УДК 537.52
МРНТИ 29.27.07
https://doi.org/10.55452/1998-6688-2023-20-1-38-44

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INVESTIGATION OF THE PROPERTIES OF MICROPARTICLES IN THE GLOW DISCHARGE STRATUM IN A CROSSED ELECTRIC AND MAGNETIC FIELD

Abstract. In this work, the behavior of charged micron-sized particles in the DC glow discharge stratum at low pressure in a crossed magnetic and electric field was experimentally studied. The experiment was conducted in a vertically oriented gas-discharge glass tube. A homogeneous magnetic field was created using a two-section Helmholtz coil. The results showed that the micron-sized dust particles move in the opposite direction to the ExB drift as the magnetic field induction increases. Once the induction reaches a specific threshold (B>10 mT), the dust particles start rotating and forming counter-rotating vortex pairs on the horizontal plane. Moreover, it was observed that the shape of the dust structures changes from a disk to an ellipsoid. The PIV (particle image velocimetry) method was employed to analyze the dust vortices' dynamic behavior, and the generation of the co-vortex rotation was explained through the dust particles' charge gradient, which was orthogonal to the ion drag force.

Key words: glow discharge, magnetic field, complex plasma.

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АЙҚАСҚАН ЭЛЕКТР ЖӘНЕ МАГНИТ ӨРІСТЕГІ СОЛҒЫН РАЗРЯДТАҒЫ МИКРОБӨЛШЕКТЕРДІҢ ҚАСИЕТТЕРІН ЗЕРТТЕУ

Аңдатпа. Бұл жұмыста айқасқан магнит және электр өрісіндегі төмен қысымдағы тұрақты токты жарқыл разрядының стратасындағы микрон өлшемдегі зарядталған бөлшектердің қозғалысы эксперименттi түрде зерттелінді. Эксперимент вертикальды бағыттағы разрядтық шыны түтікшеде жасалынды. Біртекті магнит өрісі екі секциялы Гельмгольц катушкасының көмегімен туындайды. Магнит өрісінің индукциясы артқан кезде микронды өлшемді тозаңды бөлшектер ExB дрейфіне қарама-қарсы бағытта қозғалатыны байқалды. Магнит өрісінің индукциясы белгілі бір шекті мәнге жеткенде (B>10 мТл) тозаңды бөлшектері айналмалы қозғалысқа ие болатыны және көлденең жазықтықта бір-біріне қарма-қарсы бағытталған құйынды жұптар түзілетіні байқалды. Сондай-ақ тозаңды құрылымдардың пішіні дискіден эллипсоидқа дейін өзгеретіні байқалды. Тозаңды құйындарының динамикалық қасиетін зерттеу үшін PIV (particle image velocimetry) әдісі қолданылды. Құйынның бір-біріне қарама-қарсы айналуының себебі иондық елірту күшіне ортогональды тозаңды бөлшектер зарядының градиентімен түсіндірілді.

Тірек сөздер: жарқыл разряд, магнит өрісі, комплексті плазма.

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ИССЛЕДОВАНИЕ СВОЙСТВ МИКРОЧАСТИЦ В СТРАТЕ ТЛЕЮЩЕГО РАЗРЯДА В СКРЕЩЕННОМ ЭЛЕКТРИЧЕСКОМ И МАГНИТНОМ ПОЛЕ

Аннотация. В данной работе экспериментально исследовано поведение заряженных пылевых частиц микронного размера в страте тлеющего разряда постоянного тока при низком давлении в скрещенном магнитном и электрическом поле. Эксперимент проводился в вертикально ориентированной газоразрядной стеклянной трубке. Однородное магнитное поле создавалось с помощью двухсекционной катушки Гельмгольца. Результаты показали, что с увеличением индукции магнитного поля пылевые частицы микронного размера движутся в направлении, противоположном дрейфу ExB. При достижении индукцией порогового значения (B>10 мТл) пылевые частицы начинают вращаться и формировать противовращающиеся вихревые пары в горизонтальной плоскости. Также было замечено, что форма пылевых структур меняется от диска до эллипсоида. Для анализа динамического поведения пылевых вихрей был использован метод PIV (particle image velocimetry), и возникновение сонаправленного вращения вихрей было объяснено градиентом заряда пылевых частиц, который ортогонален силе ионного сопротивления.

