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Finite size effect of dust charging in the magnetized edge plasma

K. Matyash [a,*], R. Schneider [a], F. Taccogna [a], D. Tskhakaya [b]

[a] *Max-Planck Institut für Plasmaphysik, EURATOM Association, D-17491 Greifswald, Germany*
[b] *Department of Theoretical Physics, Association Euratom-ÖAW, University of Innsbruck, A-6020 Innsbruck, Austria*

Abstract

A newly developed 3-dimensional particle–particle particle-mesh (P3M) code is applied to study the charging process of micrometer size dust grains 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 self-consistently resolve the electrostatic sheath in front of the material wall. In order to accurately resolve 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 dynamics of charging of dust grains confined in the magnetized edge plasma and its dependence on the size of the dust is investigated. The results are compared with the case of unmagnetized plasma.

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Keywords: Dust; Edge modelling; Sheaths

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1. Introduction

Dust particles of nanometer–micrometer size are formed in fusion devices due to plasma–surface interaction processes [1]. The dust particles, accumulating tritium, will pose a serious threat for the safe operation of future fusion devices. The dust particles can influence the discharge as impurity source and decrease the performance of the fusion devices [1]. In order to address these issues one has to understand the mechanisms of dust formation and its transport in the fusion device.

In this paper we investigate the charging of micrometer-sized conducting spherical dust particles in the peripheral plasma near the wall of the tokamak. The dust charge determines the electrostatic force acting on the dust particle, which is one of the basic elements for the understanding of transport of dust in fusion devices.

For this purpose we use a newly developed 3-dimensional particle–particle particle-mesh (P3M) code, 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

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[*] Corresponding author. Address: Wendelsteinstr. 1, 17491 Greifswald, Germany. Fax: +49 (0) 3834 88 2409.
E-mail address: knm@ipp.mpg.de (K. Matyash).

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charging due to absorption of plasma electrons and ions.

2. Concept of the P3M code

In previous work [2,3] we have studied the formation of dust structures in low temperature laboratory plasmas with a self-consistent particle simulation. For this purpose a 3D particle-in-cell code with Monte Carlo collisions (PIC-MCC), resolving also the sheath in front of the wall including all relevant species (neutrals, ions, and electrons) and their reactions, was developed and applied [2].

Although PIC simulation proved to be a powerful tool for studying the dusty plasmas, the PIC method has a considerable drawback. The space resolution in the PIC scheme is limited by the size of the grid which is typically of the order of a Debye length (fraction of a millimeter for low temperature plasmas). The size of the dust grains is usually much smaller than this within the micron–nanometer range. The particles in the conventional PIC algorithm are represented by charged clouds of the grid size, being able to penetrate each other [4]. This leads to high inaccuracy for inter-particle interaction when the distance becomes smaller than the cell size. In Fig. 1, we show the dependence of the inter-particle interaction force on the distance, where the distance is normalized to the cell size, as calculated with the PIC model. The interaction force is strongly deviating from the Coulomb force for small distances and tends to go to zero as the inter-particle distance decreases.

Therefore, the PIC model, being able to resolve long-range interaction between the particles (in the order of the Debye length), misses the close-range part for distances comparable with the radius of the dust grains.

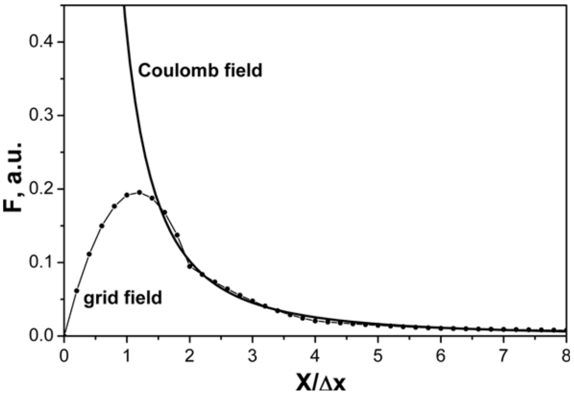

Fig. 1. Interaction force between two charged particles in PIC model.

