Journal of Nuclear Materials 390–391 (2009) 103–105

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Ion drag force on dust grains in the magnetized edge plasma

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ARTICLE INFO

PACS:
52.27.Lw
52.40.Kh
52.65.Rr
52.65.Ww

ABSTRACT

A 3-dimensional Particle–Particle Particle–Mesh (P3M) code [K. Matyash, R. Schneider, F. Taccogna, D. Tskhakaya, J. Nucl. Mater. 363–365 (2007) 458] is applied to simulate a small-size (smaller than a Debye length) spherical dust grain confined in the magnetized plasma near the material wall of a tokamak. Plasma particles (electrons and ions) are treated kinetically (Particle-in-Cell with Monte Carlo Collisions (PIC MCC)), which allows to resolve self-consistently the electrostatic sheath in front of the wall. In order to describe accurately the plasma particles' motion close to the dust grain, the PIC technique is supplemented with Molecular Dynamics (MD), employing an analytic electrostatic potential for the interaction with the dust grain. The charging of a spherical, conducting dust grain confined in the sheath potential close to the wall of a tokamak is simulated. A magnetic field normal to the wall was investigated. The ion drag force resulting from dust grain collisions with the streaming ions is calculated. This force is critical for a realistic description of the dust particle dynamics and transport in fusion plasmas.

1. Introduction

Dust particles of nanometer–micrometer size are formed in fusion devices due to plasma-surface interaction processes [2]. The dust particles, accumulating tritium, will pose a serious threat for the operation of future fusion devices. The dust particles can also influence the discharge as impurity source and decrease the performance of the fusion devices [2]. In order to address these issues one has to understand the mechanisms of dust formation and its transport in the fusion device.

For the understanding of transport of dust in fusion devices the knowledge about forces acting on the dust particles is necessary. One of the major forces acting on the dust grain is the ion drag force created by momentum transfer from the flowing ions to the dust grain. This force is critical for the dynamics of dust particles confined in the electrostatic sheath close to the material wall, as the ion flow velocity increases toward the wall, normally exceeding the sound speed in the sheath.

In this paper, we investigate the ion drag force acting on micrometer-sized conducting spherical dust particles in the peripheral plasma close to the wall of a tokamak. We utilize a 3-dimensional Particle–Particle Particle–Mesh (P3M) code [1], which allows to follow the plasma particles trajectories in the close vicinity of the dust grain and by this to include finite-size effects for dust grains, self-consistently resolving the dust grain charging due to absorption of plasma electrons and ions.

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2. The model

The P3M model combines the PIC technique with the MD approach in order to simulate finite-size effects for dust particles, being able to self-consistently resolve the background plasma. In the model, the long-range interaction of the dust grains with charged particles of the background plasma is treated accordingly to the PIC formalism. For particles which are closer to the dust grain than a Debye length, their interaction force is computed according to a direct particle–particle MD scheme using the exact Coulomb potential. This is implemented in the following way: in the computational domain, the cell in which the dust grain is located together with the neighboring cells form the "MD" region. All particles outside the MD region are treated according to the conventional PIC scheme. For plasma particles (electrons and ions) inside the MD region the electric field is calculated as: $\mathbf{E} = \mathbf{E}_{grid} + \mathbf{E}_{dust}$. Here for the calculation of the grid field $\mathbf{E}_{grid}$ we use the charge density as in the PIC part from which the dust grain contribution is subtracted. The dust contribution is accounted through the exact Coulomb electric field $\mathbf{E}_{dust}$. In order to resolve particle motion on scales of the order of the dust grain size, particles in the MD region are moved with a time step smaller than in PIC region. Particles which cross the dust grain boundary are assumed to be absorbed. The dust grain charge is updated each MD time step. This approach allowed us to follow the charged particles trajectories in the close vicinity of the dust grain and by this to include finite-size effects for dust grains, self-consistently resolving the dust grain charging due to absorption of plasma electrons and ions [1]. Our model is limited to simulations of dust particles much smaller

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doi:10.1016/j.jnucmat.2009.01.125

than a Debye length, when the charge distribution on the surface of the dust particle can be considered as uniform.

In order to compute ion drag force components, we extended the model with the ion drag force calculation module. The collision part of the ion drag force, which is due to the ions collected by the dust, is calculated by summing up the momentum of the ions absorbed by the dust grain during the averaging time Δt_{av}:

$$\mathbf{F}_{id}^{col} = \frac{\sum m_i \mathbf{v_i}}{\Delta t_{av}}, \tag{1}$$

here m_i is the ion mass and $\mathbf{v}_i$ is the ion velocity.

