# 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.**

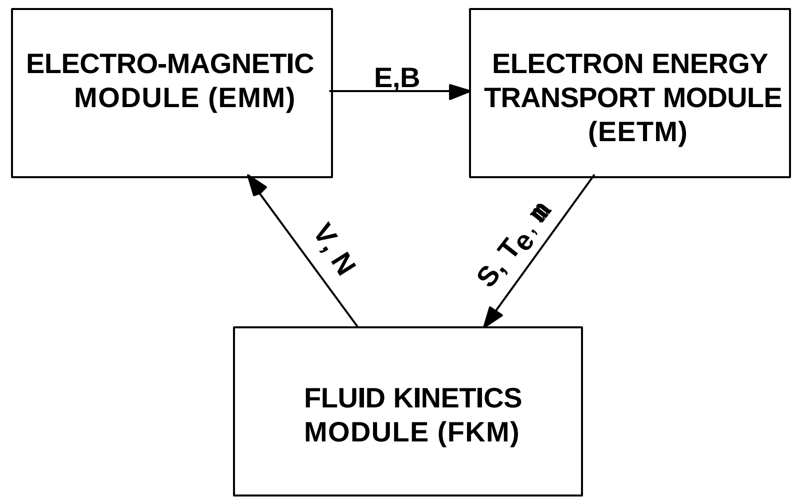
# HYBRID PLASMA EQUIPMENT MODEL (HPEM)

- **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.**



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# DUST TRANSPORT SIMULATION ( DTS )

- **The net force is:**

$$\vec{F}(\vec{r}) = M_i\vec{g}\ \text{(gravity)} + Q_i\vec{E}_i\ \text{(electrostatic)} + \sum_{ions}\sigma(\varepsilon_i)\,\Phi(\vec{r},\vec{v}_I)\,s_I\ \text{(ion-drag)} - 6\pi\mu r_i \nu K_T \frac{\nabla T}{T}\ \text{(thermophoretic)}$$

$$-\frac{6\pi\mu r_i}{C(Kn)}(\vec{v}_i - \vec{u})\ C_D(\mathrm{Re})\frac{\mathrm{Re}}{24}\ \text{(fluid drag)} - kT_i\frac{\nabla N_i}{N_i}\ (\textit{self-diffusion})$$

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

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

$$I_I = \pi a^2 N q\sqrt{\frac{2E_I}{m_I}}\left(1 - \frac{q\Phi}{E_I}\right),$$

$$I_e = \pi a^2 N q\sqrt{\frac{3kT_e}{\pi m_e}}\ \exp\left(\frac{q\Phi}{kT_e}\right)$$



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# DUST TRANSPORT SIMULATION ( DTS )

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

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

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

$$\frac{1}{\lambda_L} = \sqrt{\frac{e^2}{\varepsilon_o}\left(\frac{N_e}{kT_e} + \frac{N_I}{2E_I}\right)}.$$

# DUST TRANSPORT SIMULATION ( DTS )

- **The ion-dust momentum transfer cross-section is calculated according to the semi-analytic formula by Kilgore et al.**

$$\sigma = \beta^2 c_l \ln\left(1 + \frac{c_l}{\beta^2}\right).$$

- **Coulomb coupling parameter is calculated as follows:**

$$\Gamma_i = \frac{\dfrac{Q_i}{4\pi\varepsilon_o} \displaystyle\sum_j \frac{Q_j}{R_{ij}} \exp\left(-\frac{R_{ij} - a}{\lambda_L}\right)}{\dfrac{1}{2} m v_i^2}.$$



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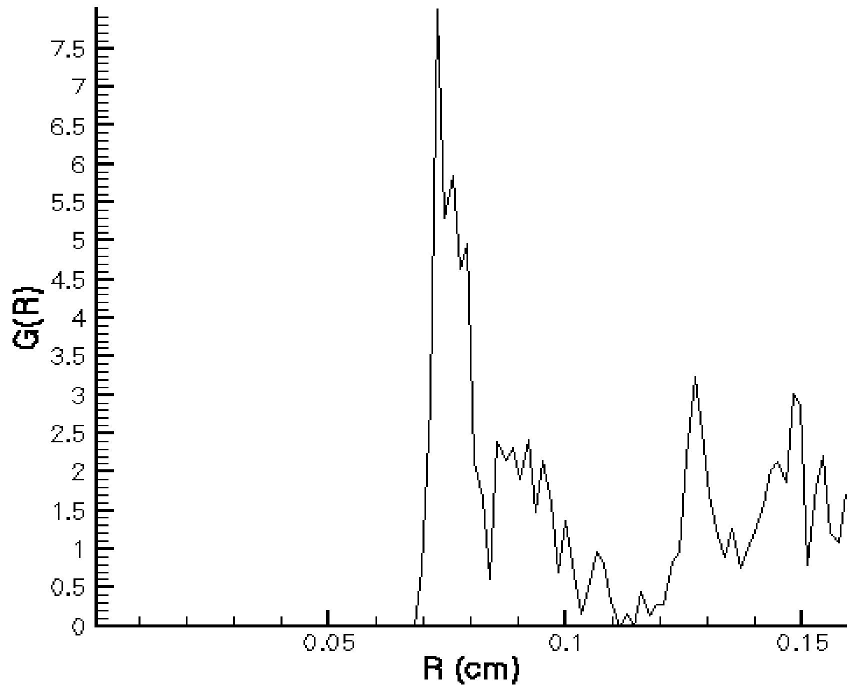
# DUST TRANSPORT SIMULATION ( DTS )

