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MODELLING DIVERTOR SOLUTIONS FOR POWER EXHAUST: IN-DEPTH EXPERIMENTAL VALIDATION IN TCV

Elena Tonello, Swiss Plasma Center, EPFL - Switzerland

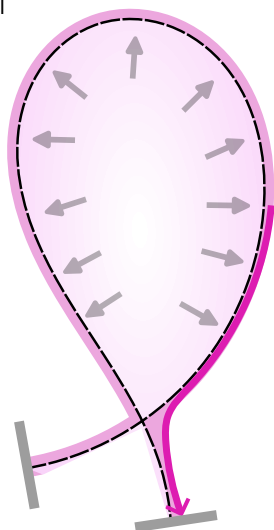


This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). The Swiss contribution to this work has been funded by the Swiss State Secretariat for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



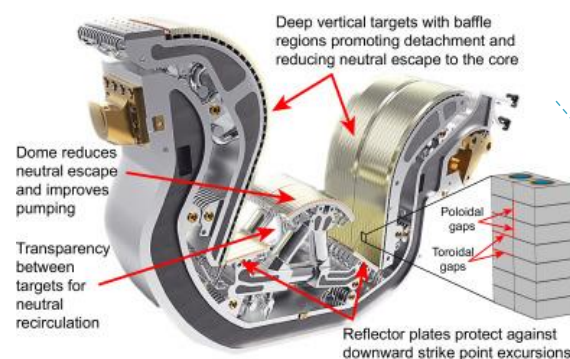
Optimisation of conventional or alternative divertors is crucial to tackle power exhaust

Power exhaust remains a critical **challenge** in the design of a fusion reactor



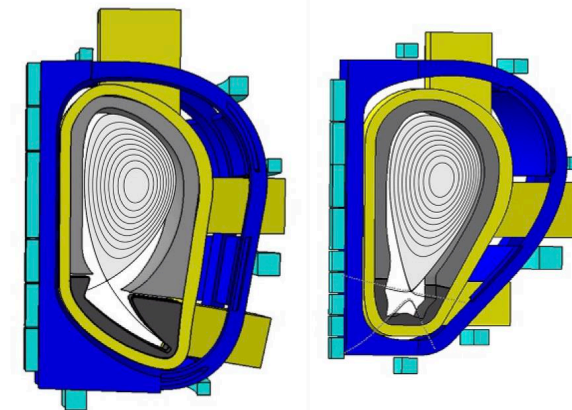
p^{SOL} needs to be effectively dissipated

ITER conventional divertor design



R. Pitts et al., Nucl. Mater. Energy, 20 100696
R. Pitts et al., Nucl. Mater. Energy, 42 101854

Different ADC designs for EU-DEMO

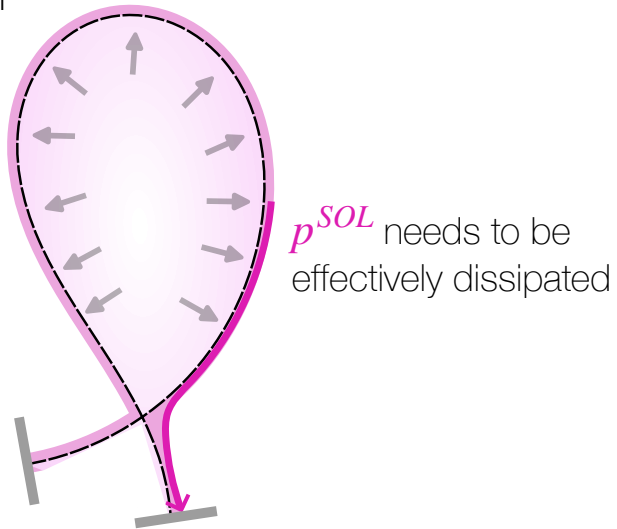


H. Reimerdes et al., Nucl. Fusion, 60 066030

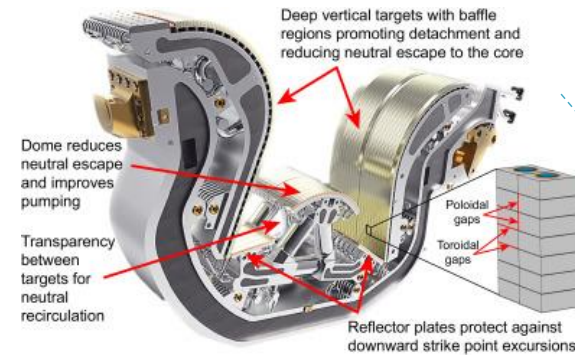


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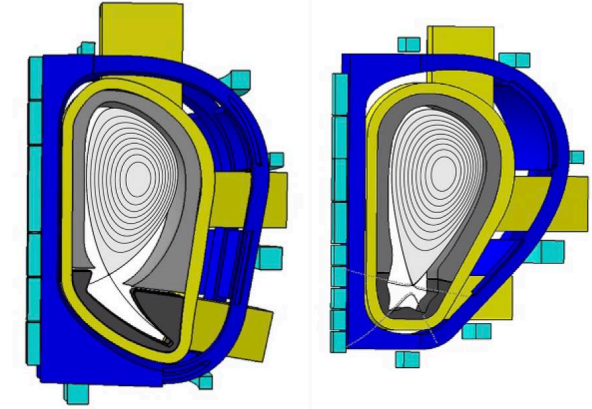


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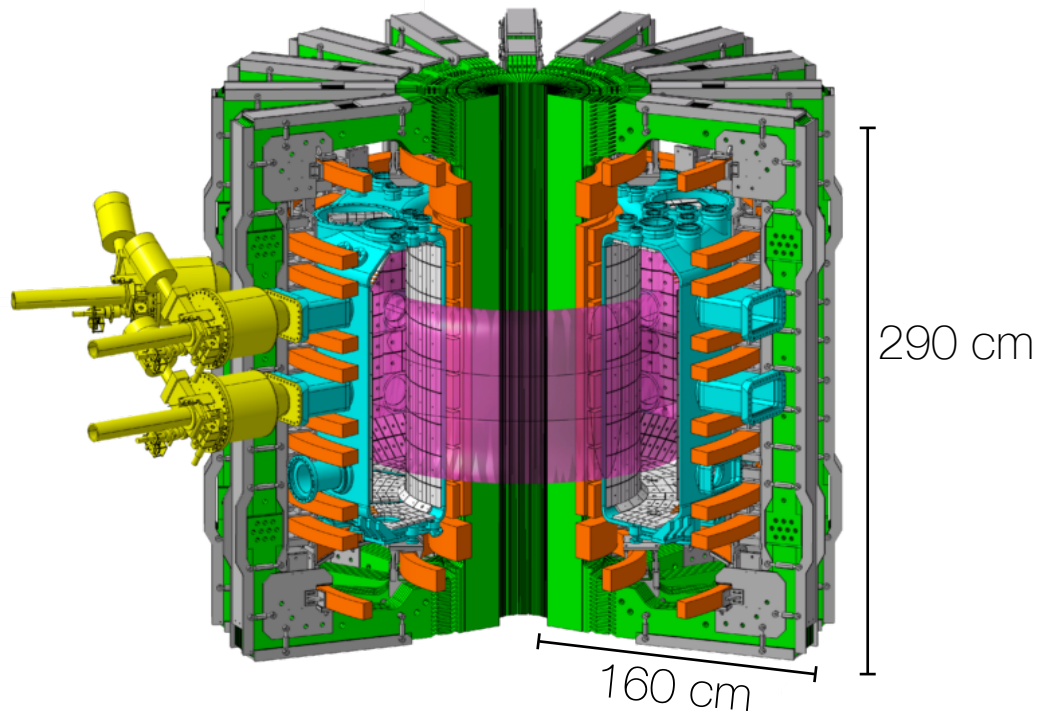
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Quantifying **performance** and **assessing integration** of PEX approached in fusion reactor design requires **numerical simulations**

Numerical code validation in existing devices is crucial



TCV: an exceptionally versatile testbed for exhaust solutions

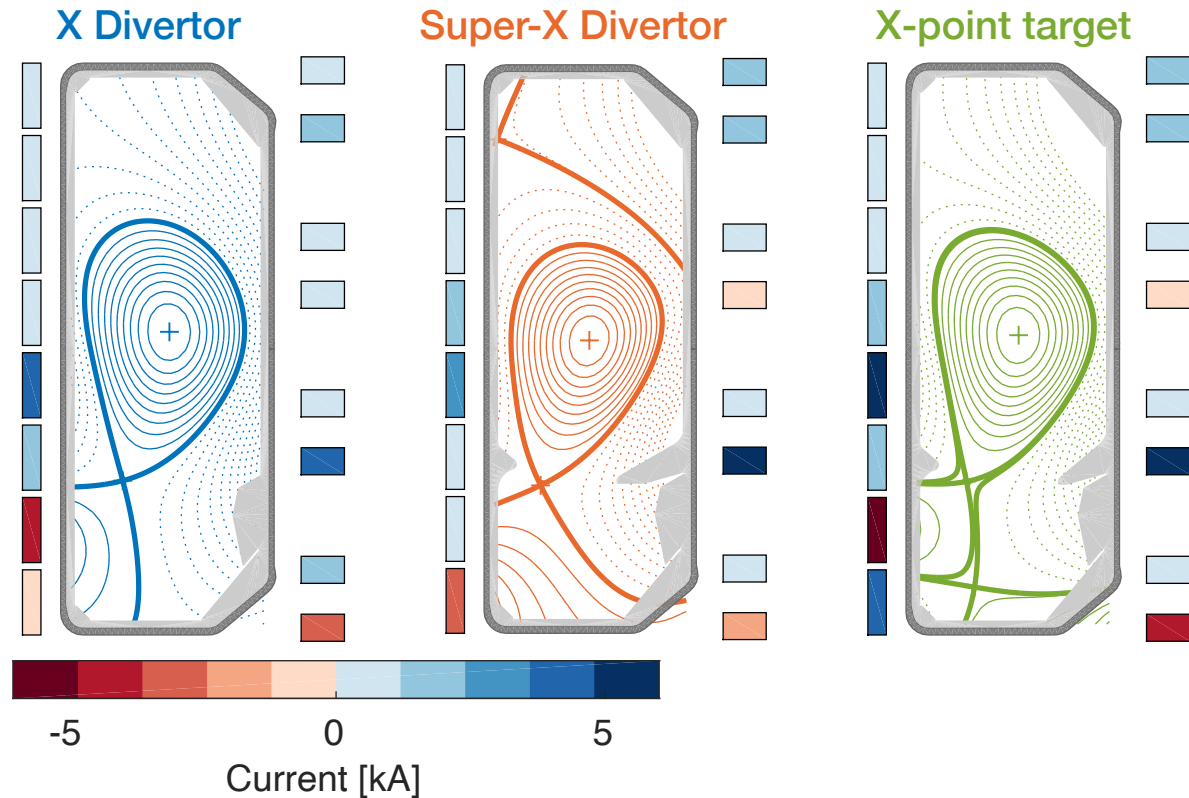


Tokamak à Configuration Variable (TCV) - Lausanne, Switzerland

C. Theiler, "Progress and innovations in the TCV tokamak research programme" - **TUE, 17:25, this conference**



TCV: an exceptionally versatile testbed for exhaust solutions

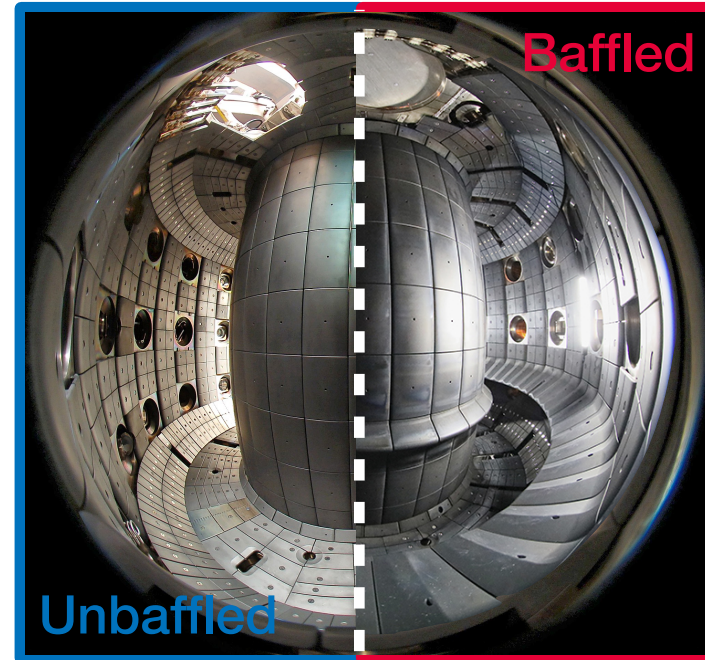
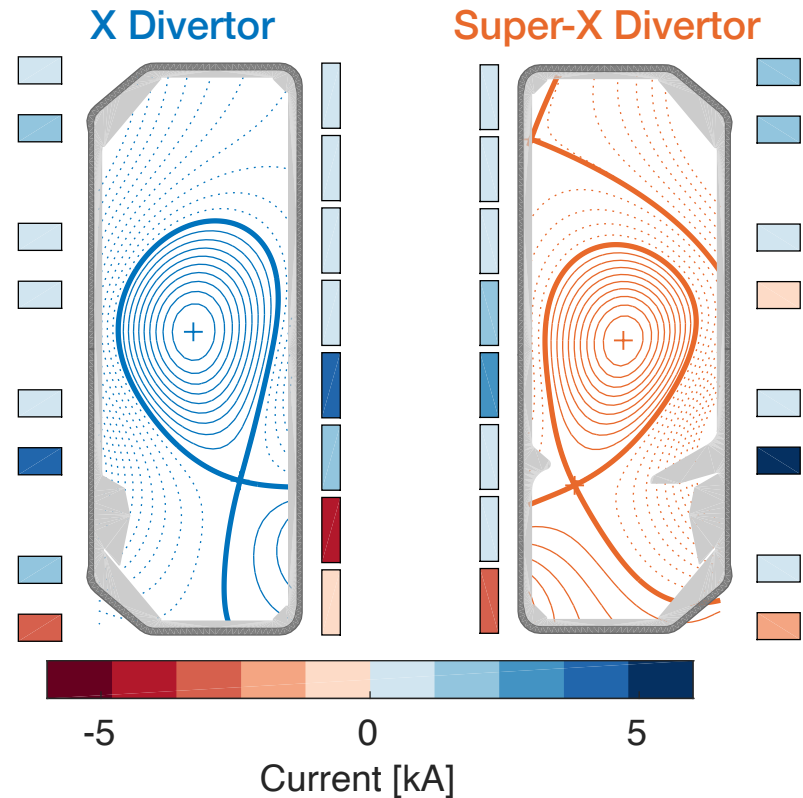


