Measurements of Finite Dust Temperature Effects in the Dispersion Relation of the Dust Acoustic Wave

Senior Honors Thesis

April 22, 2009

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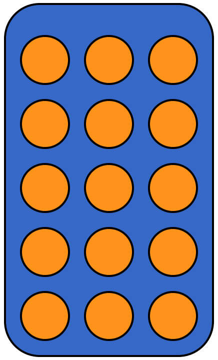
Outline

- What is a plasma?
- What is a dusty plasma?
- Previous work with dust temperature and Dust Acoustic Wave
- Experimental set up
- Experimental methodology
- Results
- Future Work

Solid



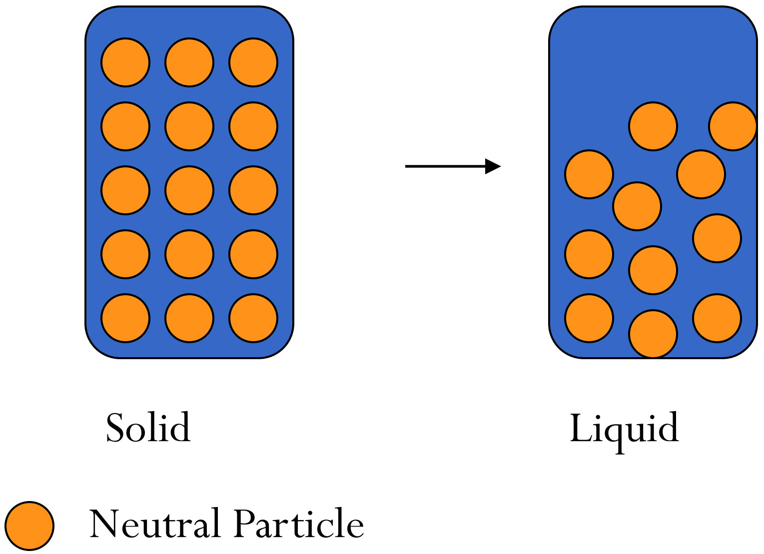
Solid

Neutral Particle

Increasing Energy →

Organized
Strong intermolecular bonding
Coulombic forces
Short range

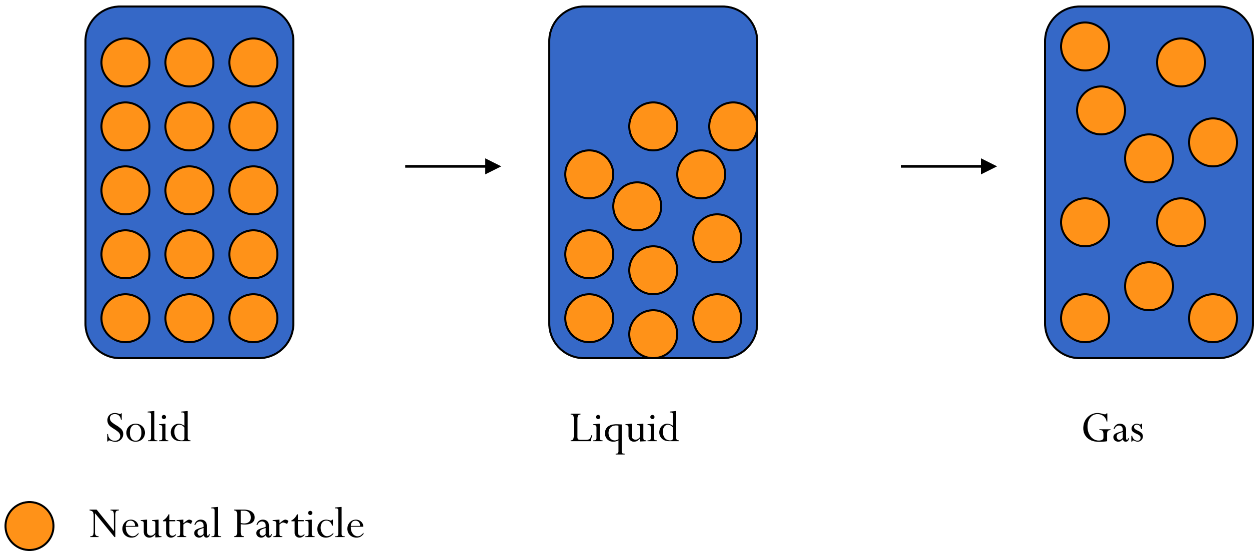
Liquid



Increasing Energy →

Loosely organized
Collisions and weak intermolecular forces
Weak coulombic forces
Short range

