Technical Physics Letters, 2024, Vol. 50, No. 8

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Dusty Plasmas in radio frequency Induction discharge in Magnetic Field

© M.S. Golubev, E.S. Dzlieva, V.Yu. Karasev, L.A. Novikov, S.I. Pavlov, I.C. Mashek

St. Petersburg State University, St. Petersburg, Russia
E-mail: maksider@yandex.ru, v.karasev@spbu.ru

Received April 10, 2024
Revised April 27, 2024
Accepted April 27, 2024

In the paper a dusty plasmas in RF induction discharge in magnetic field is investigated for the first time. In range of magnetic induction up to 0.02 T dusty plasma becomes steadily rotating. Angular velocity vector of the structure is directed opposite to the magnetic induction vector. Dependences of the speed of rotation of the structure and the average horizontal interparticle distance on the magnitude of the magnetic field were obtained. The direction of rotation, the resulting linear dependence on magnetic induction and the coincidence with theoretical estimate of the angular velocity of rotation indicate the action of the mechanism of ion drag force on the dust particles under experimental conditions.

Keywords: dusty plasma, magnetic field, RF discharge.

DOI: 10.61011/TPL.2024.08.58919.19950

Dusty plasma in the form of bulk dust structures in a magnetic field is a complex object for experimental study. Only a few papers [2,3] have been published in the five years since three-dimensional dust structures were observed in fields up to 2 T [1], and almost all of them are focused on experiments in a dust trap inside a discharge insert where an extended dust structure cannot be obtained. Monolayer dust structures are usually examined in studies in a magnetic field [4–7], and a radio-frequency (RF) capacitive discharge is used to avoid field instabilities. Instabilities arising in the magnetic field [8] are the primary source of problems in production of bulk dust structures in a DC discharge. For example, the discharge became asymmetric and the dust trap degraded in [2] in a field of 0.4−0.6 T, and levitation of dust particles was not observed in [9] in magnetic fields above 0.5 T. One possible solution to the problem of formation of stable dust structures is the use of a radio-frequency induction (RFI) discharge.

An RFI discharge was used to create dusty plasma in experiments [10,11], where dust structures of particles smaller than 4 μm were levitated in a vertical tube with a diameter sufficiently large for dusty plasma (4 cm). Individual lightweight (hollow) dust particles with a diameter of 10 μm have been observed earlier in a narrow (on the order of 1 cm) discharge chamber in a magnetic field directed across the inductor axis [12]. Thus, specific conditions in regard both to the discharge and chamber geometry and to the parameters of powder for plasma need to be established in order to produce dusty plasma in a magnetic field under an RFI discharge.

The aim and application of the present research is the development of a volumetric dust trap that is stable in a strong magnetic field. The following issues are tackled successively: production of bulk dust structures at the diffuse edge of a plasmoid in an RFI discharge; selection of the optimum conditions for stabilization of dusty plasma in a magnetic field on the order of the electron magnetization; and monitoring of its rotation velocity, size, and interparticle distance as functions of the magnitude and direction of the magnetic induction vector. The observed dynamics is compared with estimates based on the forces acting on a dust particle with the use of literature data on RFI discharges.

In accordance with experiments [10–12], an electrodeless discharge tube with a variable cross section was designed in order to optimize the discharge conditions. The total length of the tube was 60 cm; its upper half had a cross section with a diameter of 2.6 cm, the lower half was 2.2 cm in diameter, and the thickness of the glass wall was 1.5 mm. Two vacuum valves were soldered to the top of the tube. The working gas was pumped out and in through the first valve, and dust particles were supplied (from a container with bulk powder and a mesh bottom) through the second one. The lower part of the tube passed freely into the coils producing the magnetic field. The coils were spaced 7 cm apart, which made it possible to position the inductor at a chosen section of the tube and perform video monitoring of the discharge and the process of dust structure formation with lateral laser illumination. The RF inductor consisted of two turns of litz wire (21×0.07) wound tightly on a tube at a distance of 12 mm (one turn at each RF generator output). The generator was constructed based on a GU-29 lamp in a multivibrator circuit with two outputs with a common point. UIP-1 was the power source for the generator. The discharge tube was evacuated to a pressure of 10^{-4} Torr and subjected to long-term annealing with an RF discharge in neon. The following conditions were set in experiments on generation of dusty plasma: neon was the working gas, the pressure was ~ 0.3 Torr, the generator frequency was 40 MHz, and the UIP voltage and current were $U = 100-300$ V and $I = 40-100$ mA,

