Scoping studies for the divertor design in optimized stellarators

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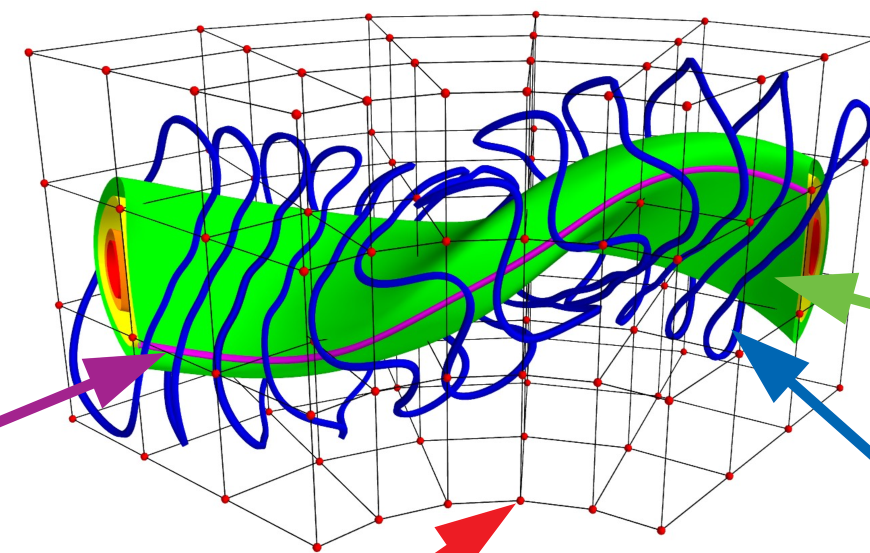
Introduction

- Control of particle and energy exhaust is essential for successful operation of next step magnetic confinement devices
- Presently, however, even a post-processing approach is not well established in stellarator optimization
- Development of reliable tool chain for assessment of divertor performance is ongoing

Toolchain for divertor load analysis:



Targets for equilibrium optimization (ROSE)

- Quasi symmetry (at s = 0.6)
- Energetic particle confinement (γ_c at s = 0.2, 0.4, 0.6)
- Presence of magnetic well
- Constraint $\varepsilon_{eff} < 0.01$

Alternative: STELLOPT

VMEC equilibrium

- 121 surfaces

→ Invited Talk by A. Bader & Poster by J. Schmitt

Coil implementation (FOCUS) initialized from REGCOIL with offset 22 cm

- Minimum coil to plasma (VMEC) boundary separation: 19 cm

→ Posters by L. Singh & T. Kruger

Vector potential on cylindrical grid (BMW)

- Volume integral over currents in VMEC domain
- Mesh resolution: 192 x 192 x 65

→ **combine information inside and outside LCFS**

Field Line Analysis (FLARE)

- 3D B-Spline based interpolation of vector potential
- Field line tracing (numerical integration of ODE):

$$\frac{dR}{d\varphi} = R\,\frac{B_R}{B_\varphi} \qquad \frac{dZ}{d\varphi} = R\,\frac{B_Z}{B_\varphi}$$

- Diffusion of field lines (optional) after trace step Δs

$$\Delta_{RZ} = \sqrt{4\,\mathcal{D}\,\Delta s}, \qquad \mathcal{D} = D_\perp / v_{th,i}$$

→ **initial scoping studies** for divertor design based on offset surfaces from VMEC boundary

