5 Modeling of dusty plasmas

5.1 Motivation

The plasmas which, in addition to electrons, ions and neutrals, also contain microscopic particles of nanometer – micrometer size are called dusty (complex) plasmas. The dust particles in such plasmas gain an electric charge, the sign and magnitude of which depends on the balance between different charging processes. The absorption of electron and ion fluxes, thermo-, photo- and secondary electron emissions are the most typical mechanisms of particle charging in complex plasmas. Such charged micro-particles substantially change plasma behavior, being responsible for unusual properties of complex plasmas.

The interest in dusty plasmas was initially formed in the astrophysics community, as such plasmas are omnipresent in space including interstellar clouds, comet tails, planetary rings, etc [Shukla, 2002]. Later, such plasmas were found in plasma technology devices used for semiconductor manufacturing, where they are formed either due to gas phase reactions or due to plasma-surface interaction. In semiconductor manufacturing and other surface modification technologies formation of the dust in the plasma reactor leads to contamination of the processed surface and as a result affects the quality of produced devices and reduces the efficiency of technological process [Selwyn, 1989]. The negative technological impact of dusty plasmas triggered research work on such plasmas in the plasma physics community [Bouchoule, 1999; Swinkels, 1999]. As a result of increased knowledge and the ability to control the particles in the plasma new applications for dusty plasmas were found [Bouchoule, 2002]. Nowadays such plasmas are successfully used for producing new materials, where incorporation of the nano- or micro-particles in the growing surface helps to produce materials with new properties. Production of ultraflexible ceramic materials [Buss, 1996] and polymorphous silicon films for optoelectronic devices with higher efficiency [Roca I
Cabarrosas, 1998] may serve as examples of technological application of dusty plasmas.

In nuclear fusion research formation of dust inside magnetic confinement fusion devices receives growing concern [Winter, 2000; Rubel, 2001; Winter, 2001; Sharpe, 2003]. Dust can be formed inside the fusion device due to erosion of plasma facing components and soft co-deposited carbon layers. Since such carbon particles can retain large amounts of hydrogen, dust contributes to the problem of inventory of radioactive tritium inside the fusion machine. Another impact of the dust particles in the operation of a fusion device is the possible degradation of the discharge performance. Such particles penetrating in the core plasma region can lead to discharge disruption [Nahihara, 1997]. Thus, in order to perform successful fusion experiments it is important to assess and understand the processes by which dust is formed and by which it interacts with the fusion device and its plasma.

In low-temperature laboratory plasmas the absorption of electrons and ions is the dominating mechanism of micro-particles charging. In such plasmas a dust particle acts as a small floating probe, receiving the net negative charge due to higher electron mobility. As a result, a particle acquires a negative floating potential [Spitzer, 1978] which repulses the electrons and accelerates the ions, balancing electron and ion currents to the particle. The typical charge of micrometer sized particles in laboratory plasmas is of the order of 10000 elementary charges. Despite the large electric charge, the charge to mass ratio for such particles remains very small, much smaller than that of ions. Due to their big mass and size the dust particles in the complex plasmas are subject to a variety of forces, which are unimportant in usual plasmas [Piel, 2002a], [Shukla, 2002]. Because of small charge to mass ratio the gravitational force becomes dominating for such particles, being comparable or even larger than electrostatic forces resulting from the plasma electric field. Collisions of the dust particles with the residual gas atoms or molecules lead to a neutral gas friction force, damping the particle motion. Momentum transfer due to collection and Coulomb scattering of the ions gives rise to the ion drag force, which in certain cases can strongly influence the particle behavior [Zafiu, 2002].

In capacitive RF discharge the gravitational force acting on the particles can be equilibrated by the electrostatic force due to a strong repulsive electric field in the RF sheath. In this case particles are trapped in the discharge and form a cloud levitating above the lower electrode. The dust particles interact with each other
through the repulsive Coulomb potential, screened by the plasma electrons and ions. In the case of strong electrostatic coupling, i.e. when the energy of the interparticle interaction is large compared to the particle thermal energy, particles self-assemble into ordered structures, known as Coulomb (plasma) crystals. The possibility of Coulomb crystallization of micrometer-sized particles in low-temperature laboratory plasmas was first theoretically predicted by Ikezi in [Ikezi, 1986]. Later, the plasma crystals were observed in laboratory plasma experiments: [Chu, 1994; Thomas, 1994; Hayashi, 1994; Trottenberg, 1995; Pieper, 1996].

