Plasma anisotropy around an infinite chain of dust particles

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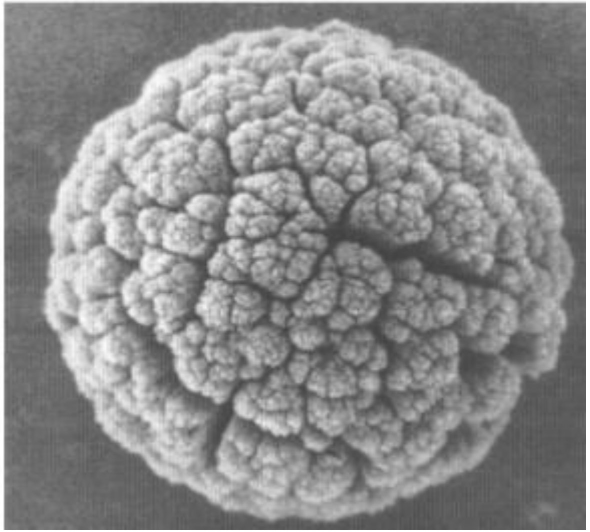
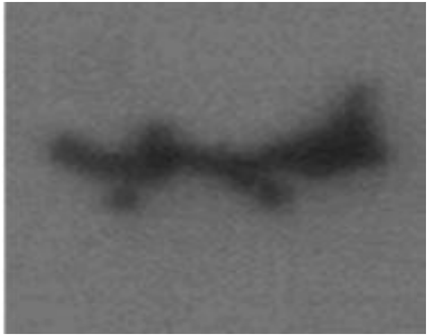
What is a dusty plasma?



L Boufendi and A Bouchoule Plasma Sources Science and Technology, Volume 3, Number 3

Ionized gas, which contains large particles of solid matter.

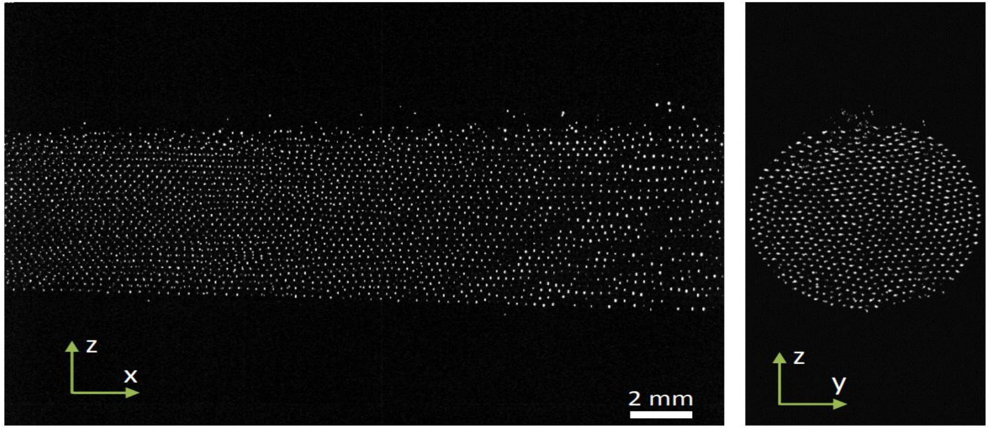
- Such particles in plasma immediately acquire a large negative charge $Z_d \approx 10^4 - 10^5 e$
- Dust particles range in size from single molecules to large clusters of millimeter-sized molecules, but they are usually micron-sized.
- They are completely different in geometry: spherical, elongated, cylindrical, in the form of shattered fragments or even in the form of snowflakes



