

OPEN ACCESS

Dynamic vortex dust structures in a nuclear-track plasma

To cite this article: V A Rykov *et al* 2003 *New J. Phys.* **5** 129

View the [article online](#) for updates and enhancements.

You may also like

- [Magnetic Imprisonment of Dusty Pinballs by a Supernova Remnant](#)
Brian J. Fry, Brian D. Fields and John R. Ellis
- [IONIZATION AND DUST CHARGING IN PROTOPLANETARY DISKS](#)
A. V. Ivlev, V. V. Akimkin and P. Caselli
- [PHOTOELECTRIC CHARGING OF DUST GRAINS IN THE ENVIRONMENT OF YOUNG STELLAR OBJECTS](#)
Andreas Pedersen and Ana I. Gómez de Castro

Dynamic vortex dust structures in a nuclear-track plasma

V A Rykov¹, A V Khudyakov¹, V S Filinov²,
V I Vladimirov², L V Deputatova², D V Krutov² and
V E Fortov²

¹ Leipunskii Research Institute for Physics and Power Engineering, Russian State Scientific Centre, Obninsk, Kaluga oblast 249020, Russia

² Institute for High Energy Densities, Russian Academy of Sciences, Moscow 127412, Russia

E-mail: rykov@ippe.obninsk.ru, filinov@ok.ru and dlv@ihed.ras.ru

New Journal of Physics **5** (2003) 129.1–129.17 (<http://www.njp.org/>)

Received 5 February 2003, in final form 11 June 2003

Published 9 October 2003

Abstract. Results are presented from Monte Carlo calculations of the electric charge on dust grains in a plasma produced during the slowing down of radioactive decay products of californium nuclei in neon. The dust grain charging is explained as being due to the drift of electrons and ions in an external electric field. It is shown that the charges of the grains depend on their coordinates and strongly fluctuate with time. The time-averaged grain charges agree with the experimental data obtained on ordered liquid-like dust structures in a nuclear-track plasma. The time-averaged dust grain charges are used to carry out computer modelling of the formation of dynamic vortex structures observed in experiments. Evidence is obtained for the fact that the electrostatic forces experienced by the dust grains are potential in character. The paper is supplemented by a video clip showing the typical dynamics of the simulated vortex dust structure.

Contents

1	Introduction	2
2	Calculation of the dust grain charge	3
3	Statistical modelling of the tracks of ionizing particles	7
4	Dust grain charging in nuclear tracks	8
5	Computer modelling of the dynamics of the formation of liquid-like dust structures	11
6	Discussion of the calculated results	13
7	Conclusion	16
	Acknowledgments	17
	References	17

1. Introduction

Dust particles are widely encountered in nature. Dust particles in the atmosphere, as well as in the chambers of technological devices, often form dust clouds. From a practical standpoint, it is important to investigate the physical properties of such clouds in order to learn to control their behaviour and to overcome their possible dangerous effects. The behaviour of dust particles in a plasma is the subject of a newly developed branch of plasma physics. The addition of even a small amount of dust to the plasma may considerably change the plasma properties. The discovery of the self-organization of dust grains into liquid-like and crystalline ordered structures has attracted special attention. To date, static dust structures having long- and short-range orders have been observed in the plasmas of stratified gas discharges [1, 2], thermal plasmas [3] and RF discharge plasmas [4]. The results of experiments on the formation of dust structures in air affected by a radioactive source were reported in [5]. Studies of the nuclear-induced plasma with dusty grains are important for developing new technologies and prospective power devices. It is well known that ordered dust structures can form when $\Gamma > 10$, where Γ is the coupling parameter, which characterizes the degree to which the plasma is nonideal and is defined as the ratio of the energy of the electrostatic interaction between dust grains to the energy of thermal motion. In the absence of screening, we have

$$\Gamma = \frac{Z^2 e^2}{aT}, \quad (1)$$

where Z is the dust grain charge in units of the electron charge e , a is the distance between the grains and T is the energy of thermal motion. The parameter Γ is fairly large in a dusty plasma in which the distances between the grains are small and their charges are large.

The objective of this paper is to produce dynamic ordered dust structures in a nuclear-track plasma created by nuclear-reaction products in inert gases and to carry out computer modelling of the processes that lead to their formation.

We apply the Monte Carlo (MC) method to calculate the time dependence of the charge of dust grains in a nuclear-track plasma that decays under the action of an external electric field into the flows of electrons and ions drifting toward the oppositely charged electrodes. We show that since the grain charge is alternately affected by electron and ion flows, it fluctuates strongly about a value smaller than that typical of a quasineutral plasma. The mean values of the grain charge agree with those measured experimentally.

Table 1. Conditions of our experiments on the formation of dynamic dust structures.

Grain diameter (μm)	Interelectrode distance (mm)	Chamber radius (mm)	Neon pressure (Torr)	High-voltage electrode potential (V)	^{252}Cf source intensity (fission s^{-1})
1.87	17	15	380	162	10^5
2.1	35	25	557	152	4×10^6

We explain theoretically the formation of the experimentally observed dynamic vortex dust structures in a nuclear-track plasma in neon in the presence of an external electric field and experimentally test our theoretical model for describing such a plasma. Numerical investigations carried out using the method of molecular dynamics (MD) make it possible to explain the characteristic features of the formation of vortex dust structures. The numerical results presented here agree qualitatively with the experimental data. Evidence is obtained of the potential character of the electrostatic forces experienced by the dust grains. The accompanying [video clip](#) shows an example of the dynamic vortex structure.

2. Calculation of the dust grain charge

Investigations of the behaviour of dust grains in a plasma created by nuclear-reaction products provide new information on the self-organizing abilities of the dust in the plasma. The dusty plasma differs considerably in properties from other plasmas, the primary difference being that it is strongly inhomogeneous in space and highly unsteady in time. In a nuclear-track plasma, a dust grain is affected by the flows of drifting electrons and ions that are cylindrically symmetric in structure (the symmetry axis being parallel to the propagation direction of an ionizing particle). Because of diffusion, the electron and ion flows spread out in the radial direction; simultaneously, because of a difference in the electron and ion diffusion coefficients, the radii of the electron and ion cylindrical flows increase to a far greater extent. As a rule, the dust grains acquire a negative electric charge, because the electrons are much more mobile than the ions. The ion flows efficiently discharge the grains. The external electric fields of both the dielectric walls of an experimental device and its electrodes can substantially redirect the drift flows of plasma particles.

