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SCATTERING OF DUST MICROPARTICLES BY COLLECTIVE OSCILLATIONS OF A PLASMA

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A special gas-discharge chamber was designed, manufactured, and tested for investigating the regularities of Brownian scattering of dust grains in plasmas produced by a stationary dc glow discharge and a stationary high-frequency electric (HFE) *discharge. An experimental procedure for studying Brownian scattering was developed. Records of dust grain scattering in the plasma are given. Mathematical processing of a large number of images of dust grains showed that the dependence of the dust grain distribution width in the images at half distance from the discharge to the sample stage on the discharge current strength is well approximated by a linear relation with a proportionality constant equal to approximately* 16 mm/A*. It is shown that the scattering is caused by collective oscillations of the plasma — pulsations of ionization type.*

Recently, active research has been carried out in the new direction of plasma physics — the physics of dusty plasma (plasmas in which small particles or drops of condensed material are suspended). This is motivated by two factors. First, the addition of a small amount of dust (for example, 10^3–10^4 cm^{-3}) to a plasma can change radically the collective properties of the plasma. Second, the dust fraction always present in the plasma composition in devices such as magnetic traps of thermonuclear reactors and facilities for plasma etching of microcircuitry frequently has a harmful effect on the operation of these devices.

Experimental studies are needed to establish the regularities of motion of the dust fraction in a plasma and to develop methods for controlling this motion (for example, for removal of dust from process installations). The goal of the work described here was to develop a special gas-discharge chamber for studies of the stochastic individual motion of dust grains in plasmas — their Brownian scattering — and the characteristics and mechanism of this scattering.

The chamber design is shown in Fig. 1. The chamber consisted of a cylindrical barrel 220 mm high and 100 mm in diameter made of Caprolon and fixed in upright position on a laboratory bench by a special support which allowed for control of the vertical chamber position using a household level. The support was fitted with pilofacturing openings for connection of a vacuum pump and a pressure transducer (PMI-10 transducer connected to a VIT-3 vacuum gauge) and for hermetic terminal lead to the probes diagnosing the plasma.

Two Caprolon branch pipes with an inner diameter of 100 mm and a length of 240 mm were attached to the top of the chamber. Electrodes made of 12Kh18N10T stainless steel and polished over the discharge surface were fixed at the ends of the branch pipes. The electrodes were connected to a stationary dc discharge supply. Placement of the electrodes in the branch pipes rather than in the main barrel is motivated by the need for eliminating injection of dust into the near-electrode discharge strata, in which there are quasistationary regions of bulk charge capable of causing significant single-direction deflection of dust particle motion.

The unit for injecting dust into the plasma is fixed at the top of the chamber, and at the bottom there is a sample stage for recording the dust grains falling on it. The height of the sample stage could be varied over a wide range.

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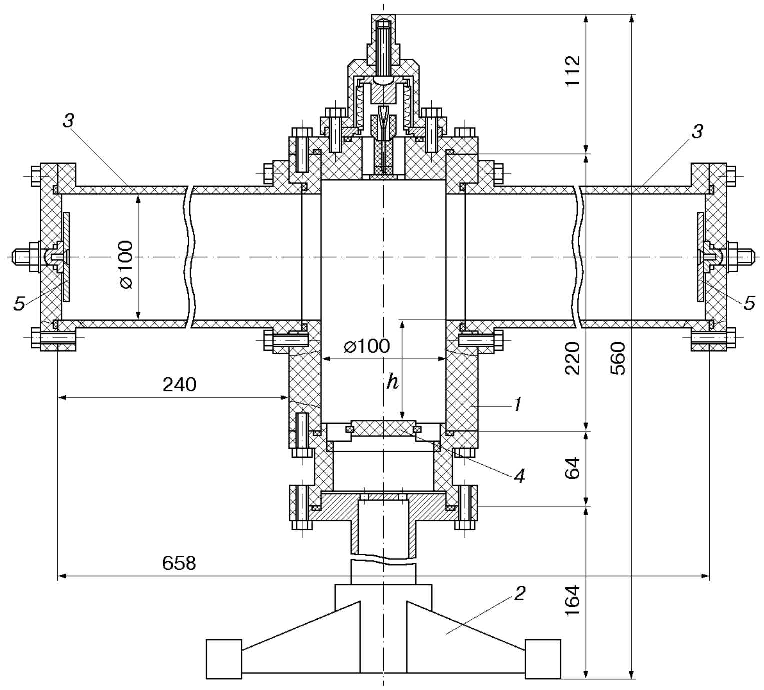

Fig. 1. Diagram of the discharge chamber: 1) barrel; 2) support; 3) branch pipes; 4) sample stage; 5) electrodes (5); h is the range of heights of the sample stage.

