Transport of collisional impurities with flux-surface density variation in stellarator plasmas

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Background / Abstract

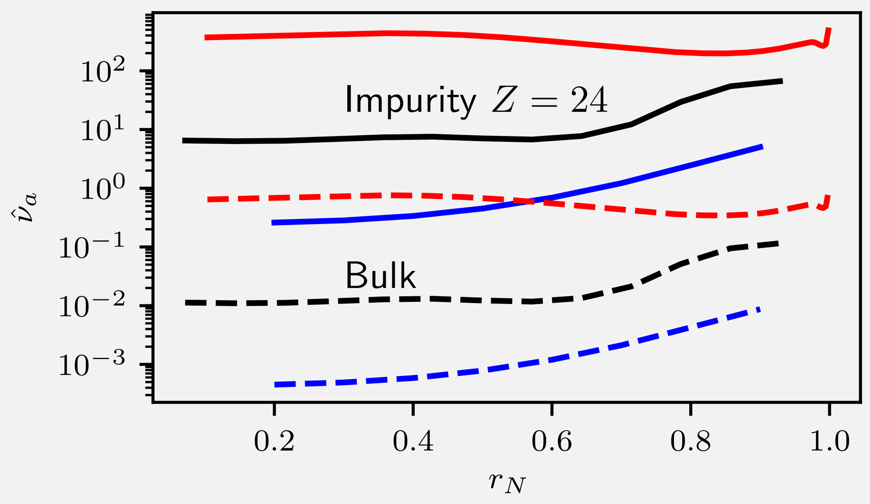
Analytical calculations for stellarators in the *mixed-collisionality* regime [1], have been extended to account for flux-surface variation in the impurity density [2, 3]. Using these results, we search for flux surface variations of the impurity density that lead to the least peaked radial impurity profiles in a W7-X and a LHD case [4]. The optimization can be approximated as minimizing D_{n_i}/D_{N_z}, and has a larger effect on the LHD case.

Mixed-collisionality regime

- Low-collisionality regime ($1/\nu$ or $\sqrt{\nu}$) bulk ion species
- Bulk ion collisionality: $\hat{\nu}_i \propto Z_{\text{eff}} n_e T_i^{-2}$
- Collisional impurity species

$$\implies \hat{\nu}_z = Z^2 \hat{\nu}_i \gg 1 \gg \hat{\nu}_i$$

- Assume $T_z = T_i$, and $Z \gg 1$



Bulk (dashed) and $Z = 24$ impurity (solid) collisionalities for example shots in W7-X, LHD, and TJ-II (not investigated here).

Particle flux

- Classical+neoclassical radial impurity flux:

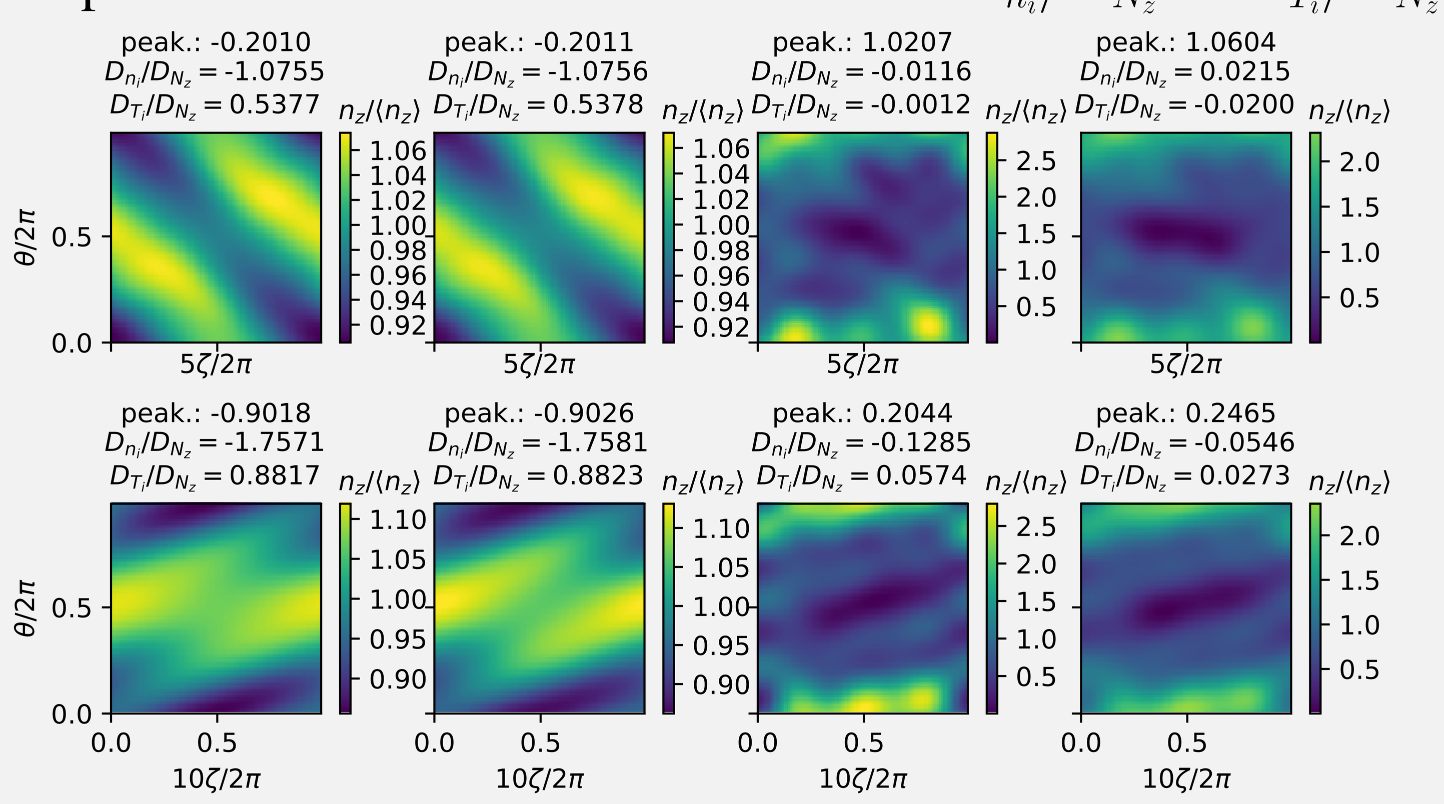
$$\frac{\left\langle \vec{\Gamma}_z \cdot \nabla r_{\rm N} \right\rangle}{\langle n_z \rangle} = -(D_{n_i}[n_z] + D_{N_z}[n_z]) \frac{e}{T} \frac{\mathrm{d}\Phi}{\mathrm{d}r_{\rm N}} - \frac{D_{N_z}[n_z]}{Z} \frac{\mathrm{d}\ln N_z}{\mathrm{d}r_{\rm N}} - D_{n_i}[n_z] \frac{\mathrm{d}\ln n_i}{\mathrm{d}r_{\rm N}} - D_{T_i}[n_z] \frac{\mathrm{d}\ln T}{\mathrm{d}r_{\rm N}}$$

- Peaking factor of N_z

$$\mathcal{P} \equiv -\frac{1}{Z}\frac{\mathrm{d}\ln N_z}{\mathrm{d}r_{\rm N}} = \left(1 + \frac{D_{n_i}}{D_{N_z}}\right) \frac{e}{T}\frac{\mathrm{d}\Phi}{\mathrm{d}r_{\rm N}} + \frac{D_{n_i}}{D_{N_z}}\frac{\mathrm{d}\ln n_i}{\mathrm{d}r_{\rm N}} + \frac{D_{T_i}}{D_{N_z}}\frac{\mathrm{d}\ln T}{\mathrm{d}r_{\rm N}}$$

Optimization of transport coefficients

- We start from a homogeneous n_z and perform gradient-driven optimization to minimize or maximize D_{n_i}/D_{N_z} or D_{T_i}/D_{N_z}



