



Numerical challenges in SOLPS-ITER modelling for STEP divertor design

Ryoko Osawa (UKAEA)

on behalf of STEP divertor team:

S. S. Henderson¹, D. Moulton¹, J. Karhunen³,
M. Kryjak^{1,2}, E. Tholerus¹, O. Myatra¹, L. Baker²,
R. Futtersack¹, A. Järvinen³, L. Xiang¹,
S. L. Newton¹, A. Tarazona⁴, A. Hudoba¹

¹UKAEA, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom

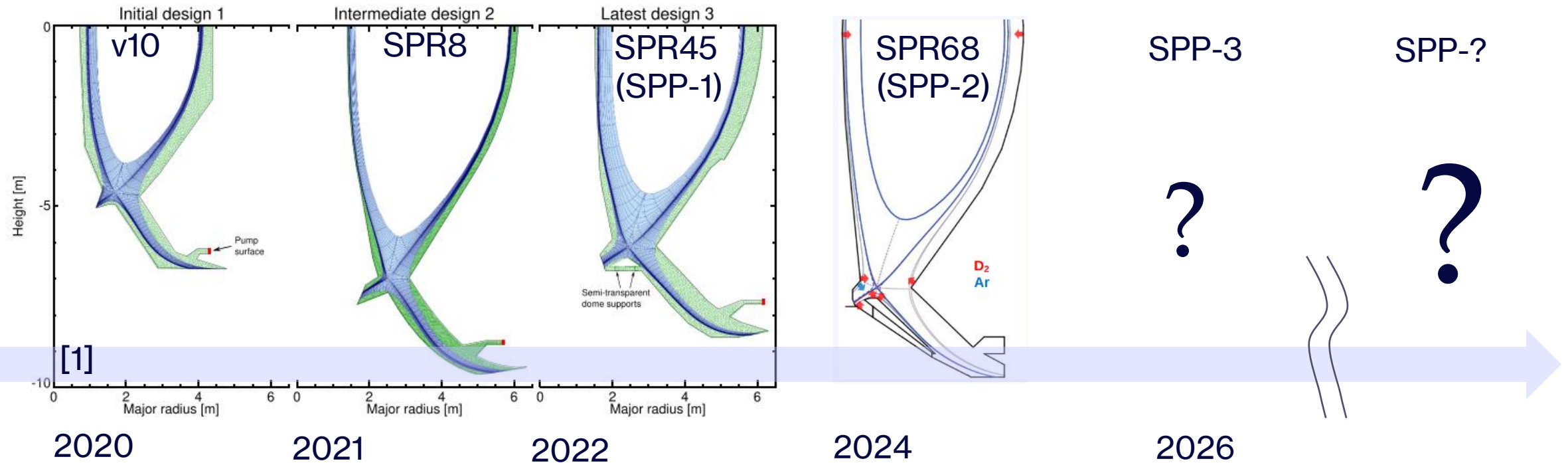
²York Plasma Institute, Department of Physics, University of York, York, United Kingdom

³VTT Technical Research Centre of Finland, PO Box 1000, 02044 VTT, Finland

⁴UKFE, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom

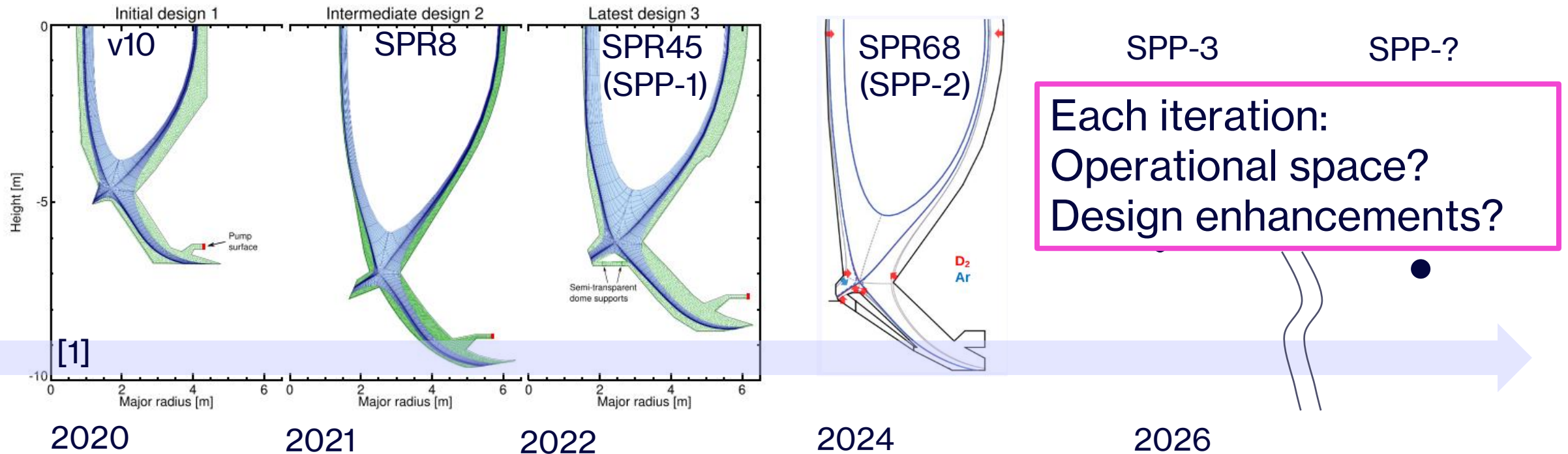
Workflow of designing STEP (Spherical Tokamak for Energy Production)

... a ST reactor with net electricity production targeting 2040 ($Q \geq 10$, $P_{\text{fus}} \sim 1.8 \text{ GW}$, $I_p = 21 \text{ MA}$, $P_{\text{sep}} \sim 150 \text{ MW}$)



Workflow of designing STEP (Spherical Tokamak for Energy Production)

... a ST reactor with net electricity production targeting 2040 ($Q \geq 10$, $P_{\text{fus}} \sim 1.8$ GW, $I_p = 21$ MA, $P_{\text{sep}} \sim 150$ MW)



Effect of **drsep** → DN [2]
Seed/fuel location [3,4]
Inner divertor geometry [1]
DLS-Extended [5]
Burn-through [Lloyd, tomorrow!]

