Ion Acoustic Waves in Plasma

Physics 480W
(Dated: Sp19 Paper #4)

I. INTRODUCTION TO THE EXPERIMENT

A. Goals of the experiments (restricted for the 4th paper)

The basic goals of these experiments are to help familiarize us with the fourth state of matter: plasma, how to create them in the laboratory (a cartoon of which is shown in figure 1), and common diagnostics for plasma characteristics and for waves. The Langmuir probe[1,2], is the one the most versatile diagnostic for plasma physics research. The student will learn how to interpret the data gathered by Langmuir probes in order to determine plasma parameters (things like plasma density and temperature) depend on discharge parameters (things like discharge voltage, heating current). Specifically, we want to make a physical argument explaining how kT_e depends on neutral pressure from the point of view of kinetic theory, for our thermionic discharge plasma (figure 2). References for this are the papers of Mackenzie and Limpaecher[3], and Braithewaite[4]. The description of these experiments is followed by a brief introduction to the plasma state of matter itself in section II, followed by more references. Among those references you'll find a paper very pertinent to these experiments, which have been done before in similar devices. The student is aware at this point in the semester of how useful it is to look at previous results wherever this is possible. Finally, parameters measured with Langmuir probes will be used to make theoretical predictions regarding *ion acoustic waves*. The phase velocity of ion acoustic waves may be measured directly using the tone-burst technique (see ref. 5 in the background reading sections and described briefly below) depend on the electron temperature, and the model we use to assess the phase velocity, the dispersion relationship, permits us to predict the speed of the waves, and so to compare theory with experiment. This is essentially the point of these experiments.

To summarize, the main results and deliverables for the experiments described here are

1. Use the planar Langmuir probe diagnostic to diagnose a 'low pressure', case 1, and a 'high pressure' plasma, case 2, and infer plasma density and electron temperature. Try to make a physical arguement for the difference in kT_e for the two cases.

2. Measure the group velocity of the ion acoustic waves for the two cases, and test simplified perturbation theory results. The dispersion relationship for ion acoustic waves predicts both phase and group velocities, given a direct measurement of kT_e using the Langmuir probe. Make a comparison between theory (calculating the phase velocity given the electron temperature) and experiment (measuring the phase velocity using the tone-burst method). Make the difference between phase and group velocity (see Piel[5], p 137ff)

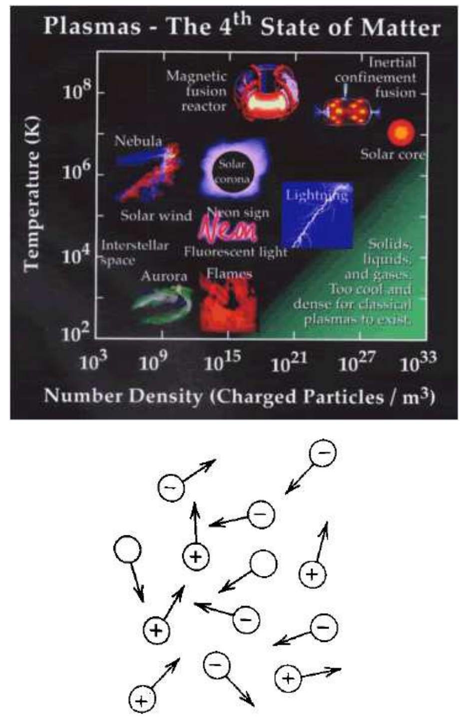

FIG. 1. Not just any collection of charged particles, with roughly equal concentrations of positive and negative charges, exhibit collective behavior distinctive of the plasma state of matter. The electron and ion densities have to be great enough and these populations have to be hot enough for 'medium like' behavior to become important. Plasma crowns our planet, above and below (the aurora), surrounds it (ionosphere, magnetosphere), and heats it (the sun and all stars are in the plasma state, and most are made of classical plasma)