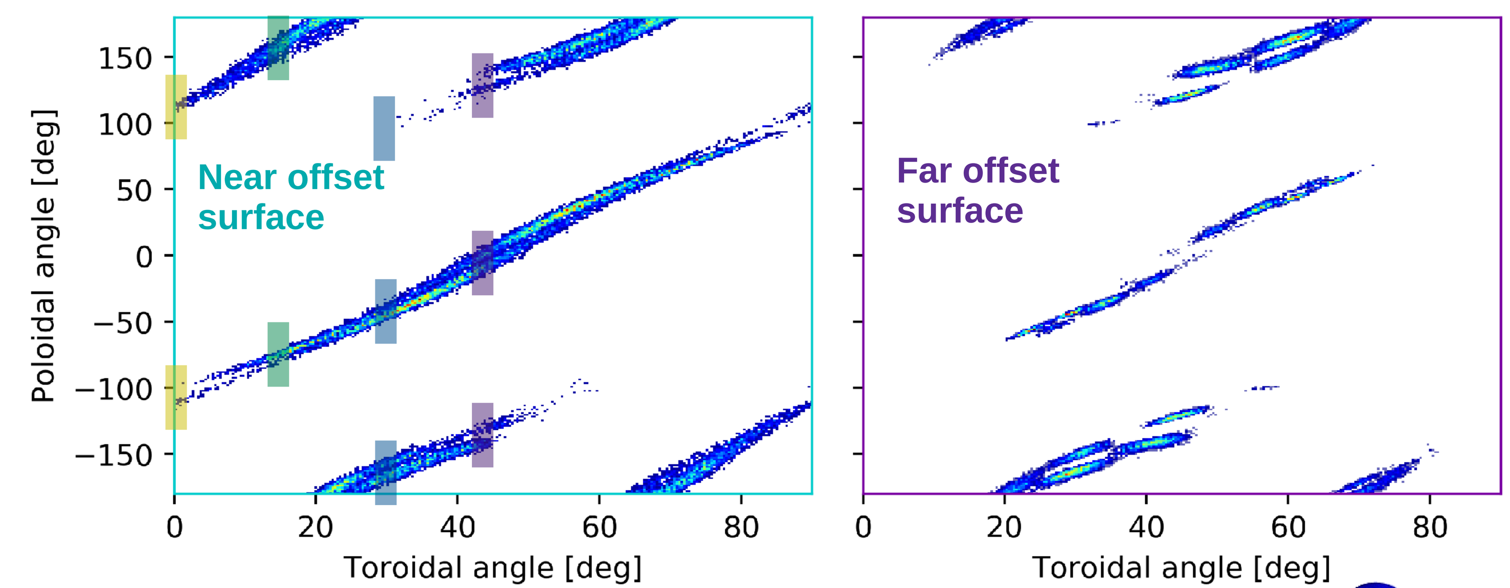
- Generate 3D finite flux tube mesh for fast **reconstruction** of field lines in transport codes:
  - Step 1: Identify inner simulation boundary from Poincaré plots
  - Step 2: Generate (quasi-orthogonal) base mesh(s) at selected toroidal positions
  - Step 3: Trace field lines to generate 3D mesh

