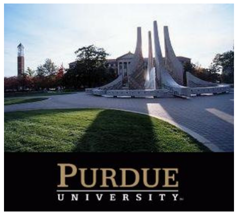

CHARGING OF DUST GRAIN CLUSTERS IN PLASMAS

G. Miloshevsky and A. Hassanein

Center for Materials under Extreme Environment, School of Nuclear Engineering, Purdue University, West Lafayette, IN, USA

Abstract

Dusty plasmas are ionized gases containing charged dust grains and exhibiting completely new physical features such as charge variability on grains, grain-grain interactions, self-organization, and formation of various stable structures. The charge on dust grains can fluctuate randomly in response to fluctuations in plasma parameters. The information about the charging of an isolated grain can not be used for interpretation of the charging in the presence of many grains. The basic processes such as grain charging in dust clusters, electric potential distribution around and within a charged dust cluster, inter-grain repulsion or attraction, electron and ion number density distributions are of particular interest. A new 2D Particle-In-Cell (PIC) computer code is developed to study the process of grain charging in dust clusters and structures. The code allows for studies of dielectric dust grains of different sizes and shapes in isotropic and anisotropic plasmas. The 2D simulation domain is a part of an infinite plasma with the plasma potential at boundaries set to zero. The dust clusters are placed near the center of the 2D simulation box. The floating potential on grains is built by collecting plasma particles. Since the PIC method provides a self-consistent fully kinetic description, no assumptions are made about the plasma screening lengths, grain charge values and effective interaction potentials. The PIC code was used to investigate the dynamics of the charging of dust clusters in contact with plasmas. The time dependent charging of dust clusters and discrete fluctuations of the charge on grains are studied. The potential variation in grain's sheath regions, distribution of number of plasma particles in the vicinity of the grains, and the effects of other grains are investigated. The energetically favorable configurations of dust clusters are found that minimize the kinetic energy of the plasma ions. This effect could be due to the changes in the electrostatic influence of grains on the plasma structure with decreasing the separation distance between them that causes the multiple potential wells to merge into a single potential well, thus changing the dynamics of the plasma ions. Alternatively, the flux of plasma particles onto grains in a cluster can be shadowed by the other grains with momentum transfers from the outer sides larger than that from the inner sides resulting in an attracting force between the dust grains.

1. Introduction

Controlled manipulation, assembly, and disassembly of finite clusters of particles are of great importance in physics and chemistry. Small 2D clusters of dust grains were investigated in several experiments utilizing an external confining potential [1-3]. It was found that the grains are arranged in stable ring-like concentric shells. It is very difficult to create the boundary-free (unconfined) dust clusters. The effects of walls, gravity, external electric or magnetic fields, ion drag forces have to be eliminated. The boundary-free cluster formation could be possible due to the non-collective attraction (shadow forces) between the like-charged grains. An attraction of dust grains in the bulk region of the plasma with isotropic plasma conditions was indeed observed in a recent experiment under microgravity conditions [4]. A boundary-free dust cluster of the spherical shape was formed from a large central grain and a number of peripheral small grains (six times smaller). The attraction between the grains was explained as due to the non-collective shadow force of plasma particles [5].

Complex plasmas represent a thermodynamically open system. The losses of electrons and ions on dust grains have to be compensated by external particle and energy sources. Although the complex plasma is a non-Hamiltonian system, it was recently demonstrated for two dust grains in a plasma sheath that the Hamiltonian description can be used to provide valuable insights into the stability of dust clusters [6]. If the plasma and energy supply is fast enough compensating the rate of plasma absorption on grains, then the equilibrium charge on dust grains is maintained by these fluxes of electrons and ions which continuously present after the equilibrium state is reached. The system relaxes to the equilibrium in several ion plasma periods. The stationary state with certain distributions of potential, electric field, electron and ion densities is established around the dusty grains. The changes of the kinetic and potential energy can indicate the charging of grains and the build-up of a sheath within a dust cluster. The kinetic and potential energy of the entire plasma-dust system can serve as an indicator for reaching the steady state. The results of our PIC simulations of small 2D dust clusters consisting of 2, 3, 7 and 19 insulating grains with variable inter-grain separations are presented. The kinetic, potential and total energy of the plasma-dust system are investigated as a function of grain configurations and separations.

