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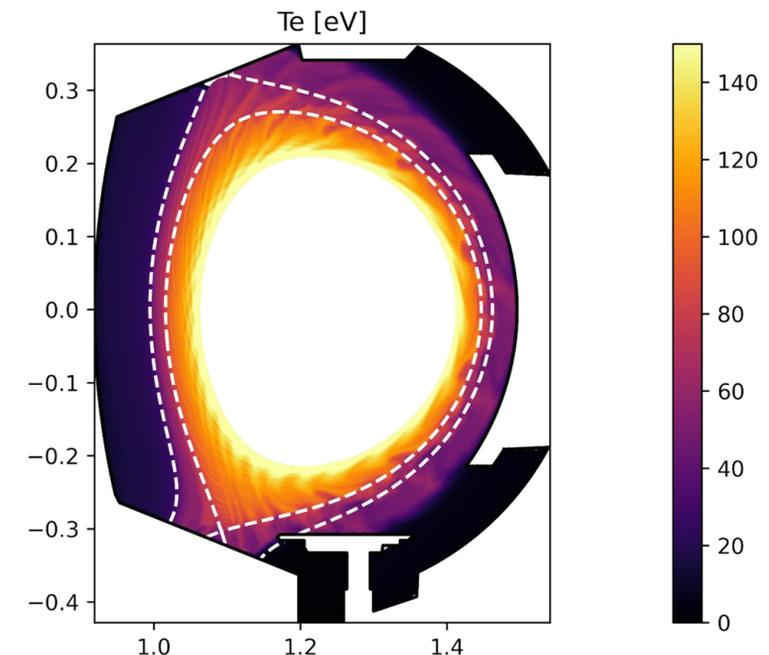
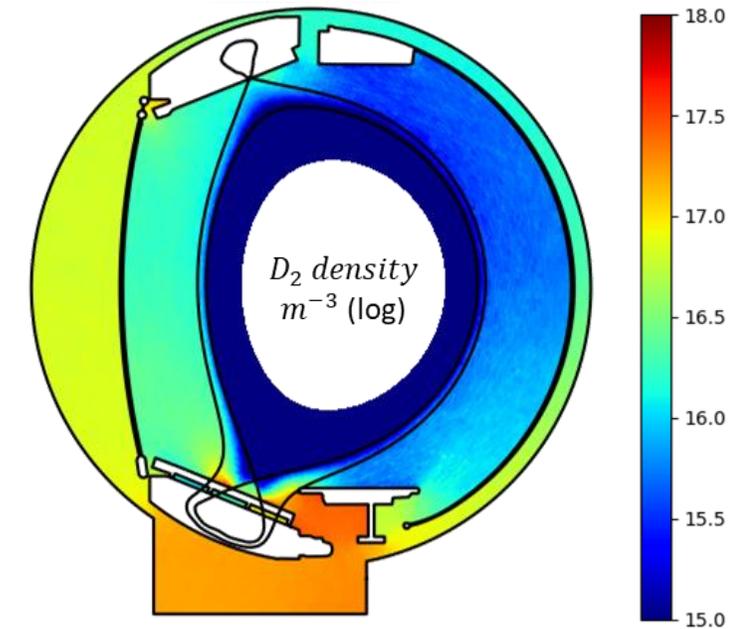


## Investigation of transport barrier formation in edge turbulent simulations

*Hugo Bufferand, G. Ciraolo, G. Falchetto, N. Fedorczak, Ph. Ghendrih, Y. Marandet, E. Serre, P. Tamain*

# The SOLEDGE3X code

- Merging of the transport code SOLEDGE2D and the turbulence code TOKAM3X  
→ Can be used in 2D (transport) or 3D (3D transport or turbulence simulations)
- Solves fluid equations for multi-species plasma based on Zhdanov closure [Raghunathan et al., PPCF, 2021]
- Electrostatic at the moment – Electromagnetic version under development
- Implements several neutral models:
  - Fluid neutrals (diffusive): very crude but fast and robust
  - Kinetic neutrals: EIRENE – high fidelity



# The SOLEDGE3X drift-ordering fluid model

Collisional closure terms

Ionization terms

External sources

“Anomalous” diffusion for  
transport simulations

- **Mass balance** (for all ion species – quasi-neutrality for electrons)

$$[1] \quad \partial_t n + \vec{\nabla} \cdot (n\vec{v}) = S_n^{iz}$$

- Velocity decomposition  $\vec{v} = v_{\parallel} \vec{b} + \vec{v}_{drifts} - \frac{D\vec{\nabla}_{\perp} n}{n}$
- **Ionization/recombination sources** involving neutrals are computed by the “neutral solver”, for instance EIRENE when using kinetic neutrals.

