# Magnetic Field Measurement of Laser-Electromagnetic Hybrid Thrusters

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A small spacecrafts which mass and power limited need a new propulsion device. The device has to realize a high specific impulse and simple structure. The paper proposed a new thruster, which is combination of laser propulsion and electromagnetic acceleration like a pulsed plasma thruster. To realize the effects, the magnetic field distribution of plasma flow is observed using a optics camera and magnetic field probe. Those probes are arranged along the plasma flow. We confirmed that gradually moving magnetic field after 1200 ns at plasma generation.

**Key Words:** Pulsed plasma thruster, Laser ablation, Magnetic field measurement

## Nomenclature

| | |
|---|---|
| *l* | : electrode channel length |
| *w* | : electrode channel width |
| *h* | : electrode channel height (it means gaps of electrode) |

## 1. Introduction

In recent years, the number of micro satellites, is superior in cost performance, increase rapidly. Those small satellites have severe limitation in mass and power, so they need high specific impulse thruster. Therefore, electricity propulsion has advantage in specific impulse, furthermore, Pulsed plasma thruster, PPT, which is kind of electricity propulsion has advantage in the simplicity of construction and the ratio of its weight per thrust power it can generate.

On the other hand, laser propulsion is a new system of space propulsion. In late years, laser is studied in each country, a laser technology develops rapidly, many laser systems became smaller and more high performance. Laser propulsion system does not need some gas tanks, valves, and piping because this system can use solid propellant. Therefore, use laser for thruster system can simplify the structure of the propulsion systems.

For compactification and high performance of propulsion system, our group devised laser-electromagnetic hybrid thruster. It has special advantage of simplifing the structure and has high specific impulse. We conduct basic study of various type of new hybrid thruster.

## 2. Method of Laser Assisted PPT, LA-PPT

Figure 1. shows the construction of 2D laser assisted PPT, LA-PPT. This thruster head is constructed by two electrode plate and solid block propellant. One of the electrode connected with capacitor bank that is fully charged. The other connected with grand. The basic idea of LA-PPT system is use of ablation plasma, has high plasma density and high initial flow rate, generated by the laser irradiation on a solid propellant. The plasma is accelerated by electromagnetic force which is provided by correlation between discharge current which flows if two electrodes are breakdown and self-induced magnetic field. Figure 2. shows photograph of appearance of a LA-PPT, and table 1. shows the size of a LA-PPT thruster head. Two metal plates are made from molybdenum, Mo, and support body is made from aluminium oxide, $Al_2O_3$. Figure 3. shows the moment of a LA-PPT operation. At the left side of this photo, the plasma shines brilliantly near by the surface of propellant. The discharge current between electrodes shine two plate electrodes. The plasma is accelerated to the right. In addition, the circular device appears in this photo is a thruster target made from macromolecule materials.

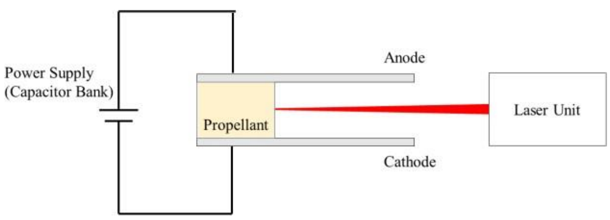


Figure 1. schematic of a LA-PPT

Table 1. Size of a LA-PPT

| Part | Width, mm |
|---|---|
| l | 50 |
| w | 10 |
| h | 15 |

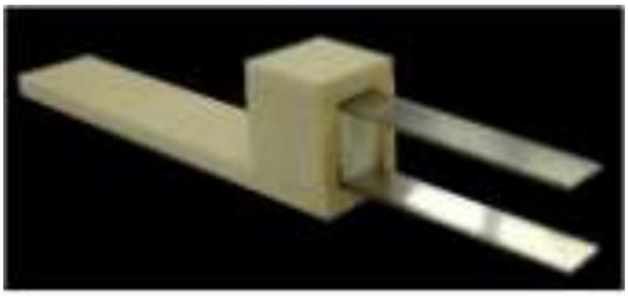

Figure 2. Appearance of a LA-PPT

## 3. Motivation

One of the most important parameter of electricity propulsion system is specific impulse. Figure 3. shows the various case of typical characteristics when the laser assisted PPT operated high specific impulse. They were operated in different electrode conditions, various electrode geometries, that means multiplied electrode length and electrode height. The plot in this figure is from our previous report. From the figure 3., specific impulse increased in proportion to energy that the capacitor bank charged. Furthermore, it shows that the more thruster heads are long, the specific impulse is high. Our LA-PPT recoded about 7200sec with 10mm electrode length and 50mm electrode height, at that time, the energy that the capacitor bank charged is about 8.6J. It is a notable recode, the specific impulse of our LA-PPT is higher than electricity propulsion systems were already put to practical use, like ion and hall thruster. A LA-PPT has assessed operations that use short pulse and high voltage operation and has recoded outstanding performance. In addition, LA-PPT has advantages of compact construction and weight.