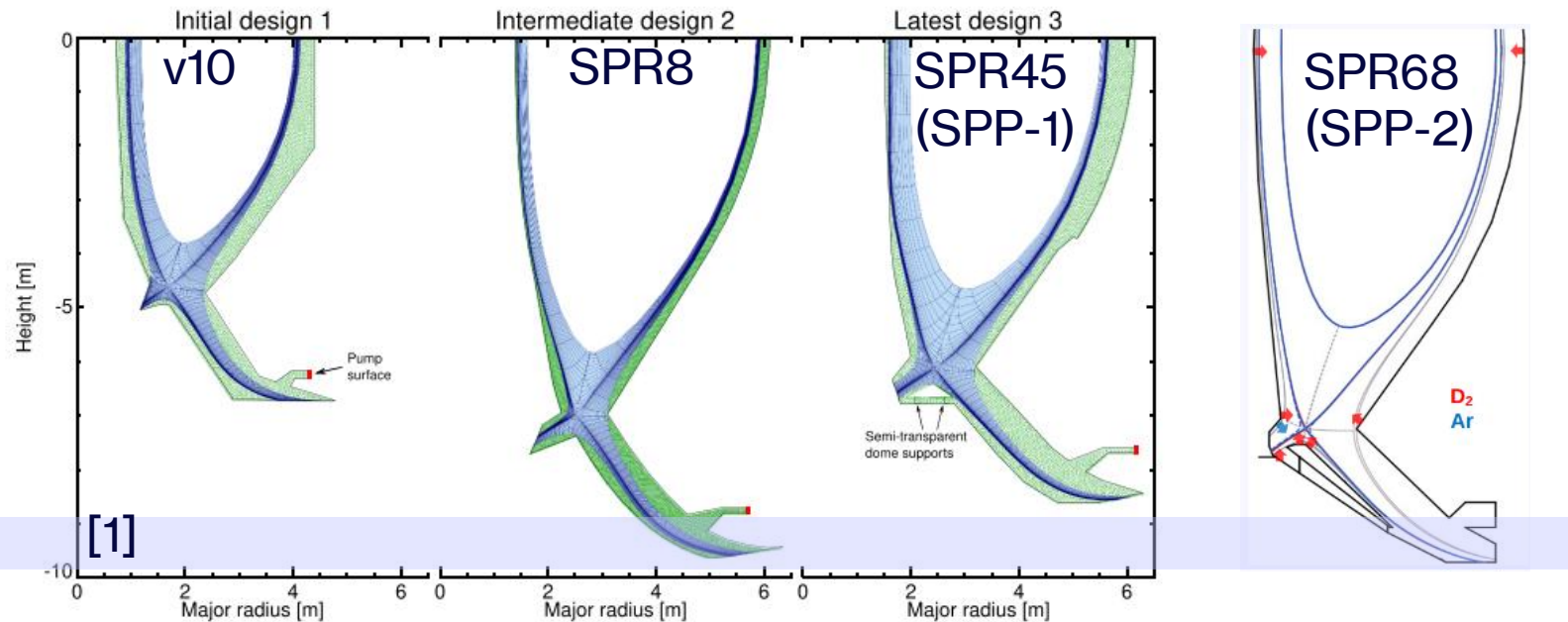
Dome
Pump (He exhaust) [6,7]
Drifts [8,9]

Fuel location [10]

- [1] S.S. Henderson et al Nucl. Fusion 65 016033 (2025).
[2] R.T. Osawa et al Nucl. Fusion 63 076032 (2023)
[3] R.T. Osawa et al Nucl. Fusion 64 106007 (2024).
[4] S.L. Newton et al Nucl. Fusion 65 096026 (2025).
[5] M. Kryjak et al 2026 Nucl. Fusion in press
[6] E. Tholerus et al under review for NF
[7] R.T. Osawa et al under review for NF
[8] J. Karhunen et al Nucl. Fusion 64 096021 (2024).
[9] J. Karhunen et al under review for JNME
[10] O. Myatra, presented at EPS26

Workflow of designing STEP (Spherical Tokamak for Energy Production)

... a ST reactor with net electricity production targeting 2040 ($Q \geq 10$, $P_{\text{fus}} \sim 1.8$ GW, $I_p = 21$ MA, $P_{\text{sep}} \sim 150$ MW)



Each iteration:
Operational space?
Design enhancements?

Not easy!!
(each SOLPS-ITER run
takes 1~3 months...)

Effect of **drsep** → DN [2]
Seed/fuel location [3,4]
Inner divertor geometry [1]
DLS-Extended [5]
Burn-through [Lloyd, tomorrow!]

Dome
Pump (He exhaust) [6,7]
Drifts [8,9]

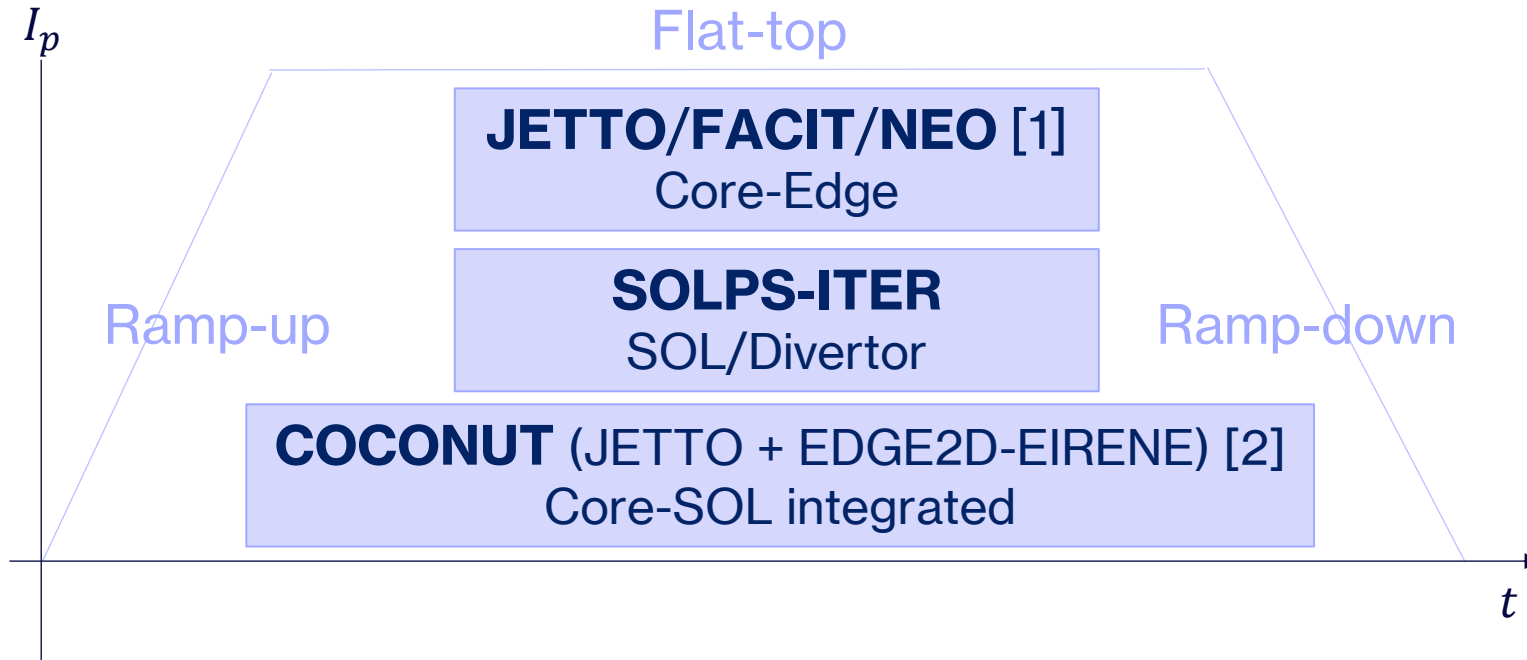
Fuel location

- [3] R.T. Osawa et al Nucl. Fusion 64 106007 (2024).
- [4] S.L. Newton et al Nucl. Fusion 65 096026 (2025).
- [5] M. Kryjak et al 2026 Nucl. Fusion in press
- [6] E. Tholerus et al under review for NF
- [7] R.T. Osawa et al under review for NF
- [8] J. Karhunen et al Nucl. Fusion 64 096021 (2024).
- [9] J. Karhunen et al under review for JNME
- [10] O. Myatra, presented at EPS26

Integration of core-edge-divertor throughout the scenario



Divertor solution has to be consistent with the core/edge, satisfying the entire scenario...



