U.S. Department of Education

Ordering Processes Within Vertically Aligned 3D Dust Clusters

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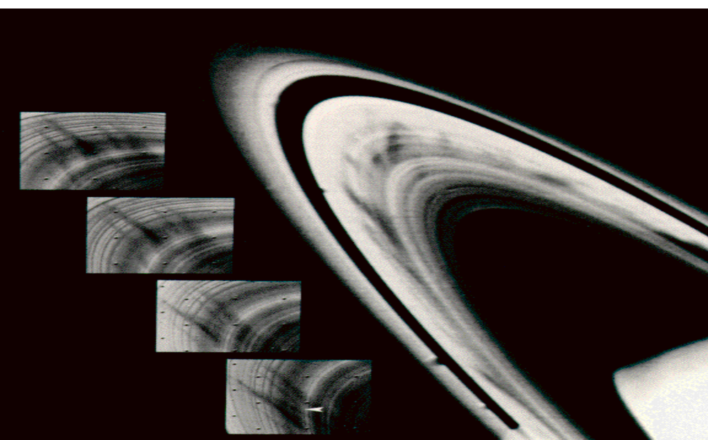
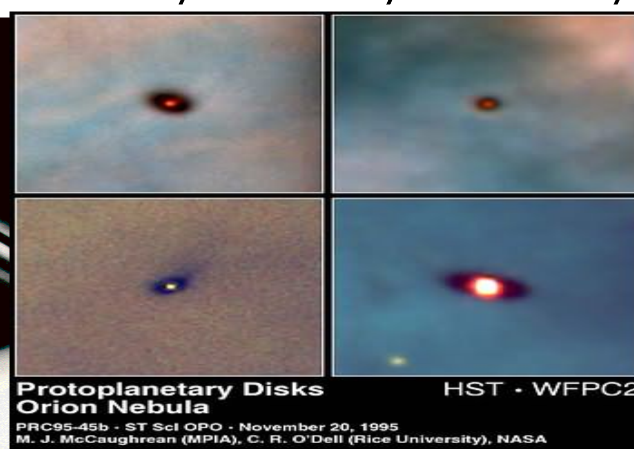
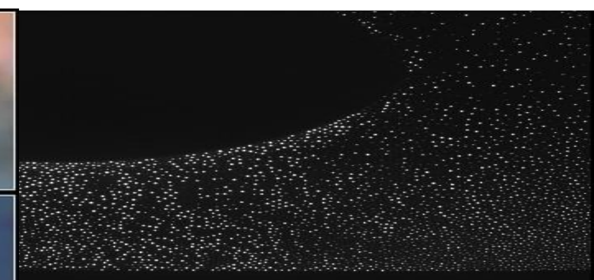
14th Workshop on the Physics of Dusty Plasma – May 26-29, 2015







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Outline

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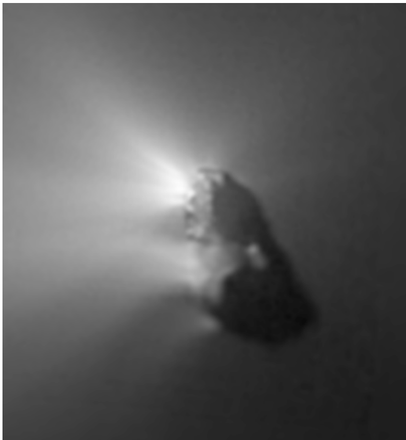
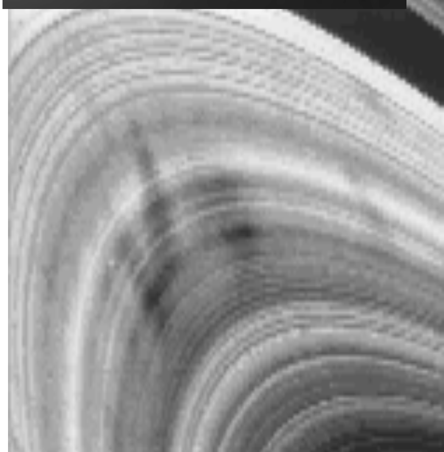
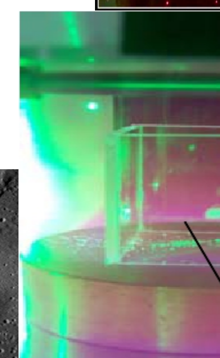
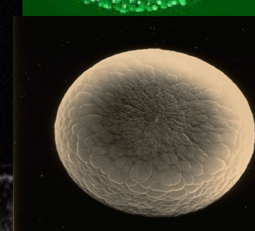
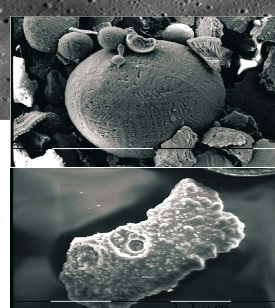
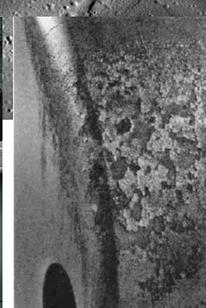
- Brief Introduction to Complex Plasma
- Vertically Aligned Particle Systems
  - The Basics!
  - Two- & Three-Particle Strings in a GEC Reference Cell
  - Two- & Three-Particle Strings in a Glass / ITO Box
- Plasma Inhomogeneity
  Non-Uniformity of the Sheath
- Conclusions





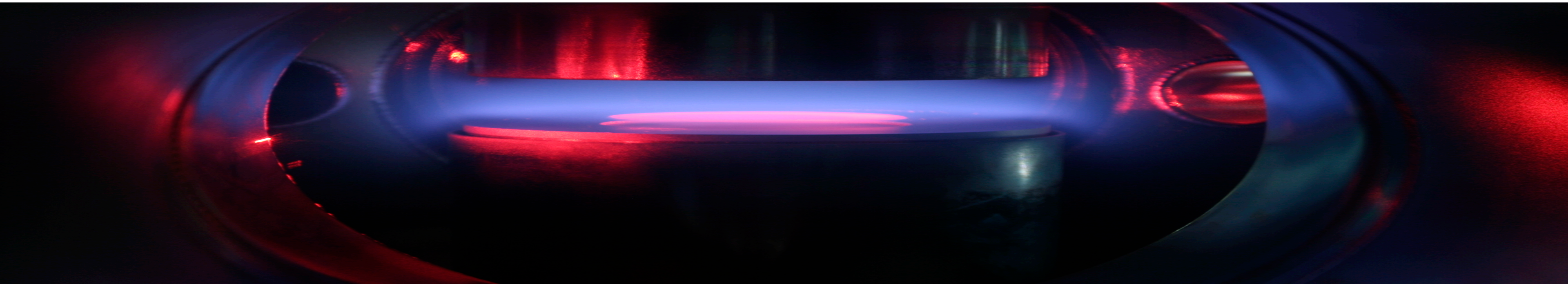



Dusty Plasma

More easily described than categorized!

- Light species – Weakly coupled
  - Electrons, positive ions, neutral atoms
- Heavy species – Strongly or weakly coupled
  - Nanometer / Micrometer-sized dust grains
  - Coupling determined by charge
    - Collection of Electrons
- Distinct mass asymmetry
  - Gives rise to dynamics on entirely different spatial and temporal scales



Strings & Clusters – The Basics! Experimental Observations

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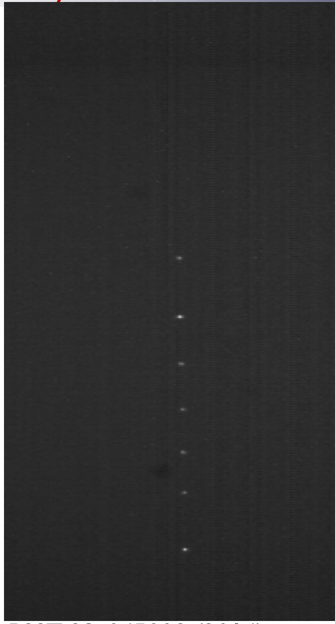
Vertically Aligned Two-Particle Strings, Extended Strings & Clusters - Glass (ITO) Box

- Vertically stacked states at or near the minimum of the system's potential well
- A physically deep potential well can provide vertical correlation with minimal ion-streaming *but* ion-streaming is required for stability

- Ordering, structure & stability depends on
  - Number of Particles
  - System Energy & Confinement
  - Interparticle Interaction
    - Ion Wakefield
    - Plasma Inhomogeneity in a Glass (ITO) Box?
    - Non-Uniformity of the Sheath Electric Field?



