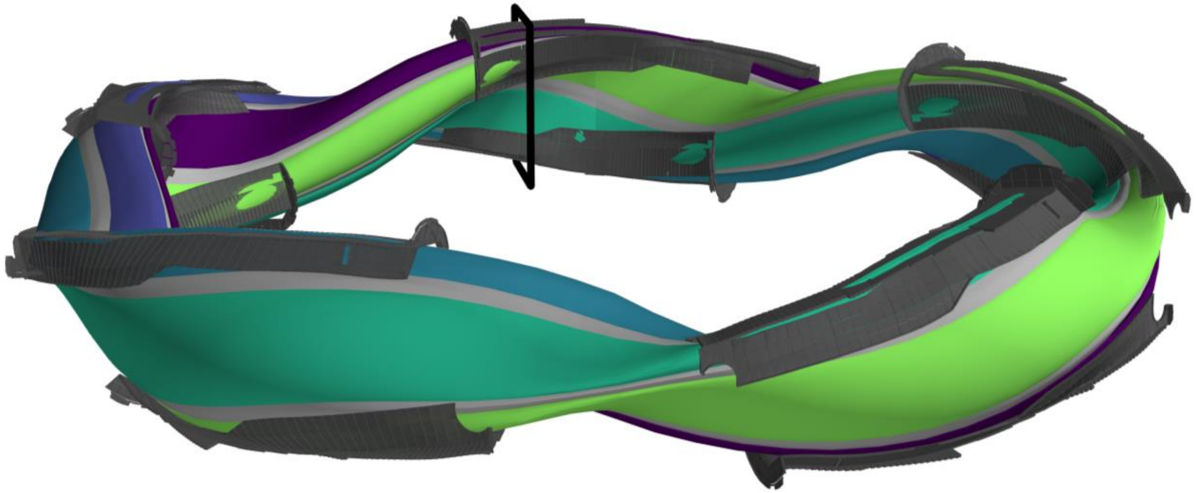
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Impurity transport in the W7-X island SOL using EMC3-Eirene

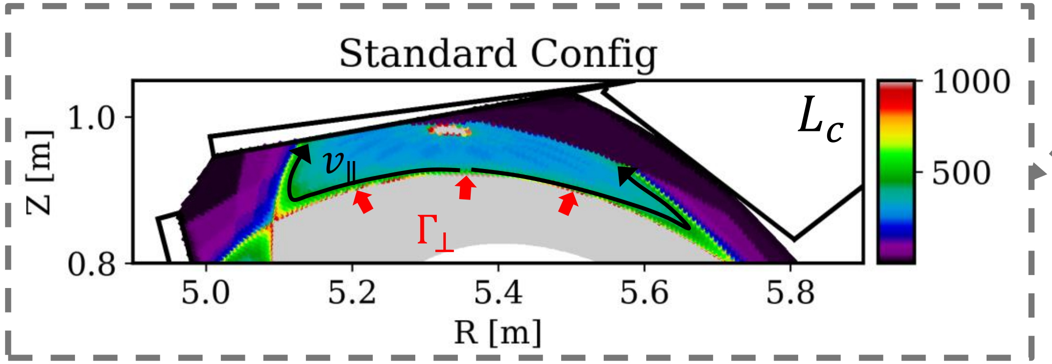
Victoria R. Winters

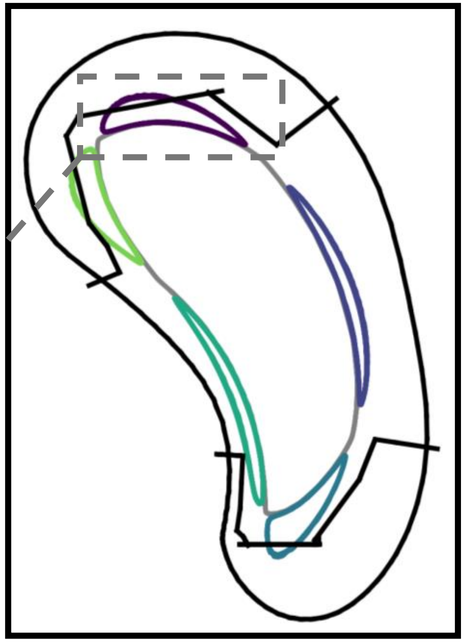
The island divertor: A promising candidate for a future stellarator reactor divertor?



Requirements for a reactor divertor:

- Stable detachment[1,2] (with impurity seeding[3])
- Sufficient impurity retention in SOL
- Helium compression/exhaust





[1] O. Schmitz et al, *Nucl. Fusion* **61** (2021) 016026
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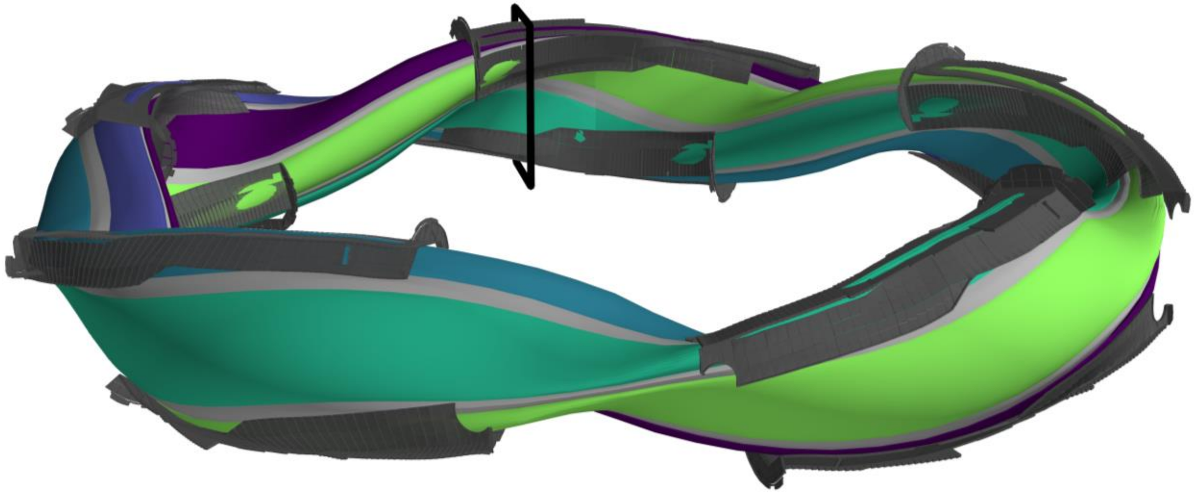

Requirements for a reactor divertor:

- Stable detachment[1,2] (with impurity seeding[3])
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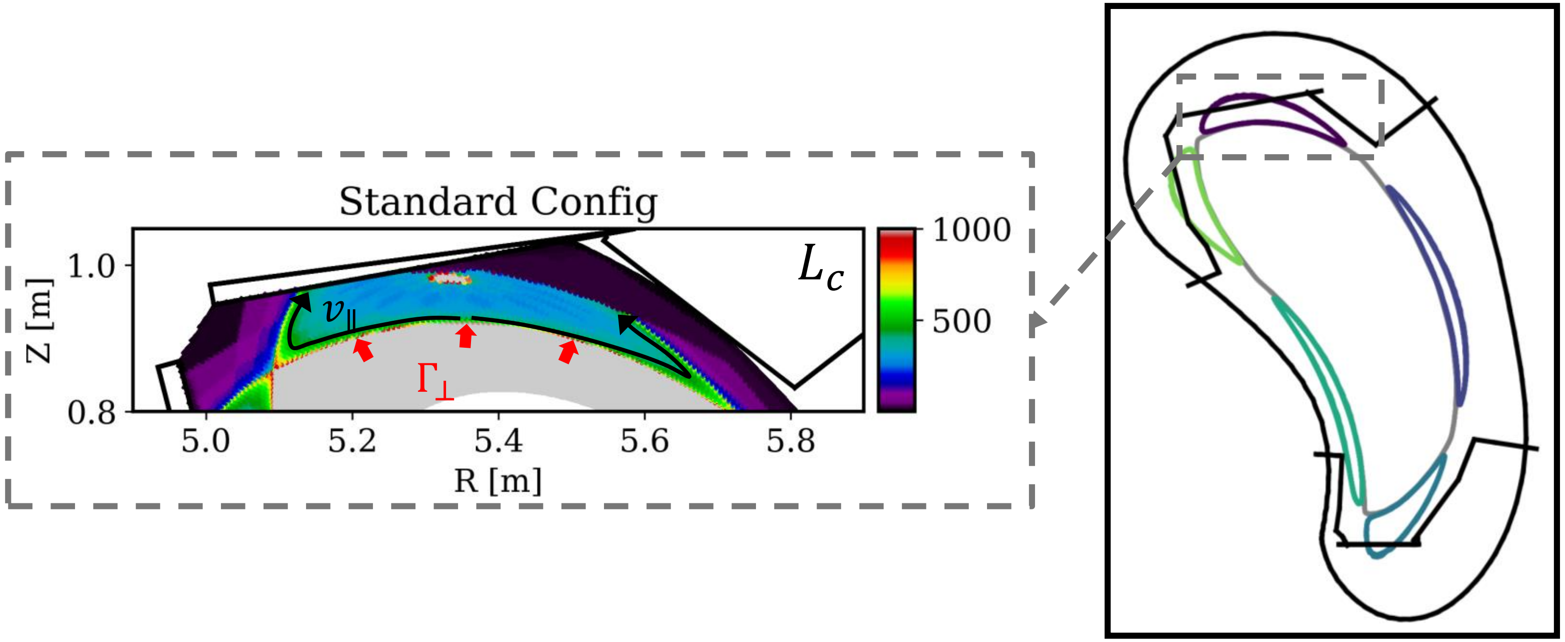
Many of these requirements depend on the SOL impurity transport!



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Impurity transport in a tokamak vs island divertor

In a tokamak, transport parallel to $\vec{B}$ is the dominant impurity leakage pathway[4,5]

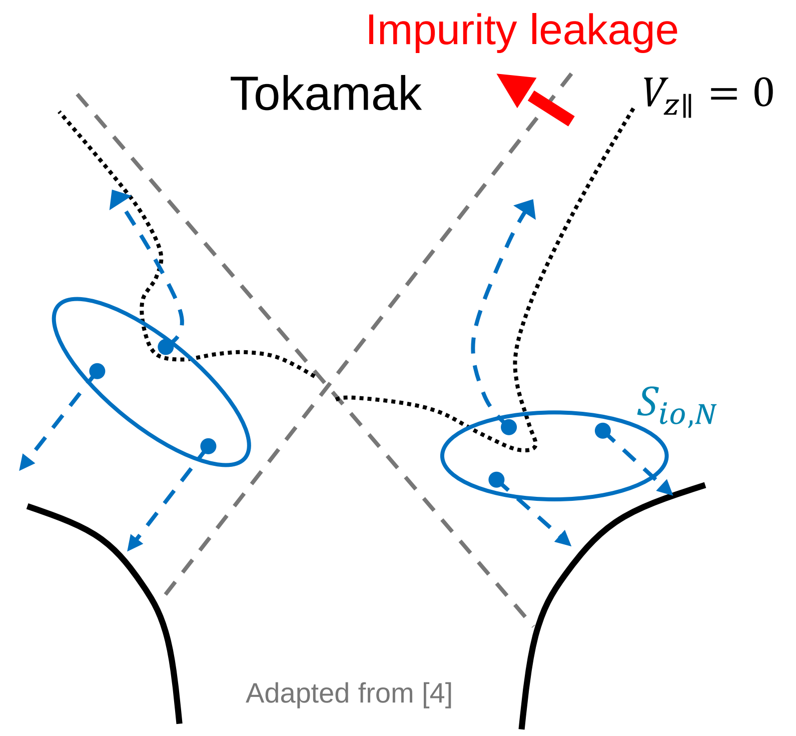
- Caused by impurity ionization beyond the impurity poloidal flow stagnation point[4,5]

- In the absence of drifts, large $\nabla_{\parallel} T_i$ leads to upstream impurity flow[4]

$$V_{z\parallel} = V_{i\parallel} + \frac{\tau_s}{m_z}\left[\beta_i \frac{\mathrm{d}T_i}{\mathrm{d}s} + \alpha_e \frac{\mathrm{d}T_e}{\mathrm{d}s} + ZeE_{\parallel} - \frac{1}{n_z}\frac{\mathrm{d}p_z}{\mathrm{d}s}\right]$$

Flow towards targets

Flow towards LCFS



Adapted from [4]

[4] I. Y. Senichenkov et al, *Plasma Phys. Control. Fusion* **61** (2019) 045013
[5] P. C. Stangeby et al, *Nucl. Fusion* **60** (2020) 106005
[6] Y. Feng et al, *Nucl. Fusion* **49** (2009) 095002
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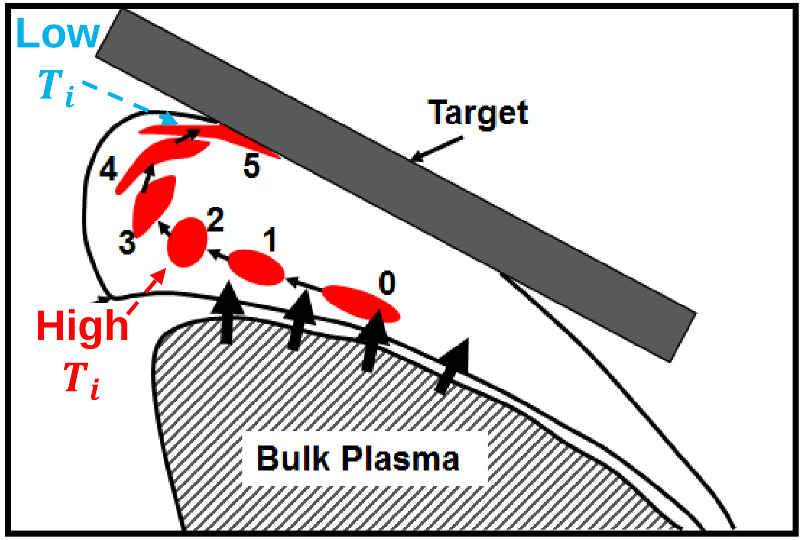
In a stellarator island divertor, ⊥- transport plays a larger role, even reducing the effects of parallel transport[6]

