THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ENGINEERING SCIENCE AND MECHANICS

CHARACTERIZATION OF THE EFFECT OF A MAGNETIC FIELD ON A LASER-SUSTAINED PLASMA

SHENG WEI
SPRING 2013

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Engineering Science
with honors in Engineering Science

Reviewed and approved* by the following:

Judith A. Todd
Department Head and P. B. Breneman Chair
Professor of Engineering Science and Mechanics
Thesis Supervisor

Akhlesh Lakhtakia
Charles Godfrey Binder Professor in Engineering Science and Mechanics
Thesis Reviewer

Samia A. Suliman
Assistant Professor of Engineering Science and Mechanics
Academic Advisor

* Signatures are on file in the Schreyer Honors College and Engineering Science and Mechanics Office.
ABSTRACT

Laser-sustained plasmas have a variety of applications in laser welding, drilling, cutting, and material processing. The interaction between a magnetic field and a laser-sustained plasma was investigated in this study using a transverse magnetic field produced by two neodymium permanent magnets applied across a laser-sustained argon plasma. A CCD camera captured the shape of the plasma when the plasma was travelling through the magnetic field. The strength of the magnetic field was measured with a tesla meter with a range up to 2 T. A magnetic field with strength of approximately 0.2 T was clearly shown to have a confinement effect on the laser-sustained plasma. Further studies are required to determine and characterize the role of magnetic-field-affected laser-sustained plasma on material processing, to further investigate the use of an electromagnet to control the laser-sustained plasma, and to characterize the effect of a coaxial magnetic field on the laser-sustained plasma.
# TABLE OF CONTENTS

Abstract.................................................................................................................................................. i

List of Figures ......................................................................................................................................... iii

List of Tables .......................................................................................................................................... iv

List of Graphs .......................................................................................................................................... iv

Acknowledgements ............................................................................................................................... v

Chapter 1 Introduction .......................................................................................................................... 1

Chapter 2 Literature Review ................................................................................................................. 4

Chapter 3 Experimental Design ........................................................................................................... 11

Chapter 4 Results and Discussion: ...................................................................................................... 21

Chapter 5 Conclusion and Future Work .............................................................................................. 33

Appendix A Magnetic Field Calculator ............................................................................................... 34

References .............................................................................................................................................. 36
## LIST OF FIGURES

Figure 1-1. Schematic of a Tokamak ......................................................... 2

Figure 2-1. Experimental Setup of Harilal et al. ........................................... 8

Figure 2-2. Result of Harilal et al. ............................................................. 8

Figure 3-1. Front View of Electromagnet Core (Solidworks) ....................... 15

Figure 3-2. Side View of Electromagnet Core (Solidworks) ......................... 15

Figure 3-3. Top View of Experimental Setup and Procedure ....................... 18

Figure 3-4. Actual Setup ........................................................................... 19

Figure 4-1. Laser-Sustained Plasma without Magnetic Field ....................... 21

Figure 4-2. Laser-Sustained Plasma in 25.2-mm Gap .................................. 22

Figure 4-3. Laser-Sustained Plasma in 22.8-mm Gap ................................. 23

Figure 4-4. Laser-Sustained Plasma in 12.7-mm Gap ................................. 24

Figure 4-5. Illustration of Position x ......................................................... 32
LIST OF TABLES

Table 3-1. Magnetic Field Strengths with Different Wire Sizes.................................14
Table 4-1. Length of Plasma in Different Gap Width.................................................26
Table 4-2. Frame Number vs. Position x (mm).............................................................31

LIST OF GRAPHS

Graph 4-1. Length of Plasma vs. Frame Number for 25.21 mm Gap with B field........27
Graph 4-2. Length of Plasma vs. Frame Number for 22.7 mm Gap with B field........28
Graph 4-3. Length of Plasma vs. Frame Number for 12.7 mm Gap with B field........28
Graph 4-4. Length of Plasma vs. Frame Number for No Magnetic Field...............29
Graph 4-5. Length of Plasma vs. Frame Number (Combined) ..................................30
First, I thank Dr. Judith Todd for giving me the opportunity to work in the Center for Multi-Scale Wave-Materials Interactions at the Pennsylvania State University. In addition, Dr. Todd provided support for materials I needed for my research. Also, I thank Dr. Abdalla Nassar for guiding my research and giving me unselfish help while he was completing his doctoral thesis and then preparing to defend it. I thank Dr. Steven Copley for advice on my experiments and for providing me with helpful criticism. My gratitude is expressed to Mr. Scott Kralik for training me on the scanning electron microscope (SEM) and helping me fabricate my electromagnet and its copper cooling stage. I am grateful to Amber Black for giving me ideas and Amar Kamat for sparing time for me in the lab and making the lab time fun.
Chapter 1
Introduction

What is a plasma?