- **Phases of the structures formed are analysed using the pair correlation function (PCF) for particles or g(r).**
- **Peaks in the PCF correspond to to the first, second, and other nearest neighbors for particles.**

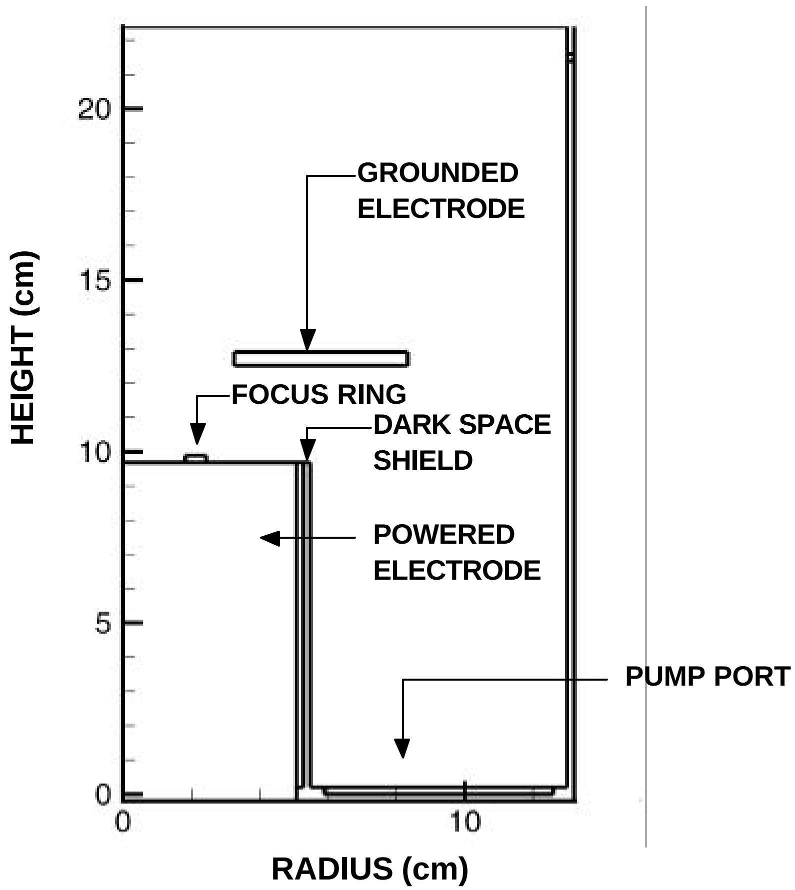



**Ar, 95 mTorr, 150 V,**

**100 particles of radius 3.8 mm.**

# 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.**



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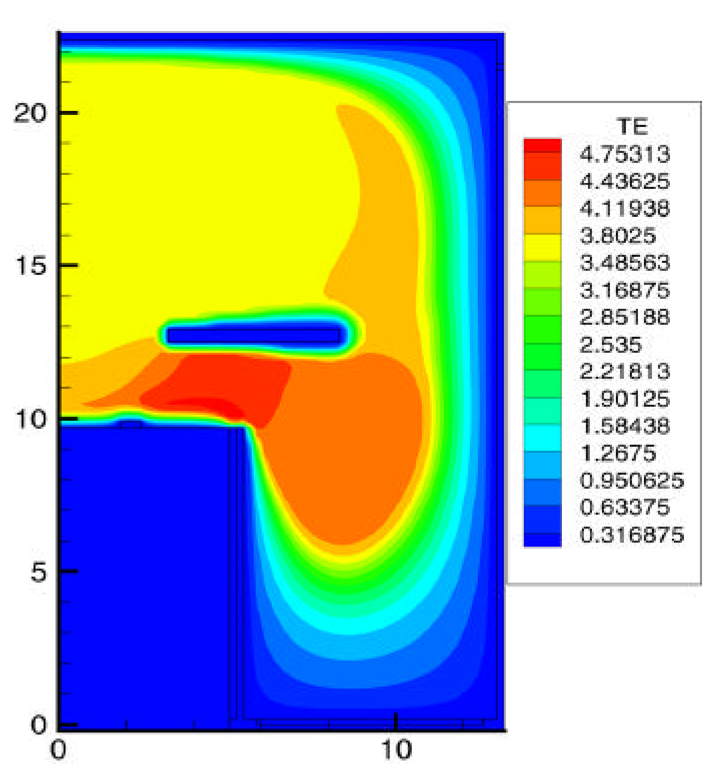
# OPERATING CONDITIONS

- **Ar at a pressure of 95 mTorr**
- **Substrate bias: 125 - 250 V**
- **Radius of dust particles : 0.01-10 mm.**
- **Gas flow : 300 sccm.**
- **$T_{GAS}$ = 350 K.**

