DISCHARGE CHARACTERISTICS OF A LASER-ASSISTED PLASMA THRUSTER

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In order to reduce the late-time ablation and to improve thrust efficiency, effects of the utilization of the laser-pulse irradiation, or assistance, were studied, which can be expected to induce plasma from a propellant in a short duration, i.e., using a short-duration conductive region of the plasma between electrodes, the short-pulse switching or discharge can be achieved. Since the use of a shorter pulse of the laser which enables a shorter duration of the pulsed-plasma in this case, the higher peak current and significant improvement of the thrust performance must be expected. In addition, depending on the laser power the laser-induced plasma occurring from a solid propellant usually has directed initial velocity, which should also improve the thrust performance compared to pure PPTs. In this study, a preliminary investigation was conducted on characteristics of pulsed discharges induced by the laser pulse irradiation for various voltages applied to the electrodes including a low-voltage mode, which can be an electrically-assisted laser propulsion mode, and a high-voltage mode, a laser-assisted electromagnetic propulsion mode. Here, a fundamental study of newly developed rectangular laser-assisted pulsed-plasma thruster (PPT) and coaxial laser assisted PPT was conducted. A DC power supply (1000 V) was used for the power source, and an Nd:YAG laser (wavelength: 1.06μm, maximum pulse energy: 1.4J/pulse, pulse width: 10 nsec) was utilized. With this system, the peak current of about 1400A with its duration of 2 usec (FWHM) was observed in a typical case. Moreover, plasma behaviors emitted from each thruster in various cases were observed with the ICCD camera. It was shown that the plasma behaviors were almost identical between low and high voltage cases in the first several hundred nanoseconds, however, the plasma emission with longer duration was observed in higher voltage cases.

INTRODUCTION

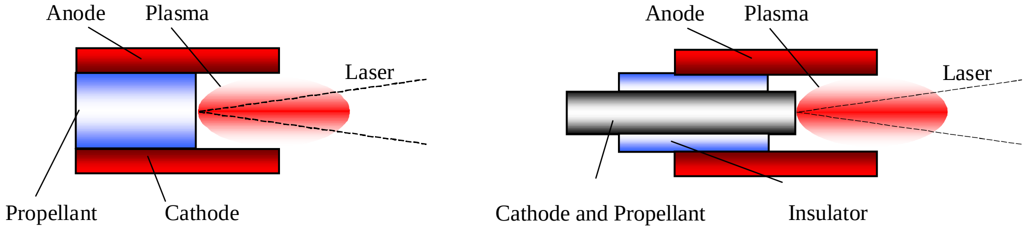
There are growing interests on pulsed-plasma thrusters, PPTs, utilizing a solid propellant, usually PTFE (Teflon), for their system simplicity and advantages on miniaturization and mass reduction for the use of attitude or orbit control thrusters for small-sized spacecrafts, despite the low efficiency.[1-4] In their operation, short pulse discharges with several-microsecond duration are induced across the exposed propellant surface between electrodes, vaporizing and ionizing the surface, and also inducing the pressure force. Then the interaction of the discharge current (tens of kA) and its self-induced magnetic field results as the electromagnetic force, or Lorentz force, acting on the plasma and inducing a directed plasma beam exhaust, or thrust. In this electromagnetic acceleration process, it is necessary to complete phase changes of the propellant, such as vaporization and ionization, and the electromagnetic acceleration at the same time within a short duration of a pulse discharge. An improvement of the thrust performance can be expected with a shorter pulse duration case, since it is capable of higher current per unit time or higher power input, namely higher thrust, and of reducing loads on electrodes. However, it is difficult to complete the process including the phase change and electromagnetic acceleration simultaneously during the discharge pulse, because there is a delay in the phase change of the solid-propellant after the pulse discharge initiation. The surface of the propellant will continue to evaporate long after completion of the discharge pulse, providing mass that cannot experience acceleration to high speeds by the electromagnetic and gasdynamic forces. The various masses including low-speed macroparticles can have quite different velocities. Since the residual vapor or plasma from the late-time evaporation of the propellant surface remains in the discharge chamber due to the delay after the pulse discharge completion, which cannot contribute significantly to the impulse bit, it has been difficult for the thruster of this type to improve the mass loss of the propellant and thrust efficiency.[1-4]

In order to reduce this late-time ablation and to improve thrust efficiency, effects of the utilization of the laser-pulse irradiation, or assistance, were studied, which can be expected to induce plasma from a propellant in a short duration, i.e., using a short-duration conductive region of the plasma between electrodes, the short-pulse switching or discharge can be achieved. Since the use of a shorter pulse of the laser which enables a shorter duration of the pulsed-plasma in this case, the higher peak current and significant improvement of the thrust performance must be expected. In addition, depending on the laser power the laser-induced plasma occurring from a solid propellant usually has directed initial velocity, which should also improve the thrust performance compared to pure PPTs. In this study, a preliminary investigation was conducted on characteristics of pulsed discharges induced by laser pulse irradiations for various voltages applied to the electrodes including a low-voltage mode, which can be an electrically-assisted laser propulsion mode, and a high-voltage mode, a laser-assisted electromagnetic propulsion mode.

