Collisional transport of heavy impurities with flux-surface density variation in stellarators

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Central accumulation of heavy impurities is a serious concern for any fusion device. It is believed to be particularly problematic in stellarators, where impurities tend to be transported in the direction of the radial electric field, which is expected to point inwards under reactor-relevant conditions. As such, impurity accumulation is observed in a wide-range of experimental scenarios, with the notable exceptions of impurity-hole discharges in the Large Helical Device (LHD), high-density discharges in Wendelstein 7-AS, and recent Wendelstein 7-X (W7-X) plasmas.

In order to understand these discharges, and the transport of impurities in stellarators in general, previously neglected effects related to electrostatic-potential variation tangential to the flux-surfaces have recently started to receive attention. Such variations are typically weak, but can still have a large effect on the transport of impurities with high charge-number Z, as has been demonstrated for collisional transport in both tokamaks[1] and stellarators[2].

For high-Z impurities, the most relevant collisionality regime is the *mixed-collisionality regime*, where the impurities are collisional and the bulk ions are in a low-collisionality regime. Recent theoretical work[3], has shown that when the bulk ions are in the $1/\nu$ regime, the transport of the impurities becomes independent of the radial electric field, which challenges the conventional explanation of the observed impurity accumulation. However, it was recently found that even small amplitude flux-surface potential variations restores the sensitivity to the radial electric field in this regime[4, 5], which again results in impurity accumulation for most cases considered. The purpose of the current work is to further explore this effect, and specifically to investigate where flux-surface potential variations cause the largest sensitivity to the radial electric field.

Theoretical framework and formulas In this work, we explore how the collisional impurity flux is affected by flux-surface variation in the impurity density n_z caused by a Boltzmann-response $n_z = N_z(\psi)\mathrm{e}^{-Ze\tilde{\Phi}/T(\psi)}$ to a given flux-surface electrostatic-potential variation $\tilde{\Phi}$. Here, $Z \gg 1$ is the impurity charge-number and $T(\psi)$ the impurity temperature which is equal to the bulk-ion temperature; N_z is a flux-function known as the *pseudo-density*; ψ labels a flux-surface and acts as a radial coordinate.

The radial flux of impurities can be written as

$$\langle \mathbf{\Gamma}_z \cdot \nabla\psi \rangle = \langle n_z \rangle \left(D_\Phi \frac{e}{T}\frac{\mathrm{d}\langle\Phi\rangle}{\mathrm{d}\psi} - D_{n_i}\frac{\mathrm{d}\ln n_i}{\mathrm{d}\psi} - D_{T_i}\frac{\mathrm{d}\ln T}{\mathrm{d}\psi} - \frac{1}{Z} D_{N_z}\frac{\mathrm{d}\ln N_z}{\mathrm{d}\psi} \right), \qquad (1)$$

where $\langle\cdot\rangle$ denotes a flux-surface average, and the transport coefficient are in general a sum of neoclassical and classical contributions $D = D^{\text{NC}} + D^{\text{C}}$, except the purely neoclassical D_Φ. These coefficients and their derivation can be found in Ref. [5]. Crucially, the transport coefficients depend on flux-surface averages of n_z, weighted by various functions of the geometry. Since $\tilde{\Phi}$ in this formulation only affects the transport through n_z, we will specify n_z directly, rather than $\tilde{\Phi}$, and speak of impurity variation on the flux-surface.

Impurity variation on flux-surface As a model for an impurity density that is localized on the flux-surface, we use an unnormalized *von Mises distribution*,

$$p(\zeta,\theta) = \exp\left\{\kappa_\theta \cos[N_\theta(\theta-\theta_0)] + \kappa_\zeta \cos[N_\zeta(\zeta-\zeta_0)]\right\} / \exp\left\{\kappa_\theta + \kappa_\zeta\right\} \qquad (2)$$

which approximates a Gaussian wrapped around a circle. Here, N_θ indicates the number of periods in θ; κ_θ is the width of the distribution and θ_0 the θ-location impurities are localized around – and likewise for ζ. Here, θ (ζ) is the poloidal (toroidal) angle in Boozer-coordinates.

Specifically, we write the impurity density as

$$\frac{n_z(\zeta,\theta)}{\langle n_z \rangle} = \frac{1}{1 + A\langle p \rangle}(1 + Ap) \qquad (3)$$

where A is the amplitude of the von Mises shaped perturbation relative to the constant background.