Ключевые слова: тлеющий разряд, магнитное поле, комплексная плазма.

Introduction

Dusty plasma refers to a type of plasma that contains electrically charged micro- and/or nanoparticles, known as dust particles, alongside neutral atoms, electrons, and ions. These dust particles can either enter the plasma from outside or be generated within it through internal processes. Compared to traditional electron-ion plasmas, dusty plasmas display several unique and peculiar characteristics, such as strong coupling [1], dust acoustic waves [2], and instabilities due to ion flux [3]. Furthermore, dusty plasma deviates from the shielded Coulomb interaction [4], making it a fascinating subject for fundamental research in plasma physics. Additionally, the significance of dusty plasma research extends to practical applications such as plasma etching, sputtering technologies in microelectronics, and the production of films and nanoparticles [5-6]. A crucial task for both fundamental research and practical applications in dusty plasma is to regulate the dynamics of dust particles through methods such as the use of external electric fields [7], laser manipulation[8], and magnetic fields[9-10]. In particular, magnetic fields are employed to control the spatial position, degree of ordering, and motion of plasma-dust structures.

There is significant interest in studying the behavior of dust particles under the influence of crossed electric and magnetic fields [11-12]. This is particularly relevant for advanced experimental facilities, such as magnetrons and ion engines for future rockets, which heavily rely on such configurations [13]. When electric and magnetic fields are crossed, an ExB drift velocity perpendicular to both fields arises, imparting additional momentum to charged particles including dust particles. The ExB drift is exploited for removing silicon particles from large-area homogeneous hydrogenated amorphous silicon films. The efficiency of silicon dust removal is directly proportional to the strength of the external magnetic field [14].

Main provisions

For the first time, rotating dust vortices in a glow discharge stratum were observed.

Materials and Methods (Experimental Part)

To study the properties of microparticles, an experimental setup based on a glow discharge was developed. In a vertically oriented discharge tube with a diameter of 3 cm, glow discharge plasma is ignited in the interelectrode space of 60 cm. The following experimental parameters were chosen as optimal: argon gas pressure of 0.36 torr and discharge current of 1.44 mA. A two-section Helmholtz coil, the axis of which is perpendicular to the discharge axis, is used as a magnetic field source. The schematic diagram of the experimental setup is shown in Figure 1.

