

## PLASMA DIAGNOSTICS OF LASER-SUSTAINED PLASMA IN A CW LASER THRUSTER

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### ABSTRACT

A laser thruster has been designed in order to establish the thruster scaling law, and to investigate experimentally the energy transport phenomena between the Laser Sustained Plasma (LSP) and the cold gas flow. This paper reports observations of the fundamental LSP behavior and optical measurements in 2kW-class laser thruster.

The image of the LSP in the chamber was taken by a CCD camera, and its position and axial length were measured. It was confirmed that the LSP position was governed by the focus position and plenum pressure. LSP oscillations were observed in the plasma production chamber and its frequency was about 500Hz at any conditions.

Preliminary spectroscopic tests were carried out. The electron temperature at the center of the LSP was deduced from the Boltzmann plot. It showed that the electron temperature was about 16000 K  $\pm$ 1000 K at 0.6 g/s and 900 W

### 1. INTRODUCTION

Laser propulsion has been investigated as one of the propulsion systems that may be used in space and in the atmosphere. The acceleration mechanism of laser propulsion is

as follows: A laser-sustained plasma (LSP) which absorbs the high power laser beam from a remote site is produced in the propellant flow. The propellant gas is heated by the LSP and gas enthalpy is recovered as thrust via a supersonic nozzle. Its payload fraction is expected to become higher than in other propulsion systems because power sources need not be loaded in the vehicle. Especially as a launcher from the ground, it has the advantage of using the air around a rocket as propellant.

Keefer et al.<sup>1,2</sup> and Mazumder<sup>3</sup> et al. investigated the fundamental behavior of the LSP and developed a numerical code on high power condition ( $\sim$ 10 kW). Also, there has been a numbers of experimental studies.

In this study, laser thrusters in the sub-kilowatt to several kilowatt classes were designed and manufactured in order to establish the scaling law of the thruster, and to investigate the energy transport phenomena between the LSP and the cold gas flow experimentally. This paper reports the fundamental experiments, focusing on the observation of the LSP, that strongly affects thruster performance. The electron temperature has been measured using a spectrometer and the LSP behavior have been observed with a CCD camera and a photodetector.

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## 2. EXPERIMENTAL APPARATUS

### 2.1 THRUSTERS

Figure 1 shows the cross sections of the two laser thrusters of 2kW-class laser and they are also designed for optical observation of LSP in the thruster. They are made up of a laser induction window, a plasma production chamber and a nozzle. The chamber downstream of the first throat is called the sub-chamber. In case of optical measurements in the sub-chamber, the quartz cylinder was replaced by the sub-chamber segment.

A zinc selenide (ZnSe) disk with anti-reflection coating was used as the laser induction window. It can transmit 10.6 μm wavelength laser beam efficiently and withstand up to 10 atm. The nozzle is made of tungsten and other thruster segments are made of stainless steel and brass. The throat diameter is 3mm and 1mm, respectively. The diameter of sub-chamber is 6mm.

To ignite plasma, a tungsten rod is used as the source of electron emission. This rod was inserted into the focal point of the laser beam and was pulled back after ignition by air cylinder.

Argon and nitrogen were used as the propellant. The flow rate of operation range was between 15 and 30 SLM. In the case of optical measurements, in general argon was used.

### 2.2 EXPERIMENTAL APPARATUS

Figure 2 shows a schematic of the experimental apparatus. In these experiments, a 2kW CW-CO<sub>2</sub> laser (Panasonic YB-L200B7T4), with 10.6 μm wavelength variable power, was utilized. The transverse mode of the laser beam is shown in Fig. 3. It is not a simple gaussian profile but rather a double gaussian profile. The beam divergence is less than 2 mrad at the laser exit. The beam diameter was magnified by a beam expander, and the expanded beam was focused in the chamber by a ZnSe plano-convex lens of 250

