TSVV3: edge fluid modelling tools towards self-consistent reactor-relevant conditions

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BACKGROUND

- Project objective: **self-consistent fluid modelling of the edge plasma in reactor-relevant conditions**
- Strategy: progressively incorporate in turbulence codes necessary ingredients to model divertor regimes + develop upstream models and numerical methods

	Self-consist. ⊥ transport	Neutrals	Impurities	Plasma and wall geom.	3D equilibria	Acceptable runtime
Mean-field		✓	✓	✓	~	~
Turbulence	✓					

- 4 edge turbulence codes involved: **FELTOR, GBS, GRILLIX, SOLEDGE3X**

MODELS

Upstream development of models:

- revised **sheath BC** for highly collisional conditions: *[D. Tskhakaya, in prep.]*

$$M_\parallel = 1 + \chi - \sqrt{\chi^2 + 2\chi} \qquad \chi = \frac{(v_{mt}(1-\alpha) + v_{ei})x_0}{2c_s \sin\theta}$$

- Landau **non-local closure** implemented in GRILLIX *[C. Pitzal, PoP 2023]*
- multi-temperature **collisional closure** *[M. Raghunathan, PPCF 2022]*
- **gyro-fluid model** including collisions and reaction terms:

$$\Lambda_N = s_n - \Delta_\perp\left(\frac{m s_{p_\perp}}{2qB^2}\right) - \nabla\cdot\left(\frac{m s_n \nabla_\perp\phi}{B^2}\right) \qquad \Lambda_{mNU_\parallel} = s_{nu_\parallel}$$

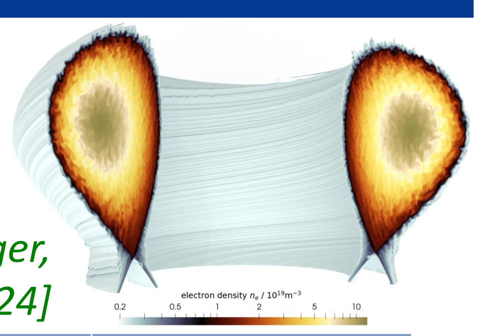
$$\Lambda_{P_\perp} = s_{p_\perp} - \Delta_\perp\left(\frac{m s_{T_\perp}}{2qB^2}\right) - \nabla\cdot\left(\frac{m s_{p_\perp}\nabla_\perp\phi}{B^2}\right) \qquad \Lambda_{E_\parallel} = s_{e_\parallel}$$

[M. Wiesenberger, J. Phys.: Conf. Series 2022]

COMPLIANT PLASMA AND WALL GEOMETRIES

ARBITRARY AXISYMMETRIC PLASMA GEOMETRY

All codes compliant with arbitrary axisymmetric magnetic geometries but with different technical choices



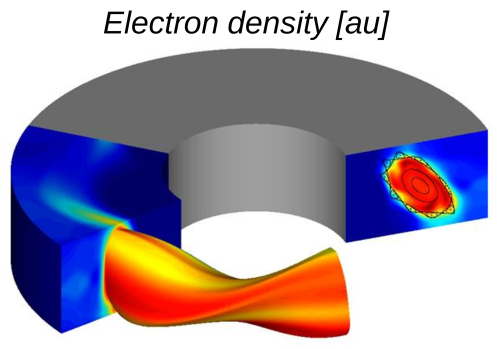
[M. Wiesenberger, PPCF 2024]

Code	Poloidal grid type	Grid alignment	Poloidal discretization	Parallel / toroidal discretization
FELTOR	Structured, Cartesian	None	Discontinuous Galerkin	FCI
GBS	Struct., Cart. or curv. (new)	None	Finite Differences	Finite differences
GRILLIX	Unstructured, locally Cartesian	None	Finite Differences	FCI
SOLEDGE3X	Locally structured, curvilinear	Flux-surface	Finite Volumes	Finite volumes

