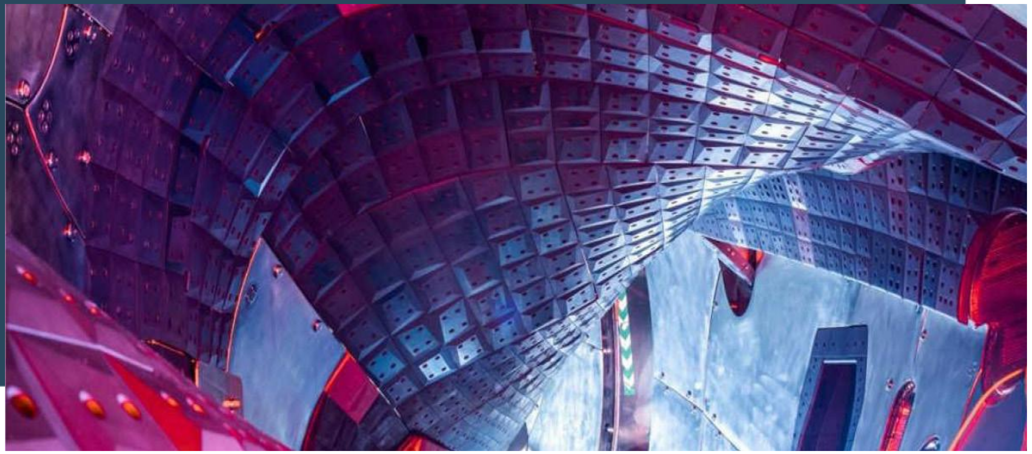
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Wendelstein 7-X

Key HELIAS Physics Uncertainties: Heat and Particle Exhaust

V. R. Winters, T. Kremeyer, V. Perseo, F. Reimold



EUROfusion

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Short review: The geometry of the island divertor[1]

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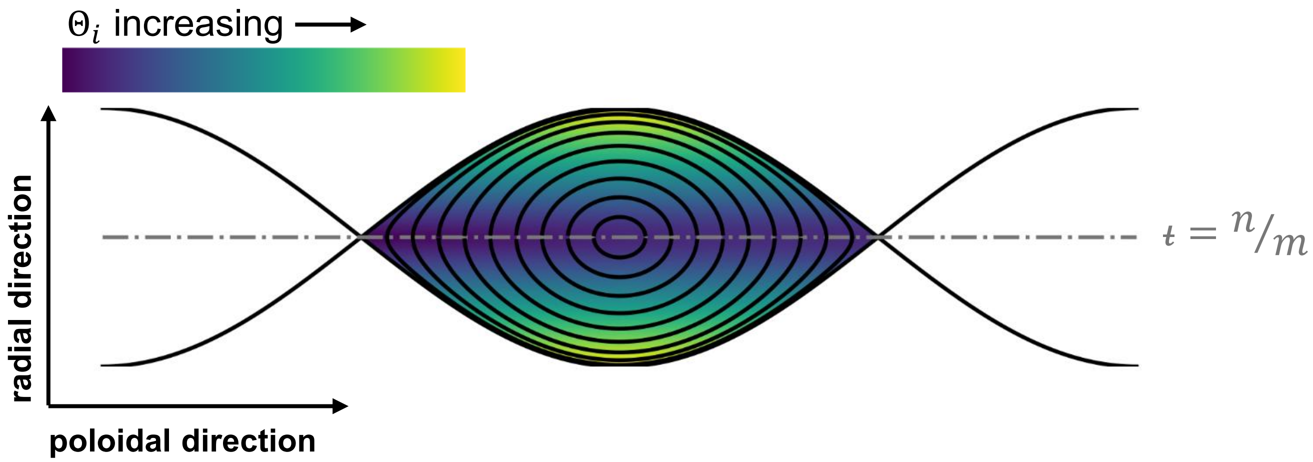
- island divertor formed by resonant surface at plasma edge
  - $n =$ toroidal mode number
  - $m =$ poloidal mode number (# of islands poloidally surrounding LCFS)



