Performance Test Results for the Laser-powered Microthruster

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Abstract. Microthrusters are useful for orienting and repositioning small craft above the atmosphere. We report technical results obtained during a successful 5-year program to develop a commercially-viable laser-powered microthruster. Its main advantage is the ability to generate a broad thrust range under programmable electronic control with minimal electrical power. The device applies millisecond-duration diode-laser pulses to a fuel tape to produce an ablation jet. By employing laser-initiated energetic polymers in our ablation fuel tapes, we obtained momentum coupling coefficients as large as 3mN/W of incident laser power, giving a continuous thrust range from 50μN to 10mN. With our standard 30m x 8mm fuel tape, fueled thruster mass is 0.5kg and 50N-s lifetime impulse is achieved. With an order-of-magnitude greater fuel mass, the thruster could accomplish re-entry or substantial orbit-raising of a 10-kg microsatellite. In its usual configuration, specific impulse is 200 seconds, and ablation efficiency, the ratio of exhaust kinetic energy to incident laser optical energy is 180%. We compare performance of several laser-initiated micropropellants which we studied, including polyvinyl nitrate (PVN), glycidyl azide polymer (GAP), and nitrocellulose (NC). All were doped with a laser-absorbing component, either carbon nanopearls with 10nm mean diameter or dyes tuned to the 920-nm laser wavelength but transparent at visible wavelengths. Our demonstrated momentum coupling coefficient is sufficient to levitate a 0.15-kg object with a 500-W laser beam having appropriate characteristics.

NOMENCLATURE

C_m	=	laser momentum coupling coefficient = F/<P>
CPU	=	central processing unit
CW	=	"continuous wave", continuous laser output rather than pulsed
DPSS	=	diode-pumped, solid state
E	=	short for "10^"
f	=	laser pulse repetition frequency
F	=	thrust
FEEP	=	field emission electric propulsion
GAP	=	glycidyl azide polymer
g_o	=	acceleration of gravity at Earth's surface
I	=	laser intensity on target
I_{sp}	=	specific impulse = v_E/g_o
L	=	length of slit focus on target
LISA	=	laser interferometer space antenna
msμLPT	=	ms-pulse micro laser plasma thruster
M	=	optical magnification ratio
MIB	=	minimum impulse bit
NC	=	nitrocellulose
nsμLPT	=	ns-pulse micro laser plasma thruster
μPPT	=	micro pulsed plasma thruster
<P>	=	average incident laser optical power
PVC	=	polyvinylchloride
PVN	=	polyvinylnitrate
*Q**	=	specific ablation energy = W/Δm
R	=	range from target to optics (cm)
v_E	=	exhaust velocity = $C_m Q^*$
W	=	total laser energy incident on target
w	=	width of slit focus on target
Δm	=	total ablated mass
η_{AB}	=	ablation efficiency = $C_m I_{sp} g_o/2$ = $C_m I_{sp}/0.204$
η_E	=	laser optical power out/electrical power in
τ	=	laser pulse duration

INTRODUCTION

Throughout the early history of extra-atmospheric propulsion, emphasis was on producing engines with ever larger thrust, culminating with the 680-kN Rocketdyne F-1 engines for Apollo and the Energiya program. Now, with the advent of micro- (≥10kg), nano- (1-10kg) and even pico-craft (<1kg), this trend is reversing. For many applications, such as pointing and positioning microsatellites, a thrust of order 100μN is desirable, together with low thrust noise and very small minimum impulse bits. This is difficult to do with conventional chemical rockets.

To meet this challenge, the field of microthrusters has evolved in the last decade, with electric propulsion as an especially interesting subset. Electric propulsion has the advantage of programmable thrust, often characterized by a minimum impulse bit (MIB) which may be as small as nN-s, and eliminates the need for storing dangerous, chemically reactive propellants on the craft. Furthermore, many electric propulsion concepts feature specific impulse I_{sp} which is much higher than is possible with chemistry. Table 1 lists some comparative parameters for electric micropropulsion [1-11].

We have developed two laser-driven devices which occupy opposite ends of the I_{sp} spectrum. The nsμLPT is competitive with ion thrusters for some applications because of its low mass. The msμLPT is designed to generate high thrust and must, by the definition of ablation efficiency η_{AB}, have low I_{sp}. Because it uses exothermic fuel tapes, we can have $\eta_{AB}>1$.