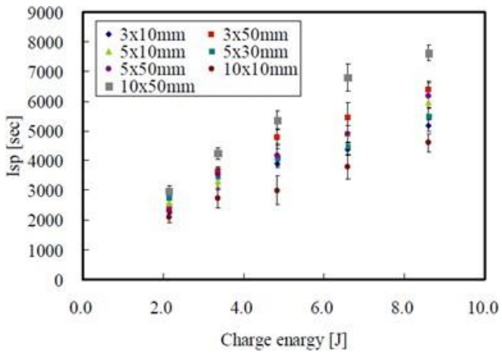


Figure 3. the various case of typical characteristics when the laser assisted PPT operated high specific impulse

## 4. Experimental Setup

### 4.1. Experimental specimen of thruster

Figure 4. shows schematic of experimental setup of a LA-PPT. Figure 5. shows Appearance of experimental setup around the vacuum chamber. A LA-PPT and capacitor bank for LA-PPT are set in a vacuum chamber. We operated a LA-PPT when the chamber's back pressure is $2.7 \times 10^{-3}$Pa.

We use a Nd-YAG laser, CONTINUUM inc, Surelite II, wave length : 1064nm, pulse width 5ns, and energy of one pulse is 400mJ, to ignite our thruster. The laser unit is set outside the chamber. The laser needs lens for attenuation and light condensing. The laser has excessive energy. we have to use an optical beam attenuator unit when the laser irradiates the high power beam through windows of the chamber. On the other hand, a condenser lens is placed in the chamber, because the lens have to be set near the surface on the propellant to focus the laser beam.

The thruster electrodes of LA-PPT require high voltage and severe current. Considering Paschen law, high voltage is necessary for the electrical breakdown between two electrodes, anode and cathode. Considering generating high Lorentz force in the thruster head, severe current is necessary for the electromagnetic acceleration. Hence two electrodes need high power supply. A regulated DC power supply cannot supply the large power, because it has a problem of power consumption and excessive fever. In this case, the large capacitance capacitor is superior to A regulated DC power supply. The electrodes connected to a capacitor bank. The capacitor bank is made of high voltage capacitors, TDK, Ultra-high voltage ceramic capacitors, UHV-3A. Each capacitor has 4.6nF capacitance, and total capacitance of the capacitor bank has 24.50nF. The capacitor bank can release electric current during the operation of a LA-PPT. The operation is extremely a short time. As for the operating time of a LA-PPT, the time which all event is over is shorter than 3us. All events move by nano seconds unit. The capacitor bank is suitable for such a condition.

If we operate some devices for short time, we have to prepare a timing of pulse. We needed a delay generator and infrared photo diode. The delay generator send a pulse signal to Nd-YAG laser and ICCD camera. The infrared photo diode can catch the laser beam, and send immediately a pulse signal to an oscilloscope. The oscilloscope recodes the discharge current of a LA-PPT by the current monitor when the oscilloscope receives the signal.