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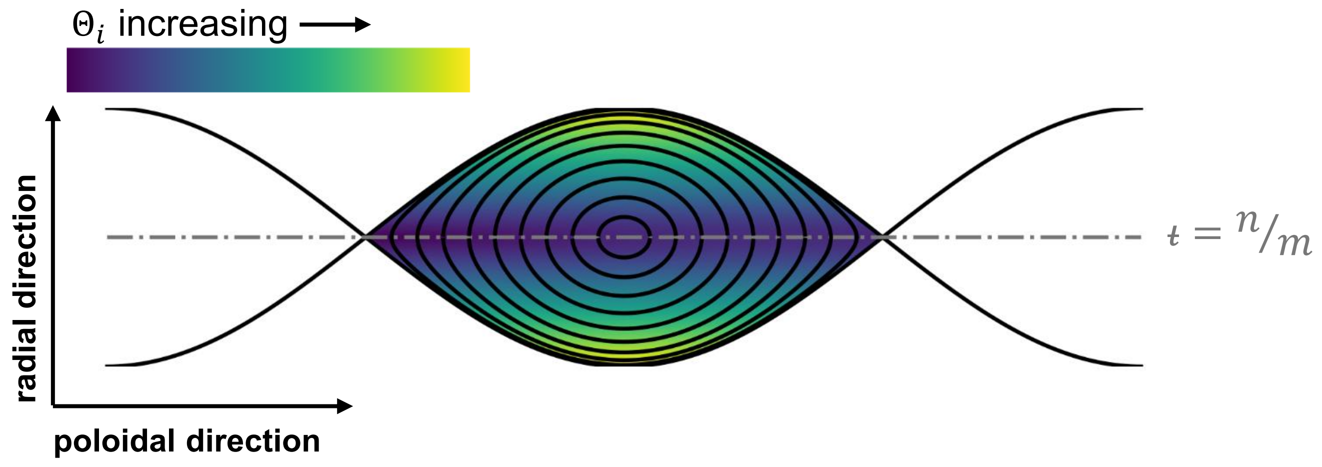
  - $\therefore \Theta_i$ determines projection of $q_\parallel, \Gamma_\parallel$ in radial/poloidal plane



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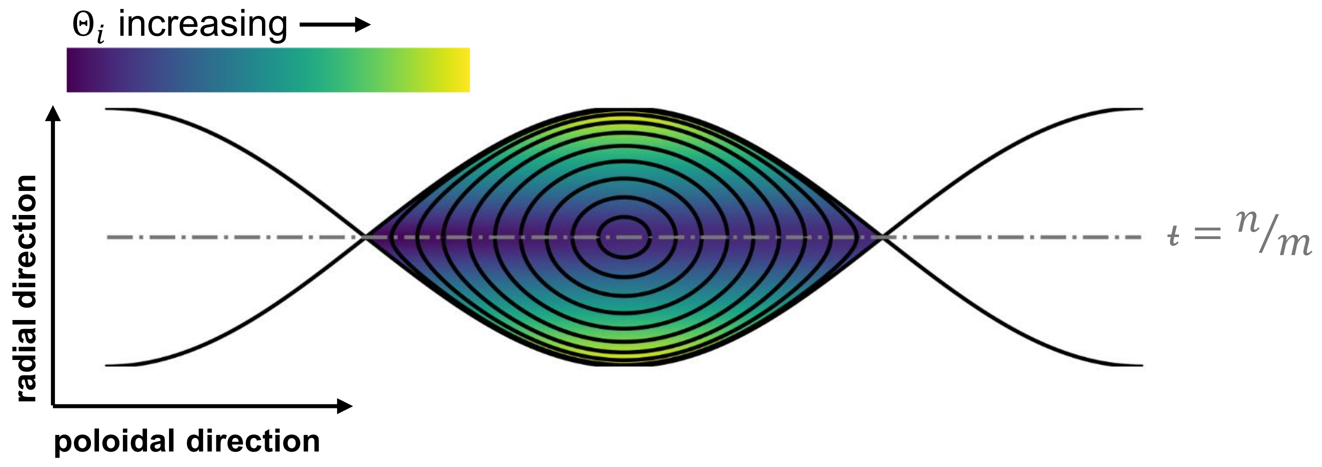
- Θ_i is used to compare importance of ∥- and ⊥-transport
  - smaller $\Theta_i \rightarrow$ smaller projection of $q_{\parallel}, \Gamma_{\parallel}$ in ⊥-plane, means ⊥-transport more important
  - larger $\Theta_i \rightarrow$ larger projection of $q_{\parallel}, \Gamma_{\parallel}$ in ⊥-plane, means ∥-transport more important



