Effects of toroidal rotation on turbulent and neoclassical impurity transport

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The presence of unavoidable impurities in fusion reactor has a strong impact on operational performance, since the burning plasma can be completely extinguished by radiative loss even with a small concentration. Recently, a strong emphasis has been placed on non-uniform distribution of impurity density over magnetic flux surfaces [1,2]. Although conventional neoclassical theory often assumes uniformly distributed densities [3], it is now widely accepted that accurate prediction of neoclassical impurity transport necessitates a proper calculation of poloidal asymmetry of impurity density, since it can enhance or reduce neoclassical transport.

Toroidally rotating plasma is often responsible for such enhanced poloidal asymmetry of heavy impurities [4]. The centrifugal force driven by toroidal rotation pushes impurities to the wall, generating a strong 'in-out' poloidal asymmetry. As previously reported [1,5], poloidal asymmetries driven by strong rotation can increase neoclassical transport by an order of magnitude and even change its direction.

In this paper, as an extension of previous work [6], the direct impact of toroidal rotation on turbulent and neoclassical impurity transport for tungsten (W), in connection with poloidal asymmetry, is investigated by means of the full-f gyrokinetic code GYSELA [7]. The main turbulence is driven by the ion temperature gradient (ITG) with adiabatic electrons. Impurities are in the trace limit, and thereby their presence does not impact the background turbulence.

Poloidal asymmetries driven by centrifugal force

In GYSELA, the injection of toroidal momentum can be accomplished by employing an adjustable source terms in the gyrokinetic Vlasov equation [8],

$$\frac{d\bar{F}_s}{dt} = \mathcal{C}_{coll} + \mathcal{S}_{heat} + \mathcal{S}_{mom} \qquad (1)$$

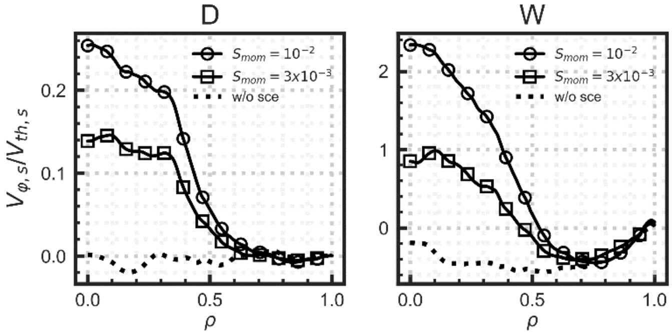

Figure 1: Radial toroidal velocity profile for deuterium (D) and tungsten (W) w and w/o momentum source.

where $\mathcal{C}_{coll}$ is the collision operator and $\mathcal{S}_{heat}$, $\mathcal{S}_{mom}$ represent the heat and toroidal momentum sources respectively.

Effective injection of toroidal momentum can be confirmed by comparing radial profiles of toroidal velocity described in Fig.1. For deuterium, Mach number ($M = V_{\varphi,s}/V_{th,s}$) is often found to be small even with additional momentum injection, while it can largely exceed unity for tungsten. Such high Mach number for tungsten can also be found in experiments. For example, Mach number for deuterium was found to be as high as $M_D \sim 0.7$ in JET operations by means of neutral beam injections (NBI) [9], which indicates that an appropriate treatment of toroidal rotation is necessary for impurity transport modelling.

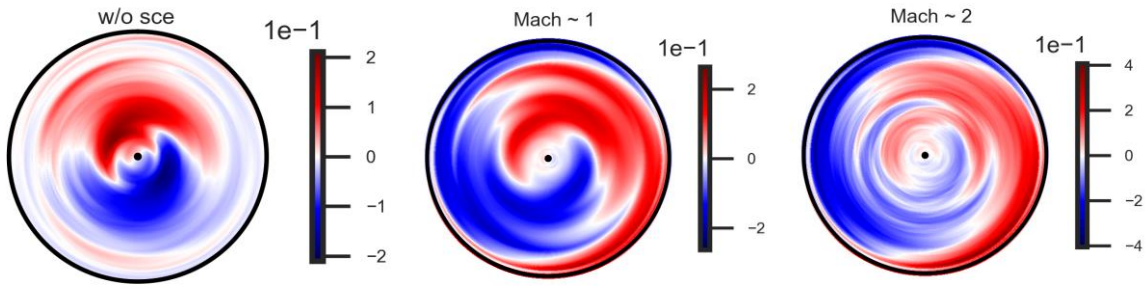

Figure 2: 2D poloidal section of perturbed W density. (Left) w/o momentum source (center) case with Mach ~1 (right) case with Mach ~ 2

In Fig.2, a comparison of poloidally inhomogeneous impurity density obtained from non-linear gyrokinetic simulations are shown for different cases. In the absence of momentum injection (Fig.2 left), toroidal velocity of both deuterium and tungsten remains low and the main contribution for poloidal W asymmetry mainly arises from the background turbulence [10]. The effects of centrifugal force become dominant for higher toroidal rotation. For the case with Mach ~ 1, approximately 20% excess of W impurities is localized in the outboard region, and this ‘in-out’ asymmetry is found to be amplified for Mach ~ 2 up to 40%.

