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The rotation of planar-2 to planar-12 dust clusters in an axial magnetic field

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Abstract. Dust clusters containing from one up to 12 particles arranged in a horizontal plane were formed in an inductively coupled rf plasma. When an axial magnetic field was applied to the dust cluster, the cluster rotated as a rigid body in the left-handed direction with respect to the field. The cluster rotation occurred at a magnetic field of tens of gauss in our experiment, which was two to three orders less than that used in previous experiments and that predicted by the models in the literature. In particular, the angular velocity dependence on magnetic field strength varied with number of particles in the cluster and with the structural configuration of the cluster. Other rotational properties such as cluster radius, angular momentum and threshold magnetic field were measured. The dependence of the radial confinement electric field on the magnetic field was also obtained. Finally, comparisons were made between our experimental results and various existing theoretical models. Possible explanations for angular velocity saturation and periodic pauses for the planar-2 configuration, which were observed in our experiments, are given.

Contents

1	Introduction	2
2	Experimental apparatus	3
3	Properties of cluster rotation	5
4	Theoretical analysis	9
4.1	Quantitative comparison with theoretical models	9
4.2	Angular velocity saturation	12
4.3	Oscillation and periodic pauses of planar-2 clusters	13
5	Conclusion	13
	Acknowledgments	14
	References	14

1. Introduction

A dust cluster can be considered as a system consisting of a small number of particles confined by an external electric field. Because of the unique physical properties related to its small size, along with the relative ease of analysis of individual particle motion, such systems have been the subject of theoretical and experimental studies. Some examples which have been reported are particle ordering, phase transition and energy spectra [1]–[5].

Currently, in the field of complex plasmas, there is a strong interest in the dynamical behaviour of these dust clusters. Such interest arises because a better understanding of the dynamics may allow dust particles to be manipulated collectively or individually. Consequently, this knowledge can be used in a wide range of applications such as the removal of dust contamination in semiconductor plasma processing, surface deposition on novel materials, fabrication of micro- and nano-scale mechanical devices and explanation for the dynamical properties observed in planetary rings and space nebulae. Crystal rotation, vortex motion, instabilities and oscillations are some of the different types of particle dynamics that have been observed and reported in the last few years [6]–[17]. In particular, crystal rotation has been studied in various plasma conditions since its first observation in a magnetized plasma [18].

In the presence of an axial magnetic field, dust Coulomb crystal rotation in a dc glow discharge was reported by Uchida *et al* [19] and in a capacitive rf discharge by Konopka *et al* [20]. Depending on the discharge conditions, either rigid-body rotation or sheared rotation was observed. In the dc discharge, the particles in the upper layers were observed to be rotating faster than the particles in the lower layers, corresponding to velocity shear in the vertical direction. A radial variation of angular velocity was reported in the rf-discharge case. The rotation was observed to be either right handed or left handed with respect to the direction of the axial magnetic field depending on the discharge parameters.

The reason such rotational behaviour arises is still not properly understood. Nunomura *et al* [21] proposed that the momentum transferred to the particles in the azimuthal direction by ion drag might be the cause of the crystal rotation. Later this idea was promoted by other authors. A simple theoretical model based on azimuthal ion drag was proposed to explain the cluster rotation in a constant magnetic field [20]. A magnetized ion fluid model [22] was used to explain the experiments reported in [19]. Whether the effect of the ion drag force is strong enough to initiate the rotation of the crystal is, however, still questionable.

