Profile prediction of negative triangularity plasma in ASDEX Upgrade using PORTALS-GX

X. Wang[1]*, P. Rodriguez-Fernandez[1], N. Howard[1], B. Vanovac[1], R. Bielajew[1], P. Mantica[2], T. Happel[3], A. E. White[1], the ASDEX Upgrade Team[4], and the EUROfusion Tokamak Exploitation Team[5]

[1] Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA [2] Istituto per la Scienza e Tecnologia dei Plasmi, CNR, Milano, Italy [3] Max-Planck-Institut für Plasmaphysik, Garching, Germany [4] See Zohm et al. 2024 (https://doi.org/10.1088/1741-4326/ad249d) for the ASDEX Upgrade Team [5] See Joffrin et al. 2024 (https://doi.org/10.1088/1741-4326/ad2be4) for the EUROfusion WPTE Team

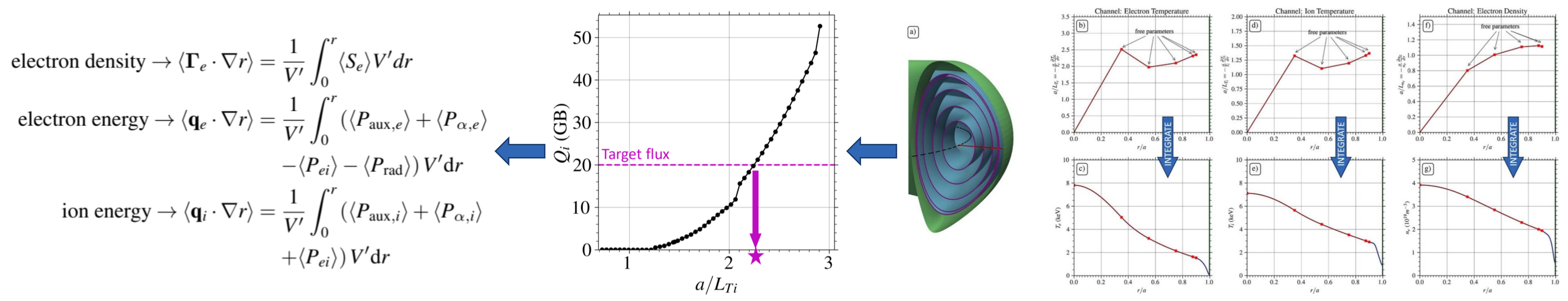
* Corresponding author's e-mail: xxw@mit.edu

67th Annual Meeting of the APS Division of Plasma Physics – Long Beach, California, USA, Nov. 17–21, 2025 – 13.03

MOTIVATION:

Towards a single framework for profile prediction of tokamaks and stellarators

Profile prediction – predicting steady state kinetic profiles from operating parameters



Steady state plasma requires flux balance in every channel, with RHS set by operating parameters

Nonlinear flux-tube gyrokinetic code computes local fluxes from gradients

Local gradients can be extrapolated and integrated to obtain kinetic profiles

Profile prediction solves the inverse problem of computing profiles from fluxes

Flux matched profiles are crucial for predicting reactor performances and constraining experimental interpretations

- Performance metrics such as $Q_{physics}$ and τ_E are functions of volume averaged density and temperature, which are highly sensitive to profile effects
- Instabilities are stabilized/destabilized by coupled effects of various gradients, and small variations within experimental uncertainty can result in very different dominant modes observed

$$\tau_E^{IPB98(y,2)} = 0.0562\, I_p^{0.93} B_T^{0.15} n_{19}^{0.41} P_L^{-0.69} R^{1.97} \kappa^{0.78} \epsilon^{0.58} M^{0.19}$$

$$\tau_E^{ISS04} = 0.134 a^{2.28} R^{0.64} P_L^{-0.61} n_{19}^{0.54} B_T^{0.84} \iota_{2/3}^{0.41}$$

Profile prediction can be done at varying levels of fidelity and accuracy

- Empirical scaling e.g. IPB98(y,2) and ISS04 provides a fast 0D estimate, but oversimplifies physics, and extrapolations are unreliable
- Profile prediction with quasilinear codes can be quick, but sensitive to choice of saturation models
- Profile prediction with nonlinear gyrokinetic codes is the gold standard, but is can be resource-intensive

