Preliminary Studies of Isotope Effects on Edge and Scrape-off Layer Turbulence at JET using Full-f Gyrokinetic Simulations

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Understanding Isotope Effects on Edge and SOL Turbulence and Transport Is Critical For Reactor Design

- Future fusion reactors will operate with D–T isotope mixtures vs. Most present-day experiments still use single-isotope plasmas (H or D).
- Transport and turbulence model validation is therefore mostly limited to H and D plasmas.
- Only JET provides reactor-relevant D–T experimental data for validation.
- Isotope effects (eg, deviations from gyro-Bohm scaling) are ***stronger*** in the edge than in the core.
- ***Isotope effects on edge turbulence and transport have not yet been explored with full-f gyrokinetics (GK).***
- ***Previous studies mainly relied on δf GK, which is not valid in the edge.***
- JET-scale full-f GK simulations of edge/SOL turbulence have only recently become feasible.

We use the GENE-X code to assess isotope effects on edge and SOL turbulence in realistic geometry with X-point (for the first time) at JET

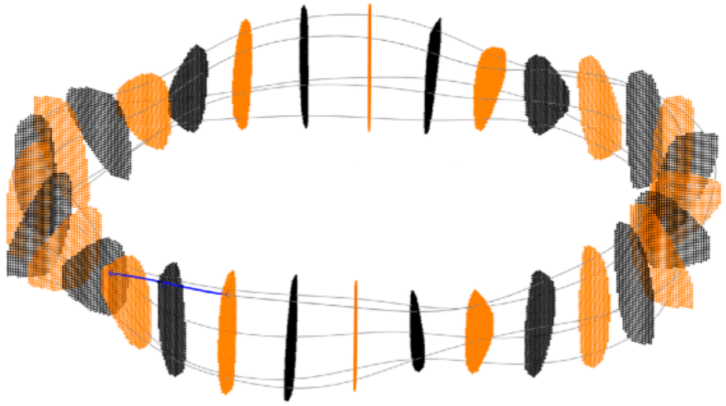
GENE-X: full-*f* GK code for Edge-SOL Turbulence in Complex Magnetic Geometry with X-points

- Solves ***full-f, electromagnetic, collisional, GK*** model (see next slide)
- ***Complex magnetic geometry*** (X-points and 3D) using **F**lux-**C**oordinate **I**ndependent (shared with GRILLIX fluids code)
- ***Originally*** designed with ***grid-based*** approach (inspired by GENE code)
- ***CPU-based*** (GPU under development) and ***massively parallelized*** (OMP/MPI)

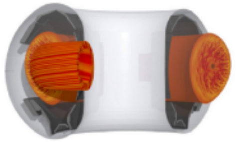
Fluid Braginskii-like
turbulence code ***GRILLIX***

[A. Stegmeir *et al.*, PPCF **60 (**2018);
W. Zholobenko *et al., PPCF* ***61*** *(2021)*]

PARALLAX (**FCI** library)

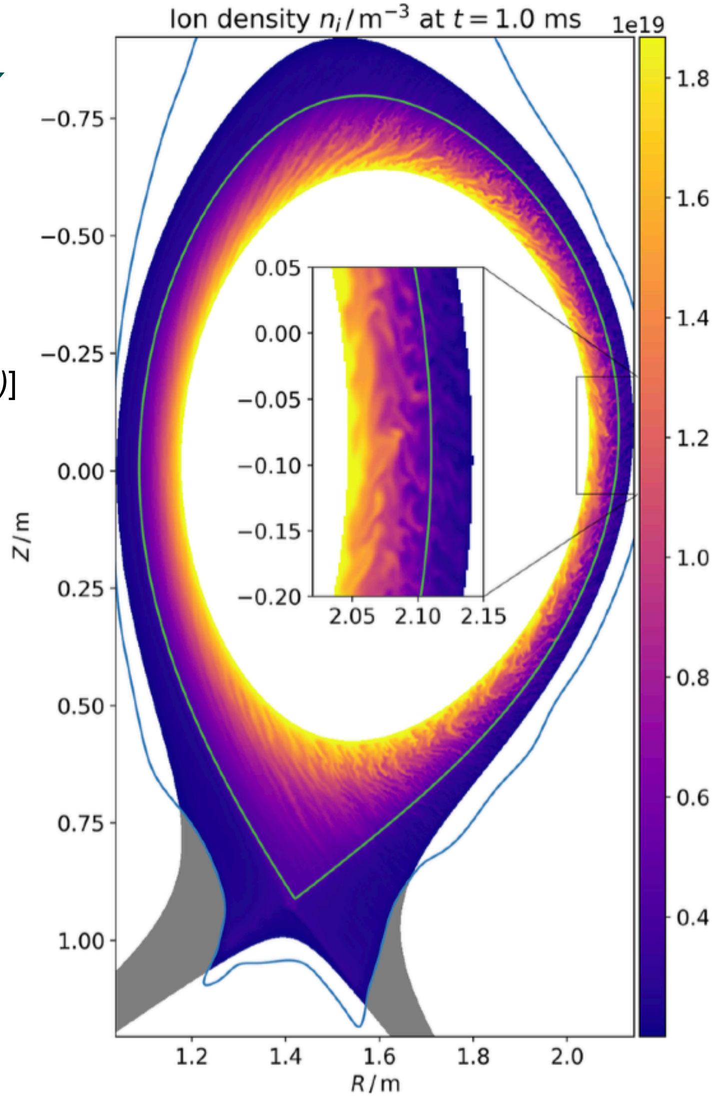


[A. Stegmeir *et al.*, *Submitted to CPC* (2024)]



[F. Jenko *et al.*, *PoP* ***7*** (2000)]

[D. Michels *et al.*, *PoP* ***29*** (2022)]



The Spectral full-*f*, Multi-Species, Electromagnetic and Collisional GK Model

Evolves ***self-consistently*** the ***spectral coefficients*** $\mathcal{N}_\alpha^{pj}$ and ***electromagnetic Fields*** ϕ_1 and $A_{\|1}$

Spectral GK Vlasov Equation for $\mathcal{N}_\alpha^{pj}$

Spectral sources and ***sinks***
(density, momentum and energy)

$$\frac{\partial}{\partial t}\mathcal{N}_\alpha^{pj} + \nabla \cdot \mathbf{\Gamma}_\alpha^{pj} + \mathcal{F}_{\alpha\ell k}^{pj}\mathcal{N}_\alpha^{\ell k} + \mathcal{D}_{\alpha\ell k}^{pj}\mathcal{N}_\alpha^{\ell k}\frac{\partial A_{1\|}}{\partial t} = \sum_\beta \mathcal{C}_{\alpha\beta}^{pj} + \mathcal{S}_\alpha^{pj} + K_\alpha^{pj}$$

Inherently multi-species (electrons, deuterium, and tritium)

Nonlinear spectral *collision operator*

$$\begin{aligned}\mathcal{C}_{\alpha\beta}^{pj} = \nu_{\alpha\beta}\Big[&-(p+2j)\,\mathcal{N}_\alpha^{pj} \\ &+ (\bar{T}_{\alpha\beta} - 1)\left(\sqrt{p(p-1)}\mathcal{N}_\alpha^{p-2j} - 2j\mathcal{N}_\alpha^{pj-1}\right) \\ &+ \bar{u}_{\alpha\beta}\sqrt{2p}\mathcal{N}_\alpha^{p-1j}\Big]\end{aligned}$$

[B. J. Frei *et al.*, *CPC* **316** *(2025)*]

Spectral Ampere law for $A_{\|1}$

$$-\Delta_\perp A_{1\|} = 4\pi \sum_\alpha \frac{q_\alpha}{c}\sqrt{\frac{\tau_\alpha}{m_\alpha}}\mathcal{N}_\alpha^{1}$$

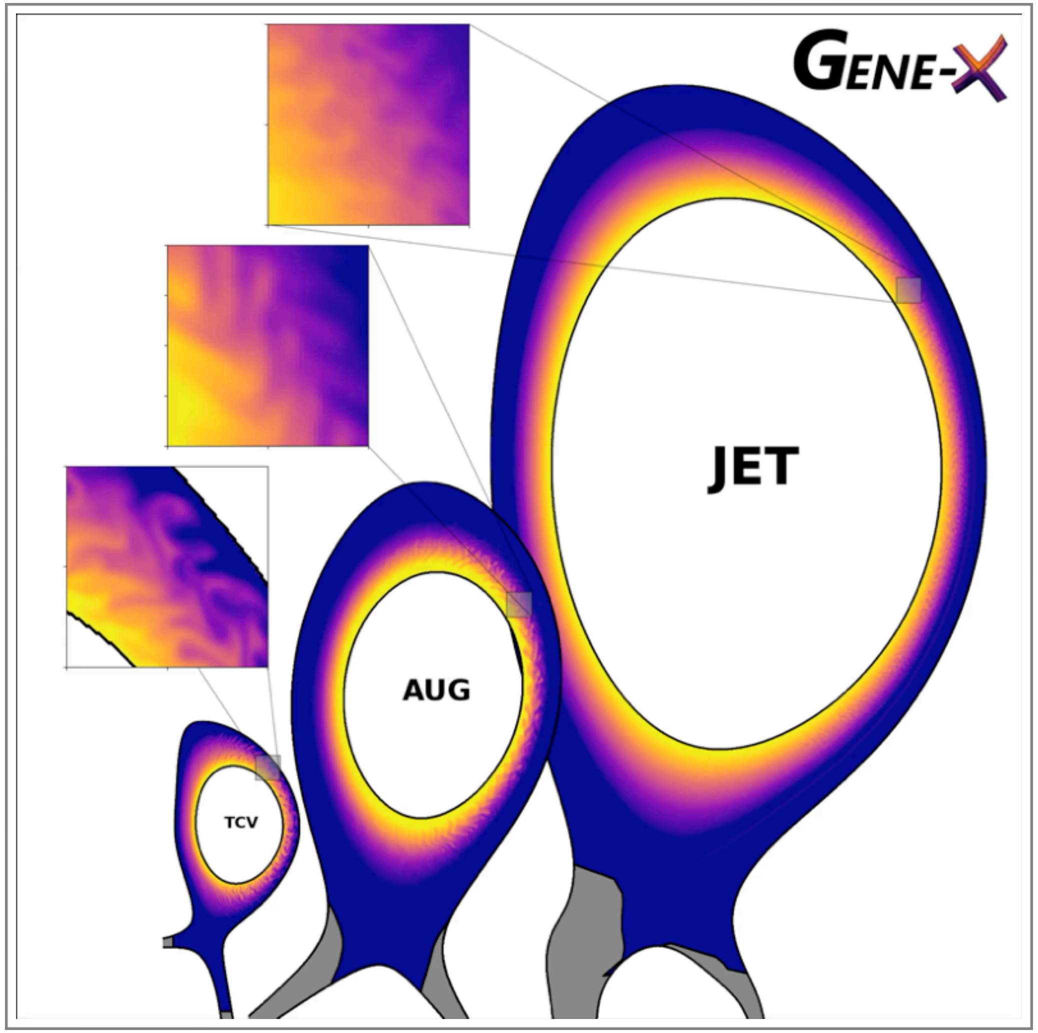
Spectral Quasi-neutrality for ϕ_1

$$-\boldsymbol{\nabla} \cdot \left(\sum_\alpha \frac{m_\alpha c^2 \mathcal{N}_\alpha^{00}}{B^2}\nabla_\perp \phi_1\right) = \sum_\alpha q_\alpha \mathcal{N}_\alpha^{00}$$

