TCV-X21 modelling using updated SolEdge-HDG with self-consistent neutrals and mesh adaptivity

On behalf of SolEdge-HDG team

Regular TSVV3 meeting | 28.05.25

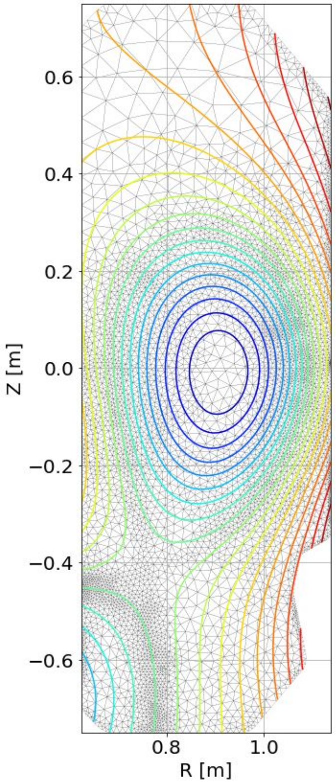
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

SolEdge-HDG

- Based on finite elements [Giorgiani G., 2018]
  Hybridized **D**iscontinuous **G**alerkin method:
  - Highly parallelizable
  - Straightforward description of complicated boundary geometries

- High-order numerical scheme:
  - Meshes are magnetic equilibrium free
  - X-points and magnetic axis cause no topological issues

- Implicit time scheme: large time steps up to steady-state
- Mesh adaptivity is implemented
  [Piraccini G., 2022]



TCV-X21 magnetic field lines on computational mesh

SolEdge-HDG physical model

- Braginskii fluid closure
- Fluid diffusive neutrals
- Cylindrical geometry with toroidal symmetry $\mathbf{B} = B^R \mathbf{e_R} + B^Z \mathbf{e_Z} + B^\phi \mathbf{e}_\phi, \quad \partial_\phi = 0$
- Single ion deuterium plasma $n_e = n_i \equiv n$
- Only parallel plasma flow $\mathbf{u} \approx u\mathbf{b}$
- Adiabatic electrons with inertia neglected $enE_\parallel = -\nabla_\parallel (nk_b T_e)$, $m_e/m_i = \mathcal{O}(10^{-3})$
- No drifts
- No neutrals energy equation $T_i = T_n$

SolEdge-HDG neutrals model

- Fully diffusive model

$$\partial_t n_n - \underbrace{\nabla \cdot (D_{n_n} \nabla n_n)}_{\text{neutral diffusion}} = S_{n_n}$$

- Neutral-neutral collisions included as in Kotov's PhD

$$D_{n_n} = \frac{e T_i[\mathrm{eV}]}{m_i \left(n(\langle \sigma v \rangle_{cx} + \langle \sigma v \rangle_{iz}) + n_n \langle \sigma v \rangle_{nn}\right)} \qquad \langle \sigma v \rangle_{nn} = s_0 T^{0.25}$$

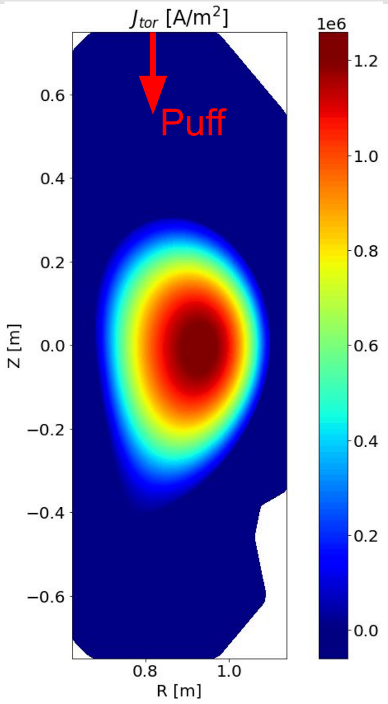
- Source-sink coupling terms are now calculated using OpenADAS data for deuterium