PORTALS accelerates this iterative process through surrogate-based optimization

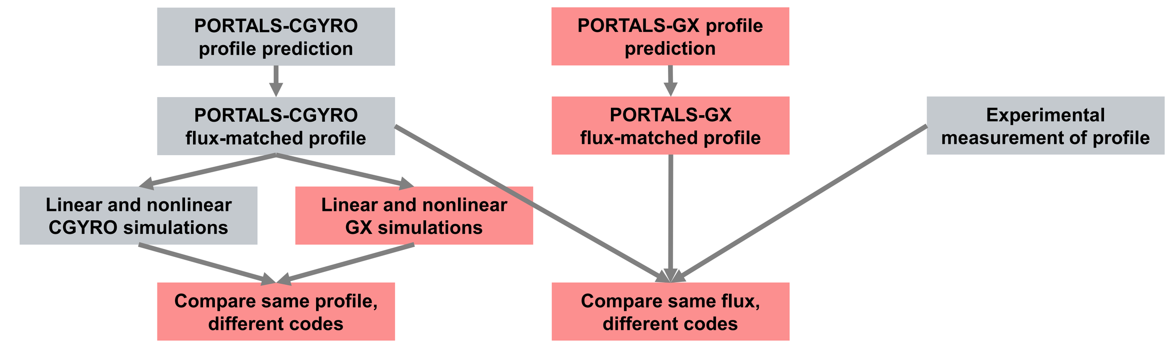
- PORTALS [1] creates surrogate models with Bayesian optimization
- Surrogate models are used to iteratively pick the next set of gradients to evaluate
- Evaluation is performed with high-fidelity nonlinear gyrokinetic codes

GX is a promising new gyrokinetic code but requires more benchmarking and validation

- Axisymmetric and non-axisymmetric geometries, efficient discretization algorithm, GPU-native [2]
- Benchmarking only done in limited cases, no attempts at validation, significant usage for stellarator profile prediction [3]

Coupling GX to PORTALS could enable a fast, high-fidelity profile prediction framework applicable to both tokamak and stellarator geometries

CONCLUSION



1. **Does GX accurately capture the full spectrum of turbulence physics?**

➢ Performed light benchmark of GX against CGYRO, comparing linear and nonlinear results for an ASDEX Upgrade (AUG) negative triangularity plasma
- ITG is well-captured, but TEM and MTM are overdamped due to simplified collision operator and geometry parameters

2. **Is GX suitable for profile prediction?**

➢ Applied GX for tokamak profile prediction for the first time, validating results with experimental profiles and PORTALS-CGYRO predicted profiles
- T_i and n_e profiles match well with experiment and PORTALS-CGYRO, but T_e profile shows discrepancy due to stronger sensitivity to TEM drive

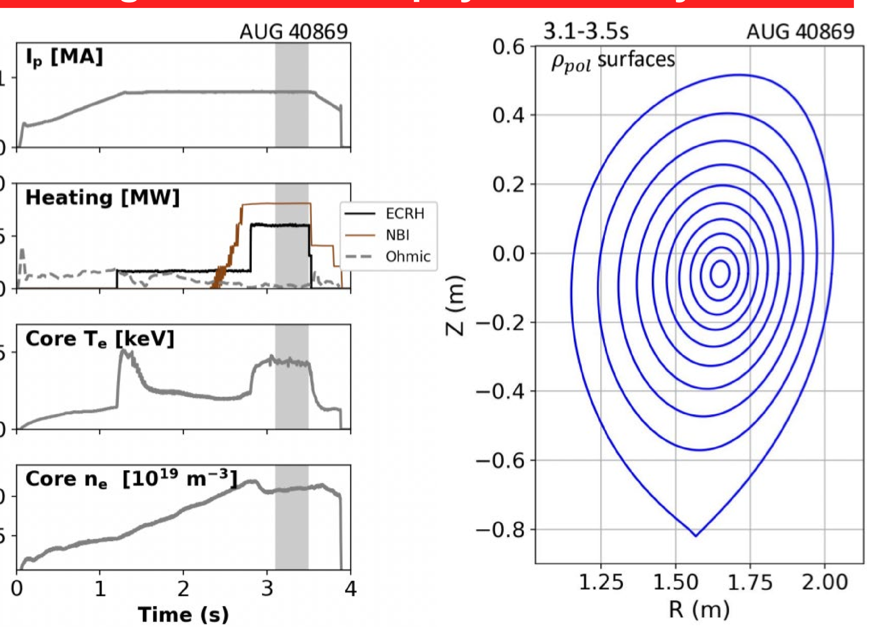
Future work:

➢ PORTALS-GX now works with both tokamak (Miller) and stellarator (VMEC) geometries, but not yet tested

STEP 1: Benchmarking GX against CGYRO at the highest available physics fidelity

ASDEX Upgrade negative triangularity plasma was used in this study

- Shot #40869 [4]
- $\delta_a \approx -0.14$
- ECRH and NBI heated
- Q_i dominant from TRANSP analysis
- H-mode
- Previously modeled with PORTALS-CGYRO [5] and ASTRA-TGLF [6]



Simulation set up with highest fidelity available within GX

- 5 radial locations: $r/a = [0.35, 0.55, 0.75, 0.83, 0.90]$
- 3 gyrokinetic species: electrons, deuterons, lumped impurities ($Z_{imp} = 5.67$)
- Finite collisionality
- Finite beta/electromagnetic effects
- ITG and TEM-scale turbulence
- Miller geometry with symmetric terms up to triangularity, no asymmetric terms
- Dougherty collision operator
- No rotations

Linear simulation resolutions:

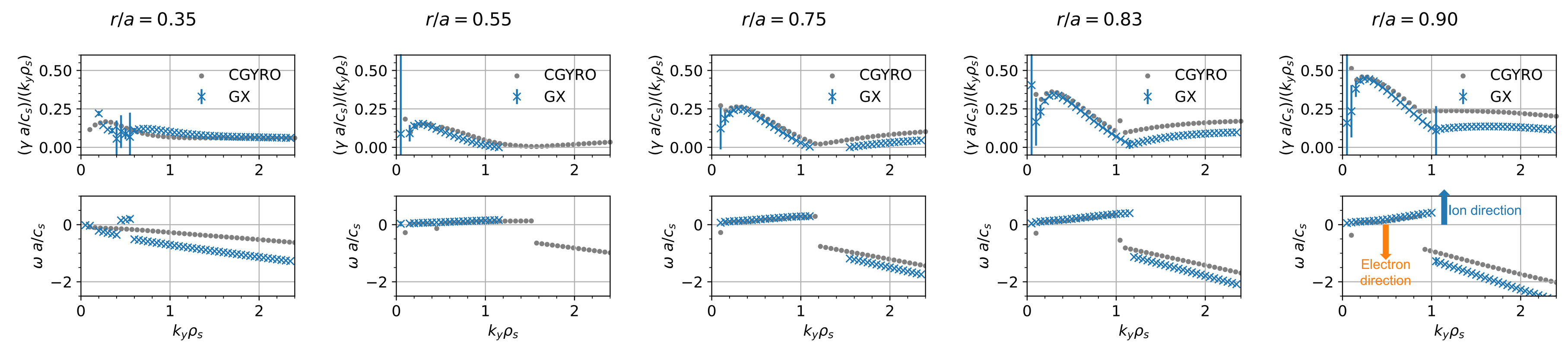
$r/a = 0.35 \sim 0.90$
$k_{y,min} = 0.050$, $k_{y,max} = 2.350$, $n_{k_y} = 48$, $y_0 = 20.0$, $L_y = 126\rho_s$ $k_{x,min} \sim \pm 0.050$, $k_{x,max} \sim \pm 0.547$, $n_{k_x} = 23$, $x_0 = 19.9$, $L_x = 125\rho_s$
32 points in z, 2 poloidal periods, 48 $v_\parallel$ moments, 16 μB moments, up to 1000 a/c_s time steps or 72 h runtime

Nonlinear simulation resolutions:

