35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.32D, P-5.152 (2008)

Dust in Tokamaks: a Comparison of Different Ion Drag Models

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Introduction

Production of dust particles during tokamak operation is a critical issue for magnetic confinement fusion. Their introduction into the reactor can have serious consequences on its performance and can constitute a safety issue [1]. For these reasons the study of dust particles in tokamaks is crucial. Direct experimental observations of such particles that would give insight into their behaviour are quite challenging, especially for micron sized grains. In this context, numerical modelling of the relevant phenomena, such as in [2], play a key role for better understanding the transport mechanisms of dust in tokamaks. From the forces acting on the solid particles, the one that influences their behaviour most strongly is the ion drag. For this reason we focus our study on this force and how adopting different models describing it can introduce differences to the behaviour of the particles. We present two approaches and compare their impact on the dynamical behaviour of solid particles. The first is based on the binary collision model as detailed in [3]. The second treatment is based on the control surface approach introduced in [4], where the drag is obtained by examining the momentum balance across a surface far from the dust grain.

We compare the two models in the dust transport in tokamaks code (DTOKS). The DTOKS code simulates the trajectories of dust particles in a plasma environment taken from the plasma edge simulation B2SOLPS5.0, currently plasma profiles from MAST (the MegaAmp Spherical tokamak) and ITER can be utilised. The solid particles are ejected from the divertor target "wetted area". The code tracks their trajectory by numerically integrating their equation of motion at each time step. For this, the background plasma environment is used to model the evolution of the charge, the forces and the energy fluxes on them.

Binary collision approach

In the binary collision approach (BC) we determine the force exerted from the ion flow to the particle by resolving the movement of a single ion particle in a spherically symmetric potential,

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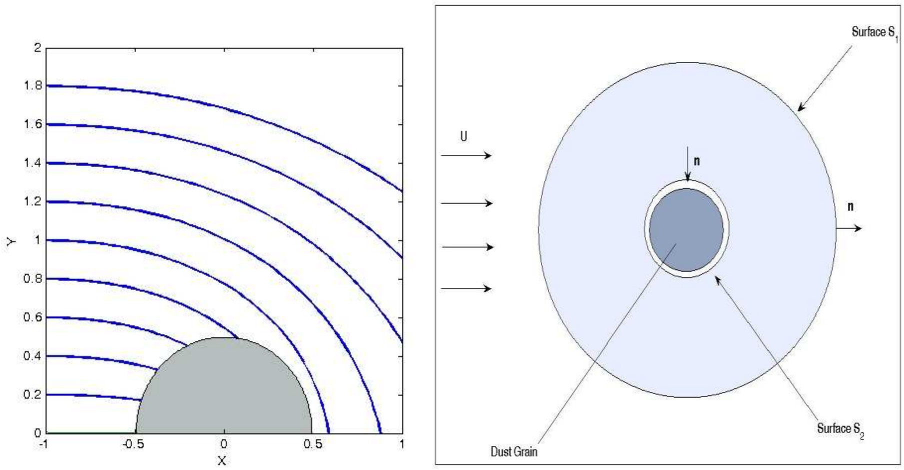

Figure 1: A graphic representation of the geometries that are used in the BC (left) and the CS (right) approaches.

see Figure 1 (left). This is assumed to be a Debye shielded potential. After finding the trajectory of an ion we can integrate over the distribution function in order to determine their collective effect.

$$F_{i,d} = m \int \mathbf{v} v f(\mathbf{v})[\sigma_c(v) + \sigma_s(v)]d\mathbf{v} \tag{1}$$

where $\sigma_c(v)$ is the cross section of charging collisions, given by the OML (Orbital Motion Limited) approach. Whereas, $\sigma_s(v)$ is the cross section due to scattering of ions in the potential of the grain and has the form

$$\sigma_s(v) = \int_{\rho_{min}}^{\rho_{max}} \frac{\rho d\rho}{1 + (\rho/\rho_0)^2} = 4\pi\rho_0^2\Gamma \tag{2}$$

where ρ is the impact parameter of the ion, $\rho_0(v) = Ze^2/mv^2$ is the Coulomb radius, where Z is the number of electron charges on the dust grain and Γ is the Coulomb logarithm.

$$\Gamma(v) = \ln[\frac{\rho_0^2(v) + \rho_{max}^2(v)}{\rho_0^2(v) + \rho_{min}^2(v)}]^{1/2} \tag{3}$$

The minimum value of the impact parameter we must take into account, is determined by the maximum impact parameter for charging collisions calculated by the OML. The maximum impact parameter is more difficult to determine. In the work of Barnes [5] this was taken as the screening length of the potential. In the more recent work from Khrapak et al [3] it was taken to be the impact parameter of ions with a distance of closest approach to the dust grain equal to the screening length, this approach has been adopted here. The final form of the ion drag according to this approach is

$$F_{id,BC} = \frac{8\sqrt{2\pi}}{3}\alpha^2 n_i m_i v_{Ti} u[1 + \frac{\rho_0(v_{Ti})}{2\alpha} + \frac{\rho_0^2(v_{Ti})}{4\alpha^2}\Lambda], \tag{4}$$

where n_i and m_i are the ion density and mass respectively, v_{Ti} is the ion thermal speed, u is the ion drift velocity, α is the grain's radius and Λ is the integrated Coulomb logarithm over the whole distribution. The first two terms in the square brackets represent the contribution to the ion drag of direct ion collisions with the dust grain and the third the contribution due to ions scattered in the grain's potential [3].