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with 16 independently powered coils - extremely flexible magnetic shaping

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TCV: an exceptionally versatile testbed for exhaust solutions



(Power EXhaust) PEX upgrade: 2019 - 2021

Four sets of dismountable baffles
allow the study different degrees
of divertor closure

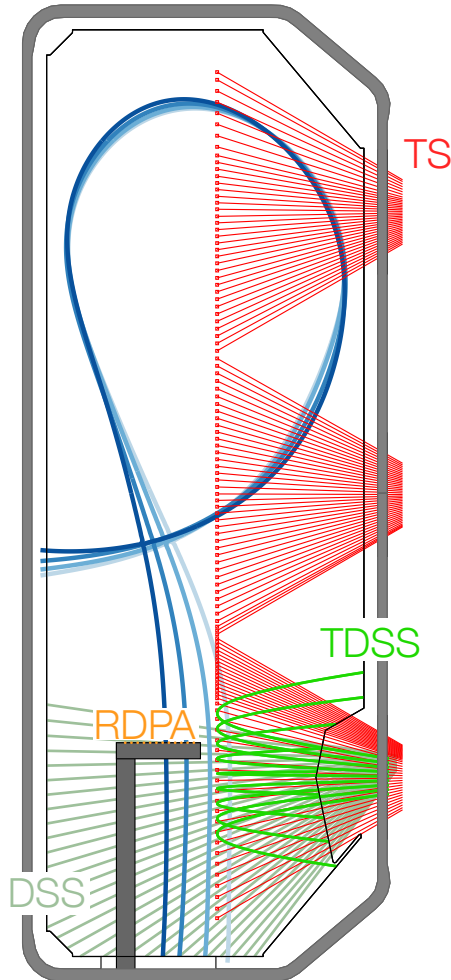
H. Reimerdes et al 2021 Nucl. Fusion 61 024002
O. Février et al 2021 Nucl. Mater. Energy 27, 100977

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TCV diagnostics as a tool that allows direct comparison between models and experiments



TCV can **simultaneously** probe many different plasma parameters, with **extensive coverage** of the plasma volume.

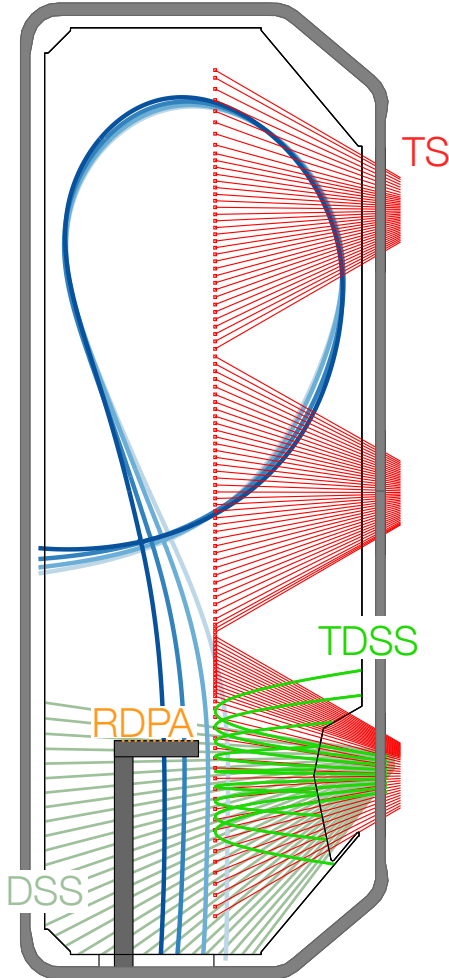
- **Electron density and temperature** (Interferometry, Thomson Scattering, Langmuir probes...)
- **Ion temperature** (Divertor Spectroscopy, CXRS...)
- **SOL flows and fluctuations** (Reciprocating Probe Array, tangential spectroscopy, Gas puff Imaging...)
- **Radiation** (Foil bolometry, AXUV, X-ray, Spectroscopy...)
- **Target heat fluxes** (IR cameras, thermocouples...)

A. Perek et al. 2019 Rev. of Sci. Instrum., 90 123514
P. Blanchard et al 2019 JINST 14 C10038
U.A. Sheikh et al. 2022 Rev. Sci. Instrum. 93 113513

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Global comparison of
diagnostics and modelling

Interpret results through
synthetic diagnostics

D. De Oliveira et al. 2021 Rev. Sci. Instrum. 92 043547
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Outline of the presentation

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Introduction

2

In-depth experimental **validation and optimisation** in a LSN TCV scenario

3

Divertor closure scan: the role of neutral compression

4

Alternative Divertor Configuration scan: the role of magnetic divertor geometry

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Predictive analysis: the **Tightly Baffled Long-Legged Divertor** (TBLLD)



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Code validation on a fixed and well diagnose scenario



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Application and interpretation of experimental results



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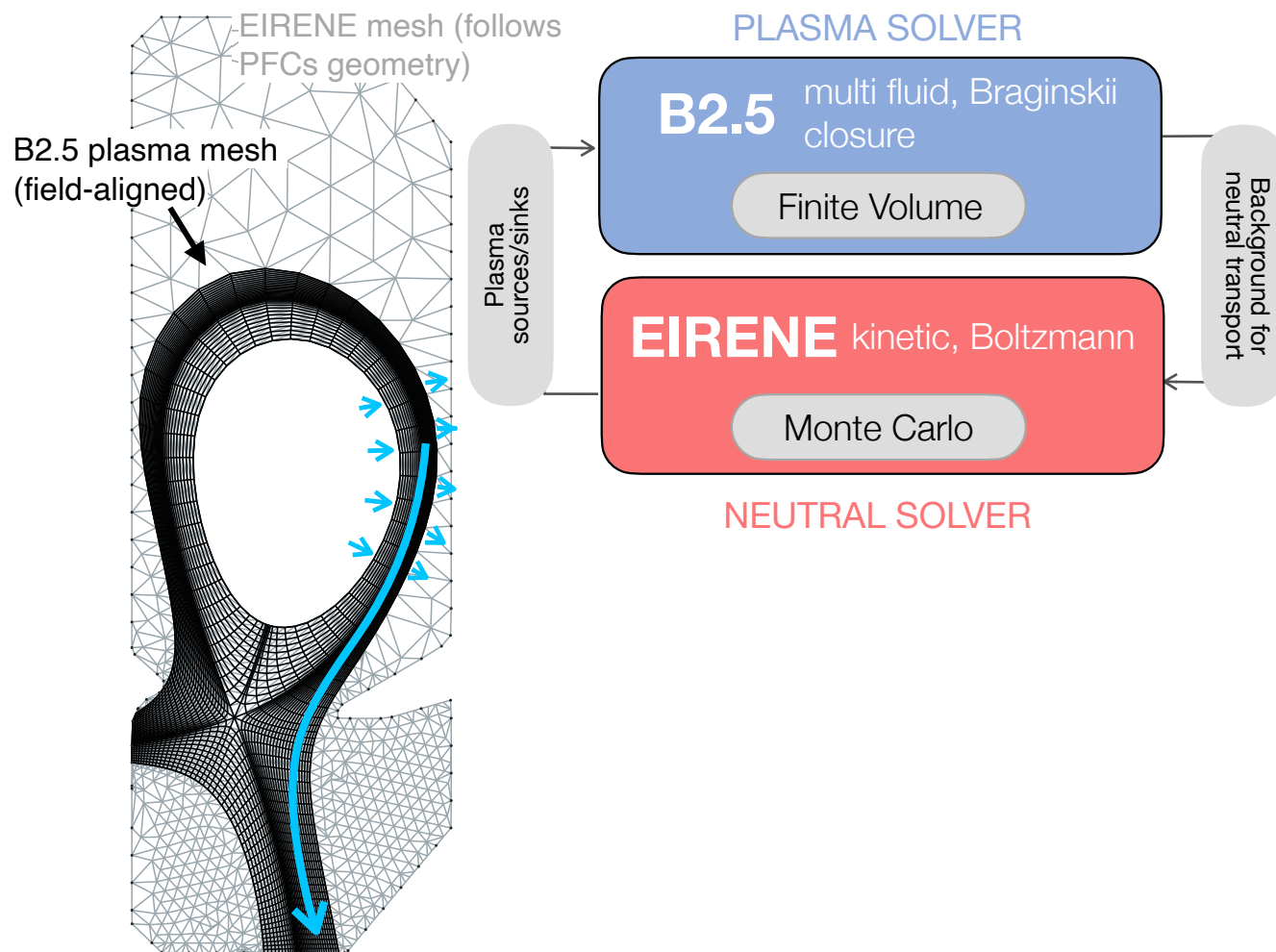
Code validation on a fixed and well diagnose scenario

Application and interpretation of experimental results

Predictive studies to design upcoming upgrades

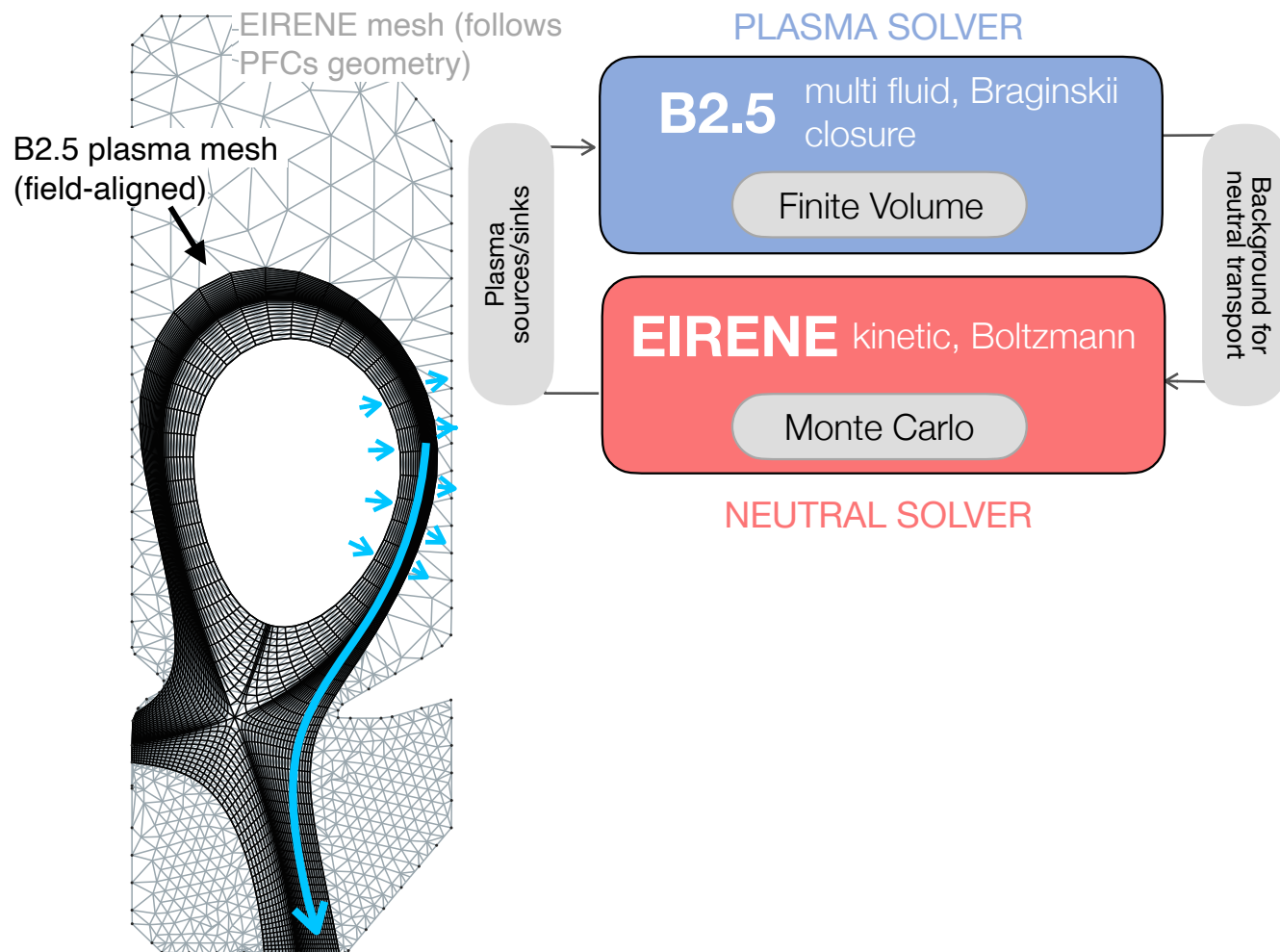


SOLPS-ITER: state of the art tool for boundary plasma modelling and divertor reactor design





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Capable of simulating **reactor conditions**:

