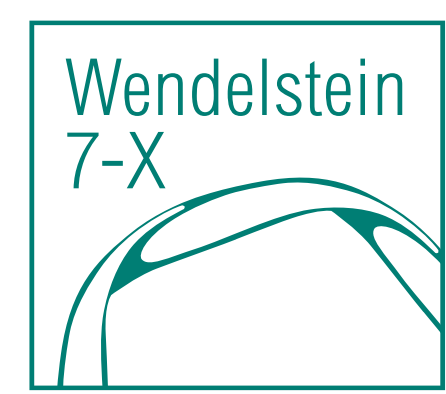


Understanding the 3D island divertor with a simplified model

N. Maaziz^{*1}, F. Reimold¹, V. R. Winters¹, S. Makarov¹, Y. Feng¹, and the W7-X Team^a

¹Max Planck Institute for Plasma Physics, 17491 Greifswald, Germany

^aSee O. Grulke et al 2026 Nucl. Fusion 66 116003



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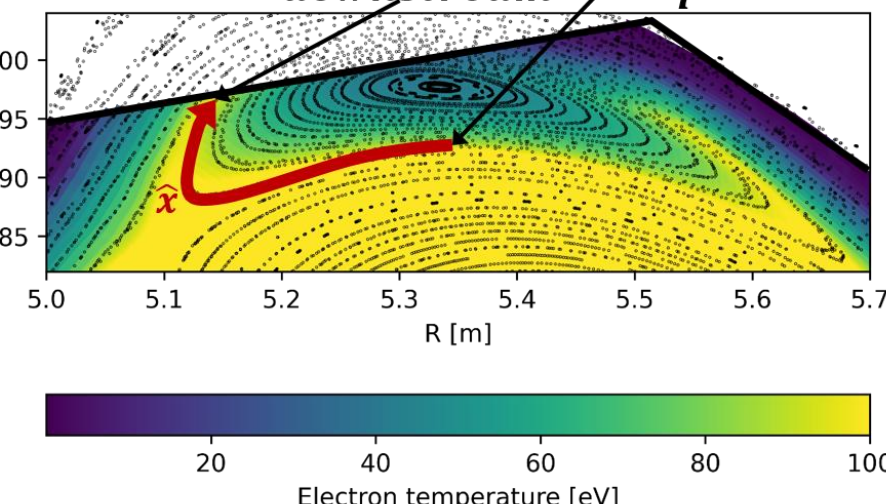
INTRODUCTION

Wendelstein 7-X (W7-X) has shown improved core performances in comparison to previous machines. However, **exhaust capabilities** remain **limited** (e.g., low **neutral pressures** $p_{n,max} \approx 0.2$ Pa). W7-X employs the **island divertor** concept, relying on magnetic islands to divert heat and particles towards targets. Increasing **density build-up** in the island divertor is required to prove **reactor-relevance** of the concept. The analysis of **3D SOLs** is challenging: **complex topologies** (e.g., target shadow region **TSR**), increased importance of **perpendicular transport** (lower field line pitch Θ). **Simplified models** are attractive: allowing to gain **understanding** and focus on **leading order** physics. Understanding **assumptions** and **limits** is crucial.

1. EXTENDED STELLARATOR TWO-POINT MODEL

0D model relating **upstream** and **downstream** quantities: [1]

- Energy: $\Theta \frac{d}{dx} \left(-\kappa_{e,i} T_{e,i}^{5/2} \Theta \frac{dT_{e,i}}{dx} \right) + \frac{d}{dx} \left(-\chi_{e,i} n \frac{dT_{e,i}}{dx} \right) = 0$
 - Pressure: $\Theta \frac{d}{dx} \left(n v_{i\parallel}^2 + \frac{p}{m_i} \right) = S_{mom}$
 - Boundary: $q_{\parallel} = \gamma n_d c_{sd} T_d$ **binormal $\perp$ transport**
- Integration and extension gives: [2]
- $T_u^{7/2} = T_d^{7/2} + \frac{7(1-f_{conv})q_{\parallel}L_C}{2\kappa_e} - \frac{7\chi(n_u+n_d)}{4\kappa_e\Theta^2} (T_u - T_d)$ f_{conv} : convected power fraction
 - $p_u = \frac{2p_d}{1-f_{mom}}$ f_{mom} : a general momentum losses parametrization
 - $q_{\parallel} = \frac{\gamma n_d c_{sd} T_d}{1-f_{cool}}$ f_{cool} : a target-localized dissipated power fraction



