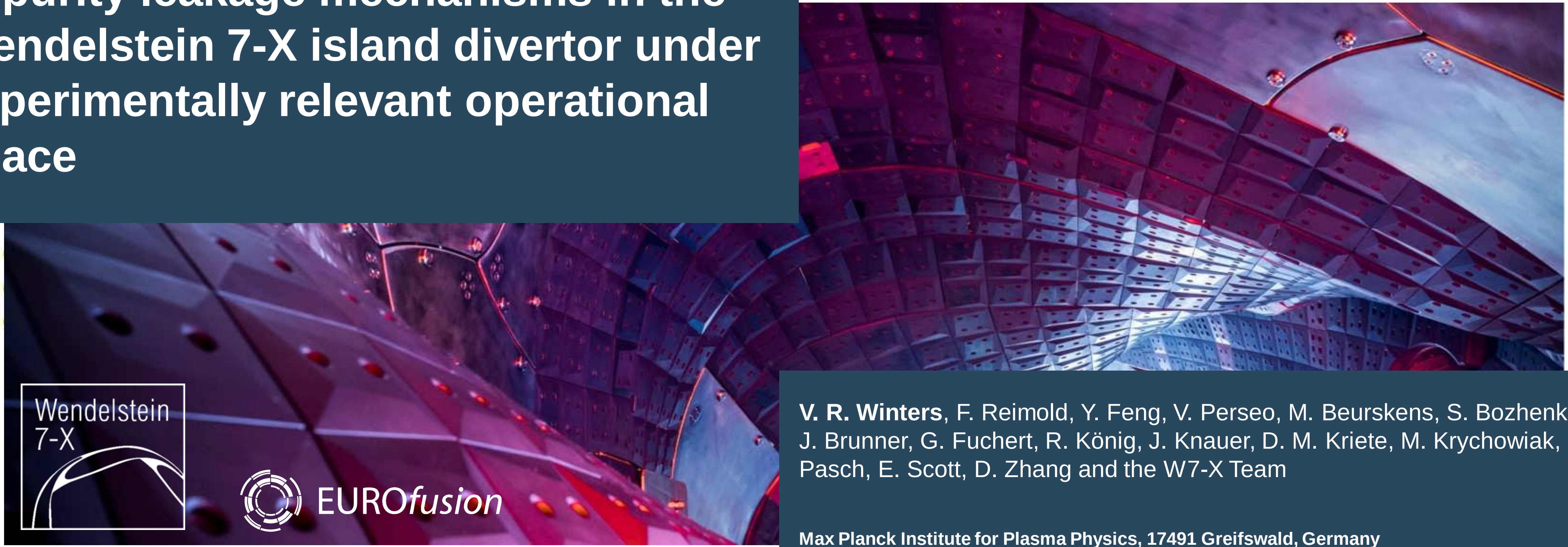
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Impurity leakage mechanisms in the Wendelstein 7-X island divertor under experimentally relevant operational space

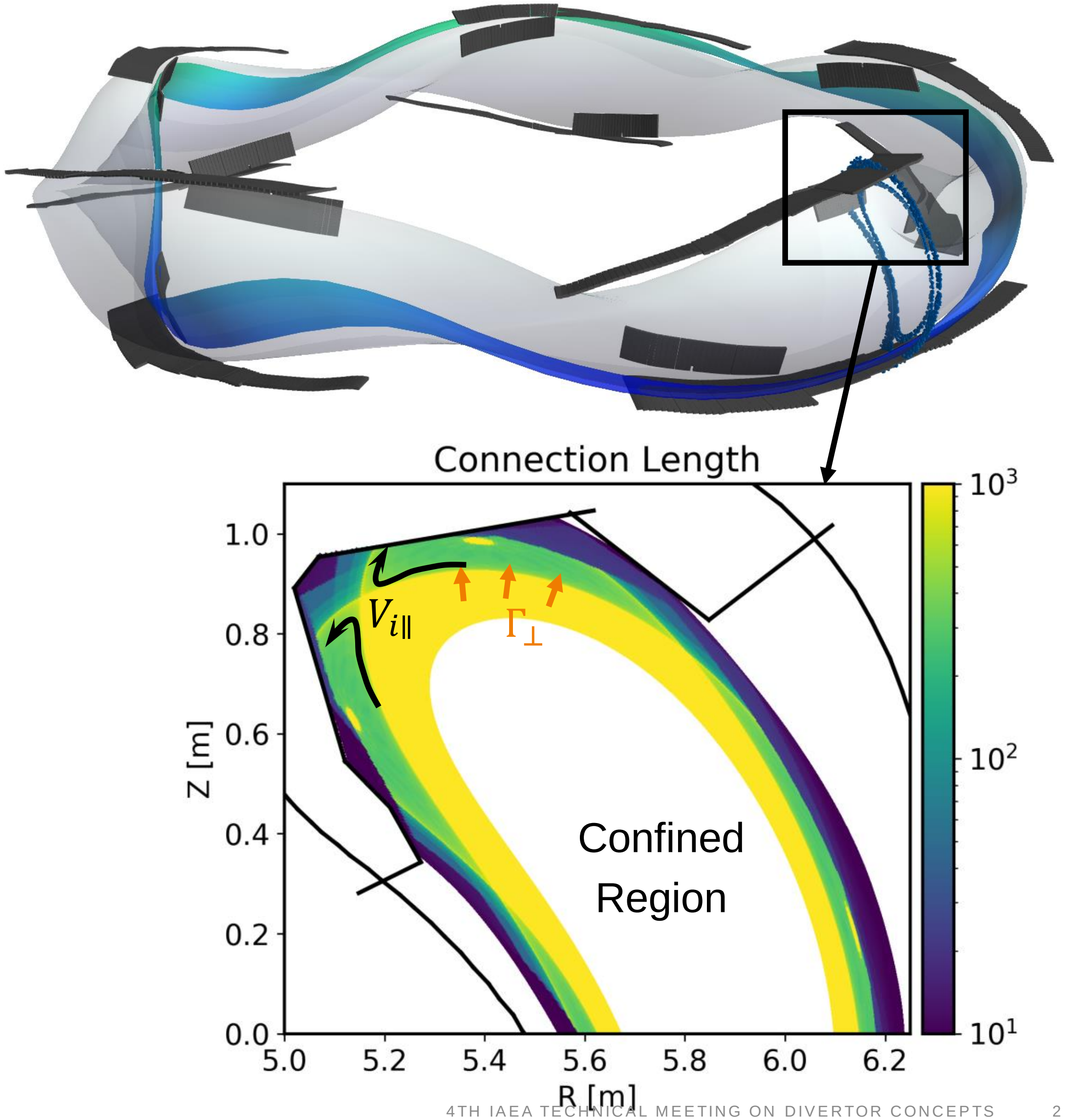


V. R. Winters, F. Reimold, Y. Feng, V. Perseo, M. Beurskens, S. Bozhenkov, K. J. Brunner, G. Fuchert, R. König, J. Knauer, D. M. Kriete, M. Krychowiak, E. Pasch, E. Scott, D. Zhang and the W7-X Team

Max Planck Institute for Plasma Physics, 17491 Greifswald, Germany

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

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 [F. Reimold]
- Sufficient particle exhaust (density control) [T. Kremeyer]

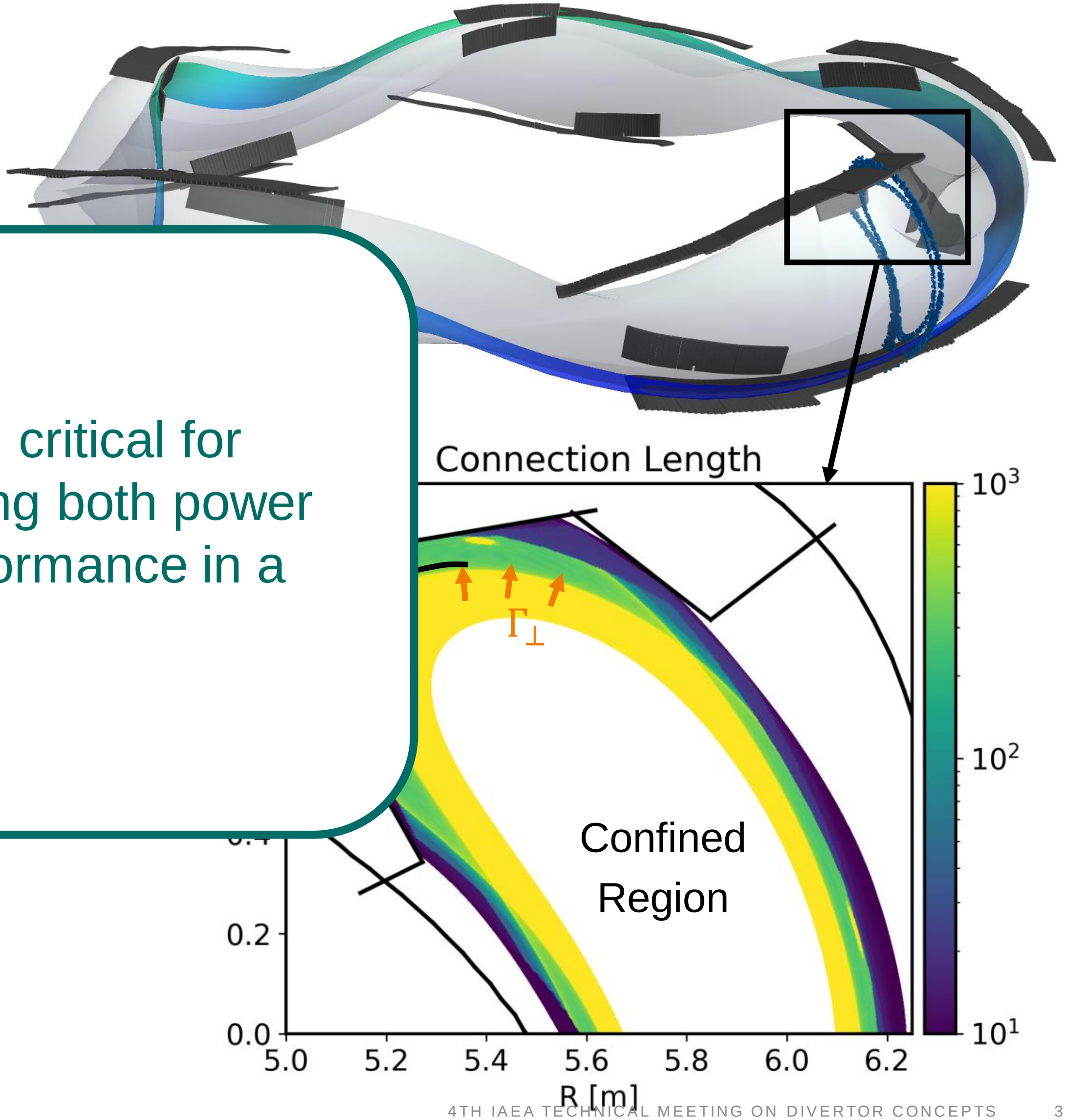
[1] O. Schmitz et al, *Nucl. Fusion* **61** (2021) 016026
[2] M. Jakubowski et al, *Nucl. Fusion* **61** (2021) 106003
[3] F. Effenberg et al, *Nucl. Fusion* **59** (2019) 106020

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

Requirements for a reactor divertor:

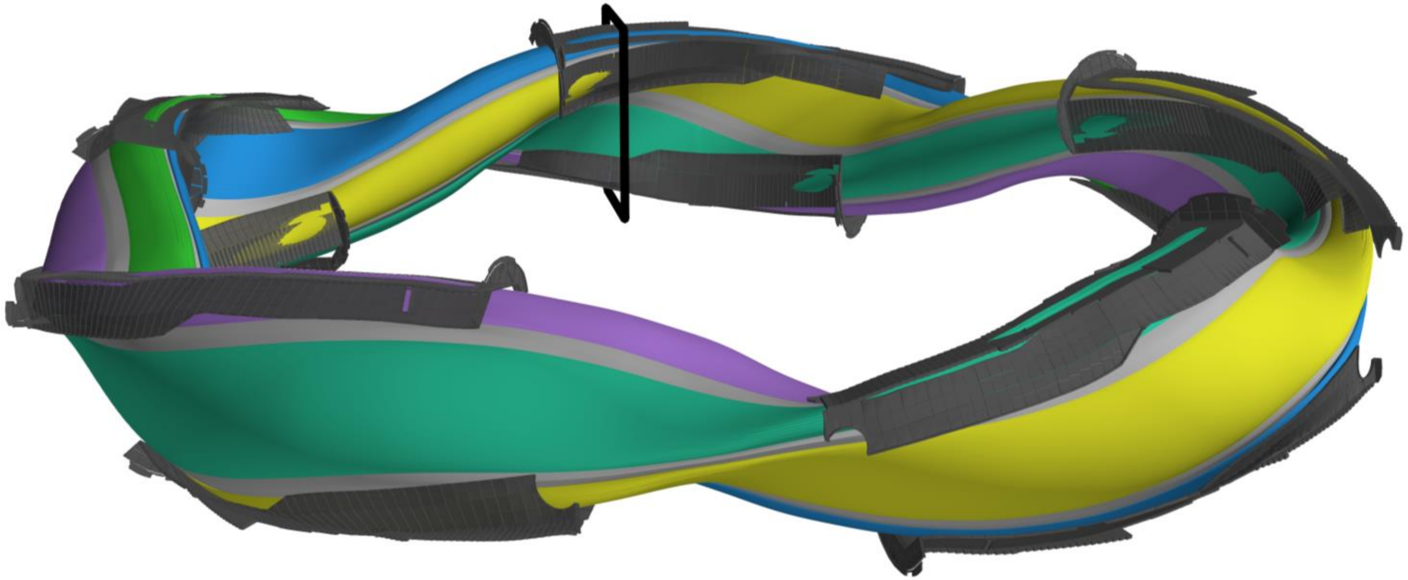
- Stable detachment[1-
- **Sufficient impurity**
- Helium compression
- Sufficient particle ex
  Kremeyer]

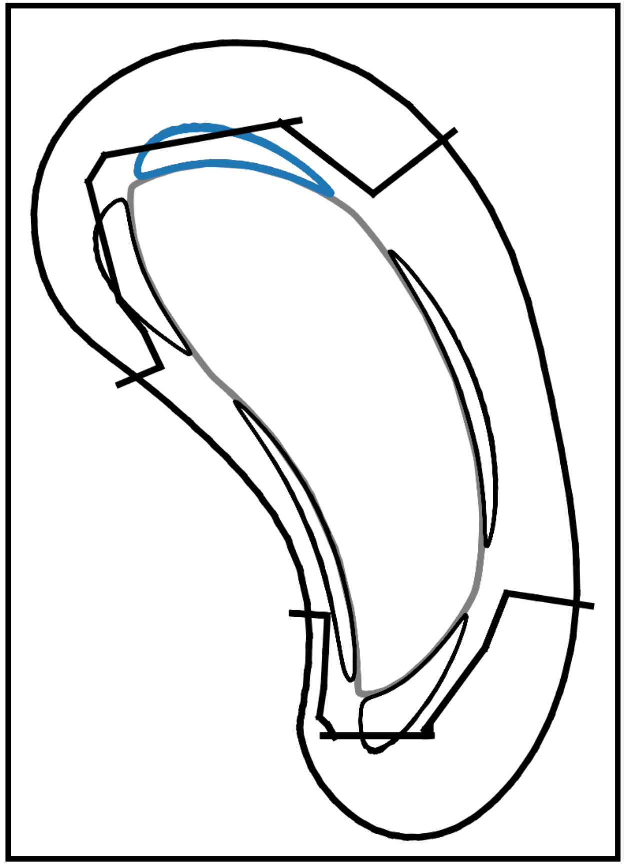
SOL impurity retention critical for simultaneously maintaining both power exhaust and fusion performance in a reactor!



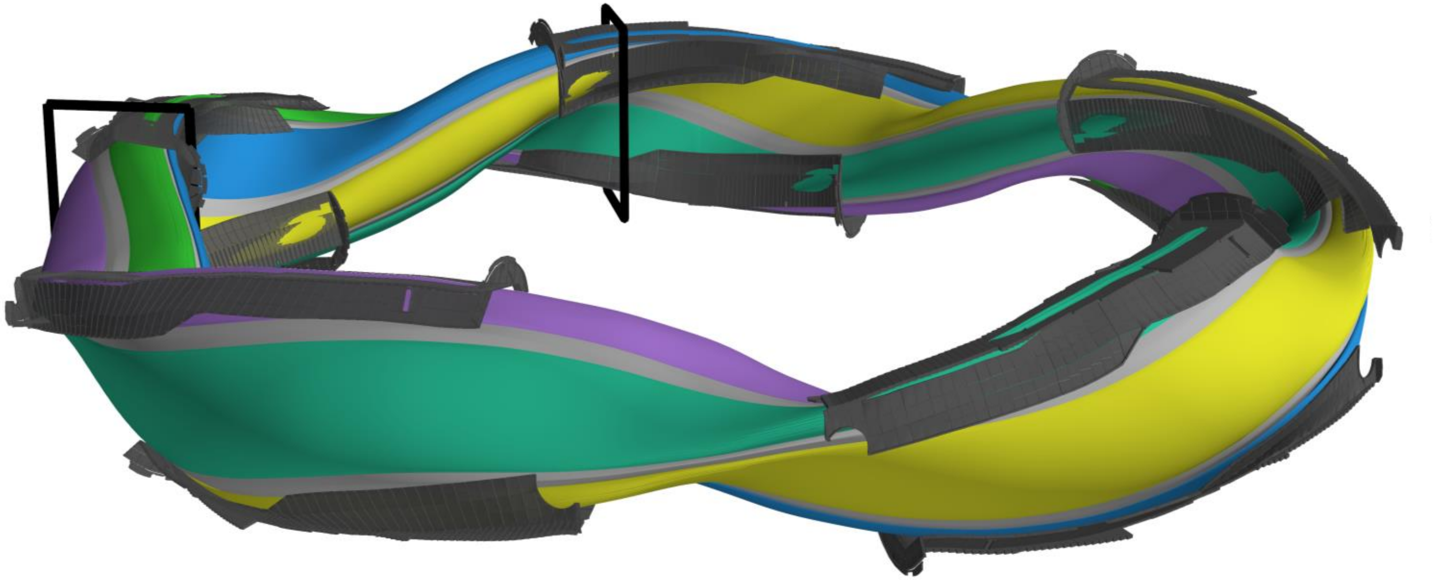
[1] O. Schmitz et al, *Nucl. Fusion* **61** (2021) 016026
[2] M. Jakubowski et al, *Nucl. Fusion* **61** (2021) 106003
[3] F. Effenberg et al, *Nucl. Fusion* **59** (2019) 106020