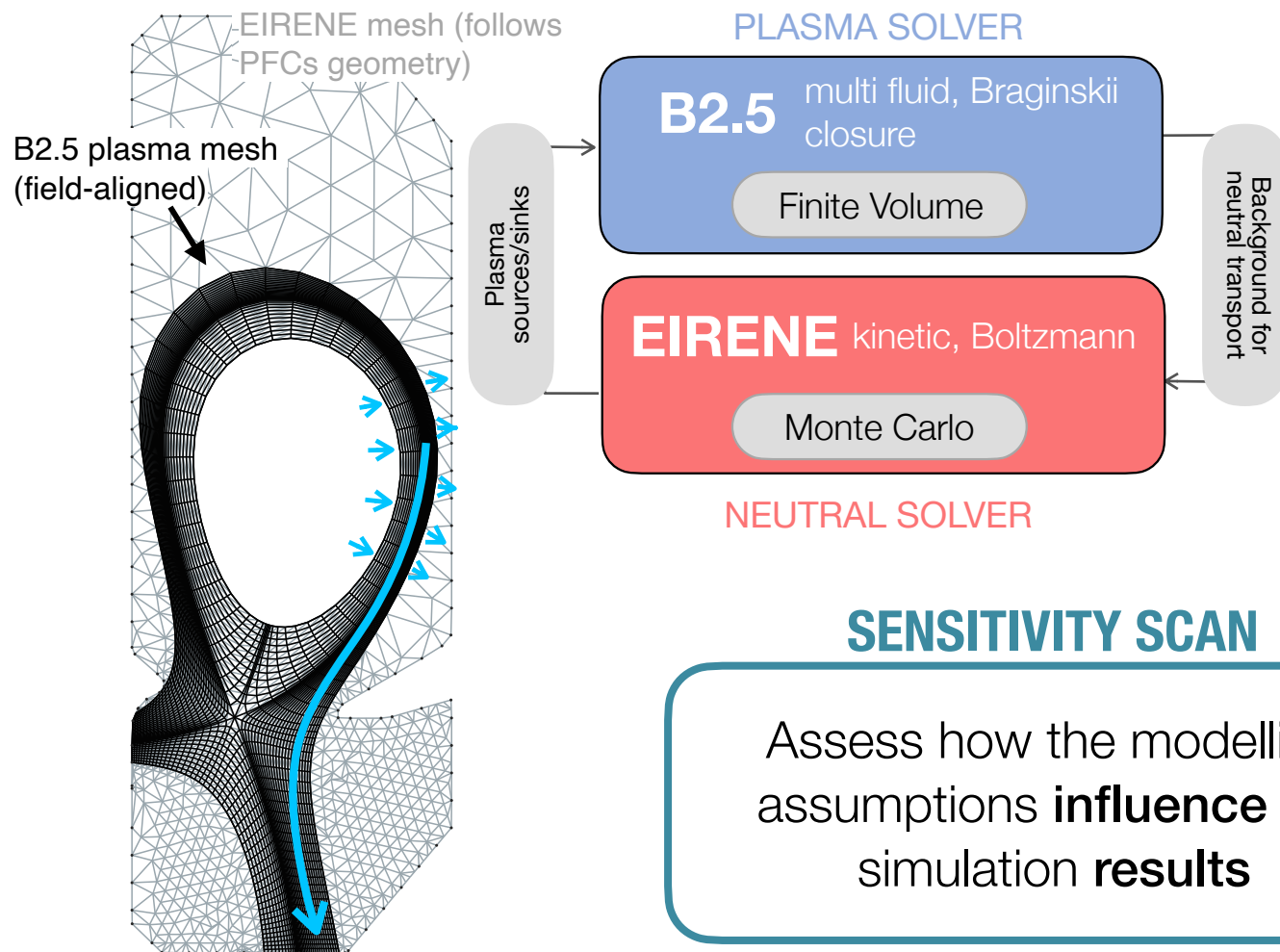
- physical size, magnetic field strength, mixed plasma species, wall geometry...

Simplifying hypotheses on **plasma transport**

- fluid plasma transport model, cross-field transport mean-field + drifts, toroidal symmetry...



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CODE VALIDATION

Robustness of the model compared to **experiments**



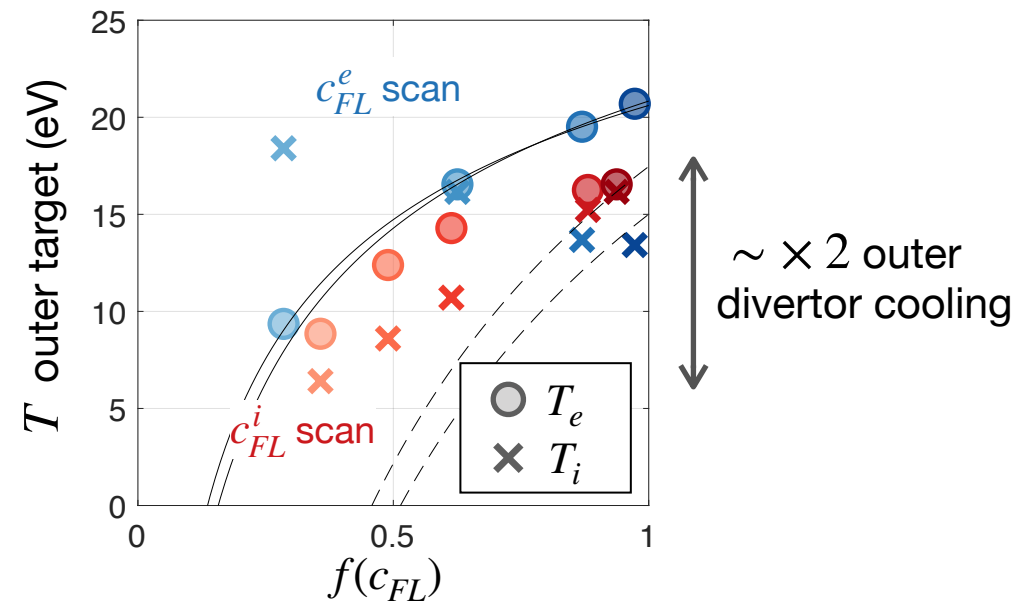
Low values of ion heat flux limiters significantly cool down the outer divertor

Conducted heat flux along the SOL: $q_{\parallel} = -\kappa_{\parallel}^{\text{lim}} \frac{\partial T}{\partial s_{\parallel}}$

$$\kappa_{\parallel}^{\text{lim}} = \frac{1}{1 + \frac{q_{\parallel}^{\text{SH}}}{c_{FL} v T n}} \kappa_{\parallel}^{\text{SH}} = f(c_{FL}) \kappa_{\parallel}^{\text{SH}}$$

$\kappa_{\parallel}^{\text{lim}} \sim \kappa_{\parallel}^{\text{SH}}$ at high collisionality

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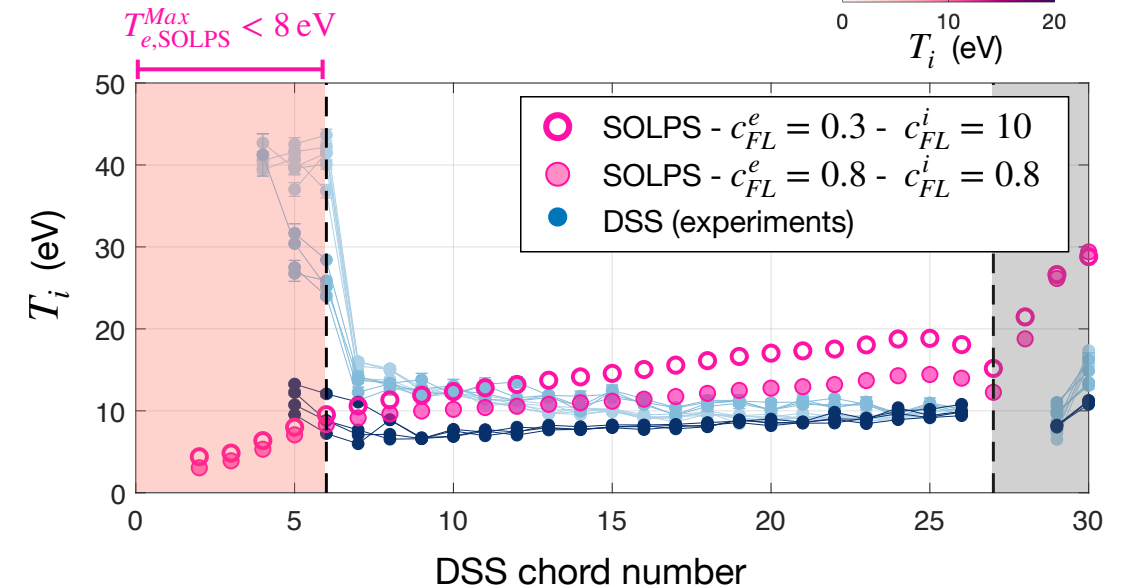
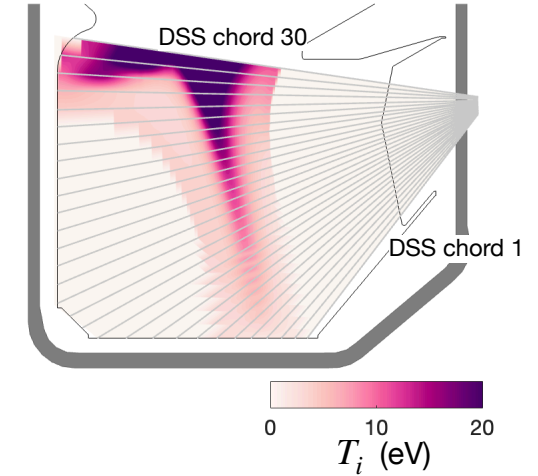
Experimentally guided flux limiter optimisation

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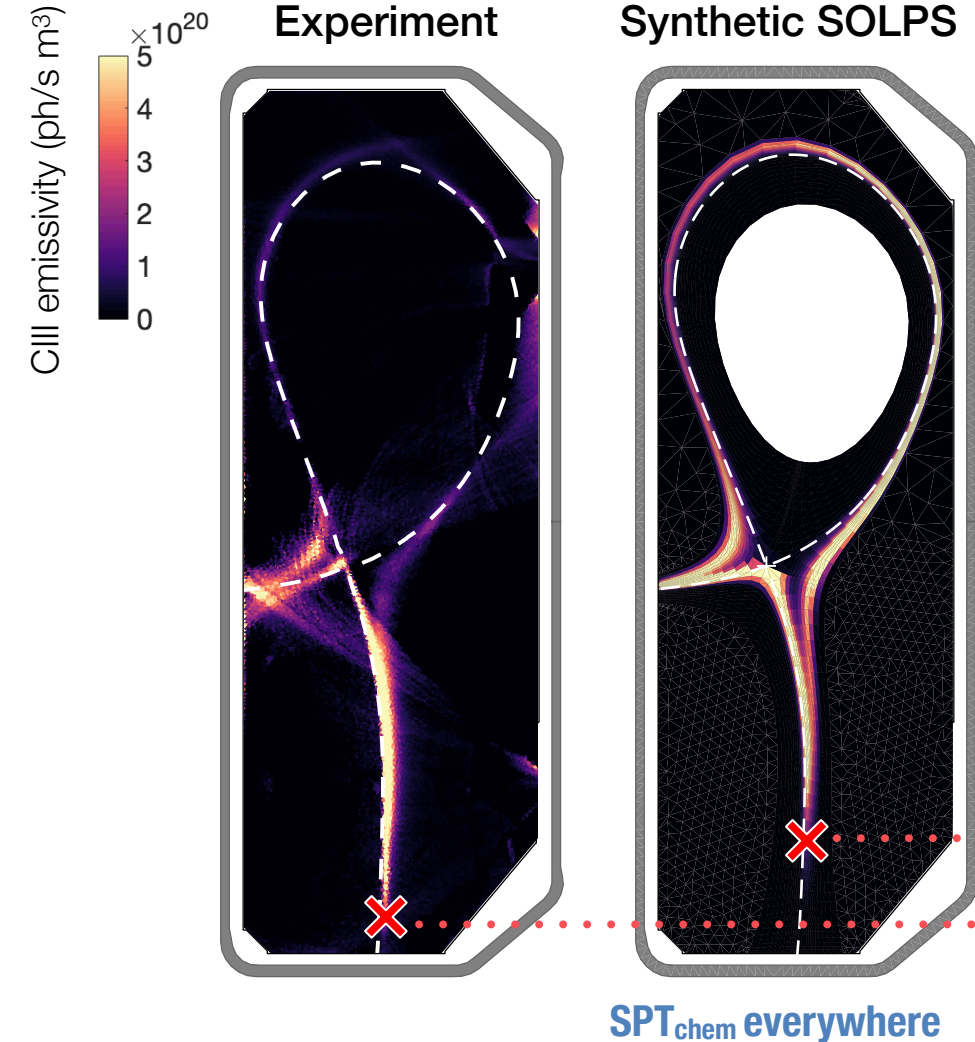




Optimisation of Carbon sources: chemical sputtering only effective at the targets

