Neutral Argon Plasma: Measurements of Electron Temperature and Density, and of Ion Acoustic Speeds

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I. INTRODUCTION

Plasma is the most common phase of matter over the universe since stars are plasmas (they are scarce to us on earth mostly because of our relatively low temperature environment). Therefore it seems worthwhile to understand the properties of this universally ubiquitous state of matter. The most tempting aspect of inquiries into plasmas is the potential for a new source of energy. Successful nuclear fussion using plasmas is expected to have the efficiency and cleanliness with respect to the atmosphere of nuclear fission while producing orders of magnitude less radioactive material and using elements more abundant than uranium 235.

II. EXPERIMENT DESIGN

A. Generating and Containing an Argon Plasma

Plasma is generated by ionizing argon gas atoms in a vacuum chamber ($10^{-4} - 10^{-5}$ torr). Ionization is through collision with electrons, which boil off a tungsten filament and accelerate towards the chamber walls held at a relative 80V discharge potential V_{dis}. The current due to electrons taken up in the chamber wall is measured as the disharge current I_{dis}. Measurements for all experiments were taken with a Langmuir probe. A schematic is drawn below (figure (**??**)). The plasma is contained by a configuration of magnets as shown in figure[ref]. Charged particles approaching the chamber wall are redirected through $\vec{v} \times \vec{B}$ force.

B. Measurement of Electron Temperature and Density

Measurements of electron temperature and density were made by taking plasma probe characteristics (see section[ref]) using a Langmuir probe. The probe was connected to a function generator. The voltage ramp of the generator swept the probe through a potential difference range known to include the plasma space potential. The voltage ramp of the generator and the current in the probe due to plasma interaction were read with an oscilloscope (Tektronix). A schematic of the experiment is drawn below (figure (2)).
Oscilloscope samples were gathered with computer program for varying neutral densities and discharge currents; discharge currents were varied by changing the current through the tungsten filament while the discharge potential was held constant. Probe currents over probe potentiasl were plotted to obtain plasma probe characteristics. A plotted probe characteristic for (ref, specify parameters) is labeled figure [ref] below. The electron temperatures were infered from the slope of the natural logarithm graph of the calculated electron probe current using equation (4) of section III A. The electron densities were calculated using equation (5) of section III A.

C. Measurement of Ion Acoustic Speed

1. *Meausrement using Grid Tone Bursts*

A wave launching grid was used to distub the plasma and pulses of oscillating potential were placed in the grid with a function generator. A Langmuir probe was placed some distance from the gird and current in the probe due to the plasma was read using an oscilloscope. An electrostatic response was observed to be essentially synchronous with the pulse manifested in the grid, and a second response resembling the waveform of the generated pulse was observed some time length afterwards. This was assumed to be caused by an ion acoustic wave cornensponding to the grid distrubance. The time length between the generated pulses and the plasma responce was measured for varying probe distances from the grid. Distances over time lengths were plotted and a linear fit was used to infer the ion acoustic wave phase velocity. A schematic of the experiment is drawn below (figure (3)).

2. *Measurement using a Lock-In Amplifier*

The experiment procedure for measuring ion acoustic waves using a lock-in amplifier was similar to that described in the above section (II C 1) where a Langmuir probe was used to measure the effects of a wave launching grid at oscillating voltage in the plasma. For these measurements the signal generator wavefunction and the probe responce signal were connected to a lock-in amplifier, where the generator wavefunction was used for a reference frequency. A schematic of the experiment is drawn below (figure (4)). The phase difference of the reference signal and probe responce was measured for varying distances of the probe from the grid. The wavelength of the ion acoustic waves was determined by plotting phase angle over probe-grid distance. The phase velocity of the