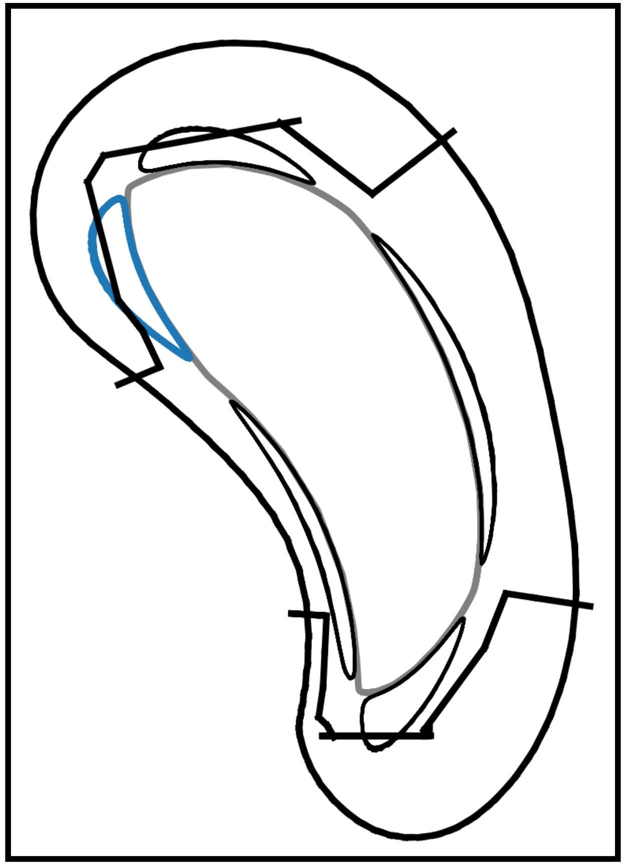
Island geometry of the W7-X SOL



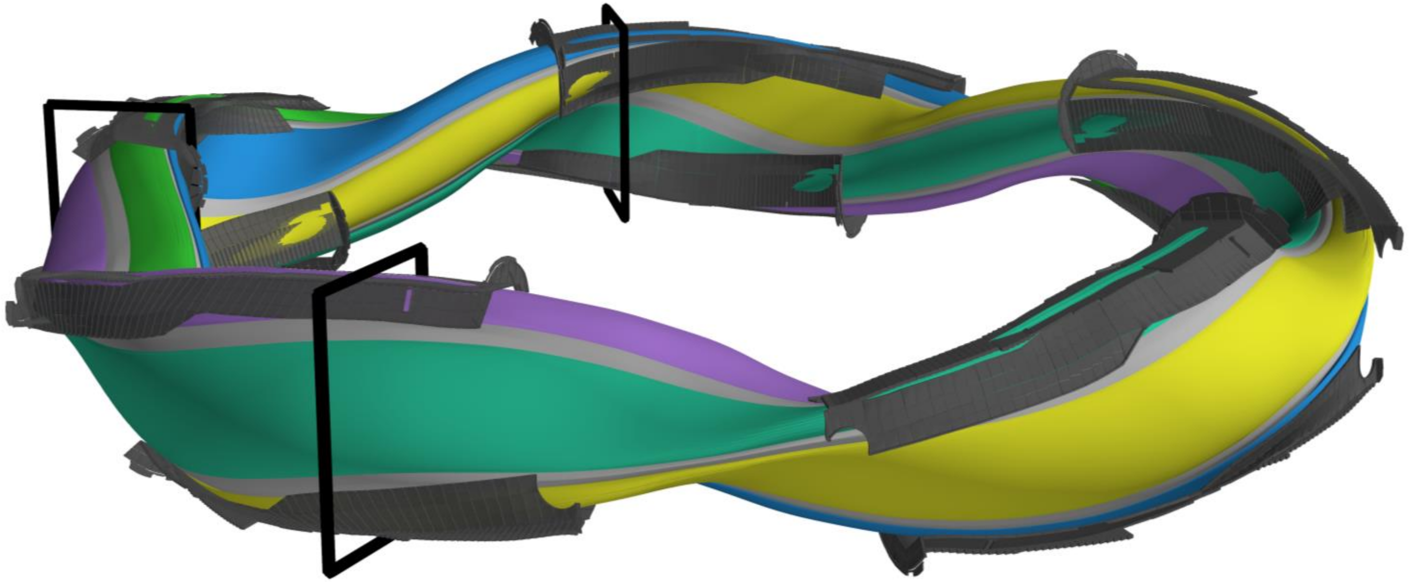


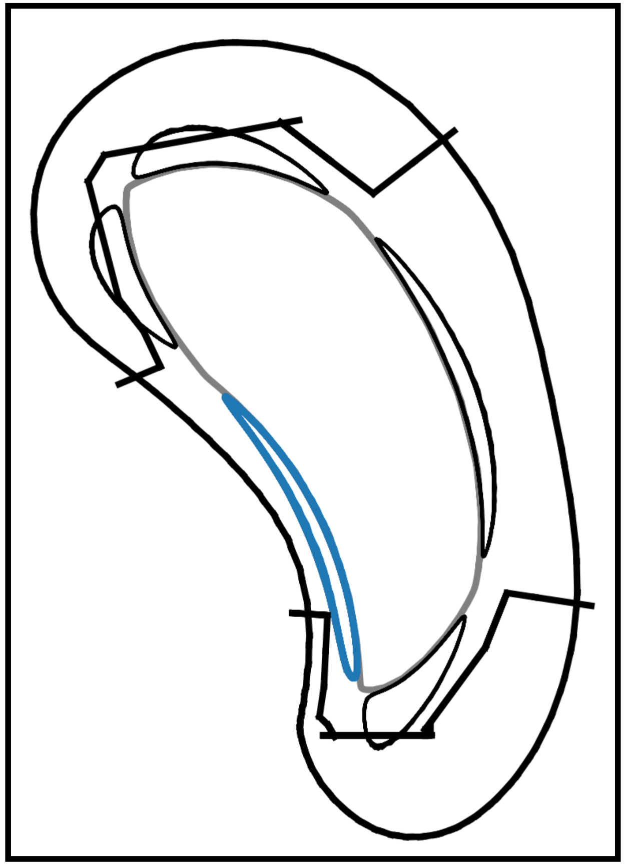
Island geometry of the W7-X SOL



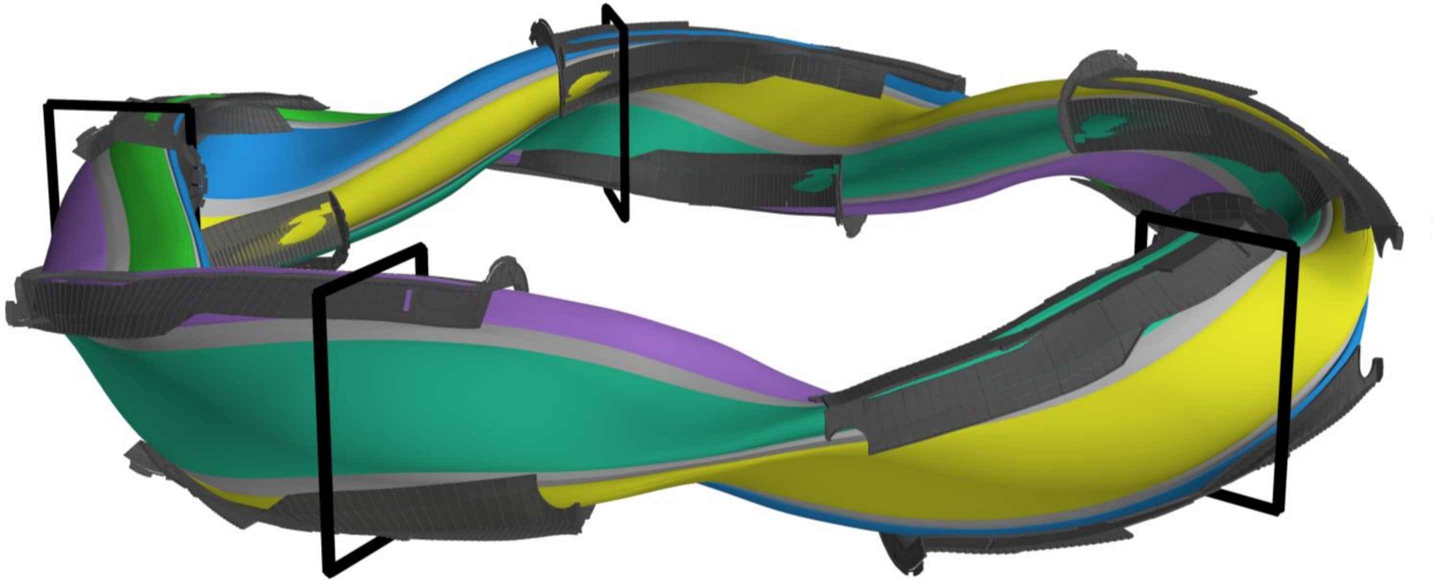


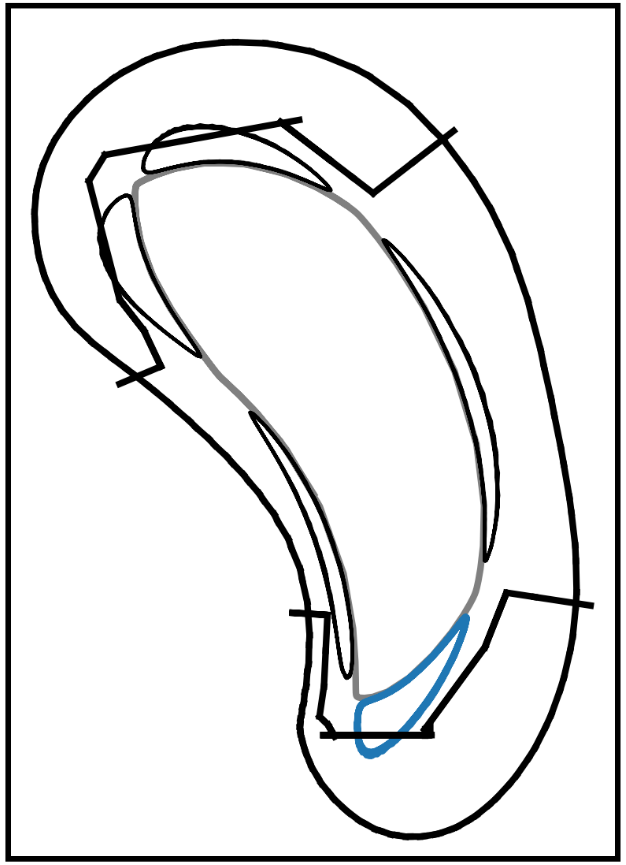
Island geometry of the W7-X SOL



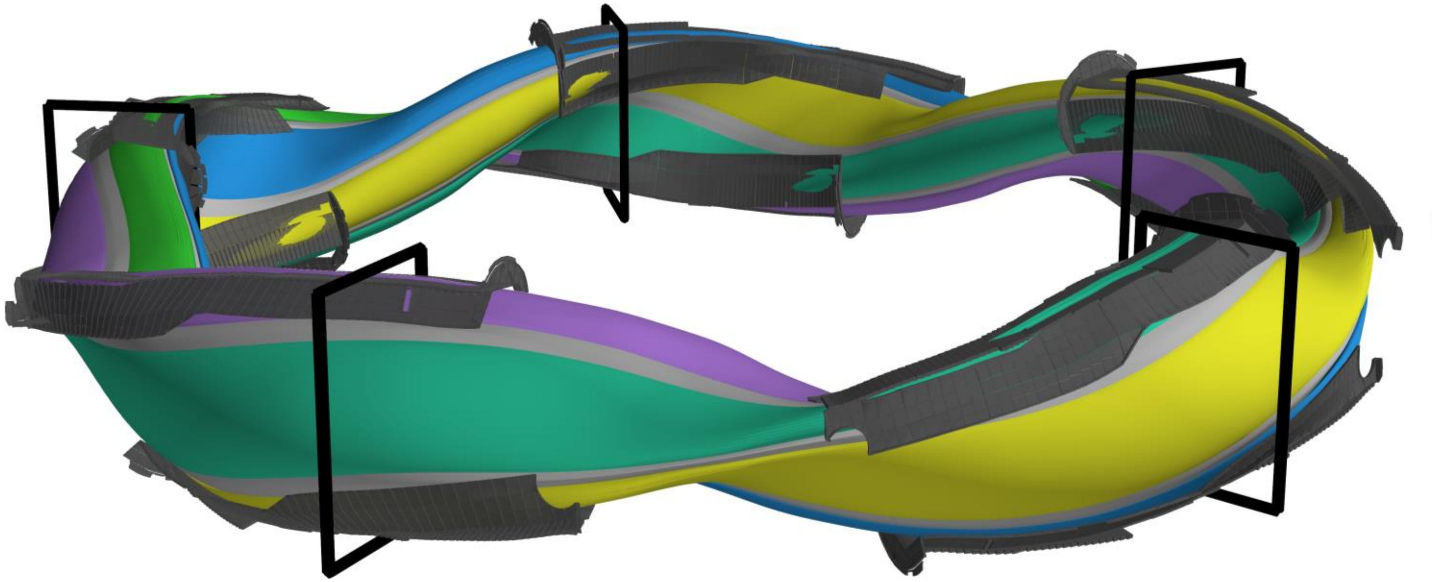


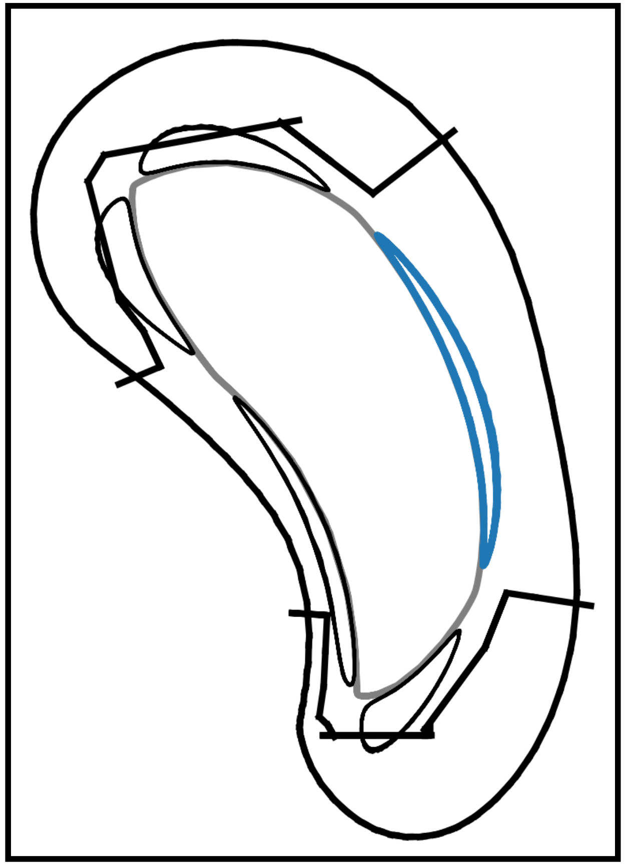
Island geometry of the W7-X SOL





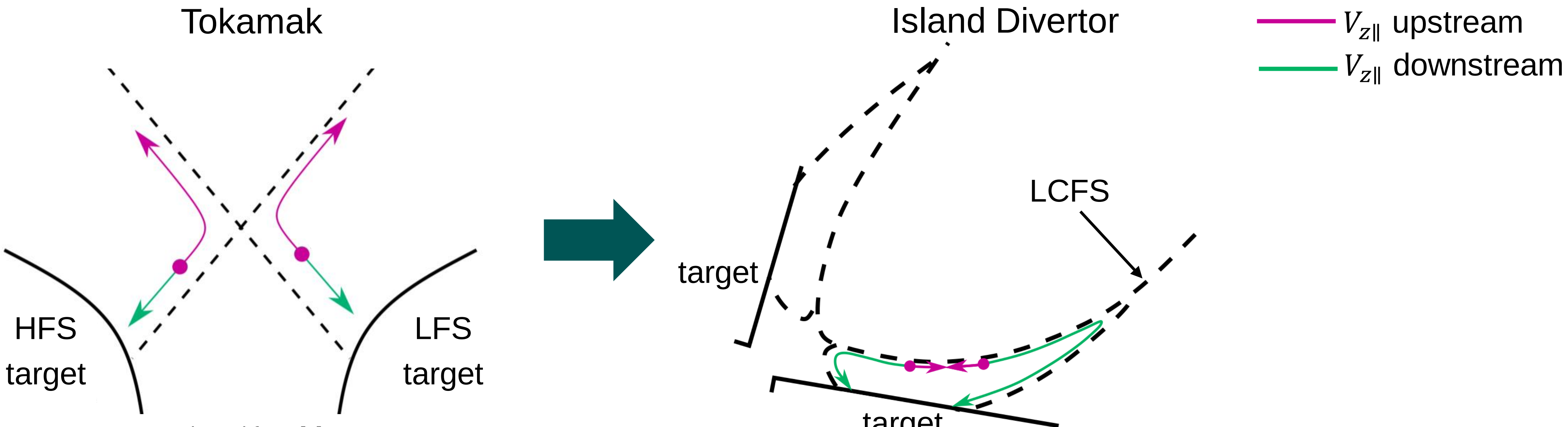
Island geometry of the W7-X SOL





Parallel impurity transport in a tokamak vs island divertor

- Parallel impurity leakage to the LCFS is caused by impurity neutral ionization beyond the impurity poloidal flow stagnation point[4,5] (dominant in tokamaks)
- **Parallel impurity transport is expected to be benign for the island divertor at operationally relevant densities[6,7]**

