A New Probe for Vorticity and Turbulence Measurements in Plasmas

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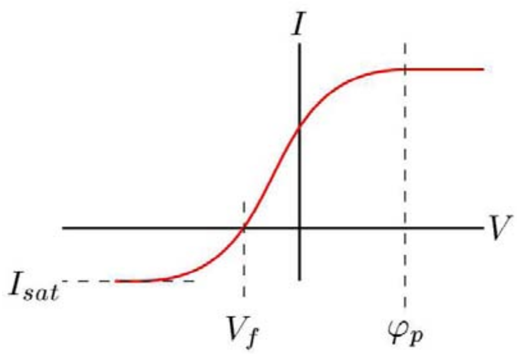
A new, 7-tip Langmuir probe was built for vorticity and correlation measurements in the Large Plasma Device (LAPD). A successful test run was made in the Baby-LAPD, and simple analysis was made of the plasma in the Baby-LAPD.

BACKGROUND

Langmuir Probe Basics

Basically, a Langmuir probe is a piece of metal stuck into the plasma. With an attached wire, we measure the voltage of or draw current from the probe. An example V-I curve for a Langmuir probe is given below:



The specifics of this curve depend on the plasma and also on where in the plasma the measurement is made.

We make use of two points on this curve to make measurements with our probe: the ion saturation current and the floating potential. The ion saturation current, I_{sat}, is collected when the probe is biased negatively with respect to the plasma — this rejects electrons and collects only ions:

$$I_{sat} = nqC_sA$$

where I_{sat} is the ion saturation current, n is the density of ions, q is the charge of the ions, $C_s = \sqrt{T_e}M$ is the sound speed of the ions and A is the area of the probe tip.

This measurement is useful in determining the mean value of and for studying fluctuations in the plasma density.

We are also interested in the plasma potential and fluctuations in the plasma potential. By drawing no current, we measure the floating potential, or the point on the V-I curve where electron collection exactly balances ion collection:

$$V_f = \varphi_p - \alpha T_e$$

where V_f is the floating potential, φ_p is the plasma potential, α is a constant and T_e is the electron temperature.

In and of itself, the floating potential isn't very interesting, but, if we assume that the electron temperature changes slowly ($\frac{dT_e}{dt} \ll \frac{d\varphi_p}{dt}$), then we know that the fluctuations in floating potential track the fluctuations in the plasma potential.

Multi-tip Langmuir Probe

The most obvious use for a multi-tip probe is to be able to measure the potential for multiple points in space at the same time, reducing the number of runs necessary to map out the potential as a function of space.

Another use is for correlation measurements. With turbulence, each shot is unique, so multiple measurements must be made in a single given shot to find any correlation between them.

A more interesting use for multi-tip probes is to measure the electric field. (Two probe tips measure a difference in potential across a small distance — $E = \frac{\Delta\phi}{\Delta d}$.) Since we know the $\boldsymbol{B}$ field (we created it in the machine) we can measure the plasma flow, $\boldsymbol{v} = \boldsymbol{E} \times \boldsymbol{B}$.

Vorticity. Originally, this probe was meant to measure vorticity in the $\boldsymbol{E} \times \boldsymbol{B}$ flow in the plasma in the LAPD[1]. The parallel component of the vorticity vector, $\boldsymbol{\omega} = \boldsymbol{\nabla} \times \boldsymbol{v}$, is given by

$$\omega = \frac{1}{B}\nabla_\perp^2 \phi(x, y, z, t).$$

Using five probe tips arranged in an "X" configuration, we make the finite difference approximation to $\nabla^2\varphi$ given by

$$\nabla^2\varphi \approx \frac{\varphi_{tl} + \varphi_{tr} + \varphi_{bl} + \varphi_{br} - 4\varphi_{center}}{h^2}.$$

where φ_{tip} is the potential of a given tip (tl = top-left, br = bottom-right, etc.), and h is the spacing between the tips, in this case 5 mm.

5-tip (7-tip) Probe Design

The basic design of the probe is shown in Fig. 1.