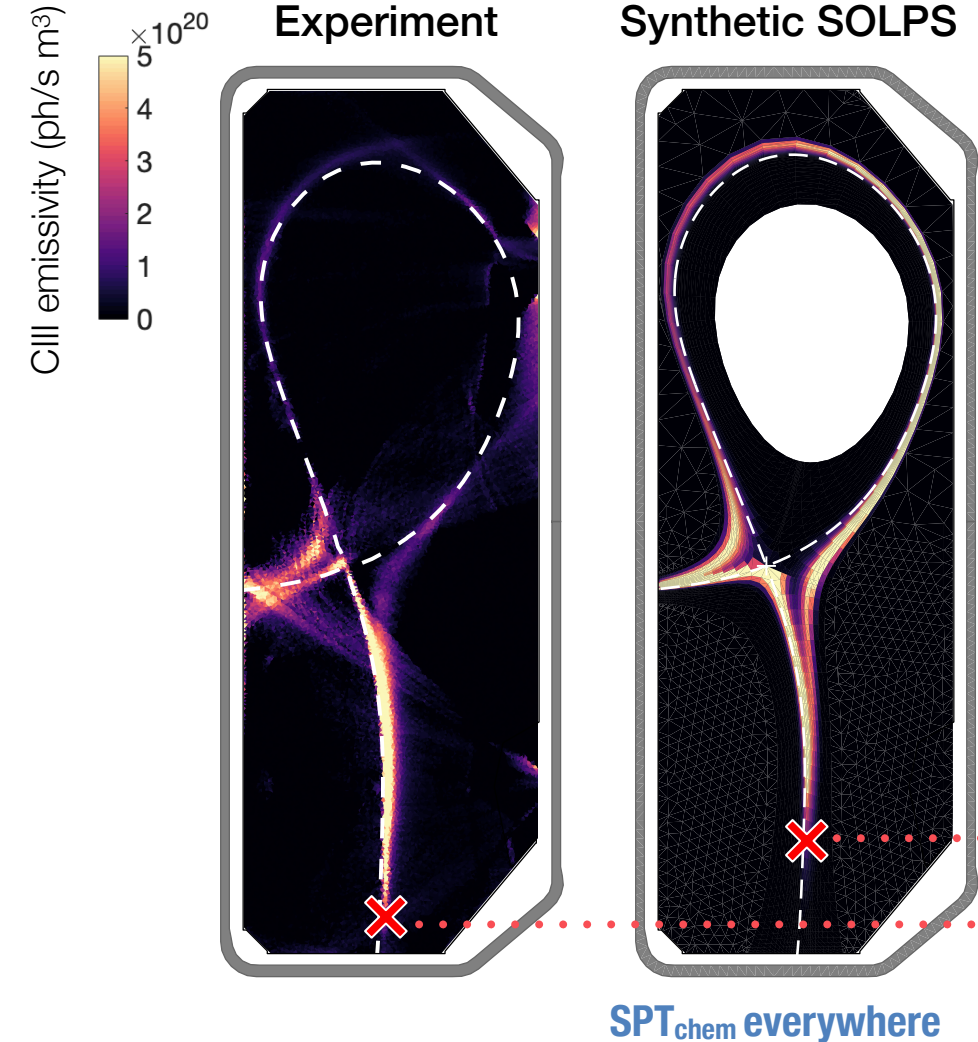
Chemical sputtering SPT_{chem} target+main chamber

- Qualitative difference: CIII emissivity peaked in the far-SOL
- CIII-front is further away from the target than in experiments





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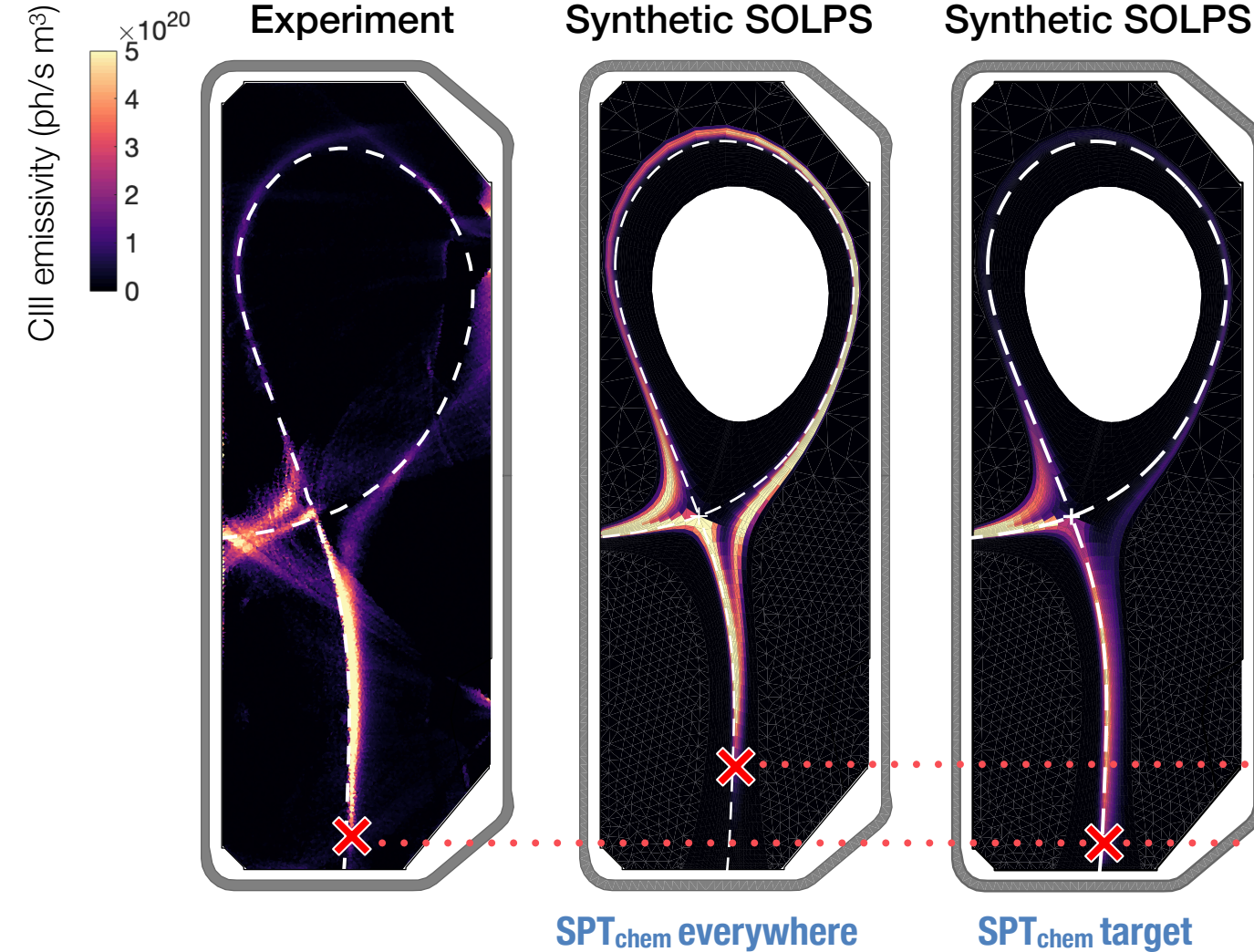
...but chemical erosion by neutrals is induced by ion flux and high wall T (only at the target)

J. Roth and C. Garcia-Rosales 1996 Nucl. Fusion 36 1647

CIII front position as an indicator of divertor conditions



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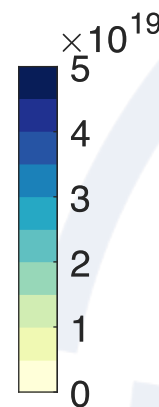
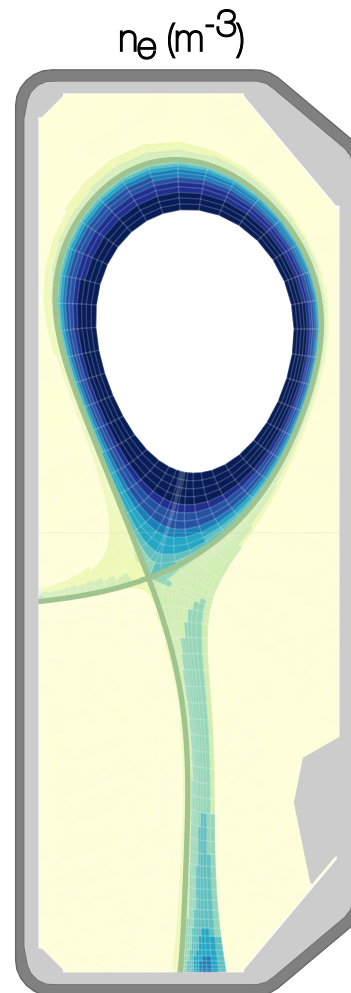
Chemical sputtering SPT_{chem} target only

- Recovers qualitative experimental emissivity pattern
- Recovers CIII front location
- However, underestimates emissivity ~factor 2

CIII front position as an indicator of divertor conditions



Multi-parameter, multi-location comparison of experiments and simulations



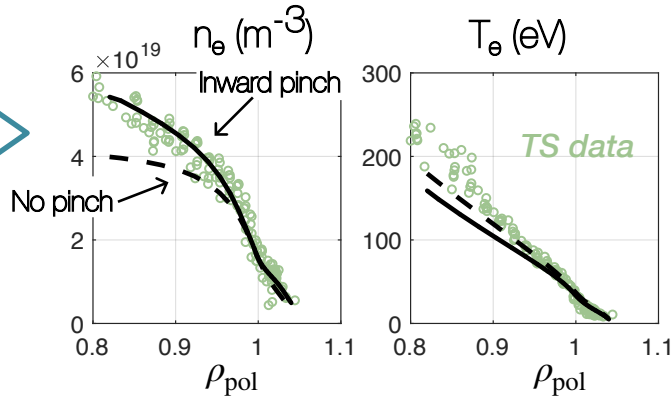


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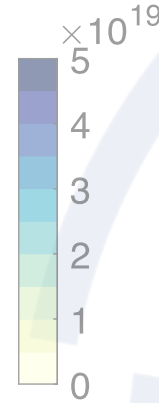
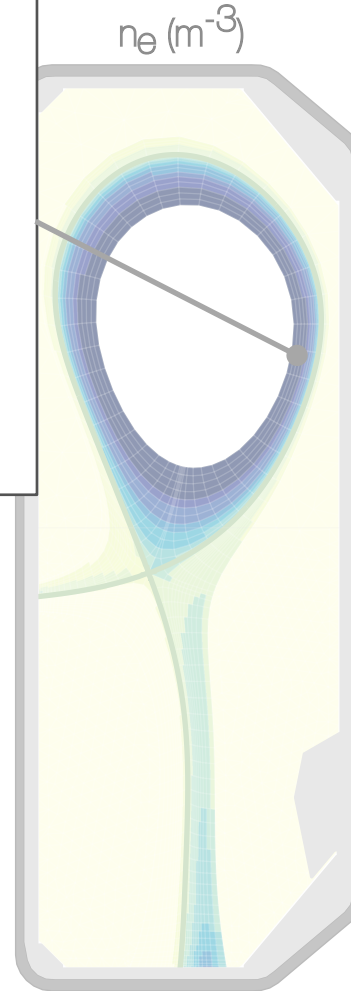
Upstream profiles

JINTRAC

$\vec{v}_{pol=0.95}^{\rho_{pinch}} \sim -1.0 \text{ m/s}$



Including $\vec{v}_{pinch}$ estimated by JINTRAC improves accuracy of upstream profiles

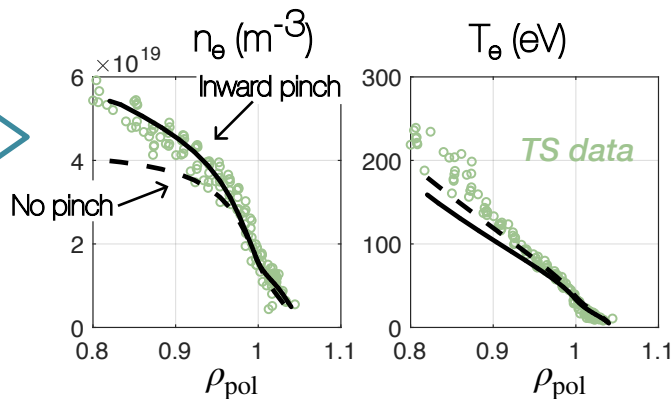




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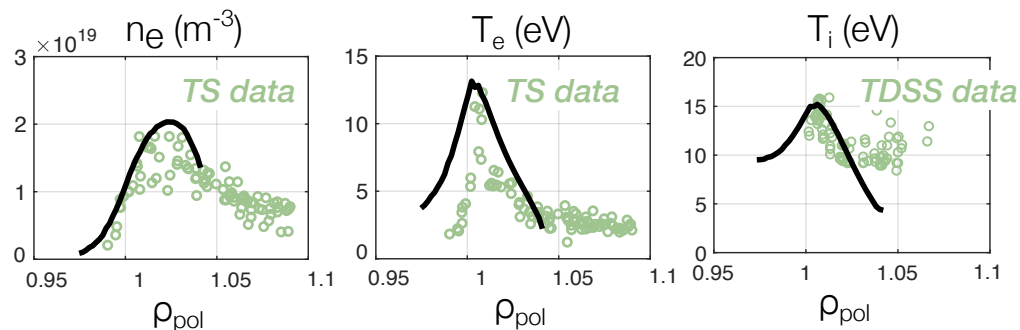
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pinch

