Two simple experiments in plasma physics

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We performed simple plasma physics experiments on a sample of argon gas. Using a Langmuir probe we obtained current voltage characteristics to determine the electron plasma temperature as a function of discharge current and neutral pressure. The electron plasma temperature remained relatively constant with a mean value of 19000 ± 995 K. The electron plasma temperature increased: from 31000 ± 620K down to 16000 ± 324 K. We also used a Langmuir probe to obtain the speed of ion acoustic waves in our plasma. At a low pressure of 1.3 mTorr we find the speed to be 2500 ± 51.2 m/s, while at a pressure of 8 mTorr the speed is 2200 ± 44.1 m/s. These values are within a factor of two of the expected theoretical values.

I. INTRODUCTION

Irving Langmuir can practically be considered the inventor of plasma physics, he practically invented the word\(^1\). Since the times of Langmuir and his utilization of the probe that shares his name, many advances have been made in the field of plasma physics. One field in which plasma is frequently used is in the etching integrated circuits\(^2\). In order to improve the usefulness of plasma it is important to understand the basics of plasma physics.

Here, we use produce a plasma in an argon gas to determine the electron temperature as a function of discharge current and neutral pressure. In section II we explain some of the theory behind Langmuir probes and ion acoustic waves. Section III explains our experimental procedure and section IV presents our results for current voltage traces and ion acoustic waves. In section V we conclude our paper and offer encouragement for the future of plasma physics.

II. THEORY

I would briefly take the time to explain the functions of a Langmuir probe as well as a brief discussion of ion acoustic waves.

A. Langmuir Probes

In order to obtain data on the electron temperature we used a Langmuir probe. A Langmuir probe is essentially a metal disk that can be electrically biased with respect to the plasma potential\(^3\). We can then sweep the voltage to methodically change electric field to attract either the ions or electrons. As the probe potential is swept through a range of voltages the electron current increases exponentially as a function of electron energy\(^3\):

\[
I_e = \begin{cases} 
I_{es} \exp\left(\frac{e(V-V_p)}{kT}\right) & V < V_p \\
0 & V > V_p 
\end{cases}
\]

(1)

where \(V\) is the probe potential, \(V_p\) is the plasma potential, and \(I_{es}\) is the electron saturation current. When the probe potential is less than the plasma potential there will also be a contribution to the current from the ions. We can then say that the total current is approximately:

\[
I = I_i - I_e,
\]

(2)

where \(I_i\) is the ion current. The plasma potential\(^4\) is defined to be the potential at which all electrons with paths which are destined to hit the probe face actually hit the probe face. As the probe potential is increased beyond the current will no longer increase – we have obtained the electron saturation current, \(I_{es}\). We can find the electron saturation current to be\(^3\):

\[
I_{es} = \frac{1}{4} e n_e v_{e,th} A
\]

(3)

where \(n_e, v_{e,th}\), and \(A\) are the electron number density, electron thermal velocity, and the area of the probe respectively. Equations 1 and 3 can be used to determine the electron number density and plasma temperature given the other variables.

B. Ion Acoustic Waves

Suppose we have a plasma that is in thermal equilibrium that then impart some sort of perturbation. We can use a similar model to sound waves dispersing through a fluid to describe the plasma. We want to determine the velocity of the electrons, the number density, and the potential. To do this we require Newton’s second law as applied to fluids, Poisson’s equation, and an equation of continuity\(^4\). These equations are listed below\(^4\):

\[
M n_i \left[ \frac{dv}{dt} + v \frac{dv}{dx} \right] = e n_i (E + v_x \times \vec{B}),
\]

(4)

\[
\nabla \cdot \vec{E} = \frac{e n_i - n_e}{\epsilon_0},
\]

(5)

and

\[
\frac{dn}{dt} + \frac{d}{dx} (n_i v) = 0.
\]

(6)
By assuming that the perturbations to each of the variables: velocity, number density, are of the form \( x = \tilde{x} \exp(i(kx - \omega t)) \), then we arrive at the ion acoustic wave equation:

\[
\frac{d^2 \tilde{\phi}}{dt^2} - C_s^2 \nabla^2 \tilde{\phi} = 0;
\]

where

\[
C_s = \frac{kT_e}{M_i}
\]

is the phase velocity of the ion acoustic waves which is dependent on the electron temperature and the mass of the ions.

