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Test-particle simulations of collisional impurity transport in rotating spherical tokamak plasmas

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1 Introduction

The use of high power counter-current neutral beam injection (NBI) in the MAST spherical tokamak has resulted in toroidal rotation velocities in excess of the sound speed in the plasma core and energy confinement times greater than those achieved with co-current beam injection [1]. However it has been shown that the irreducible transport arising from particle collisions (i.e. neoclassical transport) is enhanced rather than diminished by the presence of toroidal flows [2]. We adopt a direct numerical approach to investigate this problem, by using a test-particle full orbit code `CUEBIT` to study the collisional transport of carbon impurity ions in MAST-like plasmas with toroidal flows.

2 Model

For simplicity, we neglect the relatively small effect of transonic toroidal flows on flux surfaces and use the same equilibrium for the stationary and rotating plasmas. Specifically, we use the following solution of the Grad-Shafranov equation for stationary plasma equilibria [3]:

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

where R and Z denote distance from the tokamak symmetry axis and vertical distance from the midplane, and Ψ_0, γ, R_0 and R_b are positive constants. The plasma boundary is defined by $\Psi = 0$, where the plasma current is in the negative φ direction and $\Psi \leq 0$ throughout the plasma. The poloidal flux Ψ is defined such that

$$\mathbf{B} = -\frac{1}{R}\frac{\partial \Psi}{\partial Z}\mathbf{e}_R + B_\varphi \mathbf{e}_\varphi + \frac{1}{R}\frac{\partial \Psi}{\partial R}\mathbf{e}_Z, \quad (2)$$

where B_φ is the toroidal field and $\mathbf{e}_R$, $\mathbf{e}_\varphi$, $\mathbf{e}_Z$ are unit vectors in a right-handed (R,φ,Z) coordinate system, with φ denoting toroidal angle. Equation (1) is a solution of the Grad-Shafranov equation if RB_φ is constant and plasma pressure varies linearly with Ψ, which we assume for simplicity. Force balance in the bulk ion and electron fluids requires the presence of an electric field which must be taken into account. The electrostatic potential associated with purely toroidal rigid body rotation of a two-fluid plasma (i.e. a plasma with only trace quantities of impurity ions) is given by [4]

$$\Phi = \Omega\Psi + \frac{m_i T_e \Omega^2 R^2}{2e(T_e + T_i)}, \tag{3}$$

where e is proton charge, m_i is bulk ion mass, T_e and T_i are the electron and ion temperatures, and Ω is the toroidal rotation rate. The second term on the right hand side of equation (3) is required in order to maintain quasi-neutrality when, as a consequence of the centrifugal force associated with toroidal rotation, the electron and ion densities are not constant on a given flux surface [5]. This correction to the electric field produces a force in the inward major radial direction, thereby reducing the effect of the centrifugal force. Coulomb collisions are included in our rotating plasma by adding a drag term to the Lorentz force, resulting from collisions with bulk ions whose average toroidal velocity $v_\varphi = \Omega R$ is nonzero, and a noise term that ensures relaxation of the test particle population to a (co-rotating) Maxwellian distribution whose temperature T is equal to that of the bulk ions. In the laboratory frame the Lorentz force equation then takes the form

$$m_Z \frac{d\mathbf{v}}{dt} = Ze(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \frac{m_Z}{\tau}(\mathbf{v} - v_\varphi \mathbf{e}_\varphi) + m_Z \mathbf{r}(t) \tag{4}$$

where τ is the prescribed collision time and m_Z, Ze are the impurity ion mass and charge respectively. The presence of noise terms in the three components of equation (4) ensures that collisional pitch angle scattering is taken into account. For the case of counter-current rotation, $v_\varphi > 0$. The drag term ensures that after a sufficiently long time the minority ions acquire the same mean flow velocity as the bulk ions with which they are colliding, i.e. $v_\varphi \mathbf{e}_\varphi$. We neglect collisions of the test particles with electrons and beam ions.

3 Test-particle Simulation Results

We compute the orbits of test particle fully-ionised carbon impurity ions for three particular scenarios: $\Omega = 0$, $\Omega = 2 \times 10^5$ rad s^{-1} (counter-current rotation) and $\Omega = -2 \times 10^5$ rad s^{-1} (co-current rotation). Various majority ion density and temperature profiles, approximating measured profiles in rotating and non-rotating MAST aspect ratio plasmas, are used in the modelling (see table 1). In each case n_0 and T_0 are the central bulk ion density and temperature respectively, n_1 and T_1 denote the edge density and temperature, and Ψ_1 is the poloidal flux at the magnetic axis. Although the various models listed in table 1 are appropriate for different rotation scenarios, we have carried out simulations for every combination of profile model and rotation frequency, in order to separate effects arising purely due to rotation from those associated with the choice of profile. In each simulation the orbits of 10^4 impurity ions, initially at rest at the magnetic axis ($R = R_0$) were computed for at least one confinement time (the period taken for the number of confined ions to fall to $1/e$ of its initial value).