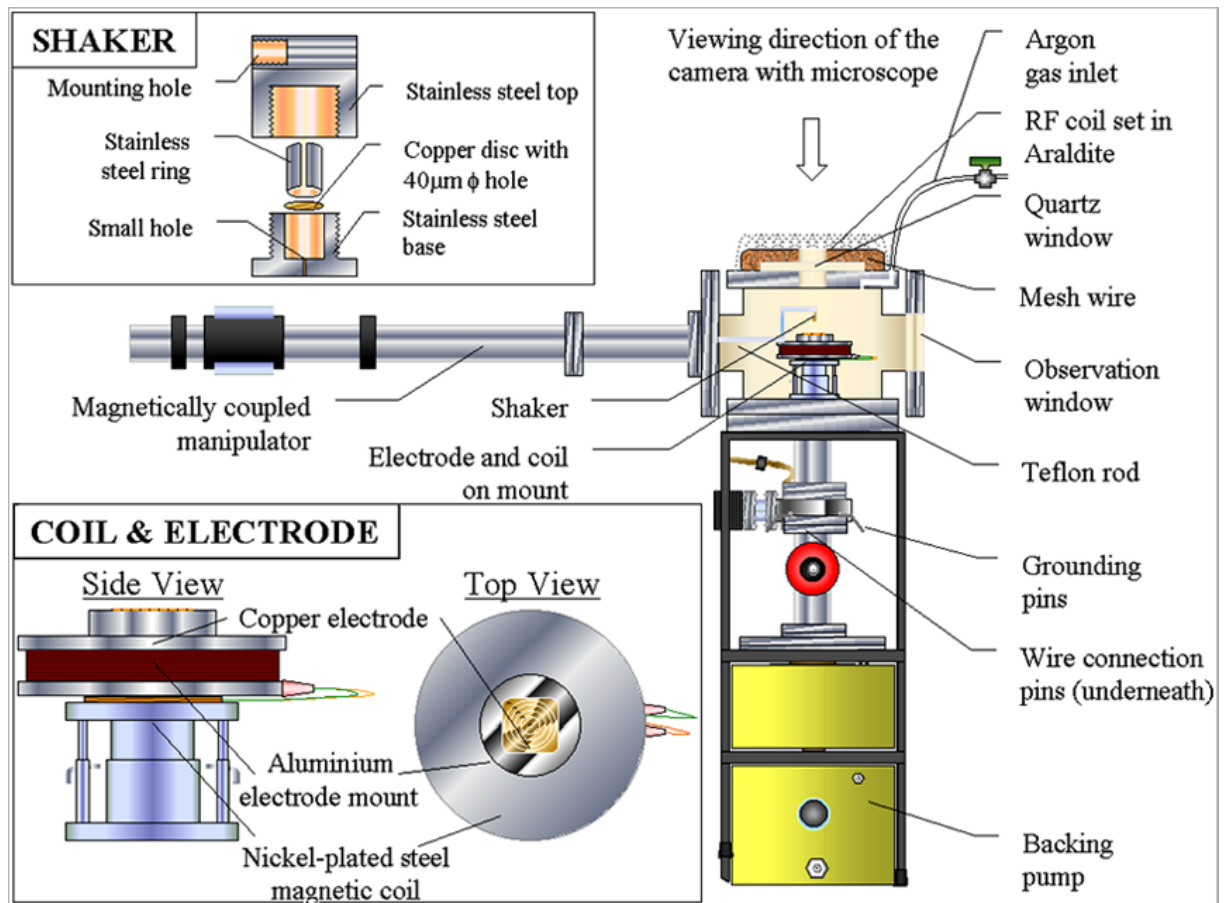


Figure 1. The experimental apparatus used to produce the dust clusters.

To get a better understanding of dust Coulomb crystal rotation under the influence of the magnetic field, dust clusters with small numbers of particles provide a simple system for study and analysis. In our experiment, the rotation of dust clusters from two to 12 particles in a magnetic field of up to 100 G was studied. Different rotational properties are presented to provide a better understanding of the driving mechanism behind the dust cluster rotation.

2. Experimental apparatus

The experiment was carried out in a stainless steel cylindrical plasma chamber with an internal diameter of 19.5 cm and internal height of 19.5 cm. As shown in figure 1, there were four evenly spaced rectangular ports 5.5 cm wide and 10 cm high on each side. Of the four, two adjacent ports had windows designed for observational purposes. The dust clusters were observed through one port using a CCD camera attached to a microscope system. A 110 L s^{-1} turbo-molecular vacuum pump was connected to one port, and a magnetically coupled manipulated dust dispenser was mounted at another. A Penning ionization gauge was used to measure the pressure near the pump inlet. Before each experiment, the chamber was evacuated to a pressure of approximately 10^{-6} Torr. A high vacuum valve between the pump and the chamber allowed the chamber to be isolated from the pump during experiments.

The top of the chamber was sealed with a quartz plate, on top of which was a planar spiral rf coil consisting of eight turns of copper tubing potted in Araldite. A 6 cm diameter hole in the centre of the coil allowed observation of the dust crystal from above using another video camera attached to a microscope similar to the one at the side window.

The bottom of the chamber had a feed-through consisting of multiple tungsten pins through a ceramic disc, providing connections to the electrode and the magnetic field coil.

Argon gas at a pressure of 100 mTorr is used for the discharge. The gas is admitted into the vacuum chamber via an inlet port next to the rf coil. A 500 mV peak-to-peak rf voltage at 17.5 MHz is provided from the signal generator is used to drive the rf coil. The signal generator consists of a synthesizer/function generator and a power amplifier with impedance matching network. When the rf coil is powered, the gas becomes ionized and stationary argon plasma is formed. Using a Langmuir probe, the plasma density and electron temperature were found to be $\sim 10^{15} \text{ m}^{-3}$ and a $\sim 3 \text{ eV}$, respectively.

The melamine formaldehyde particles used in these experiments are spherical and mono-dispersed with a diameter of $6.21 \pm 0.09 \mu\text{m}$. They are stored in a shaker, connected by a Teflon rod to a magnetically coupled manipulation device which allows rotational and horizontal movement of the shaker. The shaker (see the inset in figure 1) has a small 0.4 mm diameter hole in its base, which can be screwed off for refilling. A small copper disc with an approximately 40 μm diameter hole is placed on top of the base before the particles are tipped in. The hole in the disc ensures that only small numbers of particles come out from the shaker. A gentle rotation of the magnetically coupled device causes the Teflon rod to rotate, which makes the shaker sprinkle particles into the desired region. The shaker and rod are then pulled back to avoid obstructing the view of the dust crystal.

The electrodes, mounted on the top of the magnetic field coil, were made from conventional PCB (printed circuit board) of dimensions of $25 \times 25 \text{ mm}$. Electrically isolated annular regions were created by machining narrow circular breaks in the copper, and electrical connections to the various regions were connected by pins passing through the insulating sheet. For the production of dust clusters, a circular groove of diameter 5 mm surrounded by three 2.4 mm wide concentric annular grooves was machined on to the surface of the PCB. The centre of the electrode was designed to trap a small number of particles for this experiment while the concentric rings were for trapping particles in an annular form for future experiments. The electrode was copper plated by vapour deposition to obtain a very smooth surface. For all of the cluster rotation experiments, the centre of the electrode was powered with a positive voltage of $+10.5 \pm 0.5 \text{ V}$. The outer ring electrodes and other components in the chamber were grounded.

A 15 cm diameter, 1.5 cm thick nickel-plated steel former with 4200 turns of 0.5 mm diameter copper wire windings is used to generate a uniform axial magnetic field over a large area. The maximum current used in the coil was 1.5 A, producing a magnetic field of 100 G.