# The SOLEDGE3X drift-ordering fluid model

- **Momentum balance**

$$[2] \quad \partial_t(mn\vec{v}) + \vec{\nabla} \cdot (mn\vec{v} \otimes \vec{v}) = -\vec{\nabla}p - \vec{\nabla} \cdot \bar{\Pi} + Zen(\vec{E} + \vec{v} \times \vec{B}) + \vec{R} + \vec{S}_v^{iz} + \vec{S}_v^{ex}$$

$$\bar{\Pi} = \pi_{\parallel} \left( \vec{b} \otimes \vec{b} - \frac{1}{3} \bar{I} \right) + \bar{\Pi}^{FLR} \quad \text{where} \quad \pi_{\parallel} = -3\eta_{\parallel} \left( \nabla_{\parallel} v_{\parallel} - \vec{k} \cdot \vec{v} - \frac{1}{3} \vec{\nabla} \cdot \vec{v} \right)$$

- Parallel projection ( $\vec{b} \cdot [2]$ )

$$[3] \quad \partial_t(mnv_{\parallel}) + \vec{\nabla} \cdot (mnv_{\parallel}\vec{v}) = -\nabla_{\parallel}p - \vec{b} \cdot (\vec{\nabla} \cdot \bar{\Pi}) + ZenE_{\parallel} + R_{\parallel} + S_{v_{\parallel}}^{iz+ex} + m\vec{\nabla} \cdot (n\eta_{\perp}\vec{\nabla}_{\perp}v_{\parallel})$$

- Perpendicular momentum: ( $\vec{b} \times [2]$ )

$$\vec{v}_{\perp} = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{\vec{B} \times (\vec{\nabla}p + \vec{\nabla} \cdot \bar{\Pi})}{ZenB^2} - \frac{\vec{B} \times (\vec{R}_{\perp} + \vec{S}_{v_{\perp}}^{iz+ex})}{ZenB^2} + \frac{\vec{b}}{n\omega_c} \times [\partial_t(n\vec{v}) + \vec{\nabla} \cdot (n\vec{v} \otimes \vec{v})]$$

Drift ordering (assuming  $\omega_c^{-1}d_t \ll 1$  and  $\omega_c^{-1}\tau_{col}^{-1} \ll 1$ ):

$$\vec{v}_{\perp}^0 = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{\vec{B} \times \vec{\nabla}p}{ZenB^2} \quad \vec{v}_{\perp}^1 = \frac{\vec{b}}{n\omega_c} \times [\partial_t(n\vec{v}^0) + \vec{\nabla} \cdot (n\vec{v}^0 \otimes \vec{v}^0)] + \frac{\vec{B} \times \vec{\nabla} \cdot \bar{\Pi}}{ZenB^2} - \frac{\vec{B} \times (\vec{R}_{\perp} + \vec{S}_{v_{\perp}}^{iz+ex})}{ZenB^2}$$

*E cross B Diamagnetic*

*Polarization*

*Non-linear drifts (function of  $\vec{v}^0$ )*

Collisional closure terms

Ionization terms

External sources

“Anomalous” diffusion for transport simulations

# The SOLEDGE3X drift-ordering fluid model

- **Current balance** (Equation on  $\phi$  – vorticity equation)

$$[4] \quad \vec{\nabla} \cdot \vec{j} = 0 \quad \text{with} \quad \vec{j} = \sum Z n \vec{v} = j_{\parallel} \vec{b} + \vec{j}^* + \vec{j}_{\Pi} + \vec{j}_{pola} + \vec{j}^{ex}$$

Collisional closure terms  
 Ionization terms  
 External sources  
 “Anomalous” diffusion for transport simulations

- Parallel current expression obtained from parallel electron momentum balance (Generalized Ohm’s law)

$$j_{\parallel} = -\sigma_{\parallel} \left( \nabla_{\parallel} \phi + \frac{-\nabla_{\parallel} p_e + R_{e,\parallel}^T}{en_e} \right)$$