EXPERIMENTAL

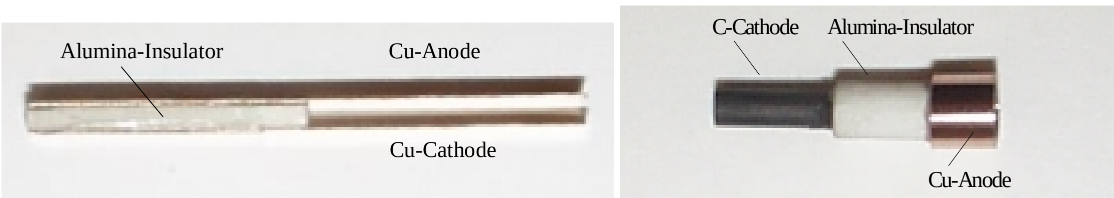
Schematics of laser-assisted plasma thrusters developed in this study are given in Fig.1. The thruster utilizes the laser-beam assistance to induce plasma, ionized from a solid propellant between electrodes, and then an electric discharge is induced in this conductive region. Since the plasma is induced through the laser ablation of the solid propellant in this system, various substances, such as metals, plastics, ceramics, etc., in various phases can be used for the propellant. Therefore, this system must be effective not only for space propulsion devices but also for plasma sources in material processing. In addition, since the plasma has initial velocity through the laser ablation, it is expected that the thrust efficiency and propellant mass loss should be significantly improved. In this study, preliminary tests on two types of thrusters, (a) rectangular type thruster inserting a solid propellant between electrodes, and (b) coaxial type thruster using one of the electrodes (cathode) as the propellant, were conducted as shown in Fig.1.

For the rectangular type thruster (Figs.1(a) and 2(a)), copper electrodes (5 mm in width, 3mm or 20 mm in length) and an alumina propellant (3 mm in height) were used. While for the coaxial type thruster (Figs.1(b) and 2(b)), a copper tube (5 mm in inner-diameter) was used for an anode and a carbon rod (3 mm in diameter) for a cathode which was also used for a propellant. A schematic of experimental setup is shown in Fig.3. A Q-sw Nd:YAG laser (BMI, 5022DNS10, wavelength: λ=1064nm, fixed pulse energy: 220 mJ/pulse, pulse width: 20 nsec) was used for a plasma source, or a laser assistance. The laser pulse was irradiated into a vacuum chamber (10^{-3} Pa) through a quartz window and focused on a target, or a propellant, with a focusing lens (f = 100 mm). Discharge current was monitored with a current monitor (Pearson Electronics, Model-6600, maximum current: 10 kA, minimum rise time: 5 nsec) and an oscilloscope (LeCroy, 9374TM, range: 1 nsec/div ~ 5 msec/div). In this study, preliminary experiments on switching, or discharge between the cathode and anode, and the discharge current characteristics of the laser-induced plasma were conducted. At the first part of the experiment, lowered voltage conditions (~ 100 V) applied on the electrodes were selected to examine discharge current characteristics under the low current range (~ 100 A). In addition, discharge current characteristics for higher current cases, or higher voltages (i.e., up to 1000 V), were also investigated.



(a) Rectangular laser-assisted plasma thruster. (b) Coaxial laser-assisted plasma thruster.

Fig.1 Schematics of laser-assisted plasma thrusters.



(a) Rectangular laser-assisted plasma thruster. (b) Coaxial laser-assisted plasma thruster.

Fig.2 Photos of laser-assisted plasma thrusters.

