Drift flows impact island divertor operation in Wendelstein 7-X

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ABSTRACT

Drift flows redistribute plasma in the island divertor SOL of W7-X

- flows are oriented in the bi-normal direction
- typical velocities of several km/s
- complex pattern of counter-streaming flows across the island
- ExB nature is indicated by electric potential, T_e measurements

Drift flow transport is very effective due to the small pitch angle

- long parallel connection lengths to the targets in W7-X (several 100m)
- → bi-normal transport is a factor 10^{-3} shortcut compared to parallel heat transport

Drift flows alter heat and particle fluxes to the divertors

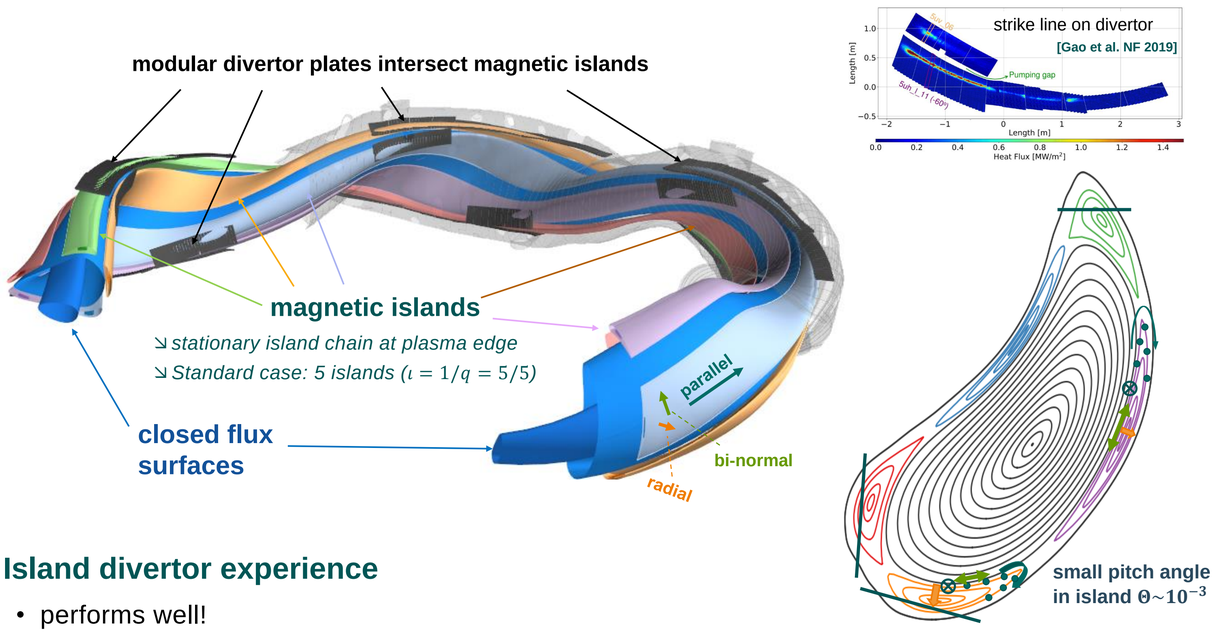
- flows provide an energy transport channel into “shadowed” regions of the SOL
- lead to asymmetries between upper and lower divertors

Velocity and impact of drift flows decreases for higher plasma densities

Challenge for modeling stellarator divertors!

- state-of-the-art 3D edge transport models (EMC3-EIRENE) do not include drifts → cannot globally + consistently reproduce W7-X experimental results
- challenge for W7-X future operation scenarios towards higher heating powers
- stellarator reactor development has to rely on predictive modeling

THE ISLAND DIVERTOR IN W7-X



Island divertor experience

- performs well!
  - ↘*long pulse operation,*
  - ↘*detachment readily achievable*
  - ↘*good impurity retention*
- many fundamental features can be modeled with EMC3-EIRENE

However:

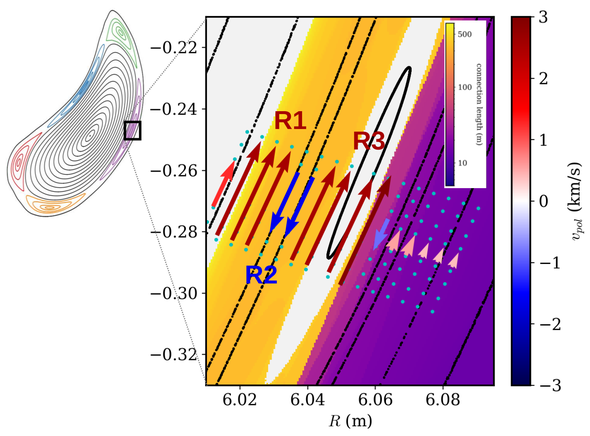
- heat and particle fluxes are not entirely predictable
- likely cause: no drift flow physics in EMC3-EIRENE

