

Small-Sized Laser Thruster for Attitude Control and Trajectory Control of Satellite

Yoshinari Minami^{1,†}, Shigeaki Uchida^{2,†} Yasuo Takahashi^{3,†}

1 Advanced Sci.-Tech. Rsch. Orgn.(Formerly NEC Space Development Division);
y-minami@mtj.biglobe.ne.jp

2 Osaka University; uchidashigeaki@gmail.com

3 Osaka University; takasy@casi.osaka-u.ac.jp

* Correspondence: y-minami@mtj.biglobe.ne.jp

Abstract: The authors proposed research of manned spacecraft by laser thruster [1, 2].

In this paper, we introduce a small-sized laser thruster for satellite attitude control and trajectory control. The target thrust is 1N laser thruster. The laser thruster uses the reaction thrust of the steam or water explosion generated by laser light irradiation. Since the laser power and propellant flow rate can be set independently and the propellant injection speed can be controlled over a wide range, both high specific impulse-low thrust mode and high thrust-low specific impulse mode can be selected by controlling the laser output with vapor or water as a propellant. This mode change can be performed by controlling a high power continuous wave (cw) laser diode output power. The thrust (F) and the specific impulse (I_{sp}) can arbitrarily be variably controlled by the laser power (P_L) and the laser power density (W/cm^2). Laser propulsion theory, outline of laser thruster, laser thruster for satellite attitude control and trajectory control are described in detail.

Keywords: laser propulsion; vapor; water ablation; high-power Laser Diode (LD); fiber laser; fuel cell; satellite; attitude control; trajectory control; laser thruster

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I. Introduction

Electric propulsion systems such as ion thrusters, Hall thrusters and MPD (Magneto Plasma Dynamic) thrusters are objects of research and development as the next generation space propulsion systems. The microwave discharge ion thruster already has made "Hayabusa (MUSES-C)" to sail in space [3]. Hayabusa is a spacecraft exploring the asteroid Itokawa in the asteroid sample return project conducted by JAXA (Japan Aerospace Exploration Agency) ISAS (Institute of Space and Astronautical Science) of Japan. Moreover, the candidate of other promising propulsion systems is laser propulsion. The concept of the laser propulsion was proposed by A. Kantrowitz in 1971 [4]. It was estimated that a one-megawatt laser system can launch a one-kilogram payload to the low earth orbits from the ground. Since then, the study of laser propulsion had been evolved in a laboratory fundamental investigation on basic characterization of laser plasma interactions. One typical example of these investigations was done by Phipps where universal scaling on impulse generation in term of laser parameters over many orders of magnitude was found [5, 6]. The optimization introduced above can be viewed on this scaling in terms of laser parameters such as intensity, wavelength and pulse width. One of the most successful demonstrations of the practical use of laser propulsion was led by L. Myrabo and F. B. Mead in July 1999 [7]. They succeeded in a vertical flight of 50 g mass to 71 m height with a maximum acceleration of 2.3G in an Air Breathing Pulse Detonation Laser method driven by a repetitively pulsed CO₂ laser of an average output power 10 kW. However, the above-mentioned laser propulsion requires both laser source and power source on the ground. Because laser propulsion vehicle cannot load such a weighty laser and power sources. Even with the successful demonstration for laser propulsion, the scheme depending on a remote laser power station will face the fatal disadvantage of not being able to fly freely. It is necessary for a space vehicle to have an independent propulsion system carrying laser source and power source on board in order to fly freely.

Such an independent laser propulsion system became possible by the recent development of semiconductor power Laser Diode (LD) technology and miniaturization technology of power supply. Incidentally, it is promising to use water to improve the thrust of laser propulsion as propellant. Laser propulsion described in this paper uses reaction thrust of the steam or water explosion generated by laser light irradiation. Neither huge air pollution nor space environmental pollution that conventional aircraft and chemical rockets cause will take place. The amount of aircrafts that exhausts CO₂ will decrease by using water as a propellant instead of the fossil fuel such as gasoline, and there is an advantage of reducing the instability that originates from the negative environmental impact, and the crude oil price fluctuation of the aircraft that will

increase in the future, too. Laser propulsion by the water explosion is not only for aerospace use but also space mission use. The Orbital Transfer Vehicle (OTV) for sightseeing that flies between on-orbit structures such as space hotel and International Space Station (ISS) or the moon will be needed when ISS operates on the Low Earth Orbit (LEO) and the space hotel is built as an outlook on the universe sightseeing tour business in the future. Not only the moon car, but also a moon vehicle that flies over the moon surface transporting cargo, and the crew will be needed for full-scale lunar base development by an international collaborative project from 2015. The laser propulsion vehicle that makes water a propellant is expected to be used as such an OTV like buses and cars in space. We investigated the laser propulsion vehicle that irradiated the laser to ice or water and had generated thrust from the steam explosion by the ablation in the second phase of Advanced Space Propulsion Investigation Committee of the Institute of Japan Society for Aeronautical and Space Science since 1997 [8, 9]. Independently, some experiments have been done in Tokyo Institute of Technology with a detailed analysis [10].

The main idea we would like to convey by the paper is the use of laser diode pumped solid state laser, DPSSL (Diode Pumped Solid State Laser) that can easily switch power density delivered on propellant resulting in variable specific impulse over an order of magnitude. This controllability has not been accessible by chemical or ion propulsion systems before due to their chemical-potential or space-charge limits. DPSSL is an emerging technology for these years thanks to the advent of high power LDs [11]. We believe that the combination of DPSSL as a power converter for a laser propulsion system and variable I_{SP} thruster is new.

The details of laser propulsion are described below.