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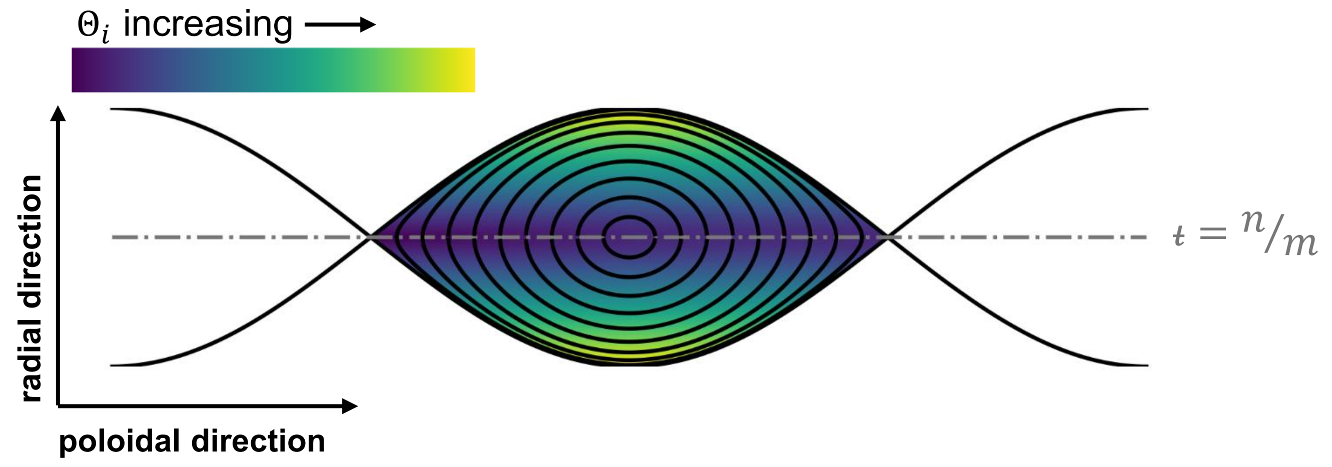


$$\Theta_{i,avg} = 2a\sqrt{\frac{\iota' b_{rm}}{Rm}}$$

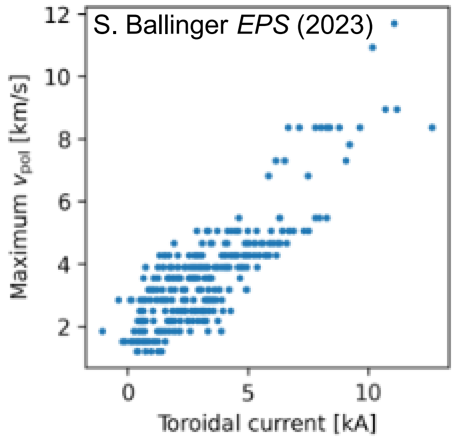
- Indicates the following parameters are important in island divertor transport:
  - ι' (shear at resonant surface)
  - b_{rm} (radial resonant field component)
  - m (poloidal mode number of islands)

