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Test-particle simulations of impurity transport in tokamak plasmas

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1 Introduction

Impurity ions are invariably present in tokamak plasmas due to interactions with plasma-facing solid surfaces, and are generally unwanted because they dilute the fusion fuel and radiate energy out of the plasma. Tungsten (W) is an impurity species that is of particular relevance for ITER since it is likely to be used in the divertor, and for this reason will, in the near future, be incorporated into a new first wall in JET [1]. It is therefore timely to study theoretically the behaviour of this species and other heavy impurity species under realistic tokamak conditions. In this paper we describe test-particle simulations of W and nickel (Ni) transport under plasma conditions similar to those in the MAST spherical tokamak.

2 Numerical method

Our simulations are carried out using `CUTIE`, a two-fluid global turbulence code in which tokamak geometry is approximated using a periodic cylinder model [2], and `CUEBIT`, a full orbit test-particle code [3]. In `CUTIE` the evolution of the two-fluid system is described by equations for plasma density, electron and ion temperature, parallel ion velocity, poloidal flux and electric potential. In `CUEBIT` collisions of impurity ions with bulk ions are modelled using a drag term, which depends on the toroidal velocity of the bulk ion fluid, and a Langevin term that ensures relaxation of the impurity ion velocity distribution to the appropriate Maxwellian [3]. Orbits are calculated in `CUEBIT` by using Chebyshev polynomials to interpolate spatially the poloidal flux and electrostatic potential computed using `CUTIE`. The impurity ions are assumed to have no influence on the fields computed using `CUTIE`, which requires $n_Z Z^2 \ll n_i$, where n_Z, Z are the impurity ion density and charge state, and n_i is the bulk ion density.

3 Results

All of the results were obtained using a `CUTIE` simulation of an H-mode discharge in MAST (shot number 18820). As a simple test of the collision scheme used in `CUEBIT`, the orbits of $N_0 = 100$ tungsten (W^{20+}) ions were tracked from a launch position at the magnetic axis, with the electric field set equal to zero and the magnetic field given by an equilibrium configuration computed using `CUTIE`. Fig 1 shows $\overline{r}$, the mean distance of the W^{20+} ions from the magnetic axis, as a function of time; the orange curve is the best-fit curve of the form $\overline{r} \propto (t - t_0)^{1/2}$ where

t_0 is the launch time. This relation follows from the fact that the one-dimensional diffusion equation

$$\frac{\partial n_Z}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial n_Z}{\partial r}\right), \tag{1}$$

has the Green's function solution

$$n_Z = \frac{N_0}{4\pi D(t-t_0)}\exp\left(-\frac{r^2}{4D(t-t_0)}\right), \tag{2}$$

when the system is unbounded and D is constant. Eq. (2) implies that

$$\bar{r} = \frac{2\pi}{N_0}\int_0^\infty r^2 n_Z dr = [\pi D(t-t_0)]^{1/2}. \tag{3}$$

Matching this result to the orange curve in Fig 1 we obtain $D \simeq 1.1\,\mathrm{m^2s^{-1}}$, which is close to the expected Pfirsch-Schlüter neoclassical diffusivity in the plasma core ($D \sim q^2\rho^2/\tau$ where q is safety factor, ρ is Larmor radius and τ is collision time) and implies a confinement time of around 500 ms.

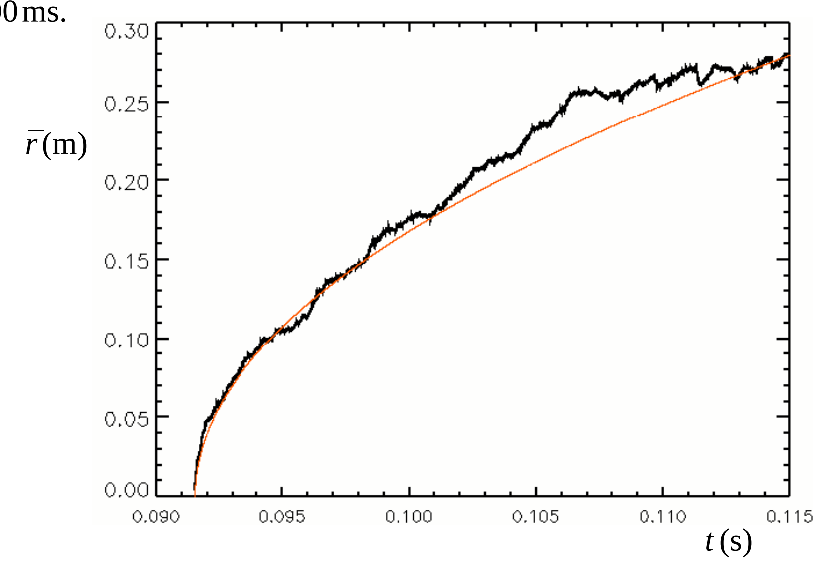

Fig 1 Temporal evolution of $\bar{r}$ for simulation with zero electric field and no fluctuations.