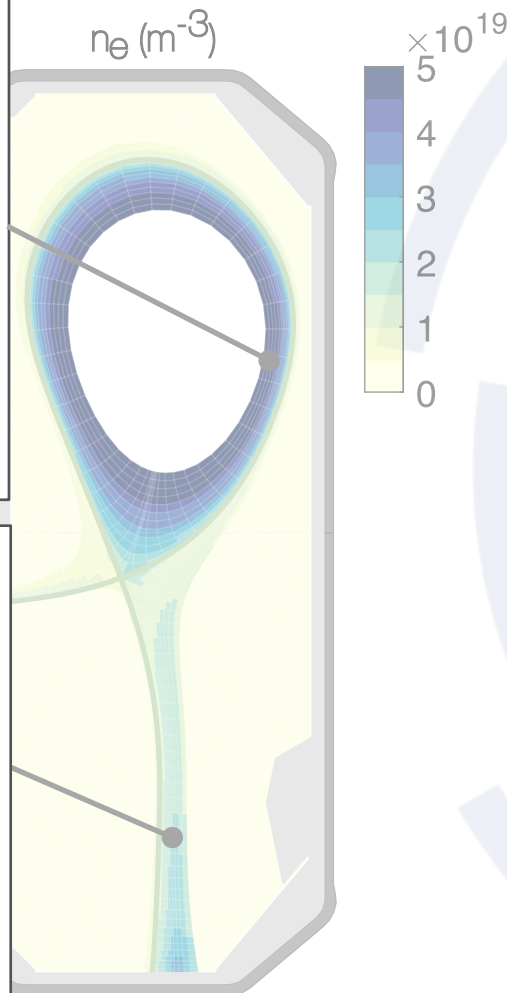


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Outer leg profiles



Optimisation of flux limiters improves accuracy on divertor conditions

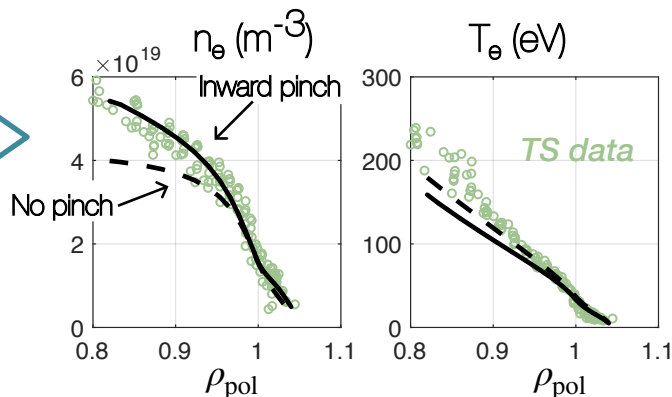




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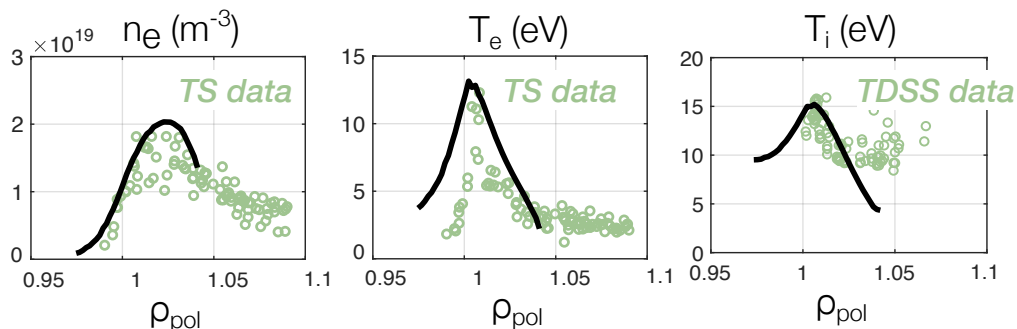
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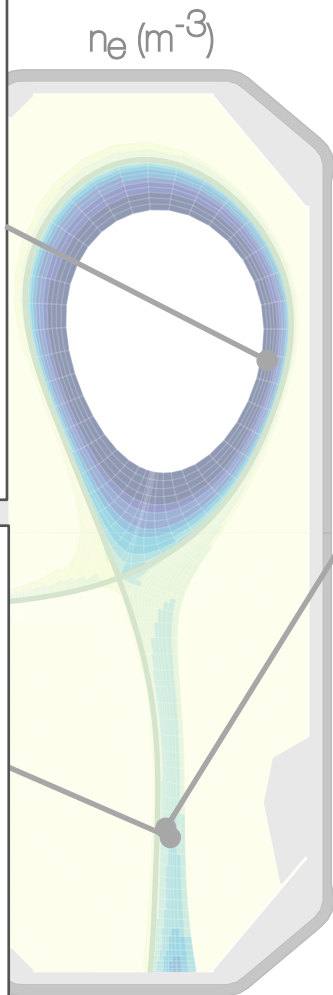


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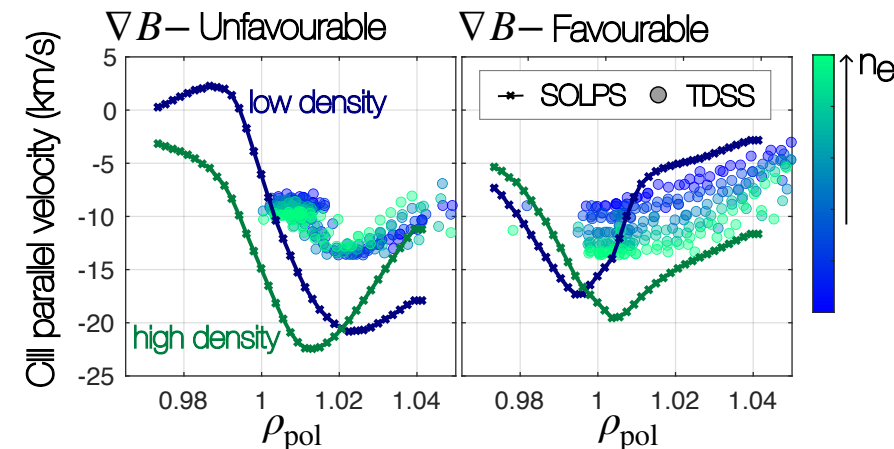
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Plasma flow profiles



Simulations recover main trends of flow profiles:

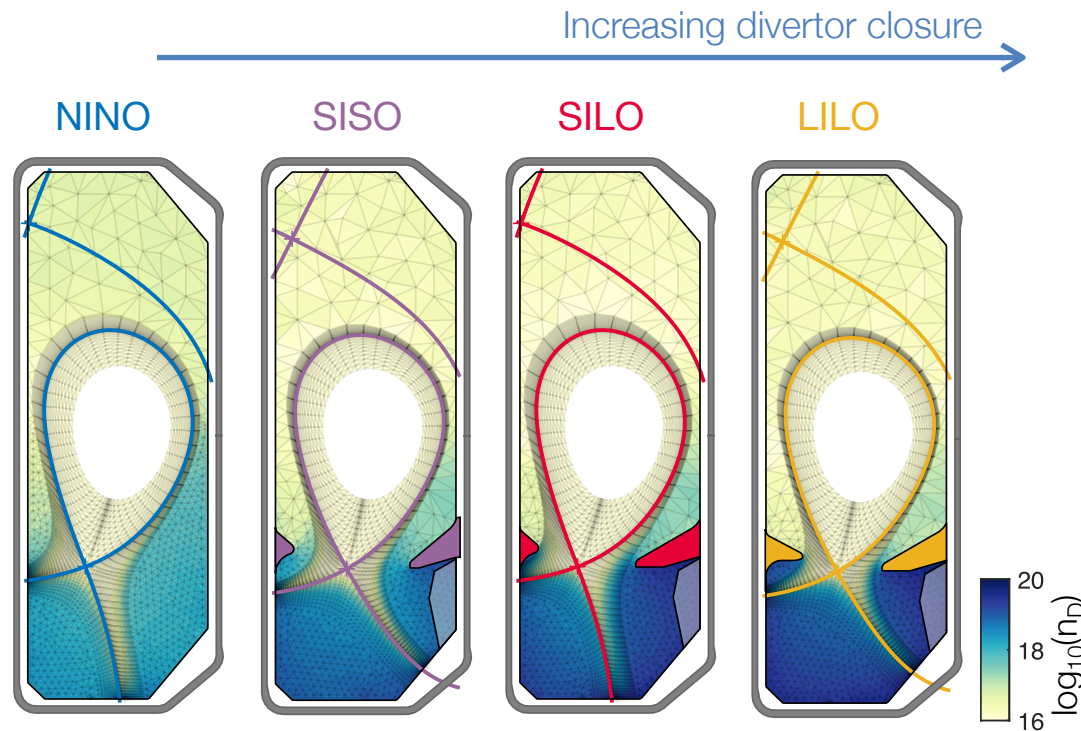
- SOL profile features in forward (favourable ∇B) and reversed field (unfavourable ∇B)
- Trends with upstream plasma density

R. Ducker et al, paper submitted to RSI



Divertor closure scan: SOLPS-ITER quantitatively reproduces the beneficial effect of divertor baffling

Increasing baffling increases divertor neutral density for the same upstream conditions.

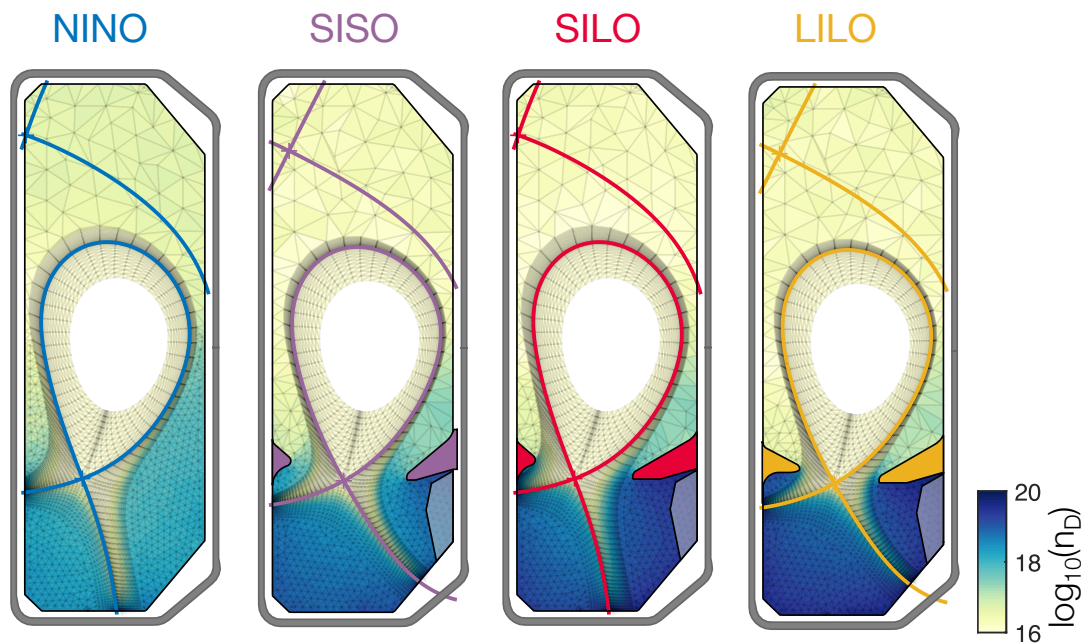




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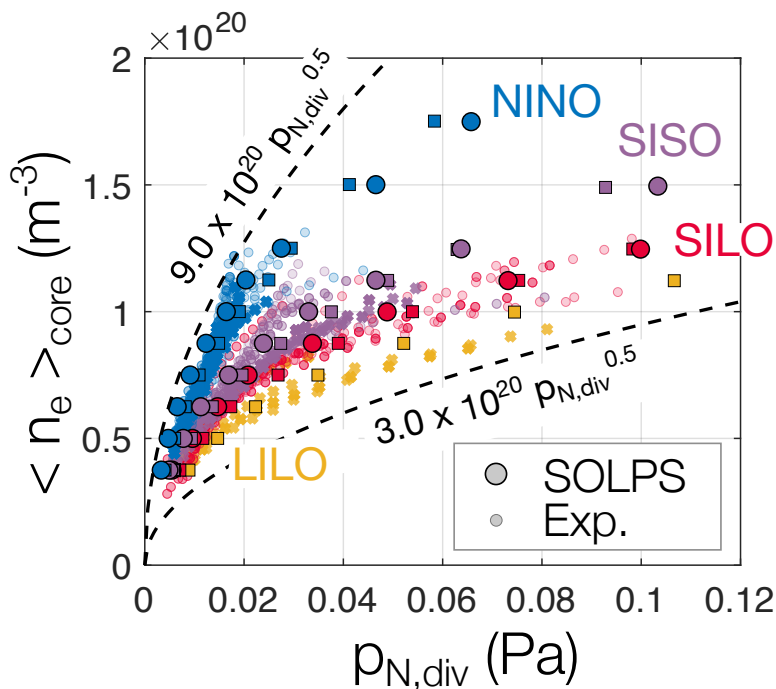
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Increasing divertor closure →



Simulations compared with a **database of 100+ TCV shots**:

- Good quantitative agreement between simulations and experiments





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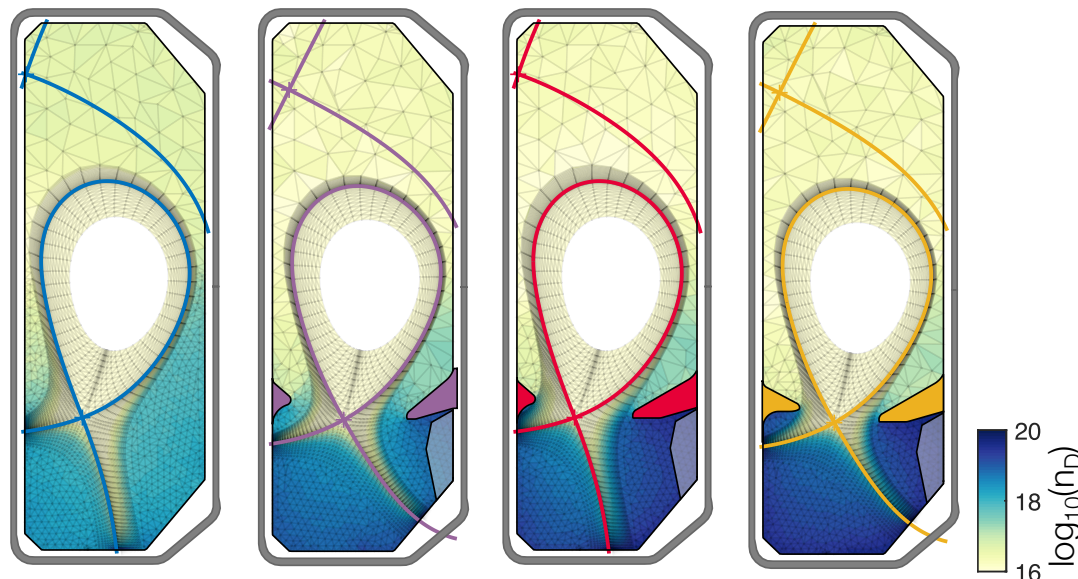
Increasing divertor closure →

