Study of a Transportation Process of Dust Particles in the Plasma of Radio Frequency Discharge

Didar Batryshev, Yerassyl Yerlanuly, Maratbek Gabdullin, and Tlekkabul Ramazanov

***Abstract*— This paper presents the results of studies of dust formations in a radio frequency (RF) discharge plasma. In particular, the behavior of dust clouds in various types of traps was investigated. The experiments were carried out in argon plasma with the following discharge parameters: gas pressure of 0.02–0.6 Torr and discharge power of 1–50 W. Two types of the ring were used as a trap—"closed" and "nonclosed." It was found that by changing the discharge parameters and using a different type of trap, it is possible to control the capture region of dust formations, and therefore, manipulate the extraction of dust particles by mass (size, in the case of monodispersity of particles). It has been observed that at a lower gas pressure the dust cloud is less affected by the traps; moreover, the wider the edge opening of "nonclosed" ring trap, the more efficient the process of extracting dust particles. The results of this paper can be useful for practical application in the processes of separation and extraction of dust particles from a plasma crystal, the study of particle interactions, and the manipulation of individual particles, etc.**

***Index Terms*— Dusty plasma, extraction, radio frequency (RF) discharge, separation.**

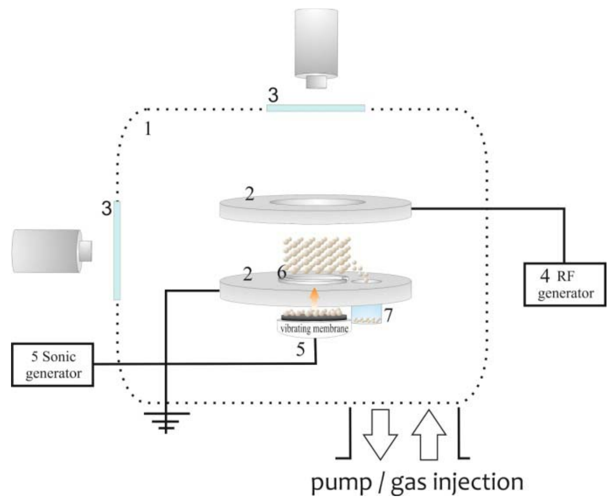

Fig. 1. Scheme of the experimental setup for investigation of the dust structure behavior.

I. Introduction

PLASMA with dust grains (a solid matter of micrometer size) is widely distributed in nature (planetary rings, comet tails, interstellar clouds) and has a practical application in technologies of microelectronics, alternative energy, etc. Today's interest in dusty plasmas is primarily associated with the processes of self-organization and the formation of ordered dust structures (cloud), the so-called *plasma crystals*. Usually, in laboratory conditions, to obtain such structures, various methods are used, such as plasma enhanced chemical vapor deposition [1], mechanical injection [2], magnetron sputtering [3], etc. But in some cases, a dust structure can be randomly formed under the influence of erosion of the plasma reactor elements by heating or radiation, for example, in the interaction process of charged particles with the walls of the reactor in International Thermonuclear Experimental Reactor [4]. Such structures may have both negative and positive effects. In the 1990s, dust formation [5], [6] in the plasma was intensively studied in order to eliminate its negative effect on the production of semiconductor devices during plasma deposition and etching processes. Today, the study of the plasma crystal is closely related not only to the solution of the fundamental problems of plasma physics, but also to the problems of astrophysics [7], [8], nanotechnology [9], materials science [10], and energy [4]. One of these problems is the dust contamination in the controlled fusion devices, and one of the solutions is the extraction of solid microparticles from the plasma medium [11] and their collection. There are a lot of works [12]–[16] devoted to the study of levitation, movement, and phase separation of micro-objects (microparticles, micro-organisms, etc.) in the plasma of gas discharges. In this paper, we present the results of the investigation of the dust cloud behavior in different traps in the plasma of radio frequency (RF) discharge, which can be useful in the solution of the dust contamination problems, dust particle, or cloud manipulations, etc.