- Recycling at the wall + puff rate in particles/sec + pump with imposed pumping speed [m^3/s]

$$-D_{n_n} \nabla n_n \cdot \mathbf{n} = -R(-D \nabla_\perp n + n u \mathbf{b}) \cdot \mathbf{n} - \Gamma_{\mathrm{puff}} \cdot \mathbf{n} + \Gamma_{\mathrm{pump}} \cdot \mathbf{n}$$

TCV-X21 simulation setup

- Steady state
- Equilibrium from TCV-X21 github page
- Ip calculated based on poloidal flux
- $D=\mu=0.2\ m^2/s$, $\chi_e=\chi_i=1\ m^2/s$ (as in SOLPS-ITER)
- Ohmic heating, Z_{eff} adjusted to have $P_{in} \approx 130$ kW
- R=0.9
- Puff adjusted to have flux on the wall around $3x10^{21}$ particles/s



Plasma current density

HDG neutrals model issue

- Due to assumption T_i=T_n the ionization term in ion energy equation “heats” plasma too much

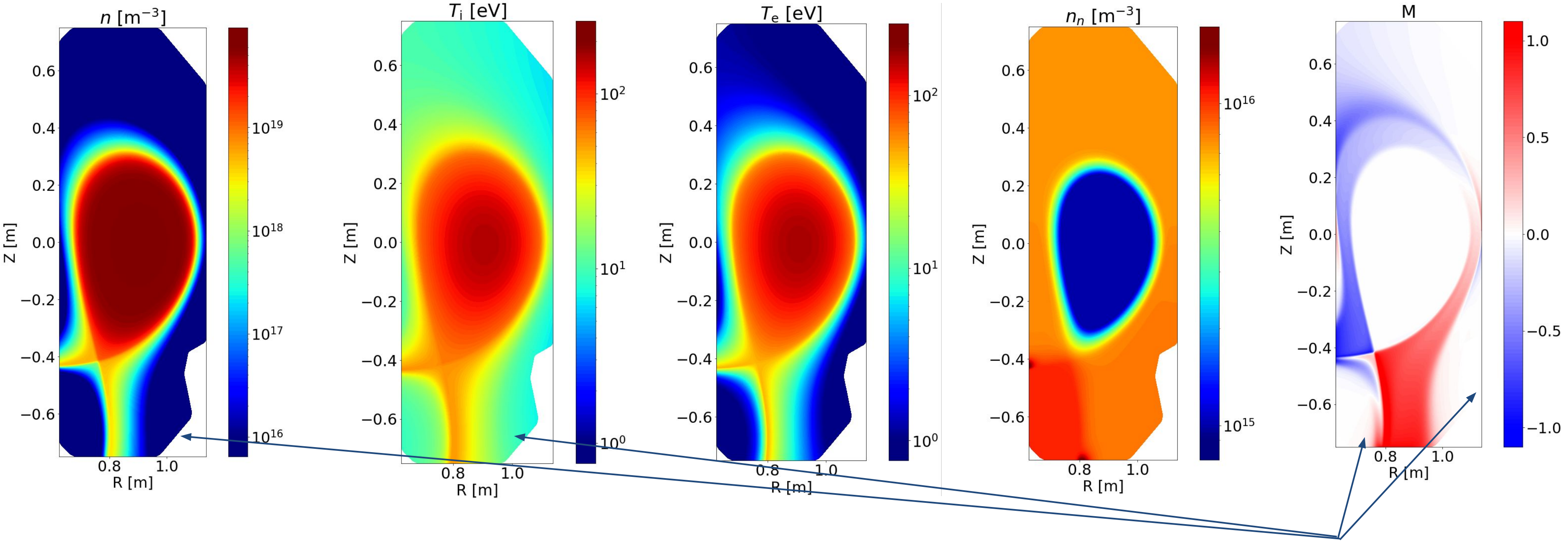
$$n_n n \langle \sigma v \rangle_{iz} R_E \left[\frac{3}{2} k_b T_i \right]$$