Spectral Ohm's law for $\partial_t A_{\|1}$

$$-\left(\frac{\Delta_\perp}{4\pi} - \sum_\alpha \frac{q_\alpha^2 \mathcal{N}_\alpha^{00}}{c^2 m_\alpha}\right)\frac{\partial A_{1\|}}{\partial t} = \sum_\alpha \frac{q_\alpha}{c}\sqrt{\frac{\tau_\alpha}{m_\alpha}}\left(\frac{\partial \mathcal{N}_\alpha^{10}}{\partial t}\right)^*$$

Spectral acceleration enables access to reactor-scale machines such as JET for the first time



First L-mode validation by P. Ulbl

[Courtesy to Ulbl P.]

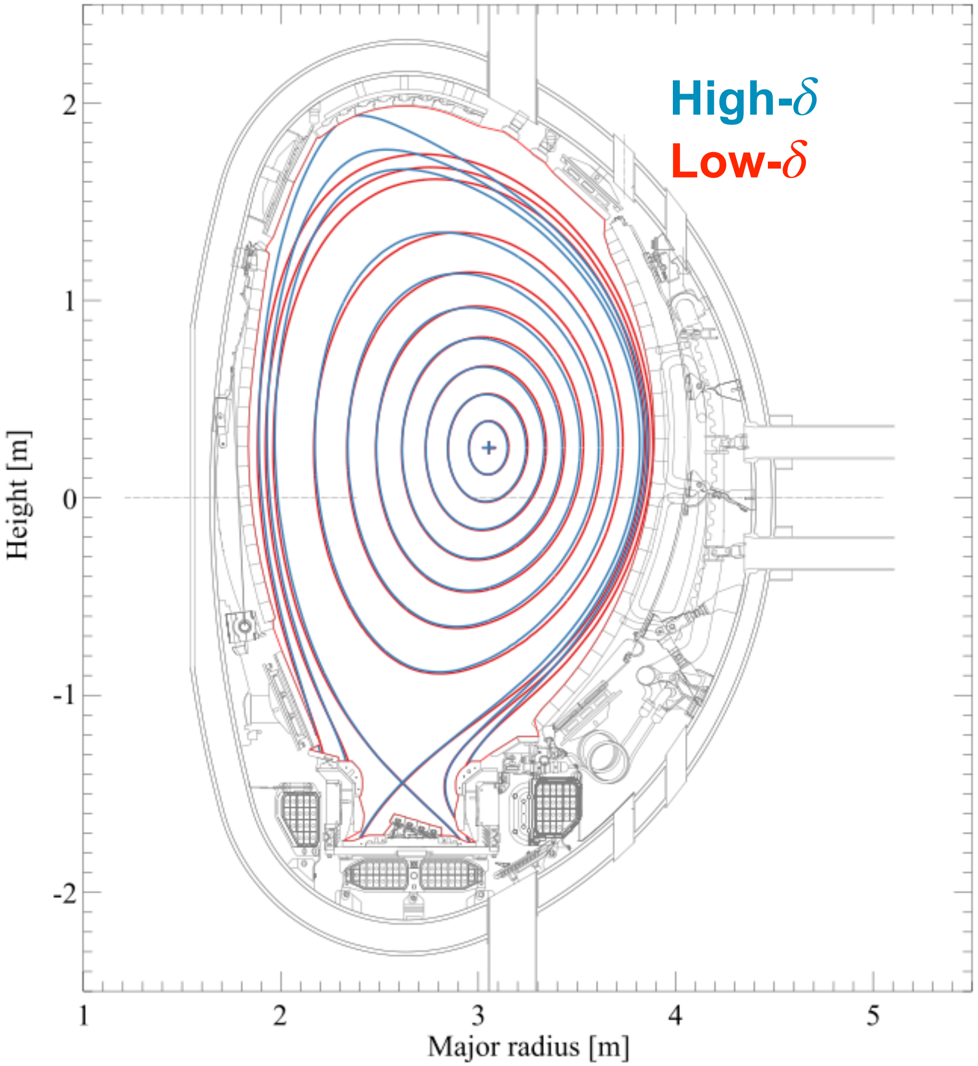
Baseline Scenario: JET-ILW type-I ELMy H-mode Plasmas

Isotope studies (DTE2 with T and D-T) on heat and particle transport in ***JET-ILW type-I ELMy H-mode*** [Schneider P. A. *et al* 2023 Nucl. Fusion 63 112010]:

- ***Baseline hydrogen scenario:*** JPN97094 (H), $I_p = 1.4$ MA, $B = 1.7$ T, $P_{NBI} = 10$ MW, $\Gamma = 1.8 \cdot 10^{22}$ / s, $\delta = 0.29$ (high δ), $\beta_N = 1.4$

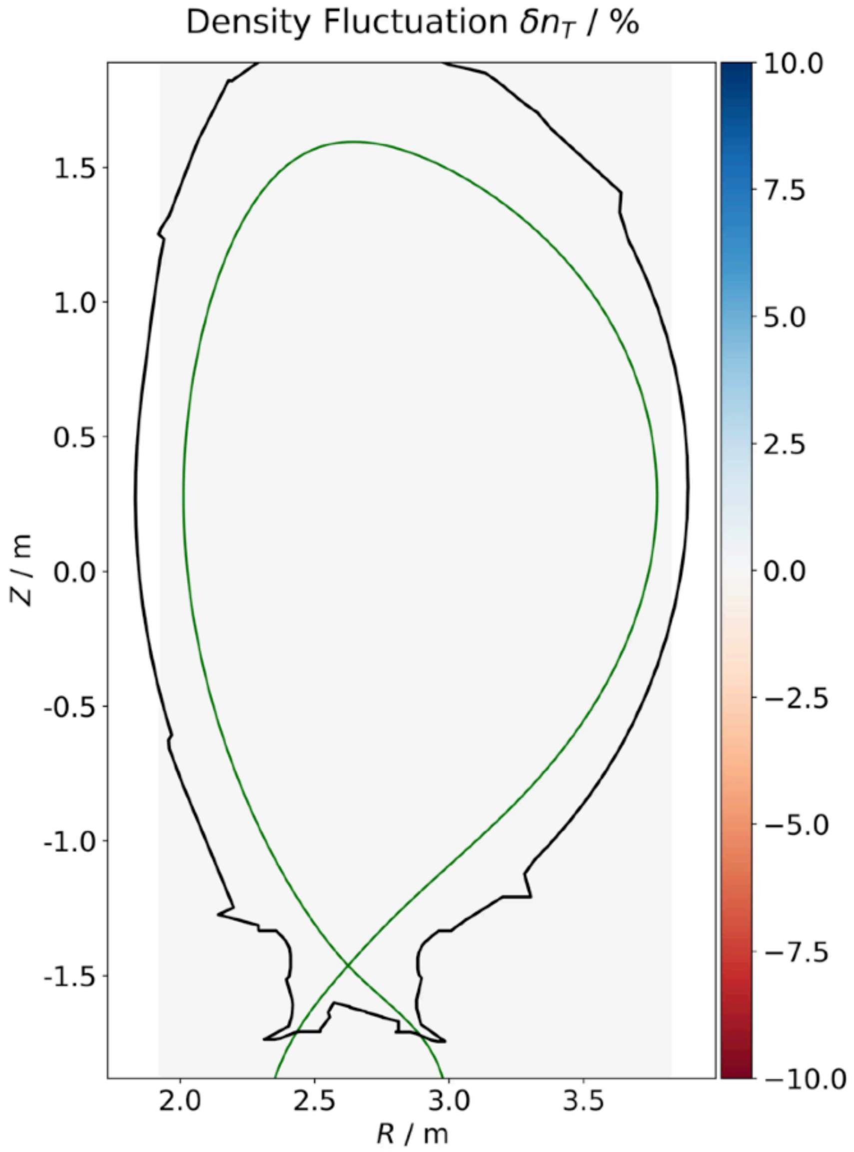
Numerical setup:

- Magnetic equilibrium of **JPN97094**(H) for all cases
- Change (only) main ion mass between simulations: $m_i/m_p = 1$ (**H**), 2 (**D**), 3 (**T**), and **DT** (3 GK species)
- Particle and heat source at $\rho_p = 0.9$ to maintain profiles close to experiments (eg. JPN97094)
- ***Edge density source at*** $\rho_p = 0.9$ with same amplitude $\Gamma = 1.8 \cdot 10^{22}$ for all isotope