Simulations were also carried out with an electric field included in the orbit-following calculations. The blue and black curves in Fig 2 indicate the temporal evolution of $\bar{r}$ with and without static turbulent fluctuations in the fields taken into account; the profile of the flux surface-averaged radial electric field obtained from `CUTIE` E_r is shown in Fig 3. It is evident that in neither case does $\bar{r}$ increase as $(t-t_0)^{1/2}$, indicating that the transport is no longer purely diffusive. Indeed in the case of the simulation without fluctuations (the black curve) there is an initial period in which $\bar{r} \propto (t-t_0)$, suggesting purely advective transport during this time. In both cases $\bar{r}$ saturates at about 0.65 m; the particle density profiles do not change significantly during the period in which $\bar{r}$ is approximately constant, although the total number of confined

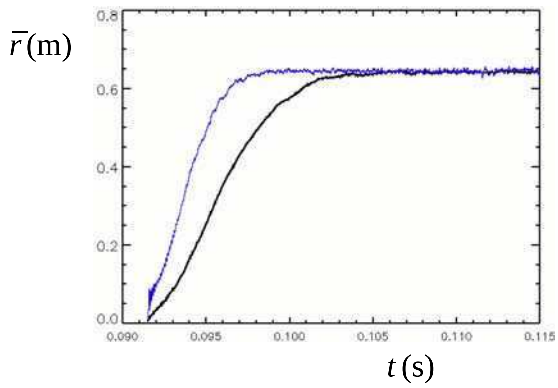

Fig 2 Temporal evolution of $\bar{r}$ for simulations with finite E_0. The blue and black curves correspond to simulations with and without electromagnetic fluctuations taken into account.

particles drops rapidly in the case of the turbulent simulation. No particle losses were observed in the 250 ms of the non-turbulent simulation.

The time taken for the number of particles in the system to fall to $1/e$ of its initial value provides a simple measure of the impurity ion confinement time. In the turbulent simulation the W^{20+} confinement time was approximately 16 ms; the confinement time of Ni^{28+} ions in the same fluctuating fields was found to be 25 ms. These figures are close to the energy confinement time in the `CUTIE` simulation (approximately 17 ms), as observed experimentally in JET, Tore Supra and TCV [4,5].

4 Discussion

The fact that no particles were lost in the non-turbulent simulation with finite E_r appears to be due to an edge transport barrier, indicated in Fig 3 by a region in which E_0 is strongly-sheared and negative ($r \simeq 65 - 75$ cm). However, this barrier was not sufficient to prevent particles from being rapidly lost in the turbulent simulation. The presence of a local maximum in E_r of about 6.5 kVm^{-1} at $r \simeq 25$ cm indicates significant co-current toroidal rotation in this region of the plasma. It has recently been shown [6] that in these circumstances heavy, incompletely-ionised impurities such as W^{20+} can undergo very rapid collisional transport due to the combined effect of trapping in a centrifugal potential well and a modification to the effective magnetic field arising from the Coriolis force in a frame co-rotating with the plasma. These effects may help to explain why the computed confinement time of W^{20+} in the presence of both collisions and turbulence is significantly shorter than that of Ni^{28+}, and the trajectory shown in Fig 4 appears to be consistent with centrifugal trapping of the W^{20+} ion in a region of the plasma with strongly positive E_r and hence rapid co-current rotation.

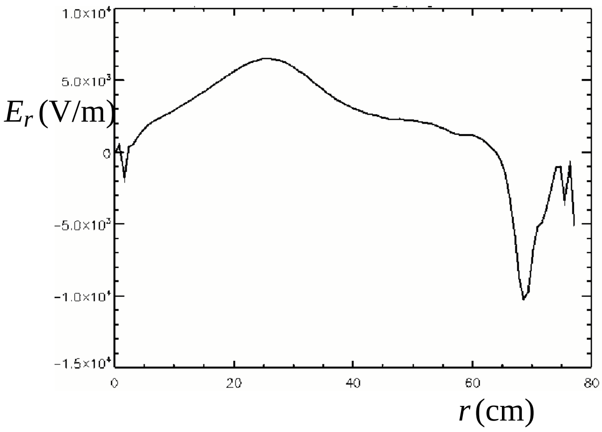

Fig 3 Flux surface-averaged radial electric field obtained using `CUTIE`.

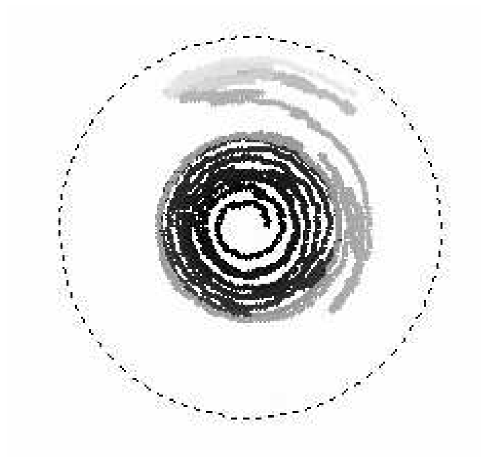

Fig 4 Trajectory of single W^{20+} ion in turbulent simulation.

5 Conclusions

We have integrated a full orbit code (`CUEBIT`) with a global electromagnetic two-fluid turbulence code (`CUTIE`) to study the collisional and turbulent transport of heavy trace impurity ions in tokamak plasmas. Applying this integrated code to the simulation of an H-mode discharge in the MAST spherical tokamak, we have found that the electric field and turbulent field fluctuations computed using `CUTIE` have the combined effect of reducing the impurity ion confinement time by a factor of around 30. The computed confinement times of tungsten and nickel ions are close to the simulated energy confinement time, in broad agreement with results from laser blow-off experiments in several tokamaks. An important caveat is that these confinement times were obtained from simulations in which spatial but not temporal fluctuations in the fields were taken into account. The possible effect of time dependence of the fluctuations on impurity transport is currently under investigation, and will be discussed in a future paper.

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