Controlled interactions of two microparticle clouds in a dc glow discharge dusty (complex) plasma

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Abstract. The control of the confinement of charged microparticles in a plasma is an important topic for the dusty plasma community. Earlier experiments have used control over individual microparticles or a single particle cloud to obtain information about the potential structure of the surrounding plasma. In this paper, experiments that make use of active control of two microparticle clouds suspended in a plasma are discussed. Here, an array of three electrodes is used to modify the potential between the two clouds. Through the application of an applied perturbation on one of the array elements, the two clouds are allowed to interact. Particle image velocimetry techniques are used to obtain spatial maps of the interaction process. The experimental measurements show that an apparent recoil occurs between the two particle clouds as a result of the interaction. A simple model is used to show that a recoil may be a possible outcome of the interaction process.

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1. Introduction

Dusty (complex) plasmas have been the focus of intense experimental exploration since the early part of the 1990s. In spite of this effort, one of the great difficulties encountered in characterizing the properties of these systems remains the development of non-perturbative diagnostics. For example, it has been well established that the presence of an electrostatic probe in a dusty plasma can cause significant perturbations to the microparticle clouds leading to the formation of void-like regions (i.e. regions in which none of the microparticles are present) [1] or inducing the formation of vortices in the particle clouds [2]. Consequently, new techniques must be developed to facilitate the diagnosis of the microparticle clouds.

One such technique involves the use of the charged microparticles themselves as miniature, electrically floating probes to measure the properties of the plasma. Typically, this involves the application of a perturbation to a single microparticle or a group of microparticles in order to force these particles to travel through a region of the plasma. By analysing the change in the velocity of the microparticles in their trajectory through the plasma, it is possible to extract detailed information on the potential structure of the plasma [3]–[7]. However, the majority of these experiments only use interactions between pairs of particles to perform these studies and often do not include investigations of the total momentum of the particles.

In this paper, an experiment that actively controls the interactions between microparticle clouds in the Auburn dusty plasma experiment (DPX) device is presented. In this study, an array of three wire electrodes is used as the control mechanism. First, the modification of the bias voltages to the array elements is used to alter and control the confinement of a single microparticle cloud in the plasma. In subsequent experiments when two microparticle clouds are present in the plasma, an applied perturbation to the bias voltages of the array wires is used to control the interaction between the two clouds. Particle image velocimetry (PIV) techniques are used to characterize the interaction process and to provide insight into the observed motion of the microparticles.

The organization of the remainder of this paper is as follows: in the next section, a brief description of the experimental setup will be presented. Results from two experiments will be discussed. The first experiment demonstrates the validity of the control mechanism using a single microparticle cloud. The second experiment then focuses on the controlled interaction of two microparticle clouds. The paper will conclude with a brief summary of the presented results.

2. Experimental setup

The experiments described in this paper are performed using the Auburn DPX device. The basic experimental configuration of the DPX device has been described extensively elsewhere [8]. Only a brief summary of the experimental hardware is given here.

The DPX device is constructed from two ISO-100 (100 mm/4 inch) inner diameter, stainless steel, six-way crosses. For these experiments, argon plasmas are generated in the device using both a biased anode \( V_a = 100–150 \text{ V} \) and a biased cathode \( V_c = -180 \text{ to } -250 \text{ V} \) at neutral pressures ranging from 80 to 150 mTorr. The anode and cathode are both circular brass discs, 2.5 cm in diameter. The cathode is placed near the geometric centre of one of the six-way crosses. The anode is approximately 4 cm above the cathode and horizontally displaced from the cathode by 2–3 cm. It is noted that the anode and cathode positions are reversed from previous experiments on DPX [6]–[8]. A schematic drawing of the arrangement of the internal components of DPX and a photograph of those components are shown in figure 1.
Figure 1. (a) Schematic drawing of the interior of the DPX device. The topmost electrode is the anode, the middle electrode is the cathode and at the bottom is the block with the array wires. (b) Photograph of the interior of the DPX device with a suspended microparticle cloud.