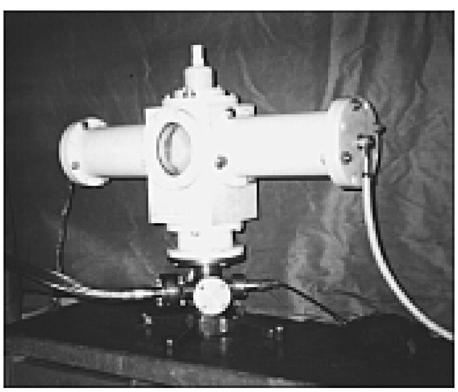

Fig. 2

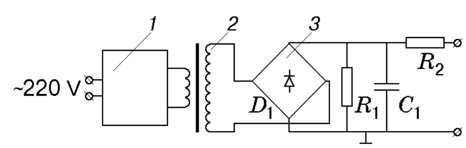

Fig. 3

Fig. 2. General view of the discharge chamber.

Fig. 3. Basic diagram of the high-voltage supply block: 1) thyristor alternating-current controller; 2) high-voltage step-up transformer; 3) diode bridge; $R_1 = 10$ kΩ, $R_2 = 600$ Ω, and $C_1 = 200$ μF.

The general view of the chamber is shown in Fig. 2. A specially designed high-voltage supply of the discharge, shown schematically in Fig. 3, was connected to the electrodes. The power supply furnishes a constant output voltage of 500–5000 V with a load current of not more than 0.5 A. When the load current exceeded the maximum permissible value, the protection block cuts off the power supply from the mains. A high-voltage transformer with a transformation ratio equal to 20 was used for circuit voltage rise. The output voltage was regulated by changing the voltage across the primary winding of the set-up transformer using a ROT-63-380-50UKhL4 thyristor alternating-current controller. Rectification was carried out by a diode bridge assembled from chains of KD210 diodes (10 pieces in each arm) and a filter based on a high-value capacitor C_1. The resistor R_2 served as the ballast.

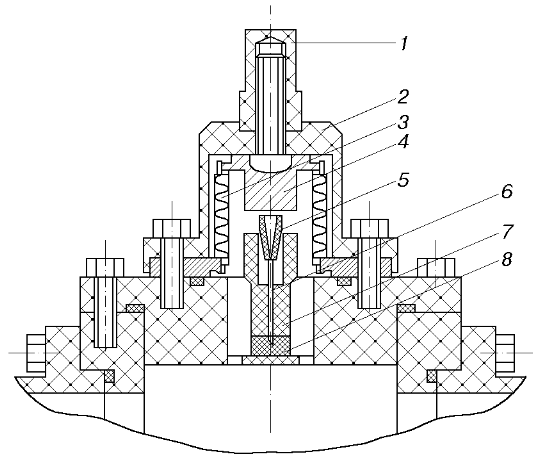

Fig. 4. Design of the dust injector: 1) driving gate; 2) injector cover; 3) sylphon; 4) needle plunger; 5) plastic container; 6) needle; 7) guide pin; 8) rubber stopper.

When the required pressure was reached in the vacuum chamber (approximately 13.3 Pa), the voltage across the electrodes of the chamber was raised to the breakdown voltage. After initiation of a glow discharge, the required discharge current was set by regulating the output voltage (check was carried out by a built-in ammeter).

In the experiments, besides the high-voltage power supply, we used an IKV-4 medical high-frequency generator operating at a frequency of 13.56 MHz with a maximum output power of 200 W. This made it possible to perform studies not only in a stationary dc glow discharge but also in a stationary HFE discharge.

