Latest updates of the SolEdge-HDG code

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OUTLINE

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The physical model

The equations considered are:

- Continuity equation

$$\partial_t n + \boldsymbol{\nabla}\cdot(nu\boldsymbol{b}) - \boldsymbol{\nabla}\cdot(D\boldsymbol{\nabla}_\perp n) = \hat{S}_n. \tag{1}$$

- Momentum equation

$$\partial_t(m_i nu) + \boldsymbol{\nabla}\cdot(m_i nu^2\boldsymbol{b}) + \boldsymbol{\nabla}_\parallel(k_b n(T_e + T_i)) - \boldsymbol{\nabla}\cdot(\mu\boldsymbol{\nabla}_\perp(m_i nu)) = \hat{S}_\Gamma. \tag{2}$$

- Total ions energy equation

$$\begin{aligned}&\partial_t(\frac{3}{2}k_b nT_i + \frac{1}{2}m_i nu^2) + \boldsymbol{\nabla}\cdot((\frac{5}{2}k_b nT_i + \frac{1}{2}m_i nu^2)u\boldsymbol{b}) - nueE_\parallel + \\ &- \boldsymbol{\nabla}\cdot\left(\frac{3}{2}k_b(TiD\boldsymbol{\nabla}_\perp n + n\chi_i\boldsymbol{\nabla}_\perp T_i)\right) - \boldsymbol{\nabla}\cdot(-\frac{1}{2}m_i u^2 D\boldsymbol{\nabla}_\perp n + \frac{1}{2}m_i\mu n\boldsymbol{\nabla}_\perp u^2) + \\ &- \boldsymbol{\nabla}\cdot(k_{\parallel i}T_i^{5/2}\boldsymbol{\nabla}_\parallel T_i\boldsymbol{b}) + \frac{3}{2}\frac{k_b n}{\hat{\tau_{ie}}}(T_e - T_i) = \hat{S}_{E_i}.\end{aligned} \tag{3}$$

- Total electrons energy equation

$$\begin{aligned}&\partial_t(\frac{3}{2}k_b nT_e) + \boldsymbol{\nabla}\cdot(\frac{5}{2}k_b nT_e u\boldsymbol{b}) + nueE_\parallel - \boldsymbol{\nabla}\cdot\left(\frac{3}{2}k_b(T_e D\boldsymbol{\nabla}_\perp n + n\chi_e\boldsymbol{\nabla}_\perp T_e)\right) + \\ &- \boldsymbol{\nabla}\cdot(k_{\parallel e}T_e^{5/2}\boldsymbol{\nabla}_\parallel T_e\boldsymbol{b}) - \frac{3}{2}\frac{k_b n}{\hat{\tau_{ie}}}(T_e - T_i) = \hat{S}_{E_e}.\end{aligned} \tag{4}$$

The neutral models

- Diffusive neutrals $\rightarrow$ N_n model

$$\partial_t n_n - \nabla \cdot (D_{n_n} \nabla n_n) = S_{n_n}$$

$$D_{n_n} = \frac{eT_i[eV]}{m_i n(\langle \sigma v_{cx} \rangle + \langle \sigma v_{iz} \rangle)}$$

- Neutral particle conservation + parallel momentum $\rightarrow$ $N_n \Gamma_{n_n}$ model

$$\begin{cases} \partial_t n_n + \nabla \cdot (n_n u_n \mathbf{b} - D_{n_n} \nabla n_n) = S_{n_n} \\ \partial_t (n_n u_n) + \nabla \cdot (n_n u_n^2 \mathbf{b} - \eta \nabla (u_n \mathbf{b})) + \nabla_{||} (n_n k_b T_n) = S_{\Gamma_{n_n}} \end{cases} \quad \eta = \frac{n_n k_b T_n}{m_i n <\sigma v>_{cx}}$$

Conservative form of the physical model

$$\begin{cases} \boldsymbol{\mathcal{Q}} - \nabla \boldsymbol{U} = \boldsymbol{0} \\ \partial_t \boldsymbol{U} + (\boldsymbol{u}_\perp \cdot \nabla)\boldsymbol{U} + \nabla \cdot \boldsymbol{\mathcal{F}} - \nabla \cdot (D_f \boldsymbol{\mathcal{Q}}) + \nabla \cdot (D_f \boldsymbol{\mathcal{Q}} \boldsymbol{b} \otimes \boldsymbol{b}) - \nabla \cdot \boldsymbol{\mathcal{F}}_t + \boldsymbol{f}_{E_\parallel} + \boldsymbol{f}_{EX} - \boldsymbol{g} = \boldsymbol{s} \end{cases}$$

where the vector of conservative variable $\boldsymbol{U}$ and its gradient $\boldsymbol{\mathcal{Q}}$ are defined as:

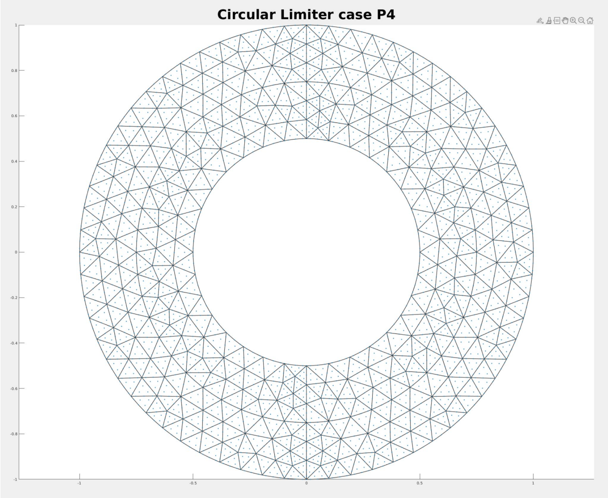
$$\boldsymbol{U} = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} = \begin{bmatrix} n \\ nu \\ nE_i \\ nE_e \\ n_n \end{bmatrix} \qquad \boldsymbol{\mathcal{Q}} = \nabla \boldsymbol{U} = \begin{bmatrix} U_{1,x} & U_{1,y} \\ U_{2,x} & U_{2,y} \\ U_{3,x} & U_{3,y} \\ U_{4,x} & U_{4,y} \\ U_{5,x} & U_{5,y} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\nabla} U_1^T \\ \boldsymbol{\nabla} U_2^T \\ \boldsymbol{\nabla} U_3^T \\ \boldsymbol{\nabla} U_4^T \\ \boldsymbol{\nabla} U_5^T \end{bmatrix}.$$

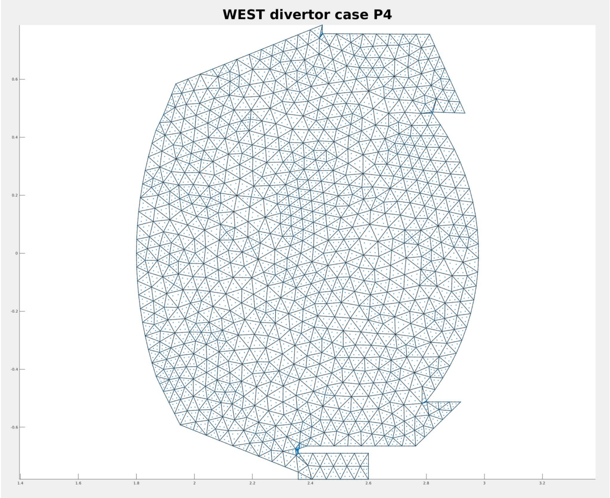
SolEdge-HDG features:

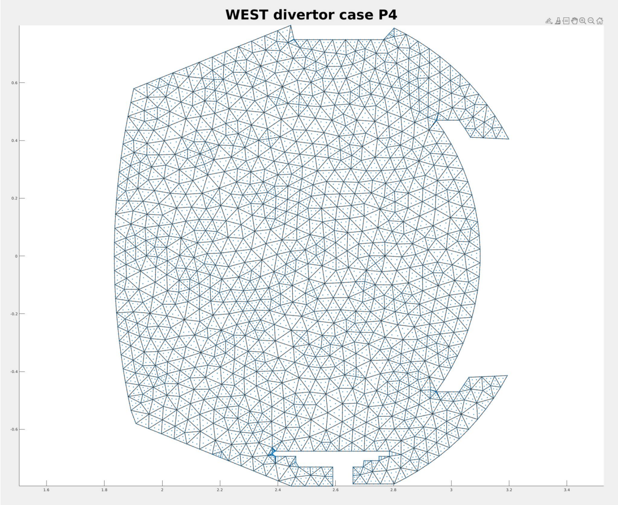
SolEdge-HDG features are:

1. Fully **implicit time** scheme
2. **2 plasma models** + **2 neutral models** (nGamma, nGammaTiTe, nGammaTiTeNeutrals) + **1 turbulent k-ε model**
3. **Solvers**:
    a. **Direct**: PASTIX/PETSc (always works)
    b. **Iterative**: PETSc/PSBLAS (only works for 2D dt < 1e-5, condition # too high)
4. **Dimensions**:
    a. 2D: always works, robust
    b. 3D: only works for Circular Limiter case or very simple WEST coarse meshes (condition # too high)
5. Handling **any type of geometry**, from CORE to WALL.
6. Handling of **Ohmic Heating** and **Puff + ad hoc additional heating**
7. Handling **variable magnetic equilibrium**
8. **h-adaptivity**
9. **Speed** and **parallelizability**:
    a. **OPENMP** example: 20 threads, 28k elements p4 triangles, 5 equations, 1M nDoF, 1 minute per matrix inversion. 2h for D = 26 –> 1 m2/s simulation.
    b. **OPENMPI** example: 24 processes, 6 threads/proc, 36k elements p6 quadrangles, 6 equations, 10M nDof, 50s per inversion, 72h for ramp up ITER discharge.