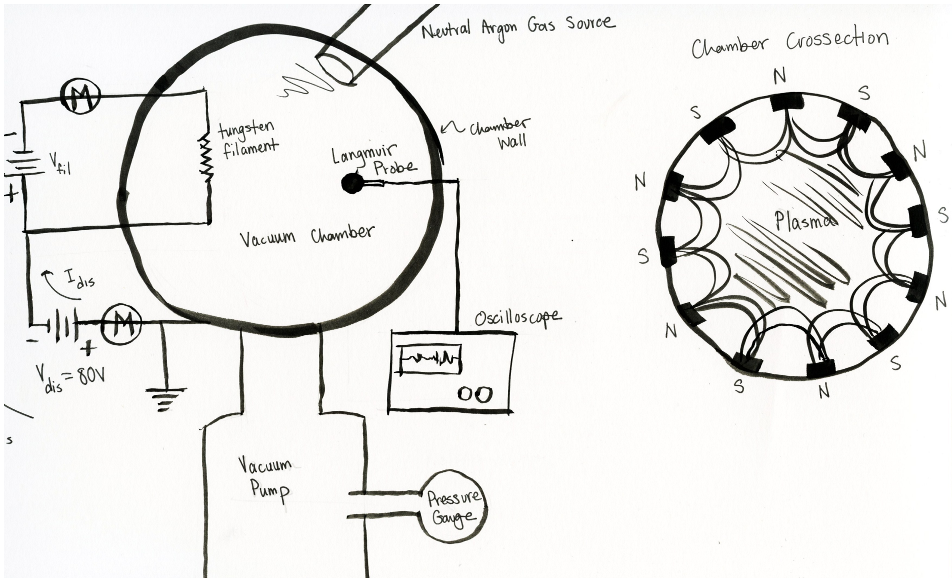

FIG. 1: Left: Argon gas flows into a vacuum chamber. Electrons boiled off a tungsten filament accelerate towards the chamber wall through 80V and collide with argon atoms. A Langmuir probe is used to measure net currents which are read using an oscilloscope.
Right: Magnets of alternating pole orientation line the chamber walls. The plasma is contained through $\vec{v} \times \vec{B}$ force with the magnetic fields.

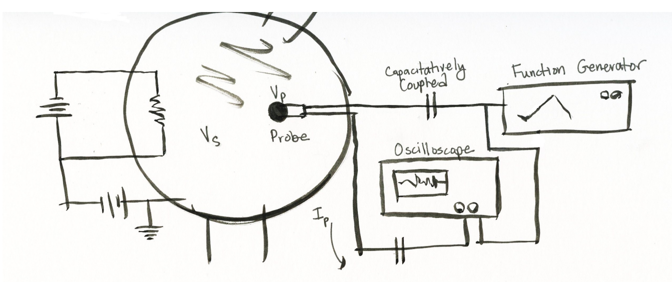

FIG. 2: Experiment schematic for measuring plasma probe characteristics.

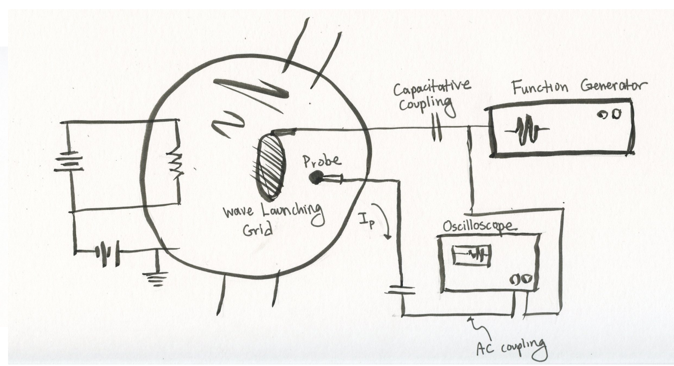

FIG. 3: Experiment Schematic for measuring ion acoustic waves using wave velocities launching grid tone bursts.

waves were calculated from the product of the generator waveform frequency and the infered wavelength.

