Collective effects, such as Ion Acoustic Waves, in the Plasma state of matter

Physics 480W
(Dated: Fa24-version a)

I. RESEARCH QUESTIONS AND OBJECTIVES

The plasma state of matter exhibits "medium-like" behavior, phenomena that cannot simply be understood in terms of "single particle effects". In a plasma, the single particles are ions, electrons, and neutral atoms[1]. Consider two "test" charged particles, so close that the total force on charge number 1 is well modeled by Coulomb's law ($F_{12} = q_1 q_2 \hat{r}_{12}/(4\pi\epsilon_o)r_{12}^2$) and all that, the thing expected between the two point charges. However in a plasma, if the two charges were sufficiently far apart, the total force on charge number 1 wouldn't change at all if charge number 2 were deleted, because the local electric field experienced by particle number 1 is far more determined by the medium of all the other charges, near and far, than by the presence or lack of presence of the test charge number 2. And what *is that characteristic distance?* Well, that distance depends on the medium-like characteristics of the plasma state of matter. There is a hierarchy of spatial scales (and times!) over which the complicate motion of large sets of particles do not easily map back onto single particle motions, phenomena such as plasma shielding, plasma oscillations, and waves, among other cool effects better understood as "collective effects".

This set of laboratory experiments explores one of these collective effects, waves, and particularly the electrostatic ion waves called ion acoustic waves (IAWs). There is a veritable zoo of waves supported by collective effects in the plasma state of matter, but IAWs occur at sufficiently low frequencies that very expensive instruments are not necessary. A modest grant (50,000 $?) would do, and ingenious physicists have been able to get some of the data we'll acquire for far less. The main research questions we will pursue are these:

1. How do the phase and group velocities of IAWs depend on the temperature of the electron population? Note: this implies that we will play around with plasma discharge parameters to see how to change plasma electron temperatures in a addition to learning to measure phase and and group velocities of IAWs.

2. How do the phase and group velocities of IAWs depend on the mass of the ions of the feedstock noble gas used to make the plasma discharge? Note: this implies that we will make plasma discharges from different noble gas feedstocks while we learn to measure the phase and and group velocities of IAWs.

And there are two parts to these experiments which we now explore in turn.

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

A. Brief introduction to plasma physics

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 a approximation, described by the term 'quasineutrality') and relatively electric field free. This collective effect is called Debye Shielding or Debye Screening. The electrostatic potential structure that forms near plasma boundaries (e.g. the vacuum chamber wall of a confined plasma) is called the plasma sheath and exists to maintain quasineutrality in the bulk of the plasma. Unless the scale length of the bulk plasma is much, much greater than the sheath length, one doesn't really have a plasma. 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 (bulk plasma) is shown in figure 1. Before describing how to create plasma in the lab, let's consider two applications of plasma physics.

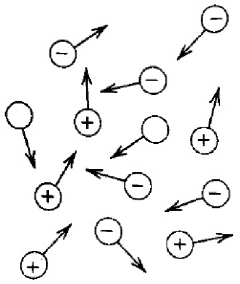

FIG. 1. Not just any collection of charged particles, with roughly equal concentrations of positive and negative charges, exhibit collective behavior distinctive of the plasma state of matter. The electron and ion densities have to be great enough and these populations have to be hot enough for 'medium 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).

Another cartoon (Fig. 2) of the plasma potential structure near a plasma boundary gives some idea of Debye screening. This helps to understand a wide array of applications called "plasma processing" or more directly, "plasma surface modification". The Plasma somehow boosts the bulk potential positively relative to its boundary where an ion-rich sheath forms. The scale length over which the sheath extends from the boundary (at $x = 0$) into a structure called the presheath is several "Debye Lengths", where the Debye Length ($\lambda_D^2 = (\epsilon_o kTe/(ne^2))$), must be very small compared with the spatial extent of the plasma, so the sheath is *thin* (see particularly Background reading # 1). Recall that we said in class that in order for plasma to *be plasma* the charge particle density, well, that of the electron population for low temperature plasma, must have a thermal temperature such that the average particle kinetic energy exceeds the average ion-electron nearest neighbor attractive electrostatic potential energy, something that is the case if the number of particles in a Debye sphere greatly exceeds.