Close-up of a W7-X case To investigate the effects of a localized impurity distribution, we evaluate the transport coefficients in a W7-X standard equilibrium (at $r_N = 0.6$, where $r_N = \sqrt{\psi_t/\psi_{t,\text{LCFS}}}$), for a series of distributions (3), all localized about $(\zeta,\theta) = (\pi/5, 4\pi/6)$ with $\kappa_\theta = \kappa_\zeta = 3$, but with different amplitudes. The resulting D's are shown in Figure 1, for $Z = 24$. Note that, D_{N_z} (not shown in the figures) is given by $D_{N_z} = -(D_{n_i} + D_\Phi)$, and is always positive. From Figure 1, we see that when $A = 0$, $D_\Phi = 0$, but

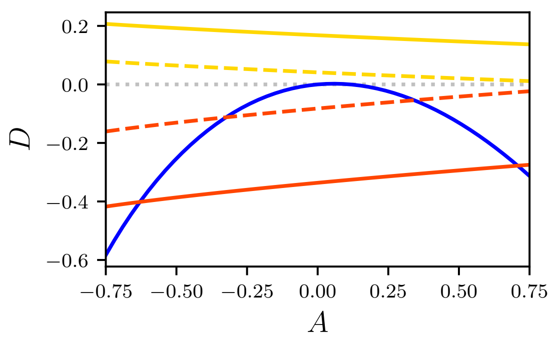

Figure 1: **Coefficients** D_Φ (blue), D_{n_i} (red), D_{T_i} (yellow); plotted against A. **Linestyles:** $D^{\text{NC}} + D^{\text{C}}$ (solid), D^{NC} (dashed).

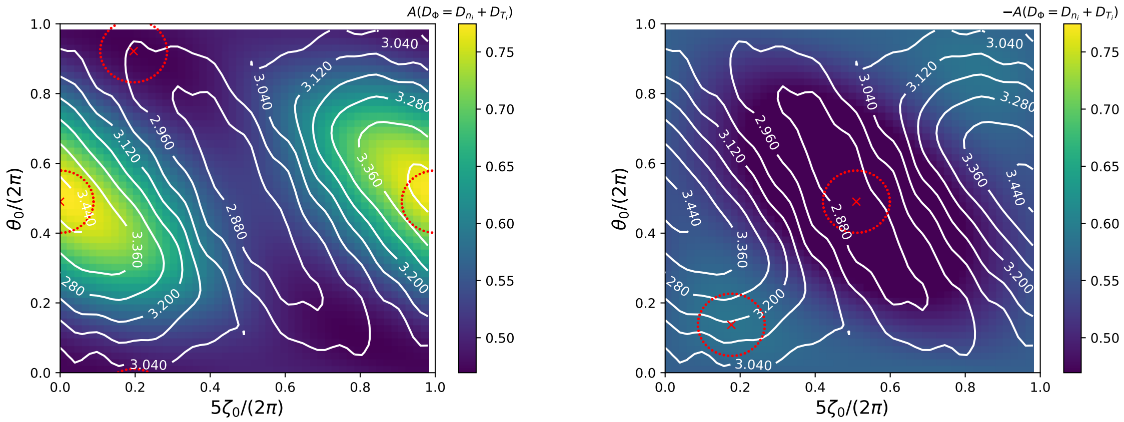

Figure 2: **Color:** Amplitude A at which $D_\Phi = D_{n_i} + D_{T_i}$, as a function of the location of the density perturbation, (θ_0, ζ_0). Left (right) figure is for positive (negative) A. **Contour:** B in units of Tesla. **Red:** Contour of the n_z resulting in maximum and minimum $A(D_\Phi = D_{n_i} + D_{T_i})$.

that sufficiently large $|A|$ causes D_Φ to dominate the other transport coefficients, leading to impurity accumulation for an inward pointing radial electric field. This behaviour is observed in the core of every magnetic configuration considered here and in Ref. [5], although the specific amplitude at which D_Φ becomes dominant varies.