Truell W. Hyde et al Agglomeration of Dust Particles in the Lab

Ordering of dust particles

D. I. Zhukhovitskii, V. E. Fortov et al
Physical Review E 86 (1), 016401 (2012).



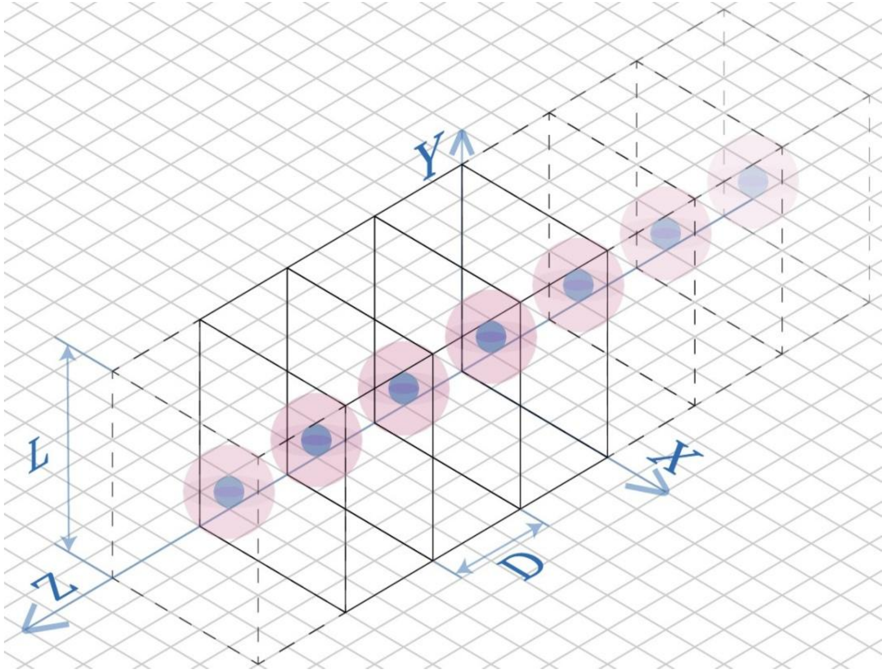
The main interest of a dusty plasma is the ordering of dust particles:

1) Destroy the walls of plasma-chemical reactors
2) Interfere with etching process
3) Allow to simulate processes occurring in gas, liquid or solid

The simplest ordered structure of dust particles is the dust particle chain.

At a date there are successful numerical models, founded on the basis of PIC. These models accurately describe the selfconsistent potential distribution near the dust particle clusters. However, in order to accelerate computational process, substantial simplifications are usually implemented.

Numerical model



The initial potential:

$$U(r,\theta) = -\frac{\tilde{Q}}{r}e^{-r} - \sum_k \frac{\tilde{Q}}{r_{k,1}}e^{-r_{k,1}} - \sum_k \frac{\tilde{Q}}{r_{k,2}}e^{-r_{k,2}} - \tilde{E}z,$$

$$\lambda_i = \sqrt{kT_i / 4\pi e^2 n_0}$$

Dimensionless variables:

$$\tilde{Q} = \frac{Ze^2}{\lambda_i kT_i}$$ - dust particle charge

$$\tilde{E} = \frac{e\lambda_i E_z}{kT_i}$$ - intensity of the external electric field

The larger sides of the main prism are joined with larger sides of other prisms, where the plasma space charge and potential distributions are identical meaning that the periodic conditions for ion density and system potential are simulated.

Selfconsistent potential

Space charge spatial distribution: $n(r,\theta)=\dfrac{n_i(r,\theta)-n_e(r,\theta)}{n_\infty}=\sum_{k=0} n_k(r)P_k(\cos\theta),$

Is expanded into Legendre polynomials for a purpose of analyses.

$$n_0(r)=\frac{1}{2}\int_0^\pi n(r,\theta)\sin\theta d\theta, \qquad \tilde{Q}_{pl}=\int_0^\infty n_0(r)r^2dr.$$

$$n_1(r)=\frac{3}{2}\int_0^\pi n(r,\theta)\cos\theta\sin\theta d\theta, \qquad \tilde{P}_{pl}=\frac{1}{3}\int_0^\infty n_1(r)r^3dr.$$