- Binormal transport within flux tubes flattens $\nabla_{\parallel} T_i$[6]



[8] König et al, *Plasma Phys. Control. Fusion* **44** (2002)

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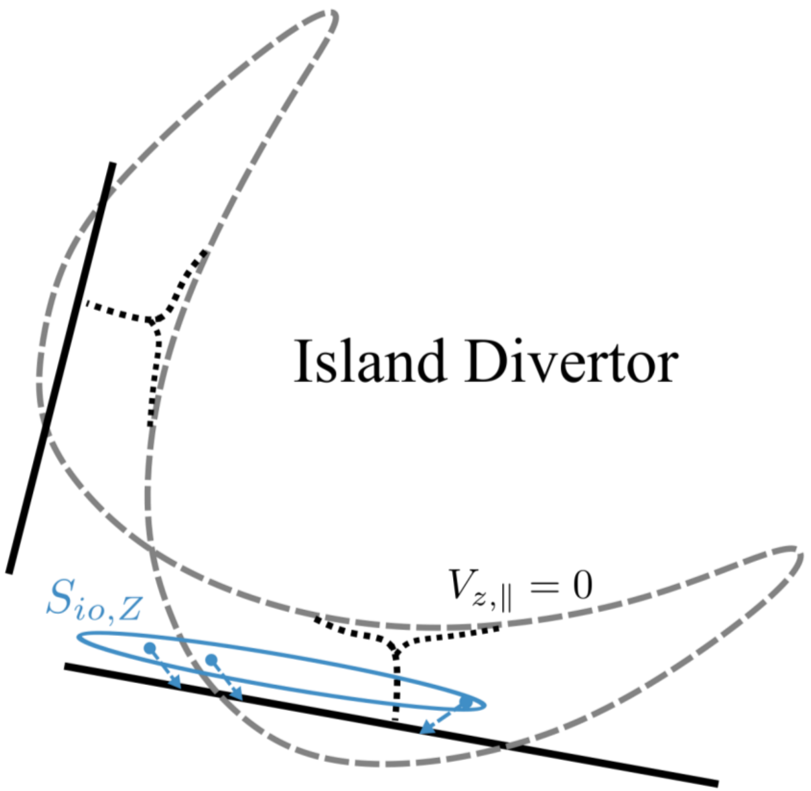
In a stellarator island divertor, ⊥- transport plays a larger role, even reducing the effects of parallel transport[6]

- Binormal transport within flux tubes flattens $\nabla_{\parallel} T_i$[6]
- Consequently, impurities flow towards the target over the majority of the island SOL[6,7]
- The dominant impurity leakage pathway is likely different to tokamaks[7]



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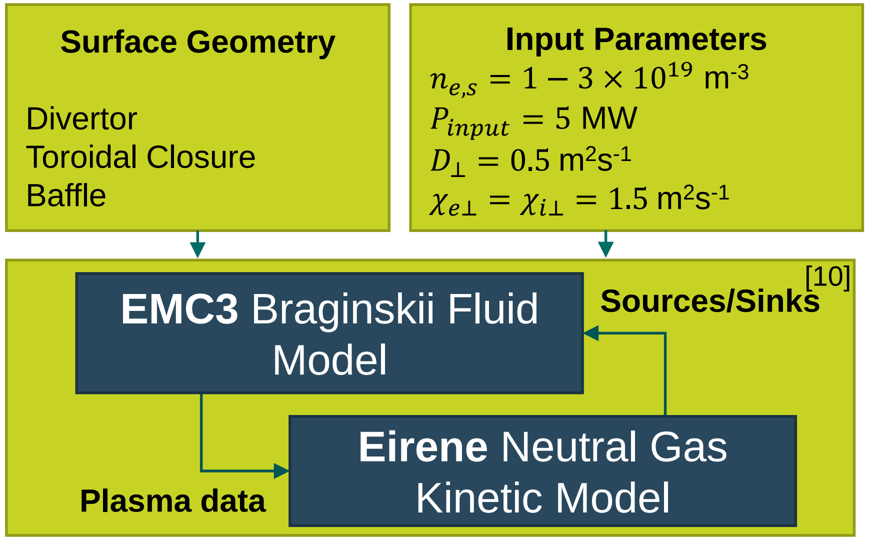
Using EMC3-Eirene to understand the dominant impurity leakage pathway

- Solves 3D plasma/neutral background in steady-state[9]
- Impurity transport parallel to $\vec{B}$ given by[11]:

$$V_{z\parallel} = V_{i\parallel} + \frac{\tau_s}{m_z}\left[(\beta_i - 1)\frac{\mathrm{d}T_i}{\mathrm{d}s} + \alpha_e\frac{\mathrm{d}T_e}{\mathrm{d}s} + ZeE_\parallel - \frac{T_i}{n_z}\frac{\mathrm{d}n_z}{\mathrm{d}s}\right]$$

- Transport perpendicular to $\vec{B}$ anomalous, $D_{Z,\perp} = D_{i\perp}$
- Simulations in **standard configuration**, with radiation from carbon
- On a **fixed plasma background,** effects of parallel and perpendicular impurity transport studied for carbon, nitrogen, neon, and helium



[9] Y. Feng et al, *Contrib. Plasma Phys.* **54** (2014) 426-431
[10] H. Frerichs et al, *Nuclear Materials and Energy* **18** (2019) 62-66
[11] P. C. Stangeby, *Plasma Boundary of Magnetic Fusion Devices* (2000)

Ion thermal force confirmed to have little to no effect on the plasma background

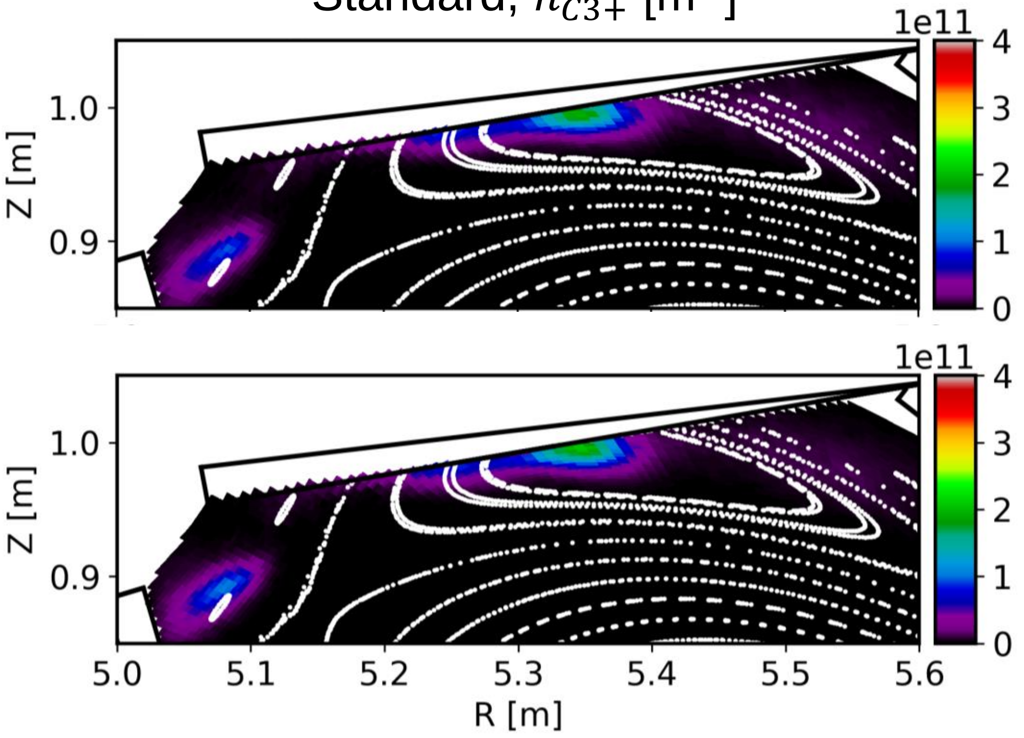
$n_{ibs} = 3 \times 10^{19}$ m^{-3}

- No significant ion thermal force – entire SOL is in a friction dominated regime