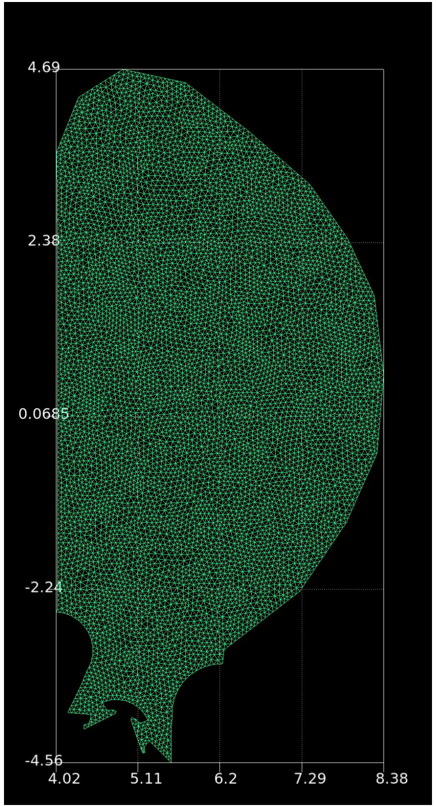
Geometries

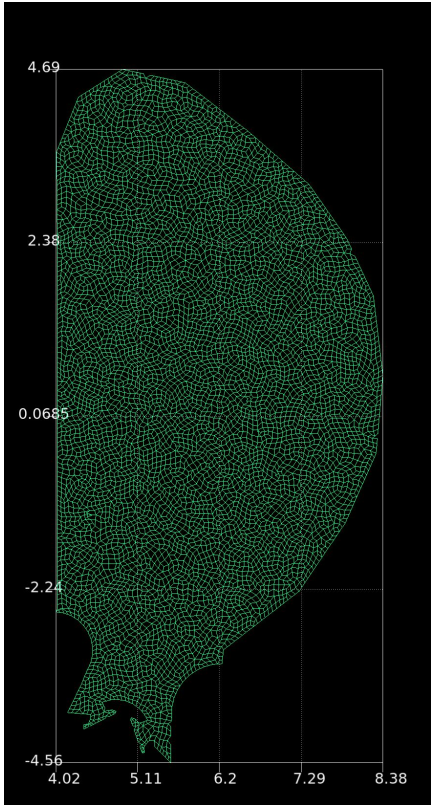

Circular Limiter case P4


WEST divertor case P4


WEST divertor case P4

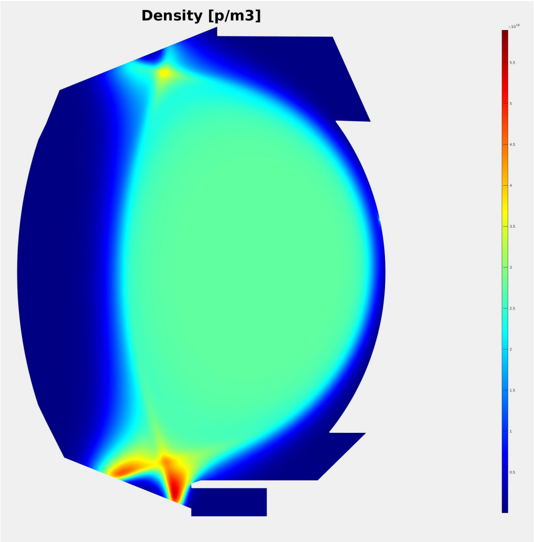
Geometries: ITER triangles and quadrangles