Selfconsistent potential is determined by the following formula**:**

$$U(\rho,z)=-\frac{\tilde{Q}}{r}-\sum_k\frac{\tilde{Q}}{r_{k,1}}-\sum_k\frac{\tilde{Q}}{r_{k,2}}-\tilde{E}z+\int\frac{n(\rho',\varphi',z')d^3r'}{|\vec{r}-\vec{r}'|}$$

$$+\sum_k\int\frac{n(\rho',\varphi',z')d^3r'}{|\vec{r}_{k,1}-\vec{r}'|}+\sum_k\int\frac{n(\rho',\varphi',z')d^3r'}{|\vec{r}_{k,2}-\vec{r}'|}.$$

Algorithm of the calculations

To calculate the selfconsistent potential distribution of solution region, the following calculation algorithm was implemented:

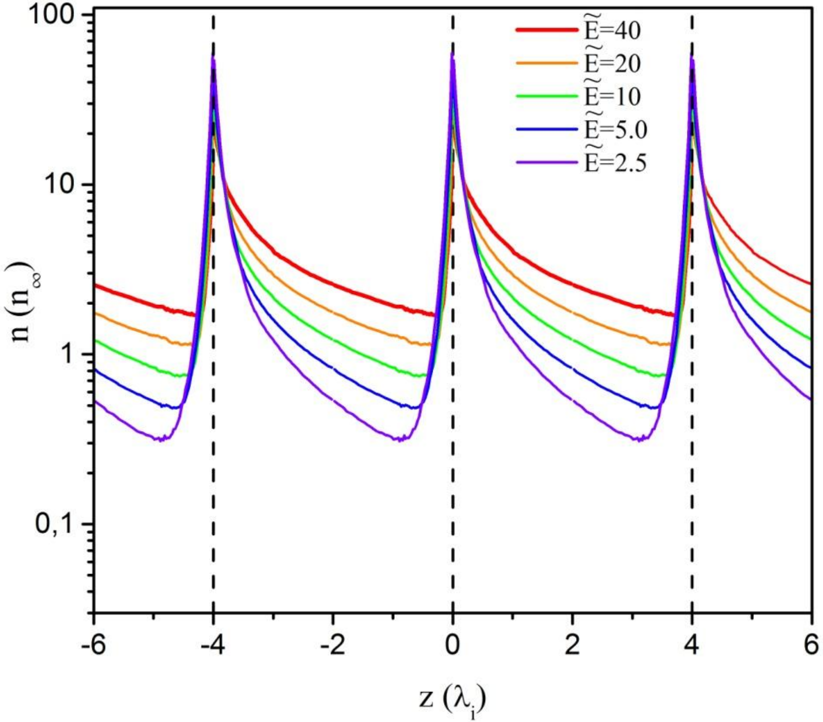
1) Ion trajectories are calculated for the initial potential and the data of time ions spent in solution region segments are accumulated.

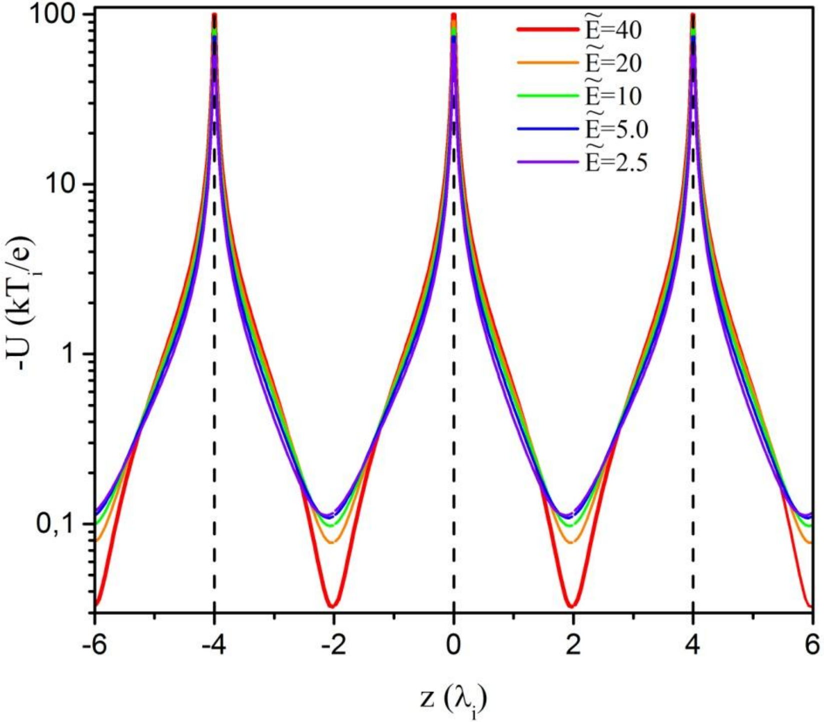
2) Accumulated spherical data for space charge spatial distribution are expanded in harmonics.

