# Plasma Diagnostics for Laser Driven Waves in a Large Magnetized Plasma

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**Abstract.** The interaction of a laser produced plasma with a large magnetized plasma is studied with various plasma diagnostics. We discuss the theory, design, and construction of three types of diagnostics: Langmuir probes, Mach probes, and $\dot{B}$ probes. A perpendicular probe geometry allows data collection extremely close to the target, including inside a diamagnetic bubble formed by the laser blowoff. Data and some preliminary analysis is presented for all three diagnostics.

## INTRODUCTION

In the 1950s R. Sagdeev proposed[1] the existence of shock waves without collisions. Later, collisionless shock waves were observed by Ness et al[2]. It has since become apparent that collisionless shock waves are a fundamental astrophysical phenomena, occurring in supernova remnants, coronal mass ejections, and are thought to be responsible for cosmic rays.

Experiments have been attempting to replicate conditions necessary for collisionless shock formation and particle acceleration, and relevant to cosmic phenomena. The necessary conditions are well documented[3, 4]. At UCLA we have the unique combination of a large ambient magnetized plasma in the LAPD and a high powered short pulse laser. With these two laboratories replication of the conditions necessary for collisionless shock wave formation should be possible.

In this paper I present the theory, design for several plasma diagnostics to measure shocks and other plasma waves, as well as data from these probes.

## DIAGNOSTIC THEORY

### Langmuir Probes

A Langmuir probe is simply an electrode inserted into the plasma. By applying a constant or time varying potential with respect to the plasma various parameters, such as the electron temperature and density, can be determined. In our experiment we use a large negative bias voltage. This rejects electrons in the plasma, and the probe only collects ions. With a sufficiently large bias the amount of ion current that can be drawn through the electrode reaches a saturation limit due to shielding effects in the plasma - essentially, extra positive charges group around the negative electrode, effectively creating a potential shield, known as the Debye sheath. From a basic plasma text we can find that the ion saturation current will be given by the equation

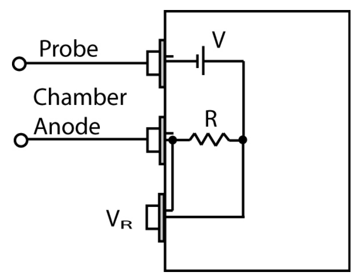


**FIGURE 1.** Langmuir Probe Electronics

$$I = 0.61 n_0 e A \sqrt{\frac{kT_e}{m_i}}, \tag{1}$$

where $n_0$ is the plasma density, $A$ is the exposed area of the electrode, $T_e$ is the electron temperature, and $m_i$ is the ion mass.

In Figure 1 we show the drive electronics for our Langmuir probes. The probe is negatively biased with respect to the chamber anode, and thus collects ion current. We measure the current across a small resistor. The measured voltage must be optically isolated from other electronics as the plasma is at a floating potential, and thus the ground of $V_R$ is at a floating potential.

### Mach Probes

A Mach probe consists of two Langmuir probes facing in opposite directions, and isolated so that one face

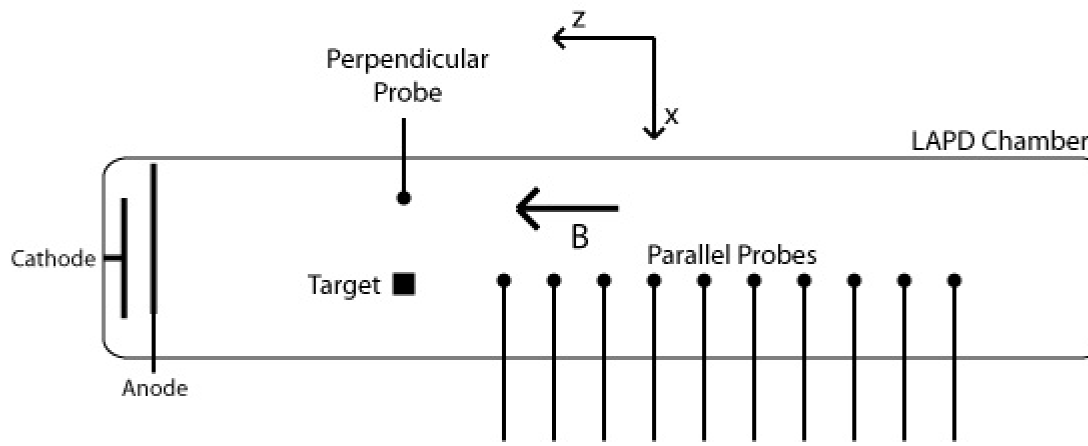


**FIGURE 2.** Experimental Overview, viewed from above, showing the probes (parallel and perpendicular) and target position in the LAPD chamber.