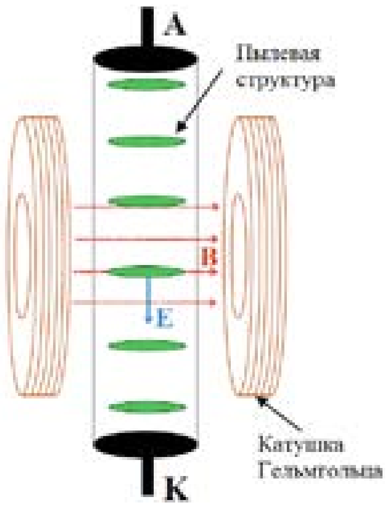
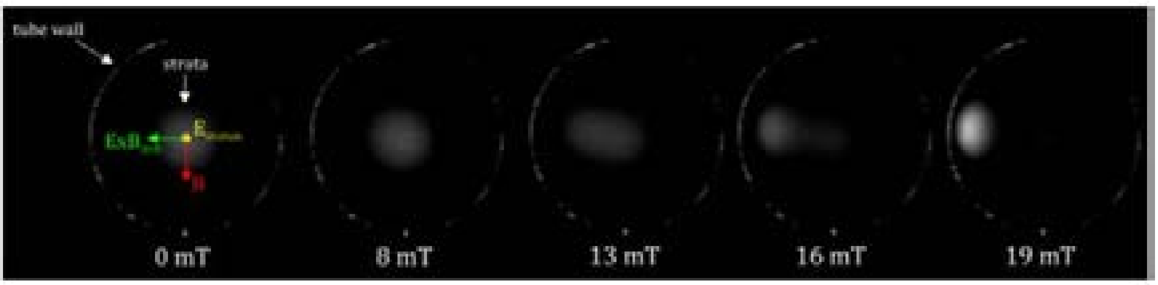
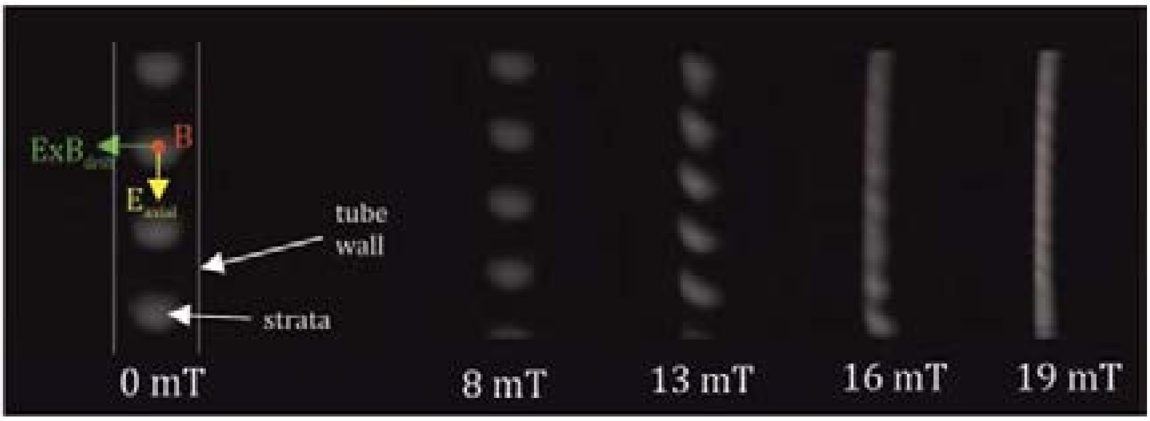


Figure 1 – Schematic diagram of the experimental setup. Anode denoted as "A" and the cathode as "K". Arrows are used to indicate the force lines of both the axial electric field and the magnetic field.

Monodisperse micron-sized dust particles of melamine-formaldehyde are initially inside the tube and fall downwards during injection with subsequent formation of a dust structure in the glow discharge stratum. It should be noted that the electric field in the stratum is sufficient to compensate the gravitational force acting on the dust particles. A Phywe Hall sensor was used to measure the distribution of magnetic field induction. It was found to be uniformly distributed in the area where the dust particles were being studied. To observe the dynamics of the dust particles, a solid-state laser was used to illuminate them, and their movements were recorded using a video camera. Before examining the behavior of the micron particles levitating in the plasma, let us first focus on the dynamics of the plasma itself, specifically the stratum in which the particles are suspended (Figure2).



(a) In the horizontal plane, the view is from the top.



(b) In the vertical plane, the view is from the side.

Figure 2 – Illustration of the glow discharge stratum in the presence of crossed electric and magnetic fields.