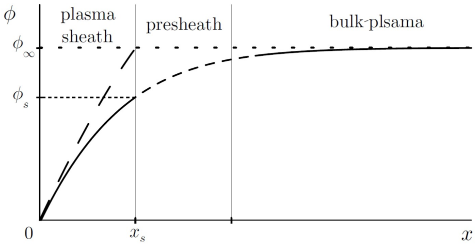

FIG. 2. The plasma potential profile near a boundary can be roughly divided between sheath, presheath, and bulk plasma. Sheath's are *thin*, relative to the other regions shown, typically several Debye lengths in extent, and much, much shorter than the extent of the presheath and bulk plasma. Note the distortion of length in this image!!! Whenever we look at an image (or create one) don't we have an obligation to tell the reader what's real, what's "to scale", etc.? This is figure 1.3 in Callen's ebook, Fundamentals of Plasma Physics, chapter 1, "Collective Plasma Phenomena".

Clearly positive ions are accelerated into the sheath and onto the boundary, sometimes with enough energy to modify the surface itself. This is the case in the plasma reactors used to etch semiconductors in ULSI industry (ultra large scale integrated circuits), now ubiquitous, not just in phones and computers, but in cars and coffee makers. But in some discharges engineered to have a fairly long distance between conducting electrodes surrounded by a tubular insulating side wall, a great deal of light can be created simply by inelastic collisions between electrons and neutrals as happen in high pressure discharge lamps and even the low power spectral lamps we use for spectroscopy experiments in PHYS 272L. This technique is also used indirectly in fluorescent lamp technology as well. Plasma etching and plasma lighting (see Fig. 3(a) and (b)) are multi-multi billion dollar industries, in which plasma technology is of central importance.

Of course, one of the major thrusts of plasma physics research has to do with realizing fusion energy, and there has been important news recently. Making fusion energy feasible has (beginning with the first research efforts beginning with the conclusion of World War II) 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 that maddening problem. Two different plasma confinement (and heating) schemes have been most successful, a) inertial confinement, *which has verified both 'ignition' and 'break-even' recently* [3], and b) magnetic confinement tokamak configurations (see Fig. 3(c)), which has been knocking on the door of break-even since the late 90's[4]. Achieving useful fusion energy is an extraordinary challenge (see, for example the list of the National Academy of Engineering Grand Challenges, `https://www.engineeringchallenges.org`) that has motivated a few generations of bright people to get involved in the work, with the result that now, the fusion start-up companies (see, e.g., `cfs.energy`) aiming to bring fusion energy to the US grid boast (have) more venture capital funding (10's of billions) than the entire US Federal research 'spend' (100's of millions). There will be an enormously great payoff for humanity if the work is ultimately successful: limitless high intensity energy for thousands of years. Fusion? there are high-paying jobs now. Roll up your sleeves, go get an advanced degree in fusion science and plasma physics and join the work!

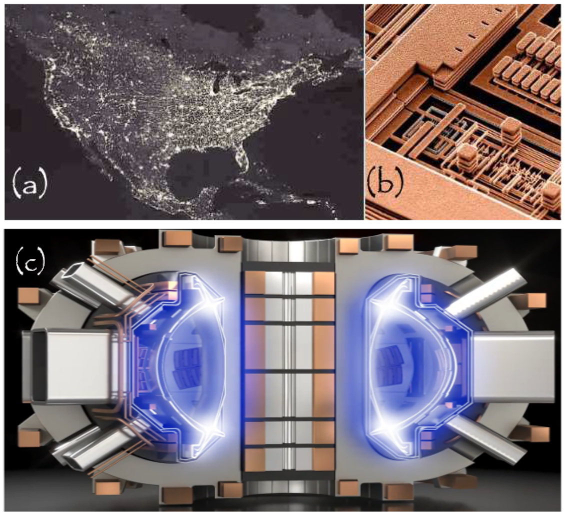

FIG. 3. (a) This NASA photograph of the US at night showing lit up cities (nearly all of the light visible derives from high current plasma discharges), dramatically shows how modern society depends on plasma based technology. (b) How much of modern society depends on ultra-large-scale-integrated circuit technology, all of which requires plasma processing for the etching of silicon? The interconnects etched with plasmas in the figure shown above in (b) are narrower than the wavelength of blue light, $0.4\mu m$. (c) Commonwealth Fusion Systems are among the many fusion energy start-up companies aiming to bring Fusion Energy to the USD grid in advance of the completion of the ITER experiments.