Three states of matter are commonly known to the public. Based on the total energy of a material in different states, scientists classify matter into solid, liquid, and gas. However, there is also a fourth state of matter that is less well known to the public. This state is the plasma state. Matter in a plasma state has much higher energy levels than that in the gaseous state. The energy levels may be so high that electrons are removed from electrically neutral species, which become ions. As whole systems, plasmas are electrically neutral. Electrons, ions, and neutral particles constantly interact with each other in the plasma. The Debye radius, beyond which the electrons will screen out the effect of an electric field from the ions, is an important parameter for describing a plasma. When the physical radius of a plasma sphere is larger than the Debye radius, the plasma is in a quasi-neutral state.

How is a plasma generated?

A plasma can be generated by many methods, including lightning, neon light, and using a high power laser. When a high-power laser beam interacts with a material, a plasma may form if the focal position of the beam is near the surface of the material. Once struck, a laser-sustained plasma (LSP) may be sustained indefinitely away from any surface.

For the experiments reported in this thesis, a 5 kW PRC Laser Corporation STS5000 CO₂ laser was used to generate an LSP. The power, the off-focal distance of the laser from the specimen surface, and the shielding gas flow rate were important parameters to be controlled. The plasma could be generated with argon gas, nitrogen gas, or a mixture of both.
First, the laser struck on a titanium plate at a certain off-focal distance to ionize titanium atoms. Freed electrons then absorbed the laser-beam energy via the inverse bremsstrahlung process [1]. These energetic free electrons collided with the shielding gas atoms, resulting in ionization of atoms and the generation of more free electrons. This process of excited electrons impacting atoms and freeing bound electrons is termed avalanche ionization. The avalanche ionization process continued until a self-sustained plasma was formed. The laser was then moved away from the titanium. The plasma was sustained indefinitely as long as the laser was turned on and the gas was flowing.

**What role does a magnetic field play in plasma physics?**

Interactions between a plasma and a magnetic field are of interest because of their importance in fusion reactors, laser-assisted processing of materials, and astrophysics. An innovative machine called Tokamak has been devised to confine and concentrate the plasma that is used for fusion.

![Figure 1-1. Schematic of a Tokamak](http://www.ipp.mpg.de/ippcms/eng/pr/fusion21/magnet/)
A diagram of the Tokamak is shown in figure 1-1. The plasma is confined within the magnetic field lines. Such confinement is important because a high collision rate is required in order for fusion to occur. The confinement concentrates the plasma and thus increases the collision rate.

According to research conducted at the Center for Multi-scale Wave-Materials Interactions at the Pennsylvania State University, an LSP can assist in material processing. Through the aid of inverse bremsstrahlung absorption, an LSP has been applied to nitride surfaces of metals such as titanium, zirconium, and hafnium [1]. Titanium nitride is a very hard material that is used to increase wear, erosion, and corrosion resistance. A plasma, acting like a reaction chamber, enhances the binding of nitrogen and titanium atoms [1].

How a magnetic field will affect this process of surface treatment is unclear. If a magnetic field can change the shape of the LSP, it may have a beneficial effect on surface treatment. An understanding of the mechanisms of magnetic field interaction with plasma is important in advancing plasma physics.

To date, the effect of a magnetic field on an LSP, generated with a high power continuous CO₂ laser, remains to be explored. The purpose of this thesis is to explore the effect of a transverse magnetic field on a laser-sustained argon plasma.
Chapter 2
Literature Review

Plasma-generation Mechanism

A laser-sustained plasma may be formed around the focal point of the laser. Three mechanisms contribute to generation of an LSP. The first mechanism is photoionization, whereby an atom absorbs photons that have higher energy than the ionization energy of the atoms in the material. The process can be expressed as [1]:

\[ A + h\nu \rightarrow A^+ + e^- , \]  \[ \text{Eq.1} \]

where \( A \) represents a neutral atom, \( h\nu \) is the photon energy, \( A^+ \) represents the ionized atom, and \( e^- \) represents an electron.

A material can also be excited by absorbing multiple photons, if the energy of a single photon is below the ionization energy. The multi-photon absorption process is described by [1]:

\[ A + n h\nu \rightarrow A^+ + e^- , \]  \[ \text{Eq.2} \]

where the integer \( n > 1 \) indicates that there are multiple photons involved per atom.

The third mechanism for ionization, the cascade breakdown, is the dominant ionization mechanism in an LSP. By analogy to a fusion reaction, in which neutrons collide with atoms, the cascade breakdown in the LSP involves electrons with high energy colliding with neutral atoms and thus inducing multiple ionization events, as described by [1]:

\[ A + e^- \rightarrow A^+ + 2e^- . \]  \[ \text{Eq.3} \]
Bremsstrahlung radiation and inverse bremsstrahlung absorption

Bremsstrahlung radiation

A plasma can radiate through bremsstrahlung radiation. Bremsstrahlung radiation includes cyclotron or synchrotron radiation [2]. The word bremsstrahlung is a German word, consisting of two parts. Bremsen means to brake and strahlung means radiation. Therefore, the word literally means braking (slowing down) radiation. During bremsstrahlung radiation, electrons in a plasma are decelerated due to interaction with ions. In other words, “Bremsstrahlung results from electrons undergoing transitions between two states of the continuum in the field of an ion” [2]. The kinetic energy lost by the electrons is converted into electromagnetic radiation (photons). According to Oppenheimer, the father of the atomic bomb, bremsstrahlung can be depicted as “shaking off of quanta from the field of an electron that suffers a sudden jerk”[2].

