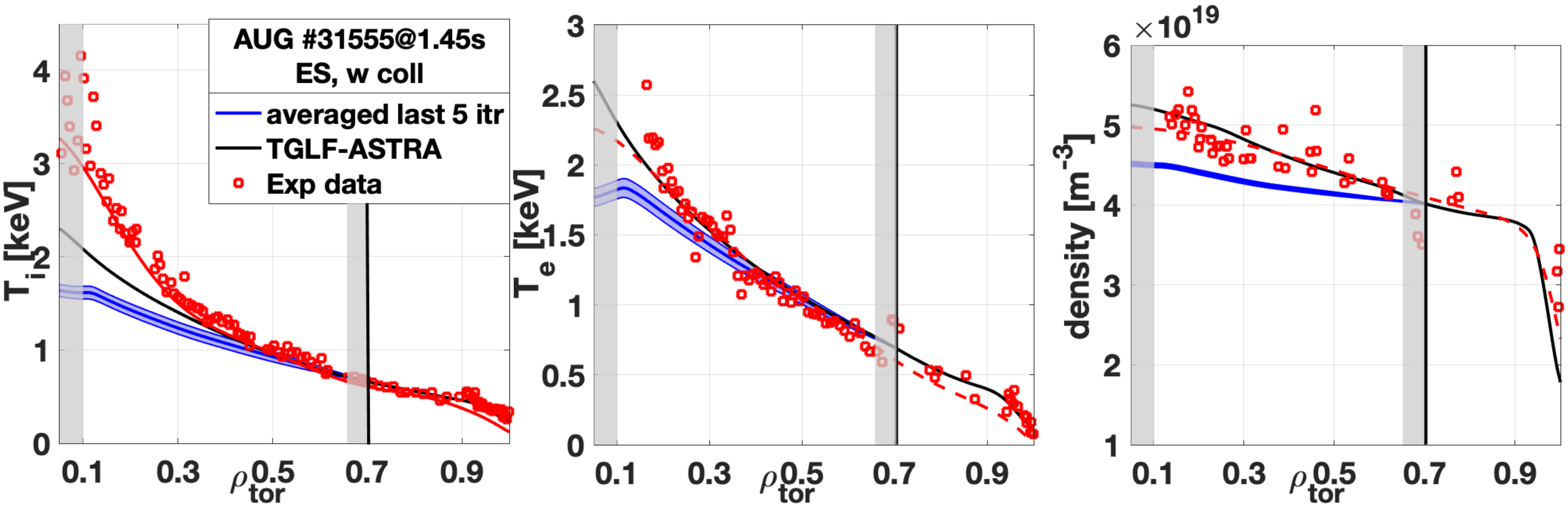
ES simulations, with collisions, no (external) toroidal rotation

- After 20 iterations (here shown [15 - 20]) turbulent fluxes match the power balance in all channels



ES simulations, with collisions, no (external) toroidal rotation

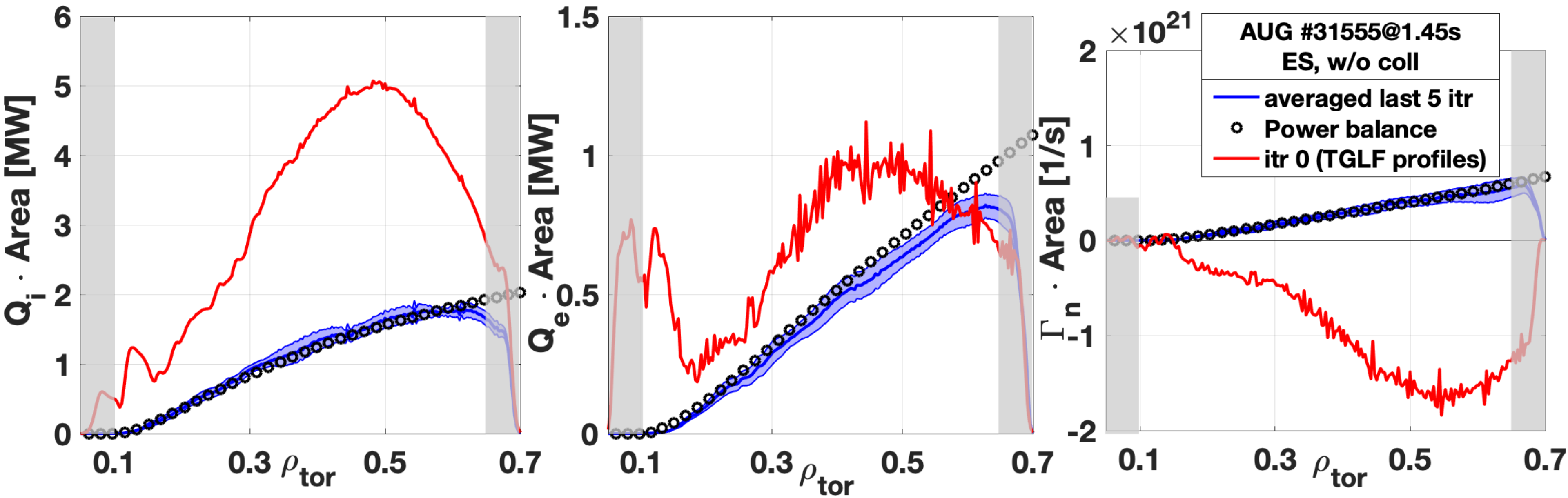
- Temperature and density profiles from GENE-Tango at iterations [15 - 20]