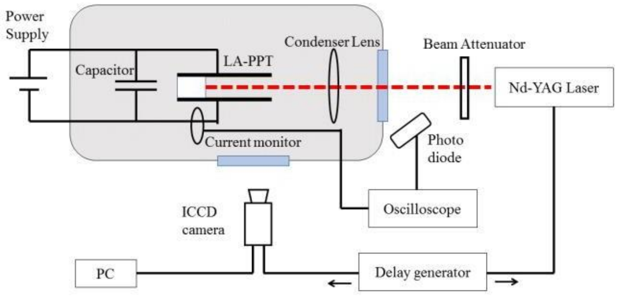


Figure 4. Appearance of a Nd-YAG laser

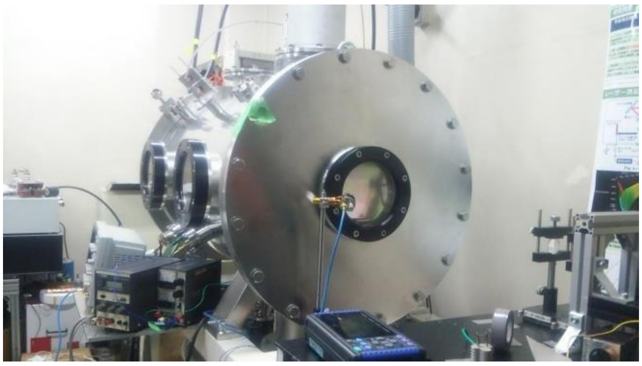

Figure 5. Appearance of experimental setup

Figure 6. Appearance of Nd-YAG laser

## 4.2. Plasma behavior observation by ICCD camera

A ICCD camera was used time-resolved optical imaging of light intensity of plasma flows. The time scale of plasma behavior is nano seconds order. We need a short expose time and continuous imaging camera to observing plasma behavior. From the observation of plasma behavior, we clarified that a front of plasma flows and plasma speed. We used an ICCD camera, ANDOR TECHNOLOGY, minimum gate width : 2ns, to verify the plasma LA-PPT generated. Figure 7. shows the plasma when momentary the laser fired.

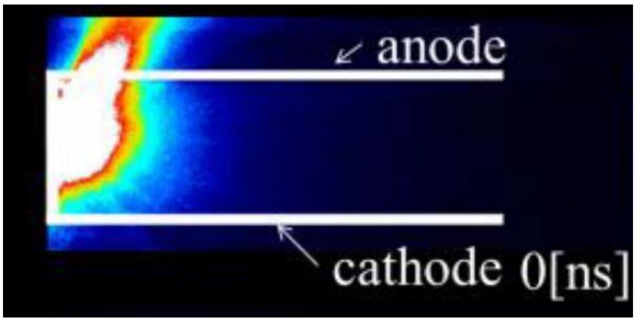


Figure 7. A typically observation data of the plasma in a LA-PPT by the ICCD camera

## 4.3. Magnetic field probe

We could not completely understand the status of plasma for only the light intensity of plasma flow. Moreover, we had to estimate the relationship between the light intensity and other plasma parameters. Therefore, we examined whether the correlation between the light intensity and magnetic fields in a LA-PPT channel.

We performed directory a magnetic field measurement by Rogowski coil to determine the self-inducted magnetic field in a LA-PPT channel between two electrodes. Figure 8. shows a magnetic field probe we made and used. The diameter of this probe is only 1mm, and this probe is made of copper wire of 0.6mm in diameter. The surface of copper wire we used is coated with enamel. This coating protected the copper wire from discharge current between electrodes. In other words, the coating behaves the electrical insulator.

If any current flows the probe, it means being magnetic fields at the point. We have to do the time integration of the current which flows in the probe to determine magnetic fields at the point. A simple circuit can integrate a wave input and can output it. Therefore, we prepared an integrating circuit. Figure 9. shows schematic of experimental setup of a LA-PPT when we measure magnetic fields. An integrating circuit is made of electric resistances and capacitors. We prepared eight circuits, because one integrating circuit is necessary in one probe. The probes and the circuits are same quantity. The oscilloscope display and recode the output signal, the signal has been integrated.

Figure 8. photo of magnetic field probe

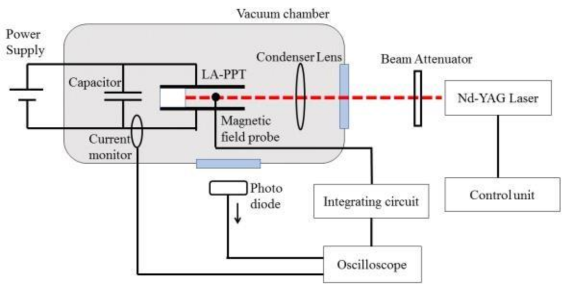


Figure 9. photo of magnetic field probe setup

### 4.3. Magnetic field measurement

Our magnetic field probe can determine magnetic field strength at the point, so we prepared this probe eight to determine a magnetic field distribution. This experimental study was performed to determine the association between light intensity of plasma flow and magnetic field of plasma. In this paper, elucidating correlation between plasma behavior and magnetic fields, we focus on plasma flow direction. Those probes were arranged flow direction in this experiment. However, the position which the plasma generated from the propellant and the position of thruster head exit, it means the terminal of the plate electrode, were arranged lengthwise, those probe lines that were this two positions were perpendicularly at plasma flow. The plasma carried out a complicated behavior at the position where the plasma generated. The terminal of thruster head is the end of the electrodes. The electrodes give the plasma the energy, so the plasma is the fastest at the point. Figure 10. shows probe arrangement this experiment for this paper.

