Dust Chain Perturbation Using Powered Zyvex S100

Audrey Burkart, Brandon Harris, Lorin Matthews, and Truell Hyde

***Abstract*—A GEC RF Cell with a glass box is used to form dust chains. A Zyvex S100 is used to affect the dust particles. The first experiment studies where dust particles closest to the lower electrode fall off of the chain due to a changing probe height or changing probe bias. In a second run, a single dust particle is oscillated in a square wave motion, resulting in underdamped motion, where the beta value can be determined. In the last experiment, a three-particle dust chain was oscillated. Through data analysis the resonant frequency and damping coefficient of each individual particle can be determined. The phase change between particles is also studied and through dispersion relation analysis the Debye length and charge can be determined and compared to previously published results.**

I. Introduction

DUSTY PLASMAS are found in the rings of various planets, in comet tails, in thunderstorms, and in fire [0]. An electronic Conference Radio Frequency Reference Cell (GEC RF Reference Cell) is often used to study dust in a plasma environment. When a glass box is centered within the cell, vertical dust chains can be formed. They can also be oscillated, creating dust lattice waves. Oscillations can be driven by various methods. This paper focuses on dust chains with driven oscillations from a Zyvex S100 nanomanipulator. A Zyvex NanoEffector probe is used to influence the dust particles. It is generally known that dust particles are negatively charged, so a negative potential on the probe will push the chain away from the probe and vice versa. The probe is mounted above the upper electrode and hangs transverse to the lower electrode. The probe can move a distance of 12 mm and the probe tip has a radius of about 50 nm [1]. Two electrodes are in the GEC Cell: a lower electrode powered by a radio-frequency signal generator, and an upper electrode 1.9 cm above that is grounded and 8 cm in diameter [1]. The upper electrode is grounded, and 0 V bias on the probe is set to equal the potential on the upper electrode.

A. Burkart is with Augustana College, Sioux Falls, SD 57197 USA. (email: arburkart10@ole.augie.edu).
B. Harris is with Baylor University, Waco, TX 76706 USA. (email: Brandon_Harris@baylor.edu).
L. Matthews is with Baylor University, Waco, TX 76706 USA. (email: Lorin_Matthews@baylor.edu).
T. Hyde is with Baylor University, Waco, TX 76706 USA. (email: Truell_Hyde@baylor.edu).

II. Method

A. Particle Drop-off Height

A glass box was inserted into the center of the bottom electrode. The inside of the box measures 10.5 mm wide, 10.5 mm deep, and 12 mm tall [3]. The Zyvex S100 is mounted above the box with the probe aligned at the center of the box. The dust particles are Melamine Formeldahyde with a diameter of 8.89μm and a density of 1.514 g/cm^3 [2].

The dust dropper was used to drop dust particles into the chamber. The system power was initially about 10 W RF system power. Once the dust was dropped into the plasma and was observed, the power was lowered slowly. At ~4 W RF, a 9-particle dust chain was established. The natural bias was -21.5 V and the pressure was at 150 mTorr. The probe was as far out of the way as possible to facilitate the formation of the chain.

The probe height was observed first. The probe was moved down until the bottom particle nearly fell out of the chain. Once recorded, the probe was moved down more. When the bottom particle fell, the height of the next bottom particle was measured. This procedure was repeated until every particle was pushed off the chain and dropped out of the plasma.

The power was then raised back to 10 W and the probe was out of the way. Dust was dropped and the power was lowered to ~3.5 W RF. The natural bias was -18.4 V. A 7-particle chain was formed. The bias on the probe was changed to be negative so that the chain was pushed lower into the box. The probe bias was measured when the bottom particle (nearest lower electrode) nearly fell, and once it had fallen.

B. Underdamped Oscillation

Dust was dropped into the reference cell and the probe was moved down to 0.6522 mm above the box edge. This height is chosen heuristically so that the probe is close enough to the dust chain to cause a visible oscillation, yet far enough away so that the chain does not fall out of the plasma. The power was at ~3 W RF. The natural bias was -21 V. The probe bias was oscillating the dust particle in square waves between -2 V and -37 V with 0.25 Hertz frequency. The power was low enough so that only one particle remained in the chain.