NINO

SISO

SILO

LILO



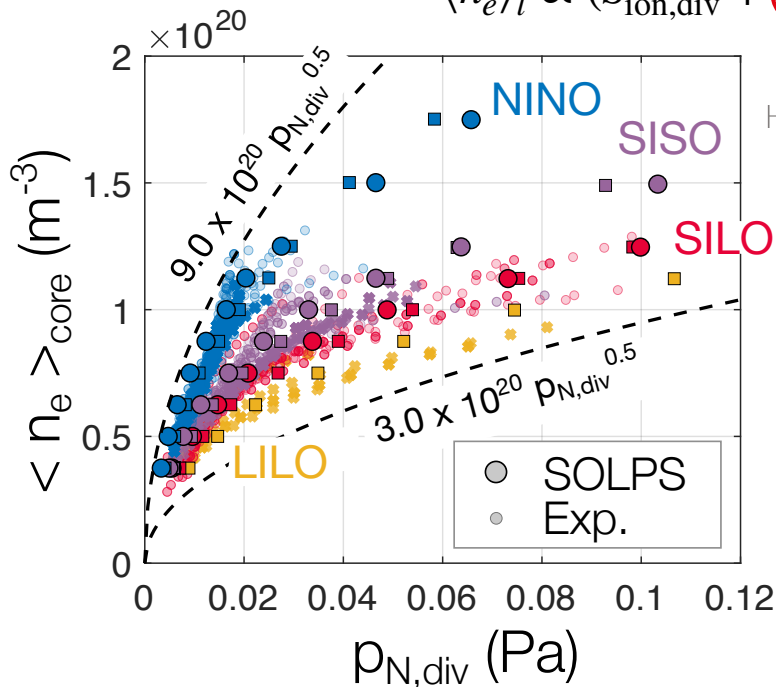
Simulations compared with a **database of 100+ TCV shots**:

- Good quantitative agreement between simulations and experiments
- Trend explained by simple analytical model:

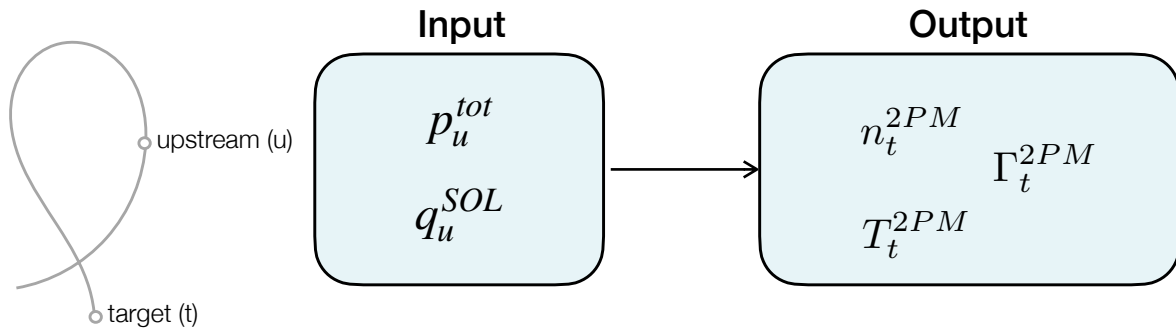
$$\langle n_e \rangle_l \propto (S_{\text{ion,div}} + C_{\text{baff}}) p_{N,\text{div}}^{0.5}$$

decreases with increasing baffling

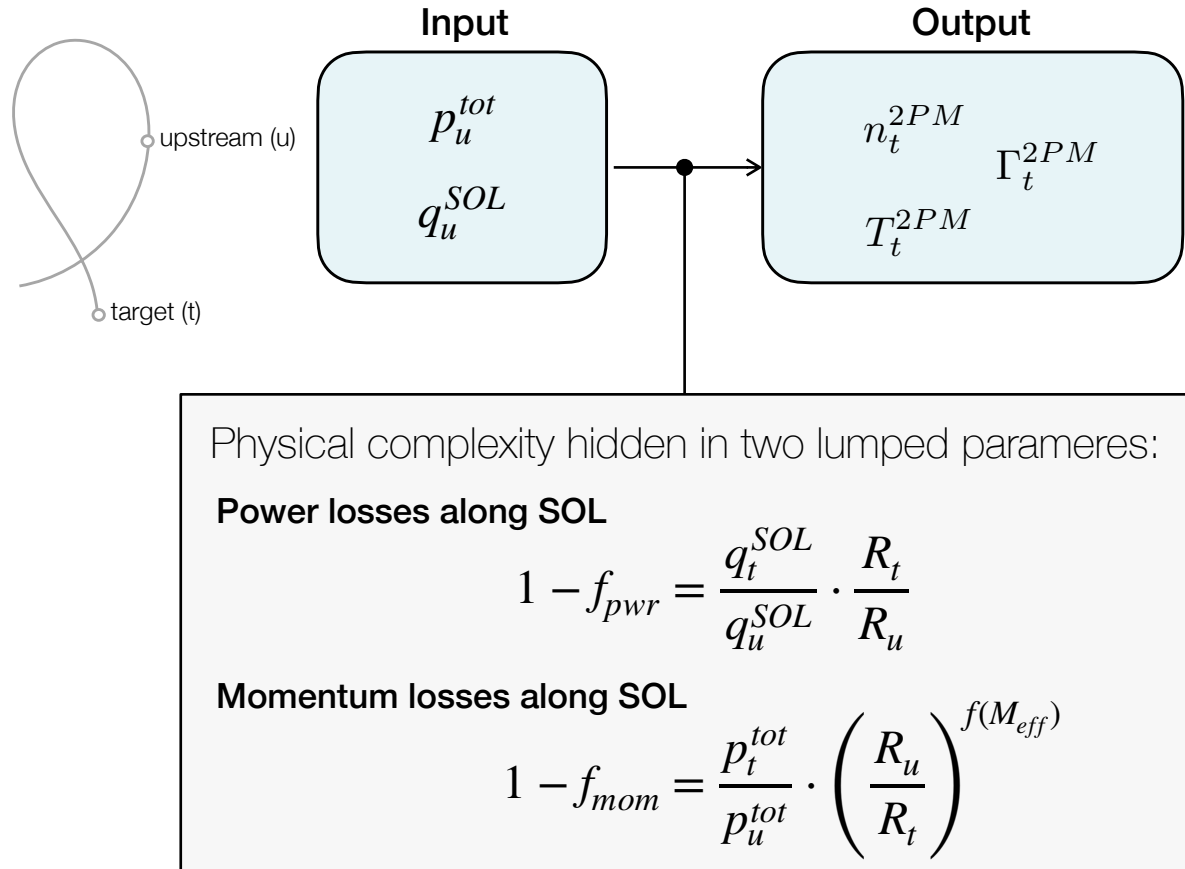
H. Reimerdes et al, IAEA-FEC 2023



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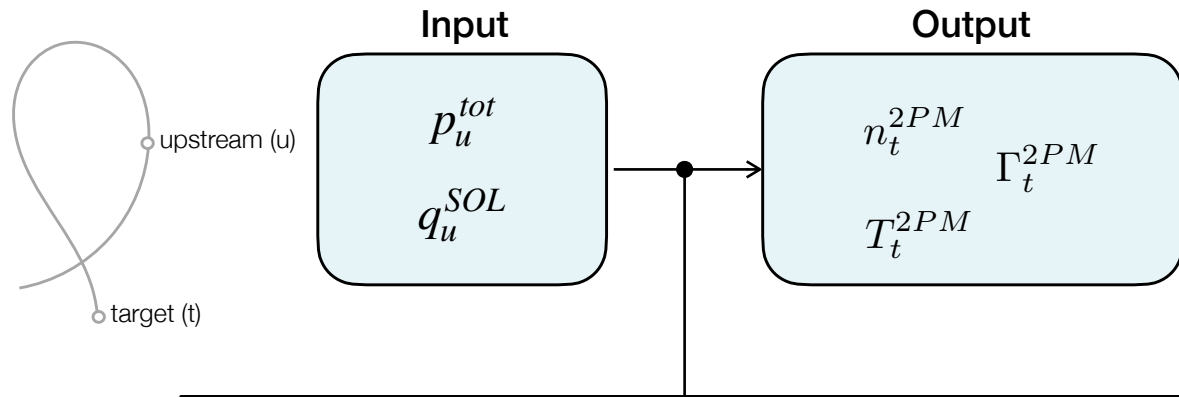


P. C. Stangeby 2018 Plasma Phys. Control. Fusion 60 044022
M. Carpita et al 2024 Nucl. Fusion 64 046019



SOLPS-ITER simulation database used to inform reduced models

Two-point model estimates main divertor target quantities given upstream plasma pressure and input power:



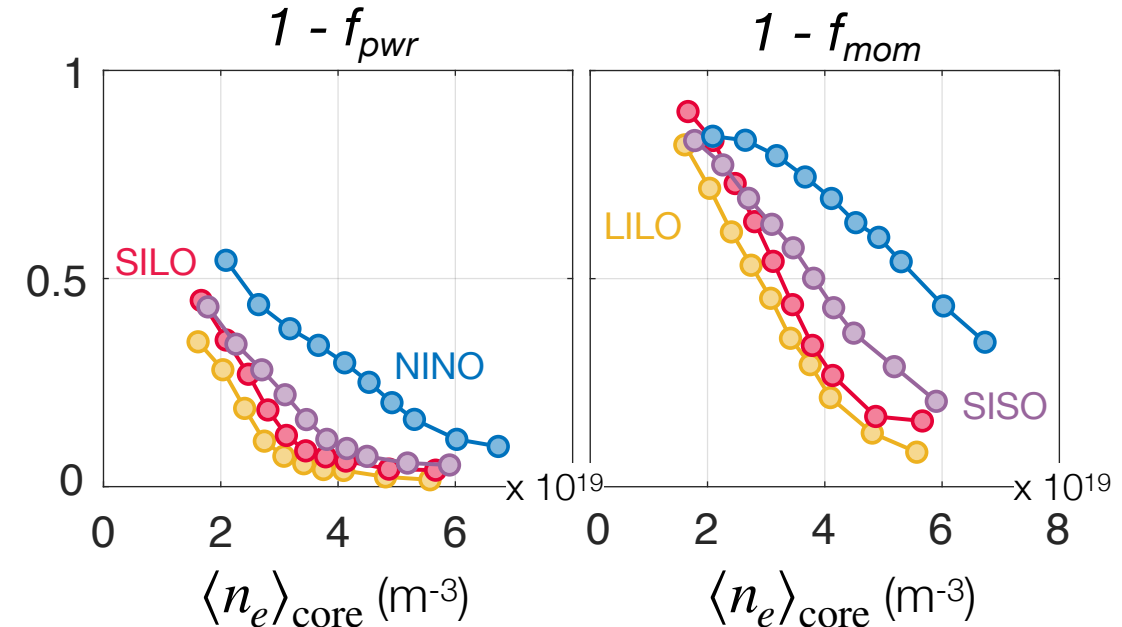
Physical complexity hidden in two lumped parameters:

Power losses along SOL

$$1 - f_{pwr} = \frac{q_t^{SOL}}{q_u^{SOL}} \cdot \frac{R_t}{R_u}$$

Momentum losses along SOL

$$1 - f_{mom} = \frac{p_t^{tot}}{p_u^{tot}} \cdot \left(\frac{R_u}{R_t} \right)^{f(M_{eff})}$$



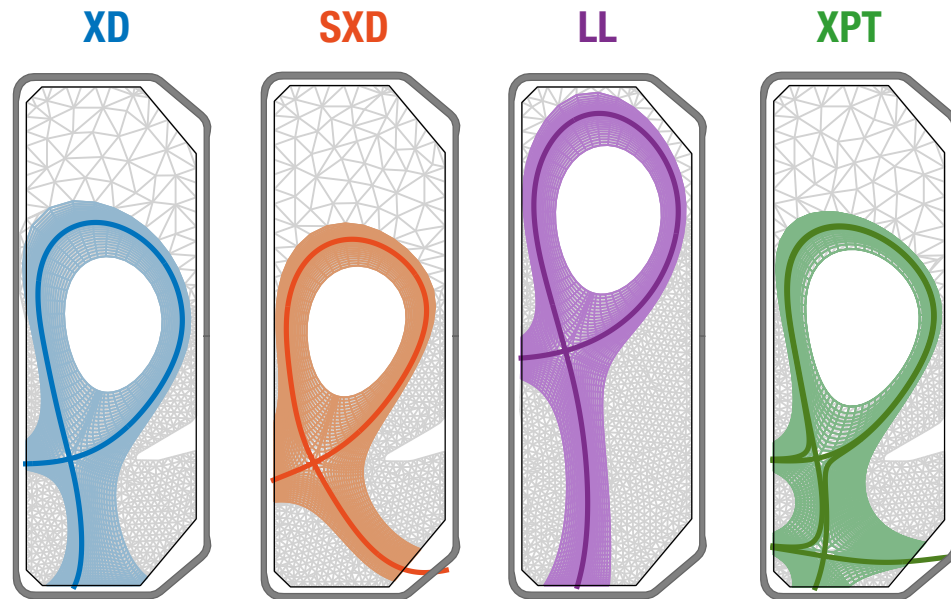
Understand and decompose contributions to f_{pwr} and f_{mom} with the help of SOLPS-ITER simulations database



Alternative divertor scan: SOLPS-ITER analysis of the power exhaust performance of ADCs

ADC-experimental database:

- TCV magnetic flexibility, carefully modifying only outer divertor leg geometry
- Each ADC is compared with a reference **LSN scenario** with matching core plasma properties.