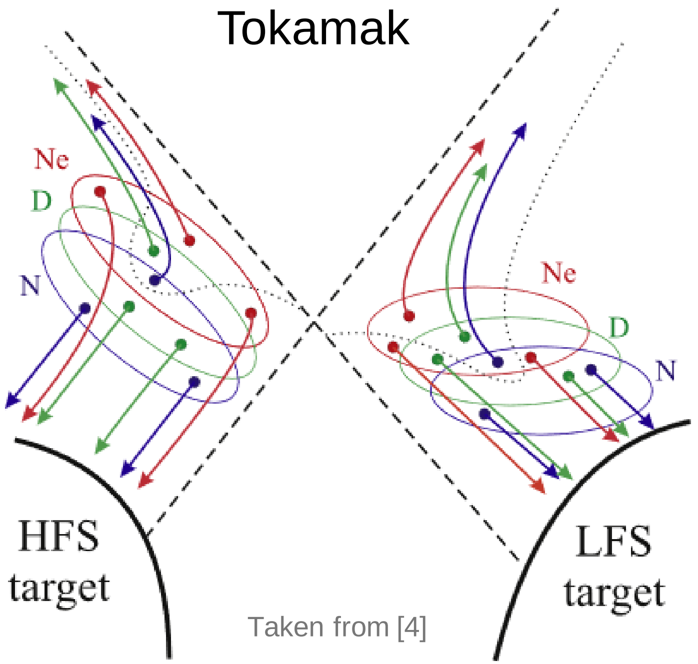


Adapted from [4]

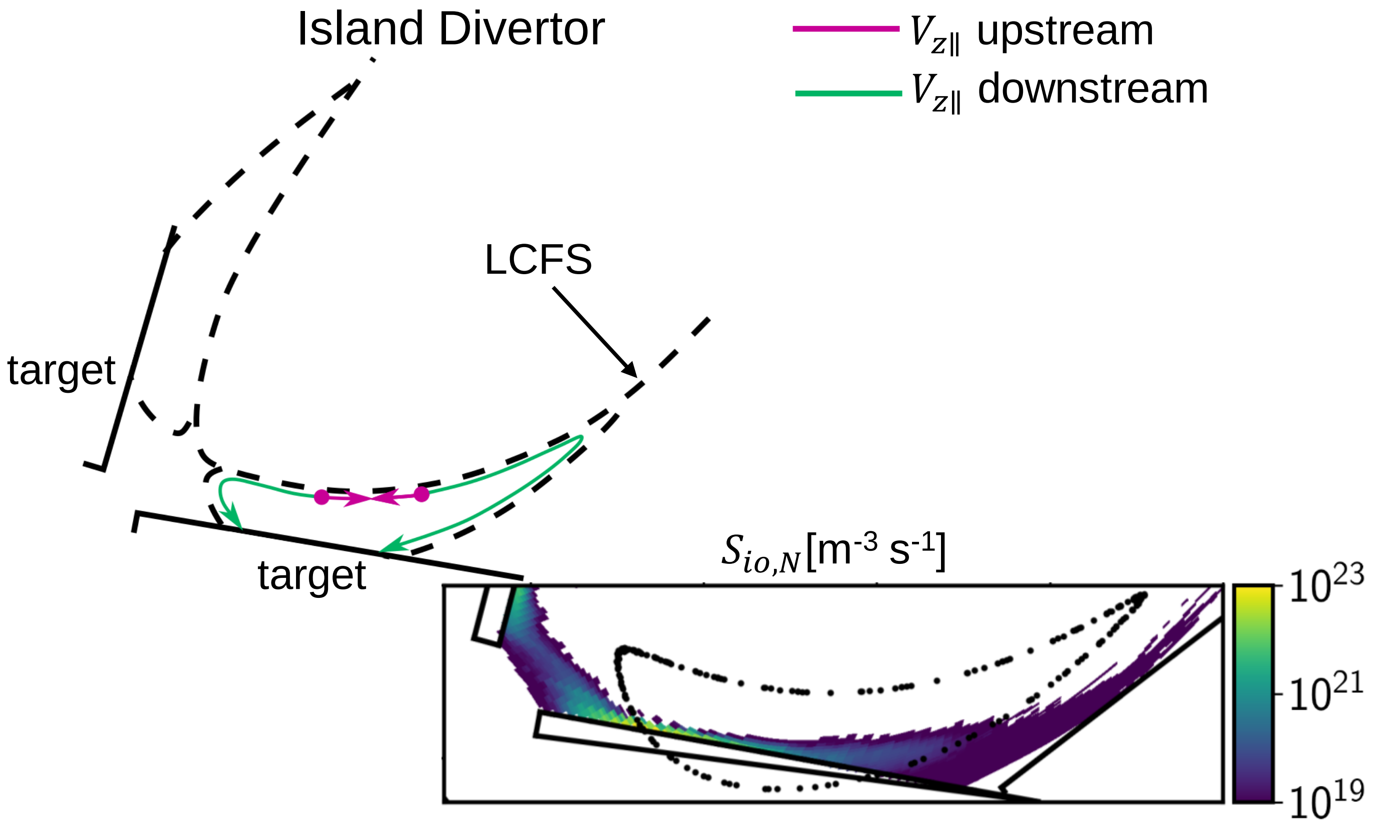
[4] I. Y. Senichenkov et al, *Plasma Phys. Control. Fusion* **61** (2019) 045013
[5] P. C. Stangeby et al, *Nucl. Fusion* **60** (2020) 106005
[6] Y. Feng et al, *Nucl. Fusion* **49** (2009) 095002
[7] V. R. Winters et al, *Nucl. Fusion* (submitted)

Parallel impurity transport in a tokamak vs island divertor

- Parallel impurity leakage to the LCFS is caused by impurity neutral ionization beyond the impurity poloidal flow stagnation point[4,5] (dominant in tokamaks)
- **Parallel impurity transport is expected to be benign for the island divertor at operationally relevant densities[6,7]**



Taken from [4]



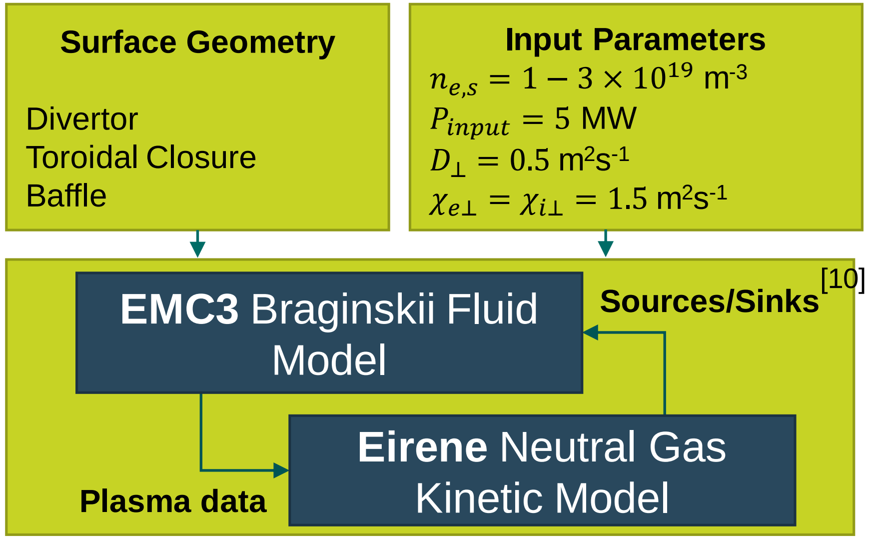
[4] I. Y. Senichenkov et al, *Plasma Phys. Control. Fusion* **61** (2019) 045013
[5] P. C. Stangeby et al, *Nucl. Fusion* **60** (2020) 106005
[6] Y. Feng et al, *Nucl. Fusion* **49** (2009) 095002
[7] V. R. Winters et al, *Nucl. Fusion* (submitted)

The EMC3-Eirene Code

- Solves 3D plasma/neutral solution in steady-state[9]
- Impurity transport parallel to magnetic field given by[11]:

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

- Perpendicular impurity transport anomalous, $D_{z\perp} = D_{i\perp}$



Surface Geometry

Divertor
Toroidal Closure
Baffle

Input Parameters
$n_{e,s} = 1 - 3 \times 10^{19}$ m^{-3}
$P_{input} = 5$ MW
$D_\perp = 0.5$ m^{2}s^{-1}
$\chi_{e\perp} = \chi_{i\perp} = 1.5$ m^{2}s^{-1}

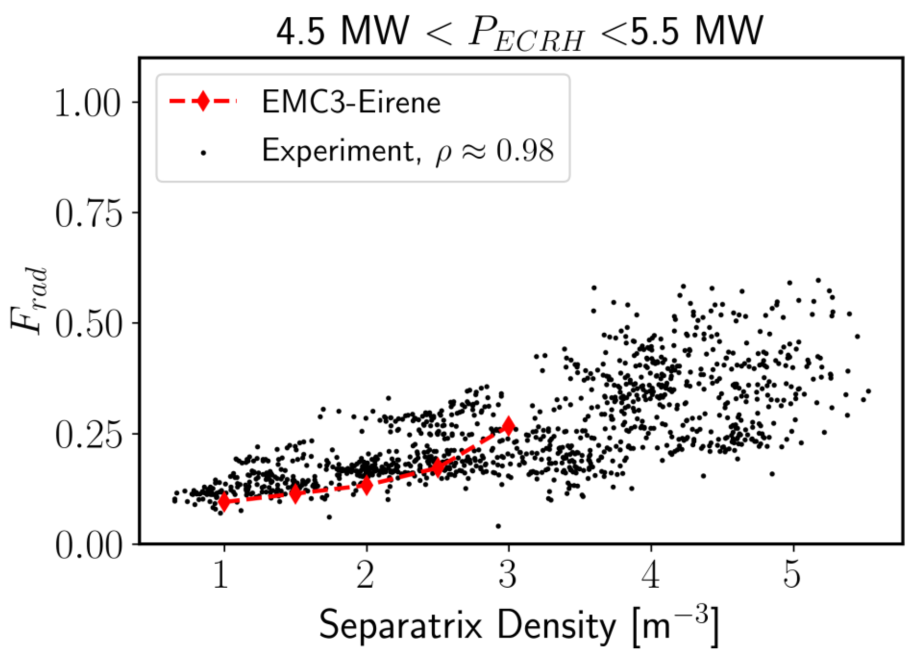
EMC3 Braginskii Fluid Model

Sources/Sinks[10]

Eirene Neutral Gas Kinetic Model

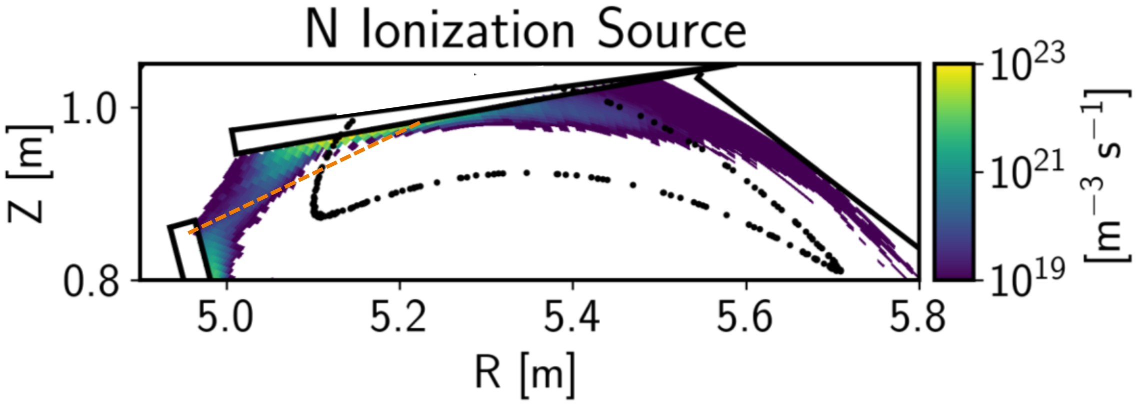
Plasma data

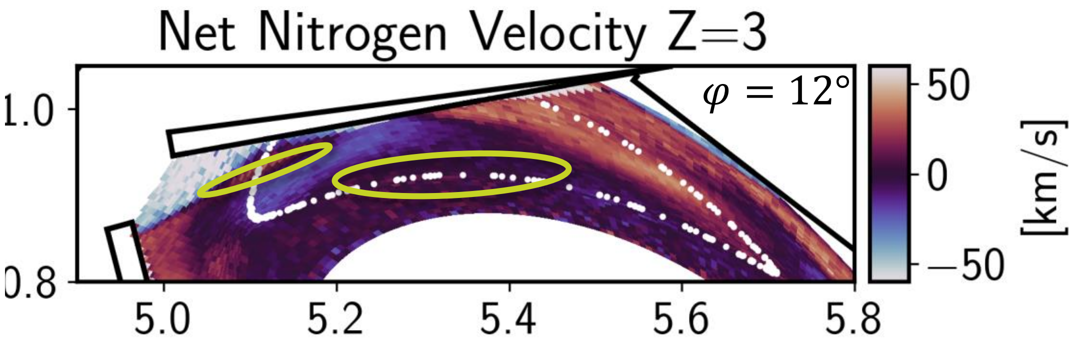
[9] Y. Feng et al, *Contrib. Plasma Phys.* **54** (2014) 426-431
[10] H. Frerichs et al, *Nuclear Materials and Energy* **18** (2019) 62-66
[11] P. C. Stangeby, *Plasma Boundary of Magnetic Fusion Devices* (2000)