The pressure was initially at 80 mTorr. After observing the driven oscillation, the pressure was lowered in 10 mTorr increments, observing the oscillation down to 50 mTorr. Observations were focused on the oscillations when the probe returned to -2 V potential. Pictures were taken at 60 frames/second.

This general equation for underdamped motion of a harmonic oscillator,

$$x(t) = e^{-\beta t}\cos(\omega_1 t - \delta) \tag{1}$$

is used to fit the motion of the dust particle when it naturally oscillates around the equilibrium point where β is the damping coefficient, ω_1 is the frequency of the damped oscillator, and δ is the phase shift [4].

C. Driven Oscillation

The probe was 1.6969 mm above the box edge and the pressure was 43 mTorr. Dust was dropped and the power was lowered to ~2.5 W RF. A 3-particle chain was formed. The natural bias was at -21 V. The probe was oscillated at 5 V peak to peak. The motion was recorded for frequencies from 1 to 11 Hertz, in increments of 1 Hertz. Pictures were taken with a high-speed camera at 125 frames/second.

1) Resonant Frequency: The equation for a driven, damped harmonic oscillator,

$$R(\omega) = \frac{F_0}{\sqrt{(\omega_0^2 - \omega^2)^2 + \beta^2\omega^2}} \tag{2}$$

is used to calculate the resonant frequency for each particle in the chain where F_0 is the amplitude, and β is the damping coefficient [3].

2) Dispersion Relation: The vertical wavelength between particles is measured and the phase shift is calculated. The dispersion relation is calculated using the following equations,

$$\beta(x) = \frac{Q^2}{2\pi\varepsilon_0 x^3}\exp(-xk_D)\left(1 + k_D x + \frac{k_D^2 x^2}{2}\right) \tag{3}$$

$$\omega(k) = \pm\left[\frac{\beta(a)}{M}\sin^2\left(\frac{1}{2}ka\right) + \frac{\beta(2a)}{M}\sin^2(ka)\right]^{1/2} \tag{4}$$

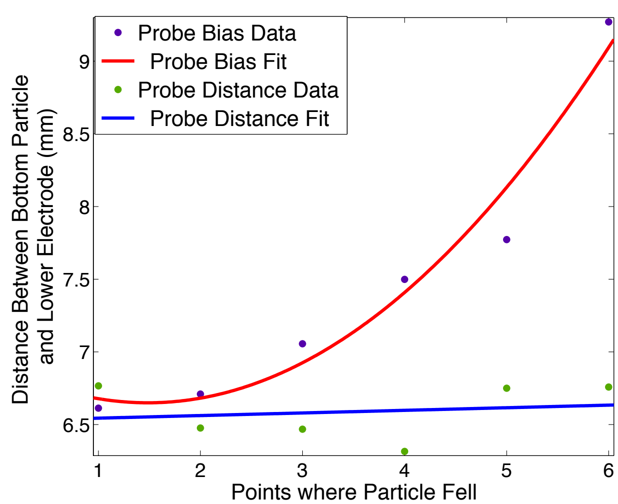
where β is the damping coefficient, Q is the particle charge, k_D is the inverse of the total Debye length, and M is the mass of one particle [5]. The bottom equation is only for 3-particle chains because it only allows for interparticle interactions between three dust particles.

III. Results

A. Particle Drop-off Height

The distance between the bottom particle and the lower electrode are measured and shown in Fig. 1. Each point represents where another particle fell out of the chain.

Figure 1 - Particle Drop-off



B. Under-damped oscillation

The particle motion is displayed in Fig. 2. The second oscillation is analyzed in which the probe returns to -2 V bias and the particle oscillates freely. Eqn. (1) is used in Figs. 3-6 to fit a curve to the oscillation.