II. Outline of Laser Propulsion

2.1 Features

The basic principle of laser propulsion is the same as for a rocket except that acceleration of propellant is done by ablation using the laser irradiation. Any materials melt and evaporate when the irradiated by a high power laser radiation. Reaction thrust is generated due to vapor molecular or ions are ejected in the direction of pressure gradient formed on the material surface. This corresponds to the jet of the rocket, and is a propulsion principle by the same momentum thrust as the rocket. The laser propulsion method is mainly classified into two kinds. The first one uses continuous wave (cw) laser for heating a propellant with a relatively high molecular weight such as water. Temperature of propellant stays relatively low and the efficiency of converting laser energy to momentum is high. The second one typically uses pulsed laser radiation to generate high temperature vapor or even ionized gas of light atomic/molecular weight such as hydrogen. One of the advantages of laser propulsion is that driving energy of propellant can be delivered from a remote laser station and no energy source needs to be on-board resulting in an increased payload. This method might be acceptable for the rocket launch from the ground or moon mission where a laser beam from a fixed laser station can reach the space craft while the beam diameter remains reasonable size for a laser power receiver before beam divergence becomes larger than space craft. For example, if one assumes the diameters of laser transmitter and receiver to be 10 and 5 meter respectively for diffraction limited infrared laser beam, the maximum transmitting distance would be 150,000 km. Beyond this distance, power receiving efficiency decreases to the square of the transmitting distance. Therefore, on-board power supply and laser system become a reasonable choice for any mission within solar system and beyond unless many laser power stations are distributed along space craft orbits which does not seem feasible. Besides beam divergence, keeping beam tracking between very long distance in free space is a challenging engineering task. It is desirable that a free flight with a compact energy source for laser driver becomes possible. This is already possible considering the recent developments of high power laser diodes and the miniaturization of a power supply. The electric power of a practical ion engine has been already supplied by the power source equipped on a satellite and spacecraft. More than an equivalent amount of thrust to ion engines can be generated by laser system wired with the current on-board power supply system.

2.2 Laser Propulsion Theory

In laser propulsion technology, velocity and fluid conditions of propellant can be controlled by the energy density of laser radiation by means of the combination of laser parameters such as wavelength, intensity and propellant. There are two important performance parameters defined for the thrust generation by laser propulsion scheme [12]. They are the specific impulse I_{SP} used in the conventional propulsion scheme and momentum coupling coefficient C_m ($N \cdot s/J = N/W$) specific to laser propulsion.

$$C_m = \frac{F}{P_L} = \frac{\dot{m}V_E}{P_L} \quad . \quad (1)$$

$$I_{SP} = \frac{F}{g\dot{m}} = \frac{\dot{m}V_E}{g\dot{m}} = \frac{V_E}{g} \quad , \quad (2)$$

where F is thrust, I_{SP} is specific impulse, g is gravitational acceleration, \dot{m} (kg/s) is propellant flow rate, V_E is exhaust velocity of propellant.

C_m is defined as a ratio of thrust F to incident laser power P_L . It is similar to the thrust electric power ratio (N/kW) of the electric propulsion. The specific impulse I_{SP} depends only on propellant speed.

Further, similarly to the electric propulsion, the following relation between thrust F and propulsion efficiency η , which is defined as the ratio of propellant kinetic energy to the laser energy, is important.

$$F = \frac{2\eta P_L}{g I_{SP}} = C_m P_L \quad , \quad (3)$$

where g is gravitational acceleration and P_L is laser power.

In addition to these, a fraction of laser power, P_L converted to propellant kinetic power; $\dot{m} V_p^2/2$ is defined,

$$\eta = \frac{\frac{1}{2} \dot{m} V_p^2}{P_L} \quad . \quad (4)$$

Combining Eqs.(1),(2),(4) give the relation among these parameters;

$$C_m \cdot I_{SP} = \frac{F^2}{P_L g \dot{m}} = \frac{\dot{m}^2 V_E^2}{P_L g \dot{m}} = \frac{2}{g} \frac{\frac{1}{2} \dot{m} V_E^2}{P_L} = \frac{2}{g} \eta \quad . \quad (5)$$

Equation (5) shows the fluid efficiency. The performance of laser propulsion is controlled by η as an upper bound; performance of laser propulsion can be controlled with the upper limit of conversion efficiency (fluid efficiency) from laser energy to plasma kinetic energy. On the other hand, specific impulse I_{SP} is determined only at speed V_E of the propellant from Eq.(2). Because C_m and I_{SP} are inversely proportional to each other from the Eq.(5), when fluid efficiency ($2\eta/g$) is determined, a trade-off of C_m and I_{SP} becomes possible. Therefore, a trade-off between efficiencies of the laser power and the propellant is possible. For instance, it is shown that the propulsion system that produces thrust by a little amount of propellant, *i.e.*, large specific impulse (large I_{SP}) and produces large thrust to the laser power (large C_m because a large amount of propellant is necessary) can design laser propulsion while reflecting the condition of reality.

In other words, selection between high C_m system and high I_{SP} system can be realized by controlling propellant exhausting velocity. The maximum energy efficiency and performance, “energy saving mode” or “propellant saving mode” of a laser thruster are determined by η and the exhaust velocity of propellant. The performance of laser propulsion scheme is not limited by the “specific” chemical energy of fuel. Thermal energy of propellant can be controlled by the ratio between propellant mass flow rate and laser power both of which are easily controlled without installing any complex devices. The propellant saving mode of high I_{SP} is the best choice for the transition to the geosynchronous orbit from a circular orbit or a deep space mission.

In the case of pulsed laser mode, since one pulse energy E (J), pulse duration τ (s), pulse repetition rate f (Hz), average laser power P_{ave} and peak laser power P_{pk} have the following relations

$$E = P_{pk} \tau \quad , \quad P_{ave} = E f \quad . \quad (6)$$

Substituting average laser power P_{ave} for P_L in Eq.(3), thrust F is given by

$$F = \frac{2\eta P_{pk} \tau f}{g I_{SP}} \quad . \quad (7)$$

Incidentally as described in Eq.(2), the specific impulse I_{SP} depends only on propellant speed V_E .

Also, from Eq.(5), trade-off between C_m and I_{SP} is possible if fluid efficiency η is determined.

High specific impulse I_{SP} or high C_m can be selected by controlling the exhaust speed of the propellant. It will control the temperature of the laser plasma.

2.3 Outline of Laser Engine System

Laser propulsion of this proposal can use water that is stable and cheap neither the oxidant nor the reducing agent with high chemical revitalization as a propellant. Moreover, the vehicle emission is only steam that has no negative impact to the global environment, and the meaning of developing such a propulsion system for the aerospace plane in the future is very high. Laser propulsion is a technology to convert the thermal energy given to the propellant by using high power density (light intensity) character of the laser into the kinetic energy and to generate the thrust. The most significant advantage of laser propulsion is the ability of controlling thermal and kinetic energies of propellant with a wide range according to the purpose of a mission. Large laser power or small laser power can be arbitrarily tuned to the target. Moreover, use of chemically stable propellant such as water results in low cost thruster and high reliability of the thruster system.