In this experiment, only monolayer clusters were studied. The dust clusters formed above the confining electrode was illuminated for observation by an 8 mW He–Ne laser. A half-cylindrical Perspex lens in front of the laser causes the beam to diverge into a horizontal sheet. The motion of the dust crystals was observed via the video images from the CCD cameras. The video output was passed through a signal filter to increase image contrast, and the processed images were recorded on videotapes at a frame rate of 50 fps (frames per second), using a shutter speed of 0.008 s. The recorded images were captured with an acquisition board. The particles were tracked using software that generated the x - and y -coordinates of the particles as a function of time.

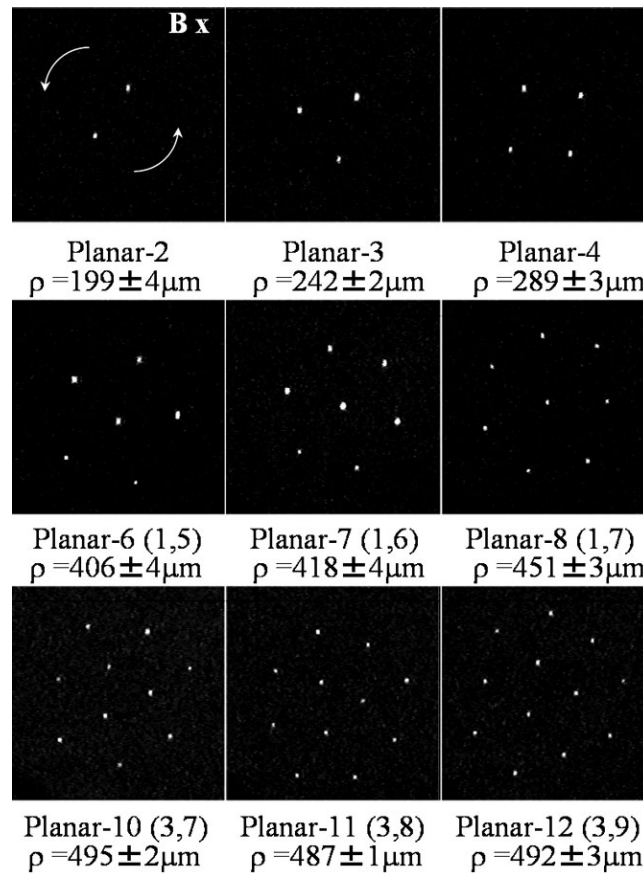


Figure 2. Images of dust clusters from two to 12 particles. The cluster radius of the different clusters is also presented.

3. Properties of cluster rotation

Dust clusters with different numbers of particles in a horizontal plane were formed. The cluster radius ρ is the average distance of all dust particles on the outer ring from the centre of rotation. The structural configuration and the cluster radius of the different clusters investigated in the experiment are shown in figure 2. The structure of the small dust clusters approximately agrees with that observed and predicted by Lin *et al* [24].

When the magnetic field B was switched off, the clusters exhibited small random fluctuations but always remained around their equilibrium position. However, when the magnetic field was switched on, the small clusters were observed to go under rotational motion. The direction of rotation was in the left-handed direction with respect to the magnetic field. That is, if the axial magnetic field is vertically up, then the direction of the cluster rotation will be clockwise when observed from above. A change in the direction of the magnetic field caused the rotation to reverse. Figure 3 shows the angular position of the particles in a planar-10 cluster as a function of time. Apart from the natural fluctuations, the particles are in phase with each other when they are in motion. Thus the cluster rotates as a rigid body.

When the magnetic field was increased stepwise by 15 G, two events occurred. Firstly, there was a decrease in the cluster radius, as shown in figure 4, the radius responding instantaneously

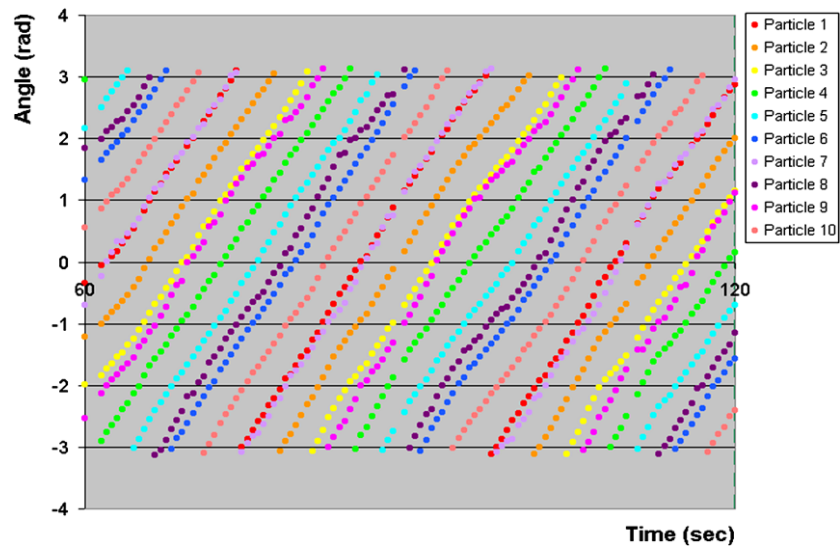


Figure 3. Angular position of the dust particles in a planar-10 cluster versus time.