DART [3]
fast, full scenario assessment

[1] G Suárez López et al, Characterization of Ar impurity screening across the H-mode pedestal in STEP using the JINTRAC code, presented at EPS2026

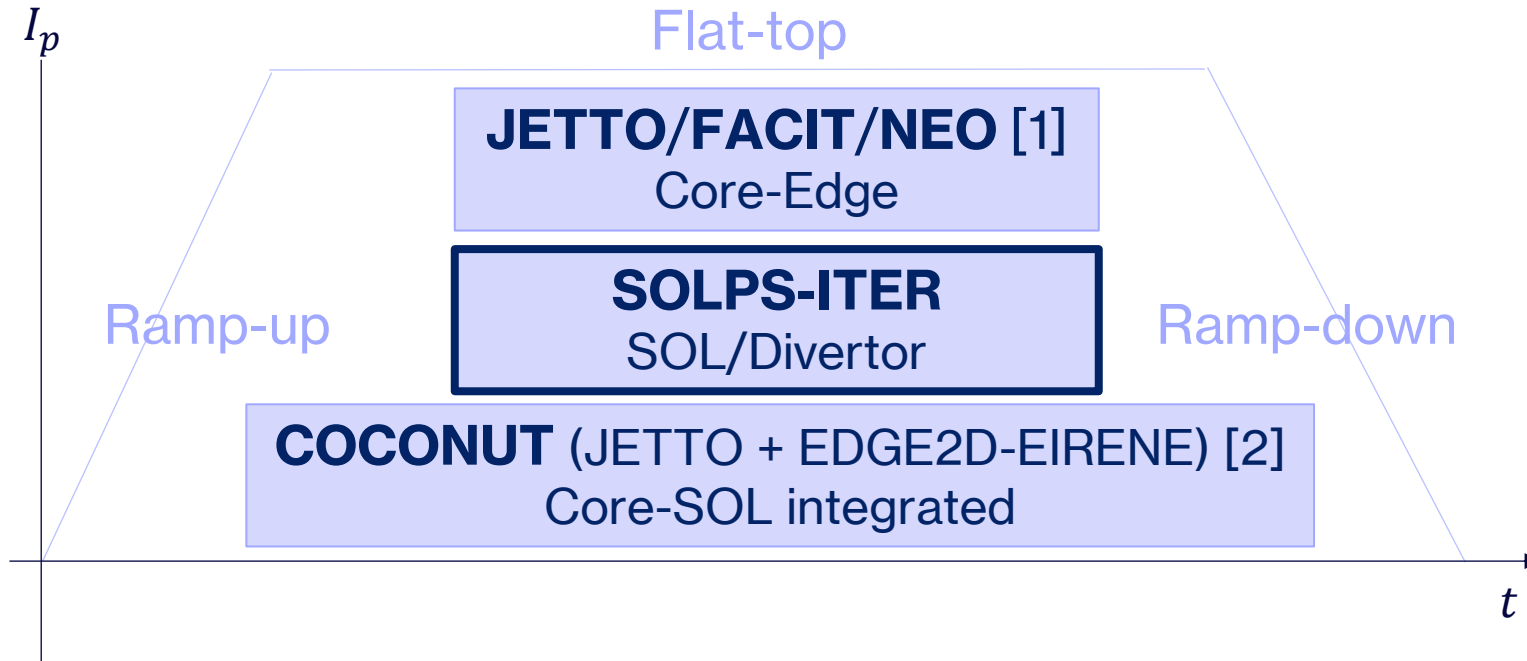
[2] E. Tholerus et al, Pumping requirements for core plasma performance in STEP using JINTRAC, presented at FEC 2026, under review for NF

[3] S.S. Henderson et al Nucl. Fusion 65 016033 (2025).

Integration of core-edge-divertor throughout the scenario



Divertor solution has to be consistent with the core/edge, satisfying the entire scenario...



DART [3]
fast, full scenario assessment

[1] G Suárez López et al, Characterization of Ar impurity screening across the H-mode pedestal in STEP using the JINTRAC code, presented at EPS2026

[2] E. Tholerus et al, Pumping requirements for core plasma performance in STEP using JINTRAC, presented at FEC 2026, under review for NF

[3] S.S. Henderson et al Nucl. Fusion 65 016033 (2025).

Today: Let's share the issues we have!

→ Please use it for your future code development!!!

SOLPS-ITER – basic equations (from SOLPS-ITER manual Jan 2025)

$n_a, V_{\parallel a}, T_i, T_e, \phi$ are solved by Braginskii-like 2D fluid equations in **B2.5**:

Continuity equation

$$\frac{\partial n_a}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \tilde{\Gamma}_{ax} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \tilde{\Gamma}_{ay} \right) = S_a^n$$

$$n_e = \sum_{a=0}^{ns-1} z_a n_a$$

Current continuity equation

$$\frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} j_x \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} j_y \right) = 0$$

Momentum equation

$$m_a \frac{\partial n_a V_{\parallel a}}{\partial t} + \frac{1}{h_z \sqrt{g}} \frac{\partial}{\partial x} \left(\frac{h_z \sqrt{g}}{h_x} \Gamma_{ax}^m \right) + \frac{1}{h_z \sqrt{g}} \frac{\partial}{\partial y} \left(\frac{h_z \sqrt{g}}{h_y} \Gamma_{ay}^m \right) + \frac{b_x}{h_x} \frac{\partial n_a T_i}{\partial x} + Z_a e n_a \frac{b_x}{h_x} \frac{\partial \Phi}{\partial x} = S_{a\parallel}^m + S_{CF_a}^m + S_{fr_a}^m + S_{Therm_a}^m + S_{I_a}^m + S_{R_a}^m + S_{CX_a}^m + S_{AN_a}^m + S_{EIRENE_a\parallel}^m$$

$$j_x^{(\parallel)} = \sigma_{\parallel} \left(\frac{1}{e n_e h_x} \frac{\partial n_e T_e}{\partial x} - \frac{1}{h_x} \frac{\partial \Phi}{\partial x} \right) - \alpha_{ex} \frac{1}{h_x} \frac{\partial T_e}{\partial x} - \frac{e b_x}{z_{eff}} \sum_{a=0}^{ns-1} n_a V_{a\parallel} (z_a^2 - z_a z_{eff})$$

Ion energy equation

$$\begin{aligned} \frac{3}{2} \frac{\partial n_i T_i}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \tilde{q}_{ix} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \tilde{q}_{iy} \right) + \sum_{a=0}^{ns-1} \frac{n_a T_i}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} V_{a\parallel} b_x \right) = \\ = Q_{\Delta} + Q_{Fab} + c_{E \times B} T_i B_z \frac{1}{h_x h_y} \left(\frac{\partial \Phi}{\partial y} \frac{\partial}{\partial x} \left(\frac{1}{B^2} \right) - \frac{\partial \Phi}{\partial x} \frac{\partial}{\partial y} \left(\frac{1}{B^2} \right) \right) \sum_{\substack{a=0 \\ z_a \neq 0}}^{ns-1} n_a + \\ + \sum_{fluid\ species} \left(\eta_{ax} \left(\frac{\partial V_{a\parallel}}{h_x \partial x} \right)^2 + \eta_a^{(AN)} \left(\frac{\partial V_{a\parallel}}{h_y \partial y} \right)^2 \right) + Q_I^{(i)} + Q_R^{(i)} + Q_i^{EIRENE} \end{aligned}$$

Electron energy equation

$$\begin{aligned} \frac{3}{2} \frac{\partial n_e T_e}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \tilde{q}_{ex} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \tilde{q}_{ey} \right) + \frac{n_e T_e}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} b_x V_{e\parallel} \right) = \\ = Q_e + c_{E \times B} n_e T_e B_z \frac{1}{h_x h_y} \left(\frac{\partial \Phi}{\partial y} \frac{\partial}{\partial x} \left(\frac{1}{B^2} \right) - \frac{\partial \Phi}{\partial x} \frac{\partial}{\partial y} \left(\frac{1}{B^2} \right) \right) - \frac{j_y^{(ST)}}{e n_e} \frac{\partial n_e T_e}{h_y \partial y} + Q_{Fei} + Q_e^{EIRENE} \end{aligned}$$

SOLPS-ITER – basic equations (from SOLPS-ITER manual Jan 2025)

$n_a, V_{\parallel a}, T_i, T_e, \phi$ are solved by Braginskii-like 2D fluid equations in **B2.5**:

Continuity equation

$$\frac{\partial n_a}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \tilde{\Gamma}_{ax} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \tilde{\Gamma}_{ay} \right) = S_a^n \quad n_e = \sum_{a=0}^{ns-1} z_a n_a$$

