PARAMETRIC STUDY OF THE FORMATION OF COULOMB CRYSTALS IN THE GEC REFERENCE CELL*

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AGENDA

• Introduction
• Description of the Dust Transport Simulation (DTS)
• Parametric trends in Plasma Crystal Formation
• Conclusions
INTRODUCTION

• Particles in low temperature, partially ionized plasmas exhibit collective behavior and form coulomb solids under certain conditions.

• The regimes of plasma operating conditions in which these structures are formed are of interest as an indication of crystal formation mechanisms.

• In this paper we discuss results from a parametric study of the formation of coulomb crystals in a GEC Reference cell.
HYBRID PLASMA EQUIPMENT MODEL (HPEM)

- A modular simulator addressing low temperature, low pressure plasmas.

- EMM produces electromagnetic fields and magneto-static fields.

- EETM produces electron temperature, electron impact sources, and transport coefficients.

- FKM produces densities, velocities, and temperature of plasma species.
DUST TRANSPORT SIMULATION (DTS)

- The fluxes and densities from the HPEM are used in the Dust Transport Simulation (DTS) to compute dust particle trajectories and locations.

- The DTS is a three-dimensional dust particle transport model.

- Forces included in the DTS are electrostatic, ion drag, thermophoretic, fluid drag by neutrals, brownian motion, self-diffusion, coulomb repulsion and gravity.
DUST TRANSPORT SIMULATION (DTS)

- The net force is:

\[
\vec{F}(r) = M_i g \text{ (gravity)} + Q_i \vec{E}_i \text{ (electrostatic)} + \sum_{\text{ions}} \sigma(e_i) \Phi(r, \vec{v}_i) s_i \text{ (ion - drag)} - 6\pi \mu_i v K T \frac{\nabla T}{T} \text{ (thermophoretic)}
\]

\[
- \frac{6\pi \mu_i}{C(Kn)} (\dot{v}_i - \dot{u}) C_D(\text{Re}) \frac{\text{Re}}{24} \text{ (fluid drag)} - kT_i \frac{\nabla N_i}{N_i} \text{ (self - diffusion)}
\]

\[
+ \frac{M_{\text{gas}} \langle v \rangle}{\Delta t} \sqrt{\pi \frac{N_{\text{gas}} \langle v \rangle \Delta t d_i^2}{4}} \text{ (brownian)} + \frac{Q_i}{4\pi \varepsilon_0} \sum_j Q_j \left( \frac{1}{R_{ij}} + \frac{1}{\lambda_L} \right) \exp \left( - \frac{R_{ij} - a}{\lambda_L} \right) i \text{ (coulomb)}
\]

- A particle's potential is calculated by equating the electron and ion currents to the surface.

\[
l_i = \pi a^2 N q \sqrt{\frac{2E_i}{m_i} \left( 1 - \frac{q\Phi}{E_i} \right)}
\]

\[
l_e = \pi a^2 N q \sqrt{\frac{3kT_e}{\pi m_e} \exp \left( \frac{q\Phi}{kT_e} \right)}
\]
DUST TRANSPORT SIMULATION (DTS)

- The charge on the particle is determined from the capacitance $C$ of the particle, where $C$ has the form

$$C = 4\pi\varepsilon_0 a \left(1 + \frac{a}{\lambda_L}\right).$$

- The debye length $\lambda_L$ is obtained by linearizing the Poisson-Vlassov equation:

$$\frac{1}{\lambda_L} = \sqrt{\frac{e^2}{\varepsilon_0} \left( \frac{N_e}{kT_e} + \frac{N_i}{2E_i} \right)}.$$
**DUST TRANSPORT SIMULATION (DTS)**

- The ion-dust momentum transfer cross-section is calculated according to the semi-analytic formula by Kilgore et al.
  \[ \sigma = b^2 c_i \ln \left( 1 + \frac{c_i}{\beta^2} \right) . \]

- Coulomb coupling parameter is calculated as follows:
  \[ \tilde{A}_i = \frac{Q_i}{4\delta \varepsilon_0} \sum_j \frac{Q_j}{R_{ij}} \exp \left( - \frac{R_{ij} - a}{\tilde{e}_L} \right) \frac{1}{2} m v_i^2 . \]
• Phases of the structures formed are analysed using the pair correlation function (PCF) for particles or \( g(r) \).

• Peaks in the PCF correspond to the first, second, and other nearest neighbors for particles.