- Given zeroth order drift expression, polarization current can be expressed:  $\vec{j}_{pola} = -\partial_t \vec{\omega} - \vec{\nabla} \cdot (\vec{v}^0 \otimes \vec{\omega})$   
 where:

$$\vec{\omega} = \frac{m_i}{B^2} \left( n \vec{\nabla}_{\perp} \phi + \frac{1}{Ze} \vec{\nabla}_{\perp} p_i \right) \quad \vec{\nabla} \cdot \vec{\omega} = \Omega \quad \text{so called vorticity}$$

- Shape of  $\phi$  equation :

$$\vec{\nabla} \cdot \left( \partial_t \left[ \frac{m_i n}{B^2} \vec{\nabla}_{\perp} \phi \right] + \sigma_{\parallel} \nabla_{\parallel} \phi \vec{b} \right) = RHS$$

- **Energy balance**  $\mathcal{E} = \frac{3}{2} n T + \frac{1}{2} m n v_{\parallel}^2$

$$[5] \quad \partial_t \mathcal{E} + \vec{\nabla} \cdot \left( \mathcal{E} \vec{v} + p v_{\parallel} \vec{b} + v_{\parallel} \bar{\Pi} \cdot \vec{b} + \vec{q} \right) = Z n e v_{\parallel} E_{\parallel} + v_{\parallel} R_{\parallel} + Q + S_{\mathcal{E}}^{iz+ex} + \vec{\nabla} \cdot \left( m n v_{\parallel} \eta_{\perp} \vec{\nabla}_{\perp} v_{\parallel} + n \chi_{\perp} \vec{\nabla}_{\perp} T \right)$$

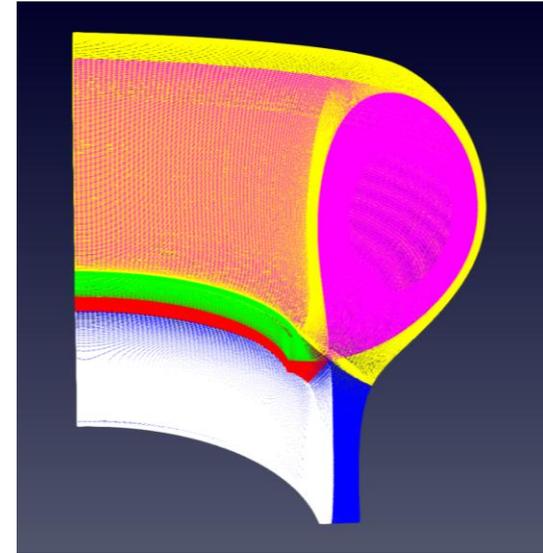
# The SOLEDGE3X implementation

- Numerical scheme
  - Finite volumes with multi-domain structured grid aligned with magnetic flux surfaces
  - **Spatial discretization:** - Advection [ $\mathcal{A}$ ]: Donat & Marquina scheme [JCP 1996] + WENO interpolation
    - Parallel diffusion [ $\mathcal{D}_{\parallel}$ ]: Günter scheme [JCP 2005]
    - Perpendicular diffusion [ $\mathcal{D}_{\perp}$ ]: Sharma & Hammet scheme [JCP 2007]
  - **Temporal discretization:** **Explicit** except parallel diffusion terms treated **implicitly**

$$\frac{X(t + \delta t) - X(t)}{\delta t} + \mathcal{A}(X(t)) + \mathcal{D}_{\parallel}(X(t + \delta t)) + \mathcal{D}_{\perp}(X(t)) = \mathcal{S}(X(t))$$

**Exception:** Electric potential equation mixing parallel Laplacian and perpendicular Laplacian treated both **implicitly** (3D problem – potential **bottleneck** for linear solvers):

$$\frac{1}{\delta t} \left( \mathcal{D}_{\perp}(\phi(t + \delta t)) - \mathcal{D}_{\perp}(\phi(t)) \right) + \mathcal{D}_{\parallel}(\phi(t + \delta t)) = \mathcal{S}(t)$$



# The SOLEDGE3X implementation

- Focus on electric potential equation

$$\frac{1}{\delta t} (\mathcal{D}_\perp(\phi(t + \delta t)) - \mathcal{D}_\perp(\phi(t))) + \mathcal{D}_\parallel(\phi(t + \delta t)) = s(t)$$