The basic goals of our experiments (less ambitious than achieving fusion) are to familiarize us with the fourth

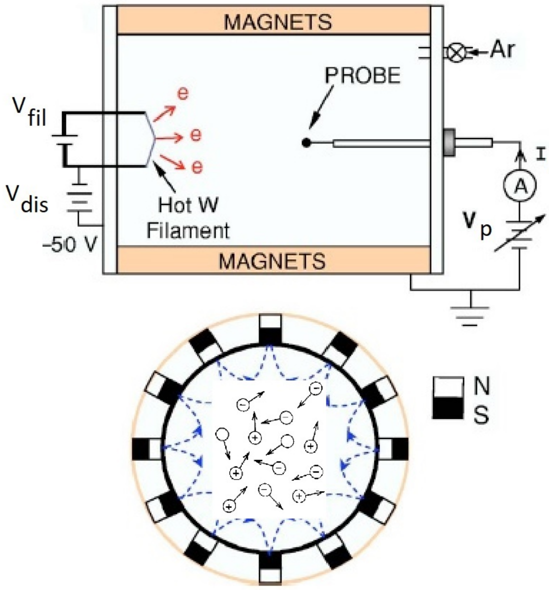

FIG. 4. Schematic of a basic device for producing a plasma, a multi-dipole hot filament plasma device with a Langmuir disk probe. The plasma is produced by electron impact ionization of argon atoms by electrons that are thermionically emitted and accelerated from a hot tungsten (W) filament. To enhance the ionization efficiency, the walls of the chamber are lined with rows of permanent magnetic 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 Background reading # 1.

state of matter (so-called): plasma, to get to know a simple way of creating laboratory plasmas for research purpose (a cartoon of which is shown in figure 4), to understand how to use an important diagnostic technique in experimental plasma physics, the Langmuir probes, and to study ion acoustic waves (leaving out of course an important technique for noise reduction, the lock-in amplifier technique). 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 4). How we proceed is described next.

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 using an external power supply called the discharge supply (V_{dis} in Fig. 4). When the discharge voltage significantly exceeds the ionization potential of the feed gas (argon, in our case, which is roughly 15.7 eV), the energetic electrons (called ‘primary electrons’), may create an ion, electron pair, in an inelastic ionization collision,

$$e_p + Ar \longrightarrow Ar^{+}e + e_p, \tag{1}$$

where the subscript denotes the primary electron, which must lose 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. There is a discharge current associated with the 'left over' electrons that find their way to the chamber wall. 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 in a research paper by Braithwaite[5], and in a chapter of a plasma laboratory experiments manual (in long use at UCLA), the so-called 180E manual that I will try to post somehow (see Background reading #2).

What to do? Using the Langmuir probe technique described in Background readings nos. 1-3, measure the $I-V$ (current-voltage) characteristic for different discharge currents ($500ma < I_{dis} < 1ma$) at fixed discharge voltage ($V_{dis} = 60V$, and for various neutral pressures in the regime of order 10^{-4} $Torr$ ($1 \times 10^{-4} < p_o < 8 \times 10^{-4} Torr$)). We will use planar Langmuir probe along with a simple probe-bias sweeper circuit, described in detail in Background reading #2 . On an $I-V$ characteristic, mark the plasma space potential, V_s, the floating potential, V_f, electron saturation current, I_{es}, and ion saturation current, I_{is}. Then 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 (exploring the neutral pressure regime, and of course, write down the physical probe area. In your lab notebook, tape in a hard copy 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. We have a Matlab script that does all this for us. Using the plots described above, recording everything in your lab notebooks (measuring circuits, plots, stored plot file names, etc.) and verify that the quantities calculated by the Matlab script

