Magnetically Guided Laser Ablation for High Specific Impulse Thrusters

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Abstract: The work presented in this paper explores the possibilities of increasing specific impulse of ALP by generating the ablative plasma in a strong magnetic field. A magnetic field of 4.5 Tesla was used to direct a laser (1064 nm YAG, 200-450 mJ/pulse) generated plasma in order to create a virtual nozzle and increase specific impulse. The work demonstrated that the magnetic field normal to the target surface serves to contain high pressure, high temperature plasma plume ejected from the surface. A pendulum was used to measure the thrust with and without magnetic field. It has been shown that for the conditions used in this experiment, magnetic field increased the thrust by a factor of 2.

I. Introduction - Ablative Laser Propulsion (ALP)

The laser ablation process has gained attention due to its wide range of industrial applications[1-5]. One critical problem in early studies of laser ablation was that the plasma, once formed over the solid surface, obstructed the laser beam reducing the absorbed power in the material. The availability of the short pico and femtosecond pulsed lasers made it possible to have laser ablation before the development of plasma and this to avoid significant absorption in the plasma. This led to the concept of ablative laser propulsion (ALP). In ALP process, laser pulse energy is absorbed in the material, followed by a supersonic ejection of highly ionized matter from the target surface. Ablation imparts an impulse to the target in the direction opposite to the jet and the target is propelled in the direction of the propagating laser beam. Based on ALP process, principal areas of research are currently underway. The first area is the development of laser ablation microthrusters [LAμT] which require micronewton level thrust[6,7].

The second area of research in ALP applications to thrusters is that of the development of ultra high specific thrust devices which are capable of providing high density atomic or molecular beams with velocities on the order of 10^6 meters per second. An important feature of ALP is that as the short pulsed laser is focused onto a solid surface, the ejection of matter from the surface is a directional process. In the absence of magnetic field the energy E of the ejected atoms varies with the angle and may be described by a simple cosine function[8] i.e. $E(\theta)=E_0\cos^n(\theta)$ where θ is the angle of ejection with respect to the surface normal, E is the energy of the ejected atoms and n varies with ablation conditions (~1.0-8.0)[9].

In the current work, research efforts are directed to explore the possibilities of increasing specific impulse of ALP by generating the ablative plasma in a strong magnetic field. A strong magnetic field (up to 4.5 Tesla) is applied such that magnetic field lines are normal to the surface in order to suppress the lateral expansion of the plasma and thus creating a virtual nozzle and increasing the specific impulse which was experimentally measured. The experimental setup and results are described in the following sections.

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II. Experimental Hardware

An Oxford Instruments liquid helium cooled, superconducting magnet was used in this study. The magnet is designed to provide a uniform field throughout a three inch cube within which experiments were conducted. In order to conduct the ablation work in a vacuum, three bores in the magnet were sealed using aluminum flanges fitted with glass windows. A vacuum pump was used to maintain the desired lower pressure in the working space within the magnet. A Spectra Physics Q switched ND:YAG laser was employed to direct energy onto the target surface. The laser was capable of producing 10 nanosecond wide laser pulses at 1064.0 nm. The energy was varied from 200 to 450 mJ/pulse. Pulse to pulse variation in laser energy was monitored using a photodiode and was observed to be less than 3%. A simple planoconvex lens was used to focus the beam onto the target material. A Stanford Research Systems digital delay timing box was used to trigger the camera and the laser Q switch to capture the plasma images with the required delays ranging from few nanoseconds to hundreds of microseconds.

A Princeton Instruments PI-MAX Intensified CCD camera was used to capture the plasma created by the laser interaction with the solid target inside the magnet. The camera is equipped with 512×512 CCD arrays and the exposure time can be varied from the nanosecond range to the hundreds of milliseconds. The camera is capable of capturing multiple frames, but the time between the two frames is limited by the readout time which, depending on the pixels being selected for capturing the image, may reach up to hundreds of milliseconds. The camera can be triggered externally and, for that purpose, a Stanford Research Systems digital delay timing box controlling the Q switch of the laser was used to trigger the camera to obtain the plasma images with and without the magnetic field, as will be seen in the following section.

III. Experimental Results and Discussions

A. Ablation under a strong magnetic field

Initial experiments were performed to identify the impact of high magnetic field on the plasma plume ejected out of the metal when an intense laser beam was focused onto its surface. Aluminum was used as the target material in these experiments. A 20.0 cm focal length lens was used to focus the beam onto the target surface. The pressure in the vacuum chamber was maintained at 10^{-5} Torr throughout this work. Plasma images without the magnetic field are shown in Fig. 1. In Fig. 1 the plasma plume is seen to evolve from the point of impact of the incident laser beam. The plasma plume expands in the forward direction and becomes diffuse after 600 ns. Figure 2 shows the results when the laser ablation takes place in a 4.5 Tesla magnetic field. The magnetic field was applied normal to the surface.