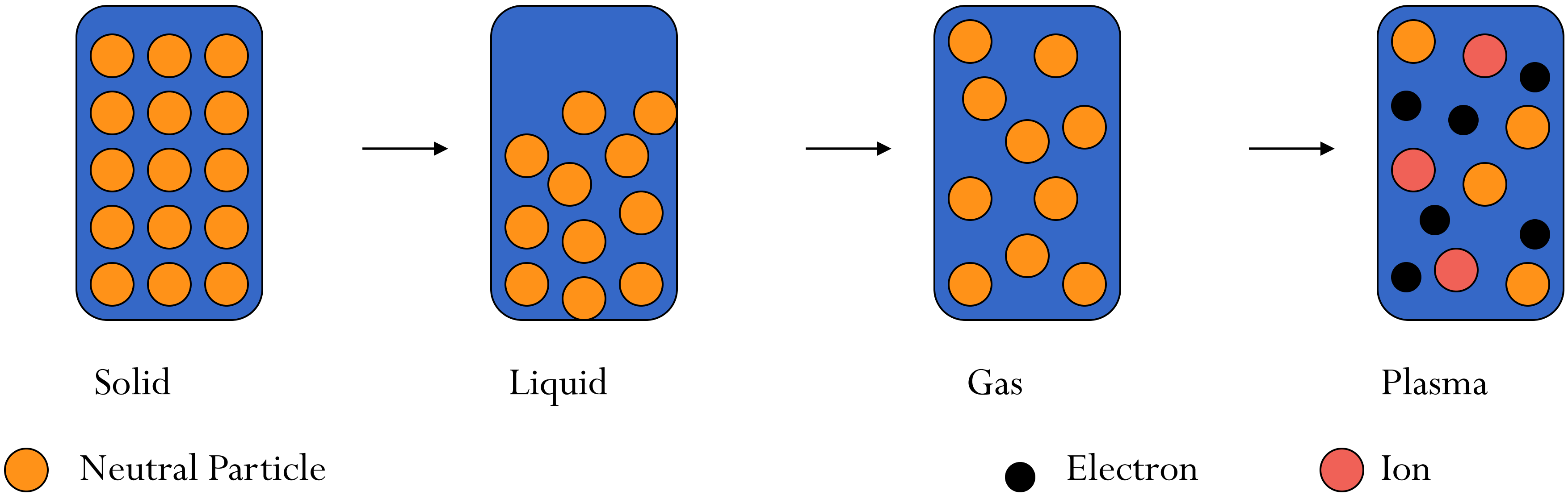
Gas



Increasing Energy →

No organization
Collisions only
Local interaction only

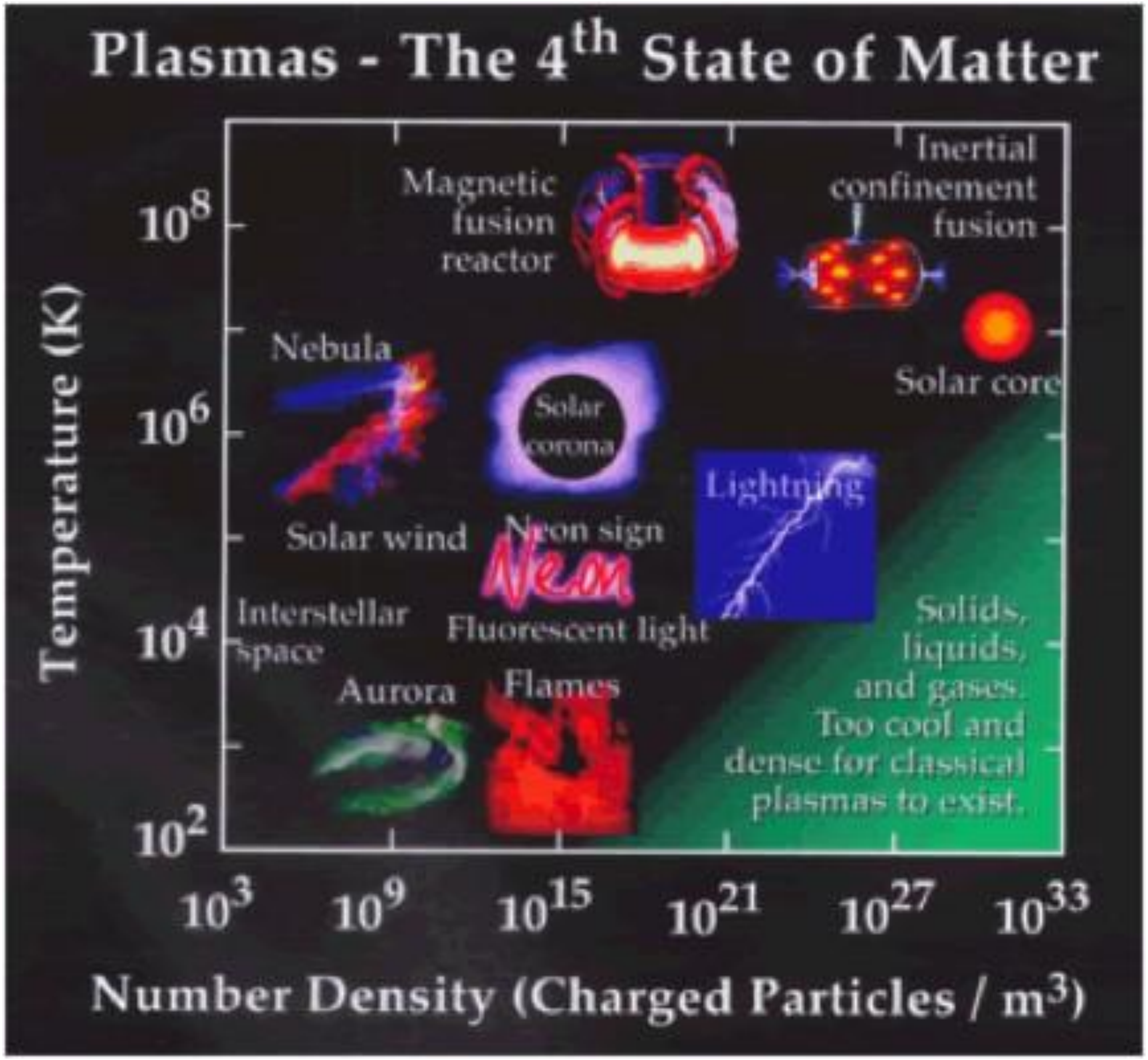
Plasma



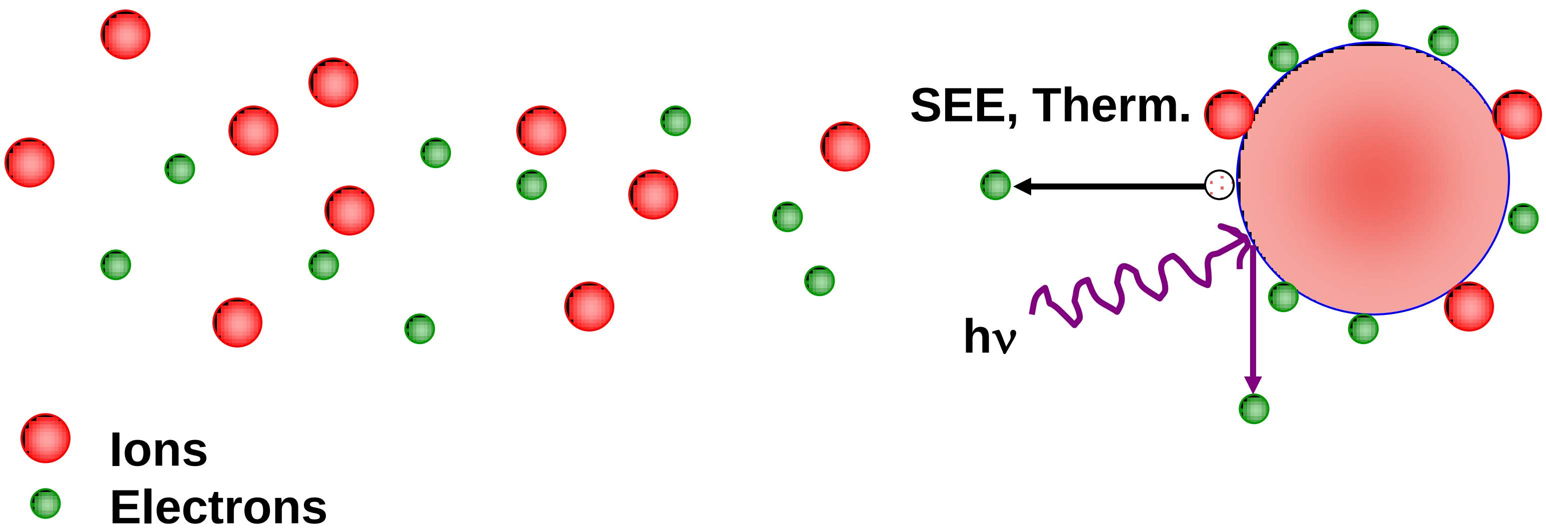
Increasing Energy →

No organization
Collisions and electromagnetic forces
Local and long range

Examples


Plasmas - The 4th State of Matter
Magnetic fusion reactor
Inertial confinement fusion
Nebula
Solar corona
Solar core
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
Temperature (K)
10^8
10^6
10^4
10^2
10^3
10^9
10^15
10^21
10^27
10^33
Number Density (Charged Particles / m^3)

Dusty Plasma



- Dust particle moves through the plasma, collects ions and electrons from the surrounding plasma - acquires a net charge.

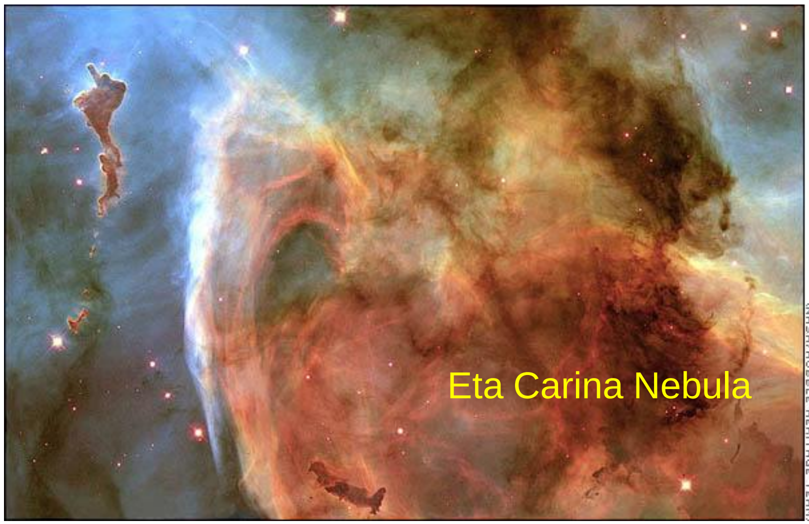
$$I_{total} = I_{electron} + I_{ion} + I_{see} + I_{thermionic} + I_{h\nu} = 0$$

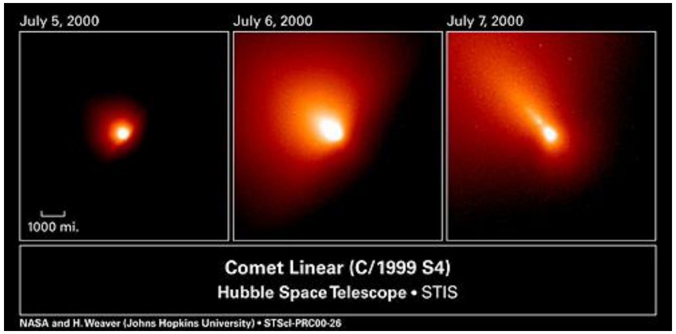
- Charge-to-mass ratio

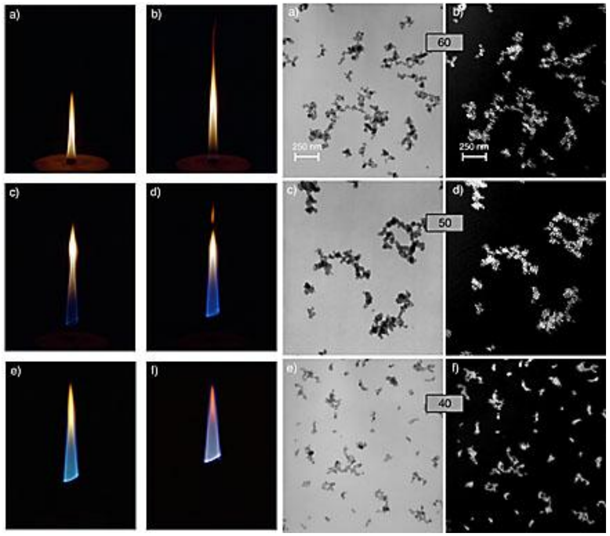
Why are they interesting?

- They’re prominent in the universe.
- Example of a complex, self-organized non-linear system that allows for direct visualization on the kinetic level via light scattering that provides a test bed for a wide range of phenomena.
- Relatively low charge to mass ratio
  - Introduces new collective phenomena (*e.g.*, wave modes such as the dust-acoustic and ion-acoustic wave)
  - Relatively long time scales for phenomena

Dusty Plasma Examples







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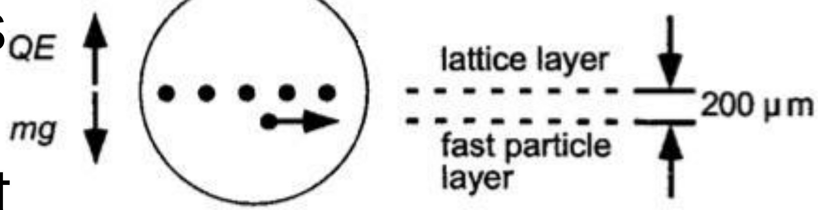
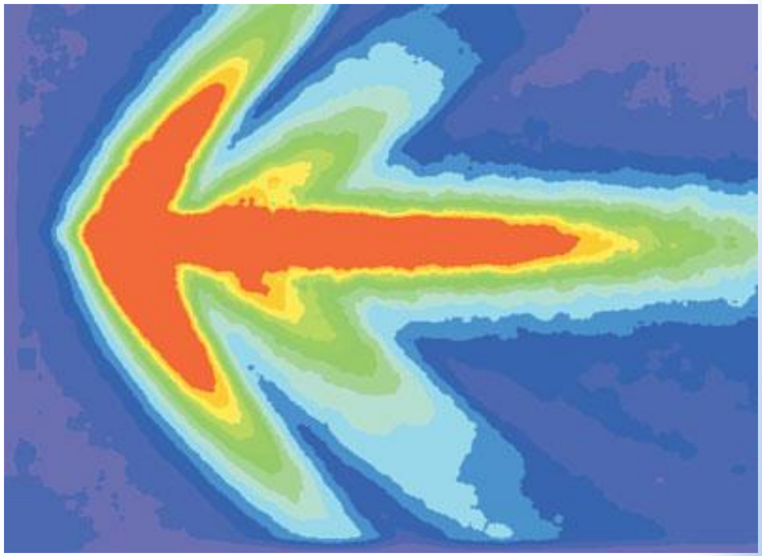
Mach Cone

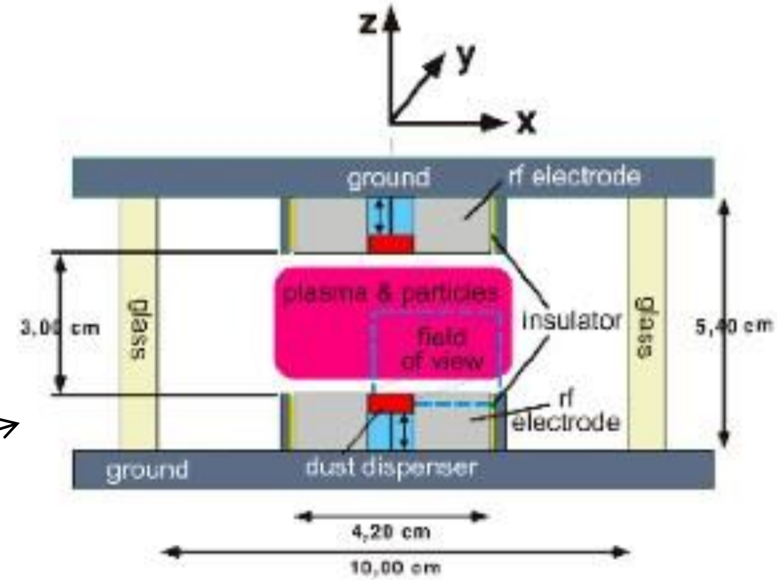
- Dust particles arranged in a monolayer, with a few particles underneath.
- Disturbance of lower layer dust particles moving at supersonic speeds compared to the natural dust speed.
- Measuring opening angle tells information about size of dust particle creating cone.
- Expected to occur in Saturn's rings, could help determine size of dust in rings.