2. Computational Model

2.1. Particle-in-Cell Code

We have developed a 2D PIC code to model the dust clusters in isotropic and anisotropic plasmas. The code is written in mixed Fortran-90/C++ language. Many technical details implemented in our self-consistent 2D PIC scheme are conventional to PIC plasma models described in classical textbooks [7]. The *fundamental steps* of our PIC implementation: 1) the electron and ion macro-particles are assigned Cartesian coordinates and velocities within a 2D computational domain; 2) the spatial grid over the computational domain is created; 3) the charge of electron and ion macro-particles in each cell is distributed among the nearest grid points; 4) the charge density on the grid is then used as the source in the Poisson's equation which is solved numerically producing the electrostatic potential at each grid point; 5) the electric field is evaluated on the grid; 6) the force due to the electric field is interpolated from the discrete grid to the plasma macro-particle locations; 7) plasma macro-particle velocities and positions are advanced on the time step. *Unique features* of our PIC model are accurate resolution of 1) finite size of small dust grains and 2) trajectories of plasma macro-particles close to the dust grains with treatment of short range forces using direct plasma particle-grain force calculations. A number of reduced time steps are used for plasma macro-particles in the vicinity of dust grains to describe their trajectories. This implementation was required to correctly determine the charge and floating potential on grains. The multi-frontal massively parallel solver, MUMPS, is used to solve the Poisson equation at each time step. It is an accurate direct method based on lower and upper matrix factorization. The MUMPS solver utilizes the MPI library for message passing and uses the BLAS, BLACS, and ScaLAPACK libraries.

2.2. Initial Set-up of Plasma-Dust System

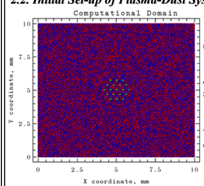

Fig. 1. Representative sketch of the computational domain used in PIC simulations of dust clusters. A dust cluster with 19 grains immersed in an isotropic plasma is shown as green spheres. For visibility, the size of grains is increased by 10 times.

- dimensions of the domain: 10x10 *mm* with grid spacing 50 *μm* (200x200 cells);
- on the domain's boundaries, the electric potential ~0 *V* (unperturbed bulk plasma);
- plasma parameters: $N_e = N_i = 10^{15}\ m^{-3}$; $T_e = 3\ eV$; $\omega_e \approx 1.8 \cdot 10^9\ s^{-1}$; $T_i = 0.03\ eV$; $\lambda_{De} \approx 407.2\ \mu m$; $\lambda_{Di} \approx 40.7\ \mu m$; $\lambda_D \approx 40.5\ \mu m$; $v_e \approx 7.3 \cdot 10^5\ m/s$; $v_i \approx 5.1 \cdot 10^3\ m/s$; $v_s \approx 5.2 \cdot 10^4\ m/s$;
- the plasma is modeled as collisionless; in a sphere with radius $\sim\lambda_{De}$, the number of plasma particles N_D~33; number of λ_{De} per domain's length ~25; time step $\sim 0.02/\omega_e \sim 10\ fs$;
- total number of macro-particles (macro-electrons plus macro-ions) initially placed within the computational domain $\sim 2 \cdot 10^6$ representing ~1 real plasma particle; number of macro-particles per cell ~50;
- new plasma particles are injected from the boundaries of the computational domain with Maxwellian velocity distributions;
- dust clusters were preconfigured from insulating dust grains with radius of 5 *μm*;
- dust clusters were placed near the center of the computational domain; in different PIC runs, the separation distance between grains was varied around λ_{De}; the charge and potential on grains was built by absorbing the plasma macro-particles until they start to fluctuate around an average value; PIC simulations were run up to ~5 *μs* (~100 ion plasma periods);

3. Computational Results

3.1. The dust cluster with 19 grains in the isotropic and anisotropic plasmas

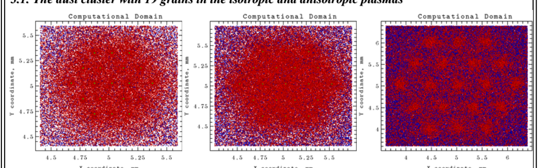

Fig. 2. The distribution of plasma electrons (blue points) and ions (red points) within the dust cluster at time ~5 μs. The average distance between grains is ~170.1 μm (left), ~237.6 μm (central) and ~572.2 μm (right).

