

Dusty plasma as a unique object of plasma physics

G E Norman¹ and A V Timofeev^{1,2}

¹ Joint Institute for High Temperatures of the Russian Academy of Sciences, Izorskaya 13 Bldg 2, Moscow 125412, Russia

² Moscow Institute of Electronics and Mathematics, National Research University Higher School of Economics, Tallinskaya 34, Moscow 123458, Russia

E-mail: timofeevalvl@gmail.com

Abstract. The self-consistency and basic openness of dusty plasma, charge fluctuations, high dissipation and other features of dusty plasma system lead to the appearance of a number of unusual and unique properties of dusty plasma. “Anomalous” heating of dusty particles, anisotropy of temperatures and other features, parametric resonance, charge fluctuations and interaction potential are among these unique properties. Study is based on analytical approach and numerical simulation. Mechanisms of “anomalous” heating and energy transfer are proposed. Influence of charge fluctuations on the system properties is discussed. The self-consistent, many-particle, fluctuation and anisotropic interparticle interaction potential is studied for a significant range of gas temperature. These properties are interconnected and necessary for a full description of dusty plasmas physics.

1. Introduction

The basic openness and self-consistency of dusty plasma system, inconstancy of the particle charge and charge dependence on the environment parameters, high dissipation, significant influence of stochastic processes and self-organization lead to the appearance of a number of unusual properties [1–3].

The study of properties and phenomena, which occur only in dusty plasmas, is presented. Precisely this meaning is put into the term of uniqueness of dusty plasmas not only in the collisional plasma and also in general physics. The beginning of this area is put in [4, 5], which are first to formulate the equation of dust particles motion with account of fluctuations in the dust particles charge, the dependence of the charge on the position in near-electrode layer and the proximity of other dust particles, gas discharge sheath features, which are specific to the forces acting on the dust particles. These features lead to a number of unique phenomena that are observed among examples of collisional low-temperature plasma only in dusty plasmas.

- (1) “Anomalous” heating of dusty plasma system. The dust particles average kinetic energy may exceed the value of the ion and neutral gas temperatures and even electron temperature and can be as high as thousands of eV [3, 6–15]. In particular, the average kinetic energy of dust particles in ordered structure can be several of eV [9, 16]. The increase of the dust particles mean kinetic energy to such values is called “anomalous” heating. The average kinetic energies of horizontal and vertical motion of dust particles differ greatly from each other [10, 11, 17, 18] when observing the phenomenon of “anomalous” heating, which leads us to the following point.



- (2) *Anisotropy of the temperatures and other features.* Dusty plasma in laboratory is observed in the gas discharge under gravity, which leads to the anisotropy and separation in the vertical and horizontal subsystems with different average kinetic energies [10, 11, 17–19], coefficients of heat and mass transfer, and other features. The average kinetic energy of the vertical and horizontal motion may differ significantly, but each of them has a normal distribution [17, 20] and may be considered as in partial equilibrium. The relaxation processes of plasma-dust system is largely influenced by dust particles charge fluctuations and its effects.
- (3) *Parametric resonance in dusty plasma system.* Significantly different mean kinetic energy of dust particles vertical and horizontal motion is based on the energy transfer mechanism between different degrees of freedom of a dusty plasma system [4, 5, 21–26]. In particular, this mechanism leads to the “anomalous” heating. One of such mechanisms is based on the parametric resonance [4, 5, 23]. Energy transfer mechanism depends on interparticle interaction potential and stochastic processes, like charge fluctuations.
- (4) *Interparticle interaction potential.* The interaction between the dust particles in plasma is self-consistent with the ambient plasma, i.e. depends on it and affects it; the interaction is many-particle one since it depends on the proximity to other dust particles; the interaction depends on the particle charge fluctuations and related effects; the interaction is anisotropic as a cloud of ions with a positive effective charge is formed under particle due to the ion flux [2, 19, 27–30]. The dependences of interparticle distance and interaction potential on temperature and gas pressure help us to describe the dusty plasmas features.
- (5) *Dust particle charge fluctuations.* The plasma fluctuations around the dust particle lead to the dust particle charge fluctuations, which significantly affect the dusty plasma dynamic characteristics [2, 3, 8, 10, 13, 14, 31–37]. The dependence of the particle charge on the distance from the electrode and the position of other dust particles results in a strong self-consistency of the system and points to the importance of collective effects. Significant charge fluctuations alter the interaction potential, make stochastic component significant and lead to a set of unique effects. Dust particle charge fluctuations has a direct impact on the “anomalous heating” of dusty plasma system, which hung up the chain of the research.