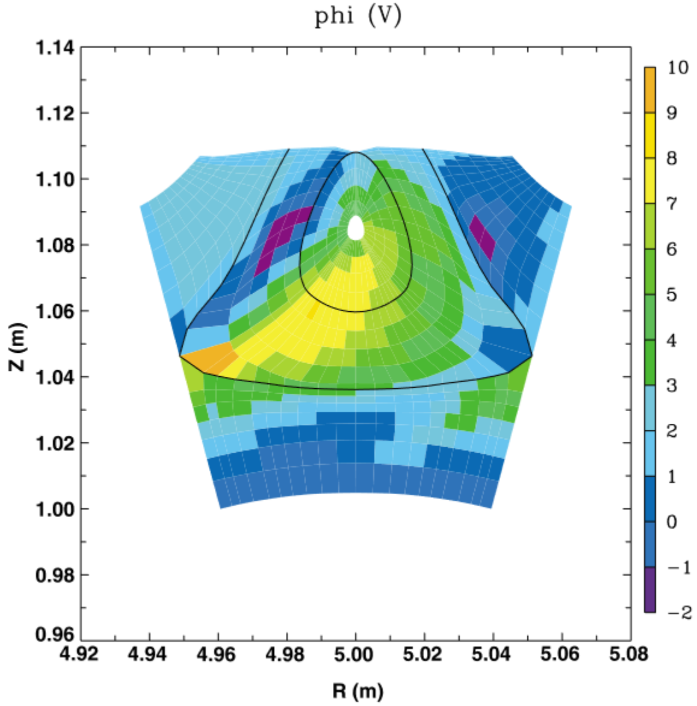
Overview: The gaps and their priorities

Gap ID	Description	Relevance (1-3)	Urgency (1-3)	Effort Required (1-3)	Total Score	Priority
GP.SOL.0	Drift effects on heat/particle transport	3	3	3	9	High
GP.SOL.1	Scaling of anomalous transport with device size/island geometry/plasma parameters	2.75	2.75	2	7.5	Medium – High
GP.SOL.2	Experimental validation of boundary physics models	2.75	2.5	2.25	7.5	Medium – High
GP.SOL.3	Core/Edge compatibility and extrapolation to different devices	2.75	2	2.75	7.5	Medium – High
GP.SOL.4	Island geometry for optimal heat/particle exhaust performance	2.75	3	1.5	7.25	Medium
GP.SOL.5	Evaluation of closed divertor on medium/reactor-sized devices (concept/modelling)	3	2.5	1	6.5	Medium

GP.SOL.0: Drift effects on heat/particle transport

- Very large v_{pol}~1 − 10 km/s measured, while $v_{\parallel}$~50 km/s ($\Theta v_{\parallel}$~0.1 km/s)
    - possibility of drifts *dominating* transport dynamics (W7-X sized device)
- To date, there are no self-consistent tools available to study how drifts affect heat/particle transport
    - Tools in late-stage development include: BOUT++, GBS, GRILLIX





[2] X. Bonnin et al, *J. Nuc. Mater.* **290-293** (2001)

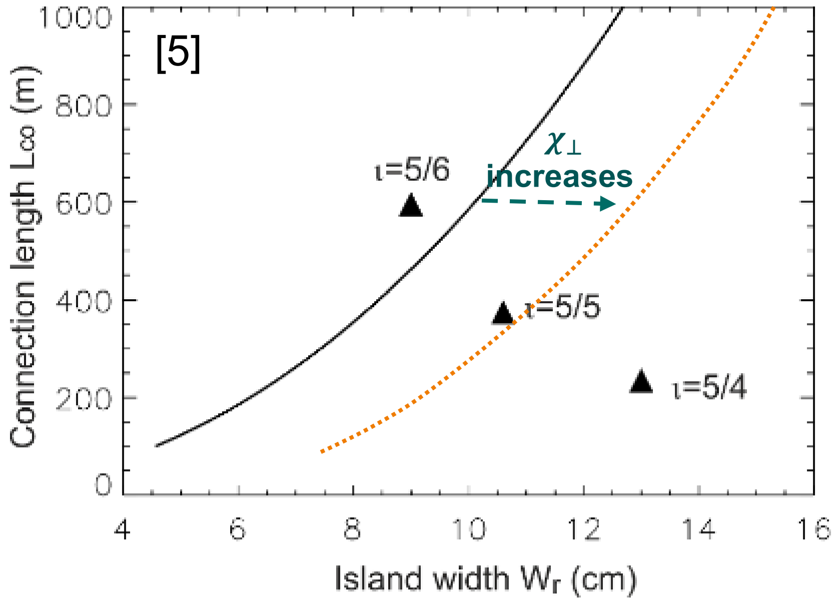
- 2D codes used in early 2000s indicate strong poloidal current loop in island on HFS, w/ poloidal flows surrounding LCFS. Difficulty in numerics[2]

Relevance:	Experimental measurements indicate that drifts may be a dominant transport mechanism in the island SOL
Urgency:	Knowledge of how drifts may alter locations of high heat/particle fluxes onto divertor is imperative for any next step device
Effort:	Numerical implementation of the potential equation in 3D is extremely challenging. Numerics specialists must be involved.