Anisotropic 3D Laplacian:  $\frac{1}{\delta t} \mathcal{D}_\perp \ll \mathcal{D}_\parallel$

- Near Neuman BC (ill-defined problem):

$$j_\parallel^{BC} = j^{sat} \left( 1 - \exp\left(\Lambda - \frac{\phi}{T_e}\right) \right) \rightarrow \nabla_\parallel \phi + \alpha \phi = \beta \quad \text{with } \alpha \ll 1$$

- Matrix of the problem poorly conditioned
- Problem too big for direct solvers. Iterative solver are used  $\rightarrow$  need for a good preconditioner
- $\rightarrow$  Best solution found so far: Algebraic multigrid preconditioner combined with Krylov solver (GMRES, BiCGS)
- Implementation based on “on the shelf” libraries: PETSc with gamg preconditioner, HYPRE with BoomerAMG preconditioner, AGMG (ULB) – only CPU platform used so far, possible extension to GPU platform foreseen.



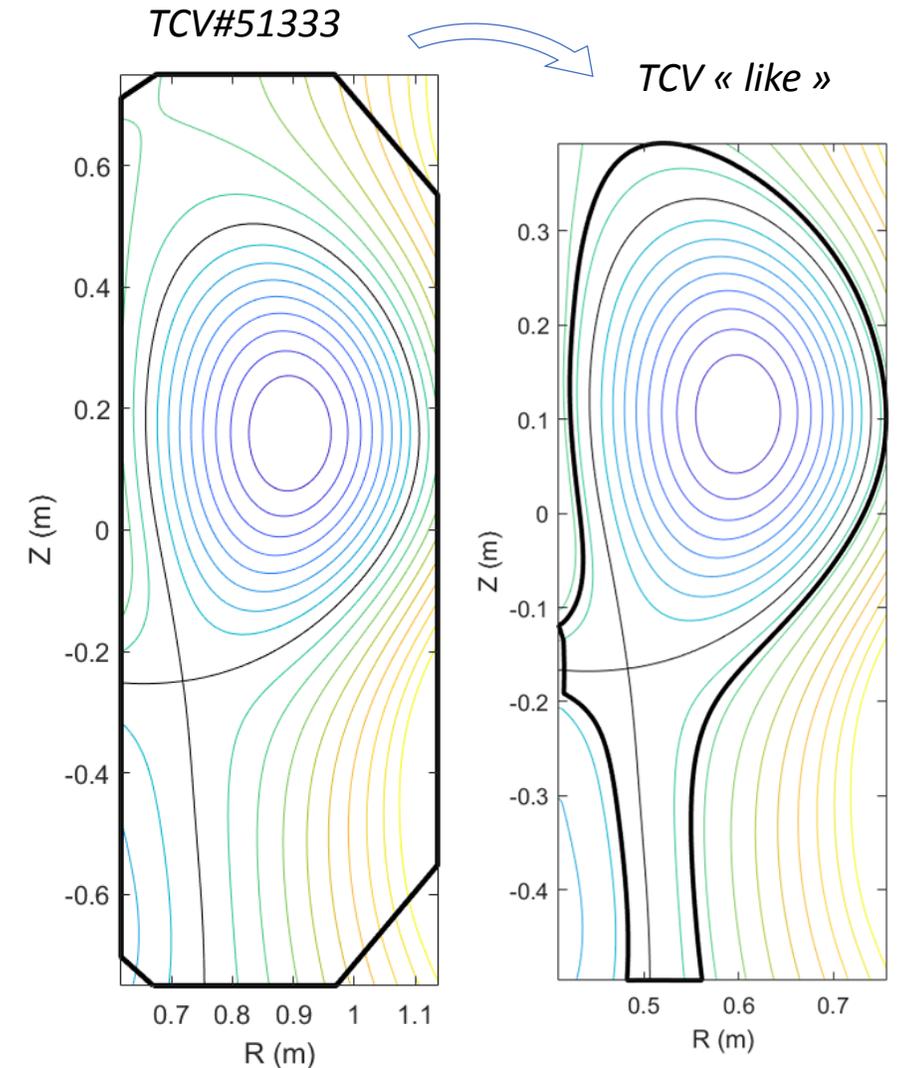
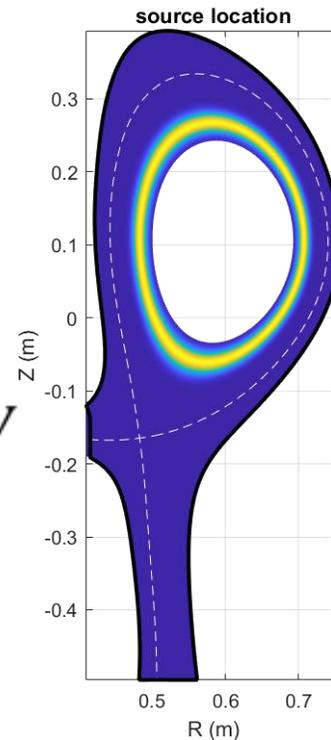
# Application to a TCV-like turbulent simulation