Bremsstrahlung radiation should be interpreted quantum mechanically. However, a semi-classical model can be used to treat most of the physics of bremsstrahlung radiation. Without solving Schrodinger’s equation, one can find the electromagnetic radiation through a calculation of the deceleration of electrons in a field of positive ions.

In order to merge classical and quantum-mechanical interpretations of bremsstrahlung radiation, the Gaunt factor is used [3,4]. In a simple case where an electron travels into the coulomb field of a single ion with charge Ze (Z is an integer and e = 1.6 x 10^{-19} C), and after assuming the spatial distribution of electrons around the ion to be uniform, the power $P$ of the bremsstrahlung radiation is found to be [2]

$$P = \frac{8\pi Z^2 e^6 n_e}{3(4\pi \varepsilon_0)^3 m c^3 \hbar} \left(\frac{k_B T_e}{m}\right)^{1/2}. \quad [Eq.4]$$
where \( n_e \) is the electron concentration of the plasma, \( \varepsilon_0 \) is the permittivity of free space, \( m \) is the mass of an electron, \( h = \frac{\hbar}{2\pi} \) is reduced Planck’s constant, \( k_B \) is Boltzmann constant and \( T_e \) is electron temperature.

**Inverse bremsstrahlung absorption**

Inverse bremsstrahlung absorption is the opposite process of bremsstrahlung radiation. Electrons in the plasma absorb photons from the environment and gain energy. This gain can be beneficial in material processing because the laser’s photonic energy can be absorbed by the plasma and then reradiated to the work piece uniformly [5-7]. According to Nassar [1], during nitriding of titanium, an LSP can provide uniform surface nitriding and may prevent oxidation.

**Magnetic field and laser-sustained plasma**

The application of a magnetic field to an LSP is of interest when magnetic fields are used to “control dynamic properties of these transient and energetic plasmas” [2]. The physics behind young stellar, solar-wind evolution, astrophysical jets, etc., depend largely on the interaction of a plasma with a magnetic field [8,9]. During the expansion of an LSP, magnetic fields can affect the plasma through various mechanisms that include: “conversion of the plasma thermal energy into kinetic energy; plume confinement; ion acceleration; and emission enhancement among others” [10]. The diameter of the plasma is proportional to \( B^{-2/3} \), where \( B \) is the strength of the magnetic field. A transverse magnetic field means that the direction of the field lines is perpendicular to the laser beam.

Mostovych et al. [11] studied the effect of a magnetic field on a laser-produced barium plasma with a transverse magnetic field of strength 0.5 to 1T, and observed that the shape of the
plasma deformed significantly. The diameter of the plasma became smaller as the plasma passed through the transverse magnetic field. A narrowing of the plasma was attributed to “the curvature of the magnet field” [10]. In addition, the plasma became a strip because of “hybrid velocity shear instabilities occurring in the boundary of the [gas] jet” [10].

Three important parameters are used in analyzing the deformation of the plasma. They are (i) the magnetic pressure \( P_B = \frac{B^2}{8\pi} \), where \( B \) is the magnetic field strength; (ii) the plasma ram pressure \( P_R = \frac{nmV^2}{2} \), where \( n \) is number of particles per unit volume, \( m \) is the mass of a single particle, and \( V \) is the speed of a moving particle; and (iii) the thermal pressure \( P_t = nkT \), where \( k \) is Boltzmann’s constant and \( T \) is the temperature.

As a result of Mostovych’s research, a confinement effect of a magnetic field on a laser-sustained argon plasma is expected in this thesis. The argon plasma will be sparked on a titanium plate and then sustained by flowing argon gas. The argon plasma will then be transported through a region in which a magnetic field generated by two permanent neodymium magnets exists. More details are provided in chapter 3.

Harilal et al. [10] used a Q-switched Nd:YAG pulsed laser of wavelength 1.06 \( \mu \text{m} \) to generate an aluminum plasma in a stainless-steel vacuum chamber. The experimental setup is shown in figure 2-1.
Figure 2-1. Experimental Setup of Harilal et al. [10]

Figure 2-1 shows that when the laser strikes a rotating aluminum plate, a laser-generated aluminum plasma is formed within the region in which the magnetic field exists. The maximum strength of the magnetic field created by the neodymium magnets was 1.3 T [10]. An intensified charged coupled device (ICCD) recorded the plasma expansion with and without the magnetic field. The following results were obtained:

Figure 2-2. Result of Harilal et al. [10]
(1) Without the neodymium magnet, the plasma expanded with no restriction in the vacuum chamber. Under the influence of a transverse magnetic field, the plume appeared to run into the side walls as the plasma expanded. Figure 2-2 illustrates this effects by comparing the plasma expansion, with and without a magnetic field, at instants of time in the range 50 to 200 ns. In the presence of the magnetic field, the plasma front experienced obvious deformation. The plasma was generated at the bottom of the picture in figure 2-2 and expanded upwards;

(2) The lifetime of the plume increased when the magnetic field was present;

(3) Emission of photons from Al+ and neutral Al species decreased considerably with distance from the surface of the aluminum plate. No emission was found beyond 8-10 mm from the surface, indicating that magnetic field has a confinement effect on the laser-generated plasma.