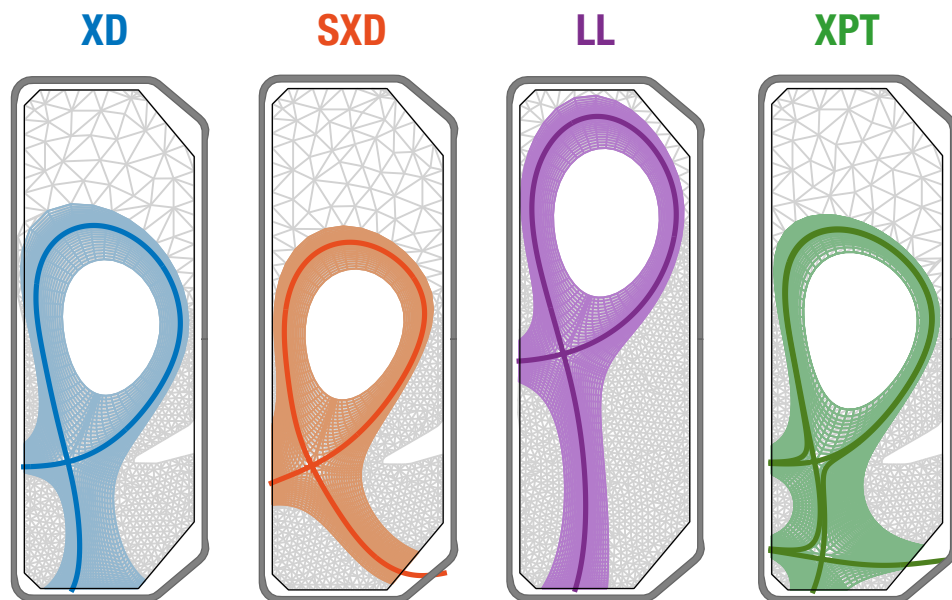
M. Carpita, Invited talk AAPPS-DPP 2025



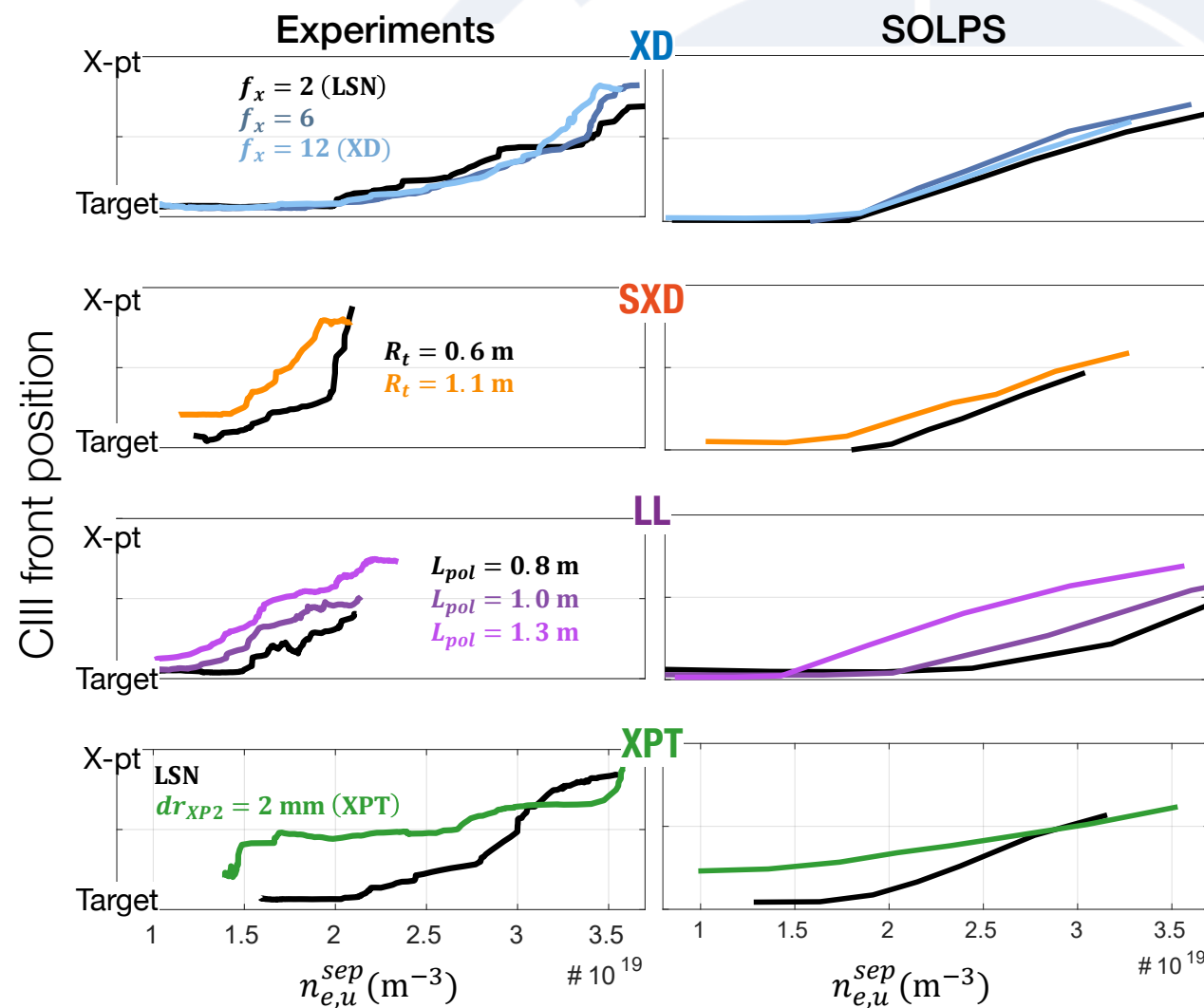
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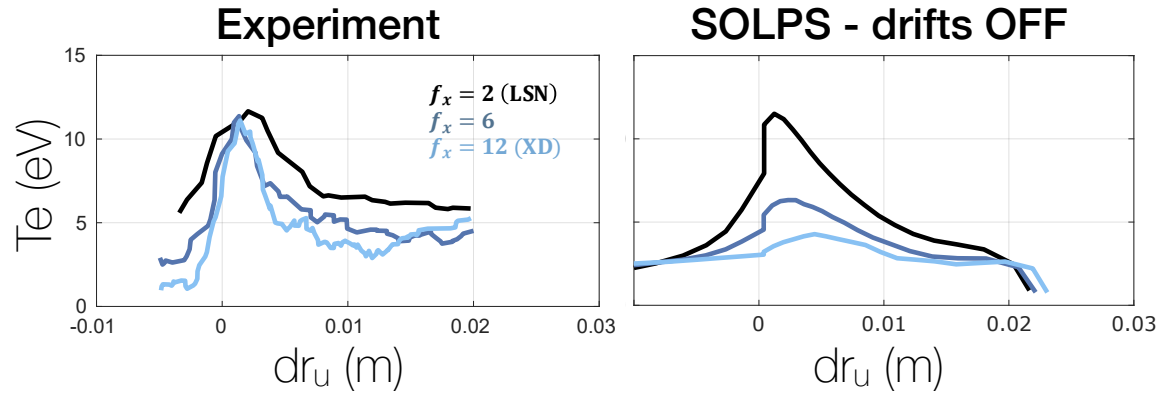


M. Carpita, Invited talk AAPPS-DPP 2025





Higher-order effects - like drifts - are important to capture ADC trends

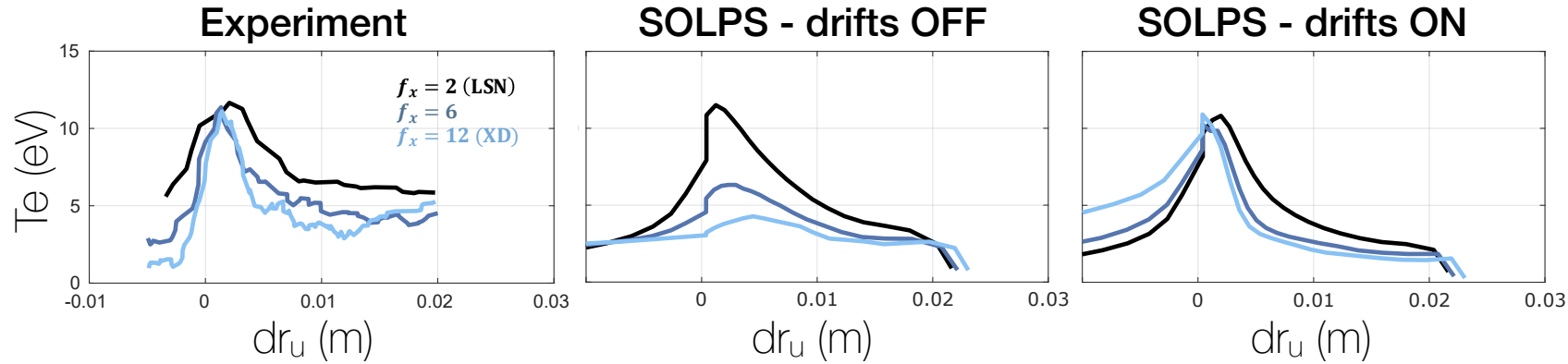


X-DIVERTOR:

- Simulations w/o drifts overestimate T_e drop with f_x



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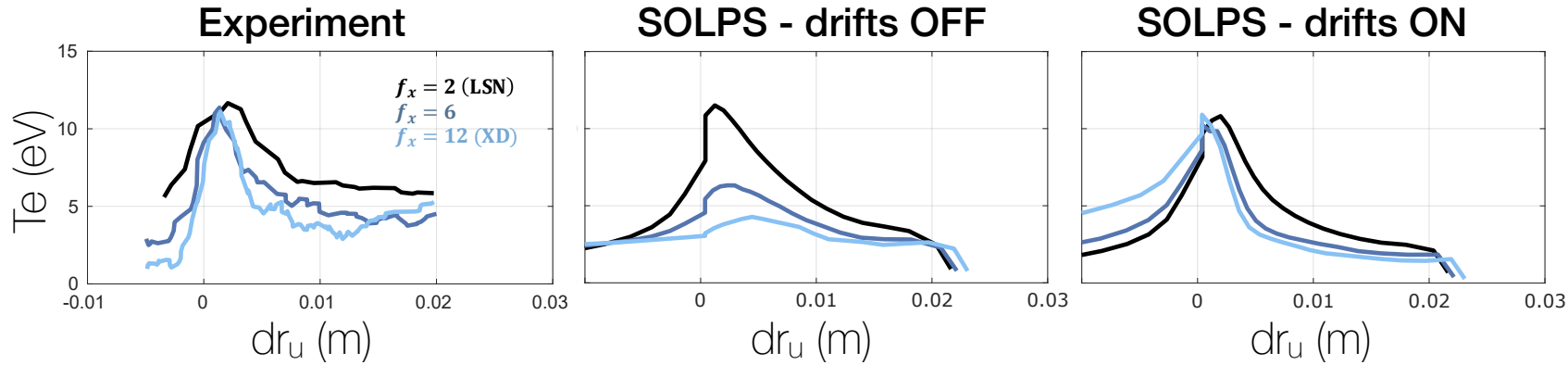


X-DIVERTOR:

- Simulations w/o drifts overestimate Te drop with f_x
- **Drifts are needed** to quantitatively estimate the effect of f_x

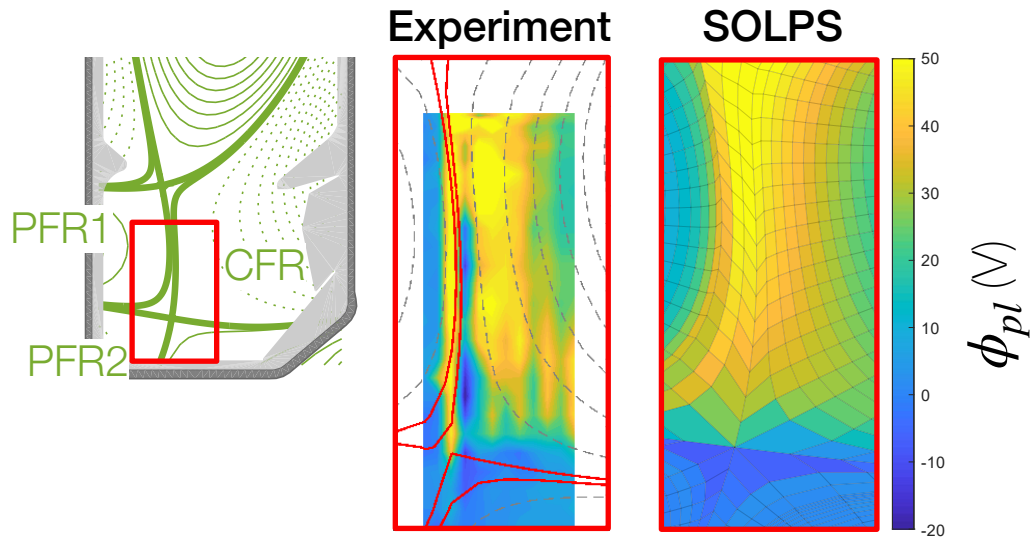


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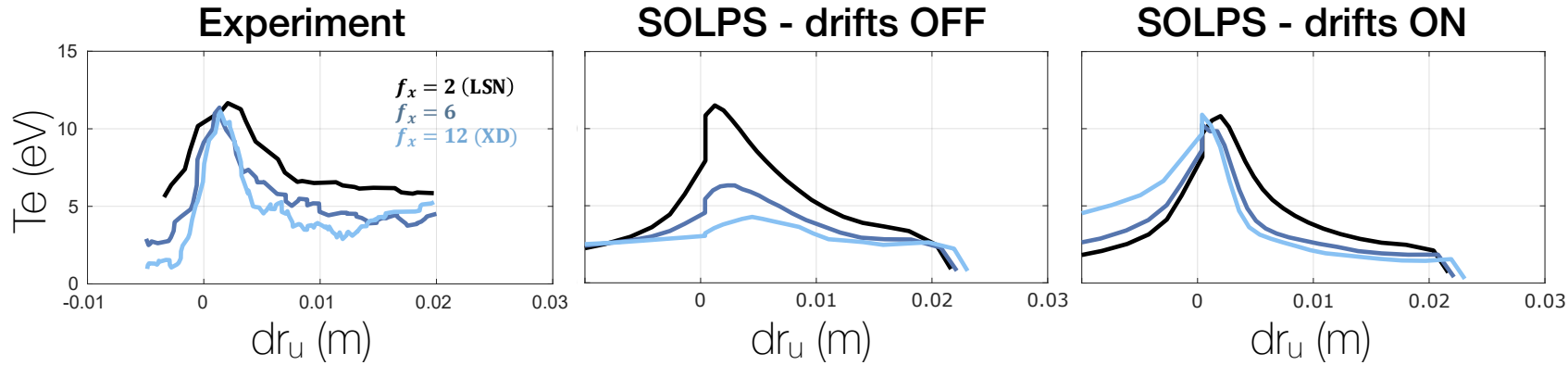


X-POINT TARGET:

- **Plasma potential well** in the **secondary PFR** is seen in both simulations and experiments