Purpose: test code ability to simulate turbulent plasma in divertor geometry including neutrals

- Equilibrium based on TCV#51333 (magnetic field rescaled by  $\frac{1}{2}$ )
- Wall geometry modified to fit a flux surface (to avoid potential artefacts due to a non-aligned wall – consequence: more closed divertor in the simulation)

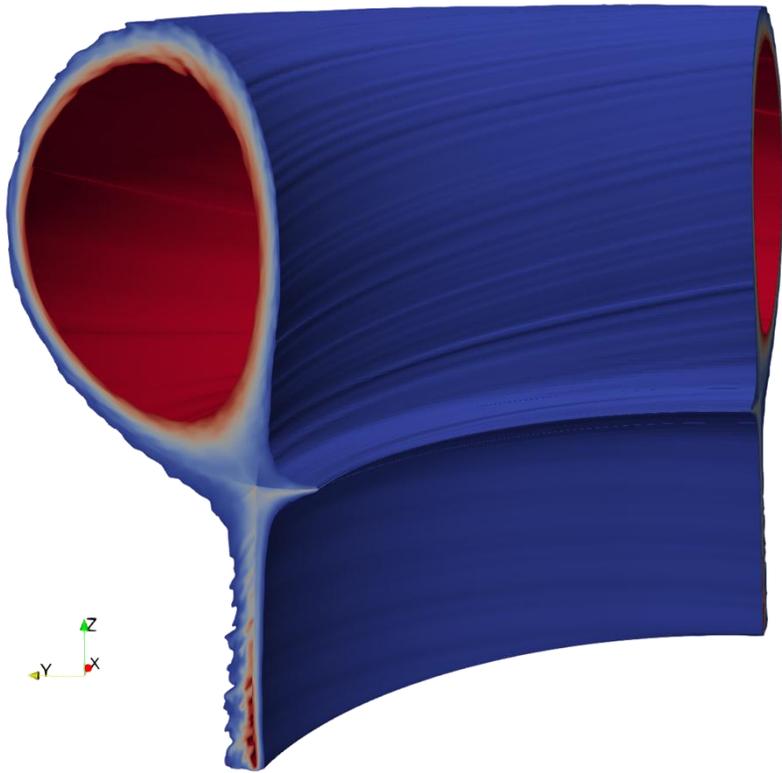
Simulation setup:

- Pure D plasma with fluid neutrals
- Anomalous diffusivities set to  $10^{-2} m^2 s^{-1}$  (classical collisional level)
- Energy source at  $\frac{r}{a} \approx 0.75$   
Power scanned between  $50kW$  and  $200kW$
- Recycling on the wall set to 80%  
Gas puff in the midplane adjusted to get  $n_e \approx 10^{19} m^{-3}$  at the separatrix
- Parallel resistivity  $\times 10$  artificially