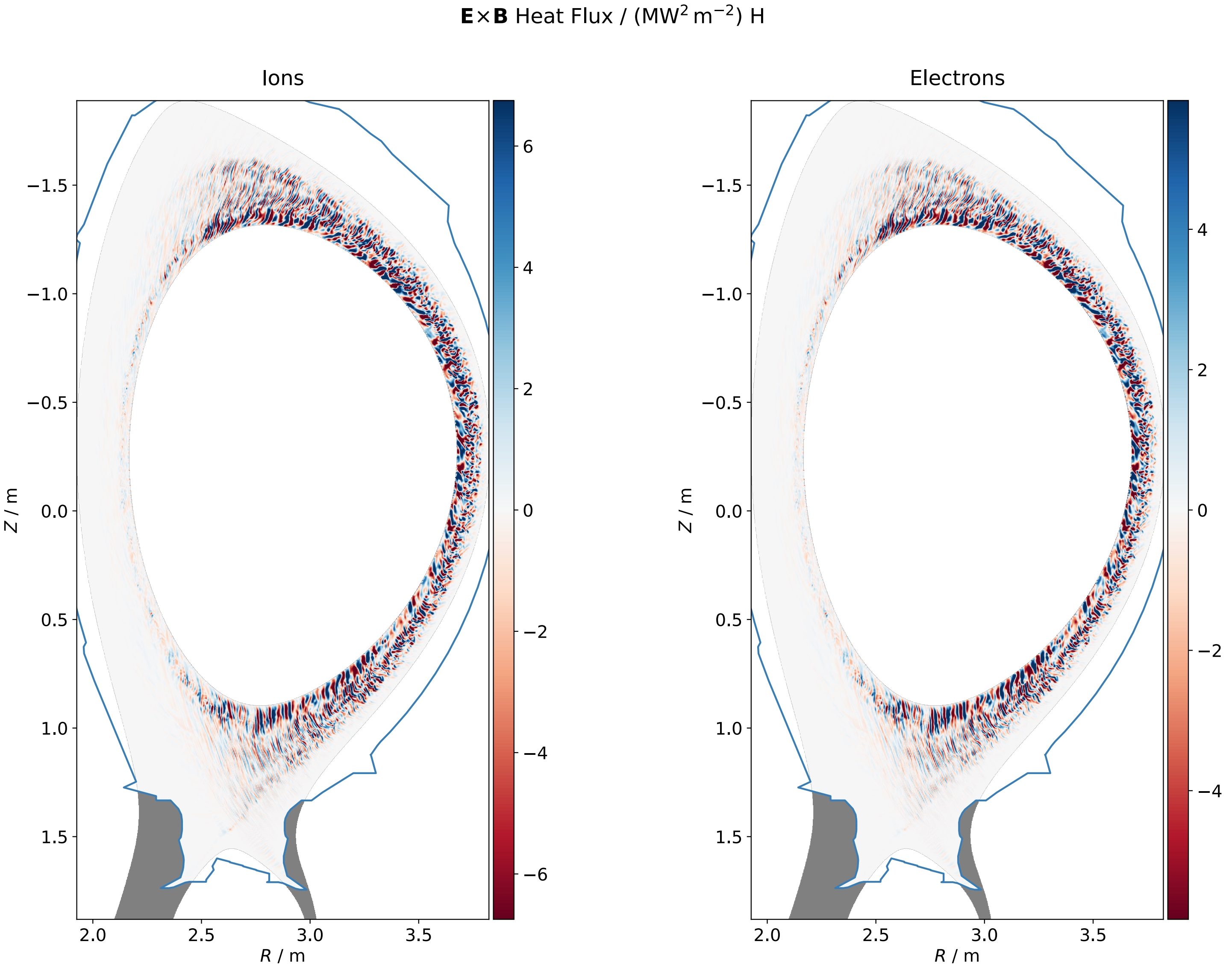


First Turbulent simulation of JET-ILW type-I ELMy H-mode

- Magnetic equilibrium of **JPN97094**(H).
- Spectral velocity-space resolution of $(N_{v_\parallel}, N_\mu) = (6{,}4)$, 32 poloidal planes and $\Delta RZ \simeq 1.4\rho_H$ at the separatrix ($N_{RZ} \simeq 7 \cdot 10^5$ points per poloidal plane.
- Saturation after $t \simeq 5$ ms (for all cases) $\Rightarrow$ ***~1.3MCPUh*** (21 days runtime) on ***Pitagora*** (8 nodes and 4 ntasks-per-node)



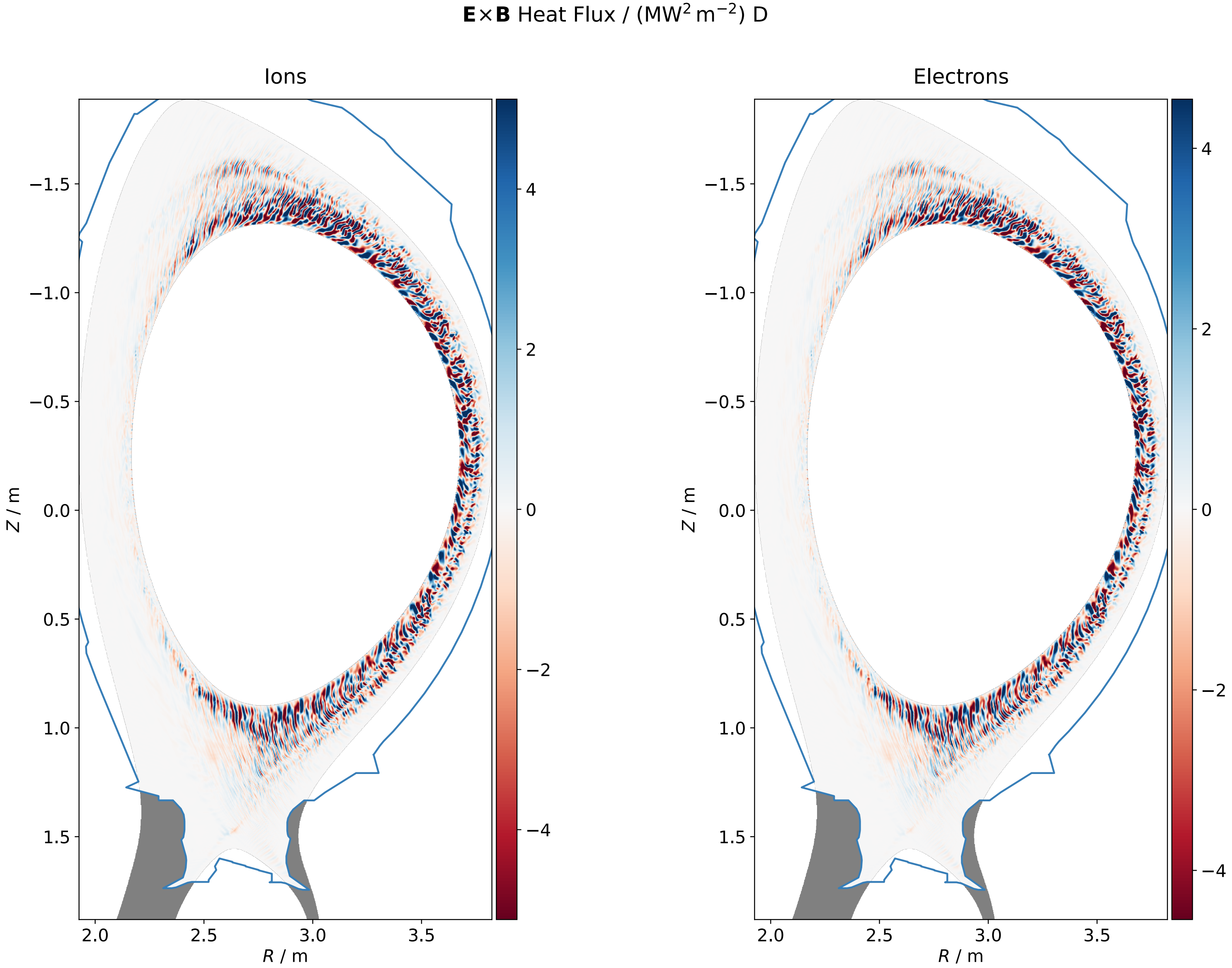
Ion Heat Flux Snapshots in H simulations