- I had to reduce Zeff to 0.3 (non-physical, of course) and even then $P_{tot,vol}$ = 140 kW, with P_{iz} = 60 kW

- First analysis will be made with this setup

- Next step will be to remove this energy term

2D poloidal plots of solution



Bohm BC is suppressed, where plasma energy content is low for stability

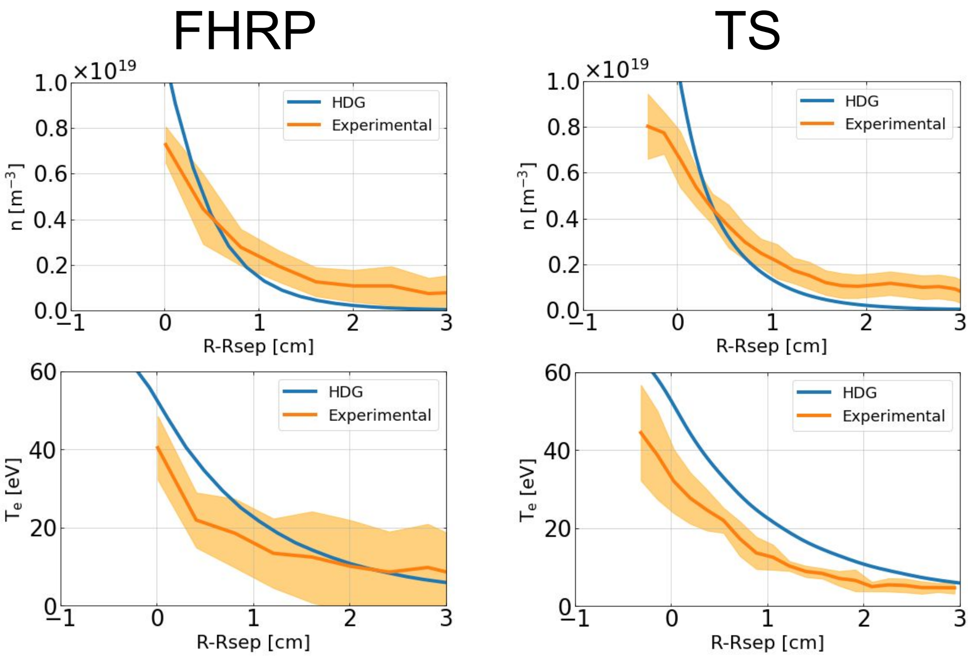
$$c_s \to c_s \cdot \frac{1}{1 + \frac{(nE)_{\mathrm{th}}}{nE_i}}$$

Midplane profiles

- Both T and n profiles in the simulation decay faster

- Higher density at the core also leads to higher Ohmic heating

- It seems that transport coefficient from SOLPS are too small for SolEdge-HDG. Why?