$r/a = 0.35$	$r/a = 0.55$	$r/a = 0.75$	$r/a = 0.83$	$r/a = 0.90$
$k_{y,min} = 0.071$, $k_{y,max} = 2.214$, $n_{k_y} = 32$, $y_0 = 14.0$, $L_y = 88\rho_s$ $k_{x,min} \sim \pm 0.059$, $k_{x,max} \sim \pm 7.515$, $n_{k_x} = 255$, $x_0 = 16.9$, $L_x = 106\rho_s$		$k_{y,min} = 0.053$, $k_{y,max} = 1.105$, $n_{k_y} = 22$, $y_0 = 19.0$, $L_y = 119\rho_s$ $k_{x,min} \sim \pm 0.051$, $k_{x,max} \sim \pm 6.531$, $n_{k_x} = 255$, $x_0 = 19.4$, $L_x = 122\rho_s$		
24 points in z, 1 poloidal period, 8 $v_\parallel$ moments, 4 μB moments, up to 1000 a/c_s time steps or 72 h runtime				

Linear comparison: correct ITG but overdamped TEM and MTM due to collision operator and shaping parametrization

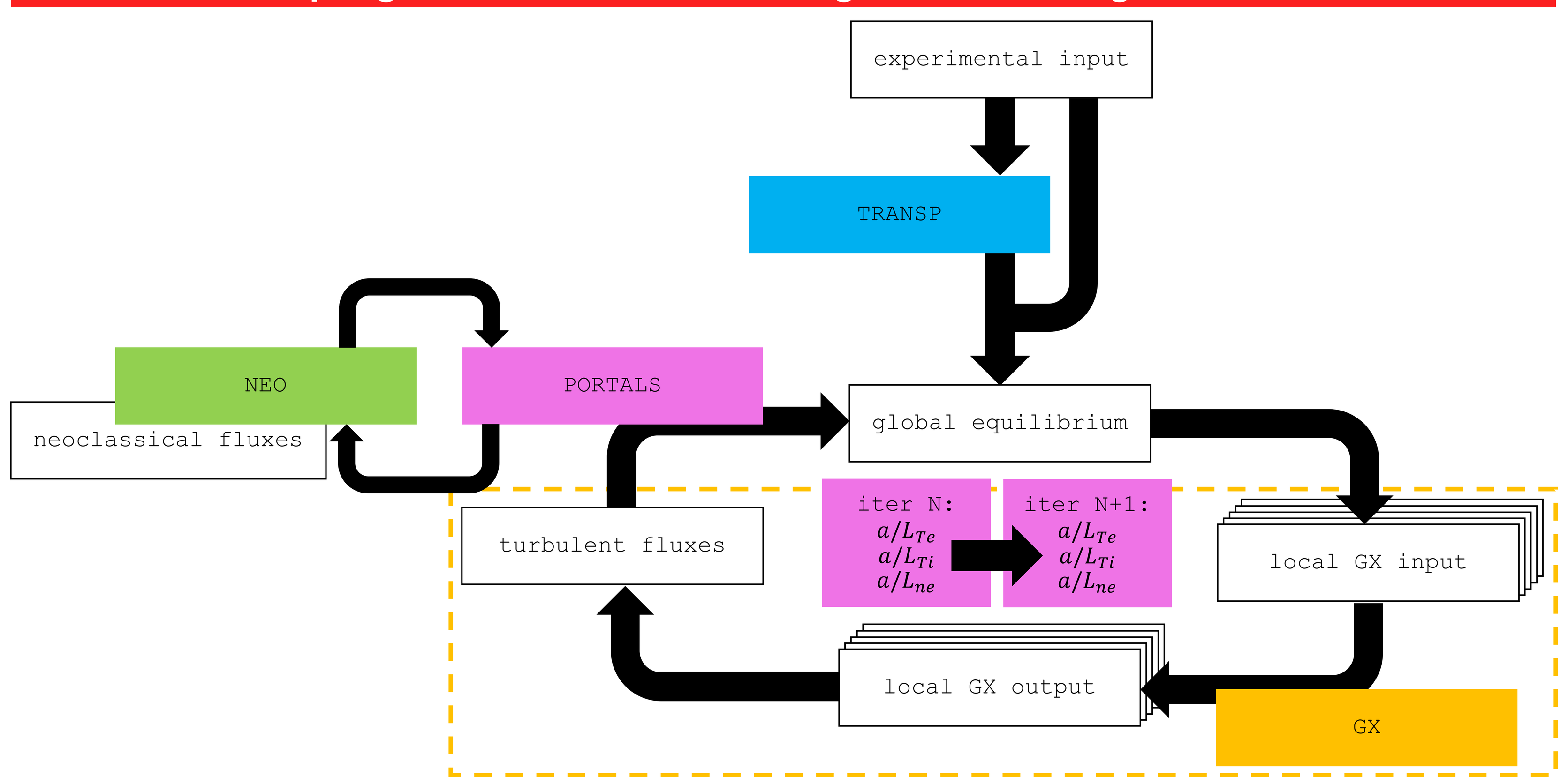
- ITG at $k_y\rho_s \leq 1$ is well captured → slight overdamping of γ likely due to reduced TEM
- MTM at $k_y\rho_s = 0.1$ is not observed → velocity dependent electron-ion collisions are important, but not captured by Dougherty
- TEM at $k_y\rho_s \geq 1$ is overdamped and real frequency overestimated
  - Collisional de-trapping mechanism requires velocity dependent electron-ion collisions, but not captured by Dougherty
  - Bounce frequency calculation is highly dependent on geometry, which is not fully captured by Miller
- Unknown mode at $r/a = 0.35$, $k_y\rho_s \leq 0.4$ → blows up at small $k_y\rho_s$ (KBM/MTM? Require further analysis to characterize)