In order to resolve accurately close-range interaction between dust grains and plasma particles, we extended our PIC model, combining it with the molecular dynamic (MD) algorithm. In the resulting particle–particle particle-mesh (P3M) model, the long-range interaction of the dust grains with charged particles of the background plasma is treated according 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: $\mathbf{E} = \mathbf{E}_{\text{grid}} + \mathbf{E}_{\text{dust}}$. Here for the calculation of the grid field $\mathbf{E}_{\text{grid}}$ 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 $\mathbf{E}_{\text{dust}}$. In order to resolve particle motion on scales of the order of dust grain size, particles in MD region are moved with 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. The P3M code is parallelized using the MPICH library.

3. Simulation

We use the P3M model to investigate the charging process of the spherical conducting dust grains due to collection of plasma electrons and ions 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: $n_{e0} = 10^{12}\ \text{cm}^{-3}$ and $T_{e0} = T_{i0} = 20\ \text{eV}$. 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. A uniform magnetic field $B = 1$ T, directed along the X axis, is applied. In 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 $n_n = 10^{13}\ \text{cm}^{-3}$ and temperature $T_n = 0.1$ eV. 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-section were collected from [5,6]. In order to compensate for reduced size of the computational domain and to be able to resolve collisional presheath, all collisions with neutrals were amplified by factor 250.

A grid with spacing $\Delta x = \Delta y = \Delta z = \lambda_{D0}/2 = 0.0166$ mm and time step $\Delta t = 0.1/\omega_{pe0} = 1.77 \times 10^{-12}$ s was used in the simulation.

The calculations were carried out on a Linux cluster with 8 AMD Athlon 2700+ MHz processors. The duration of each run was about 40 h.

The dust particles with radii $R_d = 0.2075$, 0.415, 0.83 and 1.66 μm were introduced into the system having zero charge. In the simulation, position of dust particles was fixed at the sheath near the wall at $X_d = 122.5\Delta x$, $Y_d = Z_d = 3.5\Delta y$. During the simulation dust grains, collecting plasma electrons and ions, acquired negative charge. In Fig. 2, 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 183 real electrons or ions).

In Fig. 3, we present the XY profile of potential near the dust particle with radius of 0.83 μm, taken at $Z = Z_d$. The average floating potential of the dust particles in the simulation was found $U_d = -22.5$ V. This is lower than the floating potential predicted by the orbit-limited motion (OLM) theory for non-magnetized plasma [7]. When one solves currents balance equation using the expressions for the electron and ion current from [7], taking into account local values of the electron and ion temperature and the ion flow velocity, one gets $U_d = -27$ V. The lower value of the dust potential in the simulations can be explained by the reduction of the electron current perpendicular to the magnetic field. In Fig. 4, we present profiles of the dust grain potential parallel and perpendicular to the magnetic field direction. The potential along the magnetic field is close to the screened Coulomb (Debye–Hückel) potential: $\varphi(R) = U_d \frac{R_d}{R} \exp\left(-\frac{R-R_d}{\lambda_D}\right)$. In the direction perpendicular to the magnetic field the potential is close to the unscreened Coulomb potential for distances smaller than Debye length and decays rapidly at the larger distances.

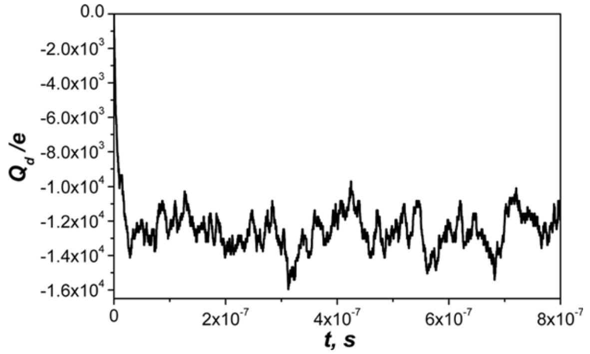

Fig. 2. Charging of a dust grain with the radius 0.83 μm in peripheral region of tokamak.