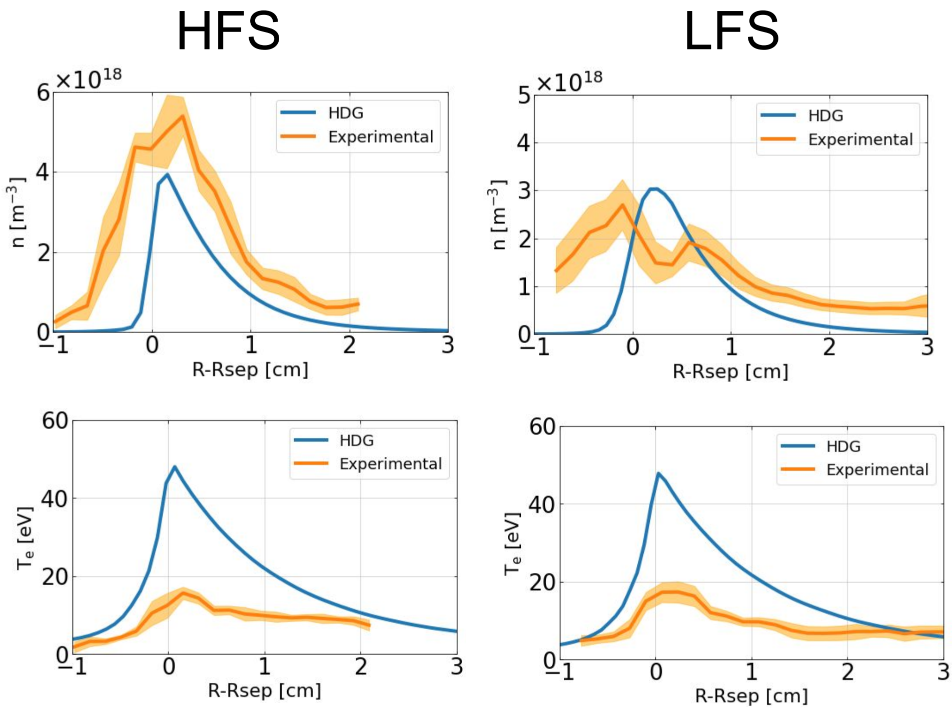


Divertor profiles

- Density profiles match better

- T is overestimated. Impurity radiation losses missing?

- Both profiles decay faster than experimental ones.
  Should I use my own diffusivities and not SOLPS ones?



Removing ionization source of energy

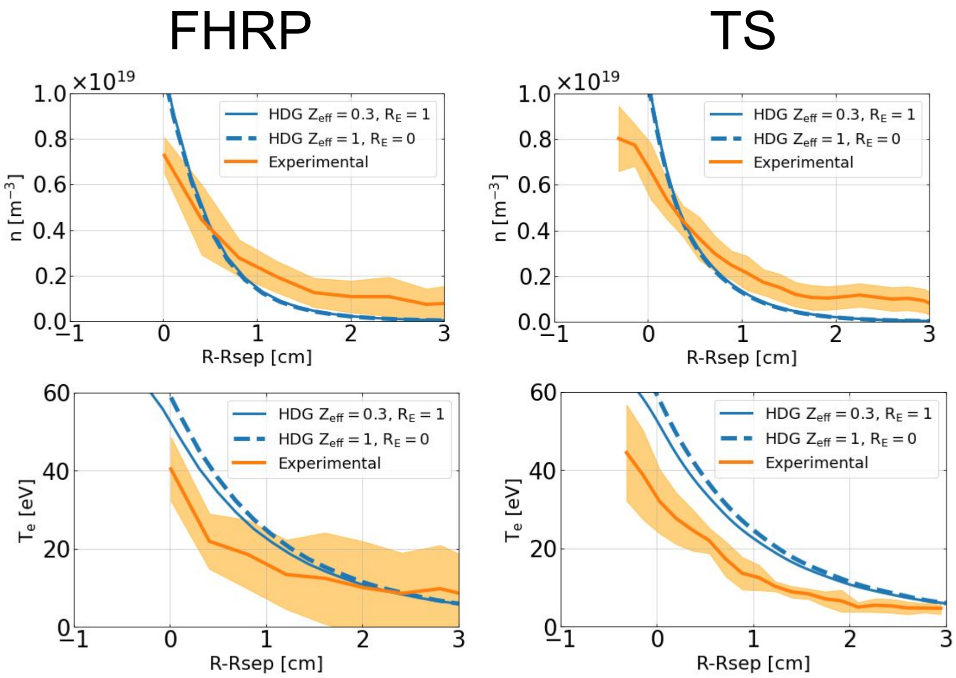
- Assuming that at first ionization energy of neutrals is negligible, we assume R_E=0

$$n_n n \langle \sigma v \rangle_{iz} R_E \left[\frac{3}{2} k_b T_i \right]$$

- D=μ=0.2 m^2/s, $\chi_e = \chi_i$=1 m^2/s (as in SOLPS-ITER)
- Zeff = 1(deuterium plasma); P_{Ohm} = 180 kW
- With the same perpendicular transport coefficients total Ohmic power is larger than in other TCV-X21 simulations (too large transport?)