(4) The temperature of the plume was found to be much higher in the presence of a magnetic field [10].

**Effect of a magnetic field on laser welding with plasma**

Peng et al. [12] have shown that a magnetic field can affect laser welding. Depending on the penetration depth and energy-transfer mode, laser welding can be classified into two types [12]. The first type is heat-conduction welding, in which a metal absorbs and transforms photonic energy into heat. Excess thermal energy will melt the metal to achieve melting and/or welding. The focal position of the laser beam may be at or above the metal surface for heat-conduction welding. The second type is keyhole welding. The focal position of the beam is usually within the metal, below the surface. In keyhole welding, the laser beam vaporizes and ionizes the vaporized metal to form a plasma which improves the absorption rate [13]. However,
the plasma can affect welding negatively in high-power applications if the energy is lost by defocusing [14,15], absorption, and/or scattering. The efficiency may be improved if a side jet is used to blow away the plasma.

Peng et al. [12] studied the control of plasma in high-power laser welding when electric and/or magnetic fields were simultaneous present. Their studies showed that the presence of a magnetic field improves the efficiency of high-power laser welding. They suggested that a magnetic field could be a possible substitute for expensive inert gases, resulting in more environmentally benign welding environment as well as savings by industry.
Chapter 3
Experimental Design

Principles of building an electromagnet

Types of electromagnets based on purpose

Based on function, electromagnets can be classified into three main types: attractive electromagnets, portative electromagnets, and field electromagnets. An attractive electromagnet is designed to attract paramagnetic materials, which, in the presence of a magnetic field, will become magnetic. A portative electromagnet is used for temporary adhesion or for providing lifting power. A field electromagnet produces a magnetic field in an air gap. For this research, an argon plasma has to be ignited and sustained at atmospheric pressure in order to study the effects of a magnetic field on the plasma. Thus, a field electromagnet was chosen.

Types of electromagnet based on shape

Electromagnets can also be classified into different categories based on their shape and include bar, horse-shoe, iron-clad, and coil and plunger electromagnets. A horse-shoe electromagnet was chosen for this research, since it can be designed and manufactured easily and provides an air gap in which to locate the laser beam and the LSP.

Magnetic circuit

A magnetomotive force in a magnetic circuit plays an analogous role to an electromotive force in an electric circuit. In a magnetic circuit, division of the magnetomotive force by the length of the magnetic circuit gives the magnetic force per unit length, known as the magnetizing force and symbolized by $H$. During the manufacture of an electromagnet, a major issue that needs to be considered is the reduction of magnetic leakage. The more uniformly the magnetic
wire is distributed over the magnetic circuit, the lesser is the leakage. Roundness and evenness of the magnetic circuit, avoidance of sharp corners and abrupt turns, all tend to reduce magnetic leakage.

**Manufacturing the electromagnet**

In order to manufacture an electromagnet, several factors must be considered. These include choosing the proper wire gauge, choosing the core materials, designing the shape of the electromagnet, and designing the cooling stage. In the following sections, each step of the design process is elaborated. A Matlab program to calculate the magnetic field and to determine the wire gauge is provided in Appendix A.

**Choosing the appropriate magnet wire**

When choosing the magnet wire, the first thing to be considered was the power source used to provide current to the magnet wire. The power source available for the experiments was rated at a maximum voltage of 30 V and a maximum current of 5 A. To achieve the largest current in a wire with the most turns, the resistance of the wire should be 6 Ω (=30V/5A). Also, a maximum possible magnetic-field strength was desired. Based on these constraining factors, a 23 gauge magnet wire was chosen using the program provided in Appendix A. As the power source provided 30V and 5A to the wire, heating was expected to be a significant problem. A magnet wire with high temperature tolerance was chosen so that the insulating material on the wire would not melt and short out the wire.
Choosing the core material

An important factor in choosing the core of the electromagnet is its magnetic permeability. As becomes evident from the calculation of the magnetic field, permeability alters the strength of the magnetic field. Iron is commonly used as the core material of an electromagnet due to its low permeability. Different types of iron and steel have different permeability depending on the percentage of carbon present. Steel with more than 0.8 weight percent of carbon is generally considered to have low permeability, while steel with less than 0.3 weight percent of carbon is considered to have high permeability. Thus, low-carbon steel is preferred.