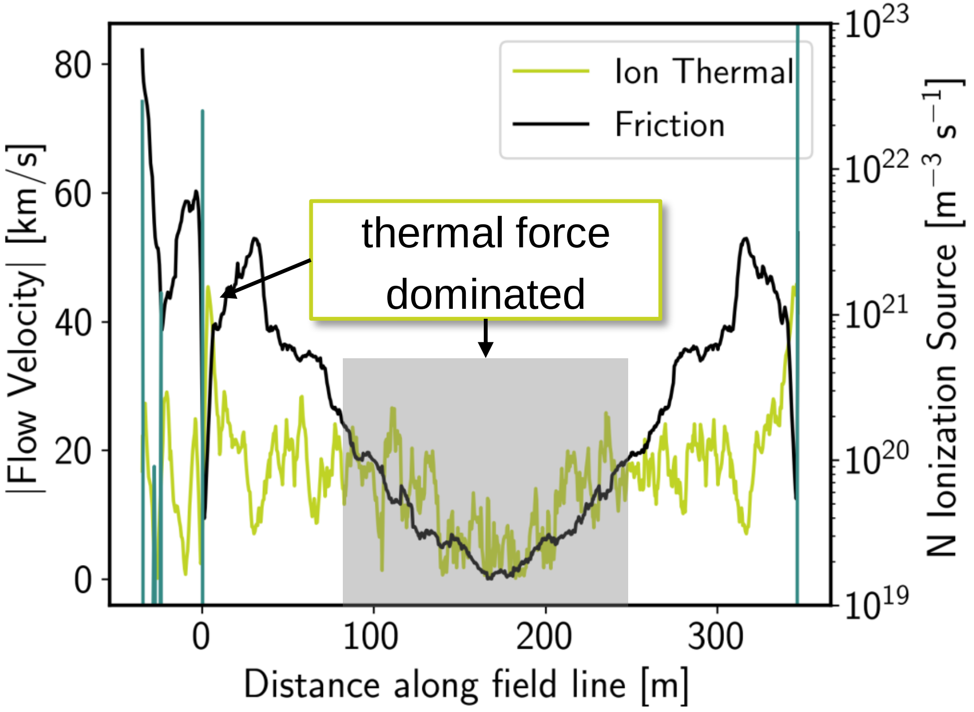


- F_{rad} comes from 4% chemically sputtered ($E_{C^0} = 0.03$ eV) carbon
- Different impurity injected in trace approximation: C, N, Ne, He with $E_0 = 0.03$ eV
- Impurities start with the same distribution as the main ion recycling flux
- **No drift effects included**

Confirmation of benign parallel transport across the entire island SOL in experimentally relevant scenarios







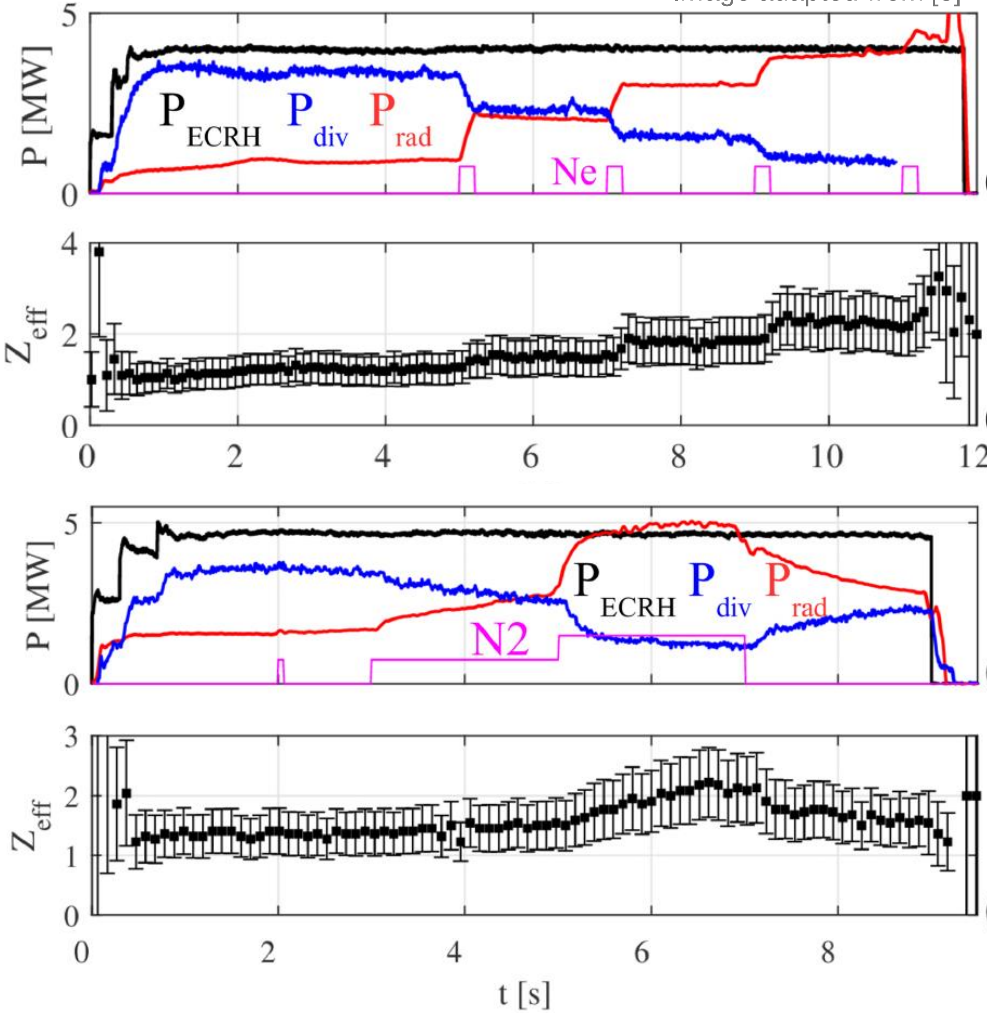
- There does not appear to be any significant ionization source in thermal force dominated regions
- How then, are impurities reaching the confined plasma?

Despite expected benign parallel impurity transport, we still see impurity contamination in W7-X!

- First measurements of nitrogen enrichment during seeding indicate low core nitrogen content (~0.1%)[8], however:
- $Z_{eff} = 1.2 - 1.5$ at low f_{rad}, increases to >2 with impurity seeding[3]

How do impurities leak to the confined plasma in the island divertor?

Image adapted from [3]



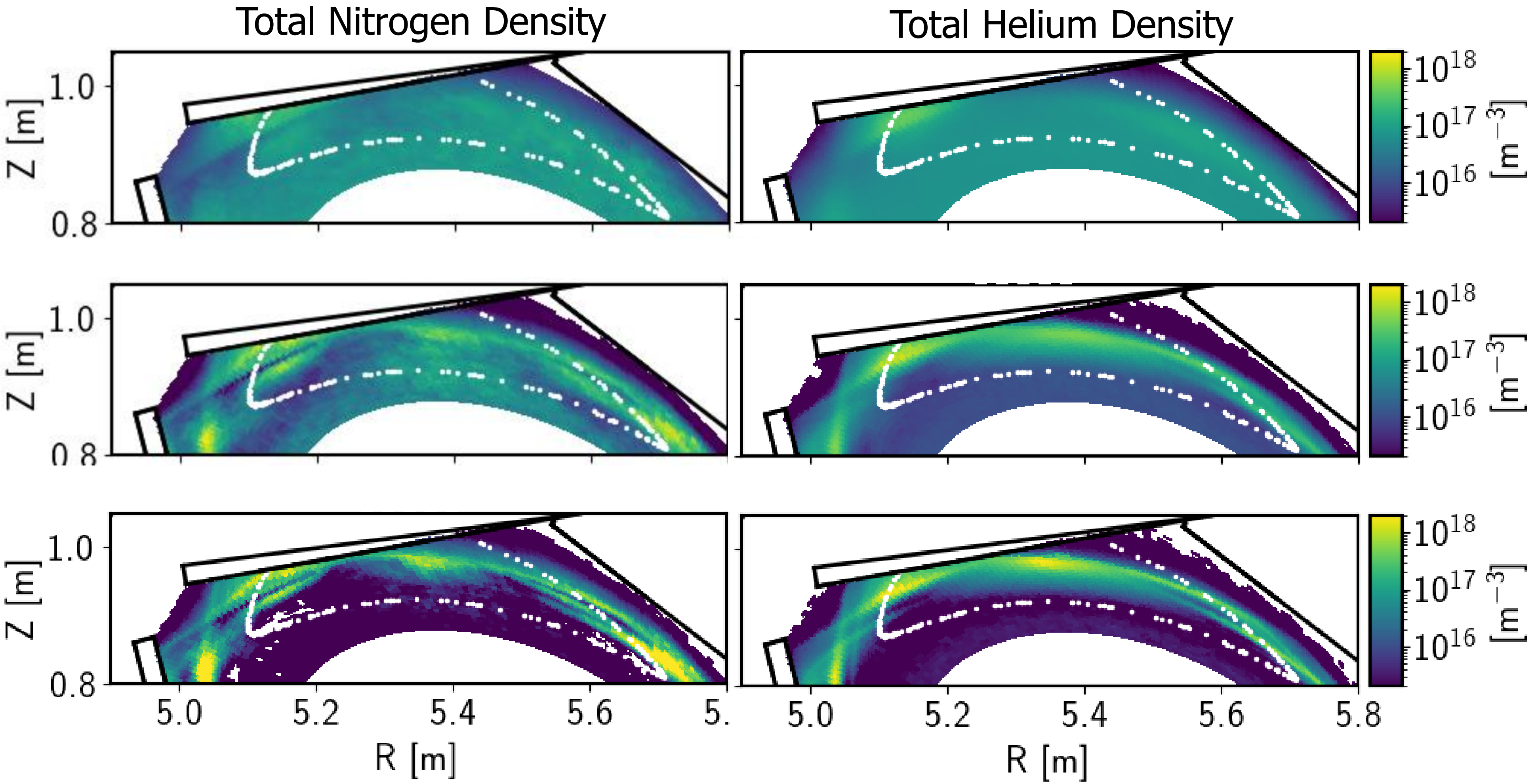
[8] F. Henke, *Master's Thesis*
[3] F. Effenberg et al, *Nucl. Fusion* **59** (2019) 106020

D_z scan on a fixed plasma background reveals perpendicular transport as dominant leakage mechanism

