Coulomb Clusters in Axial Magnetic Field

F.M.H. Cheung, A.A. Samarian, and B.W. James

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

Abstract. The rotation of Coulomb clusters with different numbers of micron-sized particles is observed in an inductively coupled dusty plasma in the presence of an axial magnetic field. The rotation is found to be dependent on the particle number and configuration. Clusters with smaller numbers of particles require a higher magnetic field strength in order to initiate the rotation, the threshold magnetic field at which the cluster begins to rotate being proportional to the square of the number of particles in the cluster. The angular velocity of clusters increases and the radius of the clusters decreases as the magnetic field strength is increased. The relation between angular velocity and magnetic field is dependent on the number of particles in the cluster.

INTRODUCTION

When micron-sized dust particles are released into the plasma, the dust particles undergo frequent collisions with the highly mobile electrons rather than the slow and heavy ions within the plasma. As a result, these dust particles accumulate thousands of electrons on their surface and become negatively charged. It is possible to levitate these dust particles in the plasma to form a 2-dimensional or a 3-dimensional lattice with an ordered structure similar to a crystal. These crystals of many (more then a thousand) particles are commonly known as dust Coulomb crystals. These systems have been shown to be an ideal model for studying strongly coupled systems, because of their unique nature, relative ease of production and simple optical imaging required. A dust Coulomb crystal with one to several particles is a dust Coulomb cluster.

The Coulomb clusters can be considered as a system of a small number of particles confined by external electric field. Such systems have been a topic of theoretical and experimental studies with respect to particle ordering, phase transition, energy spectra etc [1-4]. But up until now, no experiments had been reported on properties of such clusters in magnetic field, while some papers were concerned with the investigation of the behaviour of large plasma crystal in axial magnetic field [5-9].

EXPERIMENTAL RESULTS

Here we report the dynamical behaviour of Coulomb clusters with N number of particles, N equal from 2 to 12 in inductively coupled magnetised plasma. To our knowledge this is the first time such small crystal systems are experimentally observed to exhibit such rotational behaviour.

The experiment is conducted in a radio-frequency (rf) discharge with a printed-circuit board (PCB) electrode system. Fig. 1 shows the interior of the experimental apparatus. The dust clusters formed above the confining electrode are illuminated by a fully height adjustable He-Ne laser for observation. The motion of the dust crystals was observed under the microscope and on the televisions from the video images generated from the cameras. The images of the rotational motion were then recorded on videotapes at a frame rate of 50 fps and a shutter speed of 0.008 seconds. The particles are then tracked with a software program that outputs the x and the y-coordinates of their trajectories as a function of time for analysis.

Coulomb clusters of different number of particles in a plane were formed in the experiment. When the magnetic field was off, the clusters exhibited small random fluctuation but always remained around their equilibrium position. However when the magnetic field was switched on, the small clusters were observed to be going under rotational

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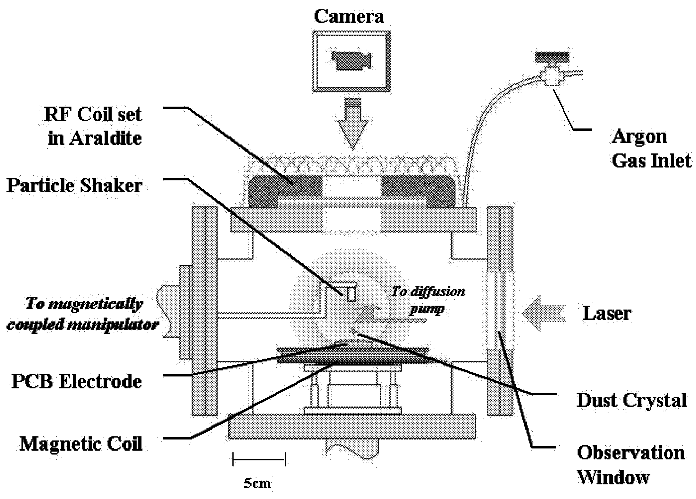

FIGURE 1. The experimental apparatus used to produce the coulomb dust clusters.

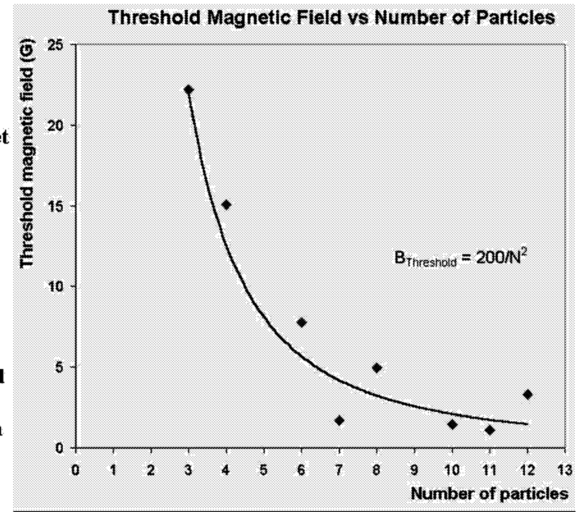

FIGURE 2. Threshold magnetic field versus number of particles.

motion. The direction of the rotation was in the left-handed direction with respect to the magnetic field. And a change in the direction of the magnetic field will cause the rotation to go counterclockwise.

Fig. 2 shows how the clusters with smaller number of particles like planar-3 and planar-4 requires a higher magnetic field strength in order to initiate the rotation. And planar-2 exhibits the highest resistance to the change in magnetic field with only momentary pauses at higher field strength. The threshold magnetic field strength at which the particles will start to rotate decreases as the number of particle increases. It should be mentioned that, in contrast with experiments in DC discharge and capacitive rf-discharge, we need only relatively small magnetic field (~ few Gauss) to rotate Coulomb clusters. It has been found that threshold value is inversely proportional to the square of the number of particle in the cluster. This means that the rotation is generated in the presence of the strong Coulomb coupling among the particles.

