Recent SOLEDGE3X improvements and first applications, towards a more realistic modelling of the generation of inverse Er

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Acknowledgements to Hugo Bufferand, Xavier Garbet, Patrick Tamain,
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OUTLINE

- ❑ TSVV1 SOLEDGE3X task and deliverables
- ❑ Progress report:
  - ❑ SOLEDGE3X model
    - Considerations on neoclassical viscosity implementation
  - ❑ Status of the implementation
  - ❑ Application to 3D turbulence with fluid neutrals in TCV-like geometry
  - ❑ Next steps
    - Set up of realistic WEST case

SOLEDGE3X milestones/deliverables

☐ Explore the impact on the inverse radial electric field formation of :

- neoclassical friction
- favorable versus unfavorable magnetic drift configuration in realistic X-point geometry

- M2.7 **Implement neoclassical friction in SOLEDGE3X** fluid edge turbulence code. Investigate its impact on the generation and dynamics of the radial electric field well via a **power scan in a limited case**, in comparison to previous results without the friction (of TSVV1 pilot) and to GK results. Investigation of QH or I mode regime. G. Falchetto 06/2022
- **D2.5** Report including statements on the relative impact of some separate ingredients playing a role in the radial electric field formation (orbit losses, ripple, **turbulence, neutrals**..)

Report or paper submitted, conference contribution X. Garbet, R. Varennes, L. Vermare, G. Falchetto 12/2022

- M4.2 Compare the generation of an inversed radial electric field in two magnetic configurations (**favourable vs unfavourable magnetic drift direction**) **in SOLEDGE3X with realistic X-point geometry and neutrals**, compare to experimental findings on one machine. G. Falchetto 06/2023
- **D4.2** Report on the study of the effect of the direction of the magnetic drift and the level of realism of the edge conditions, with respect to experimental measurements

Report, paper, or conference contribution G. Falchetto 12/2023

The SOLEDGE3X drift-fluid model [1]

- SOLEDGE3X merges SOLEDGE2D and TOKAM3X + relaxing some model assumptions
- **Electrostatic drift-fluid** equation system for a **multi-species plasma** based on Zhdanov closure

[Raghunathan et al., PPCF, 2021]

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

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

$$n_e = \sum_i Z_i n_i$$

Ionization terms
"Anomalous" diffusion
for transport simulations

- Velocity decomposition

$$\vec{v} = v_{\parallel}\vec{b} + \vec{v}_{\perp drifts} - \frac{D\vec{\nabla}_{\perp} n}{n}$$

- Ionization/recombination sources involving neutrals are computed by the "neutral solver":

-Either fluid neutrals (diffusive): very crude model but fast and robust

good approximation for recycling source and radiation power losses in the divertor

- Or kinetic neutrals EIRENE MC code : high fidelity

The SOLEDGE3X drift-fluid model [2]

- **Momentum balance**

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

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

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

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

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

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

Drift ordering (assuming $\varpi \ll \omega_c$):

$$\vec{v}_\perp^0 = \frac{\vec{E}\times\vec{B}}{B^2} + \frac{\vec{B}\times\vec{\nabla}p}{ZenB^2}$$

E x B *Diamagnetic*

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

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

The SOLEDGE3X drift-fluid model [3]

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

- **Current balance** (Equation on ϕ – vorticity equation)

[4] $\vec{\nabla}\cdot\vec{j}=0$ with $\vec{j}=\sum Zn\vec{v}=j_\parallel\vec{b}+\vec{j}^\star+\vec{j}_\Pi+\vec{j}_{pol}+\vec{j}^{ex}$

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

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

At 0th in drift ordering, polarization current can be expressed: $\vec{j}_{pol}=-\partial_t\vec{\omega}-\vec{\nabla}\cdot(\vec{v}^0\otimes\vec{\omega})$

where:

$$\vec{\omega}=\frac{m_i}{B^2}\left(n\vec{\nabla}_\perp\phi+\frac{1}{Ze}\vec{\nabla}_\perp p_i\right)$$

$\vec{\nabla}\cdot\vec{\omega}=\Omega$ vorticity

ϕ equation takes the form: $\vec{\nabla}\cdot\left(\partial_t\left[\frac{m_in}{B^2}\vec{\nabla}_\perp\phi\right]+\sigma_\parallel\nabla_\parallel\phi\vec{b}\right)=RHS$