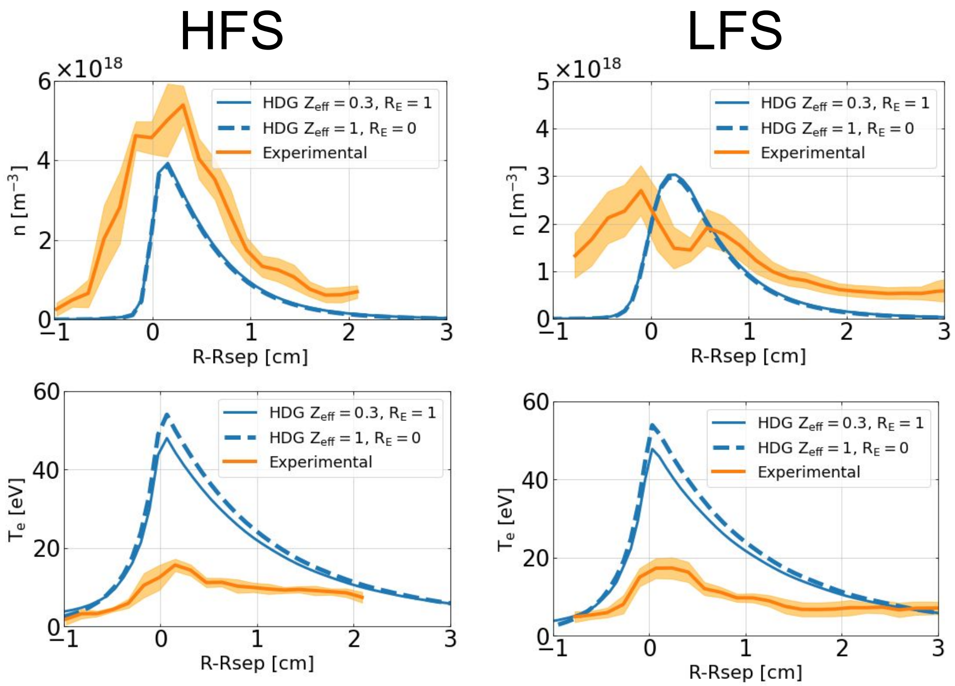
Midplane profiles

- Almost no difference in density
- Temperature is higher due to higher input power (180 kW vs 140 kW)
- To match experimental profiles one have to reduce perpendicular transport



Divertor profiles

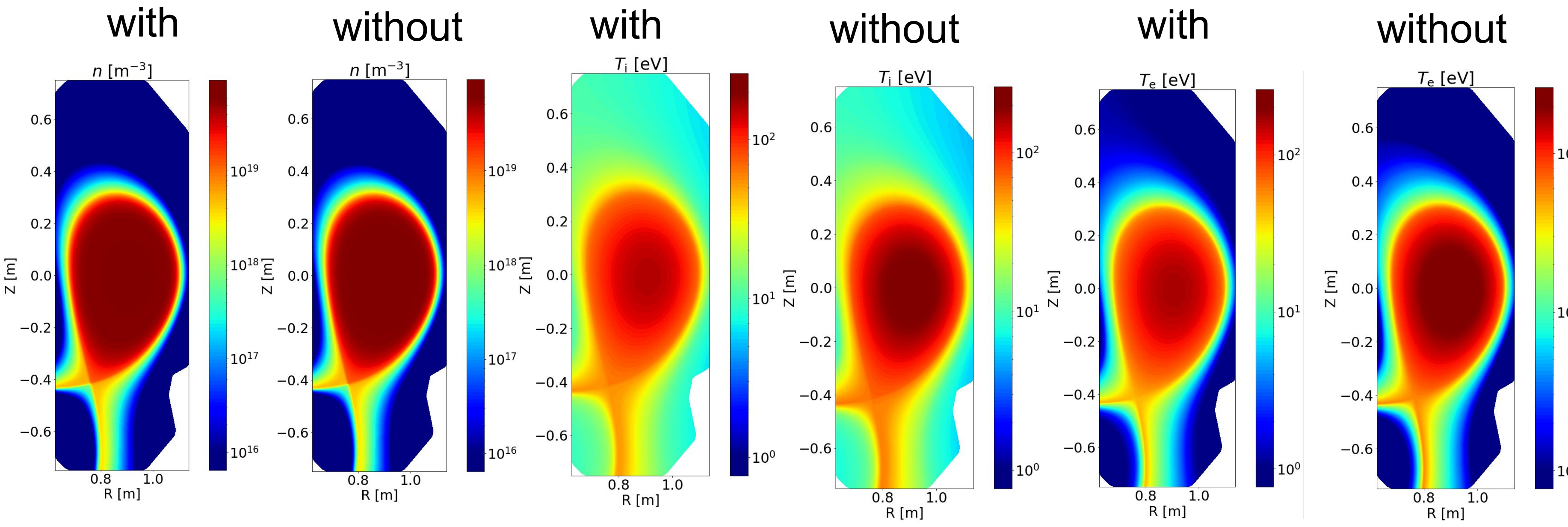
- Similar trend as at midplane
- Temperature is even higher



