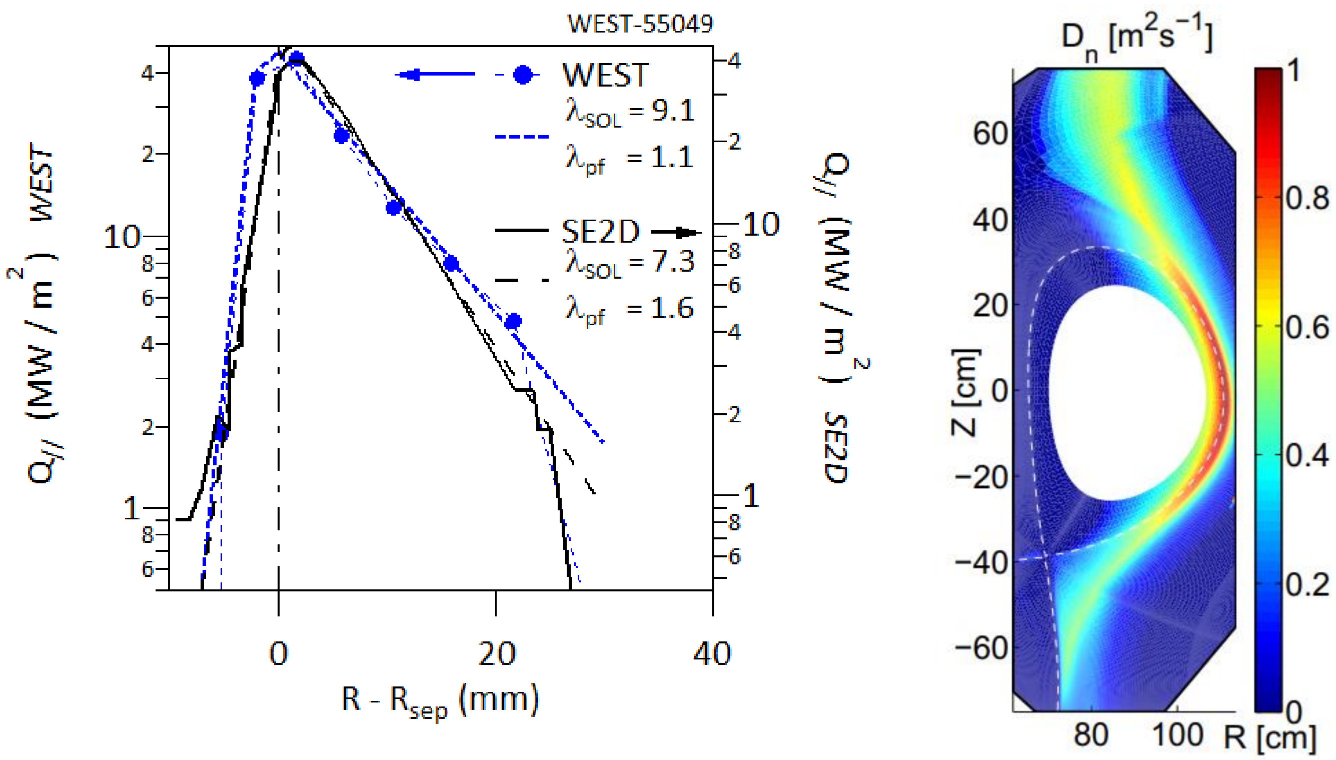
REDUCED TURBULENCE MODELS IN MEAN-FIELD CODES

- RANS(Reynolds-Averaged-Navier-Stokes)-like models developed as intermediate steps in hierarchy of models: 2 flavors developed with different methods but basically the same ingredients *[R. Coosemans, CPP 2022] [S. Baschetti, NF 2021]*

$$\frac{\partial}{\partial t}\bar{n}\kappa_{\perp} + \nabla\cdot\left(\bar{\boldsymbol{\Gamma}}_i\kappa_{\perp} + \frac{1}{2}\overline{mn\boldsymbol{V}''V''^{2}_{E\times B}} + \overline{\phi'\boldsymbol{J}'_{||}}\right) = \bar{S}_{IC} + \bar{S}_{||} + \bar{S}_{RS}$$

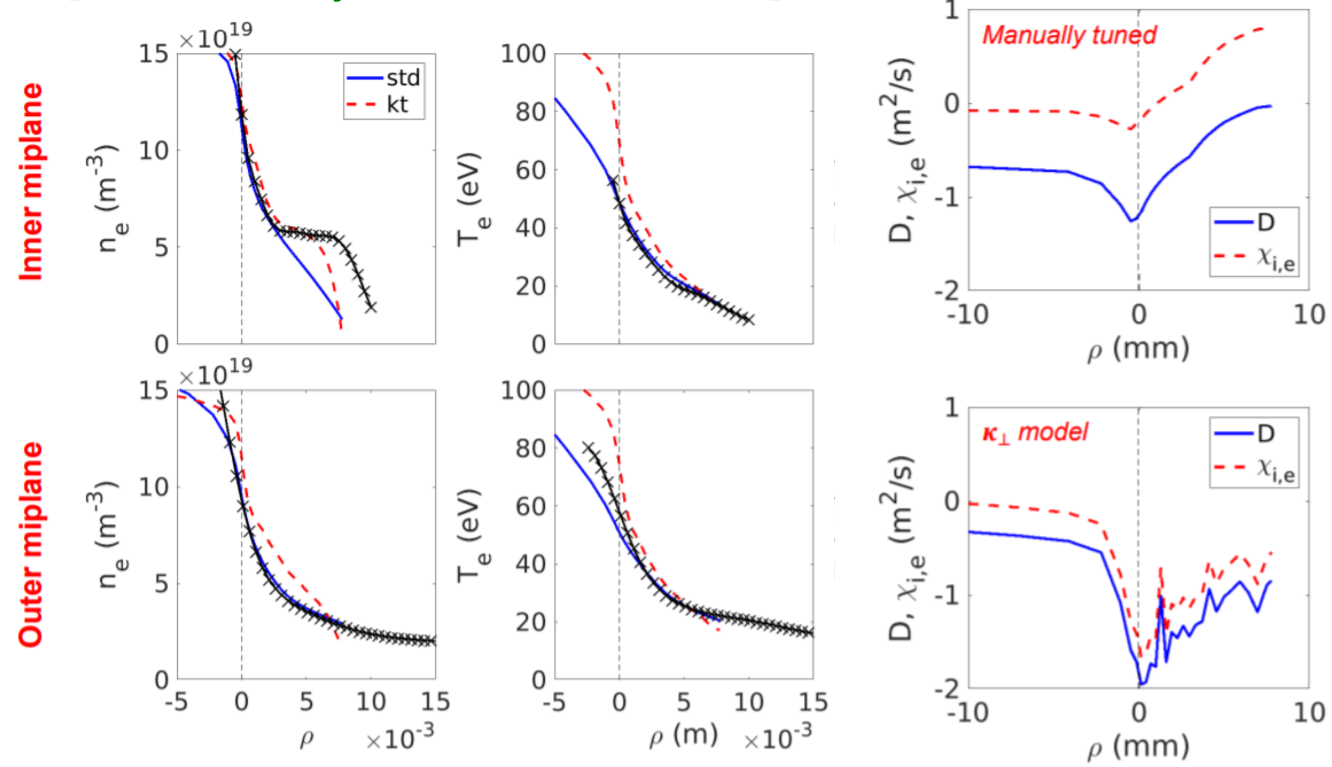
$$D_{E\times B} \sim \frac{C_D\kappa_{\perp}}{\sqrt{\kappa_{\perp}/\mathrm{m}_i}/\rho_L + C_s\left|\nabla\bar{V}_{E\times B}\right|} \qquad \chi_{E\times B} \sim D_{E\times B} \sim \eta_{E\times B}$$

- Applied to WEST (SOLEDGE3X) and C-mod (SOLPS-ITER)



[S. Baschetti, NF 2021]

[W. Dekeyser, CPP 2022]

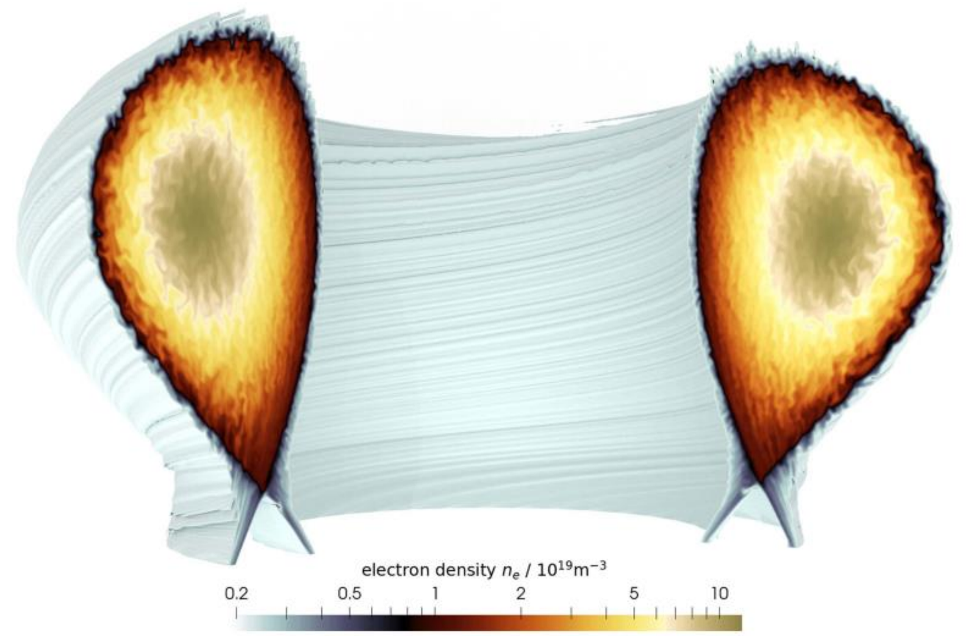


- On-going extension to include parallel dynamics, impact of recycling, DW physics…

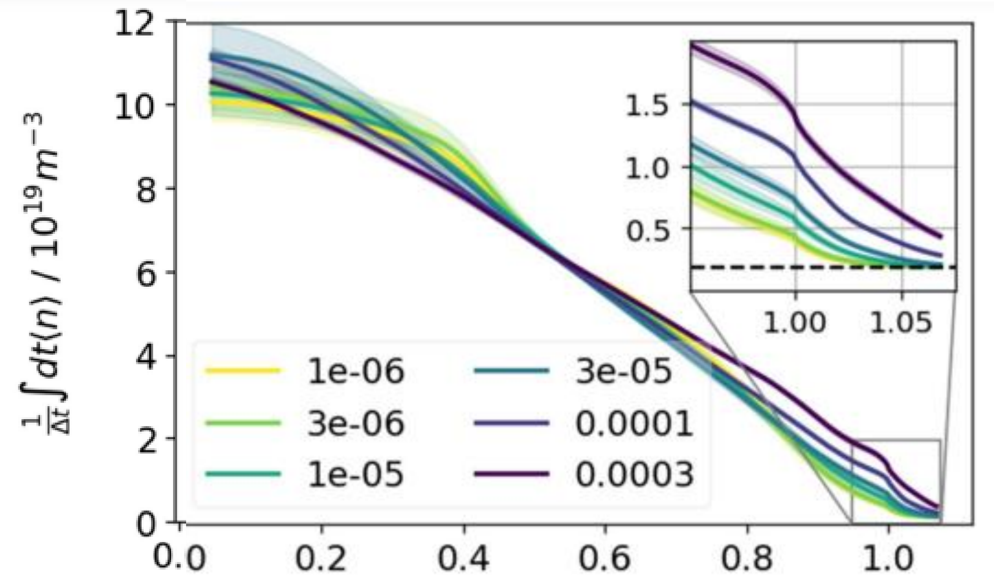
PROGRESS IN GYROFLUID TURBULENCE MODELLING

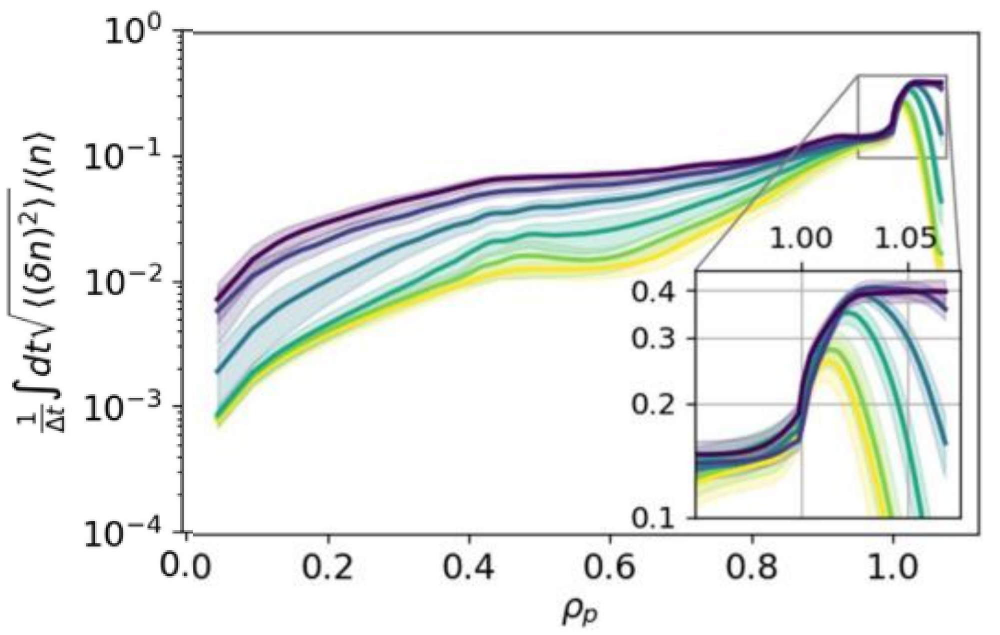
- FELTOR code: Gyrofluid plasma turbulence
  - Open source https://feltor-dev.github.io/

