Properties of Laser Plasma Instabilities Relevant to Hypersonic Aircraft

Nathaniel McDonough

(September 30, 2014)

Abstract

A laser-produced plasma can be used to model the plasma created by hypersonic aircraft. The basic physics of such plasma is under intense investigation, so that the reentry communication blackout can be fully understood. Creation and analysis of one such laser plasma in a background magnetic field is presented here. Three prominent features are observed: 1) a diamagnetic bubble that expels the background magnetic field, 2) instabilities that form in response to the magnetic field pressure and 3) differences between individual charge state behaviors.

I. Introduction

Spacecraft or aircraft traveling at hypersonic speeds can create dense plasma sheaths due to shock heating\(^1\). This plasma is known to cause radio communication blackout, which occurs for up to ten minutes during spacecraft reentry. Many techniques have been proposed to solve the blackout problem, but all of them have proved to be ineffective or too expensive. In order to develop new practical solutions to the problem, further understanding of the basic physics involved is necessary. Since an in-depth study of the hypersonic plasma is unrealistic, imitation of this plasma with a similar laser produced plasma has been proposed. A detailed study of this laser plasma and its interaction with radio waves could provide new insight on the basic physics of the hypersonic plasma.

In addition to RF signal attenuation, the signal’s frequency modulation is likely distorted by plasma instabilities\(^2\). In past experiments\(^3,4\), laser plasmas have been observed to have Rayleigh-Taylor like instabilities and diamagnetic currents that expel magnetic field lines. This report describes a preliminary study of this plasma’s properties using magnetic flux probes and fast photography. The mechanism behind the instabilities is discussed, however further experimentation and analysis is necessary to decisively identify the instabilities.
II. Experimental Setup

In this experiment, a laser-plasma was created and studied using various diagnostics. A 1J 1064nm laser pulse was sent into a chamber (under vacuum) and focused on a polyethylene target, which ejected a carbon and hydrogen plasma. (The laser’s maximum power was about 1GW and the beam’s on-target intensity was on the order of $10^{11}$ W/cm$^2$.) Figure 1 shows a CAD render of the experiment (note chamber wall removed). The plasma was magnetized using a magnetic field (0-300G) created by the Helmholtz coil positioned above and below the chamber.

![Figure 1 - Render of experimental chamber used (with side wall removed). A laser pulse (red) ablates the vertical target, which energetically expands into a plasma (yellow). The chamber sits between a Helmholtz coil that creates a vertical static magnetic field.](image)

First, the probe was moved to the center of the chamber (where the plasma is created), and the magnetic field was measured as a function of the current through the coils. $B$ was found to be linear to $I$ with a proportionality constant of $=0.89$G/A (See Figure 2). The non-zero y-intercept is due to a systematic error caused by imperfect Gauss Meter calibration.

![Figure 2 - $B(I)$ (Magnetic field as a function of current) for Helmholtz coils used. Measurement was taken at the center of the chamber.](image)

A. Calibration of Helmholtz Magnetic Field

Helmholtz coils are used to create fairly uniform static magnetic fields. In this experiment, calibration of a Helmholtz coil was performed to find magnetic field dependence on current (through the coils), and to confirm ignorable spatial variance in the field. A “Pacific Scientific 5180 Gauss/Tesla Meter” was mounted on a 3-axis motor drive (allowing volumetric data to be taken) and used to measure the vertical component of the static magnetic field in the chamber ($B_{\text{coil}}$ points up).

Second, using a constant current, a horizontal plane of data was taken, (see Figure 3). This shows the horizontal variance of the field. As expected, this Helmholtz coil creates a very uniform field, varying by about 3% per 10cm (at the worst) and the field is strongest near the center of the chamber. In this experiment, magnetized plasmas usually did not exceed 8cm in size, thus for the purposes of this experiment, the static magnetic field was assumed to be spatially uniform.
B. B-dot Probe Diagnostic

B-dot probes (three-axis, high-frequency magnetic flux probes) are commonly used to measure magnetic fields in plasmas. (Figure 4 shows the tip of a B-dot probe next to a quarter.) They exploit Faraday’s Law (a change in magnetic flux produces an electromotive force) to measure change in magnetic field:

\[ V(t) = \frac{d\Phi_B}{dt} = aNg \frac{dB}{dt} \]

In this case, ten loops of wire \((N=10\) and area=\(a\)) detect a change in magnetic flux, \(\frac{d\Phi_B}{dt}\). The signal is amplified with a gain of \(g\), providing a measurable voltage as a function of time \(V(t)\). This signal is then sampled at 300MHz and integrated (using appropriate coefficients), giving the magnetic field as a function of time:

\[ B(t) = \frac{1}{aNg} \int_{0}^{t} V(t) \, dt + B_0. \]

In this experiment, a B-dot probe was mounted on the 3-axis probe drive previously mentioned (see Figure 5). As the plasma expanded out from the target, the probe would remain stationary at a designated 3-D coordinate, measuring the change in magnetic flux. (Since each plasma was slightly different, five data sets were collected for each coordinate and then averaged.) Both horizontal and vertical planes of data were taken, allowing a time-varying picture of the magnetic field to be created.
C. ICCD Camera

Intensified charge-coupled device (ICCD) cameras provide an effective way to photograph highly-energetic laser plasma. They allow shutter speeds less than 1 ns and can detect (on the order of) individual photons\(^6\).