Assumes: i) toroidal symmetry ii) equivalence of parallel and binormal transport

2. RECYCLING REGIMES

Recycling regimes observed in tokamaks:

- **Sheath-limited** regime ($T_d \sim T_u$, $n_d \propto \frac{1}{2} n_u$)
- **Conduction-limited** regime ($T_d \propto n_u^{-2}$, $n_d \propto n_u^3$)

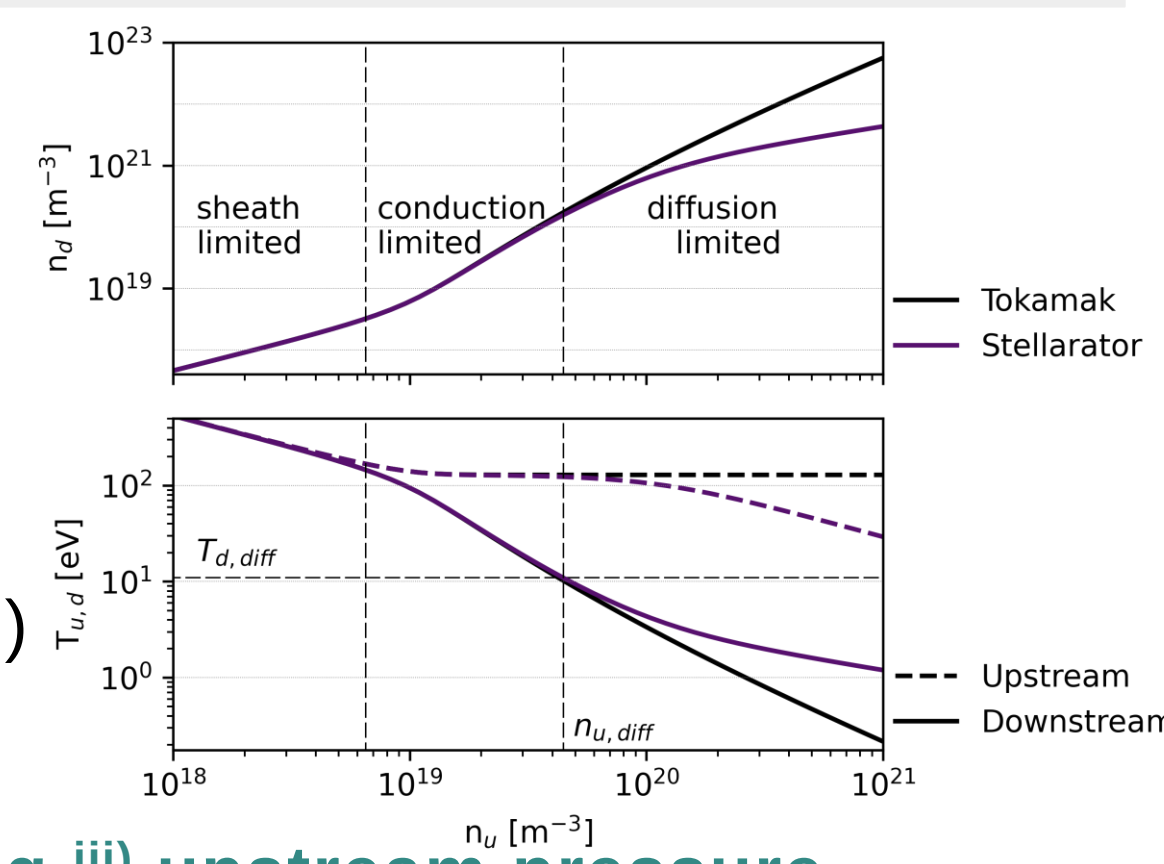
A regime specific to **stellarators**:

- **Diffusion-limited** regime (weaker scaling with n_u)