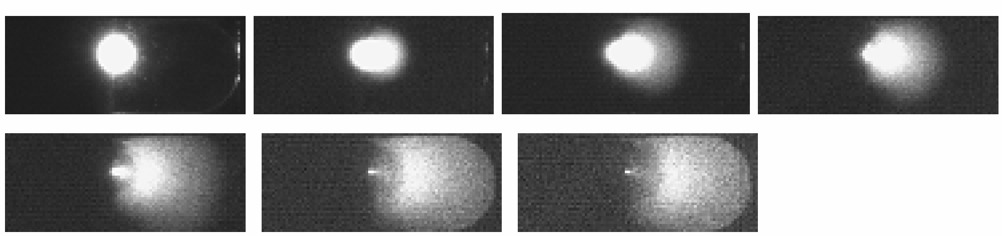

Figure 1. Plasma without magnetic field (at 10^{-5} Torr cell pressure, YAG 200 mJ/pulse @1064 nm). Frames with time delay (with respect to the laser pulse) ranging from 50 to 750 ns.

A comparison of plasma plumes in Fig. 1 and Fig. 2 clearly demonstrates the impact of the applied magnetic field on the plasma plume expansion. With the magnetic field the radial plasma motion is suppressed and the plume expansion is highly directional. In the strong magnetic field, electron cyclotron is high and the Larmore radius is small. Therefore, electron motion across magnetic field lines is suppressed, and electrons move along the magnetic field lines. The separation of charges i.e. the electrons and ions,

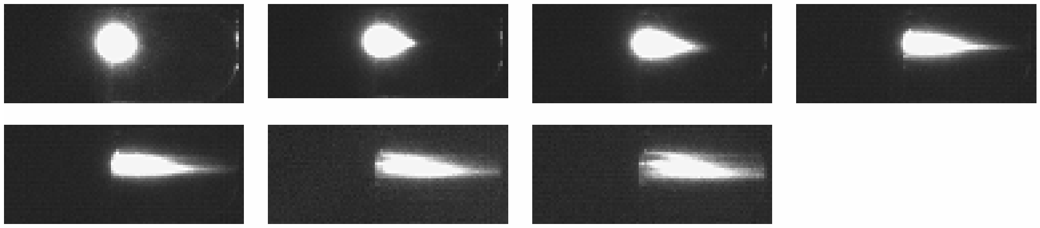

Figure 2. Plasma with 4.5 Tesla magnetic field along the laser beam (at 10^{-5} Torr cell pressuer, YAG 200 mJ/pulse @1064 nm). Frames with time delay (with respect to the laser pulse) ranging from 50 to 750 ns.

creates a strong ambipolar field which suppresses the radial expansion of the ions. The collisions between the remaining neutrals and ions also restrict the radial movement of the neutrals. As a result, a virtual nozzle is set up along the magnetic field lines resulting in a higher longitudinal flow velocity. This increase in velocity can be seen by comparing the plasma plume at similar delay times both with and without magnetic field in Fig. 1 and Fig. 2. Considering the plumes at 350 ns delay and comparing the plume's front positions propagating away from the target shows 65% increase in the plume leading edge velocity, from 32 km/s to 53 km/s. It must be noted that this increase may not represent the corresponding speed of heavy ions and neutrals in the plume.
It is important to note that magnetized plasmas respond differently to forces which are parallel and perpendicular to the direction of B. In contrast to the current study, Neogi and Thareja[10] investigated the ablative plasma in a transverse magnetic field. Their study revealed an oscillatory behavior of the plasma between the magnetic poles. The plasma behavior observed by Neogi and Thareja[10] is very different from that observed in our study where the magnetic field applied along the laser beam causes the plasma to concentrate along the magnetic field lines.

B. Thrust Measurements

For the thrust measurements in this experiment, a pendulum was used as a force balance. The pendulum consisted of a 1"x1" x 0.625" Teflon sheet suspended from two 0.003" diameter polypropylene strands. The pendulum weighed 2.0 grams and its center of mass was suspended 90.6 cm below the anchor point of the strands. The mass of the strands was neglected. Inner chamber of the magnet was used to hold the pendulum perpendicular to the applied field. An estimated period of oscillation of the pendulum was $2\pi/\sqrt{g/l}$ = 1.910 sec. Before analyzing the thrust measurements, it is important to note that the direction of the applied magnetic field, the laser beam, and the direction in which the thrust was measured were all normal to the pendulum plate surface. The direction parallel to the strands on which the pendulum was supported will be referred to as the support axis. The direction from which the pendulum was imaged will be referred to as the imaging axis. The YAG laser used in the first experiment was also used in this study. Laser pulses of approximately 300 mJ/pulse energy were focused onto the pendulum.