In this paper, we will discuss only the history and current status of the msμLPT. Its main distinguishing points in the electric micropropulsion field are its much larger thrust and thrust to power ratio C_{ms}, and its very small MIB. Small MIB is important for precisely positioning satellites, and paramount in some system architectures such as LISA [12].

Table 1. Representative electric microthruster performance

Thruster	**Thrust (μN)**	**I_{sp} (s)**	**Engine Mass (kg)**	**C_{ms} (μN/W)**	**MIB (μN-s)**	**Lifetime impulse (N-s)***
Ion [1,2]	20,000	3,100	8	40	----	2.7E6 (N-star)
Hall [3]	30,000	1,300	1.1	60	----	----
FEEP[4,5]	1400	9,000	8.7	15	1	500
Colloid [6]	20	1,000	0.5	180	4	900
Laser-electric hybrid PPT[7]	3	3,000	0.024	7	5	----
μpulsed plasma thruster (μPPT)[8,9]	30	1,000	1	20	2	320
ns-μlaser plasma thruster (nsμLPT) [10]	100	3,000	0.8	40	4E-5	40
ms-μlaser plasma thruster (msμLPT)[11]	10,000	250	0.5	550	0.05	50

*: Lifetime impulse depends entirely on the amount of fuel stored in a particular design. Areas in which laser microthrusters excel are highlighted.

THE msμLPT

The laboratory test model of the ms-pulse laser microthruster is shown in Figure 1. The micro-Laser Plasma Thruster is a sub-kg micropropulsion option. Lenses focus laser diode beams on an ablation target tape, producing miniature jets that provide the thrust. Output thrust level can be adjusted over more than three orders of magnitude by changing the pulse repetition rate and the number of lasers firing, with a particular fuel tape system. In addition, a range of ablation fuel tapes offer a factor of 40 in C_m, between 2mN/W and 50μN/W. Overall thrust range is five orders of magnitude, from 10mN to 1μN. The minimum impulse bit is 0.5 μN-s. The laser diode which causes the ablation is a low-voltage device with electrical efficiency in excess of 50%.

The operating concepts for both the nsμLPT and the msμLPT are shown in Figure 2. Historically, we have always used T-mode illumination for the ms-pulse thruster. This is because our original illumination concepts required hard focusing to