**ELECTRON TEMPERATURE**



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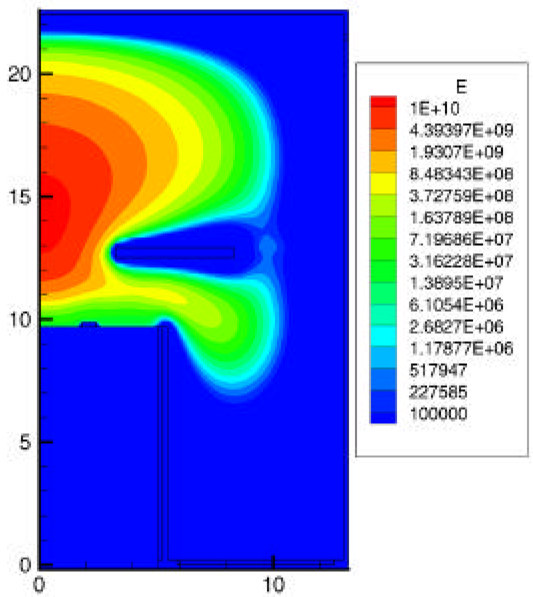
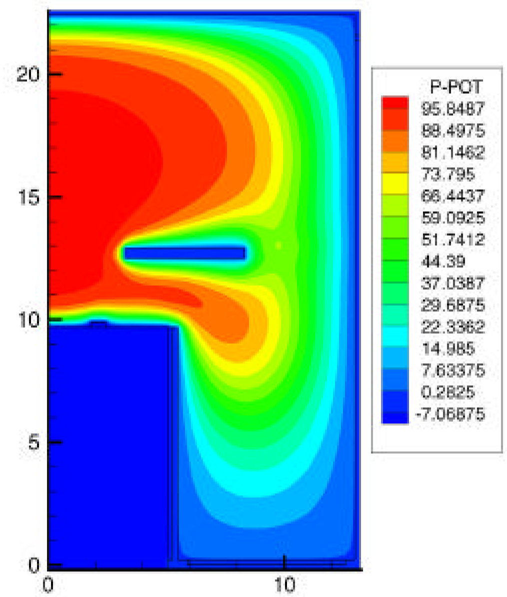
# PLASMA PROPERTIES

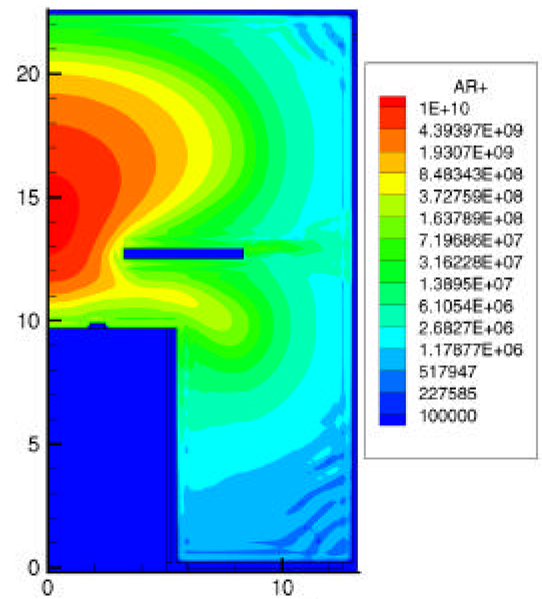
**ELECTRON DENSITY**




**PLASMA POTENTIAL**




**AR+ DENSITY**




**Ar, 95 mTorr , substrate bias 150 V**

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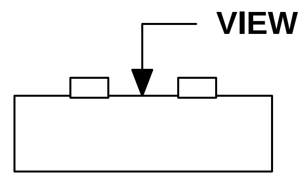
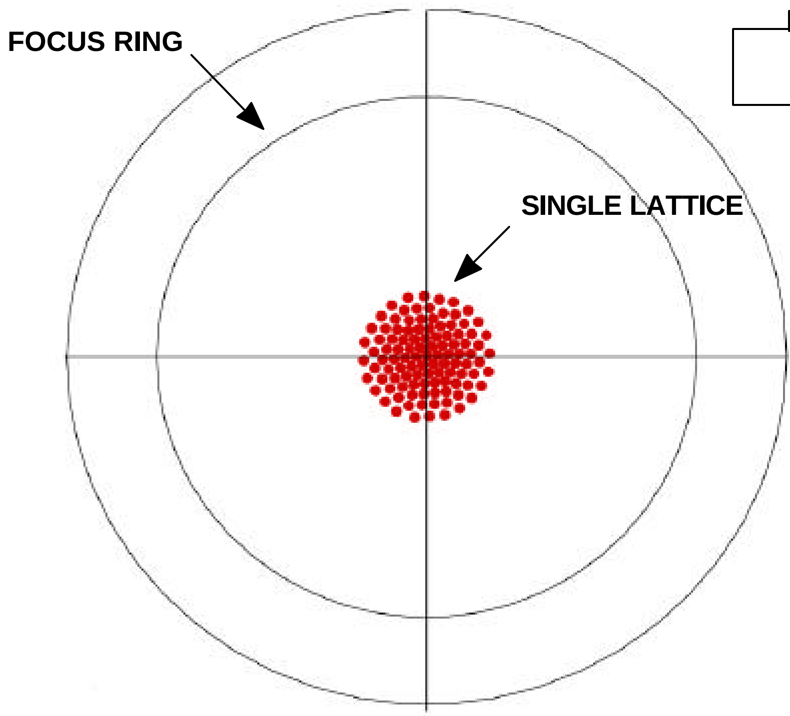
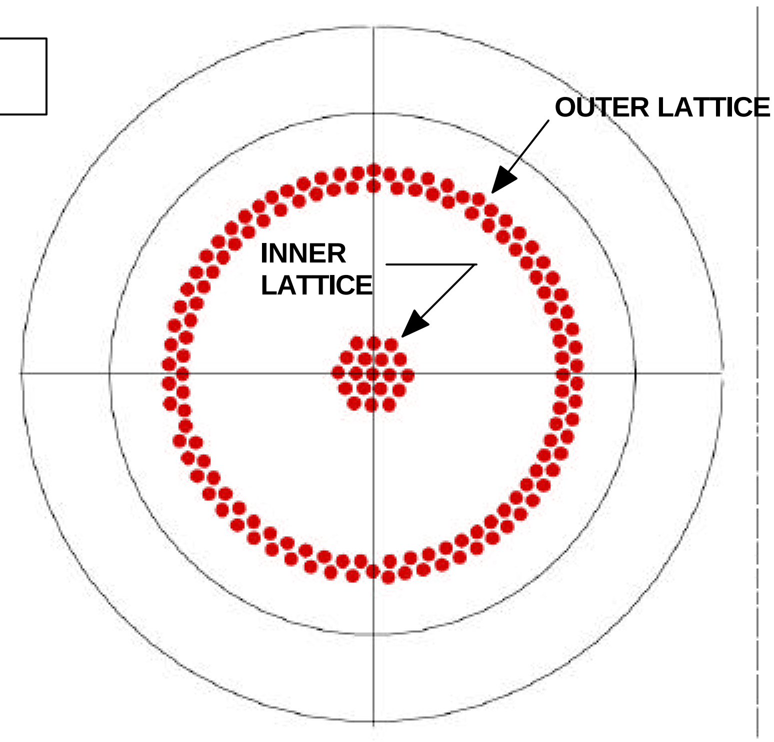
# SUBSTRATE BIAS DETERMINES MORPHOLOGY