- **Energy balance** $\mathcal{E}=\frac{3}{2}enT+\frac{1}{2}mnv_\parallel^2$

[5] $\partial_t\mathcal{E}+\vec{\nabla}\cdot\left(\mathcal{E}\vec{v}+pv_\parallel\vec{b}+v_\parallel\overline{\overline{\Pi}}\cdot\vec{b}+\vec{q}\right)=Znev_\parallel E_\parallel+v_\parallel R_\parallel+Q+S_{\mathcal{E}}^{iz+ex}+\vec{\nabla}\cdot\left(mnv_\parallel\eta_\perp\vec{\nabla}_\perp v_\parallel+n\chi_\perp\vec{\nabla}_\perp T\right)$

Stress tensor and parallel ion viscosity

In SOLEDGE3X, the stress tensor is treated as follows:

$$\overline{\overline{\Pi}} = \overline{\overline{\Pi}}_{\parallel} + \overline{\overline{\Pi}}_{\angle} + \cancel{\overline{\overline{\Pi}}_{\perp}}$$

- The perpendicular part including perpendicular collision is neglected
- $\overline{\overline{\Pi}}_{\angle}$ containing gyroviscous terms which are linked to diamagnetic effects in the fluid description is taken into account assuming ideal diamagnetic cancellation, that is considering the divergence of the diamagnetic stress tensor cancels the advection of velocity by diamagnetic velocity. Whereas the advection by second order ``∇**B**'' drift is kept.
- The parallel stress tensor embedding the parallel collisional contribution including parallel ion viscosity effects is kept

$$\overline{\overline{\Pi}} = \pi_{\parallel}\left(\vec{b} \otimes \vec{b} - \frac{1}{3}\overline{\overline{I}}\right)$$

where

$$\pi_{\parallel} = -3\eta_{\parallel}\left(\nabla_{\parallel} v_{\parallel} - \vec{\kappa}\cdot\vec{v} - \frac{1}{3}\vec{\nabla}\cdot\vec{v}\right)$$

$$\vec{\nabla}\cdot\overline{\overline{\Pi}}_{\parallel} = \left[\vec{\nabla}\cdot(\pi_{\parallel}\vec{b})\right]\vec{b} + \pi_{\parallel}\vec{\kappa} - \frac{1}{3}\vec{\nabla}\pi_{\parallel}$$

Implementation of neoclassical viscosity

Braginskji model pertinent to high collisionality edge plasma should recover Pfirsch – Schluter regime though neoclassical ordering is different : neoclassical $v \sim \varepsilon v_{thi}$ whereas Braginskjii & Zhdanov assume $v \sim v_{thi}$

From Helander Sigmar (2002)

$$< \boldsymbol{B} \cdot \nabla \cdot \overline{\boldsymbol{\Pi}}_{\boldsymbol{a}} > = 3\langle(\nabla_{\parallel} B)^2\rangle\left(\mu_{a1} u_{a\vartheta} + \mu_{a2}\frac{2qa_\theta}{5pa}\right)$$

$$= \frac{3}{2}\eta_0{}^{a}\langle W_{zz}\nabla_{\parallel} B\rangle$$

μ_{a1}, μ_{a2} parallel viscosity coefficients

In the limit $\rho_L \to 0$

$$W_{zz} = 2(\nabla_{\parallel} v_{\parallel} - \mathbf{v}\cdot\nabla_{\parallel}\boldsymbol{b}) = 2\, u_{a\vartheta}\nabla_{\parallel} B$$

missing term
in TOKAM3X model

$$< \boldsymbol{B} \cdot \nabla \cdot \overline{\boldsymbol{\Pi}}_{\boldsymbol{a}} > \equiv 3\,\eta_0{}^{\alpha}\langle(\nabla_{\parallel} B)^2\rangle u_{a\vartheta}$$

In Braginskji parallel viscosity is determined by particle flux alone (heat flux is smaller order due to the chosen flow ordering)

$\mu_{a1} = \eta_0{}^{\alpha}$ $\eta_0{}^{i} = 0.96\, n_i T_i \sqrt{2}\tau_{ii}$

OPEN QUESTION: Is there a better closure than Braginskii/Zhdanov for multi-species edge plasma without assuming a scaling on velocities?