B. Procedure

Plasmas can be created when energetic particles meet neutral atoms and molecules, causing ionization, and when sufficiently high plasma density results. In the plasma physics experiments conducted here at USD, the plasma is created by accelerating thermionically emitted electrons from hot filaments ($T_f > 2400K$) biased to a negative potential (the so-called discharge current) with respect to the vacuum chamber wall, as shown in figure 2. When the discharge voltage significantly exceeds the ionization potential of the feed gas (argon, in our case), the energetic electrons (called 'primary electrons'), may create an ion, electron pair, in an ionization collision,

$$e_p^- + Ar \longrightarrow Ar^+ + e^- + e_p^-, \qquad (1)$$

where the subscript denotes the primary electron, which must loose energy at the expense of the ionization po-

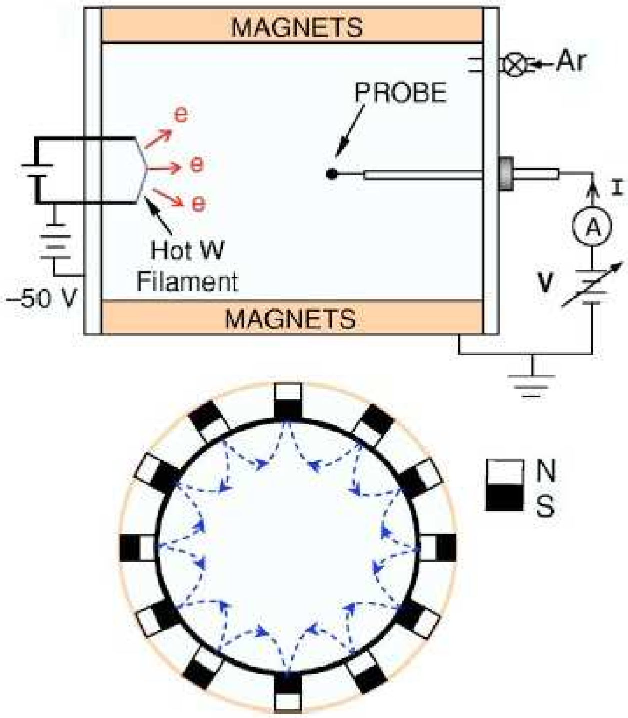

FIG. 2. Schematic of a basic device for producing a plasma, a multi-dipole hot filament plasma device with a Langmuir disk probe. The plasma is produced by electron impact ionization of argon atoms by electrons that are thermionically emitted and accelerated from a hot tungsten (W) filament. To enhance the ionization efficiency, the walls of the chamber are lined with rows of permanent magnets of opposite polarity. The lower diagram is an end view showing the arrangement of magnets. The magnetic field lines are sketched as the dotted curves. In this magnetic cusp configuration, the bulk plasma is essentially magnetic field-free. This caption was shamelessly lifted from reference 2.

tential of the neutral (and any internal energy imparted to the ion), and where ion-electron pair primarily compose the plasma. Of course, the entire collection of ions, electrons, and neutrals compose the plasma, and the collection deserves the name if it exhibits collective effects. Rows of permanent magnets of alternating polarity line the exterior of the vacuum chamber to confine the energetic primaries so that each energetic electrons can suffer many ionizing collisions before being lost to the anode (the chamber wall). The magnetic fields also help slow the loss of plasma electrons (and thus, plasma ions). The net loss of charge from the plasma to the boundary is zero, but there is a current driven by the discharge voltage from the filaments to the chamber wall, and this is called the discharge current. A very good overview of discharge physics is given by Braithwaite[4]

Measure the $I-V$ (current-voltage) characteristic for a planar Langmuir probe. How the electron plasma density and kT_e can be inferred from the $I-V$ characteristics is well described in Merlino's paper[1] and in the PHYS 180 Lab manual[2]. A worksheet will be provided to help with this. In a steady state discharge, using a simple probe-bias sweeper circuit. Mark the plasma space potential, V_s, the floating potential, V_f, electron saturation current, I_{es}, and ion saturation current, I_{is}. Subtract I_{is} from $I(V)$, and so plot the electron current on log-linear (semi-log) axes. Determine the electron temperature, T_e, and the electron plasma density, n_e. Note the discharge parameters, I_{dis}, V_{dis}, and p_o, and the probe area. In your lab notebook, tape in a hardcopy of a good $I-V$ characteristic, and a semi-log plot of the electron branch of the $I-V$ characteristic, marking the location of the plasma potential and the floating potential, and demonstrate the calculation of n_e and T_e.