E×**B** Heat Flux / ($\mathrm{MW}^2\,\mathrm{m}^{-2}$) H

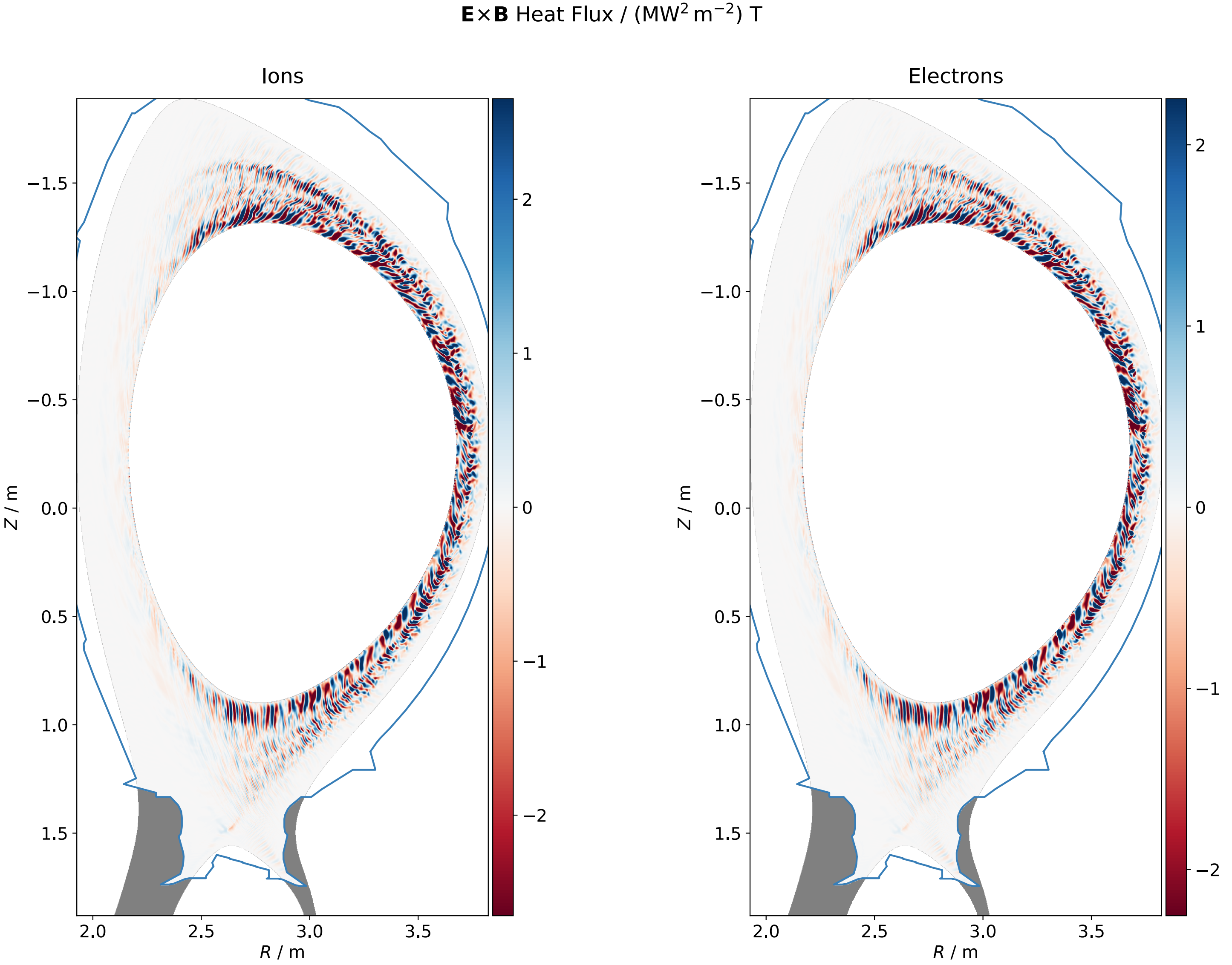
Ions

Electrons

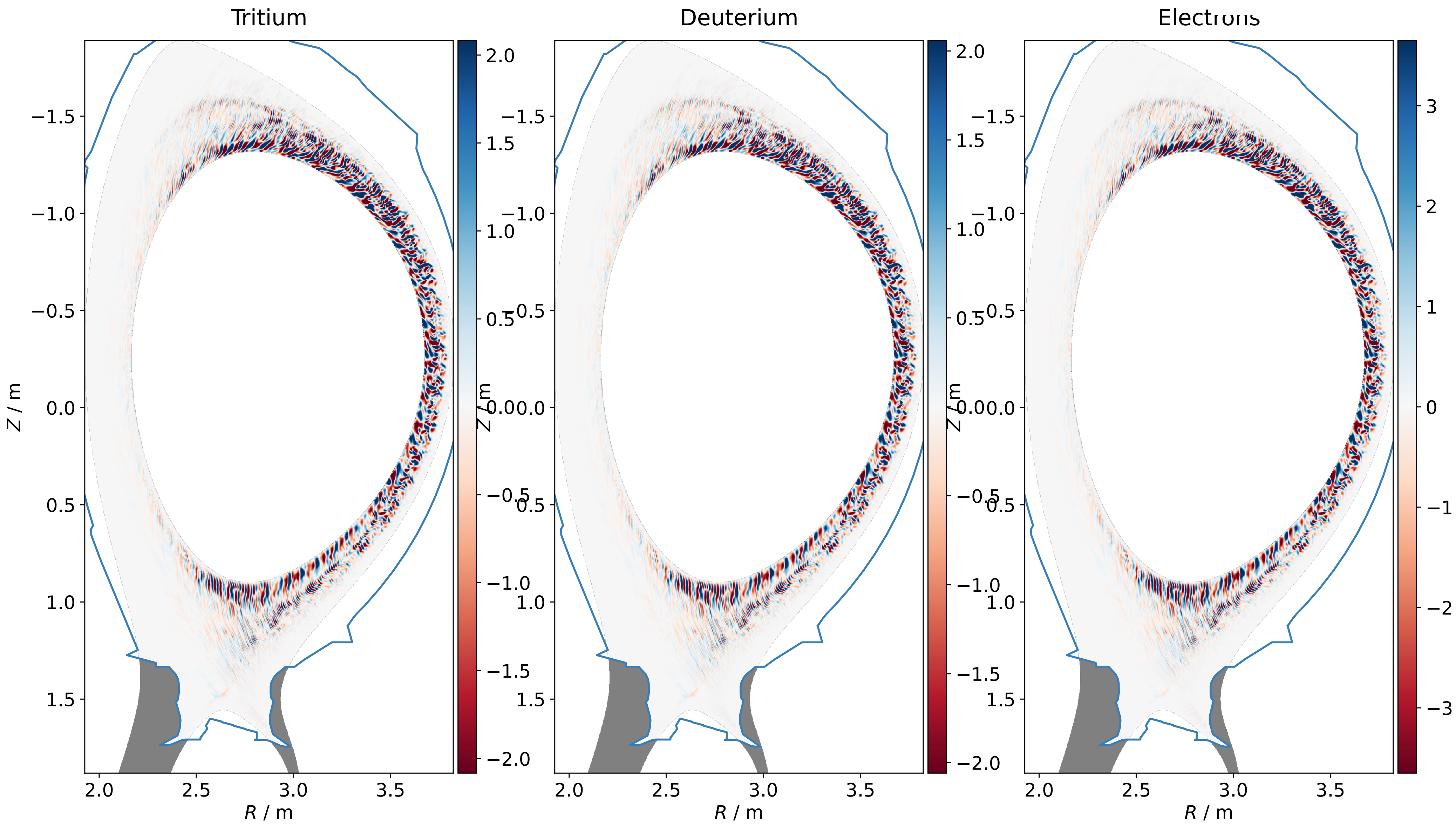
Ion Heat Flux Snapshots in D simulations



Ion Heat Flux Snapshots in T simulations



Ion Heat Flux Snapshots in D-T simulations



Power Balance at Quasi-Steady State

At quasi-steady state, the energy balance is

$$\frac{1}{V'}\frac{d}{d\psi}\left(V'\langle \boldsymbol{Q}\cdot\nabla\psi\rangle\right)\simeq 0$$

The total radial heat flux

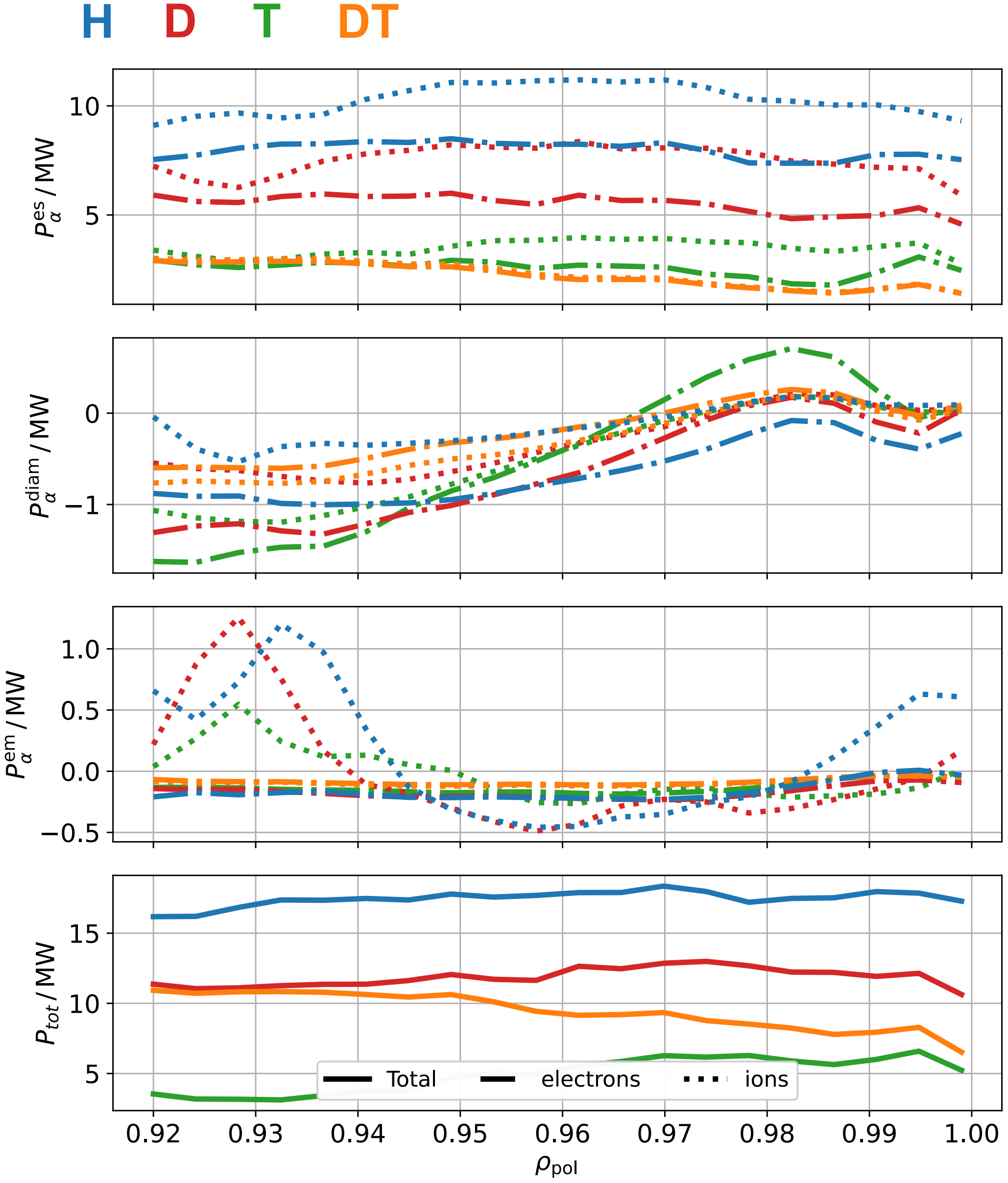
$$\boldsymbol{Q}\cdot\nabla\psi = \sum_{\alpha} \boldsymbol{Q}_\alpha\cdot\nabla\psi$$

