

Full orbit simulations of collisional impurity transport in spherical tokamak plasmas with strongly-sheared electric fields

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Introduction

The standard theory of collisional transport in toroidal plasmas, neoclassical theory [1], has been extensively studied. However, in high-performance tokamak discharges, particularly in those with strong transport barriers (TB), various effects including rotation, finite ion orbits and steep plasma gradients can challenge the analytical expressions of neoclassical transport. Typically transport in tokamaks is anomalous and greatly exceeds neoclassical predictions. However, in improved confinement regimes transport can approach the neoclassical level. Furthermore, in spherical tokamak (ST) geometry it has been demonstrated that the collisional transport of particles may exceed the neoclassical prediction due to finite Larmor radius effects [2]. In such geometries the standard drift-ordering is no longer applicable and it is not possible to treat particle motion analytically. Therefore, there is a need for a reliable numerical simulation of collisional plasmas which can include the strong gradients associated with transport barriers in ST geometry. We investigate the impact of strongly sheared radial electric fields on the collisional transport of impurity ions in a MAST-like tokamak using a full orbit, test-particle simulation approach. Previous studies of the impact of a sheared electric field on the collisionless dynamics of particles suggest that the impact is larger for minority ions than for bulk ions [3].

Method

The collisional dynamics of test impurity ions were simulated by solving the Lorentz-Langevin equation,

$$m_z \frac{d\mathbf{v}}{dt} = Ze(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \frac{m_z}{\tau_{zi}}(\mathbf{v} - \mathbf{u}) + m_z \mathbf{a}_r, \quad (1)$$

with the CUEBIT code [4]. Here m_z , Ze and \mathbf{v} are the impurity mass, charge and velocity. The addition of the Langevin terms to the Lorentz force equation allow one to model the collisional relaxation of test ions to a drifting Maxwellian distribution with temperature T_i and flow \mathbf{u} matching those of the bulk ions. Here, \mathbf{u} is taken to be zero. This assumption is consistent with reported measurements of temperatures, densities and flows in the vicinity of edge TBs in MAST [5, 6]. The quantity τ_{zi} is the classical impurity-bulk ion collision frequency, which

is a function of the local bulk ion temperature and density profiles, T_i and n_i respectively. We assume that T_i and n_i are linear functions of the flux surface label with core and edge values of $T_0 = 1$ keV, $T_1 = 0.5$ keV, $n_0 = 5 \times 10^{19} \text{ m}^{-3}$ and $n_1 = 10^{19} \text{ m}^{-3}$ respectively. The term \mathbf{a}_r models pitch angle scattering. Although the instantaneous collisions are taken to be isotropic, their cumulative effect over an impurity Larmor orbit naturally reflects the effects of the bulk ion pressure gradient, e.g. thermal forces, which leads to anisotropy in the collisions.

A model MAST-like analytical Solov'ev equilibrium was used, defined in cylindrical coordinates (R, ϕ, Z) by the poloidal flux function

$$\Psi = \Psi_0 \left\{ \frac{\gamma}{8} \left[(R^2 - R_0^2)^2 - R_b^4 \right] + \frac{1-\gamma}{2} R^2 Z^2 \right\}. \quad (2)$$

Here $R_0 = 0.964$ m, $R_b = 0.93$ m, $\gamma = 0.8$ and $\Psi_0 \simeq 0.9 \text{ Tm}^{-2}$, corresponding to a total plasma current of 1 MA. The magnetic field vector is calculated from Eq. 2 as $\mathbf{B} = RB_\phi \nabla\phi + \nabla\Psi \times \nabla\phi$ where $RB_\phi = 0.386 \text{ Tm}$. A local radially sheared electric field $\mathbf{E} = -\nabla\Phi$ is simulated by prescribing an electrostatic potential

$$\Phi(\Psi) = \Phi_0 \arctan \left(\frac{\Psi - \Psi_1}{\Delta\Psi} \right), \quad (3)$$

where the values $\Phi_0 = 60 \text{ V}$, $\Delta\Psi = 1.35 \cdot 10^{-3} \text{ Tm}^2$ and $\Psi_1 = 0.6\Psi(R_0, 0) = -0.4 \text{ Tm}^2$, corresponding to a peak electric field strength of -10.5 kVm^{-1} , are chosen to be consistent with measured values in MAST edge TBs [5]. It is assumed throughout that the fields are static; thus we neglect turbulent transport effects and model only the collisional component of transport.