Such strongly coupled dust structures may serve as a unique model system for studying the physical processes in condensed matter, such as phase transitions [Melzer, 1996; Morfill, 1999a] waves and oscillations [Homann, 1998; Piel, 2002b; Vladimirov, 2002] Mach cones [Samsonov, 1999; Melzer, 2000], etc. Due to the large mass of the dust particles the characteristic relaxation time for the plasma crystals is usually of the order of seconds, making such structures easy to observe with ordinary video-observation techniques. The interparticle distance in dusty plasma crystals is usually of the order of a fraction of millimeter, so that it is possible to observe such structures even with a naked eye. The plasma crystals represent a bridge connecting the atomic or molecular scale of matter with the macroscopic scale of a dusty particle system, giving a unique possibility to observe the processes in the condensed matter on the kinetic level.

Nowadays, complex plasmas represent one of the fastest developing branches of physics [Morfill, 2002; Piel, 2002a; Shukla, 2002; Tsytovich, 2002] attracting interest from different sides of the physical community: astrophysics, plasma technology, thermonuclear fusion and condensed matter physics.

### 5.2 Two dimensional modeling of dusty plasma

We have studied the formation of dust structures in a capacitive coupled RF discharge using a self-consistent particle simulation. For this purpose we have utilized the particle-in-cell (PIC) code with Monte-Carlo collisions (MCC) package resolving 2 spatial dimensions and 3 velocity components (see Chap. 2, Chap. 4). The dust particles were introduced in the model as additional charged species, using the Cloud-in-Cell weighting formalism (see Chap. 2.4), so that no finite size
effects for dust particles were considered. In addition to the electrostatic force the gravitational and neutral gas friction forces were also considered for the dust particles. The equation of motion of a dust particle is:

$$\frac{d\vec{v}}{dt} = \frac{q_d}{m_d} \vec{E} + \vec{g} - \beta \vec{v},$$  \hspace{1cm} (5.1)$$

where $q_d$ and $m_d$ are particle charge and mass, $g$ is gravitational acceleration and $\beta$ is the normalized friction coefficient.

As a background gas, methane with concentration $n_{CH_4} = 7 \cdot 10^{14}$ cm$^{-3}$ and temperature $T_{CH_4} = 500$ K was used. The initial electron density and temperature were chosen as $n_{e0} = 2.5 \cdot 10^9$ cm$^{-3}$ and $T_{e0} = 10$ eV respectively. The computational domain is a rectangle in an XY plane, where the Y axis corresponds to the vertical direction. The vertical size of the system is $Y_{\max} = d = 32\lambda_{po} = 1.5$ cm and the width is $X_{\max} = 16\lambda_{po} = 0.75$ cm. The lower electrode at $Y = Y_{\max}$ is grounded and the upper electrode at $Y = 0$ is powered with a sinusoidal voltage with frequency $f_{RF} = \omega_{RF}/2\pi = 13.56$ MHz. At the electrodes the absorbing wall boundary conditions for the particles were applied. In the X direction the periodic boundary conditions were applied, both for particles and the potential. The neutral gas was treated as a fixed background with constant density and temperature. Only the charged particle dynamics was followed. For the sake of simplicity only Coulomb collisions for the electrons and ions and electron-impact ionization and dissociation collisions with methane molecules (Appendix A) were considered in the simulation.

In calculations a grid size $\Delta x = \Delta y = \lambda_{po}/2 = 0.024$ cm and time step $\Delta t = 0.2/\omega_{pe} = 7 \cdot 10^{-11}$ s was used. In order to speed up the simulation, reduced masses of the ions and dust particles were used. The ion-electron mass ratio was set to $m_{CH_4}/m_e = 1600$. The mass of the dust particles was chosen as $m_d/m_{CH_4} = 640$, which gives the mass of the dust particle about 8 orders of magnitude smaller than in the laboratory experiments. In order to compensate for the decreased mass of the dust particles and match the gravitational force to the electrostatic force acting on particles in the RF sheath, the gravitational acceleration was increased by a factor of $5 \cdot 10^9$ compared to the real value. The
constant charge of the dust particles \( q_d = 5 \cdot 10^4 \cdot e \) was assumed (no charging processes were accounted for). The viscosity coefficient was set to \( \beta \Delta t = 0.0001 \), giving the characteristic time of particle slow down due to neutral gas friction \( \tau = \frac{1}{\beta} = 7 \cdot 10^{-7} \) s. Such artificial modification of the system parameters allowed us to accelerate the computation to achieve an acceptable simulation time. The calculations were carried out on an 8-processor Linux cluster in about 2 weeks.

