Charging and interaction of two-particle system within a glass box immersed in a low-vacuum argon plasma

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Abstract— **Due to Debye screening, the interaction between charged dust particles within a plasma may not be considered as a simple Coulomb force. In order to observe particle interaction, the top particle in a vertical, two-particle chain is pushed from its equilibrium position using a high-power Verdi laser, and as it returns to equilibrium will interact with the second particle. In order to isolate the particle interaction force, the electrostatic force and neutral drag force are subtracted from the net force acting on the particle by using a single particle undergoing damped oscillations in the box as a reference. The net electric field and drag force within the glass box are examined by forcing damped oscillations of a single particle, in the vertical direction by an applied DC bias between electrodes and in the horizontal direction by laser-pushing. It is found that in both the horizontal and vertical dimensions the electric field depends linearly on the particle's distance from its equilibrium position, and the linear coefficient to describe the field in turn has a linear dependence on plasma power. After isolating the particle-particle interaction force, what should be an equal and opposite interaction force between the particles is found to be asymmetric, and possible causes for this are discussed.**

Index Terms — **Ion stream, ion wake, charge deduction, complex plasma, GEC cell, asymmetric particle interaction.**

I. INTRODUCTION

WHEN an insulator is immersed within a plasma, it is subjected to a high rate of collisions with the electrons and ions which comprise the plasma. Because the average energy of the electrons and ions are equal, the electrons travel within the plasma at much higher velocities than the ions (due to their lower mass), such that they will collide with any solid object within the plasma at a higher rate per second than will the ions. Because a certain percentage of charged particles which collide with a given insulator will adhere to it, this causes the insulator to build up a negative net charge [1]–[3]. A glass box within the plasma will therefore acquire a negative charge on its walls, creating a convenient way of confining a similarly negatively-charged dust particle at the horizontal center of the box. This dust grain will levitate at a height within the box at which the electrostatic force from the bottom electrode is equal and opposite to the force of gravity.

There is no consistent effect of the electric field between electrodes on the electrons, as their randomized velocities are too large to overcome. The slower-moving ions, however, will be caused by the field to move downward (in the direction of gravity) toward the negative electrode. This downward flow is known as the ion stream. In the presence of a negatively-charged dust grain, any ions passing within its Debye radius will be electrostatically lensed, being focused into a region of positive space-charge known as the ion-wake. If a second dust particle is introduced down-stream of the first particle, it will be subjected to more ion collisions than the up-stream particle because of the ion-wake created by the up-stream particle, and therefore a portion of its negative charge will be offset, causing it to have an overall lower charge than its up-stream counterpart [1]–[4].

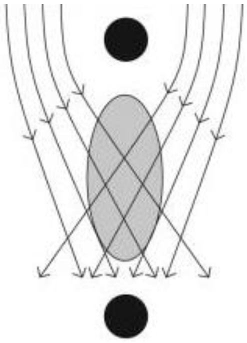

Fig. 1. Ion stream is electrostatically lensed by the up-stream (top) particle, creating a region of positive space-charge directly below it. The down-stream particle will be de-charged by this abnormally high number of ion collisions it is made to undergo.

Because of the nature of the confining forces due to the electrode and the walls of the box, the natural equilibrium position for multiple particles within the box is to form a vertical chain (at least for the RF amplitudes herein considered – 235 mV to 340 mV) [5]. If a high-powered laser is used to push the top particle away from its equilibrium position, the particle beneath it will attempt to rise upward and take the pushed particle's place. However, the pushed particle will also

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attempt to regain its position once the laser is shut off and the dominant horizontal forces acting on it are once again the box walls. The two particles are then set on a collision course, and as they approach one another the opportunity presents itself to observe their interaction for a substantial range of separation distances.

The object of this paper is to quantify the forces acting on a single, oscillating particle within the box – namely the net electrostatic force due to the box and the bottom electrode, as well as the neutral gas drag (i.e., "air resistance") – in order to subtract these forces from the two-particle case and thereby determine the interaction force between particles.