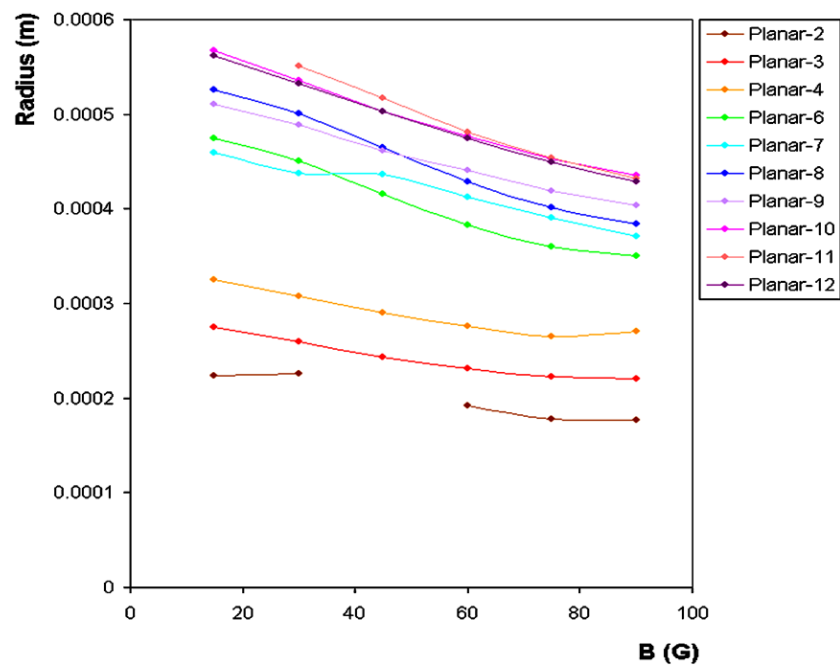


Figure 4. Cluster radius versus magnetic field strength for the different clusters.

to the change of magnetic field. Since the position of the dust particles is balanced by the equilibrium of the interparticle force and the radial confining electrostatic force, and there is no experimental evidence to suggest a change in the charge of the particles, a decrease in the cluster radius demonstrates that there is an increase in the radial electric field E_r when the magnetic field increases. Knowing the cluster radius and estimating the dust charge from the OML approximation using the probe measurements as $Z \sim 10^4 e$, the radial electric field was

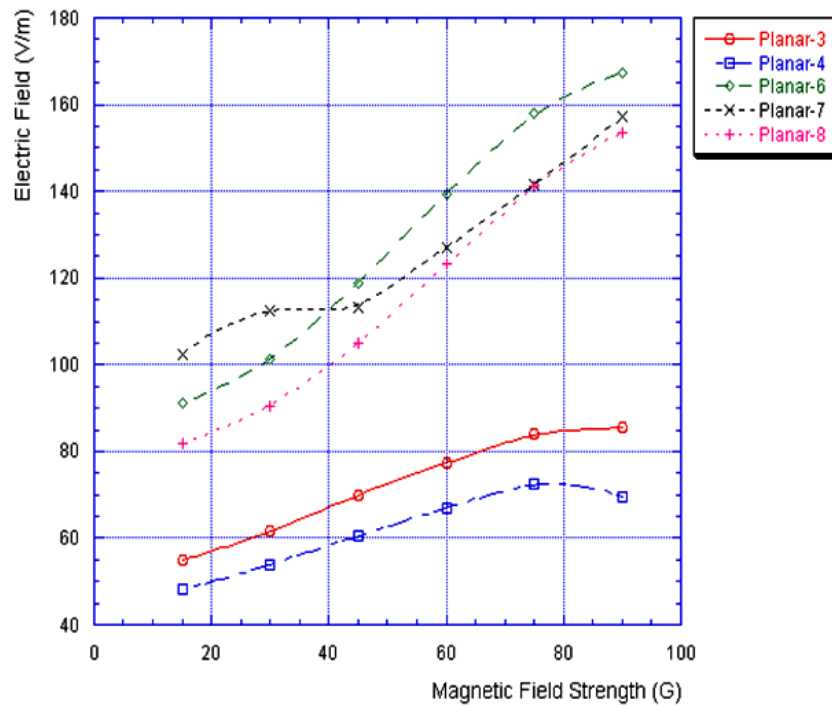


Figure 5. Radial electric field versus magnetic field strength for the different clusters.

calculated [25, 26] and plotted as a function of magnetic field (see figure 5). The graph shows that $E_r \sim B^{0.5}$ or B . Since electric field is modified by the magnetic field, it should be taken into account in the analysis of the driving force of cluster rotation.

Secondly, in general, there was an increase in the angular velocity ω of the cluster rotation. Figure 6 shows the angular velocity dependence on magnetic field strength for the different clusters. Single ring clusters like planar-3 and 4 require a higher magnetic field strength in order to initiate the rotation. Planar-2 exhibits the highest threshold for steady rotation with oscillation only at low field values and rotation with periodic pauses at higher field values. However, it should be mentioned that, in contrast with experiments in dc discharges and capacitive rf-discharges [19, 20], we need only relatively small magnetic fields ($\sim$ few gauss) to rotate Coulomb clusters.

‘One-and-a-half-ring’ clusters such as planar-6, 7 and 8, which consist of single-ring clusters with one dust particle at the centre, are much easier to rotate. The angular velocity increases linearly with magnetic field strength. For double-ring clusters such as planar-10, 11 and 12, the angular velocity increases with magnetic field but eventually levels off. From the experimentally measured values, it was found that the angular velocity dependence on magnetic field and number of particles N could be approximated by the empirical relation $\omega = \exp(-23/N)B^{8.3/N^{3/2}} - 4/N^4$.

The threshold magnetic field B_{th} at which the cluster rotation initiates decreases as the number of particles increases (see figure 7). From the experimental measured values, it was found that the threshold magnetic field could be approximated by the empirical relation $B_{th} = 200/N^2$.