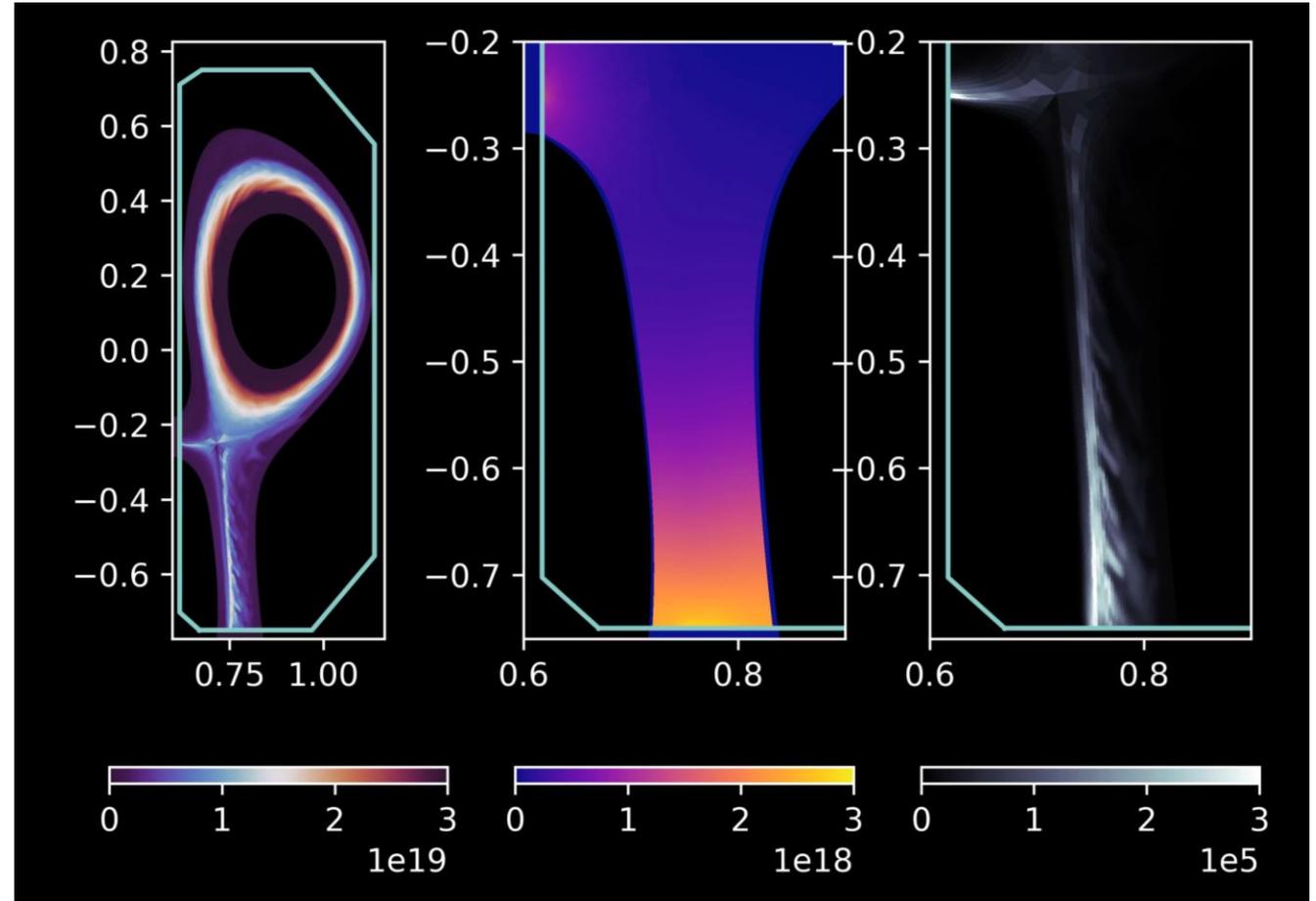


# Application to a TCV-like turbulent simulation

- Turbulence in high recycling regime is observed



Left: Density in 3D showing filaments. Right: Poloidal map of electron density ( $/m^3$ ) + divertor zoom showing neutrals density ( $/m^3$ ) and Hydrogen radiation ( $W/m^3$ ).