3) A new selfconsistent potential is calculated.

4) New dust particle charge is derived from the condition of equality of ion and electron fluxes to the surface of dust grain.

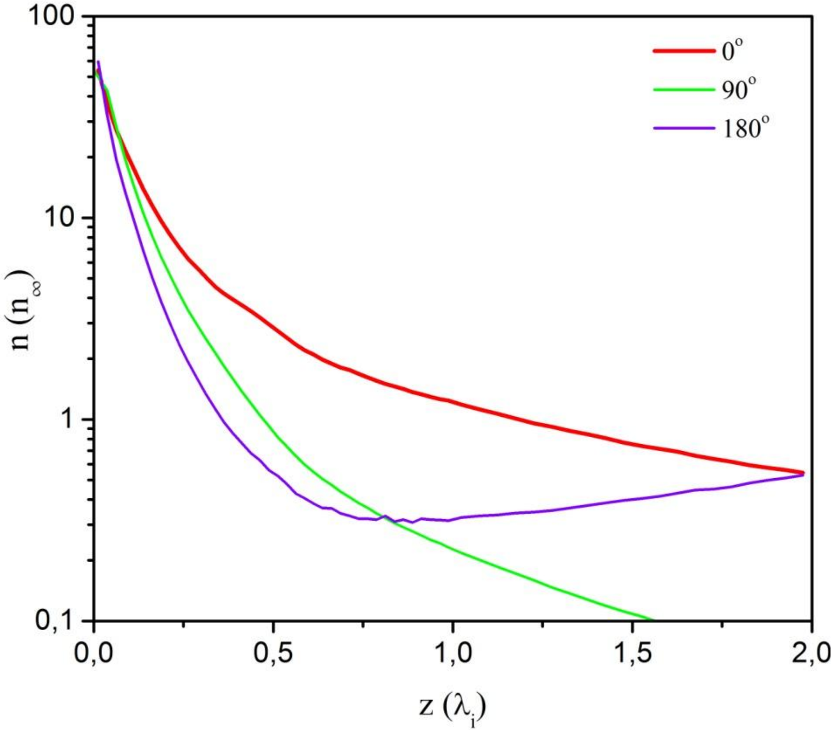
Space charge and potential spatial distributions