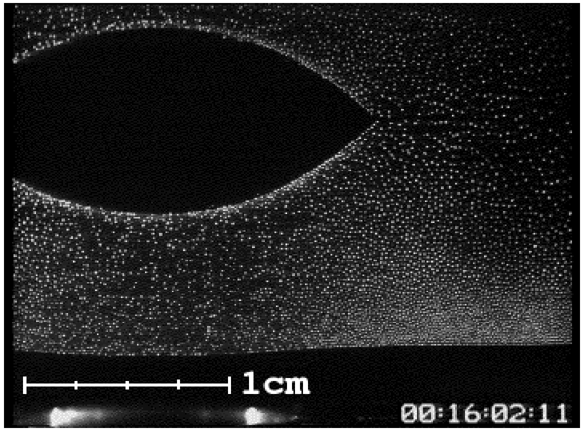




Microgravity

- Can neglect effect of Earth's gravity. Similar to eliminating first order terms
- Other smaller forces are able to be observed.
- Parabolic air flight
- International Space Station
- Instability in center of plasma causes higher ionization of atoms, resulting in ions streaming out of void, pushing dust particles away.
- Dynamic equilibrium reached with charged dust pushing back in.





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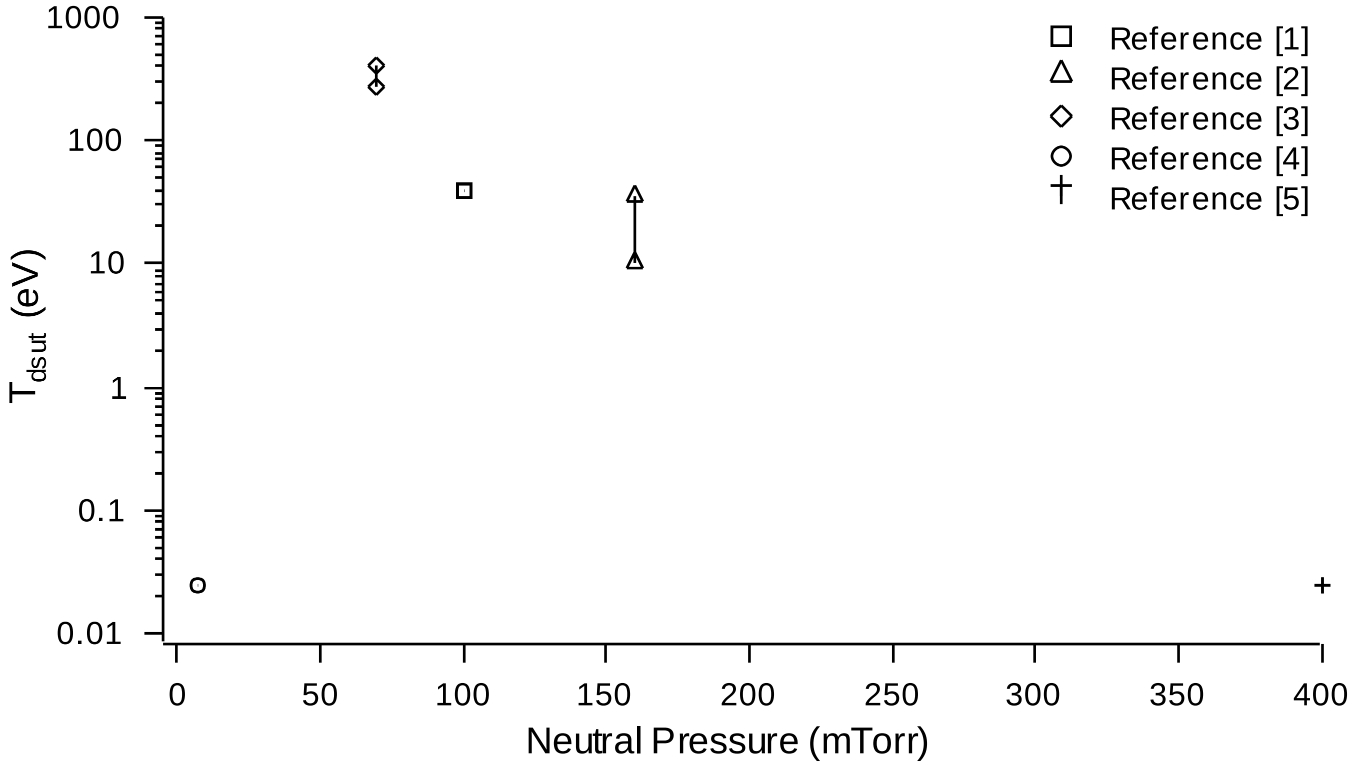
Dust Acoustic Wave

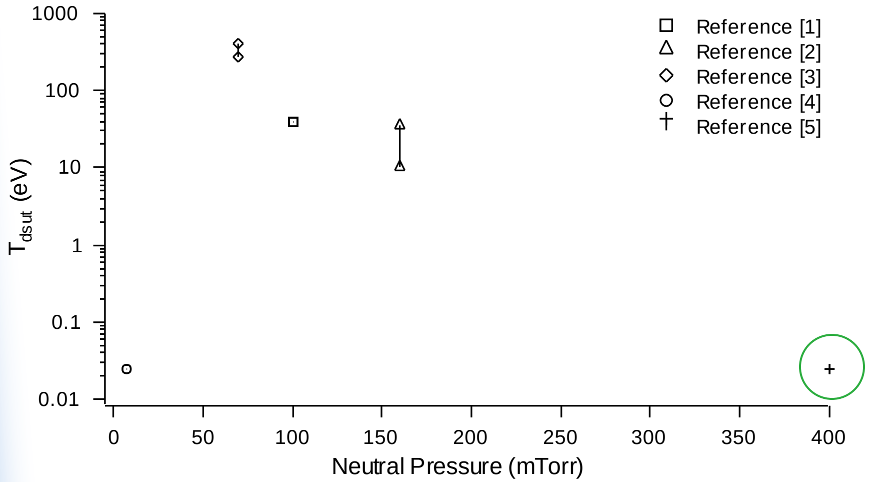
- Low frequency, compressional mode of the charged microparticle component.
- Propagation involves dynamics of heavy particles with small charge-to-mass ratios.
- Moves on the order of a few cm/s. Frequencies on order of Hz.

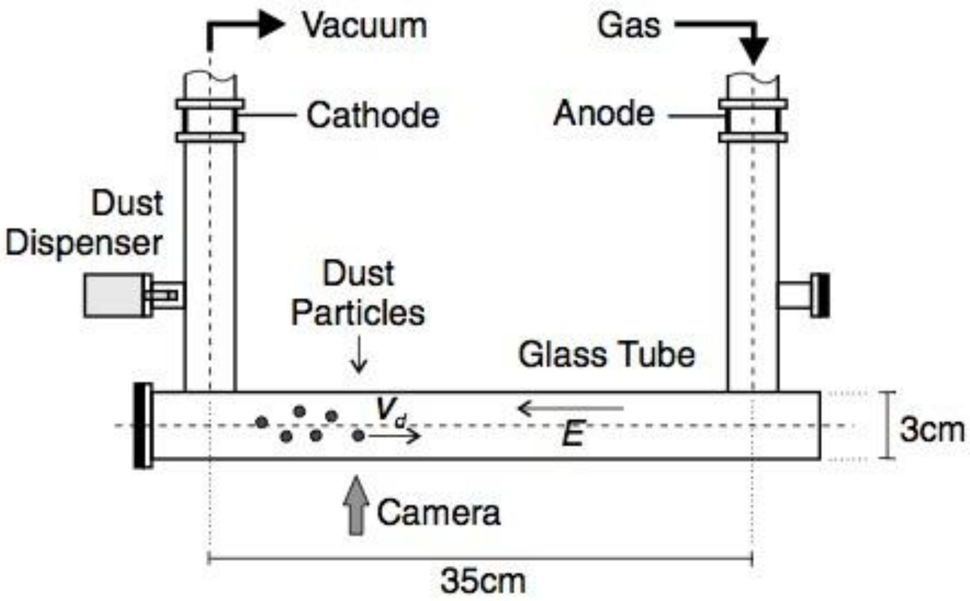
Previous Work



[1] C. Thompson, A. Barkan, N. DÕAngelo, and R. L. Merlino, Phys. Plasmas **4**, 2331 (1997).
[2] E. Thomas, Jr., R. Fisher, and R. L. Merlino, Phys. Plasmas **14**, 123701 (2007).
[3] J. D. Williams, E. Thomas, Jr., and L. Marcus, Phys. Plasmas **15**, 043704 (2008).
[4] T. Trottenberg, D. Block, and A. Piel, Phys. Plasmas **15**, 042105 (2006).
[5] S. Ratynskaia, S. Khrapak, A. Zobnin, M. H. Thoma, M. Kretschmer, A. Usachev, V. Yaroshenko, R. A. Quinn, G. E. Morfill, O. Petrov, and V. Fortov, Phys. Rev. Lett. **93**, 085001

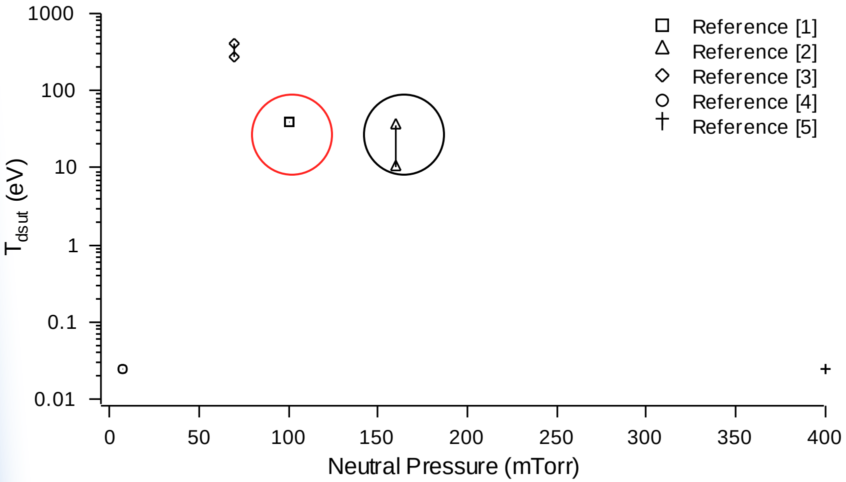
PK4

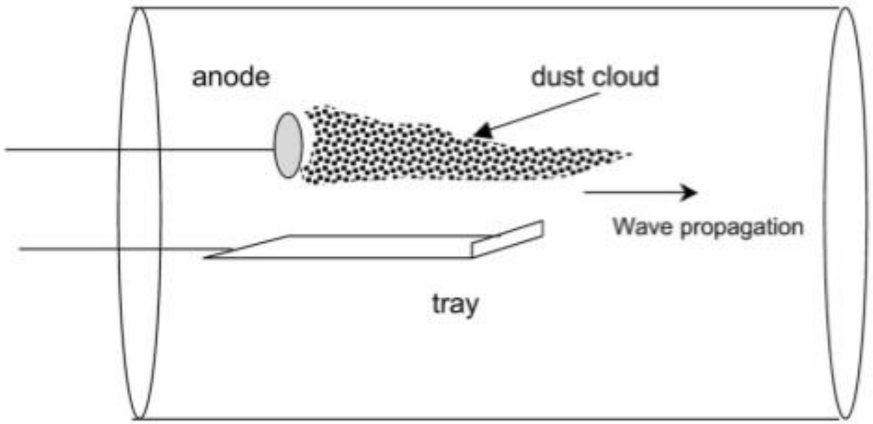




- Examining the condition necessary for the onset of the dust acoustic wave
- Theory accurately predicted the threshold condition, if the dust temperature was ~1/40 eV.