Status of SOLEDGE3X implementation

✓ New SOLEDGE3X code enables 2D/3D transport and 3D turbulent simulations for multi-species plasma.

- **Status of implementation**:

  ✓Code runs routinely in 2D transport mode (including drifts) and 3D turbulent mode in divertor geometry

  ✓**Neutrals**: coupling to fluid model tested in 2D and 3D, coupling to EIRENE tested for 2D transport only + advanced A&M model (from Kotov PPCF 2008 w/o n-n collisions) [Bufferand PET 2021, Rivals PET 2021]

  ✓ First application to power scan on TCV case including neutrals shows onset of turbulence at low power and recovers generation of E_r well accompanied by turbulence reduction around separatrix at high power

  ✓Drift and current associated to the stress tensor divergence, including parallel ion viscosity – implemented

  under test before merging into SOLEDGE3X git master branch and release

✘ **Missing terms**: polarization velocity not included in particle, parallel momentum and energy transport

✘ **Electromagnetic** version under development

Turbulence application: TCV-like case

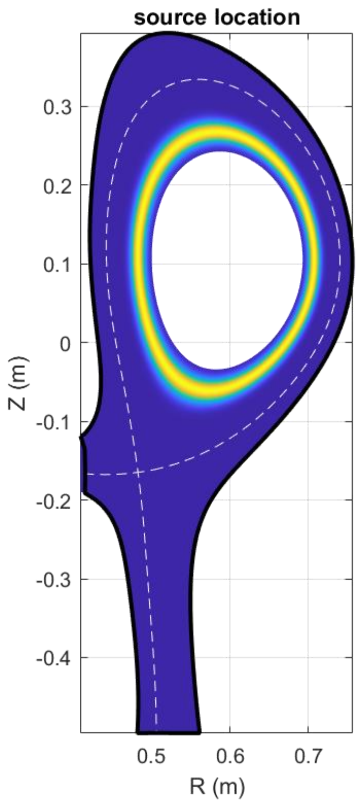
Purpose: test code capability to simulate a turbulent plasma in **divertor geometry including fluid neutrals**

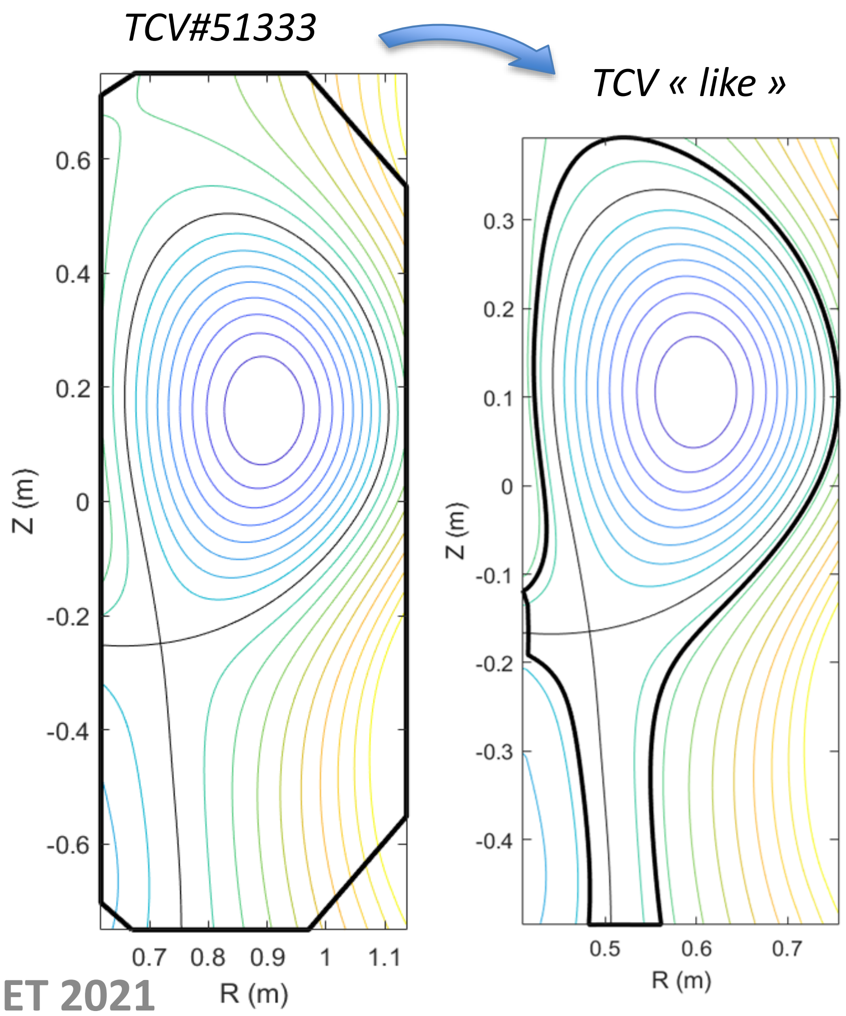
- Equilibrium based on TCV#51333 (magnetic field rescaled by ½)
- Wall geometry modified to fit a flux surface
  (to avoid potential artefacts due to a non-aligned wall
  – consequence: closer divertor in the simulation)