    [M. Wiesenberger, NF 2020; M. Wiesenberger, CPC 2019; M. Wiesenberger, JCP 2023]



- Current status:
  - Isothermal model for density and parallel velocity
  - Realistic magnetic field geometry including X-point, triangularity, shear, etc…
  - Fully parallelized and optimized for GPUs
  - Allows stable three-dimensional turbulence simulations of several milliseconds
  - Non-isothermal model with neutrals being implemented





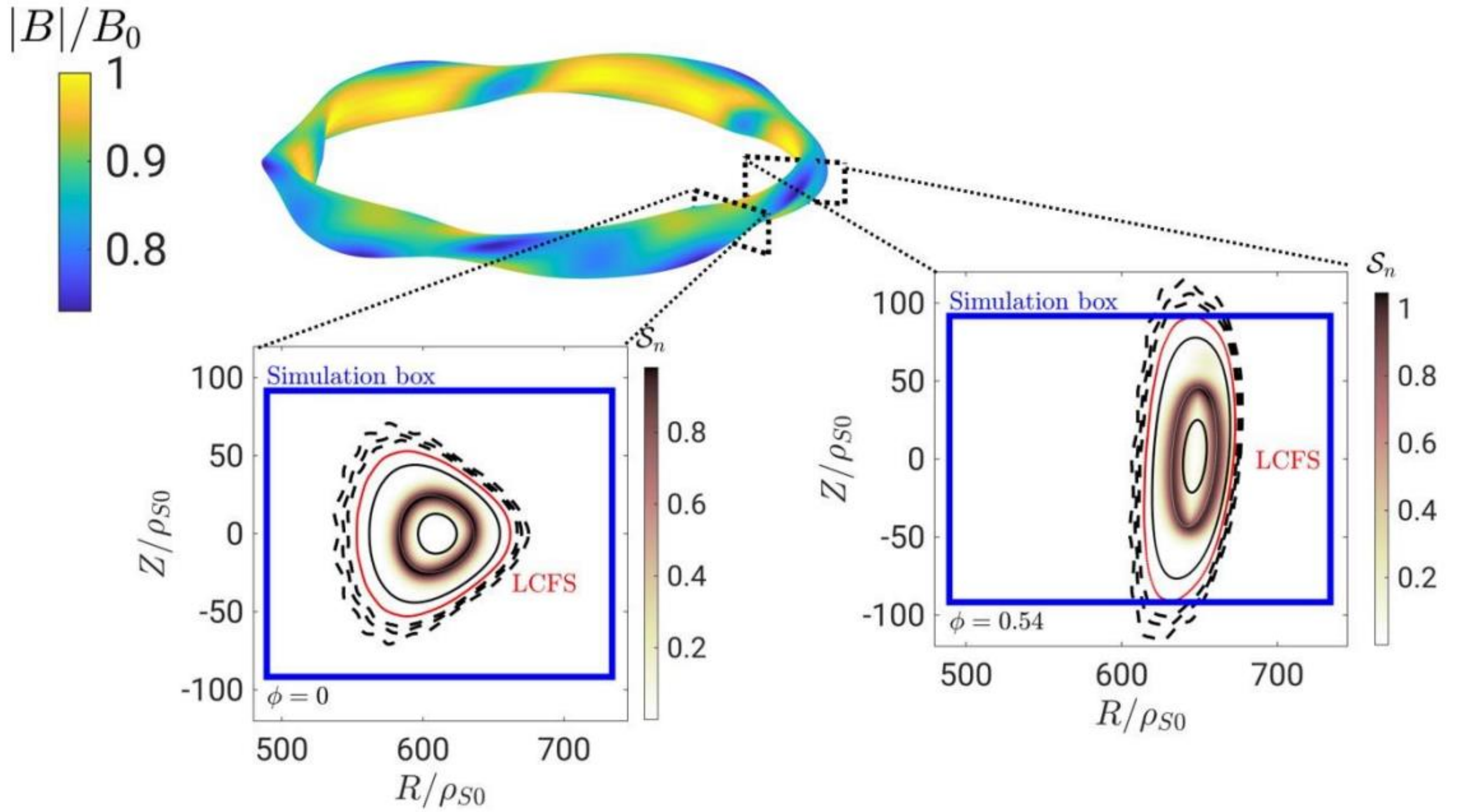
- Recently applied to impact of resistivity on turbulence

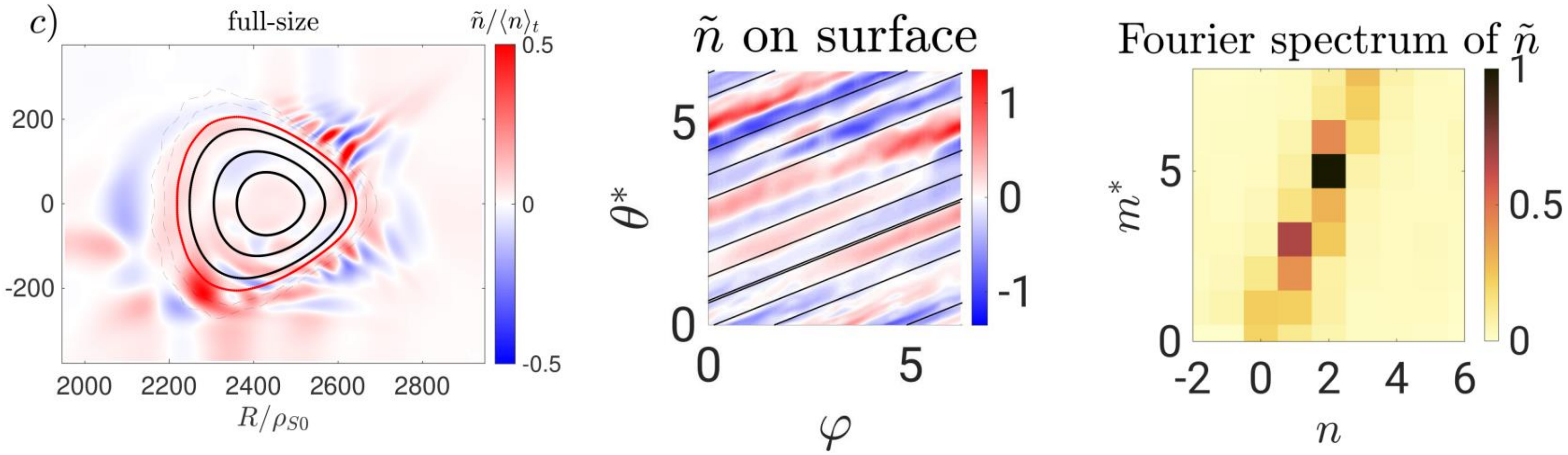
[M. Wiesenberger, PPCF 2024]

GBS AND GRILLIX TACKLING W7-AS EXPERIMENTS

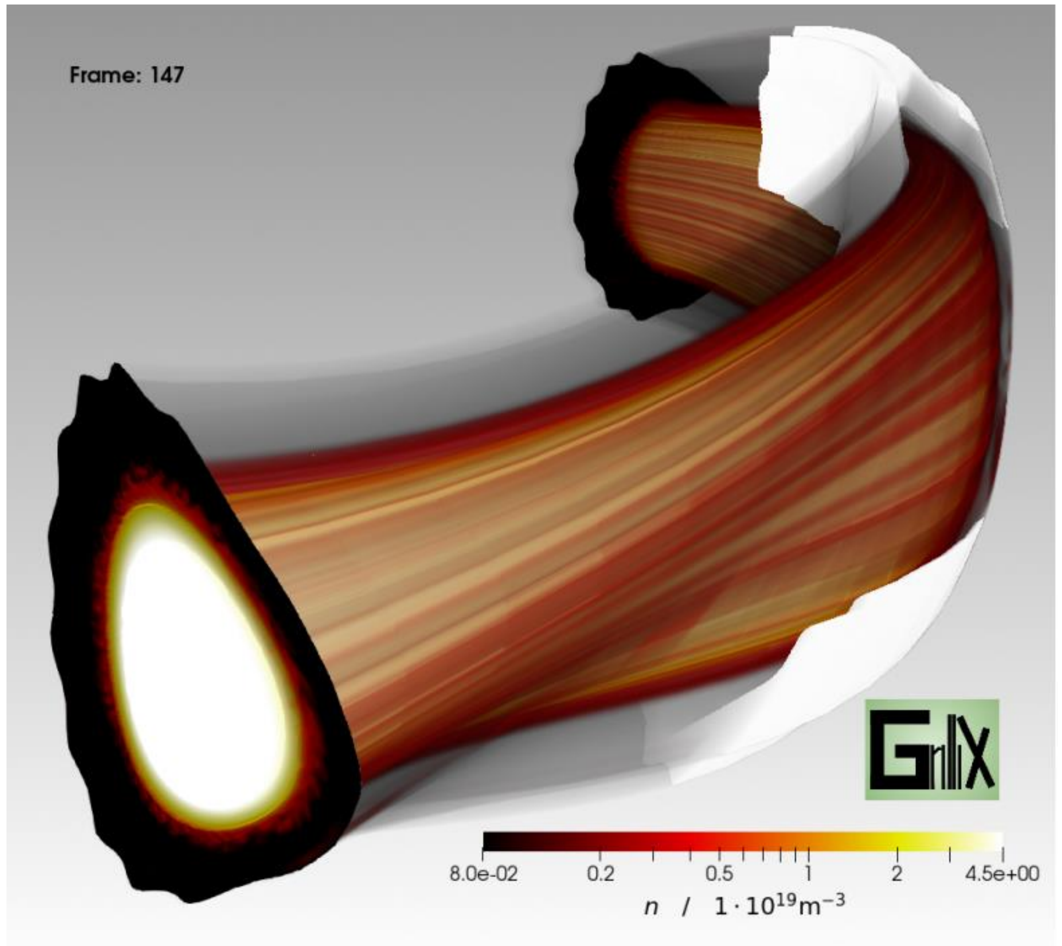
- GBS applied to W7-AS
  - Blobs present, cross-field transport dominated by the ExB in the SOL (~experiments)
  - Turbulence is ballooning driven

[courtesy Z. Tecchiolli]