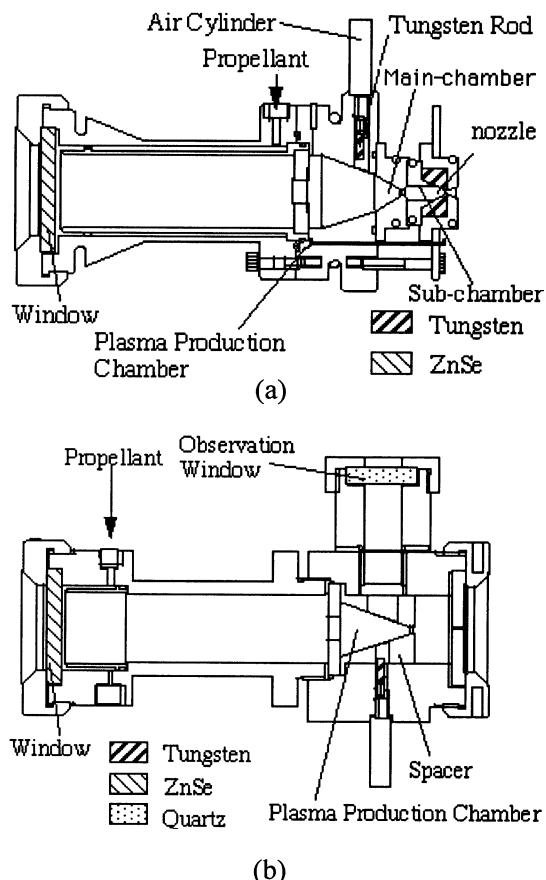


Fig. 1 Cross sections of thrusters. (a) Laser thruster (b) with observation window

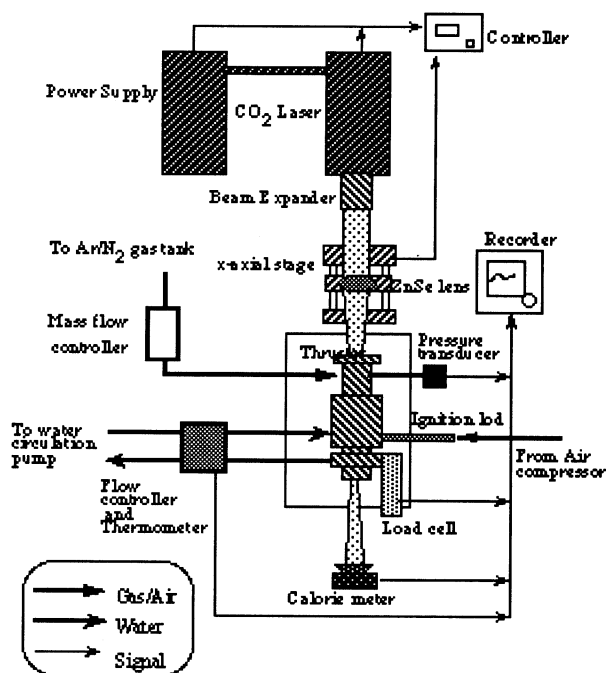


Fig. 2 Schematic of experimental apparatus.

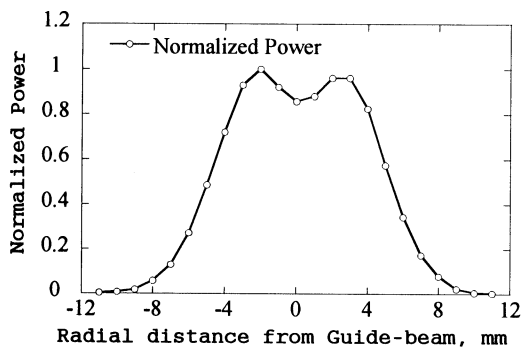


Fig. 3 Transverse mode of the laser beam.

mm focal length. This lens can be positioned in the laser beam direction using a stepping motor. The thruster was mounted onto rails, so that force-free condition has been achieved in the thrust direction. The thrust was measured by a load-cell sensor, and an alley of weights was used for calibration. The thruster was water-cooled and the temperature rise of the cooling water has been measured for estimation of the heat loss by thermocouples. The mass flow rate of propellant was regulated with a mass flow controller. The plenum pressure was regarded as the static pressure in the plasma production chamber, and was measured with a semiconductor pressure transducer. The laser energy passing through the throat was measured using a calorimeter. All of the signals from these sensors were recorded with an eight channel digital oscilloscope.

The LSP image was taken by a CCD camera (Hamamatsu Photonics C5405) and a high-speed photodetector (Thorlabs Inc. DET210/M). A band pass filter and ND some filters were attached to the camera so as to separate the argon spectra from the plasma radiation and to prevent the CCD elements from electron saturation.