II. EXPERIMENTAL SETUP

This experiment utilizes a gaseous electronics conference (GEC) radio-frequency (RF) cell, filled with argon at a vacuumed pressure of 0.100 ± 0.001 Torr. A pair of capacitively-coupled electrodes 8 cm in diameter are situated one above the other, separated by a distance of 1.90 cm. The upper electrode is grounded, while the lower electrode is powered by an RF generator at a constant frequency of 13.56 MHz. The amplitude of the input RF signal was varied between 235 and 340 mV. A glass box of 1.27 cm × 1.27 × 1.27 cm is placed in the center of the lower electrode. Melamine formaldehyde spheres are used as dust particles, having a manufacturer-specified mass density 1.514 g/cm^3 and diameter 8.89 ± 0.09 μm. A dust dropper is used to drop particles into the glass box, where they are illuminated by a vertical sheet of laser light. The particles' positions are recorded at 1000 frames per second (fps) using a side-mounted, high-speed CCD camera with a microscope lens. In order to oscillate the particles vertically, the lower electrode is additionally connected to a DC source, which was varied may be varied in frequency. In order to oscillate a single particle horizontally, the beam of high-powered laser is guided into the chamber by an adjustable optical system. The power supplied to the laser may also be controlled directly.

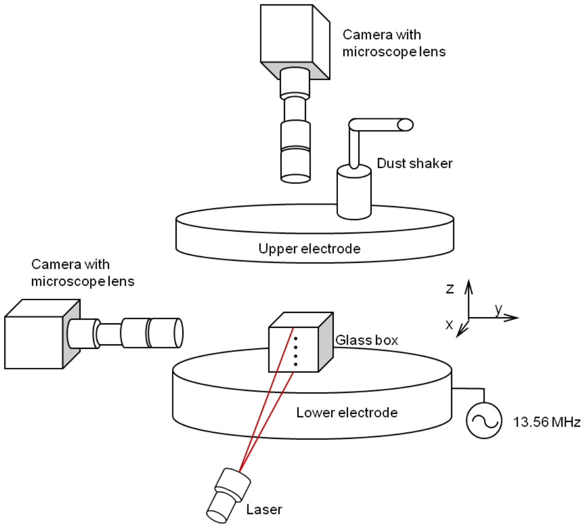

Fig. 2. Equipment and configuration used in this experiment. Note the laser shown is used to illuminate the particles in the box; the high-powered Verdi laser used to perturb the particles is not shown.

III. PROCEDURE

A. Single-Particle Vertical Oscillations

A group of dust particles were dropped into the glass box, and the plasma power was slowly reduced until only one particle remained levitating. This singe particle was then vertically oscillated by applying a DC bias to the lower electrode. The frequency of the DC bias was varied from 1 to 15 Hz, and the approximate resonance frequency was determined by observing which frequency caused the particle to reach the greatest distance from its equilibrium position. Then, while the particle was oscillating at its resonance frequency, the DC input was abruptly shut off, such that the confining forces and neutral gas drag acting on the particle caused the particle to exhibit damped oscillations until finally returning to rest at its equilibrium position. This process was repeated at RF input amplitudes of 235, 252, 270, 283, and 340 mV.

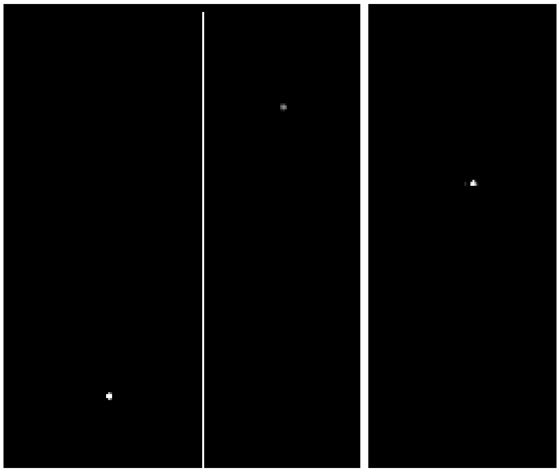

Fig. 3. Post-DC damped oscillations at 270 mV. The particle's maximum displacement from equilibrium is shown on the left, distance after two oscillations in the center, and equilibrium position on the right.