- Qualitative agreement between GENE-Tango and TGLF-ASTRA
- Both GENE-Tango and TGLF-ASTRA under-predicts the T_i peaking for $\rho_{tor} < 0.3$
- Good matching with experimental data for T_e
- Boundary condition for n_e has large uncertainties

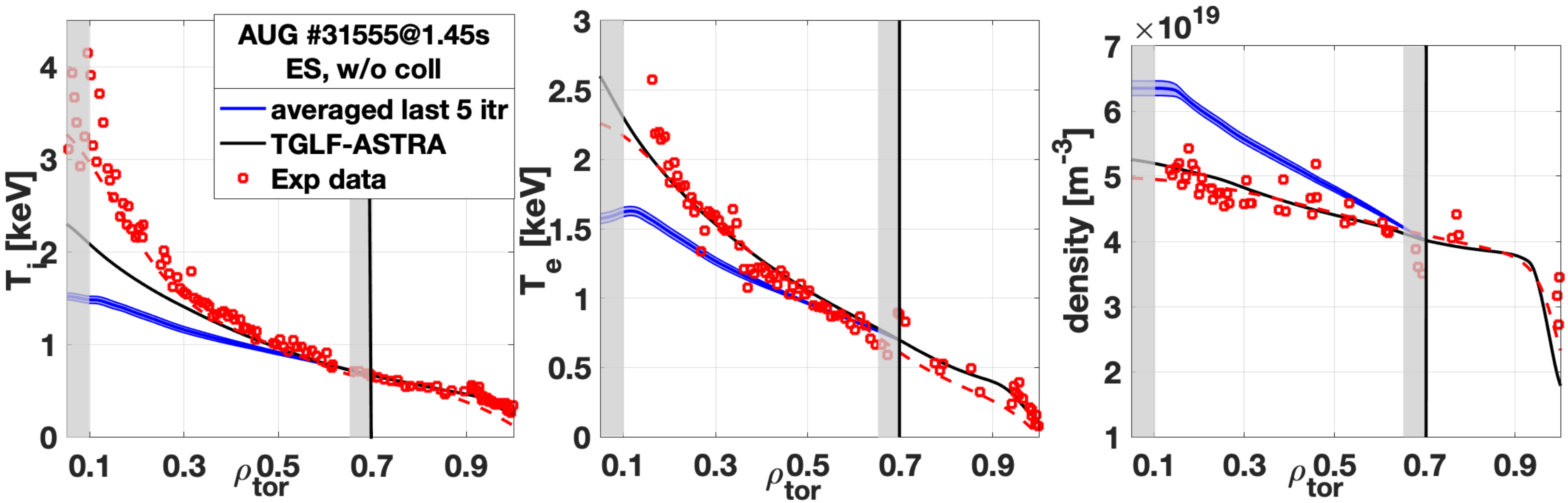
ES simulations, no collisions, no (external) toroidal rotation

- After 30 iterations (here shown [25 - 30]) turbulent fluxes match the power balance in all channels



ES simulations, no collisions, no (external) toroidal rotation

- Temperature and density profiles from GENE-Tango at iterations [25 - 30]



- TGLF-ASTRA profiles lead to inward particle flux when collisions are neglected → strong density peaking and corresponding flattening of temperature profiles.
- These results are consistent with previous studies in H-mode plasma with low collisionality (see A. Clemente NF 2012 and reference therein)

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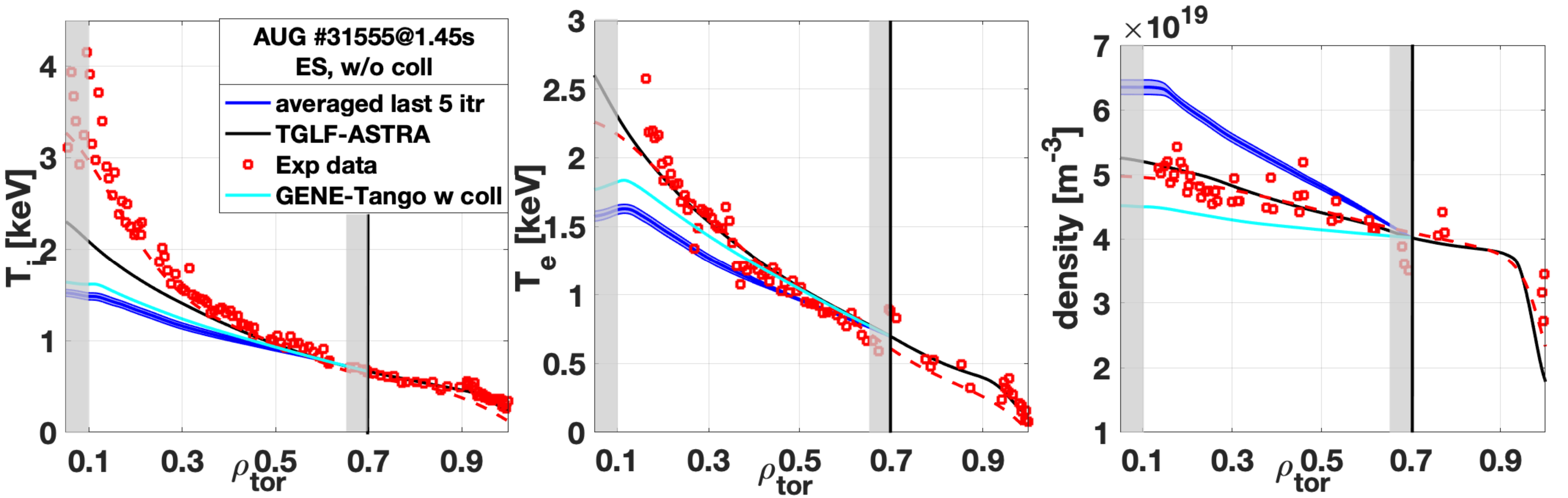