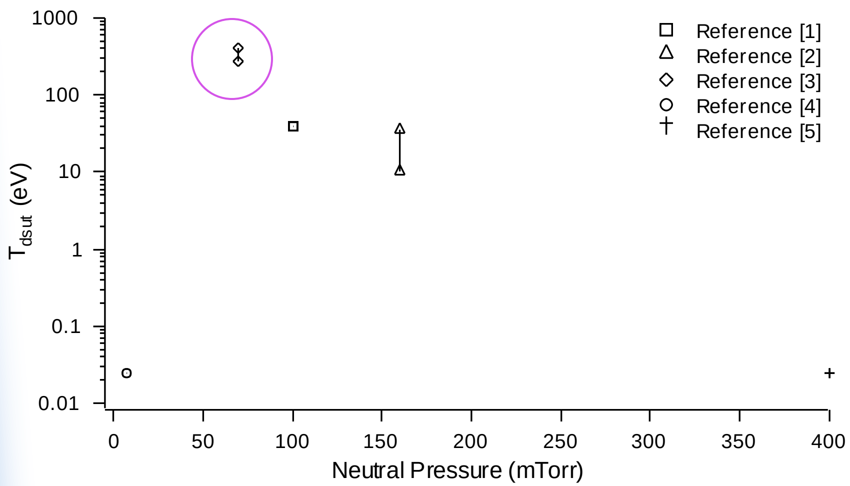
DPD

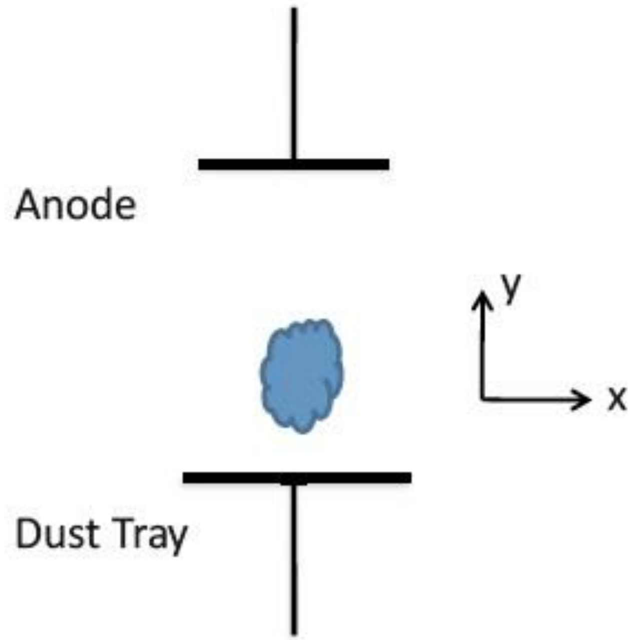




- Dispersion relationship for a horizontally propagating wave was measured by modulating the discharge current
- The temperature was found by fitting the measured dispersion relation to a a fluid model for the wave mode.

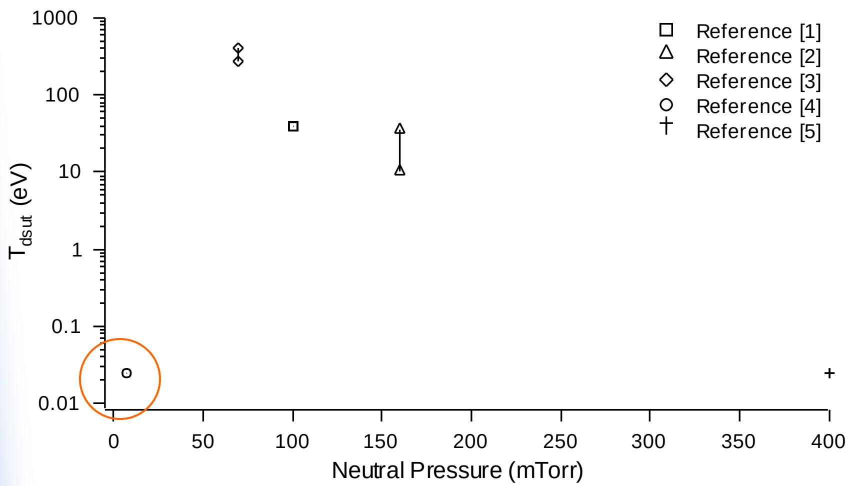
3DPX

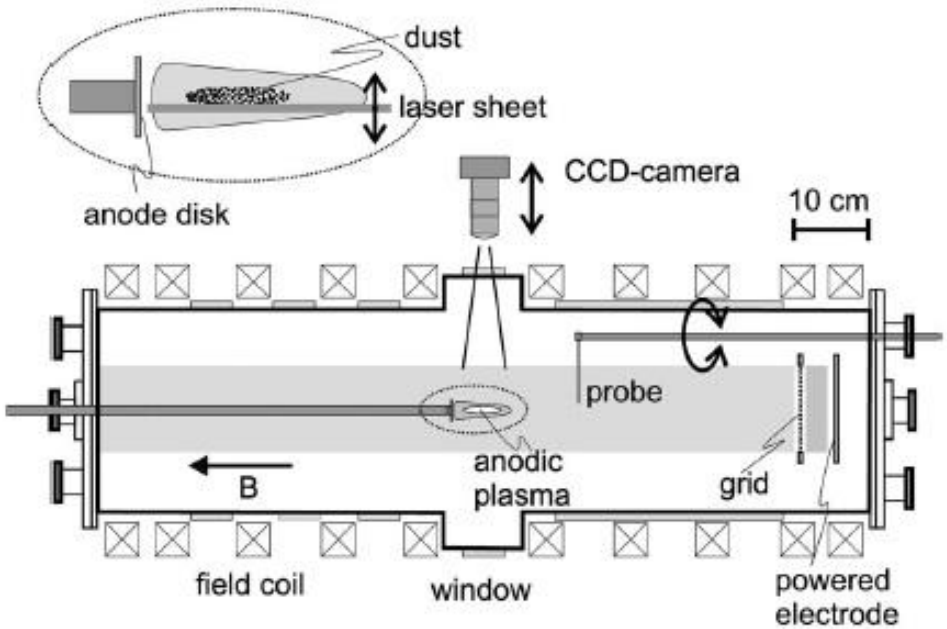




- Dispersion relationship for a vertically propagating wave was measured by modulating the discharge current
- The temperature was found by fitting the measured dispersion relation to a a fluid model for the wave mode.

Matilda II





- Dispersion relationship for a horizontally propagating wave was measured by modulating the discharge current
- The temperature was found by fitting the measured dispersion relation to a a kinetic model for the wave mode.

Procedure

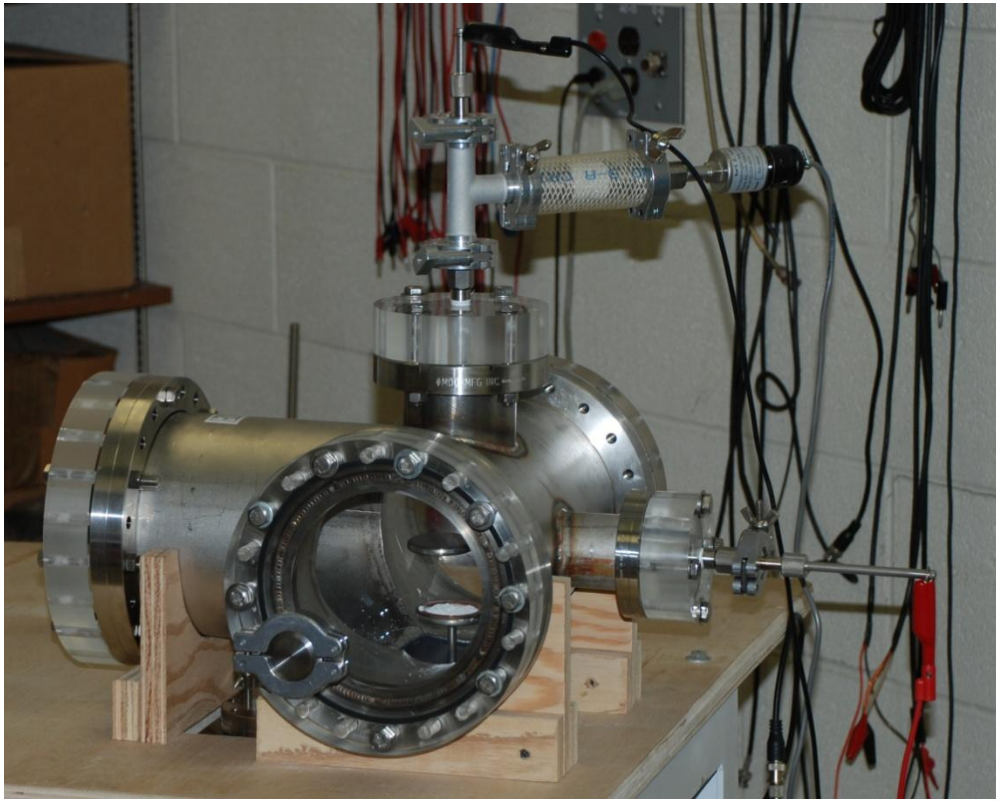
- Create a cloud containing a natural wave over a range of pressures
  - Accomplished for neutral pressures ranging from 50 to 120 mTorr
- Drive wave by modulating current
  - Capable of driving the wave mode over a range of neutral pressures, from 50 to 120 mTorr
- Measure dispersion relation
  - Measured for neutral pressures ranging from 55 mTorr to 70 mTorr
- Fit dispersion relation to extract temperature
  - Completed for p = 64 mTorr