The experimental device in which we observed the formation of levitated dust structures consists of an ionization chamber with horizontally oriented parallel electrodes. The chamber was filled with neon at a certain pressure. Dust grains were injected through a hole in the upper electrode into the interelectrode space, in which the external electric field was created. The role of the radioactive source was played by a 7 mm diameter plane layer of ^{252}Cf at the lower electrode. The numerical results presented below were obtained for the experimental conditions under which we observed liquid-like dust structures (see table 1 and figure 1).

The physical model of dust grain charging consists in the following. The ionizing particles emitted from the source are stopped in the gas over a time of several nanoseconds. The energy of the primary electrons is, on average, 90 eV [6]. In turn, the primary electrons ionize neon atoms and thus produce a plasma cloud, which is called the track of an ionizing particle. The

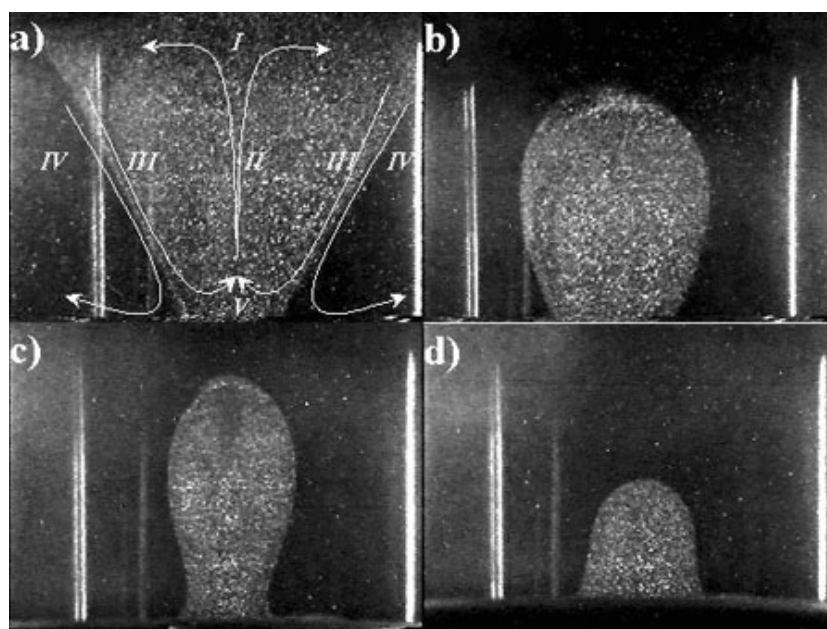


Figure 1. Evolution of a cloud of Zn dust grains. The photographs were taken (a) 2 min, (b) 4 min, (c) 4 min 30 s and (d) 4 min 45 s after the injection of the dust. The upper electrode was held at a potential of 152 V, the distance between the upper and lower electrodes was 3.5 cm and the neon gas pressure was 570 Torr. Each photograph corresponds to an observational area of $4.2 \times 3.1 \text{ cm}^2$. The main directions of the dusty grains' local motions in the regions I, II, III and IV are shown by related arrows.

degree of plasma ionization inside the track is about 10^{-8} . The length of the track is much larger than the diameter of its cross section. As time elapses, the diameter of the track increases and, correspondingly, the electron and ion densities within the track decrease. The electric field generated in the track hinders charge separation [7] and delays this process in the presence of an external electric field. However, since the electron density gradient is large, the electron diffusion eventually reduces the electric field inside the track, so that the charges begin to be separated by the external field.

Hence, the process of the formation of a track plasma and the charging of dust grains proceeds in the following two stages. The first, extremely short ($\sim 100 \text{ ns}$ [8]), stage of the track evolution is far from being studied completely. In the second, much longer (several microseconds), stage (electron drift in the interelectrode space), the dust grain charge changes after the track plasma decays into two flows, namely the flows of electrons and ions drifting toward the oppositely charged electrodes and toward the charged dielectric walls of the device.

Let us discuss the main physical assumptions underlying the mathematical description of the dynamic processes in a nuclear-track plasma. We start by considering the second stage of the formation of dust structures and charging of the dust grains, because the processes occurring in this stage have been studied in great detail. Since the electric field strength in our experiments was such that the measured current reached the saturation stage, we neglect the recombination of charged particles. When a dust grain is affected by an electron flow from the track toward the positively charged electrode (anode), it collects some of the electrons and thus acquires a

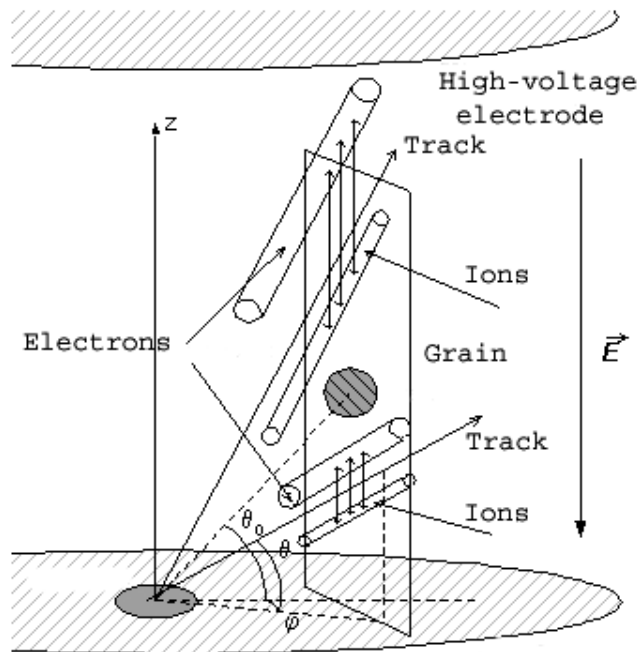


Figure 2. Schematic of electron and ion motions in the vicinity of a dust grain in an electric field and geometry for MC simulations.

negative charge. When an ion flux meets this grain, it decreases the grain's negative charge and may even charge the grain positively (figure 2). A statistical treatment of these charging processes in time constitutes the essence of the mathematical model for calculating the grain charge. The main constants for these processes were chosen from the published data so as to satisfy the conditions of our particular experiments on the formation of ordered dust structures in neon.