EM ***ES*** ***Diam (NC)***

$$\boldsymbol{Q}_\alpha = Q_{\parallel\alpha}\frac{\boldsymbol{B}_{tot}}{B} + \frac{3}{2}n_\alpha T_\alpha \frac{c\boldsymbol{b}}{B}\times\nabla\psi_\alpha + \frac{K_{\parallel\alpha}}{\Omega_\alpha}\nabla\times\boldsymbol{b} + \frac{K_{\perp\alpha}}{\Omega_\alpha}\boldsymbol{b}\times\nabla\ln B,$$

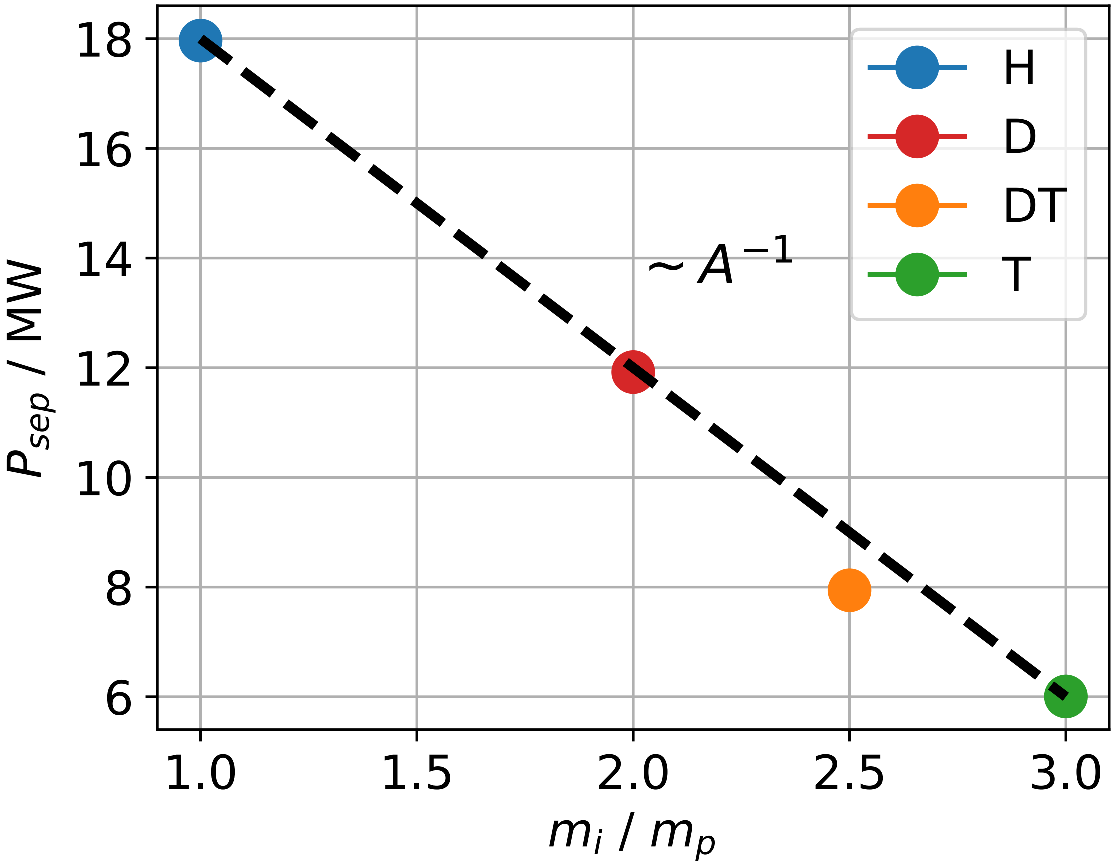
Key Takeaways:

- Power balance dominated by ES turbulent flux
- Decreasing of total power when increasing isotope mass



Scaling of Power Crossing the Separatrix

GENE-X reproduces $P_{sep} \sim 1/A_{eff}$ ***scaling***



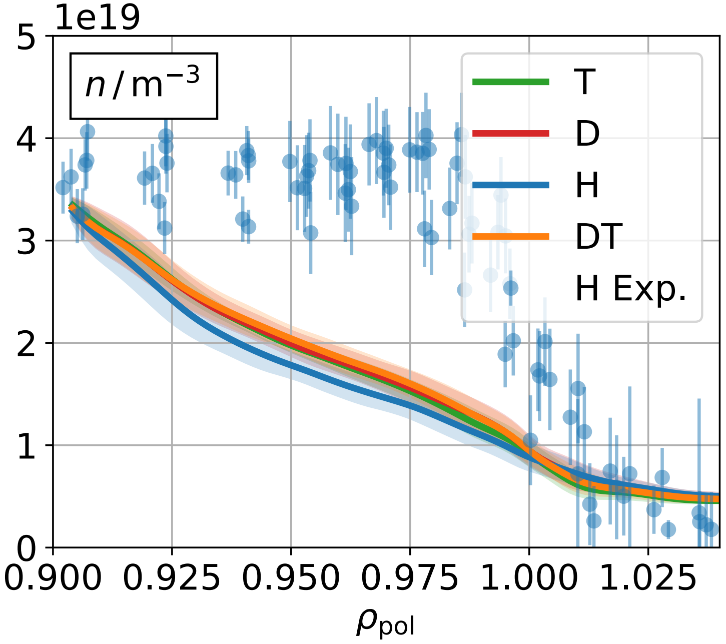
Takeaways:

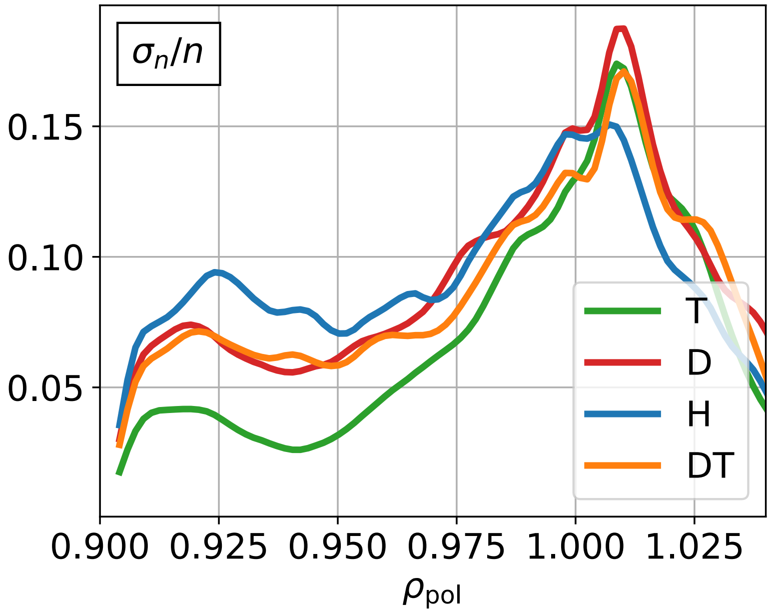
- GENE-X reproduces a clear ***anti-GyB scaling*** $P_{sep} \sim 1/A_{eff}$ (or $\tau_E \sim A_{eff}$) in agreement with previous JET H-mode ELMy experimental scaling
- P_{sep} with ***DT*** scales as $A_{eff} \sim 2.5$

Outboard Midplane Profile (OMP): Density

Only OMP profiles of **JPN97094 (H)** are shown for validation

To ensure QN, $\sum_i q_i N_i = q_e n_e$ at the BCs





Key Takeaways:

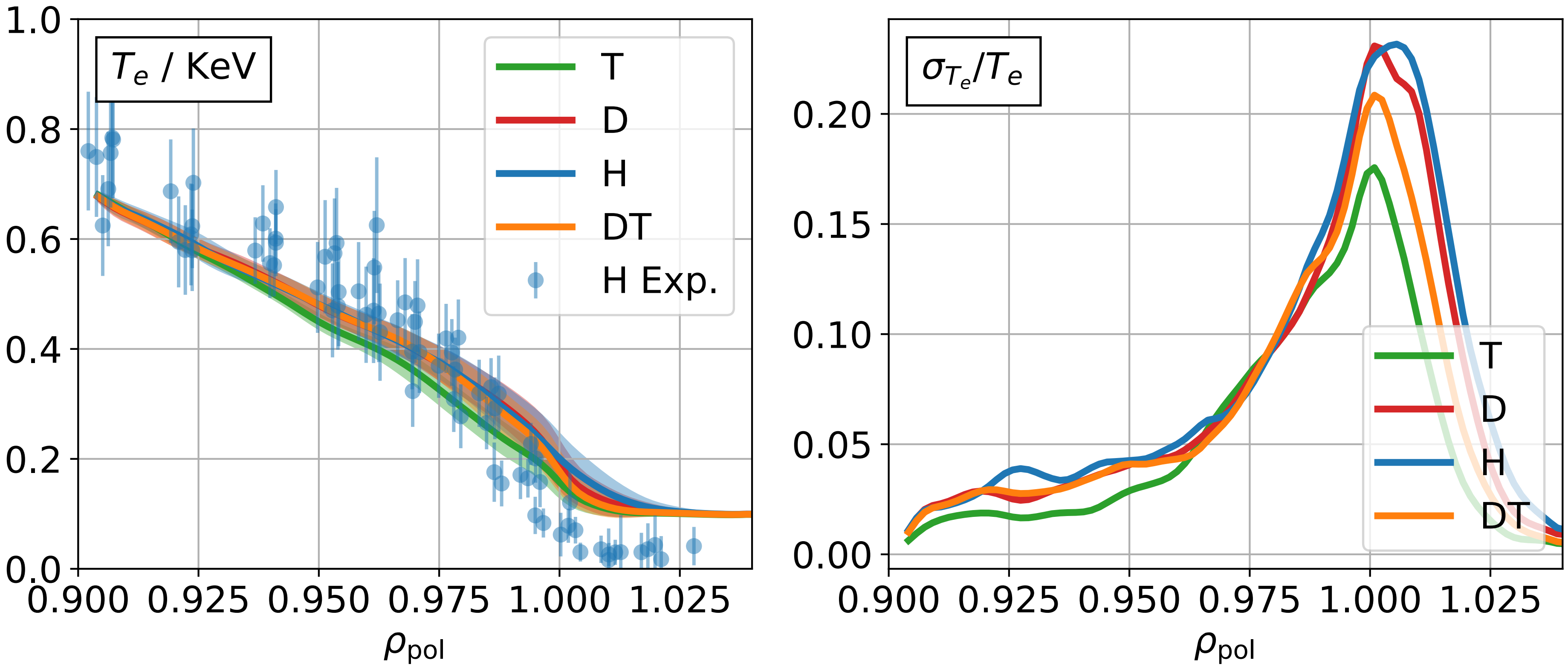
- Density significantly underestimated near separatrix $\Rightarrow$ contribution from neutrals.
- Similar density profiles for all isotopes.
- Larger fluctuation levels with heavier isotopes ($\sim 1/A_{eff}$)