B. Single-Particle Horizontal Oscillations

A single particle levitating in the box was obtained in the same manner as for vertical oscillations. The high-power laser was set at its lowest power setting (0.01 W) and aligned with the particle. At this power setting, the laser does not exert sufficient force on the particle to move it appreciably; this is therefore a convenient method to ensure the laser is in fact incident on the particle before attempting to push it. After blocking the laser's beam, its power was increased to 0.03 W. Then the laser was quickly unblocked and re-blocked, such that its beam was incident on the particle long enough to push it from its equilibrium position, but not so long that it pushes it too close to the wall of the box. Once the laser's beam was re-blocked, the particle exhibited horizontal damped oscillations until the returning to equilibrium. Laser power was varied between 0.03 and 0.15 W until a satisfactory initial displacement from equilibrium was achieved. This process was repeated at the same RF input amplitudes as the vertical oscillation case.

Fig. 4. Post-laser horizontal oscillations. The top image shows the particle's furthest displacement from equilibrium, while the bottom shows its final equilibrium position.

C. *Two-Particle Perturbation and Interaction*

Much like the procedure for obtaining a single particle, a two-particle chain was obtained by dropping a cloud of dust grains into the box and lowering the power was until only two particles remained in levitation. For the RF amplitude used, the electric field within the box is such that a vertical chain is the natural equilibrium arrangement for a system of two particles [5]. Using the same technique as was used to obtain horizontal oscillations in the single-particle case, the high-powered laser was used to push the top particle from its equilibrium position. Once the top particle is no long directly above it, the bottom particle will begin to rise upward in order to occupy the newly vacated position at which a single particle would be at equilibrium. Once the laser's beam was blocked, the perturbed particle attempts to return to its equilibrium position, only to find it occupied by the formerly bottom particle. It will then be "bounced" downward, and after some small oscillations the two particles will have switched positions. This process was repeated at the same RF input amplitudes as the single-particle oscillation cases.

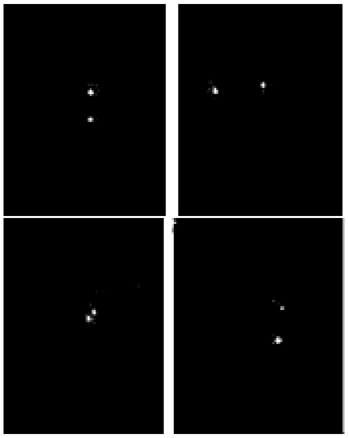

Fig. 5. Representative data for the two-particle case. The system begins at equilibrium as shown above left, then the top particle is pushed out of the chain by the Verdi laser. The lower particle rises up to a position slightly above the first particle's initial position, while the pushed particle then comes back in toward the second particle. They come within a very small distance of one another before repulsing each other such that the pushed particle now moves downward to occupy the second position in the chain. The particles exhibit small horizontal oscillations before finally settling in to their equilibrium positions.

IV. Results and Analysis

A. *Damped Oscillations and the Electrostatic Confining Force*

In order to compute the electrostatic confining force, we begin at the oscillating particle's equation of motion in each dimension:

$$ma = qE_y - m\beta v - mg \tag{1}$$

$$ma = qE_x - m\beta v \tag{2}$$

By treating the particle's motion as that of a damped harmonic oscillator, MatLab's built-in curve-fitting may then be used to find an analytic position function for the particle's motion, of the form

$$y(t) = a\exp(-bt)\cos(ct) + d.$$

The coefficient of the neutral gas drag may be then computed by

$$\beta = 2b, \tag{3}$$

where β has units of Newtons per kg-meters/second.