Fundamental edge transport directions

- **parallel**: long connection lengths to targets (~ 100m)
  - sheath physics, conductive / convective transport
  - fully included in EMC3-EIRENE
- **radial**: main gradients direction → turbulent transport
  - included in EMC3-EIRENE via prescribed diffusivities
- **bi-normal**: on flux surfaces, e.g. E_rxB drift
  - drifts are **not** included in EMC3-EIRENE

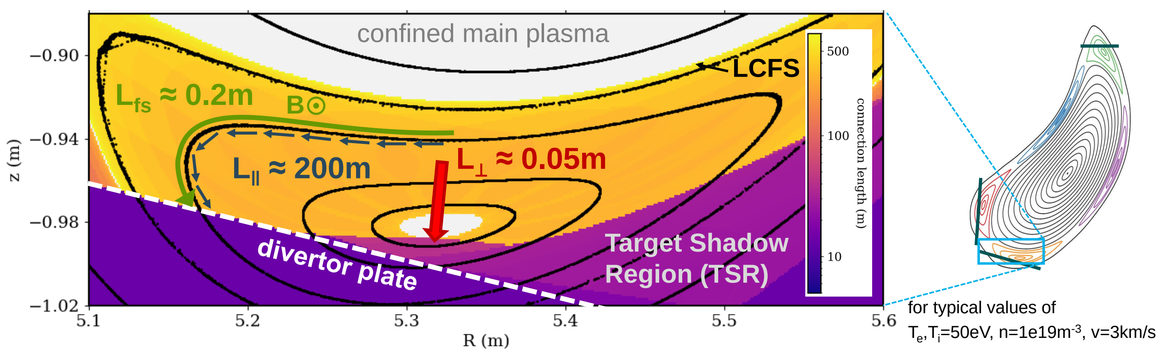
OBSERVATION OF DRIFT FLOWS

Gas Puff Imaging (GPI) [Terry et al., RSI 95 093517 (2024)]



- bi-normal flows with velocity ~km/s
- flow direction changes across the radial range of the island
- detailed flow pattern is highly sensitive to magnetic island geometry
- flow direction flips with field reversal → drift flow

CHARACTERISTIC SCALES IN THE ISLAND SOL



- **perpendicular**: short distance to target, but turbulent particle fluxes are rather small in W7-X [Killer NF 96 096038 (2021)]
- **bi-normal**: $L_{fs} \sim 10^{-3} L_\parallel$ due to small pitch angle Θ
  → effective transport channel even for moderate drift flows

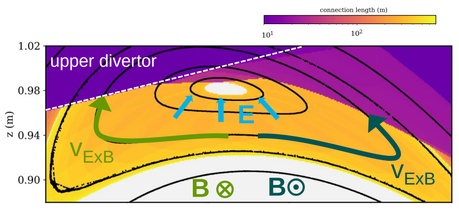
Disclaimer: this is on over-simplification for illustration.
- assumption of constant potential on island flux surfaces is not verified
- no evidence of enormous drift flow velocities up to the targets

$q_\parallel = q_{cond} + q_{conv} \sim 10\mathrm{MW/m^2}$

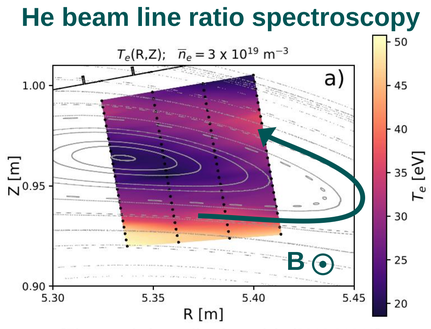
ExB drift flux
$q_{E\times B} = \frac{5}{2} T_e n_e v_{E\times B} \sim 500\mathrm{kW/m^2}$

projecting ExB flux onto the parallel direction
$q_{E\times B,eff} = \Theta^{-1} q_{ExB} > \frac{100\mathrm{MW}}{\mathrm{m^2}} \gg q_\parallel$

$E \times B$ NATURE OF DRIFT FLOWS



He beam line ratio spectroscopy



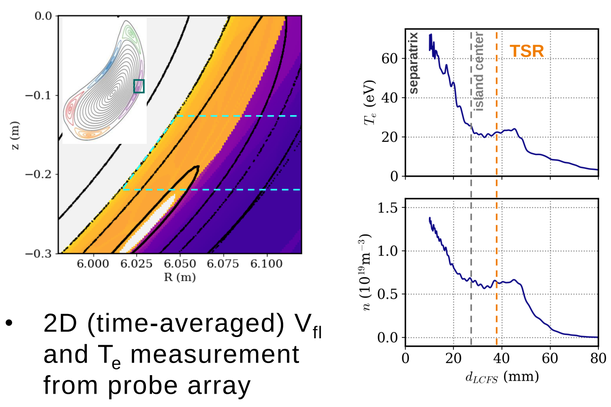
[Flom et al., https://arxiv.org/abs/2312.01240]