Under the action of the electric field, the mean energy of the electron thermal motion becomes several orders of magnitude higher than the kinetic energy of the ions and neutral atoms. The mean electron energy was calculated from the formula [9]

$$\varepsilon = 9.7E/p, \quad \text{for } E/p = 0.1\text{--}1.2 \text{ V cm}^{-1} \text{ Torr}^{-1} \quad (2)$$

where E is the electric field strength and p is the gas pressure. In our experiments, the ratio E/p was equal to $0.25 \text{ V cm}^{-1} \text{ Torr}^{-1}$. The electron drift velocity w_e corresponding to this value was taken from [10, 11]. The electron mobility μ_e was calculated from the relationship

$$w_e = \mu_e E. \quad (3)$$

The electron diffusion coefficient D_e was calculated from the Nernst–Townsend–Einstein formula, which is valid for both electrons and ions. That is why we write this formula as the general relationship

$$\frac{\mu}{D} = \frac{e}{kT}, \quad (4)$$

where e is the electron charge, k is Boltzmann's constant and T is the temperature. The electron mean free path was determined from the data on the cross section for the elastic scattering of electrons by neon atoms at the known density of a neon gas [10].

The temperature (mean energy) of the ions was set equal to that of the neon atoms. This assumption is justified in view of the effective energy exchange between ions and atoms. The ion diffusion coefficient was taken from [12]. The ion mobility was calculated from formula (4) and the ion drift velocity was calculated from a formula analogous to relationship (3). The ion mean free path was determined from the data presented in [11].

In order to simplify the analysis, the energy losses of the ionizing particles were calculated from the following analytic formulae:

$$E(x) = E_0 \left(1 - \frac{x}{R}\right)^\alpha \quad \text{for fission fragments,} \quad (5)$$

$$E(x) = E_1 \left(1 - \frac{x}{2R} - \frac{x^2}{2R^2}\right)^\alpha \quad \text{for alpha particles,} \quad (6)$$

where E_0 and E_1 are the initial energies of the ionizing particles, x is the distance from the radioactive source, R is the total path length traversed by an ionizing particle before it is stopped in a neon gas and α is the approximating parameter lying between 1 and 2. Formulae (5) and (6) were obtained by approximating the expressions that describe the energy losses of heavy ions in matter and follow from the Bethe and Lindhardt theories.

The energy losses were normalized to the energy cost of the production of one electron-ion pair (for neon, this cost is 35 eV) [13]. As usual, we assumed that the energy cost does not change as the energy of the ionizing particles decreases. In a nuclear-track plasma, the dynamics of the electric charge q of a dust grain in electron and ion flows is described by the equation

$$\frac{dq}{dt} = I, \quad (7)$$

where I is the total electron and ion current to the grain surface. The mathematical expression for this current is governed to a large extent by the ratio of the grain diameter to the mean free paths of the plasma particles. Thus, a grain diameter of 1 μm is four times smaller than the electron mean free path, but six times larger than the ion mean free path. That is why we used two different approaches for calculating the electron and ion currents to the grain surface. The electron current, which is determined by the absorption cross section for plasma electrons, was calculated from the formula [14, 15]

$$I = 2\sqrt{2\pi} n_e v_T a^2 \exp\left(-\frac{e\varphi}{T_e}\right), \quad (8)$$

where a is the grain radius, n_e is the electron density, v_T is the electron thermal velocity and φ is the potential acquired by the grain during the charging process. The charge acquired by a negatively charged grain in ion flows is determined by the currents of positive and negative ions to its surface. These currents are described by the following analytic formulae, which were obtained in the diffusion approximation:

$$I_- = \frac{4\pi D_- N_- q e^2}{T [\exp(qe^2/r_0 T_-) - 1]} \quad (9)$$

$$I_+ = \frac{4\pi D_+ N_+ q e^2}{T [1 - \exp(-qe^2/r_0 T_+)]}.$$

The charge of the grain affected simultaneously by the electron and ion flows is determined by the total current of the electrons and ions. If the electron mean free path is much larger than the grain diameter, the electron current is calculated from formula (8); otherwise, it is calculated from the first of formulae (9). For electron mean free paths comparable with the grain diameter, the electron current is calculated by matching formula (8) with the first of formulae (9). The ion current to the grain surface is calculated from the second of formulae (9). As a result, the dynamics of the grain charge is described by the equation

$$\frac{dq}{dt} = I_- - I_+. \quad (10)$$

In a nuclear-track plasma with a low degree of ionization and a low electron temperature, the dust grains acquire small charges.

3. Statistical modelling of the tracks of ionizing particles

As was already noted, the plasma created by high energy ionizing particles is strongly inhomogeneous in space and highly unsteady in time, and the degree of ionization is highest near the radioactive source of the experimental device. At relatively low intensities of radioactive sources approved for use in laboratories, the tracks of different ionizing particles do not intersect and the plasma exists for a short time in the form of long narrow tracks, whose distribution in space and time exhibits statistical regularities. Hence, the first step in calculating the charge of dust grains in a nuclear-track plasma is to model the track distribution statistically by the MC technique.

Let a dust grain be located at some distance r from a point radioactive source, and let the angle that the straight line passing through the grain and source makes with the horizontal plane be θ_0 (figure 2). The angle θ is measured from the horizontal plane and the azimuthal angle φ is measured from the vertical plane containing the grain and the source. A uniform electrostatic field is assumed to be created by two electrodes, the upper of which is held at a positive potential.

In order to economize on the computer time, among the ionizing particles emitted from the source in all possible azimuthal directions, we chose only those that generate such flows of drifting electrons for which the probability of meeting the grain is nonzero. It is electrons that, due to their large diffusivity, determine the region where the statistical track distribution should be modelled. We also took into account the fact that, for very small angles θ_0 , this region can be determined by the downward drifting ions. For the emission events modelled by this statistical sampling, our code calculates the mean time between the events which, in turn, are distributed in time according to the Poisson law [16]. Then the code statistically samples the type of ionizing particle (an α particle or a fission fragment). It is assumed that the source emits 16 α particles per one fission fragment (the second fission fragment is lost in the substrate); in other words, it is assumed that one-half of each 32 α particles are lost in the substrate. In each statistical sample of the angle θ , the code determines what type of newly produced particles can meet the grain: electrons or ions. Then, the code calculates the drift time required for a newly produced electron (or ion) to reach the grain. If this time is too short for the flow of the drifting electrons (or ions) to meet the grain, then the code stops calculating this event. Otherwise, if the flow meets the grain, the code calculates the electron (ion) density in the flow, the instant when the flow reaches the grain surface and the residence time of the grain within the flow. Because of the statistical nature of the processes in question, the grain charge may be recycled, i.e. the grain can be charged by

