Laboratory Simulations of Collisionless Shocks with a High Power Laser

Harrison Ruiz
UCLA Department of Physics and Astronomy

Dr. Christoph Niemann
UCLA Department of Physics and Astronomy

Abstract

Laboratory simulations of collisionless shocks between two plasmas in a vacuum chamber are planned for future experiments. A high power laser will be used to create a laser produced plasma, which is magnetized using a Helmholtz coil. A control box was built to remotely operate the capacitor bank, power supply, and trigger box that were used to create a current for the Helmholtz coil. This was done using a data acquisition device and a circuit board to condition signals between the data acquisition device and the power supply. The Helmholtz coil was calibrated using measurements taken from a one inch in diameter B-dot probe.

Introduction

Collisionless shocks are found in various astrophysical plasmas, such as supernova remnants, solar flares, and planetary bow shocks. One of the motivations for researching these shocks is that collisionless shocks in astrophysical plasmas are believed to be the source of very energetic cosmic rays. There are theories that these highly energetic particles could be accelerated in collisionless shocks that occur in very large plasmas.[1] By better understanding collisionless shocks we will better understand how they accelerate charged particles.

Collisionless shocks occur when the interaction between two plasmas is mediated by the electric and magnetic fields, and not through coulomb collisions between particles. The condition for this is for the mean free path of the individual particles of the plasmas to be very large in comparison to the size of the shock. When the mean free path is large enough the frequency of two body collisions is small enough that these collisions do not have any significant contribution to how the systems interact. [2]

Experimental Setup

In order to create shocks, an exploding plasma is created inside a chamber containing an ambient, magnetized plasma. This allows the two plasmas to interact and create shocks. To create the second plasma, a target, which is typically made of graphite, is placed inside the target chamber. A laser is directed onto the target and when fired will create a plasma. This plasma will then expand out and interact with the magnetized ambient plasma. This interaction is where collisionless shocks may be created. There are several ways that this experiment can be performed. One is to use the LAPD, the Large Plasma Device. This device uses an anode and cathode to create an ambient plasma, and has magnetic coils around the device to create a magnetic field throughout the chamber.

When a laser plasma expands in an external magnetic field, a diamagnetic cavity will be produced. As the plasma expands it expels the external magnetic field and creates a region called a diamagnetic cavity or bubble. This cavity can be monitored using measurements of the magnitude of the magnetic field at various regions of the chamber over time. Observing this cavity allows the amount of kinetic energy in the exploding plasma to be measured. Because of conservation of energy the energy change that occurs by pushing away the field must be equal to the amount of energy initially present in the motion of the plasma. This also allows for the coupling efficiency of the laser and the plasma to be measured.

A similar experiment can also be performed in a smaller target chamber in order to prepare the parameters of the experiments performed in the LAPD or other large target chambers. This is done because the LAPD is a user facility, and the time available with it is limited. Aside from being much smaller than the LAPD, the smaller target chamber also does not have a means of producing an ambient plasma or an external magnetic field. This requires additional equipment and devices to compensate for these missing functions. In order to generate an ambient plasma there must be two laser pulses. The first pulse is to create the ambient plasma, and the second pulse is to create the expanding plasma that will shock the first plasma.

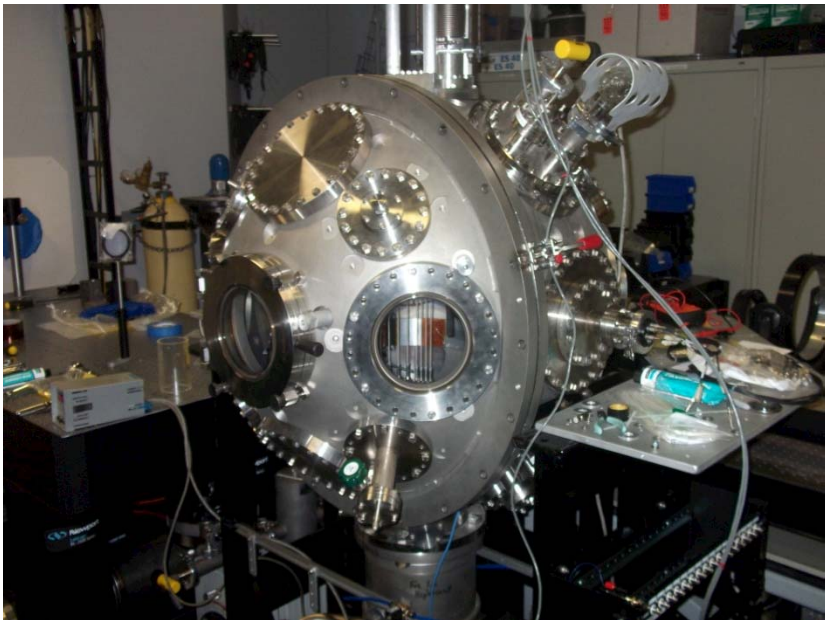

Figure 1. The target chamber used for laser plasma experiments.

