Langmuir Probes as a Diagnostic to Study Plasma Parameter Dependancies, and Ion Acoustic Wave Propogation

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Langmuir probes are versitile diagnostic tools for studying plasmas due to their ability to reveal plasma parameters such as plasma density, temperaure, and electrostatic plasma potential. As such, this experiment employs the use of Langmuir probes to study the dependencies of these plasma parameters on plasma pressure and plasma discharge current. Furthermore, the measured velocities of ion acoustic waves, created by a wave lunching grid, are compared to theoretical velocities determined from plasma temperatures, measured by Langmuir probes, to determine degree of agreement between theory and experiment. It was discovered that as plasma pressure increased, plasma temperature decreased and no clear trend was observed between plasma discharge current and plasma temperature. It was also discovered that measured ion acoustic wave velocities were consistently higher than predicted velocities based on plasma temperature by approximately $17 \pm 8\%$. The major source of uncertainty in this experiment was drifting discharge currents and electronic noise in the data.

I. INTRODUCTION

Plasmas have proven their importance to many fields and technological sectors. It is the fourth and most common state of ordinary matter (as opposed to dark matter) as they are found in stars, which warrents study simply because of prevalence. Plasmas are a prominent source of lighting due to the ability of the electrons in plasmas to excite atoms and molecules. It also is the backbone for creating integrated circuits with intricate nanodesign on the order of 400 nm in width created by plasma etching. However, perhaps the most ambitious reason for studying plasmas is also the most rewarding: to provide an understanding required to harness fusion energy, one of the most efficient sources of energy.

The goal of this experiment is much more humble than solving the energy crisis, but may help build the foundation to do so. To better understand the basics of plasmas, the effect of plasma pressure and discharge current on plasma parameters will be studied by using Langmuir probes. The agreement between experimentally measured ion acoustic wave velocity and theoretical ion acoustic wave velocity based on measured plasma temperature will also be studied using Langmuir probes. Through this experiment, a thorough understanding of the theory and use of Langmuir probes will be developped, providing a basic understanding required to pursue more ambitious plasma experiments.

First, the theory behind plasmas, Langmuir probes, ion acoustic waves, and lock-in amplifiers will be discussed in Sec. II A, II B, II C, and II D, respectively. Next, the apparatus and the experiments performed will be discussed in Sec. III. The results will then be discussed in Sec. IV and the analysis of the results will be addressed in Sec. V.

II. THEORY

A. Plasmas

Plasmas are a gas of ions, electrons, and neutral atoms that exhibit medium-like behavior, where each particle influences multiple surrounding particles, not just the closest particle. Furthermore, plasmas are quasineutrally charged and are relatively free of electric fields due to an effect known as Debye sheidling, where mobile charge carriers screen out electric fields. Insertion of a charged surface into the plasma will cause oppositely charged particles to surround it, forming a sheath to shield out the electric field. Changing the charge on the inserted surface can change the thickness of the sheath.

Plasma formation can occur in a few ways, all of which require ionization of neutral atoms. The heating of a gas can create plasmas by boiling off electrons to create a gas of charged and neutral particles. Generation of a strong electromagnetic field is another method of creating plasmas, where the large electromagnetic field strips electrons off in a gas. Furthermore, electrons from an electron source can be boiled off at very high energies that serve as primary electrons to ionize surounding gas molecules. This result is shown by

$$e_*^- + X_{(g)} \rightarrow e_*^- + X_{(g)}^+ + e^-, \tag{1}$$

where e_*^- is the primary electron, $X_{(g)}$ is the neutral gas atom, $X_{(g)}^+$ is the resultant ion, and e^- is the ionized electron, known as the secondary electron.

B. Langmuir Probe

A Langmuir probe is an instrument that can be inserted into a plasma to measure parameters that characterize the plasma. Langmuir probes are essentially ammeters inserted into plasmas to measure electron and ion currents. Parameters relevant to this experiment are the electron plasma density, n_e, which refers to the number of free electrons per unit volume, the plasma electron temperature, T_e, which is a measure of the average thermal kinetic energy of electrons in the plasma, and the electrostatic plasma potential, V_s, which is the potential of the plasma. At potentials greater than V_s, the electron current is maximized and is known as the electron saturation current. The electron saturation current is actually not a constant current, but slightly increases as the probe bias is increased due to a thickening of the plasma sheath. However, what is known as the electron saturation current is actually the electron current at V_s.