The development of equations [4, 5] and, most importantly, the analysis of their consequences constitute the fundamental problem underlying this article. Sections of the article are arranged in accordance with the unique properties mentioned above.

2. “Anomalous” heating of dusty plasma system

Dust particles are considered as material points with charge and mass. Effect of gas-discharge plasma on dust particle is simulated by a stochastic term of dust particle charge. The influence of gas discharge near-electrode layer is simulated by dependence of the electric field and dust particles charge on the distance from the electrode. The influence of other charged dust particles on ambient plasma and, consequently, on dust particle charge is simulated by the dependence of dust particle charge on the distance to other dust particles.

The simulation is carried out for parameters corresponding to the typical laboratory experiment. The simulation results allow formulating temperature dependence on parameters and the mechanism that is the main for this model and parameters. The dependencies of the vertical kinetic temperature on the system parameters can be combined into the formula

$$K_v \approx T_{\text{room}} + (1.0 \pm 0.1)a(N)m(g\delta q)^2/(\gamma\Omega), \quad (1)$$

where T_{room} is the temperature of neutral gas, which is usually 300 K, $a(N)$ is a function of number of dust particles. The resulting formula (1) for kinetic temperature consists of only five parameters: the mass m , the gravity g , the friction coefficient γ , the normalized

amplitude of charge fluctuations δq and the characteristic frequency of dust particle charge deviations Ω . Similar dependence of the vertical kinetic temperature on the system parameters is previously obtained in some theoretical papers [10, 33] in another form. The value of the vertical temperature depends weakly on the other seven parameters. Two parameters can be identified as the next parameters due to importance: number of particles and dust particle charge. Vertical temperature is nearly constant for the five remaining parameters in the typical for laboratory experiment range of parameters.

The conditions of the separation of vertical kinetic temperature of dust particles from the neutral gas temperature are estimated by the formula $(\delta q)^2/(\gamma\Omega) \approx T_{\text{room}}/(mg^2)$. The phenomenon may occur at $\gamma < 90 \text{ s}^{-1}$ or $\delta q > 0.0006$, or $\Omega < 3.6 \times 10^6 \text{ s}^{-1}$ for first set of parameters [5] close to the ones of typical laboratory experiment. The kinetic temperature of dust particles motion in the simulation does not fall below the neutral gas temperature, because the model takes into account the effect of neutral gas on dust particle motion with Langevin thermostat. This mechanism of heating is based on influence of stochastic terms in the system of equations.

3. Anisotropy of the temperatures and other features

In laboratory experiments under conditions of strong gravity the considering system has a preferred direction, and kinetic energy of horizontal motion and vertical motion can vary greatly [10, 11, 17, 38–40], which also suggests inconsistency of the kinetic temperature of the three-dimensional motion.

It has been found that the velocity of dust particles in laboratory experiments has Maxwellian distribution [10, 11, 17, 38–43].

A monolayer of dust particles in the near electrode layer of RF discharge is considered in [39]. Dust particles velocities are measured for three different degrees of heating of dust particles system, from gaseous to crystalline state. The velocity distribution is Maxwellian in all cases, and for some cases, the distribution of vertical velocities differs from the distribution of horizontal velocities. Note that both distributions are Maxwellian, but the parameters of the distributions differ from each other. Thus, if we want to introduce the concept of kinetic temperature as a characteristic of velocity distribution, then it is necessary to introduce the concepts of vertical and horizontal kinetic temperature of dust particles.