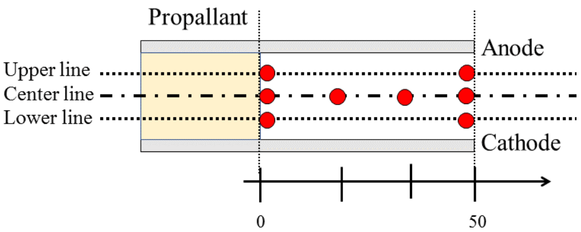


Figure 10. probe arrangements when we conduct experiment in the past

## 5. Result

Figure 11. shows a LA-PPT in operation. We observed relatively stronger magnetic fields, and the magnetic fields were induced at near propellant surface region, cathode lower side, after 1,200 to 1,600 ns. After 1,600 ns, regions of strong magnetic fields were moving downstream. Moreover, it was shown that temporal variations of the magnetic fields in regions at near propellant surface are almost in phase with a discharge current waveform.

Figure 12 shows output signals of magnetic field measured on center axis at 0 to 50 mm from propellant surface (charge voltage of Vc = 1,000 V). From these signals taken at several positions in the discharge channel, temporal variations of magnetic field distributions in the discharge channel were reproduced, as shown in Fig.13. In this figure, corresponding temporal variation of plasma images taken by an ICCD camera are also shown. From the figures, it is shown that the part of light intensity where is stronger moves dawn stream. The timing which the plasma generated and the timing which the magnetic fields appearing are not same.

In this present study, we have demonstrated that the timing the strong magnetic fields appears was 1,600ns late behind the timing the plasma generated. Moreover, the strong magnetic fields in a LA-PPT channel moves downstream in the same way as the light intensity of plasma flow. The severe current between anode and cathode and the self induced magnetic fields by the severe current provides the plasma flow with the velocity for the effect of an electromagnetic acceleration.

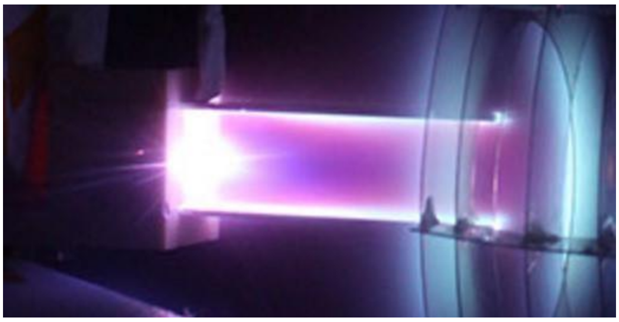

Figure 11. Operating a LA-PPT

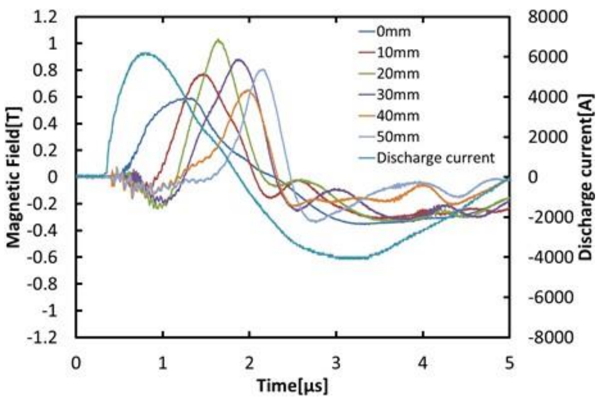


Figure 12. Output signals of magnetic field measured on center axis at 0 to 50 mm from propellant surface (charge voltage: 1,000V).