Figures 8(a)–(d) show the phase diagrams for planar-2, 3, 7 and 10 clusters at different magnetic field strengths. The phase diagrams are cylindrical plots of angular velocity against

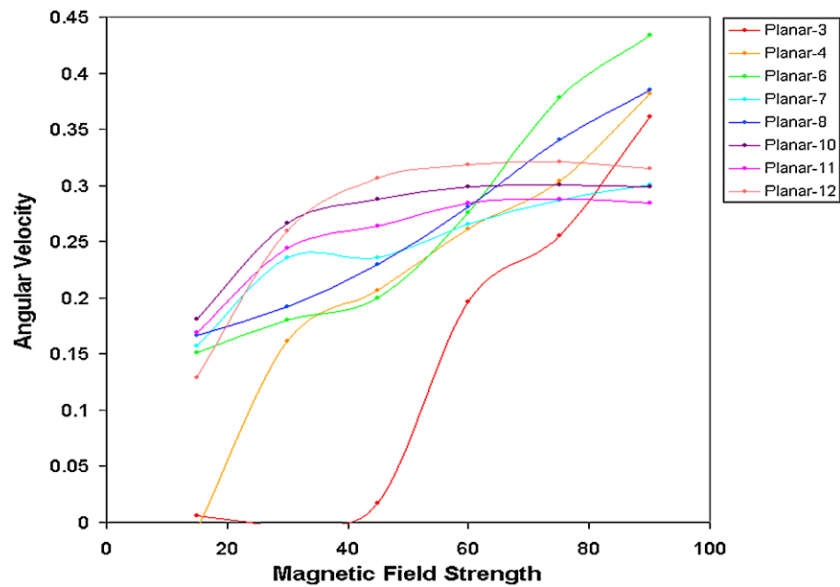


Figure 6. Angular velocity versus magnetic field strength for the different clusters.

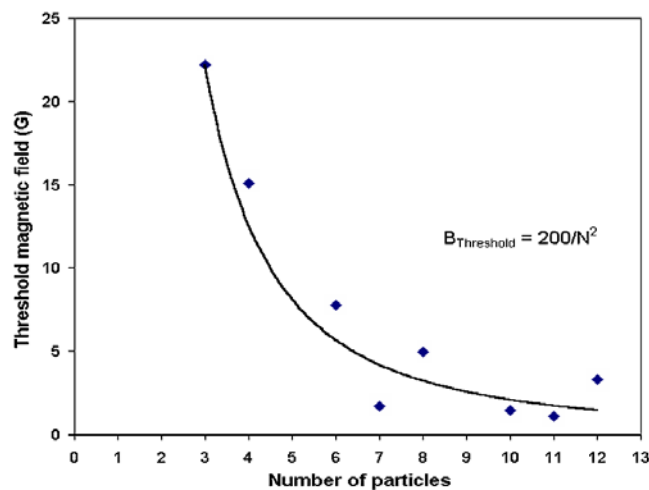


Figure 7. Threshold magnetic field necessary to initiate cluster rotation versus magnetic field strength.

angular position of the individual dust particles about the axis of rotation. The axial component represents the magnetic field strength used in rotating the particles. Consequently, for a particular magnetic field strength, a circular plot in the phase diagram can be interpreted as uniform dust cluster rotational motion, whereas a linear plot in the phase diagram can be interpreted as dust cluster oscillations about an angle.

In our experiment, oscillation was observed for low field settings in planar-2 as mentioned before, and an increase in the magnetic field strength changed the angle about which the planar-2 oscillated. For single-ring clusters, the rotation was not uniform for low magnetic field, slowing at a particular angle. However, the rotation became increasingly uniform as the magnetic field was increased. For ‘one-and-a-half-’ and double-ring clusters, the rotation was uniform.