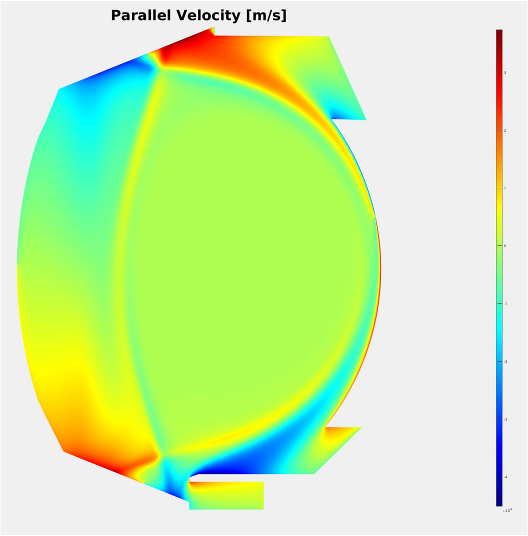


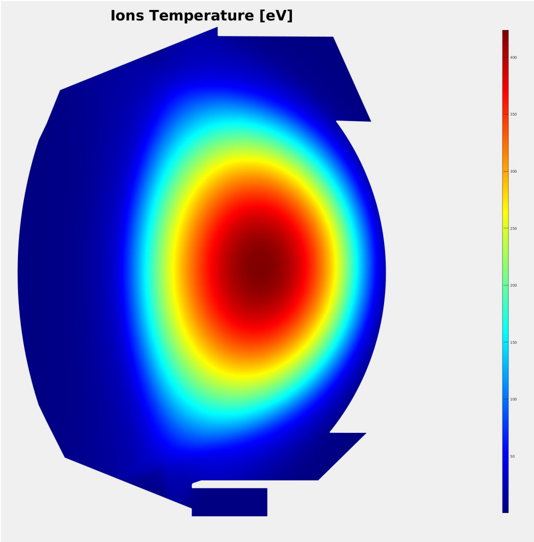


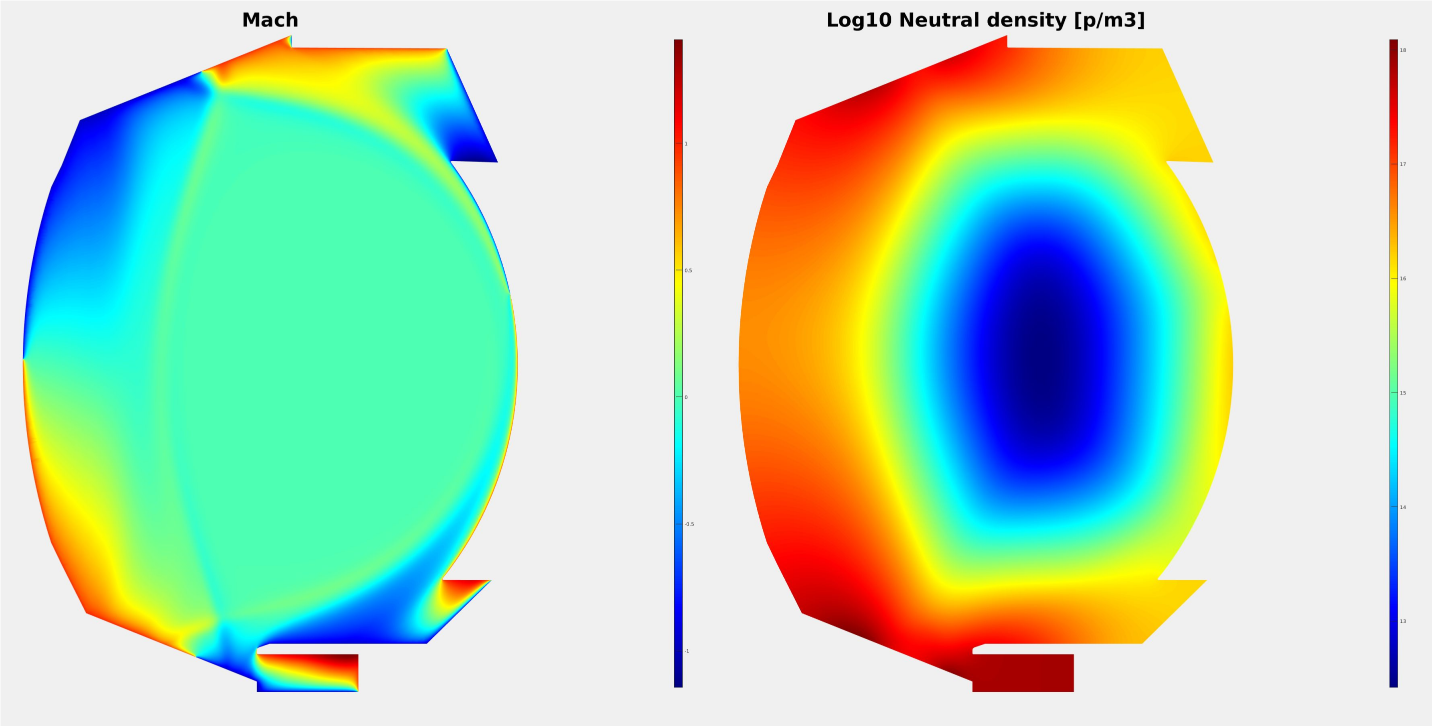
2D WEST simulations

SolEdge-HDG is a robust code for 2D simulations. Here is an example of a 2D steady state WEST simulation with NGammaTiTe with diffusive neutrals model at 1 m2/s:



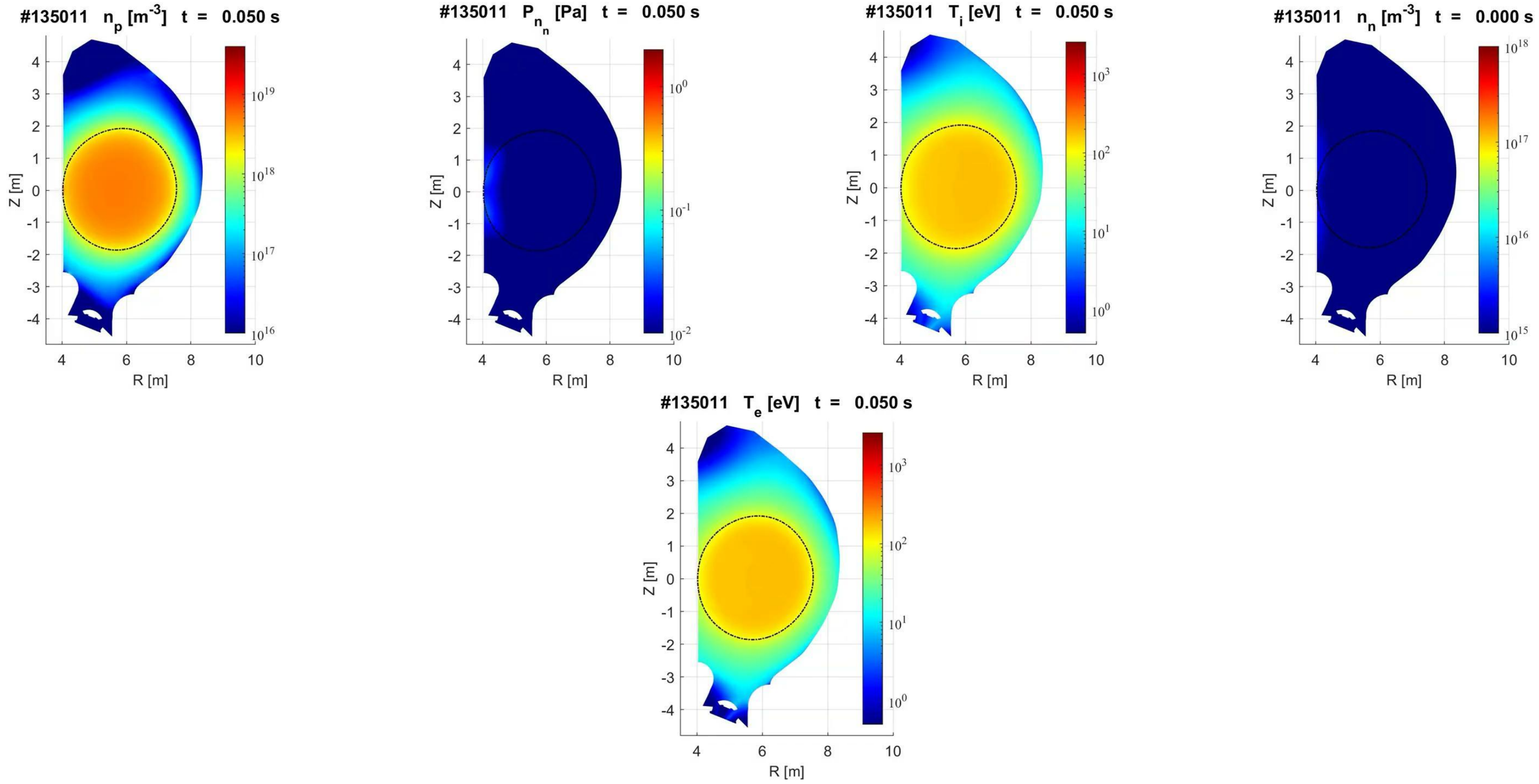




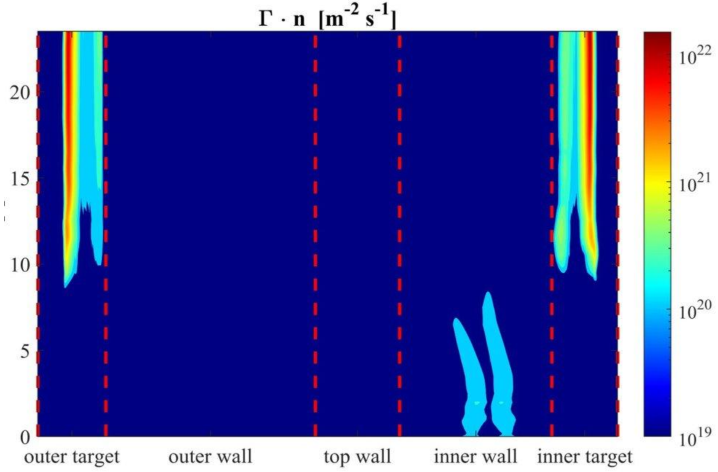


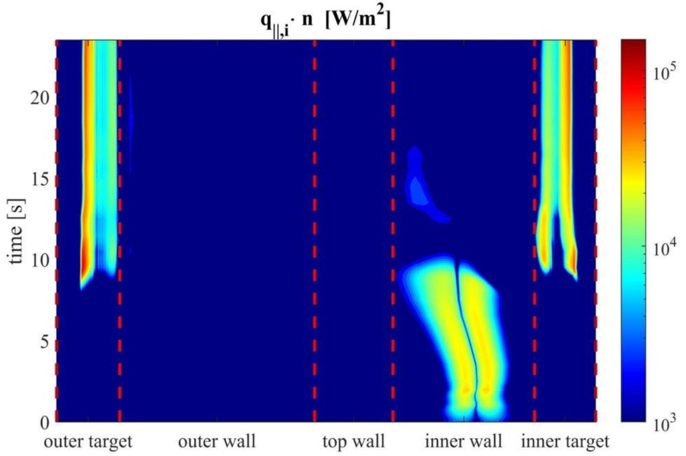
Mach
Log10 Neutral density [p/m3]
1
0.5
0
-0.5
-1
18
17
16
15
14
13

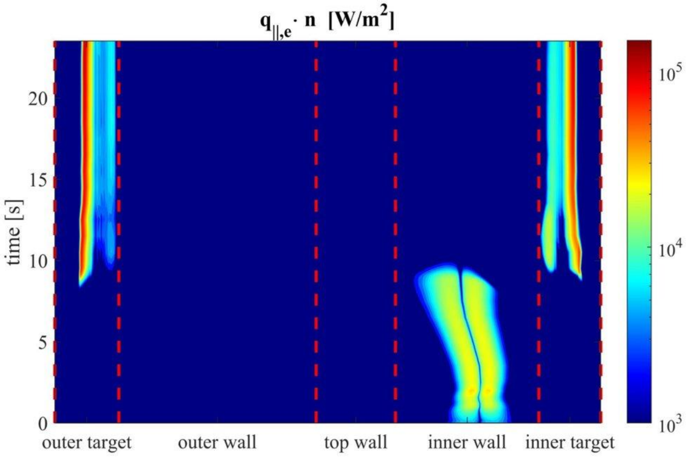