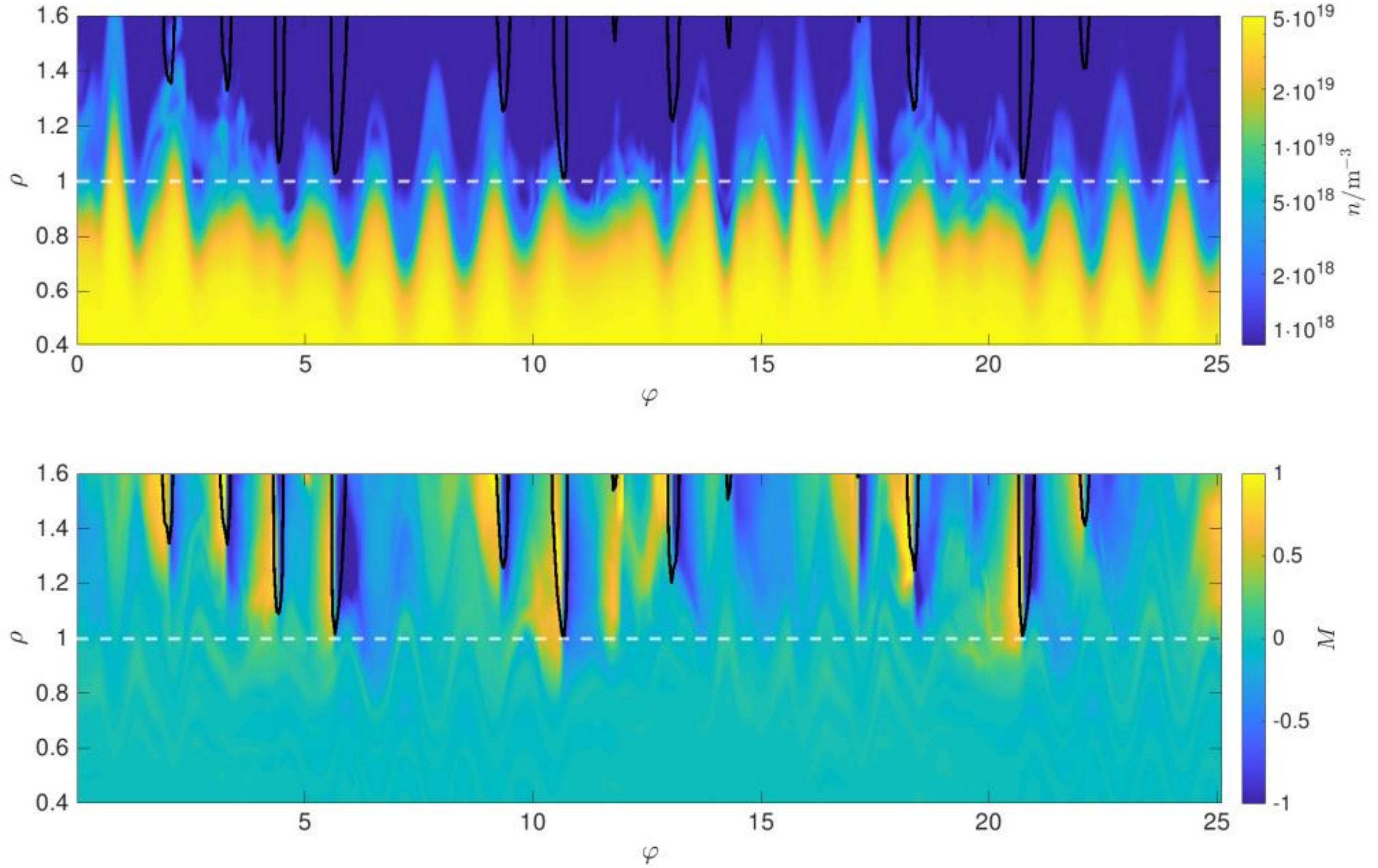


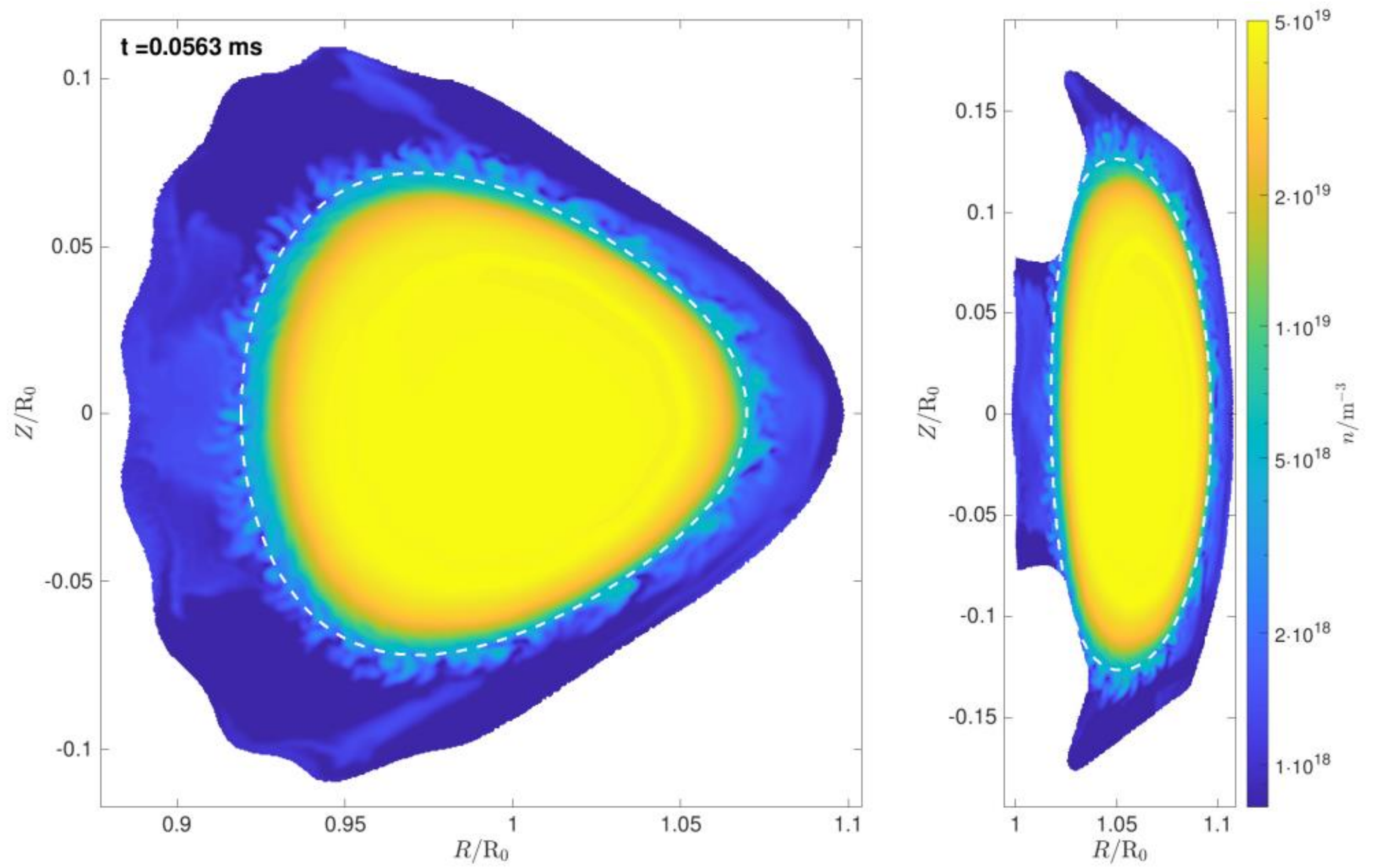


- GRILLIX applied to W7-AS:
    - Shafranov shift observed, as only background vacuum field is prescribed
    - No large scale mode so far
    - Small scale field-aligned turbulent structures
    - Parallel mode observed, representing discrete symmetry of W7-AS



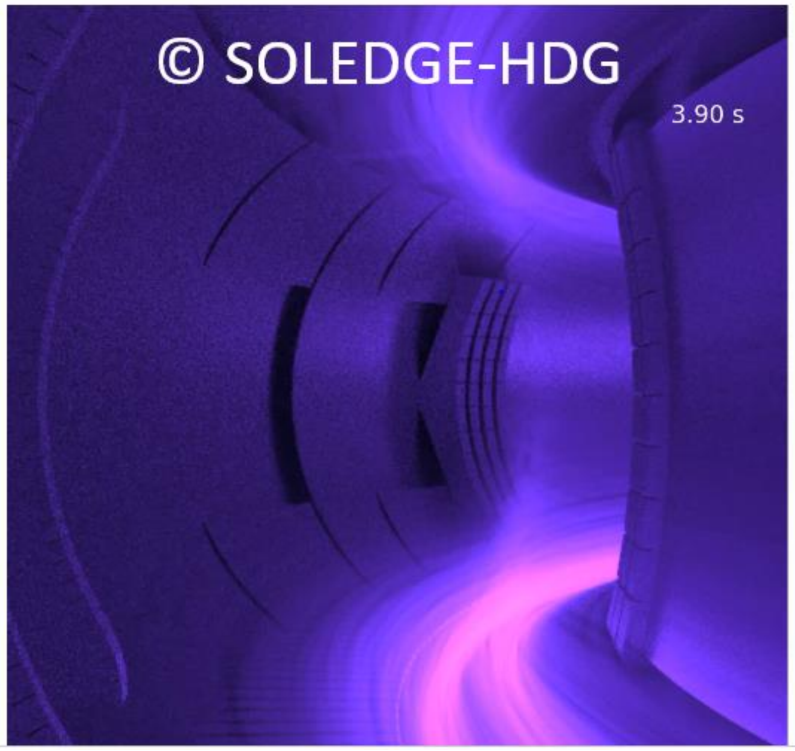
[A. Stegmeir et al, to be submitted to CPC]



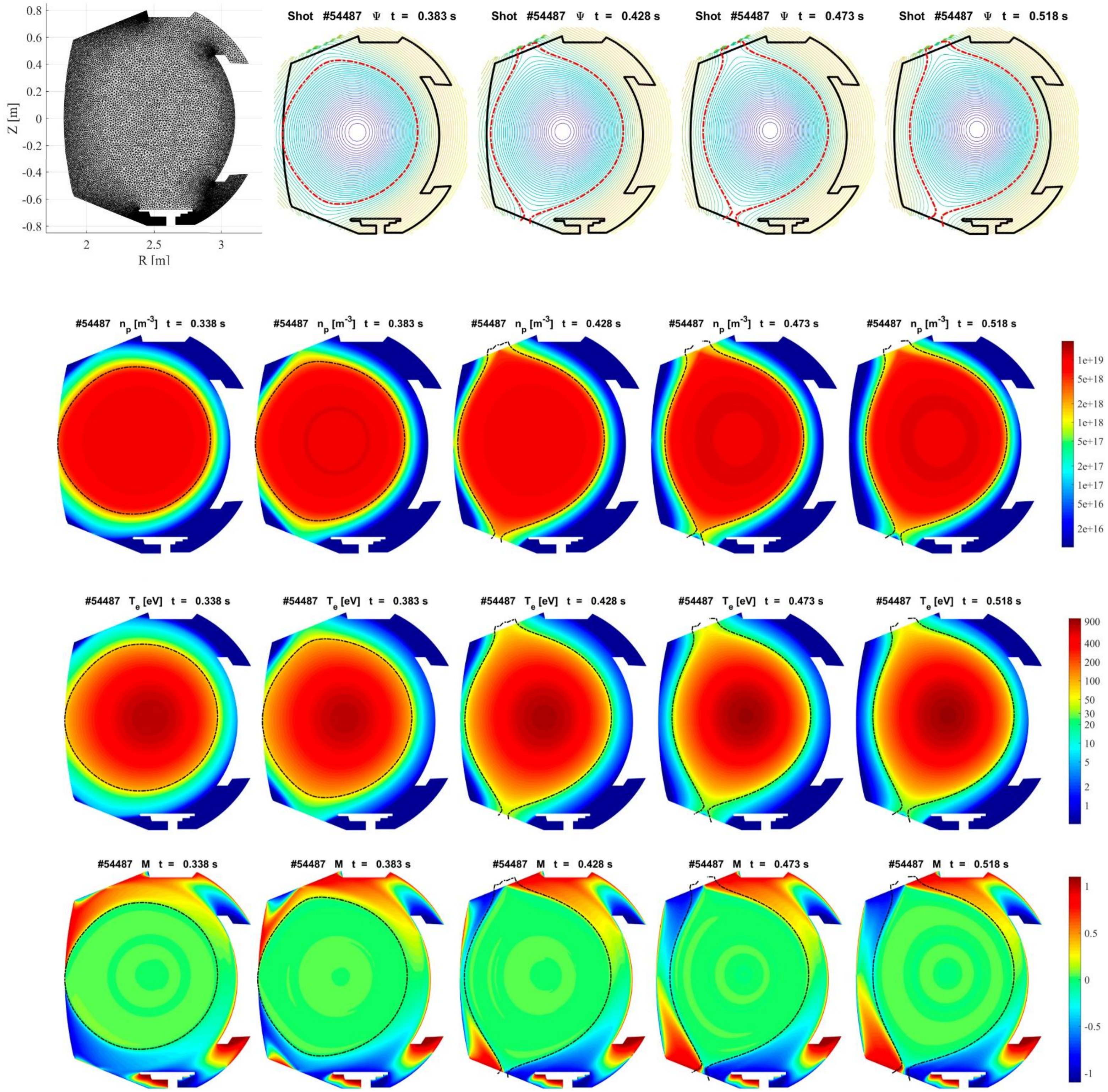


HDG APPROACH ALLOWS COMPLETE GEOMETRICAL FLEXIBILITY

- **Hybrid Discontinuous Galerkin (HDG)** approach offers accurate description of magnetic and wall geometries
  - Applied to 2D modelling of dynamic equilibrium from start-up to ramp-down
  - Combined with synthetic diagnostics to ease comparison to experiments