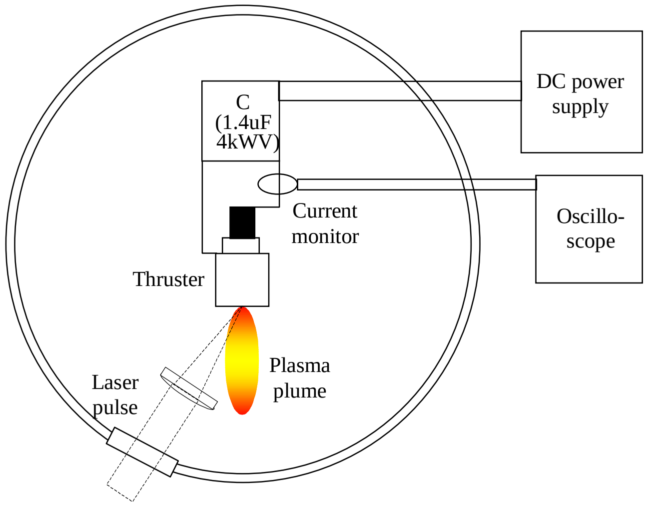
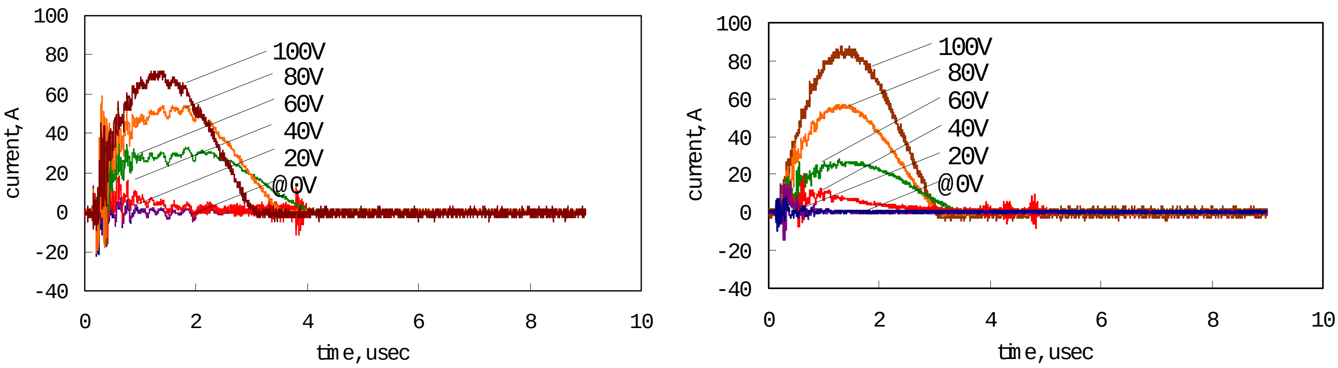


Fig.3 Schematic of experimental setup.



(a) Channel length: *l*c = 3mm.

(b) Channel length: *l*c = 20mm.

Fig.4 Temporal variations of discharge current of rectangular thrusters for low voltage conditions.

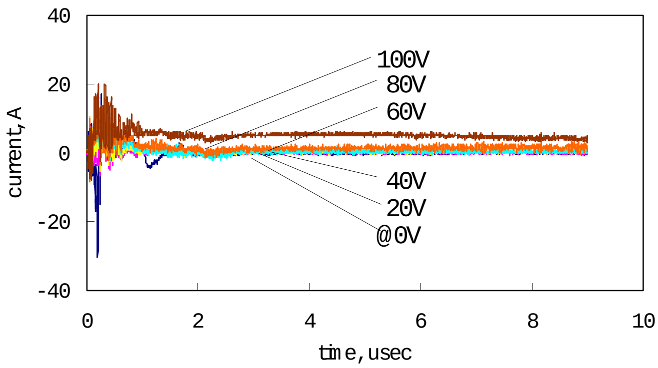


Fig.5 Temporal variations of discharge current of a coaxial thruster for low voltage conditions.

RESULTS AND DISCUTTION

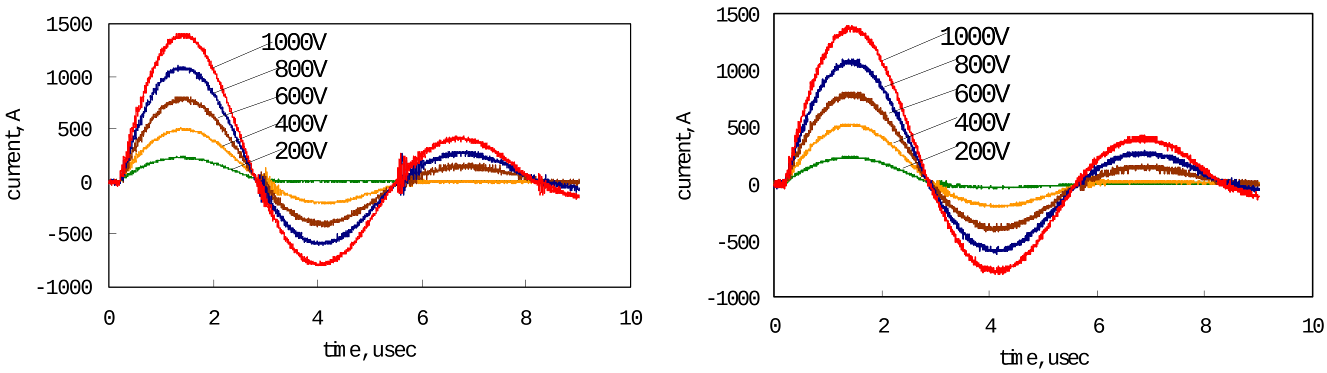
Discharge Characteristics with Laser-Induced Plasma