Laser generated thrust and the velocity of ablating gas have been measured in a number of laboratory experiments with a wide range of laser intensities, wavelengths on various target (propellant) materials. It has been clarified that ablation velocities from 100 m/s ($I_{SP}=10$ s) to 40 km/s ($I_{SP}=4000$ s) are possible by selecting a proper combination of ablating materials and laser conditions, mainly intensity. This basic data base forms a foundation of designing a laser propulsion system.

Figure 1 summarizes the relation between laser power and thrust with typical combinations of η and I_{SP} as parameters. For example, blue solid line is the case of 600-s I_{SP} that corresponds to the performance of liquid oxygen and hydrogen fuel rocket systems such as HII-A. Red dotted line with 3000-s I_{SP} corresponds to the performance of ion engines powering, for example JAXA Hayabusa, which requires only limited amount of propellant mass for large thrust. Since at 3000-s I_{SP} , the temperature of ablating gas is so high that plasma radiation loss results in low energy efficiency. Laser diodes (LDs), which have made remarkable technical progress in terms of high power generation are supposed to be a suitable choice for an on-board power source. LDs can perform at their best when used in a cw mode and are suitable for generating low I_{SP} thruster while pulsed laser devices generating high peak power are suitable for high I_{SP} thruster. An example of realizing such pulsed laser is a Diode Pumped Solid State Laser, DPSSL as shown in Fig.2 where LDs pumps a Q-switched solid state laser. The solid laser can easily generate the pulse of light by the combination of Q switch element and crystal laser medium such as Nd:YAG that can accumulate large energy and emits radiation energy instantaneously. A typical power flow of the system element for a 1000 W power supply capacity is shown in Fig.2 as an example (its outputs and efficiency). The system that generates the thrust of several milli newtons by this device is possible. The output of the LD laser power 700 W from the 1000 W power supply is obtained by assuming the conversion efficiency of the LD to be 70%. The size of the power supply fits to a standard 700 mm wide rack space. Pumping power from LDs is accumulated in the Nd:YAG medium while no lasing takes place. Considering a quantum efficiency of the Nd:YAG system and Q-switching process of 70% and 50% respectively result in a 250 W average power of the output pulse train. A peak power of 2.5×10^5 W which is high enough to generate plasma on a propellant surface is expected.

For instance, if the speed of the exhausting gas is increased, large momenta can be generated with a small amount of propellant mass and large amount of laser energy. On the other hand, if the speed is reduced, the same momentum can be obtained by smaller laser energy. The former was a condition of the electric propulsion (speed 10km/s or more of the propulsion gas) such as Hayabusa, and it was possible to fly to the asteroid using fewer propellants. When a large amount of propellant is available and large thrust is needed, latter case where speed of the exhausting gas is 5 km/s or less will be adopted. In a laser propulsion system, such engine performance can be switched. Hayabusa spacecraft (four microwave discharge ion thrusters are mounted) sailed throughout the space by means of three microwave discharge ion thrusters operating at 8 mN each simultaneously resulting in the total thrust of 24 mN. Thrust more than the equivalent can be generated using the electric power of about 1 kW (power consumption 349 W of one ion thruster) with the laser engine of a high-power LD itself or LD pumped YAG laser.

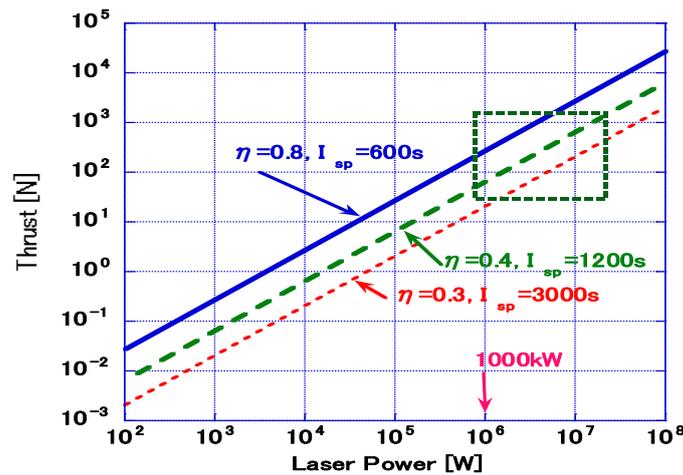


Figure 1. Relation between laser output and thrust.

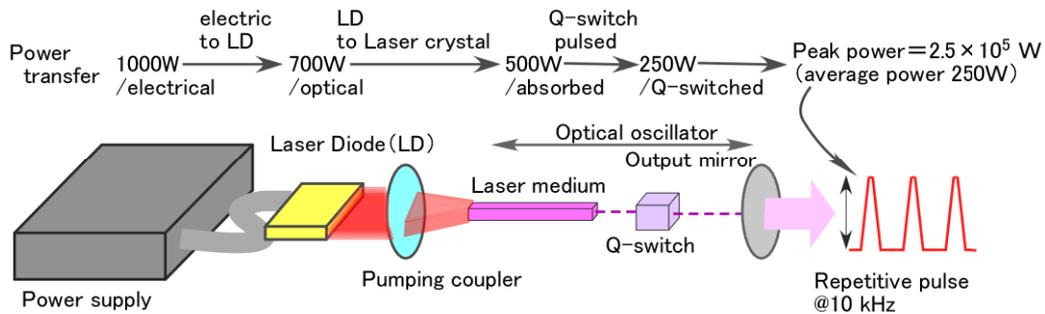
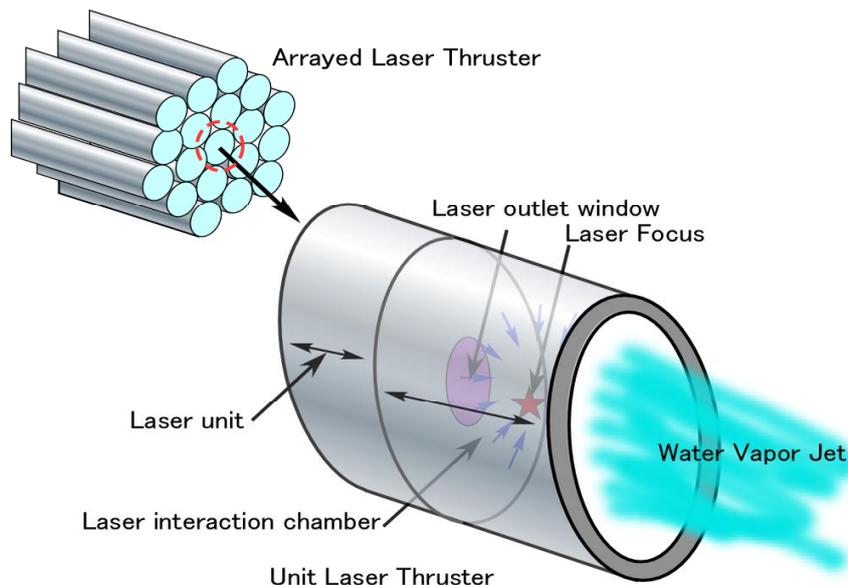


Figure 2. Example of high power pulse laser generating device with laser diode excited solid laser.