III. THEORETICAL DEVELOPMENT

A. Plasma Probe Characteristic

Shown below (figure (5)) is an oscilloscope sample for the current in a Langmuir probe due to the plasma as a function of probe potential V_p. We can account for the three regimes in turn. We consider a probe of disk geometry where the disk plane is perpendicular to the x-axis of a 3 dimensional cartesian coordinate system. Therefore particle collisions and resulting current occur only for particle velocities with an x component. If we assume a maxwellian velocity distribution for both the ions and electrons then we model currents due to either as

$$I_\alpha = A n_\alpha q_\alpha \int (\frac{2\pi k T_\alpha}{m_\alpha})^{-1/2} exp[\frac{-\frac{1}{2} m_\alpha v_x^2}{k T_\alpha}]\, dv_x, \qquad (1)$$

where α is either e or i. x_{min} accounts for only the fraction of particles with kinetic energy greater than the electrostatic potential energy $V_p - V_s$ associated with the potential difference between the probe and the plasma. For V_p of opposite sign to that of particle α charge, $x_{min} = 0$ and all approaching particle α's collide with the probe. As V_p becomes the same sign as particle α and grows, the number of particles with enough energy to collide decreases according to a maxwellian distribution. For

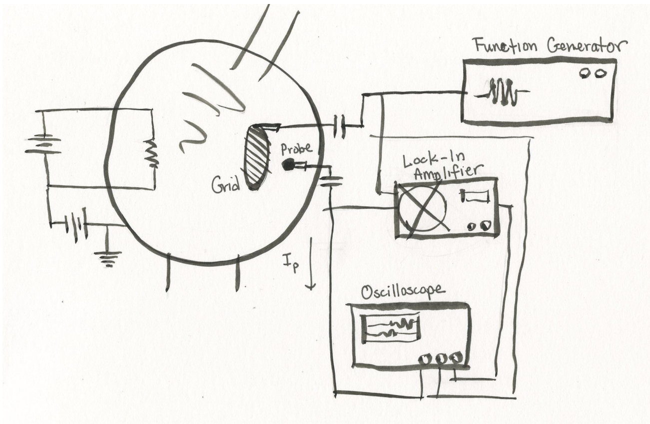

FIG. 4: Experiment Schematic for measuring ion acoustic wave velocities using a lock-in amplifier.

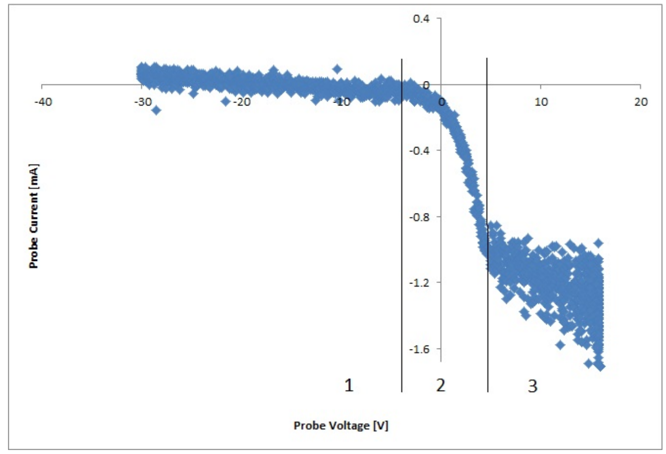

FIG. 5: Probe characteristic for a plasma of 0.2mtorr neutral pressure and 80V discharge current.

the ions with mass around 3 orders of magnitude greater than the electrons, $V_p > V_s$ results in almost no ions with speed great enough to collide with the probe and produce current. For electrons this exponential decrease is more gradual. Thus refering to figure (5), it is intuitive to assume that for regime 3 the ion current is ≈ 0, $V_p > V_s$, and that electrons over the entire maxwellian distribution are colliding; the current associated with the boundary between 2 and 3 is considered the electron saturation current, I_{es}. Regime 1 is the analogue to 3 for the ion saturation current I_{is}. Regime 2 is where we assume $V_p < V_s$ and the current is the net of I_{is} and the electron current due to the exponentially decaying number of electrons with great enough velocities. Thus in regime 2 we have that

$$I_{net} = I_{is} - An_e e \int (\frac{2\pi kT_e}{m_e})^{-1/2} exp[\frac{-\frac{1}{2}m_e v_x^2}{kT_e}]\, dv_x, \quad (2)$$

and noting that $\frac{1}{2}m_e v_{min}^2 = -e(V_p - V_s)$ we have that

$$I_{net} = I_{is} - An_e e\sqrt{\frac{kT_e}{2\pi m_e}} exp[\frac{e(V_p - Vs)}{kT_e}]. \quad (3)$$