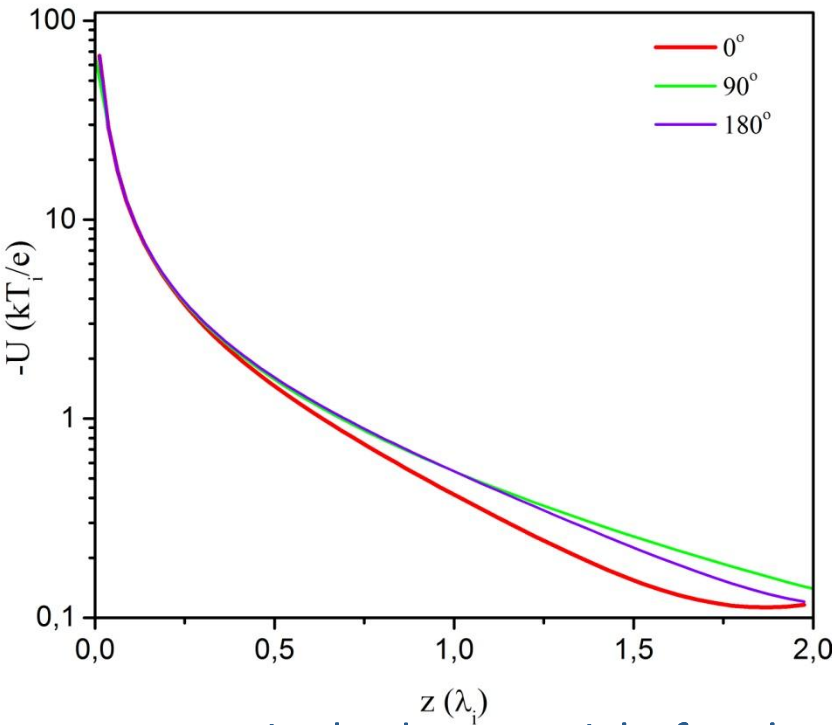




Figures show sections of the space charge and potential spatial distributions in the dust chain plane ρ = 0. These distributions satisfy the periodicity conditions. With an increase of the external electric field strength, a wake does not visibly occur.

Space charge and potential spatial distributions





Figures shows the space charge distributions near a single dust particle for three different angles of 0, 90, and 180 degrees for the $\tilde{E}$ = 2.5.