- at large separations ($>\lambda_{De}$), there are isolated dense clouds of plasma ions surrounding the dust grains;
- at separations $\sim\lambda_{De}$ and smaller, a uniform cloud of ions is formed covering the entire dust cluster;
- density of ions increases by ~8-10 times within the area of the dust cluster with decreasing its size;

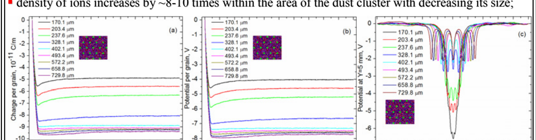

Fig. 3. Evolution of the charge (a) and potential (b) on grains, and the cut-off potential (c) on the grid at Y=5 mm for the dust cluster with various separations between grains.

- at large separations between grains, the charge and potential per grain approach values of an isolated grain: $\sim 1.0022 \cdot 10^{-10}$ C/m and -8.25 V, respectively; they decrease with decreasing the separation distance; multi-well potential on the grid transforms to a single well potential at short separations

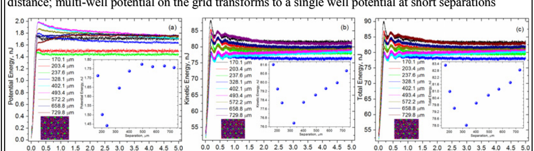

Fig. 4. Potential (a), kinetic (b) and total (c) energy as a function of time for various separations between grains.

- configurations of the plasma-dust system with inter-grain separations ~230-330 μm is energetically more favorable both in the potential and kinetic energy compared to other configurations with smaller or larger inter-grain separations; the energy for cluster dissociation is >5.4 nJ

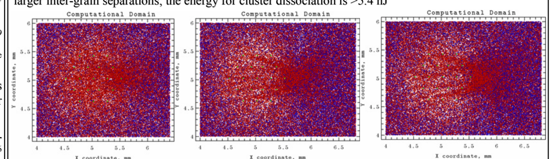

Fig. 5. The distribution of plasma ions (red points) and electrons (blue points) within a dust cluster at time ~5 μs for various ion drift velocities: $v_d = 0.8 \cdot v_s$ (left), $v_d = 1.2 \cdot v_s$ (central) and $v_d = 1.4 \cdot v_s$ (right). The separation distance between grains is ~237.6 μm. For visibility, the size of grains is enlarged by two times.

- the cloud of ions initially distributed uniformly within the dust cluster is blown out by the plasma flow forming the ion wake behind the dust cluster; the ion focusing in the wake region increases with v_d
- the dust charging, the charge and potential on grains, the screening of grains by plasma are all affected due to the asymmetric flow of plasma ions; at $v_d \geq 1.4 \cdot v_s$ it is observed that one of grains in the dust cluster becomes *positively* charged, the others acquire negative charges

3.2. The dust cluster with 7 grains in the isotropic plasma

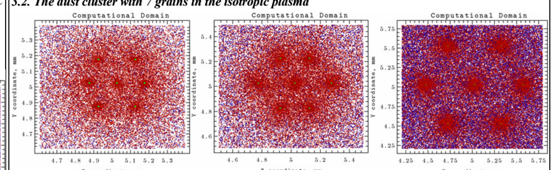

Fig. 6. Distributions of plasma electrons (blue points) and ions (red points) within of the dust cluster with 7 grains at time ~5 μs. The separation between grains is ~171.1 μm (left), ~232.9 μm (central) and ~572.4 μm (right).

- formation of the common cloud of ions covering the dust cluster is not observed for these separations since the individual ionic clouds do not completely overlap; however, the overlapping could occur at smaller separations; the similar behavior is observed for clusters with three and two grains

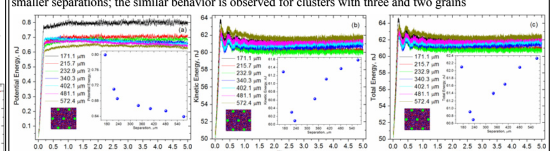

Fig. 7. Potential (a), kinetic (b) and total (c) energy as a function of time for various separations between 7 grains.