the electrons (or ions) of the next but one track before it will be charged by the electrons (or ions) of the preceding but further track. That is why the times at which each of the flows meets the grain and departs from it, as well as the density of the drifting plasma particles, are stored in the computer memory. Then, the code regulates (sorts) all of these processes in time. If the flows from different tracks overlap, the code sums the corresponding particle densities in the overlap regions. Then, the code integrates equation (10) by the Runge–Kutta method. In this equation, the currents are calculated as functions of the grain radius: the electron current is calculated from formula (8) or by matching formula (8) with the first of formulae (9), and the ion current is calculated from the second of formulae (9). In our simulations, the longitudinal and transverse diffusion coefficients for the electrons were different but, for the ions, these coefficients were assumed to be the same, which is valid for the ratios E/N (where N is the density of neon atoms) typical of our experiments ($\sim 10\text{--}17\text{ V cm}^2$) [9]. At this point, we should emphasize the following characteristic difference between the charging process in a nuclear-track plasma and in a quasineutral plasma: in the case at hand, the currents on the left-hand side of equation (10) are strongly fluctuating, which leads to strong fluctuations of the dust grain charge with time.

The numerical results obtained for a grain located at a distance of 1 cm from the source and for $\theta_0 = 45^\circ$ are illustrated in figures 3–5. Since the grain charge is negative, the ordinate shows the absolute value of the charge, for convenience in representing the results. First of all, note that the grain charge fluctuates strongly with time. On the one hand, the grain acquires a charge in electron attachment processes; on the other hand, its charge decreases substantially for less frequent events of interaction with the ions. This stems from the fact that the grain interactions with the electrons and ions are different in nature: a negatively charged grain repulses electrons but attracts positively charged ions. Since the ionizing ability of α particles is far lower than that of fission fragments, they have an insignificant impact on the process under consideration and are responsible exclusively for small-amplitude variations in the time evolutions of the grain charge (figure 3(b)).

As an example, figure 4 illustrates the results obtained for the direct impact of a fission fragment on a dust grain. As a result of secondary electron emission, the grain loses 250 electrons simultaneously [6]; however, the lost charge is soon restored.

The dependence of the mean charge of the grain on its radius is almost linear (figure 5), as is the case for a quasineutral plasma. The experimental points in figure 5 were obtained for levitated spherical monodisperse melamineformaldehyde grains, whose charge was determined from the balance between gravity and electrostatic forces with an allowance for the nonuniformity of the electric field under the hole in the upper electrode.

4. Dust grain charging in nuclear tracks

The description of plasma processes in the above slow stage, in which the drift flows of plasma electrons and ions form and charge the dust grains, is valid at sufficiently large distances from the radioactive source, i.e. in regions where the tracks occur close to the dust grains only in sufficiently rare cases. Near the source, i.e. in the region where the frequency of occurrence of the tracks close to the grain increases in proportion to $1/r^2$, the dust grain charge is determined primarily by the asymptotic behaviour of the nonequilibrium electron distribution function in the high-energy range. In this region, the grain charging process is dominated by the electrons produced by ionization in the track and also by the frequency of occurrence of the tracks close to the grain and the discharging of the grain in the flows of drifting ions. Recall that the evolution

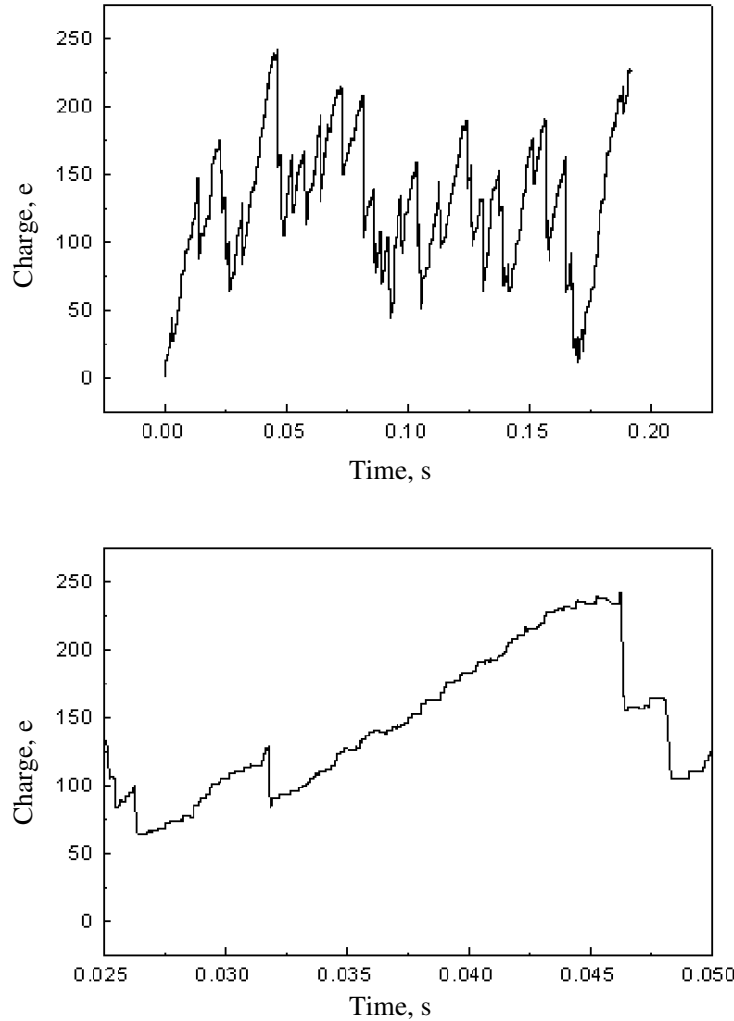


Figure 3. (a) Time evolution of the dust grain charge in a neon gas ionized by α particles and fission fragments (the time-averaged grain charge is equal to 105 electron charges) and (b) magnified fragment of the image. Here and below, the grain charge is expressed in units of the absolute value of the electron charge e .

of the tracks is extremely fast (~ 100 ns [8]) and is far from being studied completely. However, assuming that this evolution is described by the approximate expressions (5) and (6) and applying the model of grain charging that was proposed in [17, 18] yields the following estimate for the mean charge of a dust grain:

$$\langle Q(r) \rangle = C\phi_i(r). \quad (11)$$

Here, the coefficient $C \cong 4\pi\epsilon_0 R_p$ is approximately equal to the capacitance of the grain and the coordinate-dependent function $\phi_i(r)$ has the form

$$\phi_i(r) \approx \frac{R_p \gamma \epsilon \Phi_s}{2\pi N e C} \left\{ 2 \frac{dE_0(\zeta_0)}{\zeta_0^2 d\zeta_0} + 32 \frac{dE_1(\zeta_1)}{\zeta_1^2 d\zeta_1} \right\} \quad (12)$$