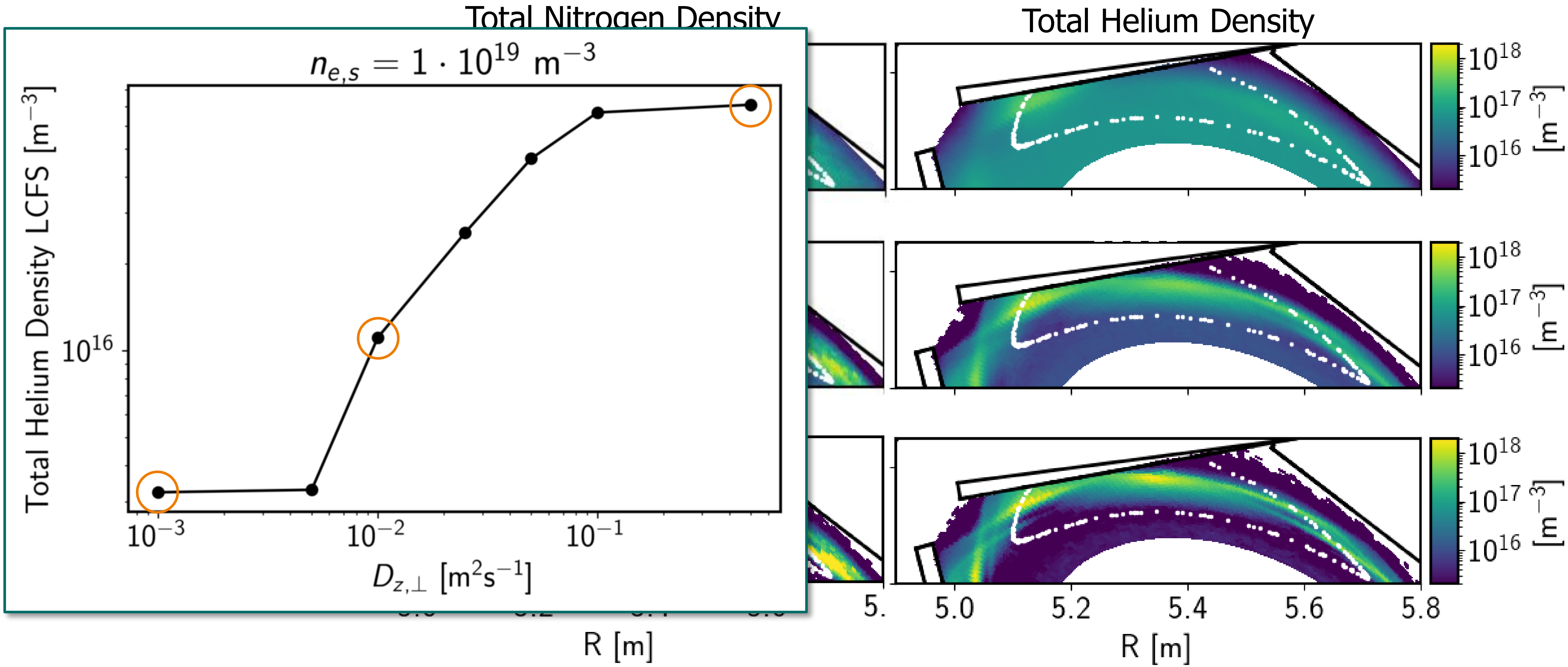
D_z = 0.5 m^{2}s^{-1}

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

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

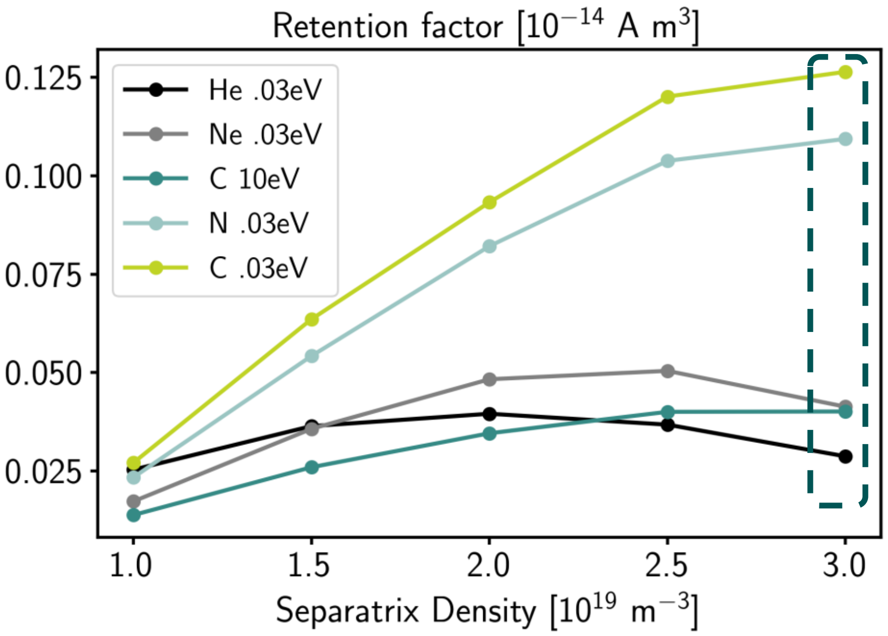


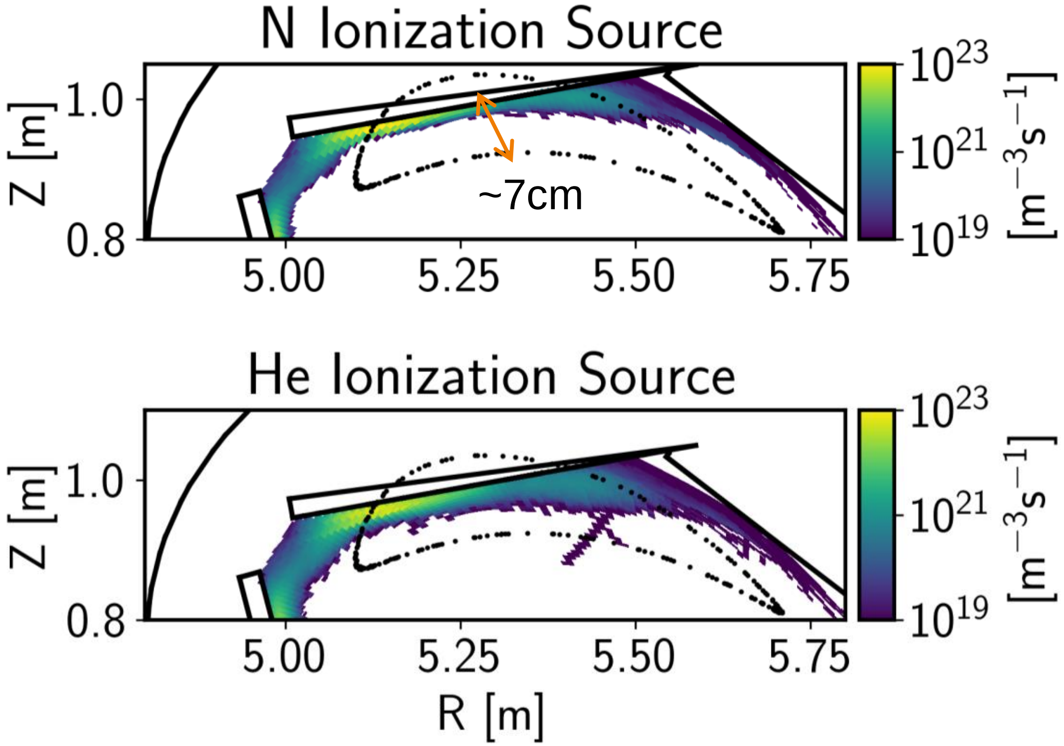
D_z scan on a fixed plasma background reveals perpendicular transport as dominant leakage mechanism



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

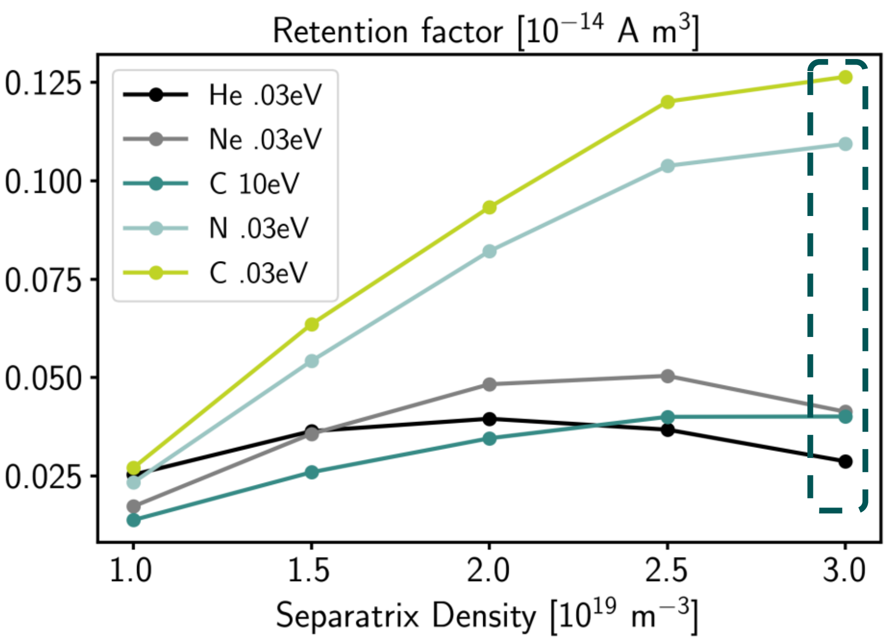
- Outward/inward radial movement of source is an accurate indicator for when retention improves/degrades
- Inward movement of source → less geometrical distance to LCFS → lower retention

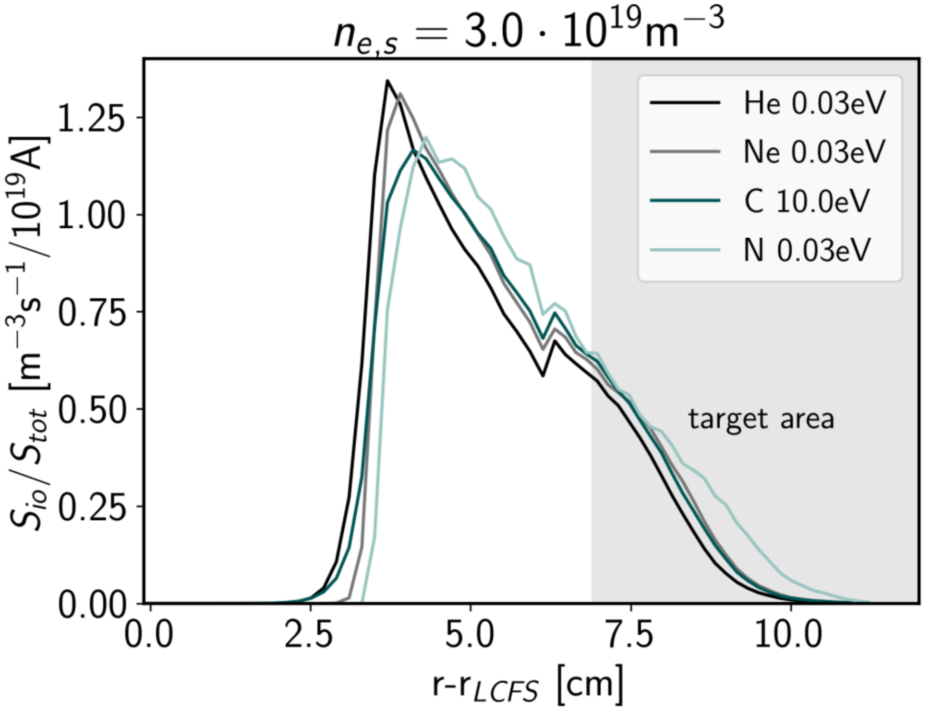




Ionization source changes plays a role in retention by bringing impurity ionization closer to the LCFS/island O-Point