Once the magnetic field is activated, there is a shift in the spatial position of the stratum that traps the dust particles, indicating a change in the path of charged particles in the presence of crossed electric and magnetic fields. The magnetic field exerts a force across the axial electric field, causing plasma particles to move perpendicularly to both forces. This causes electrons and ions to drift in the direction of the ExB drift. A clearer visualization of this process can be seen in Figure 3

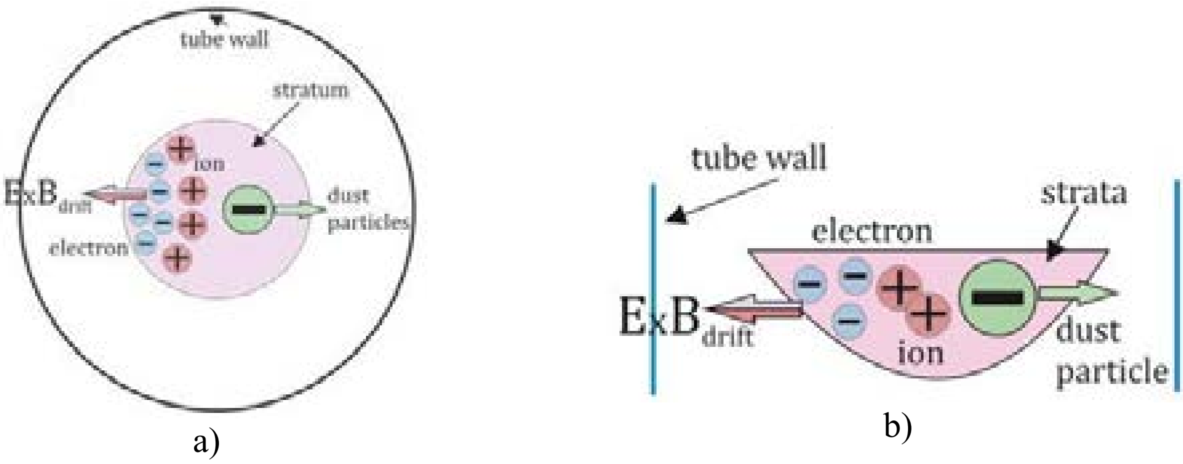
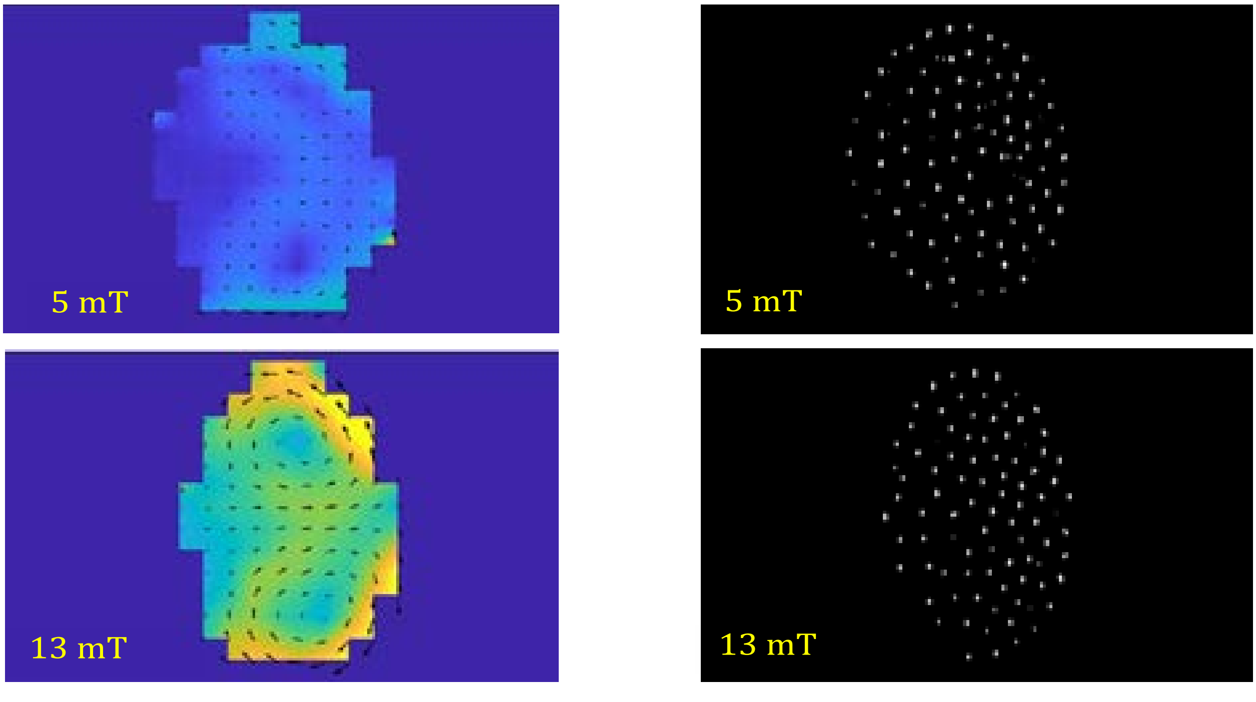
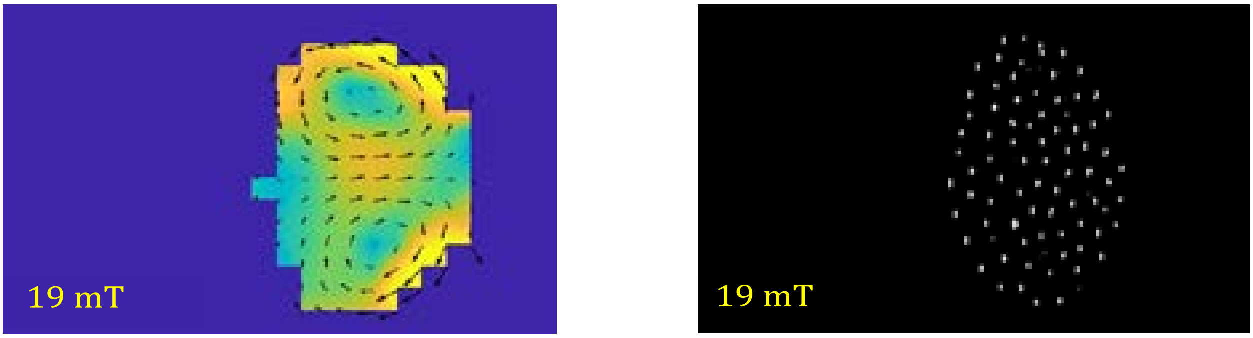