Step 1

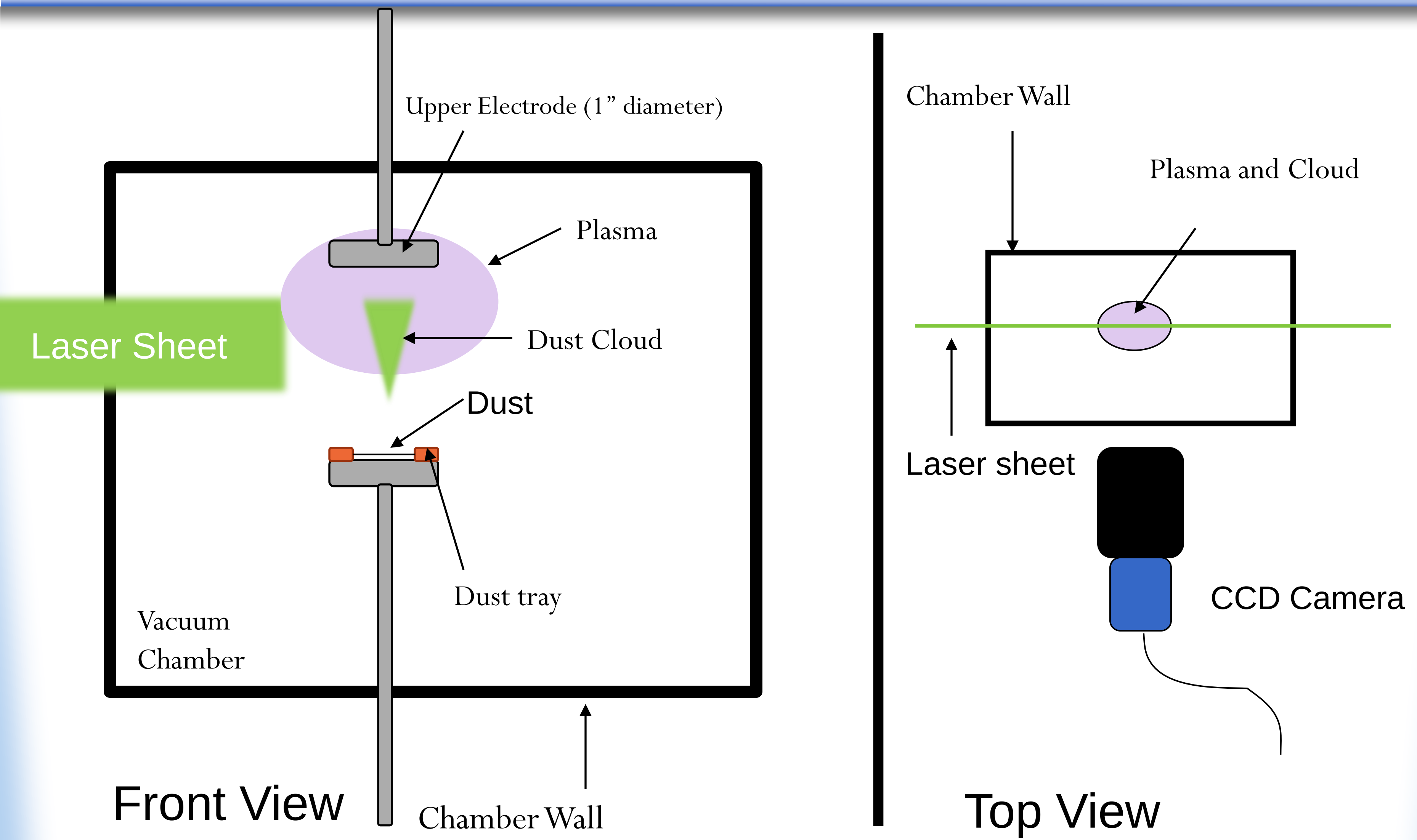
Generate the natural wave

Experimental Set Up

- Wittenberg University DUsty Plasma Experiment (WUDUPE)
  - 8 in Conflat Tee
  - Base Pressure
    - ~ 8 mTorr
- Experimental Conditions
  - DC discharge plasma
    - Argon gas
  - 50-120 mTorr
  - Silica spheres
    - d = 3±1 µm
    - m ≈ 31 pg



Experimental Sketch

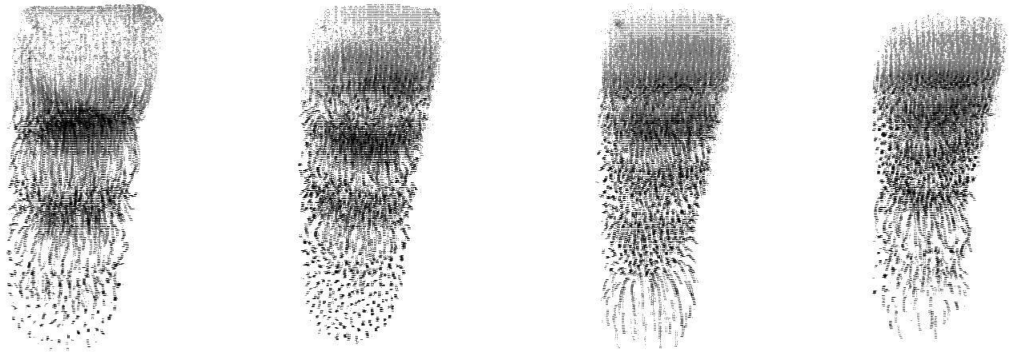


Step 2

Driving the wave

Driving

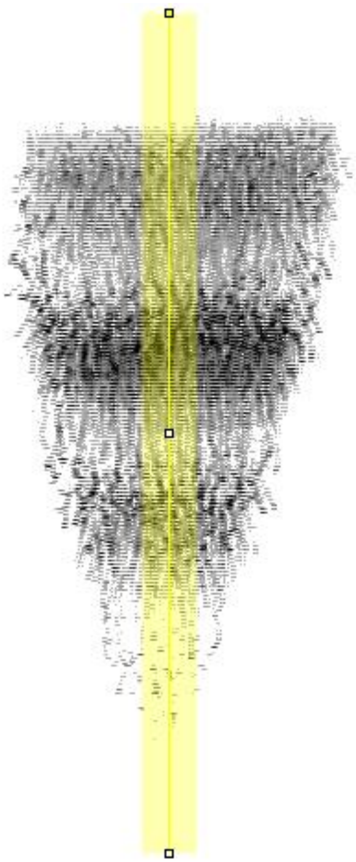
- Apply a ripple to the discharge current (0.185 - 0.3 mA) at desired frequency ($9 \leq f \leq 25$ Hz)
- Couples to natural wave mode
- Take 600 image sequences at 30fps