In the beginning of the simulation the dust particles were randomly introduced in the middle of the system. After about \( 10^{-4} \) s they formed the dust cloud levitating about \( 2 \lambda_D \) above the lower electrode. In Fig. 5.1 we present dynamics of this dust cloud plotting four particle distributions with a time interval of \( 7 \cdot 10^{-6} \) s. We can see that particles form a structure with several horizontal layers and interparticle distance of about one Debye length. The new particle (marked in blue) is added to the system. We can see how this particle joins the existing dust cloud structure above the lower electrode. When this new particle falling down approaches the cloud (Fig. 5.1a-b), the particles underneath change their horizontal position, aligning themselves in a vertical string-like structure under the newly added particle (Fig. 5.1d). We can see several such vertically aligned ‘strings’ of dust particles, so called ‘dust molecules’ in Fig. 5.1. These dust strings are rather stable, when the upper particle moves in a horizontal direction, the whole lower part of the particle string follows this motion, being attracted to the upper particle, so that the vertical alignment is conserved. Such attraction of negatively charged particles can not be explained on the basis of particle interaction through the isotropic Yukawa-type potential: \[ \phi = \frac{q_d}{4 \pi \epsilon_0 r} \exp\left(-\frac{r}{\lambda_D}\right) \]. Origination of such vertically aligned dust structures can be attributed to the positive wake-potential arising due to focusing of the ion flow by the negative dust particles [Vladimirov, 1995]. Indeed, in the sheath region, where the dust particles are levitating, the ions are flowing with velocities close to or larger than the ion sound velocity. When the ion flow encounters the negatively charged dust particle it gets focused, forming an ion beam in the wake of the particle. The dust particles downstream are attracted to this ion beam, creating a vertical string of dust particles coupled with the focused ion flow.
Figure 5.1 Evolution of dust cloud above the lower electrode (Y= 32 $\lambda_0$). a) $t = 1.4$ ms, b) $t = 1.407$ ms, c) $t = 1.414$ ms, d) $t = 1.421$ ms.

Creation of such stable vertical dust structures in which like-charges are attracted to each other due to medium polarization is similar to the Cooper pairing of the electrons in superconductivity [Vladimirov, 1995]. The physical idea of Cooper-pairing is that a test electron moving through the crystal lattice polarizes it attracting the positive ions. This positive ion wake attracts the second electron. If this attraction is strong enough to overcome the Coulomb repulsion of two electrons, the electron pair is formed and superconductivity results [Gennes, 1966]. For effective attraction the speed of the electrons relative to the ion background should exceed the sound velocity. In the case of the dust strings, however the dust particles are static and the ion flow creates polarization necessary for particle attraction.
Figure 5.2 Potential profile averaged over the RF cycle in RF discharge with dust cloud over the lower electrode ($Y = 32 \lambda_d$).
Figure 5.3 Map of potential, averaged over RF cycle. Position of the lower electrode is $Y = 32 \lambda_D$. Positions of dust particles are marked as $\bullet$.

Figure 5.4 Map of the vertical component of ion velocity, averaged over RF cycle. Position of the lower electrode is $Y = 32 \lambda_D$. Positions of dust particles are marked as $\bullet$. 
Figure 5.5 Map of horizontal component of ion velocity, averaged over RF cycle. Position of the lower electrode is $Y = 32 \lambda_d$. Positions of dust particles are marked as •.