Other alloying elements may be present along with iron. Manganese is beneficial for surface quality, strength and roundness. Phosphorus increases the strength and hardness but decreases ductility and notch impact toughness. Sulfur decreases ductility and notch impact toughness especially in the transverse direction; weldability decreases with increasing sulfur content, and machinability increases with increasing sulfur content.

After considering different steels, steel 12L14 was chosen. The alloying content of 12L14 steel is: 0.15% carbon, 0.85-1.15% manganese, no silicon, 0.04-0.09% phosphorous, 0.26-0.35% sulfur, and 0.15-0.35% lead. Steel 12L14 has high permeability because of its low carbon content and has good machinability due to its high sulfur content.

Magnetic-field strength

The magnetic-field strength is calculated using Ampere’s law. The magnetic field strength for the electromagnet configuration shown in figure 3-1 is:

\[
B = \frac{NI}{\mu_s + \frac{d}{\mu_0}},
\]

[Eq.5]
where \( N \) is the number of wire turns, \( I \) is the current, \( l \) is the length of the core, \( d \) is the air gap, \( \mu_{st} \) is the permeability of the 12L14 steel, and \( \mu_0 \) is the permeability of free space. The integer \( N \) is determined by winding the magnet wire into the trench in a layer-by-layer manner. The wire gauge was determined by the maximum number of windings that would fit into the trench when the voltage was 30 V and current was 5 A.

The Matlab code in reference A could be used to calculate the electromagnet parameters for different magnet wire gauges and to determine whether the diameters for magnet wire were feasible. Table 3-1 shows that an electromagnet with 23-gauge wire should produce a magnetic field of 939 mT.

<table>
<thead>
<tr>
<th>Gauge(AWG)</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter(in.)</td>
<td>0.0403</td>
<td>0.0359</td>
<td>0.032</td>
<td>0.0285</td>
<td>0.0253</td>
<td>0.0226</td>
<td>0.0201</td>
<td>0.0179</td>
<td>0.0159</td>
</tr>
<tr>
<td>Turns</td>
<td>3413</td>
<td>3185</td>
<td>2901</td>
<td>2604</td>
<td>2291</td>
<td>1967</td>
<td>1661</td>
<td>1377</td>
<td>1127</td>
</tr>
<tr>
<td>B field(T)</td>
<td>1.63</td>
<td>1.52</td>
<td>1.38</td>
<td>1.24</td>
<td>1.093</td>
<td>0.939</td>
<td>0.7929</td>
<td>0.6573</td>
<td>0.538</td>
</tr>
<tr>
<td>Feasibility</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Very Close</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Resitivity(ohm/kft)</td>
<td>6.385</td>
<td>8.051</td>
<td>10.15</td>
<td>12.8</td>
<td>16.14</td>
<td>20.36</td>
<td>25.67</td>
<td>32.37</td>
<td>40.81</td>
</tr>
</tbody>
</table>

Table 3-1. Magnetic Field Strengths with Different Wire Sizes
A Solidworks model for the electromagnet was devised. The front and side views of the electromagnet core are shown in figures 3-1 and 3-2, respectively.

Figure 3-1. Front View of Electromagnet Core (Solidworks)

Figure 3-2. Side View of Electromagnet Core (Solidworks)
Design of cooling stage

When the electromagnet was operating at its maximum power, the heat dissipated by the magnet wires was quite significant. Therefore, copper plates and tubes with high thermal conductivity were used to fabricate a cooling stage. To provide good contact and diminish air gaps between the cooling stage and the electromagnet, silicone gel was also used. Copper tubes were wound around a copper plate which was cut by a CO$_2$ laser. A layer of graphite was sprayed on the copper plate to increase absorption of laser energy during cutting, since copper is highly reflective to infrared radiation. The copper tubes were soldered to the cooling system. Tests on the cooling stage showed that there was no noticeable heating of the magnet wire.

Testing of Electromagnet

In order to ascertain the magnetic-field strength of the electromagnet, a tesla meter (Hangzhou Best Magnet co. Ltd) that could measure up to 2 T was purchased. When the current was 5 A through the magnet wire, the measured field strength within a 0.5-in. gap ranged from 90 mT to 100 mT. This field strength was only 1/9 of that calculated by the program.

A possible explanation for such a small field strength may be that the core comprised three sections connected with screws, as shown in figures 3-1 and 3-2. Defects in the core structure, and gaps at the connections and sharp corners and edges would contribute to the leakage of the magnetic field lines. Probing the field connections with the gauss meter revealed that the magnetic-field strengths at the peripheries of the connections were significant rather than close to zero. Further investigation is needed to discover the overall cause of the leakage. An improved design was needed to produce a strong magnetic field.
Experimental setup

Since the electromagnet did not produce a sufficiently strong magnetic field, two neodymium permanent magnets were used instead. The magnets were separated by two titanium plates. The laser power was maintained at approximately 1.9 kW and the coaxial argon gas flow rate was 23.4 l/min. Figure 3-3 shows a top view of the experimental setup for all the experiments conducted.