Standard, n_{C3+} [m^{-3}]

w/ ion thermal force

w/o ion thermal force



<u>Total carbon separatrix density</u>

- With ion thermal force: 1.4e17
- Without ion thermal force: 1.2e17
- Differences on the order of 10%

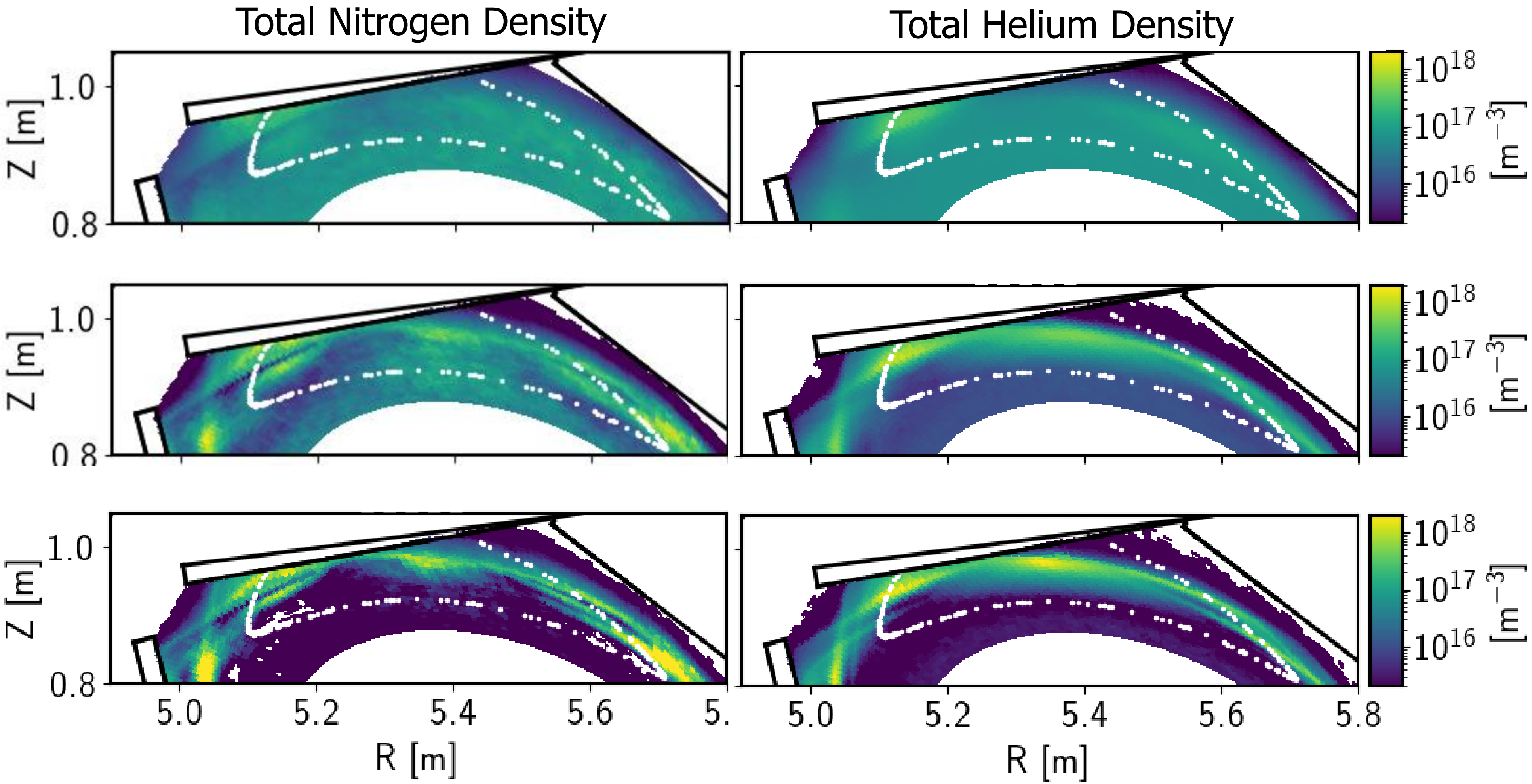
D_z scan on fixed plasma background shows perpendicular transport dominates impurity leakage

$n_{e,s} = 1 \times 10^{19}$ m^{-3} → $\bar{n}_{li} = 4 \times 10^{19}$ m^{-2}

$D_z = 0.5$ m^{2}s^{-1}

$D_z = 0.01$ m^{2}s^{-1}

$D_z = 0.001$ m^{2}s^{-1}



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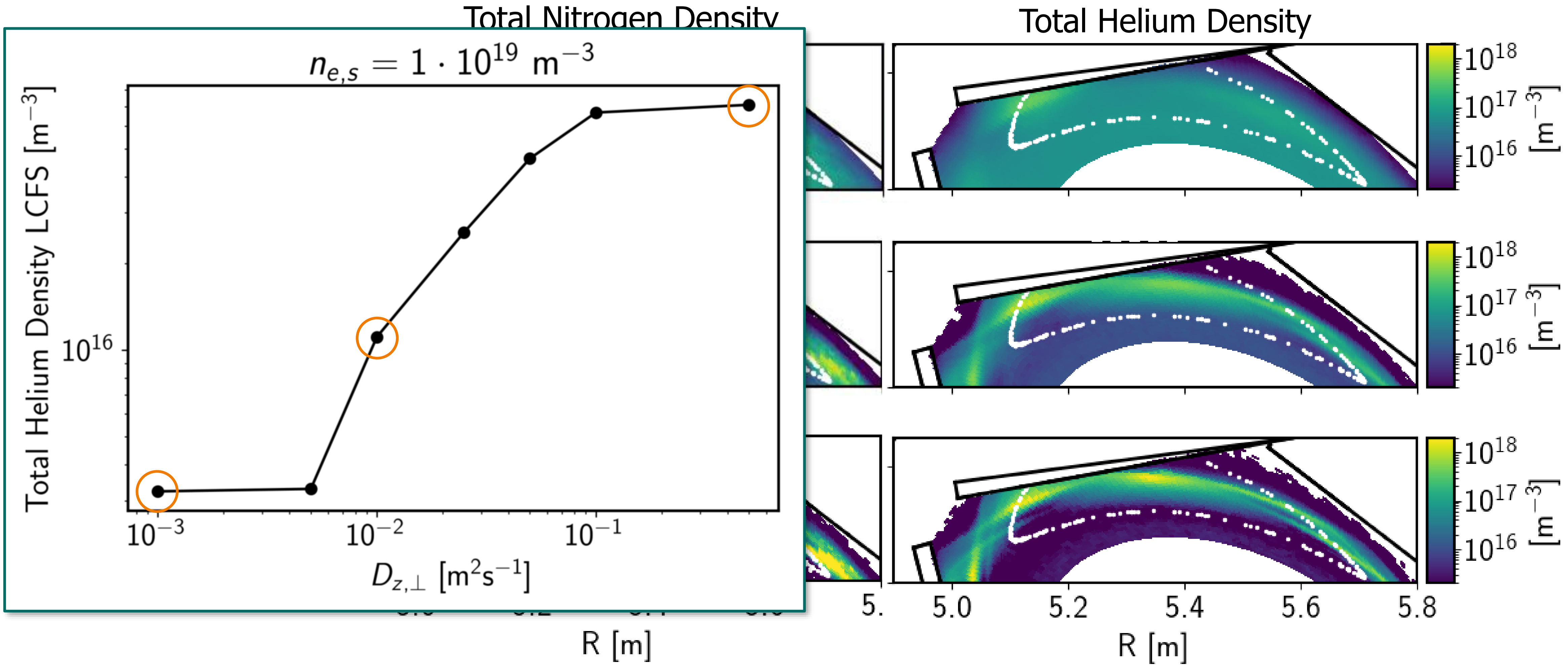

