The Effect of Laser Intensity on LSD Wave Propagation Velocity and its Application to Laser Propulsion System

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Abstract: Laser supported detonation (LSD) is the most important process in energy conversion from laser to gaseous enthalpy. One-dimensional LSD is studied in this paper. In order to prevent lateral expansion and investigate 1-D phenomenon, LSD is generated in a straight tube using a TEA-CO_2 Laser of which energy can be varied from 8 J to 10 J. Half Self-emission and Half shadowgraph (HSHS) method is used to measure propagation displacement and velocity. LSD propagates approximately 11 mm until 2.8 μs in the case of 10 J. The relationship between propagation velocity and laser intensity is obtained. This result is compared with velocity of Chapman-Jouguet condition.

Nomenclature

D_{CJ}	=	Detonation wave velocity of C – J condition
S	=	Laser intensity
t	=	Time elapsed from the starting point of laser oscillation
x	=	Displacement of ionization front
γ	=	Specific heat ratio behind the shock front
ρ_0	=	Gas density at the front of detonation wave

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I. Introduction

There are various proposals for the construction of space infrastructures such as Solar-Power Satellite (SPS), lunar base and so on. However, the extraordinary transportation cost from ground to space is one of the most significant challenges that we have to overcome in order to accelerate space development. Laser detonation propulsion is one of next-generation propulsion system and may greatly reduce the transportation cost[1]. When laser is irradiated to a vehicle, it is focused by mirrors equipped on the vehicle. This leads to the breakdown of propulsive gas, producing a plasma and the subsequent absorption of laser beam energy via invers-bremsstrahlung. This plasma propagates toward the laser beam source with supersonic speed. During the process of energy conversion from laser to thrust, Laser-Supported detonation (LSD) plays an important role because energy is converted efficiently during LSD regime[2]. During LSD regime, ionization front propagates toward laser beam source together with shock front which is analogous to chemical detonation. However, optical detonation such as LSD is much more complicated and still remains unclear. For designing an optimized thruster, LSD characteristic must be clarified.

Raizer proposed LSD model considering lateral expansion in which he demonstrated how this lateral expansion resulted in loss of enthalpy and its consequent reduction effect on the LSD wave propagation velocity[3]. However, Shimamura et al suggested that a large diameter laser will be used to launch a vehicle and the effect of lateral expansion can be negligible in that case[4]. Shimamura et al conducted optical emission spectroscopy experiment to extract electron number density and electron temperature of plasma which was generated in a quasi 1-D confinement[5]. In their experiment, however, plasma property was measured in low laser intensity region during LSD termination because high laser intensity of a line-focused beam make the extraction of plasma characteristics' values difficult.

In this paper, 1-D LSD generated in a straight tube is studied using two off-axis mirrors. In order to generate 1-D LSD, a relatively long focal length was employed. Half Self-emission and Half Shadowgraph (HSHS) method was utilized to measure propagation displacement and velocity. Finally relation between laser intensity and propagation velocity is discussed comparing attained results with Chapman-Jouguet condition which is observe in chemical detonation.

II. Experiment

TEA-CO_2 laser (wavelength: 10.6 μm, maximum energy: 10 J) was used to produce plasma for the LSD wave characteristics study. Laser is irradiated with energy of 10 J and 8 J. Temporal changes of laser power and cumulative energy in the case of 10 J are shown in Fig.1. Shot-to-shot of variation of energy was less than 5 %. The cross-section of the laser is 30 mm x 30 mm. Horizontal energy distribution is Gaussian and vertical energy distribution is top-hat shaped. Laser beam is focused by two off-axis mirrors. Horizontal direction is focused by 500-mm focal-length mirror and vertical direction is focused by 400-mm focal-length mirror. The mirrors are made of Al coated with Au of which reflectance is more than 98%. Laser was irradiated into the detonation tube whose cross-section was of 5 mm x 5 mm and the height 15 mm. In order to compare the effect of lateral expansion, the experiment was also performed by laser irradiated on to an aluminum plate with no geometrical restriction so as to measure 3-dimensional LSD propagation. The ambient gas was atmospheric air was at a pressure of 1 atm. The schematic of focusing optics is shown in Fig. 2.