For the vorticity measurements, only 5 tips were necessary (the five central tips in an "X" pattern). Two

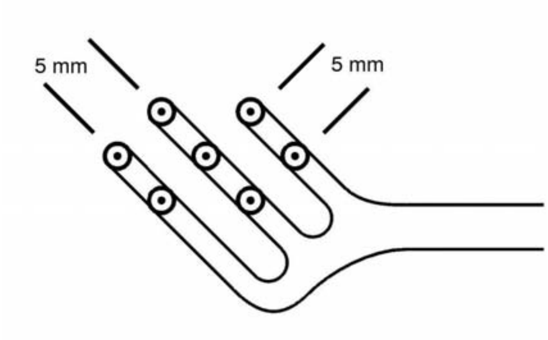


FIG. 1: 5-tip (7-tip) probe design

more tips were added (the left-most and right-most tips) to expand the spatial coverage.

The angled slats allow for the most possible space in-between the probe tips for the plasma to pass through. (The goal is to make the probe interfere with the plasma as little as possible.) The thinness of the slats was limited by the thickness of the coaxial wires attached to the probe tips.

The actual probe

Electronics for Potential Measurement

A simple op-amp circuit was used to measure the floating potential (Fig 2). The imput impedance to the op-amp was high, so as to draw very little current from the probe tip. The output impedance was low so as to drive the digitizer. The imput is AC-coupled with a frequency cut-off at about 1 KHz. The resistor used in the high-pass circuit pretty much set the imput impedance at about 10 KΩ.

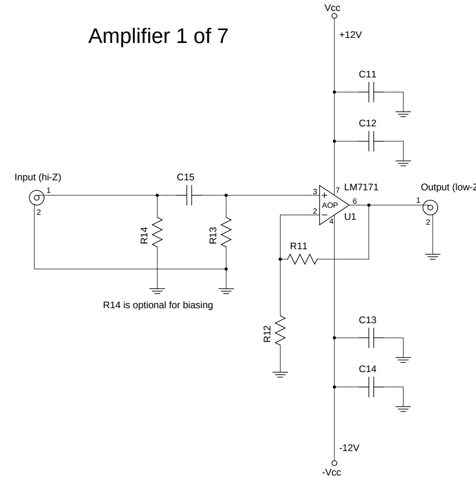


FIG. 2: Circuit for measuring floating potential

EXPERIMENTAL SETUP

The initial goal was to study vorticity (mentioned above); however, due to unexpected downtime, we were unable to perform this experiment. Instead, we assisted in the construction of an RF plasma source for the Baby LAPD and used this to test out the probe.

The probe is placed in the plasma (Fig 3):

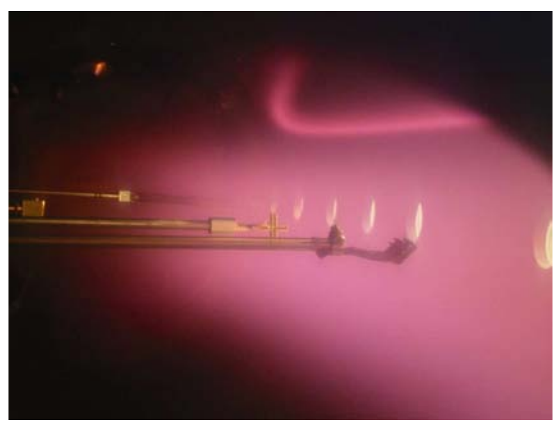


FIG. 3: Note that this is *not* a time-elapsed image. The sequence of white spots are the windows on the opposite side of the plasma chamber. The arc in the top-right is from the elctron source (generated by a filament) used to create the plasma. The closest object is the 7-tip Langmuir probe (attached to a 3/8" shaft).

The plasma was created with a ∼20,000 Volt, ∼200 Amp RF source at 1.5 MHz. The RF was pulsed 3 times a second, lasting ∼1.6 mS per pulse.

DATA

Using the potential-measurement circuit described above, we measure the potential of a single shot at a single point in space as a function of time (Fig. 4).