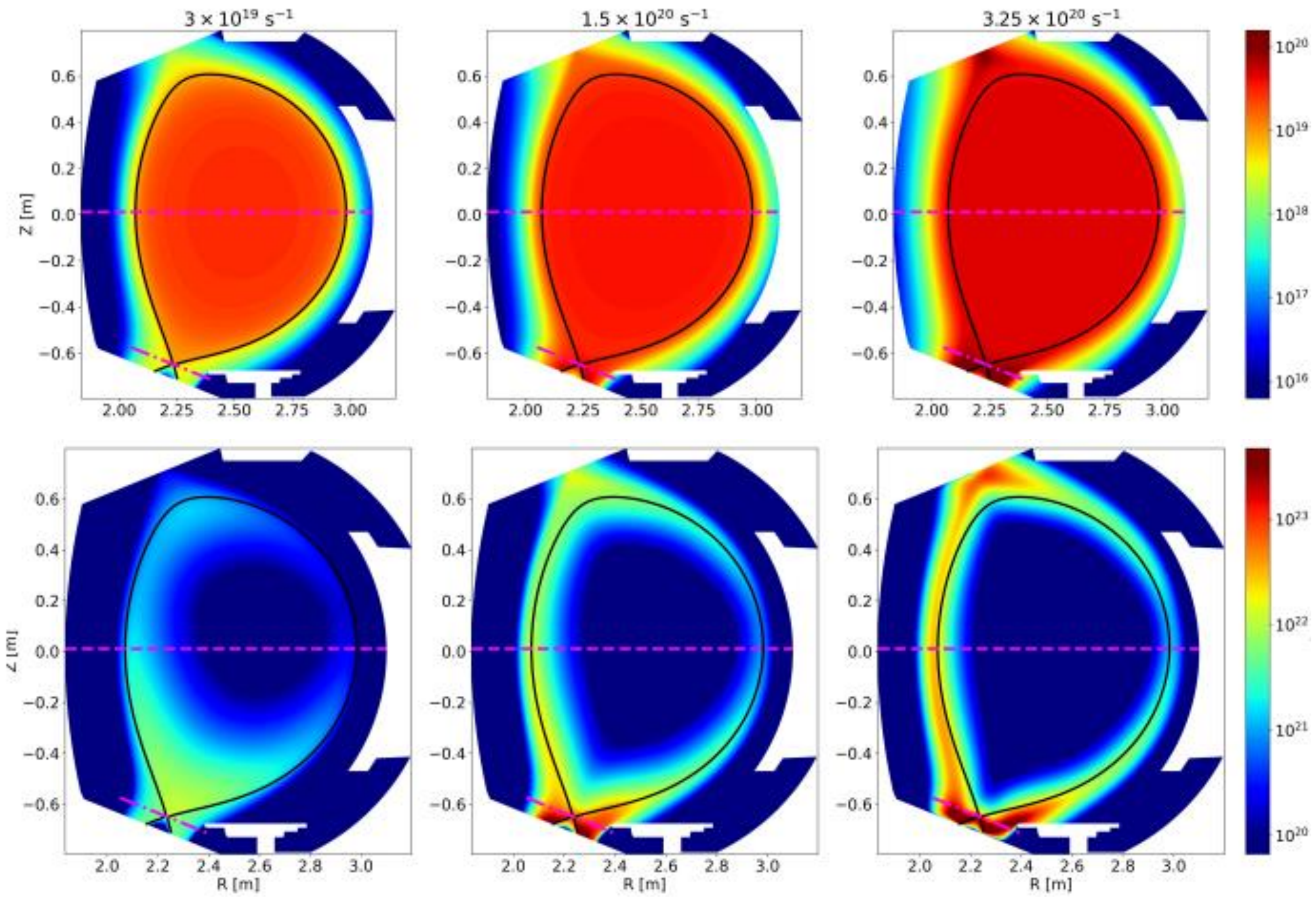
[I. Kudashev, Appl. Sci. 2022]

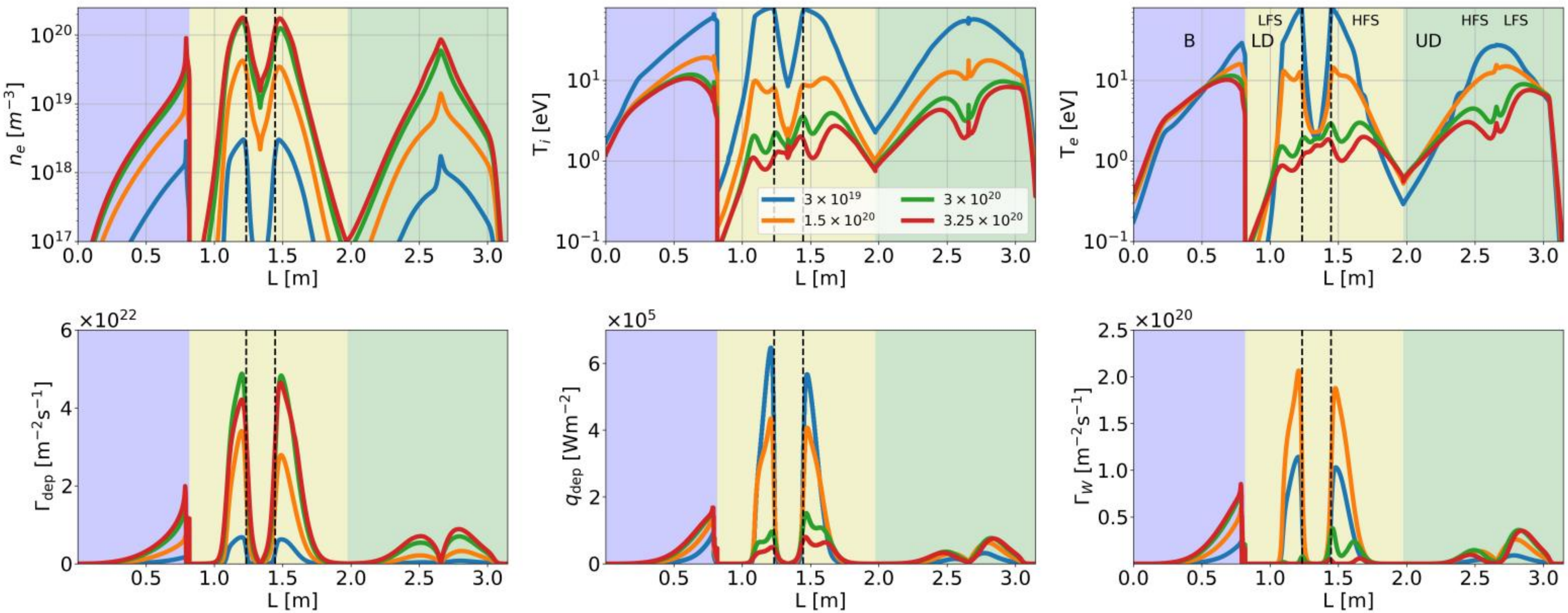


[M. Scotto, NF 2022]

- HDG approach extended with fluid neutrals model
  - Applied to WEST from attached to detached plasma,
  - Estimate W sputtering all along the wall

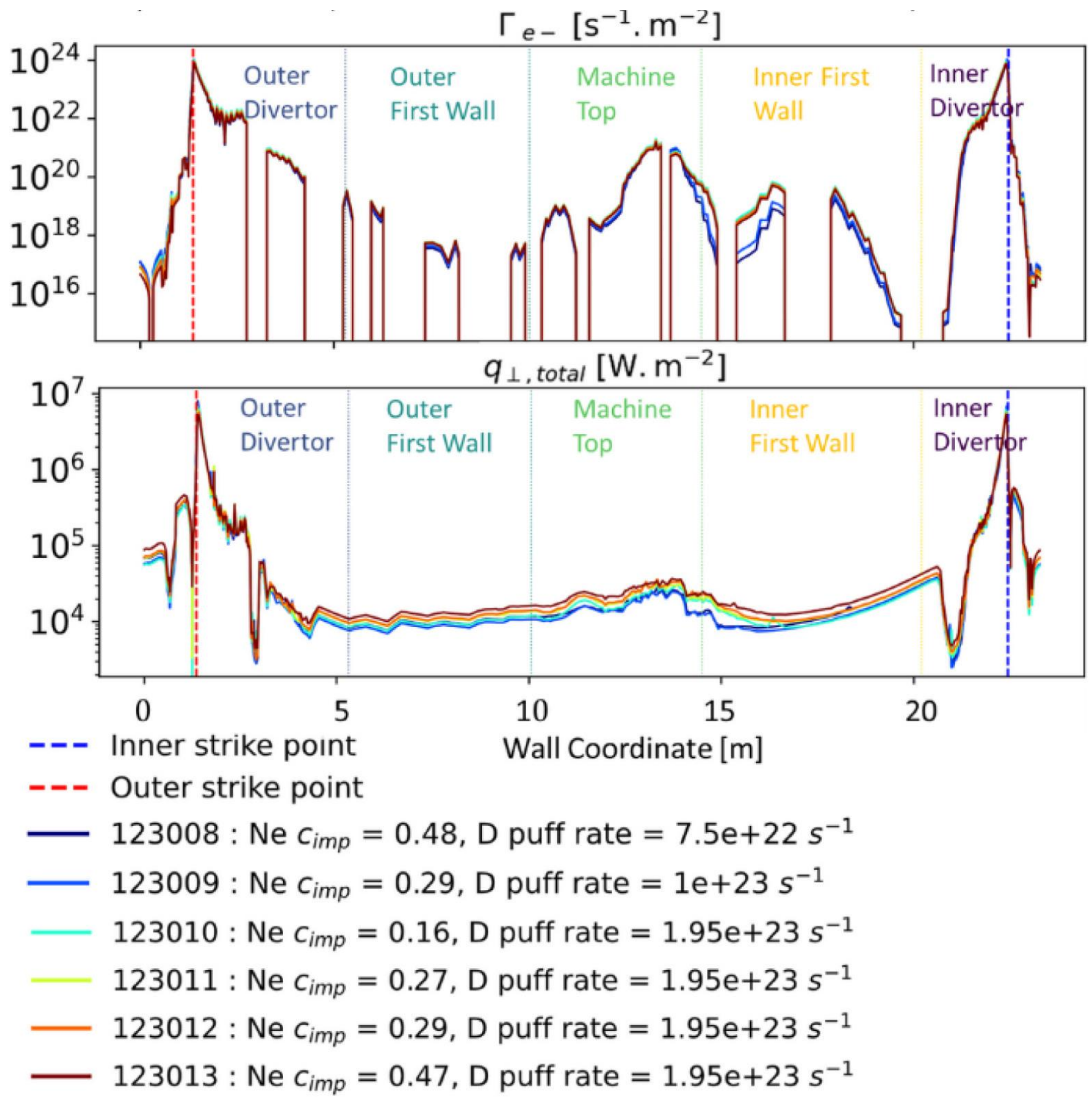
[I. Kudashev, Frontiers in Phys. 2024]