GP.SOL.1: Scaling of anomalous transport with device size/island geometry/plasma parameters

- ❑ Anomalous transport coefficients directly impact cross field momentum/energy transport[3]
  - ❑ impacts momentum conservation along fieldline (upstream vs downstream parameters) – perpendicular viscous momentum loss a main player in detachment in W7-X[4]
  - ❑ strike line width (wetted-area)
  - ❑ radiation stability in detachment[5]

<u>Relevance</u>:	Small Θ_i in stellarators → ⊥-transport important: uncertainties in cross field transport (ex: $D_\perp, \chi_\perp$) means significant uncertainties in divertor performance
<u>Urgency:</u>	W7-AS saw increases of $\chi_\perp$ with input power, indicating significant changes in a reactor compared to today's exp's
<u>Effort:</u>	Many experimental data exist, but hasn't been looked at. Device scaling remains an outstanding issue.

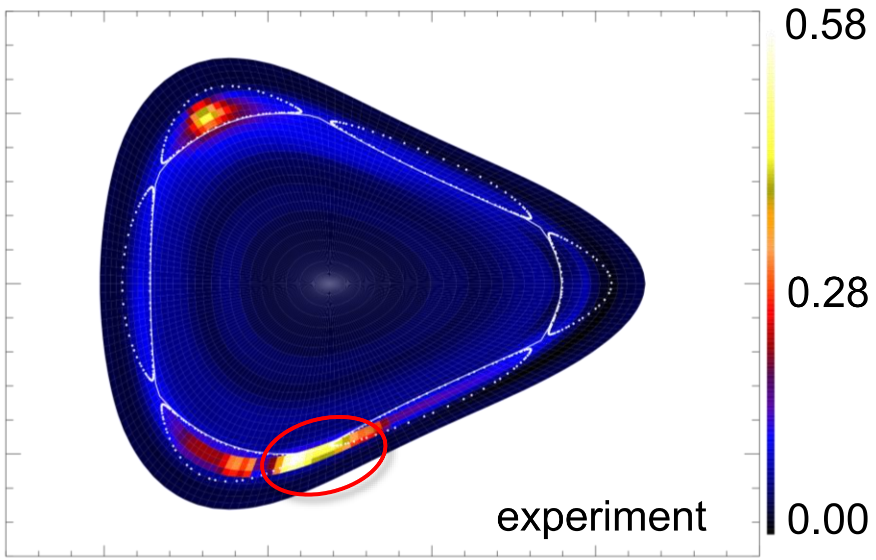


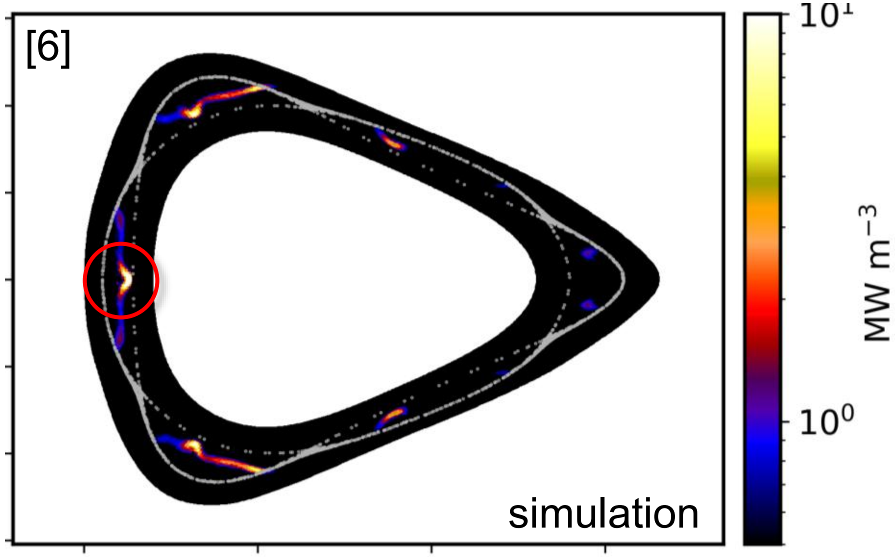
[3] Y. Feng et al, *PPCF* **53** (2011)
[4] Y. Feng et al, *Nucl. Fusion* **51** (2021)
[5] Y. Feng et al, *Nucl. Fusion* **64** (2024)

GP.SOL.2: Experimental validation of boundary physics models

- Simulation tools seem to capture qualitative features[6,7,8], however significant discrepancies remain[9,10]
  - discrepancies include parameters that could significantly affect heat exhaust – like radiation distribution
- detailed experimental comparisons shed light on where physics is missing in codes/importance of these missing aspects
- disagreements between diagnostics (like target T_e, n_e), need to be resolved!