It is found in simulation that the system of dust particles approach a partial equilibrium and velocity distribution becomes Maxwellian in a period of time smaller than the period time of several dust particles oscillations (the time required for the collection of statistics and verification of the distribution). Maxwellization of velocity distribution is explained by the influence of two stochastic processes on the system: a stochastic Langevin force and stochastic fluctuations of dust particle charge. Stochastic fluctuations of charge dominate for considered conditions, since these fluctuations lead to a Maxwellian distribution of dust particles velocities faster. Particular attention should be paid to the fact that the distribution of the vertical velocity differs from the distribution of horizontal velocity under certain conditions in the simulation, but both distributions are Maxwellian. Results for the equilibrium state for one and the same set of parameters are shown in figures 1 and 2.

Thus, the system of dust particles is divided into two subsystems, the both are in partial equilibrium [20]. Correspondingly, the concept of temperature can be introduced for each subsystem. The situation with separated temperatures for two subsystems occurs frequently in nonequilibrium systems. For example, translational, vibrational, rotational, and other temperatures are often marked out in a nonequilibrium low-temperature plasma. Horizontal and vertical motions are equalized for certain condition, the velocity distribution are also beginning to match, and then it becomes possible to talk about the temperature of the dust system without any division into additional subsystems. It is possible to divide the dynamics of dust particles

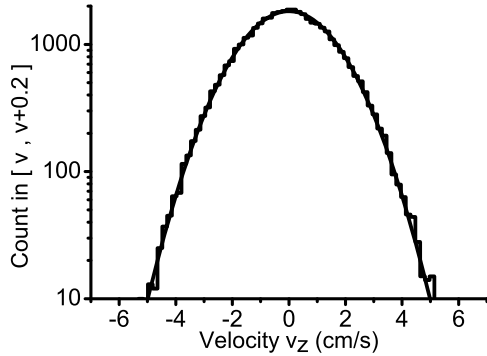


Figure 1. The distribution of horizontal velocities: histogram is the result of simulation, line is the approximation by Maxwell distribution. Distribution corresponds to the kinetic temperature 0.026 eV.

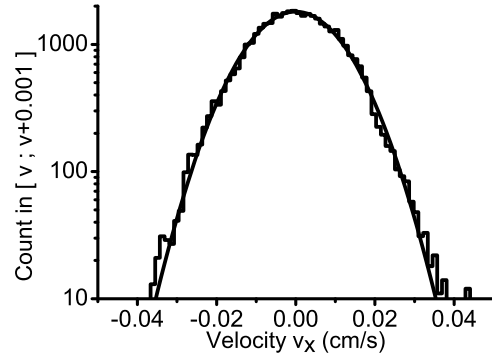


Figure 2. The distribution of vertical velocities: histogram is the result of simulation; line is the approximation by Maxwell distribution. Distribution corresponds to the kinetic temperature 538 eV.

kinetic temperature on the three basic modes:

- (1) vertical and horizontal temperatures coincide and are equal to the ambient gas;
- (2) vertical temperature is greater than the horizontal temperature and the ambient gas temperature;
- (3) vertical and horizontal temperatures coincide and are much more than the temperature of the ambient gas.

The separation of dusty plasma system on the vertical and horizontal subsystem applies not only to temperature but also to transport coefficients and other system characteristics.

4. Parametric resonance in dusty plasma system

This instability in 2D plasma crystals is associated with collective processes in dusty plasma. Therefore, the model [5] of dusty plasma should take into account collective and even small effects, those influence the dynamics of dust particles in plasma. The three-dimensional motion of a dust particle is represented by the system of equations as follows:

$$\begin{cases} m\ddot{x}_i = \sum F^{\text{inter}} + F^{\text{fr}} + F^{\text{trap}}, \\ m\ddot{y}_i = \sum F^{\text{inter}} + F^{\text{fr}} + F^{\text{trap}}, \\ m\ddot{z}_i = \sum F^{\text{inter}} + F^{\text{fr}} + F^{\text{el}} + F^{\text{grav}}. \end{cases} \quad (2)$$

The symmetry of two horizontal axes allows simplifying the system by neglecting one of them.