A CCD camera with filters installed was used to record images of the laser beam and the LSP. A 710-nm filter was used to filter out argon-plasma emissions from those of other species in the atmosphere. A 0.6 neutral density filter was used to decrease the intensity of light incident on the camera for better image quality. In figure 3-3, the direction of propagation of the laser beam is into the page.

The laser power at 1.9 kW was the lowest power that could sustain an argon plasma [1]. The laser first struck a titanium plate, with a 4-6 mm off-focal distance, to generate a titanium plasma. Electrons from the titanium plasma interacted with the argon shielding gas. Through the avalanche breakdown process, argon atoms were ionized and a sustained plasma was formed. The argon plasma was sustained indefinitely through inverse bremsstrahlung absorption of the laser energy. The laser with the argon plasma was moved into the region in which the magnetic field generated by the neodymium magnets existed. The laser stopped before hitting a ceramic block that was positioned at the end of the path to prevent damage of the support rod.
Figure 3-3. Top View of Experimental Setup and Procedure
Figure 3-4 shows the actual setup. The neodymium magnets were placed on the external surfaces of the titanium side plates to create the magnetic field in the air gap. The titanium side plates prevented contamination from other species. The laser beam traveled along the air gap and stopped before the ceramic block. The gap width was varied by placing titanium fillers in the gap, thereby varying the magnetic field strength.

A matrix of experiments to characterize the interaction of the magnetic field and the LSP was developed as follows.

1. The effect of gap width on the CCD images of the LSP as the laser beam traversed the gap length along the centerline was investigated.

2. Gap widths of 25.21 mm, 22.7 mm, and 12.7 mm were investigated.
3. The magnetic-field strength was measured for each transverse arrangement of the gap width.

4. A controlled flow rate of 23.5 l/min was used for argon and the laser power was maintained at 1.9 kW.

5. The CCD images of the LSP were analyzed for the plasma dimensions as a function of position in the gap and gap width for each of the three values of the gap width. All the videos lasted 25 seconds and had 5000 frames. The LSP lasted for around 4.3 s with 860 frames for each experiment. The motion stage on which the setup was installed travelled at a speed of 90 mm/s.
Chapter 4
Results and Discussion

Analyses of the images captured by the CCD camera, under one atmosphere pressure, showed that a magnetic field has a significant effect on the shape and position of the laser-sustained plasma. Selected frame captures demonstrate these effects in figures 4-1 to 4-4.

Figure 4-1. Laser-Sustained Plasma without Magnetic Field

Figure 4-1 shows the LSP in the absence of a magnetic field. In order to measure the length on the picture, a 10 mm scale bar, taken separately with the CCD camera, was placed in the figure. The length of the LSP was ~14.34 mm. In order to measure the length on the picture,
a 10 mm scale bar, taken separately with the CCD camera, was placed in the figure. The focal position of the laser beam was 6.56 mm below the top frame of the image. The width of the laser beam at the focal position was around ~1.1 mm.

Figure 4-2. Laser-Sustained Plasma in 25.21-mm Gap

Figure 4-2 shows the profile of the LSP when placed within a gap of 25.21 mm. The magnetic-field strength was measured as 173 mT in the middle of the air gap and 300 mT at the surface of the titanium plates. From figure 4-2, it is clear that the length of the plasma decreased to 12.87 mm and the width of the plasma at the beam focus decreased to 0.75 mm.
Figure 4-3 shows the profile of the LSP when placed within a gap of 22.8 mm. When the gap width decreased from 25.21 mm to 22.8 mm, the field strength increased to 210 mT at the center of the air gap and 310 mT at the surface of the titanium plates. The shrinkage of the length of the plasma was very obvious, the plasma length for 22.8 mm air gap being 12.54 mm. The lateral shrinkage of plasma at the focal point was not as large as that for the 25.21-mm gap. Hence, the increased strength of the transverse magnetic field did not affect the lateral shrinkage at the beam focus significantly. The focal diameter for the 22.8 mm gap was 0.95 mm compared
to 0.75 mm for the 25.21 gap. The lateral shrinkage at the focal position was still more obvious than lateral shrinkage at other positions of the same beam. Thus, in a uniform magnetic field, higher power density in the laser beam seems to relate to greater shrinkage of the plasma.