<u>Relevance</u>:	We have to be able to trust our simulation capabilities to predict behavior in future devices
<u>Urgency:</u>	Comparisons are used to inform where resources need to be spent on improving the modeling
<u>Effort:</u>	Significant experimental data exists and dedicated experiments have been performed in OP2.3. Analysis effort needs to be taken/coverage is insufficient





[6] V. R. Winters et al, *PPCF* **63** (2021)
[7] Y. Feng et al, *Nucl. Fusion* **61** (2021)
[8] V. R. Winters et al, *Nucl. Fusion* **64** (2024)
[9] D. Bold et al, *Nucl. Fusion* **62** (2022)
[10] D. Bold et al, *Nucl. Fusion* **64** (2024)

GP.SOL.3: Core/edge compatibility and extrapolation to different devices

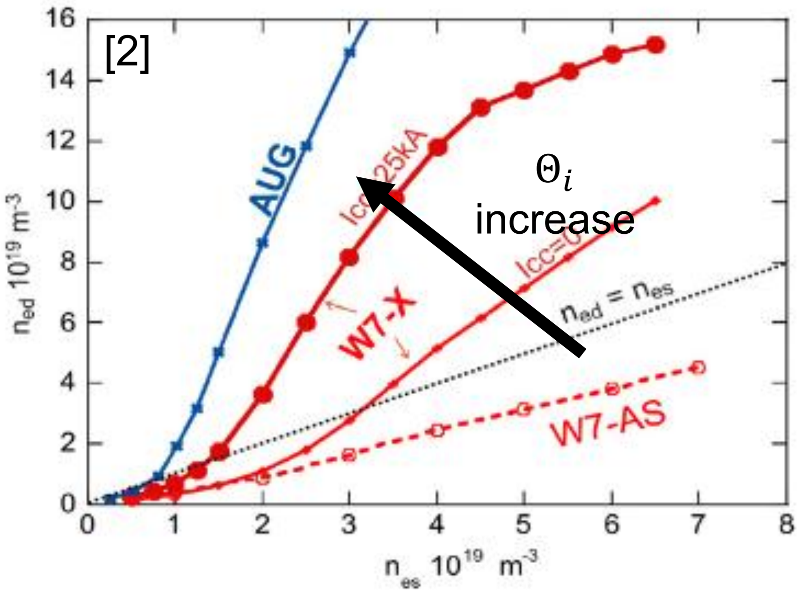
- Combining core high performance and divertor high performance has not been significantly explored in W7-X
  - Detachment in NBI-heated high performance plasmas indicate core/edge compatibility possible, but...
  - still needs to be proven for reactor-relevant high performance scenarios (e.g. pellet-fueling)
- Is this problem W7-X specific? How do we marry core/edge performance in future devices?
  - degradation of upstream pressure at high f_{rad} [3]→ problem for the core?

Relevance:	Optimum core and exhaust performance must be simultaneously achieved in future devices
Urgency:	Understanding base physics is a priority that must be tackled before core/edge compatibility can be fully considered
Effort:	It is not yet known level of core radiation required/minimum upstream parameters needed for certain downstream conditions. Significant work needed for investigation

[3] Y. Feng et al, *Nucl. Fusion* **51** (2021)

GP.SOL.4: Island geometry for optimal heat/particle exhaust

- island geometry expected to influence many aspects of divertor performance:
  - density build-up (heat/particle exhaust)



Relevance:	Island geometry is the clearest knob we have to tune the performance of the island divertor (according to modeling)
Urgency:	Island geometry must be part of the overall stellarator optimization for future devices
Effort:	So far, it is the most-studied effect and significant resources are already allocated to understanding these phenomena