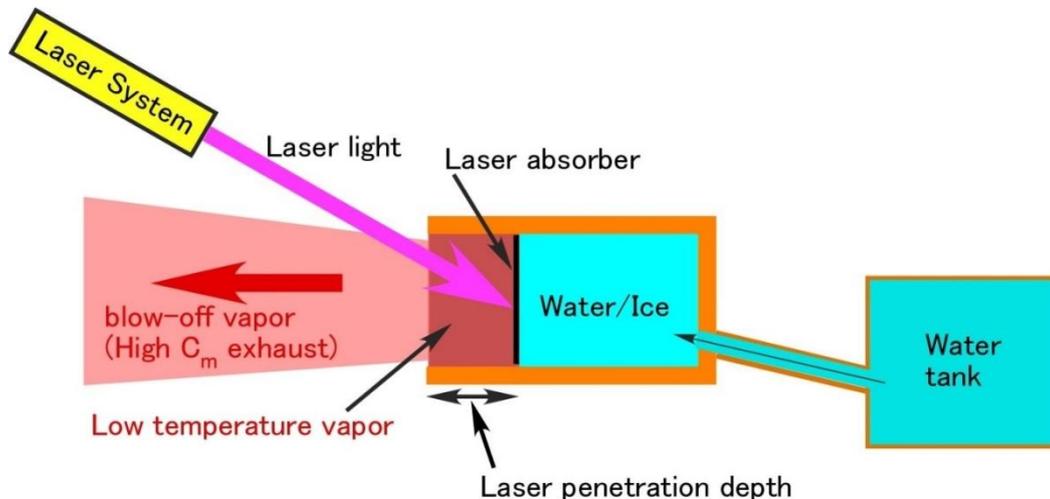
A pulsed Nd:YAG laser is suitable for high- I_{sp} propellant-saving mode with relatively low energy usage. This is because only a thin layer of water surface is heated by extremely high power density resulting in high temperature but small amount of mass ablation. Direct irradiation of water by LD, on the other hand, slowly heats relatively large volume of water resulting in low temperature vaporization and large C_m or large thrust for the propellant. Therefore, it is preferable to prepare two systems (the high power LD and LD pumped Q switch YAG laser that irradiates water directly), to switch between the high thrust low specific impulse mode (LD direct) and the low thrust high specific impulse mode (LD pumped Q switch YAG laser) according to operating conditions of earth surroundings flight and flight in space. The wavelength of CO₂ laser (10.6 μ m) is preferable to be absorbed by water. Solid state laser such as Nd:YAG seems to be a good choice for space application due to their compactness even though their wavelengths lie near infrared region that exhibits lower absorption than that of 10.6 μ m wavelength. As described above, when large thrust is more preferable than propellant mass consumption, cw laser power is suitable. When electrical power is available on board, LD pumping scheme gives better power usage than flash lamp pumping. Electrical power is consumed by LD and cooling devices. When enough solar power is available, direct solar pumping laser performs the best efficiency with the help of Cr³⁺ ion co-doping as a photosensitizer in Nd:YAG medium since Cr ions widen the absorption spectral range over the solar spectrum.

Figures 3 depict two schemes of laser driven water propellant using ablating steam explosion; (a) steam laser heating, (b) ice/water laser heating. In Fig 3 (a), water is preheated and ejected as a supersonic flow that ensures the thermal decoupling of the nozzle wall and the super-heated region by laser. Thus the temperature of propellant is not limited by the thermal durability of the wall but by laser power. Since the sound velocity of the super-heated region becomes high enough so that supersonic condition might break but the region still holds higher kinetic velocity than the "cold" region where "cold" is relative to the laser heated region.

In scheme (b), pulsed laser radiation irradiates water inside the tank through an output window on it.



(a) Laser irradiation to heating vapor.



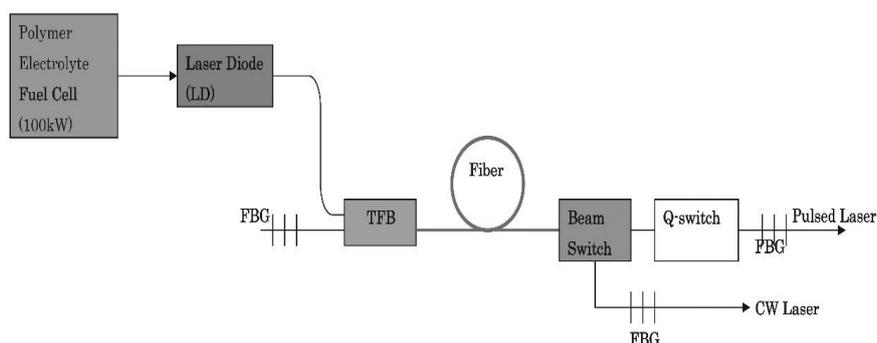
(b) Laser irradiation to water.

Figure 3. Laser engine for vapor and water supply.

Referring to Fig. 3 (b), the engine consists of a nozzle, a water tank, the water or ice stored in the nozzle, a laser system and a laser absorber. CW laser or Pulsed laser radiation irradiates water inside the nozzle. Water is supplied through a hole on nozzle from water tank. The size of the hole, in the order of millimeters is adjusted so that water is kept in the tank by its surface tension and repeatedly renewed after laser irradiation. Almost all of laser light is absorbed with a laser absorber and is changed into thermal energy here. The layer of a proper quantity of water has covered the laser absorber then thermal energy blows away the layer of this water and is transformed into kinetic energy. In case that high thrust is required, CW laser radiation irradiates water directly. Since temperature is kept low while a large volume of water is simultaneously heated compared with a pulsed laser, injection of the low-temperature propellant of large mass is made. Therefore, the large momentum coupling coefficient C_m ($N \cdot s/J = N/W$) is realized and a high thrust is obtained. In the case of pulsed laser, due to its high peak power, the surface of water is rapidly heated and injection of high-temperature propellant of small mass is made. Therefore, a high specific impulse (I_{SP}) is obtained. In other words, selection between high C_m system and high I_{SP} system can be realized by controlling propellant exhausting velocity. This mechanism corresponds to High C_m with volume absorbers by CW laser and High I_{SP} with surface absorbers by pulsed laser respectively.