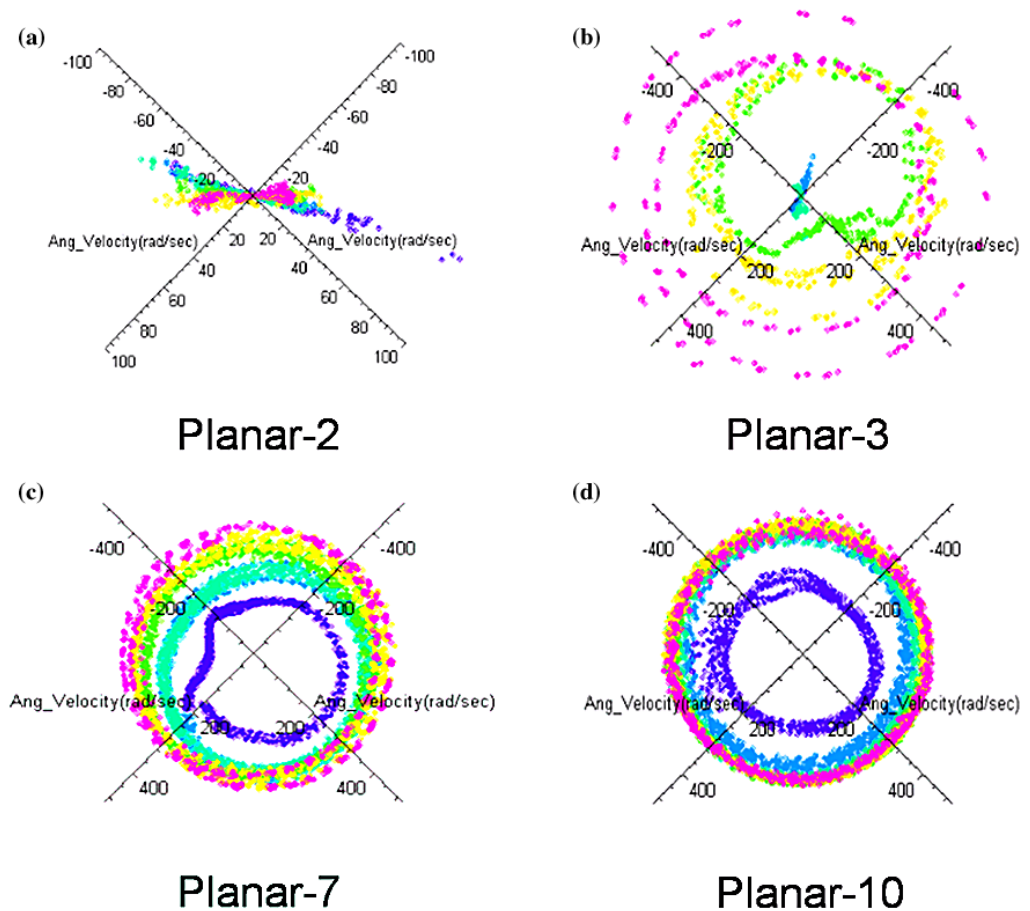


Figure 8. Three-dimensional phase diagrams of (a) a planar-2 cluster (see [animation](#)), (b) a planar-3 cluster (see [animation](#)), (c) a planar-7 cluster (see [animation](#)), and (d) a planar-10 cluster (see [animation](#)). The radial and the angular component of the plot represent the angular velocity and the angular position of the dust cluster respectively. The axial component of the plot represents the magnetic field strength used for the cluster rotation (pink—90 G, yellow—75 G, green—60 G, lilac—45 G, light blue—30 G, blue—15 G).

Since electric field is modified by the magnetic field, it should be taken into account in the analysis of the driving force of cluster rotation. Figure 9 shows in detail the dependence of the driving force, which is assumed to be equal to the neutral drag force, on the product of E_r and B .

4. Theoretical analysis

4.1. Quantitative comparison with theoretical models

The reason the magnetic field causes the dust clusters to rotate is still not properly understood. There are many models in the literature which have attempted to explain this. Here we are going to compare our experimental results with the theoretical models.

Without any assumption of the cause of the cluster's rotation, the magnitude of the

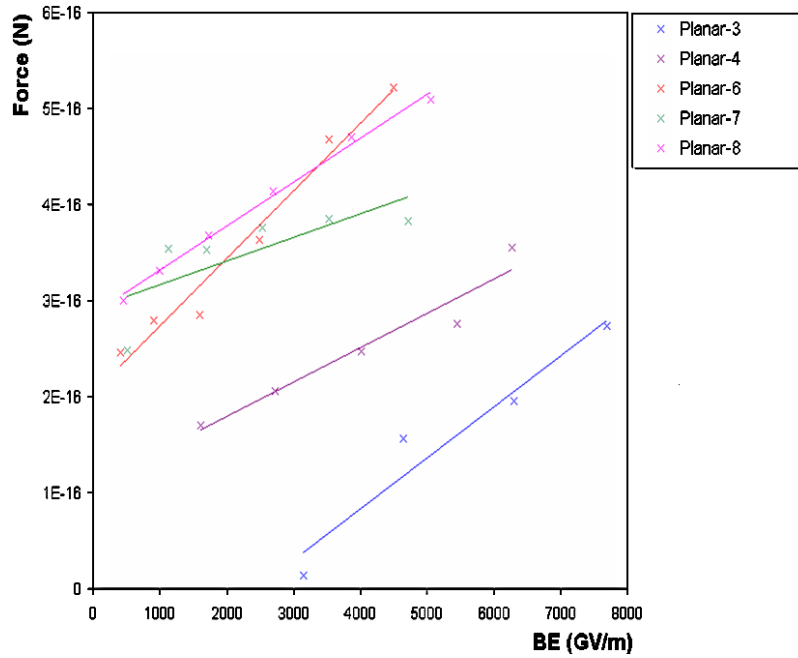


Figure 9. Driving force for the cluster rotation versus the product of the magnetic and electric field strength. Crosses are the experimentally obtained data; solid lines are the linear approximations.

driving force acting on a particle in the azimuthal direction, for rigid body rotation F_d , can be estimated based on the neutral-dust frictional force equation (under the assumption of complete accommodation of neutrals) [27].

$$F_d = -\frac{4}{3}\delta m_n n_n u_{T_n} \pi a^2 \omega \rho \quad (1)$$

where $\delta \sim 1$ is the coefficient dependent on the type of scattering; m_n , $n_n = P/kT_n$, P , T_n and $u_{T_n} = \sqrt{8kT_n/\pi m_n}$ are the mass, number density, pressure, temperature and thermal velocity of the neutrals respectively and a is the dust particle radius. For our experimental conditions ($m_n \sim 1.9 \times 10^{-13}$ kg, $T_n \sim 300$ K and $\rho \sim 10^{-3}$ m), the estimated value for the driving force is $\sim 10^{-15}$ N.

At the moment, the prevalent explanation for the cluster rotation is the ion drag model [20]. The magnitude of the ion drag force F_d in the azimuthal direction can be estimated using the analytical expression from [28] which has been widely used in the literature,

$$F_{id}^\phi = m_i n_i u_\Sigma \pi (b_c^2 + 4b_{\pi/2}^2 \Gamma) u_\phi \quad (2)$$

where m_i , n_i and u_Σ are the mass, the number density and the mean velocity of the ions respectively, b_c is the collection impact parameter, $b_{\pi/2}$ is the orbit impact parameter whose asymptotic orbit angle is $\pi/2$, Γ is the Coulomb logarithm integrated over the interval from b_c to λ_{De} , u_ϕ is the azimuthal component of ion drift velocity, μ_0 is the zero-field mobility and α_0 is a parameter for argon [29].

From a qualitative point of view, since $u_\phi \sim E \times B$ from [20], so $F_{id}^\phi \sim E \times B$. This agrees well with the dependence of driving force on the product of E_r and B we presented in figure 9. However, substituting equation (2) with our experimental conditions ($n_i \sim 10^{15}$ m³,

$u_{\Sigma} \sim 850 \text{ m s}^{-1}$, $T_i \sim T_n$, $\mu_0 \sim 1.9 \times 10^3 \text{ mbar cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $\alpha_0 \sim 3.5 \times 10^{-2} \text{ mbar cm V}^{-1}$), the estimated value for the azimuthal ion drag force is $\sim 3 \times 10^{-17} \text{ N}$. This is almost two orders lower in comparison with the driving force. Thus the explanation using azimuthal ion drag to attribute to the rotation of plasma crystals is close but not satisfactory.