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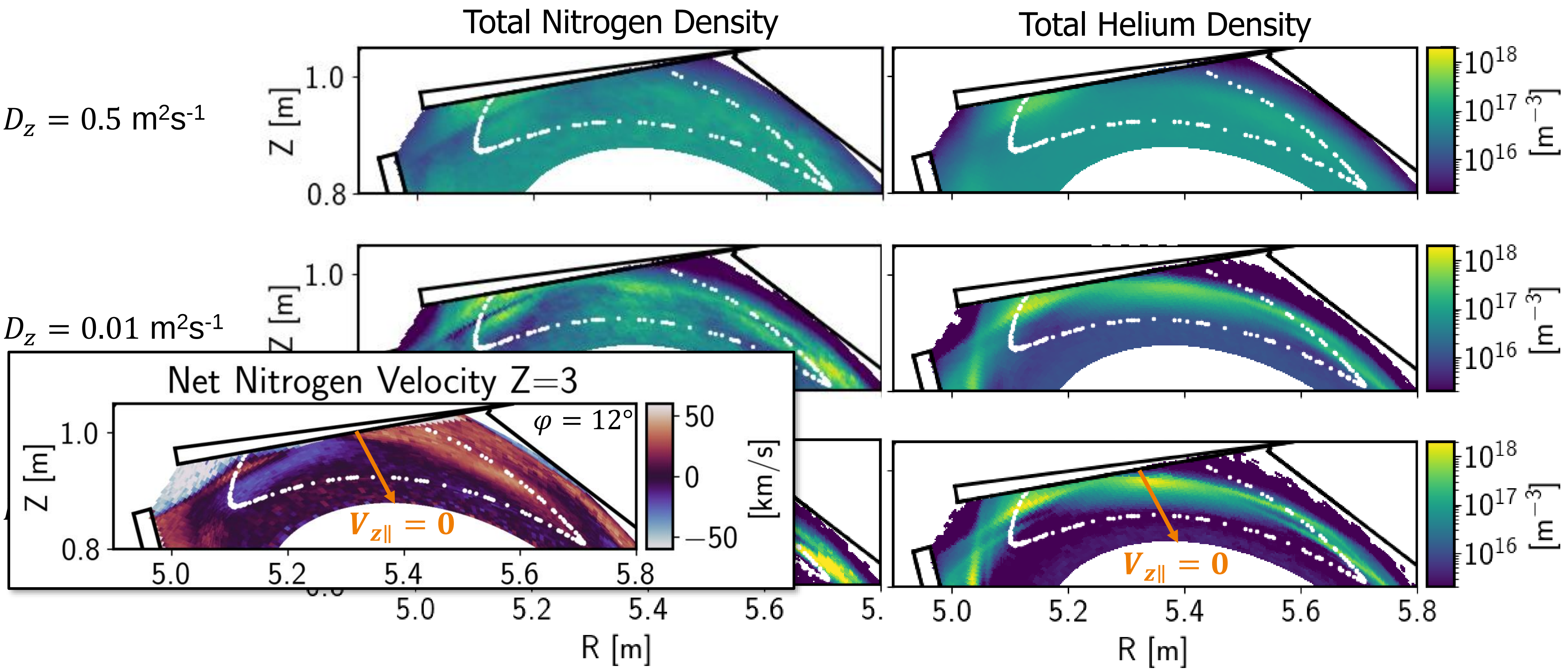
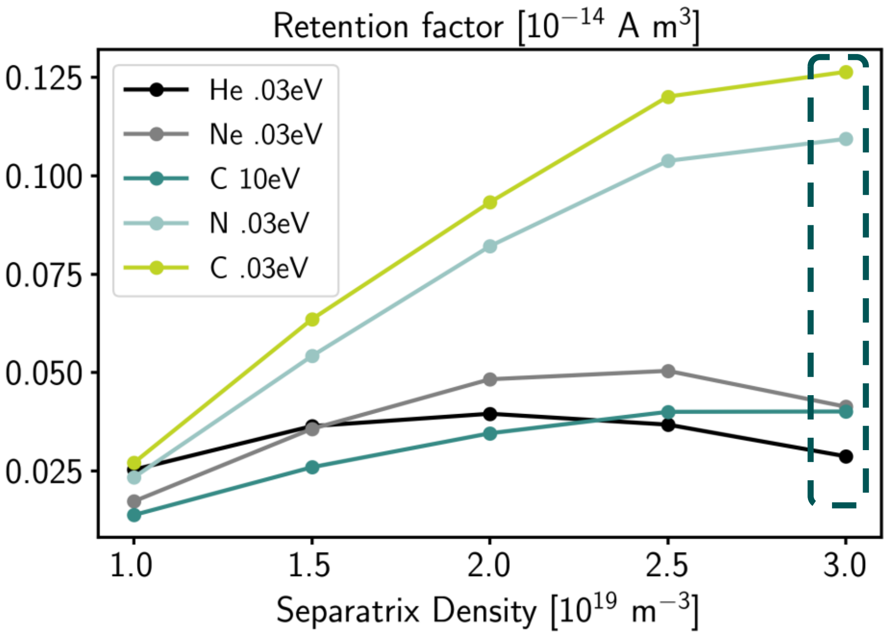
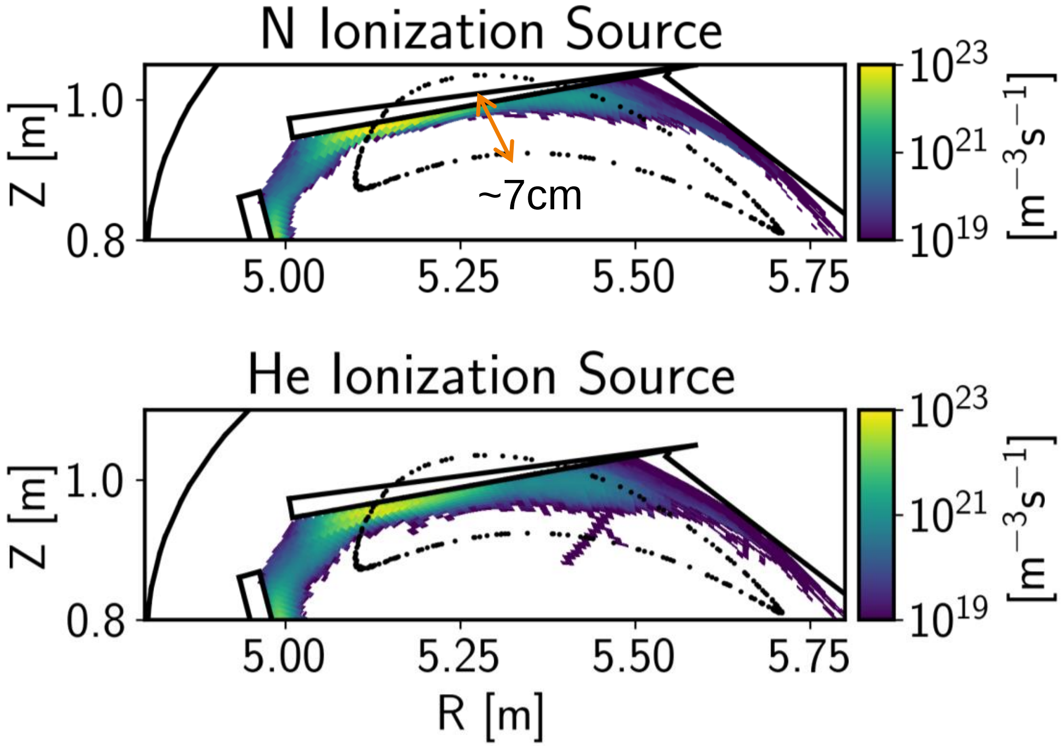


