Measuring the Charge of a Particle in an RF Dusty Plasma

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ABSTRACT

A dusty plasma is an ionized gas that contains micron-sized solid particles. The particles in a dusty plasma gain a large negative charge by collecting electrons and ions from the surrounding plasma. Consequently, the particles can be levitated by an electric field in the plasma. They can also interact with each other via Coulomb repulsion to form stable, ordered structures resembling crystal lattices called dusty plasma crystals. Because electrostatic forces are responsible for these and other phenomena, most experimental and theoretical studies of dusty plasmas require a knowledge of the particle charge. One technique to measure the charge, called the vertical resonance method, uses a video camera to measure the height of vertical particle vibrations caused by modulating the RF voltage. The resonance frequency of the oscillations, along with Langmuir probe measurements of the plasma ion density, then determines the particle charge. We formed 2-D dusty plasma crystals in an argon RF discharge and evaluated several methods of measuring the particle charge. We tested the original vertical resonance method against a new variation of the method that relies on more accurate measurements of plasma potential and particle height instead of ion density. In addition, we measured the phonon spectrum of the plasma crystals and studied the propagation of laser-induced longitudinal and transverse waves, all of which allowed an independent means of determining the charge. We are continuing to compare the charge measurements from all these methods.

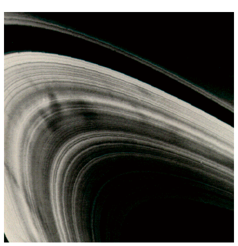
PLASMAS

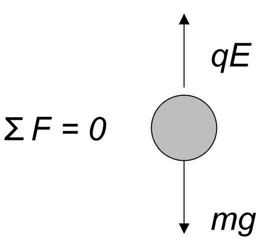
- Ionized gases containing electrons, ions, and neutral gas
- So-called "fourth state of matter"
- Exhibit fascinating electrical and magnetic properties
- Make up most detectable matter in the universe

Argon plasma in vacuum chamber

DUSTY PLASMAS

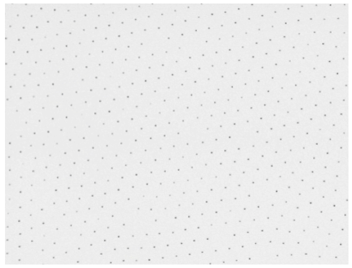
- Plasmas containing macroscopic solid particles in addition to electrons, ions and neutral gas
- Solid particles acquire large negative charge (> 1000 *e*) from bombardment by electrons and ions in plasma
- Found in the rings of Saturn, comet tails, and semiconductor plasma etching devices
- Charged dust particles can be levitated by electric fields





DUSTY PLASMA CRYSTALS

- Charged dust particles interact with each other via Coulomb repulsion
- Particles can arrange themselves into ordered lattice structure resembling that of atoms in a crystalline solid
- Referred to as dusty plasma crystals, also as Coulomb crystals
- Exhibits solid-like properties, such as transverse wave propagation, while not actually being solids



Inverted image of 2-D dusty plasma crystal

- Magnitude of charge on dust particles determines most interactions with plasma and with other particles

THEORY: VERTICAL RESONANCE METHODS

- Induce vertical oscillations of levitated dust particles in plasma by modulating levitating electric field
- Model dust particles as damped driven oscillators
- Damped driven oscillators exhibit resonance, or marked increase in amplitude of oscillations at a particular resonance frequency
- Resonant frequency depends on charge and other measurable parameters

Expression for resonant frequency ω_o:

$$\omega_o^2 = \frac{q n_i e}{m \varepsilon_o}$$

where q is the particle charge, m is the particle mass, and n_i is the plasma ion density

- Original vertical resonance method requires Langmuir probe measurement of ion density to determine charge, but density must be measured in the bulk plasma and not in the sheath region where particles are located
- Results in large uncertainties, >50 %, in value for particle charge

Thus, a variation on the vertical resonance method that calculates the resonant frequency in a different way is useful.