A spectrometer (Hamamatsu Photonics PMA-50) was used to measure plasma spectra, from which the electron temperature could be deduced. The spectrometer dispersion was calibrated with the discharge tubes. Also, the sensitivity in terms of the wavelength was calibrated with a standard illuminant. The spectrometer resolution was about 0.04

nm/channel and the exposure time was adjustable between 5 ns and 32 sec.

### 3. EXPERIMENTAL RESULTS AND DISCUSSIONS

#### 3.1 FUNDAMENTAL THRUSTER PERFORMANCE

Figure 4 shows the operating conditions in which a stable LSP is maintained in case of argon. The operation limits of laser power can be lowered with an increase in mass flow rate.

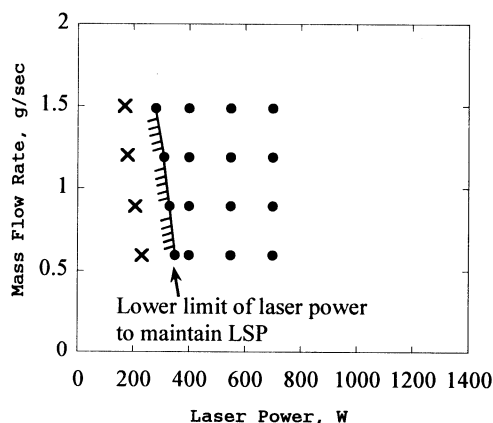


Fig. 4 Stable operating conditions using argon.

Figure 5 shows the time sequence of the thrust variation as the focal point moves from the ignition point to the sub-chamber. The plenum pressure increases gradually when the LSP approaches the first throat, and remarkably increases when it enters the sub-chamber. On the other hand, variation of thrust was small which the LSP is in the sub-chamber.

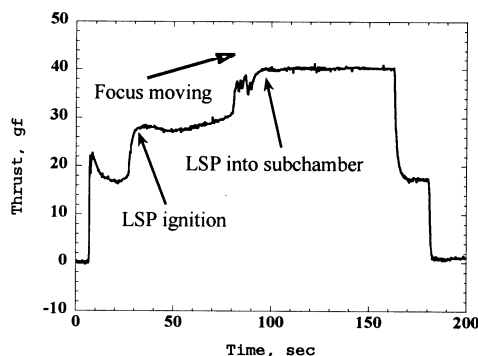


Fig. 5 Time sequence of thrust at 700 W and 0.6 g/s.

The relation between the LSP position and focal point is described in next section.

Figure 6 shows the relation between thrust and plenum pressure. The thrust was proportional to the plenum pressure at any operation condition. Therefore, it seems that the conventional chemical rockets theories can be applied to the laser propulsion in this power range.

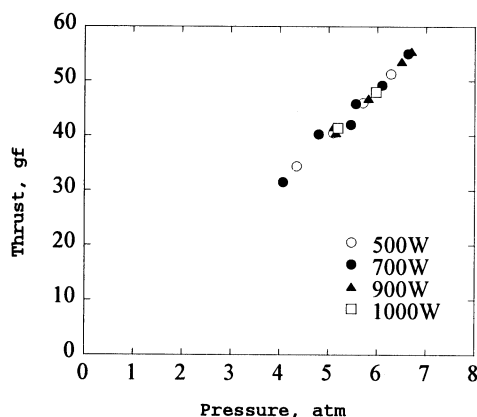


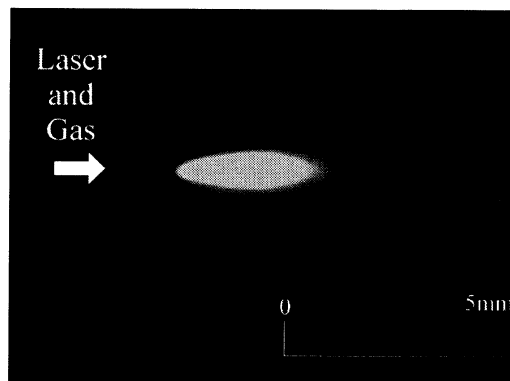
Fig. 6 Relation between thrust and plenum pressure

### 3.2 BEHAVIOR OF LSP

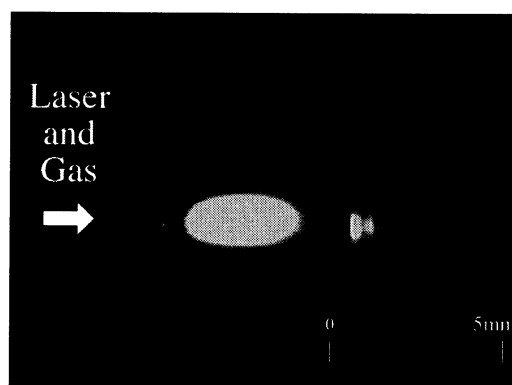
The LSP shape and axial position were measured with the CCD camera. Figure 7 shows the images of LSP in the main-chamber and the sub-chamber. In the pictures, the laser beam and propellant flow were supplied from left-hand side.