Figure 3 – Graphic representation of drift of charged particles in a crossed field a) horizontal plane b) vertical plane

Changing the trajectory of charged particles in a crossed field leads to a modification of the dust particle dynamics in the glow discharge stratum. At first, the dust particles form a disc-shaped crystal structure. However, when the magnetic field is turned on, they start moving in the direction opposite to the drift. This type of behavior of nanoparticles has been observed previously in electron resonance plasma with gas SiH4. When the magnetic field induction in the dust structure reaches about 5 mT, the vortex motion of dust particles begins, where rotational motions are observed opposite to each other (clockwise (vortex 1) and counterclockwise (vortex 2)), as shown in Figure 4.To analyze the rotational characteristics, such as the linear velocity of the dust vortices, the PIV (particle image velocimetry) method was used.

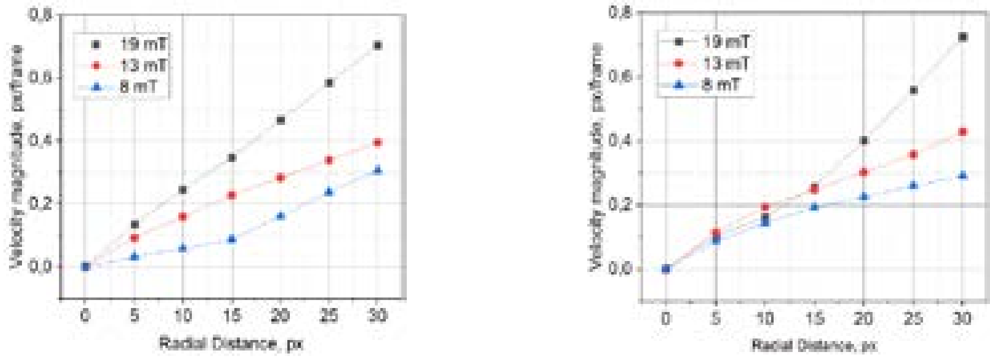




– Dust vortices in the glow discharge stratum. The direction of dust vortices is s