Binormal perpendicular diffusion dominates scaling

Detrimental for: i) density build-up ii) target cooling iii) upstream pressure

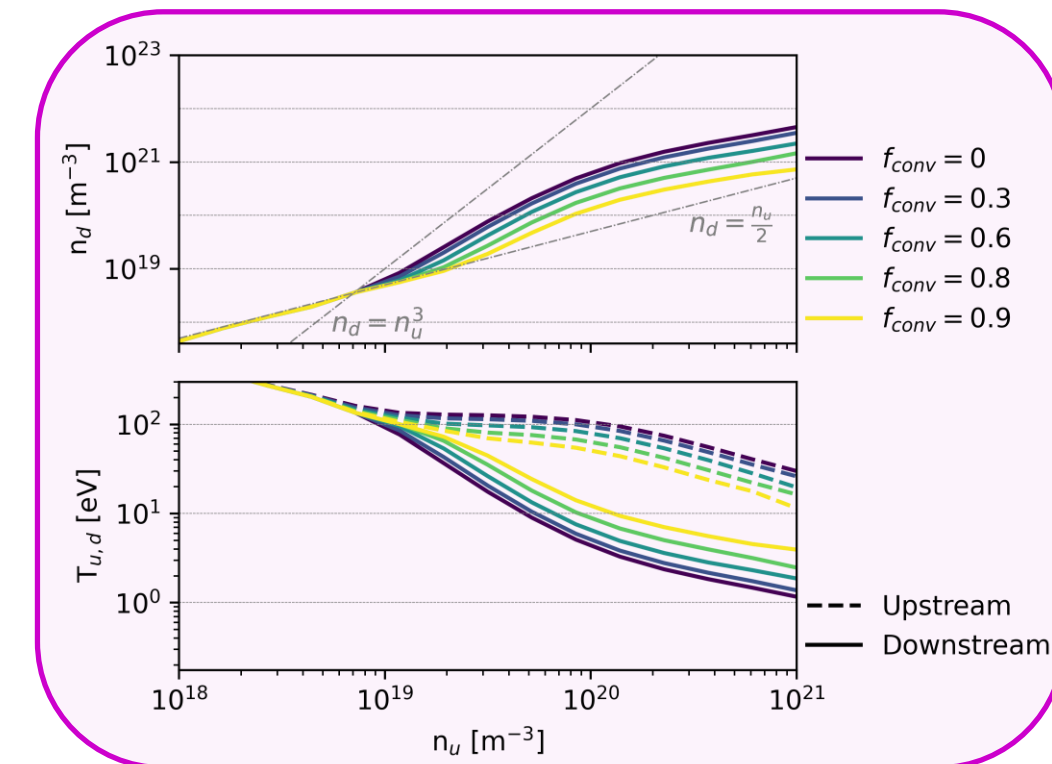
Transition temperature into **diffusion-limited** is $T_{d,diff} = T_u - \xi_{diff} \frac{2\Theta^2(1-f_{conv})q_{\parallel}L_C}{\chi(n_{u,diff}+n_d)}$