Results

A number of minority ion species were simulated by releasing 10^4 particles from the magnetic axis and the collisional dynamics of the particles followed both with and without a background sheared radial electric field. The inward directed sheared radial electric field acts as a barrier to the outward radial transport of particles, shown by an increase in the density gradients, above that in the absence of an electric field, of all species simulated at the location of the peak radial electric field (see Fig. 1). It may be demonstrated [7] that this variation of particle transport is described by a collisional drag force, with the drag force drift velocity given by

$$v_d \simeq Z \frac{E_r}{B^2} \frac{n_i}{T_i^{3/2}} \frac{m_i^{1/2} e^3 \ln \Lambda}{6\sqrt{2}\pi^{3/2} \varepsilon_0^2} = \alpha Z \frac{\Gamma_z}{n_z}, \quad (4)$$

with Γ_z the radial particle flux and n_z the minority ion density. This drift reduces the effective particle diffusivity, which depends only on the particle charge state and not its mass [7]:

$$D_{\text{eff}} = \frac{D_0}{1 + \alpha Z}, \quad (5)$$

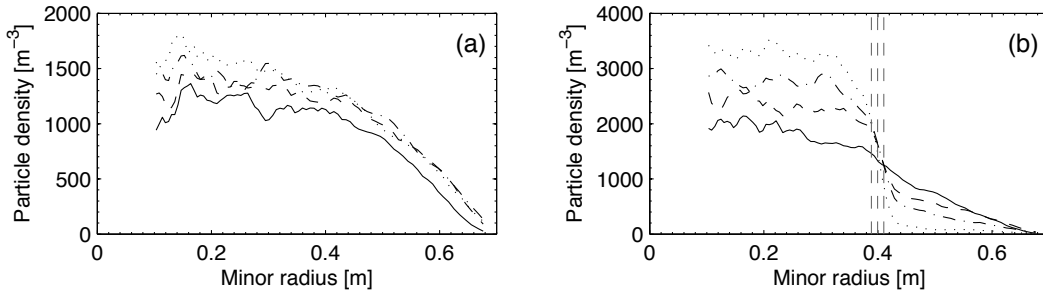


Figure 1: Minor radial impurity ion density profiles without (a) and with (b) a sheared radial electric field, \mathbf{E} . Simulated ions are He^{2+} (—), C^{6+} (---), Ne^{10+} (- · -) and W^{20+} (·····). Vertical lines indicate the peak strength and full-width half-maximum locations of \mathbf{E} .

with D_0 the diffusion coefficient in the absence of an electric field (see Fig. 2).

Variation of the width and strength of the radial electric field profile allows one to determine the scaling of particle transport coefficients with these properties of the field. It is found that the normalised effective diffusivity depends approximately only on the charge state of the minority species and not its mass. We can approximate this scaling as [7]

$$D_{\text{eff}} = D_0 \left[\frac{\Delta R}{0.2\rho_{\text{Li}}} \right]^{ZE/57} \text{ m}^2\text{s}^{-1}, \quad (6)$$

where ρ_{Li} is the bulk ion Larmor radius. This scaling has been verified to $< 10\%$ over the range $0.5\rho_{\text{Li}} \leq \Delta R \leq 4\rho_{\text{Li}}$ and $-0.65 \text{ kV m}^{-1} \leq E \leq -7.65 \text{ kV m}^{-1}$ for all impurity species simulated.

Conclusions

We have simulated realistic radial electric field profiles for edge TBs in a ST equilibrium and investigated the impact on collisional impurity transport for a range of impurity species. It has been shown that a strongly-sheared radial electric field can significantly increase the confinement of test particle ions [7]. This arises from a drift due to the drag between impurity and bulk ions (see Eq. 4). This impact on transport is strongly dependent on ion charge but is largely independent of ion mass. The negative implication of this study is the enhanced confinement of highly ionized impurity species in the vicinity of strong, negative radial electric fields.