Half Shadow and Half Self-emission (HSHS) method is utilized to visualize shock wave and ionization front of LSD simultaneously by using a DPSS (Diode Pumped Solid State) laser whose output power is 1.45 W (continuous) and has a wavelength of 532 nm as a probe beam. Images were taken by a high-speed ICCD camera (resolution: 520 x 520 pixels) with exposure time of 50 ns. The schematic of optical setup of HSHS and typical image of that are shown in Fig. 3.

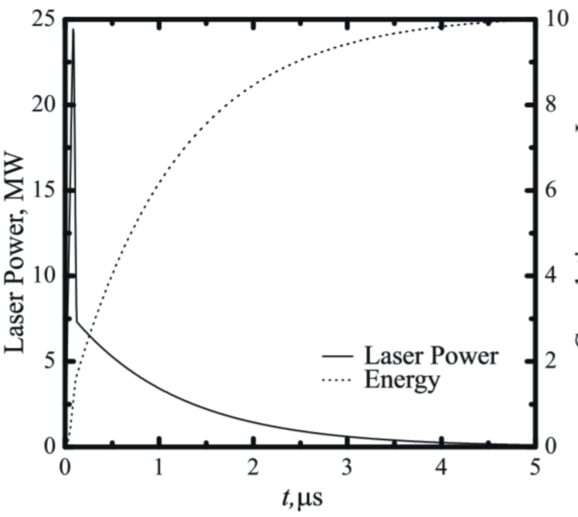

Figure 1. Power profile and cumulative energy of TEA-CO_2 laser (10 J).

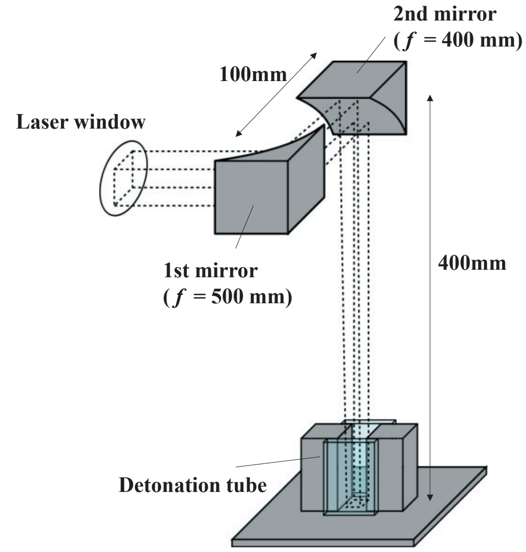

Figure 2. Schematic of focusing optics.