Figure 2 - Square Wave

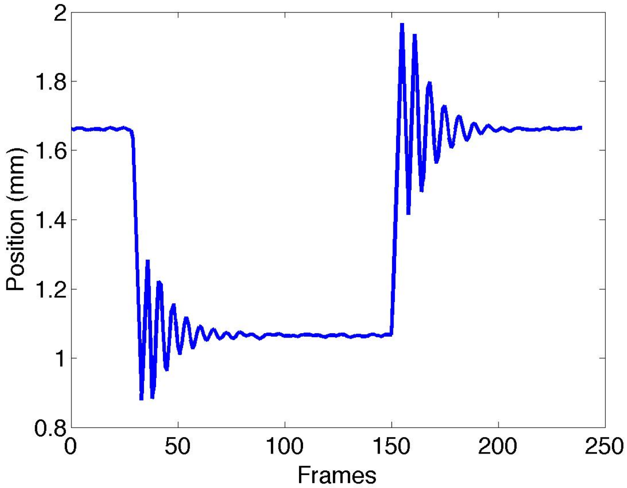


Figure 3 - 50 mTorr

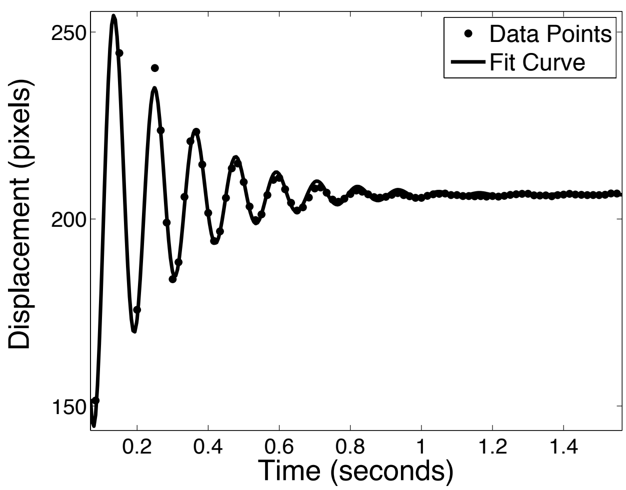


Figure 4 - 60 mTorr

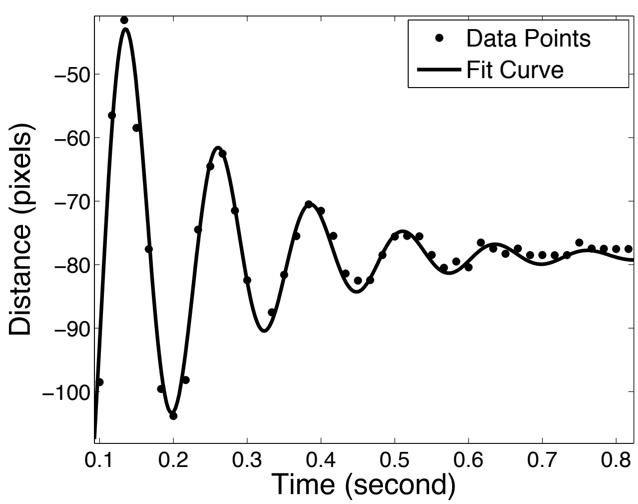


Figure 5 - 70 mTorr

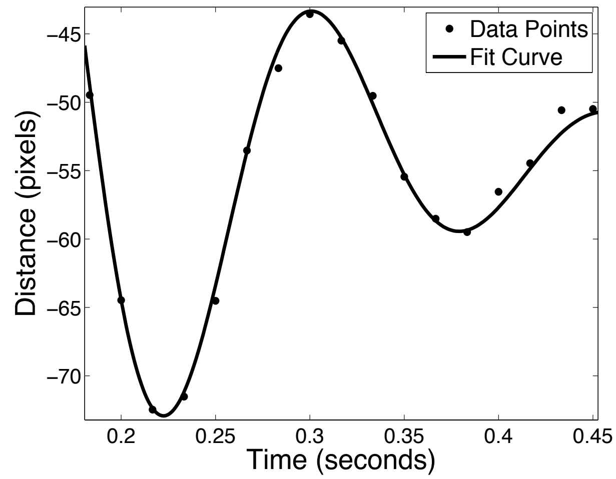
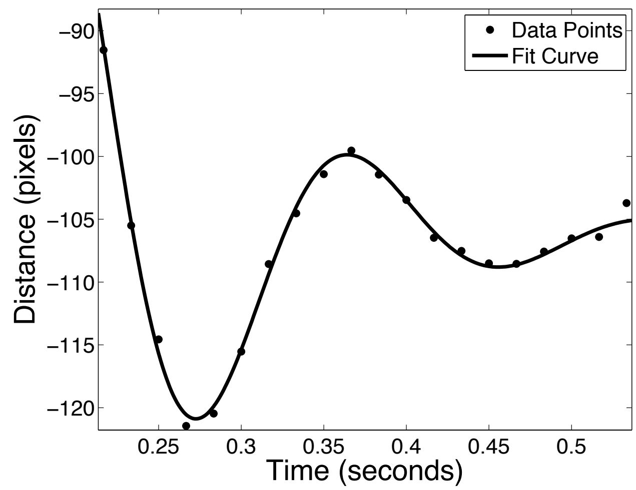


Figure 6 - 80 mTorr

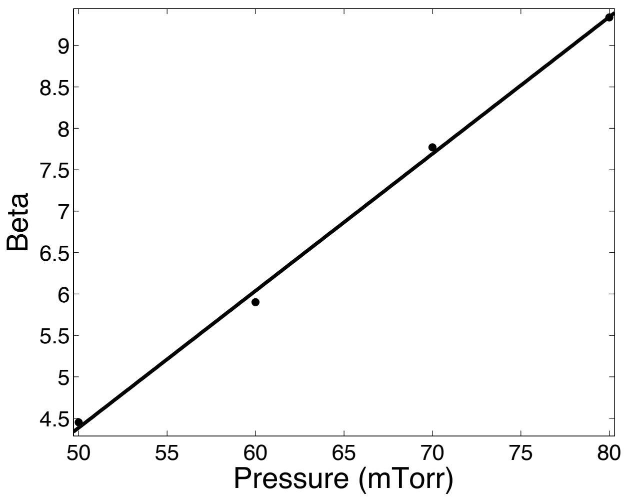


The damping coefficient is determined at each pressure and recorded in the Table 1. Fig. 7 shows the results where a linear trend is observed.