The “PI-Max4: 1024i” was used in this experiment, allowing a 3 ns exposure time. It was mounted directly outside the experiment chamber, giving it a side view of the plasma. A three-mirror periscope was also constructed (inside the chamber) to allow bottom-view pictures to be taken. Though the PI-Max could not report color data, spectroscopic information was obtained by placing filters in front of the objective. This allowed specific carbon charge states to be identified in the plasma.

III. Diamagnetic “Bubble”

During the experiment, a diamagnetic cavity was detected inside the plasma. B-dot probe data confirmed that the cavity exists (see Figure 6), and images taken by the ICCD camera suggested the existence of diamagnetic currents (Figure 8). In general, when a plasma expands in size (and the magnetic flux through it increases), it reacts with a diamagnetic current that creates a magnetic field opposite the background field in accordance with Lenz’s Law. This effectively pushes most field lines outside the cavity. In an experiment performed by Collette et. al.\(^3\), currents parallel to the background field were detected (in addition to the diamagnetic current), implying the existence of complex helical current systems. More experimentation and analysis would be required to detect these current systems in this

![Figure 6 - Time-varying magnetic field calculated from B-dot probe signal 1.5 cm from target. Laser was fired at t=0ns. As the plasma entered the location where the probe was sitting, the magnetic field was eliminated (thanks to the diamagnetic current).]
experiment.

As shown in Ripin et. al., nearly all of a plasma’s initial kinetic energy is converted to magnetic field energy as the diamagnetic bubble forms. Energy in a uniform spherical magnetic field is:

\[ E_0 = \frac{B_0^2}{2\mu_0} \cdot \frac{4\pi R^3}{3} \]

where \( B_0 \) is the background magnetic field strength. If it is assumed that 1) the plasma is spherical and the magnetic field is completely excluded from the cavity, and 2) all the plasma’s energy is entirely converted to magnetic field energy, then the stopping radius of the plasma, \( R_b \), can be found:

\[ R_b = \sqrt[3]{\frac{3\mu_0 E_0}{2B_0^2\pi}} \]

where \( E_0 \) is the total plasma energy. Thus for a 1J laser pulse and a background field of 223G, the predicted stopping radius is \( \approx 0.1 \) m which is within the same order of magnitude as the data collected (see Figure 7).

**IV. Instabilities**

The classic Rayleigh-Taylor instability is a method by which a heavy fluid and a light fluid switch places to obtain a lower energy state. A similar effect has been observed with plasmas, where the plasma is the heavy fluid and the magnetic field is the light field. In this experiment, Rayleigh-Taylor instabilities were seen on the edge of the plasma when a background magnetic field of 150G or more is used. Figure 8 shows the time evolution of the plasma.

**Figure 7** – Time-evolution of vertical magnetic field. This is a side view of the plasma; the background magnetic field points up. The laser was fired at \( t=0 ns \).
Two possible explanations for the flute formation were proposed by Ripin et al.:

1) The MHD-Rayleigh-Taylor scheme depends on a slight perturbation in the plasma boundary, which causes ions and electrons to pile up on opposite side of the perturbation (due to opposite directions of gyration), which causes a localized electric field $\delta E$.

2) The LLR (large ion Larmor radius) scheme is caused by magnetized electrons staying in the plasma and unmagnetized ions streaming out of the plasma, which creates a strong inward electric field $E_0$. The electrons then drift along the plasma edge due to the $E_0 \times B$, build up on one side of a plasma-boundary perturbation, and thus create a localized electric field $\delta E$.

Regardless of how it forms, an electric field $\delta E$ is created in localized areas of the plasma-boundary, causing electrons and ions nearby to experience $\delta E \times B$ drift. These localized growths lead to flute-like structures, which project out from the plasma body and are aligned along the static magnetic field lines. More analysis (and further experimentation) is necessary to identify the exact scheme the flutes use in this specific experiment.

V. Charge-State Analysis

This experiment involved the ablation of a polyethylene target to create a carbon and hydrogen plasma. Based on known carbon charge-state spectroscopic profiling, narrow-band filters were used to remove unwanted wavelengths of light, allowing a single charge state to be observed. By using five specific filters, five carbon charge states were detected in the plasma (see Figure 9). Comparing CII and
CIII, the higher charge-state’s flutes curl more violently in response to the Lorentz force. This suggests that, although distinct flutes can be seen when looking at all charge states together, these are composed of smaller flutes specific to each charge-state.

It should be noted that the intensity of the wavelength used for each respective charge-state was not normalized with the others, thus comparing brightness of images could lead to erroneous conclusions. Normalizing this data would be a valuable topic of further study, since it could confirm relative number densities for each charge state.

VI. Conclusion

Further analysis could be performed using the data collected. The charge state images could be normalized so that number-densities of each charge state could be compared. To do this, the intensity of the wavelength used for each charge state would have to be properly scaled relative to the corresponding charge state number density so that equal number densities of each charge state would give equal light intensities.

More experimentation is needed to determine the exact mechanism that drives the instabilities. The next stage of this experiment is to perform a detailed study of how the laser plasma responds to RF waves.
Acknowledgements

The author would like to thank Dr. Christoph Niemann for all of his expertise and for inviting the author into the laser plasma lab at UCLA. The author would like to thank the rest of the research group, especially Mr. Derek Schaeffer and Dr. Carmen Constantin, for their assistance and approachability. This REU was only possible thanks to the funding of the National Science Foundation, so the author also extends thanks to them and to Dr. Françoise Quéval for coordinating the program.

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