As another method, the latest development of high power fiber laser including a state-of-the-art fiber disk laser is evolved an impressive range of adaptations. Figure 4 shows the block diagram of laser system that switches a continuous fiber laser and Q switched pulse fiber laser.

And now, the principle of the laser steam engine is further expanded to a “laser internal combustion engine” concept, where laser radiation and water replace spark plug and hydrocarbon fuels. Such engines cycle could be a closed cycle in terms of hydro fluid and do not emit CO_2 nor harmful NO_x .



FBG: Fiber Bragg Grating

TFB: Tapered Fiber Bundle

Figure 4. Block diagram of laser system using fiber laser.

Laser diode (LD) can perform at their best when used in a CW mode and is suitable for generating low I_{SP} thruster and on the other hand a pulsed laser mode generating high peak power is suitable for high I_{SP} thruster. For instance, if the speed of the exhausting gas is increased, large momentum can be generated with a small

amount of propellant mass and large amount of laser energy. On the other hand, if the speed is reduced, the same momentum can be obtained by smaller laser energy. The former has a condition of the electric propulsion (speed 10km/s or more of the propulsion gas). In the latter when a large amount of propellant is available and large thrust is needed, where speed of the exhausting gas is 5 km/s or less will be adopted. In a laser propulsion system, such engine performance can be switched.

On the order of 500N – 1000N thrust can be obtained by the order of 1000 kW laser power as shown by the green dotted lines in Fig. 1. Figure 5 shows a plot of thrust as a function of the specific impulse I_{SP} with laser power as a parameter.

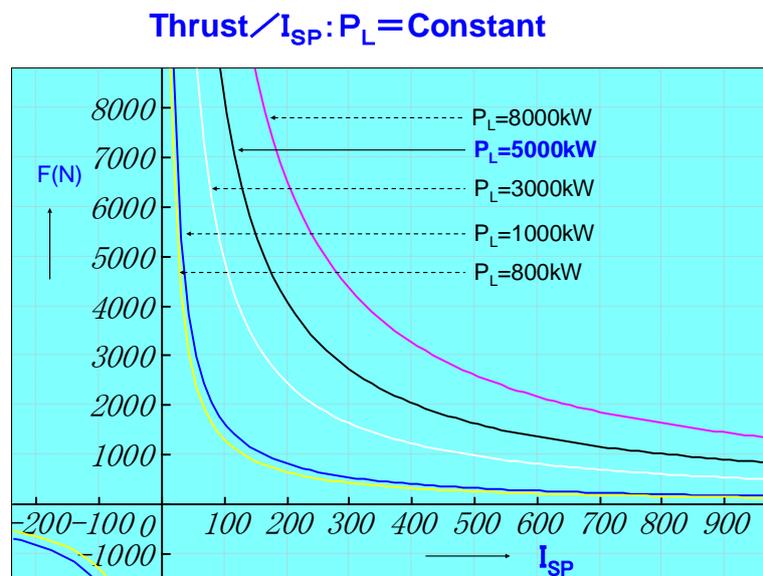


Figure 5. Relation between Thrust and I_{SP} .

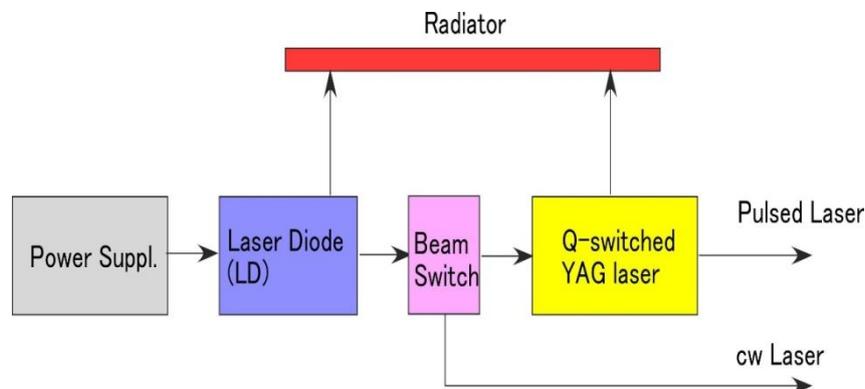


Figure 6. Laser System Block Diagram.

Figure 6 shows the block diagram of the laser system that switches between an LD pumped continuous laser (CW) and a Q switched pulse YAG laser. Laser diode is a continuous oscillation fundamentally and is suitable for the jet generation of gas with a comparatively low specific impulse. On the other hand, in order to generate a high specific impulse, the pulse operation type laser which generates a high peak pulse is suitable. The change-over system with the continuous output mode by the LD for a high thrust / low specific impulse and with LD excitation Q switch YAG laser pulse output mode for a low thrust / high specific impulse is adopted. Since the variable control of thrust and the specific impulse can be performed in relation to laser irradiation conditions (power, power density, a wavelength, pulse width, etc.), they will be controlled only by laser power and laser intensity (10^7 - 10^{14} W/cm²) if a wavelength and pulse width are determined. Control of laser power intensity is performed by position control of a condenser (i.e. control of laser spot size) which adjusts thrust and specific impulse. It has been improved sharply and the electric light conversion efficiency of LD has attained 75%. The absorption of laser light to the water is determined by a mass absorption coefficient and is dependent on a laser wavelength. As to LD, since the laser wavelength of 1 μ m is absorbed by the nozzle length of about tens of cm, it seems to be suitable for the nozzle length of a test prototype or practical use.