In a similar fashion we can arrive at the dispersion relation for ion acoustic waves:

\[
\omega^2 = \frac{\lambda_D^2 \Omega_p^2}{k^2 \lambda_D^2 + 1},
\]

where \( \lambda_D \) is the Debye shielding length, \( \Omega_p \) is the plasma frequency and \( k \) and \( \omega \) are the wavenumber and angular frequency of the plasma wave. \( \Omega_p \) and \( \lambda_D \) are defined in the following way:

\[
\Omega_p^2 = \frac{n_0 e^2}{\epsilon_0 M_i},
\]

and

\[
\lambda_D^2 = \frac{e_0 k T_e}{e^2 n_0}.
\]

It is easy to see that if the wavelength of the ion acoustic wave is much larger than the Debye shielding length then the denominator of equation 9, which describes the wave frequency as a function of wavenumber, is practically unity. This leads to the following equation that gives the phase velocity of the waves:

\[
\frac{\omega}{k} = \sqrt{\frac{k T_e}{M_i}}.
\]

This is the same as the phase velocity for ion acoustic waves in equation 7.

### III. EXPERIMENTAL METHODS

In order to create a plasma we first must evacuate the chamber using a vacuum pump and a turbo to drop the pressure even lower. The chamber is surrounded by alternating rows of magnets with opposite polarities to confine the plasma. We feed in neutral argon gas and the pressure is measured by an ion gauge. A tungsten filament is placed inside the chamber and connected to a voltage source that is determined by the discharge current. A Langmuir probe of area ‘x’ is placed inside the chamber and is connected to a sweep generator that is used to bias the voltage of the probe relative to the plasma. Our first set of experiments was to determine the electron plasma temperature as a function of discharge current and neutral pressure. To determine the temperature as a function of discharge current, we set the neutral pressure to 0.5\text{mTorr} and vary the discharge current over the range of 0.75 to 1.10\text{A}. To determine the dependence on neutral pressure we use a constant discharge current of 1\text{A} and vary the neutral pressure from 3 to 8\text{mTorr}. In either case we can use equations 1 and 3 to determine the electron temperature and electron number density. Since equation 1 relates the current to a Boltzmann factor we can take the logarithm and thus the slope is inversely proportional to the temperature in the region where the probe potential is less than the plasma potential.

The second goal of our experiments was to find the phase velocity of ion acoustic waves. To produce waves in the plasma we placed a wave launcher inside the chamber that is capacitively coupled to a function generator that produces a 3 cycle sinusoid. The Langmuir probe is then connected to ground and acts as a high-pass filter. The probe can pick up oscillatory pulses with a frequency higher than 50kHz. The Langmuir probe has resistors of 50 and 100\text{Ω} and the signal across these resistors is sent to an oscilloscope. We also send the signal from the function generator is also sent to the oscilloscope and acts as a trigger. By changing the distance between the probe and wave launcher we are able to determine the speed of the waves from the time delay between trigger and pickup. Recognize that the wavelength of these waves, \( \lambda \), must be much greater than the Debye length as defined in equation 11 so that the relation \( \frac{\Delta x}{\lambda} \) is equivalent to \( \frac{\Delta \phi}{\phi} \). We complete the above procedure at two neutral pressures: 1.3\text{mTorr} and 8\text{mTorr} and therefore can obtain current voltage characteristics to determine the electron plasma temperature. From this temperature value we can use equation 12 to then determine the phase velocity of the ion acoustic waves and compare our experiment to theory.