Interaction with other dust particles is modeled by the interaction of particle with two fixed charged points on the same horizontal line. This model allows accounting for most of the effects of particle interaction with other dust particles in this plane. Dust particles form an ordered structure and oscillate about the equilibrium position and amplitude of particle oscillations is much smaller than the average interparticle distance. Therefore, the forces acting on dust particles can be expanded in a Taylor series and some of small stochastic terms may be neglected

$$\begin{cases} \ddot{x} = -a_1x + a_2xz + a_3x^3 + a_4x^2z + \dots, \\ \ddot{z} = -b_1z + b_2z^2 + b_3z^3 + b_4x^2z + \dots. \end{cases} \quad (3)$$

Numerical evaluation of expansion coefficients shows that linear terms a_1x and b_1z have the most significant impact on the system. The following leading terms are a_4xz^2 and b_4zx^2 , where the coefficients a_4 and b_4 are equal and depend mostly on the interaction potential parameters.

The substitution of harmonic instead of the coordinate lead the equation to a form of the Mathieu equation [4, 5]. So, the parametric resonance may rise under certain conditions in this system. The parametric resonance may only occur if the vertical frequency ω_z is comparable to the in-plane frequency ω_x . In many laboratory experiments with monolayer $b_1 \gg a_1$ and as b_1 decreases and approaches a_1 , the dust monolayer may lose its stability, and a multilayer structure may appear. But in this case there is no need for b_1 be close to a_1 , because the horizontal eigenfrequency has a wide range of values due to dimensionality, nonlinear terms, also stochastic terms and other factors. The peaks of spectrum of dust particle vertical motion is also rather wide [23]. These facts lead to the intersection of the frequency ranges of vertical and horizontal motion. These facts are approved by the expansion of dust particles trajectory (simulation) in a Fourier series. Thus, the predominance of some terms and the intersection of the frequency ranges of vertical and horizontal oscillations leads to the possibility of parametric resonance [44], which pump energy from vertical to horizontal motion. The condition of parametric resonance can be represented as

$$\gamma < a_4 A_z^2 / 8\omega_z. \quad (4)$$

Second parametric resonance can occur if the amplitude of horizontal oscillations is close to the value of the amplitude of vertical oscillations. This resonance can pump energy from the horizontal oscillations in the vertical oscillations. This phenomenon can stop heating of the horizontal oscillations and bring the system to equilibrium. The condition of equilibrium of energy flows reveals relationship between the amplitudes of vertical and horizontal oscillations for the case of small frequency deviation

$$A_z^2 - A_x^2 \approx \gamma\omega_z/b_4 > 0. \quad (5)$$

This relationship between the amplitudes is valid only when this mechanism operates the exchange of energy between vertical and horizontal oscillations.

5. Interparticle interaction potential

The dusty particles interaction potential is self-consistent with the ambient plasma, i.e. depends on it and affects it; the interaction is many-particle one since it depends on the proximity to other dust particles; the interaction depends on the particle charge fluctuations and related effects; the interaction is anisotropic as a cloud of ions with a positive effective charge is formed under particle due to the ion flux [2, 19, 27–30].

A substantial change in the potential interaction can be observed while the temperature of neutral gas changes from room to cryogenic ones both in experiments and in numerical simulations. Technological difficulties hindered the progress of experimental work in this direction for a long time. Significant reduction of the screening radius as the temperature decreases to cryogenic one reduces greatly the interparticle distance that allows determining the interaction potential and its temperature range. Furthermore, the decrease in temperature leads to a unique structures [45], such as the formation of dense luminous dust particles at a temperature of about 4 K.