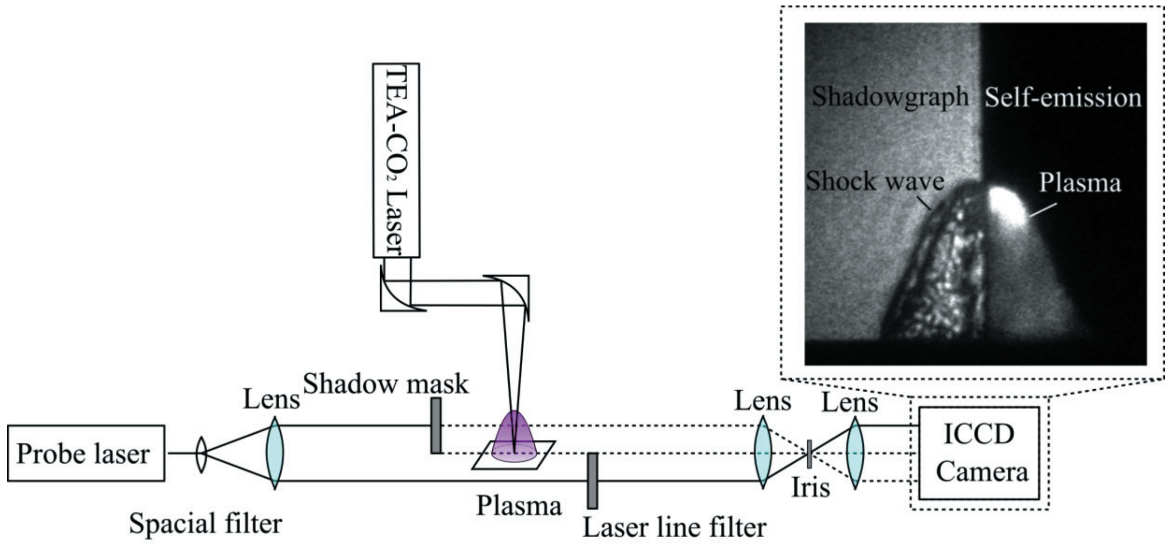

Figure 3. Optical setup of HSHS and a typical image of HSHS.

III. Experimental result and discussion

Figures 5 and 6 show HSHS pictures of LSD propagation with energy of 10 J in tube and without tube, respectively. Also, Figures 7 and 8 are pictures of 8 J. From these pictures, the relationship between displacement of ionization wave front and elapsed time from beginning of laser oscillation was obtained and x - t diagram is shown in Fig. 9. In Fig. 5 and 6, it was observed that LSD terminated at about t = 2.8 μs. In the case of 8 J, in Fig. 7 and 8, termination is observed at about t = 2.6 μs. In Fig. 9, there is no big difference between propagation displacement in tube and without tube. According to experiment conducted by Ushio et al[6], termination time of LSD was extended by quasi 1-D confinement such as wedge nozzle. In their experiment, focal-length was 48 mm and this relatively short focal-length could achieve a small focused spot size. Because of this small focused spot size, leakage of plasma from an area where light flux of laser comes is relatively high. In the case of this study, however, focal spot was large and the flow of plasma in laser light channel is sufficiently higher than lateral leakage from the channel. Thus, 1-D tube did not worked effectively as confinement.

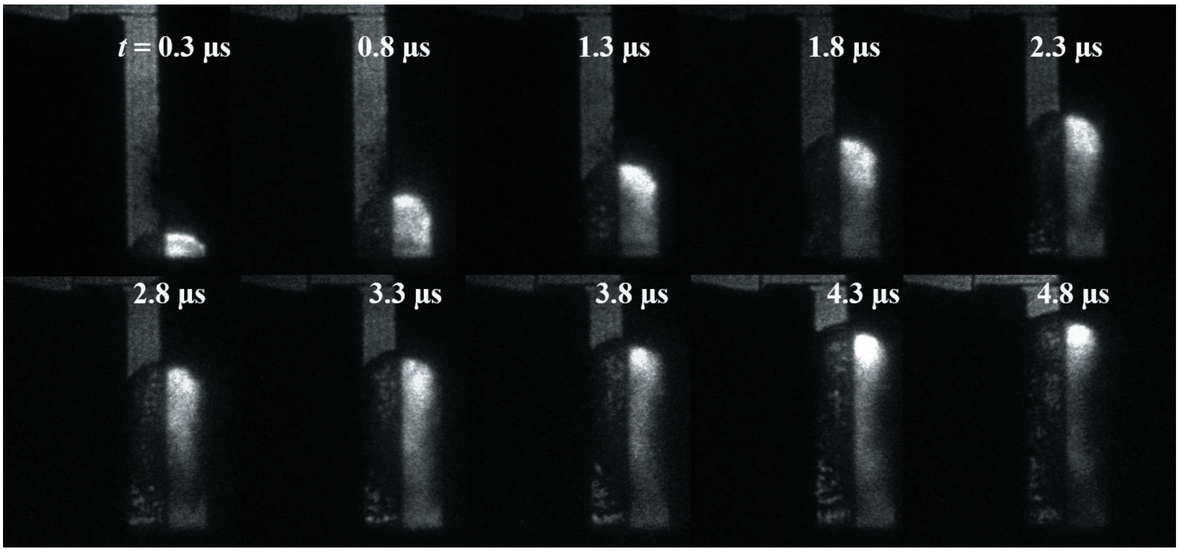

Figure 5. LSD propagation with 1-D tube (10 J). Elapsed time from laser beginning of oscillation is