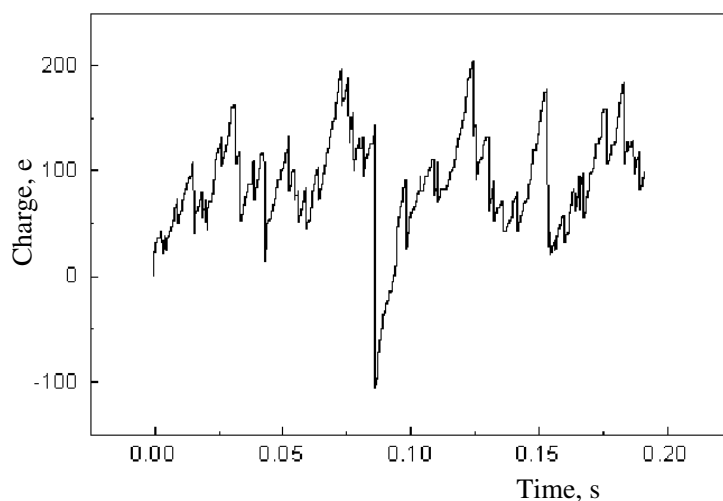


Figure 4. Calculated time evolution of the dust grain charge in a neon gas ionized only by 90 MeV fission fragments. The time 0.075 s corresponds to the direct impact of a fission fragment on a dust grain (as a result, the grain loses 250 electrons).

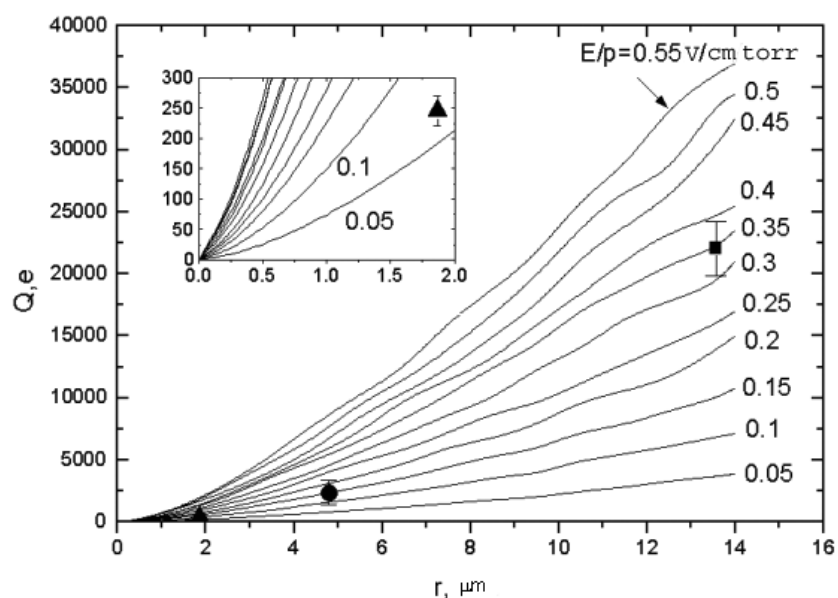


Figure 5. Calculated dependence of the grain charge on the ratio E/p and the grain diameter in Ne at a pressure of 380 Torr. The grain is at a distance of 3 cm from the radioactive source, with the angle that the straight line passing through the grain and source makes to the horizontal plane of the source being 75° . The distance between the electrodes is 3.5 cm. The symbols stand for the experimental results: the full square corresponds to $E/p = 0.3 \text{ V cm}^{-1} \text{ Torr}^{-1}$ and $r_d = 13.57 \text{ } \mu\text{m}$, the full circle refers to $E/p = 0.155 \text{ V cm}^{-1} \text{ Torr}^{-1}$ and $r_d = 4.82 \text{ } \mu\text{m}$ and the full triangle is for $E/p = 0.09 \text{ V cm}^{-1} \text{ Torr}^{-1}$ and $r_d = 13.57 \text{ } \mu\text{m}$. The inset shows a magnified fragment of the figure for grains with small diameters and low charges. $E/p = 0.55 \text{ V cm}^{-1} \text{ Torr}^{-1}$.

where $N = (2E_0 + 32E_1)$, ε is the energy cost of the production of an electron–ion pair, $\zeta_i = r/R_i$, r is the distance from the ionization source, R_p is the grain radius, R_0 is the total path length traversed by a fission fragment before it is stopped, R_1 means the same for the α particles, E_0 is the initial energy of a fission fragment and E_1 means the same for α particles. Hence, the mean charge $\langle Q \rangle$ of the grain is a prescribed function of its spatial coordinates.

Clearly, in experiments with dust grains of different diameters, the values of the ratio E/p are different. On average, the condition for spherical grains of radius r_0 to be in equilibrium yields the relationship

$$\langle Q \rangle E = mg = \frac{4}{3}\pi\rho r_0^3, \quad (13)$$

where m is the mass of a grain and ρ is the density of the matter. For the mean strength of the electrostatic field, the characteristic mean grain charges calculated in units of the electron charge from this relationship range from 100 to 1000.

The functional behaviour of the single dust grain charge versus the spatial coordinates was obtained by matching the dependences obtained for small and large distances (figure 6) between the grain and the radioactive source. However, in numerical modelling of the many-particles dynamic vortex structures the effect of electron and ion recombination on the grains should be taken into account. As a result the main contribution to the grain charge is given only by the tracks nearest to this dusty particle and, according to (12), the grain charge increases as the radioactive source is approached.

5. Computer modelling of the dynamics of the formation of liquid-like dust structures

Since this is the first paper in which an attempt is made to model the formation of vortex structures from dust grains in a nuclear-track plasma, our theoretical approach does not pretend to completely describe the dust behaviour under the experimental conditions in question. Our main objective here is to develop a reasonable model for describing the most characteristic features of the grain behaviour in a plasma and to reveal the main physical mechanisms for the formation of a potential trap that ensures the levitation of the dust grains. That is why it is expedient to carry out numerical modelling for the experimental conditions under which vortex structures are stable. In this context, it is most reasonable to model the structures like that shown in figure 1, which were observed to form in a nuclear-track neon plasma at pressures from 188 to 562 Torr.

