ABSTRACT
of the dissertation for the degree of Doctor of Philosophy (PhD)
Specialty 6D060400 – Physics

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PROPERTIES OF PLASMA-DUST STRUCTURES IN AN EXTERNAL MAGNETIC FIELD

This Ph.D dissertation is devoted to an experimental study of the structural and dynamic properties of plasma-dust structures in a stratified glow discharge in external uniform and nonuniform magnetic fields at low pressures

Relevance of the dissertation theme:

Plasma, commonly referred to as the "fourth state of matter," is the most common form of matter in the visible universe. When an external source of energy is applied to a mixture of atoms or gas molecules, most commonly in the form of direct heating or an applied constant or alternating electric field, one or more electrons can be released from the atom, thus forming plasma. This process produces a gaseous system consisting not only of electrically neutral atoms and molecules, but also of negatively charged electrons and positively charged ions. This system can both create electromagnetic fields and react to them collectively, which allows the plasma to exhibit properties inherent to both liquids and gases.

In this dissertation the dusty plasma will be considered, which is the object of study in a specific section of plasma physics. Dusty plasma (also called complex plasma, colloidal plasma) is a four-component system consisting of ions, electrons, neutral particles, and charged solid particles (i.e., the dust component). Under laboratory conditions, the dust component consists of particles ranging in size from a few nanometers to several tens of micrometers. In the space, solid dust particles can be several meters in size. Thus, the dust component can be considered as macroscopic compared to other plasma components.

To date, laboratory studies of dusty (complex) plasmas have been focused on studying the dynamics of charged microparticles in plasmas without the presence of a magnetic field. In the vast majority of these studies it is the competition between gravitational and electric forces that determines the zero-order equilibrium; i.e. in order to suspend microparticles in plasma, it is necessary to compensate the gravitational force directed downward on the particles by other forces. After suspension in plasma, the particle dynamics is determined by interparticle electrostatic forces (e.g., Coulomb screening), neutral and ion drag forces. However, in the presence of a magnetic field, all forces acting on the dust particles, which are charge-dependent, are potentially subject to change. Moreover, the charging mechanism of dust particles will also be modified by the magnetic field, as the dynamics of ions and electrons become dominated by the acting magnetic force. Also, at sufficiently high magnetic field strength, the direct magnetic force acting on the dust particles may become comparable with other forces acting on it.

In 1996, a research group from Nagoya University conducted experiments and numerical analysis to study the effect of the azimuthal ion flux caused by the $\vec{E} \times \vec{B}$ drift on the behavior of dust particles in a magnetized electron cyclotron resonance (ECR) based cylindrical discharge plasma. The results of the analysis on the distribution of deposited silicon dioxide particles and micron-sized dust particles in an axial magnetic field equal to 870 Gs showed that the azimuthal force of ion drag can cause the removal of dust particles from the plasma at low pressure. These results have shown the perspective application of magnetic forces in microelectronics process units to control the transport characteristics of dust particles in order to remove them from the operating area.

In addition, the properties of dust particles under the influence of applied magnetic field in RF, induction, magnetron and other types of discharges were studied in laboratory conditions. However, dusty plasma in the glow discharge in the presence of magnetic field has been studied practically insufficiently nowadays. In this dissertation work, dusty plasma was studied in a stratified low-pressure glow discharge under the influence of an external magnetic field. The above fundamental and applied problems testify to the ***relevance*** of the described topic and the presented problem.

The main goal of work: experimental study of the structural and kinetic properties of the glow discharge dusty plasma in an external magnetic field.

The object of the research: low-temperature dusty (complex) glow discharge plasma.

The subject of the study is dynamics of plasma-dust structures in a stratified glow discharge in uniform and nonuniform magnetic fields.

In order to achieve the above stated goal, it is necessary to do the following tasks:

– to design, assemble, and set up an experimental setup to study the effect of an external magnetic field on a dusty plasma;

– to study of properties of plasma-dust structures in uniform and non-uniform weak magnetic field;

– to study the properties of plasma-dust structures in a strong magnetic field on the experimental installation Cryo-Magn Room (St. Petersburg State University).

Scientific novelty of the dissertation results.

For the first time in this work:

– the effect of an nonuniform magnetic field on plasma-dust structures in a DC glow discharge in an argon noble gas was investigated;

– a model describing the rotation of plasma-dust structures in the glow discharge stratum caused by the radial component of the magnetic field was developed;

– the effect of a strong non-uniform magnetic field on the rotation dynamics of plasma-dust structures in the glow discharge stratum in helium gas was studied.

The main provisions for the defense:

– the non-uniform magnetic field near the ends of the Helmholtz coil causes plasma-dust structures rotation in a DC glow discharge in argon gas at pressures of 0.2-0.25 torr and currents of 1.3-1.8 mA induction from 5 to 28 mT;

– in a DC glow discharge, the azimuthal circular ion flux caused by the radial component of the nonuniform magnetic field exceeds the axial component by 10^4 times in magnitude;

– the non-uniformity of the magnetic field blocks the effect of inversion of plasma-dust structures rotation in the magnetized complex plasma of the glow discharge at a pressure of 2.4 torr and a current of 1 mA.