Outboard Midplane Profile (OMP): Electron Temperature

Only OMP profiles of **JPN97094 (H)** are shown for validation

Key Takeaways:

- Lower T_e close to separatrix
- Larger fluctuation levels with heavier isotopes ($\sim 1/A_{eff}$)

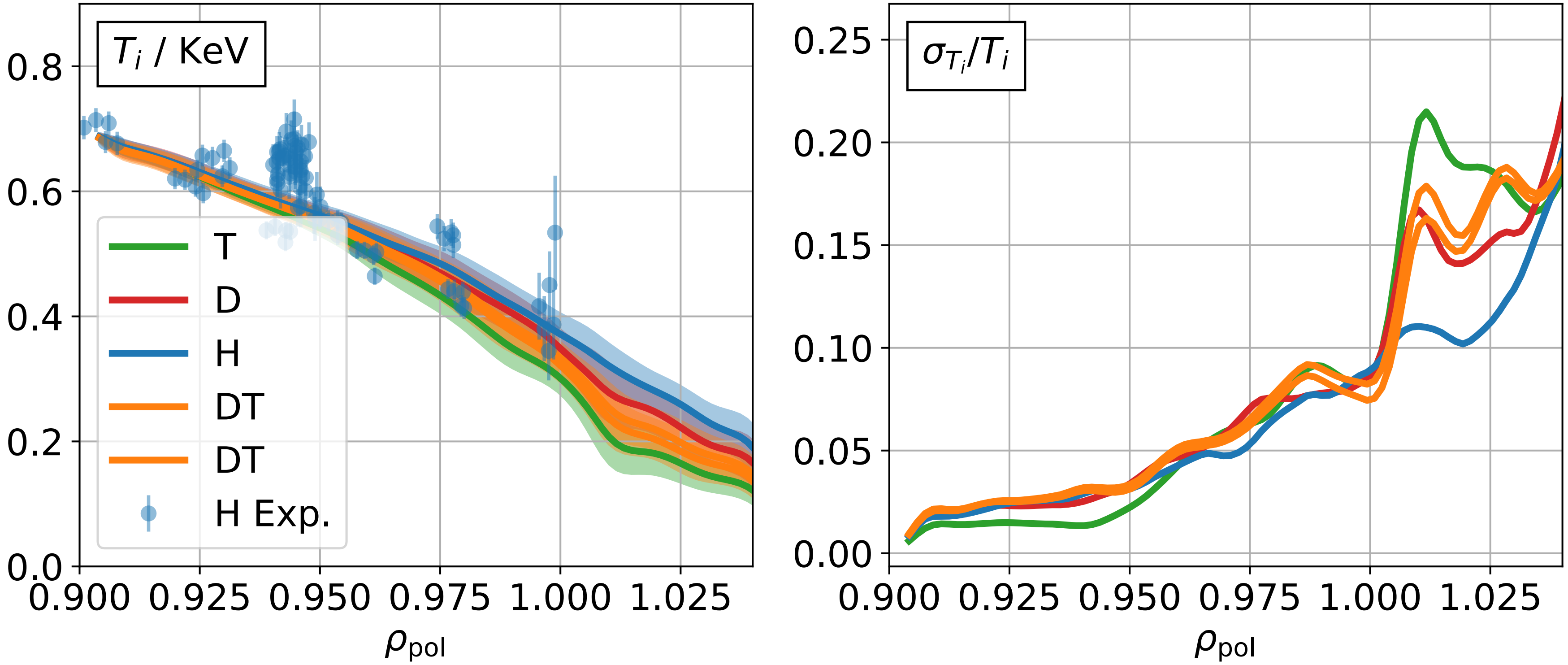


Outboard Midplane Profile (OMP): Ion Temperature

Only OMP profiles of **JPN97094 (H)** are shown for validation

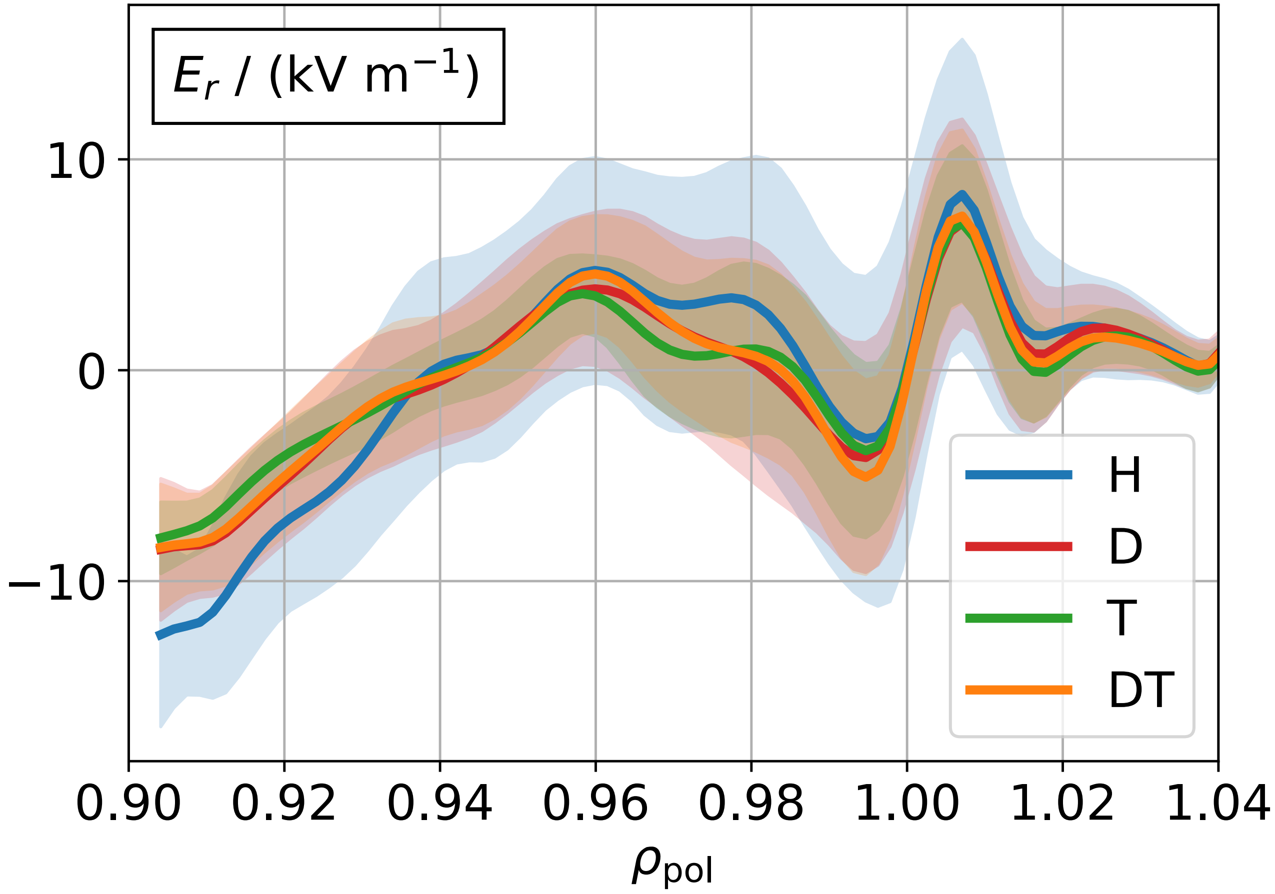
Key Takeaways:

- Lower T_i close to separatrix
- Larger fluctuation levels with heavier isotopes ($\sim 1/A_{eff}$)