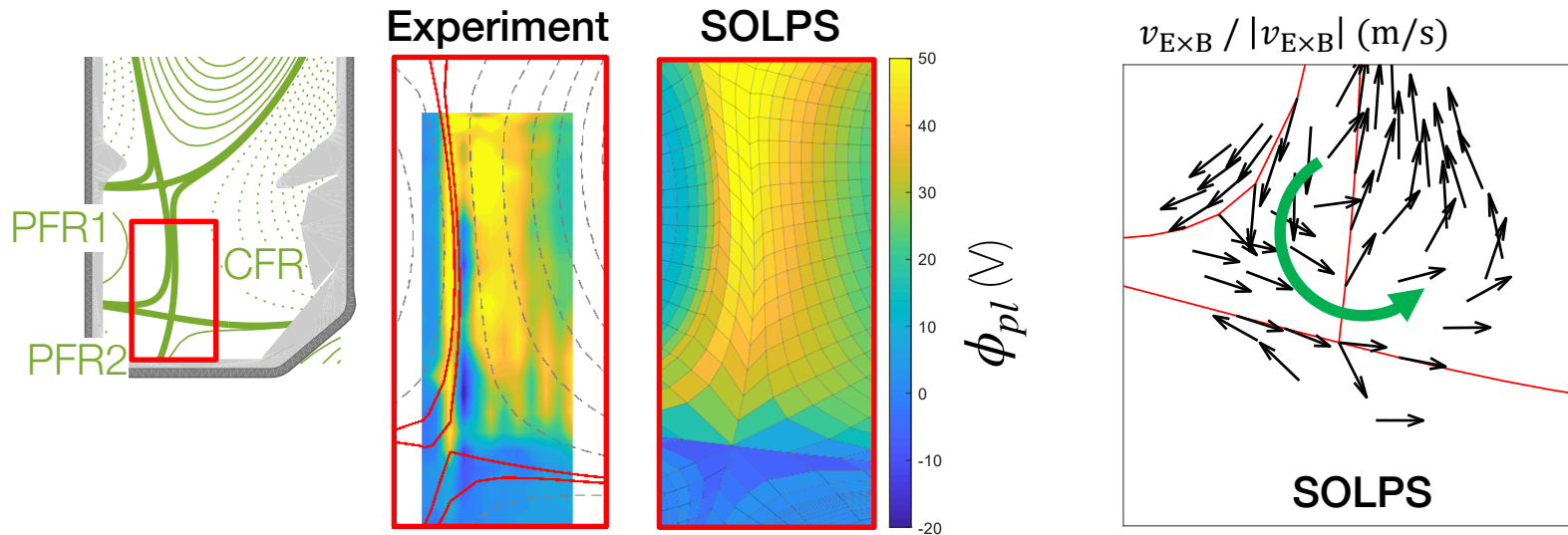


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- Simulations w/o drifts overestimate Te drop with f_x
- **Drifts are needed** to quantitatively estimate the effect of f_x

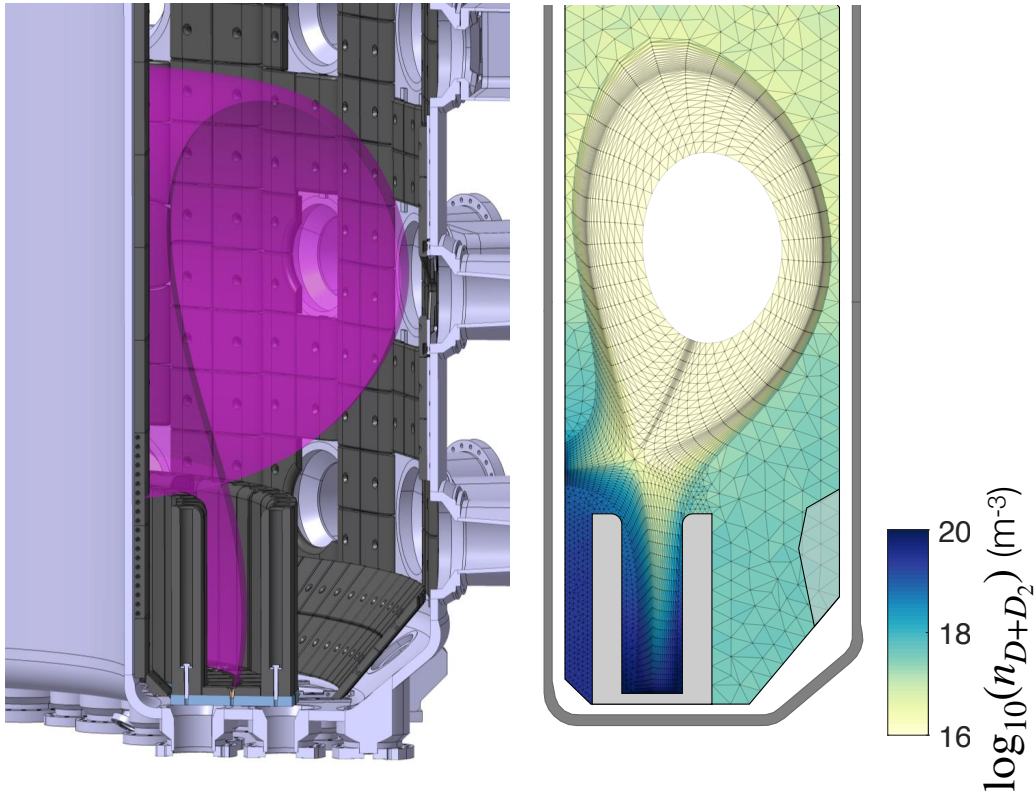


X-POINT TARGET:

- **Plasma potential well** in the **secondary PFR** is seen in both simulations and experiments
- Produces **$E \times B$ convective cell** pushing particle towards CFR and cooling down outer target



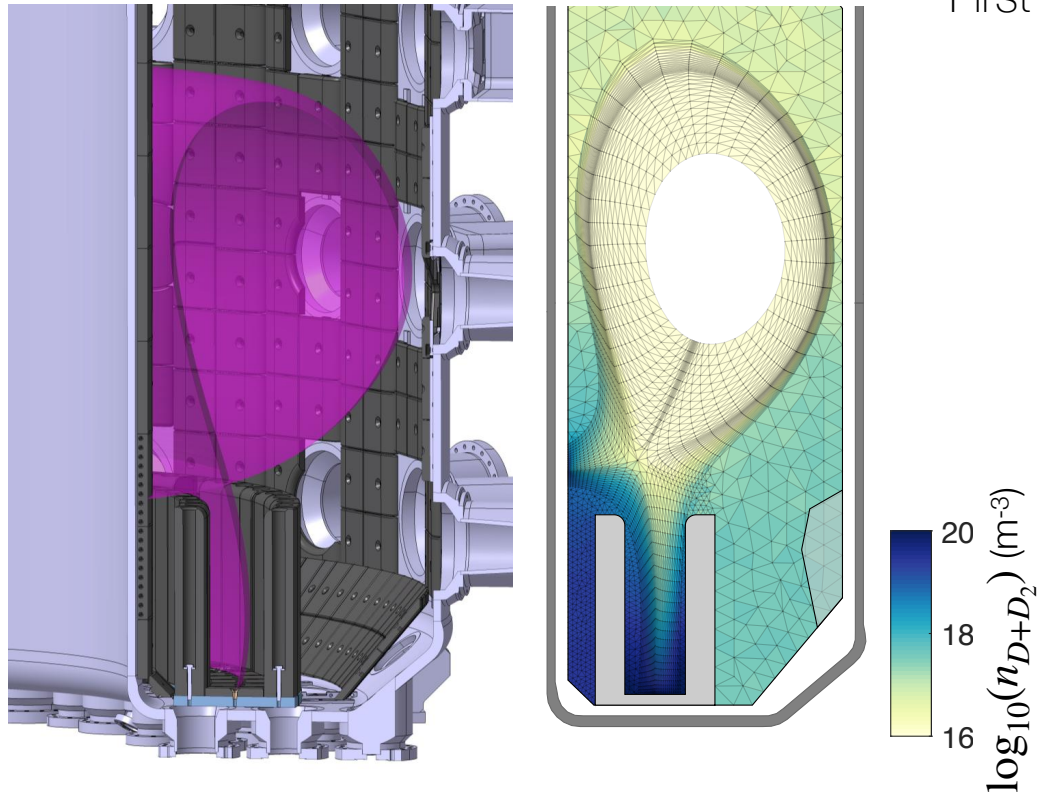
The TBLD upgrade: predictive studies show significant improvements in the power exhaust performance



H. Reimerdes, “Implementation of a Tightly Baffled Long-Legged Divertor in TCV” - **WED, 14:00, this conference**



The TBLLD upgrade: predictive studies show significant improvements in the power exhaust performance



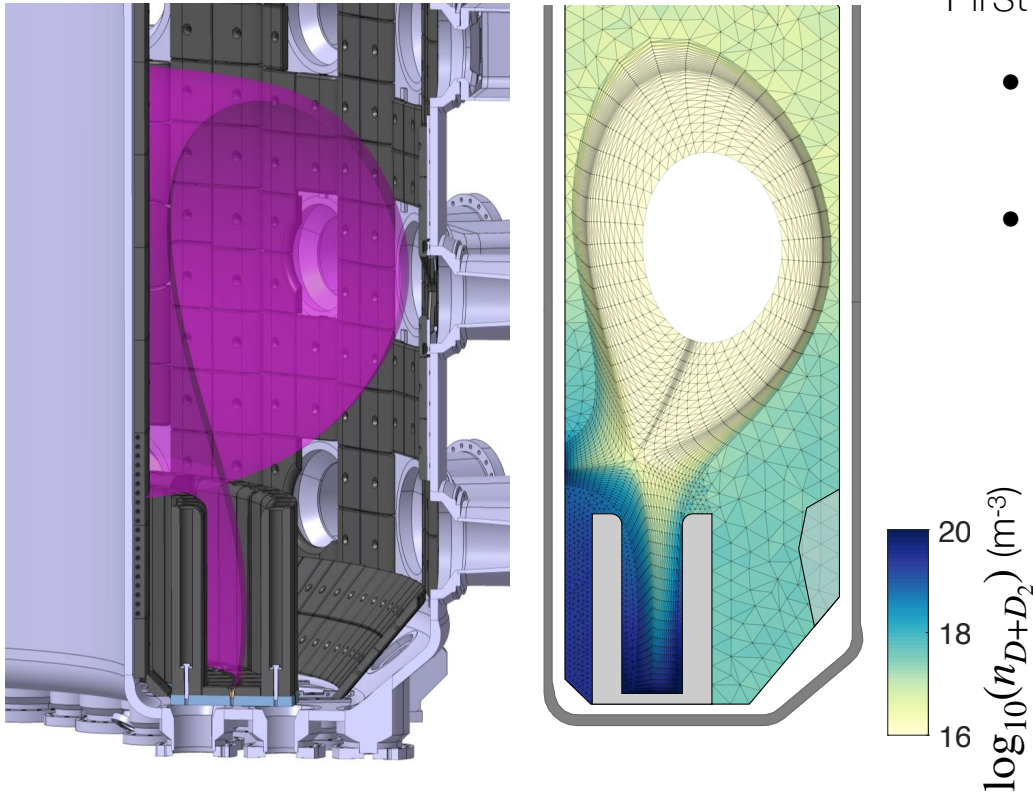
First SOLPS-ITER simulations of the finalised TBLLD geometry.

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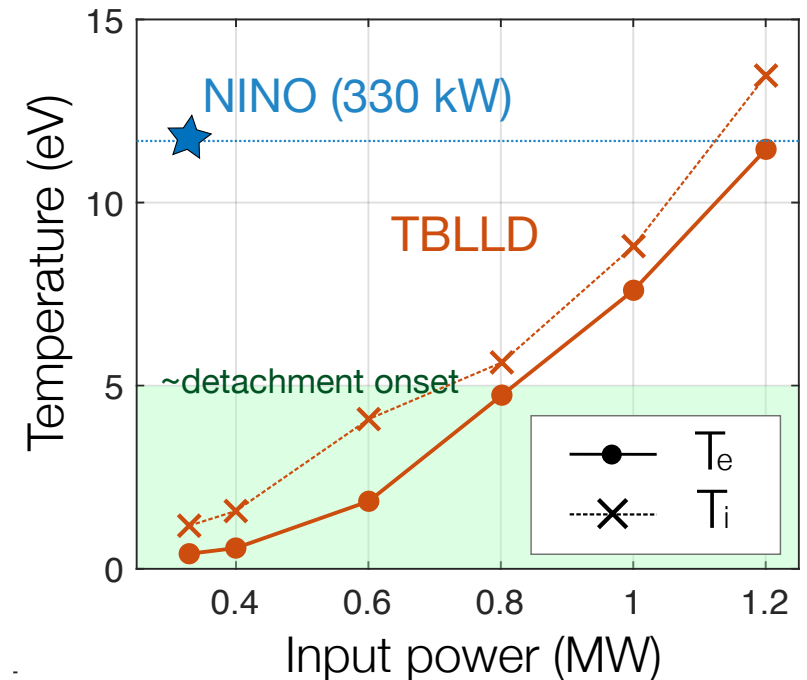


The TBLLD upgrade: predictive studies show significant improvements in the power exhaust performance



First SOLPS-ITER simulations of the finalised TBLLD geometry.

- Outer target **temperature x10 lower** compared to unbaffled TCV at the same input power.
- TBLLD geometry has same outer target conditions as unbaffled geometry, injecting **x4 power**



H. Reimerdes, "Implementation of a Tightly Baffled Long-Legged Divertor in TCV" - **WED, 14:00, this conference**

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Conclusions and perspectives

Significant step forward on edge-code validation and optimisation using TCV controlled experiments

- Controlled **experimental databases** are crucial for code validation: highlight the **role of mid-size tokamaks** in producing these databases
- Large databases of reliable and validated simulations allow us to assess when **reduced models** are sufficient and when **higher-order effects** should be included





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Next...

- Extend the validation to **H-mode** scenarios in TCV
- Move to **wide-grid** to include far-SOL dynamics and main-chamber plasma-wall n



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