The role of poloidal asymmetries in impurity transport

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If the density of the impurity ions is poloidally asymmetric then the zero-flux impurity density gradient (the peaking factor) can be reduced. The convective impurity flux can even change sign if the asymmetry is sufficiently large. This effect is most effective in low-shear plasmas with the impurity density peaking on the inboard side and may be a contributing factor to the observed outward convection of impurities in the presence of radio frequency (RF) heating.

Introduction Poloidal asymmetries of impurities in tokamaks can arise due to toroidal rotation, neoclassical effects, asymmetry in impurity source location or the presence of RF heating. In the case of RF heated plasmas, the asymmetry is a result of the increase in the hydrogen-minority density on the outboard side. These particles tend to be trapped on the outside of the torus and the turning points of their orbits drift towards the resonance layer due to the heating. The poloidal asymmetry in the hydrogen-minority density gives rise to an electric field that pushes the other ion species to the inboard side [1]. In the case of highly-charged impurities, this effect is amplified by their large charge Z. In the tokamak edge, where the plasma is sufficiently collisional, also steep radial pressure or temperature gradients can give rise to an in-out asymmetry. These effects have been observed in e.g. Alcator C-Mod [2], and it has been shown that the observations are in qualitative agreement with neoclassical theory. The sign and magnitude of these asymmetries depend sensitively and nonlinearly on magnetic geometry, fraction of impurities in the plasma and rotation. Neoclassical theory also predicts an up-down asymmetry, which is caused by the ion-impurity friction. If the impurity density varies over the flux surface, in general we can write $n_z = n_{z0}\mathcal{P}(\theta)$, where $\mathcal{P}(\theta) = 1$ if the impurities are evenly distributed over the flux surface. A poloidal asymmetry can be modelled by $\mathcal{P}(\theta) = \left[\cos^2\left(\frac{\theta-\delta}{2}\right)\right]^n$, where δ is the angular position where the impurity density has its maximum. The peakedness of the asymmetry grows with n.

Since impurity transport is usually dominated by drift-wave turbulence, in this work we focus on the effect of the impurity poloidal asymmetry on impurity transport driven by microinstabilities. We assume that the neoclassical processes that cause the asymmetry are not affected significantly by the fact that the cross-field transport is dominated by fluctuations, and that the equilibrium part of the electric field is not large enough to cause poloidal asymmetries in the main ion and electron densities. For simplicity we consider only the collisionless, electrostatic case and neglect the effect of rotation. We assume large-aspect-ratio, low-beta, toroidal symmetry and circular cross section. The eigenvalues and electrostatic potential are obtained from GYRO, and the results for the peaking factors have been benchmarked to GYRO in the poloidally symmetric case. Our results show that inboard accumulation gives rise to negative peaking factors (outward impurity convection and hollow impurity profile), both in ion temperature gradient (ITG) and trapped electron (TE) mode driven turbulence [3,4].

Peaking factor The quasilinear impurity particle flux is given by $\Gamma_z = -k_\theta \mathrm{Im}[\hat{n}_z\phi^*]/B$ where $\mathrm{Im}[\cdot]$ denotes imaginary part, k_θ is the poloidal wave-number, $\hat{n}_z$ is the perturbed impurity density, B the equilibrium magnetic field, ϕ^* is the complex conjugate of the perturbed electrostatic potential ϕ. The peaking factor (a/L^0_{nz}, where a is the minor radius and L^0_{nz} is the impurity density scale length for zero flux) is obtained from $\langle \mathrm{Im}[\hat{n}_z\phi^*]\rangle = 0$, where $\langle\cdots\rangle = (1/2\pi)\int_{-\pi}^{\pi}(\cdots)d\theta$.