Ar, 95 mTorr, 150 V, 100 particles of radius 3.8 \( \mu \text{m} \).
MODIFIED GEC REFERENCE CELL

- A modified GEC Reference cell was used for the simulations.
- A focus ring was used to confine the particles.
- Lower electrode is powered at 10 MHz, upper electrode is grounded.
- Dust particles are generated between the electrodes.
- Simulation time is 8 s.
OPERATING CONDITIONS

- Ar at a pressure of 95 mTorr
- Substrate bias: 125 - 250 V
- Radius of dust particles: 0.01-10 µm.
- Gas flow: 300 sccm.
- \( T_{\text{GAS}} = 350 \text{ K.} \)
PLASMA PROPERTIES

Ar, 95 mTorr, substrate bias 150 V
For Ar, 95 mTorr and a particle size of 3.8μm splitting into 2 lattices is observed at higher substrate biases.
EFFECT OF SUBSTRATE BIAS ON THE COULOMB CRYSTAL

- For typical conditions (Ar, 95mTorr), the substrate bias was varied from 125 V to 250 V.
- At higher voltages particles are observed to split into 2 sub-lattices.
- Larger radial forces at higher voltages push particles into an outer lattice.
EFFECT OF PARTICLE RADIUS ON THE COULOMB CRYSTAL

• Particle radius was varied from 0.1\(\mu\)m to 10 \(\mu\)m keeping the number of particles in the lattice constant at 150.

• For 0.1 \(\mu\)m we observe two distinct and well-separated lattices. The upper lattice is disk shaped and well above the central electrode.

• For 10 \(\mu\)m particle radius we observe a single lattice near the bottom electrode. The effect of gravity becomes important for larger particles.

• For intermediate radii, the upper lattice is found to disperse and become sparsely populated.
EFFECT OF PARTICLE RADIUS ON LATTICE MORPHOLOGY

• Splitting of lattice observed at smaller radii for Ar, 95 mTorr and a substrate bias of 150 V.
EFFECT OF PARTICLE RADIUS ON THE COULOMB CRYSTAL

Particle radius 0.1\(\mu\)m

Net Force in Z-direction

Particle Trapping Locations

Ar, 95 mTorr, substrate bias 150 V
EFFECT OF PARTICLE RADIUS ON THE COULOMB CRYSTAL

Particle radius 1μm

Net Force in Z-direction

Particle Trapping Locations

Ar, 95 mTorr, substrate bias 150 V
EFFECT OF PLASMA DENSITY ON INTERPARTICLE SPACING

- The ion and electron densities were varied while keeping other conditions constant.

- At low plasma densities we observe a slight increase in interparticle spacing because of an increase in the particle temperature.

- A monotonic decrease is observed at higher plasma densities because of reduced shielding length.
The effect of the number of particles on interparticle spacing was studied for different voltages.

Interparticle spacing is found to be in good agreement with experimentally observed trends.

Interparticle spacing is found to decrease with increase in number of particles.
EFFECT OF NUMBER OF PARTICLES ON INTERPARTICLE SPACING

Interparticle spacing for 3.8μm particles (Ar, 95 mTorr, substrate bias 150 V).

![Graphs showing interparticle spacing for different numbers of particles](image-url)
EFFECT OF NUMBER OF PARTICLES ON INTERPARTICLE SPACING

- Maximum spacing is observed for 225 V. However, no clear correlation of spacing with voltage is observed.

Interparticle spacing for 3.8μm particles as a function of number of particles for Ar, 95 mTorr
EFFECT OF NUMBER OF PARTICLES ON THE COULOMB COUPLING FACTOR

- Coulomb Coupling factor increases with increase in number of particles.

Coulomb coupling factor as a function of the number of particles for Ar, 95 mTorr and a substrate bias of 150V.
EFFECT OF PRESSURE ON THE COULOMB CRYSTAL

- Pressure was varied from 95 mTorr to 1 Torr.

- For Ar, 150 V and 3.8µm particles,
  - Increase in pressure decreases coulomb coupling factor because higher ion fluxes lead to higher particle velocities and temperatures.
  - Increase in pressure decreases interparticle spacing.
CONCLUSIONS

• Abrupt splitting into 2 lattices observed for higher voltage.

• Particles of smaller size prefer forming 2 sublattices.

• Interparticle spacing decreases and coulomb coupling factor increases with increase in the number of particles in the lattice.

• Interparticle spacing decreases monotonically for higher electron and flux densities.

• Increase in pressure decreases the coulomb coupling factor and interparticle spacing.