(1) Low-voltage mode

At a first part, lowered voltage conditions (0 ~ 100 V), applied to electrodes, or charged to a capacitor, were selected to examine discharge current characteristics under the low current range (~ 100 A). Temporal variations of discharge current for rectangular type thrusters are shown in Figs.4(a) and (b). Here, positive values on an ordinate mean the positive current from anode to cathode. It is confirmed that the electric discharge is achieved even under low voltage conditions (~ 100 V). Also it is confirmed that the maximum current of + 30 A can be obtained even with a 0 V case. It can be seen that the current, e.g. a 60 V case for *l*c = 3 mm, abruptly rises up to its first peak value (+ 40 A) within 100 nsec after the laser pulse irradiation, and drops down to minimum value (– 10 A) at 500 nsec. At about 1500 nsec it reaches the second peak value (+ 30 A). After oscillating with about sub-hundred nsec period, its amplitude converges zero at about 4 usec for 60 V, and 3 usec for 100 V. For higher voltage cases this period tends to become shorter. Comparing different channel length cases, it is shown that higher peak currents can be obtained with a longer channel case.

Temporal variations of discharge current for a coaxial thruster are shown in Fig.5. Similar to rectangular cases, the current, e.g. a 60 V case, rapidly increases to its peak value (+ 10 A) within 10 nsec after the laser pulse irradiation, and drops down to minimum value (– 10 A) at 20 nsec. After oscillating with about sub-hundred nsec period, its amplitude converges zero at about 1000 nsec. At higher voltage cases (ex. 100 V), higher peak current and longer pulse width are observed, which is followed by the long second pulse. A possible cause of the second long pulse in the coaxial thruster is probably due to residual plasma left in and/or around a discharge chamber with low current density, conducting small portion of the current, and also to plasma induced from a cathode surface at the first discharge, however, details of these mechanisms are not clear at the moment.

Although conventional pulsed plasma thrusters (PPTs) have been driven with several-kilovolts at several-microsecond pulse-discharges[1-4], it is shown that much shorter pulse discharges can be achieved under much lower voltage conditions with the laser-assisted discharges. It has been reported that pulsed plasma with hundred-nanosecond duration is induced through a nanosecond laser pulse irradiation on a solid target.[5-7] So it is expected that within this duration a conductive region of the plasma enables short switching, or a short electric discharge, between electrodes. Therefore, it is presumed from these results that measured current patterns must depend on plasma behaviors, or pulses, which can be actively controlled with the incident laser pulses. In laser ablation processes, it has been reported that the electron emission first occurs after laser pulse irradiation, followed by the ion emission with higher degrees of ionization after several nanoseconds, after which those with lower degrees of ionization follow.[5-7] Therefore, the first positive peaks of the discharge current in Figs.4 and 5 are probably due to the current by electrons. While the following negative peak of the current may be due to positive ions and/or to oscillation of the electrons, details of these points are not yet clear.



(a) Channel length: *l*c = 3mm. (b) Channel length: *l*c = 20mm.

Fig.6 Temporal variations of discharge current of rectangular thrusters for high voltage conditions.

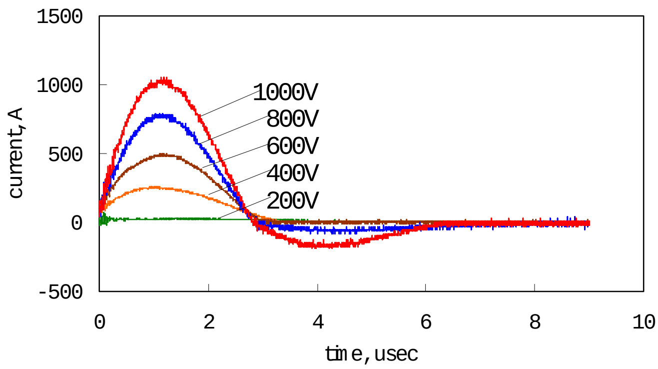


Fig.7 Temporal variations of discharge current of a coaxial thruster for high voltage conditions.

(2) High-voltage mode

Temporal variations of discharge current of rectangular thrusters are given in Figs.6(a) and (b), for high-voltage mode cases, where higher voltages (upto 1000 V) are applied to electrodes. From the figure, the current, e.g. at 1000 V, abruptly rises and reaches a maximum value, 1400 A, at 1.5 usec, after which it falls down to a minimum value (– 750 V) at 4 usec and converges zero at about 10 usec. Comparing with the low current mode cases shown in Fig.4, the current peak is significantly high in high voltage cases.

The plots of the current for a coaxial thruster in high-voltage mode cases are shown in Fig.7. It is shown that the current, e.g. at 1000 V, increases rapidly and reaches 1000 A at 1.5 usec, and falls down to – 300 A at 4 usec, after which it converges zero at 6 usec. Comparing with the low-voltage mode case shown in Fig.5, higher maximum current and longer pulse width can be obtained.