3. PARAMETER SENSITIVITY

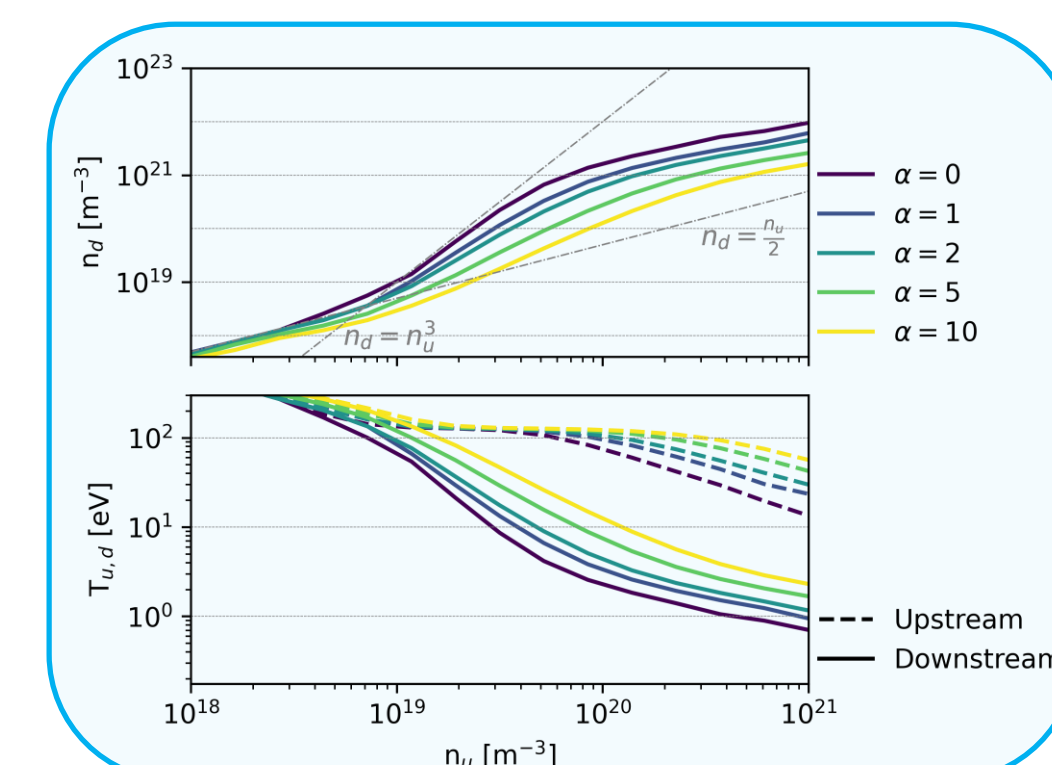
Convected power fraction f_{conv} :

- Increased f_{conv} reduces density build-up
- Limits temperature gradient ($T_u - T_d$):
 - Hinders target cooling
 - Saturates upstream pressure
- Conduction-limited regime weakened
- Larger $T_{d,diff}$, start of diffusion-limited regime



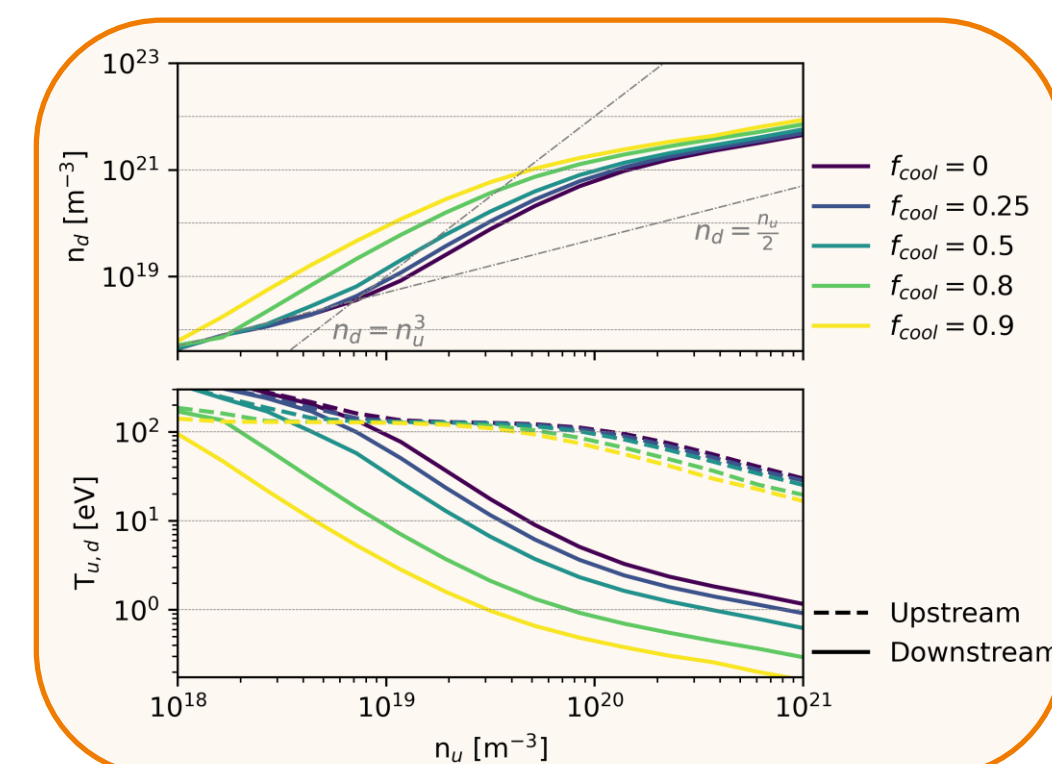
Momentum losses f_{mom} :