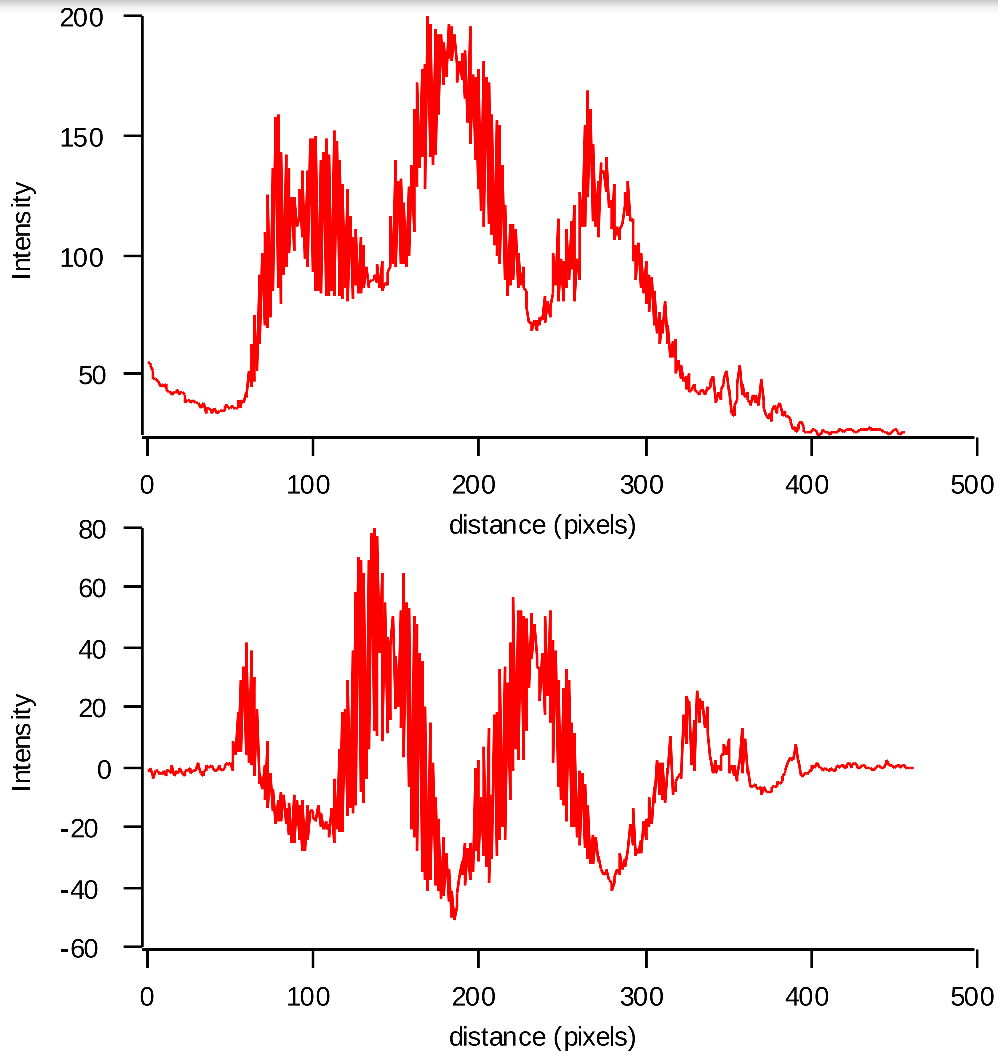


Step 3

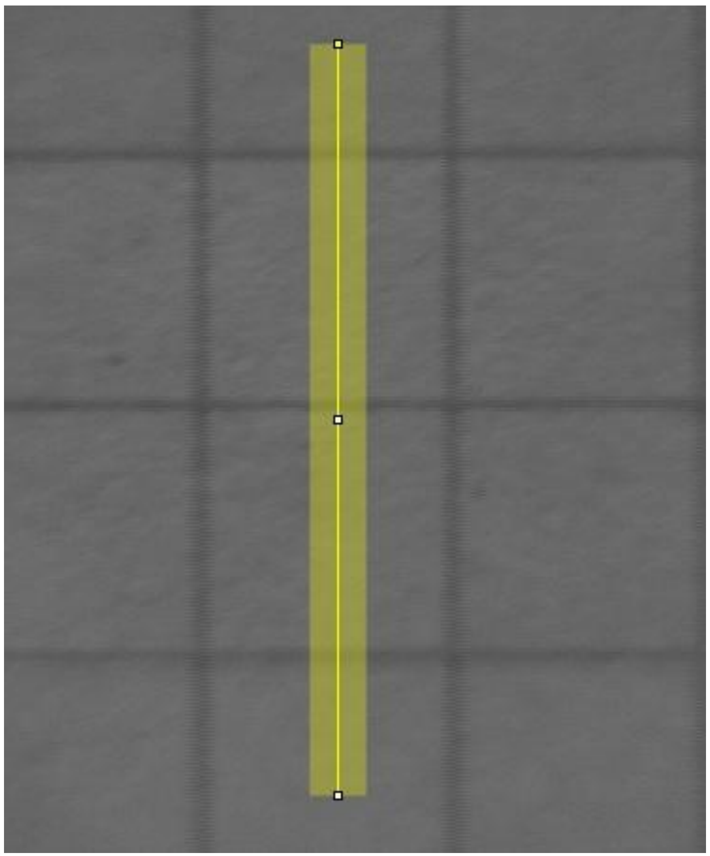
Measure dispersion relation

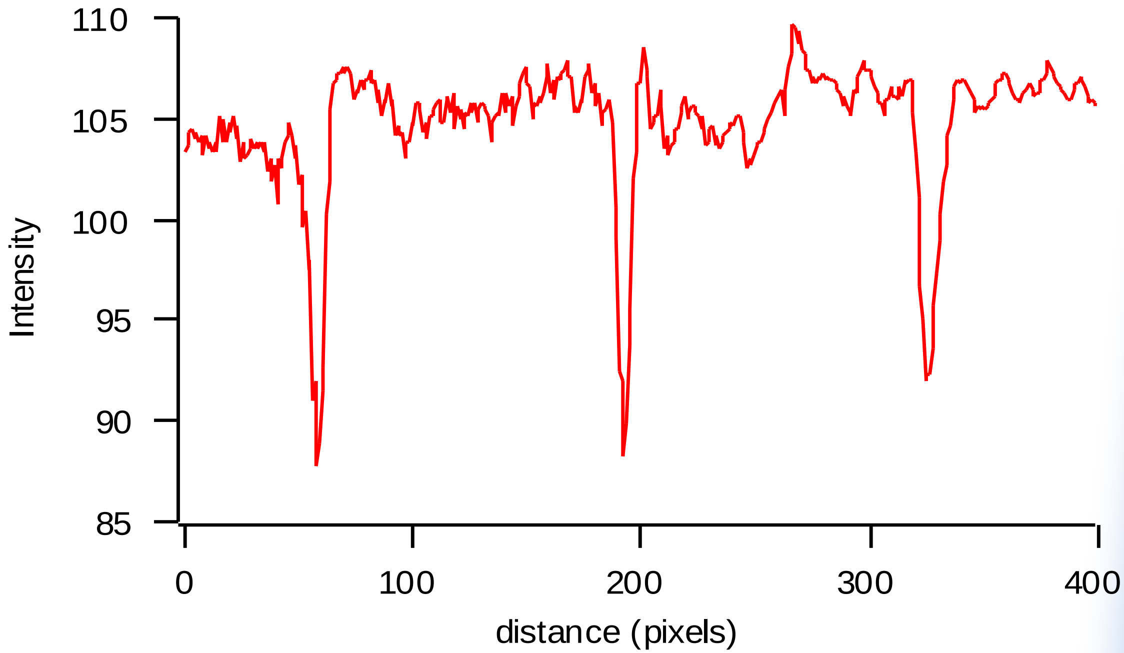
Finding Wavelengths



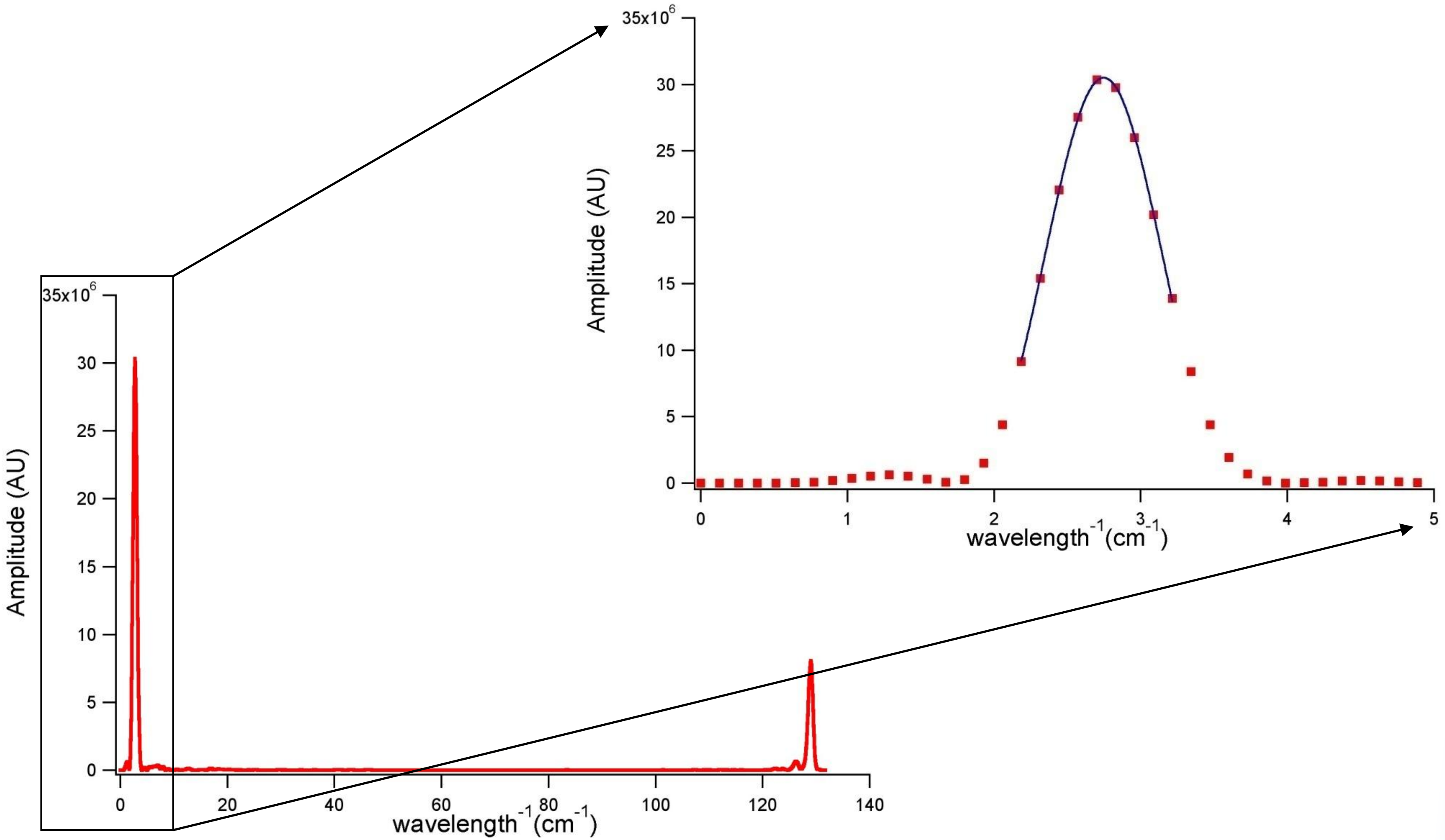


Calibration





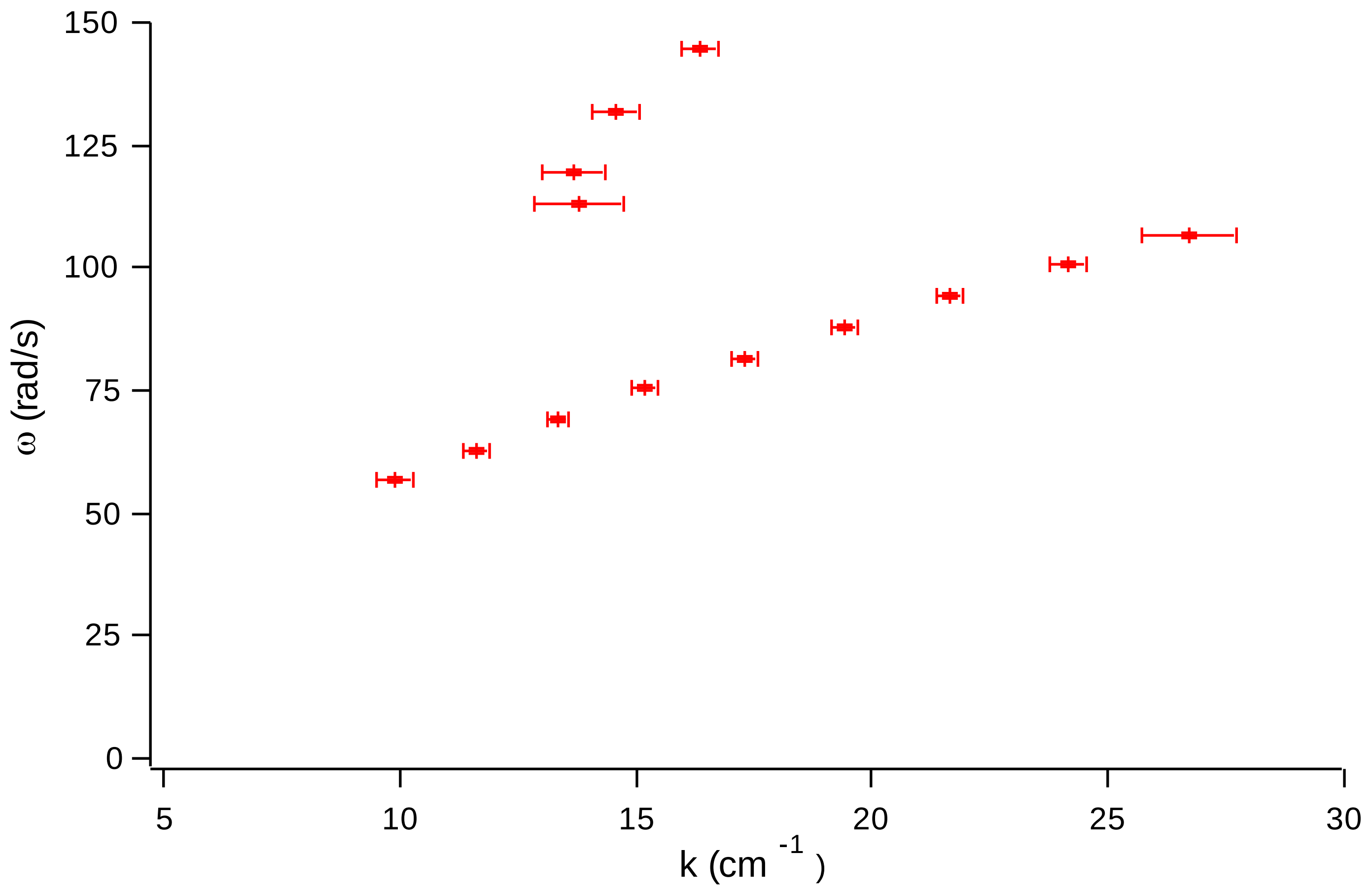
Fourier Transform



Experimental Parameters

Dust Parameters	Experimental Parameters	Plasma Parameters
$r_d = 1.5 \times 10^{-6}$ m $\rho_d \sim 2500$ kg/m^3 $m_d = 3.5 \times 10^{-14}$ kg $n_d = 3.03 \times 10^{10}$ m^{-3} $Z_d \sim 6750$ eV	$I_{discharge} = 1.185$ mA $I_{P\text{-}P,\ modulation} = 0.24$ mA P = 64 mTorr	$n \sim 1.35 \times 10^{14}$ m^{-3} $T_i \sim 0.025$ eV $T_e \sim 3$ eV $\lvert E \rvert = 140\ {}^{V}/_{m}$

Pressure = 64 mTorr



Step 4

Fit the dispersion relations

Theory

- Dispersion relation used in the work of Williams *et. al.*:

Ion term

Electron term

$$1-\frac{\omega_{pi}^2}{(\omega-ku_{io})(\omega-ku_{io}+i\nu_i^{eff})-k^2v_{ti}^2}-\frac{\omega_{pe}^2}{(\omega+ku_{eo})(\omega+ku_{eo}+i\nu_{en})-k^2v_{te}^2}$$

Vacuum term

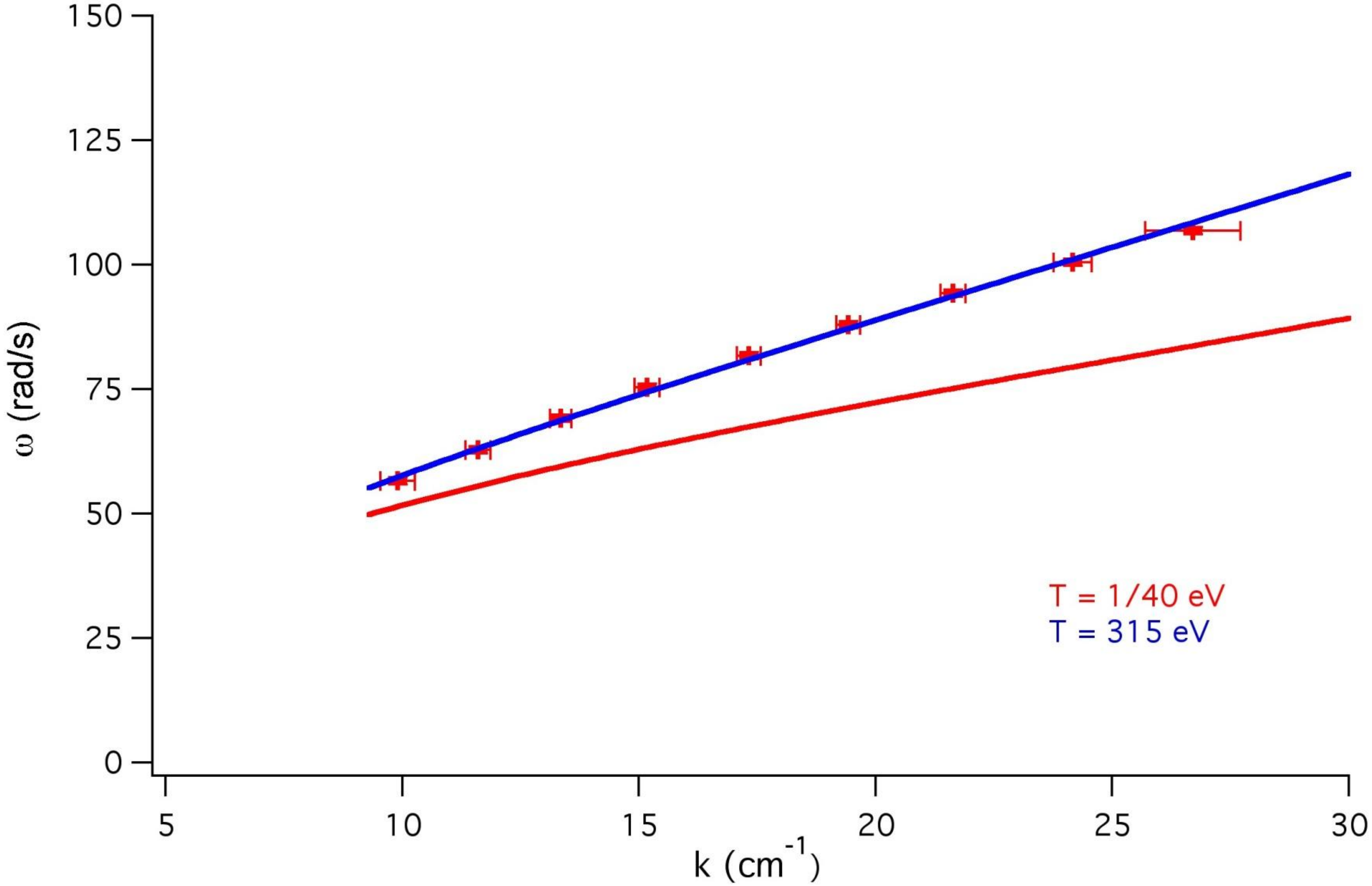
$$-\frac{\omega_{pd}^2}{\omega(\omega+i\nu_{dn})-k^2v_{td}^2}=0$$

Dust term

- Where is the dust temperature dependence?

$$v_{td}=\sqrt{\frac{k_BT_D}{m_d}}$$

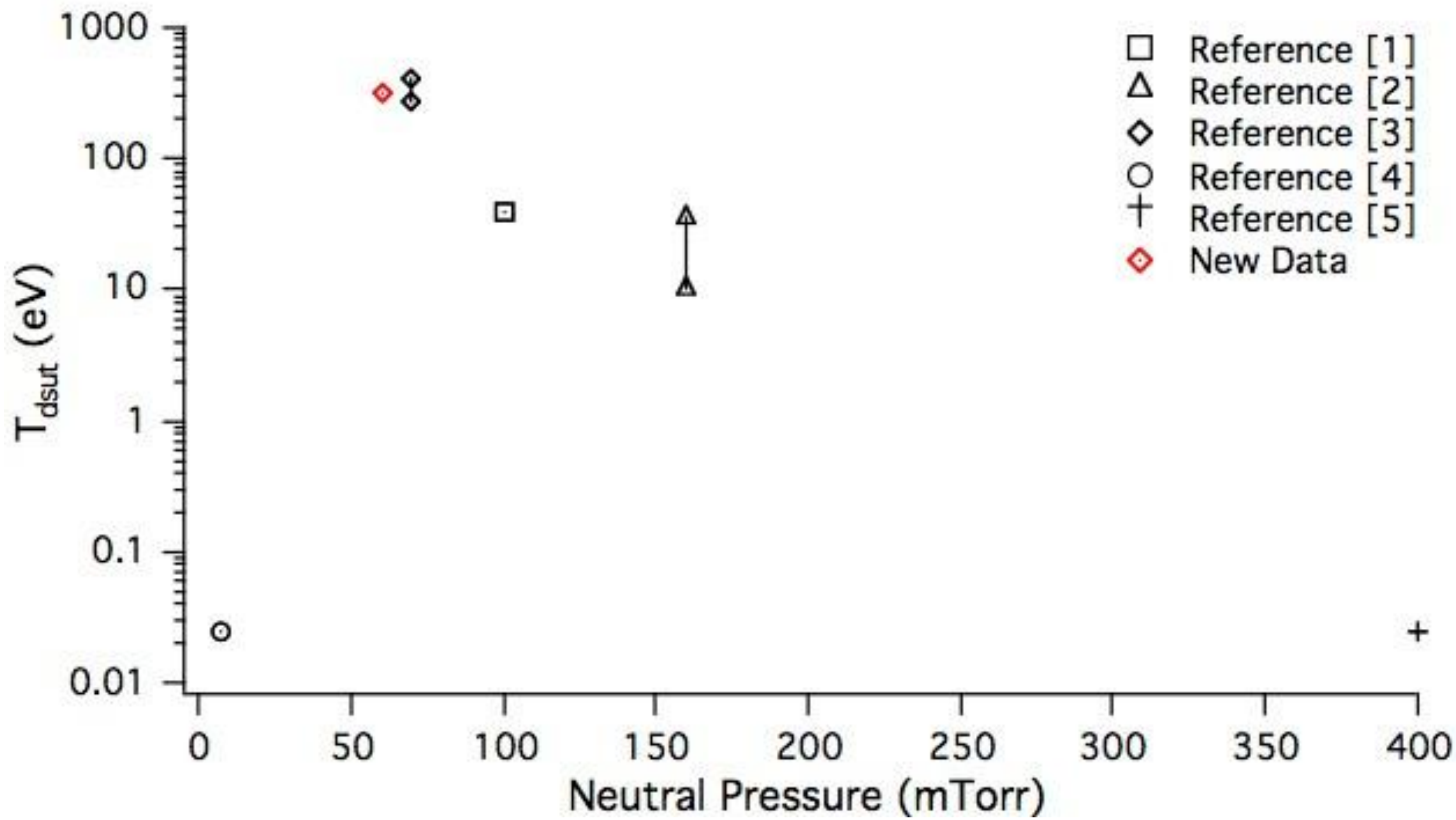
Dispersion Relation With Fit



Limitations

- To model the measured dispersion relation, fluid model was used.
  - breaks down at shorter wavelengths (*i.e.*, longer wavenumbers), particularly at smaller values of the dust temperature
  - increasing role of collisions at higher neutral pressures can also limit the validity of the model.
- The charge (Z_d) computed using OML theory tends to be larger than observed in experiment - particularly at higher values of neutral pressure.
  - A reduced charge results in a smaller slope in the calculated dispersion relation and requires an even larger value of the dust kinetic temperature to match the experimental measurements.