PSST, 23, 045008 (2014)
PRL, 113, 025002 (2014)
PRE, 90, 1, 013107 (2014)
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IEEE TSP, 41, 4 (2013)
PRE, 88, 043103 (2013)
PRE, 87, 053109 (2013)
PRE, 87, 053106 (2013)
POP, 19, 013707 (2012)
POP, 18, 8 (2011)
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PRE, 82, 036401 (2010)
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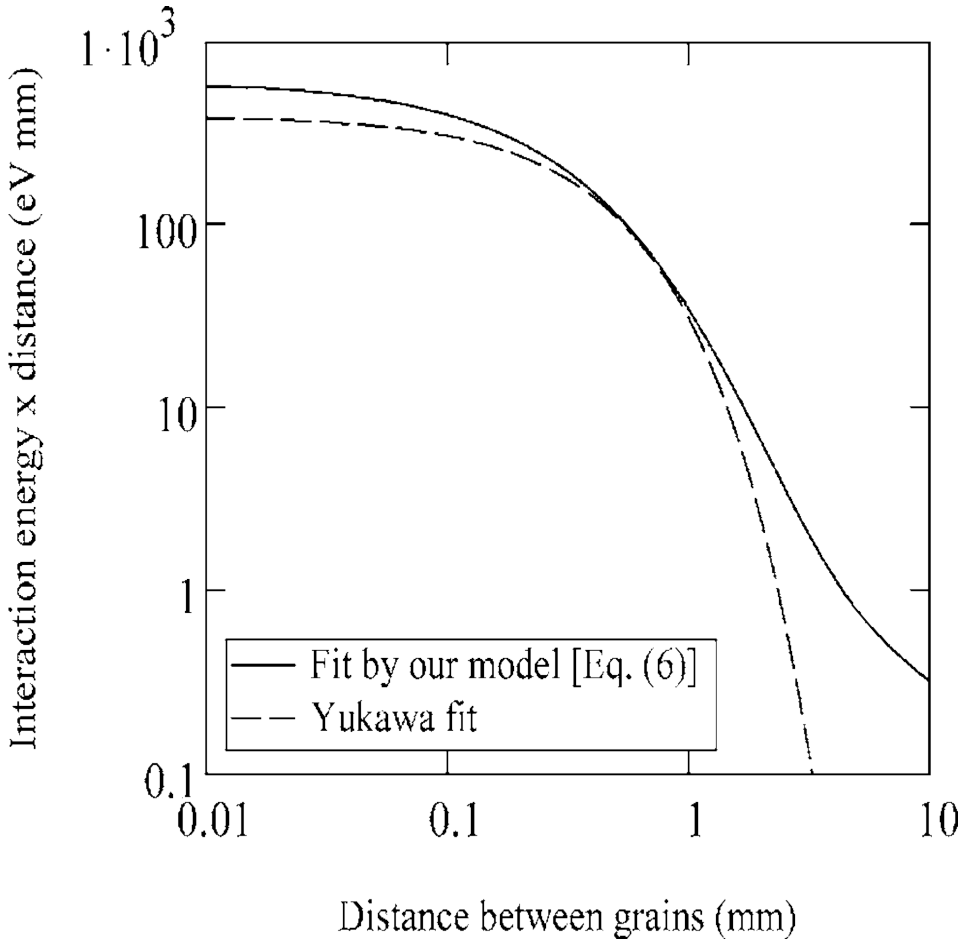
NJP, 11, 063030 (2009)
NJP, 11, 063024 (2009)

Block, Carstensen, Ludwig, Miloch, Greiner, Piel, Bonitz & Melzer, Contrib. Plasma Phys. 52, 10, 804 – 812 (2012)

Two-Particle Strings (No Box)

Plasma Inhomogeneity
Non-Uniformity of the Sheath



Analytical Method

Assumptions

- Grain screening due to ions only
- Mobility-limited ion drift with velocity much larger than the thermal velocity of neutrals

Conclusions

- Current experimental results *cannot* be used as justification for

  assuming (1) Yukawa potential or (2) dominant role of electrons in grain screening (*Both* analytical expression and Yukawa potential provide same experimental results.)

Impact

- Plasma Particle Interaction
- Interparticle Interaction
- Wakefield/Shielding

R. Kompaneets, Konopka, A. Ivlev, Tsytovich and G.E. Morfill, POP, 14, 052108 (2007)

Two-Particle Strings (No Box)

Plasma Inhomogeneity Non-Uniformity of the Sheath

A point nonabsorbing charge q located at **r** = **0** and immersed in an inhomogeneous plasma consisting of Boltzmann electrons and cold flowing singly ionized ions.

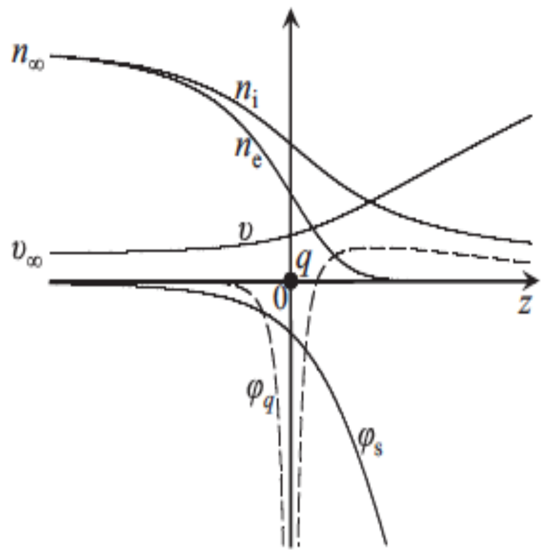


FIG. 1. Sketch of the problem. The solid curves illustrate the unperturbed sheath, showing the electric potential $\varphi_s(z)$, ion number density $n_i(z)$, electron number density $n_e(z)$, and ion flow velocity $v(z)$. The dashed line shows the potential perturbation φ_q (on the z axis) due to the immersed charge $q < 0$.

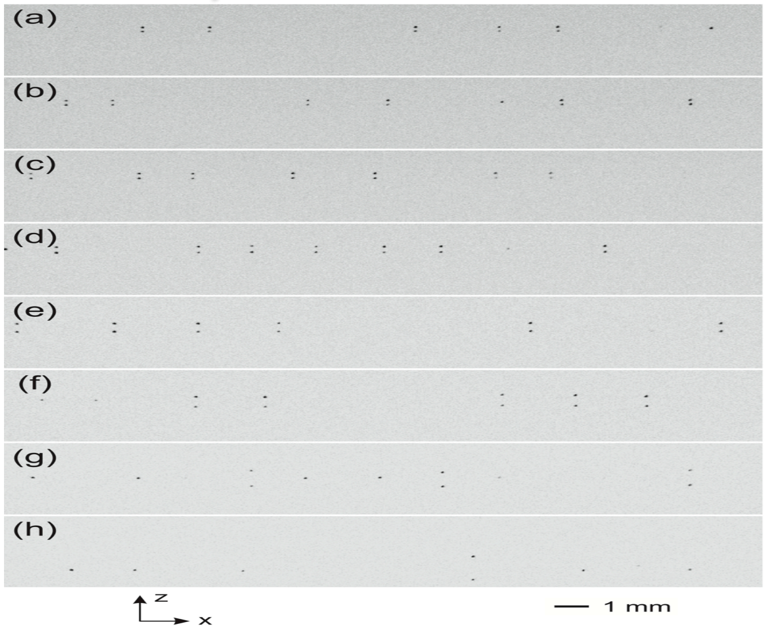
- Particle interaction with plasma
  - Assumptions
    - Collisionless Bohm sheath model
    - Levitation in the sheath / presheath
    - No wall
  - Resulting plasma inhomogeneity modifies the wake (shielding) and is dependent (in part) on the Field Inhomogeneity Length