2.4 Status of Power LD and Power Supply Development

High power LD technology has made remarkable progress in the recent years. Arraying and stacking technologies made over kW level LD device possible. The conversion efficiency of LD from electricity to optical is 50 to 70% at most. As shown in Fig.2, a 1-kW power supply can drive a 250 W average power from a Q-switched DPSSL. Technological developments of space compatible power supply have already reached the level that satisfies the above application. For example, power source employed by Hayabusa supplies 350 W to the $\mu 10$ ion thruster (voltage: 1.5 kV, current: 143 mA, power: 349 W). The system total power is 1050 W when three thrusters are in operation. Other examples are under development for a Hall thruster; they are 1350 W (300 V and 4.5 A) and 5 kW (anode voltage 275 V, discharge current 16 A, output power 4.4 kW) power supply being developed for 200 mN PPU (460 mm by 333 mm by 91 mm and 95 kg) [13]. Both the laser system and the power supply can be on board so that a laser space vehicle results that is not constrained by a remote laser station and is free to fly. However, the power supply above-stated PPU and solar cells (0.13 kW/m²) are not enough due to their small values.

Recently, Fuel Cell (FC) technology has already made remarkable progress. For example, a Polymer Electrolyte Fuel Cell (PEFC) generates electric power of 100 kW or 85 kW is now in practical use for Japanese motor cars [14–19]. The most promising PEFC is manufactured by HONDA and used in FCV (Fuel Cell Vehicle). This PEFC has the following performance: Power 100 kW, Weight 67 kg, Size 20 cm×40 cm×65 cm (52 L cubic volume). Also, PEFC manufactured by NISSAN, which is used in FCEV (Fuel Cell Electric Vehicle) is also promising. Its performance is 85 kW power, 43 kg weight, 11 cm×50 cm×62 cm size (34 L cubic volume). On the other hand, the lithium ion battery is loaded into the domestic Electric Vehicle at present. It is laminated type lithium ion battery of 95 kW (24 kWh, 182 kg). Also research and development of high-output metal/air battery (metal fuel cell) are carried out as a promising power supply such as Magnesium Fuel Cell and Lithium Fuel Cell. As an evaluation at present, a small lightweight Polymer Electrolyte Fuel Cell (PEFC) is desirable from a viewpoint of the practical use by the domestic car. A lithium ion battery needs lightweight-sizing considerable in weight. Moreover, although the metal fuel cell of magnesium and lithium is in a research trial production stage, it will be strongly expected as a fuel cell of high power and small light weighting in near future.

Furthermore, a Phosphoric Acid Fuel Cell (PAFC) of 10000 kW is now developed for business use. As is well known, fuel cell has the features of small-size, light weight, high energy density and actual achievement for space use (i.e., Gemini spacecraft, Apollo spacecraft, and Space Shuttle). Consequently, a fuel cell of PEFC type is to be used for laser power supply. The total energy being provided by one fuel cell depends on quantity of the hydrogen gas. The energy density of hydrogen gas is 12.7MJ/m³ (3.5kWh/m³), that is, 12.7kJ per liter. According to the Japanese domestic car, an enhanced fuel cell system uses 70-MPa high-pressure hydrogen tank. Its tank capacity is 156 liters. Therefore, a single-fueling of 70-MPa high-pressure hydrogen tank supplies the energy of 1.4GJ (12.7kJ/liter×156liter×700=1.4GJ) to the fuel cell of PEFC type of 100kW.

Concerning high-power laser, 100-kW LD is a stage that can be manufactured by budgetary boost in Japan. Apart from above stated laser thruster for OTV [20], small size laser thruster is applied to satellite as attitude control or trajectory control. As compared with OTV, laser power and power supply becomes small. The required power supply can be used as the same value as ion thruster, which is supplied from satellite.

III. Laser Thruster for Attitude Control and Trajectory Control of Satellite

3.1. Prologue

A thruster is a small rocket engine used to control the orbit and attitude of a satellite. In the spacecraft such as the artificial satellite or the like, a one-component thruster which decomposes a propellant by catalytic decomposition to generate high temperature / high pressure gas to obtain thrust, a fuel and an oxidizer are mixed, a combustion gas is injected, two-liquid thrusters are used. A 1-N thruster for satellites is a small propeller used for attitude control and orbit control of satellites, which is mounted on a plurality of satellites. It is a device that produces thrust by catalytically decomposing hydrazine as a propellant and generating high temperature gas, and is composed of a propellant valve, a gas generating part, and a thermal control device (heater, temperature sensors) that supply propellant.

Along with the recent trend of larger satellites and longer operation, there is a growing demand for longer thruster thrust and lower performance deterioration at the end of operation.

Figure 7 shows an example of the configuration of a 20-N thruster used in satellite. The thruster consists of three parts: a propellant valve that controls the supply of the propellant, an injector that mixes and combusts the propellant, and a combustor that the propellant burns.

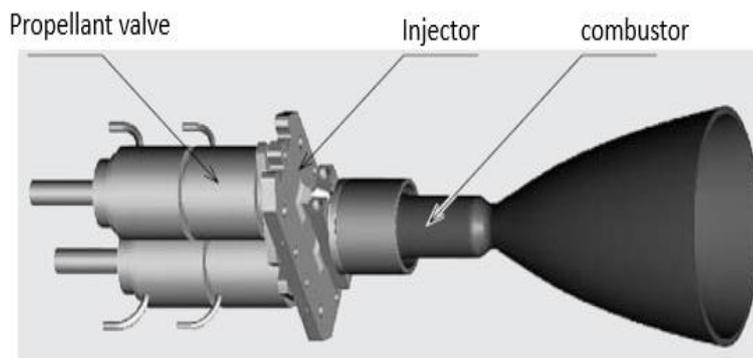


Figure 7. Image of thruster and main component
 (<http://www.mhi.co.jp/technology/review/pdf/425/425250.pdf>).

The authors have studied laser thruster using water as a propellant since 2007 and have submitted papers to journal magazine [1, 2]. Preceding idea of thrusters using water as a propellant has been realized in WATER THRUSTER of the US COMET - 1 satellite in 2017, not in Japan. First of all we introduce the outline of DSI (Deep Space Industries) Comet-1 CubeSat and Microsatellite Water Thrusters. The Comet-1 line of thrusters are simple, launch-safe, and cost-effective electro thermal propulsion systems that use water as a propellant. The Comet-1 design is scalable from CubeSat to small microsatellites, with a highly-flexible interface suitable for a wide range of spacecraft sizes. Comet-1 is the first propulsion offering by DSI on its roadmap to create an ecosystem of safe, robust, and cost-effective propulsion technologies today that can be supplied by space resources in the future.