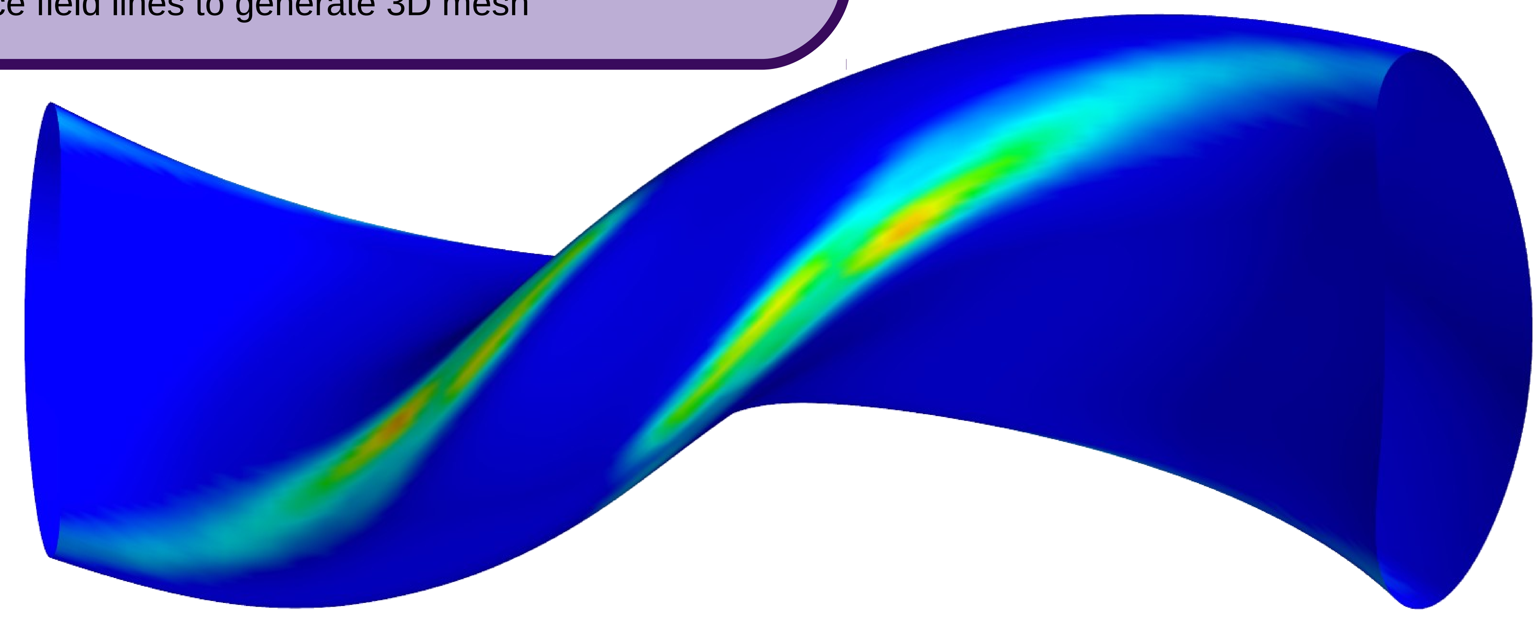
Field line strike maps identify "helical troughs"

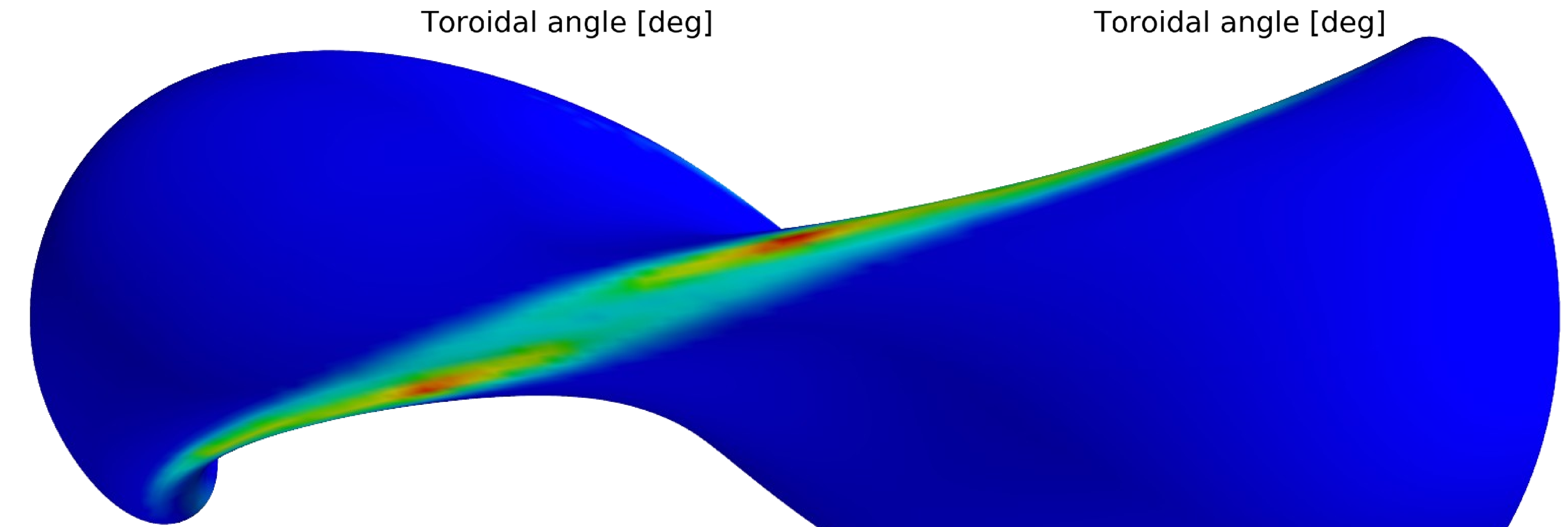
[E. Strumberger, Contrib. Plasma Phys. **32** (1992) 212]