Note that

$$\begin{aligned} ln(I_{is} - I_{net}) &= ln(An_e e\sqrt{\frac{kT_e}{2\pi m_e}}) + \frac{-eV_s}{kT_e} + \frac{eVp}{kT_e} \\ &= Const. + \frac{e}{kT_e}V_p \end{aligned} \quad (4)$$

and therefore we can infer T_e from the slope of a graph of the natural logarithm of the negative of a probe characteristic.

We can infer the electron density by noting that from our definition of I_{es} we have that

$$\begin{aligned} I_{es} &= An_e e \int_0^\infty (\frac{2\pi kT_e}{m_e})^{-1/2} exp[\frac{-\frac{1}{2}m_e v_x^2}{kT_e}]\, dv_x \\ &= An_e e\sqrt{\frac{kT_e}{2\pi m_e}}. \end{aligned} \quad (5)$$

Since we can infer I_{es} from the probe characteristic and use the value of T_e calculated from (4) we can calculate a value for n_e.

IV. ION ACOUSTIC WAVES

The following derivation was published by Tonks and Langmuir **??**. Let all subscript i's denote an ion characteristic and all subscript e's denote an electron characteristic. Consider a 3 dimensional cartesian coordinate system where a uniform distribution of ions and electrons, densities n_e and n_i respectively, are confined between two finite x-coordinates. For a model of a planewave propagating along the x-axis, let each ion be displaced in the x-coordinate by some small amount ξ where ξ is a function of x. Then

$$dn_i = -n_i \frac{d\xi}{dx}. \quad (6)$$

If we assume that the electron density exhibits a boltzman relation and the displacements of the electrons are small, then

$$n_e = n_{e0}e^{e\phi}T_e \approx n_{e0}(1 + \frac{e\phi}{T_e}), \quad (7)$$

where n_{e0} is the initial uniform density, e is an electron charge, ϕ is the electrostatic potential, and the electron temperature T_e already includes the Boltzman constant and is in units of electron volts. If we consider Poisson's equation and Newton's second law of motion we also have that

$$\frac{d^2\phi}{dx^2} = \frac{-e}{\epsilon_0}(n_i - ne) \tag{8}$$

and

$$m_i\frac{d^2\xi}{dt^2} = e\frac{d\phi}{dx}, \tag{9}$$

where m is the mass. Solving for equations (6) through (9) simultaneously, and assuming a plane wave solution of the form,

$$\xi = exp^{[i(wt-kx)]} \tag{10}$$

it can be found that

$$v_{phase} = \sqrt{\frac{T_e}{m_i}}. \tag{11}$$

The ion acoustic wave phase velocity depends on the electron temperature and the ion mass. We can analyze a measured ion acoustic wave speed by infering an electron temperature using (11) and comparing the value to the electron temperature calculated from a probe characteristic.

V. LOCK-IN AMPLIFIERS

VI. RESULTS

A. Electron Temperature and Density

1. Varying Neutral Pressure

Electron temperatures and densities were calculated for neutral pressures in the range 0.1-0.9mtorr. It was found that calculated electron temperature decreased as neutral pressure increased. Calculated temperatures ranged from 38000K (3.3eV) at 0.1mtorr to 18000K (1.6eV) at 0.89mtorr. The general trend was for higher neutral pressures to correspond to lower electron temperatures, as shown in figure (6).

2. Varying Discharge Current

There was no strong trend in calculated electron temperature for varying discharge current. All but one measurement found the electron temperature between 20000K and 24000K, as shown in figure (7).

B. Measured Ion Acoustic Wave Phase Velocity Using Tone Bursts

At a neutral pressure of 0.15 mtorr the wave phase velocity was calculated to be 2800m/s, while at a neutral pressure of 0.74 mtorr the phase velocity was calculated to be 2500m/s. Velocities calculated using expression (11) for electron temperatures infered from Langmuir probe characterisitics were 2500m/s and 2100m/s respectively.