collects current only from one direction while the other face collects current in the opposite direction. If there is a plasma flow perpendicular to the Langmuir probe faces the flow will impact one face, called upstream, but the opposite downstream face can be thought of as in an eddy caused by the body of the probe itself. In this case the upstream probe will collect a higher saturation current than the downstream probe. From the literature[5, 6] we can write that

$$V_d \propto ln(\frac{I_{\text{upstream}}}{I_{\text{downstream}}}) \tag{2}$$

with a constant of proportionality $\pi e T_e/4m_i v_{ti}$, where $v_{ti}$ is the thermal velocity of the ions.

## $\dot{B}$ Probes

The easiest way to determine a time varying magnetic field is to actually measure the time derivative of $\vec{B}$, knowing the initial field. We know that Faraday's Law of Induction states that the EMF induced across a conducting loop is

$$V = -\frac{d\Phi_B}{dt}. \tag{3}$$

We can write the magnetic flux as

$$\Phi_B = \int_S \vec{B} \cdot \vec{ds}, \tag{4}$$

and assuming that the field is constant over the conduction loop the above simplifies to

$$\Phi_B = A_{loop}(\vec{B} \cdot \hat{x}) \tag{5}$$

where $\hat{x}$ is the unit vector normal to the area of the loop. Taking the derivative and inserting (5) into (3) simply gives that

$$V = -A_{loop}\dot{B}_x \tag{6}$$

## EXPERIMENTAL DESIGN

The Large Plasma Device at UCLA (LAPD) is capable of producing a 17m long 60cm diameter He or Ar plasma at a 1Hz repetition rate. The plasma lasts approximately 10ms with a nominal density of $1-4\times10^{12}$ $1/\text{cm}^3$. The plasma is strongly magnetized with a background field of 300-1800 Gauss.

The laser used produces a 5ns FWHM pulse with 25J of energy at 1064nm, circularly polarized. The laser is focused onto a graphite target in the background LAPD plasma to $10^{14}$ W/cm$^2$ peak intensity. The target is mounted from the top of the plasma chamber and is vertically translatable - for each shot the laser is incident on a fresh spot on the target. Additionally the target rotates so the laser plasma blowoff can be oriented either perpendicular to the background field or at a 45° angle to the field.

Langmuir, Mach, and $\dot{B}$ probes are inserted from the sides of the chamber perpendicular to the target or down the machine from the target. The perpendicular probe can be placed up to 0.5cm from the target. A schematic of the overall diagnostic setup is shown in Figure 2. The Perpendicular probe is either a $\dot{B}$ probe or combination Langmuir/Mach probe. The parallel probes are a series of $\dot{B}$, Mach, and Langmuir probes. We couple the probes to a long stainless steel tube with a BN plug. The stainless steel tube is used for vacuum feedthrough as well as probe position adjustment.

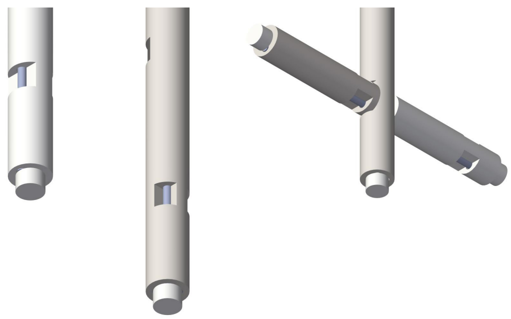

**FIGURE 3.** Mach Probes: from left to right: single parallel flow probe, double parallel flow probe, double perpendicular flow probe

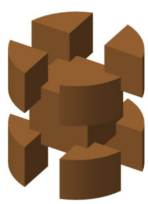

**FIGURE 4.** $\dot{B}$ core. Each axis is wound around the center cube, and the eight feet keep the coils in place.

## PROBE DESIGN

### Langmuir Probes

We build our Langmuir probes by using small (2.39mm OD) alumina tubes double or quad bored. Tantalum wires (0.25 - 0.51mm diameter) are inserted through the bored alumina, exposed to the plasma. Each Langmuir probe is biased with respect to the plasma chamber anode with a 70V battery. The voltage is measured across a 10Ω resistor, optically isolated.