[2] Y. Feng et al, *PPCF* **53** (2011)

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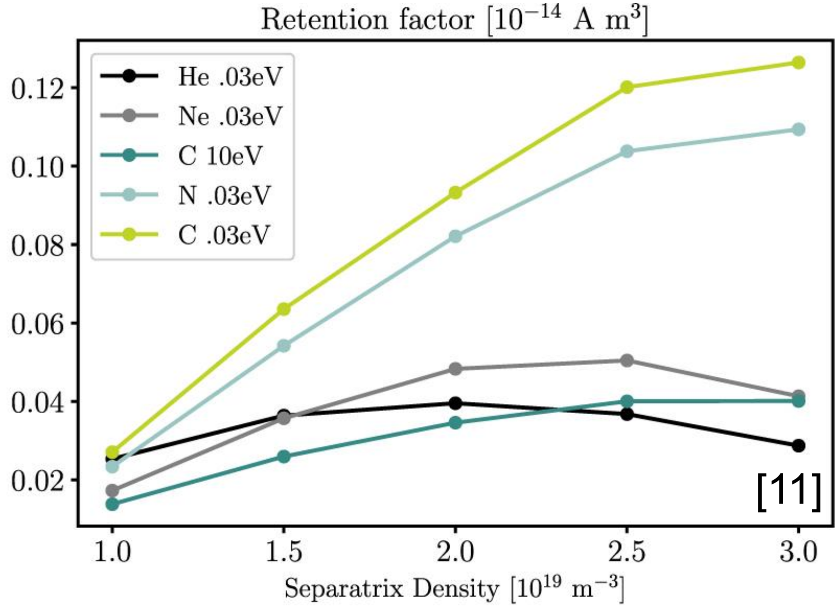
  - impurity transport/screening (heat exhaust, He-exhaust, core performance)



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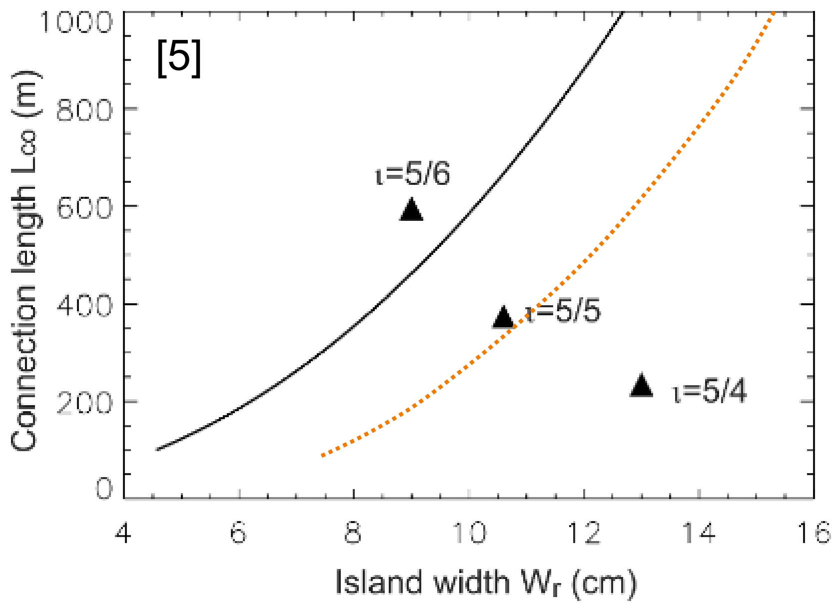