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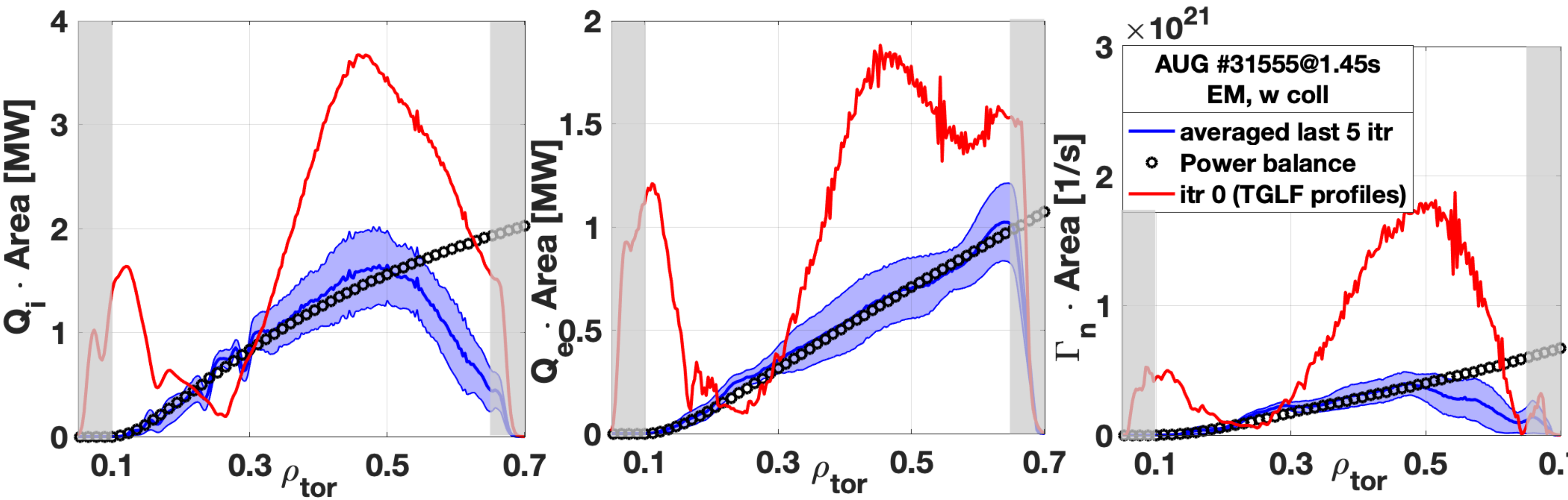
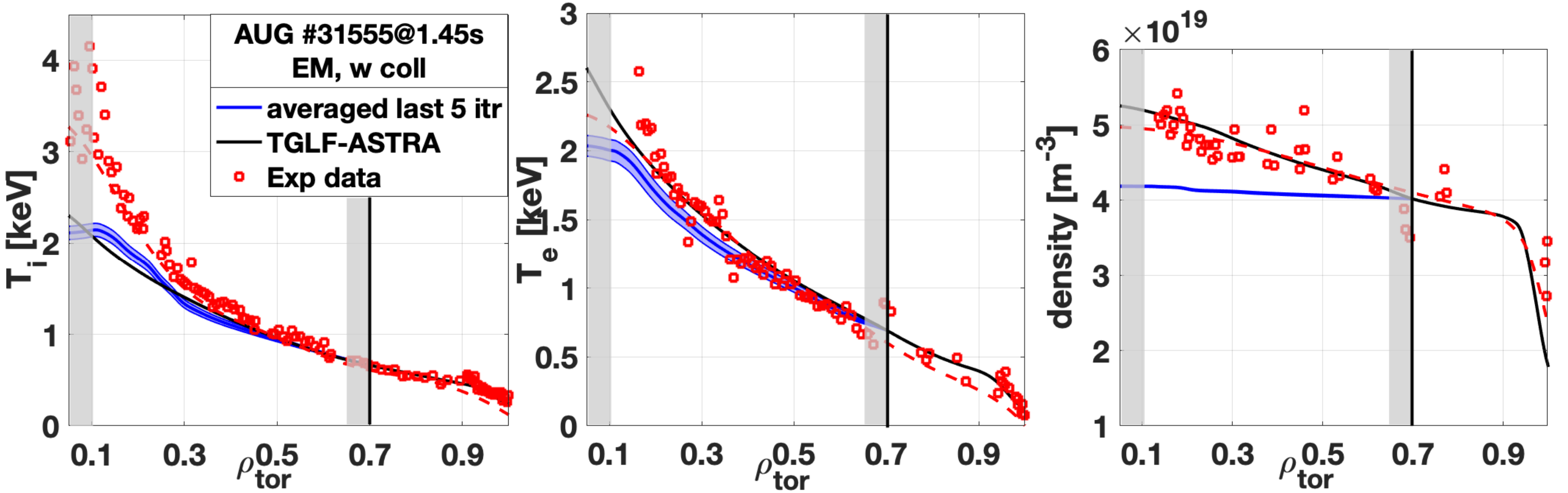
EM simulations, with collisions, no (external) toroidal rotation