Isotropic harmonic of the space charge spatial distribution

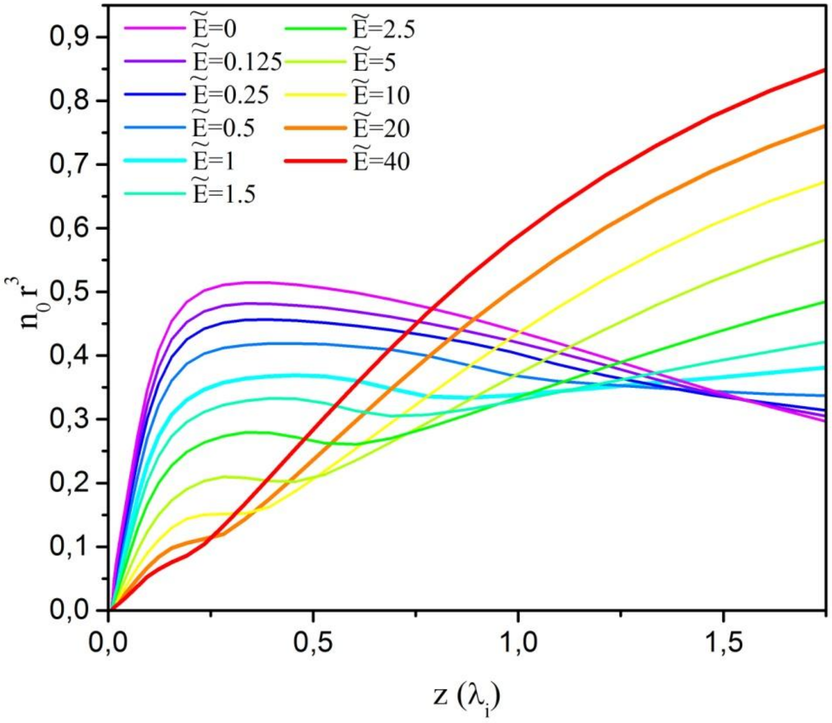
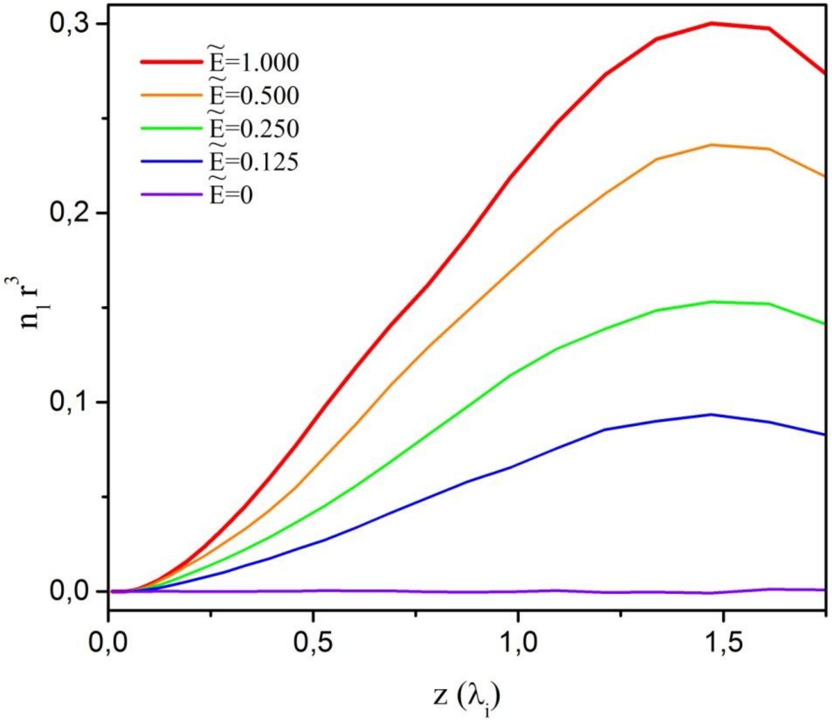
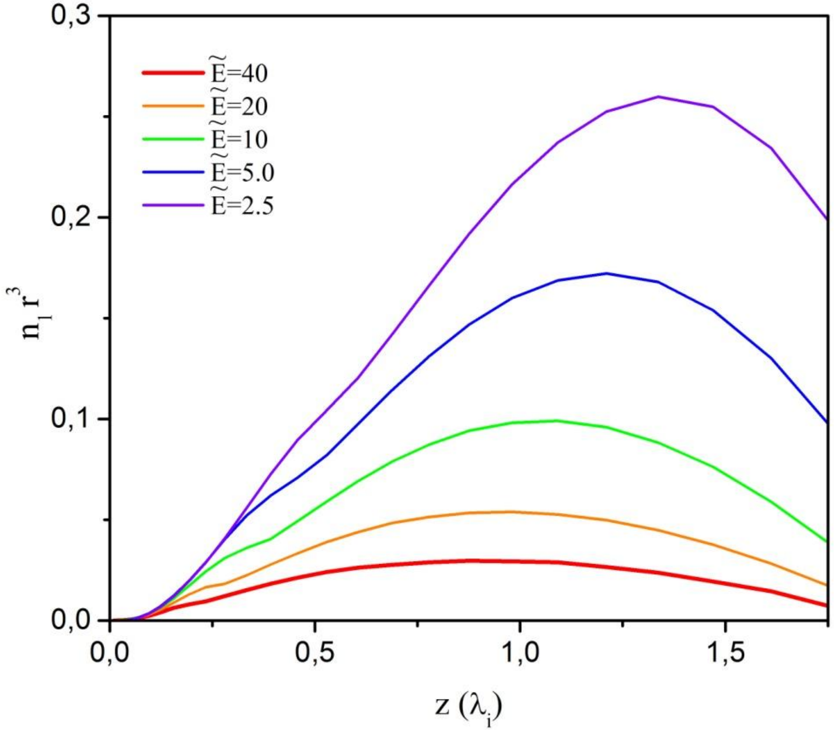


Figure show the dependence of the function $n_0(r)r^2$ on the external electrostatic field strength. The isotropic harmonic $n_0(r)$ is represented with factor r^2 because the same factor is used in the integral of plasma charge. The function $n_0(r)r^2$ shown in this Figure is the total plasma charge distribution in the close vicinity of a dust particle, at a radius of 2 λ_i.