Figure 5.6 Map of the ion density, averaged over RF cycle. Position of the lower electrode is $Y = 32 \lambda_d$. Positions of dust particles are marked as •.
Figure 5.7 Profile of the horizontal (top) and the vertical (bottom) component of electric field averaged over RF cycle. Position of the lower electrode is $Y = 32 \lambda_d$. 
Figure 5.8 Smoothed profile of the horizontal (top) and the vertical (bottom) component of electric field averaged over the RF cycle. Position of the lower electrode is $Y = 32 \lambda_d$. 
Figure 5.9 Profile of the horizontal (top) and the vertical (bottom) electron temperature averaged over RF cycle. Position of the lower electrode is $Y = 32 \lambda_D$. 
The stable vertically aligned dust strings were observed in laboratory experiments [Pieper, 1996] and obtained in the numerical simulations [Melandso, 1996; Schweigert, 1996]. The analytical models for wake-field potential of dust particles in the ion flow were developed in [Vladimirov, 1995; Lampe, 2000].

In Fig. 5.2 we plot potential profile averaged over the RF cycle in the discharge. We can see how the dust cloud near the lower electrode changes the sheath potential in comparison with the unperturbed zone near the upper electrode. In the Fig. 5.3 we present the potential map near the lower electrode, marking the dust particle positions. We can note that the position of each dust particle corresponds to the local potential minimum. Strip-like structures in the potential along vertical dust strings can also be distinguished. In the Fig. 5.4 we present the map of the vertical ion velocity component. Here we can see how ions are accelerated in the sheath toward the electrode in the averaged RF potential. The vertical ion velocity follows the potential structure, showing the ion streams accelerated along the dust strings. We can see that in the dust layer the ions become essentially supersonic.

On the map of the horizontal component of the ion velocity in Fig. 5.5 we can see how ion flow is focused by the upper dust particles. These focused ion flows aligned along the vertical dust strings can be seen in the Fig. 5.6, where the ion density is plotted. The density in the ion flow along the dust strings is a factor of 2 larger than its average value.

In the Fig. 5.7 we present the Y and X electric field components profiles averaged over the RF cycle. As we can see, the amplitudes of the vertical and horizontal electric field are of the same order of magnitude, showing that the forces of electrostatic interaction between particles are rather isotropic. In Fig. 5.8 the electric field components smoothed by filtering out the Fourier harmonics with wavelength smaller than two Debye lengths ($\lambda < 2\lambda_D$) are presented. We can see that due to smoothing the horizontal component of the electric field (Fig. 5.8a) vanishes, showing that there is no net electrostatic force in the horizontal direction. In contrary, the smoothed vertical electric field component (Fig. 5.8b) remains roughly of the same magnitude, clearly showing the uniform pedestal-like structure in the area occupied by the dust cloud. This net vertical electric field is responsible for the electrostatic force, which balances the gravitation, levitating particles over the electrode.

In Fig. 5.9 we plot the perpendicular and parallel electron temperature components. We can see that the electron temperature is rather uniform and
isotropic over the bulk discharge region with mean temperature $\langle T_e \rangle \approx 1.7$ eV. In the sheath region near the lower electrode the electron temperature increases to the $T_e \approx 2.1$ eV, which can be addressed to the stochastization of the electron flow motion in the dust layer.

### 5.3 Three dimensional simulation of plasma crystal

In order to model the formation of three-dimensional dust crystals, we performed full 3d particle simulation of the strongly coupled dusty plasmas in capacitive RF discharge. For this purpose the full 3d version of the PIC MCC code was used. The plasma parameters were chosen similar to those used in the 2d model described above – the methane plasma with $n_{e0} = 2.5 \cdot 10^9$ cm$^{-3}$, $T_{e0} = 10$ eV, $n_{CH_4} = 7 \cdot 10^{14}$ cm$^{-3}$ and $T_{CH_4} = 500$ K. The computational domain represents a 3d box with dimensions: $Y_{\text{max}} = d = 32 \lambda_{D0} = 1.5$ cm, $X_{\text{max}} = Z_{\text{max}} = 8 \lambda_{D0} = 0.38$ cm, where $Y$ corresponds to the vertical direction and $d$ is the electrode spacing. The lower electrode at $Y = Y_{\text{max}}$ is grounded and the lower at $Y = 0$ is powered. The electrodes act as an absorbing wall. Periodic boundary conditions were applied in the X and Z directions both for particles and for the potential. A grid with spacing $\Delta x = \Delta y = \lambda_{D0}/2 = 0.024$ cm and time step $\Delta t = 0.2/\omega_{pe} = 7 \cdot 10^{-11}$ s was used in the simulation. The ion mass was reduced to $m_{\text{CH}_4}/m_e = 1600$. Dust particles with constant charge $q_d = 5 \cdot 10^4 e$ and mass $m_d/m_{\text{CH}_4} = 18560$ were assumed. The gravity was increased by a factor of $9 \cdot 10^3$. The viscosity coefficient in Eq. 5.1 was set to $\beta \Delta t = 0.001$, which gives the characteristic time for a particle slowing down due to neutral gas friction $\tau = 1/\beta = 7 \cdot 10^{-8}$ s. The calculations were carried out on a 16-processor Linux cluster in approximately one month.
Figure 5.10 Side (top) and top (bottom) view of 3D plasma crystal.
At the beginning of the simulation the dust particles were injected into the discharge at random positions. After about $10^{-4}$ s particles were settled in an ordered structure above the lower electrode. In Fig. 5.10 we present the top and side views of this dust structure. We can see that particles are divided in three horizontal layers with a separation of about one Debye length (for convenience we highlighted the layers with different colors).