2D ITER ramp up discharge phase



Spatio-Temporal Map of plasma quantities at wall coordinates: General Overview







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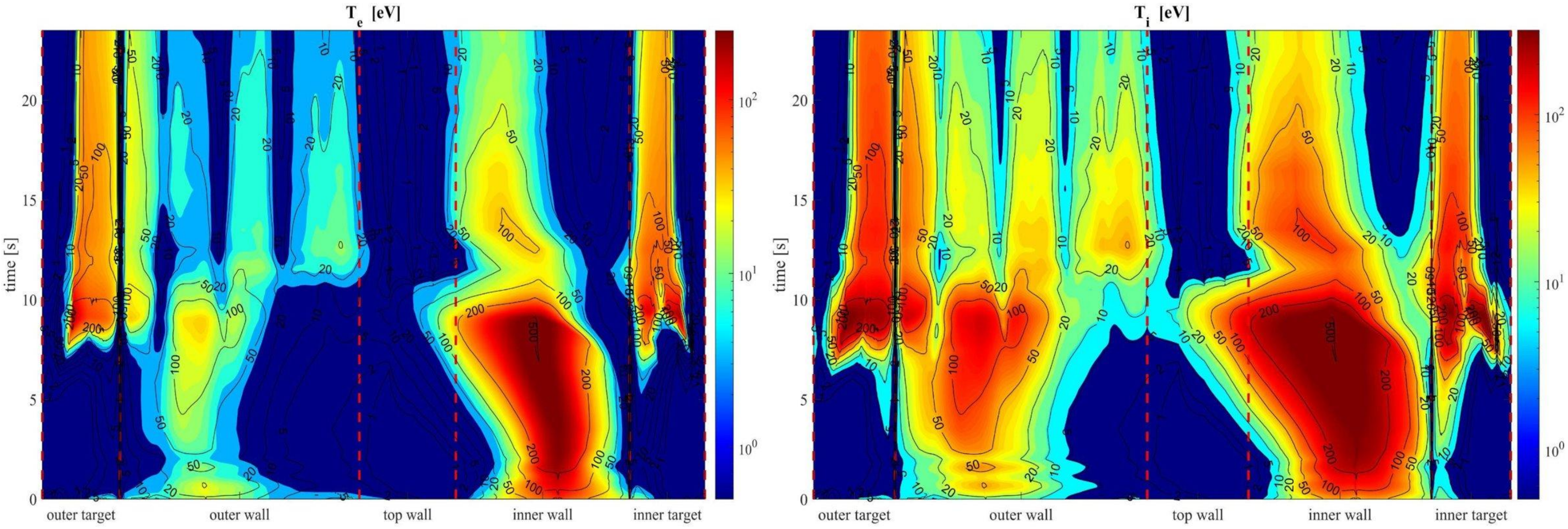