$$L_E = E\left(\frac{dE}{dz}\right)^{-1}$$

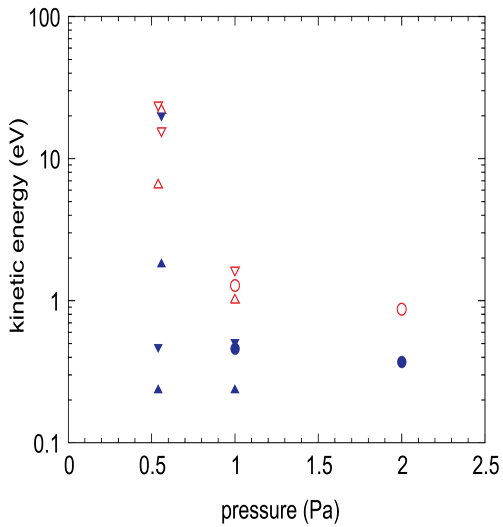
  - For a two-particle pair
    - Oscillatory wake structure in the ion flow direction disappears
    - Wake becomes considerably weaker
    - Screening of the Coulomb potential is weaker in the perpendicular direction – *Weakens / eliminates positive attraction in this direction?*
    - Modifies the interparticle interaction

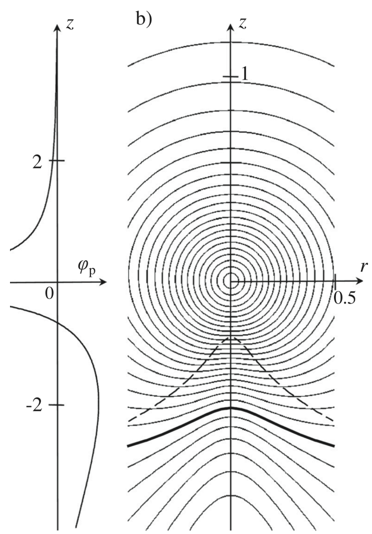
R. Kompaneets, A.Ivlev, V. Nosenko and G.E. Morfill, PRE, 89, 043108 (2014)

Two-Particle Strings (No Box)



rf Voltage – 352V to 58V (P to P)
~15 mTorr (2 Pa)

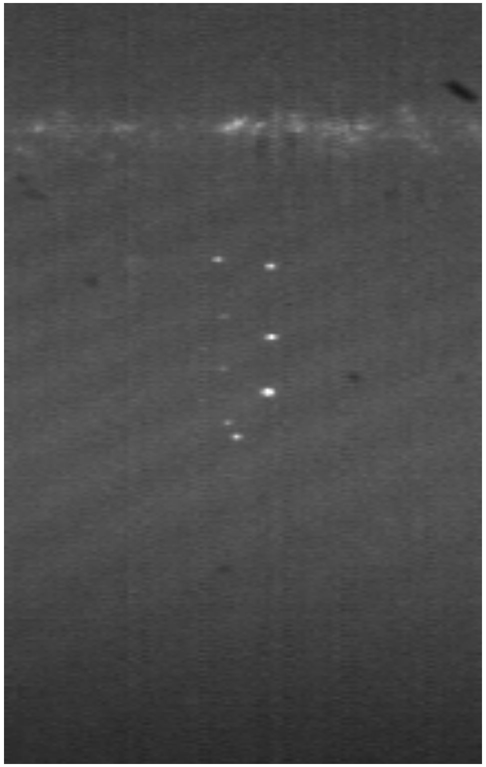


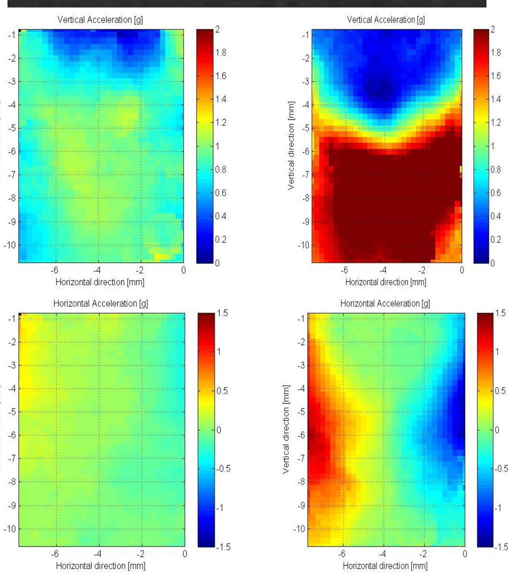


- Ordering/Structure
  - Non-Uniformity of the sheath
    - Vertical Confinement (lower particle)
      - Larger than the interparticle repulsion *and / or* positive space charge produced by the ion wakefield
  - Horizontal Wakefield
    - Lateral confinement on particle (>5 mTorr – 2 Pa)
- Stability
  - Particle Pair Disruption (<3.75 mTorr – 0.5 Pa) driven by thermal energy when it grows larger than the disappearing lateral confinement force

V. Nosenko, A.V. Ivlev, R. Kompaneets and G. Morfill, POP, 21, 113701 (2014)

Questions





Plasma Inhomogeneity
Non-Uniformity of the Sheath

- Question #1: What is the difference between the wake created by a particle in an inhomogeneous plasma
  - As approximated by a collisionless Bohm sheath model, and
  - As measured in a glass box?

- Question #2: “Essential qualitative changes introduced by the inhomogeneity…….generic features characterizing wakes in inhomogeneous plasma *flows* –

R. Kompaneets, A.Ivlev, V. Nosenko and G.E. Morfill, PRE, 89, 043108 (2014)

Two- & Three-Particle Strings
How Does This Translate to a Glass Box?

Ordering, structure & stability depends on

Ion Wakefield

- Wakefield in Glass Box?

Non-Uniformity of the Sheath?

Plasma Inhomogeneity?

- Confinement provided by

  Glass / ITO Box
  - Conducting / Insulating
  - Non-Linear Field
  - New Sheaths!
  - Particle(s) close(?) to Wall*
  - Plasma Absorption(?) by Dust**

Modifies

- Shielding Length
- Plasma – Particle Interaction
- Wake
- Interparticle Interaction

*Order of magnitude larger than the electron Debye length at the sheath edge

**Dust collective effects are often attributed to plasma absorption

Two- & Three-Particle Strings (Glass Box)