Current continuity equation

$$\frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} j_x \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} j_y \right) = 0$$

Momentum equation

$$m_a \frac{\partial n_a V_{\parallel a}}{\partial t} + \frac{1}{h_z \sqrt{g}} \frac{\partial}{\partial x} \left(\frac{h_z \sqrt{g}}{h_x} \Gamma_{ax}^m \right) + \frac{1}{h_z \sqrt{g}} \frac{\partial}{\partial y} \left(\frac{h_z \sqrt{g}}{h_y} \Gamma_{ay}^m \right) + \frac{b_x}{h_x} \frac{\partial n_a T_i}{\partial x} + Z_a e n_a \frac{b_x}{h_x} \frac{\partial \Phi}{\partial x} = S_{a\parallel}^m + S_{CFa}^m + S_{fra}^m + S_{Therma}^m + S_{Ia}^m + S_{Ra}^m + S_{CXa}^m + S_{ANa}^m + S_{EIRENEa\parallel}^m$$

$$j_x^{(\parallel)} = \sigma_{\parallel} \left(\frac{1}{en_e h_x} \frac{\partial n_e T_e}{\partial x} - \frac{1}{h_x} \frac{\partial \Phi}{\partial x} \right) - \alpha_{ex} \frac{1}{h_x} \frac{\partial T_e}{\partial x} - \frac{eb_x}{z_{eff}} \sum_{a=0}^{ns-1} n_a V_{a\parallel} (z_a^2 - z_a z_{eff})$$

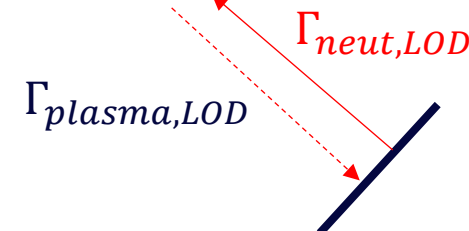
Ion energy equation

$$\begin{aligned} \frac{3}{2} \frac{\partial n_i T_i}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \tilde{q}_{ix} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \tilde{q}_{iy} \right) + \sum_{a=0}^{ns-1} \frac{n_a T_i}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} V_{a\parallel} b_x \right) = \\ = Q_{\Delta} + Q_{Fab} + c_{E \times B} T_i B_z \frac{1}{h_x h_y} \left(\frac{\partial \Phi}{\partial y} \frac{\partial}{\partial x} \left(\frac{1}{B^2} \right) - \frac{\partial \Phi}{\partial x} \frac{\partial}{\partial y} \left(\frac{1}{B^2} \right) \right) \sum_{a=0}^{ns-1} n_a + \\ + \sum_{fluid\ species} \left(\eta_{ax} \left(\frac{\partial V_{a\parallel}}{h_x \partial x} \right)^2 + \eta_a^{(AN)} \left(\frac{\partial V_{a\parallel}}{h_y \partial y} \right)^2 \right) + Q_I^{(i)} + Q_R^{(i)} + Q_i^{EIRENE} \end{aligned}$$

Electron energy equation

$$\begin{aligned} \frac{3}{2} \frac{\partial n_e T_e}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \tilde{q}_{ex} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \tilde{q}_{ey} \right) + \frac{n_e T_e}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} b_x V_{e\parallel} \right) = \\ = Q_e + c_{E \times B} n_e T_e B_z \frac{1}{h_x h_y} \left(\frac{\partial \Phi}{\partial y} \frac{\partial}{\partial x} \left(\frac{1}{B^2} \right) - \frac{\partial \Phi}{\partial x} \frac{\partial}{\partial y} \left(\frac{1}{B^2} \right) \right) - \frac{j_y^{(ST)}}{en_e} \frac{\partial n_e T_e}{h_y \partial y} + Q_{Fei} + Q_e^{EIRENE} \end{aligned}$$

Part of the source terms coming from **EIRENE**



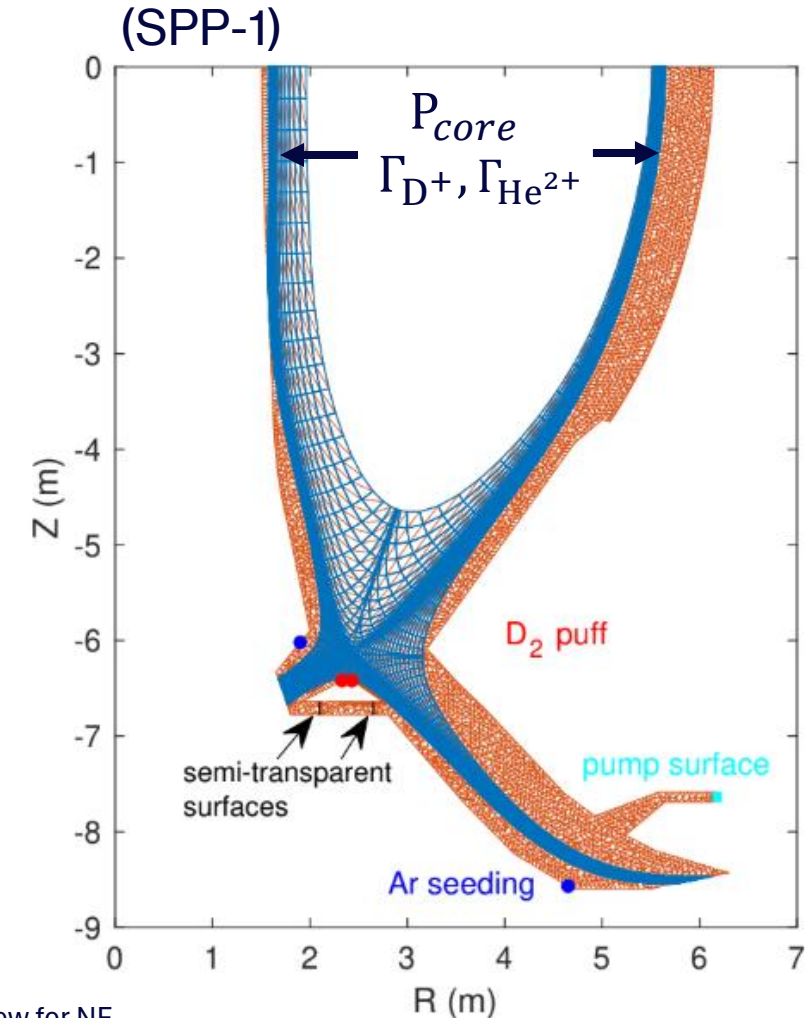
In EIRENE
Launch neutral species from each “stratum” (e.g. lower-outer divertor recycling $\Gamma_{neut,LOD}$)

SOLPS-ITER setup for STEP flat-top simulation (CDN)



SOLPS-ITER 3.0.8 for steady state (flat-top) simulation [1]

- Plasma species : D^+ , Ar^{1-18+} , He^{1-2+} (not bundled)
- Kinetic neutral model (EIRENE), no drift
- $P_{core} = 200$ MW, $\Gamma_{He^{2+}} = 6.4 \times 10^{20}/s$, $\Gamma_{D^+} = 1.45 \times 10^{22}/s$,
 $\Gamma_{Dpuff} \sim 9 \times 10^{22}/s$, $\Gamma_{Arseed} = 1.0 \times 10^{20}/s$
- $f_{rec} \sim 0.99$ at pump surface for $S_{pump} \sim 20$ m³/s
- Tungsten wall (full recycling, $T_{wall} = 1100$ K)
- Constant anomalous radial transport coefficients for $\lambda_q \sim 1$ mm
- Zhdanov closure [2,3] off



[1] R.T. Osawa et al under review for NF

[2] Zhdanov V. 2002 Transport Processes in Multicomponent Plasma English edn (New York: Taylor & Francis)

[3] S.O. Makarov et al, Phys. Plasmas 28, 062308 (2021)