Table 1 – Beta Values

Pressure (mTorr)	Beta	Beta from [1]
50	8.902	10.2
60	11.802	12
70	15.542	14
80	18.676	15.5

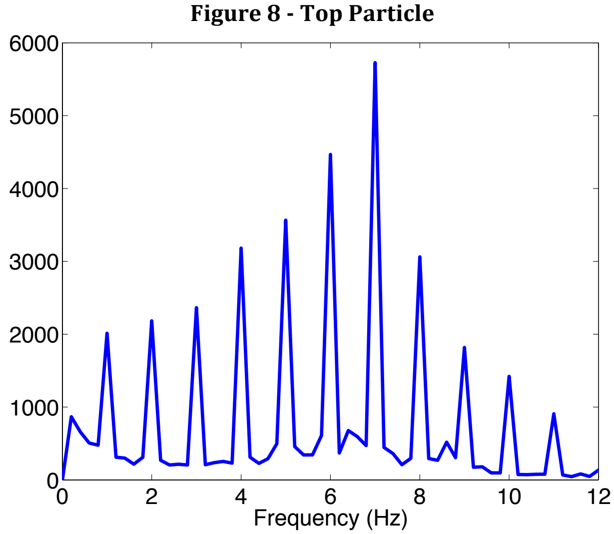
Figure 7



C. *Driven Oscillation*

1) Resonant Frequency: A sum of Fourier transforms at each of the driving frequencies is shown for each particle in Figs. 7-9. A curve is later fit in Figs. 11-13 only to the driving frequencies, which are on the x-axis, and the y-axis values are internally consistent but arbitrary.