Recently, Khrapak *et al* [30] suggested that equation (2) might have underestimated the magnitude of the ion drag force. Using the theory from [30], the ion drag force can indeed have value up to 10^{-15} N provided that the ions are in subthermal flow ($u \ll u_{T_i}$, where u and u_{T_i} are the drift velocity and thermal velocity of the ions respectively). However, with our experimental conditions, the ion drift velocity seems to be comparable to if not higher than its thermal velocity. In such a case, the ion drag force will have a value close to the estimated value from equation (2).

Interestingly, equation (2) does not take into account the divergence of the axial magnetic field in real experiments. Since the sheath electric field is at least ten times the magnitude of the radial electric field, only a small tilt in the angle of the magnetic field away from vertical will increase the magnitude of the azimuthal component of ion drag force [25].

Ishihara *et al* [23] attempted to use coupling between the Lorentz force and the harmonic oscillation as the explanation for the cluster rotation, predicting an angular frequency for cluster rotation in weak magnetic field given by

$$\omega = \pi(a^2 - 1)\omega_C \quad (3)$$

where a is the normalized initial radial displacement, $\omega_C = ZB/m_d$ is the cyclotron frequency and m_d is the mass of the dust particle. However, the angular frequency of the cluster rotation estimated using equation (3) is $10^{-4} \text{ rad s}^{-1}$ for our experimental conditions ($a \sim 1.2$, $B \sim 100 \text{ G}$, $m_d \sim 1.9 \times 10^{-13} \text{ kg}$), which is three orders less than observed in our experiment. Moreover, the angular velocity in equation (3) is independent of the number of particles in the cluster and depends on initial radial displacement, which is quite different to our experimental observation.

Sato *et al* [22] also made predictions of the dependence of the angular velocity on the strength of the magnetic field using collisional fluid theory for magnetized ions. The resulting angular frequency of cluster rotation is given by

$$\omega = \frac{n_i \sigma_i u_{T_i}}{n_n \sigma_n u_{T_n}} \frac{F_r \rho}{m_i} \left[\frac{\Omega_i}{(v_i^2 + \Omega_i^2)} \right] \quad (4)$$

where σ_i and σ_n are the collisional cross-sections of ions and neutrals respectively, u_{T_i} is the thermal velocity of the ions, F_r is the radial confinement force, v_i is the ion–neutral collision frequency and Ω_i is the ion cyclotron frequency. Using equation (4), the estimated value of the angular velocity is $\sim 10^{-1} \text{ rad s}^{-1}$ ($u_{T_i} \sim u_{T_n}$, $\sigma_i/\sigma_n \sim 10^4$, $v_i \sim 2.2 \times 10^6 \text{ s}^{-1}$ and $\Omega_i \sim 2.4 \times 10^4 \text{ rad s}^{-1}$). This is in close agreement with our experimental result. However, the model does not show any angular velocity dependence on the number of particles. Moreover, the value of magnetic field strength which equation (4) predicts for the occurrence of angular velocity saturation is $> 5000 \text{ G}$ (when $\Omega_i > v_i$), which is far beyond what we have observed in our experiment ($\sim 30 \text{ G}$).

It should be stressed that, unlike in the experiment performed by Sato *et al* [22], the ion–neutral collisional mean free path ($\sim 4 \times 10^{-4} \text{ m}$) in our system is of comparable size to our dust cluster. So the collisional fluid description of the ions might not be appropriate in this case. A comparison of our experimental results with a model using magnetized ions in the local collisionless fluid stage will be investigated in the future.

Another possible mechanism for explaining the rotation is a dust charge gradient across the cluster in the presence of a transverse non-electrostatic force [31]. The charge variation can

be present in complex plasma systems due to inhomogeneity of the bulk plasma surrounding the dust particles, due, for example, to gradients of temperature T_e (T_i) and density n_e (n_i) of electrons (ions) in the plasma. The presence of the magnetic field is expected to modify the radial profile of electron and ion density. This effect is presumably due to the magnetization of the electrons. For our experimental conditions, the Larmor radius for electrons and ions are 6×10^{-5} m and 2×10^{-2} m respectively. Hence the electrons are highly magnetized and the ions are partially magnetized. As the ratio of electron gyrofrequency to electron–neutral collisional frequency is about 1.5 (for ions, this ratio < 0.01), the ambipolar diffusion will be determined by the ions when the magnetic field is present. The change of radial distribution of n_e (n_i) leads to an increase in the dust charge spatial gradient $\beta_r = \partial Z(r)/\partial r$. As one can see from phase diagrams (figures 8(a)–(d)) there is a preferred direction in our system. In such a case, the angular velocity of rotation can be estimated from [32] by

$$\omega = F_{non}\beta_r/2m_dZ\nu_{fr} \quad (5)$$

where F_{non} is a non-electric force, Z is the dust particle charge and ν_{fr} is the collisional frequency. For the non-electric force, different forces can be considered. For example, if we assume the thermophoretic force, ω is given [31] by

$$\omega \text{ (rad s}^{-1}\text{)} = \beta_r/\langle Z \rangle (\text{cm}^{-1}) \frac{\partial T}{\partial r} \text{ (K cm}^{-1}\text{)}/2.8P \text{ (Torr)}. \quad (6)$$

The temperature gradient $\partial T/\partial r$ in the sheath is about 0.5 K cm^{-1} , the charge gradient $\beta_r/\langle Z \rangle$ is 0.05 cm^{-1} , giving a value for ω of 0.2 rad s^{-1} which is very similar to the measured value.