- **For Ar, 95 mTorr and a particle size of 3.8μm splitting into 2 lattices is observed at higher substrate biases**




A single lattice observed at lower substrate bias




Splitting into 2 lattices observed with increase of substrate bias to 250 V



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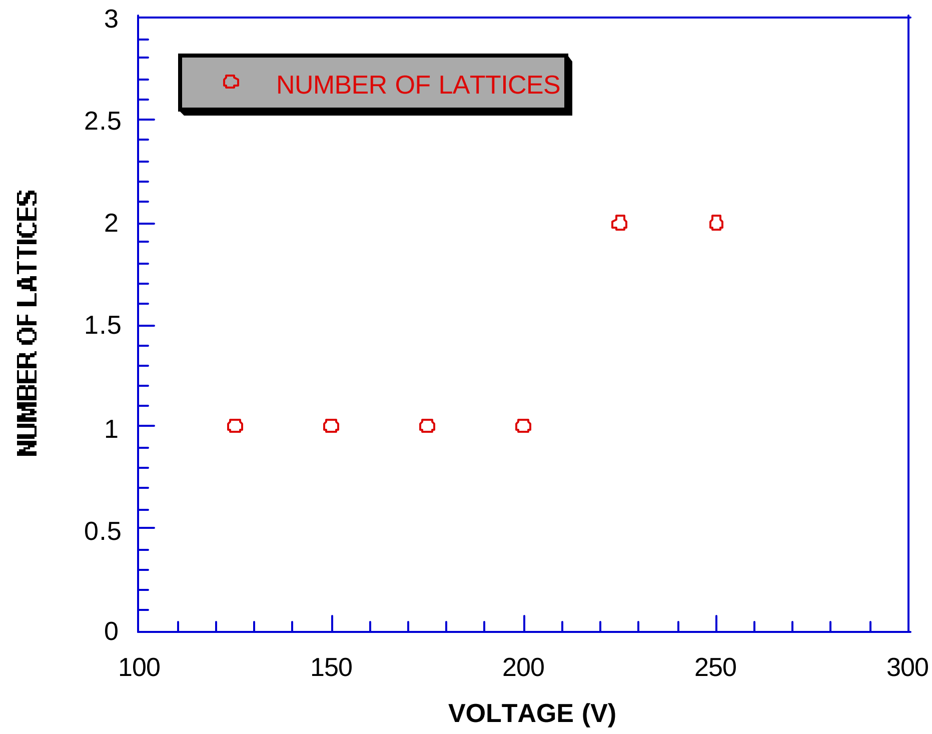
# EFFECT OF SUBSTRATE BIAS ON THE COULOMB CRYSTAL

- **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.**



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# EFFECT OF PARTICLE RADIUS ON THE COULOMB CRYSTAL

- **Particle radius was varied from 0.1μm to 10 μm keeping the number of particles in the lattice constant at 150.**

- **For 0.1 μm we observe two distinct and well-separated lattices. The upper lattice is disk shaped and well above the central electrode.**