If a probe is inserted and biased at potentials less than V_s, one would assume that the electron current into the probe will immediately drop to zero due to repulsion away from the probe. However, the electron current actually gradually decreases to zero following a Boltzmann distribution, which can be explained by the fact that the repulsion may not be enough to stop random electron collisions with the probe until very low biases due to the distribution of electron velocities.

As explained above, if a probe is inserted into a plasma and biased to a specific voltage with respect to the chamber confining the plasma, depending on the bias, ions and electrons will collide with the probe at different rates. One can imagine a negatively biased probe having a higher ion current than electron current because the negatively biased probe will attract positively charged ions and repel negatively charged electrons. The converse of this statement is also true. Thus, at any given bias, the current detected by the probe is the sum of the electron current (negative by convention) and the ion current (positive by convention). If the voltage bias on the probe is swept across a range of voltages, a Langmuir trace, shown in Fig. 1, below, is observed, which represents the net current across a range of biases. Langmuir traces are modeled by

$$I \approx I_i - I_e^* \exp\left(\frac{e(V - V_s)}{kT_e}\right), \tag{2}$$

where I is the current measured by the probe, I_i is the ion current, I_e^* is the electron saturation current, V is the applied potential bias on the probe, k is the Boltzmann constant, and e is the elementary charge. Furthermore,

$$I_e^* = \frac{1}{4} n_e e \nu_e A_p, \tag{3}$$

where ν_e is the electron thermal velocity and A_p is the area of the probe.

It is important to note that the ion or electron current has dependance on the thermal velocity of the ions or electrons. The thermal velocity of a given particle is given by

$$\nu_p = \sqrt{\frac{kT_p}{m_p}}, \tag{4}$$

where ν_p is the particle's thermal velocity, T_p is the particle's plasma temperature, and m_p is the particle's mass. Thus, it can be seen that the electron current will generally be greater in magnitude than the ion current due to the significant mass difference. However, as the probe's bias is decreased below the float potential, V_f, where the ion current is equal in magnitude to the electron current, the ion current will be greater than the electron current magnitude because the bias is attracting more ions than electrons, and, indeed, will eventually even repel the electrons if the bias is decreased enough.

It is now obvious that from a Langmuir trace, Eq. 2, 3, and 4, the relevant plasma parameters T_e, n_e, and V_s can all be determined for plasmas created under varying conditions and their trends examined.

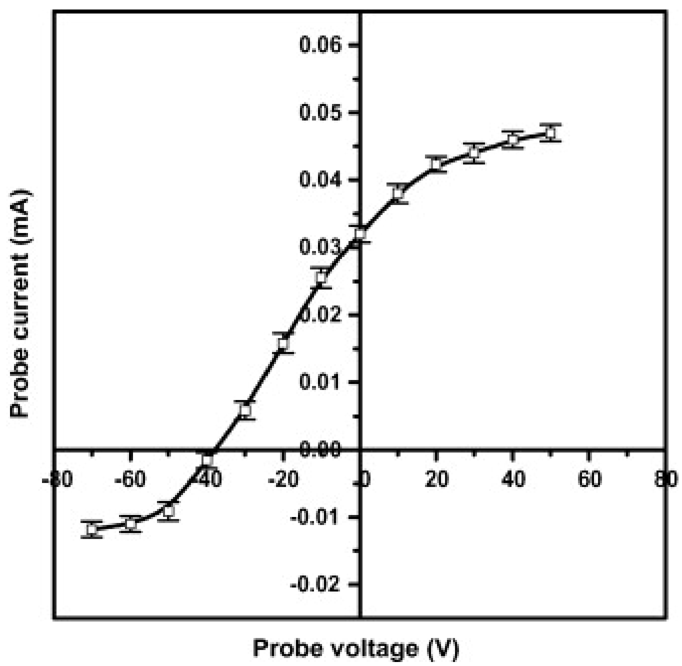

FIG. 1. Sample Langmuire trace.