If parallel compressibility is neglected, an approximate analytical expression for the peaking factor can be derived as

$$\frac{a}{L^0_{nz}} = -\frac{Z\tau_z}{k_\theta\rho_s}\frac{\mathrm{Im}\left\{\left\langle\mathcal{P}(\theta)\left[|\phi|^2\left[C_d(\tilde{\omega}_{Dz})+T_d(\tilde{\omega}_{Dz},L_{Tz})\right]\right]\right\rangle\right\}}{\mathrm{Im}\left\{\left\langle\mathcal{P}(\theta)\frac{1}{\bar{\omega}}\left[|\phi|^2\left[1+C_d(\tilde{\omega}_{Dz})\right]\right]\right\rangle\right\}}, \tag{1}$$

where $C_d = (3\tilde{\omega}_{Dz}/2-b_z)(1+5\tilde{\omega}_{Dz}\mathcal{F}^1_{7/2}/2)$ represents the curvature drift and $T_d = \tilde{\omega}_{*z}\eta_z \times (3\tilde{\omega}_{Dz}/2-b_z)\left[3/2-5\left(1-3\tilde{\omega}_{Dz}/2\right)\mathcal{F}^1_{7/2}/2\right]$ represents thermodiffusion, $\omega_{*z} = -k_\theta T_z/e_zBL_{nz}$ is the diamagnetic frequency, $\omega_{Dz} = \omega_{Dz0}(\cos\theta + s\theta\sin\theta)$ is the magnetic drift frequency, $\omega_{Dz0} = -2k_\theta v^2_{Tz}/3\omega_{cz}R$, ω_{cz} is the cyclotron frequency, q is the safety factor, s is the magnetic shear, $b_z = b_{z0}\left(1+s^2\theta^2\right)$, $b_{z0} = (k_\theta\rho_{sz})^2$, $\eta_z = L_{nz}/L_{Tz}$, where L_{nz} and L_{Tz} are the density and temperature scale lengths, $\bar{\omega}$ is ω normalized to c_s/a, and $\tau_z = T_e/T_z$. The tilde denotes normalization to ω. The effect of drift resonances is incorporated in $\mathcal{F}^a_b$, where $\mathcal{F}^a_b(\tilde{\omega}_{Dz}) = {}_2F_0\left(a,b;;\tilde{\omega}_{Dz}\right)$, and ${}_2F_0$ denotes a generalized hypergeometric function. Note, that no ansatz for the perturbed electrostatic potential is used (instead, these are obtained by GYRO). The expression (1) is valid for both TE and ITG mode driven turbulence, and in the derivation we only kept linear terms in b_z and used the constant energy resonance (CER) approximation $[v^2_\perp + 2v^2_\parallel \to 4(v^2_\perp + v^2_\parallel)/3]$. The largest term in (1), which usually gives rise to an inward flux in the poloidally symmetric case, is the one proportional to the curvature drift. This term is reduced or even becomes negative if the impurities accumulate on the inboard side and this is the main reason for the reduced peaking factor. The rest of the terms are proportional to $1/Z$ and are small for high-Z impurities. The sign of the terms due to thermodiffusion depend on the underlying instability. In the poloidally symmetric case they would give rise to an outward flux if the turbulence is ITG-dominated and an inward flux in the opposite case. However, in the in-out asymmetric case this is also changed. The terms proportional to b_z stem from the finite Larmor radius parameter and are usually small. Figure 1a illustrates that for strongly peaked asymmetries if δ is close to π (inboard accumulation), the sign of the peaking factor changes. Fig. 1b shows that in this particular JET-like case [5] the peaking factor is very sensitive to the peakedness of the asymmetry in the case of in-out asymmetry ($\delta = \pi$). The sign change occurs around $n \simeq 3$. However, if the impurities are accumulated on the outboard side ($\delta = 0$), a/L^0_{nz} grows with n, but it is less sensitive to the peakedness of the asymmetry. An up-down asymmetry reduces a/L^0_{nz}, but not as much as the in-out asymmetry and a sign change is not expected to occur.