Conclusions

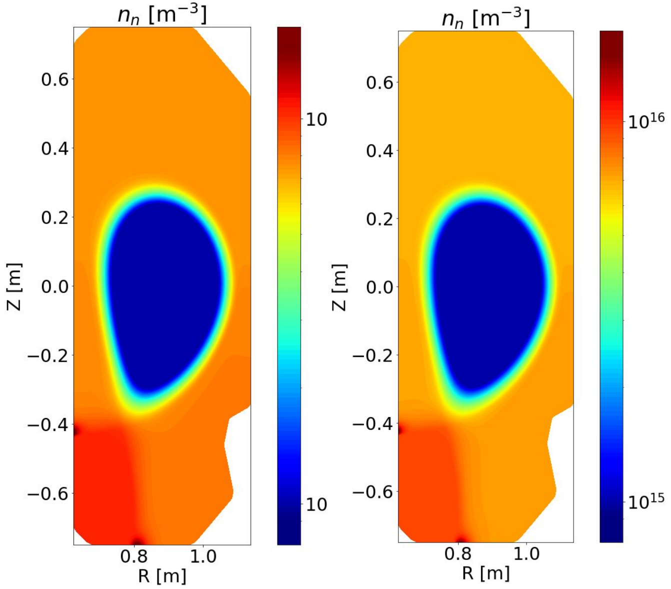
- TCV-X21 modelling pipeline is developed and tested for SolEdge-HDG
- Mesh adaptivity nicely catches separtrix and divertor legs
- In the absence of neutral energy equation one should be careful with neutral-ion energy coupling
- SOLPS-ITER set of transport coefficients result in too large gradients of n and T
- Density is generally in better match than temperature
- Change of power input from “fake” neutral one to Ohmic source leads to almost no change in profiles