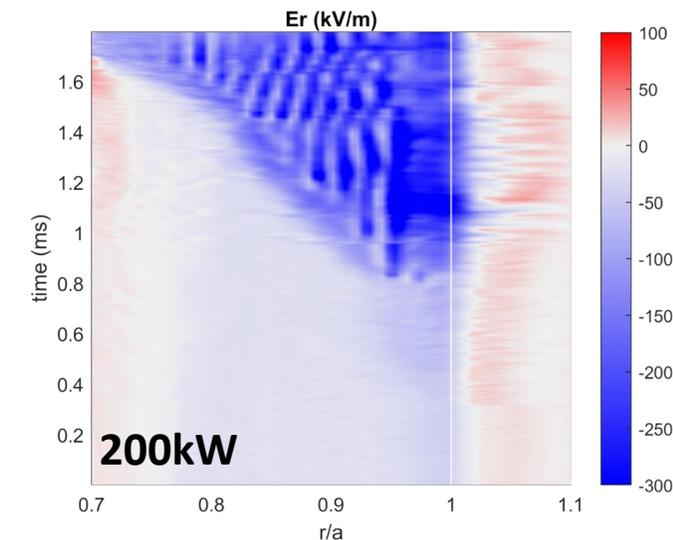
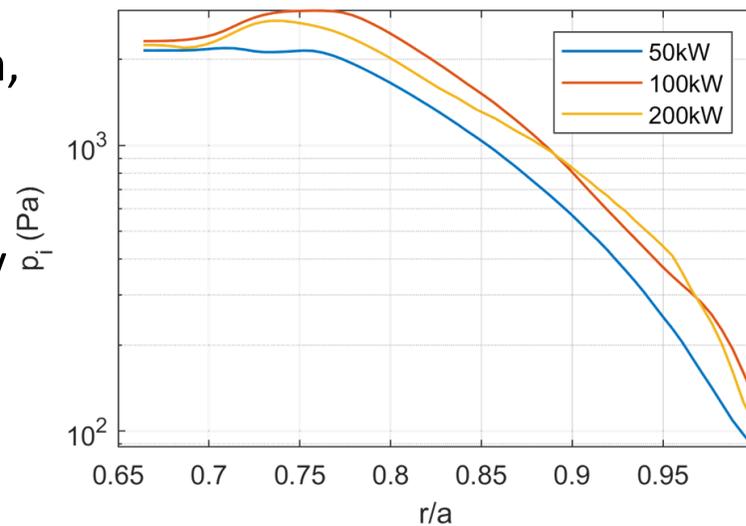
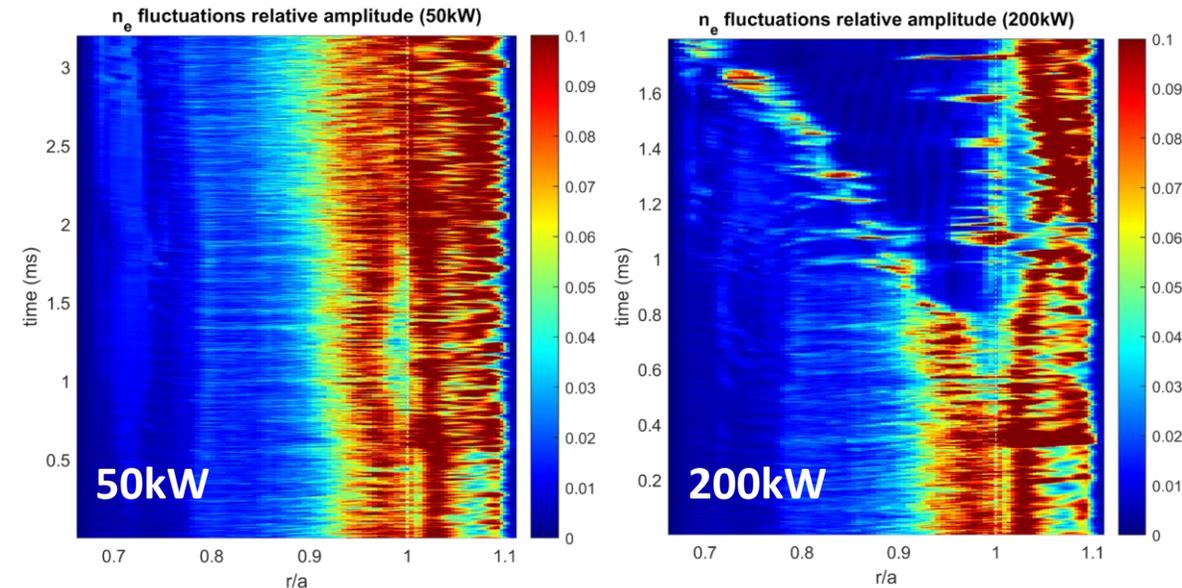


# Application to a TCV-like turbulent simulation

Evidence of turbulent suppression around the separatrix at high power

- Well developed turbulence at low power (50kW)  
Avalanches cross the separatrix
- Reduction of fluctuation level around the separatrix at higher power (100kW and 200kW)
  - The “gap” propagates from separatrix inward
  - Associated with higher  $E \times B$  shear
  - Stationary zonal flows observed in the low turbulence region
- Though, 1ms after turbulence reduction, no clear steepening in pressure profile
- $E_r$  takes very high values: missing term to control plasma rotation? Ion viscosity effects