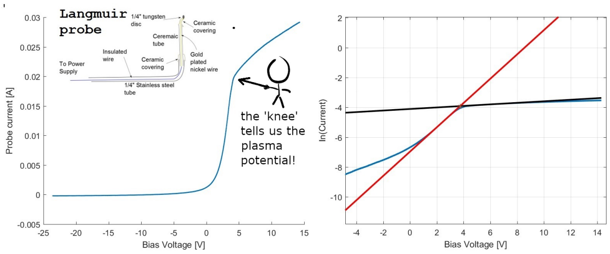

FIG. 5. Fabrication notes for a Langmuir probe in the inset, with I-V or IV characteristics along with a semilog plot of *just the electron current drawn to the probe.* The semi-log plot shows linear fitting curves to both the electron branch of the IV characteristic ($V_p \geq V_{pl}$) and the ion branch, ($V_p < V_{pl}$). Note that in the ion branch, the electron current swamps the ion current until the floating potential is reached.

are correct. Then use the calculated values. Calculate also the fractional ionization of the plasma in each case, as a function (ratio?) of the neutral pressure. Does the result surprise you? Try to find two cases of different T_e, one hot and one cold that differ by at least a factor of two, two such cases, for both Ar and He discharges (so, four separate cases). Why design the experiment like this?

A bit more about technique. As mention above, we'll use Matlab to control data acquisition for both both probe current and prob bias voltage waveforms. Although there are a number of methods for determining the plasma parameters we care about (n_e, λ_D, and most importantly, T_e) all of these require a determination of the plasma potential, and the so-called 'crossing method' is described in Merlino's paper (Background Reading #1, see especially Fig. 5 of that paper). This is visually described in Fig. 5.

As you read through this procedure, you will be struck by the instruction to make detailed records in your lab notebook. This instruction serves multiple important purposes. Lab notebooks are used for documentation. If the experiment is conducted over multiple weeks, one needs one's own notes for capturing 'know-how'. What set of discharge parameters were used to obtain what particular outcomes of importance? What were the instrument settings? What were your reflections on the meaning of the results at the time? Can you obtain the same squiggles next time? All of this work necessary has a footprint in the paper you will write. If the work flow of the paper moves from experiment to analysis (it's OF COURSE more convoluted than that) it helps to have a good experimental record from which to draw from to compose the paper. The papers your write, *individually* are 80% of the weight of your grade in PHYS 480.

III. PART II: COLLECTIVE EFFECTS—ION ACOUSTIC WAVES

A. Introduction and objectives

The plasma state of matter supports a variety of collective effects one of which is longitudinal ($\mathbf{k} \parallel \tilde{\mathbf{E}}$), electrostatic ($\tilde{\mathbf{B}} = 0$, see particularly Background reading #4) waves. The nomenclature used here for fluctuating, propagating quantities, small perturbations to an equilibrium value, is a 'tilde' – `\tilde` in LaTeX – set on top of such a quantity. 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, ***for two or three different noble gasses (e.g. Ar, He, Xe, Kr)***, 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.

B. Sketch of procedures

1. *Tone-burst method*

Capacitively couple the Agilent function generator (fg) to the Wave Launching Grid. The Langmuir probe may and will be used as the detector. It will be capacitively coupled to ground so as to make a high pass filter ($f_{cut-off} \approx 10Hz$). 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. Is this a measure of phase or group velocity? A sample data set for IAWs in ArII is shown Fig. 6.