Manuscript received September 29, 2018; revised February 6, 2019 and April 25, 2019; accepted June 18, 2019. Date of publication July 12, 2019; date of current version August 9, 2019. This work was supported by Kazakhstan Ministry of Education and Science (2018–2020) under Grant BR05236730. The review of this paper was arranged by Senior Editor T. Hyde. *(Corresponding author: Didar Batryshev.)*

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Digital Object Identifier 10.1109/TPS.2019.2925907

II. Experiment

The experiments were carried out in a setup, the structure of which is shown in Fig. 1. The working chamber consists of two parallel disk electrodes (2); the upper one is RF and the bottom is grounded electrode, side windows (3) for laser illumination (532 nm, 1–220 mW) and visualization of a dust cloud, an RF generator (13.56 MHz) with a matching box (4) for plasma ignition, a sonic generator (5) (1 Hz–1 MHz) for mechanical injection of microparticles (1–100 μm) into the plasma medium, a ring trap (6) for radial capture of the dust cloud, and a container (7) under the bottom electrode for collecting extracted microparticles.

In our previous work [17], we described a separation process of polydisperse microparticles and nanoparticles in the plasma of RF discharge. As a result, a new method of extraction of small dispersed dust particles by mass using a nonclosed ring trap and the so-called *electrical trap* has been developed. In this paper, we tried to understand the dust cloud behavior in different trap types in RF plasma by a discussion of the transportation process of dust particles and considering the screening effect.

Experiments were carried out in the RF discharge of argon (Ar) gas with the following parameters: pressure of 0.02–0.6 Torr, RF power of 1–50 W. The hole in the center of the lower grounded electrode was covered with an iron mesh, which served as a part of the electrode and above it a ring trap was pasted for capture of a dust cloud. Two types of traps were used—“closed” and “nonclosed.” One of these rings (nonclosed) has a cut with different sizes (2.5, 5, and 7.5 mm); the second ring is continuous (closed). The diameter and height of all the rings are the same 5 cm and 5 mm, respectively.

After the generation of RF plasma, polydisperse microparticles were injected by a sonic generator to form a dust cloud (Fig. 1). It is known that microparticles in RF plasma levitate due to the balance of two main forces—gravitation and electrostatic. By changing the impact of second force by modifying equipotential surfaces in the RF plasma near the bottom electrode it is possible to manipulate the microparticles in the dust cloud. The process of extraction of small-dispersed microparticles is described in detail in [17]. The collection of extracted microparticles was carried out through the open part of the nonclosed ring in a container (7) under the bottom electrode.

Fig. 2 shows a simple case of extraction of all levitated microparticles into the container. The schematic illustration of this simple case is shown in Fig. 3, where it is seen that the open ring weakens the capture area of the dust cloud and forms a “channel” for extraction and collection of microparticles. However, in some cases, another phenomenon takes place, when a barrier appears and prevents extraction (Fig. 4). And it does not matter what kind of rings were used, whether closed or nonclosed.

To study the appearance and disappearance of the barrier, further experiments were conducted to investigate the behavior of a dust cloud using closed and nonclosed rings at various values of the discharge power. In experiments to study the dynamics of dust particles, the value of the discharge power varied in the range from 1 to 50 W with a step of 5 W, in two directions (with gradual increase and decrease).

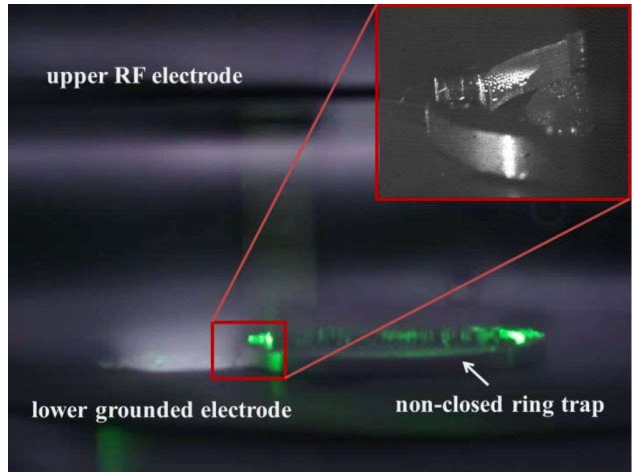

Fig. 2. Extraction process of levitated microparticles from the dust cloud. Red square: flow of microparticles falling down into the container.