Results

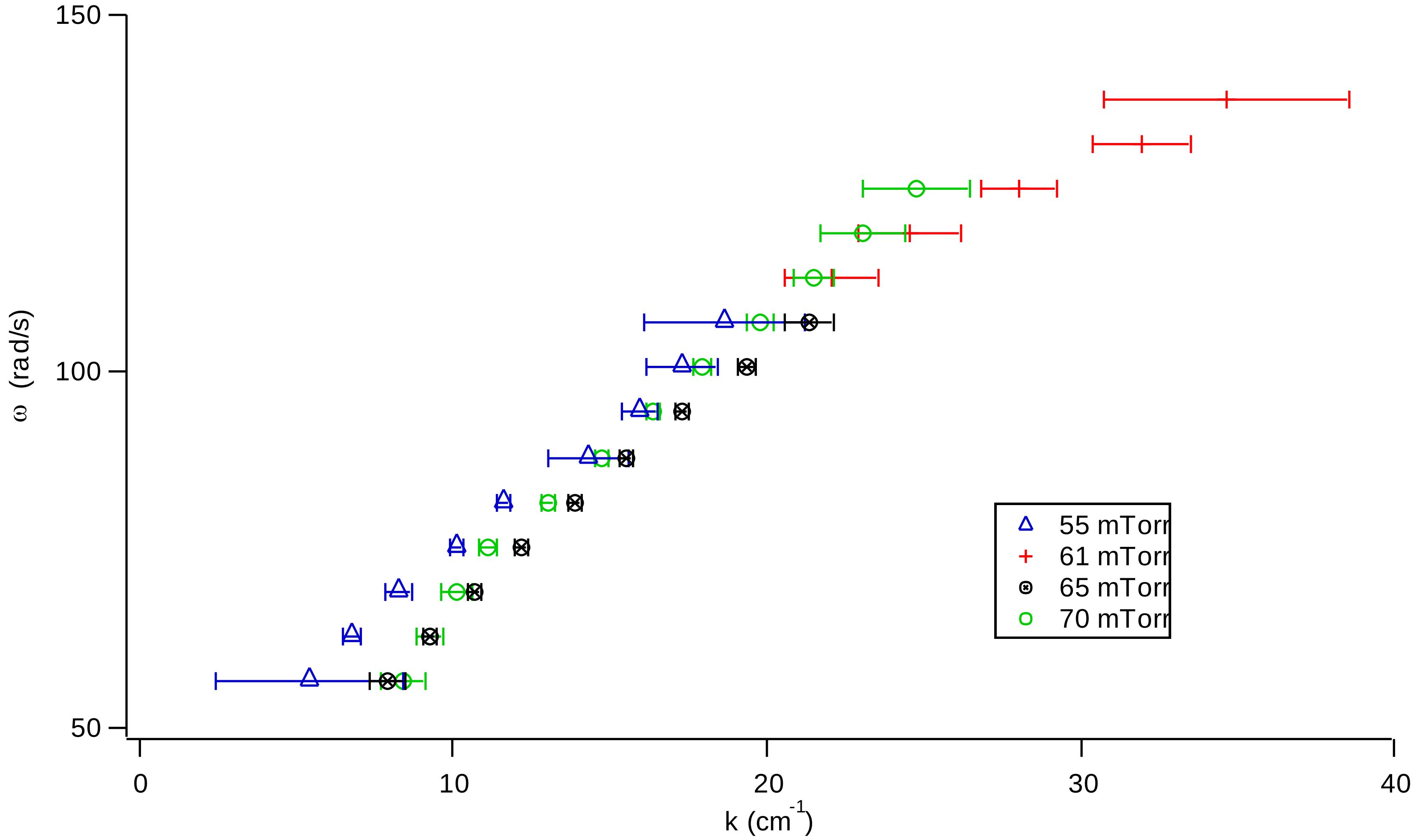


1000
100
10
1
0.1
0.01
T_{dsut} (eV)
0
50
100
150
200
250
300
350
400
Neutral Pressure (mTorr)
Reference [1]
Reference [2]
Reference [3]
Reference [4]
Reference [5]
New Data

Conclusions

- Create a cloud containing a natural wave over a range of pressures
  - Done for pressures ranging from 50 mTorr to 120 mTorr
- Drive wave by modulating current
  - Driving for pressures ranging from 50 mTorr to 120 mTorr
- Measure dispersion relation
  - Measured for pressures ranging from 55 mTorr to 70 mTorr
- Fit dispersion relation to extract temperature
  - Fit for 64 mTorr

Other Pressures



Acknowledgements

- Dr. Andrew Zwicker
- Dr. Jeremiah Williams

Modified Dispersion Relation

$$1-\frac{\omega_{pi}^2}{(\omega-ku_{io})(\omega-ku_{io}+i\nu_i^{eff})-k^2v_{ti}^2}-\frac{\omega_{pe}^2}{(\omega+ku_{eo})(\omega+ku_{eo}+i\nu_{en})-k^2v_{te}^2}$$

$$-\frac{\omega_{pd}^2}{\omega(\omega+i\nu_{dn})-k^2v_{td}^2}=0$$

where

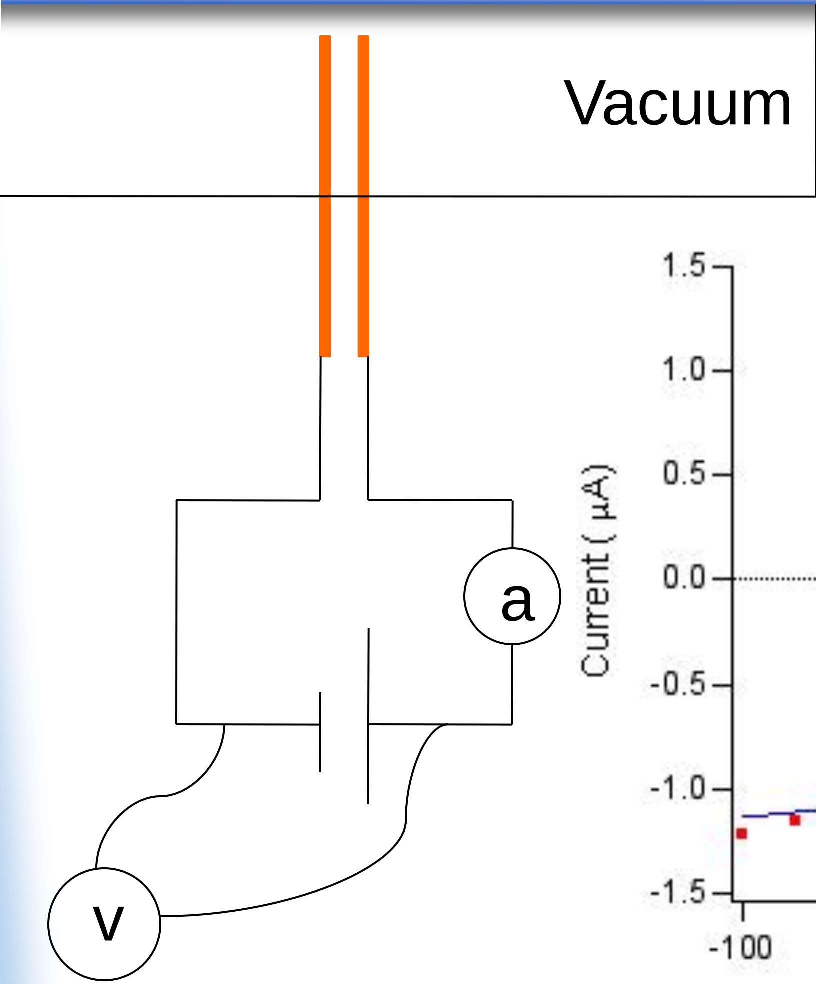
$$u_{\alpha 0}=\frac{q_\alpha E_0}{m_\alpha \nu_{\alpha n}} \qquad V_{t\alpha}=\left(\frac{k_B T_\alpha}{m_\alpha}\right)^{1/2} \qquad \omega_{p\alpha}=\left(\frac{n_\alpha q_\alpha^2}{\varepsilon_0 m_\alpha}\right)^{1/2} \qquad \nu_{en}=n_n\sigma_{en}v_{te} \qquad \nu_{dn}=\tfrac{8\sqrt{2\pi}}{3}\left(1+\tfrac{\pi}{8}\right)\frac{r_d^2 n_n m_n v_{tn}}{m_d}$$

$$\nu_i^{eff}=\nu_{in}+\nu_{id}=n_n\sigma_{in}v_{ti}+\frac{m_d n_d}{m_i n_{io}}\tfrac{8\sqrt{2\pi}}{3}\left(1+\tfrac{\pi}{8}\right)\frac{r_d^2 n_{io} m_i v_{ti}}{m_d}\left(1+\frac{\beta_T\lambda_D}{2r_d}+\left(\frac{\beta_T\lambda_D}{2r_d}\right)^2\Lambda\right)$$

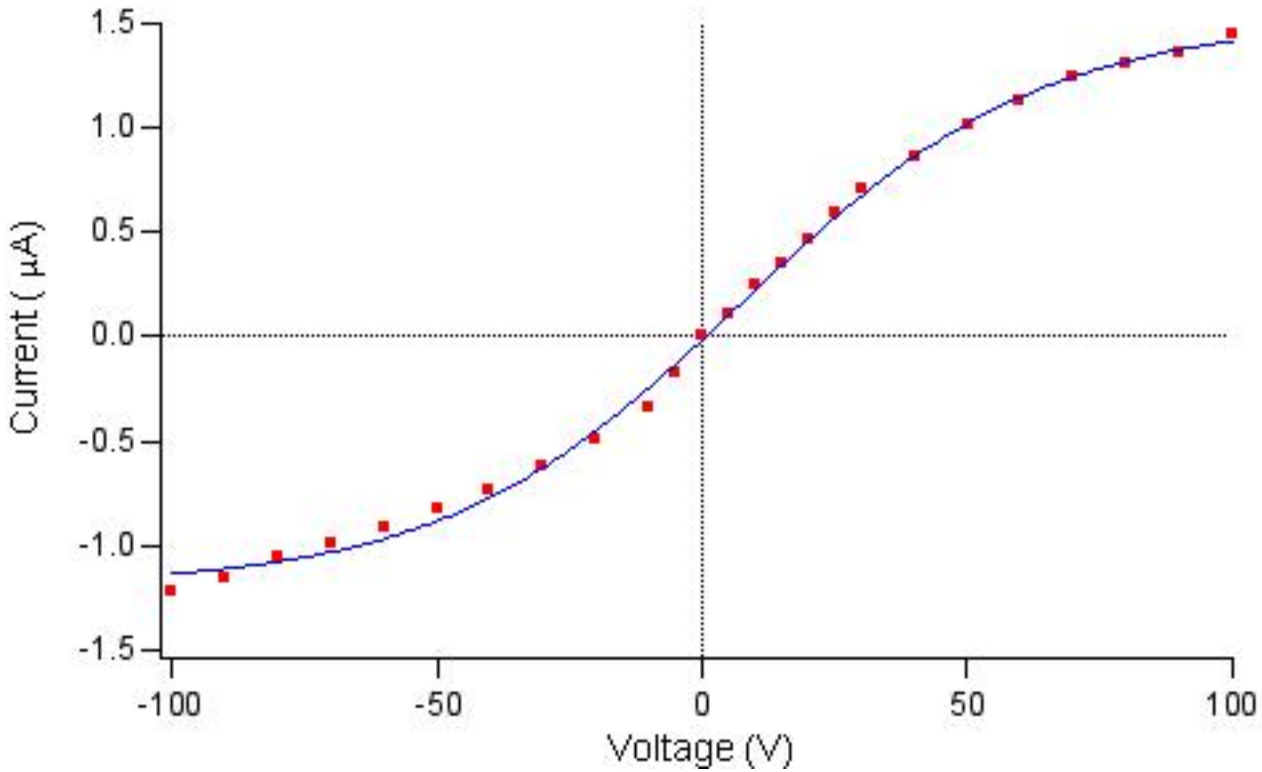
$$\lambda_D=\frac{\lambda_{De}\lambda_{Di}}{\sqrt{\lambda_{De}^2+\lambda_{Di}^2}} \qquad \lambda_{D\alpha}=\sqrt{\frac{\varepsilon_o T_\alpha}{n_{\alpha o} q_e}} \qquad \beta_T=\frac{Z_d q_e}{4\pi\varepsilon_o\lambda_D T_i} \qquad \Lambda=\int_0^\infty \exp\{-x\}\ln\left\{\frac{2x+\beta_T}{2r_d x+\beta_T}\right\}dx$$

[5] R. L. Merlino and N. D'Angelo, Phys. Plasmas, **12**, 054504 (2005).
[6] S. Ratynskaia, *et. al.*, Phys. Rev. Letters, **93**, 085001 (2004).

Probe Measurements



$$I(V) = I_{sat} \tanh\left(\frac{V}{2T_e}\right)$$



OML Reduced Charge