When looking on the particle structure from above (Fig. 5.10b) we can note that particles tend to form ‘triads’, as particles belonging to three different layers are aligned vertically. This is the same type of alignment, observed for the 2-dimensional case (Fig. 5.1), which is caused by the polarization of the ion flow in the sheath region. Thus the dust formation on Fig. 5.10 shows a quasi-two-
dimensional structure of vertically aligned horizontal layers with a similar structure. We analyzed the upper particle layer using two-dimensional static structural methods. In the Fig. 5.11 we plot the Voronoi diagram\(^1\) for the upper dust layer, connecting the nearest-neighbor bonds identified using a Delaunay triangulation\(^2\). As we can see from the Voronoi diagram the layer shows a rather distorted hexagonal structure pattern. On the Delaunay triangulation we marked each particle with seven close bonds with black circles, and particles with five bonds with blank circles, leaving the particles with six bonds unmarked. We can see that the hexagonal structure is prevailing, although with a number of defects. The pairs of neighboring particles with 5 and 7 close bonds form the numerous dislocation defects [Pieper, 1996].

\[\text{Figure 5.12} \text{ Images within a 3D volume of Coulomb crystals formed by 9.4 mm diameter polymer spheres in a 1.4-torr Kr discharge. The particle images appear longer in the vertical direction due to the infinite thickness of the laser sheet. Figure from [Pieper, 1996].}\]

\(^1\) A Voronoi diagram of a set of 'sites' (points) is a collection of regions that divide up the plane. Each region corresponds to one of the sites, and all the points in one region are closer to the corresponding site than to any other site [Drysdale, 1993].

\(^2\) The Delaunay triangulation of a point set is a collection of edges satisfying an 'empty circle' property: for each edge we can find a circle containing the edge's endpoints but not containing any other points [Drysdale, 1993].
The temperature of the dust particles in the simulation was estimated as $T_d \approx 2 \text{eV}$. We also calculated the Coulomb coupling parameter for the dust particles in the crystal, which is given by the ratio of the mean energy of Coulomb interaction between two particles to the particle thermal energy:

$$\Gamma = \frac{q_d}{4\pi \varepsilon_0 r_d k T_d} \exp\left(-\frac{r_d}{\lambda_d}\right), \quad (5.2)$$

where $r_d$ is the distance between the neighboring particles and $k$ is the Boltzmann constant. In our case $r_d \approx \lambda_d$ and the coupling parameter is $\Gamma \approx 500$. This small value of Coulomb coupling parameter may explain the high level of disorder in observed crystal structure. Usually in laboratory experiments the well established crystalline structures were observed when $\Gamma \sim 10^3 - 10^4$ [Zuzic, 2000; Melzer, 1996]. The structure obtained in our simulation may correspond to the intermediate state described as 'vibrational' in [Morfill, 1999a; Morfill, 2002], which is characterized by a reduced order and the increased vibrational temperature of the particles.