In addition to needing two laser pulses, a magnetic field is also required for the experiment. This magnetic field is created using a Helmholtz coil. A Helmholtz coil consists of two identical coils separated by a distance equal to their radii. This creates a magnetic field at the center that is nearly uniform over a large space in the coil, about 20cm. The magnetic field at the center of the two coils is given by the following equation, where n is the number of turns per coil, R is the radii of the coils, and I is the current running through the coils:

$$B = (\frac{4}{5})^{\frac{3}{2}} \frac{\mu_0 n I}{R} \quad (1)$$

This magnetic field will magnetize the first plasma so that the second plasma is interacting with a magnetized plasma. The Helmholtz coil used has a radius of 28cm.

The Helmholtz coil is operated using a capacitor bank, a power supply, and a triggering circuit to supply the current that runs through the coil. This allows a capacitor bank to be charged for about one minute and then to discharge its stored energy into the coil over about half of a second. The capacitor bank used can store a maximum of 4.3kJ of energy and can be charged to a maximum potential of 900V, which is the voltage rating of the capacitor bank. This system prevents the need for a larger, more expensive power supply and the need for a cooling system. For safety reasons this coil and the equipment used to run current through it needed to be able to be operated remotely. In order to do this a control box needed to be built. This control box uses a data acquisition device to take measurements and send out signals. It also uses a circuit board to condition and isolate signals between the data acquisition device and other components.

This control box was built to be able to remotely control the power supply and the capacitor bank. It can control the potential that the power supply is brought up to when charging the capacitor bank. It also has two controls that are used to allow the capacitor bank to be charged and to dump the energy stored if necessary. Since many of the signals sent or received from the data acquisition device were not of the exact voltage or current required for the other components, a circuit board was needed to condition signals. This board uses relays, optocouplers, resistors, and operational amplifiers for this function.

The schematic of the circuit board can be seen in Figure 2. The board contains single pole single throw, normally open(SPST-NO) relays and a double pole double throw relay(DPDT). These relays are switches that are switched by running current through a coil. The coil creates a magnetic field that will flip the switch. Optocouplers were also used to keep the power supply and the data acquisition device electrically isolated. The optocouplers contain an LED that emits light when a certain voltage is present on the input side of the device. There is a receiver on the other end, that sends out a signal when light is present. This allows for a signal to be sent between two devices without them actually being physically connected. This protects the devices from damage that could be caused by voltage spikes or large currents. Two power drivers were used to amplify the signal from the DAQ to flip the relays.

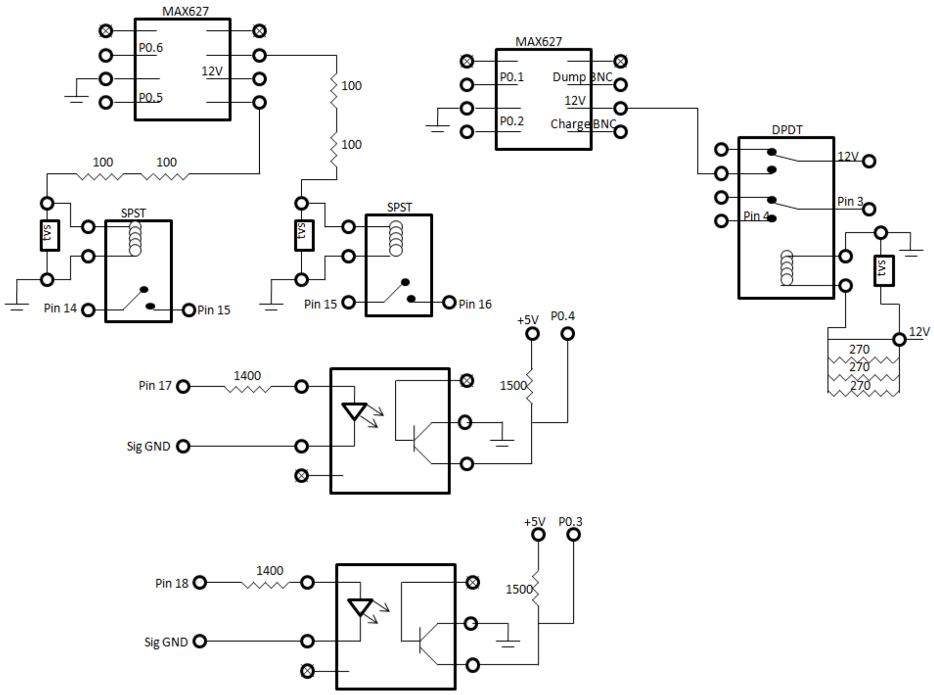

Figure 2. The schematic of the circuit board.