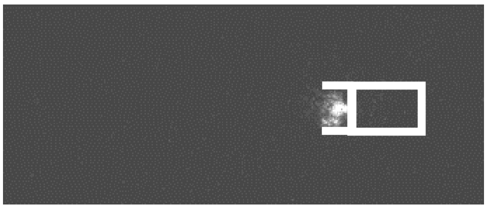
From these results, it is found that the discharge duration at the low-voltage case (~ 40 V) is as long as the duration of laser-induced plasma. Therefore, the discharge in the low-voltage case must be controlled with the incident laser pulse, or laser-induced plasma. While in the high-voltage case, the discharge duration is much longer than that of laser-induced plasma. In this case, the laser-induced plasma should be leading the main discharge from a capacitor, where some amount of the propellant surface must be vaporized through the main discharge.

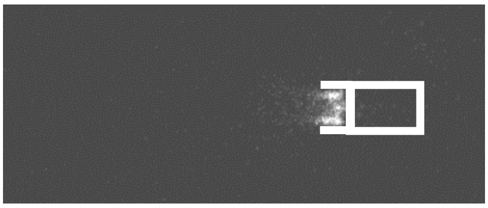
The difference of current waveforms between high-voltage and low-voltage conditions is probably due to the difference of discharge processes in both cases. In the low-voltage case, discharge energy of the capacitor (= $CV^2/2$) is relatively small compared to the laser energy, however, in the high-voltage case, higher energy must be discharged. Considering ratios of the laser energy to these discharge energies, the discharge process in the high-voltage mode must be defined as the laser-assisted electric discharge, or the laser-assisted electric propulsion mode, while in the low-voltage mode with smaller electric energy, as the electrically-assisted laser-induced process, or the electric-assisted laser propulsion mode. As shown in these figures, there is a significant difference in the current waveforms between two types of thrusters.

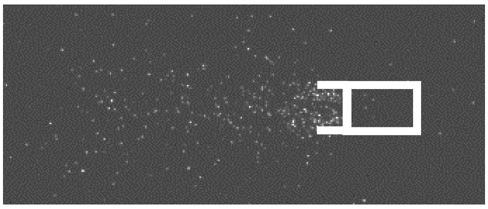
Discharge Plasma Observation by ICCD Camera

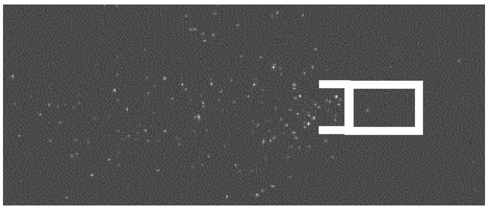
ICCD camera images (gate width: 10nsec) of exhaust plasma plumes from a rectangular thruster (channel length: 3 mm) are shown in Figs.8 and 9, for 0 V and 1000 V cases, respectively. After the laser irradiation, the small spot plasma at the center of an exposed propellant surface is induced. At 50 nsec and 100 nsec in both figures, plasma is scattered along both anode (upper plate) and cathode with almost symmetric distribution. Comparing Figs.8 and 9, it is shown that plasma behaviors are almost identical between those two cases upto 400 nsec. At 500 nsec of 1000 V case, an asymmetric emission is occurring near the anode edge. After which the plasma emission decreases with time in 0 V case, while in 1000 V case, still inducing the emission. Corresponding the current forms of Fig.4, the plasma is visible upto 1.5 usec in 0 V case, while in 1000 V case, much longer upto 10 usec.


(a) 10 nsec .


(b) 50 nsec.


(c) 100 nsec.


(d) 500 nsec.


(e) 1000 nsec.

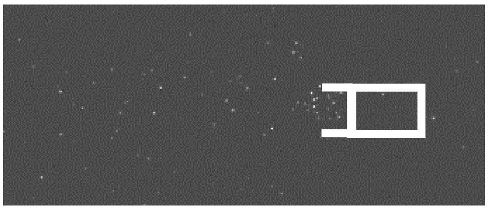
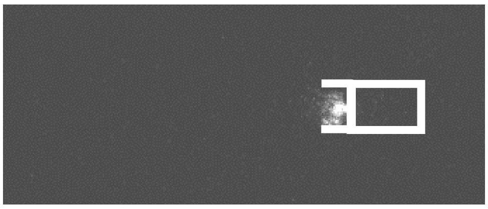
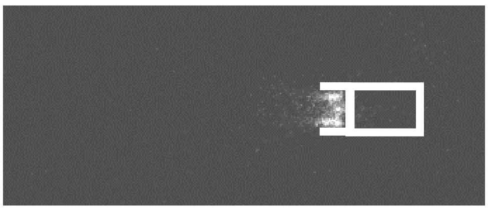
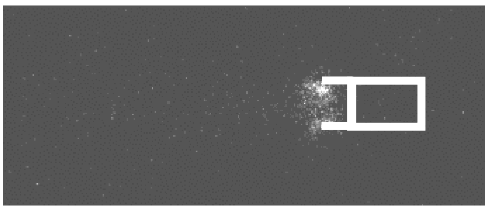

(f) 1500 nsec.