Table 1: MAST bulk ion temperature/density profiles

Model No.	Temperature profile	Density profile
1	$T_0\,(\Psi/\Psi_1) + T_1$	$n_0\,(\Psi/\Psi_1) + n_1$
2	$T_0\,(\Psi/\Psi_1) + T_1$	$n_0\,(\Psi/\Psi_1)^{1/2} + n_1$
3	$T_0\,(\Psi/\Psi_1)^{1/2} + T_1$	$n_0\,(\Psi/\Psi_1) + n_1$
4	$T_0\,(\Psi/\Psi_1) + T_1$	$[n_0\,(\Psi/\Psi_1) + n_1]\exp\{m_i\Omega^2(R^2 - R_0^2)/4T\}$
5	$T_0\,(\Psi/\Psi_1) + T_1$	$[n_0\,(\Psi/\Psi_1)^{1/2} + n_1]\exp\{m_i\Omega^2(R^2 - R_0^2)/4T\}$
6	$T_0\,(\Psi/\Psi_1)^{1/2} + T_1$	$[n_0\,(\Psi/\Psi_1)^{1/2} + n_1]\exp\{(m_i\Omega^2(R^2 - R_0^2)/4T\}$

Table 2: Computed confinement times (ms) of trace C^{6+} ions for cases in Table 1

Model No.	Stationary	Counter-rotating	Co-rotating
1	216.4	101.3	86.8
2	163.3	61.0	49.8
3	318.4	150.5	116.4
4	216.4	64.3	51.8
5	163.3	63.3	49.8
6	223.0	127.5	94.4

Table 2 indicates that there is a strong dependence of confinement time on the temperature and density profiles of the bulk plasma: broadening the temperature profile for a given rotation scenario significantly increases the confinement time, while a broadening of the density profile generally degrades the confinement. For every profile model, the impurity ions are optimally confined when the plasma is non-rotating and least well-confined when it is co-rotating. It is useful to plot the final positions of the ions inside the plasma in (R,Z) space for the three cases, using profile model number 1, as shown in figure 1: the black curves tracing out sectors of the plasma boundary indicate the poloidal locations at which ions are lost from the system.

4 Discussion

It is clear that the ions are strongly displaced outboard by the net effect of the centrifugal force and the radial electric field. In the counter-rotating case all impurity ion losses occur outboard of the magnetic axis; this is also true in the co-rotating case, with the losses concentrated in an even narrower range of poloidal angles. The fact that losses occur both above and below the

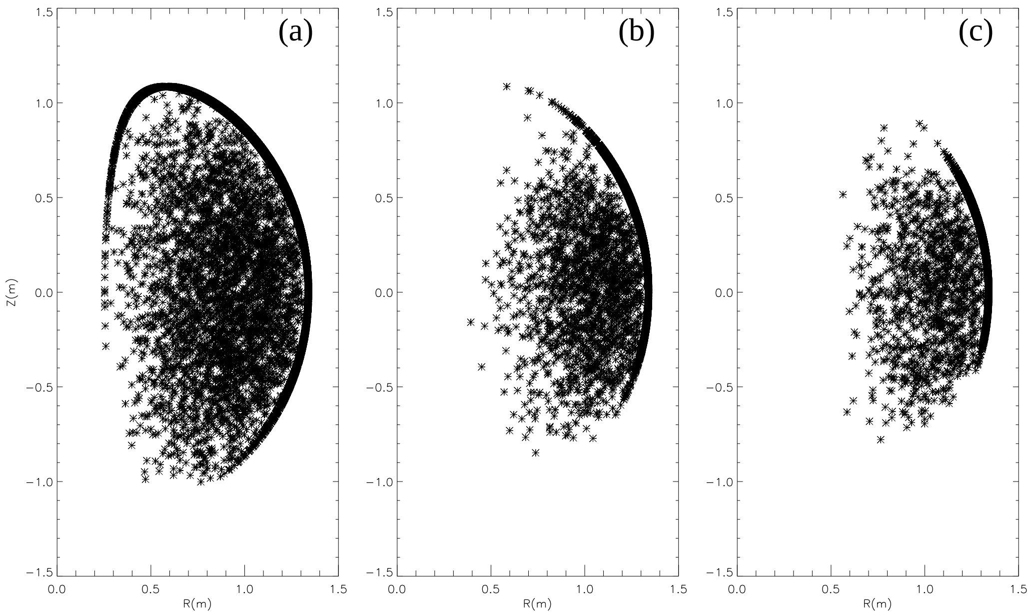

Figure 1: Distribution of impurity ions in (R,Z) plane for (a) $\Omega = 0$, (b) $\Omega = 2\times10^5$ and (c) $\Omega = -2\times10^5$ rad s^{-1}.

midplane suggests that the confinement degradation in the rotating cases is due mainly to an enhancement in neoclassical transport, arising from the fact that the ions are displaced outward by the centrifugal force, encounter a lower magnetic field on average, and are thus subject to a higher neoclassical diffusion rate since this scales as ρ^2 [2] rather than being due to centrifugal and electric field modifications to the drift velocity. However in all cases there is a significant up-down asymmetry, suggesting that drifts play some role: most losses occur above the midplane, and all the vertical drifts are in the positive Z-direction.

Details of further results using subsonic rotation velocities and also singly-ionised carbon ions are discussed in McKay *et al* [6].

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