### IV. RESULTS AND DISCUSSION

#### A. Electron Temperature

The electron temperature as a function of current was practically constant around a temperature of 19000 ± 995\text{K} or approximately 1.6eV. The error value determined here is the standard deviation of the mean of the temperatures at each current. The values of electron temperature versus current are plotted in figure IV-A. The error bars in the figure are 3% of the calculated value. We chose to use these error bars to account for the error in the discharge current value as well as in calculating the slope of the lines. The value of the discharge current only read out two digits past the decimal point and thus we are unsure of the accuracy of the discharge current after this value.
FIG. 1. Electron temperature in electron volts as a function of current in amps. Recognize that these values are practically constant over the range of currents. The error bars are set at 0.03 times the temperature value. The reasoning for this is discussed in this section.

FIG. 2. Current voltage characteristic for three discharge currents increasing from bottom to top. Notice that in the electron current region all three grow at approximately the same rate implying that they have the same temperature.

One can prove to themselves that the temperatures should be the same by examining a the current voltage characteristics plotted on top of one another as seen in figure IV A. This figure shows that the growth rates in the electron current regions are practically the same so it makes sense that the electron plasma temperatures are the same.

In contrast to the constant electron plasma temperature with varying current, as we increase the neutral pressure the electron plasma temperature tend to go down. This can be seen in figure IV A. The error bars here are again the 3% error bars that take into account the variability in discharge current as well as slope calculation methods. Figure IV A shows the current voltage characteristic of three neutral pressures increasing from bottom to top. Since the rates of the electron current region are proportional to $T^{-1}$, a shallower slope is indicative of a higher electron plasma temperature, in agreement with figure refkTvP.

At a neutral pressure of $8mTorr$ we determine the phase velocity to be $2200 \pm 51.2 \frac{m}{s}$. From equation 8 we find the velocity to be $1600 \pm 41 \frac{m}{s}$. Our experimental value is within a factor of 2 of the experimental value. The error here comes from the accuracy of the calipers as well as fluctuations in the current about 1mA. Table 1 shows the distances the probe was pulled out and the time step between the initial pulse and the arrival. We display these results in graphical form with a best fit

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<th>$\Delta x$ (cm)</th>
<th>$\Delta t$ (10$^{-5}$ sec)</th>
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TABLE I. Time between initial pulse and the pickup by the Langmuir probe. For each trial the probe was pulled out by 1cm. We determine the phase velocity of the waves from the slope $\frac{\Delta x}{\Delta t}$. 
line. We also plot the theory curve set to pass through the initial point.

We compiled similar data for the a neutral pressure of 1.3mT. We see in table 2 that the phase velocity is 2200 ± 44.1 m/s. The same sources of error that arise in the 8mT data are the same for these trials. The theoretical value for the phase velocity is 3000 ± 90 m/s. The two values to not overlap and thus the error does not explain the discrepancy.

Of particular interest is the fact that the velocity of waves increases with decreasing neutral pressure. This makes sense from a conceptual point of view because there is less damping that can occur by collisions and contact with the ions. This could have been deduced from the current voltage traces in our first experiments.

FIG. 5. Plot of our ∆x as a function of ∆t along with the best fit line and the theory curve fit through the first data point for 8mT neutral pressure.

V. CONCLUSION

We have described two simple plasma physics experiments. From the current voltage traces we were able to determine the relation between electron plasma temperature and current as well as the relationship to neutral pressure. Through the use of ion acoustic waves we were able to show that at lower neutral pressure ion acoustic waves travel faster. From this information we add to the current knowledge in the field of basic plasma physics and its future applications.

<table>
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TABLE II. Time between initial pulse and the pickup by the Langmuir probe for a neutral pressure of 1.3mT. For each trial the probe was pulled out by 1cm. We determine the phase velocity of the waves from the slope \( \frac{\Delta x}{\Delta t} \).