- After 28 iterations (here shown [23 - 28]) turbulent fluxes match the power balance in all channels



EM simulations, with collisions, no (external) toroidal rotation

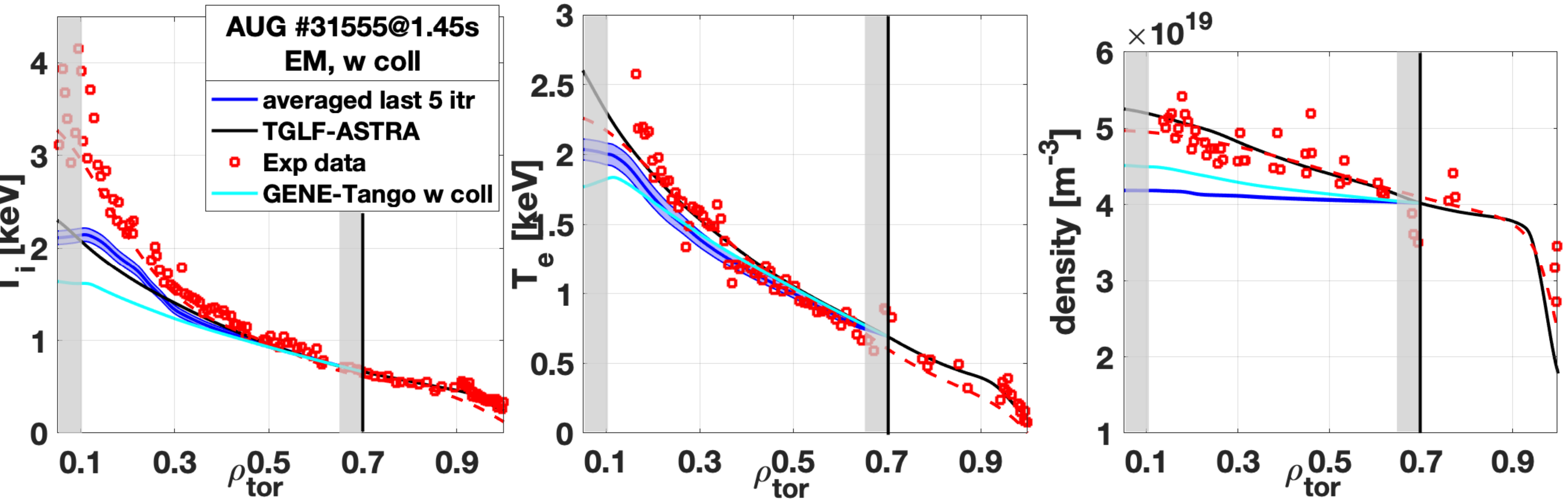
- Temperature and density profiles from GENE-Tango at iterations [23 - 28]



- When electromagnetic effects are included, T_i peaking observed but still far from experiment → T_i flattens for $\rho_{tor} = [0.4 - 0.7]$ (similarly T_e)
- Density profile flattens compared to the electrostatic case (consistent with T. Hein et al PoP 2010) → electromagnetic effects produce an outward flux of passing electrons in ITG turbulence.

EM simulations, with collisions, no (external) toroidal rotation

- Temperature and density profiles from GENE-Tango at iterations [23 - 28]