The particle's motion was also fitted to a Fourier function of the form

$$f(t) = a_0 + \sum_{n=1}^{n=8}\left(a_n\cos\frac{n\pi t}{L} + b_n\sin\frac{n\pi t}{L}\right).$$

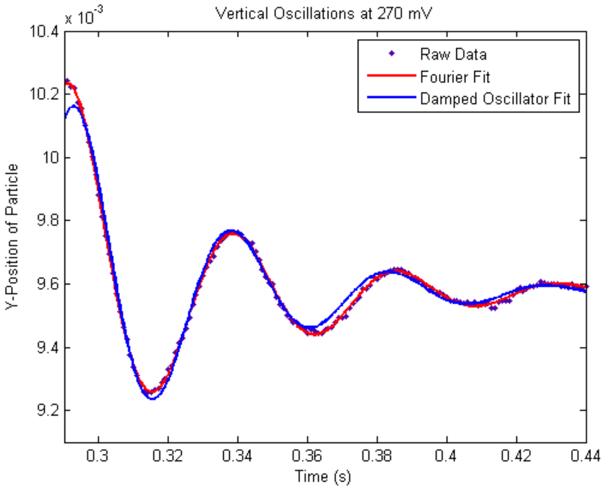

Fig. 6. Representative data for single-particle damped oscillations in the vertical direction. Vertical position is given as the particles height, as measured from the bottom of the box. Also shown are the fitted functions obtained in MatLab.

The Fourier solution is much easier for MatLab to compute, and therefore served primarily as a convenient tool used to obtain the particle's velocity and acceleration functions by differentiation. Using the particle's velocity and acceleration, the confining force acting on the particle may easily be determined by

$$F_y = qE_y = ma + m\beta v + mg$$
$$F_x = qE_x = ma + m\beta v$$

When plotted vs. the particle's position, it would appear the electric field has a very nearly linear dependence on distance from equilibrium.

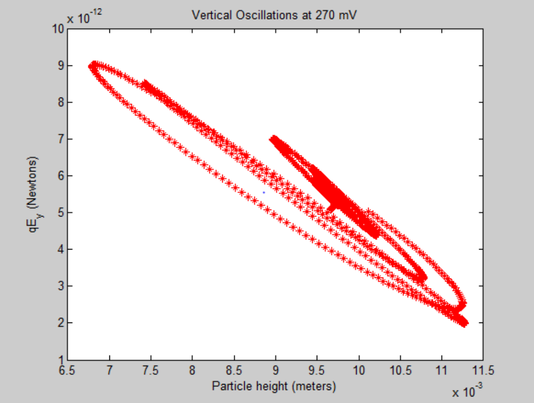

Fig. 7. The vertical component of the electric field, as dependent on height within the box.

The electric within the box may be simply described by the equations

$$E_y = k\Delta y$$
$$E_x = h\Delta x,$$

where h and k are the linear coefficients of the field, which themselves vary almost linearly with the plasma power.

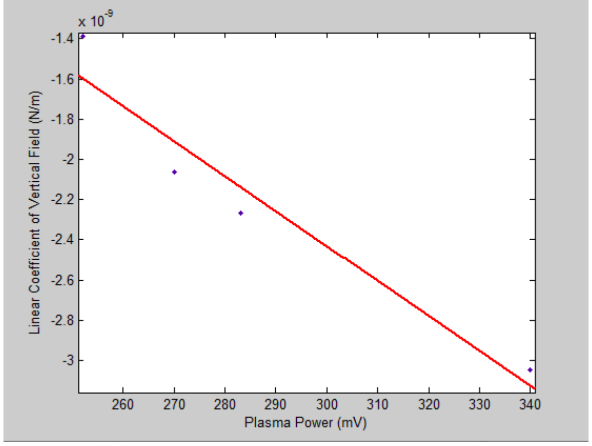

Fig. 8. The linear coefficient of the vertical component of the electric field decreases with increasing plasma power.