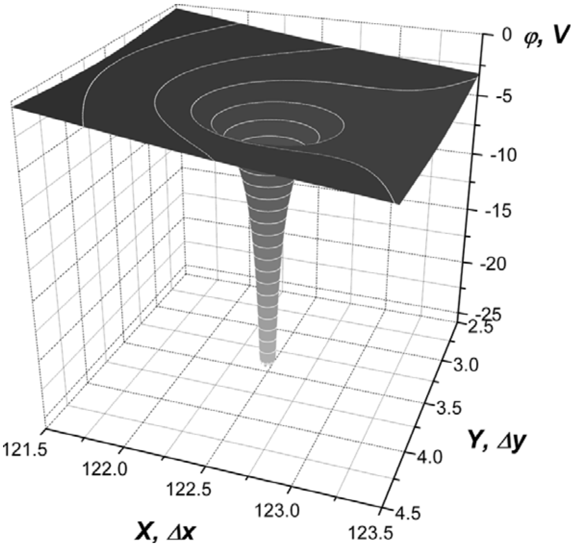

Fig. 3. XY profile of potential near dust grain with the radius 0.83 μm.

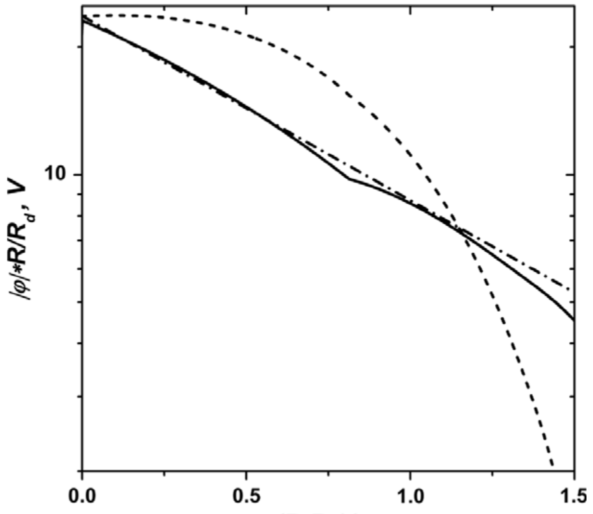

Fig. 4. Profiles of dust grain potential. Solid line corresponds to the direction along the magnetic field, dash line – perpendicular to the magnetic field. Dash-dot line represents the Debye–Hückel potential.

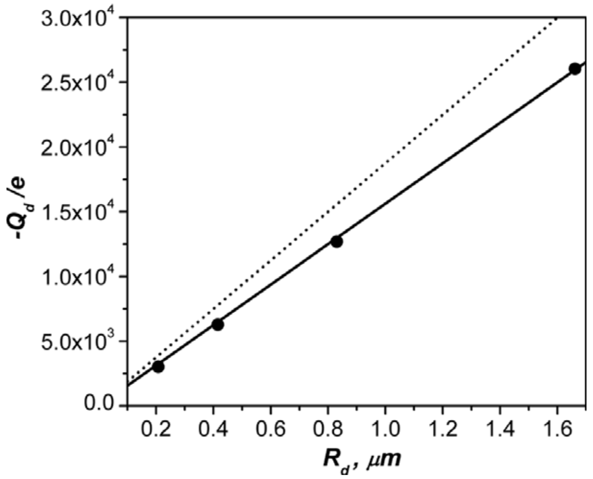

Fig. 5. The dependence of the dust charge on the radius of the dust particle.

In Fig. 5, we present the time averaged charge for particles with different radii (circles). The dust charge scales almost linearly with the particle radius and is in very good agreement with the value obtained for a spherical capacitor

$$Q_{\mathrm{d}} = 4\pi\varepsilon_0 R_{\mathrm{d}} U_{\mathrm{d}}, \tag{1}$$

when the dust potential $U_{\mathrm{d}} = -22.5$ V from the simulation is used (solid line in Fig. 5). Substitution of the dust potential from OLM theory ($U_{\mathrm{d}} = -27$ V) in the Eq. (1) yields noticeably higher dust charges (dotted line in Fig. 5).

4. Summary

A 3D P3M model for dusty plasma was developed and tested. The model implies a fully kinetic description for all species in the plasma, being able to resolve the finite size effects for dust grains. The charging process for the spherical conducting dust grains in the magnetized plasma in the peripheral region of a fusion device was studied. The model developed is able to provide important insight into the charging process of the dust particles in the peripheral region of the fusion device. In future, this model will also be used for the simulation of small electric probes in magnetized plasmas.

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