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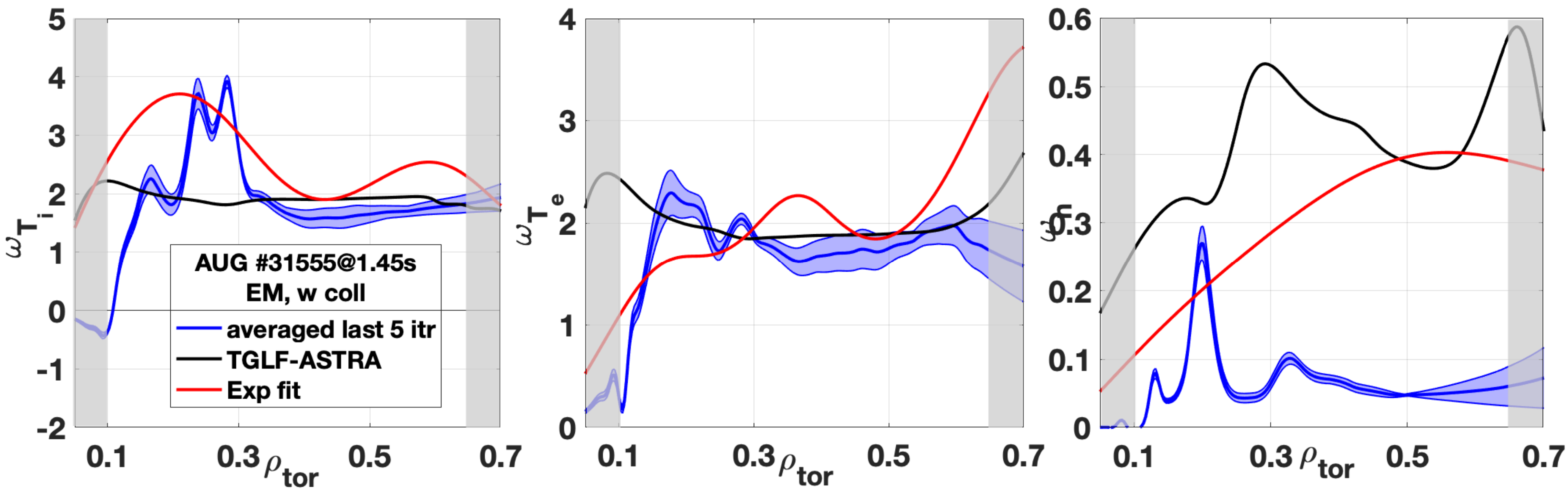

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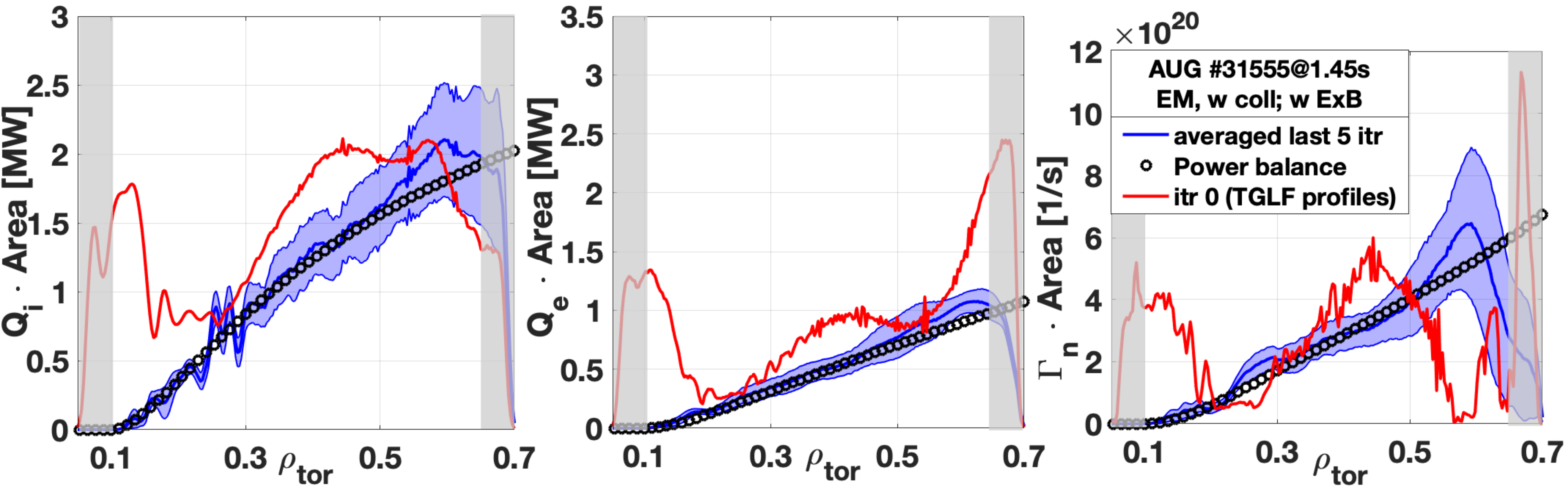
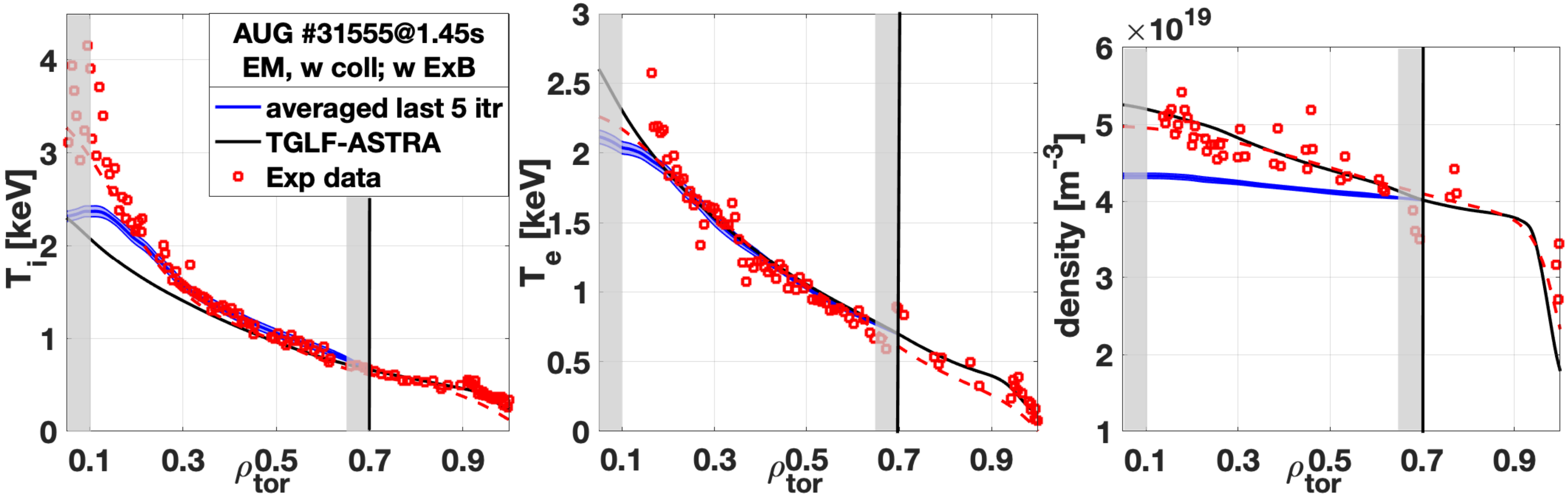
EM simulations, with collisions, with (external) toroidal rotation