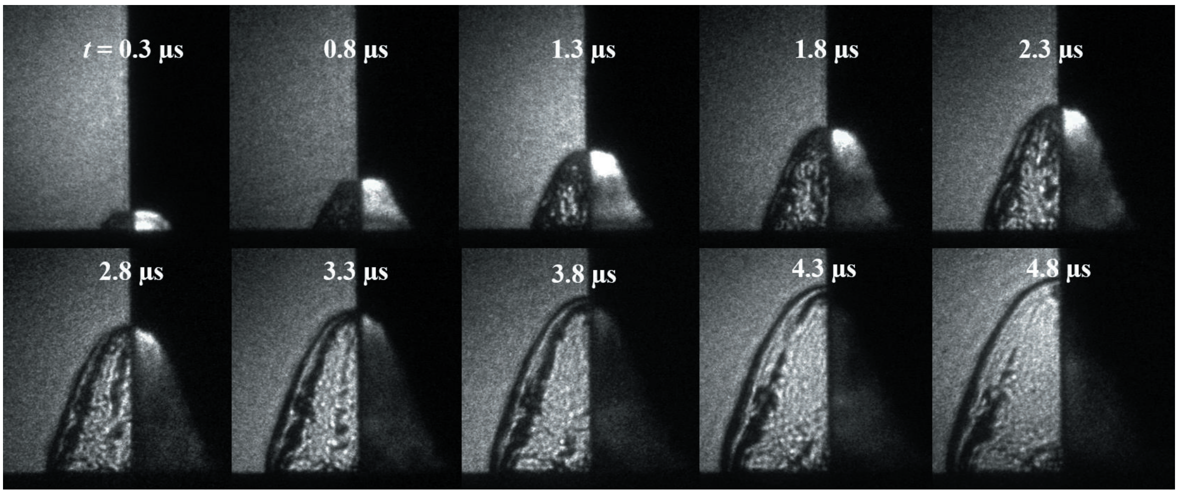

Figure 6. LSD propagation without tube (10 J). Elapsed time from beginning laser oscillation is shown.

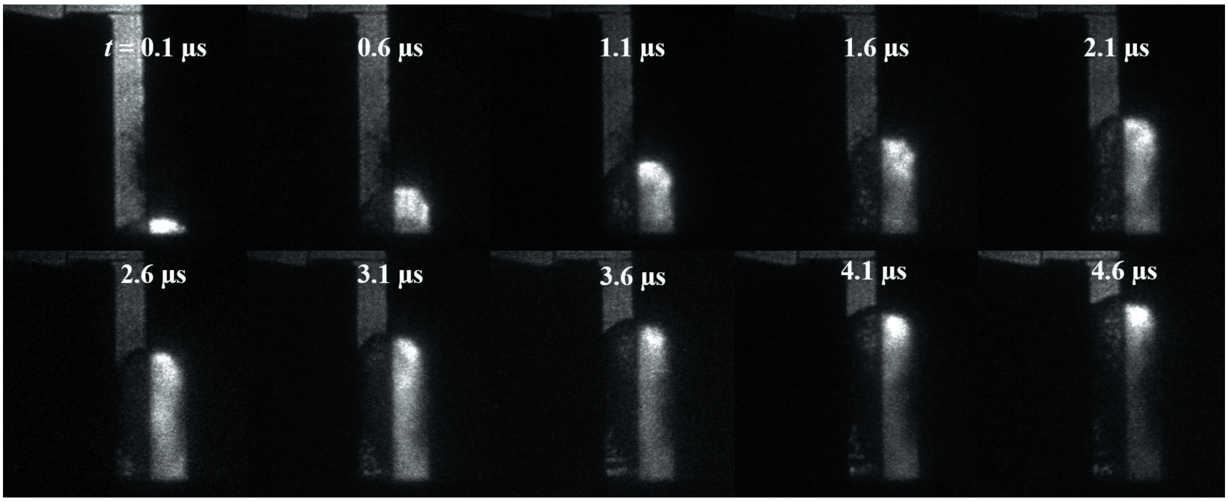

Figure 7. LSD propagation with 1-D tube (8 J). Elapsed time from beginning laser oscillation is shown.