- **For 10 μm 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.**



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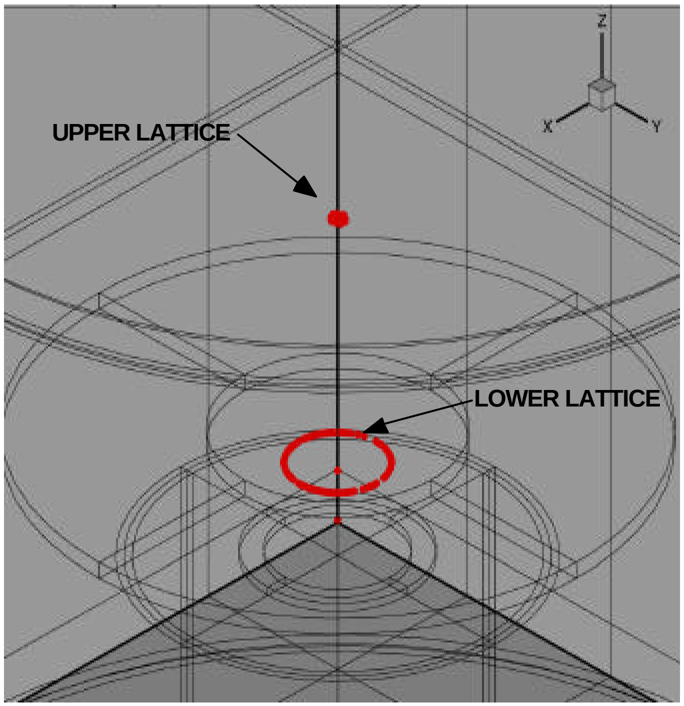
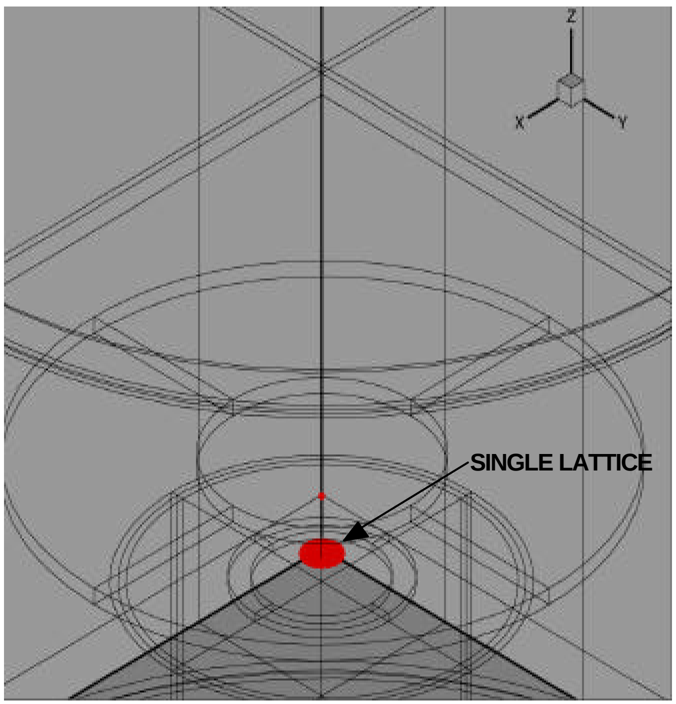
# EFFECT OF PARTICLE RADIUS ON LATTICE MORPHOLOGY

- **Splitting of lattice observed at smaller radii for Ar, 95 mTorr and a substrate bias of 150 V.**




**0.1 μm PARTICLES ARRANGING IN 2 LATTICES**




**10 μm PARTICLES ARRANGING IN A SINGLE LATTICE**

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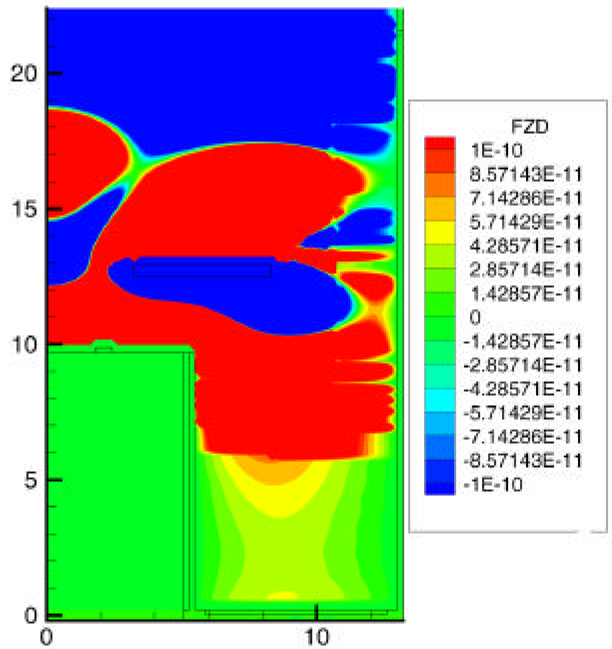
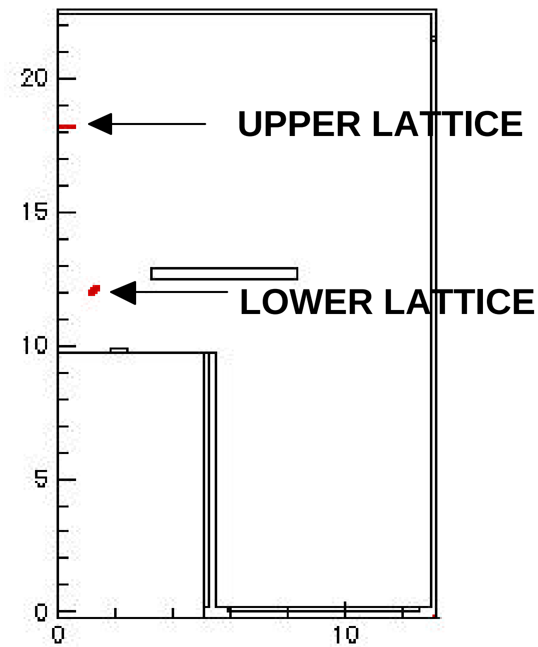
# EFFECT OF PARTICLE RADIUS ON THE COULOMB CRYSTAL