[7] V. R. Winters et al, *Nucl. Fusion* (submitted)

Ionization source changes plays a role in retention by bringing impurity ionization closer to the LCFS/island O-Point

- Outward/inward radial movement of source is an accurate indicator for when retention improves/degrades
- Inward movement of source → less geometrical distance to LCFS → lower retention

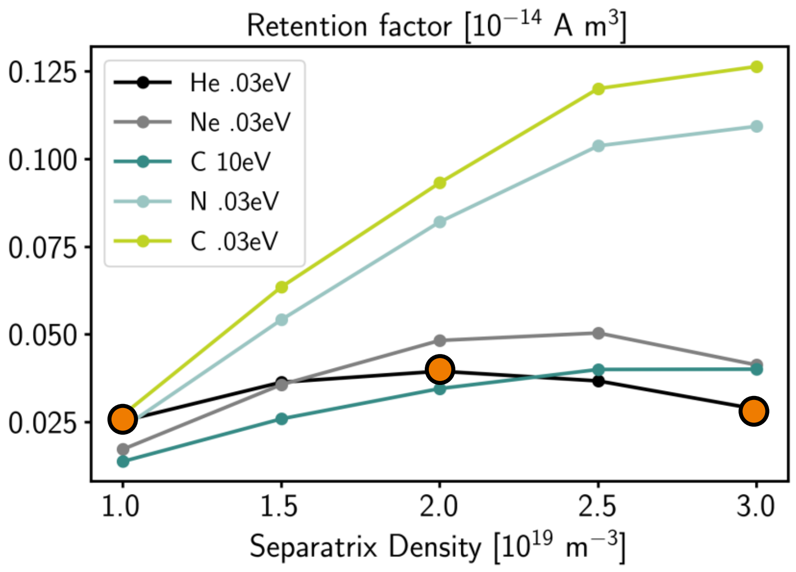


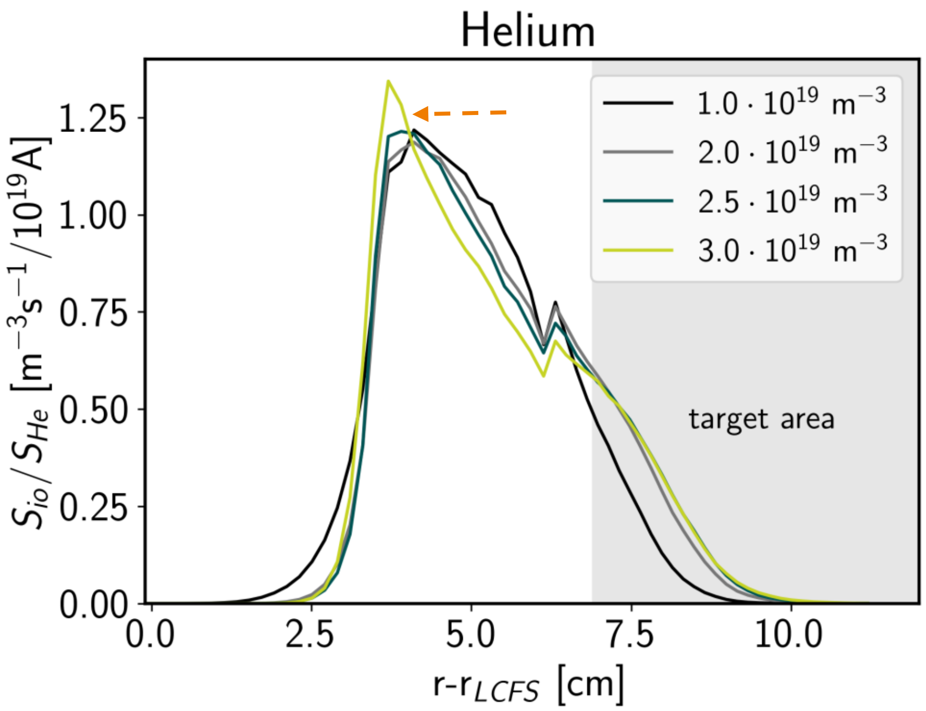


[4] V. R. Winters et al, *Nucl. Fusion* (submitted)

Ionization source changes follows well the differences in observed impurity retention

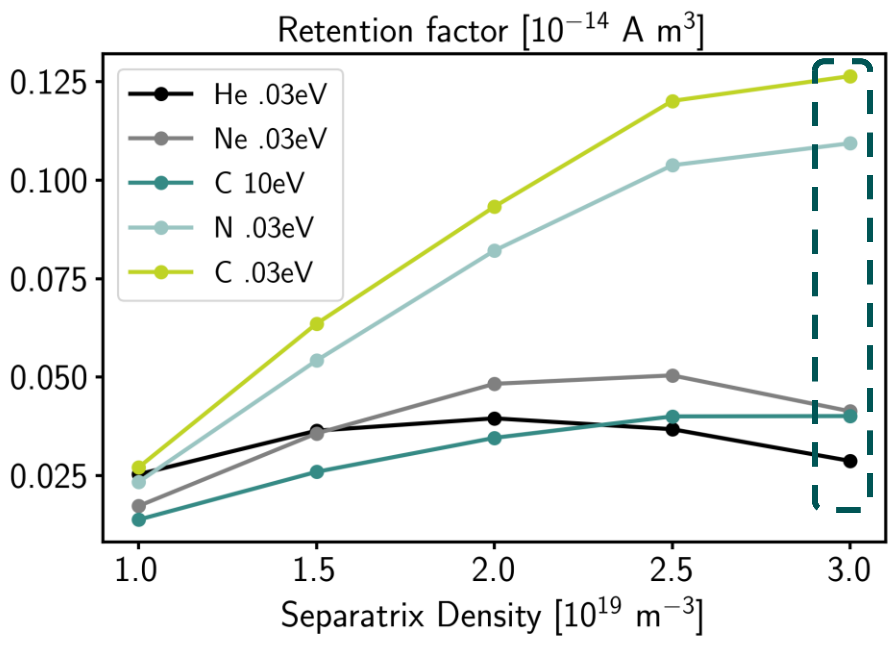
- Radial profile of impurity ionization source shows different movement with increasing $n_{e,sep}$ depending on the species
- Outward/inward radial movement of source is an accurate indicator for when retention improves/degrades
- Inward movement of source → less geometrical distance to LCFS → lower retention