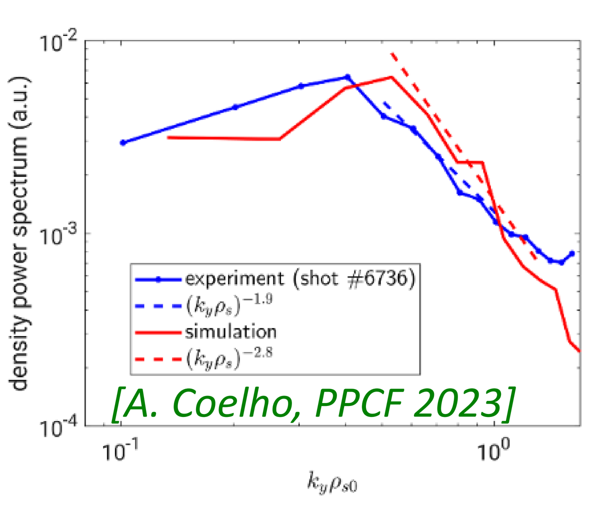
3D MAGNETIC EQUILIBRIA - STELLARATORS

GBS and GRILLIX extended to 3D magnetic equilibria

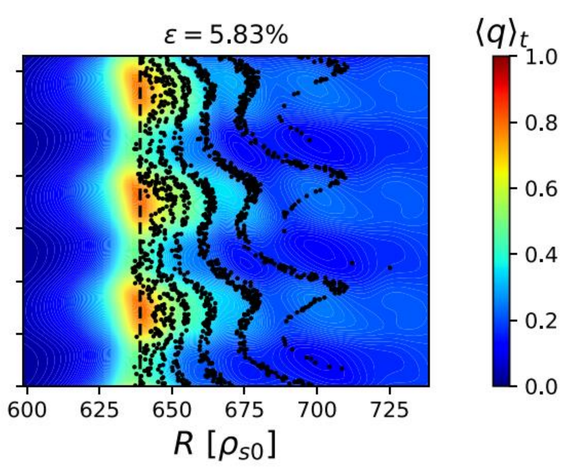
- GBS confronted to **TJ-K** and applied to **RMPs**
  - Experimentally observed large scale quasi-coherent mode recovered
  - Turbulence smoothens heat flux foot prints of RMPs
- GBS and GRILLIX now tackling **W7-AS**



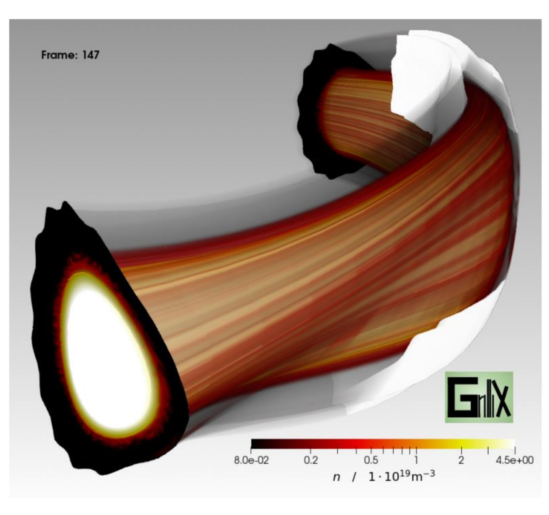
[A. Coelho, NF 2022]



[A. Coelho, PPCF 2023]



[T. Boinnard, NF 2023]

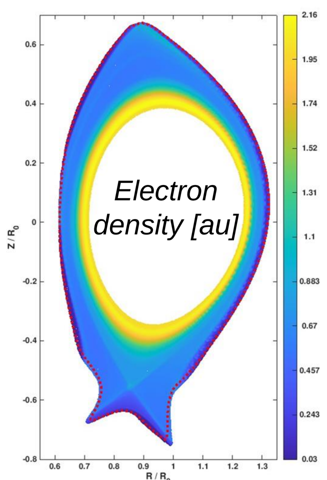


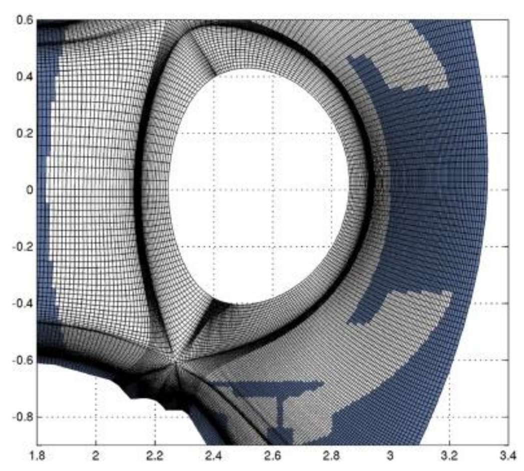
[A. Stegmeir, to be submitted to CPC]

CAPTURING ACCURATELY THE WALL GEOMETRY

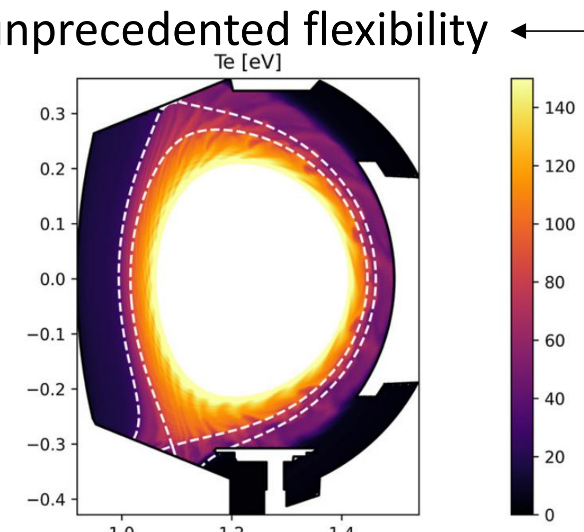
Major challenge but mandatory for accurate density regimes