## Particle radius 0.1μm

**Net Force in Z-direction**




**Particle Trapping Locations**




**Ar, 95 mTorr, substrate bias 150 V**

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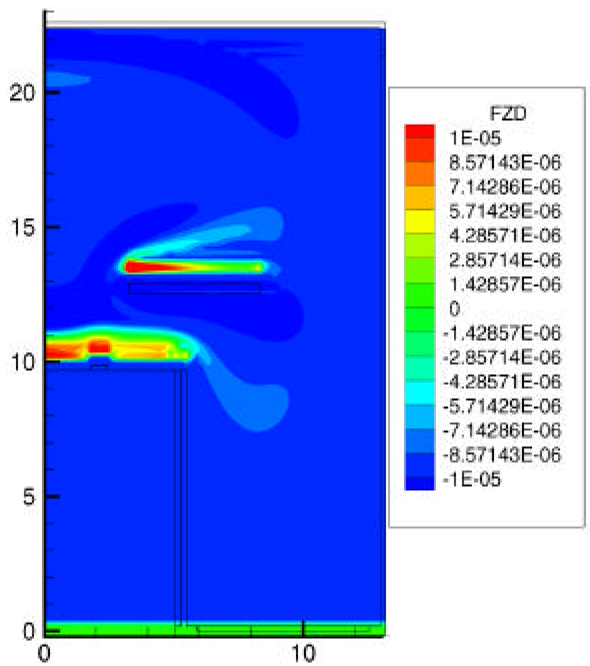
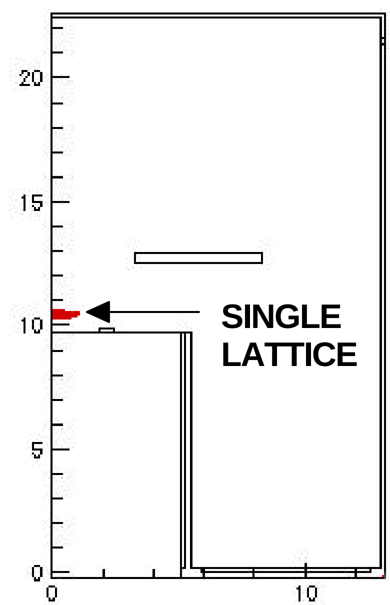
# EFFECT OF PARTICLE RADIUS ON THE COULOMB CRYSTAL

## Particle radius 1μm

**Net Force in Z-direction**




**Particle Trapping Locations**




**Ar, 95 mTorr, substrate bias 150 V**

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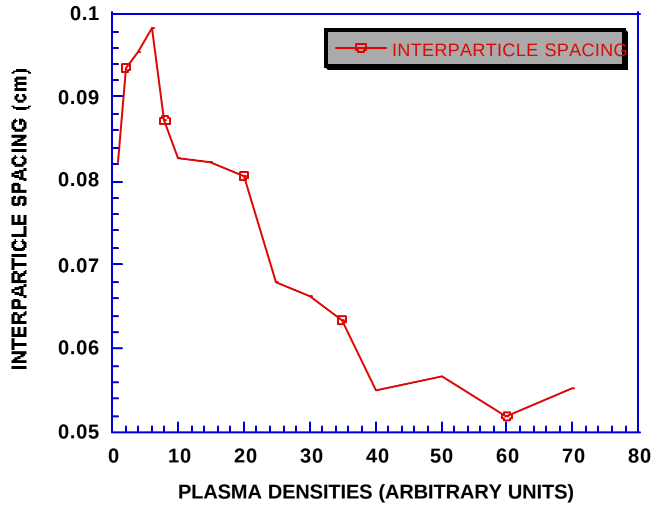
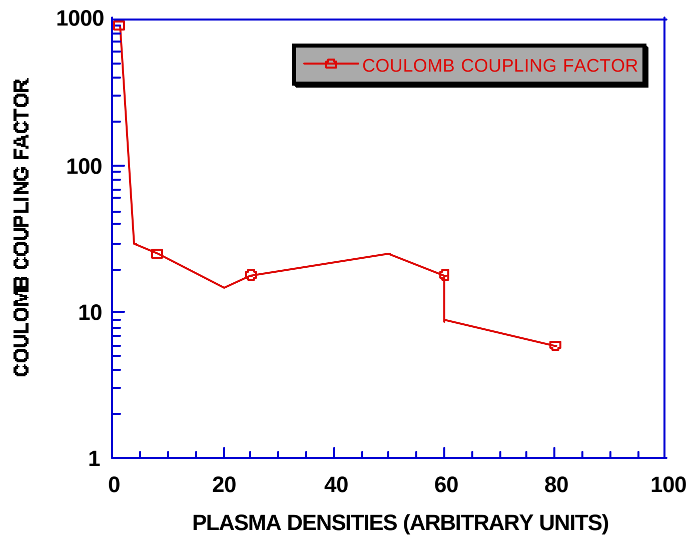
# EFFECT OF PLASMA DENSITY ON INTERPARTICLE SPACING

- **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.**

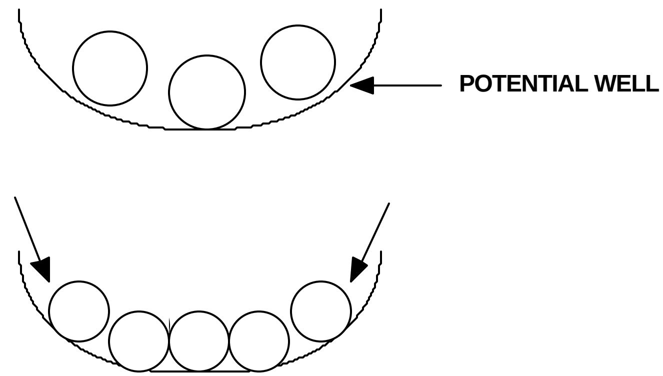
- **A monotonic decrease is observed at higher plasma densities because of reduced shielding length.**