When the magnetic field was increased, two events occurred. Firstly, in general, there was an increase in the angular velocity of the cluster as shown on Figure 3. In particular, the angular velocity of the single-ring clusters (planar-2 to planar-8) seems to increase linearly as magnetic field strength increases. And for the double-ring clusters (planar-10 to planar-12), the angular velocity of the cluster increases very quickly and then saturates even when magnetic strength increases. This phenomenenon is similar to the saturation under the kG magnetic fields reported in [8]. In [10] the possible explanation of saturation was proposed, below we suggest a new explanation of this fact.

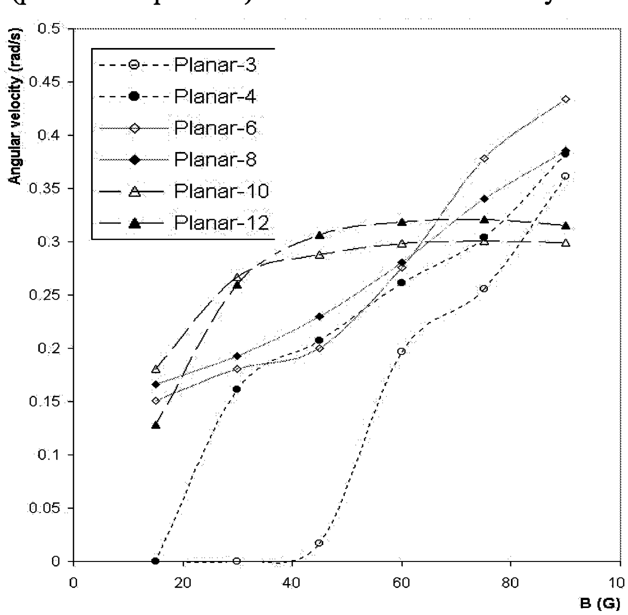

FIGURE 3. The variation of angular velocity of the cluster with the magnetic field strength.

Secondly, there was a decrease in the radius of the cluster. The total angular momentum L, which is summed over all particles in a particular crystal structure is independent on the magnetic field. This is an indication that the increase in angular velocity, accompanied by a contraction of the cluster is a result of the conservation of angular momentum. The angular momentum per particle is obviously independent to the change in magnetic field. But it is also independent on the number of particles there are in the cluster going under rotation.

Now the magnitude of the driving force for the cluster rotation can be easily calculated from the neutral friction force in the azimuthal direction. The obtained value is about 10-16N. On the other hand, there are many models in calculating the value of the ion drag force. But the upper limit of the ion drag force from all these models are less than 10-17N (under the assumption that the gas is at rest). It is easy to see that in comparison with the friction force, the ion drag force is about an order less. Thus the explanation using azimuthal ion drag to attribute to the rotation of plasma crystals is close but not satisfactory.

Another item that we should take into account is the divergence of the axial magnetic field. Since the sheath electric field is at least ten times the magnitude to the radial electric field, only a small tilt in the angle at which the magnetic field bends away from the vertical axis will affect the ion drag drift velocity.

From the experiment, dependence of radial electric field on magnetic field was observed (see Figure 4). Obtained data show that radial electric field is linearly proportional to the magnetic field. Since electric field is modified by the magnetic field, it must be taken into account in the analysis of the driving force of cluster rotation.

The Larmor radii for electrons and ions are $6x10^{-5}$m and $2x10^{-2}$m respectively. So the electrons are highly magnetized compared to the ions. And because the ratio of electron gyrofrequency to electron-neutral collisional frequency is about 1.5 (for ions, this ratio <0.01), the electrons will tend to be localized at the center of the system. As a result, the non-uniform distribution of the charge density will lead to a change in the electric potential profile. In fact, this phenomenon can explain the saturation in angular velocity for double-ring clusters mentioned earlier. As the magnetic field increases, the radial electric field at the center of the cluster will change into the opposite direction. Consequently, the particles on the inner ring of the cluster will attempt to rotate in the opposite direction. However, due to the strong interparticle force, the cluster remains as a rigid body. And so the net torque on the whole cluster will decrease. Thus saturation of double-ring cluster rotation occurs.

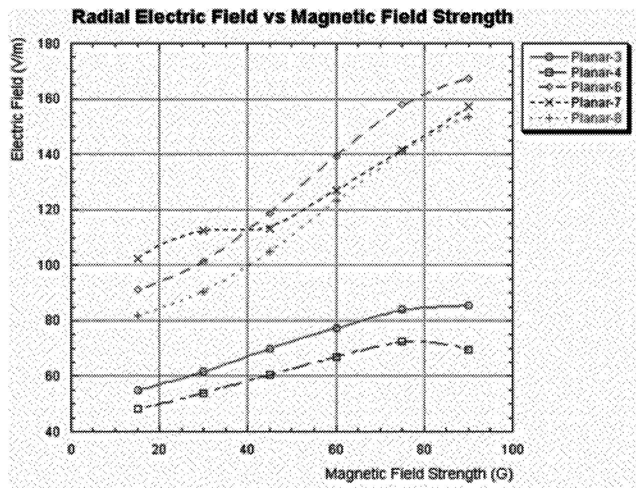

FIGURE 4. Radial electric field dependence on axial magnetic field.

It was demonstrated from the experiment that the rotation of small dust coulomb clusters is possible with the application of an axial magnetic field. It is easier to initiate the rotation of the clusters with larger number of particles than smaller number of particles at very low magnetic field strength. The angular velocity of the clusters increases while the radius of the clusters decreases as the magnetic field strength increases.

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