Resilient edge properties facilitate non-resonant divertors

[A. Bader et al., Phys. Plasmas **24**, 032506 (2017)]







Plasma boundary modeling (EMC3-EIRENE)

- Steady state balance equations for main plasma species:

Particles:

$$\nabla\cdot\left[n u_\parallel \mathbf{e}_\parallel - D_\perp \mathbf{e}_\perp \mathbf{e}_\perp \cdot \nabla n\right] = S_p$$

Parallel momentum:

$$\nabla\cdot\left[m_i n {u_\parallel}^2 \mathbf{e}_\parallel - \eta_\parallel \mathbf{e}_\parallel \mathbf{e}_\parallel \cdot \nabla u_\parallel - D_\perp \mathbf{e}_\perp \mathbf{e}_\perp \cdot \nabla\left(m_i n u_\parallel\right)\right] = -\mathbf{e}_\parallel \cdot \nabla n \left(T_e + T_i\right) + S_m$$

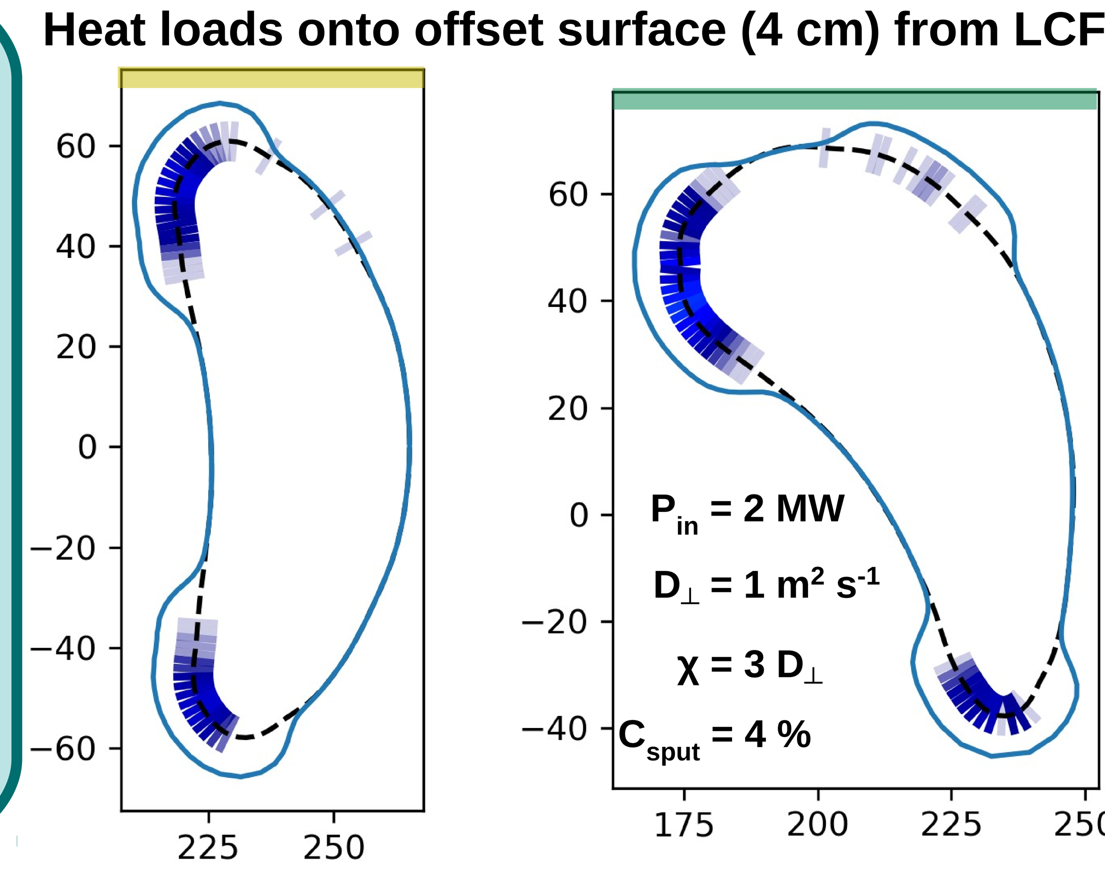
Energy:

$$\nabla\cdot\left[\frac{5}{2} T_e \left(n u_\parallel \mathbf{e}_\parallel - D_\perp \mathbf{e}_\perp \mathbf{e}_\perp \cdot \nabla n\right) - \left(\kappa_e \mathbf{e}_\parallel \mathbf{e}_\parallel + \chi_e n \mathbf{e}_\perp \mathbf{e}_\perp\right)\cdot \nabla T_e\right] = +k\left(T_i - T_e\right) + S_{ee} + S_e^{(\mathrm{cool})}$$

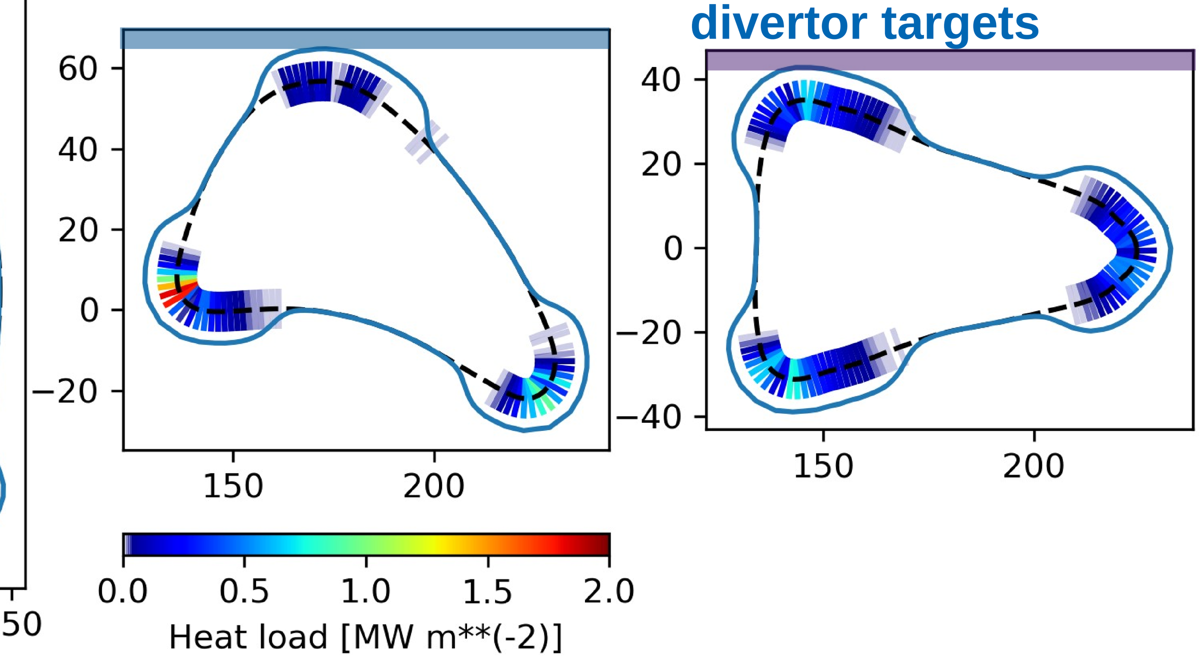
$$\nabla\cdot\left[\frac{5}{2} T_i \left(n u_\parallel \mathbf{e}_\parallel - D_\perp \mathbf{e}_\perp \mathbf{e}_\perp \cdot \nabla n\right) - \left(\kappa_i \mathbf{e}_\parallel \mathbf{e}_\parallel + \chi_i n \mathbf{e}_\perp \mathbf{e}_\perp\right)\cdot \nabla T_i\right] = -k\left(T_i - T_e\right) + S_{ei}$$