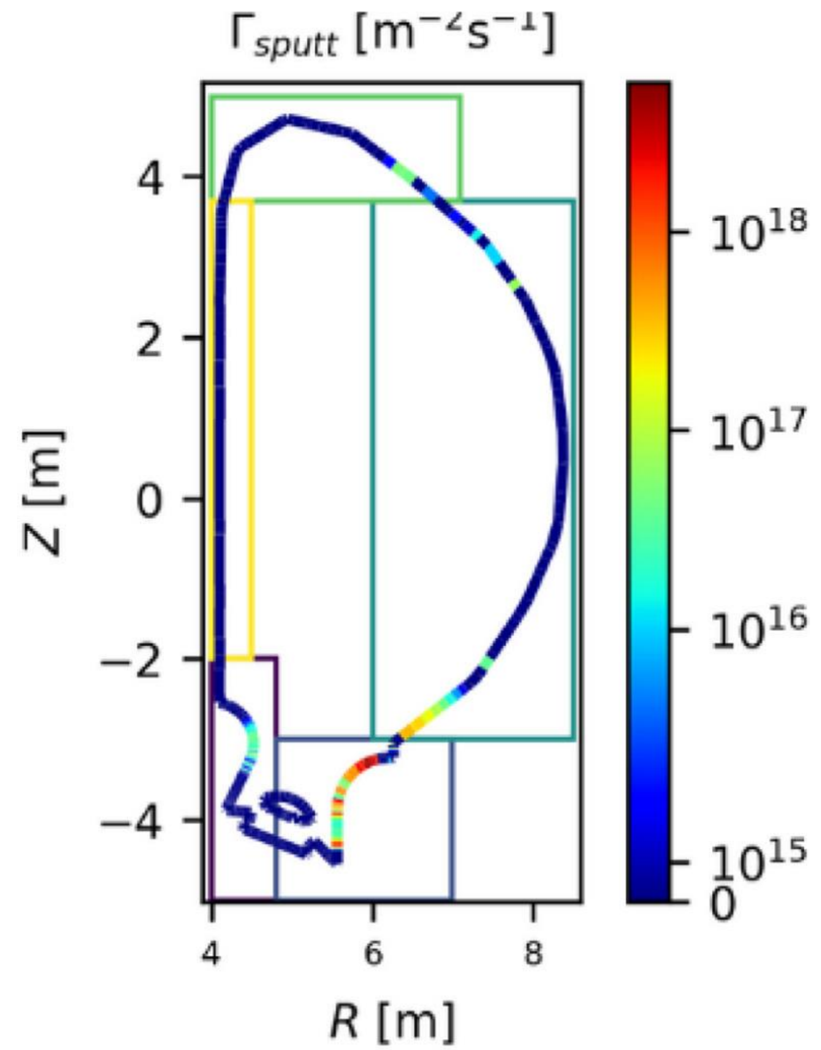


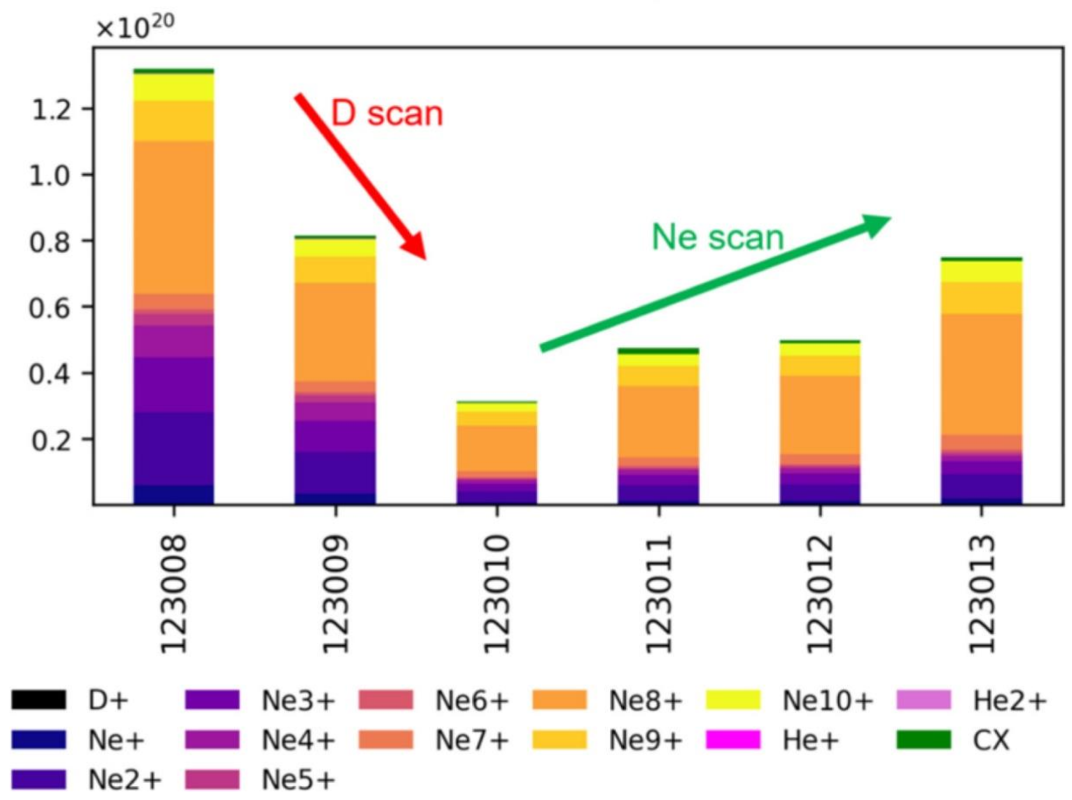


UP-TO-THE-WALL HIGH POWER ITER SIMULATIONS

- After low power PFPO plasmas *[N. Rivals, submitted to NF]*, SOLEDGE3X simulations up-to-the-wall for high power seeded FPO Scenario
  - First self-consistent W gross-erosion evaluation for ITER rebase-lning





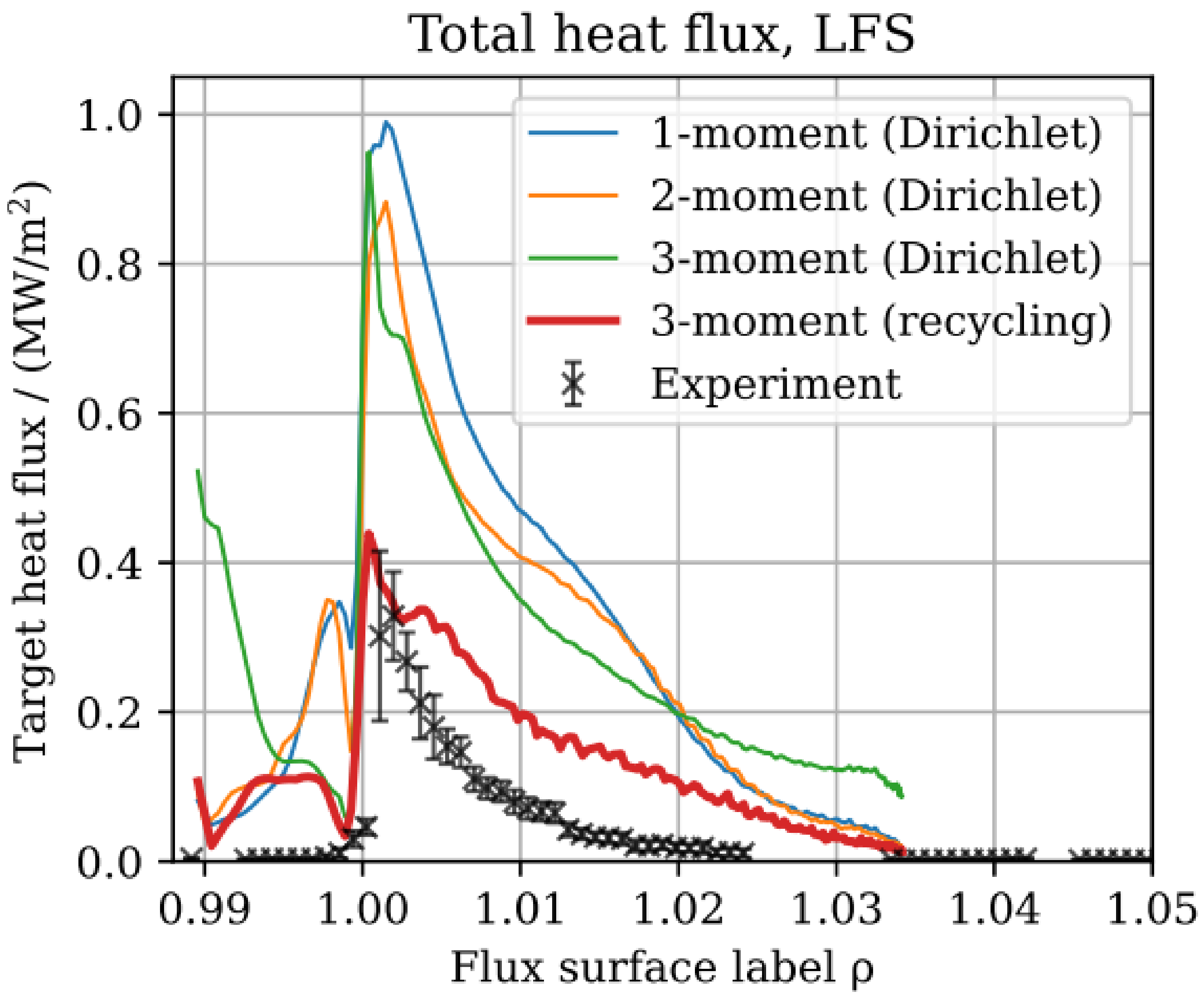


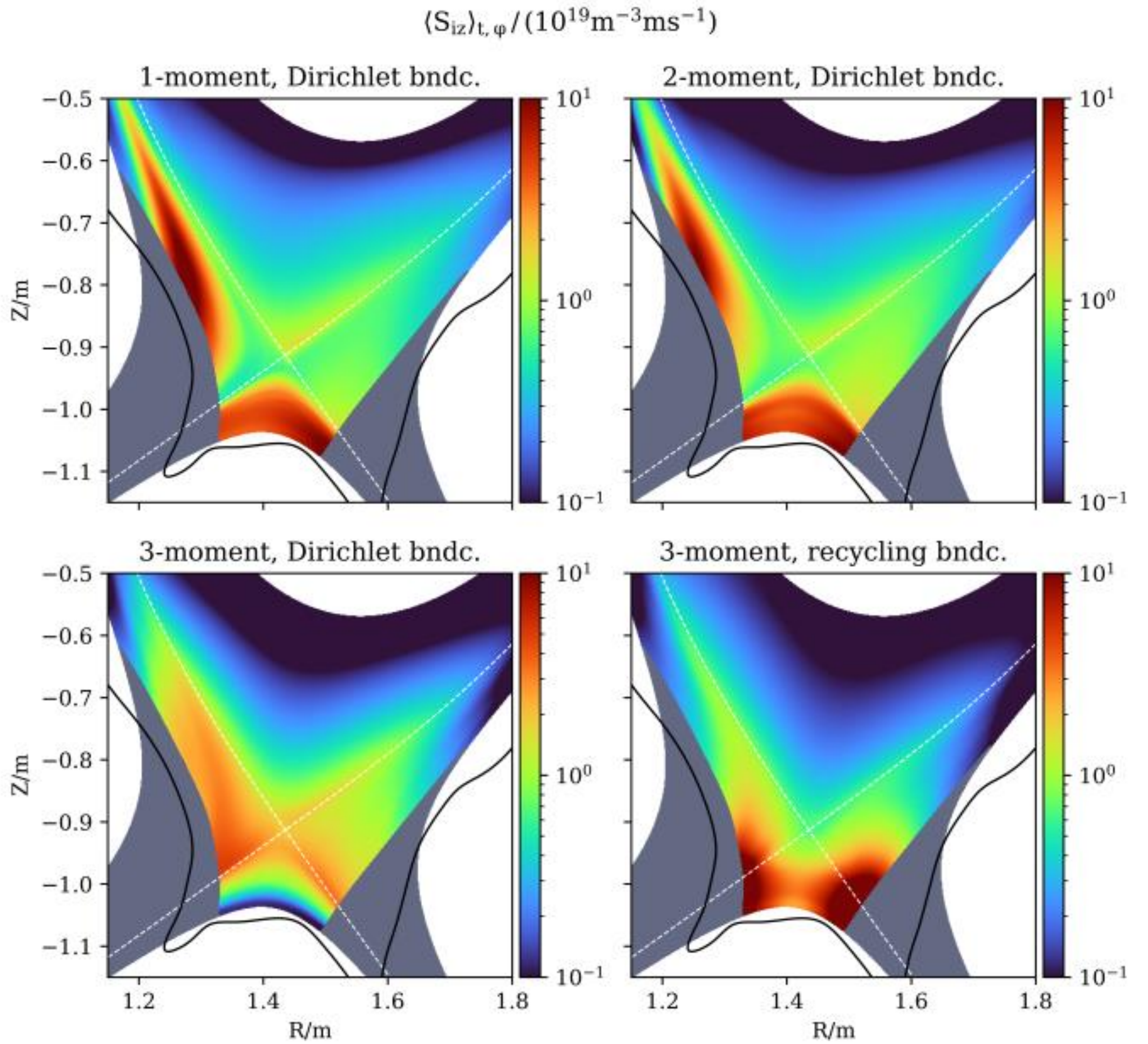
[S. Sureshkumar, NME 2024]

SELF-CONSISTENT NEUTRALS RECYCLING IN GRILLIX

- Advanced fluid neutrals model implemented in GRILLIX
  - Highlights importance of self-consistent recycling boundary cond.