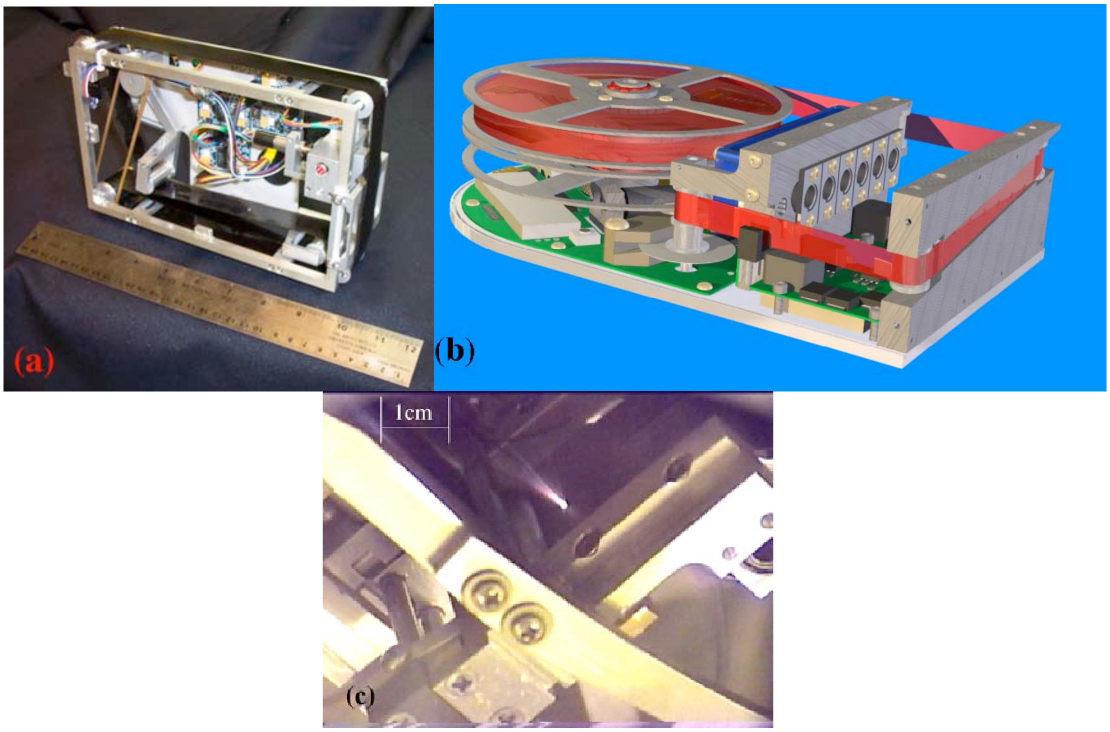

Figure 1 The msμLPT. (a): Laboratory test model. The fuel tape in this version is 2.54cm x 1m, and can run for 5 hours at nominal 100μN thrust. (b): Interior view of the prototype msμLPT thruster. Here, the 0.8cm x 30m fuel tape can run 44 hours at 100μN thrust. (c): Jet produced by the msμLPT.

achieve the intensity required to make a jet, even on a polymer fuel tape, and the proximity of the optics to the jet caused rapid deposition of opaque contaminants from the jet in R-mode.

Several different schemes for bringing the beam to target have been explored [Figure 2]. The advantage of the slit-shaped focal spot is that, in the final, commercial version of the thruster, we can eliminate the traverse drive which is present in the laboratory test model to move the laser spot across the fuel tape. This will be done by changing the tape width to 8mm and placing 6 lasers side by side so that each can illuminate its own 1.33-mm-wide section of the tape.

These devices are made possible by the fact that high-brightness diode lasers [13] have become available with optical power up to 5W from a single 100µm x 1µm facet, electrical efficiency in excess of 50%, 100% duty cycle, and operating case temperature up to 95C. Mean time between failures (MTBF) for these diodes is 430,000 hours operating at 35C junction temperature with 6.5W CW optical output [14].

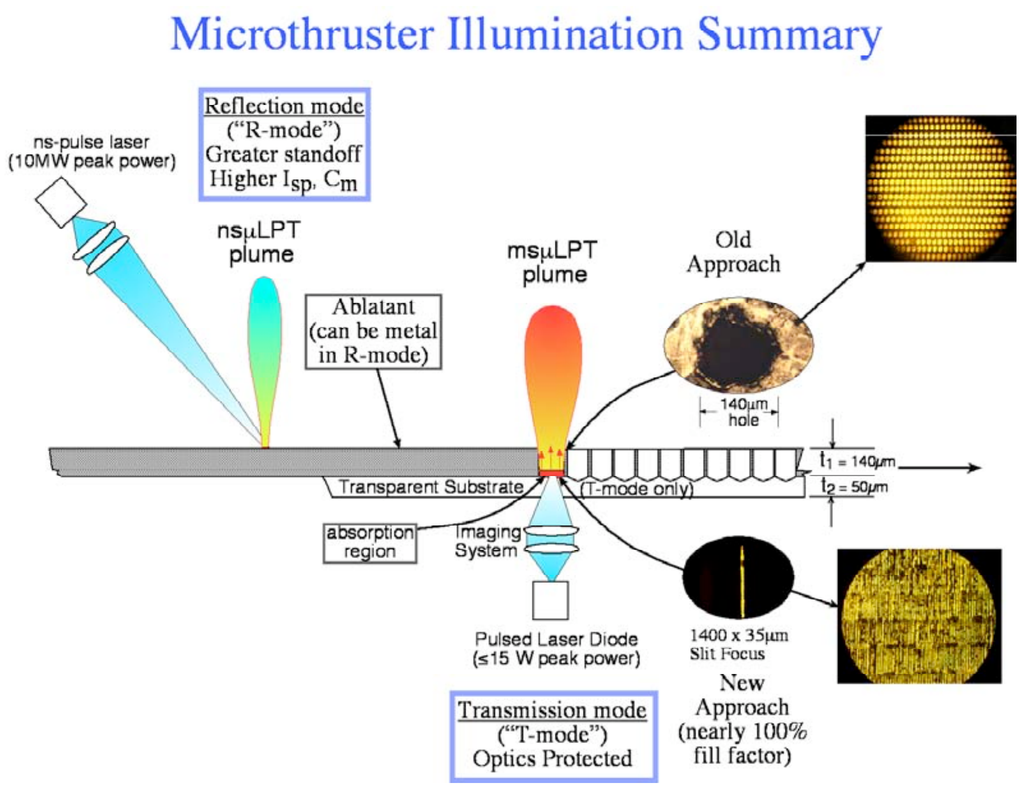

Figure 2. Illumination designs in R-mode (for ns pulses) and T-mode (for ms pulses).