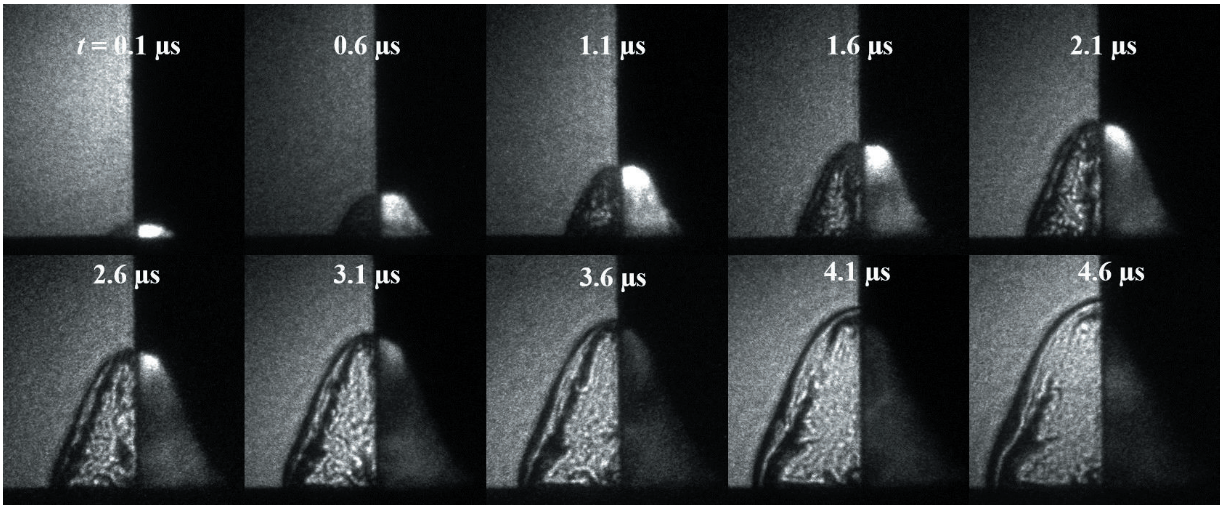

Figure 8. LSD propagation without tube (8 J). Elapsed time from beginning laser oscillation is shown.

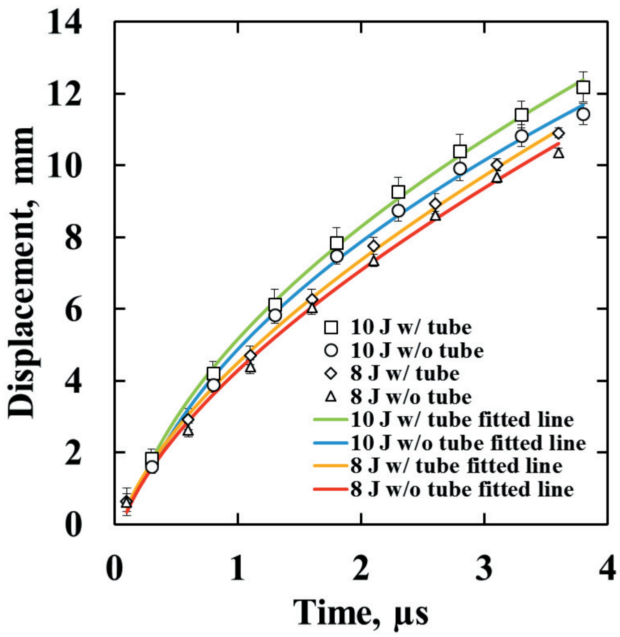

Figure 9. Displacement of ionization front vs. elapsed time from beginning of laser oscillation