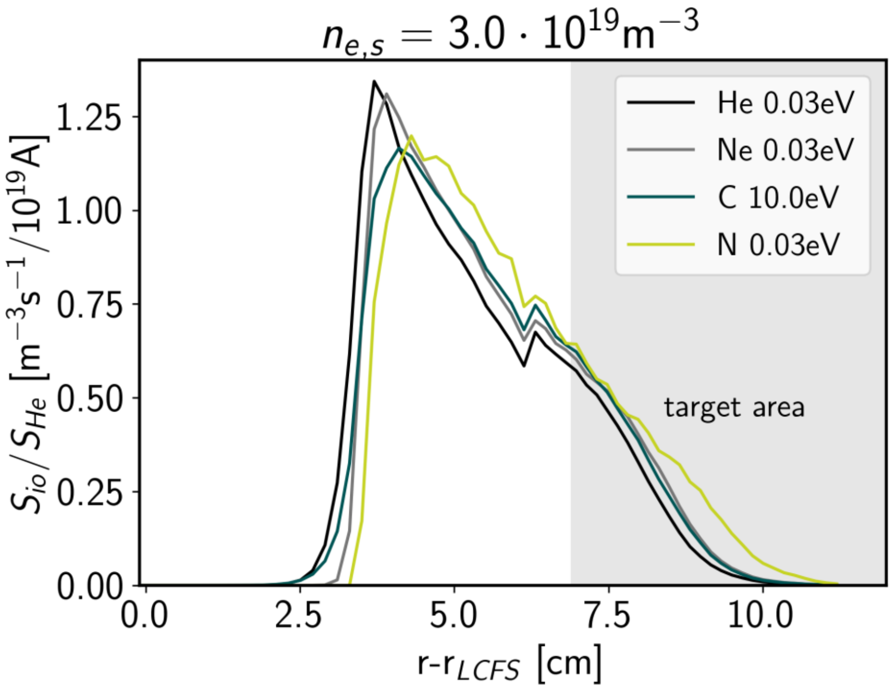




Ionization source changes follows well the differences in observed impurity retention

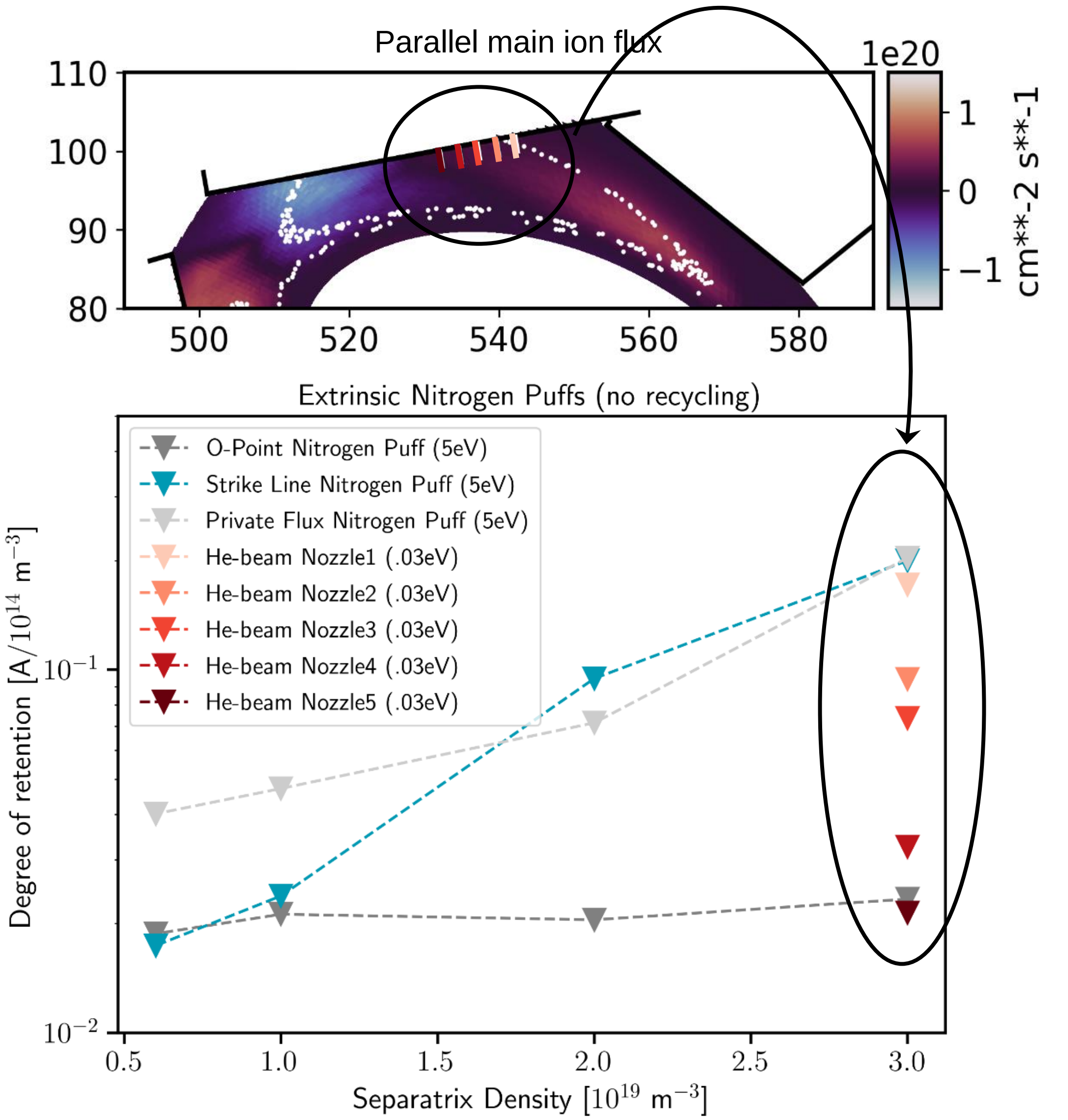
- The retention factor also shows consistent behavior between species – Helium is ionized furthest upstream while Nitrogen is ionized furthest downstream





How can we test this in experiment?