Challenges/Uncertainties in the simulations

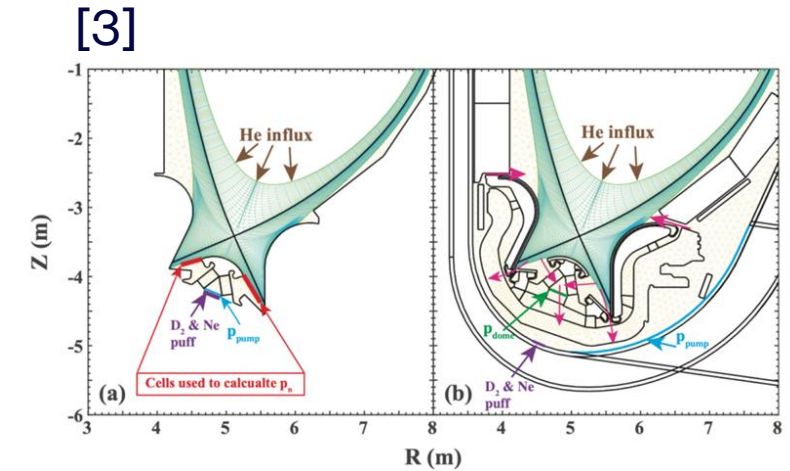


Ongoing/Planned

- Helium transport model (Zhdanov closure, experimental validation [1])
- Drifts [2]
- Sub-divertor module [3]
- Extended grid [4]

Future plan

- Atomic/molecular physics (e.g. Ar reaction rate, Three body recombination, opacity)
- Radial transport (e.g. ballooning transport)
- Toroidal asymmetry
- DT [5]
- Sheath boundary (with drifts)
- Tungsten transport



Biggest two challenges:

Up-down asymmetry
Particle balance

[1] A. Zito et al, Nucl. Fusion 65 046022 (2025).

[2] J. Karhunen et al under review for JNME

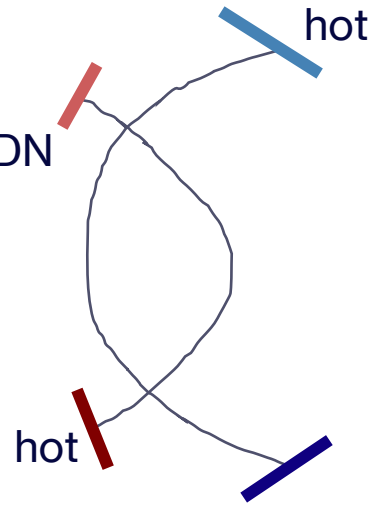
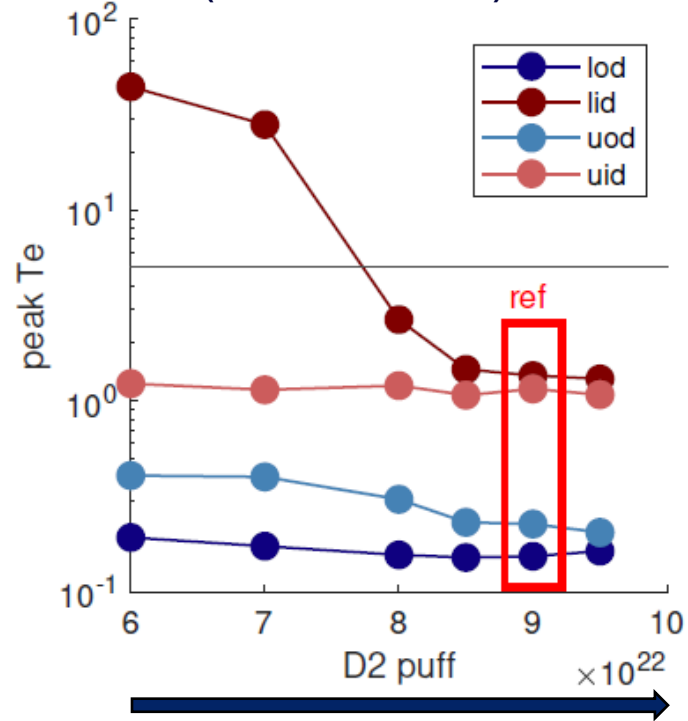
[3] A. A. Pshenov et al., Nucl. Mater. Energy 42 101851 (2025).

[4] W. Dekeyser et al, Nuclear Materials and Energy 27 100999 (2021).

[5] S.O. Makarov et al Nucl. Fusion 63 026014 (2023).

Up-down asymmetry in SOLPS-ITER

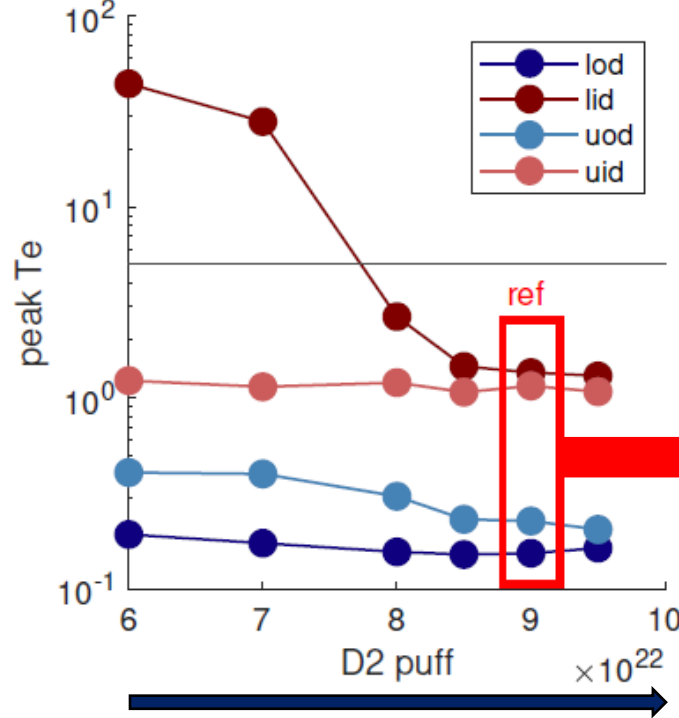
SOLPS-ITER (kinetic neutral) on STEP CDN



Smaller up-down asymmetry by detaching further
(i.e. higher collisionality)

