Numerical simulations of the charging of dust particles by contact with warm plasmas

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Results from numerical studies of the charging of isolated dust particles in drifting plasmas are presented. The dust particles can have different shapes and sizes, and they are either perfectly insulating or perfectly conducting bodies. It is found that in drifting plasmas, dust particles acquire an electric dipole moment. For conducting dust, the electric dipole moment is induced by the anisotropy in the surrounding plasma potential, and it is lower in magnitude and opposite in the direction as compared to the insulating dust particles. The total charge on the dust grains and the formation of the plasma wake behind the dust are also discussed. The dust charging is simulated in two spatial dimensions by a Particle-In-Cell code, with the dust surface imposing boundary conditions within the simulation area.

Introduction

The interactions between dust grains and warm plasmas represent a variety of complicated problems, which often can not be addressed by analytical studies, not even when individual dust grain is considered [1]. In the present paper we study the charging of individual dust particles in warm plasmas by numerical methods. The analysis is carried out with a 2D Particle-In-Cell code in Cartesian coordinates [2], where the dust particle is placed inside the simulation area and imposes additional boundary conditions for plasma. In this study, we consider two basic types of dust particles, which can be made of perfectly insulating or perfectly conducting material.

The shapes of the dust particles considered here are shown in Fig. 1. They represent a shape as close as possible to circle with a given grid resolution (Fig. 1a), and an irregular shape that includes cavities and extrusions (Fig. 1b).

Figure 1: Dust grain shapes on the computational grid.

The simulation box in this simulation is 200×200 grid points, which gives the simulation area of 100×100 λ_D with the grid spacing of $0.5\ \lambda_D$. We use a typical plasma particle density $n_{e,i} = 10^{10}$ m^{-2}, and have ca. 2 simulation particles representing the plasma particle. The electron to
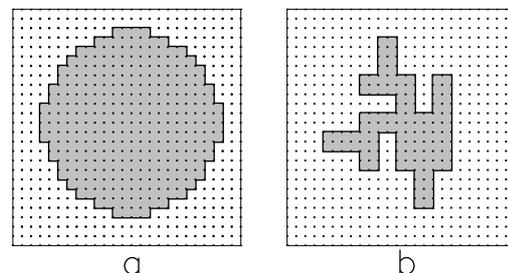
ion temperature ratio is $T_e/T_i = 3$. For increasing the computational efficiency, we use an ion to electron mass ratio $M/m_e = 120$. We find this ratio, after comparison with the experiments for realistic mass ratios, to be sufficient for giving credibility to the results. The present numerical code was verified by reproducing plane Langmuir probe characteristics for thermal plasmas, and plasmas with ion-beams that were obtained under laboratory conditions [3].

Numerical results

We observe the development of an electric dipole moment on the dust particle in the presence of an ion drift (Fig. 2). This electric dipole moment develops on both insulating and conducting dust particles, but it differs in magnitude and direction for the two cases. It becomes significant for supersonic velocities and saturates for Mach numbers larger than approx. 2. For insulating dust this electric dipole moment develops due to the anisotropic collection of plasma particles on the dust surface [4]. Thus, its direction is parallel to the ion flow velocity. For the conducting dust the electric dipole moment is induced by the anisotropy in the potential distribution around the dust particle (i.e., the wake formation). The electric dipole moment magnitude is here approximately 5 times lower than for the insulating dust, and its direction is antiparallel to the ion drift velocity.

Other numerical results also revealed the development of an electric dipole moment on the insulating dust, but for the conducting dust it was there implicitly assumed that the charge is distributed isotropically on the dust surface [5]. In the present work, we chose a different approach for studying a dust particle of size of a few λ_D, and allowed the surface charge to be redistributed in accordance with the surrounding plasma potential, in such a way that the potential inside the dust was kept constant.

Figure 2: Normalized electric dipole moment for insulating a) and conducting b) dust grain as a function of the plasma drift velocity U. The shape of the dust grain given by Fig. 1a) is illustrated by ●, while the shape given by Fig. 1b) is illustrated by △.

Plasma is being absorbed by the dust, and thus there is a net negative charge on the shadow side of the dust particle in the presence of ion drift. For the conducting dust it results in the local negative potential with respect to the dust, and the conductor short-circuiting implies a local positive surface charge density on the dust. This local negative potential behind the particle
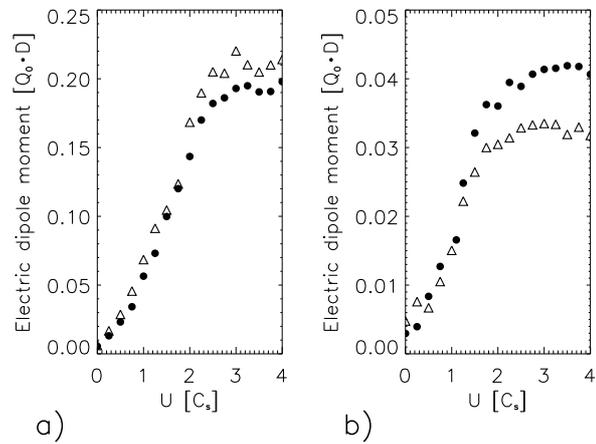
attracts ions, but the potential drop with respect to the dust leads to an effectively repulsive force on the ions at the dust surface.