Typical plasma conditions in the DPX device, based upon single Langmuir probe measurements, give a density of \( n_0 \sim 5 \times 10^{15} \, \text{m}^{-3} \), an electron temperature of \( T_e \sim 3\text{–}6 \, \text{eV} \), an ion temperature \( T_i \leq 0.05 \, \text{eV} \) and a plasma potential \( V_p \sim 160\text{–}200 \, \text{V} \). These are typical measurements for dc glow discharge dusty plasmas.

The microparticles in the plasma become suspended between the cathode and an electrically floating (\( V_b \sim 120 \, \text{V} \)) aluminium block in the plasma. This rectangular block electrode (49.0 mm \( \times \) 22.8 mm \( \times \) 14.7 mm) is directly below the cathode and has two 3.6 mm deep depressions separated by a centre-to-centre distance of 20 mm. Generally, when the block is placed within 3–5 cm of the cathode, the presence of the two depressions on the block aids in the formation of two microparticle clouds. For distances greater than 5 cm, a single cloud is formed. It is noted that the microparticle clouds generally form 8–12 mm above the block. Even for electron densities \( n_e \sim 1 \times 10^{15} \, \text{m}^{-3} \), the trapping location of the clouds relative to the block is still considerably larger than the Debye shielding length of the plasma, \( \lambda_{De} \sim 0.5\text{–}1 \, \text{mm} \). Nonetheless, this is a fairly typical experimental observation in dc glow discharge dusty plasma experiments and remains a significant difference between observations in dc- and rf-based dusty plasma experiments.

The three wires of the control array are placed between the two depressions on the block electrode. The wires, labelled 1–3 in figure 1, are 18-gauge solid copper wires and are each separated from each other by 6 mm. Each wire is independently biased in order to manipulate the microparticle clouds. The specific bias voltage configurations for each of the experiments will be described later in this paper.

Microparticles are placed into the DPX chamber by making a small pile on an electrically floating 2.5 cm \( \times \) 2.5 cm tray. The location of this tray is adjusted to ensure that it is below the level of the block electrode to minimize the effect on the potential structure between the block
and the cathode. The microparticles are $2.9 \pm 1.0 \mu m$ diameter silica microspheres—which are the same particles that have been used in earlier studies on DPX. The particles have a mass density of $2500 \text{ kg m}^{-3}$ and, based upon the average radius of $\langle r \rangle = 1.45 \mu m$, the particles have a mass of $m_d \sim 3.2 \times 10^{-14} \text{ kg}$.

To measure the transport of the microparticles in the plasma, the PIV technique is used [9, 10]. The application of PIV to dusty plasma experiments has been discussed in earlier papers [8, 11]. The system consists of a pair of pulsed (15 Hz) Nd:YAG lasers. The lasers are frequency doubled to operate at a wavelength of 533 nm and have a maximum energy of 25 mJ/pulse. The PIV measurement involves the use of a pair of 20–30 ns long laser pulses. The two laser pulses that illuminate the microparticles, one from each laser, are separated by a time interval $0.004 \text{ ms} \leq \Delta t_{\text{laser}} \leq 30 \text{ ms}$. The key feature of the system is that the firing of the lasers is synchronized to the frame-grabbing rate of a 1000 $\times$ 1000 pixel charged coupled device (CCD) camera. This ensures that each illumination by the lasers is captured on a separated video frame. Pairs of images are then compared using a rectangular grid of $n \times n$ pixel interrogation regions (where $n = 16, 32, 64$ or $128$). An average two-dimensional velocity vector in the plane of the laser sheet is computed from the displacement of the particles in each of the interrogation regions.

Through the use of the PIV diagnostic tool, the spatial and temporal evolution of the microparticle velocity measurements are obtained from sequences of image pairs. The image pairs are separated in time by $\Delta t_{\text{sep}} \sim 133 \text{ ms}$, a value that is set by the reset time of the camera and laser system. While the separation time is too long to provide true particle tracking, the ability of the PIV system to take snapshots of the dusty plasma evolution—especially in the presence of known, applied perturbations—facilitates detailed and reproducible measurements of dusty plasma phenomena.