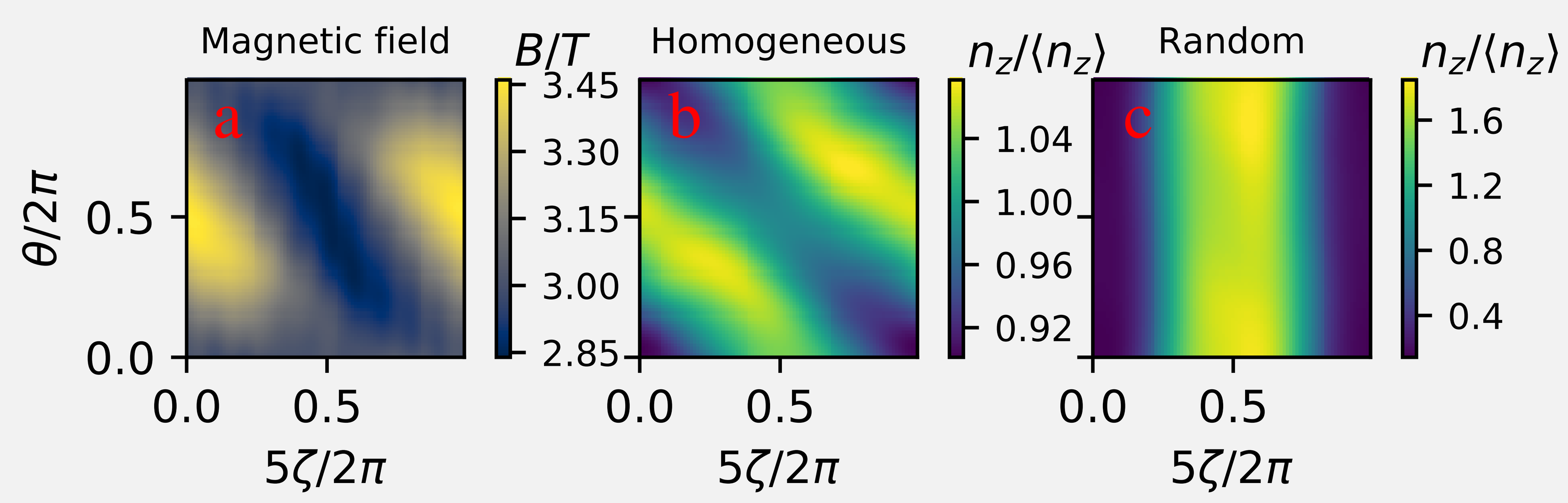
Top: W7-X ($r_N = 0.6$). Bottom: LHD ($r_N = 0.44$)

Left→right: Min. D_{n_i}/D_{N_z}; max. D_{T_i}/D_{N_z}; max. D_{n_i}/D_{N_z}; min. D_{T_i}/D_{N_z}

- $D_{n_i} \approx -0.5 D_{T_i}$ when min. (max.) D_{n_i}/D_{N_z} (D_{T_i}/D_{N_z})

$\implies$ **Can minimize peaking factor by minimizing** D_{n_i}/D_{N_z}

W7-X Magnetic field and optimized flux-surface impurity density



a: W7-X magnetic field at $r_{\rm N} = 0.6$.
b: Local optimum $\mathcal{P}$ reached from a homogeneous initial n_z.
c: Minimum of several local optima initialized with several random n_z.

Flux-surface impurity density variation

- Collisional (Maxwellian) impurity parallel to B:

$$T\nabla_\| n_z + Zen_z \nabla_\| \Phi = R_{z\|} \qquad R_{z\|} : \text{parallel friction force}$$

- If $\Delta \equiv Z^2 \rho_* \hat{\nu}_i \ll 1$: friction force is smaller than electric field

$$\implies n_z = N_z \mathrm{e}^{-Ze\Phi/T} \qquad N_z, T : \text{flux functions} \qquad (1)$$

- Φ, n_z: flux-function, unless at least one species deviates from (1).

Mechanism for this:

- If $\Delta \sim 1$, the impurity density directly violates (1). Relevant in TJ-II.
- Fast particles can deviate from (1), driving significant n_z variation for $Z \gg 1$.
- Helically trapped particles also deviate from (1).

- We consider $\Delta \ll 1$, with n_z (or Φ) specified as input.

$\implies$ n_z can be varied to optimize transport.