The vertically aligned horizontal layers with a flat hexagonal symmetry form the simple hexagonal structure. Such structures can not be obtained with particles interacting through the isotropic potential. For isotropic potential the close-packed three-dimensional structures, like face-centered cubic (fcc) and body-centered cubic (bcc) are energetically more favorable [Pieper, 1996]. The origin of the simple hexagonal structure may only be explained by the symmetry braking with the attractive wake fields, arising from the focusing of the ion flow below the dust particles. This ion flow attracting the downstream particles leads to the vertical alignment of the particles of the lower layers. In the horizontal plane the potential remains symmetrical, thus a flat hexagonal structure, which is the minimum energy state for a two-dimensional symmetric potential is developing.

The quasi two-dimensional dust crystal structures with simple hexagonal structure were observed in laboratory experiments with plasma crystals [Pieper, 1996; Melzer, 1996]. In Fig. 5.12 we present the picture of the dust crystal with a simple hexagonal structure obtained in a capacitively coupled RF discharge in Krypton with $p = 1.3$ Torr, $n_e \approx 10^9 \text{ cm}^{-3}$ and RF bias voltage $U_{\text{RF}} = 43 \text{ V}$ [Pieper, 1996].
5.4 Simulation of dusty plasma under microgravity

On the Earth the dusty plasmas are dominated by the gravitational force. Thus plasma crystals can be obtained only in the sheath region where the electrostatic force balances the gravity. The gravitational force sets a strict limit on the size of particles which can be levitated in the discharge. In the sheath region the electric field is strongly non-uniform, so the change of the electrostatic force over the lattice separation \( \Delta F = q_d \frac{dE_y}{dy} r_d \) becomes comparable with the interparticle interaction forces \( \text{forces} = \frac{q_d^2}{4\pi\varepsilon_0 r_d} \exp\left(-\frac{r_d}{\lambda_0}\right) \). This and the influence of the wake-field effect due to focusing of the supersonic ion flow in the sheath region limits the possibility to create large 3D plasma crystals in laboratory plasmas [Zafiu 2002].

![Diagram](image.png)

**Figure 5.13** The void formation in the PKE-Nefedov experiment. Figure from [Nefedov, 2003].
Figure 5.14 Void formation in a 2-dimensional dusty plasma.
Figure 5.15 Map of potential, averaged over RF cycle (microgravity case). Positions of dust particles are marked as ●.

Figure 5.16 Map of the Y component of ion velocity, averaged over RF cycle (microgravity case). Positions of dust particles are marked as ●.
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Figure 5.17 Map of the X component of ion velocity, averaged over RF cycle (microgravity case). Positions of dust particles are marked as ●.

Figure 5.18 Map of the ion density, averaged over RF cycle (microgravity case). Positions of dust particles are marked as ●.
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Figure 5.19 Profile of the X (top) and Y (bottom) component of electric field averaged over RF cycle (microgravity case).
Figure 5.20 Smoothed profile of the X (top) and Y (bottom) component of electric field averaged over RF cycle (microgravity case).
In order to eliminate the gravitational force a microgravity plasma experiment was suggested. A series of microgravity experiments were performed during parabolic flights [Morfill, 1999b] and onboard of space station ‘MIR’ [Fortov, 1998] and the International Space Station (ISS) [Nefedov, 2003]. Under microgravity the particle behavior is determined by the weaker forces, like ion drag, thermophoresis and the electrostatic force in the bulk plasma. These forces are unimportant in comparison with the gravitational force in laboratory experiments. The microgravity experiments have shown that the large 3D structures are formed in the bulk region of the discharge, surrounding the dust-free zone in the middle – the so called ‘void’. In Fig. 5.13 we show a picture of the void, observed in the PKE-Nefedov experiment on the ISS [Nefedov, 2003]. Formation of the void shows that the confining electrostatic force, resulting from the weak ambipolar electric field in the middle of the discharge, is overpowered by the outward oriented force. Up to now it is still unclear which force is responsible for the void formation [Zafiu 2002]. The best candidates are the thermophoretic force, caused by momentum transfer from the neutral gas molecules in the presence of the gas temperature gradient [Shukla, 2002] and the ion drag force, which results from momentum transfer due to the ion-dust collisions.

In order to simulate the dusty plasma under microgravity we applied the two-dimensional dusty plasma model described in Chapter 5.2. The gravitational force acting on the dust particles was set to zero, all other simulation parameters remained unchanged. In order to include the ion-drag force in the model, the Coulomb collisions between the ions and the dust particles were treated according to the general Coulomb collision algorithm described in (Chap. 2.6.2). The thermophoretic force was neglected in the current simulation. In order to account for thermophoresis it is necessary to resolve the neutral gas dynamics in the model, what results in considerable slowing down of the simulation.