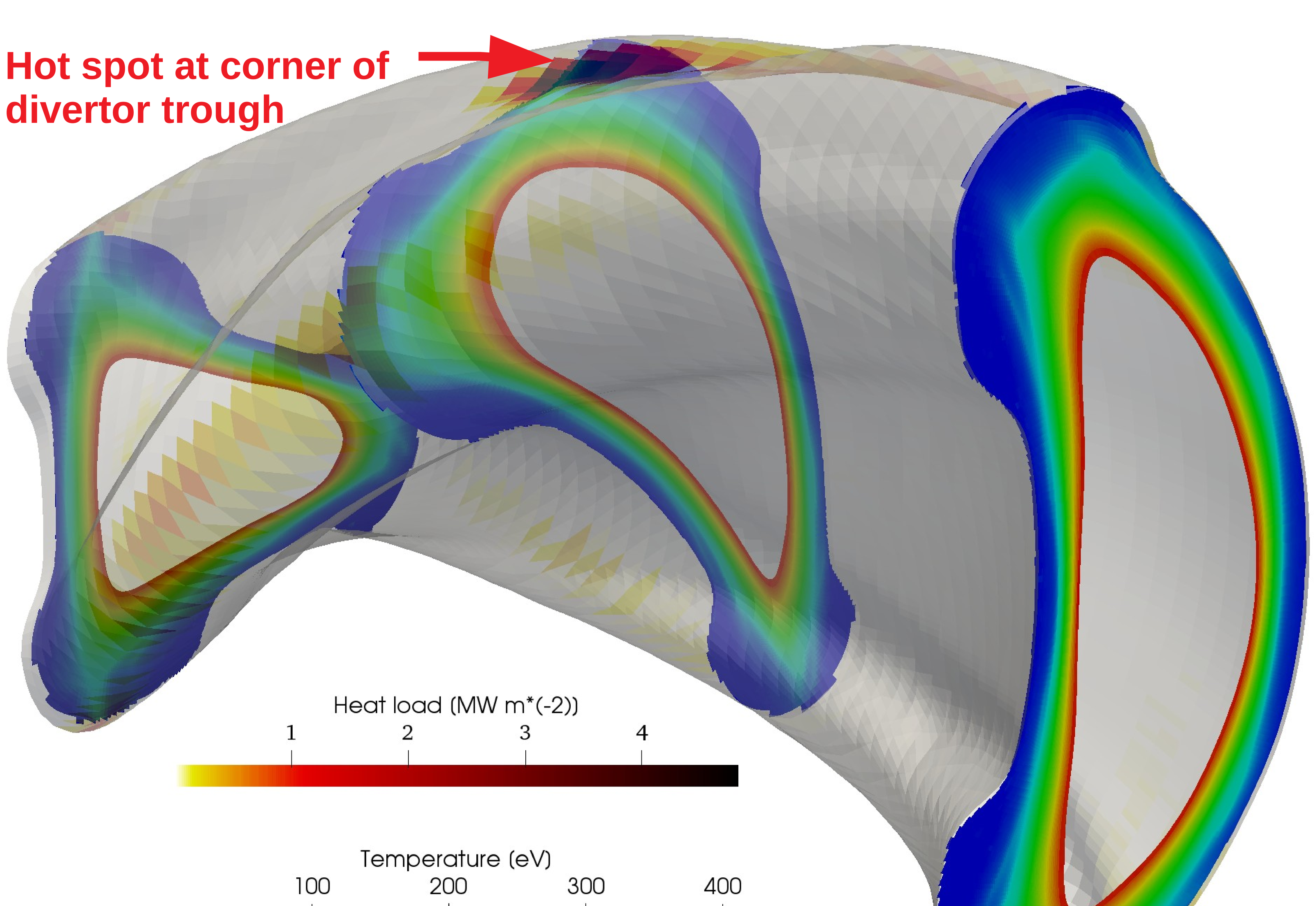
- Trace impurities (Carbon) affect the main plasma by cooling of electrons
- Iteration between edge plasma (EMC3) and neutral gas solver (EIRENE) required for self-consistent simulations