Impurity optimization

To see how D_X is affected by n_z flux-surface variations, optimize a Fourier-representation of n_z:

$$\frac{n_z}{\langle n_z \rangle} = a_{00} f_{00}(\theta,\zeta) + \sum_{n=1}^{N} [a_{n0} f_{n0}(\theta,\zeta) + b_{n0} g_{n0}(\theta,\zeta)] + \sum_{n=-N}^{N} \sum_{m=1}^{M} [a_{nm} f_{nm}(\theta,\zeta) + b_{nm} g_{nm}(\theta,\zeta)].$$

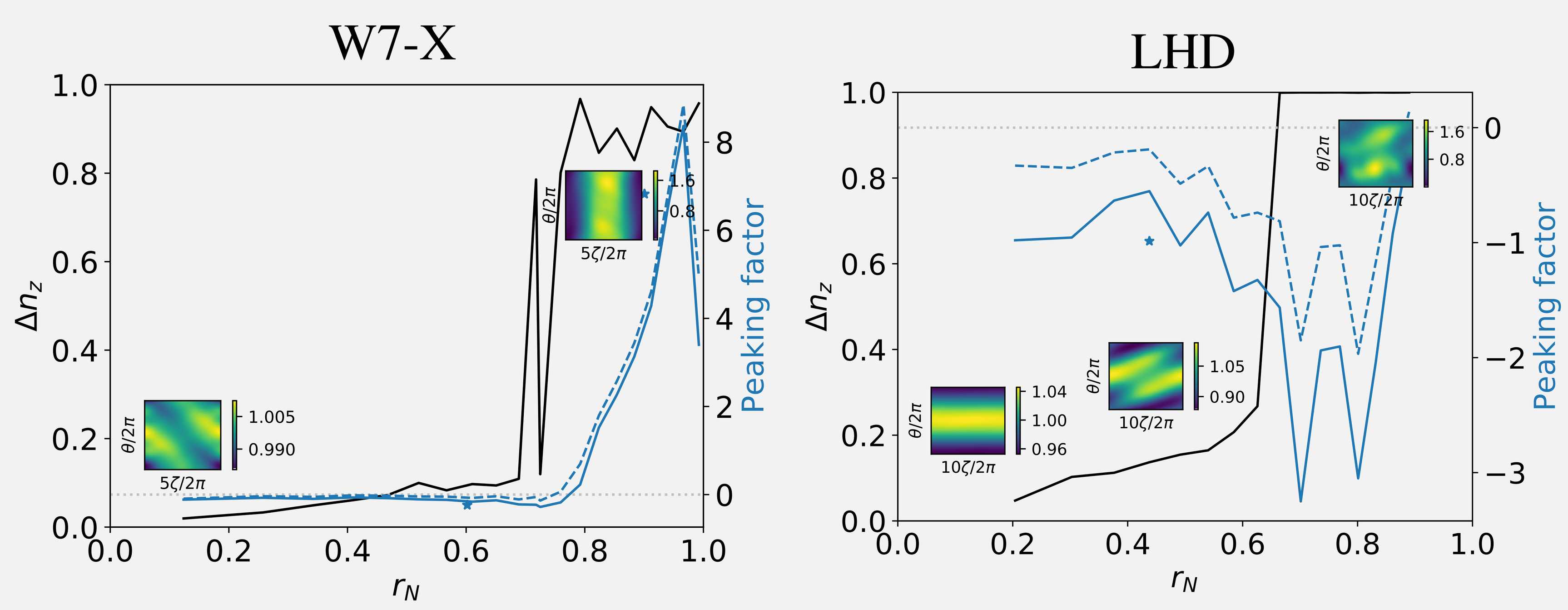
$$f_{nm}(\theta,\zeta) = 1 + \epsilon + \cos(m\theta - N_{\rm p} n\zeta)$$

$$g_{nm}(\theta,\zeta) = 1 + \epsilon + \sin(m\theta - N_{\rm p} n\zeta)$$

Optimization of n_z with 49 Fourier components ($M = N = 3$)

Amplitude of optimal n_z for different radii

- For different radii $r_{\rm N} = \sqrt{\psi_t/\psi_{t,\text{LCFS}}}$
- $\Delta n_z = \max(|n_z/\langle n_z \rangle - 1|)$, from homogeneous initial n_z



Δn_z (black solid), Initial $\mathcal{P}$ (dashed), Optimized $\mathcal{P}$ (solid), Minimum of optima from random initial n_z (star)

- Higher $r_{\rm N}$ $\implies$ strong flux surface variation for optimum
- NOTE: Different kind of optima found at higher $r_{\rm N}$
- **Largest gain from optimizing n_z in the LHD case**

References

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[3] S. Buller et al., Journal of plasma physics 84 (2018) 905840409.
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EUROfusion

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