C. Ion Acoustic Waves

Because plasmas are a gas consisting of negatively charged, positively charged, and neutrally charged particles that are able to affect multiple other particles surrounding it (via electrostatic and electromagnetic interactions), these particles can be considered interconnected. Furthermore, because plasmas consist of charged particles, they can couple to electric and/or magnetic fields to generate waves. One can imagine a positively biased grid insterted within a plasma causing nearby ions to be repelled away, which creates a temporary local ion pressure increase and, through electostatic interactions, repel farther ions away, a process that can propogate and become a wave. This same argument can be used for electrons within the plasma with the exception that rather than being repelled, electrons are being attracted by the grid. Because the electrons are significantly less massive than the ions, this wave of electrons occurs at a much smaller time scale than the wave of ions. Furthermore, the electrons would then experience a restoring force from the ions that have not moved (in this time scale), pulling the electrons back to their original location. Thus, if there were a Langmuir probe present in the plasma during this event, it would observe two separate waves, an instantaneous response due to the initial tone burst of the grid interacting directly with the probe, and a delayed response due to the electron and ion wave.

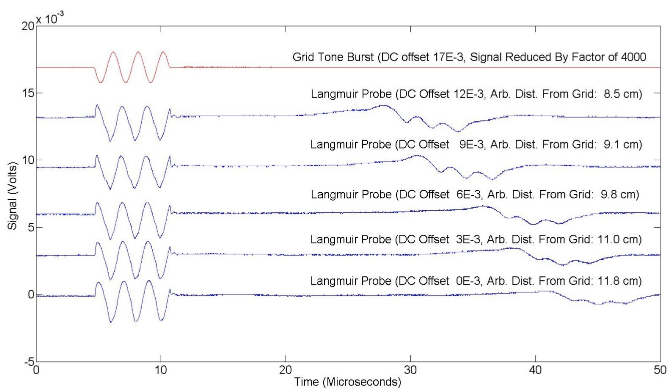

FIG. 2. The time separation between the instantaneous wave and the electron/ion wave increases as distance between probe and launching grid increases.

The time delay between the instantaneous response and the electron/ion wave is equivalent to the time required for the elecron/ion wave to travel from the grid to the Langmuir probe. Thus, as the distance between the launching grid and the Langmuir probe were increased, the time delay between the two waves should also increase, as seen in Fig. 2, above. If the distance between the grid and the Langmuir probe is known, the velocity of the wave can be calculated simply by

$$\nu = \frac{x}{t}, \tag{5}$$

where ν is the speed of the wave, x is the distance between the grid and the Langmuir probe and t is the time delay between the two waves.

While empirically determining the velocity is important, it is more rewarding to derive an equation that will allow the prediction of wave velocity in a plasma based on measurable plasma parameters such as pressure and density. Thus, if waves are indeed possible within plasmas, there must be a relation between plasma pressure, plasma density, and the wave's velocity that can be determined.

Since plasmas are fluids,

$$\rho\left(\frac{\partial \nu}{\partial t} + (\nu \cdot \nabla)\nu\right) = -\nabla p \tag{6}$$

and

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \nu) = 0, \tag{7}$$

Newton's second law for fluids and equation of continuity, respectively, both apply. Furthermore, because plasmas are gases,

$$pV^{\gamma} = Const, \tag{8}$$

the equation of "state" also applies. In Eq. 6, 7, and 8, above, ρ, ν, p, t, and γ are density, wave velocity, pressure, time, and specific heat ratio, respectively. Now that there are three equations containing the three variables from which a relation is desired (ρ, ν, and p), a relation can be determined if one exists. There must also be constraints in the initial plasma system: $\nu_0 = 0$ (there is initially no bulk velocity within the plasma), $\nabla p_0 = 0$, and $\nabla \rho_0 = 0$ (no initial equilibrium gradient in pressure or density). Now, perturbation theory can be applied, where a small perturbation is delivered to the system with respect to each of the three variables, with the perturbed variable being much smaller than the corresponding initial equilibrium variable. When this system is solved, one solution is for the perturbed density, which yields