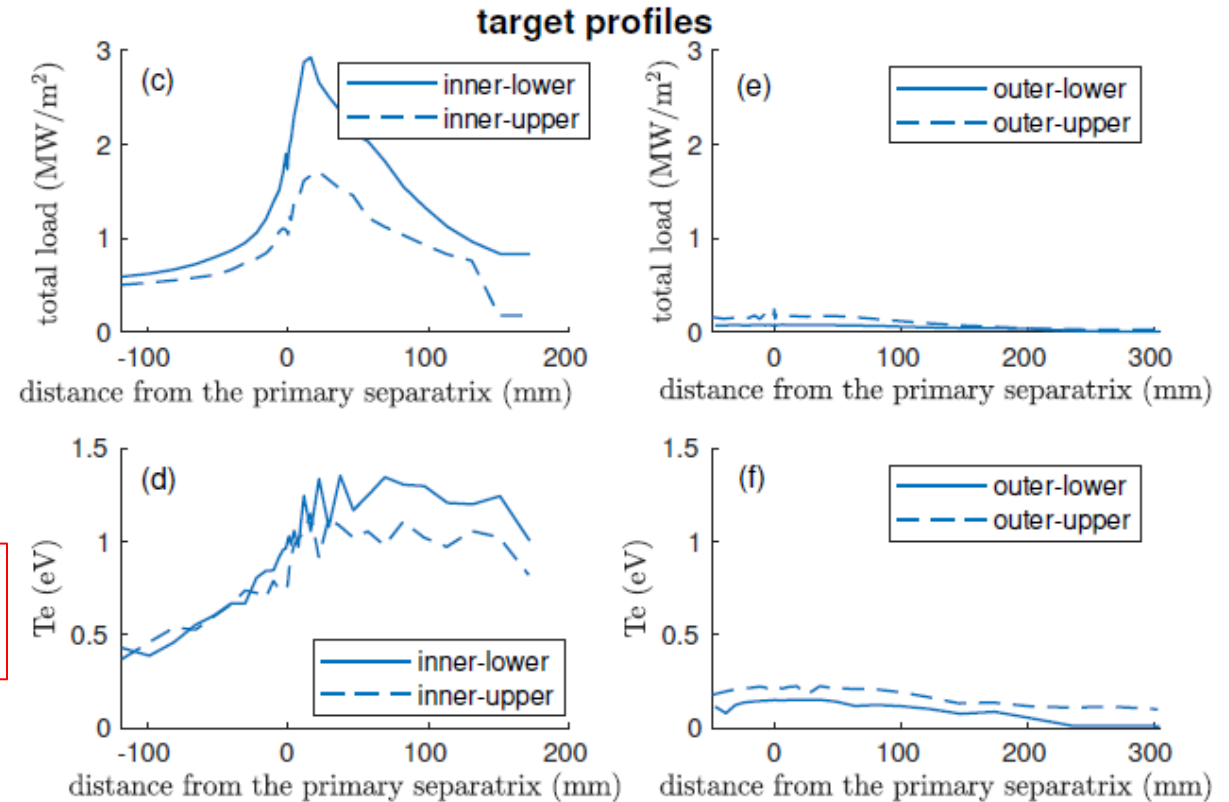
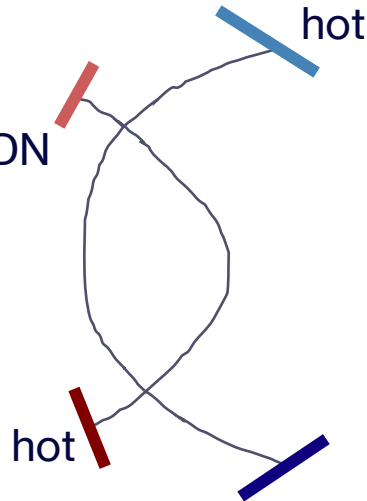
Up-down asymmetry in SOLPS-ITER

SOLPS-ITER (kinetic neutral) on STEP CDN



**Deeply-detached
reference case**

Smaller up-down asymmetry by detaching further
(i.e. higher collisionality)

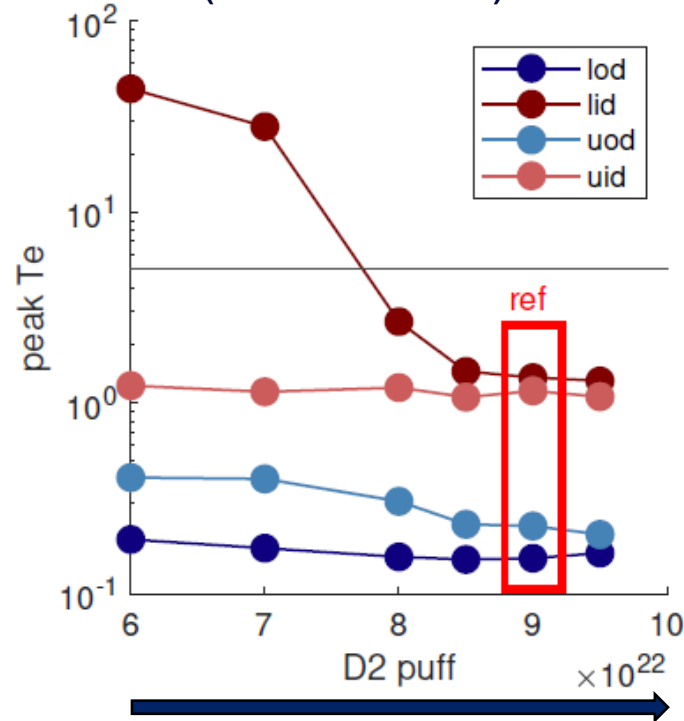


$$n_{e,sep,OMP} \sim 3.5 \times 10^{19} \text{ m}^{-3}$$

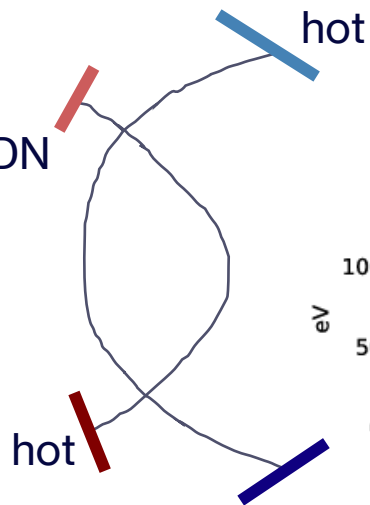
$$T_{e,sep,OMP} \sim 300 \text{ eV}$$

Up-down asymmetry in SOLPS-ITER (not only in STEP)

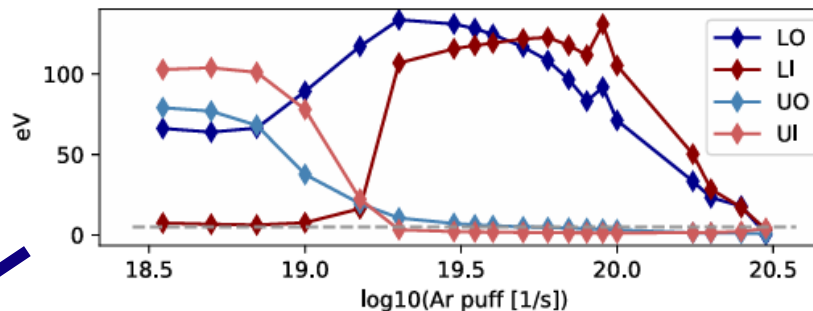
SOLPS-ITER (kinetic neutral) on STEP CDN



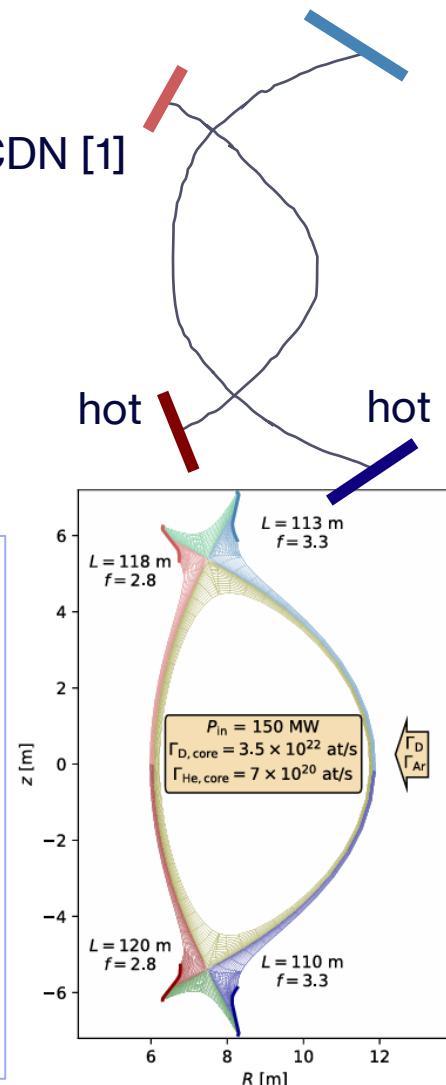
Smaller up-down asymmetry by detaching further (i.e. higher collisionality)



SOLPS-ITER (fluid neutral) on DEMO CDN [1]



- Asymmetry also in DEMO [1] (not in MAST-U) ... driven by outer up-down asymmetry due to Ar, influencing inner via PFR transport (original cause: asymmetric grid[2])
- Symmetric results would widen our operational space with lower upstream Ar.
- Can we avoid it?