The clear Mach cone is observed in the potential distribution behind the conducting dust (Fig. 3). Such a Mach cone is not as clearly observed for the insulating dust. For this case, the positive charge is building up on the dust surface facing the ion flow, while the electron flux to the surface prevails on the shadow side. The ion trajectories are bended: incoming ions are reflected by the accumulated positive charge, and they are focused behind the wake on the shadow side of the dust. Here, the negative surface charge attracts ions. As a result of the anisotropic charge collection, there is an electric field present inside the insulating dust, which could in principle cause the disruption of a dust
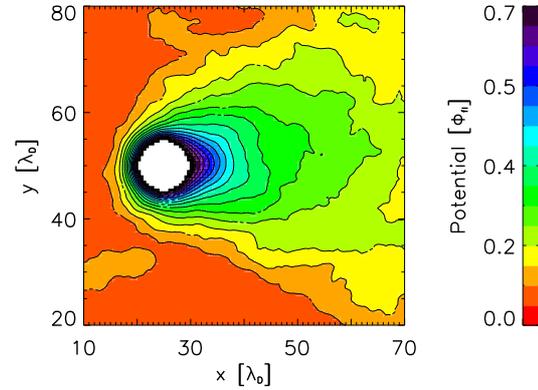

Figure 3: The time asymptotic potential distribution around the perfectly conducting dust grain in plasma flowing with velocity $U = 2C_s$, for the particle with shape given by Fig. 1a).

grain. In particular, the irregularities on the dust surface lead to strong gradients in potential and these fine structures can be easily destroyed (Fig. 4). The short-circuiting of the conductors make the dust irregularities less vulnerable to the plasma. The ambipolar electric field, together with the potential of the dust, acts to sustain a steady state potential distribution.

The total charge on a dust particle in a drifting plasma is shown in Fig. 5. These results are similar to previous 3D simulations for an insulator, but differ for a conductor [5][6]. The observed strong decrease in the total charge on the conducting particle may be argued with reference to the anisotropic potential distribution around dust and corresponding electric dipole moment. This is here found to be important already for dust radii of a few λ_D. The charge in Fig. 5 is normalized with the analytical charge for the 2D dust of radius R embedded in thermal plasma. The normalizing charge is given by the expression:
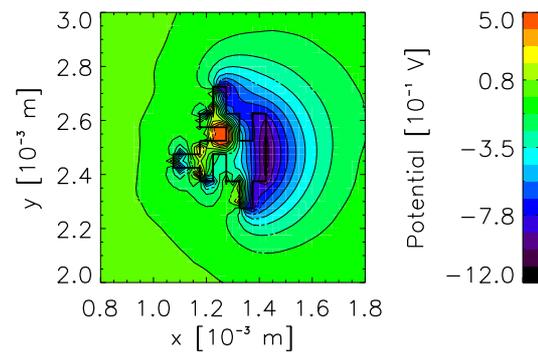

Figure 4: Potential distribution around the irregular dust grain in a plasma flowing with velocity $U = 2C_s$. The particle shape given by Fig. 1b.

$Q_0 = 2\pi\varepsilon_0\Phi_{fl}R/\lambda_D \cdot K_1(R/\lambda_D)/K_0(R/\lambda_D)$, where K_0 and K_1 are the modified Bessel functions, and Φ_{fl} is a floating potential defined as:

$$\Phi_{fl} = -\frac{\kappa T_e}{2e}\left(\ln\left(\frac{M}{2\pi m}\right) + 1\right). \tag{1}$$

The floating potential defined by (1), is derived for Boltzmann distributed electrons and cold ions which are accelerated to the Bohm velocity, and it includes also the potential drop in the pre-sheath. We find that this expression is a good approximation to the floating potential that was obtained in the numerical experiment.

References

[1] V.E. Fortov, A.V. Ivlev, S.A. Kharpak, A.G. Kharpak, and G.E. Morfill, Physics Reports **421**, 1-103, 2005

[2] C.K. Birdsall, and A.B. Langdon, Plasma Physics via Computer Simulation, Adam Higler, 1991

[3] W.J. Weber, R.J. Armstrong, and J. Trulsen, J. Appl. Phys. **50**, 4545-49, 1979

[4] A.V. Ivlev, G. Morfill, and V.E. Fortov, Phys. of Plasmas **6**, 1415-1051, 1999

[5] G. Lapenta, Phys. Plasmas, **5**, 1442-47, 1999

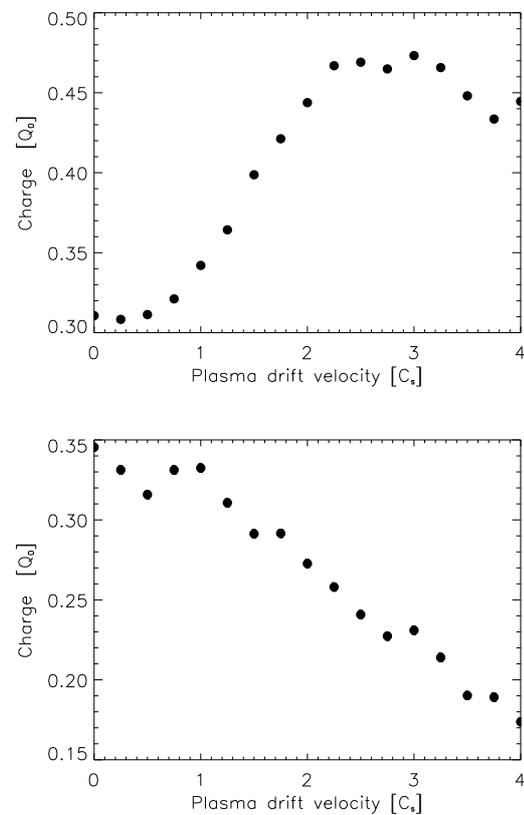[6] I.H. Hutchinson, Plasma Phys. Contr. Fusion, **47**, 71-87, 2005

Figure 5: The normalized average charge on insulating (top) and conducting (bottom) dust particle for different plasma flow velocities. The particle shape given by Fig. 1a.