In order to investigate the levitation of dust grains and their mutual interactions, it is necessary not only to establish the mechanism for their charging but also to reveal the nature of the forces acting upon them. At present, several different mechanisms are being discussed in the literature that affect both the balance between gravity and the electrostatic forces experienced by the levitated dust grains and the interactions between them (see [6, 17, 18] for details). Here, we investigate the complex dynamic problem under consideration by a simplified approach that makes it possible to trace the formation of dynamic vortex structures and their evolution using a reasonable amount of computer time. First, because of the comparatively small charges of dust grains and comparatively large mean distances between them, we neglect their mutual interactions. Second, because of the low intensity of the radioactive source and low degree of ionization of the nuclear-track plasma created by it, we ignore the drag forces exerted on dust grains by drift ion flows, which are directed primarily downward, i.e. toward the grounded electrode (with the radioactive source) and the dielectric wall of the device. In future studies, we

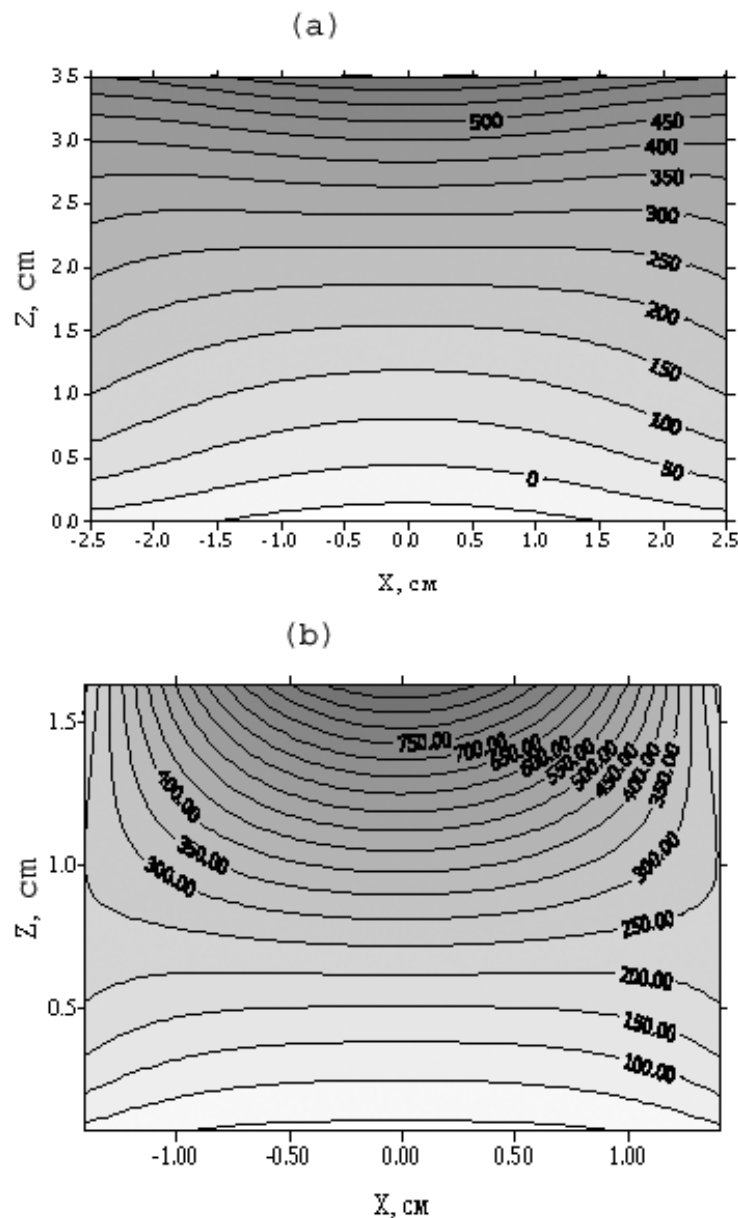


Figure 6. The contours of constant grain charge (in units of e) versus the spatial coordinates under the conditions given in table 1 for a grain diameter of (a) $2.1 \mu\text{m}$ and (b) $1.87 \mu\text{m}$. The x axis lies in the plane of the source, which is located at the point $(0, 0)$.

are going to consider how the drag forces influence the formation of dynamic vortex structures. In the model developed here, we take into account the interaction of grains with the electrostatic fields of both the electrodes of the device and its walls, the weight of the grains and the effect of their friction with the buffer gas. The levitation of dust grains results from the balance between the gravity force associated with the mass of the grain and the electrostatic forces of the device, in which case the electrostatic fields are governed equally by the internal plasma processes and by

the processes of recombination and adsorption of the charges on the walls. In our experiments, the electrostatic trap was created by the electrostatic fields of both a negative surface charge on the walls of the device and a positive charge of the electrode with a hole. The effect of the steady state positive space charge induced in the plasma near the radioactive source is insignificant because the electron mobility is much higher than the ion mobility. This effect will be taken into account in ongoing studies. Numerical modelling of the vortex structures of charged dust grains in the electrostatic trap of the device requires the use of convenient analytic expressions for the electrostatic potential that should correctly reflect its physical nature. The numerical results presented in this paper were obtained from the expressions derived in [17].

Dynamic vortex dust structures in a nuclear-track plasma were simulated using the standard method of MD. This method usually assumes calculations for a finite number N of particles in a cell of size L . In order for the computations to take a reasonable amount of time on available computers, we restricted our simulations to $N = 200$ – 1000 . Accordingly, in order for an MD cell to capture the characteristic dust structure, the linear cell size was chosen to be equal to $L = 100r_D \approx 3$ cm, which approximately corresponds to our experimental conditions. Note that such a small cell size, as well as a smaller number of dust grains in comparison with that in the experiments, substantially relaxed the requirements on computational resources and made it possible to reduce the run time of the code to about 10 h. Let us note that general behaviour of the dynamic vortex dust structures does not depend on the number of particles in a MD cell for large enough particle numbers (200–1000). We modelled levitated dust grains in an electrostatic trap with the potential derived in [17]. The characteristic potential at the chamber wall was varied in the range from 0.5 to 3 V. The z axis was directed downward, i.e. along the direction of the gravity force. The initial spatial distribution of dust grains and their initial velocities were specified with the help of computer-generated random numbers, distributed uniformly within the interval from zero to unity.