h-Adaptivity

SolEdge-HDG has recently been equipped with **h-adaptivity**:

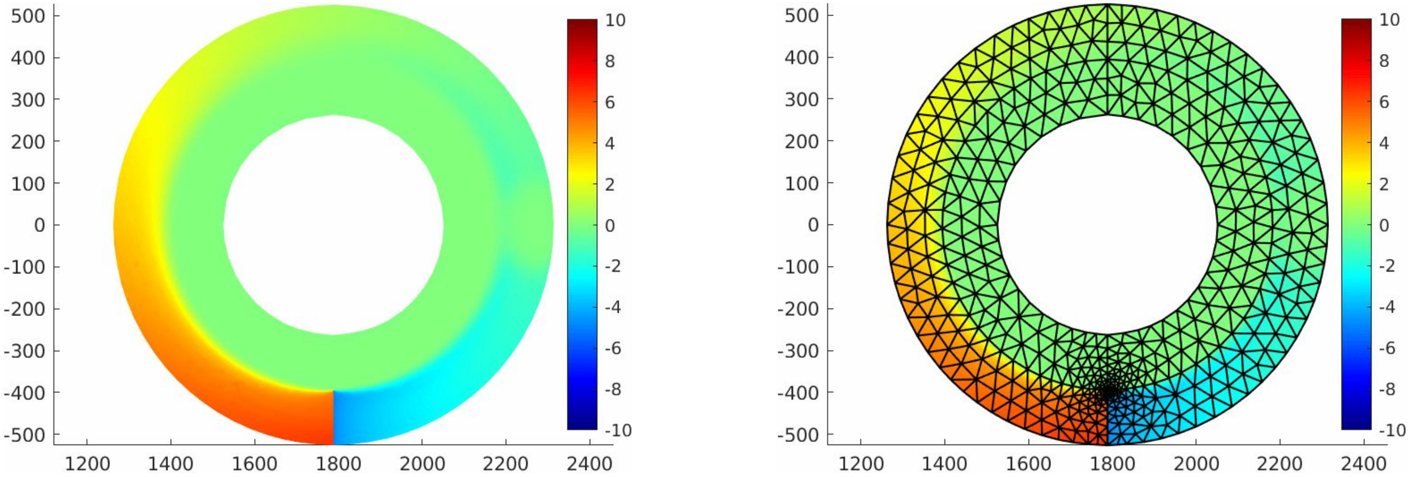
1. the mesh is **locally refined** where and when spurious oscillations are detected on the physical variables and/or their gradient (**error indicator**)
2. the mesh is l**ocally refined** in order to achieve a input value of relative difference between the physical variables of the solution at order p and its projection at order p + 1 (**error estimator**)

This allows to to:

1. **create meshes** of any given number of elements just by changing the input relative difference of the estimator
2. **refine only where is needed** in order to avoid costly overrefinement (more robust, fast and computationally cheaper) and save user time

Results on h-adaptivity: circular case

The first tests were made on the **NGamma** model, starting with a steady state solution and adding a gaussian density “**blob**” close to the separatrix. The system is then left evolve in time. Refinement is performed either every **t time steps** or when the **NR scheme diverges**.