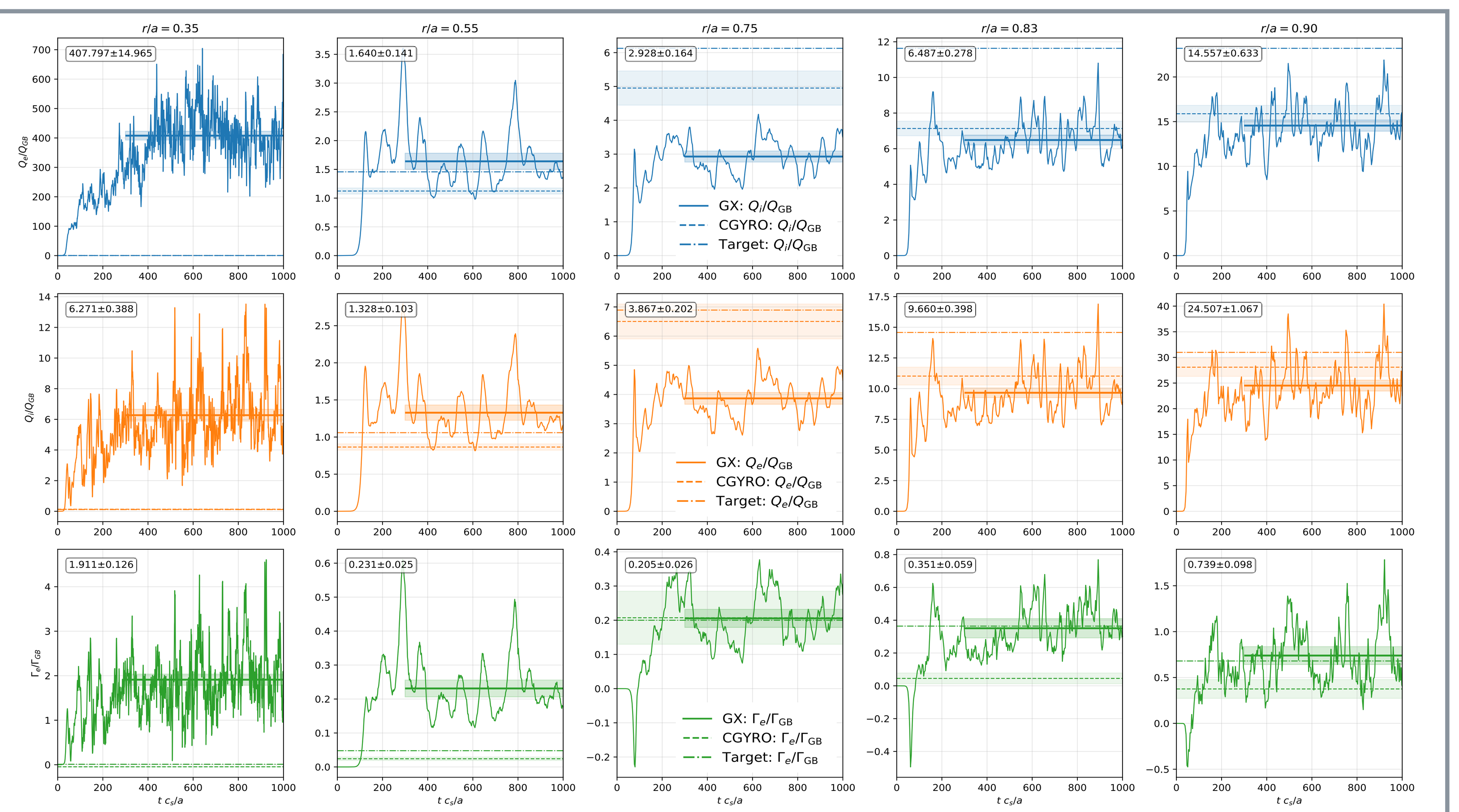


Nonlinear comparison: ITG-dominant locations are well-matched

- At $r/a = 0.55 \sim 0.90$, generally decent agreement (within ~10%) despite inconsistent linear results
- At $r/a = 0.35$, fluxes are overestimated