- 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





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

Tuning the island size

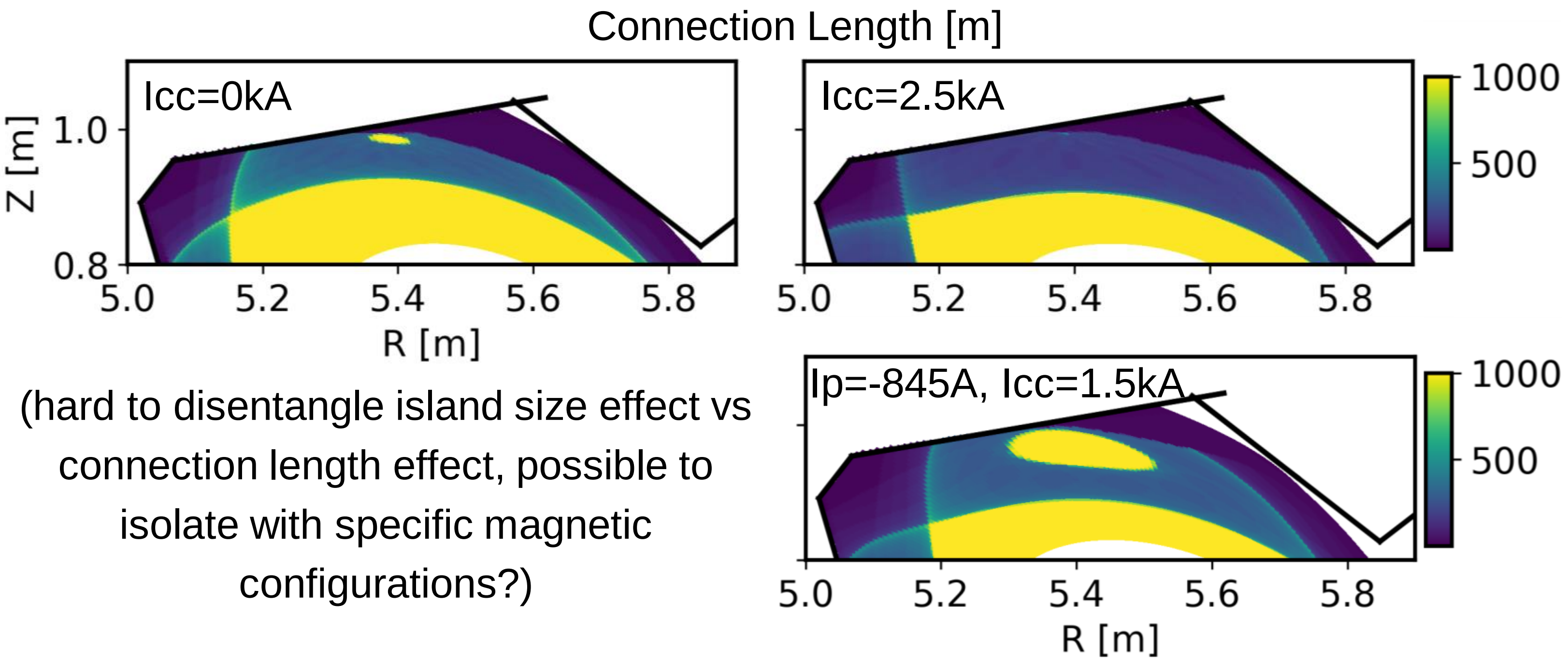
- Increasing island size could improve impurity retention[12]

[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]



(hard to disentangle island size effect vs connection length effect, possible to isolate with specific magnetic configurations?)

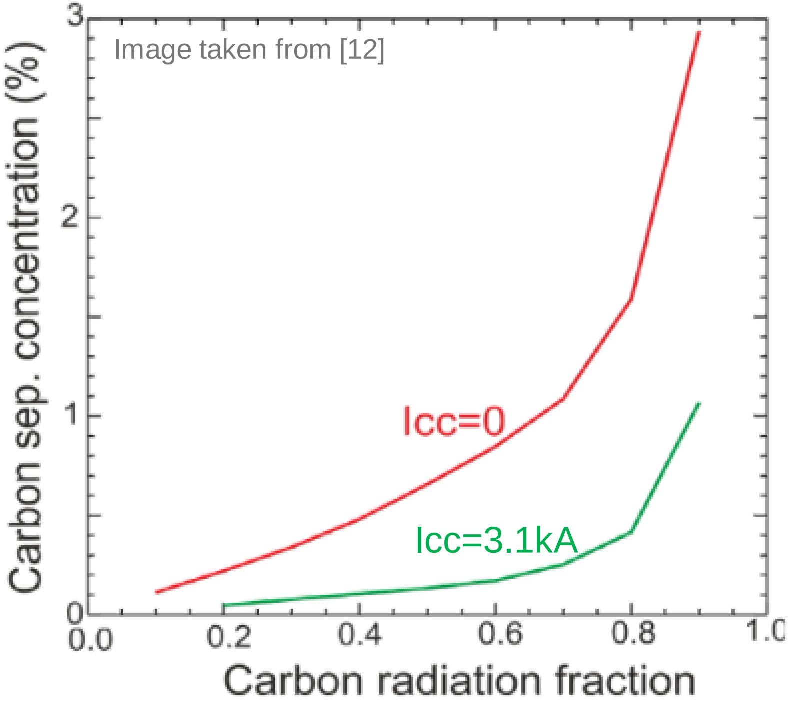


Image taken from [12]

Both configurations to be tested in this current experimental phase!

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

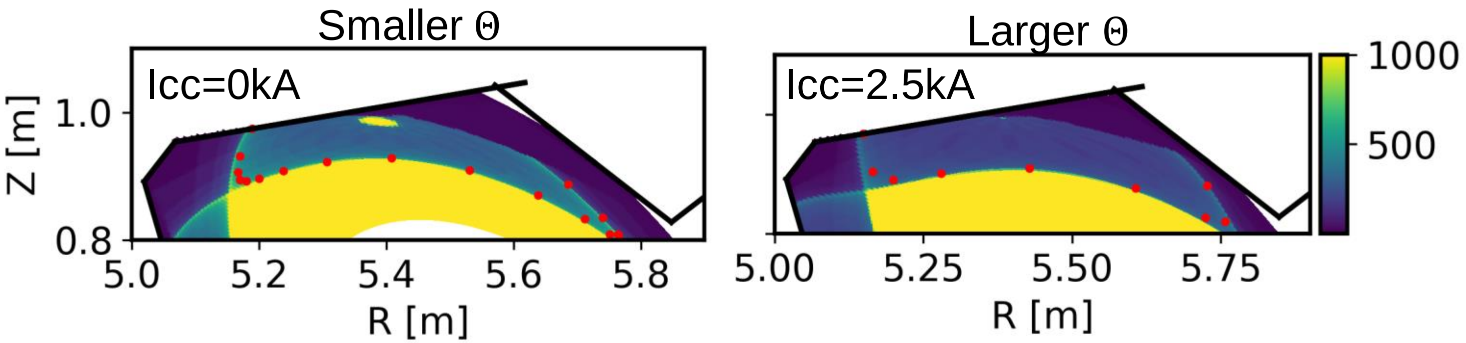
So, what knobs can we turn to minimize impurity leakage in a future reactor island divertor?

Tuning the island size

- Increasing island size could improve impurity retention[12]

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

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

Tuning the island size

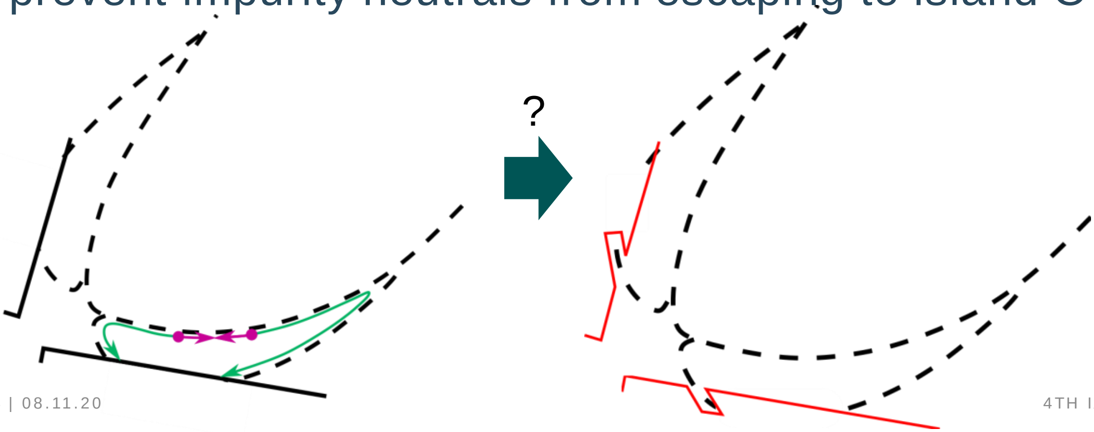
- Increasing island size could improve impurity retention[12]

Tuning island rotational transform

- Decreasing L_c 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?

Modification of divertor geometry

- Closing the divertor would prevent impurity neutrals from escaping to island O-point region/keep them further from LCFS



[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]

Tuning island rotational transform

- Decreasing L_c 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?

Modification of divertor geometry

- Closing the divertor would prevent impurity neutrals from escaping to island O-point region/keep them further from LCFS (reduces magnetic flexibility in future)

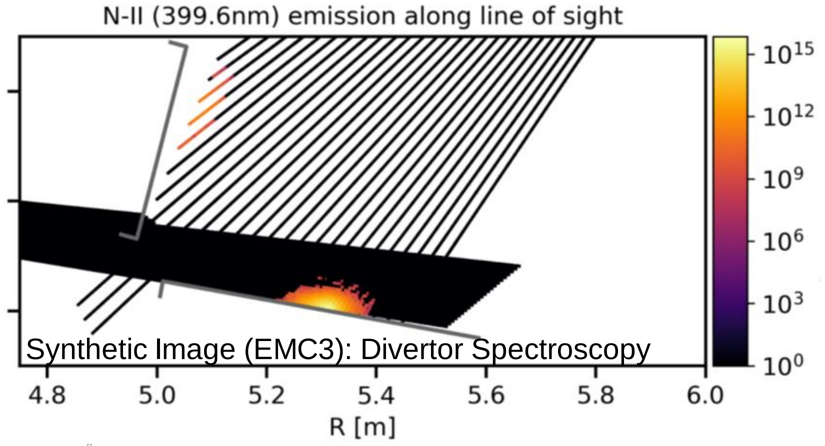
Island Elongation?

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

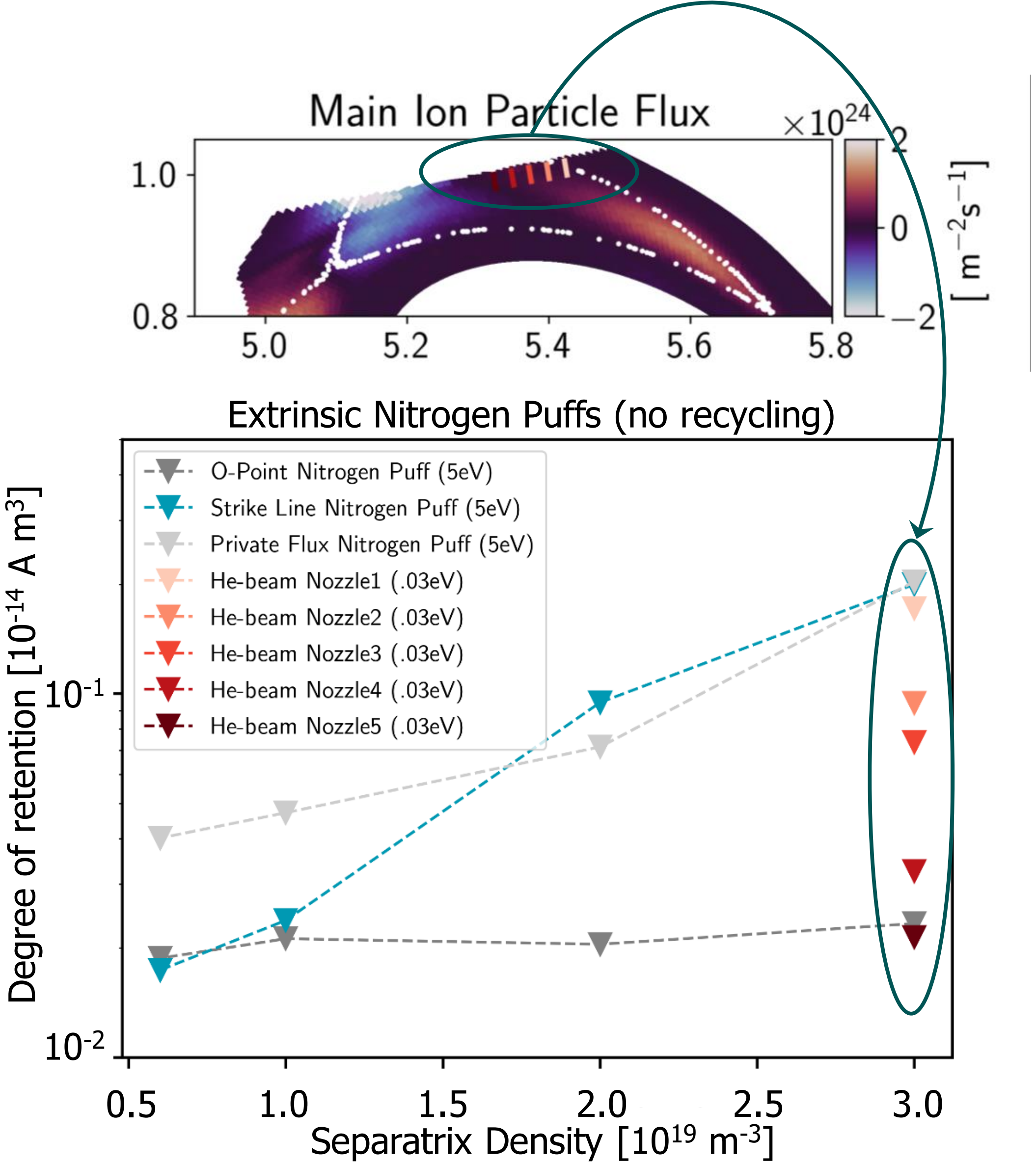
Outlook: Looking to the next experimental campaign