- Novel modified resonance method does not require ion density measurement
- Instead, uses more accurately measured particle height and plasma potential
- Assumes linear variation of sheath electric field with height

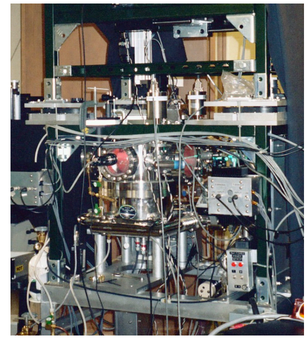
Modified method expression for resonant frequency

$$q = \frac{me(x + g/\omega_o^2)^2}{2(V_{dc} - V_p)}\omega_o^2$$

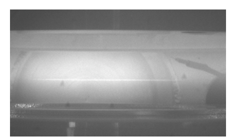
where x is the particle height, g is the acceleration due to gravity, V_{dc} is the electrode self-bias, and V_p is the plasma potential.

EXPERIMENTAL SETUP

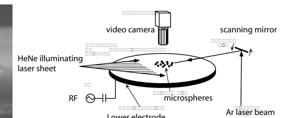
- Argon gas discharge: apply radiofrequency alternating voltage across gas in modified GEC cell vacuum chamber



- 13.56 MHz, ~100V peak-to-peak RF voltage, 8 - 20 W RF power
- ~20 mtorr Ar gas pressure
- $T_e \approx 2$ eV, $V_p \approx 21$ V, $n_i \approx 3 \times 10^{15}$ m^{-3}
- 8.09 ± 0.18 m diameter plastic microspheres dispersed via shaker
- Particles levitated in sheath electric field above horizontal planar electrode
- Radially parabolic potential provided horizontal confinement
- Particles illuminated with HeNe laser and imaged with top and side view video cameras
- Langmuir probe inserted into chamber to measure electron temperature, ion density, and plasma potential
- Ar laser incident on plasma crystal induced longitudinal and transverse waves for further charge measurement techniques



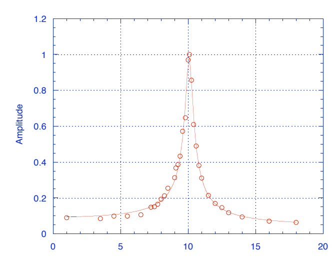
Side view image of particles (illuminated line). Note Langmuir probe in background.



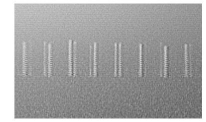
Schematic overhead diagram of experimental setup.

VERTICAL RESONANCE METHOD RESULTS

PARTICLE VERTICAL RESONANCE CURVE



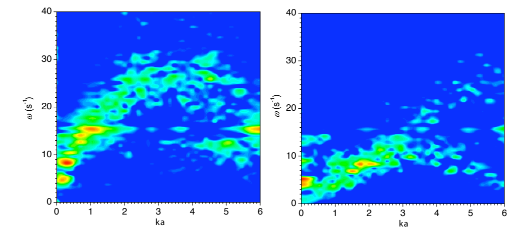
$\omega_o/2\pi = 10.08 \pm 0.01$ Hz



Time-exposed image of particles vibrating vertically due to modulated voltage. Similar images were used to measure particle oscillation amplitudes.

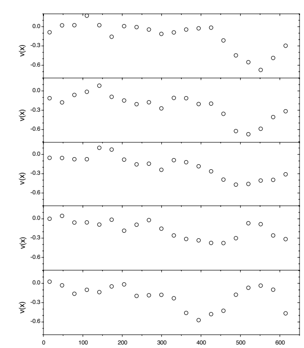
SOUND SPEED METHODS

- Sound speed provides an alternate method for determining the particle charge that is completely independent of vertical resonance methods
- Sound speed is a material property of a plasma crystal that is determined by the charge of the constituent particles
- Natural phonons are waves that occur due to natural thermal motion of particles
- Phonon spectrum yields information about dispersion relation (information about how fast waves of different frequencies propagate) that determines charge



Phonon spectra for longitudinal phonons (left) and transverse phonons (right). Regions colored against the blue background represent the dispersion relations that will be fitted to determine particle charge.

- Sound speed determined from laser-induced longitudinal and transverse pulses provides another measurement of particle charge



Velocity profiles for a laser-induced longitudinal pulse at different times., where time increases downward. The horizontal velocity of particles in vertical bins was calculated, giving x velocity as a function of x position. The particles moved with a negative velocity. Observe pulse incident from right, propagating towards the left (towards x = 0) and decaying in magnitude.

FUTURE WORK

Further analysis of the results from all methods, particularly the sound speed methods, remains. Charge calculations from all the methods will be compared, and the modified vertical resonance method evaluated.

ACKNOWLEDGEMENTS

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