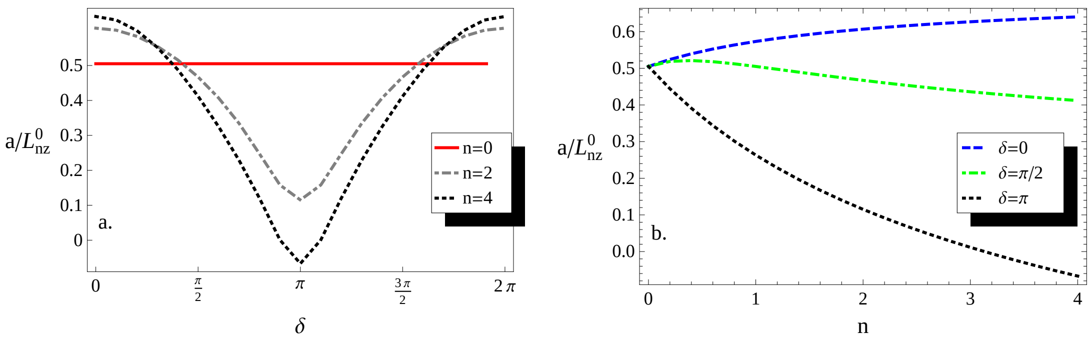

Figure 1: *Peaking factor for nickel for various asymmetry maxima and strengths: (a) as a function of* δ *for three different values of* n*; (b) as a function of* n *for various values of* δ*. The rest of the parameters are* $r/a = 0.3$, $R/a = 3$, $k_\theta \rho_s = 0.3$, $q = 1.7$, $a/L_{ne} = 1.3$, $a/L_{ni} = 0.86$, $T_i/T_e = 0.85$, $a/L_{Te} = 0.2$, $a/L_{Ti} = 0.3$, $s = 0.22$, $n_z/n_e = 10^{-3}$ *and* $\rho_s/a = 0.0035$.

Figure 2a shows the peaking factor for nickel as a function of ion and electron temperature gradients for different values of δ and $n = 4$, with (a,c) and without (b,d) parallel compressibility. The peaking factors are computed numerically, without assumptions on the magnitude of b_z or the CER approximation [4]. Parallel compressibility has a significant effect. This is mainly due to the fact that inclusion of parallel compressibility introduces a dependence on the derivatives of the real and imaginary parts of the electrostatic potential. Although the absolute value of the potential is almost unchanged, the real and imaginary parts are significantly affected by the change in the temperature gradients. Therefore, the peaking factor is much more sensitive to the temperature gradients if parallel compressibility is included. Note that in certain cases also up-down asymmetry may generate a negative peaking factor.

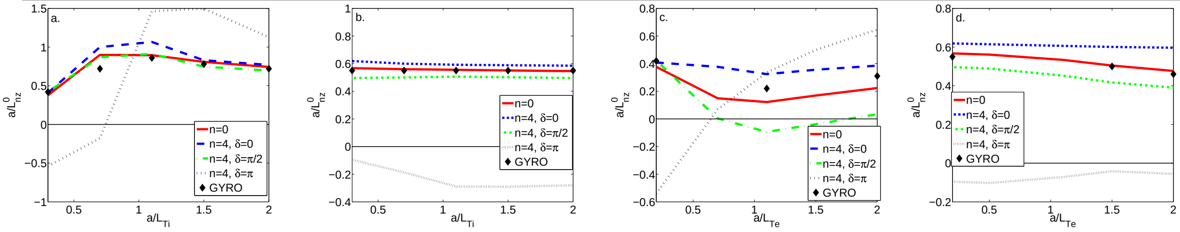

Figure 2: *Peaking factor for nickel as a function of ion temperature gradients (a,b) and electron temperature gradients (c,d) for different values of* δ *and* $n = 4$*, with (a,c) and without (b,d) parallel compressibility. Solid red line* $n = 0$*, out-in asymmetry (blue, dashed), up-down asymmetry (green, dash-dotted), in-out asymmetry (black, dotted). Diamonds are peaking factors calculated by GYRO (for* $n = 0$*).*

Conclusions In-out poloidal asymmetry of the impurity density can lead to negative peaking factor in both ITG and TE mode dominated cases. The reduction of the peaking factor due to poloidal impurity asymmetries may be a contributing factor to the observed impurity flow reversal in the presence of RF-heating. According to recent observations from JET [5], the higher the applied ion cyclotron resonance heating power the lower is the peaking factor until it eventually changes sign and becomes negative. The reason for this may be that as the ICRH power is raised, the impurities are pushed to the inboard of flux-surfaces. The in-out asymmetry can then lead to a change in the impurity flux from inward to outward as demonstrated here. The more asymmetric the distribution becomes, the lower is the peaking factor. The point is that if the impurities are accumulated on the inboard side (regardless of reason), they will not be sucked into the plasma by the combined effect of the poloidal dependence of their density, magnetic drift frequency, and the electrostatic potential. The physical reason for this is that the magnetic drift frequency changes sign at the inboard side, so if the impurities are mainly accumulated there, their averaged flux will change sign.

References

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