### 3. Single cloud experiments

The first experiments performed in this investigation focused on the manipulation of a single particle cloud in the DPX chamber. The background plasma is generated at an argon neutral pressure of 110 mTorr. The anode and cathode bias voltages are $V_a = 108 \text{ V}$ and $V_c = -222 \text{ V}$.

An image sequence of this manipulation process is shown in figure 2. Here, a particle cloud is suspended above the array and block assembly. In image 1, the reference image, the three array wires are grounded to the vacuum vessel walls ($V_{\text{wire}} = 0 \text{ V}$). Since the plasma potential of the dc glow discharge plasma is close to the anode bias voltage, this condition represents the largest negative bias on the array wires with respect to the surrounding plasma.

In the subsequent images (images 2–6), the bias voltage on the array wires is altered to characterize their effect on the confinement of the microparticle cloud. The wire(s) that are biased in each frame are indicated by a ‘+’ or a ‘∗’. The applied bias voltages are listed in table 1. It is noted that in each case, the bias voltage on the array wires remains negative relative to the surrounding plasma.

The most obvious impact of the applied bias is the modification of the shape of the particle cloud. In images 2–4, where only a single array wire is biased, the particle cloud becomes extruded towards the biased wire. In image 5, where two wires are biased, and in image 6, where three wires are biased, an even larger impact on the particle cloud is observed. These images are consistent with observations of other experiments that the application of bias voltages to probes near a microparticle cloud can modify the confinement of the microparticle clouds in the plasma.

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Figure 2. Six-image sequence showing the effect of applied bias voltages to the array wires on the confinement of a single microparticle cloud. Image 1 is the reference image. Refer to table 1 for the order in which the bias voltages are applied. The wire(s) that are biased in each frame are indicated by a ‘+’ or a ‘∗’.

Table 1. Bias voltages applied to array elements.

| Image number | Wire 1 (V) | Wire 2 (V) | Wire 3 (V) |
|--------------|------------|------------|------------|
| 1            | 0          | 0          | 0          |
| 2            | 0          | 70         | 0          |
| 3            | 70         | 0          | 0          |
| 4            | 0          | 0          | 70         |
| 5            | 70         | 0          | 70         |
| 6            | 70         | 41         | 70         |

4. Double cloud experiments

For the double cloud experiments, two microparticle clouds are suspended above the block/array assembly as shown in figure 1(b). In this experiment, the plasma is generated at an argon neutral pressure of 77 mTorr and with an anode bias voltage of $V_a = 173$ V and a cathode bias voltage of $V_c = -203$ V. Bias voltages are applied to wire 1 ($V_1 = 118$ V) and wire 3 ($V_3 = 127$ V) to keep the two clouds separated from each other. Wire 2 of the array is used as a control or ‘gate’. A square wave pulse from $V_2 = 40$ to 140 V is applied to wire 2 using the electronic components indicated in figure 3. By adjusting the duration of this applied pulse, it is possible to allow the two microparticle clouds to interact.

In figure 4, each image shown is the first of a pair of PIV images. The two PIV images used to compute the velocity vectors are separated in time by an interval $\Delta t_{\text{laser}} = 1.5$ ms. Each pair of images in the sequence is separated by $\Delta t_{\text{sep}} = 133$ ms. Two clouds are shown in these images. The first is the large cloud on the left side of the image. The second is a small cloud that is initially hovering above array wire 3, the rightmost wire in the array.
Figure 3. Schematic drawing of the circuit used to apply the perturbation voltage to array wire 2. ARB = arbitrary waveform generator; BOP = bipolar operational amplifier; PS = power supply.

Figure 4. Image sequence of the interaction between two particle clouds. Images 7–18 of a 30-image video sequence are shown. Each image in the sequence is separated by $\Delta t_{\text{sep}} = 133$ ms. There are two microparticle clouds shown. The first is the large cloud on the left side of the image. The second is a small cloud that is initially hovering above array wire 3 (the rightmost wire in the array). During the collision process, after the perturbation is applied, the two clouds move towards each other, eventually colliding above wire 2.

The time and space evolution of this process are recorded using the PIV technique. Figure 4 shows a portion (images 7–18) of a 30-image video sequence. During the first second ($\Delta t = 1$ s) of the process (corresponding to images 0–8), before the application of the perturbation to wire 2, the particle clouds are suspended at fixed positions in the plasma. This can be observed in the images labelled 7 and 8 in figure 4.

