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 $D_{\nu}/D_N$, and has a larger effect on the LHD case.

Mixed-collisionality regime

- Low-collisionality regime ($1/\sqrt{\nu}$ or $\sqrt{\nu}$) bulk ion species
- Bulk ion collisionality: $\nu_i \propto Z e^{2 n_i} T^{-2}$
- Collisional impurity species
  $$\Rightarrow \nu_i = Z^{\nu_i} \gg 1$$
- Assume $T_e = T_i$ and $Z \gg 1$

Impurity optimization

- Peaking factor of $N_i$
  $$P = \psi N_i = \frac{1 \ln N_i}{\ln \rho_i} = \left(1 + \frac{D_{n_i}}{D_N} \frac{\ln n_i}{\ln N_i} + \frac{D_{\nu_i}}{D_N} \frac{\ln \nu_i}{\ln N_i}\right)$$

Optimization of transport coefficients

- We start from a homogeneous $n_i$ and perform gradient-driven optimization to minimize or maximize $D_{\nu_i}/D_N$ or $D_{\nu_i}/D_N$.

References


Flux-surface density variation

- Collisional (Maxwellian) impurity parallel to $B$:
  $$T \nabla n_i + Z n_e \nabla \phi = R_{\parallel}$$
- $R_{\parallel}$: parallel friction force
- If $\Delta \equiv Z^{\nu_i} \ll 1$: friction force is smaller than electric field
  $$\Rightarrow n_i = N e^{\phi i} \frac{N_{\nu_i}}{T_i}$$
- $\Phi, n_i$: flux-function, unless at least one species deviates from (1).

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

We consider $\Delta \ll 1$, with $n_i$ (or $\phi_i$) specified as input.
$$\Rightarrow n_i$$ can be varied to optimize transport.

Impurity optimization

To see how $D_X$ is affected by $n_i$, flux-surface variations, optimize a Fourier-representation of $n_i$:
$$n_i = a_{00} \Theta(\theta, \zeta) + \sum_{n=1}^{N} a_{n0} \Theta(\theta, \zeta) + b_{0n} \Theta(\theta, \zeta) + \sum_{n=1}^{N} b_{n0} \Theta(\theta, \zeta)$$

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

Amplitude of optimal $n_i$ for different radii

- For different radii $r_N = \sqrt{\psi_s / \psi_{HFS}}$
- $\Delta n_i = \max (|n_i| - |n_i|)$, from homogeneous initial $n_i$

Minimization of optima from random initial $n_i$ (star)

- Higher $r_N \Rightarrow$ strong flux surface variation for optimum
- NOTE: Different kind of optima found at higher $r_N$
- Largest gain from optimizing $n_i$ in the LHD case

W7-X

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