$$\left(\frac{\omega^2}{k^2} - \gamma\frac{p_0}{\rho_0}\right)\rho_1 = 0,$$

which can be rearranged as

$$\frac{\omega}{k} = \sqrt{\gamma\frac{p_0}{\rho_0}}.$$

However, $\frac{\omega}{k}$ is simply the wave velocity, thus yielding

$$\nu = \sqrt{\gamma\frac{p_0}{\rho_0}}. \tag{9}$$

Following further substitution to allow relation of wave velocity to plasma parameters, it is found that

$$\nu = \sqrt{\frac{kT_e}{m_i}}. \tag{10}$$

D. Lock-in Amplifier

While the wave velocity can be determined by using a grid tone burst (sudden voltage bias on the grid) and measuring the time between the two waves received, higher precision can be achieved by using a continuous wave bias on the grid, which yields a superposition of the two waves being received by the Langmuir probe. This signal can be analyzed by a Lock-in amplifier, a device that can reduce the noise of a signal by attenuating all signals that do not match an input reference signal's frequency. Since the two waves will be of the same frequency but one is phase shifted with respect to the other, the lock-in amplifier can determine the phase shift that yields the superimposed signal and the amplitude of the constituent waves. Knowing the frequency of the continuous wave bias on the grid and finding the wavelength of the phase shift as a function of distance between the grid and the probe, the speed of the ion acoustic wave can be determined by

$$c = \lambda f, \tag{11}$$

where c is the speed of the wave, λ is the wavelength phase shift as a function of time, and f is the frequency of the continuous wave bias.

A lock-in amplifier takes an input signal and multiplies it with a reference signal and runs the output through a low pass filter. The reference signal is continuously phase shifted during the multiplication event until the mean of the output is maximized, which means that the input signal's phase is matched with the reference signal's phase. This means that the signal that is hidden in the noise has been found. However, because there is still high frequency noise, the signal is still not completly clear. Running the output thorugh a low pass filter then filters out high frequency noise, which yields the lower frequency signal. This process yields information about the phase shift of the signal with respect to the reference, as well as the amplitude of the signal, relatively free from noise.

III. EXPERIMENTAL

A. Apparatus

The apparatus consists of a plasma confinement chamber, as shown in Fig. 3, below, an oscilloscope, two function generators, and a lock-in amplifier. The plasma confinement chamber has multiple components. A vacuume pump, argon gas line, and ion gage are attached to the chamber to allow changing of plasma pressure and allow filling of the chamber with argon gas, which serves as the neutral gas. A tungsten filament is used as an electron source and electrons are boiled off of the filament by applying a voltage V_{fil} through the filament. The filament is also biased with respect to the plasma chamber by a voltage V_{dis}, the discharge voltage, which allows control of the energy carried by the primary electrons. A Langmuir probe is inserted inside the chamber and can optionally be connected to a voltage ramp (function generator) that biases the probe with respect to the plasma chamber. Furthermore, it is connected to the oscilloscope. Finally, an ion acoustic grid-wave launcher is also inside the plasma chamber and connected to a separate function generator and blocking capacitor and oscilloscope to allow launching of either continuous wave or tone bursts. The lock-in amplifier can also be optionally connected to the Langmuir probe and the grid launcher, outputting to the oscilloscope.

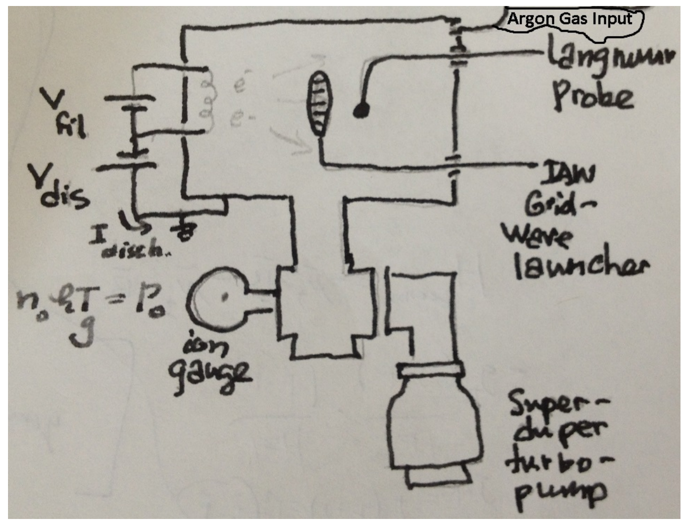

FIG. 3. Schematic of the plasma chamber.