6. Discussion of the calculated results

Here, we present the results of numerical simulations carried out by the standard method of MD for a cylindrical volume in space. Figure 7 shows parts of the grain trajectories inside a planar vertical axial layer of small radial thickness. The trajectories were calculated at three successive times. The arrows indicate the direction of the grain motion. The physical cause of the onset of dynamic vortex structures is the dependence of the charges of both dust grains and the device walls on the distance from the source. In fact, let us consider a grain located near the upper electrode, in which case the grain's negative charge is small because its distance from the source is large. Under the action of the gravity force, which exceeds the electrostatic force of attraction toward the upper electrode, the grain starts falling downward, i.e. toward the lower electrode. In such motion, the grain charge first decreases and then begins to increase. A downward moving grain experiences increasingly strong radial fields of the dielectric walls, whose charge, in turn, increases near the radioactive source. The radial forces bend the grain trajectory and cause the grain to move toward the device axis and toward the radioactive source at the axis. On the other hand, as the charge on the grain increases, it is affected by the increasingly strong upward-directed electrostatic force of the positively charged upper electrode. Because of inertia, the grain passes the equilibrium position and its charge continues to increase until the electrostatic force becomes larger than the gravity force. The grain begins to move upward, keeping its radial velocity component unchanged, until the gravity force becomes larger than the

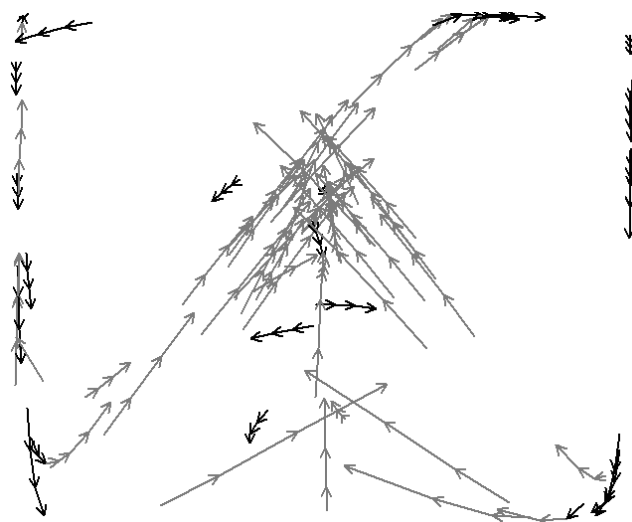


Figure 7. Schematic representation of a thin layer of the vortex dynamic structure obtained using the method of MD under the assumption that the forces acting upon the grains are potential. Each part of the grain trajectories calculated at three successive times is shown by three successive arrows. The black and grey arrows refer to the grains moving downward and upward, respectively. The radioactive source is at the centre of the bottom of the frame.

electrostatic force. Then, this cycle of the grain's motion repeats itself. As a consequence, most of the grain trajectories are very similar in shape to the infinity symbol. In the axial region of the device, the grains move predominantly upward, while in the peripheral region near the walls, the grains fall downward. As a result, a dynamic vortex structure forms that consists of dust grains rotating in the same direction as the vortex structures observed in our experiments.

We stress the following important feature of the results obtained here. In our study, the main attention is focused on energy transfer from the radioactive source, which creates the plasma, to the disperse grains. The energy-transfer mechanism is associated with the variation in the charge of a moving dust grain. The charge of the grain is a function of its spatial coordinates and also depends on the energy parameters of the inhomogeneous plasma close around it. Hence, the above system of levitated dust grains is an open system, which exchanges energy with its surroundings. Following [2, 18], we assume that the electrostatic forces acting upon the grains are potential in character. As a result, these forces (which are defined as minus the spatial gradient of the potential energy) are described by two types of terms. The terms of the first type are formally similar in structure to those describing the Coulomb forces of particles with coordinate-dependent charges. The terms of the second type (non-Coulomb correction) account for the dependence of the charges on spatial coordinates and are represented in terms of the gradients of the grain charges and the gradient of the surface charge on the dielectric walls of the device. Note that the effect of the surface charge is equivalent to that of an effective macroparticle. Non-Coulomb forces are directed opposite to the gradient of the absolute value of the grain charge and displace a dust cloud toward the region where the grain charges and, accordingly, the Coulomb repulsion energy in the device are both minimum.

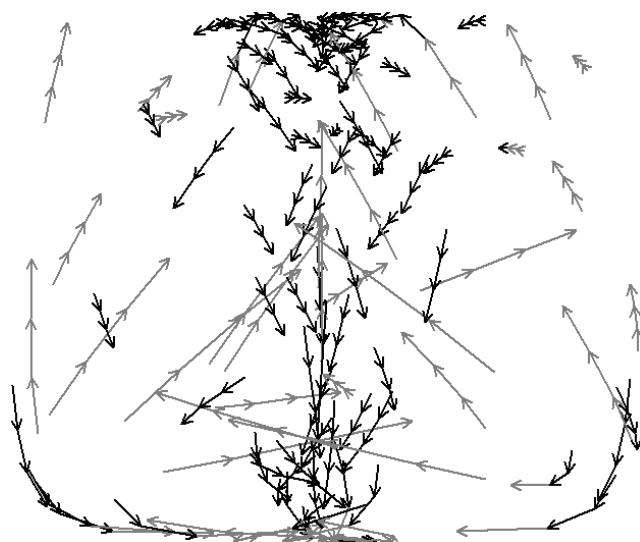


Figure 8. Thin layer of a dynamic structure analogous to that in figure 7. The parts of the grain trajectories were calculated under the assumption that the forces acting upon the grains are nonpotential.

In the alternative approach [19], the electrostatic forces acting upon the dust grains in a plasma are assumed to be Coulomb forces $|F| \sim q(r_1)q(r_2)/|r_1 - r_2|$ with coordinate-dependent grain charges. However, as was noted in [19], these forces cannot be represented in terms of the gradient of a certain effective potential. Consequently, the terms describing these forces do not contain the charge gradient, as is the case with terms of the second type.

The results obtained from the alternative approach [19] for the same parameters and the same model device as in figure 7 are illustrated in figure 8, which again shows parts of the grain trajectories inside a thin planar vertical axial layer, calculated at three successive times. We can see the formation of a vortex structure in which the grains rotate in two opposite directions which, however, contradicts our experimental observations. Hence, a comparison of the results of numerical modelling with experimental data clearly indicates the potential character of the forces acting upon the grains in a nuclear-track dusty plasma.