Three potentials (Debye potential, Gurevich potential and others) are used to describe dusty particles interaction in order to get the theoretical dependence of interparticle distance on temperature and pressure of the neutral component. Experimental data was taken from [46] and from the experiments performed in JIHT RAS in 2010–2012 by I S Samoylov, V P Baev *et al* [47]. The estimated value of the screening length in dusty plasma is in one order of magnitude larger

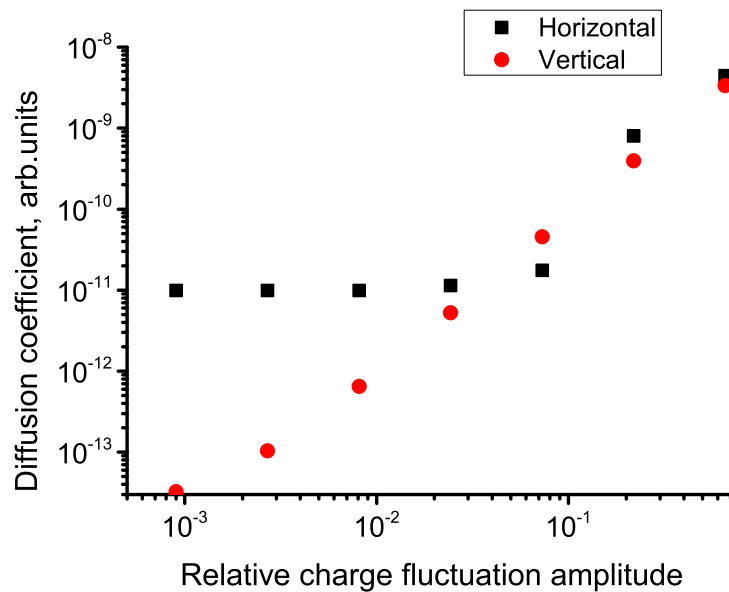


Figure 3. The dependence of the diffusion coefficient in the vertical and horizontal directions on the relative amplitude of dust particles charge fluctuations.

than the ion Debye length. The experimental data fitting leads to the estimation of effective screening length $\lambda_{\text{scr}} \approx 8\lambda_D$ in the temperature range 200–275 K for pressure 8.5 mBar for the Debye–Hückel potential.

6. Dust particle charge fluctuations

Dust particles charge fluctuations significantly affect the dynamic properties of plasma-dust system. The diffusion coefficient is calculated on the basis of the Einstein relation. It is shown that the diffusion coefficient differs significantly in the vertical and horizontal directions, and greatly depends on the amplitude of the dust particle charge fluctuations (figure 3). It is worth noting that the dependence of the diffusion coefficient of the charge fluctuation amplitude differs substantially in different directions, but this difference decreases as the system approaches the partial equilibrium.

7. Conclusions

The uniqueness of dusty plasmas lies in the properties and phenomena that occur only in dusty plasmas. These features of dusty plasmas are interconnected and their description is necessary for a full description of the dusty plasmas physics.

- (1) *“Anomalous” heating of dusty plasma system.* Dust particles under certain conditions can acquire kinetic energy of the order of 10 eV and higher, far above the temperature of gas and temperatures of ions and electrons in the discharge. The evidence of this phenomenon is found in laboratory experiments [6–12]. Despite such kinetic energy dust particles can form a crystalline structure [9,16,48,49]. The mechanism for “Anomalous” heating of dusty plasma system is proposed.
- (2) *The anisotropy of temperature and other features.* The average kinetic energy of horizontal and vertical motion can differ from each other greatly [10,11,17,39]. The dusty plasma system is divided into two subsystems that are in partial equilibrium. The concept of

temperature can be introduced for each subsystem. The processes of relaxation [50] are studied and applicability limits of the thermodynamic relations for dusty plasma with temperature anisotropy are determined.