Obtain $I-V$ characteristics at different neutral pressures, say, something close to $1mTorr$ (but just less, so the ion guage doesn't such itself off), and something close to $1\times10^{-4}mTorr$. This will give a relatively cold and a relatively hot plasma, and one can then see how neutral pressure is like an electron temperature knob. Why we want such a knob we be made clear presently. Calculate the fractional ionization of the plasma as a function of neutral pressure and discuss. Does the result surprise you? In your paper, you'll want to capture the essence of the parameter studies and try to interpret the trends in the graphs. The background reference help a great deal here, especially MacKenzie's paper and Braithwaites. The main result of the paper is comparing ion acoustic wave measurements to theory. We treat this next.

C. Part II: collective effects—ion acoustic waves

The plasma state of matter supports a variety of collective effects one of which is longitudinal ($\mathbf{k} \parallel \tilde{\mathbf{E}}$), electrostatic ($\tilde{\mathbf{B}} = 0$) waves. These low frequency waves follow as the result of introducing a perturbation of the ion density which thereafter propagates in the medium (the plasma). Your mission is to introduce such a perturbation into the plasma and then to measure the speed of propagation. These waves are weird. They are analogous to sound waves in air, but the ions do not provide the pressure swings: the electrons do. How and why does *that* work? What is the speed of the waves? A worksheet will be provided to lead through the steps to derive it, beginning from simple assumptions, arriving at

$$\omega^2 = \frac{C_s^2 k^2}{1 + k^2\lambda_D^2}, \tag{2}$$

where $C_s = \sqrt{T_e/M}$, is the *phase velocity of ion acoustic waves in the limit of long wavelengths*, also called the ion acoustic speed, ω and k have their usual meanings, and λ_D is called the Debye length.

D. Sketch of procedure: Tone-burst pulse delay Method

The method we adopt for our measurements is called the tone-burst method in which a signal is applied to a mesh-grid immersed in the plasma, and picked up remotely by a Langmuir probe. The method is well described in the 180 Lab manual[6]. Capacitively couple the

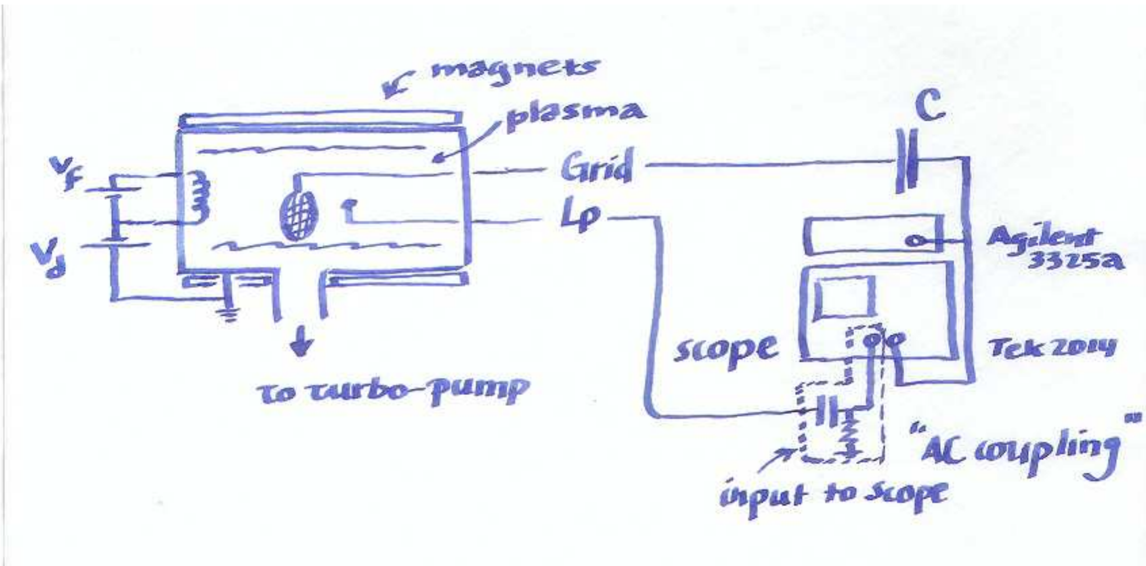

FIG. 3. Block diagram of wave set-up.