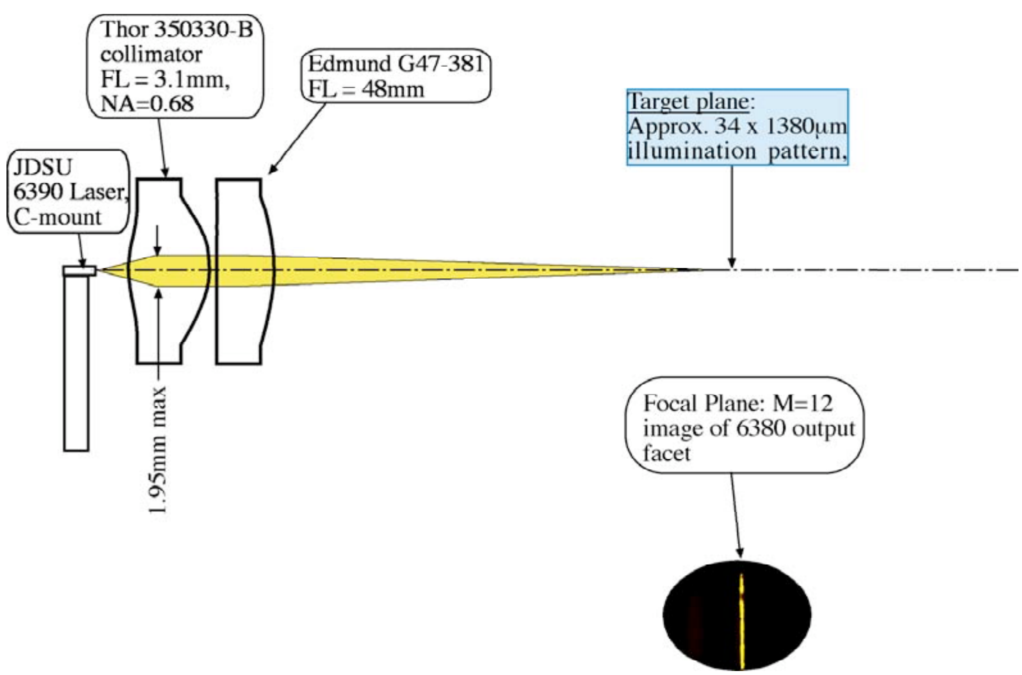

Figure 3. Target focusing optics create a magnified image of the diode laser output facet on the target, preserving its brightness.

The laser intensity requirement for creating jets on polymers is approximately given by

$$I = B\tau^{0.5} \tag{1}$$

where $B = 480$ MW/m^2 [15].

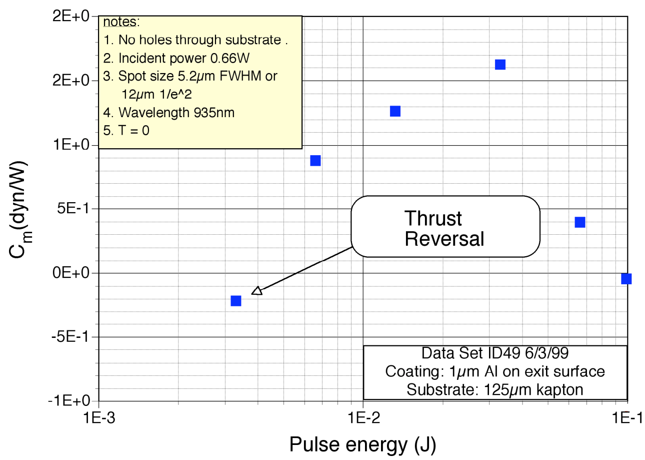

Figure 4. Measurements showing the possibility of T-mode illumination were noted as “reversal” in early measurements of R-mode thrust using an aluminized kapton surface. These measurements were done with a diffraction-limited laser diode.

With τ=2ms and slit dimensions w and L, Eq. (1) gives for the required peak laser power $P = BwL\tau^{0.5} = 1.2$W to reach ignition threshold. In practice, we have found P = 5W is the minimum power required to give optimum C_m. The optical design which develops this “slit focus” is shown in Figure 3.