Simulation setup:

- Pure D plasma with **fluid neutrals**
- Anomalous diffusivities set to $10^{-2} m^2 s^{-1}$
  (classical collision level)
- Energy source at $\frac{r}{a} \approx 0.75$
  Power scan $50\ \ 100\ \ 200\ kW$
- Recycling on the wall set to 80%
  Gas puff at outer midplane adjusted to get
  $n_e \approx 10^{19} m^{-3}$ at the separatrix
- Parallel resistivity artificially $\times\ 10$

$N_\psi \sim 92$; $N_\theta \sim 736$; $N_\varphi = 64$ (1/4 torus)
grid points $\sim 4 \cdot 10^6$

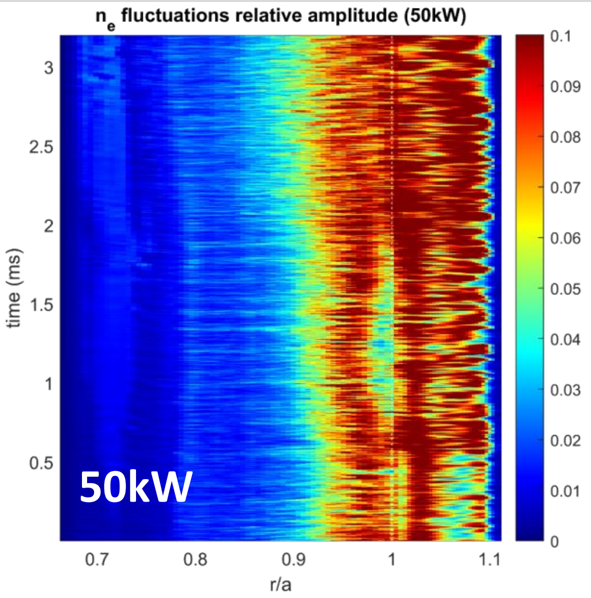


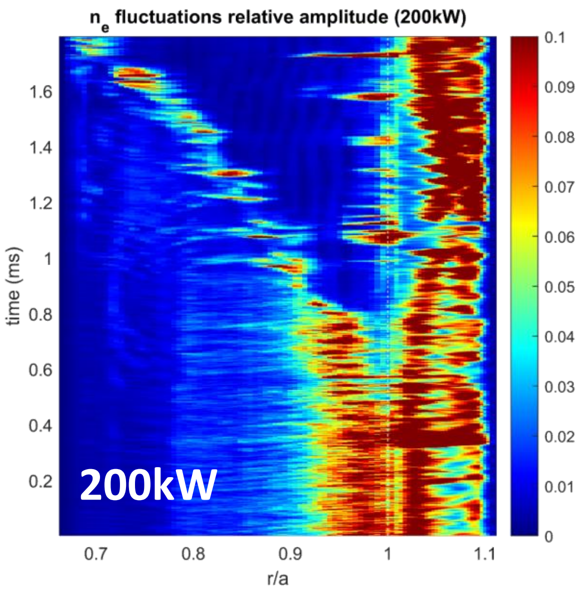


Courtesy H . Bufferand PET 2021

Turbulent suppression near separatrix at high power

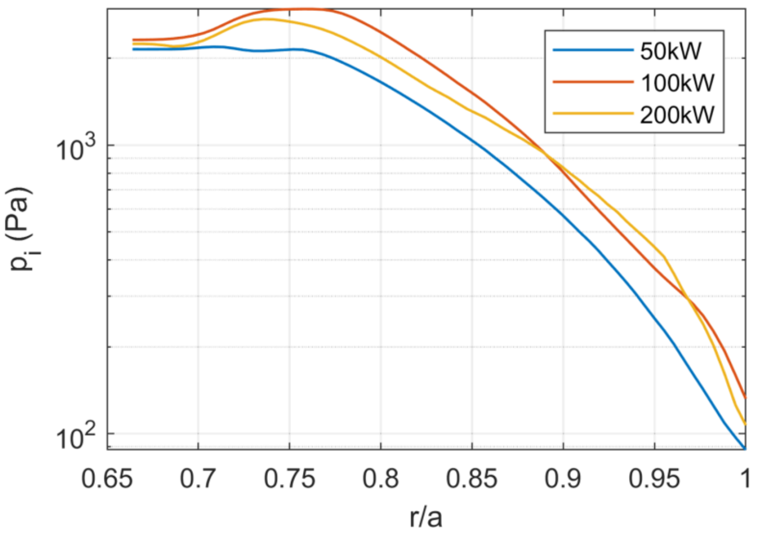
- Well developed turbulence at low power ($50kW$)
  Avalanches cross the separatrix
- Reduction of fluctuation level around the separatrix at higher power ($100kW$ and $200kW$)
  “gap” propagates from separatrix inward
  Associated with higher $E \times B$ shear