Experimental Validation of Modeling Results Upcoming!

- Comparison of retention magnitude of different species using LR spectroscopy
- Is the flow stagnation region the dominant leakage mechanism? Direct fueling of this area possible
- Magnetic configuration effects (island size/connection length)
- Synthetic diagnostics help us more directly compare simulation and experimental results



Synthetic Image (EMC3): Divertor Spectroscopy



Summary

Parallel impurity transport is benign in the W7-X island divertor

Perpendicular transport is the limiting factor for impurity retention in the W7-X island SOL

- Impurities leak to the LCFS via perpendicular transport across flow stagnation region
- Ionization length still affects impurity retention by changing distance between ionization front and LCFS

Several avenues to explore to optimize the impurity retention of the island divertor concept

- Tuning island size, rotational transform, shape and target geometry are all possible options for future devices

Simulation validation is still ongoing and in its beginning stages!

Back-up Slides

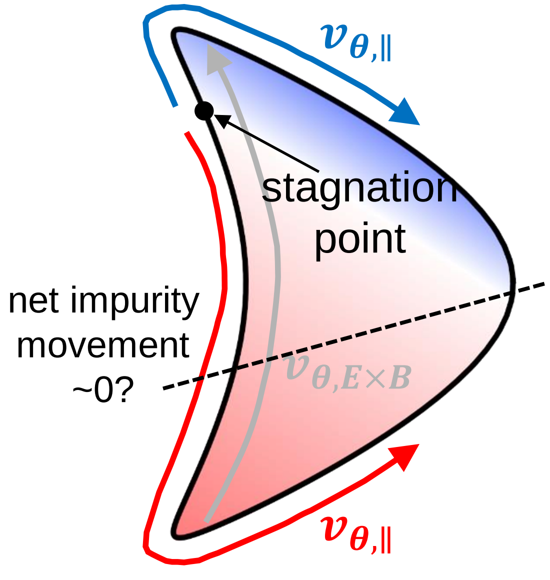
A qualitative note on drift effects

- Poloidal $\vec{E} \times \vec{B}$ drifts shift location of max pressure along field line, poloidally shifting the main ion flow stagnation point[13]

- Additionally, Poloidal $\vec{E} \times \vec{B}$ drifts affect impurities by moving them into (or out of) the flow stagnation region

- Qualitatively, there should be a location in the island where the $v_{\theta,E\times B}$ exactly mitigates the poloidal projection of the parallel impurity flow $v_{\theta,\|}$
  - Long impurity dwell times in this location – consequences for transport?

- Radial drift effects not yet clear



[IMG] D. M. Kriete

---

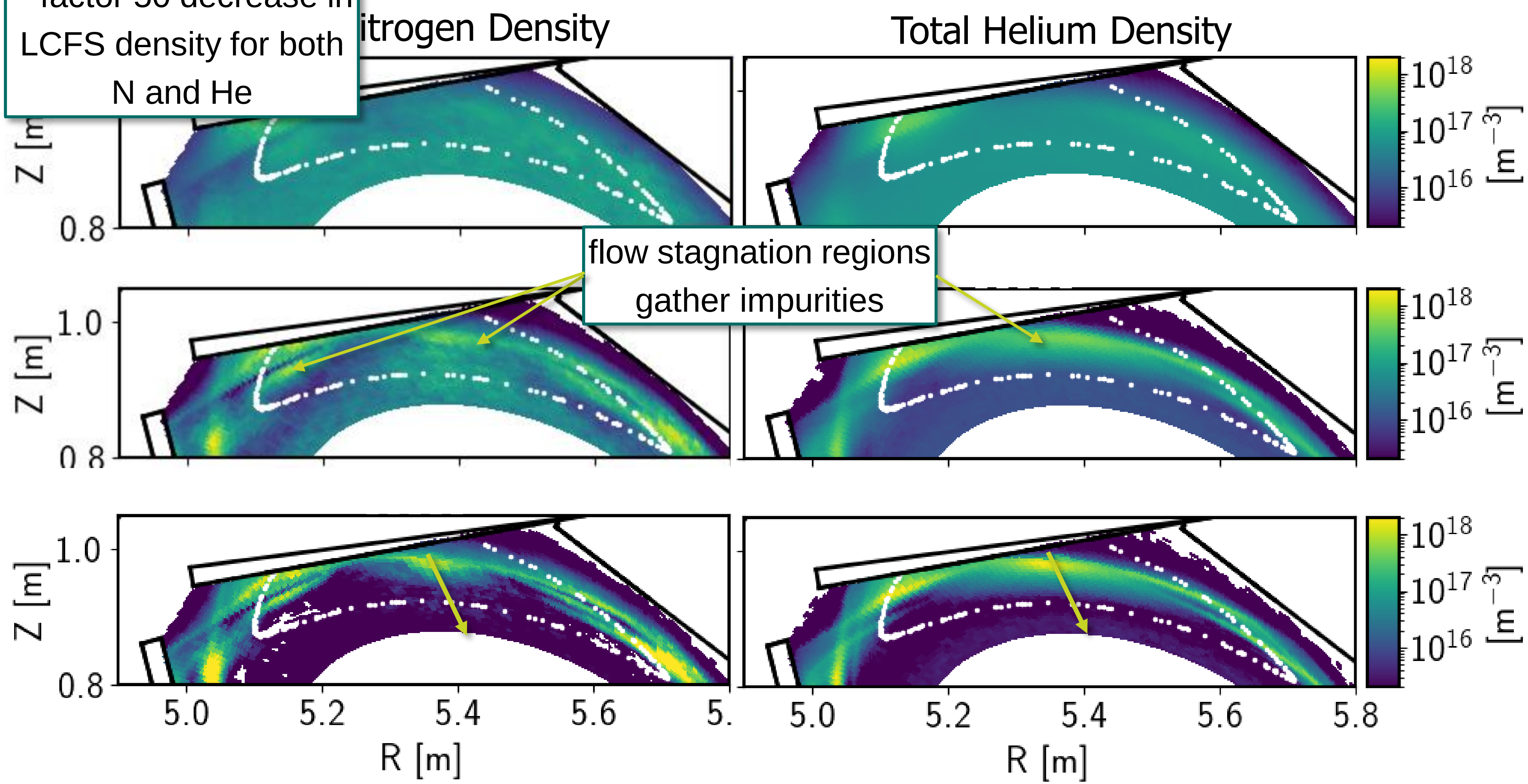
[13] D. M. Kriete et al, *Nucl. Fusion* (submitted)

D_z scan on a fixed plasma background reveals perpendicular transport as dominant leakage mechanism

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

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

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



~ factor 50 decrease in LCFS density for both N and He

flow stagnation regions gather impurities

Why is Helium better retained than other impurities at low density?

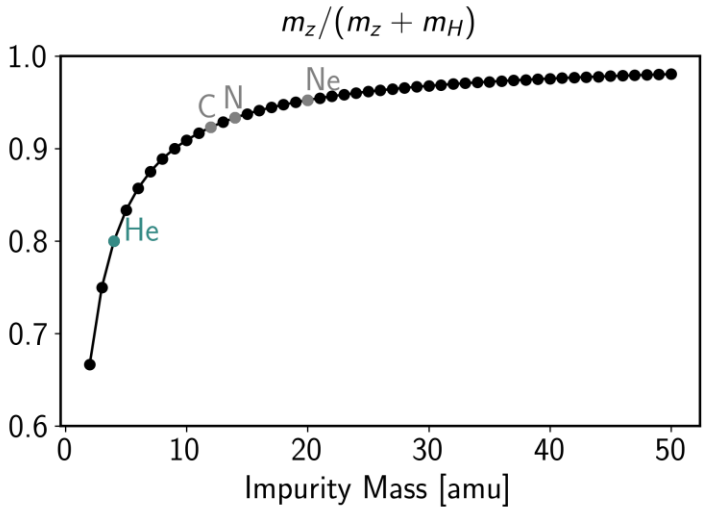
- Parallel impurity flow velocity approximated by:

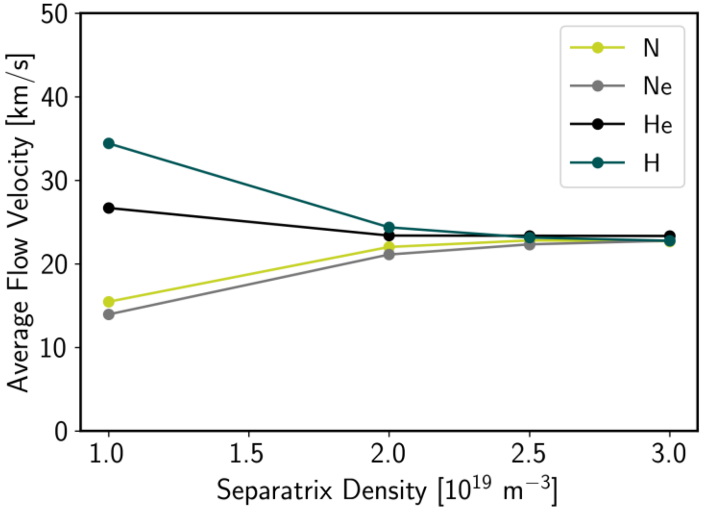
$$V_{z\parallel} \approx V_{i\parallel} + (\beta_i - 1)\frac{\tau_s}{m_z}\frac{\mathrm{d}T_i}{\mathrm{d}s}$$

- Both β_i, τ_s/m_z depend on “reduced mass”: ${}^{m_z}/_{m_z+m_H}$

- Both friction and ion thermal fluid forces represent collisional processes: similar mass of Helium and Hydrogen leads to more efficient momentum transfer→ reduced ion thermal force, increased friction

- Lower flow velocities → longer impurity dwell time → more perpendicular transport → lower retention





Why is Helium better retained than other impurities at low density?

- Parallel impurity flow velocity approximated by:

$$V_{z\parallel} \approx V_{i\parallel} + (\beta_i - 1)\frac{\tau_s}{m_z}\frac{\mathrm{d}T_i}{\mathrm{d}s}$$

- Both β_i, τ_s/m_z depend on “reduced mass”: ${}^{m_z}/_{m_z+m_H}$

- Both friction and ion thermal fluid forces represent collisiona similar mass of Helium and Hydrogen leads to more efficient transfer→ reduced ion thermal force, increased friction

- Lower flow velocities → longer impurity dwell time → more p transport → lower retention