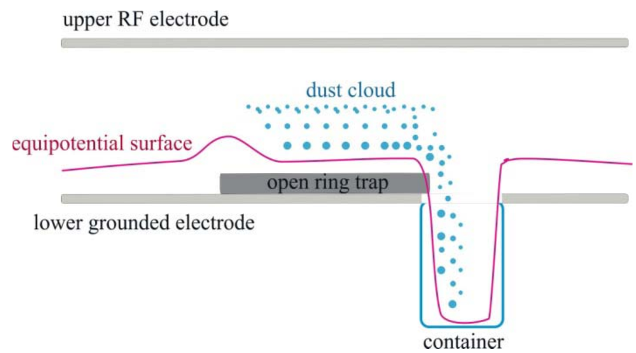

Fig. 3. Distribution of the equipotential surface in the RF plasma near the bottom electrode.

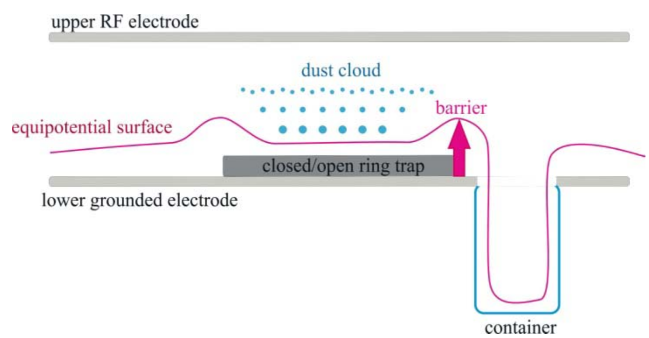

Fig. 4. Formation of a barrier, which prohibits the extraction process.

III. Results and Discussion

The results of investigation of the barrier appearance and disappearance at different discharge parameters and types of traps are presented in Table I.

It is seen that the extraction process occurs “+” in all the range of RF power and gas pressure values and in the case when the nonclosed ring trap with the edge opening of 7.5 mm is used. This process is similar to that shown in Fig. 3. However, in the case of using the nonclosed rings with edge openings of 2.5 and 5 mm, a barrier appears with increasing gas pressure. This case is similar to that shown

TABLE I
INVESTIGATION OF BARRIER APPEARANCE AND DISAPPEARANCE IN THE MICROPARTICLE EXTRACTION PROCESS

Trap	Size of edge opening, mm		Pressure, Torr					
			0.02	0.04	0.06	0.1	0.3	0.6
			"+" and "-"means disappearance and appearance of a barrier, "↑" and "↓" means gradual power increase and decrease in range 1 - 50 W					
Ring	non-closed/ open	2.5	↑+ ↓+	↑+ ↓+	↑+ ↓-	↑- ↓-	↑- ↓-	↑- ↓-
		5	↑+ ↓+	↑+ ↓+	↑+ ↓+	↑+ ↓+	↑- ↓-	↑- ↓-
		7.5	↑+ ↓+	↑+ ↓+	↑+ ↓+	↑+ ↓+	↑+ ↓+	↑+ ↓+
	closed	0	↑+ ↓+	↑+ ↓+	↑- ↓-	↑- ↓-	↑- ↓-	↑- ↓-
Plasma sheath length			~ 1.2 cm	~ 1 cm	~ 8 mm	~ 5 mm	~ 4 mm	~ 3 mm

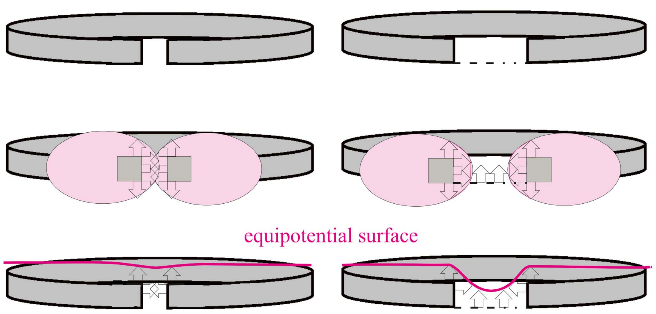

Fig. 5. Difference between the electric fields of two different open ring traps at the same value of RF power. Arrows: plasma sheath length (characteristic screening length of the ring field).

in Fig. 4, and the possible explanation for this is the overlap of the electric fields (Fig. 5) created by the edges of the ring, thereby forming a barrier to the process of extracting microparticles. The question then arises: why there are no barriers at lower values of gas pressure in the case of using closed and nonclosed (2.5 and 5 mm) ring traps? The answer to the question is increasing the role of horizontal separation in the dust cloud, which means that the lighter microparticles are located in the higher flat equipotential surface in the RF plasma. Fig. 6 shows the distribution of the lower equipotential surface in the RF plasma. It is seen how the lighter dust particles easily escape the closed ring. In this case, the barrier height is lower than the location of the lightest microparticles.