To see how this specific amplitude (henceforth denoted by A_Φ) varies depending on where the perturbation is located, we scanned the position of the perturbation in θ and ζ, and extracted A_Φ for each θ_0, ζ_0. The result is presented in Figure 2. For $A > 0$, A_Φ is greatest around the maximum of B, and is smallest around a point along the valley in B where the minima is located. For $A < 0$, the minimum in $|A_\Phi|$ is located at the minimum of B, while the maximum is located at the edge of the ridge where the maximum of B is located. The greatest $|A_\Phi|$ (of any sign) is located around the maximum of B, while the smallest is around the minimum of B. This indicates that larger perturbations can be admitted around the maximum without causing an inward electric field to accumulate impurities.

Radial scan Having established that impurities localized around maxima (minima) of B causes the transport to be the least (most) sensitive to the radial electric field, we next perform scans in radius with the impurities localized at the maximum and minimum of B on each flux-surface. The resulting A_Φ for each radius and scan is presented in Figure 3. At outer radii, closer to the coils, the magnetic field develops sharper features on the flux-

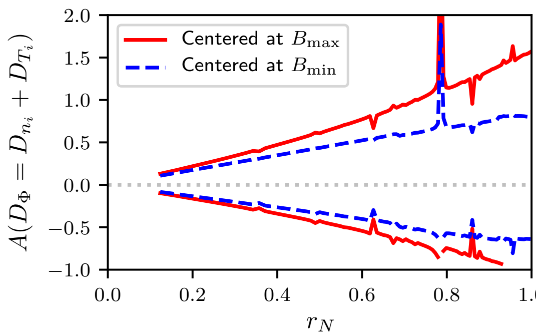

Figure 3: A at which $D_\Phi = D_{n_i} + D_{T_i}$ for perturbations centered around $B_{\max}$ and $B_{\min}$, as a function of radius.

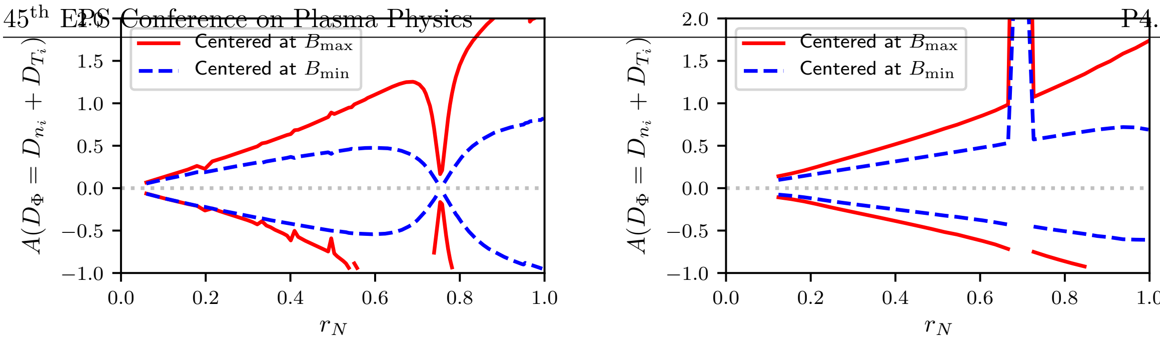

Figure 4: Scans corresponding to those in Figure 3, but for an TJ-II equilibrium (left) and a high-mirror W7-X equilibrium (right).

surface, and higher amplitudes are needed for D_Φ to dominate. The magnitude of the negative A_Φ is smaller than that of the positive, meaning that impurity decumulation around the extrema causes D_Φ to dominate faster than accumulation.

Radial scans in different configurations To see whether the above results extrapolate to different magnetic configurations, similar scans were performed for a W7-X high-mirror equilibrium [6] and a TJ-II equilibrium [2]. The results are shown in Figure 4. By comparing with Figure 3, we see that both W7-X configurations have similar A_Φ. Away from the large dip at the $8/5$ rational surface at $r_N = 0.755$, the TJ-II configuration has roughly the same A_Φ, although it increases a bit more sharply with radius. It should be noted that even when the radial electric field does not dominate the impurity transport in the sense that $|D_\Phi| > |D_{T_i} + D_{n_i}|$, an inward electric field can nevertheless have a large deleterious effect and make temperature screening impossible in practice.

Lastly, it should be noted that, since the D's depend non-linearly on n_z, the above sensitivities to the amplitude of localized perturbations may not translate to sensitivities to perturbations of other shapes.

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