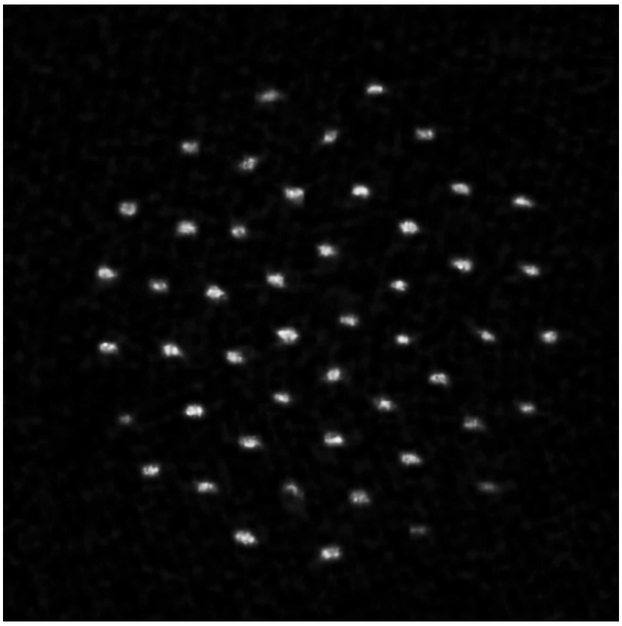

Figure 1. Photographic image of a horizontal section of the dust structure. The conditions are as follows: neon is the working gas, the pressure is 0.33 Torr, melamine formaldehyde particles $2\,\mu$m in diameter are used, $B = 18$ mT, and the image width is 2.7 mm.

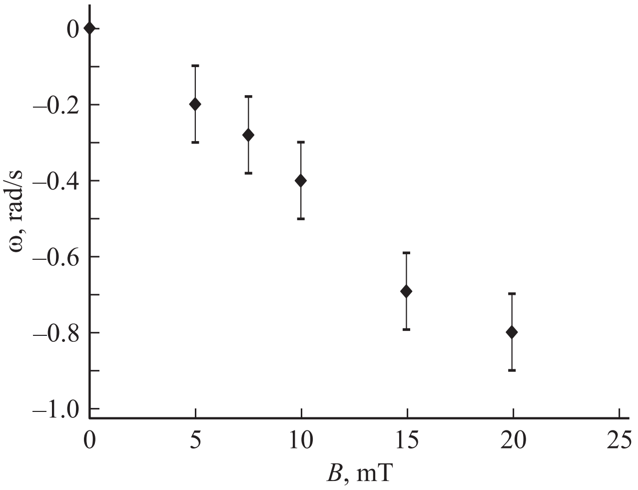

Figure 2. Dependence of the angular rotation velocity of the central section of the dust structure on magnetic induction. The conditions are the same as in Fig. 1.

respectively. According to our estimates, the power input into the discharge was no greater than 0.4 W.

In preliminary experiments in zero magnetic field, calibrated spherical melamine formaldehyde particles $5\,\mu$m in size with a density of $1.5\,\mathrm{g/cm^3}$ were used. Levitation of particles was not observed when a discharge was initiated in the upper (wide) part of the tube. A single dust chain was found in the lower (narrow) part of the tube. Dust particles were then replaced by smaller particles ($d = 2.05 \pm 0.05\,\mu$m) of the same density. Under the same conditions (source voltage $U = 100$ V and a source current of 80 mA), a single dust chain in the upper part of the tube and a narrow dust structure in the lower part were observed. This dust structure was examined experimentally in a longitudinal magnetic field under the specified conditions.

It was positioned in a uniform magnetic field between coils. The rotation velocity was measured in the middle horizontal section of the dust structure, which contained at least two shells, in order to avoid threshold effects [13]. The magnetic field was limited to 0.02 T, which corresponds to the magnetization of electron component $\omega_e \tau_e = 3$, where ω_e is the cyclic frequency and τ_e is the time interval between electron collisions. This exceeds the rotation inversion magnetic field for bulk dust structures in a neon glow discharge, allowing one to make a comparison with a dust trap in a glow discharge [1,3].