by orders of magnitude due to pile up at low $k_y\rho_s$ → flux-matched condition may significantly reduce gradient and stabilize this mode

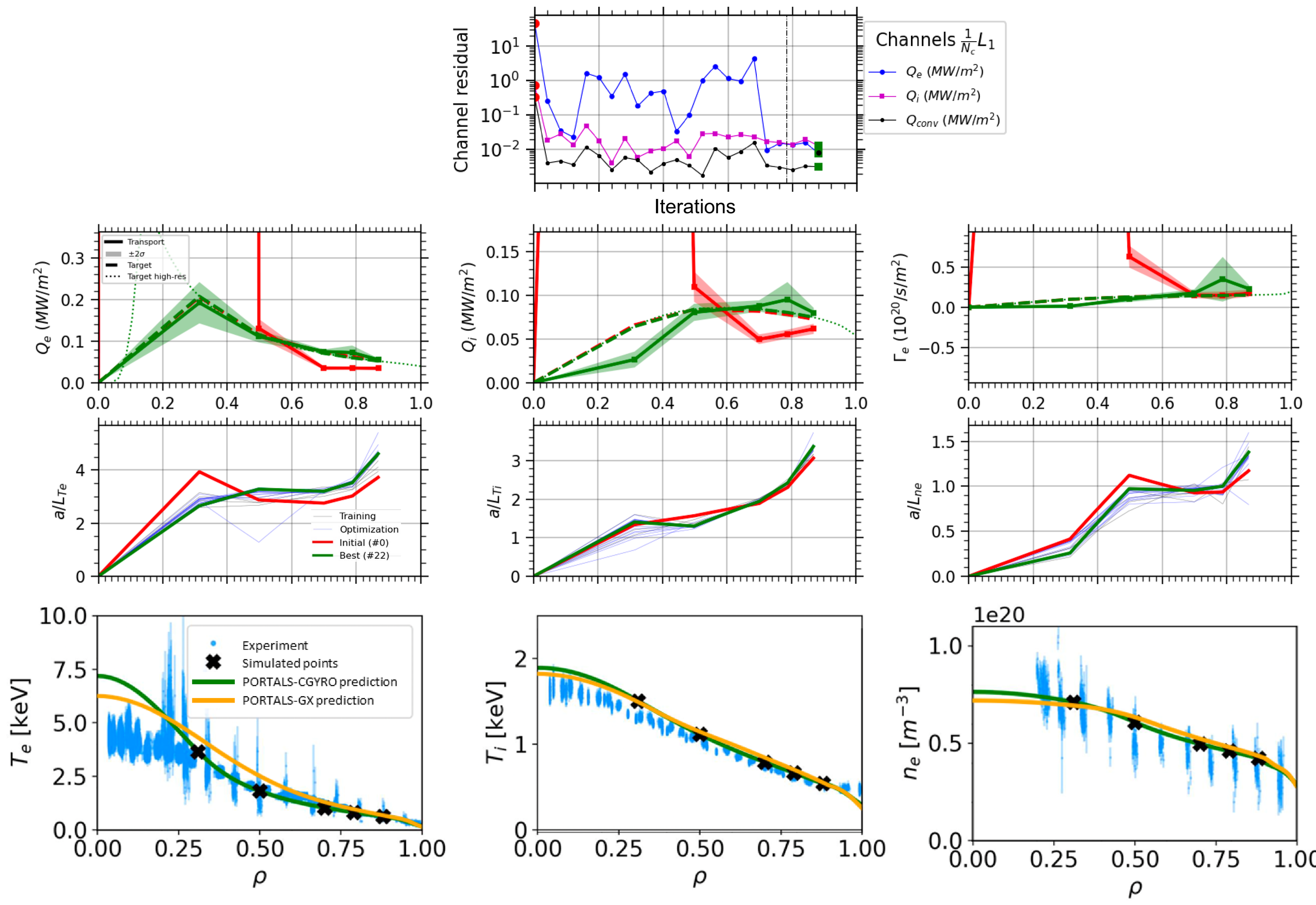
STEP 2: Coupling GX to the PORTALS integrated modelling framework