Uncompressed images of the pendulum and its supporting strands were recorded at 35 Hz on a Retiga 1300i CCD camera. These images were processed on a PC using MATLAB. To determine the position of the pendulum, ten rows of pixels containing only the supporting strands and the uniform, unfocused background were averaged. The accuracy of the locating method used in this analysis was found to be about ¼ pixel, or 15 microns.

A total of eight runs, four without any magnetic filed (B=0) and four with magnetic filed (B=4.5 T) were made using the pendulum force balance. Pendulum position for all eight cases have been shown in Fig. 3. A least-squares, sinusoidal curve fit (amplitude, offset, frequency, and phase) was determined for each data set before and after the laser strike. The intersection of these two curves gives a more precise method of synchronizing the image timing with the laser timing. The change in velocity caused by the laser ablation was then derived from the two sinusoidal curve fits at their intersection. It is clear that the magnetic field causes a dramatic improvement in imparted momentum from laser ablation, however, in spite of employing the same laser energy, the variations from case to case were observed, probably due to mode beating in the laser. It is important to note that in few cases where the laser did not strike the target at its center of mass, various modes of oscillation did occur for the pendulum used in this experiment. The experimental results revealed that these modes of oscillations were weakly coupled. No changes in amplitude or phase were observed in the measurements presented in Fig. 3 for the pendulum struck off-center.