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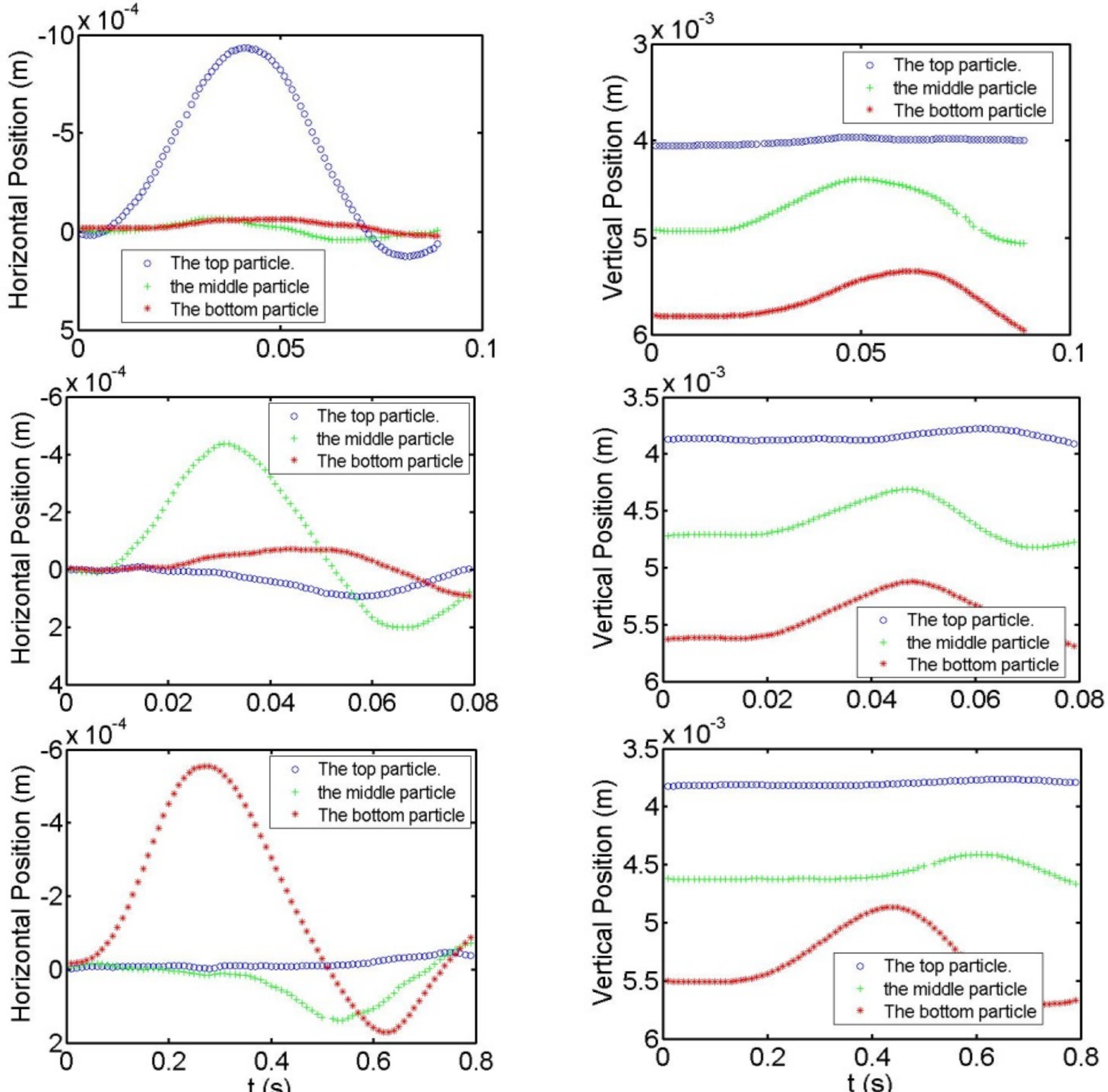
Ion Wakefield

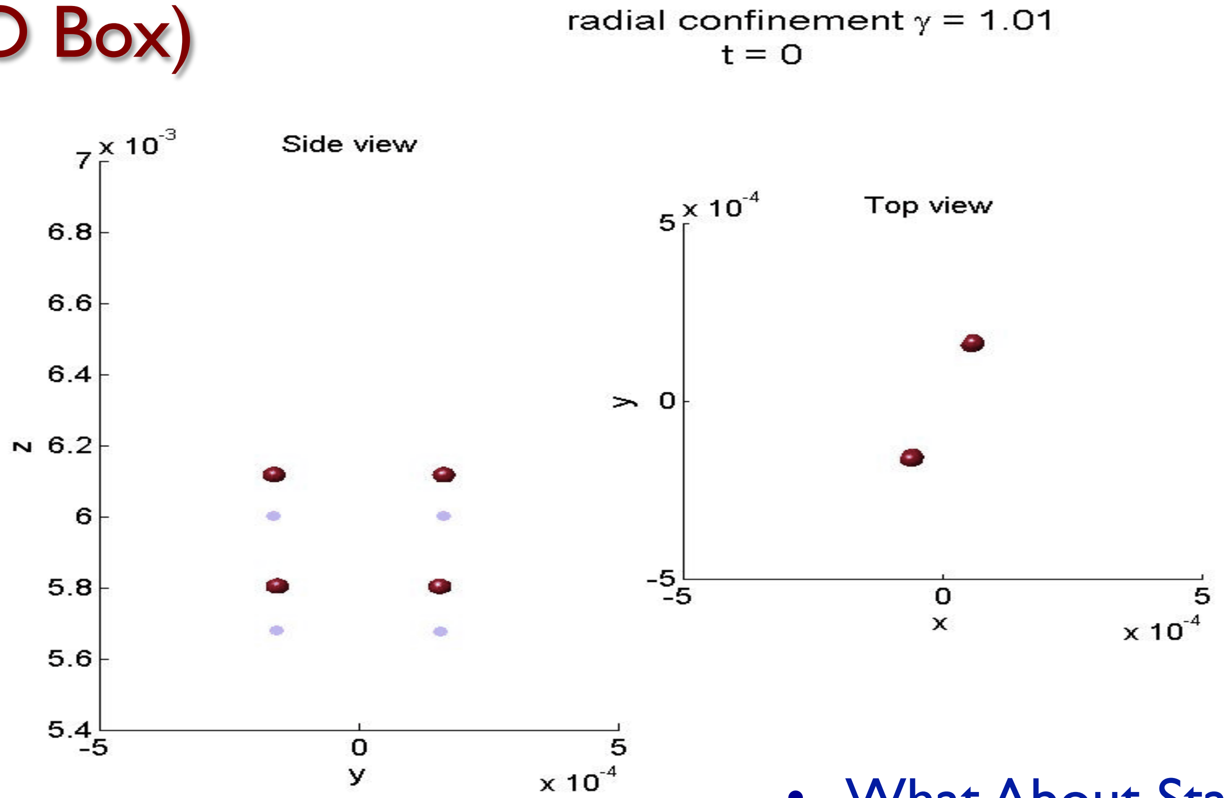


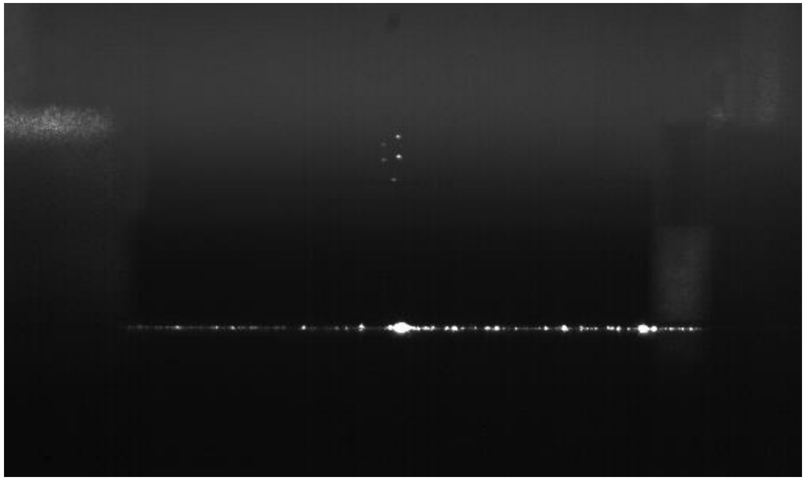
30 mW / 0.02 s (Pulse Cycle) / 100 mTorr (Argon) / 1.3 W (RF)

M. Chen, L. Matthews and T.W. Hyde, PRE, In Submission (2015)

Two-Particle String Clusters (ITO Box)

Ion Wakefield





- What About Stability & Chain Formation?
  - ***Requires*** wakefield confinement for stable chain formation
  - Assumes uniform sheath in an ITO box

Wakefield – q = 0.3Q (Dynamic Wakefield)
Fixed n_i
n_e – Sheath Dependent
Increasing Isotropic Confinement

Two-Particle String Clusters (ITO Box)

