I. PART I: THE LANGMUIR PROBE AND THE DC DISCHARGE PLASMA

A. Perspective and objective

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'. 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 approximation) and relatively electric field free. This collective effect is called Debye Shielding. The electrostatic potential structure is called the plasma sheath. How the plasma creates the sheath remains a curious problem of research in basic plasma physics, involving self-consistent, nonlinear plasma dynamics. A cartoon of a microscopic view of this state of matter is shown in figure 1.

![Cartoon of plasma sheath](image)

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. There is more to it of course. Plasma behave weirdly and unexpectedly, and its mysterious glory actually crowns our planet, above and below (here of course I mean the aurora).

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 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 lighting. Plasma technology is very practical, and very important to society. Understanding plasma science is therefore very important. Two applications of plasma science are highlighted in figure 2.

![NASA photograph of US and plasma etched interconnects](image)

FIG. 2. (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. Perhaps an even greater example of this is the extent to which modern industry depends on integrated circuits, nearly all of which (and not just computers, 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, 0.4µm.

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!

The basic goals of these experiments are to help familiarize us with the fourth state of matter (so-called): plasma, and to get to know a simple way of creating laboratory plasmas for research purpose (a cartoon of which is shown in figure 3). Finally, we want to understand how Langmuir probes work. The Langmuir probe 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 such as density, temperature, and electrostatic plasma potential, and how these parameters depend on the discharge parameters of a magnetically confined thermionic discharge plasma (figure 3). Why do some call plasma the universe’s first state of matter? Please sort this out and submit written solutions to the first 4 tutorial questions prior to the first tutorial meeting!

B. References

1. For fun, please peruse the website, 

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

   to get some insight into this particular state of matter.


3. Ch. 3 [3.1-3.5] in Melissinos.

4. Collective Effects, Chapter 1 in “Fundamentals of Plasma Physics”, a web book, written by Dr. James Callen, University of Wisconsin-Madison. Dr. Callen is an eminent plasma physicist, one of the few in the National Academy of Sciences.

C. 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 3.

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,

$$e_p + Ar \rightarrow Ar^+ e + e_p, \quad (1)$$

where the subscript denotes the primary electron, which must loose energy at the expense of the ionization potential 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[2]

Measure the $I - V$ (current-voltage) characteristic for a planar Langmuir probe (see reference 2 above) in a steady state discharge, using a simple probe-bias sweep 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 semilog 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 discharge currents (500ma < $I_{dis}$ < 1,500ma) and fixed discharge voltage and neutral pressure, ($V_{dis} = 80V$, say, and $p_o5 \times 10^{-4}$torr), and do the same for different neutral pressures ($1 \times 10^{-3} < p_o < 8 \times 10^{-4}$torr) for fixed discharge voltage and discharge current (say, 60V and 1amp, respectively). Evaluate the results and show how the plasma density, temperature, and potential depend on the discharge current, and neutral pressure. Plot the data and tape the hardcopy into your notebook, and try to account for the curves qualitatively. Calculate the fractional ionization of the plasma as a function of neutral pressure. Does the result surprise you?

As you read through this procedure, you will be struck by the instruction to make detailed records in your lab notebook. This instruction serves two purposes: 1) we must always be keeping good records, for this is a critically important research skill, something of great value whether you got to work in industry or in national or university laboratories, and 2) there will be no separate paper due for part I of the plasma experiment...the paper will be for part II on ion acoustic waves, but you will need this data and diagnostic skill with Langmuir probes for part II.

II. PART II: COLLECTIVE EFFECTS—ION ACOUSTIC WAVES

A. Perspectives and Objectives

The plasma state of matter supports a variety of collective effects one of which is longitudinal ($k \parallel \vec{E}$), electrostatic ($\vec{B} = 0$) 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?

B. Background reading

The essential references are these:

- ‘Waves in Plasmas’, Ch.4 in Introduction to Plasma Physics and Controlled Fusion Vol.1, Chen, 2nd Ed., Plenum Press (1984). This is the most didactic reference. There is a copy of this text in the filing cabinet in the lab (ST290).
- Controlled Landau Damping of Ion-Acoustic Waves I. Alexeff, W. D. Jones, and D. Montgomery Phys. Rev. Lett. 19, 422-425 (1967). This is a good reference to see what the time delayed tone burst looks like. We have to worry about noise to make the signal

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

Capacitively couple the Agilent function generator (fg) to the Wave Launching Grid. The Langmuir probe (Heruclean diagnostic, hero of the previous plasma laboratory experiment) will be used as the detector. 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 cut-off 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
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.

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 below.

III. QUESTIONS TO PONDER

These are all found on our public course website.[3]

[3] Questions like these will be posed during the final oral exam, and during each tutorial session.