This effect is more important for STs than for conventional tokamaks, primarily due to the strong B dependence in Eq. 4. For example, in the MAST-like equilibrium used above the Ware pinch velocity is $v_{\text{Ware}} \simeq qE_\phi/\varepsilon B \sim 5.6 \text{ ms}^{-1}$ and the drag force drift velocity is $v_d \sim 8.2 \text{ ms}^{-1}$ for C^{6+} (assuming $B = 0.4 \text{ T}$, $E_r = -10 \text{ kV m}^{-1}$, $E_\phi = -0.3 \text{ V m}^{-1}$, $n_i = 3 \times 10^{19} \text{ m}^{-3}$, $T_i = 500 \text{ eV}$, $q = 3$ and $\varepsilon = 0.4$). Typical values for a large conventional tokamak, such as JET, are $v_{\text{Ware}} \sim 0.4 \text{ ms}^{-1}$ and $v_d \sim 0.02 \text{ ms}^{-1}$ (with $B = 3 \text{ T}$, $E_r = 20 \text{ kV m}^{-1}$, $E_\phi = -0.04 \text{ V m}^{-1}$, $n_i = 3 \times 10^{19} \text{ m}^{-3}$, $T_i = 5 \text{ keV}$, $q = 3$ and $\varepsilon = 0.1$).

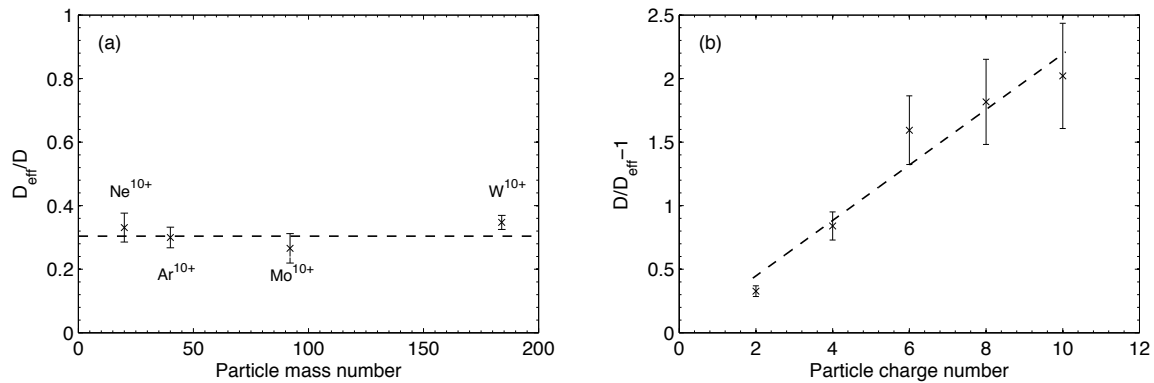


Figure 2: Scaling of particle diffusivity with (a) particle mass for $Z=10$ and (b) particle charge for constant mass number of 20.

Finally, whilst the effect of bulk plasma rotation was neglected in the present study, one would expect transport barriers to be associated with flows of the bulk ions (e.g. zonal flows). For impurity ions in particular inertial effects will become important in rotating plasmas. Strong toroidal rotation can cause heavy, incompletely-ionised impurities such as W^{20+} to undergo rapid collisional transport [8]. One therefore expects competition between this enhanced transport and the improved confinement resulting from sheared radial electric fields.

Acknowledgments

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References

- [1] S. P. Hirshman and D. J. Sigmar, *Nuclear Fusion* **21**, 1079 (1981)
- [2] D. A. Gates, H. E. Mynick and R. B. White, *Phys. Plasmas* **11**, L45 (2004); M. Romanelli *et al.*, *Plasma Physics and Controlled Fusion* **53**, 054017 (2011)
- [3] R. D. Hazeltine, *Phys. Fluids B* **1** 2031 (1989)
- [4] R. J. McKay *et al.*, *Plasma Physics and Controlled Fusion* **50**, 065017 (2008)
- [5] H. Meyer *et al.*, *Nuclear Fusion* **49**, 104017 (2009)
- [6] A. R. Field *et al.*, *Plasma Physics and Controlled Fusion* **51**, 105002 (2009)
- [7] C. G. Wrench, E. Verwichte and K. G. McClements, *submitted to Nuclear Fusion* (preprint available at arxiv.org/abs/1106.1981)
- [8] K. G. McClements and R. J. McKay, *Plasma Physics and Controlled Fusion* **51**, 115009 (2009)