- After 29 iterations (here shown [24 - 29]) turbulent fluxes match the power balance in all channels



EM simulations, with collisions, with (external) toroidal rotation

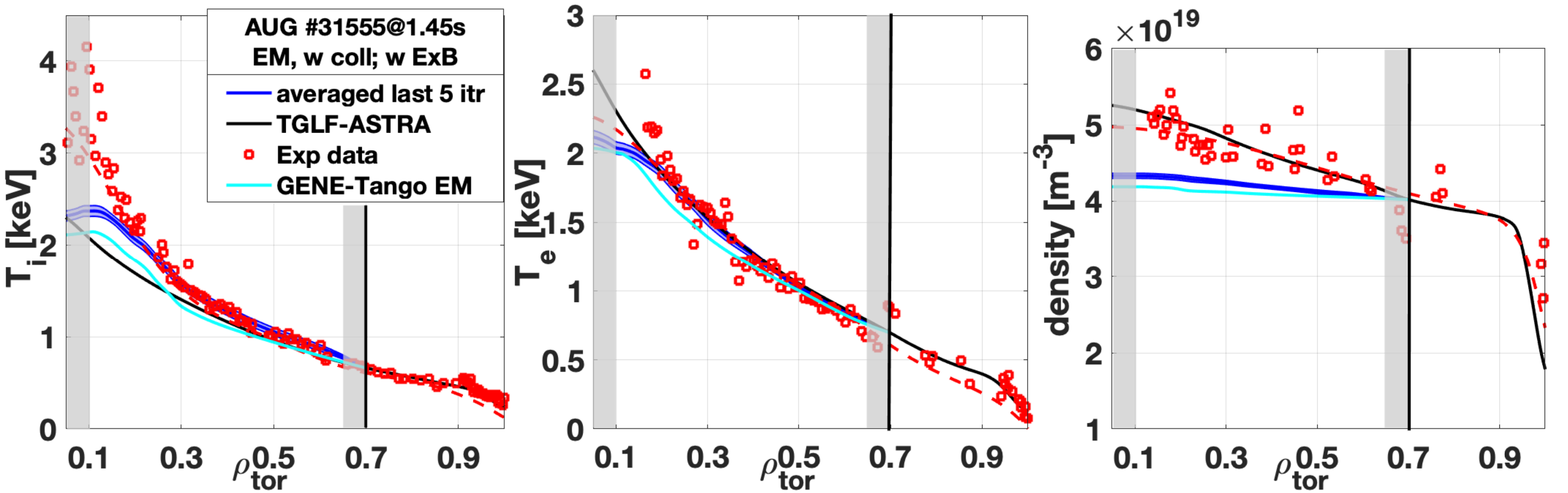
- Temperature and density profiles from GENE-Tango at iterations [24 - 29]



- When electromagnetic effects and toroidal rotation included, T_i peaking observed and not captured with reduced models → T_i under-estimated on-axis since fast ions are still neglected.
- Density profile mildly recovers, but still below measurements.