Outboard Midplane Profile (OMP): Radial Electric Field

No measurement of E_r available for validation

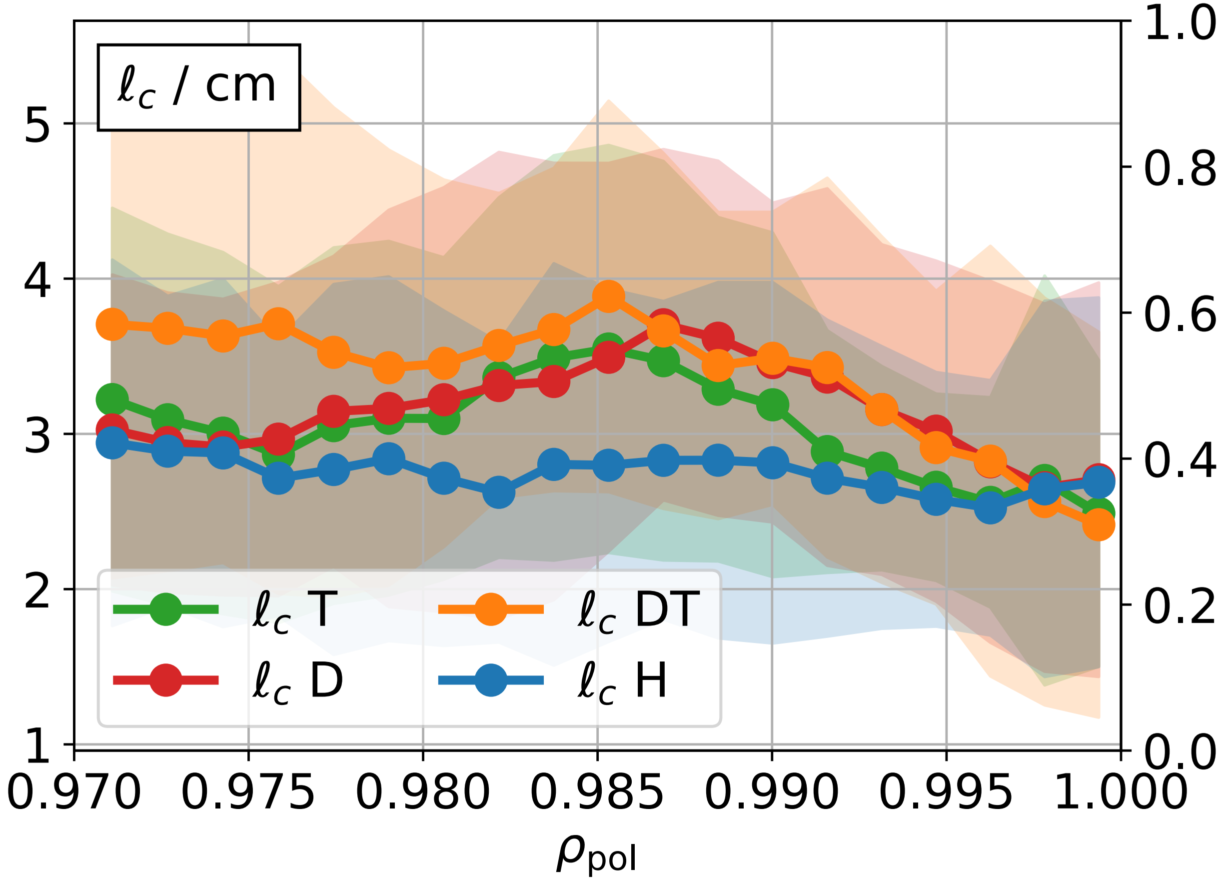


Key Takeaways:

- Similar E_r for all isotope ⇒ Similar E_r shear
- Force balance analysis still need to be performed to identify main drive (diamagnetic vs flows)

Radial Correlation Length at the OMP

Radial correlation length ℓ_c defined as $C(\ell_c)/C(0) = e^{-1}$ (C is the auto-correlation function)

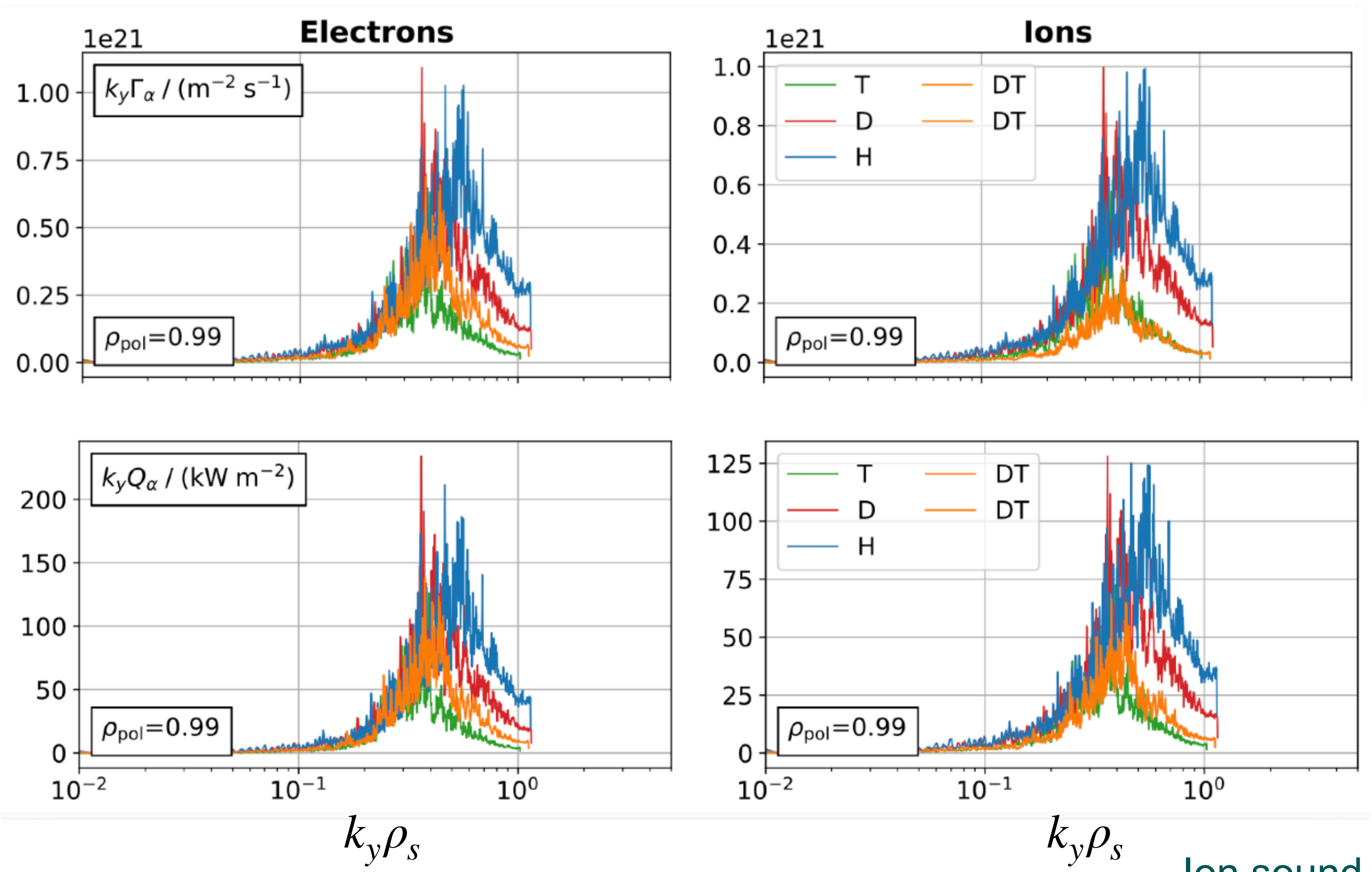


Key Takeaways:

- ℓ_c small for H (smaller turbulent structures)
- No obvious distinction between D, T and DT
- Larger reduction of ℓ_c for T than D and DT, for similar E_r shear.

Fourier Analysis of Particle and Heat Fluxes

Analysis on a single flux-surface



Key Takeaways:

- Reduction of Fourier amplitude with increasing isotope mass
- Shift of spectrum peak towards lower $k_y\rho_s$
- Similar phase-shift between isotopes

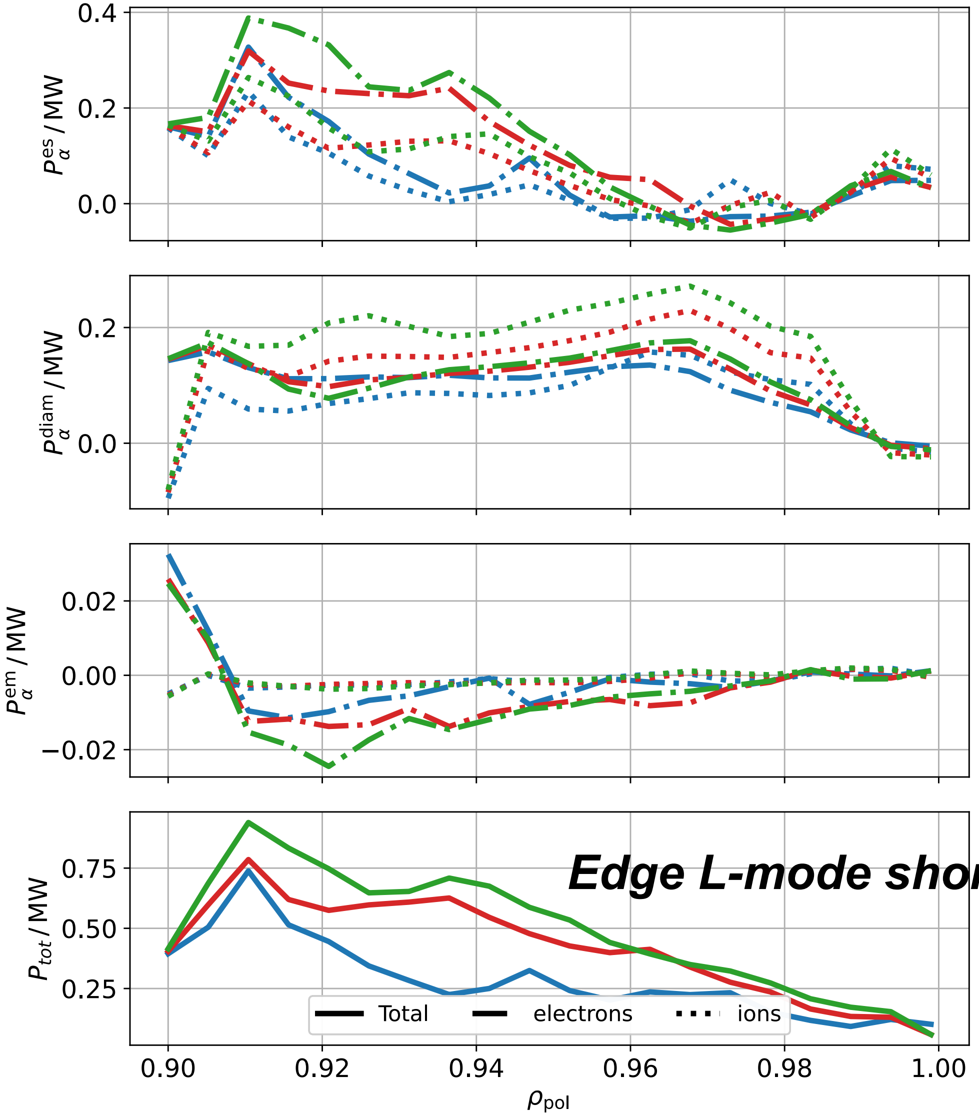
Ion sound speed ρ_s with m_p (proton mass)

Shortfall of Transport in L-mode ….