FUEL TAPE DEVELOPMENT

We first became aware that T-mode illumination of the target was possible in measurements we were making in 1999, in R-mode [Figure 4]. The aluminum coating on the back surface ablated, producing enough impulse to more than counter the impulse of the ablating front surface at low fluence, despite its being only 0.5μm thick. We then set about maximizing this effect.

Transparent Layer

The technical problems involved turned out to be more difficult than we initially imagined. In this configuration, the intensity that can be transmitted through the transparent layer is limited by its optical damage threshold. In addition, some ablation occurs below the threshold and provision (limited intensity, distance, protective windows) must be made for the protection of the illumination optics from the backstreaming material.

Polyimide resin was a very good material for the transparent layer, but finding materials that would adhere to it was difficult. Cellulose acetate was found to have the very best optical damage resistance, transparency in the 920nm region and adhesion, but outgassing in vacuum was a severe problem. We settled on polyimide and solved the adhesion problem.

Ablating Layer

At τ=2ms, no metals or metal oxides and only some polymers have sufficiently low thermal conductivity and specific heat to reach plasma threshold with the intensity that can be transmitted through a transparent polymer layer. Even pure carbon doesn't satisfy these requirements. We began with PVC as the "host" or carrier which will be heated to the temperature for plasma formation, and nanopearl carbon (typically 1 – 2% by mass) as the laser absorber. This system typically achieved C_m = 60μN/W and I_{sp} = 750s and η_{AB} = 20%. Because we wanted maximum C_m to be the leading feature in the msμLPT (maximum I_{sp} is the leading feature of the nsμLPT) and also wanted better ablation efficiency, we went in search of exothermic polymers for the absorbing layer. We tried PVN, nitrocellulose and GAP, which gave progressively better results. Also, two different laser absorbers were used [Table 2]. We found that 2% nanocarbon gave less coating stickiness, but, since carbon is an undesirable exhaust component, we have pursued 1% carbon and greater concentrations of the crosslinker IPDI in the GAP

Table 2. Representative performance of various ablating layer compositions

Ablatant	Absorber	C_m (μN/W)	I_{sp} (s)	η_{AB} (%)	Energy Content (kJ/kg)
PVC	5% nanocarbon	60	750	20	Endotherm
GLYN	2% nanocarbon	1280	116	73	2661
GAP	Epolin 2057 IR dye	1300	200	125	2500
GAP	1% nanocarbon	3000	160	235	2500
PVN	5% nanocarbon	116	2890	164	4941

formulation.

The ablation efficiency η_{AB} is a critical determinant of performance, because it controls the laser optical power which must be delivered to achieve a given thrust, and that parameter, ultimately, is the major factor determining C_{ms}, the "system momentum coupling coefficient," thrust per watt of input electrical power onboard the craft. At this writing, we are still exploring the relative advantages of the last two entries in Table 2. Between these two, the IR dye, which is tuned to our 920-nm laser wavelength, has better I_{sp} and further illumination optimization may well deliver equal ablation efficiency. The dye has the advantage that less elemental carbon is deposited from the exhaust.

The coupling coefficient C_m = 3mN/W shown in Table2 is sufficient to levitate a 0.15-kg object with a suitably configured 500-W laser.

ELECTRONICS

Amplifier and Switch Efficiency

We selected devices to provide high efficiency from "wall plug to output thrust" Our earlier design used an amplifier where only part of the power was delivered to the laser diode. This amplifier was most efficient when operating at full power or close to zero volts drop across the output transistor. The new design does not amplify but switches the full power supply voltage to the laser diode. A power MOSFET with very low on-state resistance is used so that only minimal power is lost in the switch. This approach requires precise control of the power supply voltage, which in turn sets the laser current. This control is discussed below.

High Efficiency DC-DC Converters

We developed DC-to-DC converters capable of delivering 25 watts at efficiencies greater than 80%. The converters will operate over a 6 to 35 V DC input range. This makes an ideal interface to space platforms operating at 24-28 volts. The converters are controlled by a digital potentiometer, which in turn is controlled by the onboard microprocessor. This provides the precise voltage control necessary for the "super capacitor" and MOSFET switch. These converters are also used to provide power for the microprocessors and the motor.