Figure 8 - Top Particle



The middle particle has more interparticle interactions from the top and the bottom, causing the peaks in between the driving frequencies. Only the peaks at the driving frequencies were used for the following calculations to be consistent with the analysis of the top and bottom particles.

Figure 9 - Middle particle

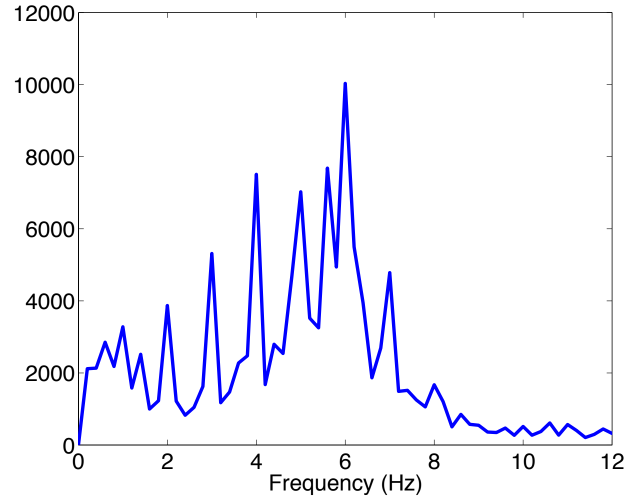


Figure 10 - Bottom particle

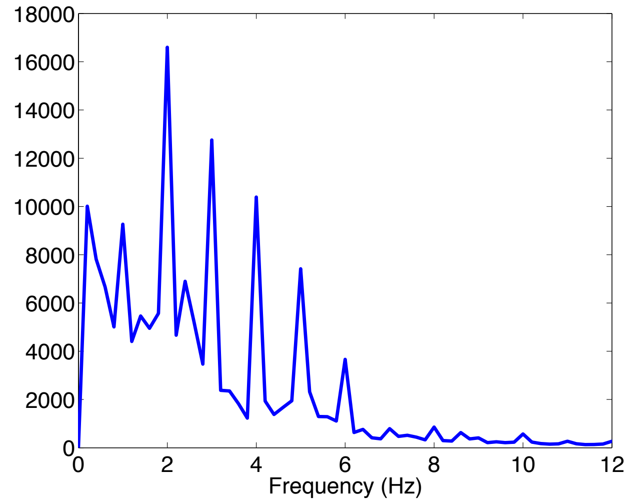
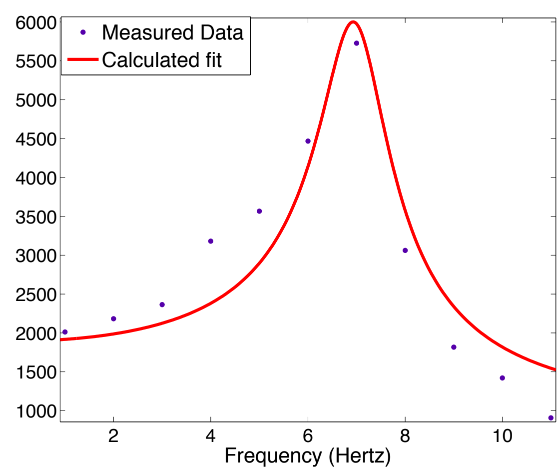


Figure 11 - Top Particle



The fitted curves in Figs. 11-13 are found using Eqn. (2). The peak in each figure shows the resonant frequency for each particle.