- Scan α , strength for $1 - f_{mom} = \left(1 + \frac{\alpha}{T_d}\right)^{-1}$ [3,4]
- Increasing α degrades conduction-limited regime
- Transition to diffusion-limited regime unchanged
- Mostly shifts parameters to higher n_u
- Largely depends on the parametrization



Target-localized dissipated power fraction f_{cool} :

- Increased f_{cool} beneficial for density build-up
- Conduction-limited regime transition earlier in n_u
- Positive impact of f_{cool} saturates at large n_u
- Lower $T_{d,diff}$ (due to lower $n_{u,diff}$)
- Important: detachment expected for $f_{cool} \geq 0.5$



4. EMC3-EIRENE TWO-POINT MODEL FORMATTING

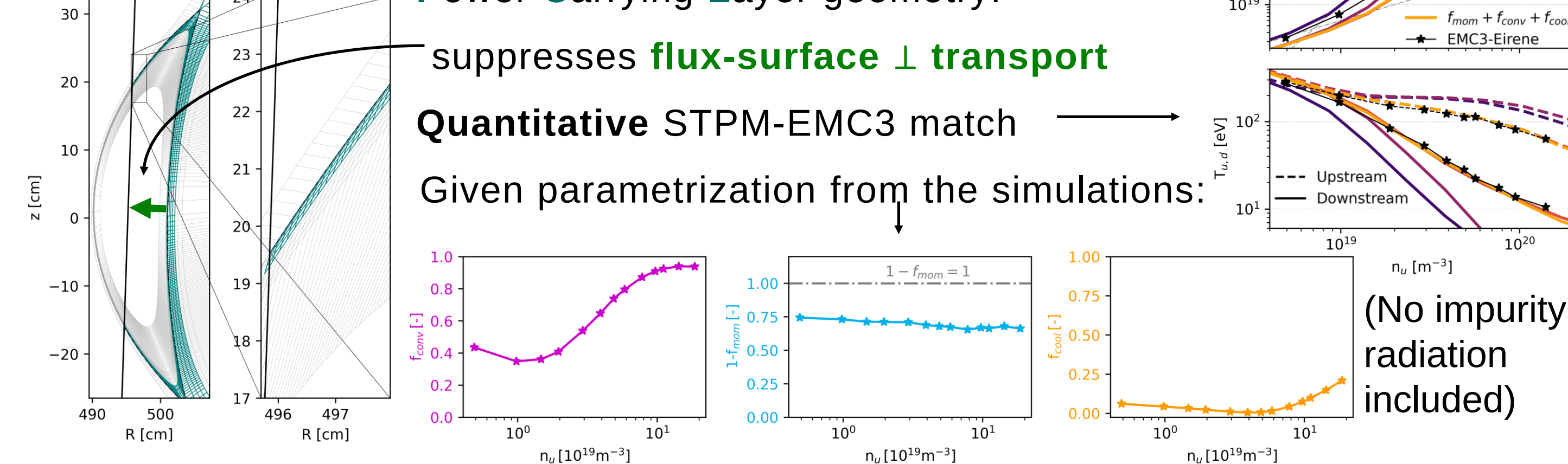
EMC3-Eirene: 3D fluid plasma (without drifts) with kinetic neutrals

PCL geometry — Power Carrying Layer geometry:

suppresses **flux-surface $\perp$ transport**

Quantitative STPM-EMC3 match

Given parametrization from the simulations:



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October 6th-9th

*Corresponding author:
nassim.maaziz@ipp.mpg.de

5. 3D EFFECTS IN PCL GEOMETRY

I. Target-induced abrupt parallel profile variations:

Toroidally discontinuous target $\rightarrow$ localized particle sources

Causing abrupt features in parallel profiles:

- T_i profile non-monotonic: **ionization losses**
- Spike in p_{dyn} / Drop in p_{stat} : **flow-driven**
- n_i slow increase, then sharp drop: **pressure conserved prior to ⁽²⁾ then not $\rightarrow \perp$ transport dominant**

Effect strong at final passage ⁽²⁾ due to larger s_p ($\delta \sim 3.5$ cm):

low T (large gradient required) and large n (large $\perp$ transport)