B. Varying Plasma Gas Pressure

Langmuir traces are obtained by placing the Langmuir probe inside the plasma and sweeping the bias. Traces are taken as the plasma pressure is varied with all other parameters remaining constant. The grid launcher is not used.

C. Varying Discharge Current

Langmuir traces are obtained by placing the Langmuir probe inside the plasma and sweeping the bias. Traces are taken as the discharge current is varied with all other parameters remaining constant. The grid launcher is not used.

D. Measuring Velocity

The grid launcher is connected to a function generator to generate a tone burst of approximately four wavelengths. A Langmuir probe is inserted and used to record ion acoustic waves generated by the grid launcher. After data is collected from the probe, the distance from the grid to the Langmuir probe is increased and the experiment repeated. This experiment is run with two different plasma pressures. A Langmuir trace is also collected for each plasma pressure. The distance between the grid and the probe is recorded along with the time delay between the two waves recorded by the probe.

E. Measuring Velocity with Lock-in Amplifier

A function generator is connected both to the grid launcher and the lock-in amplifier as a reference signal. The Langmuir probe is connected to the lock-in amplifier as signal in. The function generator for the grid launcher is set to generate a continuous wave and an oscilloscope reads from the Langmuir probe, the lock-in amplifer, and the function generator. The $\Delta\theta$ and V_{signal} are recorded as the distance between the Langmuir probe and launcher grid is increased.

IV. RESULTS

As the plasma pressure was increased, the electron temperature was found to decrease, as illustrated in Fig. 4, below. Furthermore, as the discharge current was increased, there seemed to be no clear trend in electron temperature, as illustrated in Fig. 5, below. The effects on electron density and plasma potential have not yet been analyzed. From the tone burst experiment, we also found that higher plasma pressures yield lower wave velocities and lower plasma potentials but higher electron densities. Comparing the measured velocities with velocities calculated from measured electron temperatures in the tone burst experiment, we found that the measured velocities were, on average, about $17 \pm 8\%$ higher than velocities calculated from T_e. The same comparison with the continuous wave experiment also found measured velocities (from the lock-in amplifier) to be about 9% higher than wave velocities predicted by measured T_e. These results are summarized in Tab. I, below.

In analyzing data that involved Langmuir traces, a best fit line was first found to characterize the ion saturation curve. This line was then subtracted from the whole Langmuir trace to yield an approximate electron current curve. The curve is then reflected about the x axis to allow a semi-log plot of the curve, with y axis being logarithmic. This allowed for better identification of the "knee," which is where the electron current switches from being exponential to approximately linear. The electron saturation current and plasma space potential are extracted from the "knee." The voltage corresponding to I_e^*/e on the curve identified as the electron temperature (in units of eV). Through this information, the plasma density could be solved from Eq. 3 and Eq. 4.

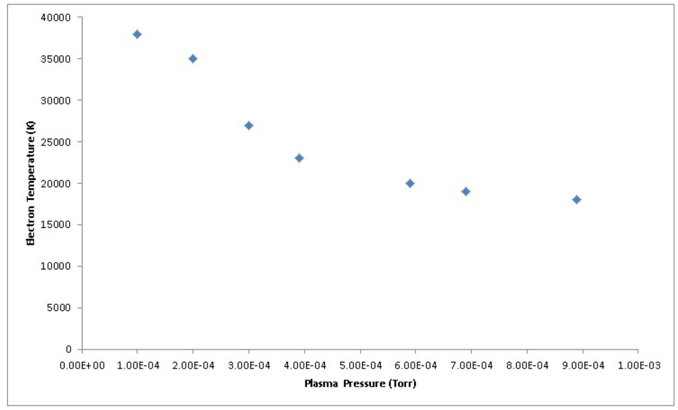

FIG. 4. Plot of pressure vs T_e shows that T_e decreases as pressure is increased.