4.2. Angular velocity saturation

As mentioned previously, the angular velocity of the dust cluster was observed to saturate for double-ring clusters. For double-ring clusters such as planar-10, 11 and 12, the angular velocity increased with magnetic field but eventually levelled off. Sato *et al* [22] reported similar findings. However, in their experiment, the angular velocity saturation is independent of the number of particles in the dust cloud [33]. Moreover, the value of magnetic field strength which their model predicts for the occurrence of angular velocity saturation is far beyond what we observed in our experiment ($\sim 30 \text{ G}$).

A possible explanation for the angular velocity saturation is ambipolar diffusion of ions and electrons due to the magnetic field. Another effect of magnetization of electrons is a change from ion-limited ambipolar diffusion to electron-limited ambipolar diffusion [34]. This will change the ambipolar electric field. This phenomenon can explain the saturation in angular velocity for double-ring clusters mentioned earlier. As the magnetic field increases, the radial electric field (a combination of the confining field and the ambipolar field) at the centre of the cluster will eventually decrease. Consequently, the driving force acting on the particles in the inner ring of the cluster will decrease. Since the moment of inertia of the double-ring cluster does not change and the cluster remains as a rigid body due to the strong Coulomb interaction between the particles during rotation, the net effect will be a decrease in the total torque of the dust cluster system. As a result, the angular velocity of the dust cluster decreases. Thus saturation of double-ring cluster rotation occurs.

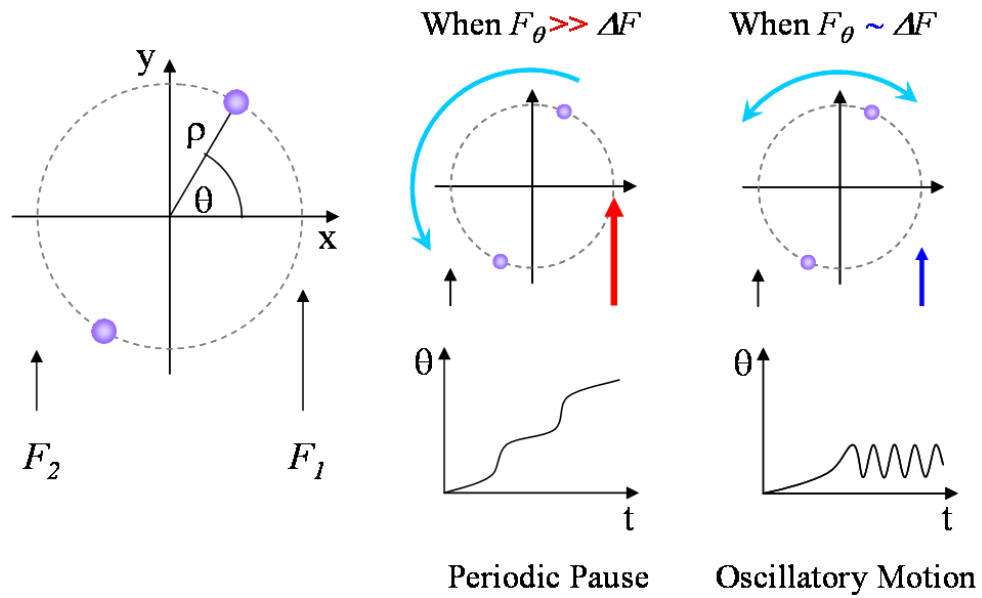


Figure 10. Translational force gradient acting on a planar-2 cluster can result in oscillation and periodic pauses.

Our model will still be consistent with the results of Sato *et al* because a larger confinement potential was used in their experiment. Hence a larger magnetic field would be necessary for them to observe the saturation effect.

4.3. Oscillation and periodic pauses of planar-2 clusters

Here a preliminary model is proposed to explain the oscillations and periodic pauses of planar-2 clusters, which were observed in our experiment. If there is a force gradient across the dust cluster plane,

$$\Delta F \sim F_1 - F_2, \quad F_1 > F_2 \quad (7)$$

where F_1 and F_2 are the unidirectional forces that act normally on each of the two particles, then the cluster will experience a net torque of $M \sim F_1 \rho \cos \theta - F_2 \rho \cos(\theta + \pi)$. This net torque will provide an additional azimuthal component F_θ to drive the cluster into rotation. Depending on the magnitude of F_θ , the cluster rotation will degenerate into either oscillation (when $F_\theta \gg \Delta F$) or periodic pauses (when $F_\theta \sim \Delta F$) as shown in figure 10.

In other words, the total driving force for the dust cluster rotation is a summation of the ion drag force F_{id}^ϕ and the translational gradient force F_θ . If F_θ is not present, then the dust cluster will go into uniform rotation. If F_θ is present, then, depending on the nature, the dust cluster will either oscillate or go into periodic pauses.

5. Conclusion

It has been demonstrated by 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 with lower magnetic fields than is the case for small number of particles. The angular velocity of the clusters increases, while the radius of the clusters decreases, as the magnetic field strength increases. Comparison was made between the theoretical and experimental values of angular velocity. It was demonstrated that although ion drag might be the driving mechanism for the dust cluster rotation, it is not sufficient to fully explain the magnitude of driving force measured in our experiment. Divergence of magnetic field and translational force gradient might need to be taken into account along with the ion drag force to better explain the obtained value of driving force. Possible explanations were proposed for angular velocity saturation of double-ring clusters, oscillation and periodic pause of planar-2 clusters.

Acknowledgments

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See also poster presented in

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