  Stationary zonal flows observed in the low turbulence region
  Similar to [Giacomin, J. Plasma Phys., 2020]

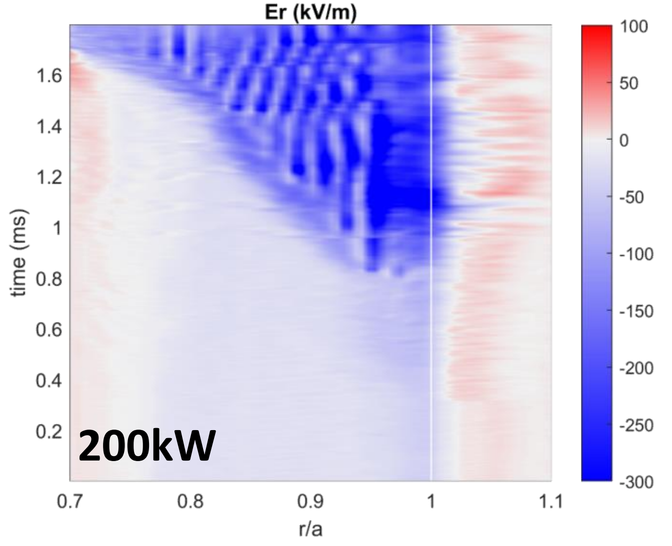




- 1ms after turbulence reduction, no clear steepening in pressure profile
  local steepening near separatrix
- E_r well recovered though **very high value**

missing a term to control plasma rotation?
Ion viscosity effects
[Sigmar & Helander, Zholobenko et al., PPCF 2021]





Courtesy H . Bufferand PET 2021

Next steps

Neoclassical viscosity impact study: plan towards M2.7 and deliverable 2022

- 2D transport simulations – verification of P-S neoclassical transport
- 3D turbulence reference case in circular bottom limiter geometry with $\eta=0$

  (same parameters as GYSELA : Tore Supra rescaled with ½B ¼ of torus)
- 3D turbulence simulations in circular bottom limiter case with parallel ion viscosity - power scan

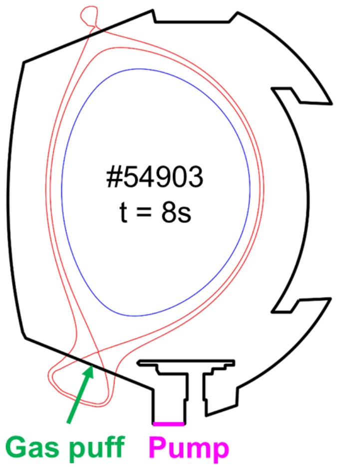
Magnetic drift impact: plan towards M4.2 and deliverable 2023