To understand the processes shown in Fig. 5 better, we will consider the screening effect. For a point charge, the screening length is given by the known Debye length (radius). For the considered gas discharge, with drastically different temperatures of electrons and ions, the Debye lengths of electrons and ions are several hundreds of micrometers and about 100 μm, respectively. For determining the screening length of the ring

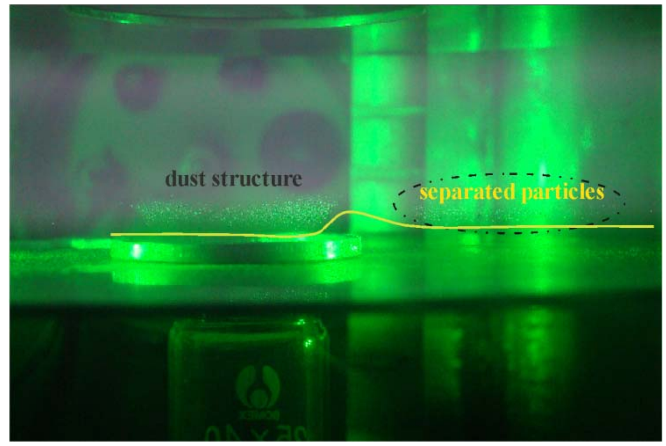

Fig. 6. Extraction of microparticles at the pressure of 0.04 Torr using a closed ring trap. Yellow line: distribution of the lower equipotential surface in RF plasma.

field, for which the pointlike test charge screening model is not applicable, the characteristic screening length could be evaluated experimentally by observing the plasma sheath length. Indeed, the ring trap is a charge absorbing macroscopic material (metal), as an RF electrode. The sheath length at different gas pressures was experimentally estimated as the distance between the surface of the bottom RF electrode and the location of the lowest levitating dust particles. Its values are presented in Table I. It is seen that a decrease in the gas pressure leads to an increase in the sheath length (i.e., characteristic screening length of the ring field) and, conversely, the sheath length decreases with an increase in the gas pressure [17]. Therefore, at a lower gas pressure, the lighter dust particles in the dust cloud are located at a farther distance from the ring. It is clear that at farther distances the nonmonotonicity due to the presence of the ring is smoothed out. It means that at a lower gas pressure, lighter dust particles are less affected by the ring trap, and the extraction process proceeds, as shown in Fig. 6. Similarly, the impact of a small edge opening of the ring trap on the extraction process depends upon the screening length at the given discharge parameters (pressure). If the opening length is smaller or equal than the screening length, the edge opening does not affect the dust particles and vice versa.

So to put it another way, the occurrence of the potential barrier can be explained as follows. The barrier is due to the charge space that follows the shape of the electrode and the trapping ring. If the RF power is increased the electron density increases, and thus, the sheath width decreases and the barrier height decreases too. In the case of a partly open ring trap, the potential barrier occurs (stopping the extraction process) if the opening length is smaller or equal than the screening length [Fig. 5 (left)]; moreover, the barrier height decreases if the opening length becomes longer, and in this case, the barrier height equals the plasma sheath length and occurs only due to the bottom electrode shape [Fig. 5 (right)]. Thus, by tuning the RF power and/or the pressure, it is possible to adjust the width of the sheath in order to release the smaller (lightest) particles that are located on the top of the polydisperse dust particle cloud.

IV. Conclusion

In this paper, the dust cloud behavior and its manipulation in different trap types in the plasma of RF discharge were considered. The obtained results show that the extraction process of microparticles from dust cloud depends not only on the types of trap but also on the discharge parameters. It has been observed that at a lower gas pressure, the dust cloud is less affected by the trap; moreover, the wider the edge opening of "nonclosed" ring trap, the more efficient the process of extracting the dust particles. However, in some cases, a barrier appears and prevents the extraction of microparticles even in the case of using a nonclosed ring trap and vice versa. Thus, this paper presents the results of the experimental studies of the causes of the appearance and disappearance of the barrier preventing the process of microparticles extraction, and also gives some explanations based on the consideration of the screening effect. The obtained results can be useful in the solution of the dust contamination problems, dust particle, or cloud manipulations, etc.

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