Pulsed Currents

Peak operating current can be as large as 60A during maximum thrust conditions. These pulsed currents must come from the μLPT, since otherwise they would have to

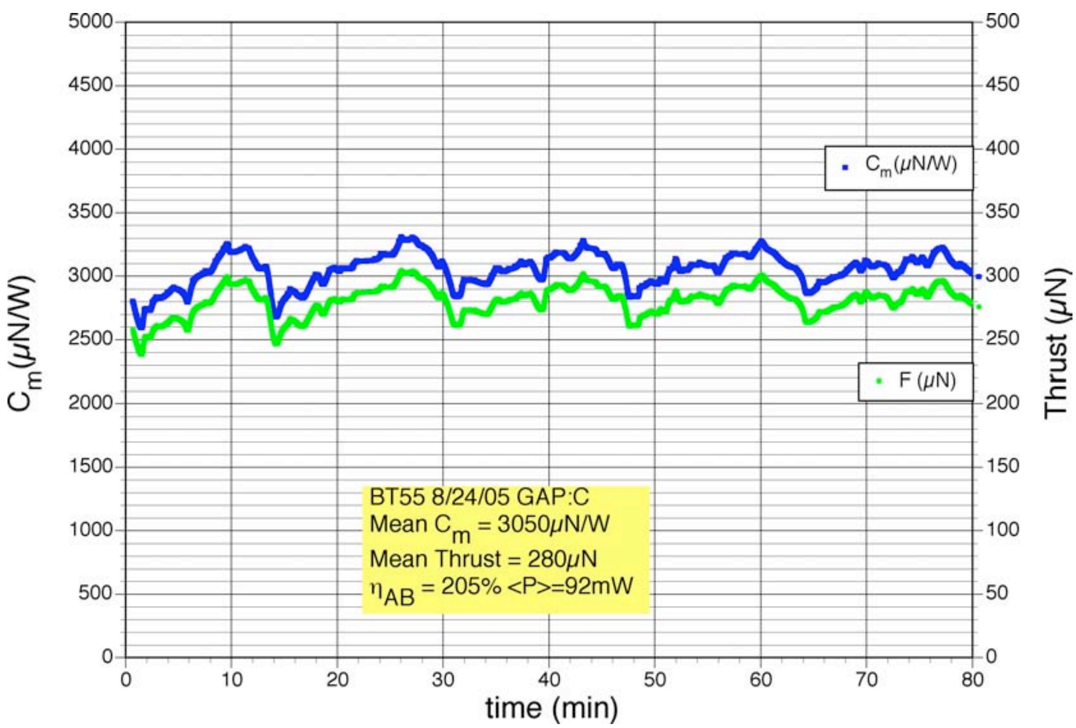

Figure 5. Performance of the test model μLPT. The fuel tape in this version is 2.54cm x 100cm. Thrust variations are due to ablation coating thickness variations. Standard deviation relative to the mean is 4.3% for both in this case. Mean C_m in this 80 min. run was 3050μN/W. The test was deliberately terminated and did not end in failure of any component.

come from the host platform. If these high currents were not internal to the uPT, then long connecting wires would degrade laser performance and could possibly upset the platform's power systems as well. This problem was solved by the use of AVX "super capacitors" that supply the pulse current to the laser diodes. The DC-DC converters recharge the capacitors. This eliminates large pulse currents that would be required from the host platform.

By using the combination of high performance MOSFET's, high efficiency DC-DC converters, and "super capacitors" we have developed a unique laser diode driver

Table 3. Prototype predicted performance	
At normal thrust level:	100 μN
Laser sequence	Sequential, in pairs
Laser average power (mW)	45
Laser repetition frequency (Hz)	1.89
Operating lifetime (hrs)	44
Electrical average power input (W)	2.0
System C_m(μN/W)	50
At maximum thrust level:	10 mN
Laser sequence	Parallel
Laser average power (W)	4.54
Laser repetition frequency (Hz)	63
Laser duty cycle (%)	9.5
Operating lifetime (min)	79
Electrical average power input (W)	18.3
System C_m(μN/W)	550
Tape coating material	GAP:Cnanopearls
Tape coating thickness (μm)	140
Ablatable mass (grams)	44
Tape length (m)	30
Tape width (mm)	8
Type of laser	JDSU 6390
Laser peak power (W)	8
Laser pulse duration (ms)	1.5
Coupling coefficient C_m(μN/W)	2200
Specific impulse (s)	250
Focal spot dimensions [L x w (μm)]	1333 x 40
Number of lasers	6
Lifetime impulse (N-s)	48
Dimensions [L x w x t (cm)]	15.2 x 10.2 x 4.3
Volume (cm^3)	667
Mass (kg)	0.54

design that will accept a wide input voltage while precisely controlling diode currents greater than 10 amps per laser.