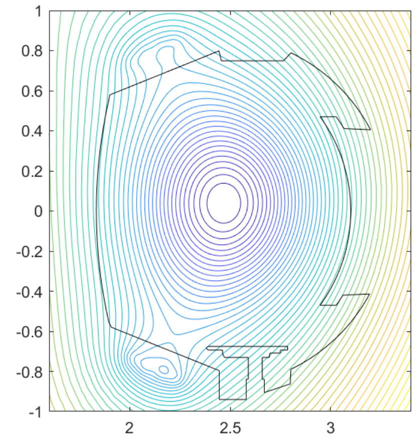
- WEST #54903 LSN @t = 4.8s
- Compare to reversed B field case: USN
- Higher q_{95} to verify the effect observed experimentally
- Increase power in USN case

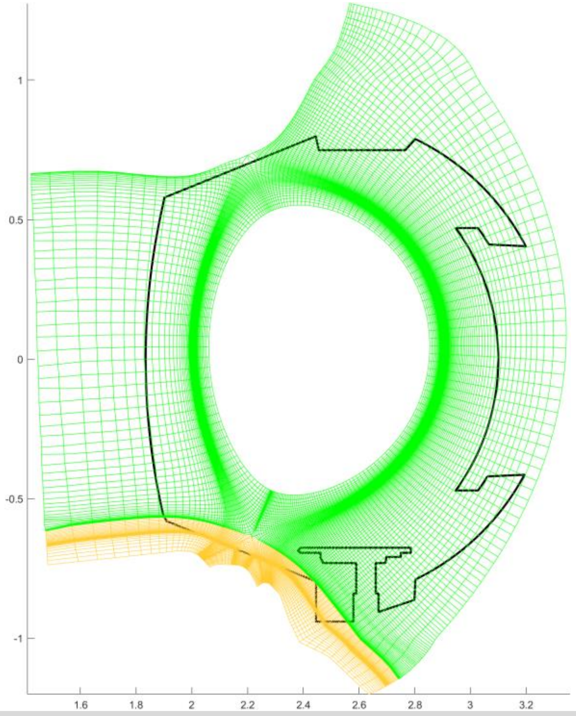
2D transport application + drifts and kinetic neutrals: WEST case

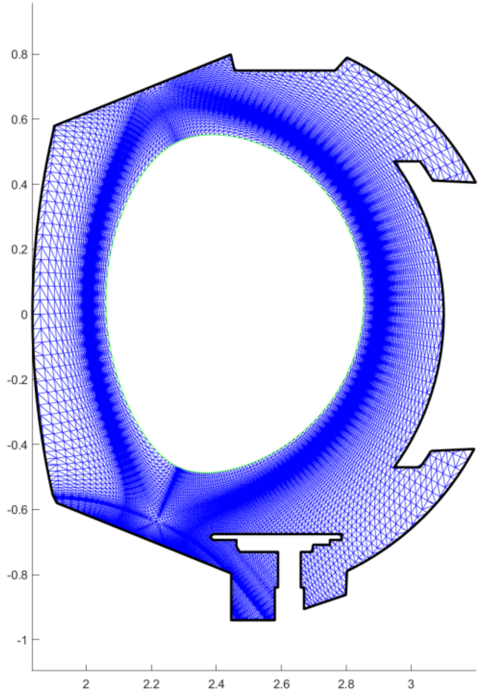
WEST #54903
2D SOLEDGE3X-EIRENE simulation setup

- LSN
  Pure D
- Upstream density = 1.6e^{19} part/m^3
- Input power $P_{\mathrm{in}} = P_{\mathrm{heat}} - P_{\mathrm{rad}}^{\mathrm{core}} \simeq 450\ \mathrm{kW}$
- $D = \nu = 0.3\ \mathrm{m^2 s^{-1}}, \chi_\mathrm{e} = \chi_\mathrm{i} = 1\ \mathrm{m^2 s^{-1}}$
- Recycling coefficient R$_{\mathrm{wall}}$ = 1, R$_{\mathrm{pump}}$ = 0.95









Courtesy M. Peret, H. Yang