Practical and theoretical importance of the dissertation.

The results obtained in this dissertation are valuable for the development of dusty plasma physics and low-temperature plasma physics generally. They will be very useful for a deep understanding of the rotational mechanisms of dust structures in the glow discharge stratum. The new information obtained is necessary to describe the stratified discharge in a magnetic field.

It is known that in certain cases the presence of dust particles in the plasma environment is undesirable and creates difficulties in the production of many types of microelectronic devices (e.g., image sensors, plasma displays, thin-film solar cells, etc.) that require the use of an etching, sputtering or plasma-assisted polymerization process. Dust particles deposited on plasma-treated surfaces can destroy or reduce the quality of electronic devices. To solve this problem, it is necessary to be able to control and manipulate the dynamics of the dust particles in order to prevent them from depositing on the substrate. In such cases, an axial or radial magnetic field generated by a moving magnetic coil can be used to trap and move them outside the area of the substrate's working zone. Thus, controlled plasma magnetization can become the basis for a method of dust particle cleaning in the preparation of microelectronic devices.

The processes of interaction of plasma with the surface of the first wall materials significantly affect the efficiency and operating times of power installations based on controlled thermonuclear fusion. It is known that a design feature of these facilities is the presence of magnetic coils and the unavoidable presence of large magnetic fields both in the near-wall region and in the region of the plasma itself. In addition, the formation of a large number of dust particles in the near-wall region as a result of contact between the plasma column and the first wall material is reliably known to date. On this basis, we can conclude that the study of the interaction between the magnetic field and the dusty plasma is a significant task for optimizing the operating characteristics of fusion power plants.

Validity and reliability of the results. The results are confirmed by publications in foreign journals with a high impact factor and in publications recommended by the Committee on the Control of Education and Science of the MES RK, and in the works of international scientific conferences in the near and far abroad.

The personal contribution of the author lies in the fact that the entire volume of the thesis, the choice of the research method, the assembly, the adjustment and the modernization of the experimental facilities, the conducting of experiments and the analysis of the obtained data were carried out by the author independently. The setting of tasks and discussion of the results were carried out jointly with the scientific supervisors.

Publications. According to the materials of the dissertation, 22 publications were published: 5 in journals from the List of CCSES MES RK for publication of the main results of the thesis for the PhD degree and 4 articles in foreign journals with impact factor included in the international information resource Web of Science (Clarivate Analytics) and Scopus, 13 thesis in the Proceedings of International Scientific Conferences.

Approbation of the dissertation. The results obtained in the dissertation were presented and discussed:

– at the 24th International Conference on Phenomena in Ionized Gases "ICPIG" (2017, Estoril, Portugal);

– at the 8th International Conference on Dusty Plasma Physics "ICPDP" (2017, Prague, Czech Republic);

– at the 15th International Workshop on Dusty Plasma Physics (2018, Auburn, Alabama, USA);

– at the 9th International Conference on Plasma Physics and Plasma Applications "PPPT-9" (2018, Minsk, Belarus);

– at the 9th International Scientific Conference "Actual Problems of Modern Physics" (Abdildin Readings) (2018, Almaty);

– at the International Conference of Students and Young Scientists "FARABI ALEMI" (2018-2021, Al-Farabi Kazakh National University, Almaty);

– at the 25th International Conference on Phenomena in Ionized Gases "ICPIG" (2019, Saporo, Japan);

– at the 17th International Workshop "Complex Systems of Charged Particles and Their Interaction with Electromagnetic Radiation" (2019, Moscow, Russia);

– at the 2nd Annual Meeting of the Kazakh Physical Society (2019, Almaty, Kazakhstan);

– at the Scientific-Coordination Session "Physics of Nonideal Plasmas" (2020, Moscow, Russia);

– at the International Conference on Non-ideal Plasma Physics (2021, Dresden, Germany);

– at the 47th European Physical Society Conference on Plasma Physics "EPS-XXXXII" (2021, Virtual Conference).

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Relation of the dissertation theme to the plans of scientific research. The dissertation was fulfilled in accordance with the plans of the following fundamental scientific research works (SRW) SC RK MES «Grant funding of scientific research» on the themes:

- “Investigation of the properties of low-temperature complex plasma in an external magnetic field” (2018-2020, AP05133536);
- “Investigation of structural and kinetic properties of dusty plasma in a glow discharge in electric and magnetic fields” (2018-2020, AP08855651);

The scope and structure of the thesis. The thesis consists of an introduction, 3 sections, conclusion and list of references from 149 titles, contains 91 pages of basic computer text, including 54 figures and 5 table.