At the region boundary where the polynomial expansion of the space charge is performed ($r < 2\ \lambda_i$), the value of $n_0(r)r^2$ increases rapidly.

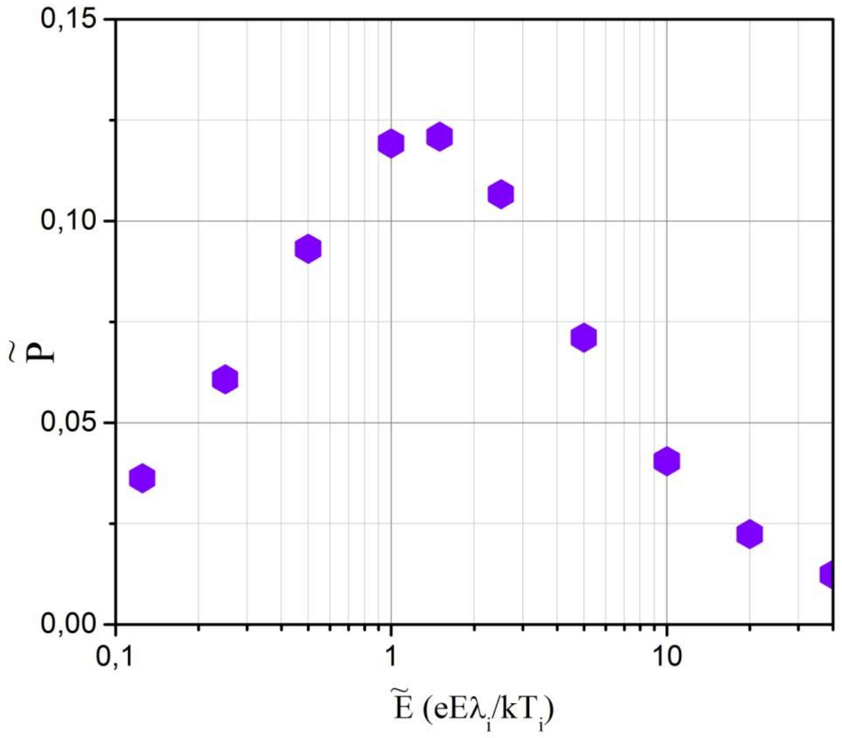
Anisotropic harmonic of the space charge spatial distribution





Figures show the dependencies of the function $n_1(r)r^3$ on $\tilde{E}$. For the larger values of $\tilde{E}$ the stronger the field, the flatter the distribution of the space charge in the plane of the dust particle chain becomes and the smaller $n_1(r)r^3$ becomes.

Dipole moment



The results obtained concerning the anisotropy induced in the computational domain can be characterized by a single dependence. This Figure shows that at the beginning, when the intensity of the external electrostatic field increases, the dipole moment of the system grows lineary. However, then the growth rate begins to decline, until the dipole moment reaches its maximum at $\tilde{E} \approx 2$.

After this point a gradual decrease of $\tilde{P}$ begins. In other words, with an increase of the external field strength in the range $\tilde{E}$ = 2–40, the anisotropy, which was induced by the electric field, decreases.

Conclusion

In this work new numerical model was presented. The model allows to calculate selfconsistent spatial distributions of space charge and plasma potential around an infinite chain of spherical dust particles, at a fixed distance between them. It was shown that obtained spatial distributions satisfy the established periodicity conditions.

The appearance of a local maximum in the potential spatial distribution, which grows with increasing field intensity, was demonstrated.

The dependencies of the first anisotropic harmonic of the Legendre polynomial expansion and dipole moment on the strength of the external field are presented. These dependencies show how the anisotropy changes in a solution region with successive amplification of the field strength. It is shown that for small field values, the anisotropy induced in the solution region grows smoothly. However, after overcoming the threshold value, it begins to slowly decline, which ultimately leads to the potential spatial distribution being close to symmetrical.