For calculation of the orbital part of drag force, which is due to momentum transfer from ions scattered in the dust electric field, we sum up the Coulomb force for all ions inside the MD region during the averaging time:

$$\mathbf{F}_{id}^{orb} = -\frac{e\sum_j \mathbf{E}_{dust}^j}{\Delta t_{av}/\Delta t_i^{MD}}, \tag{2}$$

here Δt_i^{MD} is the ion time step inside the MD region.

3. Simulation

We use the P3M model to investigate the ion drag force acting on the spherical, conducting dust grains confined in the peripheral plasma near the material wall of a tokamak. We consider a hydrogen plasma with electrons, H^+ ions and atomic hydrogen. The initial plasma parameters were chosen to be relevant to tokamak plasma: $n_{e0} = 10^{12}$ cm^{-3} and $T_{e0} = T_{i0} = 20$ eV. The computational domain represents a 3D box with length $X_{\max} = 64\lambda_{D0} = 2.13$ mm and width $Y_{\max} = Z_{\max} = 4\lambda_{D0} = 0.13$ mm. Absorbing walls, perpendicular to direction X, are located at $X = X_{\max}$ and $X = 0$. At boundaries in the Y and Z directions, periodic boundary conditions are applied, both for the particles and for the potential. At the walls the potential is fixed at zero. In our paper we have concentrated on studying the importance of elementary processes for a dust grain in a magnetized plasma. Thus, we decided to reduce the complexity of the system and use a uniform magnetic field of 1 T normal to the wall (directed along the X axis). In the center of the simulation domain, an ambipolar source of electrons and H^+ ions is implemented. The atomic hydrogen was treated as a fixed background with constant density $n_n = 10^{13}$ cm^{-3} and Maxwellian distribution with $T_n = 2$ eV (corresponding to the Franck-Condon energy range). Only the charged particle dynamics was followed. For simplicity, only Coulomb collisions between charged species, electron–hydrogen elastic collisions and momentum transfer and charge-exchange collisions between H^+ ions and atomic hydrogen were considered in the simulation. Corresponding cross-sections were collected from [3,4]. In order to compensate for the reduced size of the computational domain and to be able to resolve the collisional presheath, all collisions with neutrals were amplified by a factor 200. Taking into account that in the simulations the shortest mean free path – for charge-exchange collisions was about $\lambda_{CX} \approx 0.3X_{\max}$, electrostatic sheathes in front of the wall and around dust particles could be regarded as collisionless.

A grid with spacing $\Delta x = \Delta y = \Delta z = \lambda_{D0}/2 = 0.0166$ mm and time step $\Delta t = 0.1/\omega_{pe0} = 1.77 \cdot 10^{-12}$ s was used in the simulation. The size of the MD region in the simulation was set to $\Delta X_{MD} = \Delta Y_{MD} = \Delta Z_{MD} = 3\Delta x$. In order to ensure accurate solution for the electron and ion trajectories close to the dust, subcycling for the electrons and ions inside the MD region was used. The electron and ion time steps inside the MD region were set to $\Delta t_e^{MD} = 0.02\Delta t$ and $\Delta t_i^{MD} = 0.1\Delta t$, correspondingly. The initial number of the computational particles per Debye cube was set to $N_{D0} = 2000$. In total 8000000 computational particles were used in the simulation.

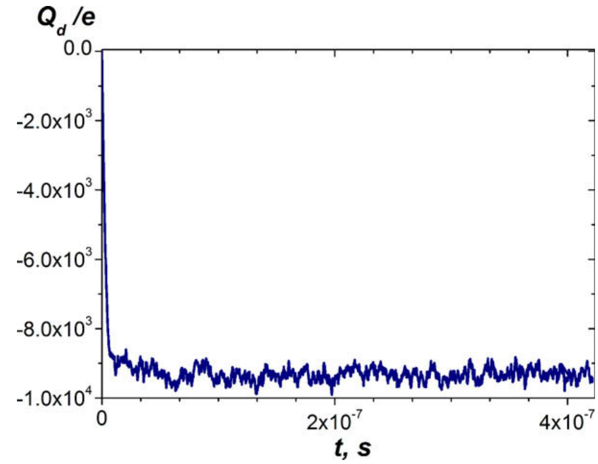

Fig. 1. Charging of a dust grain with the radius 0.83 μm in peripheral region of tokamak.