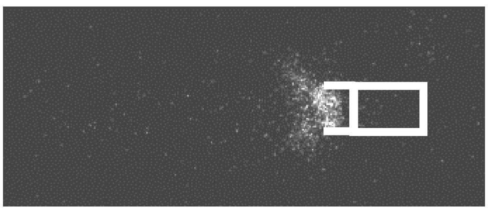
Fig.8 ICCD images (gate width: 10nsec) of exhaust plasma plume from
a rectangular thruster (channel length: 3 mm, anode: upper plate) for charged voltage: 0 V.


(a) 10 nsec .


(b) 50 nsec.


(c) 100 nsec.


(d) 500 nsec.


(e) 1000 nsec.

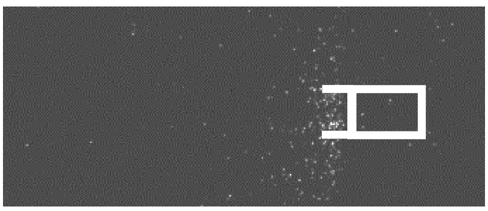
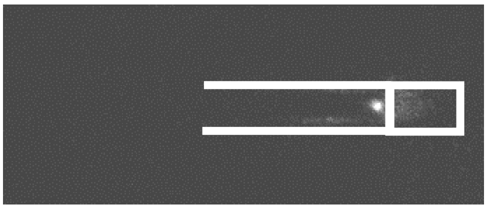
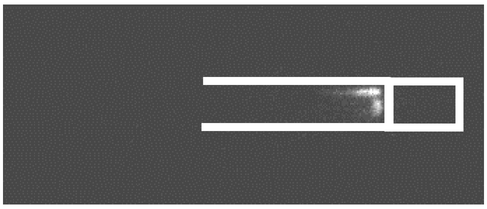
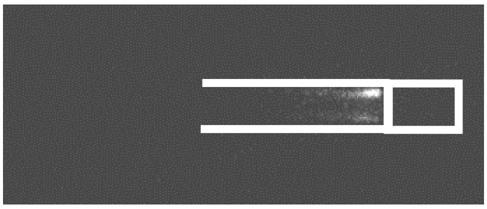
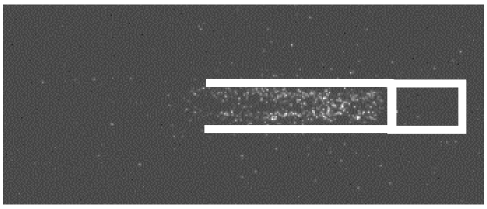

(f) 5000 nsec.

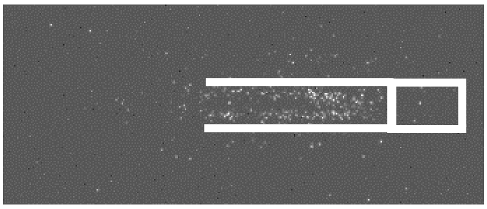
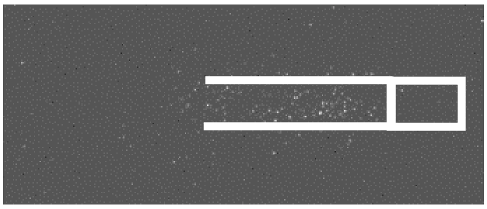
Fig.9 ICCD images (gate width: 10nsec) of exhaust plasma plume from
a rectangular thruster (channel length: 3 mm, anode: upper plate) for charged voltage: 1000 V.

(a) 10 nsec . (b) 50 nsec.

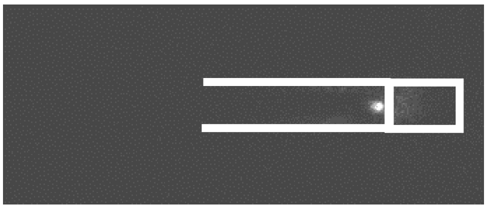
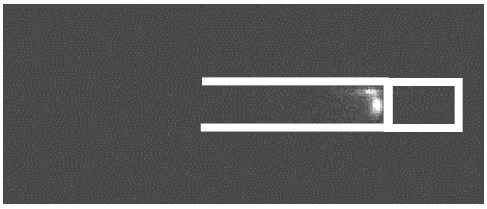



(c) 100 nsec. (d) 500 nsec.

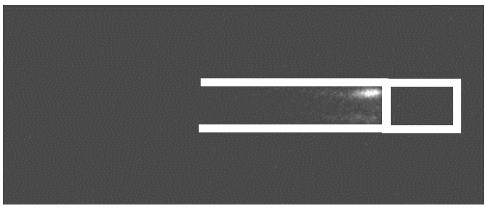
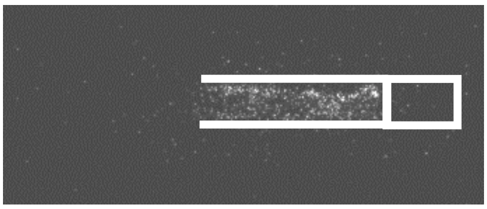



(e) 1000 nsec. (f) 1500 nsec.