II. Perpendicular transport into TSR

Vicinity of TSR with large density

$\rightarrow$ perpendicular transport

TSR transport scan, depletion strength $\rightarrow$

Some target effect scales with TSR transport:

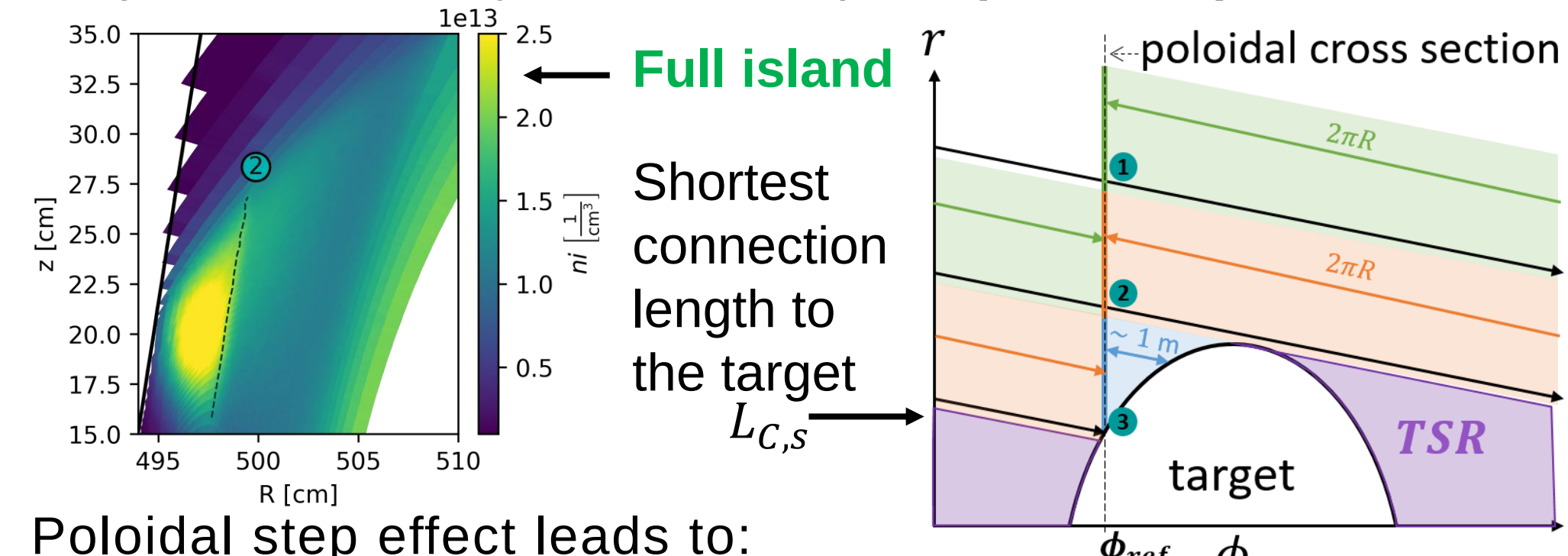
- n_i increase, p_{stat} drop, and T_i dip independent of transport strength
- For similar s_p , larger drop for p_{stat} and $n_i \rightarrow$ TSR transport effect

Magnitude of pressure and density drop related to $\perp$ transport into TSR

$\supset$ Further quantitative analysis left for future work

III. Steps in shortest connection length to target

Target discontinuity leads to steps in **poloidal profiles**:



Poloidal step effect leads to:

- Strong gradient at step drives $\perp$ transport $\rightarrow$ flattens step
- Drifts flows along interface, redistributing heat/particles (not in EMC3)