B. *Two-Particle Interaction*

Again using MatLab's built-in curve-fitting tool, this time using only a Fourier fit, an analytic equation was obtained for the motion of each of the two particles in both the x- and y-directions, and subsequently differentiated to obtain equations for each particle's velocity and acceleration.

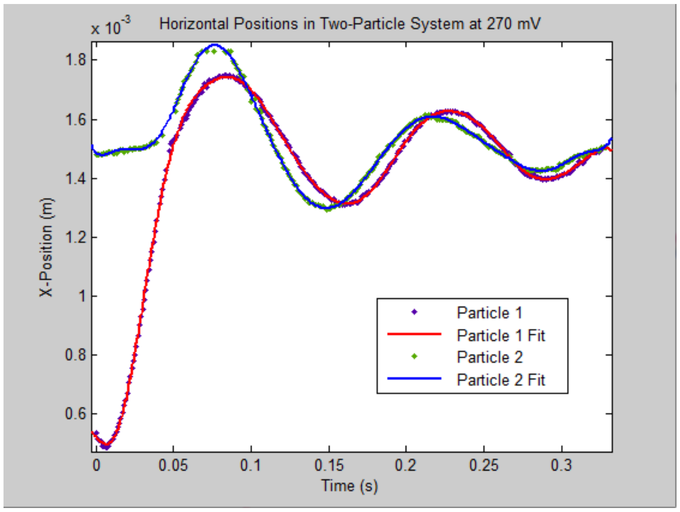

Fig. 9. Horizontal position of each of the two particles in the box. At t = 0, the laser beam was blocked and particle 1 was thereby allowed to return toward the center of the box.

A MatLab algorithm was then designed to consider the position of the first of the two particles, find the y-acceleration experienced by the vertically oscillated single particle when it was at the same location within the box, and to subtract this acceleration from the net acceleration experienced by the particle in the two-particle case. This algorithm was also applied to the second particle, and was repeated for both particles to find and subtract the x-acceleration of the horizontally oscillated single particle. Only the x-component of the particle's separation and interaction force was considered for the window during which the first particle was moving horizontally toward the second particle (i.e., immediately after the laser beam had been blocked), and only the y-component was considered for the window immediately following the particle's moment of closest approach after the 1st particle's attempt to return to equilibrium and extending until the particle's maximum displacement downward. After carrying out these calculations, the remaining accelerations of each of the two particles should be due entirely to their interactions with one another.

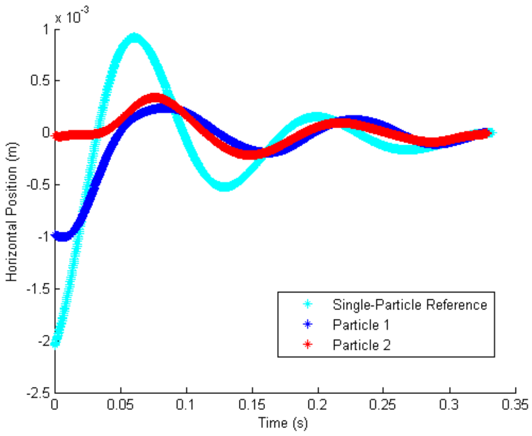

Fig. 10. The horizontal positions of each of the particles in the two-particle case, overlaid with the horizontal position of the single particle during its damped oscillations at the same power (270 mV). The algorithm to subtract

from each of the two particles the net force acting on the single particle took into account both position in the box as well as velocity in determining the most similar one-particle case.

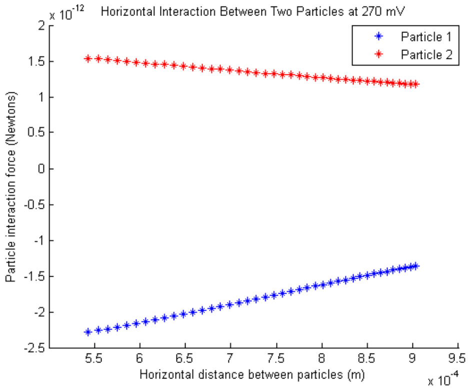

Fig. 11. X-component of the inter-particle interaction force as a function of horizontal inter-particle distance.