Table 1 shows specification of this thruster. Figure 8 shows the external view of Comet 1.

Table - 1

SPECIFICATIONS: COMET-1-750*

Performance

Specific Power	2.52 – 2.8 W/mN
Specific Impulse	175 – 200 s
Nominal Power Consumption	0.25 W idle, 25 W thrusting
Maximum Power Consumption	100 W
Warmup Time	1 minute
Minimum Impulse Bit	50 mNs

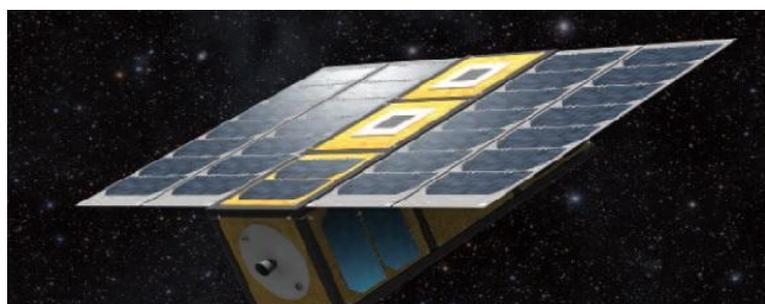


Figure 8. External view of Comet 1
 (Copyright © 2016 Deep Space Industries, Inc. Comet-1 is a trademark of Deep Space Industries, Inc. All rights reserved.).

Next we describe the Laser Thruster for Attitude Control and Orbit Control of Satellite.

3.2. Small-sized Laser Thruster for Attitude Control and Orbit Control

3.2.1. Required Performance

In this section, we will examine the laser thruster for attitude control and orbit control with thrust of 0.1 N to thrust of 1 N, on condition that specific impulse (I_{sp}) is comparatively-low.

Figure 9 shows a plot of the thrust by I_{sp} as a function of the laser power. On the order of 1000 N thrust can be obtained by the order of 1000 kW laser power shown by the pink arrow. It can be seen that a several tens N of thrust is obtained by the order of several tens kW of laser power.

Next, we state that the thrust of which extent is obtained by LD technology and fuel cell technology at present. A 5-kW LD of the stack array structure is now commercially available. The laser power of 70 kW is obtained by using fourteen 5 kW LD. Accordingly, approximately 110 N in thrust is provisionally calculated for $I_{sp}=100$.

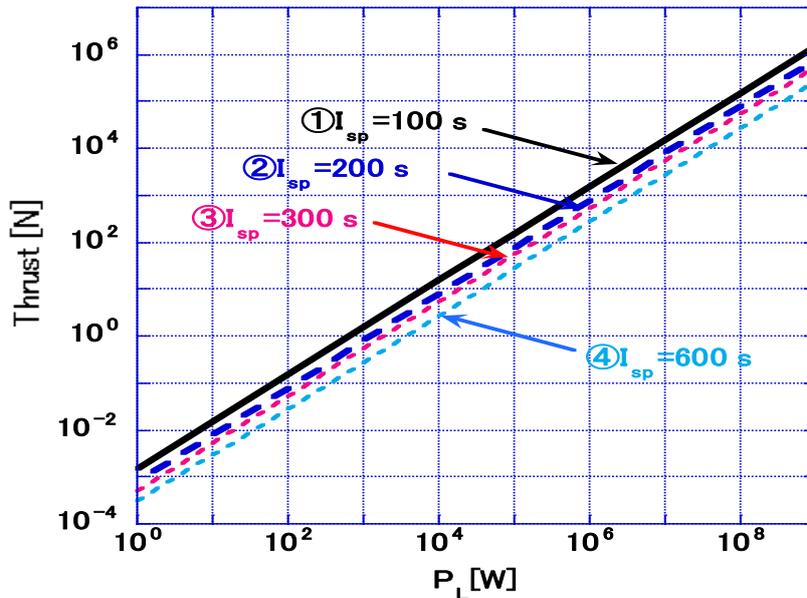


Figure 9. Relation between Thrust and Laser Power for Low I_{sp} .

We would like to consider a specific impulse (I_{sp}) of 600 or 300 seconds as a thruster.

The specific impulse of liquid oxygen and hydrogen fuel rockets is about 440 seconds (LE-7).

Figure 9 shows the relation between thrust and laser power for $I_{sp}=300$ & 600.

However, a large thrust with low power consumption is preferable, so we would like to calculate it with a specific impulse (I_{sp}) of 300 seconds.

3.2.2 Laser thruster for attitude control and orbit control of satellite

Attitude control and orbit control thrusters require a large thrust. It is better that the C_m is larger.

As shown in Fig. 9, in the case of specific impulse (I_{sp}) of 300 seconds, the thrust of 0.5N to 1N can be attained by laser power of 1kW to 2kW.

We can use two CW LD stack modules; e.g., L11408-15-940: 1.2kW, Multi-stage jet package (Hamamatsu Photonics) as shown in Figure 10 (unit: mm). Then we get thrust of 1N using two CW LD stack module.



Figure 10. External view of L11408-15-940; High-power Laser Diode CW Stack Bar Module L11048 Series CW 100W/bar. (<https://www.hamamatsu.com/resources/pdf/lsr/L11408E.pdf>)

Furthermore, we can also use High-power fiber coupled diode laser as shown in Figure 11.