The ellipse-shaped LSP whose major axis was in the laser beam axis were observed, and it spreads in the sub-chamber more than in the main-chamber. It seems that the velocity around LSP and the mass flux streaming into it increased and the diameter of laser beam decreased at that point.

It is confirmed that the LSP position was controlled by the focus position and the plenum pressure. Figure 8 shows the relation between plenum pressure and axial distance from the laser focus. As the plenum pressure increases, the LSP position moves upstream away from the focus, on the contrary, as the pressure decreases, the LSP moves



(a)



(b)

Fig. 7 Images of LSP taken by CCD camera. (a) in the sub-chamber (b) in the main-chamber

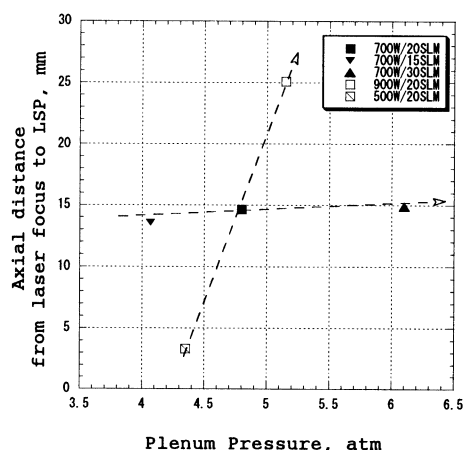


Fig. 8 Relation between plenum pressure and axial distance from focus.

downstream toward the focus. Keefer et al. reported similar result<sup>1</sup>. However, the gradient was dependent on the laser power and mass flow rate.

An oscillation of the LSP, toward the axial

direction has been observed in thruster. To estimate the amplitude of oscillation and axial length of the LSP, about 40 images were taken by the CCD camera at each operating condition. In each image, the position of maximum intensity which was regarded as a position of LSP and the FWHM of the intensity distribution in a CCD image as an axial length of it were measured. Assuming normal distributions for each respective value, the axial length of the LSP and amplitude of oscillation determined from the standard error is shown in Figs. 9 and 10. Figure 9 shows that, for increasing values of plenum pressure, the LSP axial length gets smaller with increasing mass flow rates but, on the other hand, gets larger as the laser power is increased. Furthermore, the oscillation amplitude was almost constant in value regardless of the pressure, as shown in Fig. 10.

Using a high-speed photodetector, the time variation of intensity at any point of the plasma was measured to deduce the frequency of oscillation. Figure 11 shows the results of FFT analysis at the conditions of 700W. The oscillation frequency was about 500Hz at any conditions in Fig. 12.

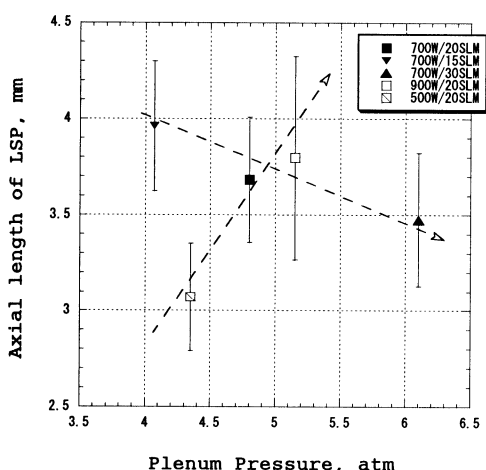


Fig. 9 Relation between plenum pressure and axial length of LSP.

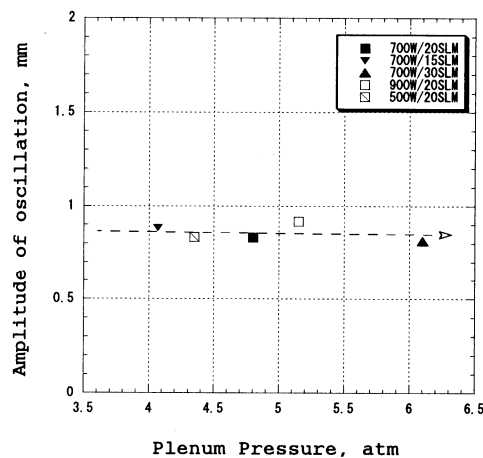


Fig. 10 Relation between plenum pressure and amplitude of LSP oscillation.