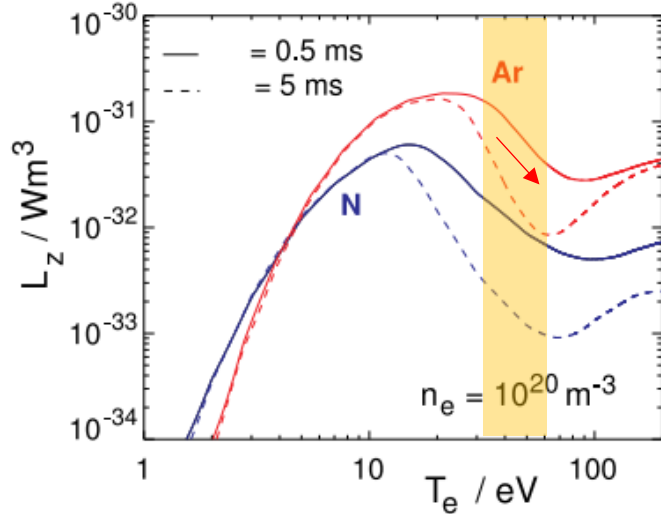


[1] L. Aho-Mantila et al, Nuclear Materials and Energy 26, 100886 (2021).

[2] V. Rozhansky, et al., Nucl. Fusion 52(10) (2012) 103 017

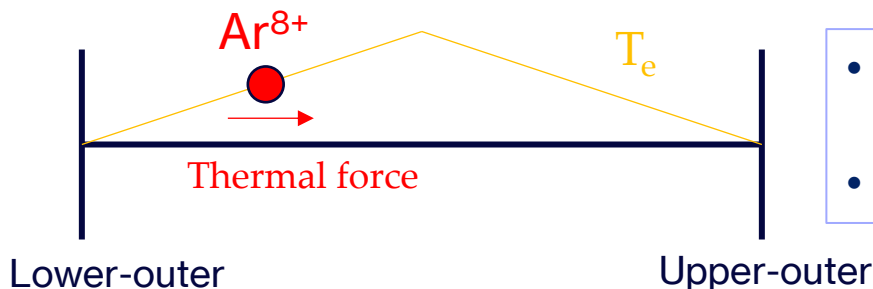
Mechanism of the up-down asymmetry in STEP

Cooling function L_z [1]

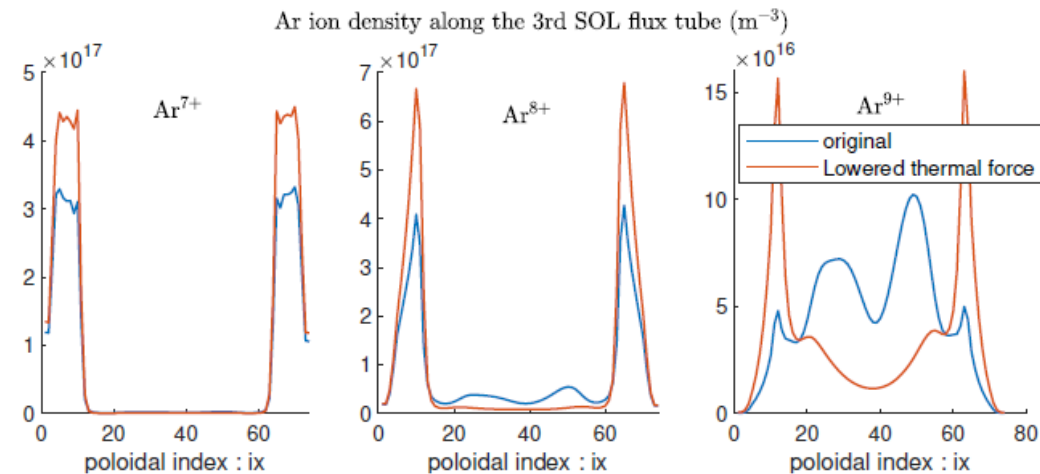


$$dL_z/dT_e < 0$$

$$\left(\frac{d}{dT_e} (L_z/T_e^2) < 0 \right) [2]$$



- Unstable radiation power loss when $\frac{dQ_{rad}}{dT_e} < 0$ ($T \nearrow \rightarrow Q \searrow \rightarrow T \nearrow$) [2]
- Additionally, thermal force on Ar^{8+} seems to enhance the asymmetry... (pushed to hot region by the thermal force $\rightarrow$ lower $L_z \rightarrow$ higher dT ?)



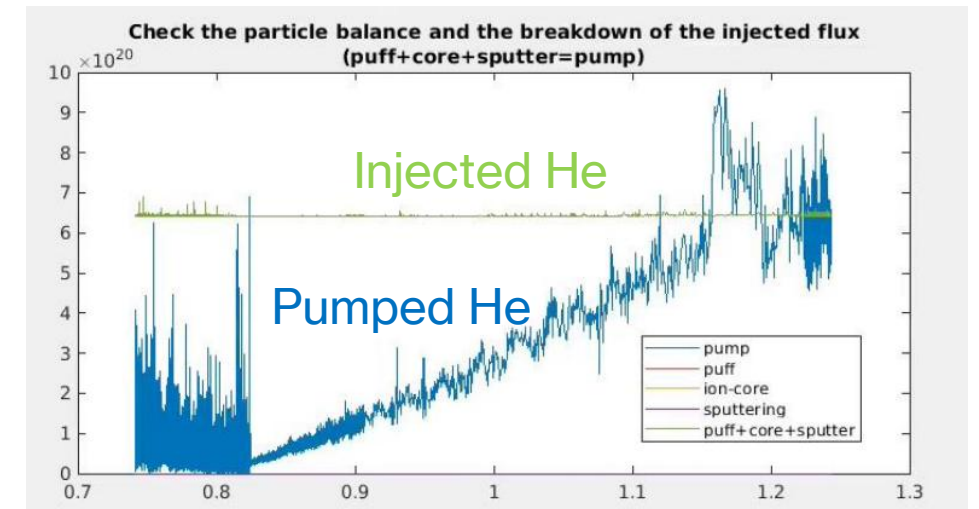
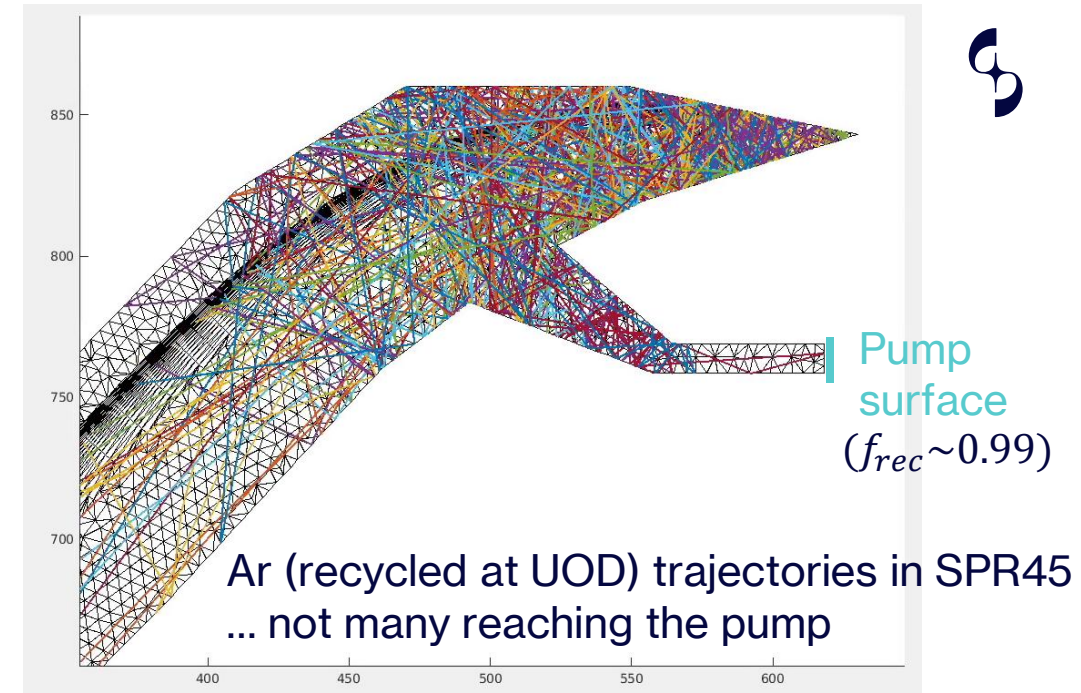
- In reality, non-zero drsep and drifts dominate the up-down asymmetry $\rightarrow$ difficult to study experimentally
- Testing feedback schemes on front locations to force symmetry

[1] A. Kallenbach et al, Nuclear Materials and Energy 18 166-174 (2019).