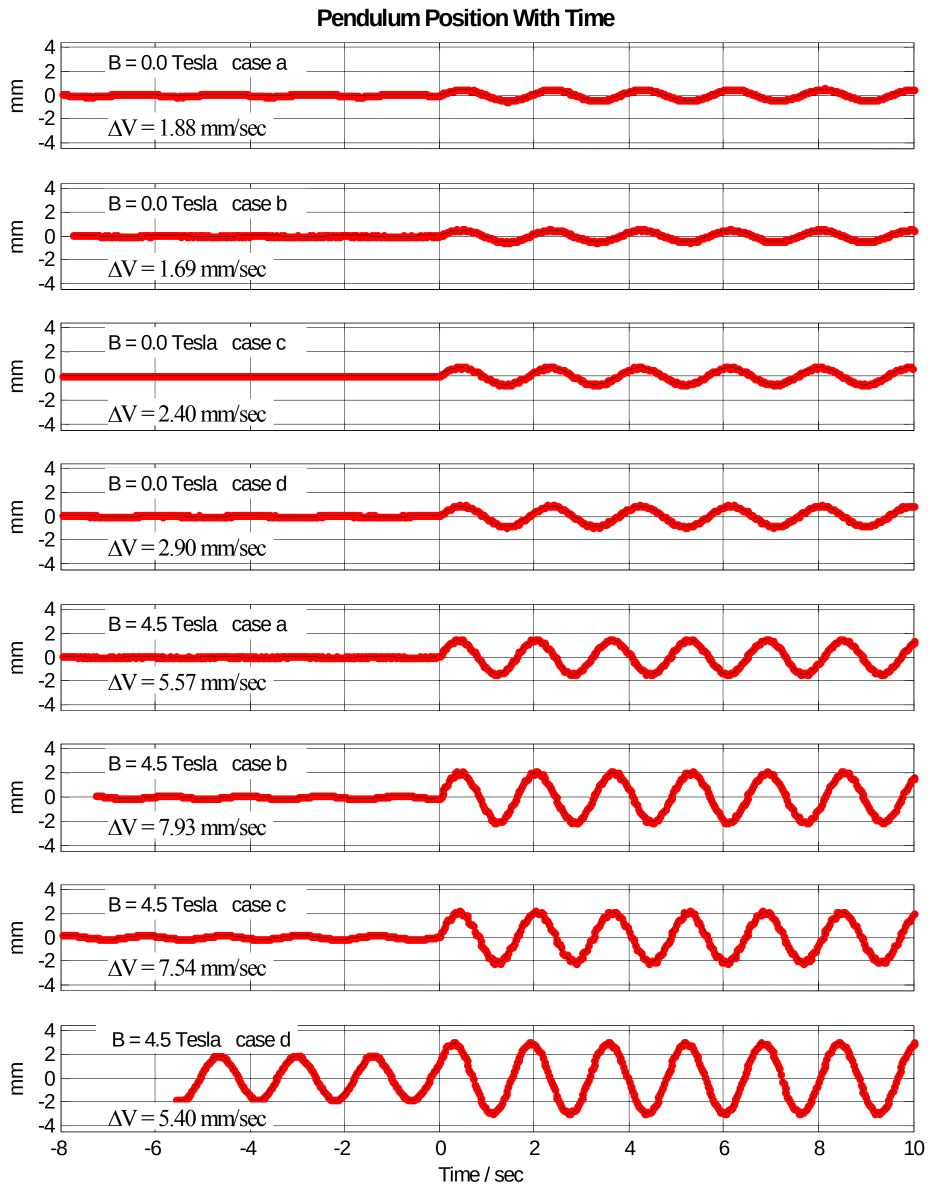

Figure 3. Pendulum position plotted with time with no applied magnetic field (four cases) and with an applied field of 4.5 Tesla (four cases).

The momentum data are shown in Fig. 4. The considerable spread was a cause for concern. The apparent uncertainty far exceeded both the uncertainty in the momentum measurement procedure and the variation in laser power. However, as previously discussed, mode beating in the laser can cause shot-to-shot variations in the peak intensity of laser pulses which, in turn, causes the observed spread in the momentum data. Another source of error might have been due to variations in both time and in space of the surface of the pendulum. Each ablation was observed to discolor large portions of the pendulum and cover the pendulum with slight quantities of soot, therefore changing the surface properties.

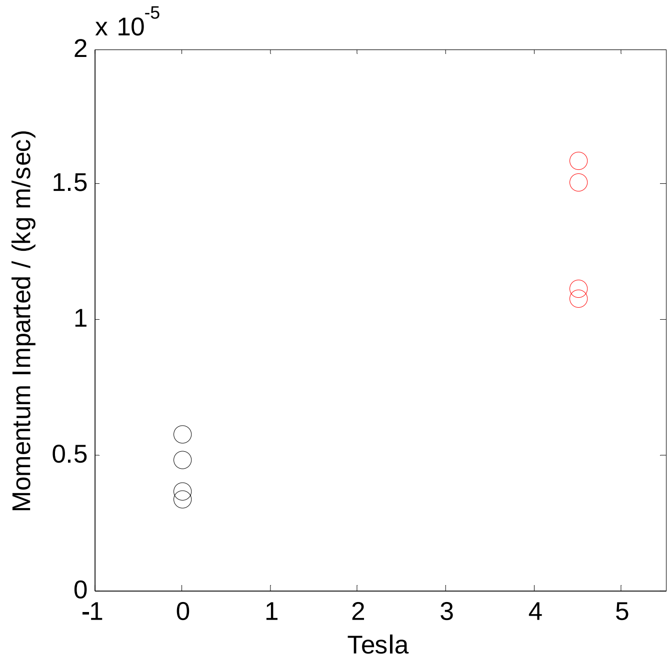

Figure 4. Momentum imparted to the pendulum for all eight cases shown in Figure 3.

Ideally, the applied magnetic field would act as a virtual nozzle and would increase the thrust imparted to the pendulum. In order to investigate the maximum thrust, the following two cases are considered:
Case1. All mass is ejected at uniform speed over a hemispherical distribution.
Case2. The same mass is ejected normal to the surface of the pendulum with the same speed as case 1.
The difference in thrust between case 1) and case 2) corresponds to the best possible effect we could expect from a virtual magnetic nozzle. The difference is easily calculated and found to be precisely a factor of 2. While a factor of 2 does fit within the spread of momentum data shown in Fig. 3, the data do seem to suggest stronger effect. This, in turn, implies an enhancing effect of the magnetic field beyond the simple redirection of momentum. Perhaps confining the plasma allows more efficient heating by the laser. Note that the magnetic confinement and redirection of the ablated plasma plume can potentially be used for local control of the thrust vector. Further experiments are required to investigate this possibility.

IV. Conclusions

In this paper, the possibility of using magnetic field to direct a laser generated plasma and to increase thrust was studied. Experimental results demonstrate that a strongly magnetic field normal to the target surface dramatically altered the evolution of the plasma plume. The magnetically confined plasma moves along the magnetic field lines, and its leading edge expands more rapidly under the influence of magnetic field. Pendulum movements of the thrust showed that the directionality of the plasma motion in the strong magnetic field increased the thrust by a factor of 2.

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