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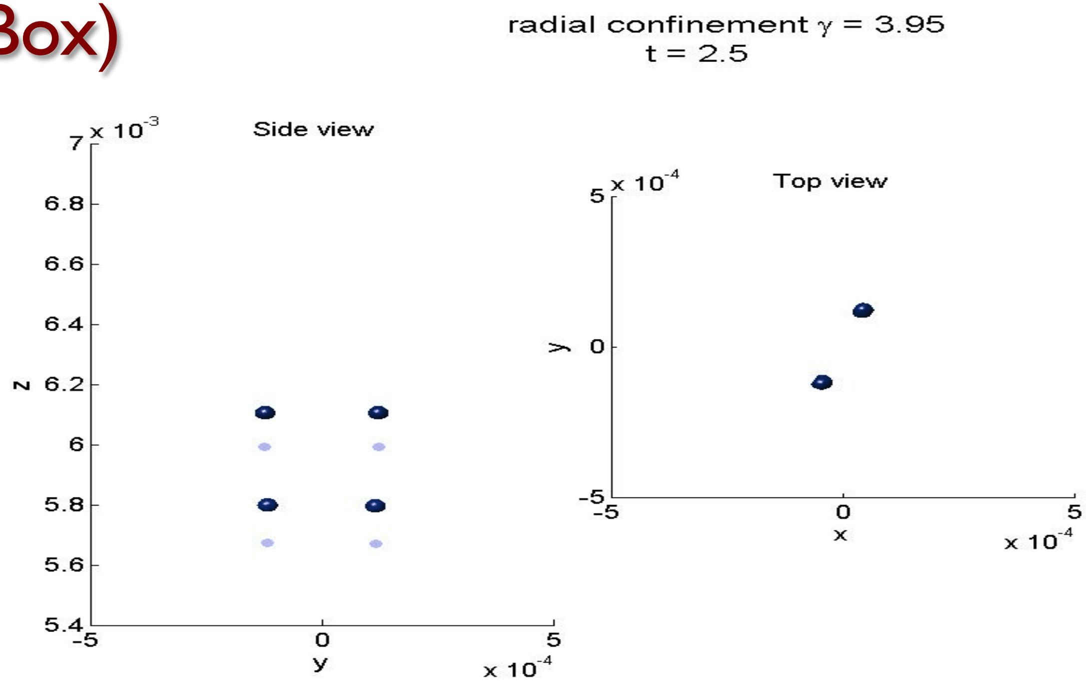
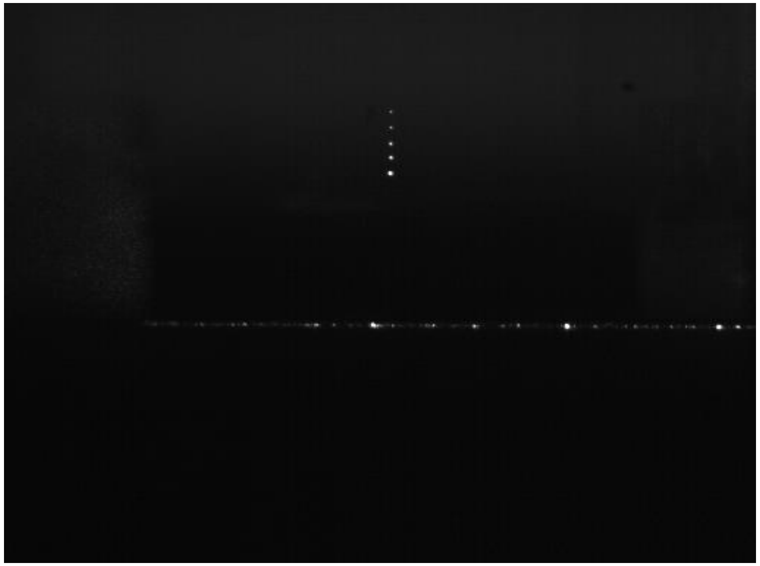
Ion Wakefield

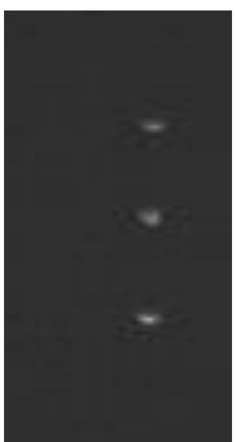




- What About Stability & Chain Formation?-
  - ***Requires*** wakefield confinement for stable chain formation
  - Assumes uniform sheath in an ITO box

Wakefield – q = 0.4Q (Dynamic Wakefield)
Fixed n_i
n_e – Sheath Dependent
Increasing Isotropic Confinement

Results



Ion Wakefield

- There **is** a wakefield within the box as evidenced by
  - Apparent positive space charge (i.e., attractive force in agreement with numerical simulations without box - see reference below) located below top particle in a two-particle chain and below both top and middle particles in a three-particle chain
  - Vertically –
    - Asymmetric interaction between top and lower two particles and between middle and bottom particles
    - Downstream particles dominated by nearest upstream neighbor
  - Horizontally
    - Wakefield attraction observed near center of the box where net horizontal confinement is small
  - Particle Pair Stability
    - Directly impacted by wakefield

M. Chen, L. Matthews and T.W. Hyde, PRE, In Submission (2015)

Block, Carstensen, Ludwig, Miloch, Greiner, Piel, Bonitz & Melzer, Contrib. Plasma Phys. 52, 10, 804 – 812 (2012)

Two- & Three-Particle Strings (Glass Box)

Ordering, Structure & Stability

- Ion Wakefield
  - Wakefield in Glass Box – Yes!
  - Wakefield Aids in
    - Particle Alignment Vertically & Horizontally
    - Two-Particle Pair Stability

- Non-Uniformity of the Sheath?
  Plasma Inhomogeneity?

Modifies
- Plasma – Particle Interaction
- Interparticle Interaction
- Shielding Length
- Ion Wakefield

M. Chen, L. Matthews and T.W. Hyde, PRE, In Submission (2015)

Two- & Three-Particle Strings (Glass Box)

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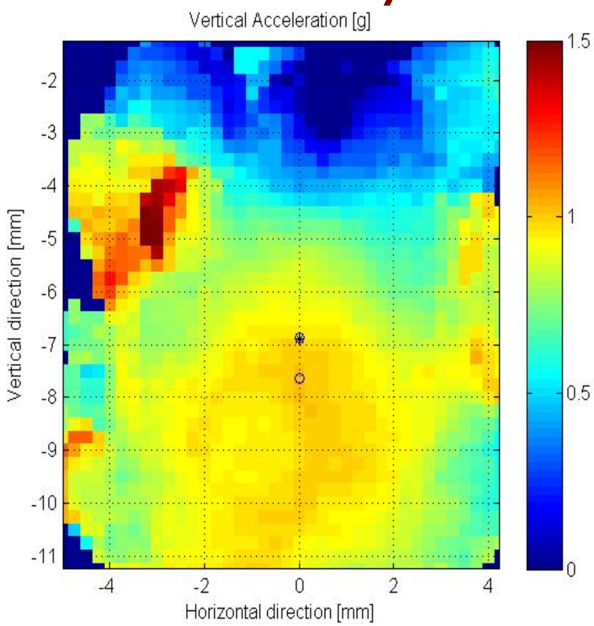
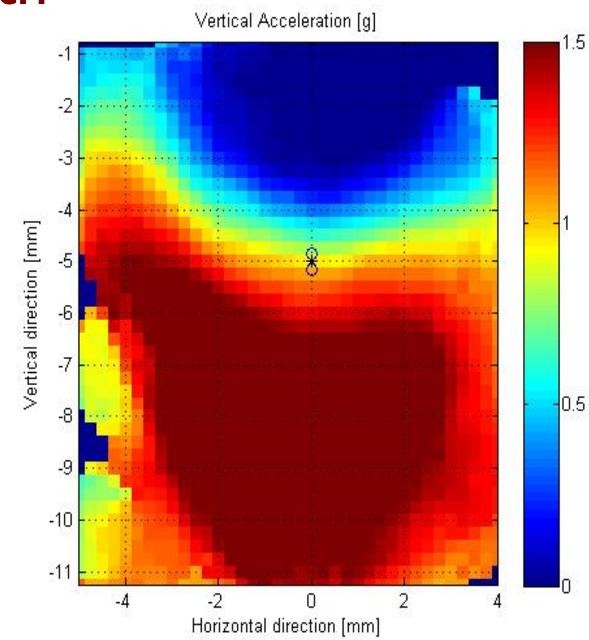
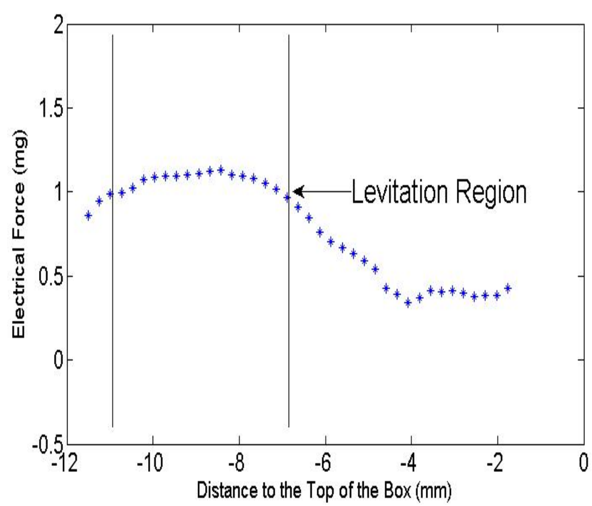
Plasma Inhomogeneity
Non-Uniformity of the Sheath