The impact of the perturbation to bias voltage on wire 2 can first be seen in image 9. Here, a general vertical displacement of the particle cloud occurs, consistent with the observations from the single cloud experiment as shown in figure 2. The remaining nine images (images 10–18) show the subsequent motion of the two particle clouds.

Figure 5 shows an expanded view of one of the images, image 10, in which the two-dimensional velocity vectors obtained using the PIV diagnostic are also shown. This shows that the boundary of the larger cloud is initially located near $x = 15$ mm and the smaller cloud is initially located near $x = 35$ mm. After the bias voltage on wire 2 is modified, there is a flow of
Figure 5. Detailed view of image 10 (from figure 4) that shows the two-dimensional velocity vectors obtained using the PIV diagnostic.

microparticles from both clouds to an intersection region above wire 2. This can be observed in images 14–16 as the two particle clouds are shown to converge.

The PIV technique is used to obtain instantaneous two-dimensional velocity maps for each image pair. This allows details of the particle motion that would otherwise be difficult to extract from particle tracking techniques to be revealed. A contour map of the time and space evolution of the velocity of the particle clouds is shown in figure 6. Here, the horizontal axis represents position measured in millimetres for the images. The vertical axis represents the image number, i.e. time. The colour contours represent the horizontal component ($v_x$) of the velocity measured in units of mm s$^{-1}$ obtained at a constant horizontal ‘slice’ through the images at $y = 13.04$ mm or approximately 8 mm above the height of the wires. The location of wire 2 is indicated in figure 6 as a vertically dashed line located at $x \approx 24$ mm.

In figure 6, both the time and space evolution of the interaction process are presented simultaneously. Recall that at the beginning of the interaction process, the two particle clouds are spatially separated by some 20 mm in the plasma. Once the perturbation is applied, the two particle clouds begin to move towards each other, eventually converging above wire 2. The directed motion of the two particle clouds is indicated by the generally positive velocity contours to the left of wire 2 and the generally negative velocity contours to the right of wire 2.

By images 14 and 15 ($t \sim 0.5$ s) as shown in figure 4, the two clouds have begun to merge into each other. This can also be observed in figure 6 along the horizontal lines indicated by images 14 and 15. Here, the right-moving particles (i.e. motion in the $+x$-direction) from the larger cloud are shown to interact with the left-moving particles (i.e. motion in the $-x$-direction) from the smaller cloud. The deceleration and eventual reversal of the motion of the particles from the smaller cloud as they interact with the larger number of ‘rightward-moving’ particles from the larger cloud are shown near the boundary region as the velocity measurements progress in time through images 16–18.

In addition to the reversal of particles from the smaller cloud, a region of ‘leftward-moving’ (i.e. negative $v_x$) particles develops in the larger cloud during the last few images around $x \approx 23$ mm. It is proposed that this may be a recoil phenomenon that occurs due the exchange of momentum between the two particle clouds.

5. Analysis of particle motion

To interpret the observed particle motion, it is necessary to consider both the horizontal and vertical motion of the particle clouds. Figure 7 shows a measurement of the average horizontal and vertical position of the smaller of the two clouds (from the left side of the images shown
Figure 6. Contour plot of the time and space evolution of the interaction process between the two microparticle clouds. The horizontal axis represents position measured in millimetres for the images. The vertical axis represents the image number (10–18) or time, as measured using image 10 as a reference for $t = 0$ s. The colour contours represent the horizontal component ($v_x$) of the velocity measured in units of mm s$^{-1}$ obtained at a constant horizontal ‘slice’ through the images at $y = 13.04$ mm. The location of wire 2—the location at which the two particle clouds come together—is indicated by the vertically dashed line located at $x \approx 24$ mm.

in figure 4). Here, only the motion of the cloud from images 10–18 is considered. Figure 7 shows that as a result of the applied perturbation, there is a horizontal displacement of the particle cloud by $\Delta x \sim -7$ mm without a significant vertical displacement. This suggests that after the initial vertical displacement of the particle clouds, the vertical forces present in the system—gravitational forces, the vertical component of the electrostatic force, and ion drag forces—rapidly come into equilibrium and have very little impact on the observed motion and ‘collision’ of the two particle clouds. As a consequence of the aforementioned observation, this analysis will focus on characterizing the horizontal forces that are acting upon the microparticle clouds as a result of applied perturbation.