[K. Eder et al, submitted to PPCF]

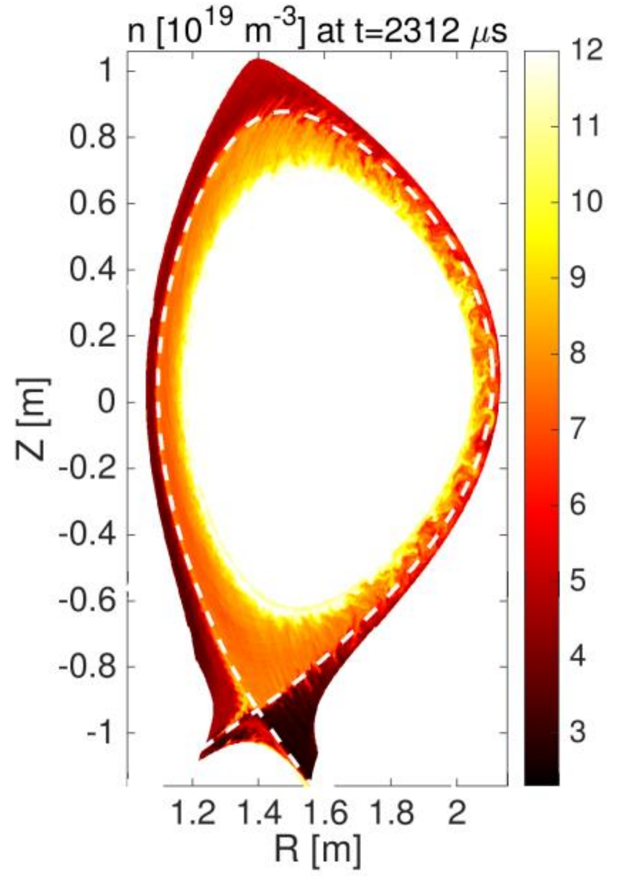


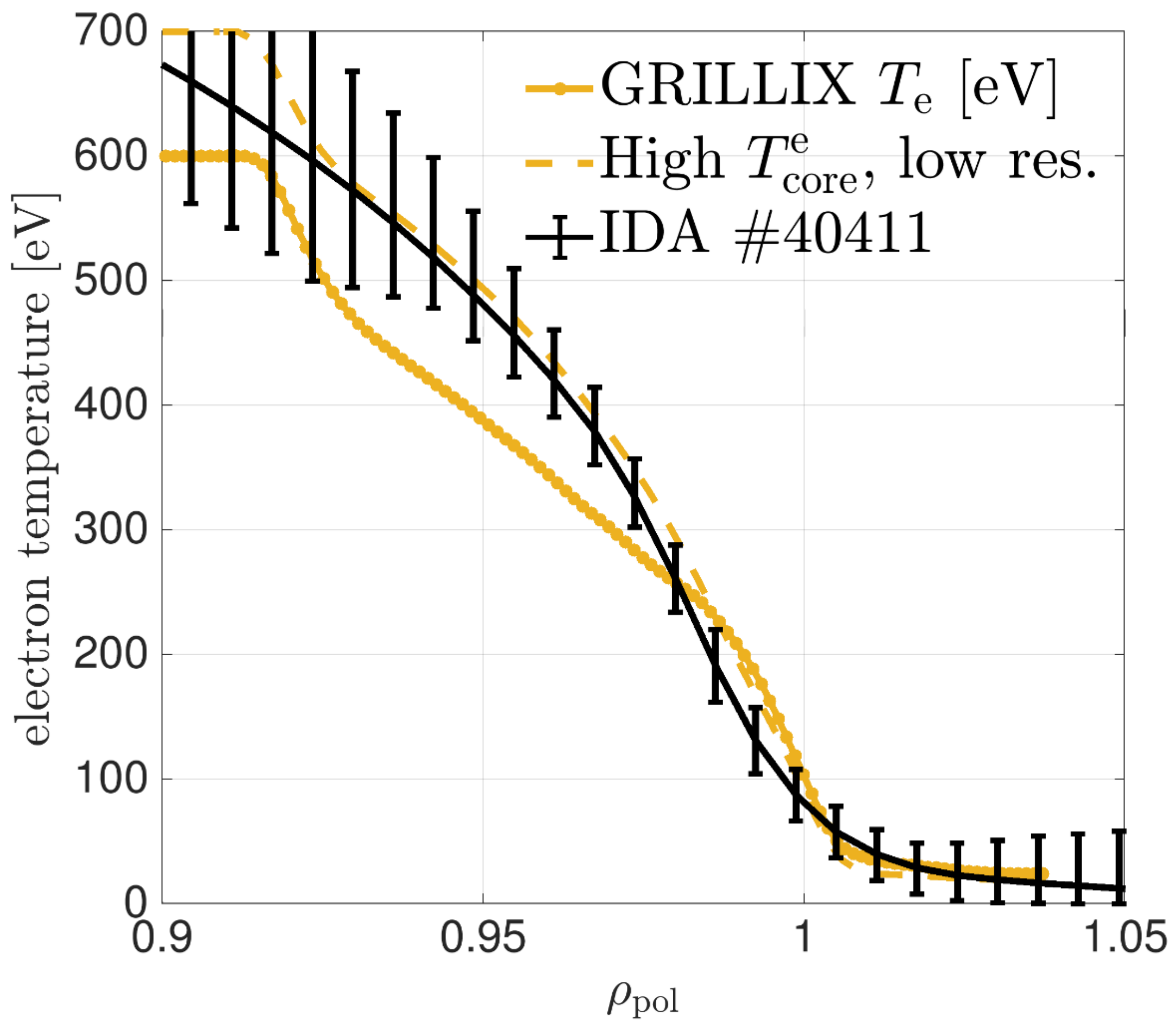


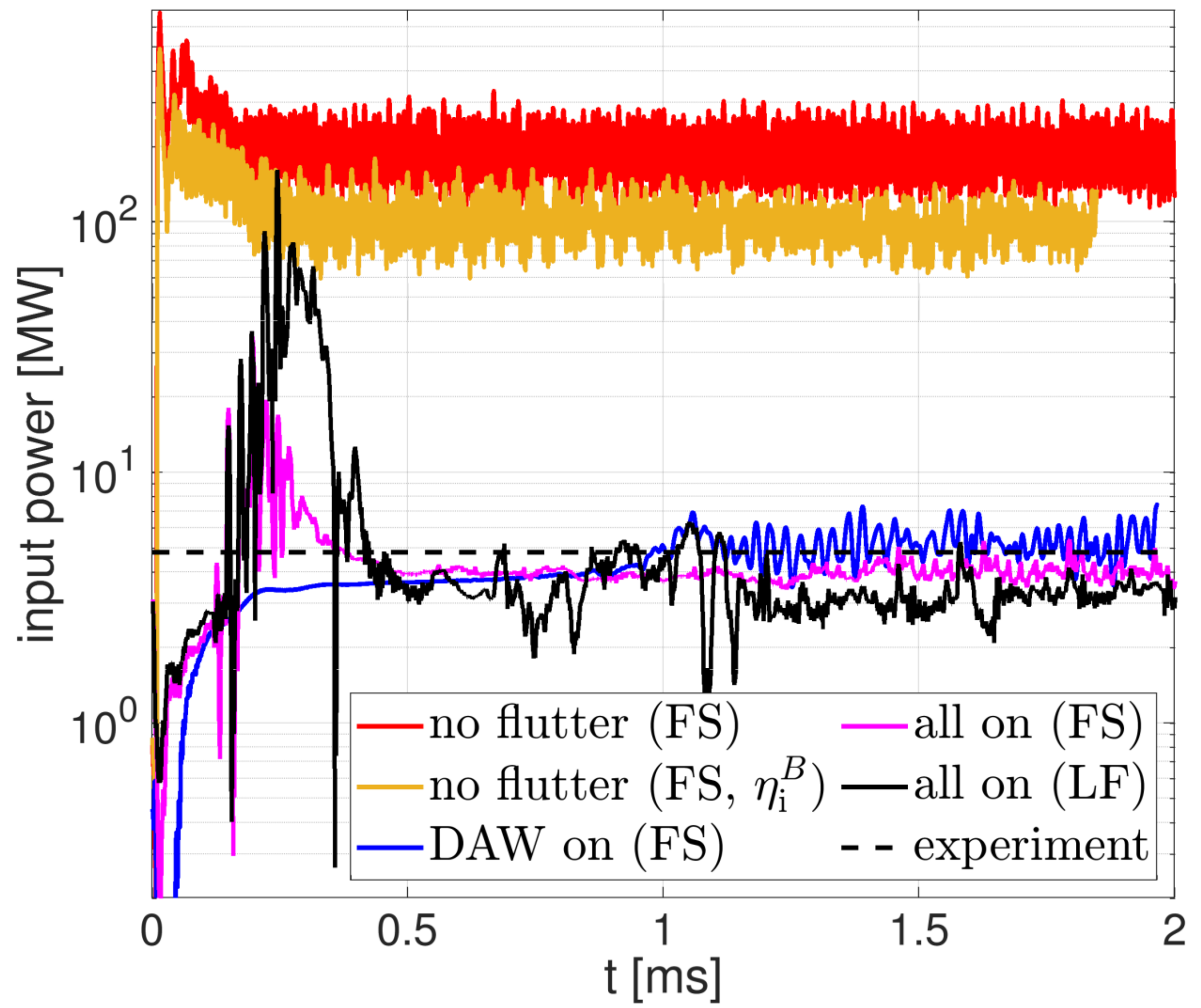
TURBULENCE IN H-MODE CONDITIONS

- GRILLIX extended to tackle **H-mode conditions** (high β, low $\nu_\star$)
  - Full-EM model with flutter terms incl. for current
  - Landau-fluid trans-collisional closure *[C. Pitzal et al, PoP 2023]*
- Applied to ASDEX-U H-mode modelling:
  - **Full-EM model required** to recover experimental power
  - Landau-fluid does not change much w/r to flux-limited SH

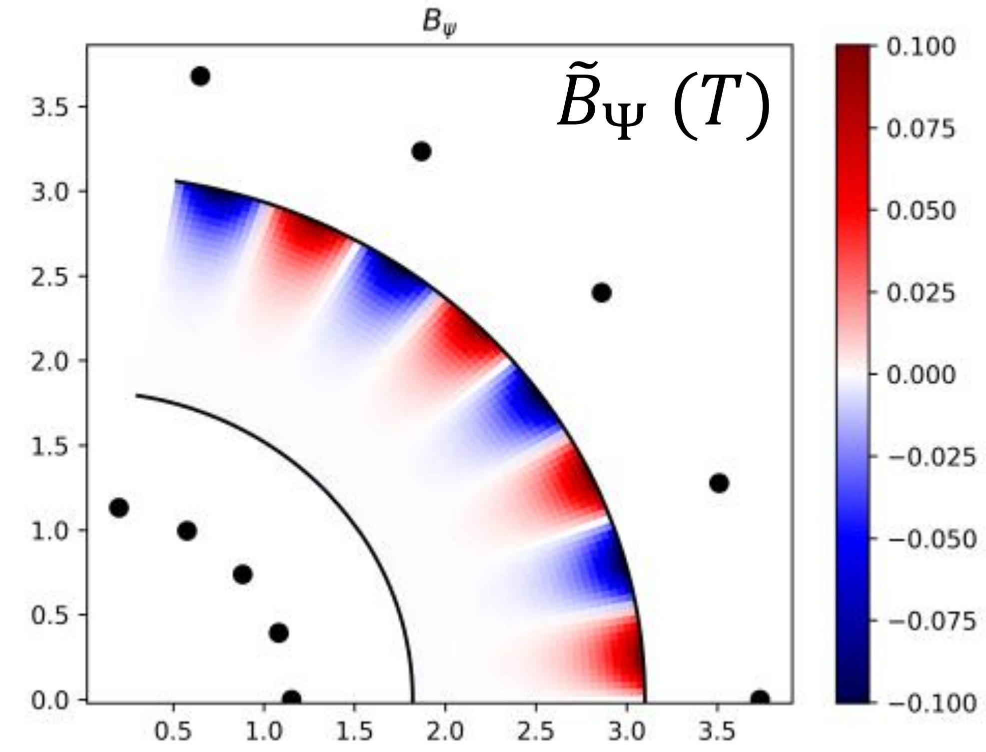
[W. Zholobenko et al, NF 2024]