[2] A S Kukushkin and S I Krashenninnikov, Plasma Phys. Control. Fusion 61 (2019) 074001 (8pp).

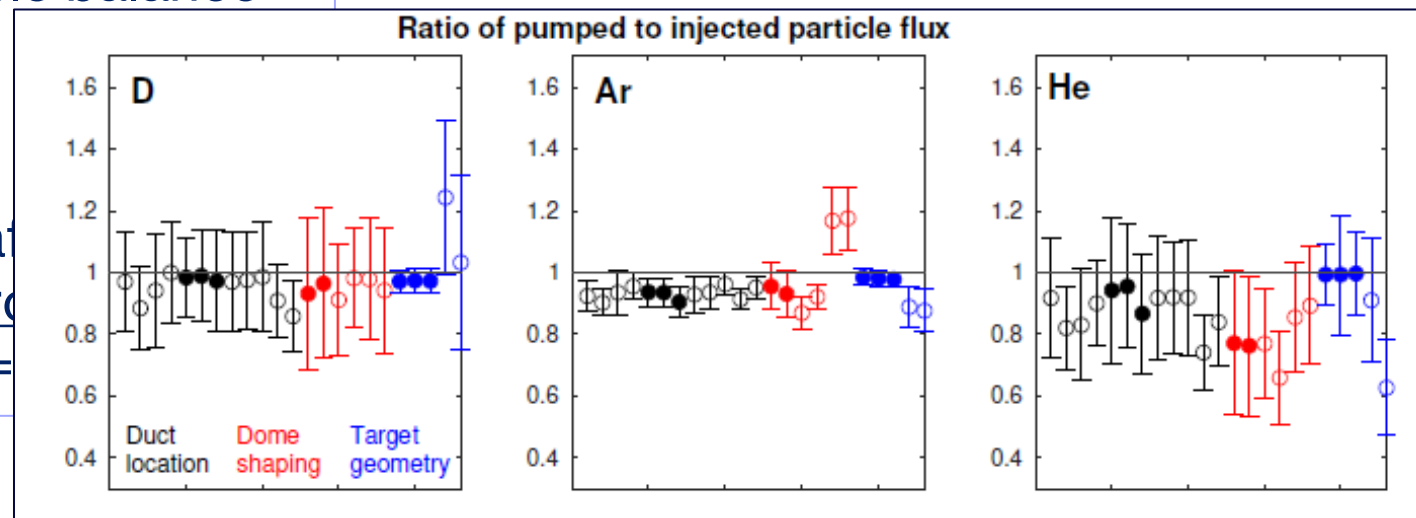
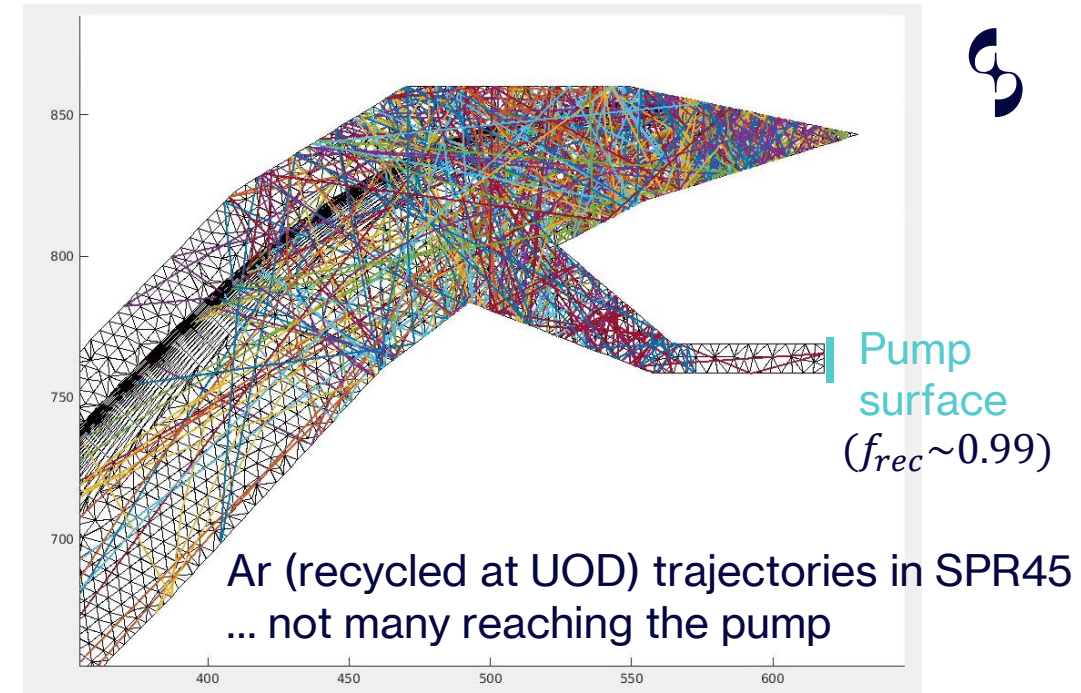
Particle balance with SOLPS-ITER

- The problem started to occur already in v10 (D, Ar): **injected >> pumped** for Ar
- Turning on Speed-up scheme [1] → improved Ar particle balance (still not He on SPR45)
 - “effective” source (i.e. rescaling)
depending on (injected – pumped)
- Optimising the distribution of the number histories to each stratum → improved He particle balance (better statistics is key?)
- Further optimisation is still needed for cases with harder pumping
- Switching off the speed-up scheme (after convergence) requires a significant drop of the time step to keep the balance (e.g. $dt=9e-8$ in v10)



Particle balance with SOLPS-ITER

- The problem started to occur already in v10 (D, Ar): **injected >> pumped** for Ar
- Turning on Speed-up scheme [1] → improved Ar particle balance (still not He on SPR45)
 - “effective” source (i.e. rescaling) depending on (injected – pumped)
- Optimising the distribution of the number histories to each stratum → improved He particle balance (better statistics is key?)
- Further optimisation is still needed for harder pumping
- Switching off the speed-up scheme (at convergence) requires a significant drop in time step to keep the balance (e.g. $\Delta t = 10^{-10}$ s)



It is a long-standing issue caused by coupling between B2.5 and EIRENE --- A concern in future codes?

Conclusion

Towards quantitative assessment of STEP SOL/divertor

Within SOLPS-ITER:

- Particle balance ... adjust the number of histories for future cases
- Asymmetry ... control front locations via Ar seeding etc. to force symmetry (ongoing), doing DDN simulations, turning on drifts
- Extended grid to assess side-wall/dome loads
- Include sub-divertor modules for better consistency with the pump modelling (concern: particle balance)
- Experimental validation (e.g. He transport)

Integration with the core:

- Consistency between JINTRAC/COCONUT and SOLPS

Thank you for your attention!!