Figure 4-4. Laser-Sustained Plasma in 12.7-mm Gap

Figure 4-2 shows the profile of the LSP when placed within a gap of 12.7 mm. As the gap width was further decreased, vertical shrinkage was much more obvious, reducing the plasma length to 11.7 mm. The width at the beam focus was essentially unchanged at 0.93 mm.
Table 4-1 shows the length of the plasma as the plasma travelled across various gaps with or without magnetic field. The video started when the laser struck the titanium plate and ended when the laser was turned off.
<table>
<thead>
<tr>
<th>Frame No.</th>
<th>Plasma Length Without Magnetic Field (mm)</th>
<th>Plasma Length with 25.21 mm Gap (mm)</th>
<th>Plasma Length with 22.7 mm Gap (mm)</th>
<th>Plasma Length with 12.7 mm (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.48</td>
<td>13.73</td>
<td>14.05</td>
<td>14.05</td>
</tr>
<tr>
<td>40</td>
<td>13.48</td>
<td>13.73</td>
<td>14.05</td>
<td>14.05</td>
</tr>
<tr>
<td>80</td>
<td>13.46</td>
<td>13.73</td>
<td>13.91</td>
<td>14.05</td>
</tr>
<tr>
<td>120</td>
<td>13.46</td>
<td>13.73</td>
<td>13.84</td>
<td>14.05</td>
</tr>
<tr>
<td>160</td>
<td>13.48</td>
<td>13.73</td>
<td>13.84</td>
<td>14.05</td>
</tr>
<tr>
<td>200</td>
<td>13.48</td>
<td>13.73</td>
<td>13.84</td>
<td>14.05</td>
</tr>
<tr>
<td>240</td>
<td>13.48</td>
<td>13.73</td>
<td>13.84</td>
<td>13.73</td>
</tr>
<tr>
<td>280</td>
<td>13.26</td>
<td>13.23</td>
<td>14.01</td>
<td>13.73</td>
</tr>
<tr>
<td>320</td>
<td>13.36</td>
<td>14.05</td>
<td>14.01</td>
<td>13.73</td>
</tr>
<tr>
<td>360</td>
<td>13.46</td>
<td>13.73</td>
<td>13.33</td>
<td>13.73</td>
</tr>
<tr>
<td>400</td>
<td>13.26</td>
<td>13.7</td>
<td>13.66</td>
<td>13.75</td>
</tr>
<tr>
<td>440</td>
<td>13.48</td>
<td>13.73</td>
<td>13.66</td>
<td>14</td>
</tr>
<tr>
<td>480</td>
<td>13.49</td>
<td>13.92</td>
<td>13.66</td>
<td>12.83</td>
</tr>
<tr>
<td>520</td>
<td>13.48</td>
<td>13.72</td>
<td>13.7</td>
<td>13.73</td>
</tr>
<tr>
<td>560</td>
<td>13.48</td>
<td>13.8</td>
<td>12.01</td>
<td>11.36</td>
</tr>
<tr>
<td>600</td>
<td>13.48</td>
<td>11.94</td>
<td>13.15</td>
<td>13.73</td>
</tr>
<tr>
<td>640</td>
<td>13.48</td>
<td>13.92</td>
<td>14.05</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 4-1. Length of Plasma in Different Gap Width
Graphs 4-1, 4-2, and 4-3 show the length of plasma as a function of frame number when the plasma was in the 25.21-mm, 22.7-mm, and 12.7-mm gaps respectively. Graph 4-4 shows the length of plasma without a magnetic field. Graph 4-5 combines all the graphs into one graph for comparison.

Graph 4-1. Length of Plasma vs. Frame Number for 25.21 mm Gap with B field
Graph 4-2. Length of Plasma vs. Frame Number for 22.7 mm Gap with B field

Graph 4-3. Length of Plasma vs. Frame Number for 12.7 mm Gap with B field
Graph 4-4. Length of Plasma vs. Frame Number for No Magnetic Field
Graph 4-5. Length of Plasma vs. Frame Number (Combined)
In the graph for the plasma length without magnetic field, minimal shrinkage was observed, although small fluctuations in the plasma length occurred. These fluctuations could be contributed by instability of the gas flow, instability of the laser power, or confinement by the titanium side plates. However, as shown in graph 4-5, these effects were negligible compared to the effect of the magnetic field on the LSP. The transverse magnetic field thus clearly had significant effects on the laser sustained plasma. When the LSP was in the center of the magnetic field (frames 560 to 600), the shrinkage effect was most obvious, as shown in graphs 4-1, 4-2, and 4-3. Before the plasma reached its maximum shrinkage, the length of plasma fluctuated due to the peripheral magnetic field’s influence.

The relationship between the frame number and position within the gap is as shown in table 4-2.

<table>
<thead>
<tr>
<th>Frame Number</th>
<th>Position x (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>520</td>
<td>9</td>
</tr>
<tr>
<td>560</td>
<td>27</td>
</tr>
<tr>
<td>600</td>
<td>45</td>
</tr>
<tr>
<td>640</td>
<td>63</td>
</tr>
</tbody>
</table>

Table 4-2. Frame Number vs. Position x (mm)

Position x is illustrated in figure 4-5.
Position x indicates location of the plasma within the region in which magnetic field exists.