The chamber is furnished with a system of movable double probes with their associated power sources, which are used to determine plasma parameters.

To study the Brownian motion of dust grains, one need a precision injector for accurate injection of particles into a plasma. Various devices for particle injection into a plasma were considered:

— a mesh container of particles placed at the top of the chamber and shaken mechanically [1, 2];
— a vibrating diaphragm (loud speaker) placed at the bottom of the chamber and throwing the particles up;
— a rotating blade cylinder placed horizontally inside the chamber and throwing the particles up [3, 4].

The first two devices were examined in the present work. It is established that the indicated methods and devices do not satisfy the required conditions because there is a considerable spread of the initial coordinates and velocities with which dust grains are injected into the plasma. Therefore, we designed a precision needle injector intended for introduction of dust into a plasma. Subsequent experiments confirmed the high service performance of this device.

The injector design is shown in Fig. 4. The basic part of the injector is a medical needle, which consists of a thin metal tube with one end cut at an angle of about 10° and with a plastic container at the other end. The design allows for the use of expendable medical needles of various diameters and lengths. The guide pin of the injector held the needle in a vertical position with a deviation of not more than $\pm 0.7°$.

Injection of dust into the plasma was carried out as follows. Before assembly of the chamber, the needle was pinned along the guiding pin on the rubber stopper at its geometrical center, and then a small portion of dust grains was poured in the container of the needle. Previously, it was established that the optimal portion for handling in the present experiments should contain approximately 10^2–10^3 particles. The assembly of the needle with particles, the stopper, and the guide pin was seated at the top of the chamber barrel, after which the cover was put down on the injector. Using special marking, the needle edge was always oriented at the same azimuthal angle relative to the vertical axis of the chamber.

After the chamber was covered and sealed hermetically, it was evacuated. It should be noted that the pressure in the volume under the injector cover and the chamber pressure were always identical owing to special holes in the seat of the needle with the stopper. In this case, injection of dust grains occurs without a pressure gradient and does not change the discharge burning conditions. After the required residual gas pressure was attained, high