V. DISCUSSION

As can be seen from the spiral-shape of the electric field when graphed vs. the position of the particle (Fig. 6), it would appear that the force acting on the particle is to some extent affected by the particle's velocity. It is as yet unclear whether this is due to a change in the particle's charge or whether the change is in the confining force itself. However, it would seem intuitive that the confining parameters would be unaffected by the motion of the particle, and therefore it appears likely that the particle's charge is somehow affected by its velocity or at least by its position within the box.

In transitioning between 270 and 283 mV, there is very little change in the linear coefficient describing the horizontal field within the box, even though the vertical coefficient continues to decrease linearly as expected based on the other data. It has been previously shown [*Insert citation*] that the plasma conditions within the box undergo a fundamental change when increasing the plasma power within this range, and it is therefore assumed that this inconsistency in the coefficient's value is due to such a change in plasma conditions.

At most power settings, there was substantial over-lap between the position of the single particle in its oscillations and each of the two particles in the two-particle case. In some cases, however, using the point of the single-particle's oscillations at which it was closest to the position of one of the two particles required choosing an oscillation at which the single particle was moving with substantially greater velocity than either of the particles in the two-particle case at that position. If the electrostatic force acting on the particle does indeed vary with velocity as previously seen, then this could be a source of significant error. This especially applies to the down-stream particle, because at most plasma powers the single-particle only descended that low on its first oscillation, when it would have had the greatest velocity.

For all plasma powers, the force exerted by the two particles on one another appears to be asymmetric in both the horizontal and vertical dimensions. One possible explanation is that the positive space-charge which forms between the two particles as a result of the up-stream particle's ion wake affects the two particles differently. Of course each of the particles would observe the same magnitude of space charge, but depending on the shape of the wake the charge could be concentrated nearer to one of the particles than the other. Another possibility is that the ion wake caused by the down-stream particle could be acting on the down-stream particle while remaining a negligible factor as far as the up-stream particle is concerned. This would make sense, considering that the down-stream particle seems to be repulsed more strongly downward by the up-stream particle than vice-versa; at least a part of this additional force may in fact be due to the attractive force of the down-stream particle's ion wake pulling downward.

Another likely cause would be that the down-stream particle's net charge is reduced by the ion wake of the up-stream particle, and therefore the confining force subtracted from its equation of motion is over-estimated because the single oscillating particle used as a reference was not subjected to any ion wake and therefore had a higher charge. This difference in assumed and actual charge of the down-stream particle would manifest itself in an asymmetry of inter-particle force. If this is indeed the case, then it would not be a matter of great difficulty to obtain the charge ratio of the up-stream particle as compared with that of the down-stream particle by simply taking the difference in force exerted on the up-stream by the down-stream and on the down-stream by the up-stream and considering this disparity to be equal to the difference in the confining force exerted on a de-charged and non-de-charged particle. This difference, in conjunction with the magnitude of the confining force felt by a non-de-charged particle, would yield the charge-ratio of the two particles.

VI. CONCLUSION

In this paper it has been shown that, apart from a comparatively small dependence on particle velocity, the electrostatic confining force acting on a particle within the glass box has a n approximately linear dependence on the particle's displacement from its equilibrium position. This effect is consistent in both the horizontal and vertical dimensions.

Additionally, it has been shown that the linear coefficients to describe the horizontal and vertical fields within the box decrease linearly with increasing plasma power, with the exception being for the transition from 270 to 283 mV, at which there seems to be a change in plasma conditions.

Finally, the particle-particle interaction force between an up-stream and down-stream particle has been approximated, though its accuracy is suspect due to the asymmetry of the force and the known factors causing a discrepancy between the forces acting on the down-stream particle and those acting on the reference single-particle.

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