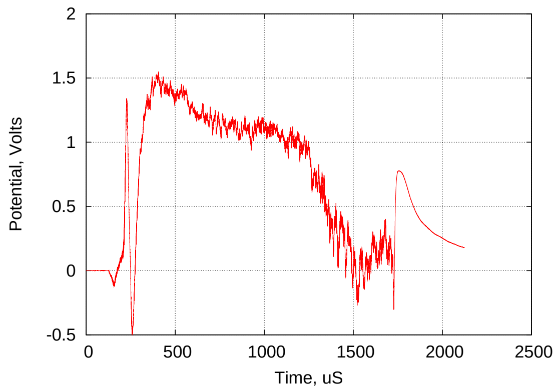


FIG. 4: Typical data collected from a single shot on a single tip. The overall, large-scale shape is casued by the plasma discharge time, which was approximately 1.6 mS.

To further characterize the plasma in the Baby LAPD, we used other electronics to use three of the probe tips in a triple Langmuir probe configuration to measure the floating potential (V_f), electron temperature (T_e, Fig. 5) and plasma density (I_{sat}, Fig. 6).

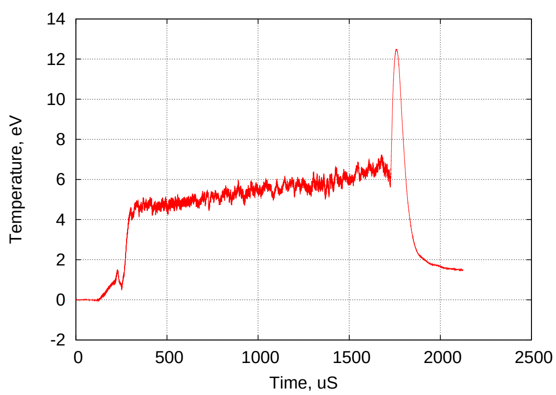


FIG. 5: Typical temperature during a single shot

Potential as a function of Radius

We looked at the basic structure of the plasma in the newly-completed Baby LAPD first by looking at the potential radially along the plasma (Fig 7 and Fig 8).

As hoped, we see that the signal is peaked near the RF antenna. Surprisingly, when the RF is on, we see a large electric field indicating a more complex structure to the plasma. As soon as the RF is switched off, the electric field vanishes.

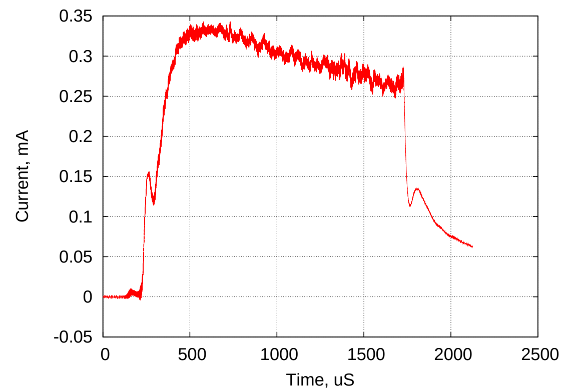


FIG. 6: Typical ion saturation current during a single shot

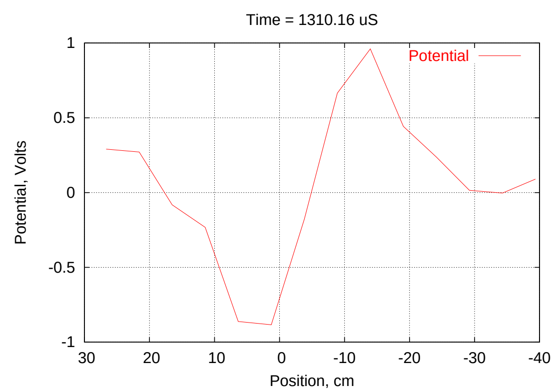


FIG. 7: We don't know the full structure of the large E-field shown here (the large swing in potential from negative to positive).

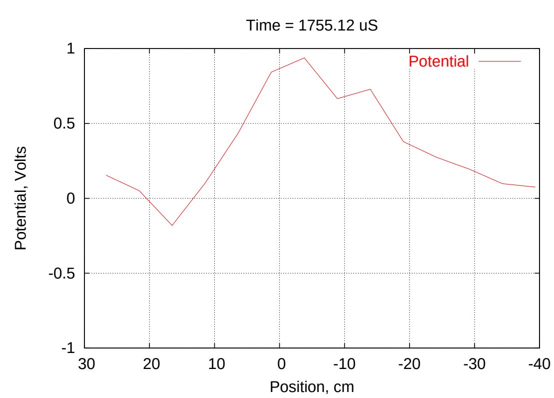


FIG. 8: The large electric field vanishes the moment the RF source is turned off

Power Spectrum

We found the average power spectrum of the plasma by running an FFT on all of the potential shots and averaging the transforms together (Fig. 9).