- (3) *Parametric resonance in dusty plasma system.* Dust particle vertical motion heating and energy transfer from the vertical to horizontal motion is studied in the experiment [51]. The mechanism of energy transfer on the basis of parametric resonance allows us to describe the experimental growth rate of the kinetic energy and the energy spectrum of the motion of dust particles, which indicates the existence of the parametric resonance in dusty plasmas.
- (4) *Interparticle interaction potential.* The dependence of dust particle interparticle distance on gas temperature [46] and methods for interaction potential restoration [52] show the complexity of potential. The self-consistent, many-particle, fluctuation and anisotropic interparticle interaction potential is studied for significant range of gas temperature. The estimated value of the screening length in dusty plasma is in one order of magnitude larger than the ion Debye length.
- (5) *Dust particle charge fluctuations.* It is shown that fluctuations of dust particles charge significantly influence dynamic properties of dust particles system, in particular, diffusion coefficient. Dust particles charge fluctuations influence dynamic properties in the horizontal plane and vertical differently.

Acknowledgments

This work is supported by the Russian Science Foundation (project No. 14-19-01295).

References

- [1] Fortov V E, Khrapak A G, Khrapak S A, Molotkov V I and Petrov O F 2004 *Usp. Fiz. Nauk* **174** 495
- [2] Tsytovich V N, Morfill G E, Vladimirov S V and Thomas H M 2008 (*Lecture Notes in Physics* vol 731) (Springer Berlin Heidelberg)
- [3] Vaulina O S, Petrov O F, Fortov V E, Khrapak S A and Khrapak A G 2009 *Dusty plasmas: experiment and theory* (Moscow: FIZMATLIT)
- [4] Norman G E, Stegailov V V and Timofeev A V 2011 *J. Exp. Theor. Phys.* **113** 887–900
- [5] Norman G E and Timofeev A V 2011 *Phys. Rev. E* **84** 056401
- [6] Schweigert V A, Schweigert I V, Melzer A, Homann A and Piel A 1996 *Phys. Rev. E* **54** 4155–4166
- [7] Melzer A, Homann A and Piel A 1996 *Phys. Rev. E* **53** 2757–2766
- [8] Zhakhovskii V V, Molotkov V I, Nefedov A P, Torchinskii V M, Khrapak A G and Fortov V E 1997 *JETP Lett.* **66** 419–425
- [9] Schweigert I V, Schweigert V A, Bedanov V M, Melzer A, Homann A and Piel A 1998 *J. Exp. Theor. Phys.* **87** 905–915
- [10] Quinn R A and Goree J 2000 *Phys. Rev. E* **61** 3033–3041
- [11] Samarian A A, James B W, Vladimirov S V and Cramer N F 2001 *Phys. Rev. E* **64** 025402
- [12] Ivanov Y and Melzer A 2005 *Phys. Plasmas* **12** 072110
- [13] Ivlev A V, Zhdanov S K, Klumov B A, Tsytovich V N, de Angelis U and Morfill G E 2004 *Phys. Rev. E* **70** 066401
- [14] de Angelis U, Ivlev A V, Morfill G E and Tsytovich V N 2005 *Phys. Plasmas* **12** 052301
- [15] Vaulina O S, Lisina I I and Lisin E A 2015 *Europhys. Lett.* **111** 50003
- [16] Samsonov D, Zhdanov S K, Quinn R A, Popel S I and Morfill G E 2004 *Phys. Rev. Lett.* **92** 255004
- [17] Williams J and Thomas E 2007 *Phys. Plasmas* **14** 063702
- [18] Nosenko V, Goree J and Piel A 2006 *Phys. Plasmas* **13** 032106
- [19] Knappek C A, Ivlev A V, Klumov B A, Morfill G E and Samsonov D 2007 *Phys. Rev. Lett.* **98** 015001
- [20] Timofeev A V 2015 *J. Phys.: Conf. Ser.* **653** 012137
- [21] Feng Y, Goree J and Liu B 2012 *Phys. Rev. E* **86** 056403
- [22] Couëdel L, Nosenko V, Ivlev A, Zhdanov S, Thomas H and Morfill G 2010 *Phys. Rev. Lett.* **104** 195001
- [23] Semyonov V P and Timofeev A V 2015 *J. Phys.: Conf. Ser.* **653** 012138
- [24] Shukla P K 2000 *Phys. Rev. Lett.* **84** 5328–5330
- [25] Melzer A, Schella A and Mulsow M 2014 *Phys. Rev. E* **89** 013109