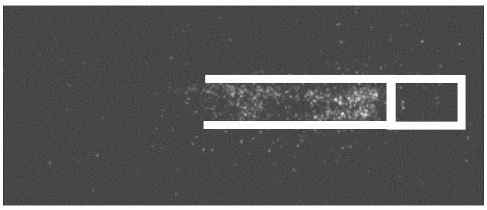
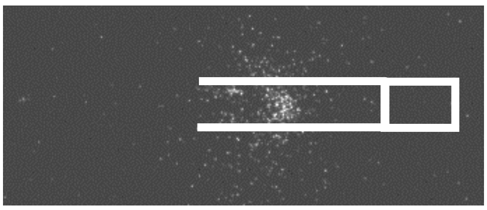
Fig.10 ICCD images (gate width: 10nsec) of exhaust plasma plume from
a rectangular thruster (channel length: 20 mm, anode: upper plate) for charged voltage: 0 V.

(a) 10 nsec . (b) 50 nsec.

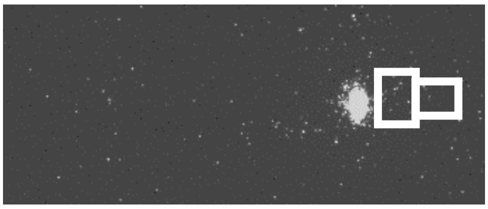
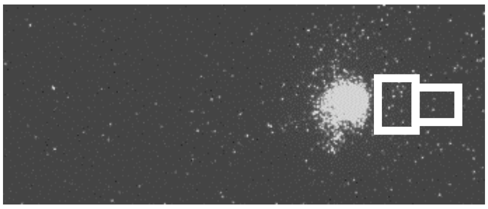



(c) 100 nsec. (d) 500 nsec.

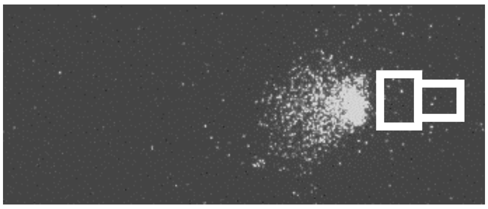
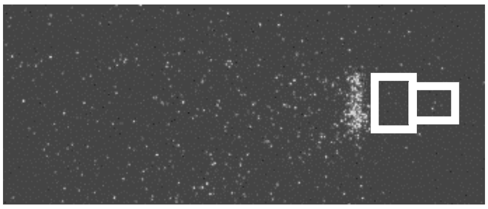



(e) 1000 nsec. (f) 5000 nsec.

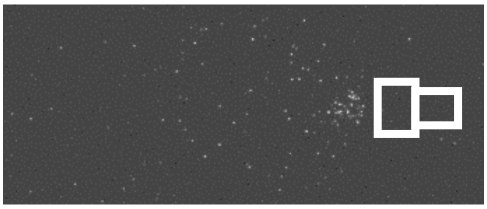
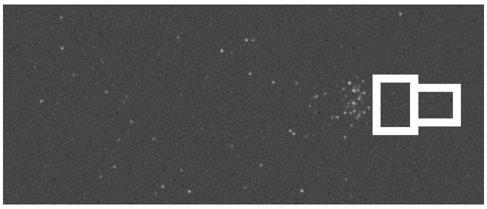
Fig.11 ICCD images (gate width: 10nsec) of exhaust plasma plume from
a rectangular thruster (channel length: 20 mm, anode: upper plate) for charged voltage: 1000 V.

(a) 10 nsec . (b) 50 nsec.

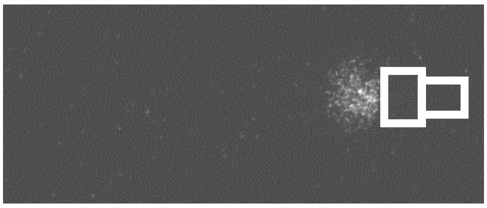



(c) 100 nsec. (d) 500 nsec.

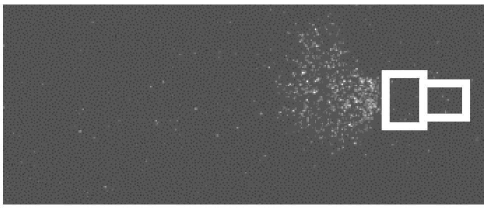
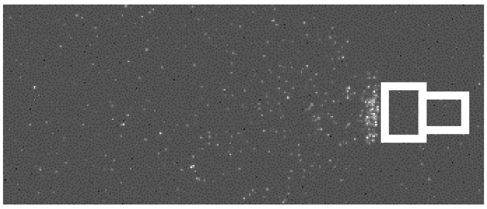



(e) 1000 nsec. (f) 1500 nsec.