It is clear that as a result of the applied perturbation of the potential on wire 2, the plasma potential in the region of the particle cloud will be changed, resulting in a change in the equilibrium position of the particle clouds. An outstanding question, however, is whether the interaction between the two particle clouds can give rise to an apparent recoil.

To explore this, consider the motion of the particles to be governed by three forces: the horizontal component of the electrical force, the neutral drag force and a screened dust–dust interaction force.

$$m_j \ddot{x}_j = -q_j E_x(x) + m_n N(\pi r_d^2) v_n \dot{x}_j + \sum_{k \neq j} \left( \frac{1}{4\pi \varepsilon_0} \right) \frac{q_j q_k}{x_{jk}^2} e^{-\left(x_{jk}/\lambda_{de}\right)}.$$  \hspace{1cm} (1)
In the first two terms of equation (1), $x_j$ is the $j$th microparticle, $m_j$ is the microparticle mass, and $q_j$ is the particle charge—approximately 4000 elementary charges for these experimental conditions. $E_x(x)$ is the $x$-component of the electric field, $m_n$ is the mass of the neutral atoms (argon for this experiment), $N$ is the neutral gas density, $v_{tn}$ is the thermal velocity of the neutrals (assuming 300 K neutral temperature) and $r_d$ is the radius of the microparticles. In the final term of equation (1), a screened Coulomb force is used to describe the dust–dust interaction force.

Two components are required to use equation (1) to model the motion of the microparticle clouds in the plasma. First, a model of the potential structure in the region near the particle clouds is developed. In this model, the potential structure due to the aluminium block, the three array wires and a background plasma potential (assumed to be constant) are included. Here, the potential due to the block and array wires is Debye screened using an $r_s = 1 \text{ mm}$ screening length ($\sim 2\lambda_{De}$).

$$\psi(x, y) = \psi_0 + \psi_b e^{-r_b(x,y)/r_s} + \sum \psi_{wi} e^{-r_{wi}(x,y)/r_s}.$$  \hspace{1cm} (2)

Here, $\psi_0$ is the background plasma potential ($\sim 160 \text{ V}$), $\psi_b$ is the potential of the block relative to the surrounding plasma ($\sim 40 \text{ V}$) and $\psi_{wi}$ is the potential of each of the array wires relative to the surrounding plasma potential. It is noted that in this simple model, the potential due to the wires is modelled similarly to a probe in a plasma, the potential being Debye screened as a function of distance from the wire. $r_b$ and $r_{wi}$ are the distances from the block and wire to the point $(x, y)$, respectively. The block is located at $y = 0 \text{ mm}$ and extends from $x = -18.5$ to $+30.5 \text{ mm}$. The wires are located at $y = 1$ and at $x = 0, 6$ and $12 \text{ mm}$. For reference, in the model the particle clouds will be placed at a height of $y = 9 \text{ mm}$.

A two-dimensional contour map of the resulting potential structure is shown in figure 8(a). The figure indicates that there is a rapid change in the potential as the distance from the blocks and wires increases, as expected. However, there remains a small gradient in the potential.
Figure 8. (a) Contour plot of the plasma potential in the region above the block electrode and array wires. (b) Contour plot of the strength of the $x$-component of the electric field above the block and array wires.

The location of the dust particles, this gradient gives rise to a weak electric field ($\sim 2-10$ V m$^{-1}$) in the horizontal direction. A contour map of the strength of the horizontal component of the electric field is given in figure 8(b).

The second component of the model is the use of aggregate ‘superparticles’ to model the behaviour of the particle clouds. The smaller cloud is modelled as a single particle. The larger cloud is modelled as two particles: a smaller one at the leading edge of the cloud and a larger particle behind it. While this model certainly does not include all of the details of the interactions, it will be shown that this analysis can provide some insight into the interaction of the two particle clouds.