### Mach Probes

Our Mach probes are constructed of the same alumina tubes. We use a diamond bonded thin saw blade to cut notches into the alumina bores exposing the wire. 3D models are shown below in Figure 3. 'Parallel' and 'perpendicular' here refer to the orientation of the measured flow compared with the direction of the background field.

### $\dot{B}$ Probes

Our $\dot{B}$ probes consist of a high temperature plastic core (1.3mm diameter), which we wind in three axes to give us $\dot{B}_x$, $\dot{B}_y$, and $\dot{B}_z$. We use extremely thin copper wire in a twisted pair for each axis, with a differential amplifier to combine the induced voltage of each wire in the pair. The plastic core is shown in Figure 4.

## DATA AND ANALYSIS

For the Langmuir and Mach probes we calculate the ion saturation current (1) from the measured voltage $V_r$ in Figure 1. We correct for the optical isolator gain and phase, measured with a network analyzer. For the $\dot{B}$ probes we use calibration data using both a Helmholtz coil setup and a straight wire to generate known fields. We also use a network analyzer to examine the probe's gain and phase response over the frequency range of the digitizer used in the experiment.

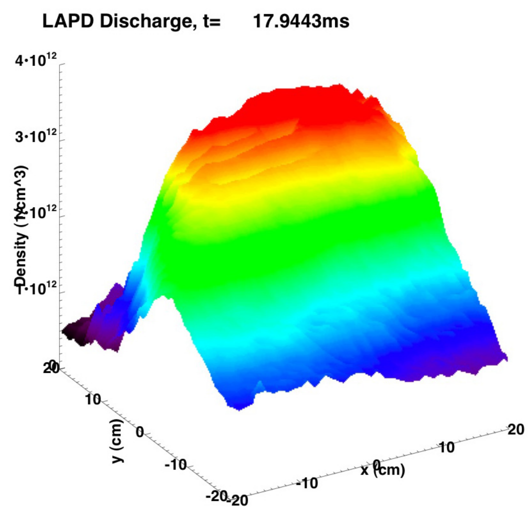


**FIGURE 5.** Density vs x and y, LAPD background He plasma

Shown in Figure 5 is Langmuir probe data taken over a two dimensional plane, showing the radial density profile of the background plasma. The plasma density for the conditions used is nominally $2 \times 10^{12}$ $1/\text{cm}^3$. Our error here is due to large uncertainties in the exposed probe area, which is less than 1 mm$^2$.

In Figure 6 we present data from the perpendicular Langmuir probe. The laser fires at $t = 0$. Here the probe is 7cm from the target. Figures 7 and 8 depict the perpendicular Langmuir and $\dot{B}$ data versus x, 0.28$\mu$s and 0.96$\mu$s after the laser fires.

We observe several interesting features in this data. First, we see large negative spikes several hundred nanoseconds after the laser fires in the Langmuir probe data.

We know that the expanding laser plasma is expelling the magnetic field through the formation of a diamag-

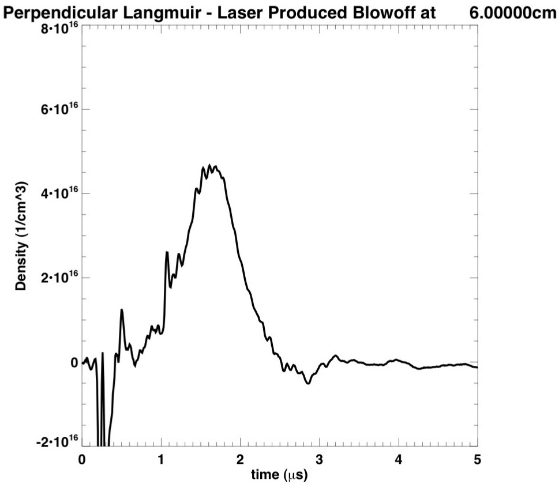


**FIGURE 6.** Density vs time for the perpendicular Langmuir probe. We estimate $T_e = 500$eV for the blowoff in these calculations.