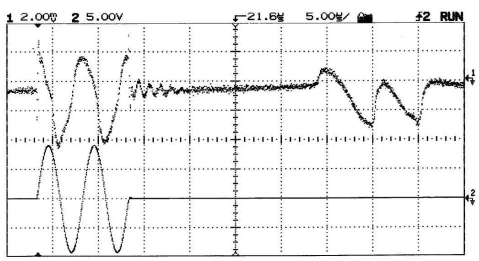

FIG. 4. Grid and probe are separated by some variable distance; the time delay between the tone burst applied to the grid and the moment of its appearance on the probe can be varied by changing this distance. Note that the directly coupled signal is distorted in a way that the propagating signal is not.

Agilent function generator (fg) to the Wave Launching Grid. The Langmuir probe will be used as the detector, as shown in figure 3. It to will be capacitively coupled to ground so as to make a high pass filter ($f_c \approx 50kHz$). The signal across the termination resistor can go to the scope, say Ch.2 (any scope could be used but the Tektronix TDS series scopes have the best digitizers). The output the fg should go also to the scope, say Ch.1, and this channel should be used to trigger the scope. Choose an excitation frequency well above cutoff frequency and well below the ion plasma frequency. There will always be a direct pick up signal on the probe (a sort of speed of light coupling of the grid signal) but the signal we look for is the one that takes a measurable time to propagate to the probe. The time delay between the received pulse and the sent signal should depend on the speed of those waves in the medium. The time delay should increase as the probe is steadily moved away from the grid. Measure the delay time as function of separation between grid and probe and so determine the speed of the waves. A sample data set for IAWs in ArII is shown in figure 4.

E. Background reading

1. "Langmuir Probe Diagnostic in Dr. Severn's Lab", see the manual's folder on BB! The .m files are found in the "common data set" found there too.
2. Agilent Arbitrary Waveform Generator Manual.
3. Ch. 3 [3.1-3.5] in Melissinos.

II. PERSPECTIVES OF THE PLASMA STATE OF MATTER ITSELF

Plasmas are sort of like flames on steroids: seething hot collections of ions, electrons and neutral atoms which exhibit *collective effects*, or, 'medium-like behavior'[5,7] For example, in plasmas, terrifically great electric fields arise over a very short distance at material boundaries that keep the electrons in the plasma and push the ions out, just enough to make the net loss of charge zero. The plasma stays neutral (to a first a approximation) and relatively electric field free. This collective effect is called Debye Shielding. The electrostatic potential structure is called the plasma sheath, and is several Debye lengths thick, as shown in fig. 5 below. How the plasma creates the sheath remains a curious problem of research in basic plasma physics, involving self-consistent, nonlinear plasma dynamics.

The energy ions get *in* the sheath, however, is even greater than that required to form it in the first place. The kinetic energy gained in falling through the sheath potential is used for an enormous variety of plasma processing[8] applications (e.g., ultra large scale integrated circuits, surface modification, and so on). But the kinetic energy in the bulk plasma is useful too. For example, the kinetic energy of the electrons efficiently excites atoms and molecules into high energy states, leading to subsequent spontaneous emission of photons which, directly (in high current gas discharges) and indirectly (in fluorescent tube discharges) provide an important source of

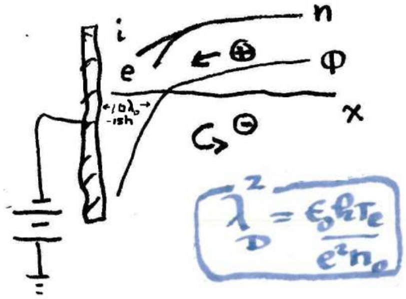

FIG. 5. Schematic of the plasma bounded by a negatively biased boundary wall. Ions flow to the wall down the potential hill $\phi(x)$, while electrons are repelled. Net space charge appears at the sheath edge, where the gradients in the ion density and electron density diverge. The inset box exhibits an expression of the Debye length.