With/without energy source from neutrals

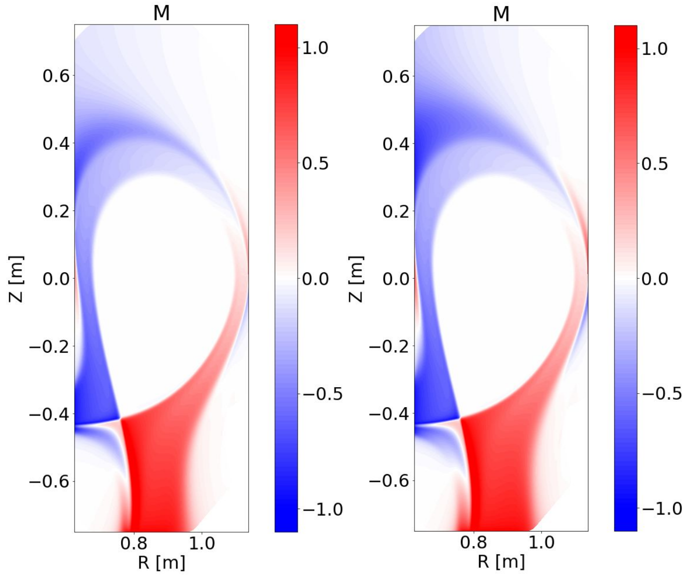


With/without energy source from neutrals

with without



with without



SolEdge-HDG system of equations

- Continuity equation

$$\partial_t n + \underbrace{\nabla \cdot (n u \mathbf{b})}_{\parallel \text{ advection}} - \overbrace{\nabla \cdot (D \nabla_\perp n)}^{\perp \text{ anomalous diffusion}} = S_n$$

- Neutral continuity equation

$$\partial_t n_\mathrm{n} - \underbrace{\nabla \cdot (D_{n_\mathrm{n}} \nabla n_\mathrm{n})}_{\text{neutral diffusion}} = S_{n_\mathrm{n}}$$

- Momentum conservation

$$\partial_t (m_\mathrm{i} n u) + \underbrace{\nabla \cdot (m_\mathrm{i} n u^2 \mathbf{b})}_{\parallel \text{ advection}} + \underbrace{\nabla_\parallel (k_\mathrm{b} n (T_\mathrm{e} + T_\mathrm{i}))}_{\text{pressure stress}} - \overbrace{\nabla \cdot (m_\mathrm{i} (n \mu \nabla_\perp u + u D \nabla_\perp n))}^{\perp \text{ anomalous diffusion}} = S_\Gamma$$

SolEdge-HDG system of equations

- Electron energy conservation

$$\partial_t\left(\frac{3}{2}k_b n T_e\right) + \underbrace{\nabla\cdot\left(\frac{5}{2}k_b n T_e u\mathbf{b}\right)}_{\parallel\ \text{advection}} - \overbrace{\nabla_\parallel(n k_b T_e)}^{\parallel\ \text{electric field}} - \underbrace{\nabla\cdot\left(\frac{3}{2}k_b(T_e D\nabla_\perp n + n\chi_e\nabla_\perp T_e)\right)}_{\perp\ \text{anomalous diffusion}}$$

$$\underbrace{-\nabla\cdot(k_{\parallel e}T_e^{\frac{5}{2}}\nabla_\parallel T_e\mathbf{b})}_{\parallel\ \text{heat conductivity}} - \overbrace{\frac{3}{2}\frac{k_b n}{\tau_{ie}}(T_e - T_i)}^{\text{temperature-exchange}} = S_{E_e}$$

- Ion energy conservation

$$\partial_t\left(\frac{3}{2}k_b n T_i + \frac{1}{2}m_i n u^2\right) + \underbrace{\nabla\cdot\left(\left(\frac{5}{2}k_b n T_i + \frac{1}{2}m_i n u^2\right)u\mathbf{b}\right)}_{\parallel\ \text{advection}} + \overbrace{\nabla_\parallel(n k_b T_e)}^{\parallel\ \text{electric field}}$$

$$\underbrace{-\nabla\cdot\left(\frac{3}{2}k_b(T_i D\nabla_\perp n + n\chi_i\nabla_\perp T_i)\right) - \nabla\cdot\left(\frac{1}{2}m_i u^2 D\nabla_\perp n + \frac{1}{2}m_i\mu n\nabla_\perp u^2\right)}_{\perp\ \text{anomalous diffusion}}$$

$$\underbrace{-\nabla\cdot(k_{\parallel i}T_i^{\frac{5}{2}}\nabla_\parallel T_i\mathbf{b})}_{\parallel\ \text{heat conductivity}} + \overbrace{\frac{3}{2}\frac{k_b n}{\tau_{ie}}(T_e - T_i)}^{\text{temperature-exchange}} = S_{E_i}$$