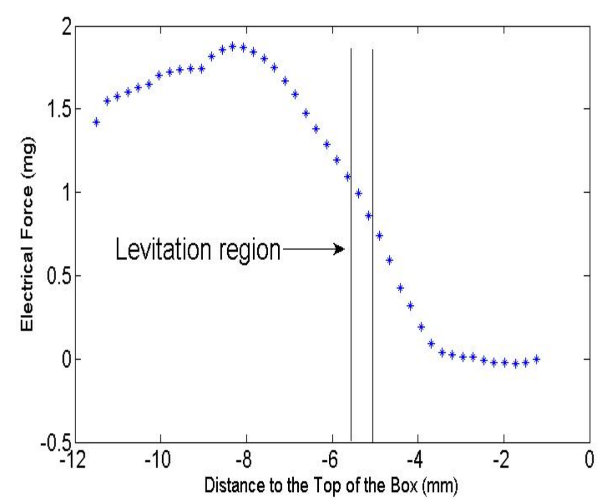
- Vertical acceleration for free falling particles in a glass box at 2W(L) and 8W(R)
- Equilibrium Position
  - '*'– Single particle
  - 'o' – Particle pair





- Vertical electric field force at centerline of box for 2W(L) and 8W(R)





Field Inhomogeneity Length

$$L_E = E\left(\frac{dE}{dz}\right)^{-1}$$

17 μ / PMMA / ½" glass box

M. Chen, L. Matthews and T.W. Hyde, PRE, In Submission (2015)

M. Chen, L. Matthews and T.W. Hyde – This Workshop - POSTER

14th Workshop on the Physics of Dusty Plasma – May 26-29, 2015

Two-Particle Strings (Glass Box)

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Plasma Inhomogeneity
Non-Uniformity of the Sheath

Sheath Electric Field

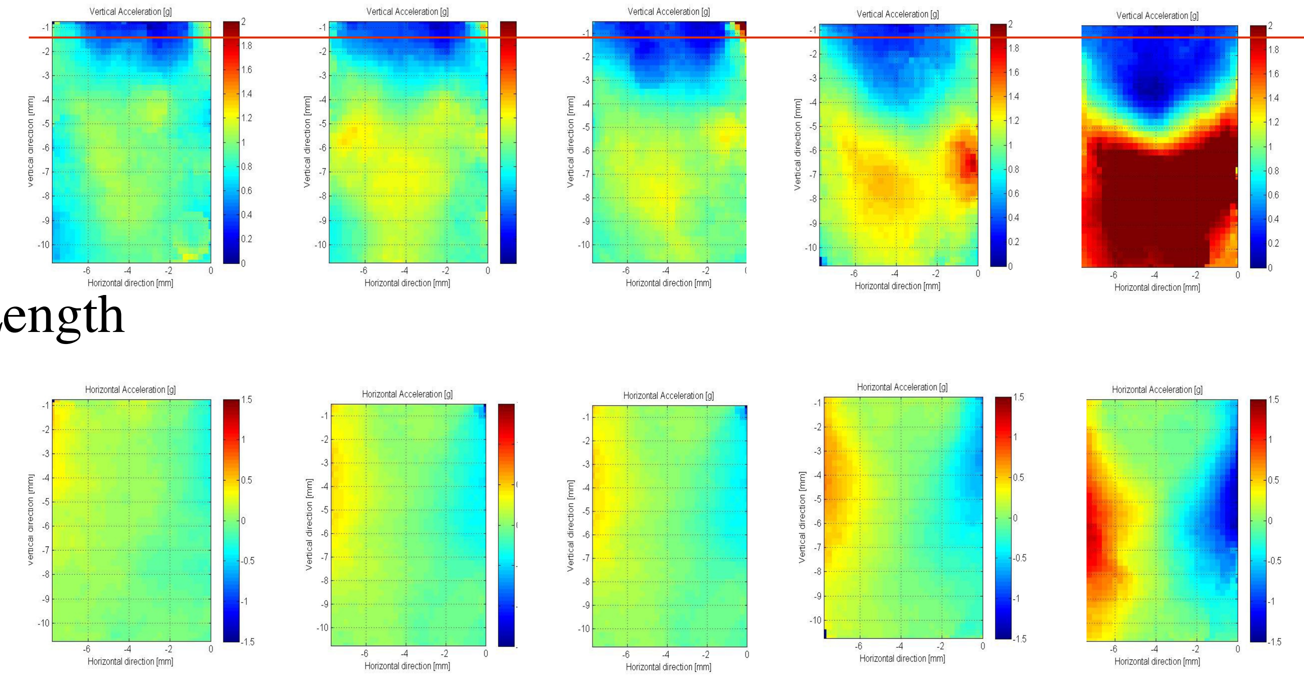
$$E = -\frac{d\phi}{dz}$$

Field Inhomogeneity Length

$$L_E = E\left(\frac{dE}{dz}\right)^{-1}$$

$$\phi = \phi_s + \phi_q$$

$$\phi = \phi_s + \phi_q + \phi_B$$



375 mV | 420 mV | 432 mV | 490 mV | 775 mV

ϕ_s = Sheath Potential

ϕ_q = Potential perturbation due to particle charge (wake potential)

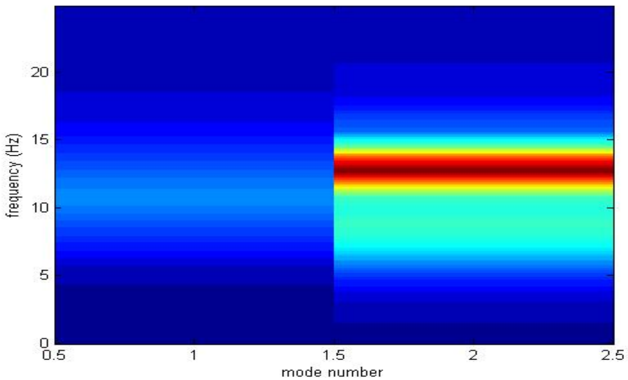
ϕ_B = Sheath Potential (Box Walls)

R. Kompaneets, A. Ivlev, V. Nosenko and G.E. Morfill, PRE, 89, 043108 (2014)

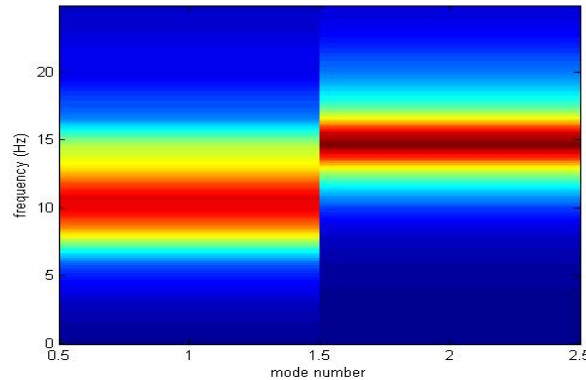
Two- & Three-Particle Strings (Glass Box)