# EFFECT OF NUMBER OF PARTICLES ON INTERPARTICLE SPACING

- **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.**

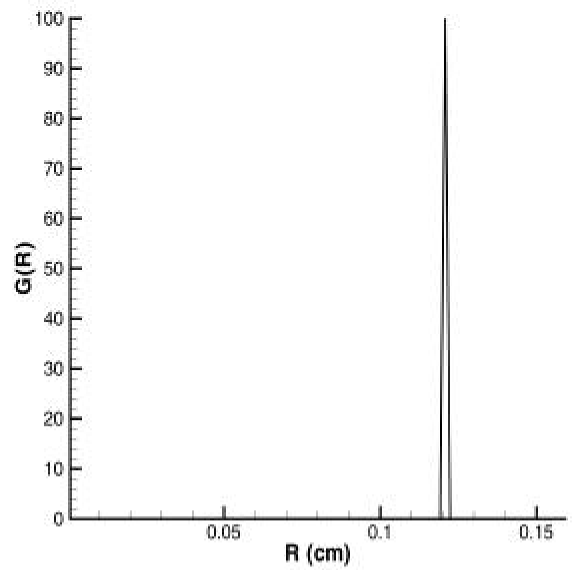



**INCREASE IN NUMBER OF PARTICLES DECREASES INTERPARTICLE SPACING**

# EFFECT OF NUMBER OF PARTICLES ON INTERPARTICLE SPACING

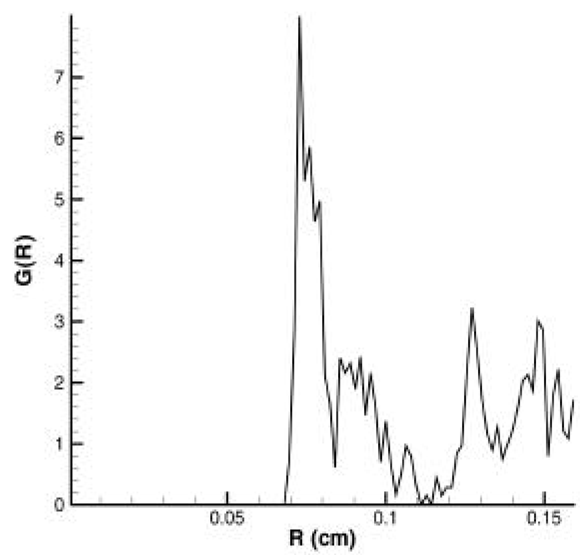
**Interparticle spacing for 3.8μm particles (Ar, 95 mTorr, substrate bias 150 V).**

**0.11 cm**



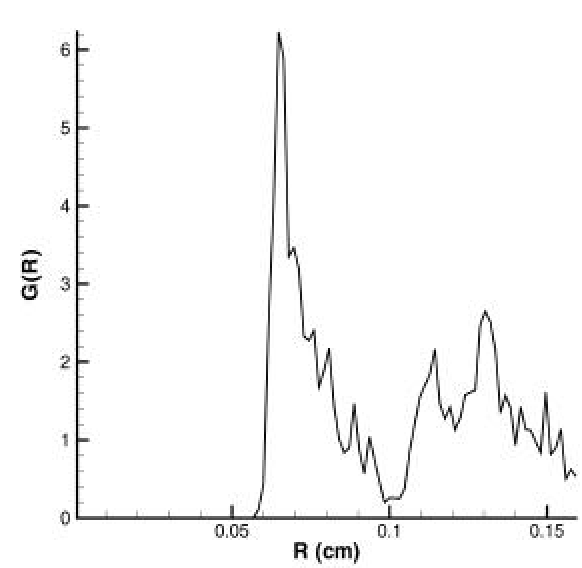

**7 particles**

**0.075cm**




**100 particles**

**0.065cm**




**200 particles**



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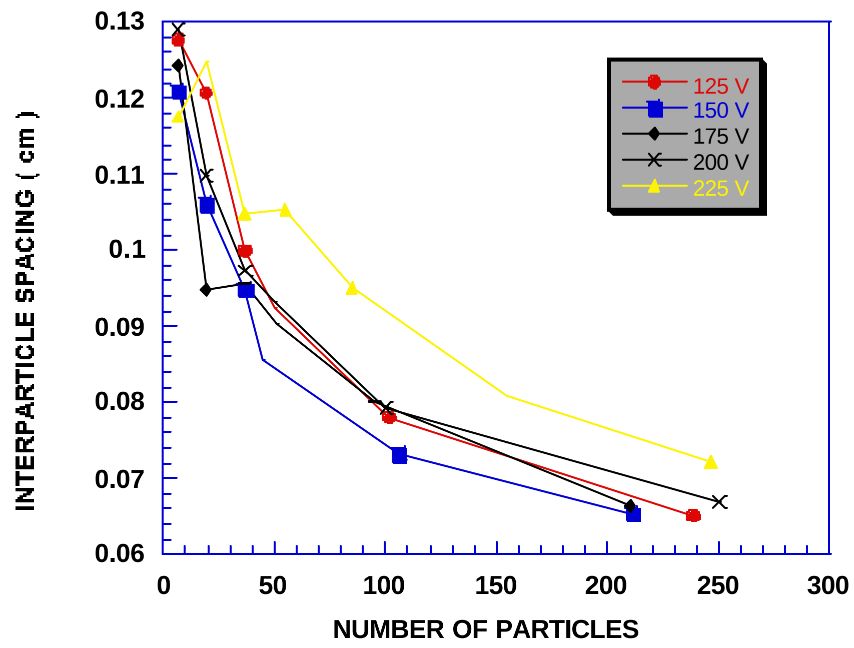
# EFFECT OF NUMBER OF PARTICLES ON INTERPARTICLE SPACING