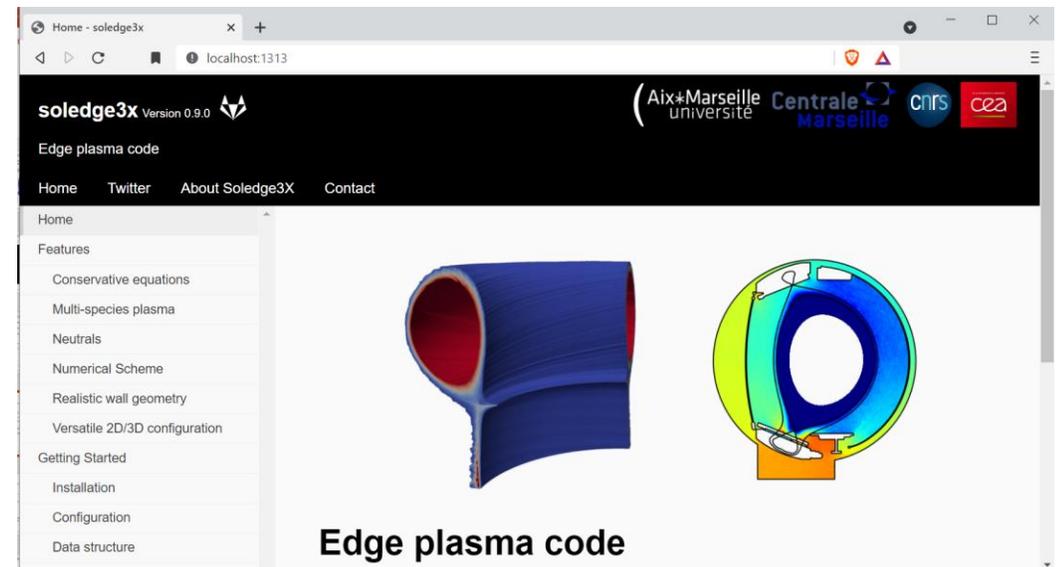
[Sigmar & Helander, Zholobenko et al., PPCF 2021]



# Summary

- New SOLEDGE3X code enables 2D/3D transport and 3D turbulent simulations for multispecies plasma.
  - First application to power ramp on TCV like case including neutrals shows onset of turbulence reduction around separatrix at high power
    - Similar results with other codes: e.g. GBS [Giacomin et al., J. Plasma Phys., 2020]
- though ion viscosity effects on current balance missing (ill controlled plasma rotation)

- Missing terms to be implemented and simulations to be re-launched at higher resolution (now possible thanks to better strong and weak scaling with algebraic multigrid iterative solvers)
- More information on code website [www.soledge3x.com](http://www.soledge3x.com) (under construction)



# Drift waves

- Impact of missing polarisation drift in continuity equation
- Full model (B. Scott):

$$\omega = \omega_L = \frac{c_s}{\lambda_p} \frac{k_y \rho_s}{1 + k_{\perp}^2 \rho_s^2} \quad \gamma = C \frac{\omega_L^2}{k_{\parallel}^2} \frac{k_{\perp}^2 \rho_s^2}{1 + \Gamma k_{\perp}^2 \rho_s^2}$$

- Without  $v_{pola}$  (linear analysis of the system  $n, j_{\parallel}, \phi, u_{\parallel}$ )

$$\omega = \omega_L = \frac{c_s}{\lambda_p} k_y \rho_s \quad \gamma = C \frac{\omega_L^2}{k_{\parallel}^2} k_{\perp}^2 \rho_s^2$$

- Wrong drift waves at the  $\rho_s$  scale. For scale smaller than  $\rho_s$ , drift growth over estimated. Though, sub Larmor radius scales not really look at or even resolved  $\rightarrow$  filtering

# The SOLEDGE3X implementation

- Status of implementation:
  - ✓ Code runs routinely in 2D transport and 3D turbulent. 3D transport simulations with non-axisymmetric wall OK.
  - ✓ **Neutrals:** fluid model OK in 2D and 3D, EIRENE 2D transport only for now
  - ✗ **Missing term:** polarization velocity not included in particle, parallel momentum and energy transport
  - ✗ **Missing term:** Drift and current associated to stress tensor divergence (ion viscosity)