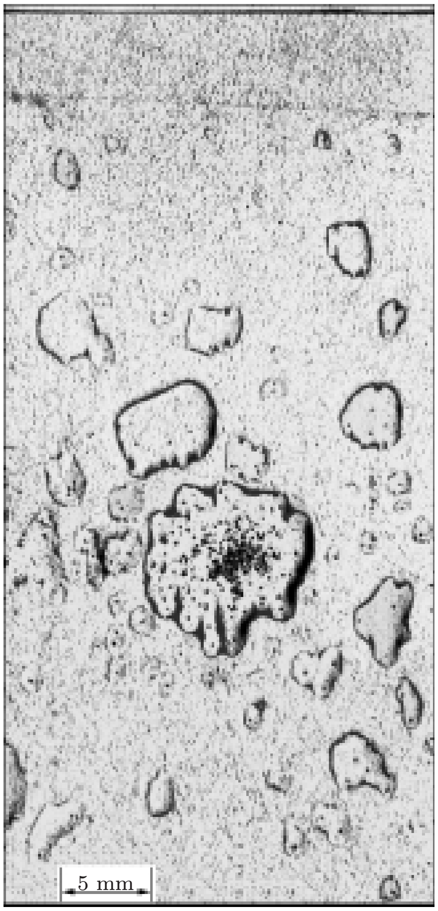

Fig. 5

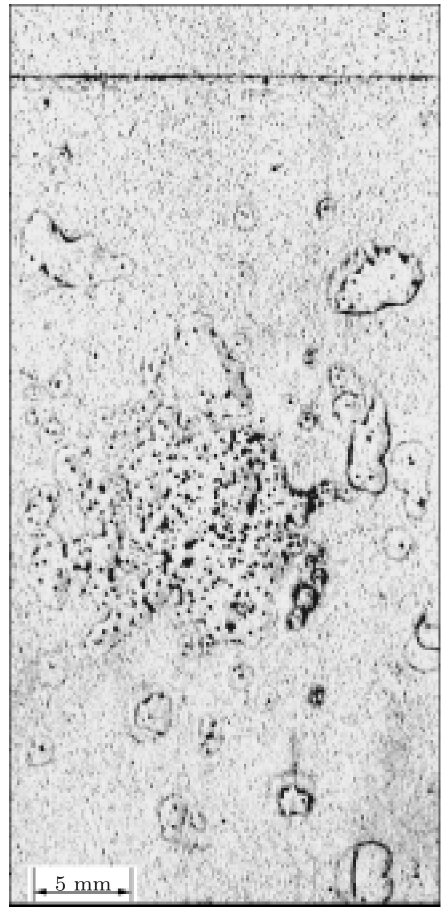

Fig. 6

Fig. 5. Image of a dust cloud in unionized air with a residual pressure of 13.3 Pa.

Fig. 6. Image of a dust cloud in an air plasma at a pressure of 13.3 Pa (discharge current $I = 0.3$ A).

voltage was applied to the electrodes. After the required discharge burning regime was established, the driving gate began rotating slowly, transmitting translational motion downward to the needle plunger through the sylphon. As soon as the needle pierced the stopper, the dust grains was poured from the needle into the plasma under the action of gravity. The initial particle velocity was low compared to the final velocity of fall on the sample stage. Because after piercing the stopper, the needle end was in contact with the discharge plasma and acquired a considerable potential, all metal parts of the injector were covered with dielectric caps, and the spanner wrench for rotation of the gate was grounded.

A sample stage with controlled height was placed at the bottom of the chamber. On the stage there was a recording element which produced images of the dust cloud falling on the stage. The velocity of a falling dust grain is rather high, and, therefore, it is necessary to exclude rebound from the recording element. As recording elements we used object plates produced by the "Star Frost" firm, which were previously coated with a layer of a transparent glue (office silicate, polyvinyl acetate, dextrin glue, etc.). It is established that allowed to stand in vacuum for a long time (up to 10 min during an experiment), the glue layer is dehydrated, and dust grains are not attached to the object plate. Therefore, finally as the recording element, we used a transparent cellophane film with one side coated with a glue layer (household adhesive tape produced by the "Rusi Star" firm). After demounting of the chamber at the end of each experiment, the film with the particles glued to it was pasted tightly, without wrinkles, to an object plate (working region 60×25 mm and thickness 1 mm) and was marked, after which the samples could be stored for a long time. Nevertheless, it was not possible to completely paste the film with dust grains to the object plate because at the location of dust grains between the plate and the film there were small

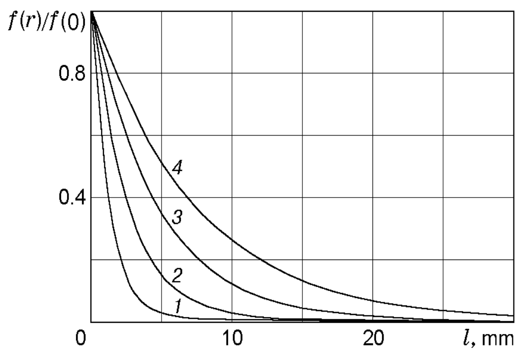

Fig. 7

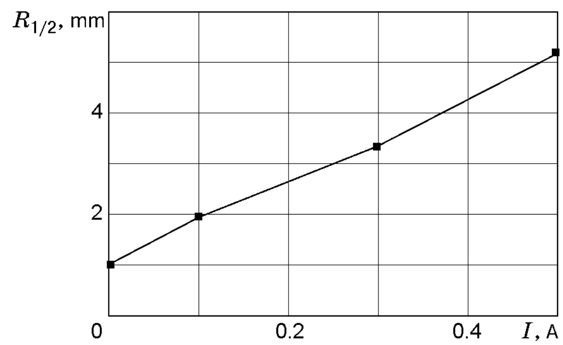

Fig. 8

Fig. 7. Plots of normalized grain size distribution functions obtained from results of processing of images of dust clouds: curve 1 refers to unionized air and curves 2, 3, and 4 refer to $I = 0.1$, 0.3, and 0.5 A, respectively.

Fig. 8. Distribution function width at half height versus discharge current.

air bubbles, which can be clearly seen in the photographs given below. These bubbles, however, do not complicate image processing.