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




**Interparticle spacing for 3.8mm particles as a function of number of particles for Ar, 95 mTorr**

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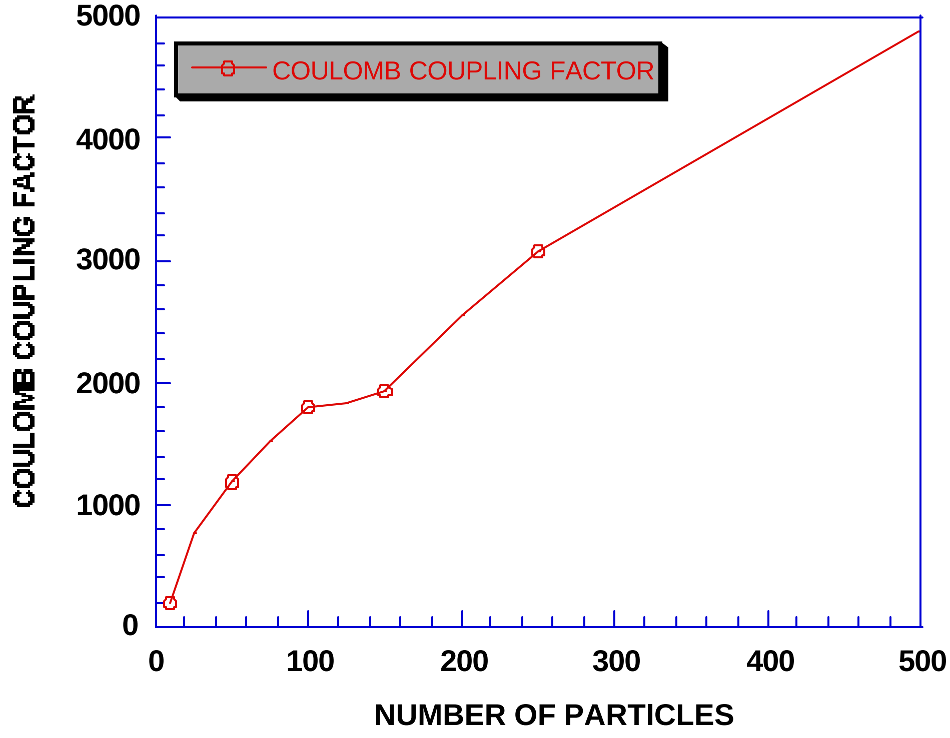
# EFFECT OF NUMBER OF PARTICLES ON THE COULOMB COUPLING FACTOR

- **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.**



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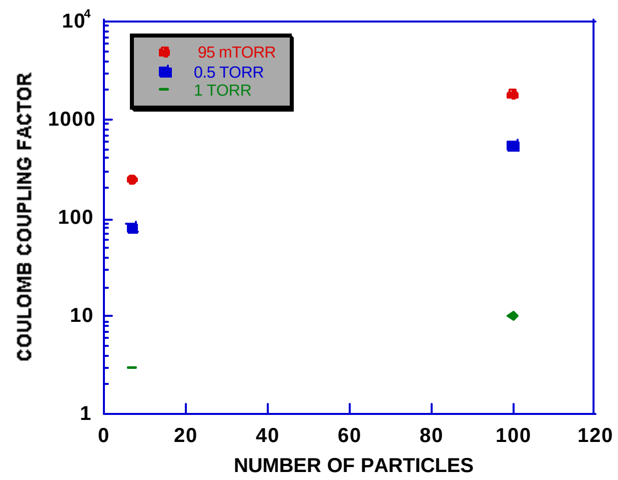
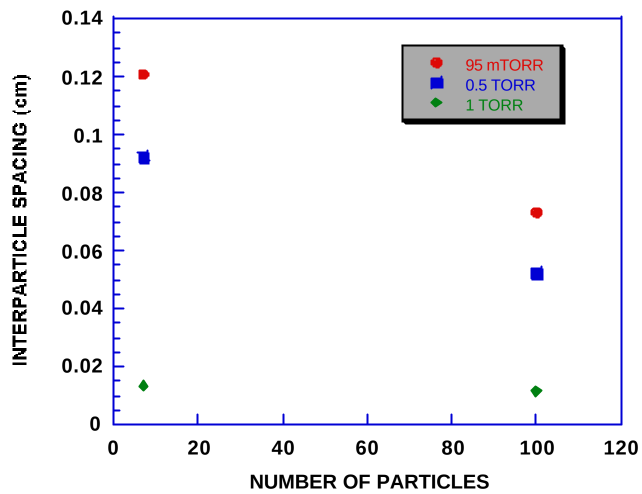
# EFFECT OF PRESSURE ON THE COULOMB CRYSTAL

- 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.



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# 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.



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