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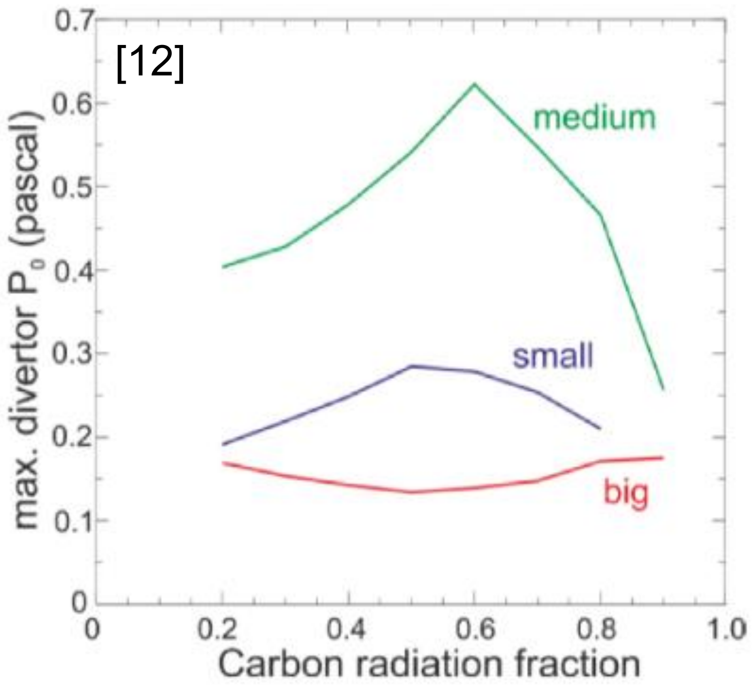
  - density build-up (heat/particle exhaust)
  - impurity transport/screening (heat exhaust, He-exhaust, core performance)
  - radiation stability (heat exhaust)
- Besides Θ_i, other geometrical parameters also influence processes listed above:
  - W_r - physical width of the island
  - fraction of island field lines intercepted by targets (size of „island remnant“)
- More practical considerations: preferred resonance? ex: $\iota = 1$ sensitive to error fields, or minimization of island distortion as a function of toroidal angle?



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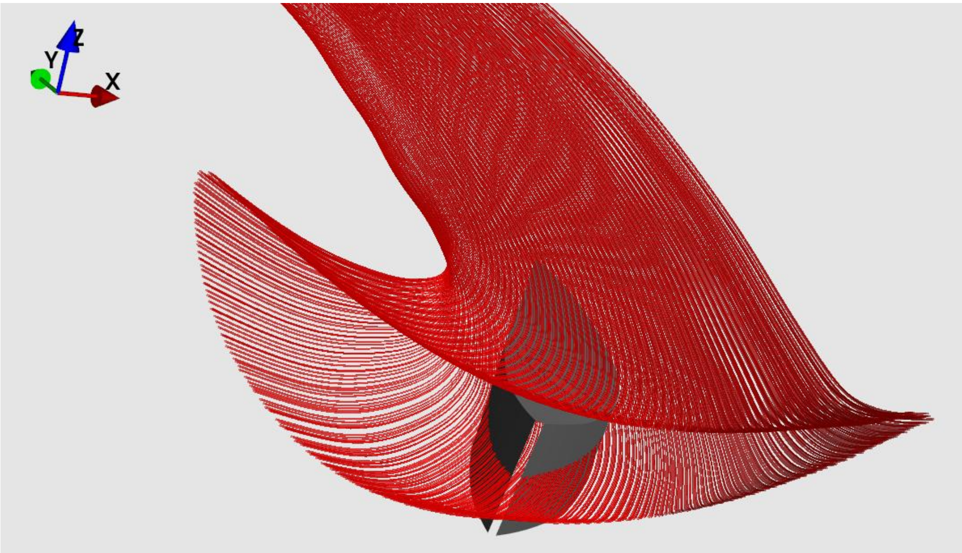
[5] Y. Feng et al, *Nucl. Fusion* **64** (2024)
[12] Y. Feng et al, *Nucl. Fusion* **56** (2016)

GP.SOL.5: Evaluation of closed divertor on medium/reactor scale devices (concept/modeling)

- W7-X employs open divertor concept
  - mostly unexplored: impact of closed divertor geometry on heat/particle exhaust in the island divertor
  - requirement for closed divertor at reactor scale?

- Given exploratory nature of the topic, our assessment *only takes into account initial design and modeling*
  - full-fledged experimental design, engineering, and implementation *not considered* when assigning priority



A. Kharwandikar, *TG Edge, Divertor and PWI* (17.07.24)

Relevance:	Closed divertor may be required in future devices to improve heat/particle exhaust
Urgency:	To design a next step device, it must be known how much of an effect a closed divertor has on performance → significant complexity involved in construction/cooling
Effort:	First modeling results with existing tools can already take place, but only preliminary calculations have been performed