The produced dust structure was three-dimensional under the indicated conditions. It contained up to 30 particles in its horizontal cross section. Its length in the vertical direction was close to 3 mm (i.e., 10−12 dust layers). The dust cloud was in a liquid non-filamentary state. The photographic image of a typical horizontal section is shown in Fig. 1. In a magnetic field, the dust structure began to rotate with a negative projection of angular velocity onto the magnetic induction vector. The bottom part of the structure rotated slower than the rest of it. The central section of the structure was illuminated by a horizontal laser plane and imaged with a video camera from above. Figures 2 and 3 show the dependences of the angular rotation velocity of the chosen section and the horizontal interparticle distance, respectively, on magnetic induction.

The following features of the obtained data are worth noting. Dusty plasma formed easily and remained stable within the specified magnetic field range. The electrostatic, gravity, and ion drag forces specify the vertical balance of forces acting on a particle. The dependence of the angular velocity on magnetic induction turned out to be linear; in its direction and trend, it indicates that the magnetic field acts through ion drag [14]. With axial and radial gradients of plasma density and electron temperature present, an alternative rotation mechanism associated with vortex flows of electrons in a magnetic field [15–17], which induces rotation in the opposite direction, could be activated, but it did not manifest itself. Notably, no deviations from the linear dependence were observed in the region of velocity inversion under glow discharge conditions (in a field of about 0.005 T) [1,2].

The quantitative interpretation relies on the assumption of stationary rotation of dust particles under the influence of ion drag and the Epstein drag force of rarefied gas (when the mean free path of a gas particle exceeds the size of a dust particle). The angular rotation velocity of a dust particle depends linearly on magnetic field and is specified

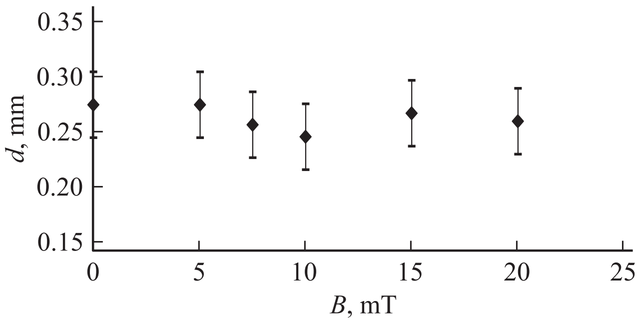

Figure 3. Dependence of the horizontal interparticle distance on magnetic induction. The conditions are the same as in Fig. 1.

by the following expression:

$$\omega = \frac{en_i v_{Tn} v_{Ti} \tau_i U_{ir} B \left\{ 1 + \frac{z\tau}{2} + \frac{z^2\tau^2}{4}\Pi \right\}}{\xi p r_d}, \tag{1}$$

where $\tau = \frac{T_e}{T_i}$, $z = \frac{z_d e^2}{aT_e}$ is the dimensionless charge of a particle, z_d is its charge number, a is the particle radius, U_{ir} is the ion radial flow velocity, τ_i is the interparticle collision time, v_{Ti} and v_{Tn} are the thermal velocities of gas ions and atoms, Π is the modified Coulomb logarithm integrated with the ion velocity distribution function, p is the gas pressure, r_d is the distance from a particle to the tube axis, and ξ is the accommodation coefficient (on the order of unity). The rest of notation is standard. Literature data were used for quantitative assessment [11,18,19]. The estimate of $\omega = 0.8$ rad/s corresponding to the conditions established near a diffuse plasmoid boundary is in good agreement with the experiment (Fig. 2).

The radial interparticle distance remains unchanged within the examined range of magnetic induction values. The obtained interparticle distances (Fig. 3) reveal that the density of the dust component in the horizontal section is comparable with the density under glow discharge conditions with minimal power input.

Thus, dusty plasma has been produced for the first time under the conditions of an RFI discharge in a magnetic field. The angular rotation velocity of the dust structure was measured in magnetic fields up to 0.02 T. The angular velocity vector of the structure was directed opposite to the magnetic induction vector. The magnetic-field dependence of the mean radial interparticle distance was determined. The direction of rotation, the proportionality to magnetic induction, and the magnitude of angular velocity are indicative of influence of the ion drag mechanism on dust particles under the experimental conditions.