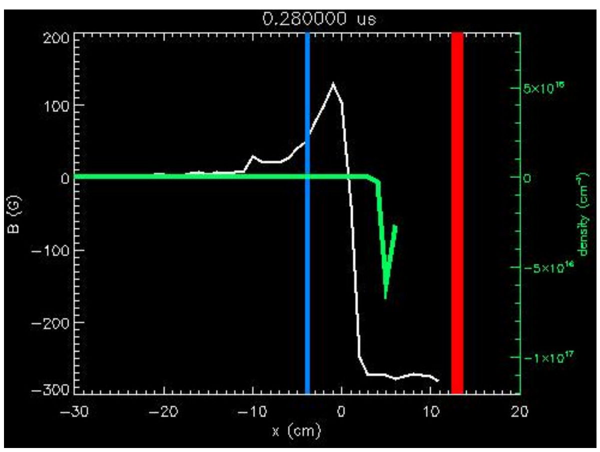


**FIGURE 7.** $|\vec{B}|$ and the density vs x, perpendicular probes, $0.28\mu$s after laser

netic bubble - in Figures 7 and 8 the field reaches -275 Gauss. The initial background field was 275G so this corresponds to a completely expelled field. The expansion pushes the background field lines in front of it. We know that in a magnetized plasma the electrons, due to a very small gyroradius, roughly follow the field lines. We suspect that the negative spike corresponds to electrons following the field lines towards the laser blowoff. This will occur because the laser creates fast electrons that very quickly fly away from the target down the axis of the chamber. This creates a net positive charge in the blowoff region, which can accelerate electrons to a high enough energy to overcome the probe bias.

We would expect the electrons to hit the Langmuir probe at the same time that the field is rapidly changing

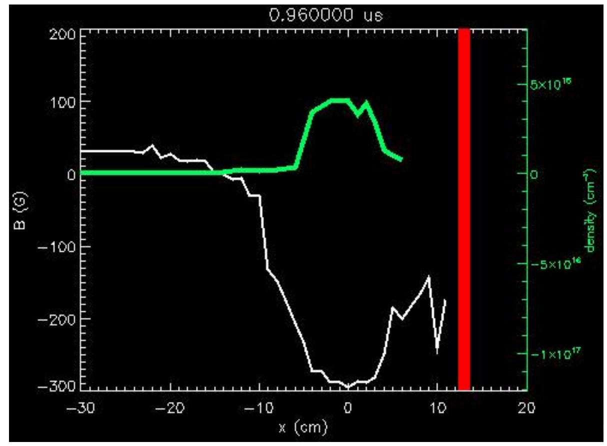


**FIGURE 8.** $|\vec{B}|$ and the density vs x, perpendicular probes, $0.96\mu$s after laser

on the $\dot{B}$ probe. This seems to suggest that the Langmuir probe has some delay on the order of 100-200ns.

We then see a large positive pulse, from approximately $1\mu$s to $2\mu$s, visible in Figures 6 and 8. This corresponds to the arrival of the laser plasma at the probe position. We observe that the laser plasma is several orders of magnitude greater than the background plasma. We can also perform a simple time of flight estimate for the bulk laser plasma:

$$v = \frac{\text{distance}}{\text{time}} = \frac{7\text{cm}}{1.5\mu\text{s}} = 46.6\frac{\text{km}}{\text{s}} \qquad (7)$$

This is much slower than estimates of the fast ion blowoff speed (400-600 km/s) but consistent with a much lower average kinetic energy per ion in the blowoff. If there is a delay in the Langmuir probe data, the velocity would be greater.

In Figure 9 we plot data from a perpendicular Mach probe, also 7cm from the target. The ordinate axis is the drift velocity in arbitrary units - since we do not know the electron or ion temperatures we cannot calculate exact values and simply examine the natural logarithm of the ratio of the signals from the upstream and downstream signals, as in Equation (2). We observe a broader pulse than in the simple density data, implying that the Mach probe is more sensitive to the entire bubble rather than just the high density center.