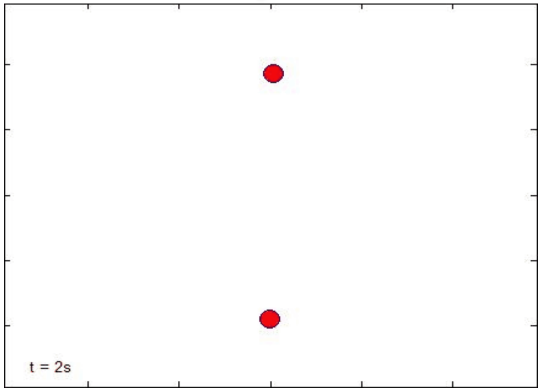
Mode Spectra

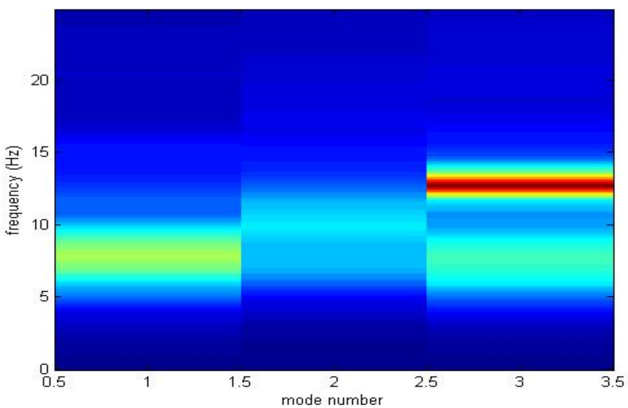
Horizontal Spectra

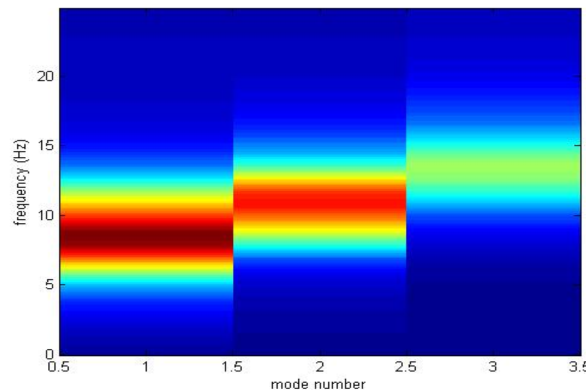


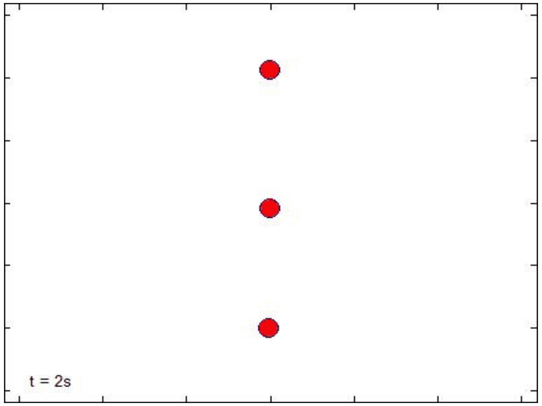
Vertical Spectra











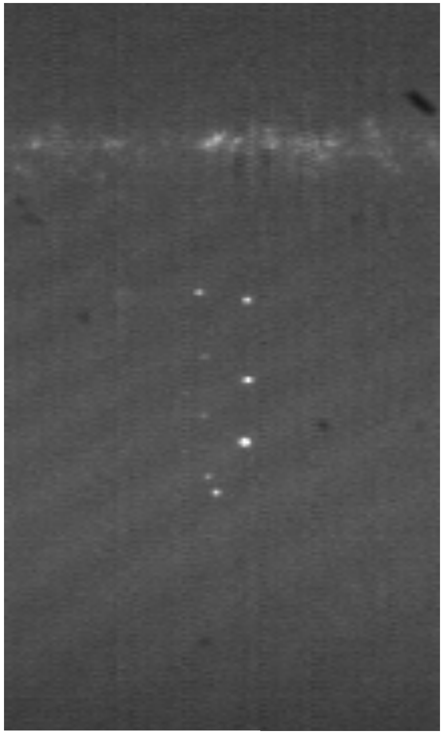
- Vertical - Clean vertical spectra lines indicate pure Coulomb interaction
- Horizontal - Possible mode coupling reflecting the effect of an ion wake

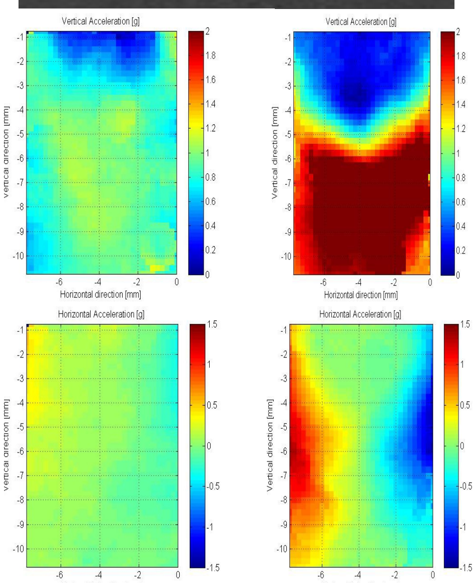
K. Qiao, J. Kong, E.V. Oeveren, L. S. Matthews, and T.W. Hyde, Phys. Rev. E 88, 043103 (2013)

Nosenko, et al., Phys. Plasmas 21, 113701 (2014)

Melzer, et al., Phys. Rev. E 89, 013109 (2014)

Results





Confinement

- Available Energy Phase Space
- Horizontal and Vertical Alignment
- Structural Ordering (1D, 2D, 3D)

Wakefield

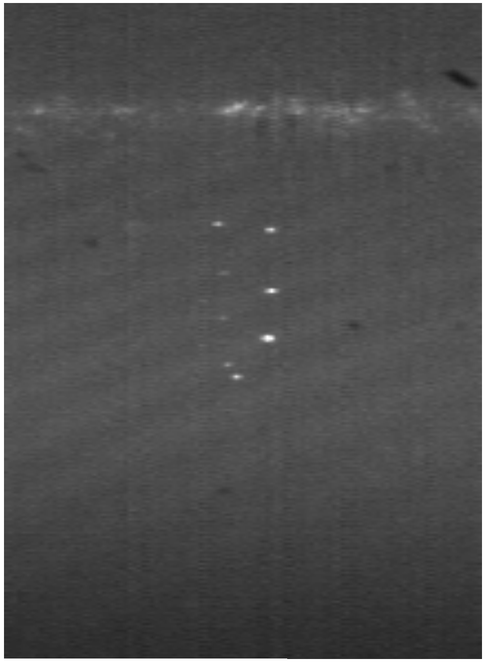
- Vertical and Horizontal Alignment
- Stability

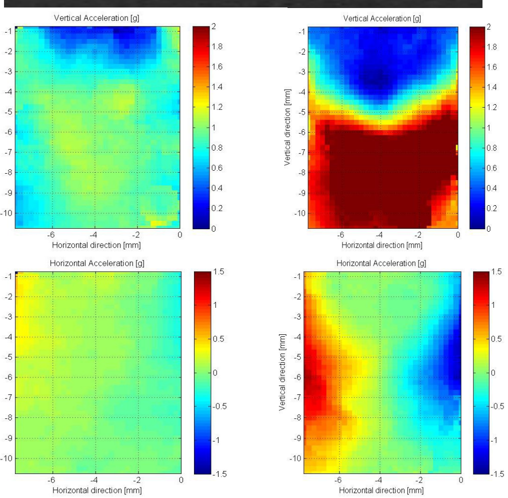
Plasma Inhomogeneity
Non-Uniformity of the Sheath

- Vertical Alignment
  - Coulomb screening
  - Weaker in the perpendicular direction
- Horizontal Alignment / Dust Pair Stability
  - Stability of vertical dust pairs dependent on wake effect
  - Horizontal alignment dependent on wake effect
- Structural Ordering (1D, 2D, 3D)
  - At powers higher than 2W, the non-uniformity of the sheath confinement created by the box suppresses
    - The ability to form extended vertically aligned strings
    - Most other forces (the wake field force)
  - At powers less than 2W, for a particle pair case, the lower particle does not appear to repel the top particle
- Mode Spectra
  - Vertical direction - The interparticle interaction appears to be almost purely Coulomb in nature
  - Horizontal direction - The interparticle interaction shows a nonreciprocal attraction (ion wake effect)