Steady state work flow:

Before adaptivity:

- do a few time steps to initialize
- start steady state simulation at D = 26 m2/s
- simulation crashes
- manually create a new mesh
- repeat n times
- convergence to desired D

With adaptivity:

- do a few time steps to initialize
- start steady state simulation at D = 26 m2/s
- let adaptivity handle the crashes and the remeshing
- convergence to desired D

Results on h-adaptivity: WEST case, reducing diffusion (D)

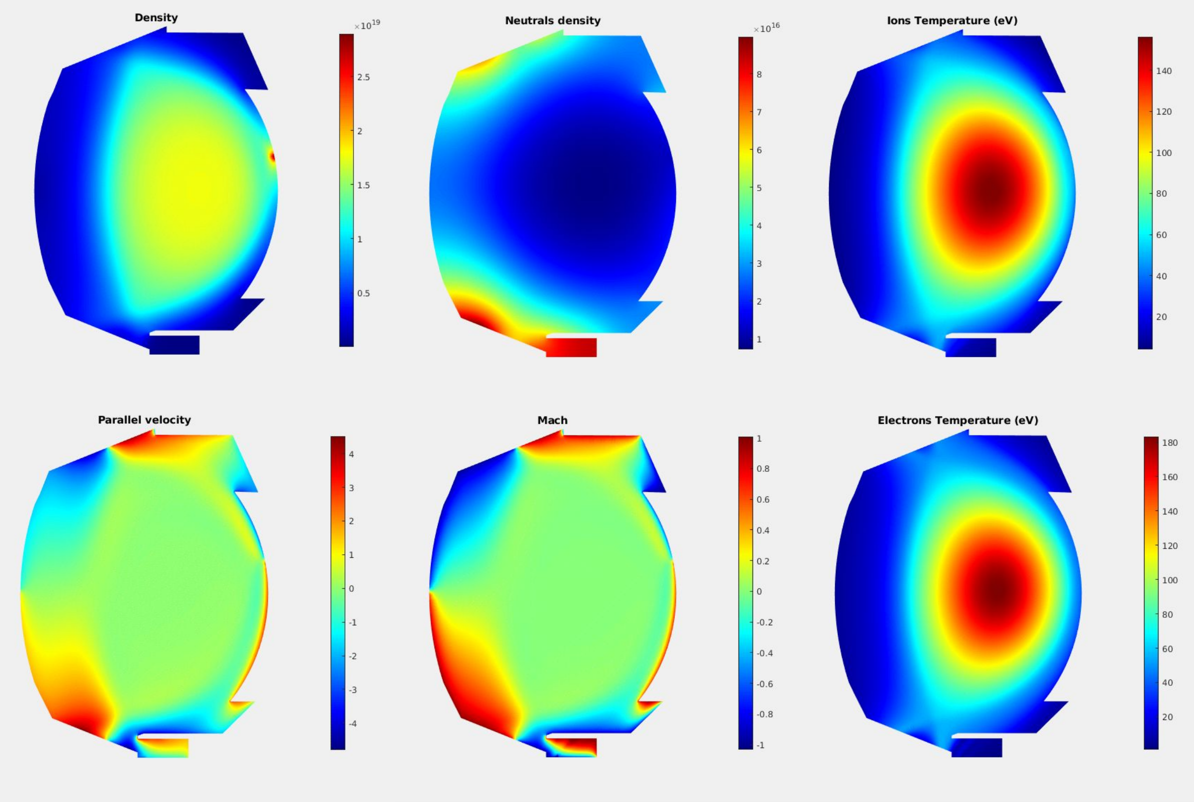
Model: **NGammaTiTe** with **diffusive neutrals.**

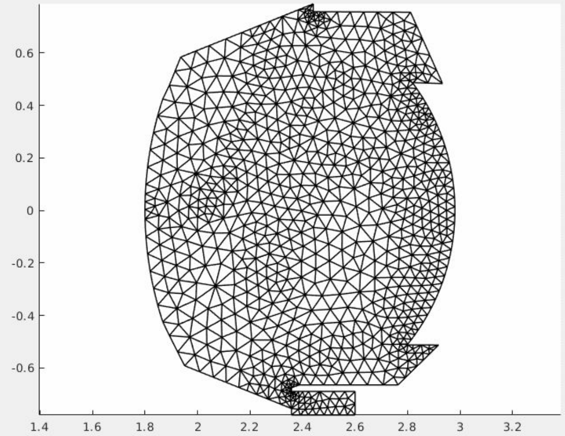
The simulation is started at **D = 26** m2/s and then **progressively reduced** till **D ~ 0.37** m2/s.

Adaptivity is called every time diffusion is reduced and in case of divergence of NR scheme.

The **error estimator** is based on the **Mach** number while the **error indicator** is based on **all physical variables**.

Results on h-adaptivity: WEST case





Conclusions

SolEdge-HDG is a **robust**, **fast** and highly **parallelizable** high order code that allows to compute **steady** or **transient** simulations on **any geometry** and **magnetic field** configuration.

The **fully implicit** scheme allows **fast steady state simulations**.

So far, for practical uses, only the **2D** version is **performant**, problems with the condition number hinder the possibility to use the 3D version.

The newly implemented **h-adaptivity** is a valuable tool to improve code **robustness**, **speed**, **precision** and save user and machine **time** and **resources**.

Thank you for your attention

Questions:

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