Figure 4 – Dust vortices in the glow discharge stratum. The direction of dust vortices is shown by an arrow.
a) Processed frames using the PIV method b) Original frames

The PIV method was utilized to automatically determine the linear velocity of rotating particles based on the velocity map presented in Figure 4, for discharge current values of 1.4 mA. The velocity map indicates that the dust particles located in the peripheral region of the discharge layer exhibit higher velocity than those closer to the center, which is consistent with the vortex characteristics. Figure 5 illustrates the relationship between the linear velocity of rotating vortices along the radius at various magnetic field inductions at 1.4 mA. It can be observed that the velocity of the vortices increases with an increase in magnetic field induction.



a) Vortex I b) Vortex II

Figure 5 – The dependence of linear velocities of dust particles in vortices on radial distance

Results and Discussion

Studying the behavior of dust particles suspended in the glow discharge stratum proved to be an intriguing subject. Upon activation of the transverse magnetic field, various types of dust particle movement can be observed. It has been noted that for B<10 mT, charged particles such as electrons and ions undergo migration towards the electric drift. The presence of charge causes heavy micron particles to be expelled in the opposite direction. As illustrated in the schematic diagram, Figure 6 provides evidence of the formation of rotating vortices originating from two sources. By superimposing two frames (first frame at 0 mT and second frame at 8 mT), it becomes clear how the plasma (comprised of ions and electrons) and charged dust particles move in opposite directions upon activation of the magnetic field. This phenomenon is driven by two mechanisms: ion drag force and charge gradient. Upon reaching the critical point where B>10 mT, rotating vortices can be observed rotating in the opposite direction. The schematic diagram in Figure 6 illustrates the direction of the force, which is perpendicular to the direction of the transverse magnetic field generated by the coil. This causes the dust vortices to rotate in different directions, which was observed during the experiment. Therefore, it is anticipated that dust particles would rotate co-directionally in the horizontal plane. Similar behavior has been observed in a strong magnetic field in the RF discharge, and previous studies have reported that the rotation of vortices could be attributed to the charge gradient of microparticles, even in the absence of a magnetic field [16-18].

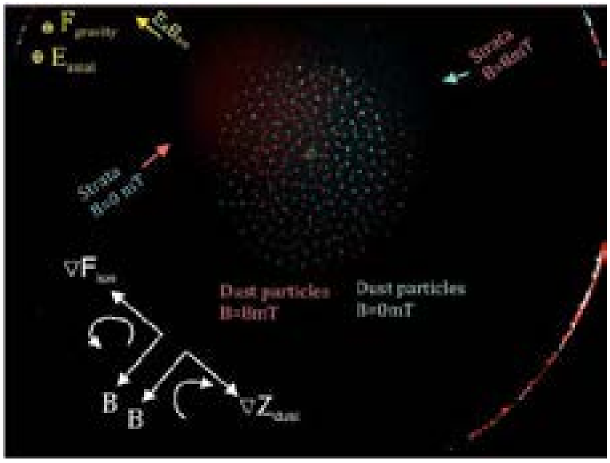


Figure 6 – Two primary mechanisms are responsible for the rotation of dust vortices.

Conclusion

In summary, in the experiment, the co-rotational motion of dust vortices in the glow discharge stratum was recorded in ExB field configuration. The rotational properties were studied using the PIV method, and two different mechanisms were identified. The orthogonal alignment of the magnetic field direction with ion and charge gradients created dust vortices rotating in opposite directions from each other in the horizontal plane. Further theoretical calculations will be necessary to provide a more detailed qualitative analysis, and this will be a focus of future research.

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