The obtained results enable the use of a dust trap in an RFI discharge for examination of bulk dusty plasma in a strong magnetic field.

Funding

This study was supported by the Russian Science Foundation (grant No. 22-12-00002).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] E.S. Dzlieva, L.G. Dyachkov, L.A. Novikov, S.I. Pavlov, V.Yu. Karasev, Europhys. Lett., **123** (1), 15001 (2018). DOI: 10.1209/0295-5075/123/15001

[2] E.S. Dzlieva, L.A. Novikov, S.I. Pavlov, V.Yu. Karasev, L.G. Dyachkov, Plasma Sources Sci. Technol., **29** (8), 085020 (2020). DOI: 10.1088/1361-6595/aba8cd

[3] E.S. Dzlieva, L.A. Novikov, S.I. Pavlov, V.Yu. Karasev, L.G. Dyachkov, Plasma Sources Sci. Technol., **28** (8), 085020 (2019). DOI: 10.1088/1361-6595/ab36ac

[4] M. Schwabe, U. Konopka, P. Bandyopadhyay, G.E. Morfill, Phys. Rev. Lett., **106** (21), 215004 (2011). DOI: 10.1103/PhysRevLett.106.215004

[5] E. Thomas, Jr., B. Lynch, U. Konopka, R.L. Merlino, M. Rosenberg, Phys. Plasmas, **22** (3), 030701 (2015). DOI: 10.1063/1.4914089

[6] M. Choudhary, R. Bergert, S. Mitich, M.H. Thoma, Phys. Plasmas, **27** (6), 063701 (2020). DOI: 10.1063/5.0004842

[7] A. Melzer, H. Krüger, S. Schütt, M. Mulsow, Phys. Plasmas, **26** (9), 093702 (2019). DOI: 10.1063/1.5116523

[8] A.V. Nedospasov, Sov. Phys. Usp., **18** (8), 588 (1975). DOI: 10.1070/PU1975v018n08ABEH004914.

[9] A.R. Abdirakhmanov, V.Yu. Karasev, E.S. Dzlieva, S.I. Pavlov, L.A. Novikov, M.K. Dosbolayev, S.K. Kodanova, T.S. Ramazanov, High Temp., **60** (Suppl. 2), S153 (2022). DOI: 10.1134/S0018151X21040015.

[10] Yu.V. Gerasimov, A.P. Nefedov, V.A. Sinel'shchikov, V.E. Fortov, Tech. Phys. Lett., **24** (10), 774 (1998). DOI: 10.1134/1.1262263.

[11] V.E. Fortov, O.F. Petrov, A.D. Usachev, A.V. Zobnin, Phys. Rev. E, **70** (4), 046415 (2004). DOI: 10.1103/PhysRevE.70.046415

[12] V.Yu. Karasev, E.S. Dzlieva, S.I. Pavlov, L.A. Novikov, I.Ch. Mashek, Tech. Phys., **64** (1), 42 (2019). DOI: 10.1134/S1063784219010158.

[13] V.Yu. Karasev, E.S. Dzlieva, S.I. Pavlov, L.A. Novikov, A.I. Eikhval'd, I.Ch. Mashek, Tech. Phys., **65** (2), 190 (2020). DOI: 10.1134/S1063784220020085.

[14] *Complex and dusty plasmas: from laboratory to space*, ed. by V.E. Fortov, G.E. Morfill (Taylor & Francis Group, N.Y., 2010).

[15] L.D. Tsendin, Sov. Phys. Tech. Phys., **15**, 1245 (1971).

[16] A.V. Nedospasov, Phys. Rev. E, **79** (3), 036401 (2009). DOI: 10.1103/PhysRevE.79.036401

[17] A.V. Nedospasov, Europhys. Lett., **103** (2), 25001 (2013). DOI: 10.1209/0295-5075/103/25001

[18] Yu.P. Raizer, *Gas discharge physics* (Springer-Verlag, Berlin, 1991).

[19] A.A. Kudryavtsev, A.S. Smirnov, L.D. Tsendin, *Fizika tleyushchego razryada* (Lan', SPb., 2010), p. 385 (in Russian).

Translated by D.Safin