- [26] Antonov N N, Gavrikov A V, Ivanov A S, Petrov O F, Timirkhanov R A and Fortov V E 2012 *J. Exp. Theor. Phys.* **114** 1072–1077
- [27] Filippov A V, Zagorodny A G, Momot A I, Pal' A F and Starostin A N 2007 *J. Exp. Theor. Phys.* **105** 831–845
- [28] Khrapak S A, Klumov B A and Morfill G E 2008 *Phys. Rev. Lett.* **100** 225003
- [29] Fedoseev A V, Sukhinin G I, Dosbolayev M K and Ramazanov T S 2015 *Phys. Rev. E* **92** 023106
- [30] Sukhinin G I, Fedoseev A V, Antipov S N, Petrov O F and Fortov V E 2013 *Phys. Rev. E* **87** 013101
- [31] Matsoukas T 1996 *J. Vac. Sci. Technol.* **14** 624
- [32] Khrapak S A, Nefedov A P, Petrov O F and Vaulina O S 1999 *Phys. Rev. E* **59** 6017–6022
- [33] Vaulina O S, Khrapak S A, Nefedov A P and Petrov O F 1999 *Phys. Rev. E* **60** 5959–5964
- [34] Shotorban B 2014 *Phys. Plasmas* **21** 033702
- [35] Popel S I, Gisko A A, Golub' A P, Losseva T V, Bingham R and Shukla P K 2000 *Phys. Plasmas* **7** 2410
- [36] Popel S I, Golub' A P, Losseva T V, Bingham R and Benkadda S 2001 *Phys. Plasmas* **8** 1497
- [37] Ivlev A V, Zhdanov S K, Klumov B A and Morfill G E 2005 *Phys. Plasmas* **12** 092104
- [38] Thomas E and Williams J 2006 *Phys. Plasmas* **13** 055702
- [39] Nosenko V, Goree J and Piel A 2006 *Phys. Plasmas* **13** 032106
- [40] Quinn R A and Goree J 2000 *Phys. Plasmas* **7** 3904
- [41] Fortov V E, Vaulina O S, Petrov O F, Vasil'ev M N, Gavrikov A, Shakhova I, Vorona N, Khrustalyov Yu, Manohin A and Chernyshev A 2007 *Phys. Rev. E* **75** 026403
- [42] Nosenko V, Zhdanov S K, Ivlev A V, Morfill G E, Goree J and Piel A 2008 *Phys. Rev. Lett.* **100** 025003
- [43] Wolter M and Melzer A 2005 *Phys. Rev. E* **71** 36414
- [44] Landau L D and Lifshitz E M 1959 *Theoretical Physics. Mechanics* (London: Pergamon)
- [45] Polyakov D N, Vasilyak L M and Shumova V V 2015 *Surf. Eng. Appl. Electrochem.* **51** 143–151
- [46] Antipov S N, Asinovski É I, Kirillin A V, Maorov S A, Markovets V V, Petrov O F and Fortov V E 2008 *J. Exp. Theor. Phys.* **106** 830–837
- [47] Samoylov I S, Baev V P and Amirov R 2010 *Experimental data*
- [48] Schweigert V A, Schweigert I V, Melzer A, Homann A and Piel A 1998 *Phys. Rev. Lett.* **80** 5345–5348
- [49] Schweigert V A, Schweigert I V, Nosenko V and Goree J 2002 *Phys. Plasmas* **9** 4465
- [50] Feng Y, Goree J and Liu B 2010 *Phys. Rev. E* **82** 036403
- [51] Vasilyak L M, Fortov V E, Morfill G E, Ivlev A V, Pustynnik M Y, Polyakov D N, Thomas H M and Vetchinin S P 2011 *Contrib. Plasma Phys.* **51** 529–532
- [52] Vaulina O S, Lisin E A, Gavrikov A V, Petrov O F and Fortov V E 2010 *J. Exp. Theor. Phys.* **110** 662–674