2. *Lock-in method*

Again we capacitively couple the Agilent function generator (fg) to the Wave Launching Grid, as with the previous method. The Langmuir probe will again be used as the detector, and it will be will be capacitively coupled to ground as before, except that we'll include a 10 $k\Omega$ resistor in parallel to ground at the AC coupled oscilloscope input (see input A on the SR830 Lock-in Amplifier; an image of the Lock-In is shown as a boxed inset in Fig. 7). The reference input should also be connected to the output of the Agilent fg. The output can be set on display so that numbers may be conveniently recorded in one's lab notebook. Toggle the value of the reference phase until the signal (the so-called 'X' output, displayed either in volts or as a % of full scale) is nulled. Then move the Langmuir probe systematically so as to increase (or reduce) the path length between grid and probe. Only the propagating portion of the signal on the probe will shift in phase. Measure the Lock-in output as a function of path length (position of the probe relative to the grid). One sees a sinusoidal function created by constructive (or destructive) interference between the received signal and the reference signal. The method then measures the spatial periodicity of the propagating wave. Knowing λ, one can calculate C_s, the phase velocity of ion acoustic waves. Do we measure the phase or the group velocity in this way?

C. Background readings for both parts of the experiment

The essential references are these:

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

2. *Chapter I, Plasma Production, and Chapter II, Plasma Diagnostics, through section 1*, `180E_Lab_Manual.pdf`

3. `Updated_Langmuir_Probe_Diagnostic.pdf` Our current diagnostic "How-To" for Langmuir probes in the Severn Plasma lab.

4. 'Waves in Plasmas', Ch.4 in *Introduction to Plasma Physics and Controlled Fusion* Vol.1, Chen,3nd Ed., Springer 2016. Focus on particularly on sections 1, 5 and 6. (1984).

5. 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)

6. Controlled Landau Damping of Ion-Acoustic Waves I. Alexeff, W. D. Jones, and D. Montgomery Phys. Rev. Lett. 19, 422-425 (1967).

7. Agilent Arbitrary Waveform Generator Manual.
8. Stanford Research Systems Dual-channel Lock-in Amplifier Manual (SR830.pdf)

9. *Introduction to Plasma Physics and Controlled Nuclear Fusion,* F.F. Chen, 3rd. Ed., Springer 2016, Ch.1.

10. *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. This is a deeper treatment than Chen's, great for the curious. I'll try to post this, but you can find all of his chapters and appendices (cool resource!). Just google "fundamentals of plasma physics AND Callen", and follow the links to the author's url.

11. For fun, please peruse the website,

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

    to get some insight into this particular state of matter.

12. Ch. 3 [3.1-3.5] in Melissinos, for a necessary electronics "refresher".

---

[1] — or molecules (!), but let's not consider the many complications that arise in molecular plasma! Let's instead consider only single ion species plasma created in the lab from neutral noble gas atoms.

[2] K. R. MacKenzie, R. J. Taylor, D. Cohn, E. Ault, and H. Ikezi, App. Phys. Lett. **18**, 529 (1971).

[3] see particularly Nature, News Features, *Nuclear-fusion breakthrough: this physicist helped to achieve the first-ever energy gain* Nature **624**, 500-501 (2023), from 15 Dec. 2023, and the article, *US nuclear-fusion lab enters new era: achieving 'ignition' over and over*, Nature 625, 11-12 (2024) from the same issue, both written by Jeff Tollefson.

[4] Surf over to the Wikipedia article *Timeline of nuclear fusion*, and examine the year 1998, but have a look more broadly!