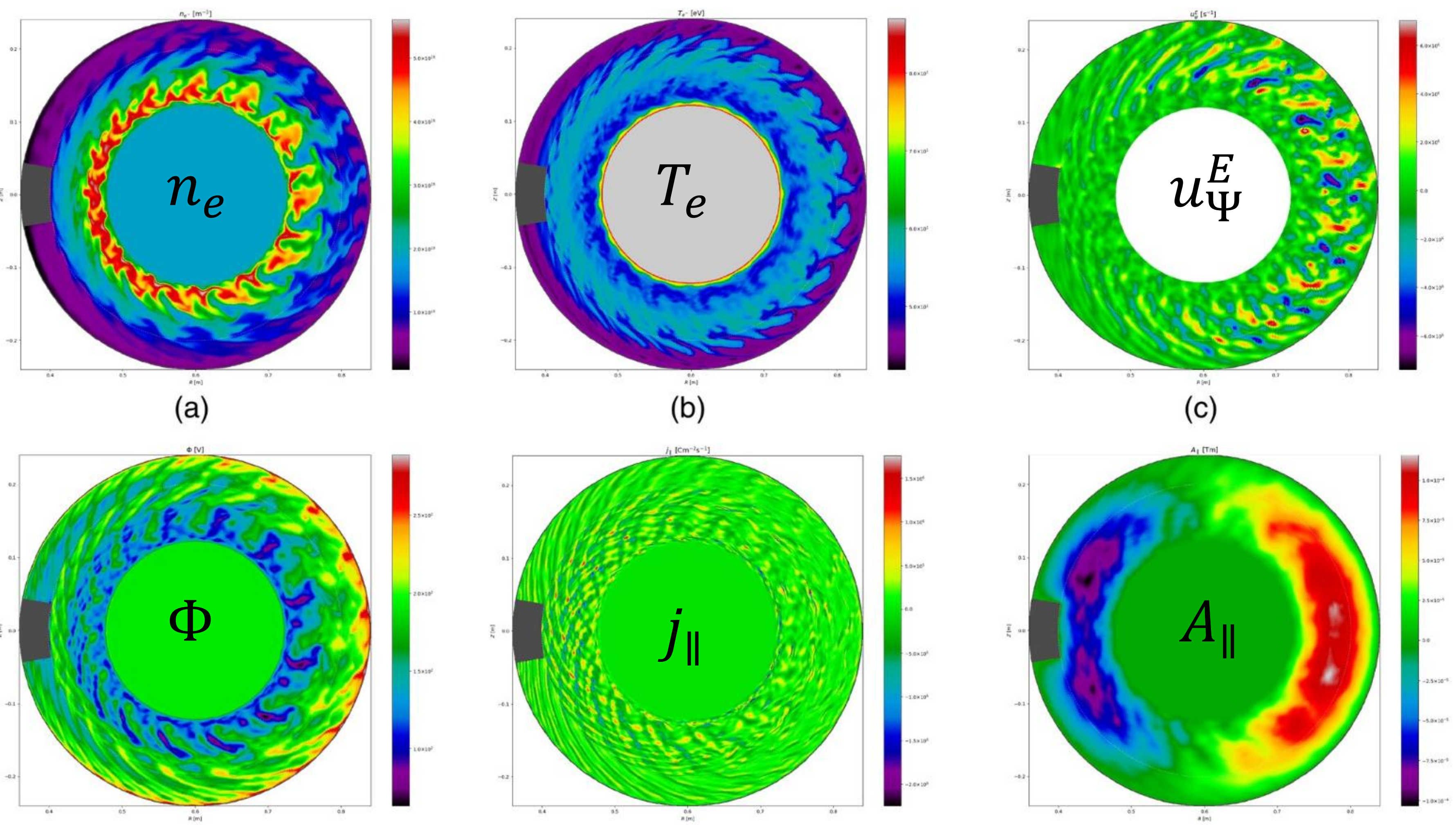


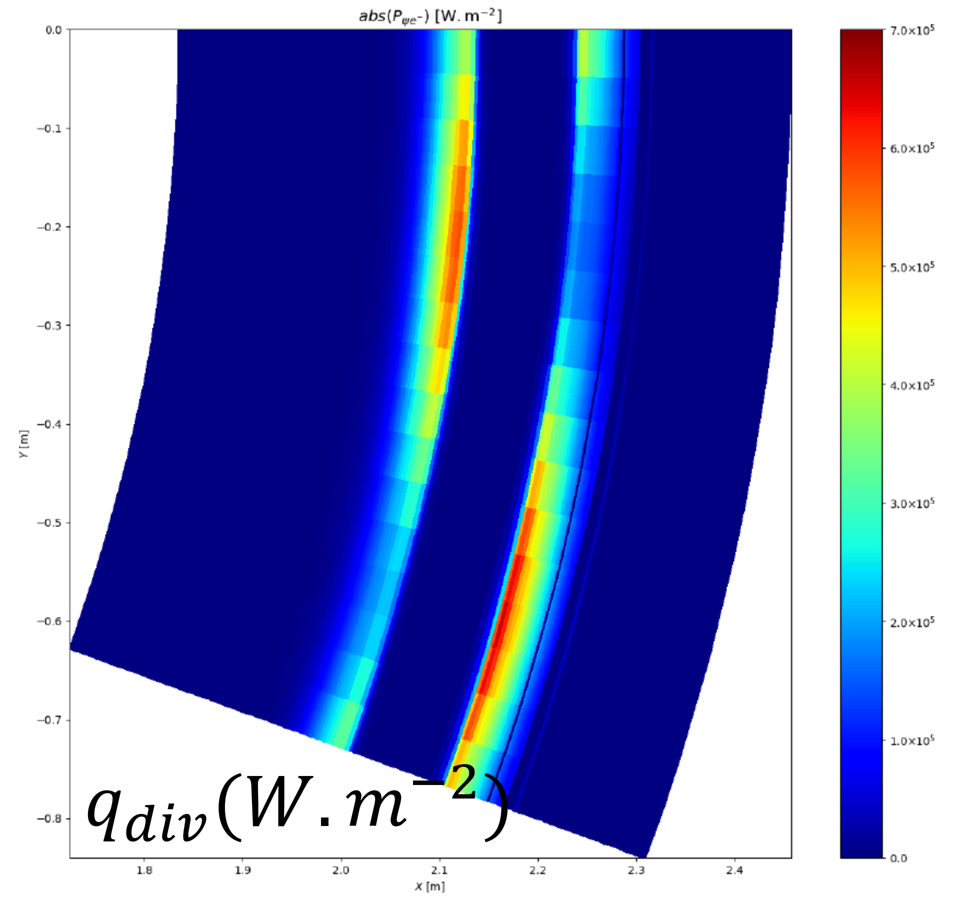


- Full **EM model** (incl. Flutter) implemented in SOLEDGE3X
  - Strong impact on turbulent transport, in line with findings in GRILLIX
- Allows modelling of 3D perturbed magnetic configuration (e.g., RMPS)
  - Applied to modelling of ripple in WEST



[R. Düll et al, NME 2024]



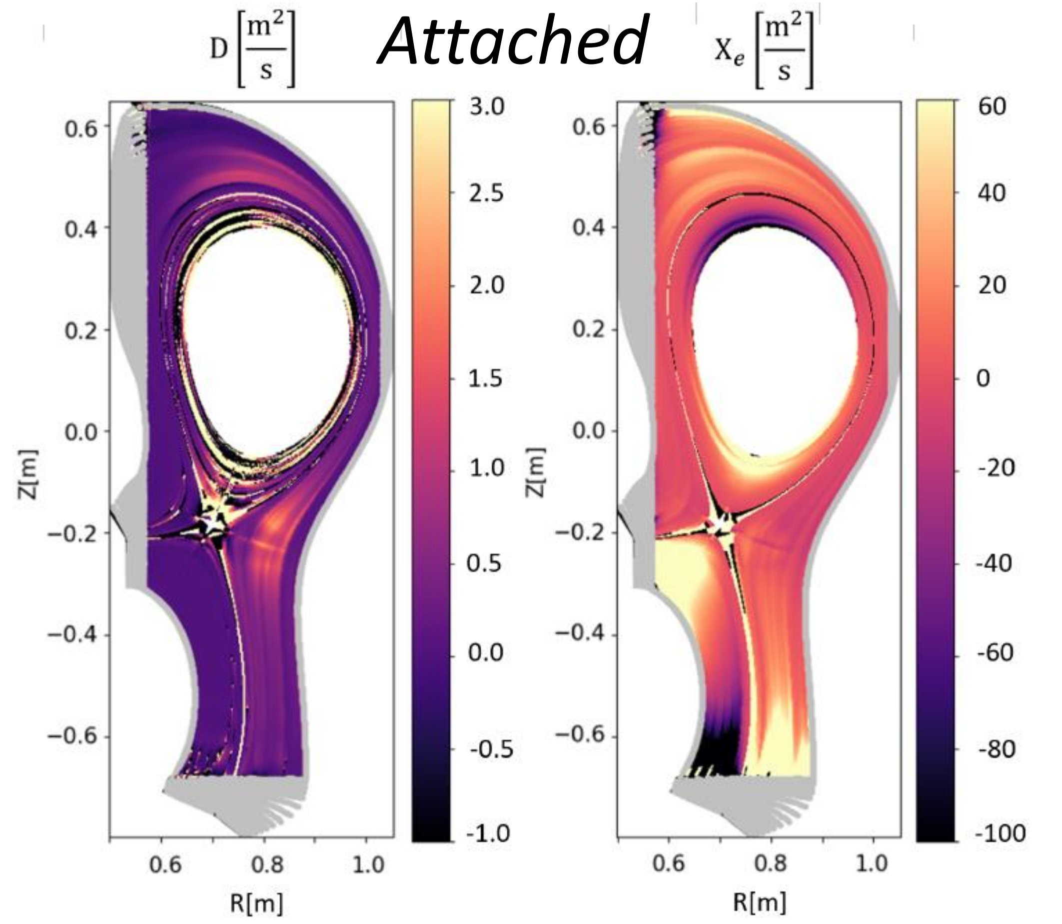


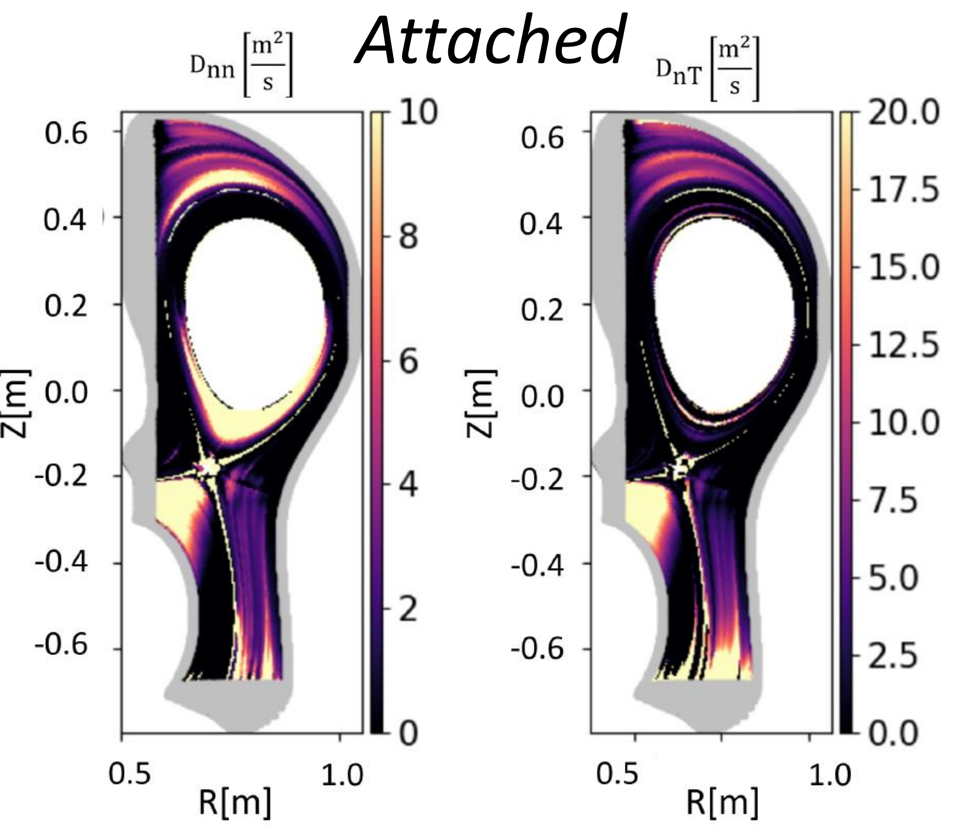
[R. Düll et al, CPP 2024]