EM simulations, with collisions, with (external) toroidal rotation

- Temperature and density profiles from GENE-Tango at iterations [24 - 29]



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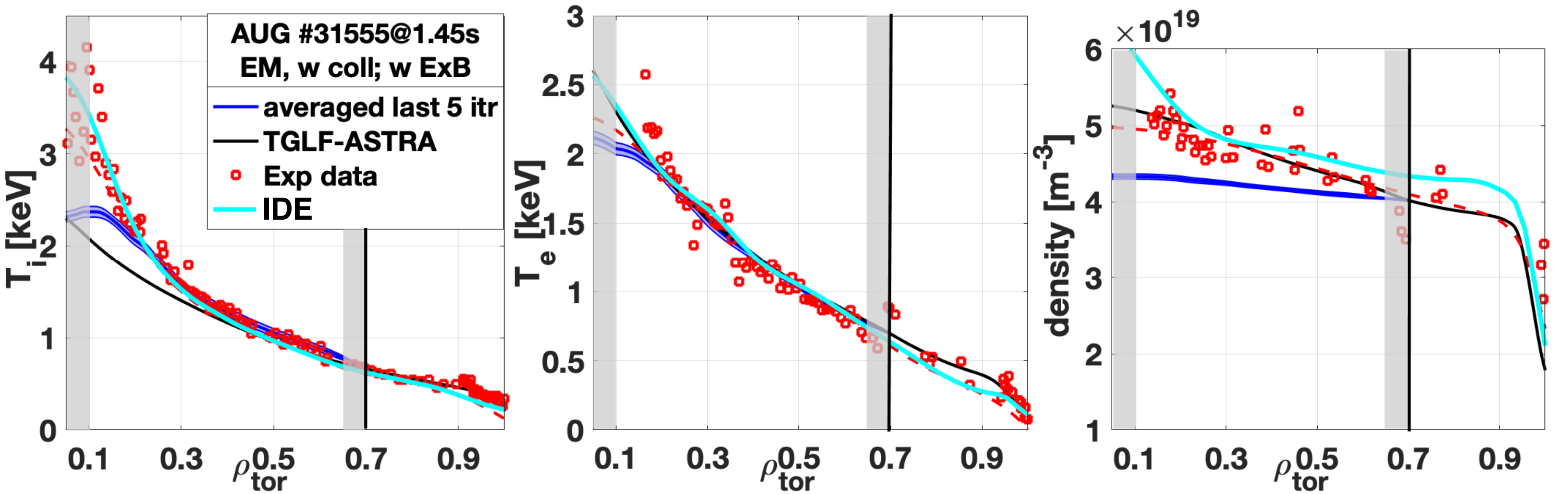

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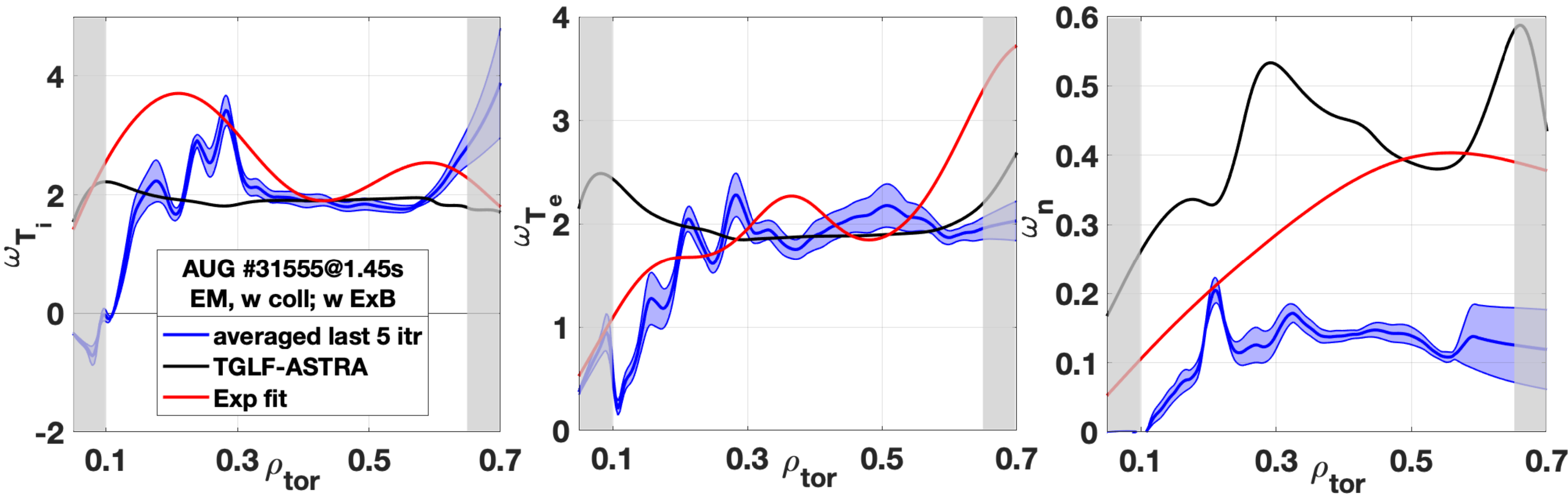

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Speed up compared to confinement time