Turbulent and neoclassical impurity transport in toroidally rotating frame

A non-negligible impact of strong toroidal rotation on both turbulent and neoclassical impurity transport has been presented in [5]. The main approach therein, was to calculate each transport channel independently; (i) turbulent transport through the gyrokinetic formulation in the toroidally co-moving frame and (ii) neoclassical transport by means of Hinton ordering [4], but without considering frictional effects at the lowest order. In GYSELA, however, thanks to the additional terms on the right sight of Eq.(1), both turbulent and neoclassical transports can be treated self-consistently in the laboratory frame including frictional effects as well.

In the case of trace impurities ($\alpha = N_z Z^2/N_i \ll 1$), the turbulent impurity flux can be decomposed as:

$$\Gamma_z = -D_z\left(\frac{\partial N_z}{\partial r} + C_T\frac{\partial T_z}{\partial r} + C_P\frac{\partial q}{\partial r} + C_u\frac{\partial \omega_z}{\partial r}\right) \qquad (2)$$

where the terms represent turbulent diffusion, thermo-diffusion, curvature-driven transport and roto-diffusion respectively. Depending on the nature of dominant instabilities or magnetic curvature profiles, those terms exhibit different features; (i) the diffusion coefficient increases (decreases) with impurity charge Z in case of TEM (ITG) turbulence. (ii) the thermo-diffusion and roto-diffusion are directed inward (outward) in case of TEM (ITG) turbulence and (iii) the curvature-driven transport is directed inward (outward) for positive (negative) magnetic shear. Recent studies with the bounced-averaged gyrokinetic code TERESA have found consistent results in qualitative agreement with the quasi-linear approach [11, 12, 13].

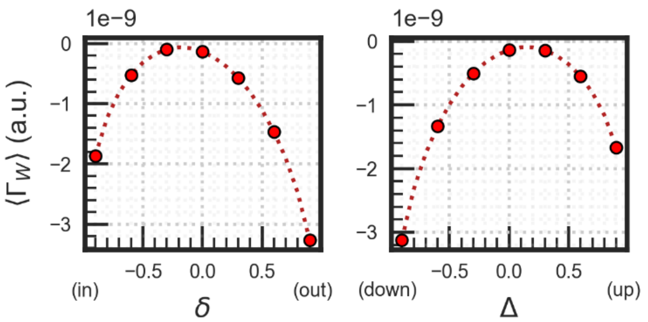

Figure 3: Neoclassical W-flux as a function of δ='in-out' / Δ='up-down' asymmetry parameter. The reconstructed density $\widetilde{N_W} = \delta cos\theta + \Delta sin\theta$ is used to calculate neoclassical flux while other terms, i.e. $N_i, T_i\ T_W, \nu_{zi}$ are taken from GYSELA simulations.

In general, neoclassical impurity transport can be expressed as a function of density, temperature and collisionality: $\Gamma_{neo,W} \propto (N_i, N_W, T_i, T_W, \nu_{zi})$. In contrast to the assumption made by standard neoclassical theory, a non-uniform distribution of impurity density has to be included for a correct prediction of neoclassical flux. In Fig.3, neoclassical W-flux calculated from a reconstructed density $\widetilde{N_W} = \delta cos\theta + \Delta sin\theta$ are expressed as a function of δ='in-out' / Δ='up-down' asymmetry parameter respectively. As δ=Δ=0 represents a uniform impurity density, the importance of including poloidal asymmetry can be clearly identified since neoclassical flux are strongly enhanced as δ and Δ increase.

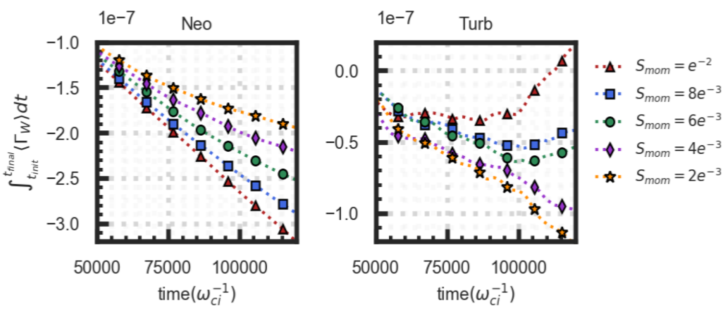

Figure 4: W impurity flux with different magnitudes of the momentum source. (Left) neoclassical flux (right) turbulent flux.

Consistently with the previous results in Fig.2 and 3, non-linear simulations with GYSELA reproduce enhanced neoclassical flux as the magnitude of injected momentum source increases, leading outboard localization of W impurities (Fig.4). While strong density inhomogeneity driven by toroidal rotation has a direct impact on neoclassical transport, its contribution to turbulent transport is found to be negligible. Instead, toroidal rotation is directly linked to the roto-diffusion in Eq.(2), which in turn leads to an outward turbulent flux in case of ITG-turbulence. This term, proportional to A/Z where A is the mass number of the impurity, can often match the diffusive part especially in case of heavy impurities [13].

In summary, in toroidally rotating plasma, the rotation-induced poloidal asymmetry increases impurity neoclassical transport inwardly leading to deleterious core accumulation of impurities. In contrast, turbulent transport is directed outwards as toroidal rotation increases due to the roto-diffusion term. Within the framework of non-linear gyrokinetic simulations, numerical results obtained by GYSELA are in qualitative agreement with the analytical description.

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