- the potential energy of the plasma-dust system increases with decreasing the inter-grain separation; the system of 7 grains is energetically stable with the inter-grain separation ~232.9 μm due to a minimum of the kinetic energy of plasma ions; the energy for cluster dissociation is ~1.8 nJ; this behavior of the potential and kinetic energy is also observed for the dust clusters consisting of three and two grains

3.3. The dust cluster with 3 grains in the isotropic plasma

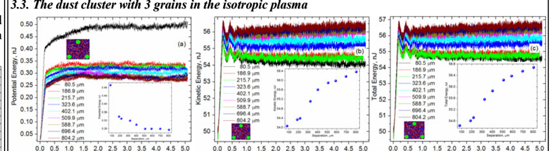

Fig. 8. Potential (a), kinetic (b) and total (c) energy as a function of time for various separations between 3 grains.

- the potential energy of the plasma-dust system is a decreasing function of inter-grain separation; the kinetic energy of ions reaches a minimum at inter-grain separations about two ion Debye lengths; the energy for cluster dissociation is ~2 nJ

3.4. The effect of dust grains on the plasma

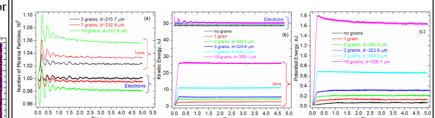

Fig. 9. Evolution of the number of electrons and ions (a) in the computational domain, the kinetic energy of electrons and ions (b), and the total potential energy (c) of the plasma-dust system with the dust clusters containing various number of grains.

- with increase of the number of grains in the computational domain: 1) the number of ions increases while the number of electrons drops; 2) the kinetic energy of ions grows substantially, while the kinetic energy of electrons fluctuates slightly; 3) the potential energy of the plasma-grain system increases

Summary

- The focus of this work was on understanding the underlying physical processes involved in the charging of preconfigured dust clusters in isotropic and anisotropic plasmas. During the charging in the isotropic plasma, the grains acquire both the large negative charge and the floating potential at which the electron and ion currents onto the grain's surface cancel each other. The sheath is built and plasma distribution is changed within the dust cluster. At high ion drift flows, the charge on one of grains in the dust cluster switches to a positive value.
- The number density of ions in the vicinity of a dust cluster is much greater than that in an unperturbed plasma. Each dust grain is surrounded by a dense cloud of ions. At small separations between grains these ionic clouds overlap forming a uniform cloud of ions within the area of a dust cluster. The number density of plasma electrons is much lower within the dust cluster. The cloud of ions is blown out by the ion drifting flow forming the ion wake region behind the dust cluster.
- The number of ions in the computational domain and their kinetic energy increase with increasing the number of grains in the cluster. The number of electrons decreases and their kinetic energy is nearly unchanged. The kinetic, potential and total energies of the plasma-dust system are all affected by the change of inter-grain separations.
- There are energetically favorable configurations of dust clusters with certain inter-grain separations even for 2 and 3 grains when the total energy of the plasma-dust system is lower by ~1-2 nJ compared to dust configurations with well separated grains. The energy minimum is shifted to larger inter-grain separations with increase of the size of dust clusters. The energetically favorable configurations could be due to the qualitative change in the plasma structure within the dust cluster with variations of the inter-grain separations.
- For dust clusters with 7 and 19 grains and inter-grain separations $\sim 2\lambda_{De}$, the charge on grains and the floating potential per grain are yet different from those corresponding to a single isolated grain. This indicates long-range, non-linear plasma effects in the presence of dust clusters and plasma perturbations at distances much exceeding the electron Debye length.
- The observed stable configurations of grains *does not ensure the long-term thermal stability of dust clusters*. We need to consider that these are dynamically evolving systems due to the complicated interplay between the charging and the screening as well as the presence of external sources of plasma particles.

References

1. W.-T. Juan *et al.*, Phys. Rev. E **58**, 6947 (1998).
2. M. Klindworth *et al.*, Phys. Rev. B **61**, 8404 (2000).
3. A. Melzer *et al.*, Phys. Rev. Lett. **87**, 115002 (2001).
4. A. D. Usachev *et al.*, Phys. Rev. Lett. **102**, 045001 (2009).
5. V. N. Tsytovich et al., *Micro-particle Collective and Non-collective Pair Interactions*, Lect. Notes Phys. **731**, 197-245 (2008).
6. J. D. E. Stokes *et al.*, Phys Rev E **78**, 036402 (2008).
7. R. W. Hockney and J. W. Eastwood. *Computer Simulation Using Particles*. McGraw-Hill, New York, N.Y., 1981.

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