When the plasma was located in the middle position of the neodymium magnets, the effect of magnetic field on the LSP was the strongest.
Chapter 5
Conclusions and Future Works

Through these experiments, a magnetic field was shown to have a deforming effect on a laser-sustained argon plasma. The magnetic field shrunk the plasma vertically and laterally. As the gap size between two neodymium magnets decreased, the magnetic-field strength within the air gap increased. The stronger magnetic field caused more obvious vertical shrinkage of the plasma. The lateral shrinkage was not as pronounced as the vertical shrinkage. Preliminary experiments indicated that lateral shrinkage did not appear to be directly proportional to the strength of the transverse magnetic field. The plasma shrunk more laterally where the power density of the laser beam was high. The lateral shrinkage was most clearly observed at the focal position. Since the plasma shrinks both laterally and vertically, the volume of the plasma should decrease. Thus, bremsstrahlung radiation and inverse bremsstrahlung absorption should increase due to the decreased volume.

Future studies should investigate the role of a magnetic field on material processing with laser-sustained plasma. An improved electromagnet design will have to be designed and be fabricated. The magnetic field could be controlled by varying the input current to the electromagnet to see if the LSP can be controlled by varying the magnetic field. The effect of a coaxial magnetic field on LSP should also be explored.

The results of this research may improve processing of materials by the application of a plasma in a more controlled manner. The plasma, which may be undesirable in many laser-assisted processing applications, could become a useful tool if its properties were controlled by applying a magnetic field. The results of this research may also help physicists better understand the influence of magnetic field on a laser-sustained plasma.
function [ N,n1,t,B] = turnsCalc( d,l,rho,v,i,a,b,dt,gw)
% For the input arguments, d is the diameter of wire for a certain gauge; l
% is the length of the trench; rho is the resitivity in unit of ohm per ft.
% v is the maximum voltage and i is the maximum current; dt is the depth of
% trench; gw is the width of the air gap.

% For the output arguments, N is the number of cycles; n1 is the number of
% layers; t is the thickness of all the layers.

% Calculate the amount of wire needed to produce maximum current

ohm = v/i;
w1 = ohm/rho*1000;

% Convert from feet to inch
w1 = w1*12;
sl = w1;

% lay down the wire in two loops
n1 = 0; %initialize the number of turns
N=0; % initialize the number of cycles

while w1>0
    tl = l; %tl - trench length

        while tl>0 && w1>0
            w1 = w1-2*(a+n1*d)+(b+n1*d));
            tl = tl-d;
            N = N+1;
        end;

    n1 = n1+1;
end;

% Calculation of the B field produced
B = N*i/(18.196/39.37/(1000*4*pi*10^-7)+gw/39.37/(4*pi*10^-7));
% Determine if the thickness is greater than the trench width

t = nl*d/1.155;

fprintf('The number of turns is %d.
', N);
fprintf('The number of layers is %d.
', nl);
fprintf('The thickness of the layers is %d in.
', t);
fprintf('The magnet field produced is %dT.
', B);
fprintf('The length of the wire is %dft.
', s1/12);

if t > dt
    fprintf('This wire size is not feasible.
');
else
    fprintf('This wire size is feasible.
');
end;

end
REFERENCES


Objective: To obtain an engineering internship/co-op position

Education:
The Pennsylvania State University, University Park, PA
Schreyer Honors College
Bachelor of Science, Engineering Science (Honors Curriculum in College of Engineering) with minor in Nanotechnology
May 2013
Master of Science, Engineering Science and Mechanics
May 2014
GPA: 3.96/ 4.00
Dean’s List Every Semester
Thesis Title: Characterization of the Effect of Magnetic Fields on Laser-Sustained Plasmas

Publication:
Undergraduate Publication in International Journal of Mathematical Education in Science and Technology
May 2011
Title: “Finding Sums for an Infinite Class of Alternating Series”

Working Experience:
Undergraduate Researcher at the Center for Multi-wave Material Interaction, May 2012 – Present
Penn State, University Park
• Study the effect of magnetic fields on laser-sustained plasmas
• Results can possibly save money spent on expensive gases for industries

IT service desk consultant at Knowledge Commons in Pattee Library, July 2012 – Present
Penn State, University Park
• Solve computer issues for students and staff at the University

Teaching Assistant for Engineering Science and Mechanics Department January 2013 – Present
Penn State, University Park
• Hold office hours to answer students’ questions and proctor exams

Leadership:
Translator and peer mentor in a study abroad program to China January 2011 – June 2011
• Taught Mandarin to nine fellow students
• Served as the translator and peer mentor
• Organized daily activities during the trip

Activities:
Member of Tau Beta Pi Engineering Honors Society September 2011 – Present
Member of Penn State Formula SAE September 2012 - Present
Thon Chair at PSU Society of Engineering Science September 2011 – May 2012
Volunteer in Navajo Nation, Arizona during Spring Break 2012 March 2012

Honors:
Ambassador Travel Grants, Schreyer Honors College May 2011
Summer Discovery Grant for Undergraduate Research May 2012
Richard P. McNitt Scholarship in Engineering Science and Mechanics Department July 2012

Skills:
Computer: SOLIDWORKS, Microsoft Office, C++, Java, MATLAB
Language: Fluent in English, Mandarin, and Cantonese
Personal: Strong Communication Skills, Good Team Leader and Player, Responsible