The control surface approach

In the control surface approach (CS), which was introduced by Allen [4], the force on the dust particle is determined by considering the flux of momentum through a surface, S_1, around the grain. If we consider a second outer surface, S_2, see Figure 1 (right), the loss of momentum between the two surfaces at steady state must be equal to zero.

$$\int\int_{S_1}[\rho(\mathbf{v}\cdot\hat{\mathbf{n}})\mathbf{v} + p_e\hat{\mathbf{n}} - \mathbf{T}\cdot\hat{\mathbf{n}}]dS + \int\int_{S_2}[\rho(\mathbf{v}\cdot\hat{\mathbf{n}})\mathbf{v} + p_e\hat{\mathbf{n}} - \mathbf{T}\cdot\hat{\mathbf{n}}]dS = 0 \tag{5}$$

where the first term in the integral is the ion momentum contribution, the second represents the electron pressure, and the third is Maxwell's stress tensor, giving the contribution of electromagnetic forces. Because the second surface can be placed arbitrarily far from the particle we can make the calculation of the integral tractable. So the total force, assuming cold ions and a potential flow, can be calculated.

$$F_{id,CS} = \int\int_{S_1}[\rho(\mathbf{v}\cdot\hat{\mathbf{n}})\mathbf{v} + p_e\hat{\mathbf{n}} - \mathbf{T}\cdot\hat{\mathbf{n}}]dS = m_i u I\,\hat{\mathbf{u}}_z \tag{6}$$

where I is the flux of ions on the dust grain. In the present paper I has been computed using the OML approach.

Conclusions

We have considered two different models for calculating the force on a dust grain due to the plasma flow. In the BC approach this force was attributed to the momentum that the drifting ions transfer to the dust grain either through direct collisions or Coulomb scattering. In the CS approach this force is not restricted to the contribution of ions as also the electrons and the electromagnetic stresses are taken into account. In the cold ion approximation the drag is equal to the initial momentum of the ions that hit the dust grain. The two approaches, as it can be seen from Figure 2, give different estimates for the force in question. In the high density and $\beta \approx 1$

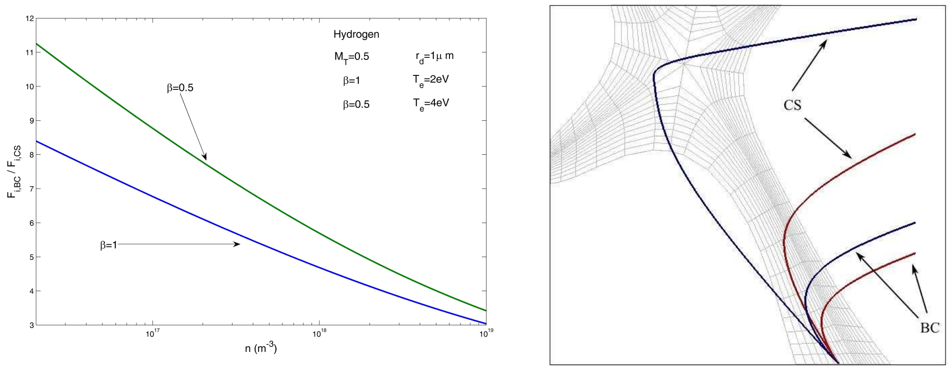

Figure 2: (Left) The ratio of the ion drag force given by the BC and CS approaches for plasma conditions as a function of the plasma density for different values of the $\beta = T_i/T_e$ ratio. (Right) Comparison of the trajectories of a micron carbon particle injected into MAST with an initial velocity of $10m/sec$.

regime, more appropriate for tokamaks, the BC approach gives a larger estimate, by a factor of the order of 4, compared with the CS approach. The impact of this difference to the dynamical behaviour of a dust grain in the case of MAST can be seen in Figure 2 (right). For a micron sized dust grain with an initial velocity of 10 m/sec, in the BC approach all the particles are expelled from the plasma due to the higher force exerted on the particle in both the poloidal and toroidal directions. In this case, no particles reach areas of high energy fluxes where they would ablate. However, in the CS approach it is easier for particles injected towards the X-point to reach further into the plasma and ablate. It is concluded that the determination of the ion drag force plays a crucial role in the better prediction of the behaviour of dust grains in tokamaks, which would allow realistic assessment of the impact of dust to tokamak operation.

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