Heat loads onto offset surface (4 cm) from LCFS confirm helical troughs

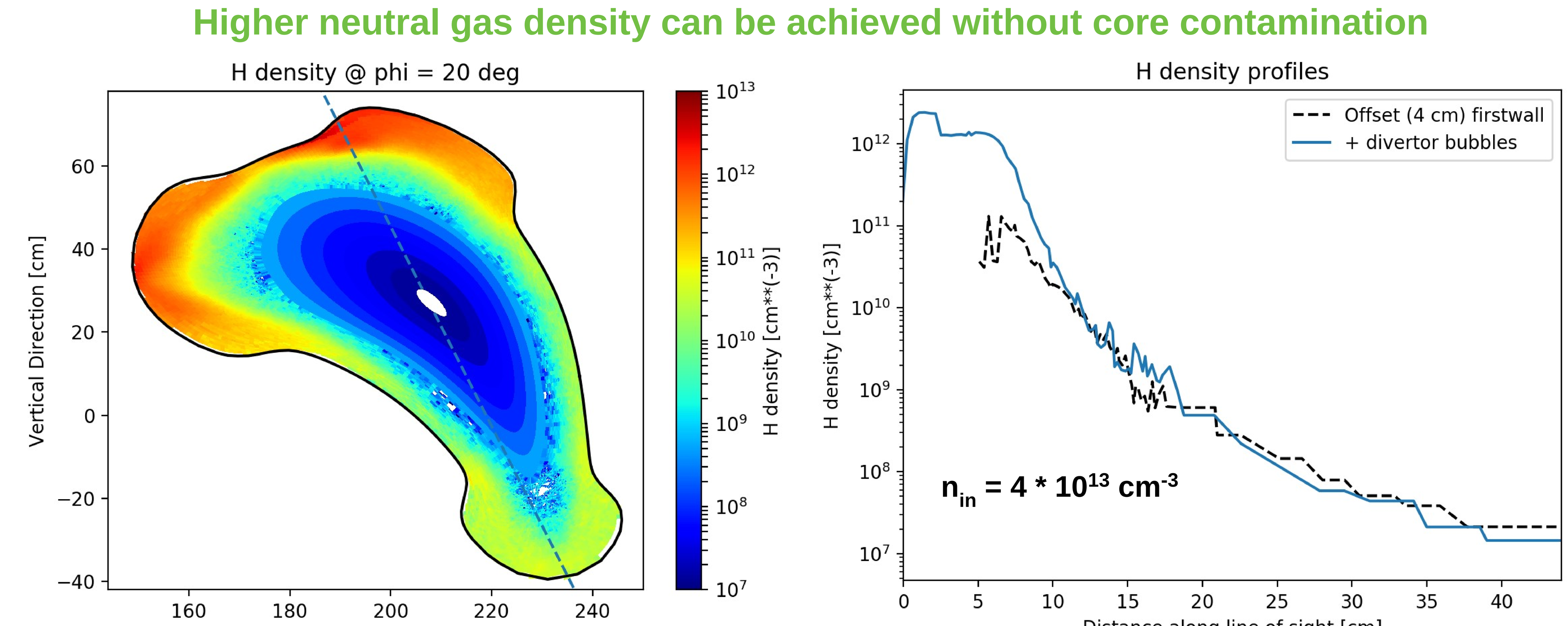


Construct bubble around helical troughs for divertor targets





Higher neutral gas density can be achieved without core contamination



Outlook

- Optimize divertor bubble and include target plates for smoother distribution of heat loads
- Baffles may further increase neutral gas compression
- Density scan for evaluation of high recycling and detachment access

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