- T_e peak in TSR
- T_e minimum at island center

→ electric fields can drive drift flows

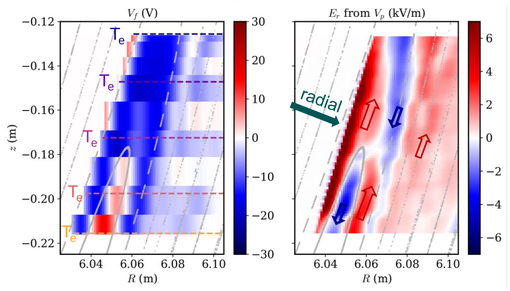
- not reproducible with EMC3-EIRENE

Reciprocating Langmuir probes



- 2D (time-averaged) V_{fl} and T_e measurement from probe array
- $E_r = -\nabla\Phi_{plasma} = -\nabla(V_{fl} + 2.8T_e)$

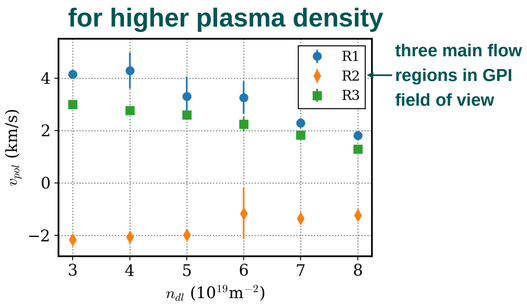
→expect bi-normal $\frac{E_r \times B}{B^2}$ flows, v~km/s



[Killer et al.,NF 65 056026 (2025)]

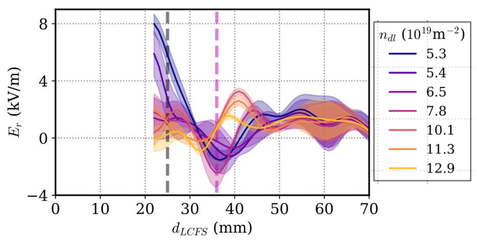
DENSITY DEPENDENCE OF DRIFT FLOWS

GPI flow velocities decrease for higher plasma density



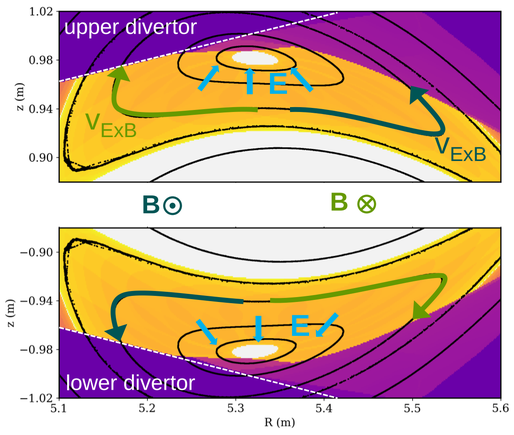
three main flow regions in GPI field of view

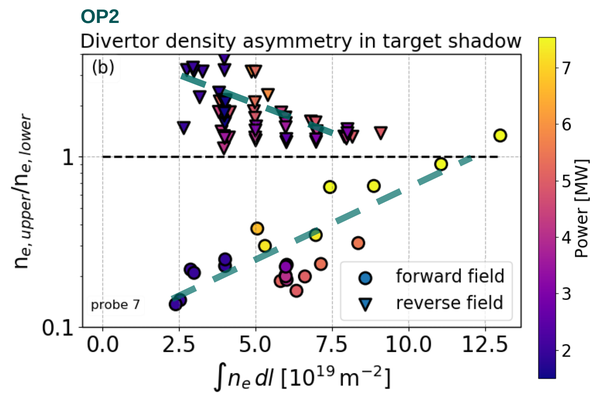
electric fields decrease for higher plasma density

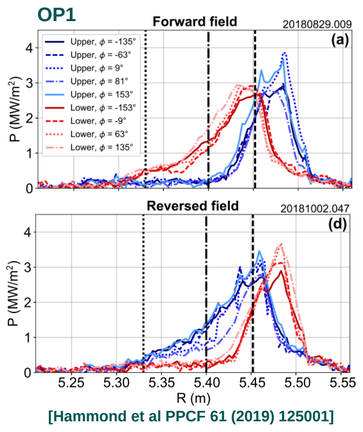


DIVERTOR ASYMMETRIES FROM $E \times B$ FLOWS

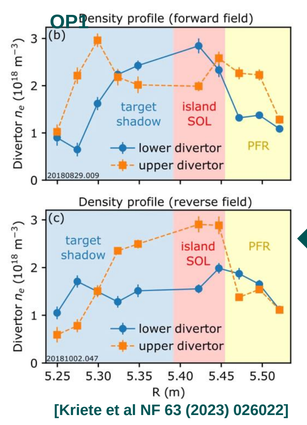
bi-normal drift flows point into / out of the TSR







[Hammond et al PPCF 61 (2019) 125001]



[Kriete et al NF 63 (2023) 026022]

- up-down asymmetry decreases for higher plasma densities

→possibly indicating reduced role of drift flows

- confirmation of previous experiments (“OP1”, with test divertor in different magnetic configuration)

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