We also have data with the target oriented at 45° from the background field. In this case the blowoff will travel down the machine and can be observed with probes much further away. Figures 10 and 11 plot data from a parallel Mach probe 65cm away from the target in the 45° blowoff case. The laser fires at $t = 0$. These plots show the signal intensity vs x position and time. Red/white is scaled to the highest signal value, and blue/black the lowest. Figure 10 shows the face of the Mach probe facing

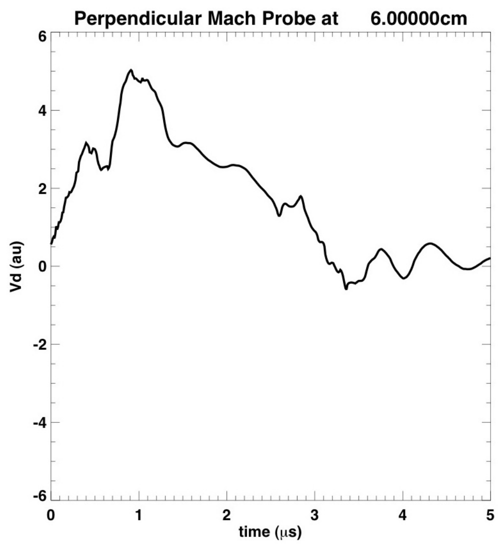


**FIGURE 9.** Perpendicular Mach probe

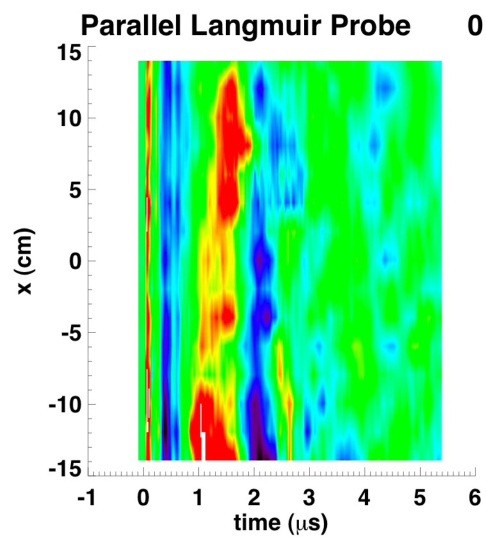


**FIGURE 10.** Parallel Mach probe, target face.

the target, and Figure 11 the face turned away from the target.

We can see that in Figure 10 there is a large positive signal approximately $1\mu$s after the laser fires for $x \leq -10$cm, but there is no corresponding signal on the back face (Figure 11). This suggest that we see some sort of flow or 'ion beam' at those positions, which is consistent with preliminary Monte Carlo simulations of fast blowoff ions. On both faces we see a signal at $x = 10$cm, which would suggest a dense plasma cloud moving through the machine. Further studies and simulations of this data is required for a complete physical understanding of the data.

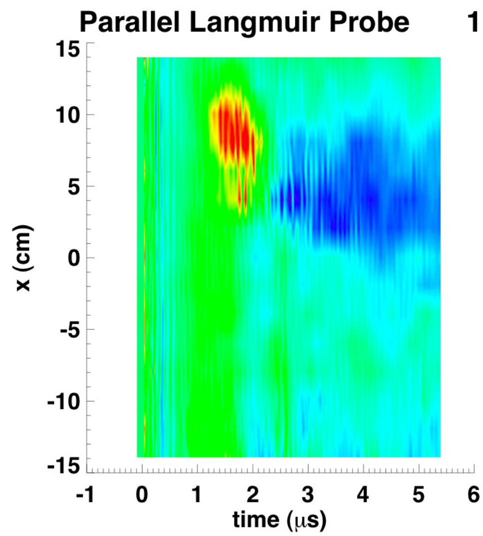


**FIGURE 11.** Parallel Mach probe, non-target face.

## CONCLUSIONS

We have designed and built Langmuir probes, Mach probes, and $\dot{B}$ probes. We present data and some preliminary analysis for data collected with these probes of laser driven waves in the LAPD. We observe the laser blowoff very close to the target with all types of probes, including inside the diamagnetic bubble formed. We also observe blowoff ions traveling down the length of the machine when the target is positioned at 45°. Data analysis is ongoing, and we expect to publish further results.


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