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Dust in Magnetized Plasmas

Alex Samarian

School of Physics, the University of Sydney, NSW 2006, Australia

Overview of recent progress in studies of magnetized dusty plasmas is presented. Dust dynamic under the influence of an applied magnetic field in various types of discharges and conditions (including dust dynamic in the magnetized plasma sheath) is examined. The various dust driven mechanisms in magnetized plasma are considered and comparison experimental and theoretical data is performed. Influence of magnetic field on dust structures are analyzed as well as dust stabilization (freezing) in the alternating magnetic field.

1. Introduction

Dusty (complex) plasma is a complex object capable of self-organization, which has been subjected to intensive investigation during the last twenty years. Under typical laboratory conditions, the grains generally carry negative charge owing to various processes in the ambient plasma. A typical feature of dusty plasma is strong interaction between charged dust particles, which may result in formation of ordered structures of liquid and crystal types. The presence of the massive dust grain in the plasma introduces spatial and temporal scales over which kinetics of individual dust can be investigated [1-3].

One of the ways of studying the dynamic (kinetic) characteristics of a dust is studying its response to various external excitations. The laboratory dusty plasma in the presence of external perturbation is a useful experimental model for investigating of dusty plasma structures in space and industrial and power facilities. Dusty plasma may be affected, in particular, by an external magnetic field. Dust dynamics under the influence of a magnetic field in various types of dusty plasmas had long been studied in the last decade [4-26].

For example, the structure and the motion of the Saturn rings such as spokes on the B rings or ever changing structure of the F rings are believed to be influenced not exclusively by the gravitational field but also by the magnetic field [27]. Studying the effect of magnetic field is further of interest when considering the behavior of dust particles in the wall plasma of tokamaks. It is well known that significant amount of dust particles are present in fusion devices due to flaking, blistering, and violent arcing on chamber walls. Recent studies showed that dust particles can acquire very high speeds due to accelerated plasma flow in magnetic field and contaminate the core plasma, which ultimately lowers the performance of fusion devices [28,29].

2. Dust Dynamic in Magnetic Field

In the laboratory, dust dynamic under the influence of an applied magnetic field in various types of discharges and conditions have been studied. Effects of the azimuthal ion flow induced by $E \times B$ drift on single dust particle in a magnetized cylindrical electron cyclotron resonance (ECR) plasma was reported by Nunomura [4]. The first observation of dust crystal rotation using an axial magnetic field of variable strength was made in a dc argon glow discharge by Sato [6]. Sydney Complex Plasma Lab (*CPL*) reported the experimental investigation in the rotation of large crystals and three-dimensional clusters in an inductive rf argon discharge [10,11]. Later *CP*L began to investigate planar dust clusters under the influence of magnetic field [12]. Because planar dust clusters are two-dimensional and have a smaller number of particles, their simplicity allows for easier analysis and hence a better understanding in the driving mechanisms for dust rotation. Yokota rotated a UV-induced annular crystal consisting of fine aluminum particles about the magnetic dipole axis of a spinning magnetized miniature sphere with field $B \approx 0$ to 50 G in order to mimic some of the mechanisms in planetary ring formation [26].

Konopka [5] observed rotation of monolayer dust crystals induced with a cylindrical permanent magnet of strength B = 140 G in a capacitive rf helium discharge. Ishihara studied the precession of single dust particle placed in the plasma with the presence of an external magnetic field [7]. In his model, the dust particles were suggested to rotate about its axis due to the ion drift in the $E \times B$ field. Sato extended their dust rotation experiment to not only dc but also rf argon glow discharges with much stronger variable magnetic field up to $B \approx 10000$ G [6]. The motivating point about the use of stronger magnetic field is that the dust particles become partially magnetized when $B > \approx 4000$ G. As well, this group managed to rotate dust crystals with particles of different diameters ($a \approx 0.1$ to a few tens μm), but qualitatively did not observe any effect of particle size on the rotation. Interestingly, Sato [6] also observed the phenomenon of "angular velocity saturation" at $B \approx 4000$ G, the value predicted in the following year by Kaw using collisional fluid theory for magnetized ions [8]. Karasev and Vasil'ev continued studies of dust rotation in magnetized plasma in DC discharge plasma [16,17,21,25]; while Konopka performed experiments in magnetic fields up to flux densities of 2.3T [15,24] and reported a dust particles pattern formation similar to one observed by Huang [19].

The most accepted explanation of dust rotation in magnetic field is that the dust particles are rotated by ion drag force [4,7,8]. Indeed as for a magnetized dusty plasma, particles are located in a region with a radial confining electric field, a vertical magnetic field applied will result in an azimuthal $\mathbf{E} \times \mathbf{B}$ ion drift (the ion rotation direction is in turn determined by a competition between $\mathbf{E} \times \mathbf{B}$ and diamagnetic rotations of the ions in the collisional magnetized plasma) and therefore a rotation of particles on the horizontal plane. However, the experimentally observed motion of plasma-dust structures cannot be explained by the forces of ions only. So many various mechanisms are discussed in literature: from ambipolar diffusion [17, 22] to magnetomechanical effect [20], the coupling between harmonic oscillations and the Lorentz force on the dust particles was considered by Ishihara [9].

3 Dust Dynamic in Magnetized Sheath.

The presence of dust in the plasma provides an important diagnostic tool. For example, in bounded plasma, sheath characteristics can be studied in considerable detail by using fine dust probes. This is due to the fact that the charge on the grain is a function of local plasma conditions and thus, study of the dust dynamics in such a surrounding can provide information on the electron and ion fluxes, on the sheath potential, and on the electric field. Therefore, it is important to investigate the charged dust behavior inside a magnetized sheath, which will provide a useful guide in measuring the sheath characteristics.

It was found that the charge on the dust determines its trajectory and dust performs the spiraling motion inside the sheath. The location of the turning spiral is determined by the number of negative charge on the dust, which in turn is a function of the dust radius. The back and forth spiraling motion finally causes the dust to move in a small, narrow region of the sheath. The temporal behavior of the spiraling dust motion appears like a damped harmonic oscillation, suggesting that the plasma drag force causes dissipation of the electrostatic energy.

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