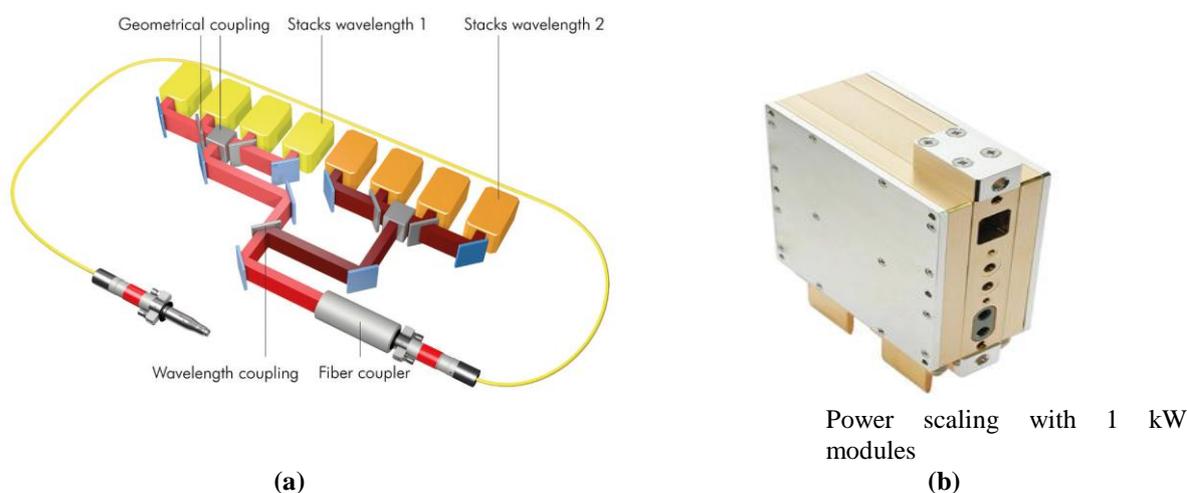


Figure 11. ROFIN's High-power fiber-coupled diode lasers: (a) overall configuration drawing, Inside a ROFIN diode laser, multiple diode laser modules – each providing an optical output power of 1kW – are combined together and coupled into a multi-mode single core fiber. Each module is monitored individually and can be replaced on site if necessary; (b) external view of one module of 1kW. (http://www.rofin-baasel.co.jp/products/Diode_lasers/Low_Power_Diode_Lasers/DF_Series_PDF_051316.pdf)

Converting electrical power directly into laser radiation – that's the by far most efficient way. Inside a ROFIN diode laser, multiple diode laser modules – each providing an optical output power of 1kW – are combined together and coupled into a multi-mode single core fiber. Each module is monitored individually and can be replaced on site if necessary.

As laser output 2 kW can be obtained with fiber unit 2 in series ($P_L = 2000$ W, $I_{SP} = 300$ s, $\eta = 0.8$), thrust $F = 1.088$ N ≈ 1 N is generated.

Accordingly, even if any laser diode is used, a thrust of 1 N laser thruster is possible.

3.3 Laser thruster for trajectory control of spacecraft

As described in Chapter 2, it is shown that the propulsion system that produces thrust by a little amount of propellant, *i.e.*, large specific impulse (large I_{SP}) or produces large thrust to the laser power (large C_m because a large amount of propellant is necessary) can design laser propulsion while reflecting the condition of reality.

In other words, selection between high C_m system and high I_{SP} system can be realized by controlling propellant exhausting velocity. Since the laser power and propellant flow rate can be set independently and the propellant injection speed can be controlled over a wide range, both *high specific impulse - low thrust mode* and *high thrust - low specific impulse mode* can be selected by controlling the laser output by using vapor or water as a propellant. The propellant saving mode of high I_{SP} is the best choice for the transition to the geosynchronous orbit from a circular orbit or a deep space mission. Laser diode (LD), which has made remarkable technical progress in terms of high power generation is supposed to be a suitable choice for an on-board power source. LD can perform at their best when used in a pulsed laser mode generating high peak power is suitable for high I_{SP} thruster. For instance, if the speed of the exhausting gas is increased, large momentum can be generated with a small amount of propellant mass and large amount of laser energy.

Technological developments of space compatible power supply have already reached the level that satisfies the above application.

In conclusion, thruster for deep space navigation and trajectory control does not need high thrust but rather high specific impulse.

Accordingly, it is not necessary to use a high power CW laser, but it may be a laser diode of about several hundred watts, using pulse laser (not CW). Figure 12 shows High-power Laser Diode Bar Module L11398-16P940 16stacks Pulsed stack module (100W/bar; unit: mm). Thrust $F = 0.272$ N is obtained under the condition of pulsed output $P_L = 500$ W, $I_{SP} = 300$ s, $\eta = 0.8$ by using a 5-stage stack (LD: 100 W / bar). In the case of one LD 100W/bar, thrust $F = 54$ mN is obtained.

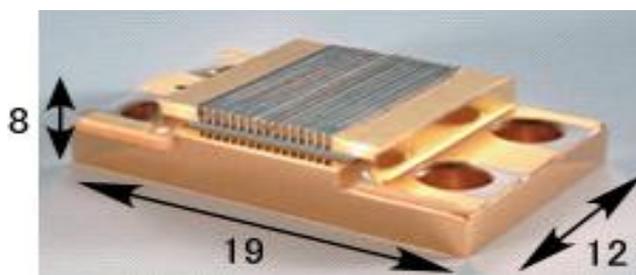


Figure 12. High-power Laser Diode Bar Module L11398-16P940 16stacks Pulsed stack module. (<https://www.hamamatsu.com/jp/en/product/category/1001/1007/L11398-16P940/index.html>)

Figure 13 shows a comparison of the thrust of the ion thruster and the laser thruster at the same power. The required power supply can be used as the same value as ion thruster, which is supplied from satellite as shown in Fig. 13.

Application to Satellite

- Attitude Control or Trajectory Control
- Small size laser thruster is used
- Thrust by laser thruster (100W LD) : 16mN
212W(1.9V, 112A)
- Thrust by ion thruster: 8mN
350W(1.5kV, 143mA)



Figure 13. Comparison between laser thruster ($I_{sp}=1000s$, $F=16mN$, $P_L=100W$) and ion thruster.

3.4 Development test plan

We will perform the development of propulsion engine for satellite attitude control and thrust generation experiment in the laboratory (stationary state).

Firstly, experiment with laser irradiation on propellant (water) and acquire basic data on propulsion performance. At the same time, we will study the fuel cell for laser output.

Secondly, we determine the specific impulse and thrust of the laser thruster for satellite attitude control. And also we determine required specifications for fuel cells for laser, and perform basic design such as laser thruster specification examination (thrust, specific impulse, laser power, condensing characteristics etc.). We will perform several tests by BBM (Bread Board Model).

IV. Conclusions

The possibility of small-sized laser thruster for attitude control and trajectory control of satellite is investigated. Due to the latest developments of high power LD and fuel cell, a laser thruster that carries both laser device and power supply on board is found to be feasible.

Two modes of thruster operation are possible; high I_{sp} with low thrust and low I_{sp} with large thrust. Two modes can be switched within a vehicle by changing the mode of laser operation; cw low power mode and pulsed high peak power mode. The most significant advantage of laser thruster is that water can be a propellant resulting in a safe, reliable and economical propulsion system. Future work is needed to establish the experimental parameters required to attitude control and trajectory control of satellite.

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