Larger step at final passage because of large parallel gradients near the target

Challenges interpretation of W7-X measurements and requires validation

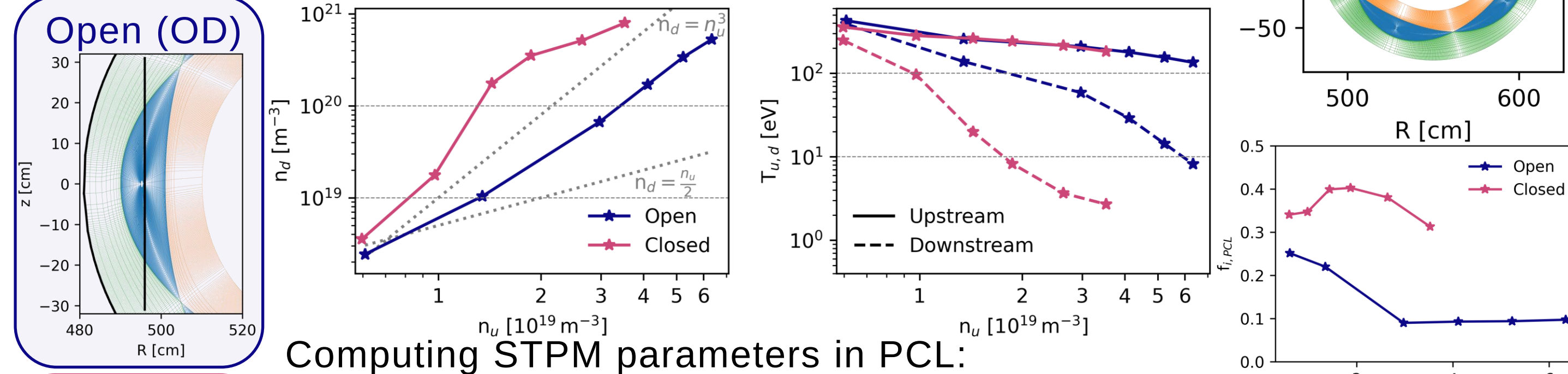
6. APPLICATION TO 3D SOL

Full HaGrid geometry (Hamiltonian Grid [5]), includes both

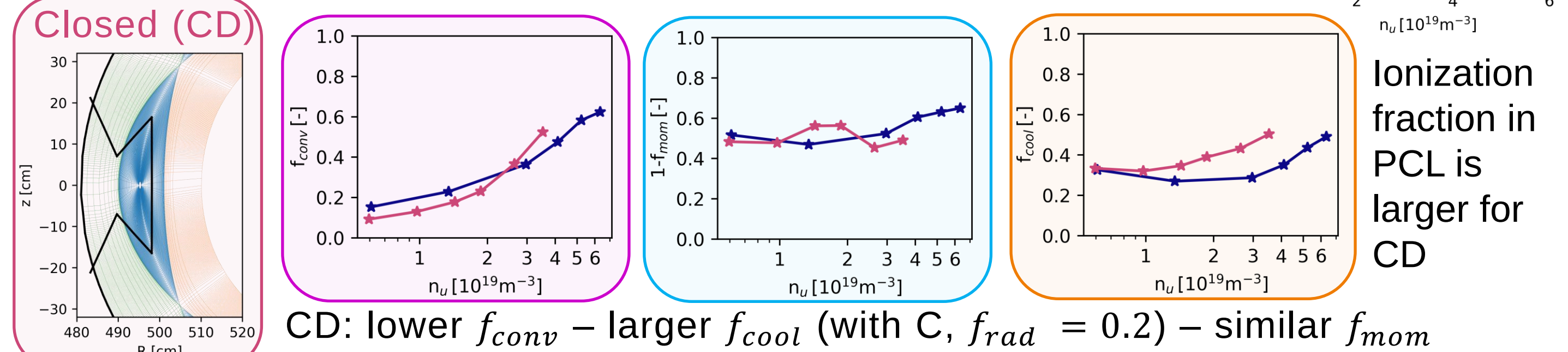
$\perp$ transport directions: i) **binormal** ii) **flux-surface perpendicular**

Targets:

Larger density build-up for closed divertor:



Computing STPM parameters in PCL:



CD: lower f_{conv} – larger f_{cool} (with C, $f_{rad} = 0.2$) – similar f_{mom}

Increased exhaust efficiency via neutrals access to cold private flux region

CONCLUSION

- Simplified models help understanding leading order physics of complex 3D SOL
- Extension of stellarator two-point model allows for two-point model formatting
- 3D effects arise from discontinuous target, requiring experimental validation
- Closed divertor improves density build-up via ionization in power-carrying layer
- Reduced convection – Increased target cooling – Similar momentum losses
- Increased particle exhaust efficiency but power exhaust efficiency to be assessed

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