In the present work, corundum particles with a diameter of (60 ± 5) μm were used. We took into account that in studies of Brownian motion, the mass (and size) of dust grains should not be too large (in order that diffusion can be recorded) and not too small (to exclude possible levitation of the particles in the plasma). The particle density was $3.7\cdot10^3$ kg/m^3, the volume was $1.1\cdot10^{-13}$ m^3, and the mass was $4.28\cdot10^{-10}$ kg (from $3.2\cdot10^{-10}$ to $5.3\cdot10^{-10}$ kg).

It was established experimentally that for particles with a size of 60 μm, a medical needle with a channel diameter of (900 ± 50) μm is more appropriate because in needles of smaller diameter there is clogging of the channel, and in needles of larger diameter there is a wide spread of initial particle velocities.

Results of experiments in air at a pressure of 13.3 Pa are given below. The base of flight of dust grains from the needle to the sample stage is 100 mm. In this case, the time of free fall is about 140 msec, and the final fall velocity is 1.4 m/sec. A blowup of a dust cloud in unionized air obtained by recording with an optical scanner with a resolution of 1000 dpi is presented in Fig. 5. Figure 6 shows an image of a dust cloud scattered by a plasma at a discharge current of 0.3 A, which corresponds to an electron concentration of $5\cdot10^7$ cm^{-3} (from results of probe measurements). Visual inspection of the images showed that in all regimes, the "center of gravity" of dust clouds practically was not displaced from the vertical axis of the needle within a small statistical error, and the image shape did not change. This is probably due to the fact that under the experimental conditions, the thermal velocities of the plasma electrons and ions are higher than their directed velocities. At the same time, with increase in discharge current, the area of particle scattering increased. A quantitative dependence can be obtained by mathematical processing of the images.

After digitization of a large number of images, we calculated the dependences of the number of dust grains on the distance from the "center of gravity" of the images (Fig. 7). It can be seen that an increase in discharge current and, hence, in plasma electron concentration leads to expansion of the distribution function. The dependence of the distribution function width at half height on the discharge current is well approximated by a linear dependence with a proportionality constant of about 16 mm/A (Fig. 8).

Originally, it was suggested that the considerable scattering of the dust grains is caused by their collisions with gas molecules and ions. Furthermore, in the absence of a discharge current, scattering by ions was not observed.

The averaged force of entrainment of a dust grain for scattering by particles is $f_\alpha \sim m_\alpha n_\alpha v_{T\alpha}$ (m_α, n_α, and $v_{T\alpha}$ are the mass, concentration, and thermal velocity of a particle of sort α, respectively), and the degree of ionization of the gas is approximately equal to 10^{-6}. Therefore, in order that the force of entrainment with ions exceed the force of entrainment with neutral particles, the effective diameter of a dust grain (i.e., the scattering cross section) for scattering by ions must be about 10^7 times the real diameter, taking into account the thermal velocities of the ions. This, however, seems unrealistic because the Debye radius is estimated at about 0.1 mm, i.e., it is comparable to the dust grain size.