Figure 12 - Middle Particle

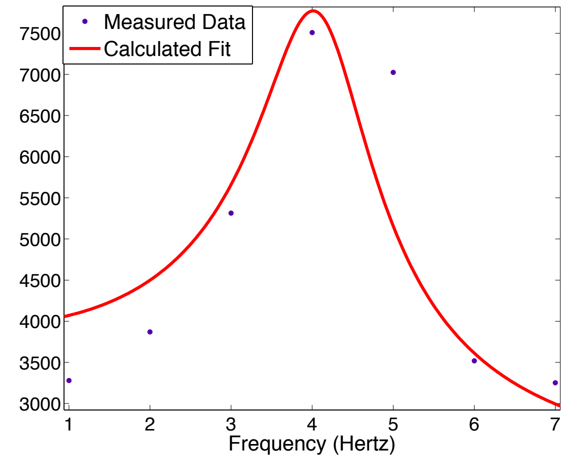
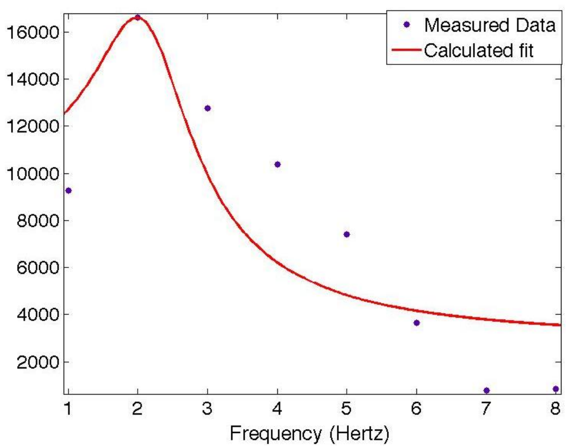


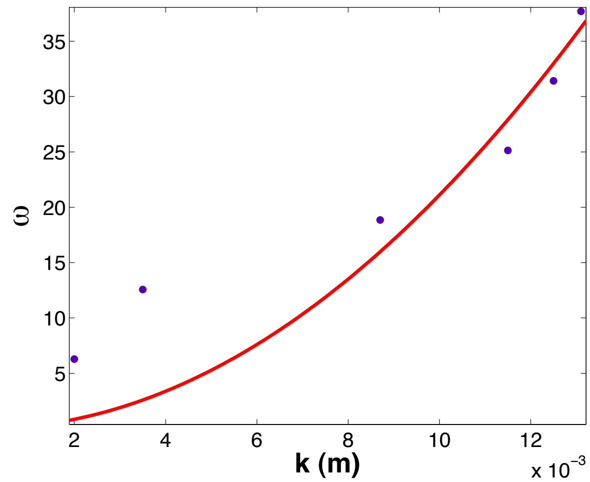
Figure 13 - Bottom Particle



Particle	β	Resonant Frequency (Hz)
Top	9	7
Middle	9	4
Bottom	9	2

2) Dispersion Relation

Figure 14 – Dispersion Relation



IV. DISCUSSION

A. Particle Drop-off Height

Changing the probe height has relatively no effect on the height of the bottom particle. On the contrary, changing the probe bias causes the bottom particle to move upwards in height. When the bias is changed, the force pushes the chain down towards the bottom electrode. Yet, the height of the bottom particle is moved upwards as the bias increases. This could be due to the fact that the chain is decreasing in particles, which allows more room for inter-particle interaction. This also may suggest that the force of the lower electrode is stronger than the force of the probe bias at long range. It is assumed that forces resulting from the box do not influence any forces on the chain in the vertical direction, although they do cause the formation of chain.

B. *Under-damped oscillation*

By fitting Eqn. (1) to the natural oscillatory undamped motion, a β value is determined for oscillations at different pressures. After plotting the determined β values with the changing pressure, a curve is fit. This curve is linear, which matches the result for a beta value in [2]. Not only does the trend match, but the values are also close to those from [2]. These results confirm that this underdamped motion formed by using the probe to perturb the dust height from equilibrium is an accurate method to measure the damping coefficient.