The spike at ∼1.5 MHz is from the RF source and is to be expected. The spikes at higher frequencies are

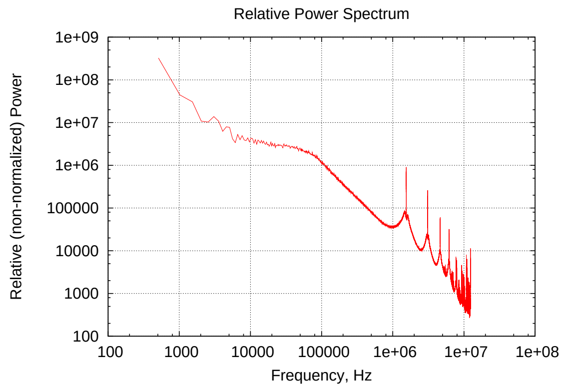


FIG. 9: The spectrum suggests broadband turbulence

most likely due to harmonics from fundamental 1.5 MHz frequency.

The tail on the left side is from the shot itself (the shot was for ∼1.6 mS; we see signal in the ∼1 KHz range...)

The power spectrum exhibits broadband turbulence in the 10 KHz to 1 MHz range (evident from the flattening in the power spectrum followed by a power-law roll-off). It is not clear what is driving this turbulence, but RF produced fast electrons are a possibility. The wings around the RF line (and harmonic lines) suggest possible nonlinear interactions between the RF source and the broadband turbulence.

Coherency

To characterize the turbulence seen in the potential measurements, we used the multiple tips to find spatial correlations in the potential fluctuations. To find the coherency, γ, we use

$$\gamma^2 = \frac{|<\varphi_1 \varphi_2^*>|^2}{|\varphi_1|^2 |\varphi_2|^2}$$

where φ_1 is the Fourier transform of the potential from one probe tip and φ_2 is the Fourier transform of the potential from another tip.

The arrangement of the multiple tips allows us to look simultaneously at the coherency across several different distances — 5, 7, 10 and 14 mm (Fig. 10).

Obviously, there is very high correlation at 1.5 MHz and the harmonics, as the RF signal should be uniform over the volume of the Baby LAPD. Looking at the correlation vs. distance, we can extrapolate that, in the 10–100 KHz flat region, the correlation length is about 5 cm, which is approximately the ion gyro-radius. This is not definitive in identifying the source of the turbulence, but it's a start.

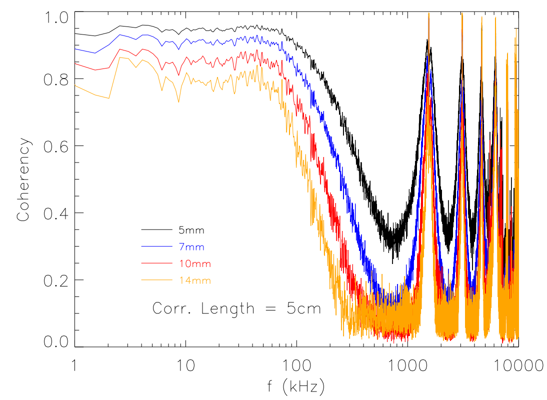


FIG. 10: Coherency versus frequncy and distance. The wings in the RF show decorrelation effects, indicating that they are a real effect in the plasma (and not direct pick up like the RF signals + harmonics).

IN CONCLUSION...

This was a nice test of a new probe and its electronics, and also a good chance to get my feet wet using Python for data analysis.

I thank UCLA and the National Science Foundation for making this REU experience possible. I offer my sincere gratitude to Francoise Queval and Professor Walter Gekelman for all their hard work in making this summer happen. And, of course, I thank Professor Troy Carter for his time and his patience.

[1] W. Horton, J. C. Perez, R. D. Bengtson, and T. A. Carter (2003), internal Proposal.