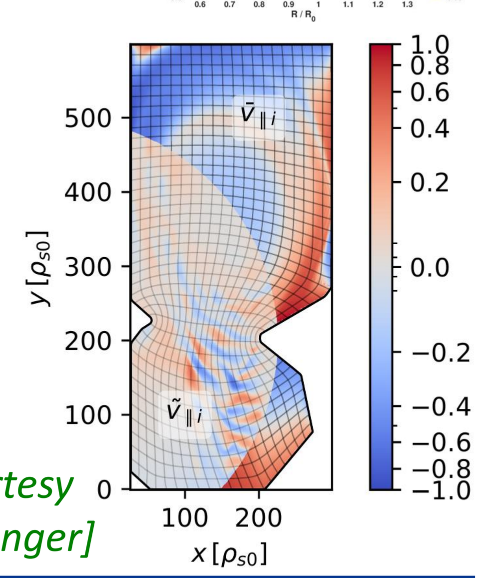
- **Immersed boundaries** in SOLEDGE3X, GRILLIX, FELTOR
- Combined with **penalization** in GRILLIX and FELTOR *[A. Stegmeir, CPC 2023]*
- **Curvilinear grid** in SOLEDGE3X and GBS
  - E.g.: SOLEDGE3X ITER simulations up-to-the-wall
- **HDG** approach offers unprecedented flexibility





[H. Bufferand, NF 2021]



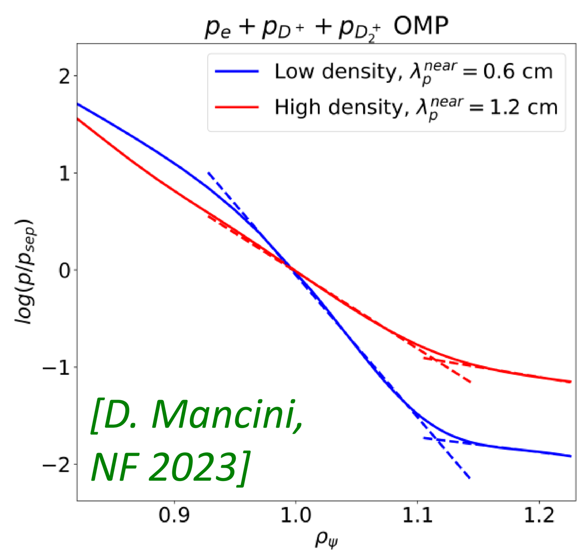


[Courtesy L. Stenger]