ASDEX Upgrade #31555 : ES, with collisions, no toroidal rotation

- GENE run time (20 itrs) ~ 8.1ms
- Confinement time ~ 44.2ms

→ 5.4 speed-up

ASDEX Upgrade #31555 : ES, no collisions, no toroidal rotation

- GENE run time (30 itrs) ~ 12.7ms
- Confinement time ~ 52.2ms

→ 4.1 speed-up

ASDEX Upgrade #31555 : EM, with collisions, no toroidal rotation

- GENE run time (28 itrs) ~ 11.7ms
- Confinement time ~ 48.2ms

→ 4.1 speed-up

ASDEX Upgrade #31555 : EM, with collisions, with toroidal rotation

- GENE run time (29 itrs) ~ 11.7ms
- Confinement time ~ 50.1ms

→ 4.3 speed-up

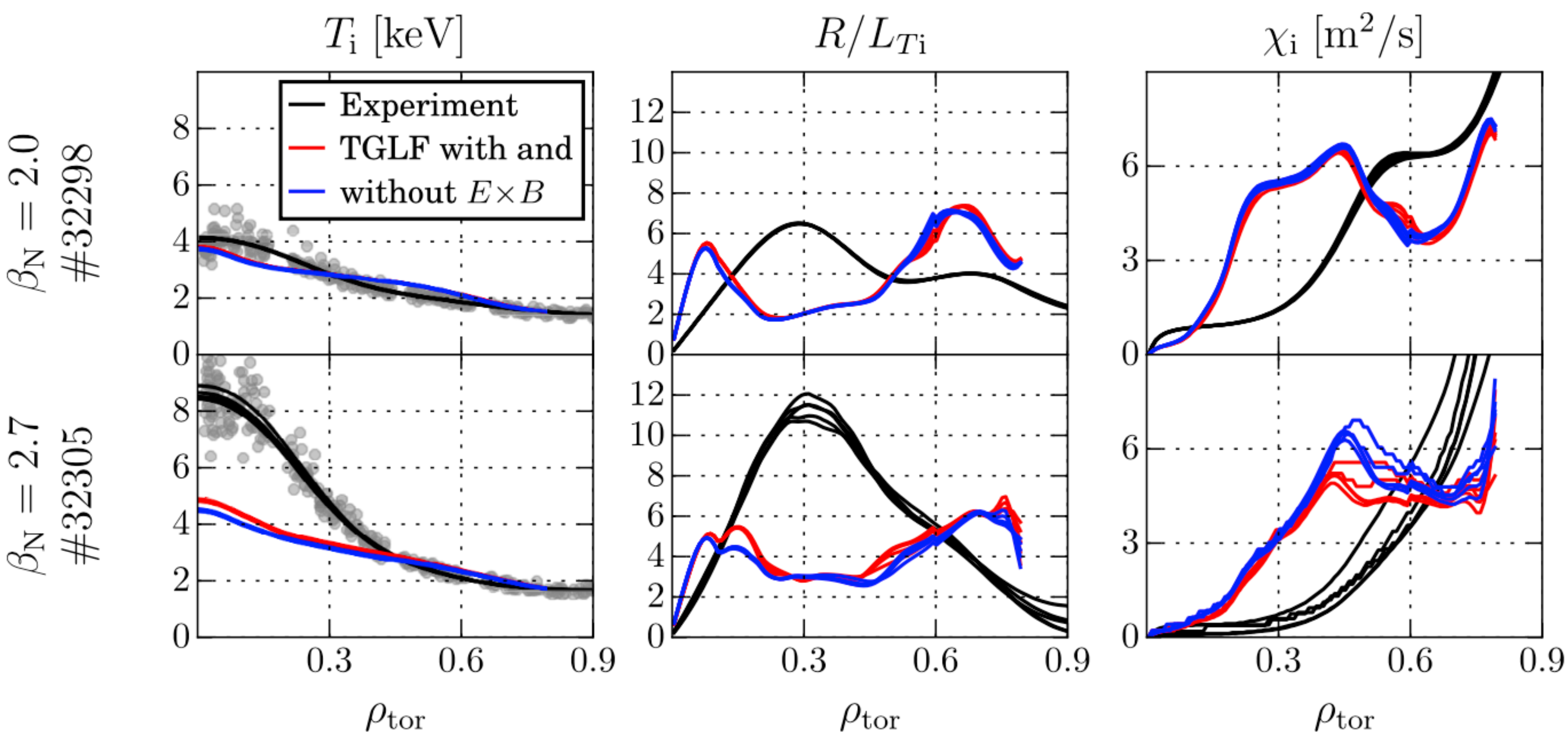
Outlook

Next steps with GENE-Tango:

- Profile prediction including fast particles and alphas
- Transport barrier analyses, profile prediction for W7-X (Alejandro B. Navarro)

GENE-Tango simulations with supra-thermal particles:

- Reduced turbulent models do not reproduce profiles in strong EM regimes and large fast particle concentration (see e.g., P. Mantica PPCF 2020).



- Possible first test case for GENE-Tango with fast ions could be ASDEX Upgrade discharge #32305 (A. Bock NF 2017).

Conclusions and upcoming milestones:

Next steps:

- Model fast ion effects on plasma confinement up to transport time scale extend/develop GENE-Tango.
- Address feedback loop between (i) energetic ion effects on micro-turbulence, (ii) their impact on the bulk profiles and, in turn, (iii) the repercussion on supra-thermal particle deposition profiles.
- Understand/predict fast ion effects on transport/plasma profiles e.g., turbulence suppression, formation of internal transport barriers.
- Model alpha-particles and capture their effect on plasma performances

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Thank you for your attention!