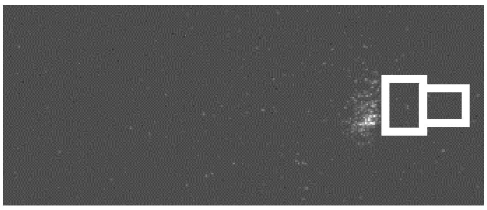
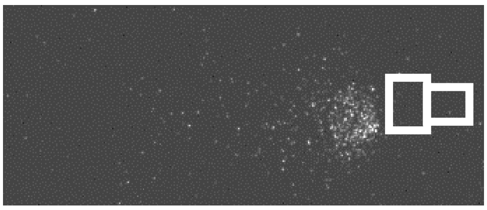
Fig.12 ICCD images (gate width: 10nsec) of exhaust plasma plume from a coaxial thruster (channel length: 2 mm) for charged voltage: 0 V.

(a) 10 nsec . (b) 50 nsec.

(c) 100 nsec. (d) 500 nsec.

(e) 1000 nsec. (f) 5000 nsec.

Fig.13 ICCD images (gate width: 10nsec) of exhaust plasma plume from a coaxial thruster (channel length: 2 mm) for charged voltage: 1000 V.

ICCD images of exhaust plasma plumes from a longer rectangular thruster (channel length: 20 mm) are shown in Figs.10 and 11, for 0 V and 1000 V cases, respectively. Again after the laser irradiation, the small spot plasma at the center of an exposed propellant surface is induced. At 50 nsec in both figures, a plasma emission is occurring along the anode (upper plate), and also is asymmetric. The luminous structure parallel to electrodes shown to be evolving in the upper electrode is typical of breakdown waves, commonly known as streamers.[9] Although any canted current sheet structures, typical to rectangular pulsed-plasma thrusters,[9] are not observed in these cases, an "X"-shaped current sheet, or symmetrically canted current sheets from both electrodes, can be seen after 500 nsec. Comparing Figs.10 and 11, it is shown that plasma behaviors are almost identical between those two cases upto 700 nsec. At 1000 nsec of 1000 V case, a plasma emission is occurring near the electrodes edge. After which it decreases with time in 0 V case, while in 1000 V case, still inducing the emission near the electrodes edge. Regarding the current forms of Fig.4, the plasma is visible upto 1.5 usec in 0 V case, while in 1000 V case, much longer upto 10 usec.

ICCD images of exhaust plasma plumes from a coaxial thruster are shown in Fig.12 and Fig.13 for 0 V and 1000 V cases, respectively. In the 0 V case, images of the plasma emission is intensified than the other cases, since the emission strength is very low. Comparing Figs.12 and 13, it is shown that plasma behaviors are almost identical between those two cases upto 1000 nsec. After which the plasma emission decreases with time in 0 V case, while in 1000 V case, still inducing the emission. Corresponding to the current forms of Fig.5, the plasma is visible upto 1.5 usec in 0 V case, while in 1000 V case, much longer upto 10 usec.

From these results, it is found that a discharge mechanism of the low voltage mode cases is not similar to that of the high-voltage mode. As discussed above, the former case can be categorized to the electric-assisted laser propulsion mode with the shorter discharge duration, and another case, to the laser-assisted electric propulsion mode with much longer discharge duration, probably inducing larger impulse.

CONCLUSION

Novel laser-assisted plasma thrusters were developed and tested, in which plasma was induced through a laser beam irradiation onto a target, or a laser-assisted process, and accelerated by electrical means instead of a direct acceleration only by using a laser beam. A fundamental study of newly developed rectangular laser-assisted pulsed-plasma thruster (PPT) and coaxial laser assisted PPT was conducted. Inducing the short-duration conductive plasma between electrodes with certain voltages, the short-duration switching or a discharge was achieved.

At low-voltage conditions (~ 100 V), applied to electrodes, or charged to a capacitor, it was confirmed that the electric discharge can be achieved even under low voltage conditions. From these results, it was found that the discharge duration at the low-voltage case was as long as the duration of laser-induced plasma. Therefore, the discharge in the low-voltage case must be controlled with the incident laser pulse, or laser-induced plasma. While in the high-voltage case (~ 1000 V), the discharge duration was much longer than that of laser-induced plasma. In this case, the laser-induced plasma should lead the main discharge from a capacitor, where some amount of the propellant surface must be vaporized through the main discharge. Considering ratios of the laser energy to these discharge energies, the discharge process in the high-voltage mode must be defined as the laser-assisted electric discharge, or the laser-assisted electric propulsion mode, while in the low-voltage mode with smaller electric energy, as the electrically-assisted laser-induced process, or the electric-assisted laser propulsion mode. There were significant differences in the current waveforms between two types of thrusters in various voltage modes.

Moreover, plasma behaviors emitted from each thruster in various cases were observed with the ICCD camera. It was shown that the plasma behaviors were almost identical between low and high voltage cases in the first several hundred nanoseconds, however, the plasma emission with longer duration was observed in higher voltage cases.

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