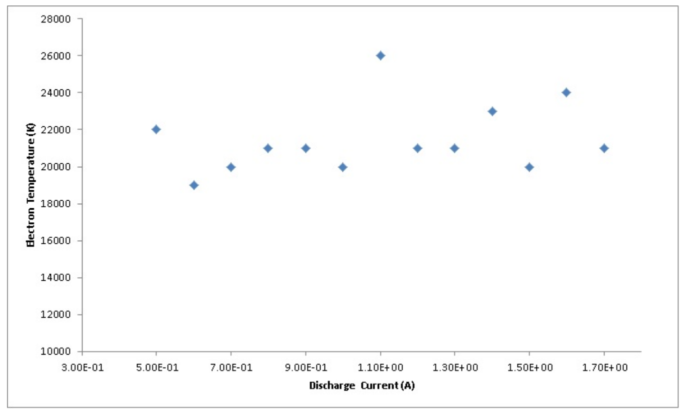

FIG. 5. Plot of discharge current vs T_e shows no clear correlation between T_e and discharge current.

In determining wave velocity from T_e, Eq. 10 was used. To determine wave velocity from measured time delays between two wave and the distance between the launching grid and the probe, the time delay is plotted against the distances and a best fit line was determined. The slope of these lines are the wave velocities and is shown in Fig. 6, above.

To determine wave velocity from lock-in amplifier data, the key is to use Eq. 11, above, where f is the frequency used to drive the continuous wave grid launcher from the

TABLE I. Summary of tone burst (TB) and continuous wave (CW) ion acoustic wave measurements.

Pressure (mtorr)	ν (km/s)	V_s (V)	n_e	T_e (eV)
0.15 (TB: Time of Flight)	2.8	—	—	3.2
0.15 (TB: Langmuir)	2.4	5.0	1.8E17	2.4
0.56 (CW: Lock-in)	2.4	—	—	2.4
0.56 (CW: Langmuir)	2.2	—	—	2.1
0.74 (TB: Time of Flight)	2.5	—	—	2.6
0.74 (TB: Langmuir)	2.0	3.6	4.2E17	1.6

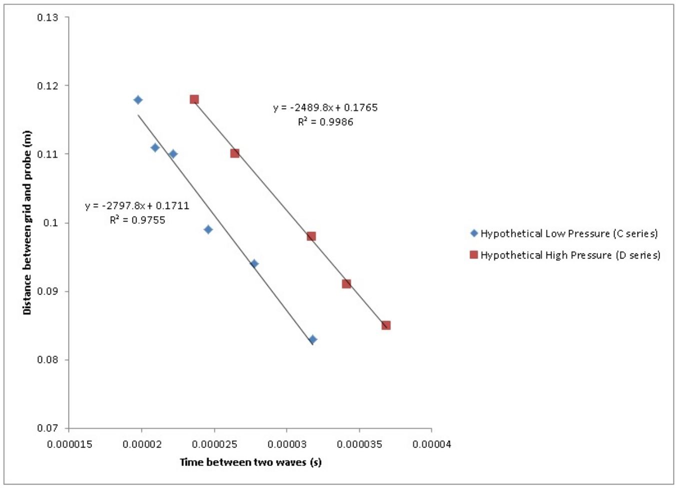

FIG. 6. Data used to determine wave velocity in tone burst experiment.

frequency generator, c is the speed of the wave, and λ is the wavelength measured from a plot of distance between grid and probe versus signal strength or phase shift.

V. DISCUSSION

It is reasonable that increasing discharge current does not have much effect on T_e because more electrons will be ejected due to higher current, however, the primary electron's energy is still governed by the discharge voltage, which was not changed. Thus, T_e was not expected to vary much as discharge current was increased, which it didn't.