Conclusions

Plasma Inhomogeneity
Non-Uniformity of the Sheath



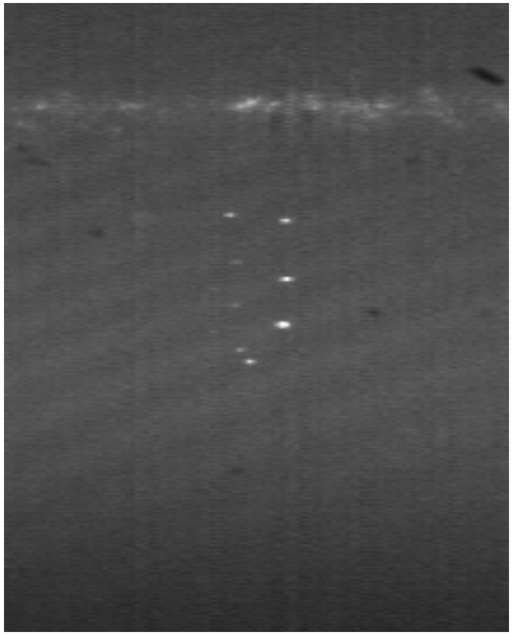


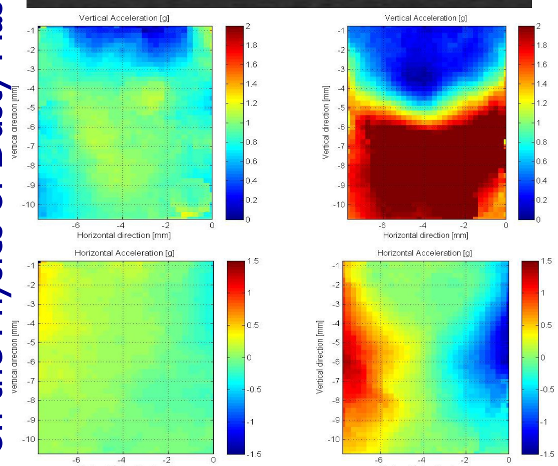
- Measured - Free-Falling Particles as Probes
  - Resulting plasma inhomogeneity modifies the wake (shielding) and is dependent (at least in part) on the Field Inhomogeneity Length
  - Oscillatory wake structure in the ion flow direction appears substantially weaker (or is overwhelmed by sheath electric field)
  - Wake appears substantially weaker (or is overwhelmed by sheath electric field)
  - Screening of the Coulomb potential appears to be weaker in the perpendicular direction – So,
    - Weakened / eliminated positive attraction in this direction – In certain cases

- Measured - Mode Spectra Analysis
  - Stronger interparticle interactions in two-dimensional plasma crystals
  - Difficulty in experimentally realizing a molecular-type interaction potential in two-dimensional plasma crystals

A.V. Ivlev, S. K. Zhdanov, S.A. Khrapak, and G. E. Morfill, Phys. Rev. E 71, 016405 (2005)
T. Peter, J. Plasma Phys. **44**, 269 (1990)
Nosenko, et al., Phys. Plasmas 21, 113701 (2014)
Melzer, et al., Phys. Rev. E 89, 013109 (2014)

Conclusions





Plasma Inhomogeneity
Non-Uniformity of the Sheath

SO…..

- Surprisingly (or maybe not!) similar agreement between both numerical and experimental results with and without a box

And –

- Current experimental results cannot be used as justification for assuming (1) Yukawa potential or (2) Dominant role of electrons in grain screening since both the analytical expressions and Yukawa potential (confinement) provide many of the same experimental results

- Standard Disclaimer!
  - The disappearance of the ion wake effect in the vertical direction could be caused by the sheath field inhomogeneity, or one of a host of other mechanisms such as ion-neutral charge-exchange collisions or the ion velocity distribution

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V. Ivlev, S. K. Zhdanov, S.A. Khrapak, and G. E. Morfill, Phys. Rev. E 71, 016405 (2005)
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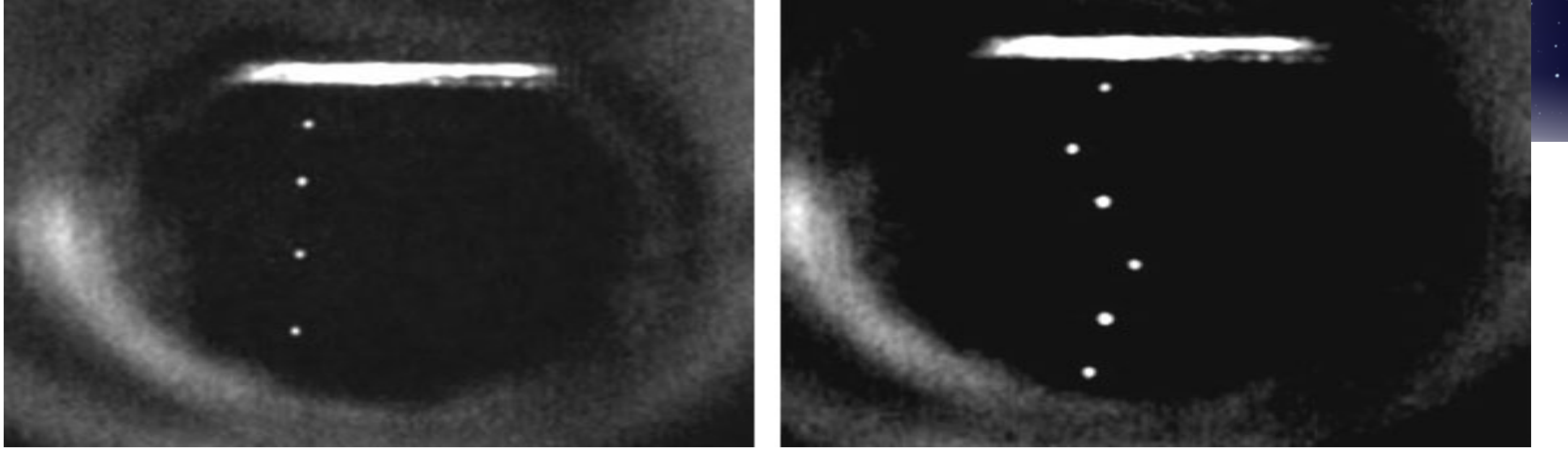
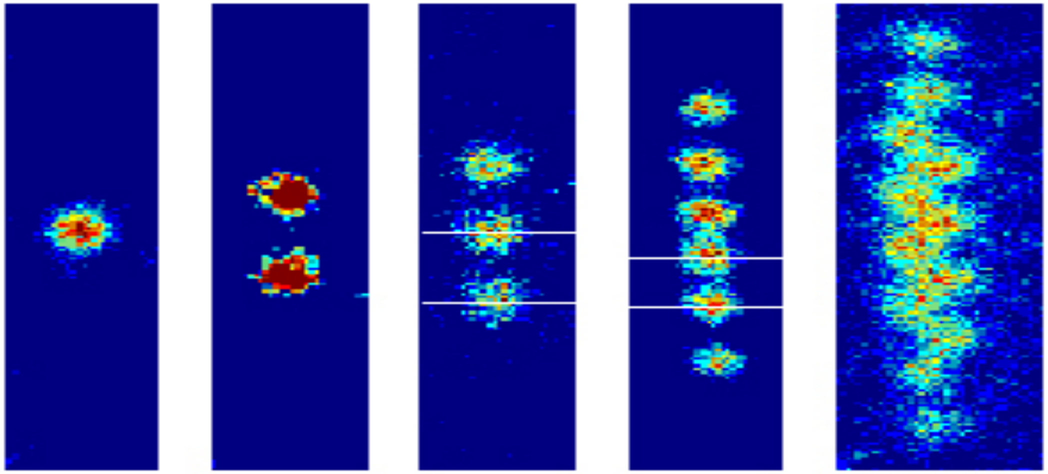


THANK YOU FOR YOUR ATTENTION! QUESTIONS?



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