The calculations were carried out on a Linux cluster with 2 Intel Quad-Core Xeon processors. The duration of each run was about 96 h.

The dust particles with radii R_d = 0.2075, 0.415, 0.83 and 1.66 μm ($0.0125\Delta x, 0.025\Delta x, 0.05\Delta x$ and $0.1\Delta x$, correspondingly) were introduced into the system having zero charge. In the simulation, the position of dust particles was fixed at the sheath entrance at $X_d = 120.5\Delta x, Y_d = Z_d = 3.5\Delta y$, where the ions become supersonic. The ion flow velocity at the dust particle position corresponds to Mach = 1.13. During the simulation the dust grains, collecting plasma electrons and ions, acquired negative charge. In Fig. 1 we present the evolution of the electric charge of a dust grain with a radius of 0.83 μm. A fast initial charging takes place due to the collection of electrons, while equilibration takes place on the ion time scale. The equilibrium dust charge is subject to stochastic fluctuations due to the discrete nature of charge carriers (in the simulation one computational particle represents 18.3 electrons or ions). In the Fig. 2 we present the time averaged charge for particles with different radii (circles). The dust charge scales almost linearly with radius as expected for a spherical capacitor:

$$Q_d = 4\pi\varepsilon_0 U_d R_d (1 + R_d/\lambda_D) \tag{3}$$

Solid line in Fig. 2 represents Eq. (3), where the dust potential U_d is determined self-consistently in the simulation. In the simulation the dust potential was found to be independent of the dust radius $U_d = -16.4 \pm 0.9$ V. The small variation in the dust potential is addressed to the plasma parameters fluctuation during the different runs.

For comparison we plot the dust charge obtained in the frame of the Orbital Motion Limited Theory (OML) [5,6] (the comprehensive review can be found in [7]) using the plasma parameters from the simulation as a dashed line in Fig. 2.

The dust potential can be determined from the current balance equation for the dust particle:

$$I_e = I_i \tag{4}$$

The electron current on the dust particle can be written as:

$$I_e = \pi R_d^2 e n_e v_{e,th} \exp\left(\frac{eU_d}{k_B T_e}\right), \tag{5}$$

here $v_{e,th} = \sqrt{\frac{8k_B T_e}{\pi m_e}}$ is the electron mean thermal velocity, k_B is the Boltzmann constant, T_e is the electron temperature, m_e is the electron mass. For the ion current we use the formulation from [8]:

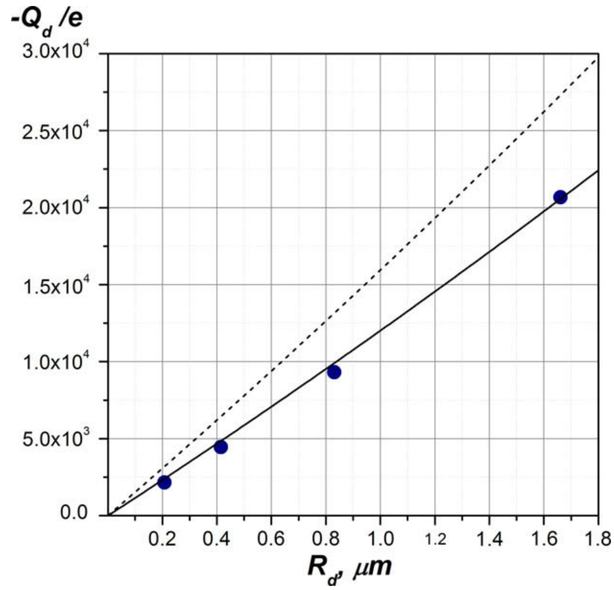

Fig. 2. The dependence of the dust charge on the radius of the dust particle.