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

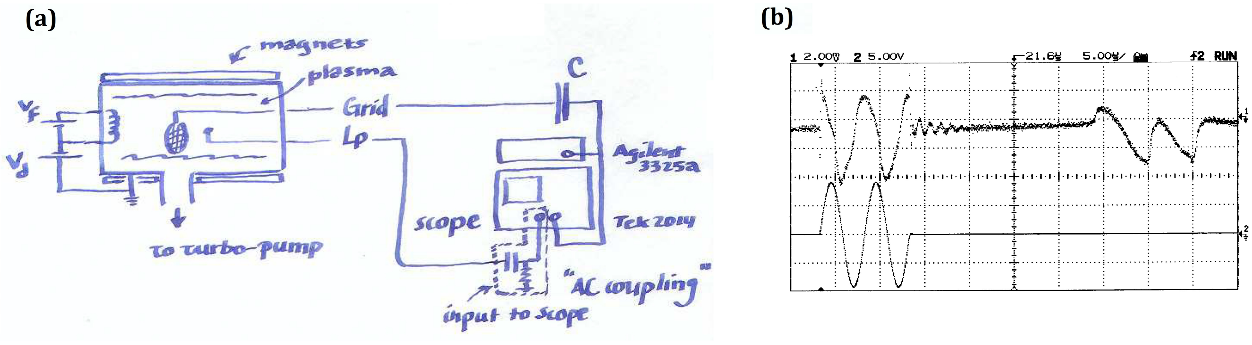

FIG. 6. (a) Grid and probe are separated by some variable distance; the time delay between the tone burst applied to the grid and in (b) the oscilloscope displays the moment of its appearance on the probe, which can be varied by changing this distance. Note that the directly coupled signal is present and distorted in a way that the propagating signal is not. The oscilloscope trace may be captured using an NI "virtual instrument" called Grab Trace.vi

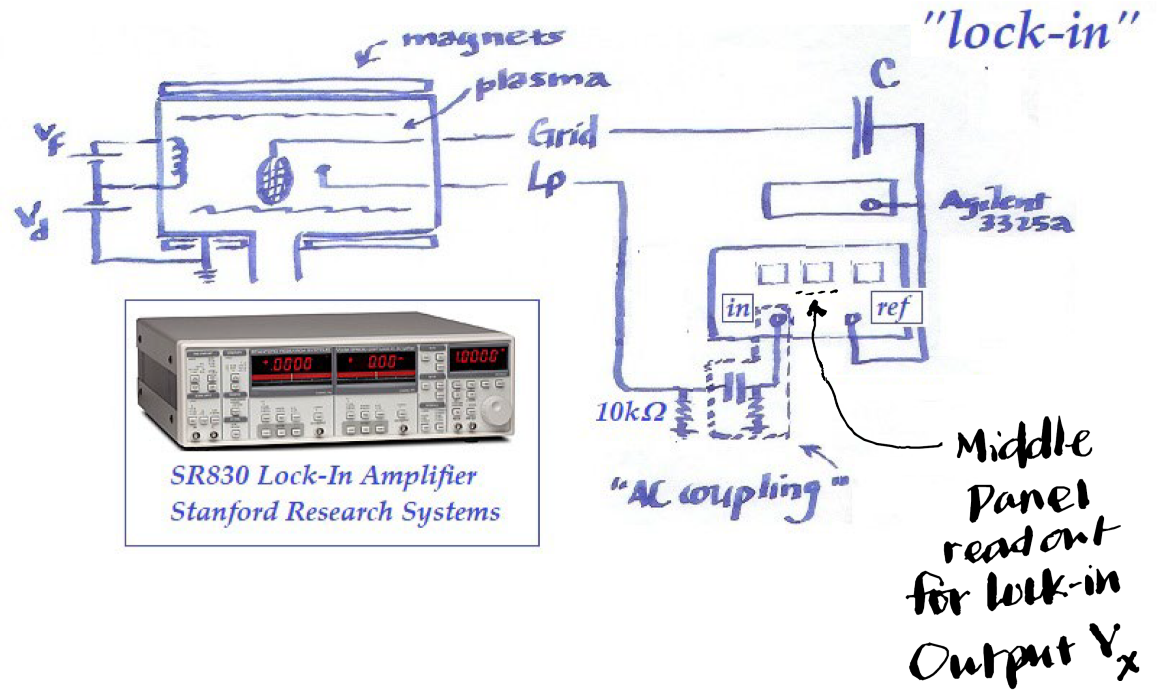

FIG. 7. Block diagram of Lock-in amplifier set-up. Two inputs on the SR830 Lockin-in are used, 'in', AC coupled, and reference-in or just 'ref', which accepts the rf signal that is also coupled to the grid. In this way, and phase-referenced comparison of the signal picked up by the Langmuir probed and can be compared with the input signal. Note, if the wave is traveling in the plasma, we expect the phase and amplitude to vary as a function of the separation between grid and probe-tip.