In figure 5.14 we show the simulation results, plotting the particle distribution after $t \approx 10^{-2}$ s. As we can see the dust particles are symmetrically distributed in the system and the void has formed in the middle of the discharge.

In Fig. 5.15 we present the potential map with marked particle positions. We can see that particles are located in the local potential minimums. However in contrast to the case with acting gravitation force (Chapter 5.2, Fig. 5.3) no strip-like patterns are observed in the potential structure. In the Fig. 5.16 the map of the longitudinal ion velocity component is shown. As we can see, in the area occupied by the dust the ions are essentially subsonic. Thus, no wake-field effects take place.
in this case [Vladimirov, 1995] and no aligned dust particle structures are formed. In the map of perpendicular ion velocity component (Fig. 5.17) we can see how the ion flow gets focused meeting the dust particle and diverges immediately after it, forming the ‘8’-like structures in horizontal ion velocity. Due to this no focused ion flows are formed, as we can see from the ion density plot in Fig. 5.18. The X and Y electric field components averaged over RF cycle are presented in the Fig. 5.19. In the Fig 5.20 we plot the electric field components smoothed by filtering out the short wave-length components ($\lambda < 2\lambda_D$). Similar to the case observed in the Chapter 5.2, the perpendicular component of the electric field creates no net force, while the longitudinal electric field in the area occupied by the dust is non-zero, being responsible for the electrostatic force, which balances the ion-drag confining the dust in the bulk region.

Thus with the PIC simulation we have shown that the ion-drag force can overcome the electrostatic force in the middle of discharge and lead to the void formation in the dusty plasma under microgravity conditions.

Recent laboratory experiments on the radial expulsion of free-falling dust particles from the bulk region of the capacitive RF discharge [Zafiu 2002; Zafiu 2002b] have shown that the ion-drag force exceeds the thermophoretic force for the most of the discharge regimes, proving that the ion drag plays crucial role in the void formation.

### 5.5 Principal results

The analysis of dusty (complex) plasmas was motivated by the interest in such systems in astrophysics, plasma technology, fusion and solid state physics. We used our PIC model to study the basic physics of the dust particles, trapped in a capacitive RF discharge. In this case, the gravitational force acting on the particles can be equilibrated by the electrostatic force due to a strong repulsive electric field in the RF sheath. The trapped dust particles form a cloud levitating above the lower electrode. They interact with each other through the repulsive Coulomb potential, screened by the plasma electrons and ions. In the case of strong electrostatic coupling, i.e. when the energy of the interparticle interaction is large compared to the particle thermal energy, particles self-assemble into ordered structures, known
as Coulomb (plasma) crystals. Due to the large mass of the dust particles the characteristic relaxation time for the plasma crystals is usually of the order of seconds, making such structures easy to observe with ordinary video-observation techniques. The interparticle distance in dusty plasma crystals is usually of the order of a fraction of millimeter, so that it is possible to observe such structures even with a naked eye. The plasma crystals represent a bridge connecting the atomic or molecular scale of matter with the macroscopic scale of a dusty particle system, giving a unique possibility to observe processes in the condensed matter on the kinetic level.

Dust particles form vertical strings, in which negative particles are attracted due to polarization of the ion flow (wake-field effect). This agrees with stable vertically aligned dust strings observed in laboratory experiments.

A quasi 2 dimensional (simple hexagonal) structure is formed by the dust in which flat layers with hexagonal symmetry are vertically aligned due to the unidirectional strong ion background flow towards the electrode in the sheath. This is supported by the observation of a simple hexagonal dust structure in experiments.

In the case of zero-gravity conditions, our simulations showed void formation in the middle of the discharge which is in agreement with experiments onboard of the International Space Station (ISS). For this condition, the particle behavior is determined by forces which are usually unimportant in comparison with the gravitational force in laboratory experiments (ion drag force, thermophoretic force). In the PIC simulation we demonstrated that the ion-drag force alone is able to overcome the electrostatic force in the middle of the discharge and lead to the void formation.