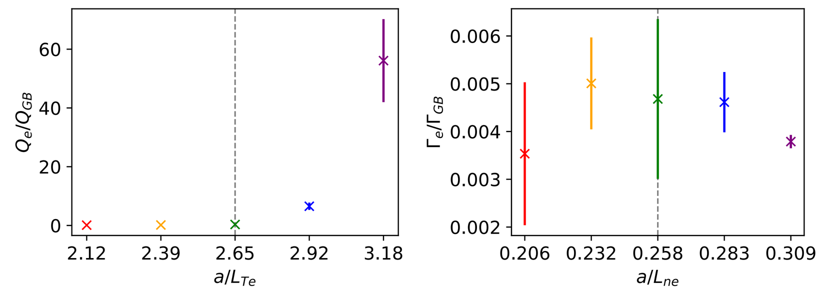
STEP 3: Validating PORTALS-GX predicted profile with experimentally measured profile

10 – 20 GPU node-hours/simulation × 5 radial locations × 23 iterations = **1,725 GPU node-hours**



T_i and n_e profiles match well with experiment and PORTALS-CGYRO, but T_e profile shows discrepancy

- Flux-matched on all locations besides $r/a = 0.35$ due to strong profile stiffness
- Q_i is primarily driven by ITG, which is most strongly affected by a/L_{Ti} → good ITG physics = good T_i profile
- Q_e is primarily driven by TEM, which is most strongly affected by a/L_{Te} → bad TEM physics = bad T_e profile
- Γ_e is also driven by TEM, but insensitive to a/L_{ne}



REFERENCES

[1] Rodriguez-Fernandez, P., et al. Nuclear Fusion 64.7 (2024): 076034.
[2] Mandell, Noah R., et al. Journal of Plasma Physics 90.4 (2024): 905900402.
[3] Guttenfelder, W., et al. Journal of Plasma Physics 91.3 (2025): E83.
[4] Vanovac, B., et al. Plasma Physics and Controlled Fusion 66.11 (2024): 115005.
[5] Bielajew, Rachel, et al. Bulletin of the American Physical Society (2024).
[6] Aucone, L., et al. Plasma Physics and Controlled Fusion 66.7 (2024): 075013.

ACKOWLEDGEMENT

This work is supported by the Agency for Science, Technology and Research (A*STAR), Singapore, under the National Science Scholarship (PhD), and by the United States Department of Energy under Award DE-SC0014264. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme under Grant Agreement No. 101052200[JS1]. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. This research used resources of the MIT Office of Research Computing and Data, and the National Energy Research Scientific Computing Center (NERSC), a Department of Energy User Facility using NERSC award FES-ERCAP0031419.