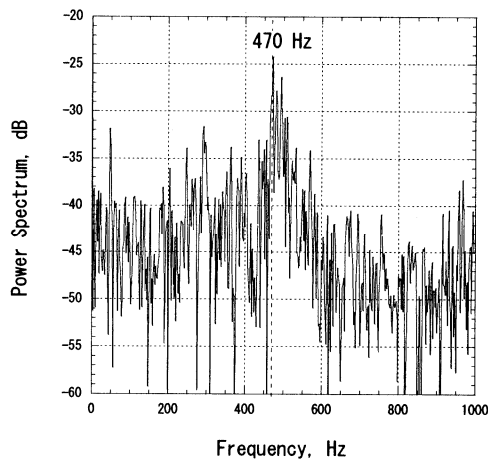


Fig. 11 FFT results of LSP oscillation at 700 W 0.6 g/s.

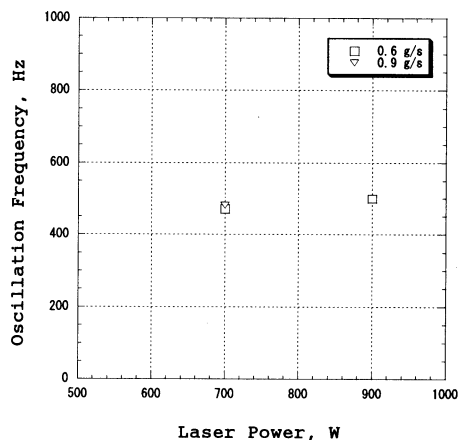


Fig. 12 Oscillation frequency of LSP.

### 3.3 SPECTROSCOPIC RESULTS

The electron temperature was deduced by measuring the argon LSP spectra using a spectrometer. The Oscillating LSP made it difficult to observe the temperature distribution so that the spectra at the specified point were measured using a telescope.

In order to be able to capture the 500 Hz LSP oscillations, the exposure time of the spectrometer was set to 1 ms. This value is the lower exposure time limit, providing sufficient spectrum intensity. A sampling of 50 sets of spectrum data was obtained for subsequent statistical analysis. Figure 13 shows the Boltzmann plot at 900W and 0.6g/s.

The error bar in the graph was determined by statistical standard error and the ratio of spectrum and radiation as S/N ratio. Almost all plots, several principal quantum numbers, were near the line so that it was realized the LTE on this point.

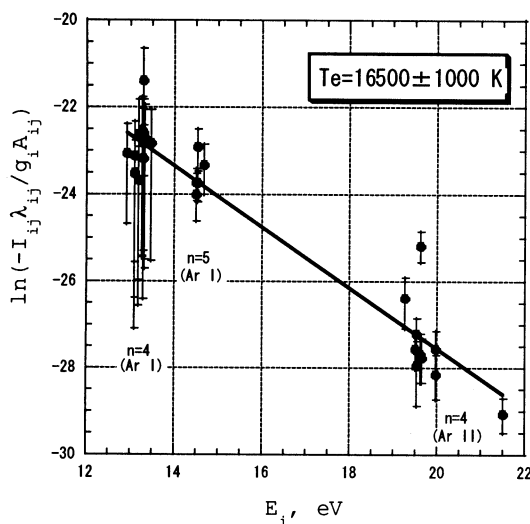


Fig. 13 Boltzmann plot of argon LSP at 900W and 0.6 g/s.

### 4. CONCLUSIONS

- 1) The thrust is strongly related to the plenum pressure in the given power range.
- 2) It was confirmed that the LSP position was governed by the focus position and the plenum pressure.

- 3) The oscillation of the LSP toward the axial direction has been observed with an oscillation frequency of about 500Hz at any conditions.
- 4) The preliminary tests of spectroscopic analysis were carried out. The electron temperature of LSP was deduced about  $16000 \text{ K} \pm 1000 \text{ K}$  at 0.6 g/s and 900 W.

### 5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by Takahashi Industrial and Economic Research Foundation.

### REFERENCES

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