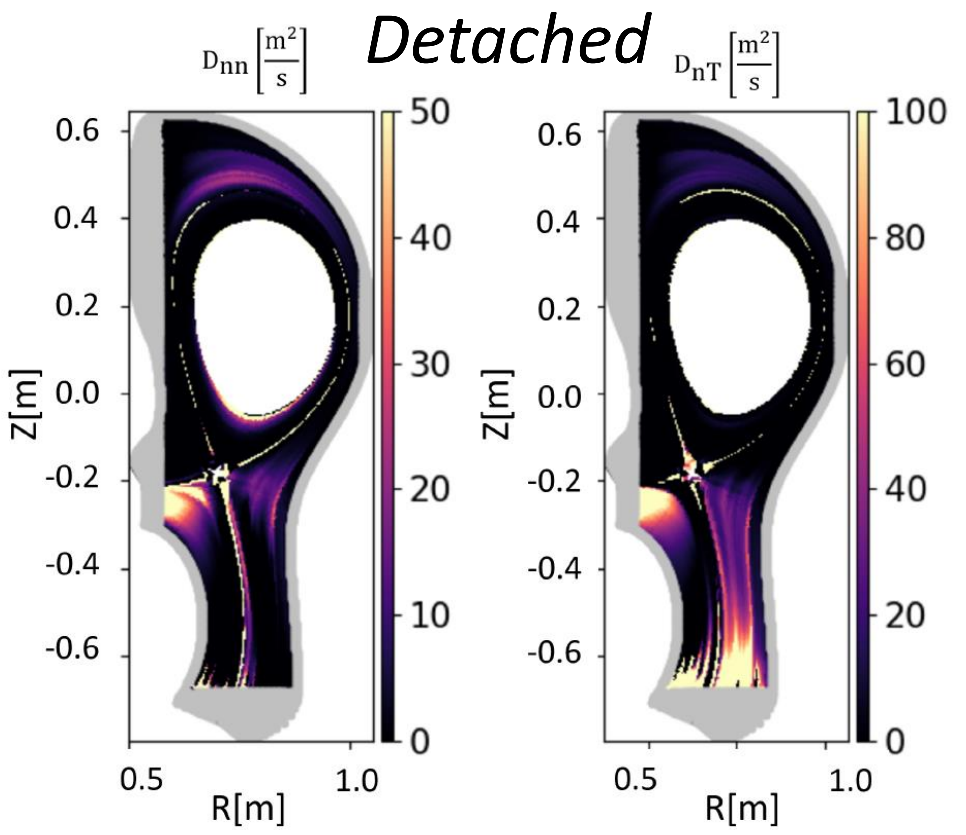
RECOMMENDATIONS FOR MEAN-FIELD MODELLING

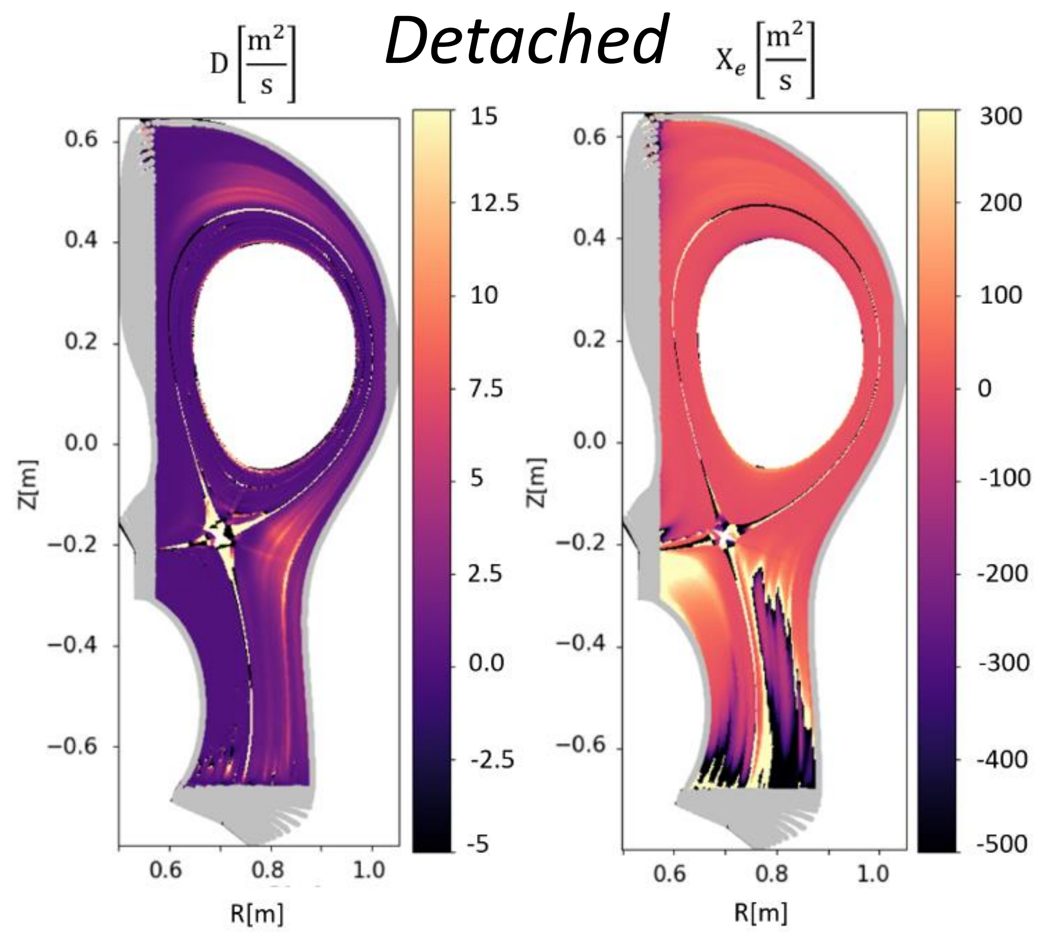
- Preliminary **recommandations for mean-field** codes from simulation in detached conditions:
  - 5-fold increase of diffusion coefficients
  - Issue with classic transport model for heat
  - Different transport models behave better

$$\begin{bmatrix} \dfrac{\Gamma_n^{\psi,\mathrm{anom}}}{n_e} \\ \dfrac{\Gamma_{E\alpha}^{\psi,\mathrm{anom}}}{n_\alpha T_\alpha} \end{bmatrix} = -\begin{bmatrix} D_{nn} & D_{nT,\alpha} \\ D_{nT,\alpha} & \frac{3}{2} D_{nn} \end{bmatrix} \begin{bmatrix} \dfrac{\vec{\nabla} n_e \cdot \vec{n}^{\psi}}{n_e} \\ \dfrac{\vec{\nabla} T_\alpha \cdot \vec{n}^{\psi}}{T_\alpha} \end{bmatrix}$$





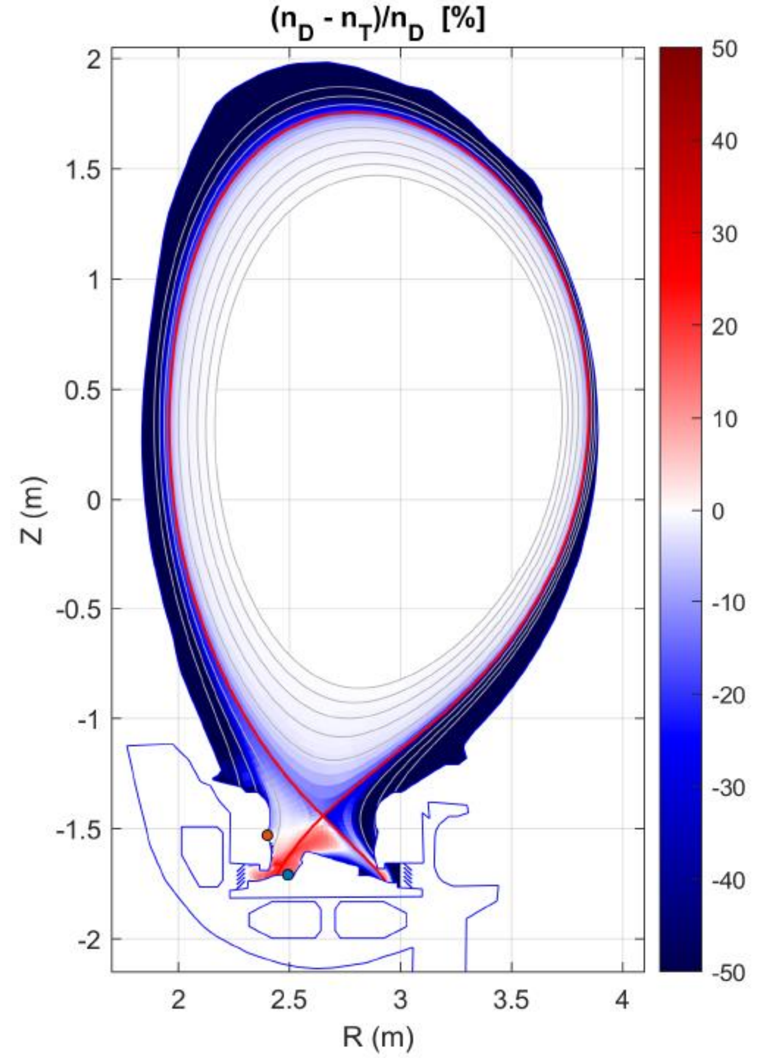




[V. Quadri et al, PhD Thesis 2024]

TOWARDS TURBULENT TRANSPORT OF IMPURITIES

- Zhdanov closure (non trace impurities) implemented in GBS and SOLEDGE3X:
  - Applied to D-T-Ne cases => D/T imbalance in divertor *[H. Bufferand, PPCF 2022]*
  - Extension to 3D turbulence raises questions on tractability of numerical algorithm
- Common validation against dedicated TCV pulse in high-density regime started



PERSPECTIVES FOR 2025 AND BEYOND

- Carry on **upstream development of models and numerical methods** where remaining issues identified:
  - Sheath boundary conditions in trans-collisional conditions for MS plasmas
  - Reduced turbulence models (incl. implementation in SOLPS and SOLEDGE3X)
  - More advanced fluid neutrals models, including boundary conditions
- Pursue **code acceleration**:
  - upscaling towards large scale machines (with ACH)
  - strategy to get 3D turbulence simulations to convergence in reasonable time
- Progressive **mutualization** of specific parts of codes:
  - E.g., kinetic neutrals solvers from GBS and SOLEDGE3X
- Progressively stronger focus on **confrontation to experiments** in relevant regimes in relation with WPTE:
  - Detachment: TCVX23 experiment as reference case, also XPR on WEST / AUG
  - Includes development and usage of synthetic diagnostics based on IMAS
  - Confrontation to stellarator experiments (W7-AS then W7-X)
  - Propose key recommandations to mean-field community on transport model