C. *Driven Oscillation*

1) *Resonant Frequency:* For the top particle, the resonant frequency is 7 Hertz and the β value is 9, which matches the value from [2]. For the middle particle the resonant frequency is 4 Hertz and the β value is also 9. For the bottom particle the resonant frequency is 2 Hertz and the β value is also 9. Because the β matches other results, this reaffirms the value asserted in [2]. Other peaks are observed in the Fourier transforms, yet only the peaks at driving frequencies are used for fitting a curve. The other peaks between the driving frequencies are probably due to interparticle interaction. The resonant frequencies differ by 2-3 Hertz between each particle, which suggests that each particle can be oscillated individually while keeping the other particle at a lower amplitude oscillation.

2) *Dispersion Relation:* The equation from [5] provides a good fit for the dispersion relation in the vertical oscillating chain. The equation was originally derived for a horizontal oscillating chain. According to these results, the equation also holds true for vertical oscillating chains, despite the major differences between horizontal chains and vertical chains. In a vertical chain the charge on the particles may vary throughout the chain. The electric field from the lower electrode may also change throughout the chain. The plasma density is not uniform, which causes the Debye length to not be constant. Equ. (4) is derived without accounting for neutral drag. According to [5], if the pressure is below 50 mTorr, neutral drag does not play an important role in the dispersion relation. A model including neutral drag can be applied and may decrease error. Despite these causes for error, the fit is quite close, which may mean that these effects are not as significant as previously assumed.

According to the values from [2], the value Q/e should be 1.264×10^{20} electrons at 43 mTorr. Our calculated value of Q/e is 5.911×10^{19} electrons, which is on the same order of magnitude. The Debye length calculated from [2] is around 1100 µm. Our value for the Debye length is 719.42 µm, which is also in rough agreement and plausible. We have reason to believe that our value may be more accurate than that found in [2] since their Debye length changed quite rapidly over a small change in pressure. Yet, the results derived in [2] were not calculated from experiments with a glass box. Perhaps the glass box has some effects that influence the results. The results are close enough though to confirm a general range and provide room for more research.

V. Conclusion

In the particle drop-off experiment, changing the probe bias has more influence on the height of the bottom particle than changing the probe height. This suggests that the probe height and probe bias have very different effects on the dust or plasma that directly changes interparticle distance.

In the square wave experiment, beta values are determined and a relationship is found between the damping coefficient and the pressure. The results also match those from [2] quite well.

The last experiment shows resonant frequencies for every particle. These different values mean that control over individual particles oscillating more than its neighbors can be possible for further experiments. A beta value is determined by fitting a curve to the Fourier transforms. This beta value matches that from [2].

The dispersion relation was also studied and shows promising results. The calculated Q and Debye length are similar to that from [2] despite being calculated from [5], which was derived for horizontal dust chains. Not only do these results compare to those from [2], but they also provide more insight into the forces on a vertical dust chain.

Acknowledgment

The authors would like to thank the CASPER Program, the Baylor Physics Department, and Jorge Carmona-Reyes. **This research was funded by the**

NSF through grant number PHY-1002637.

REFERENCES

[0] P. K. Shukla and B. Eliasson, “Colloquium: Fundamentals of dust-plasma interactions,” *Reviews of Modern Physics*, January 7, 2009.
[1] Zyvex S100 Nanomanipulator. (2007). Retrieved from http://www.zyvex.com/Documents/Zyvex S100.PDF
[2] Zhuanhao Zhang, Ke Qiao, Jie Kong, Lorin Matthews, and Truell Hyde, “A Simple Method to Measure the Interaction Potential of Dielectric Grains in a Dusty Plasma,” to be published.
[3] Jie Kong, Truell Hyde, Lorin Matthews, Ke Qiao, Zhuanhao Zhang, and Angela Douglass, “One-dimensional vertical dust strings in a glass box,” to be published.
[4] Taylor, John. (2005). *Classical Mechanics.* University Science Books. Chapter 3: Oscillations.
[5] Frank Melandsø, “Lattice waves in dust plasma crystals,” *American Institute of Physics,* August 12, 1996.