The model simulates the motion of the two particle clouds in the laboratory frame. Both clouds are given an initial velocity towards each other and their subsequent motion is modelled using equation (1). The positions and velocities of the smaller cloud and the leading edge of the larger cloud are then plotted and compared to the experimental observations.

The first result of this model is shown in figure 9(a). Here, the measured average velocity of the smaller cloud is compared with results from the model. The figure shows that there is general agreement between the magnitude and time evolution of the velocity until the two clouds come into contact with each other around $t \sim 0.5$ s. This is consistent with the observations presented in section 4 and the data presented in figures 4 and 6. It is noted that there are oscillations in the velocity that are present in the model that are not present in the experimental data, although there may be an indication of oscillatory behaviour near $t \sim 0.9$ s. Recall that the PIV diagnostic has a temporal resolution of $\Delta t_{\text{sep}} = 0.133$ s, which is not sufficient to resolve all of the details of the motion. However, this first result suggests that this model can give results that can match the experimental observations.

Figures 9(b) and (c) give the results of two classes of results from the model. Each plot shows the position (in millimetres) of the large and small clouds as a function of time (in seconds). The upper curve in each plot represents the motion of the smaller cloud (leftward moving) and the lower curve represents the motion of the larger cloud (rightward moving). In general, both
Figure 9. (a) Comparison between the model (solid curve) and experimental data (circles) for the horizontal velocity (in mm s$^{-1}$) of the smaller cloud as a function of time. (b) Model results for the motion of both the large (solid line) and small (dashed curve) clouds. Here, the ratio of the number of particles between the smaller cloud and the leading edge of the large cloud is $N_{\text{small}}/N_{\text{large}} \sim 1.5$. The arrow indicates the observation of a possible recoil effect—a reversal in the motion of the particles—in the particles from the large cloud. (c) Similar results as in (b) are shown for the case $N_{\text{small}}/N_{\text{large}} \sim 0.75$. No recoil is observed in this case.
Thus, it is concluded that the model gives three key results. First, the model does give qualitative, and perhaps quantitative, results that appear to be consistent with the experimental observations of the particle motion. Second, the model shows that, under the appropriate simulation conditions, it may be possible for a recoil between the two particle clouds to occur. And third, the model suggests that there may be additional features of the motion that are simply not revealed due to the limited time resolution of the PIV diagnostic. Although this model is not sophisticated enough to contain all of the details of the experiment, it does reveal the key physical phenomenon of recoil-like behaviour between the two particle clouds. Furthermore, it suggests that in order to continue these experiments, a combination of PIV and other visualization techniques should be used to reveal the details of the motion of the particles during the interaction process.

6. Summary

Measurements have been performed to control the confinement and interaction of microparticle clouds in the Auburn dusty plasma experiment. Two experiments are performed. In the first experiment, the shape and confinement of a single microparticle cloud is manipulated through the application of bias voltages to an array consisting of three wires. This process is shown to be consistent with observations of earlier studies.

In the second experiment, two microparticle clouds are suspended in the plasma and are allowed to interact through applied bias voltages to the array wires. Particle image velocimetry techniques are used to characterize the time and space evolution of the interaction process. For the measurements presented in this paper, it is shown that the collision between the two clouds can produce a recoil-like phenomenon. A simple, one-dimensional model for the particle motion is developed that shows that recoil may be possible as a result of the interaction between two particle clouds.

The long-term objective of this experiment is to develop a reliable method for using microparticles from one particle cloud to ‘probe’ the potential structure of a second cloud as was done using the particle streams observed in earlier experiments [6]. Larger particle velocities than have been obtained in these initial studies will probably be required in order to overcome the recoil effects. In future experiments, it is planned to use a more developed array to obtain a greater degree of control over the microparticles and their interaction process. This new array will consist of up to 64 individual wires. The trapping potential wells will be created by biasing groups of these wires to form steady-state and moving electrostatic traps. Thus, it will be possible to perform detailed and reproducible investigations of microparticle cloud interactions. With this additional degree of control, considerably more detailed information about the interaction process can be obtained.

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