- Impurity retention picture may change depending on impurity seeding valve
- First experiments performed in OP2.1



[12] Y. Feng et al, *Nucl. Fusion* **56** (2016) 126011

So, what knobs can we turn to minimize impurity leakage in a future reactor island divertor?

Tuning the island size

- Increasing island size could improve impurity retention[12]

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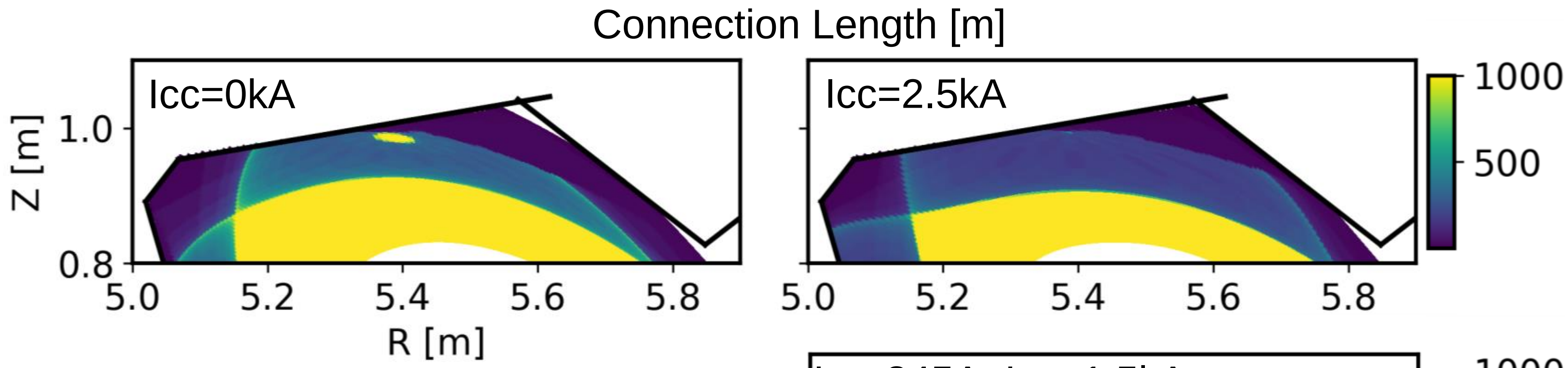
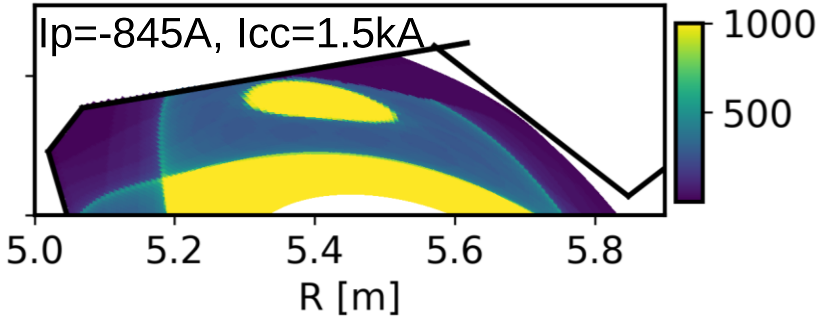
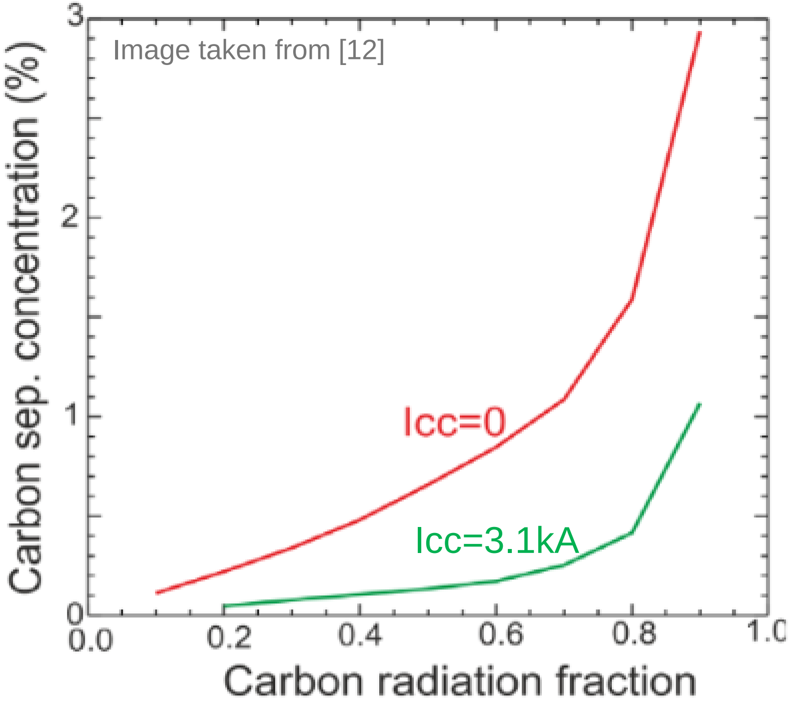


(confined island size can have an effect on the impurity retention as well[12])





Both configurations to be tested in this current experimental phase!

[12] Y. Feng et al, *Nucl. Fusion* **56** (2016) 126011

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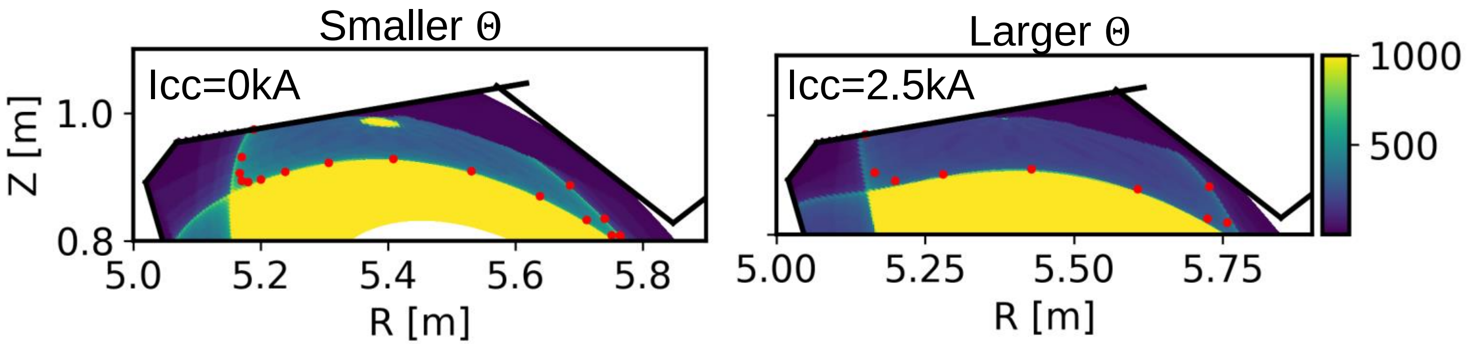
Tuning island rotational transform

- Decreasing L_c (increasing island rotational transform Θ) in the island allows access to a higher recycling regime – larger SOL density requires lower impurity content for similar radiation levels
  - Optimum rotational transform to keep benign parallel transport/high divertor density?



[12] Y. Feng et al, *Nucl. Fusion* **56** (2016) 126011