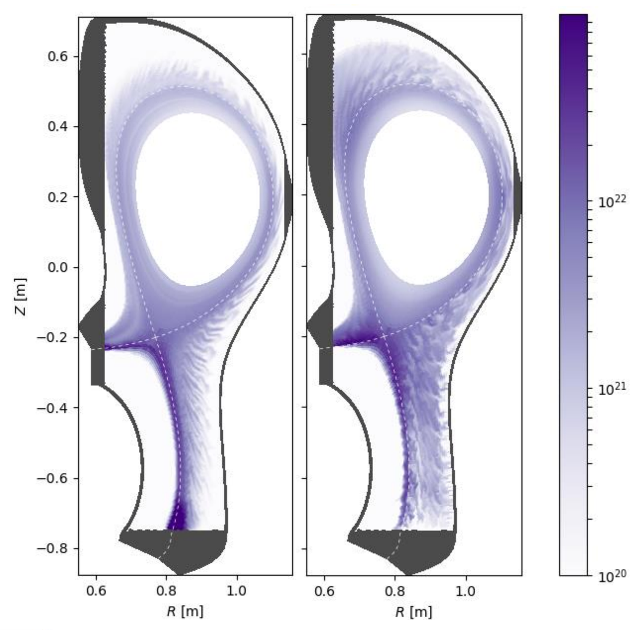
TURBULENCE IN DISSIPATIVE DIVERTOR REGIMES

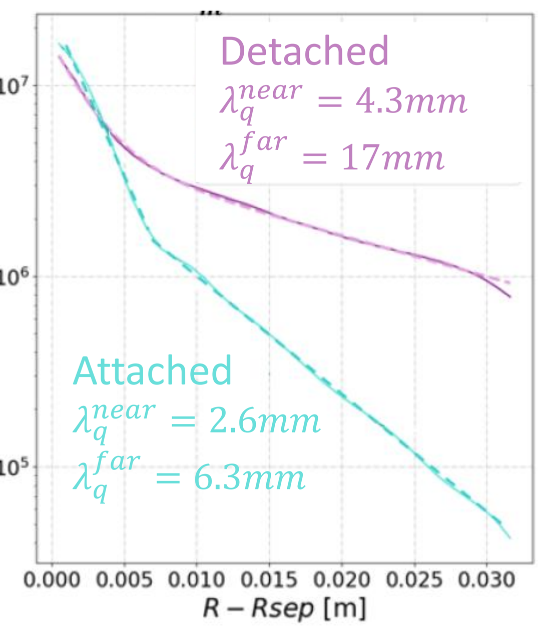
- GBS, GRILLIX and SOLEDGE3X feature **self-consistent neutrals** models
  - kinetic (method of characteristics) in GBS
  - kinetic (EIRENE) in SOLEDGE3X, but limited to 2D or low resolution 3D
  - fluid (CX-dominated model) in SOLEDGE3X and GRILLIX
- First simulations of turbulence in **detached divertor regime**
  - Significant impact on turbulence => flattening of profiles
  - Recommendations for mean-field modelling
  - Common validation against dedicated TCV experiment (WPTE-RT05)

[D. Mancini, PSI 2024]

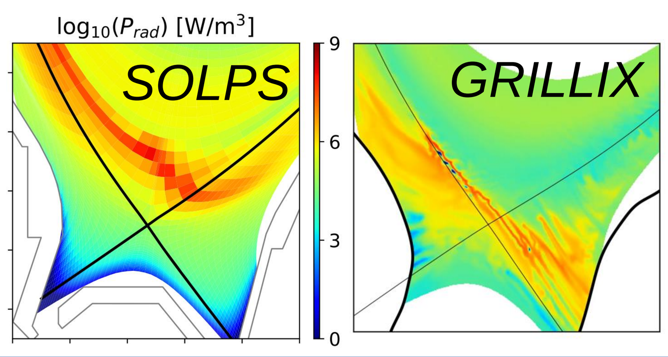


[D. Mancini, NF 2023]





[V. Quadri et al, NME 2024]

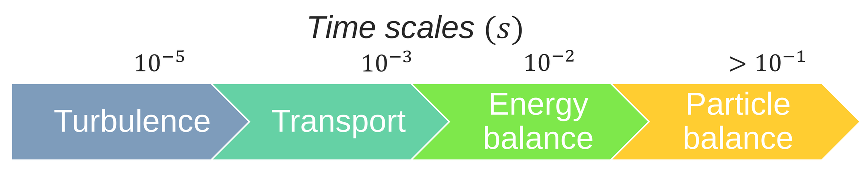


- Proof-of-principle modelling of turbulence in **X-point radiator** regime *[K. Eder, talk @ PSI 2024]*

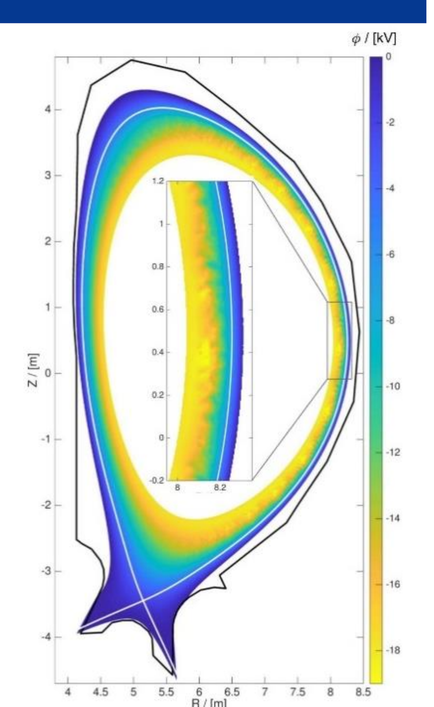
UPSCALING SIMULATIONS

- Strong effort invested in parallel towards upscaling simulations to reactor size *[M. Guido, JSC (2024)]*
  - Effort centered on linear solvers and GPU-ization
  - ITER size case in GRILLIX *[A. Stegmeir, CPC 2023]*
- Impact of neutrals possibly challenging:

$$\tau_{eq,n} \approx \frac{\tau_{transp}}{1-R} \qquad R_E \sim 25\% \text{ ☺} \qquad R_n > 99\% \text{ ☹}$$



➢ need scheme to accelerate convergence (e.g., *[E. Kaveeva, NF 2018]*)



[ITER size case with GRILLIX]

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 (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) 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.