C. Measured Ion Acoustic Wave Phase Velocity Using Lock-In Amplifier

Using function generator signals with frequencies of 100kHz and 150kHz the wave phase velocity was calculated to be 2700m/s and 2400m/s respectively for a neutral pressure of 0.56 mtorr. Velocities calcuated from corresponding probe characteristics were 2400m/s and 2200m/s respectively (the discharge current shifed slightly over the experiment).

VII. DISCUSSION

Overall the calculated electron temperatures were higher than expected: between 2 and 3 eV instead of the expected 1.5 to 2 eV range. However the values are not unreasonable except for one or two measurements at the lowest neutral pressures. The trend for varying neutral pressures satisfies intuition because we expect that for greater neutral pressures the electrons experience more collisions and therefore have a lower average kinetic energy. The lack of strong trend for varying discharge current could be explained as follows. The increased discharge current was not due to an increased discharge voltage it was due to an increased filament current. Therefore the increased discharge current corresponded to more electrons taken in by the wall rather than electrons with a greater kinetic energy taken in by the wall. If the kinetic energy of the electrons was unchanged then we would expect the temperature to remain unchanged.
The measured ion acoustic wave phase velocities for each method were within 80

[1] Tonks L and Langmuir I 1929 Phys. Rev. 33 195

[2] Plasma Physics Laboratory, Physics 180E. Unknown origin.

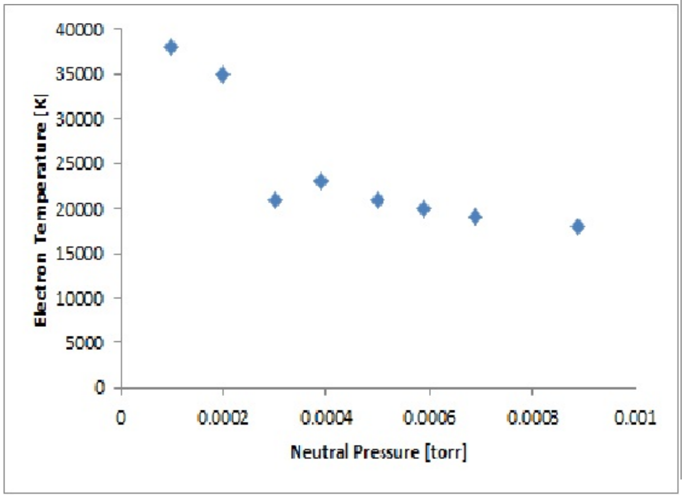

FIG. 6: Calculated electron temperature over different neutral pressures.

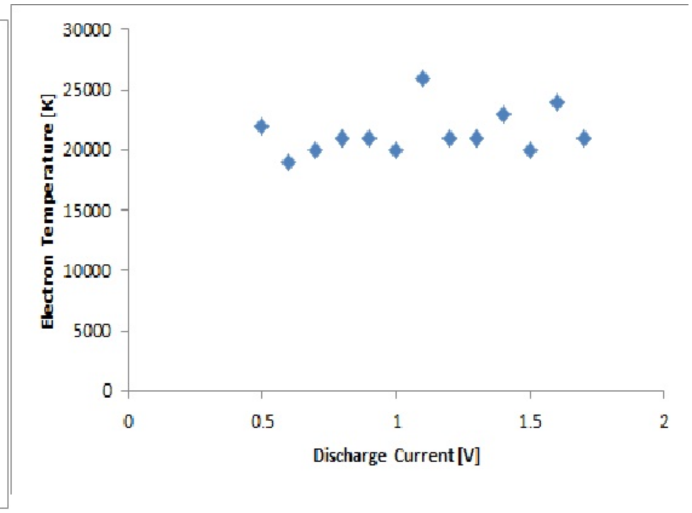

FIG. 7: Calculated electron temperature over different discharge currents. All measurements taken at 0.51 mtorr $\pm$0.01mtorr.

[3] Dr. Severn. University of San Diego Physics Department.