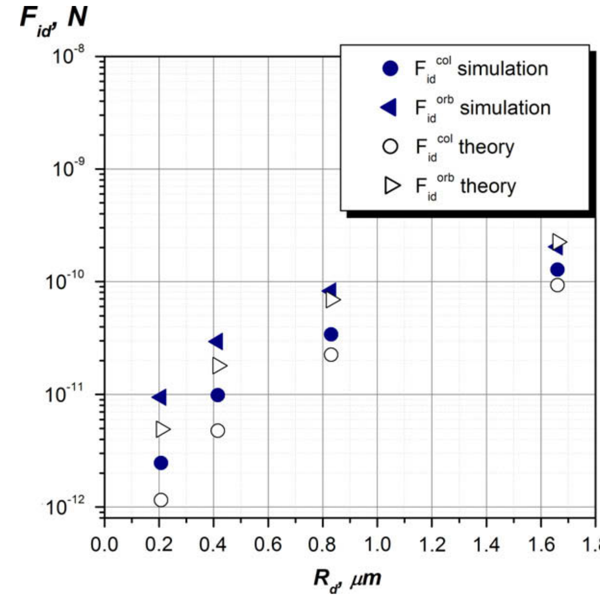

Fig. 3. The dependence of the ion drag force on the radius of the dust particle.

$$I_i = \pi R_d^2 e n_i v_{i,s} \left(1 - \frac{2eU_d}{m_i v_{i,s}^2}\right) \tag{6}$$

here $v_{i,s} = \sqrt{v_{i,f}^2 + \frac{8k_BT_i}{\pi m_i}}$ is the ion "total" velocity, $v_{i,f}$ is the ion flow velocity, T_i is the ion temperature, m_i is the ion mass. Solving Eqs. (4)–(6) numerically we found $U_d = -21.9$ V. Substituting this value into Eq. (3) we obtain the dust charge.

As we can see, OML gives about 30% higher values of the dust charge and potential compared with the simulation. This difference is attributed to the reduction of the electron current to the dust particle perpendicular to the magnetic field, as the electron Larmor radius for the simulation parameters is $r_{ce} \approx 0.5\lambda_D$.

In Fig. 3 we present the averaged over the time ion drag force components for the dust particles with different radii obtained in the simulation (filled symbols) and calculated using OML approach (empty symbols). For calculation of the collection part we used expression from [8]:

$$F_{id}^{col} = \pi b_c^2 m_i v_{i,s} n_i v_{i,f}, \tag{7}$$

here $b_c = R_d\sqrt{1 - \frac{2eU_d}{m_i v_{i,s}^2}}$ is the collection impact parameter.

For the orbital part we applied:

$$F_{id}^{orb} = 2\pi b_{\pi/2}^2 m_i v_{i,f}^2 n_i \ln\left(\frac{b_{\pi/2}^2 + \lambda_D^2}{b_{\pi/2}^2 + b_c^2}\right) \tag{8}$$

which is valid approximation when $v_{i,f}/v_{i,th} > 1$ [9]. Here $v_{i,th}$ is the ion thermal velocity, $b_{\pi/2} = eQ_d/4\pi\varepsilon_0 m_i v_{i,f}^2$ is the impact parameter corresponding to $\pi/2$ scattering angle.

For the calculation of the ion drag force components the U_d and Q_d obtained in the simulation were used in Eqs. (7) and (8). As we can see, the total ion drag force obtained in the simulation is in very good agreement with OML results for larger particles. For R_d = 0.83 and 1.66 μm the difference is 12% and 4% correspondingly. For R_d = 0.2075 and 0.415 μm the deviation is about 50%. Overall good agreement of the simulated values for the ion drag force with the OML results can be explained by the fact that in our system the magnetic field does not influence the ion motion on the scale of the electrostatic sheath around the dust particle as the ion Larmor radius is $r_{ci} \approx 10\lambda_D$. Thus, the OML approach for the ion drag calculation is still valid, provided that the correct values for the dust charge and potential are used.

4. Summary

A 3D P3M model for the dust particle in plasma was used to study the charging process for the spherical conducting dust grains in the magnetized plasma in the peripheral region of a fusion device and to self-consistently obtain the ion drag force components. The model developed is able to provide important insight into the charging process of the dust particles. The results of the simulation were compared with those of the OML theory. It was found that for parameters of the simulation the OML approach is still giving acceptable results for the estimation of the dust charge, potential and the ion drag force. Overall good agreement of the simulated values for the ion drag force with the OML results can be explained by the fact that in our system the magnetic field does not influence the ion motion on the scale of the electrostatic sheath around the dust particle as the ion Larmor radius is much larger than Debye length. For more accurate results and especially in the case when OML approximation is breaking down (at higher collisionality and for stronger magnetic field) the P3M model is preferable.

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