Simulations of L-modes discharges based **Lo-Cascio G.** *et al., NF 2025,* with **H, D** and **T**

Key Takeaways:

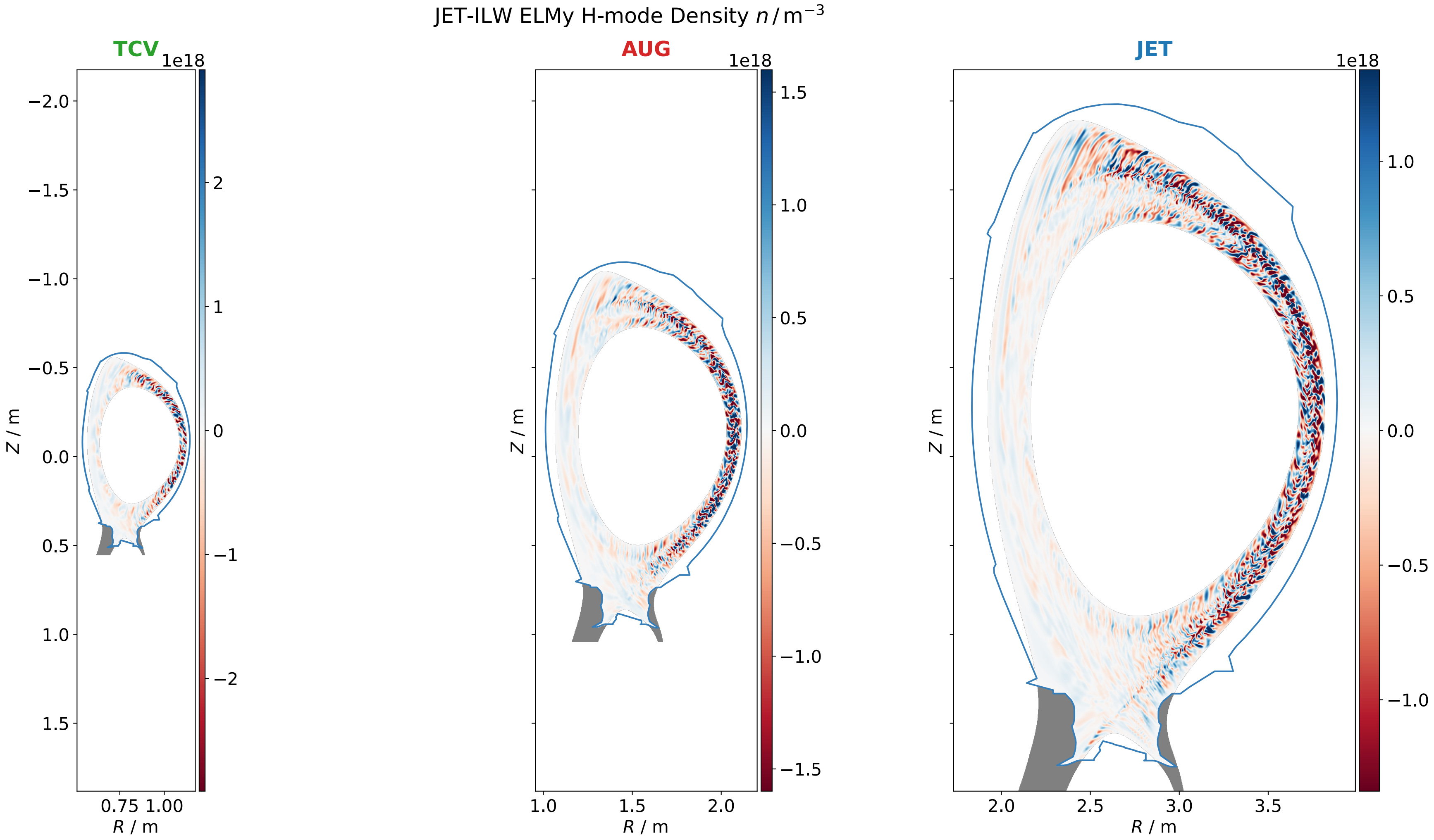
- Transport extremely low towards the separatrix even after ~10 ms…
- Dominated by slow profile evolution (diamagnetic fluxes)
- Slow propagation of turbulent structures due to machine size



Edge L-mode shortfall…

Machine Size Effects: from TCV to JET

Rescaling JET H-mode baseline to TCV and AUG size by changing $L_{ref} \sim R_0$



Conclusions and Outlook

- Performed the first edge and SOL turbulence simulations at JET with different isotopes (H, D, T) including DT
- Preliminary analysis show $1/A_{eff}$ of the power crossing spearatrix
- Small difference in the OMP profiles, but higher level of fluctuations obtained with decreasing isotope mass.
- Turbulent spectrum peaks towards lower wavenumber with higher isotopes
- Radial electric field similar; hence similar ExB shear.
- ***Isotope effects on the turbulent fluxes caused by different levels of fluctuations.***
- ***Shortfall turbulent transport in L-mode simulations …***

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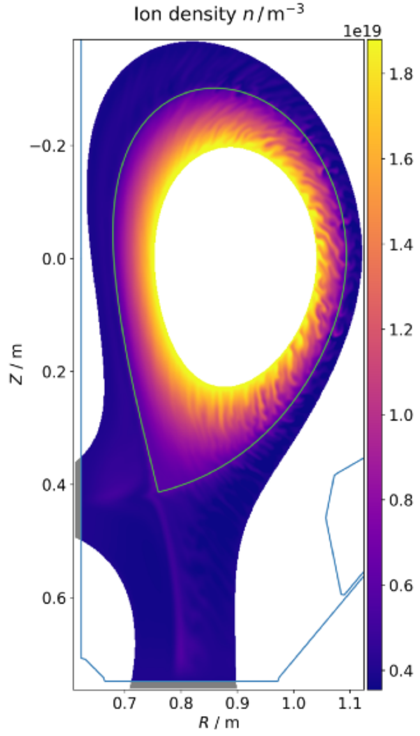
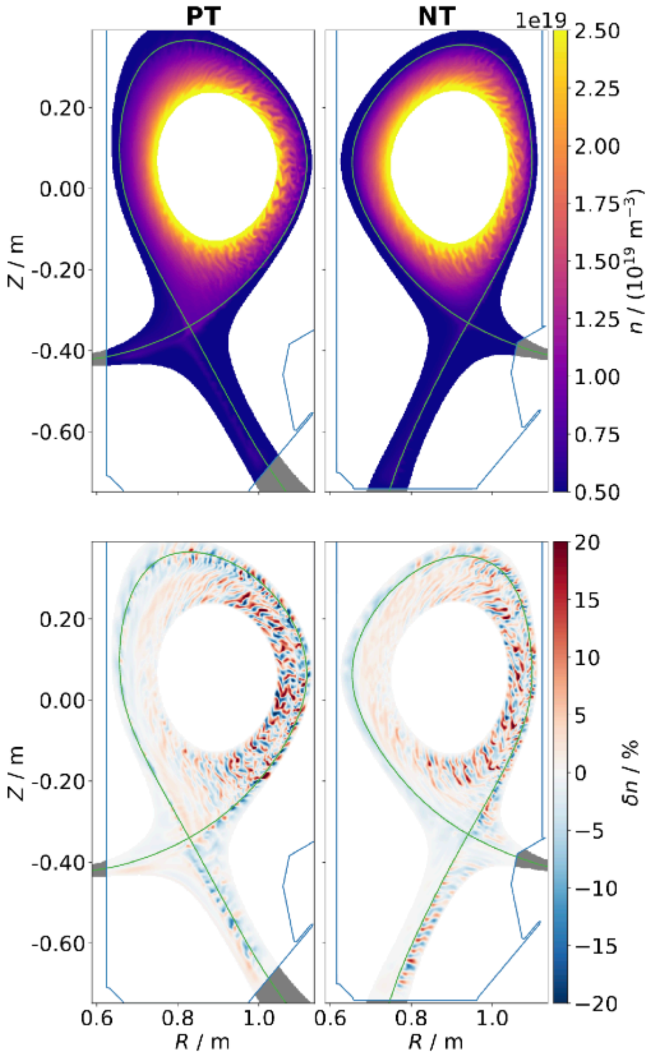
Backup slides

GENE-X Validated in Numerous L-mode Scenarios and Medium-Sized Devices (TCV and AUG)

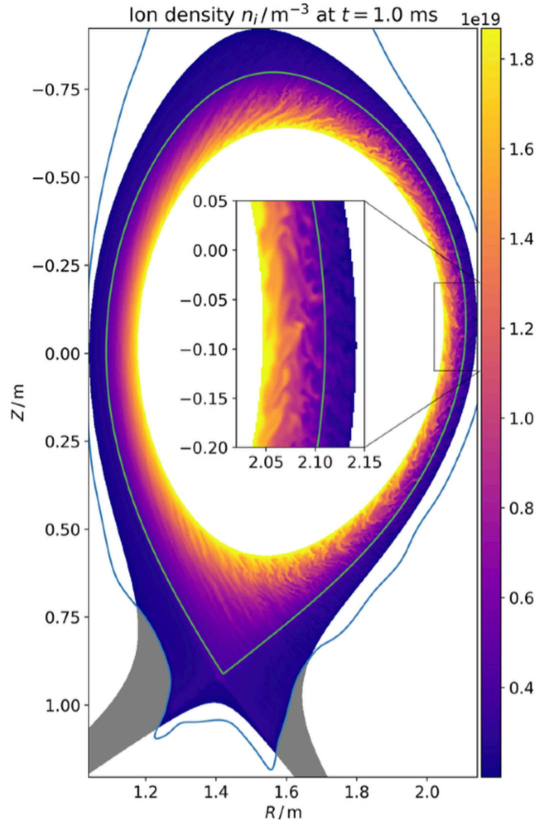
[P. Ulbl *et al.*, *PoP* **30** (2023)]



[P. Ulbl *et al.*, *NF* **64** (2025)]



[D. Michels *et al.*, *PoP* **29** (2022)]



Requires $\gtrsim 2$ MCPUh on $\gtrsim$ 512 (CPU) nodes $\Rightarrow$ Prohibits efficient applications