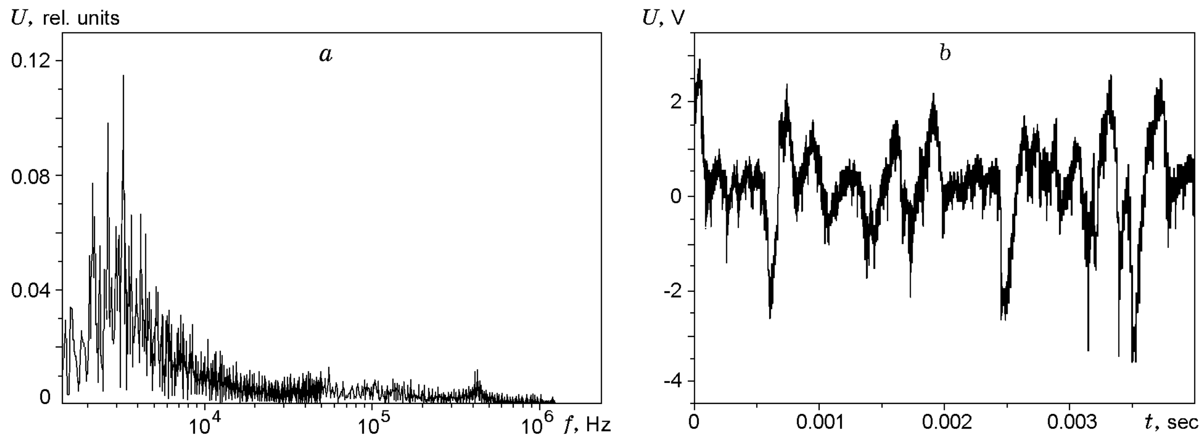

Fig. 9. Typical spectrum of collective oscillations of plasma (a) and a fragment of the record of plasma oscillations (b).

At this stage, the assumption of scattering by neutral particles and ions was rejected. We also considered the other explanations: dust grains, charged during flight through the plasma, impart a considerable electric charge to the recording adhesive film, which hinders further deposition of the particles and leads to their scattering with approach to the film. To verify this hypothesis, we performed experiments with injection of about 10^4 dust grains. It is established that the scattering process does not depend on the amount of dust grains, and, hence, the hypothesis on scattering by the charged film also was rejected. The close relative position of some dust grains in Fig. 6 confirms the aforesaid.

We also considered a different mechanism of scattering of dust grains. It was assumed that the original scattering of dust grains is caused by irregular filling of the needle with dust grains and their motion along the needle after piercing of the stopper, when they moved in contact with each other and with the inner walls of the needle. After the particles came out of the needle, the distances between them increase, collisions ceased, and marked scattering by neutrals did not occur. The increased scattering of dust grains in the plasma is caused by interaction of charged dust grains with collective oscillations of the plasma. To verify this assumption, we performed the following control test: dust grains were injected in an unionized gas at a pressure of 13.3, 133, and $1.33 \cdot 10^4$ Pa. In these experiments, no difference in the amount of scattering was revealed. This suggests that the scattering by neutrals is insignificant, and with allowance for the above-mentioned estimates, the scattering by ions is also small.

Thus, because during the residence time in the plasma, dust grains acquire a considerable charge [according to evaluations by the procedure of [5], the charge is $8 \cdot 10^{-14}$ C and the charging time (about 0.5 msec) is much smaller than the time of their flight], the dynamics of particles should be influenced by collective oscillations of the plasma. The collective oscillations of the plasma were recorded using a single probe, which was placed at the center of the vertical cylindrical cavity of the vacuum gas-discharge chamber. For recording, the probe was connected to a device with output to a "Tektronix TDS 3054" digital memory oscillograph. Probe signals were recorded at various scans and, hence, at various time steps of discretization. The signals were processed using the fast Fourier transform algorithm. A typical spectrum of a signal thus obtained is shown in Fig. 9. It contains two oscillation regions: oscillations in the range of 2–5 kHz due to irregular ionization pulsations related to the strata (i.e., ionization turbulence described in [6]) and oscillations with a frequency of about 400 kHz, which corresponds to ion-sound oscillations. Since the indicated types of oscillations differ markedly in frequency (the amount of scattering is inversely proportional to the squared frequency) and the inertia of dust grains is rather high, it is concluded that the major contribution to the scattering of the dust grains is from irregular ionization pulsations.

Since the scattering of dust grains during motion in the injector needle and the scattering by plasma oscillations are statistically independent (because they occur on different segments of motion), the amount of scattering is additive in these factors. Hence, the difference in width between the distribution functions in the plasma and the unionized gas determines the contribution of the scattering in the plasma. From results of these evaluations taking into account the calculated charge of a dust grains, we can estimate the electric field amplitude in the ionization pulsations. It is several kilovolts per centimeter at a discharge current of 0.5 A, typical of conditions of the present experiments.

Thus, the regularities of Brownian scattering of dust grains in a plasma by collective oscillations of the plasma were determined using the designed discharge chamber with an injector of dust grains fitted with instruments for recording images of a dust cloud. As far as we are aware, scattering of dust grains by collective oscillations of a plasma was observed in our laboratory experiments for the first time. We are grateful to P. Schram (Eindhoven Technological University, Netherlands) for critical remarks, which improved the paper.

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