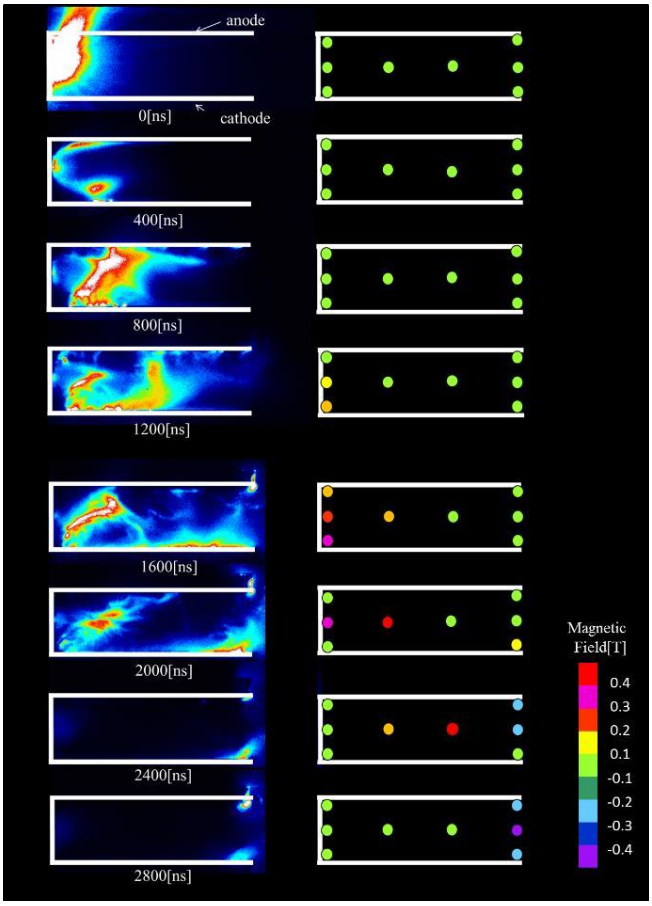


Figure 13. The light intensity of plasma, left and the magnetic fields in a LA-PPT channel, right. Therefore, the time division is 400us.

## 6. Conclusion

We estimated the experimental results why the appearing magnetic fields is late behind the light intensity of plasma flow. Compared the light intensity of plasma and the magnetic fields, the strong magnetic fields appeared the space between the propellant side surface and the brilliant light intensity of the plasma. Moreover, the plasma flows from the propellant surface through the exit of electrodes, and considering Maxwell's equations, the magnetic fields are made by the current. Hence, we found out the deeply association between the discharge current and the light intensity of the brilliant plasma. We found out experimentally that a magnetic field appears on the point where the plasma was after movement of the plasma.

In addition, after moving the stronger magnetic fields, negative direction magnetic field has been observed near the terminal of electrodes. In this experiment, we determine only one dimension magnetic field. If we want to the strength of the magnetic fields in a LA-PPT channel, we have to measure three dimensional magnetic fields per one point, and we have to take geometric mean.

The magnetic fields behavior is very complex. However, we need to clarify the behaviors to electromagnetic acceleration mechanisms and to design more excellent and more robust electromagnetic thruster, like MPD or PPT.

## References


1) Myers, R. M., et al., Small Satellite Propulsion Options, AIAA Paper,(1994),pp. 94-2997.
2) T.E. Markusic., et al. "Photographic,magnetic, and interferometric measurements of current sheet canting in a pulsed electromagnetic accelerator" AIAA Paper, 2001, 2001-3896
3) Jahn, R. G.: *Physics of Electric Propulsion*, McGraw-Hill, 1968, pp.198-316.
4) Horisawa, H., and Kimura I.: Fundamental Study on Laser Plasma Accelerator for Propulsion Applications, *Vacuum*, 65, 2002, pp.389-396.
5) Horisawa, H., et al., Beamed Energy Propulsion: AIP Conference Proceedings, 664, 2003, pp.423-432
7) Horisawa, H, High Isp Mechanism of Rectangular Laser-Electromagnetic Hybrid Acceleration Thruster, IEPC, International Electric Propulsion Conference, IEPC-2011-274, pp. 7-8
8) Y. Oigawa, N., Akashi, H., Hosokawa, H., Horisawa: *AIAA Paper*, AIAA-2014-3537 (2014).
9) Hideyuki Horisawa, Shigeru Yamaguchi and Ikkoh Funaki, Forward Plasma Emission through Laser–foil Interaction with Nanosecond Lasers, Applied Physics A, s00339-011-6442-9, 2011.
11) Mashima, Y., Yamada, O., Horisawa, H., and Funaki, I., High Isp Mechanism of Rectangular Laser Electromagnetic Hybrid Acceleration Thruster, 32nd International Electric Propulsion Conference, Wiesbaden, IEPC-2011-274, Germany, Sept.11-15, 2011.
12) Hideyuki Horisawa, Shigeru Yamaguchi and Ikkoh Funaki, Forward Plasma Emission through Laser–foil Interaction with Nanosecond Lasers, Applied Physics A, s00339-011-6442-9, 2011