The effect of the frictional forces exerted by the buffer gas on the dust grains is illustrated in figures 9 and 10 which show parts of the grain trajectories inside a vertical axial layer of small radial thickness in the model device, calculated at three successive times. The frictional forces were calculated from Stokes' law. The computations were carried out using the above two approaches. We can see that, under the action of the frictional forces, the linear dimensions of the dynamic vortex structures of dust grains become several times smaller than in the initial stage and the structures themselves evolve to a nearly steady stable state analogous to that simulated by the MC method in [18]. The calculated time evolution of the vortex structures agrees qualitatively with the experimental observations illustrated in figure 1. The supplemental [video clip](#) shows the simulated 3D motion of the dusty particles in the chamber of our experimental device. Red particles are moving upwards, while yellow particles are moving down. With time evolution the size of the vortices becomes smaller due to the friction energy losses. Detailed analysis of this motion is discussed above and the schemes of the trajectory in the thin axis layers are presented in figures 7 and 9.



Figure 9. Late stage of the time evolution of the dynamic structure shown in figure 7 under the long-term action of the frictional forces exerted by the buffer gas on the dust grains.



Figure 10. Late stage of the time evolution of the dynamic structure shown in figure 8 under the long-term action of the frictional forces exerted by the buffer gas on the dust grains.

7. Conclusion

The main results of our investigations can be summarized as follows. The spatial dependence of the dust grain charges has been calculated. The experimentally observed formation of the dynamic vortex structures of dust grains under the action of an external electric field in a nuclear-track plasma in neon has been explained theoretically. The theoretical model of such a plasma has been tested experimentally. The physical mechanisms for levitating dust grains and forming dynamic vortex structures in a nuclear-track plasma in neon have been investigated both theoretically and experimentally. The MC method has been applied to trace the time evolution of the dust grain charge in a nuclear-track plasma, which disintegrates under the action of an external electric field into the flows of electrons and ions drifting toward the electrodes. The dynamic vortex dust structures that form under the action of an external electric field in a nuclear-track plasma in neon has been explained theoretically and the theoretical model of such a plasma has been tested experimentally. Numerical simulations carried out using the method of MD made it possible to explain the characteristic features of the formation of vortex dust structures. It has

been shown that the non-Coulomb forces, which are described by the terms proportional to the gradients of the charges and, along with the Coulomb forces, act on the dust grains, reverse the rotation of vortex dust structures. The resulting direction of rotation agrees with our experimental observations, thereby qualitatively indicating the potential character of the electrostatic forces of interaction between the grains. We have also analysed the effects of friction between the buffer gas and the dust grains on both the evolution of dynamic vortex dust structures and the formation of the steady-state structures that were investigated previously by the MC method [18]. The results of calculating these effects numerically agree qualitatively with our experimental data. The paper is supplemented by a video clip showing the typical dynamics of the simulated vortex dust structure.

Acknowledgments

We are grateful to A N Starostin for discussing this work and valuable remarks. We also thank A I Chusov for his help in preparing the experimental device and his assistance in experiments. This work was supported in part by the Russian Foundation for Basic Research, project no 00-02-17620.

References

- [1] Fortov V E *et al* 1996 *Pis. Zh. Eksp. Teor. Fiz.* **64** 86 (Engl. transl. 1996 *JETP Lett.* **64** 92)
- [2] Belotserkovski O M *et al* 1999 *Zh. Eksp. Teor. Fiz.* **115** 819 (Engl. transl. 1999 *Sov. Phys.–JETP* **88** 449)
- [3] Fortov V E *et al* 1997 *Zh. Eksp. Teor. Fiz.* **111** 889 (Engl. transl. 1997 *Sov. Phys.–JETP* **84** 489)
- [4] Gerasimov Yu V, Nefedov A P, Sinel'shchikov V A and Fortov V E 1998 *Pis. Zh. Tekh. Fiz.* **24** 62 (Engl. transl. 1998 *Tech. Phys. Lett.* **24** 774)
- [5] Fortov V E *et al* 1999 *Dokl. Akad. Nauk* **366** 22 (Engl. transl. 1999 *Dokl. Phys.* **44** 279)
- [6] D'yachenko P P and Rykov V A 1997 *At. Energ.* **82** 365
- [7] Budnik A P and Dobrovol'skaya I V 1996 *Preprint* No 2498 Institute of Physics and Power Engineering, Obninsk
- [8] Budnik A P, Sokolov Yu V and Vakulovskiy A S 1994 *Hyperfine Interact.* **88** 185
- [9] Raizer Yu P 1987 *Gas Discharge Physics* (Moscow: Nauka) (1991, Berlin: Springer)
- [10] Huxley L G H and Crompton R W 1974 *The Diffusion and Drift of Electrons in Gases* (New York: Wiley) (1976, Moscow: Mir)
- [11] Golant V E, Zhilinskii A P and Sakharov I E 1977 *Fundamentals of Plasma Physics* (Moscow: Atomizdat) (1980, New York: Wiley)
- [12] McDaniel E W and Mason E A 1973 *The Mobility and Diffusion of Ions in Gases* (New York: Wiley) (1976, Moscow: Mir)
- [13] Rossi B B and Staub H H 1949 *Ionization Chambers and Counters: Experimental Techniques* (New York: McGraw-Hill) (1950, Moscow: Inostrannaya Literatura)
- [14] Tsytovich V N 1997 *Usp. Fiz. Nauk* **167** 57 (Engl. transl. 1997 *Phys. Usp.* **40** 53)
Nefedov A P, Petrov O F and Fortov V E 1997 *Usp. Fiz. Nauk* **167** 1215 (Engl. transl. 1997 *Phys. Usp.* **40** 1163)
- [15] Smirnov B M 1990 *Aerosols in Gas and Plasma* (Moscow: Inst. Vys. Temp. Akad. Nauk SSSR)
- [16] Abramov A I, Kazanski Yu A and Matushevich E S 1970 *Foundations of Experimental Methods in Nuclear Physics* (Moscow: Atomizdat)
- [17] Vladimirov V I *et al* 2001 *Fiz. Plazmy* **27** 37 (Engl. transl. 2001 *Plasma Phys. Rep.* **27** 36)
- [18] Zobnin A V *et al* 2000 *Fiz. Plazmy* **26** 445 (Engl. transl. 2000 *Plasma Phys. Rep.* **26** 415)
- [19] Zhakovski V V *et al* 1997 *Zh. Eksp. Teor. Fiz. Pis. Red.* **66** 392 (Engl. transl. 1997 *JETP Lett.* **66** 419)