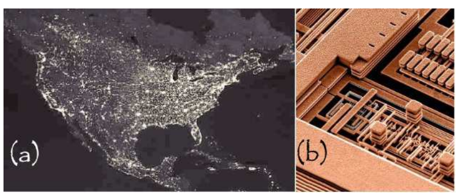

FIG. 6. (a) This NASA photograph of the US at night: nearly all of the light visible derives from high current plasma discharges, and dramatically shows how modern society depends on plasma based technology. An even greater example of this is the extent to which modern industry depends on integrated circuits, nearly all of which (and not just for computers and cell phones, but cars, clocks, and coffee makers, etc., etc.) are manufactured using plasma processing technology. The interconnects etched with plasmas in the figure shown above (b) are narrower than the wavelength of blue light, $0.4\mu m$.

lighting. Plasma technology is very practical, and very important to society. Under- standing plasma science is therefore very important. Two applications of plasma science are highlighted in figure 6.

Of course, the major thrust of research in the physics of plasmas has to do with realizing fusion energy. Making fusion energy feasible has proved to be a much more difficult problem to solve than was the case for fission energy. Understanding the unexpectedly rich variety of medium-like behaviors of the plasma state of matter has been part of the problem. Solving the (engineering?) problem of shielding a fusion plasma held at 150 million degrees from another superconductor held at a temperature near absolute zero, with only a few centimeters of separation is also part of the problem. It is a challenge that has motivated a couple of generations of bright people to get involved in the work. There will be an enormously great payoff for humanity if the work is ultimately successful: limitless high intensity energy for thousands of years. And yes, that does sound too good to be true, and no, we wouldn't expect any endeavor with such an enormous payoff to be easy...the claims that *should* sound *not* credible are those that offer such a payoff with relative ease. Hold on to your wallet and don't invest. Fusion? Well, be ready to roll up your sleeves and join the work. It is still a massive undertaking for humanity (well, for the plasma physicists anyway). Fusion is coming!

[1] *Understanding Langmuir probe current-voltage characteristics*, R. Merlino, Am. J. Phys. **75**, 1048, (2007)

[2] Chapter II, PHYS 180 Lab Manual, "Basic Plasma Diagnosis," section 1, Langmuir Probe, p40-45.

[3] Rudolf Limpaecher and K. R. MacKenzie, "Magnetic Multipole Containment of Large Uniform Collisionless Quiescent Plasmas", Review of Scientific Instruments 1973 **44** 726 (1973).

[4] N. St. J. Braithwaite, Plasma Sources Sci. Technol. **9** 517 (2000).

[5] *Ch.2 Definition of the Plasma State of Matter*, A. Piel, from *Plasma Physics: An Introduction to Laboratory, Space, and Fusion Plasmas,* (Springer-Verlag, Berlin) (2010).

[6] Chapter IV, PHYS 180 Lab Manual, "Ion Acoustic Waves", sections 1,2, and 5, p.79-84, 89-97. Also, good references include: "Propagation and Damping of Ion Acoustic Waves in Highly Ionized Plasmas A. Y. Wong, N. D'Angelo, and R. W. Motley Phys. Rev. Lett. 9, 415-416 (1962), and "Controlled Landau Damping of Ion-Acoustic Waves," I. Alexeff, W. D. Jones, and D. Montgomery Phys. Rev. Lett. 19, 422-425 (1967).

[7] For fun, please peruse the website,

`http://www.plasmas.org/basics.htm`

[8] M A Lieberman and A J Lichtenberg, " Principles of Plasma Discharges and Materials Processing, " 2nd edn. (Hoboken, NJ: Wiley) Ch.1 (2005).