After the control box was built and setup, the coil was calibrated using the peak magnetic field. A linear fit was made so that the approximate potential required on the capacitor bank could be found for any magnetic field value. This could also be done theoretically by using equation 1 and finding the peak current for various voltages on the capacitor bank. The experimental values are useful to verify that the theoretical model matches this specific device.

Results

The testing and calibration of the coil were done using B-dot probes, which had previously been constructed using the method described in [3]. These probes consist of a 1 inch in diameter coil that when placed inside the chamber will react to a magnetic flux flowing through it. The change in flux will create a potential across the coil. This potential is measured and the raw data is viewed as a graph of potential versus time. Faraday's Law gives us the following relationship between potential difference across a coil and the rate of change of magnetic field, where a is the known area of the coil and n is the known number of turns in the coil:

$$V = -an\frac{dB}{dt} \quad (2)$$

From this we see that if we simply integrate the function describing potential over time we can get the magnetic field value as a function of time. Once the integration is performed and the magnetic field as a function of time is obtained, the peak magnetic field value is determined and used for the calibration. The raw data and the integrated data are shown in Figure 3.

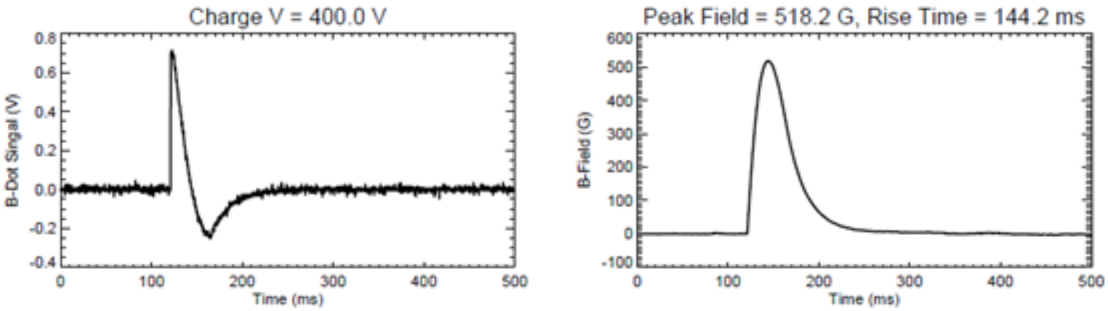

Figure 3. The raw data is shown in the graph on the left and the integrated data is shown on the graph on the right.

This process was performed for eight different potential differences on the capacitor bank and the results are shown as the calibration curve in figure 4.

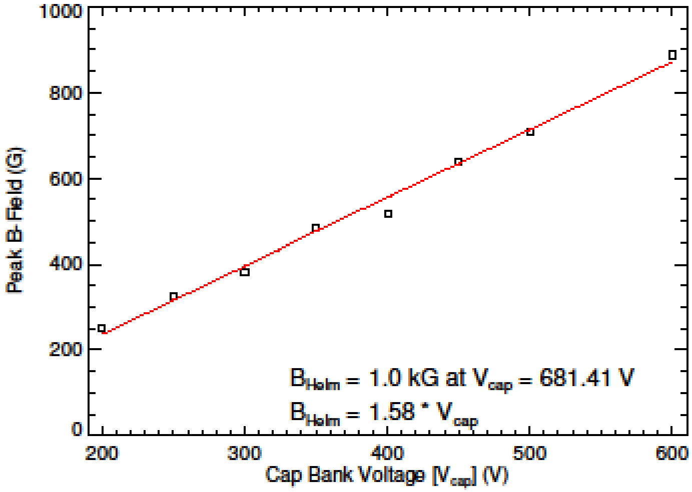

Figure 4. The calibration curve for the peak magnetic field at the center of the Helmholtz coil.

Conclusion

The magnetic field data from the Helmholtz coil came out to a very nearly linear fit. This allows for greater predictability in the peak magnetic field created for a particular potential on the capacitor bank. With the control box allowing the entire system to be operated remotely, the experimental setup is ready to be used for magnetized, laser produced plasma experiments. These experiments can then generate data on how a diamagnetic cavity forms inside the chamber. Knowledge of how this diamagnetic cavity will form will be helpful in later experiments at the LAPD or other plasma devices. These future experiments will have the possibility of producing collisionless shocks.

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