By differentiating a fitted curve of $x - t$ diagram in Fig. 9, propagation velocity of LSD wave was obtained. Laser intensity was calculated by dividing laser power by focused beam cross-section. The relationship between laser intensity and propagation velocity of ionization front is shown in figure 6. Raizer proposed that propagation velocity of LSD wave corresponds to Chapman-Jouguet (C – J) detonation[3]. The velocity of C – J detonation D_{CJ} is

$$D_{CJ} = \left[2(\gamma^2 - 1)\frac{S}{\rho_0} \right]^{\frac{1}{3}} \tag{1}$$

Here, γ is specific heat ratio behind the shock front, S is laser intensity and ρ_0 is the density of ambient gas. In the experiment of Shimamura et al[5], electron temperature of plasma produced by same CO_2 laser was around 20000 K. According to Zel'dvich and Raizer, γ is estimated as 1.175 at 20000 K[7]. Thus, γ is assumed to be 1.175. Figure 8 shows that propagation velocity obtained from experiment and velocity of C – J detonation. There is no big difference between results of in tube and without tube. Laser intensity at termination of LSD was around 10-20 GW/m^2 and this value shows good agreement with experiment conducted by Ushio et al[6]. There are certain region that propagation velocity of LSD with energy of 8 J is higher than that of 10 J. According to Eq. (1), propagation velocity is determined by laser intensity uniquely. This contradiction may arise from that Eq. (1) is deduced from hydrodynamic equation assuming a steady state or not only laser intensity but also plasma properties depend on the propagation velocity. Around high intensity region, the velocity of LSD wave is higher than that of C – J. This result suggests that LSD is overdriven detonation because propagation velocity of LSD wave is determined only by development of discharge, not by interaction between shock wave and heating such as that of the ZND model in chemical detonation. In other words, shock wave is driven by plasma which acts like a piston in a strong overdriven detonation.

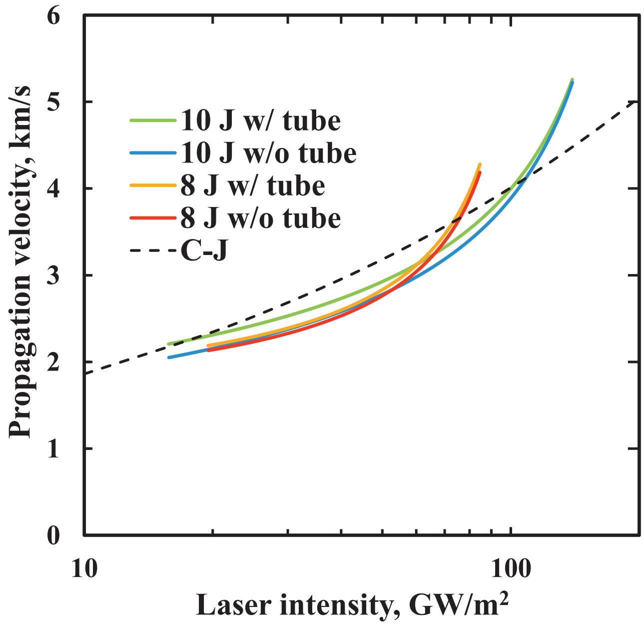

Figure 10. Propagation of ionization front vs. laser intensity

IV. Conclusion

In order to measure 1-D LSD, laser with energy of 10 J and 8 J was focused into a straight tube using two mirrors which have 400 mm and 500 mm focal-length respectively. Displacement of ionization from ignition point was measured by HSHS method. There was no big difference between displacement of ionization front measured in the 1-D tube and without tube. In addition, propagation velocity of detonation wave was compared with that of C – J condition. Propagation velocity may not be determined only by laser intensity but also plasma properties behind shock wave. At high intensity region, propagation velocity of LSD exceeded that of C – J condition and this result suggested that LSD is overdriven detonation.

Acknowledgment

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