TEST MODEL PERFORMANCE

Figure 5 shows the measured performance of the test model (Figure 1) using a GAP:1%C fuel tape. We have accumulated 36 hours of operating time with the test model thruster.

PREDICTED PERFORMANCE

The tested prototype msμPT will have the performance shown in Table 3, and Figure 6 shows the device. The lifetime impulse indicated in the Table is thought to be adequate for most applications involving normal attitude and position adjustment of microsatellites during their lifetime. However, lifetime impulse can easily be augmented to 500N-s by adding just 0.5kg of fuel tape, resulting in a device with 0.9 kg mass. Such a micro-engine could re-enter a 10–kg satellite flying in low Earth orbit.

CONCLUSIONS

Ablative laser propulsion is a vital technology which must be pursued. It can be a tipping point to getting us off the planet. But we must have realistic applications which have the potential of competitively occupying a unique niche. One of these is the laser microthruster, of which there are now two examples, operating with ms-duration and ns-duration laser pulses, respectively.

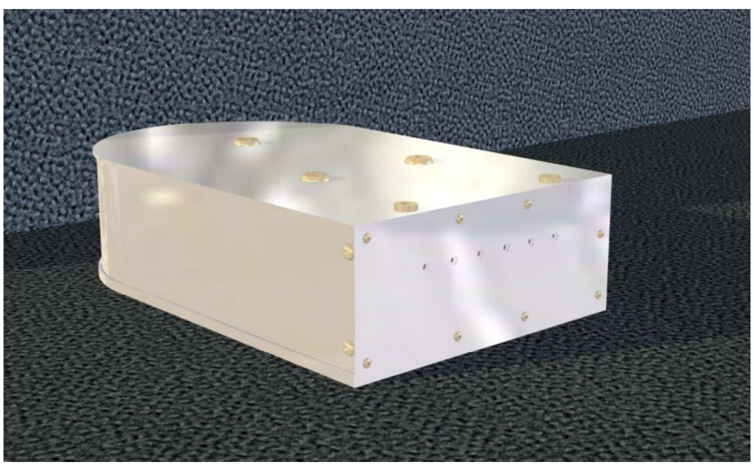

Figure 6. The msμLPT prototype. The six output ports on the front face are fired in balanced pairs to maintain a centered thrust axis.

The msμLPT has demonstrated C_m = 3000μN/W at P = 5W, τ = 2ms, allowing a design which can generate 550μN thrust per watt of total electrical power (including power required to drive motors, CPU and electronics), a considerably larger C_{ms} than offered by competing technologies, while providing 10mN maximum thrust and a 100:1 operating thrust ratio. Ablation efficiency is excellent, complete thruster mass is 0.5kg and minimum impulse bit is 50nN-s. The demonstrated momentum coupling coefficient is sufficient to levitate a 0.15-kg object with a 500-W laser beam having appropriate characteristics. A msμLPT with 0.5kg of fuel could re-enter a 10-kg microsatellite from low Earth orbit.

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REFERENCES

1. J. Mueller, "Thruster options for microspacecraft: a review and evaluation of state-of-the-art and emerging technologies," in *Progress in Astronautics and Aeronautics* **187**, M. Micci and A. Ketsdever, eds., American Institute of Aeronautics and Astronautics, Reston VA (2000) p. 80
2. J. Brophy, R. Kakuda, J. Polk. J. Anderson, M. Marcucci, D. Brinza, M. Henry, K. Fujii, K. Mantha, J. Stocky, J. Sovey, M. Patterson, V. Rawlin, J. Hamley, T. Bond, J. Christensen, H. Cardwell, G. Benson, J. Gallagher, M. Matranga and D. Bushway, "Ion Propulsion System (NSTAR) DS1 Technology Validation Report" (2000) available from http://nmp-techval-reports.jpl.nasa.gov/DS1/IPS_integrated_Report.pdf
3. J. Mueller, *op. cit.,* p. 83
4. *ibid.,* p. 88
5. M. Andrenucci, F. Ceccanti, M. Saverdi and M. Saviozzi, "Qualification status of the FEEP-5 electric micropropulsion subsystem," paper AIAA 2005-4261, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Tucson, 10-13 July 2005
6. J. Mueller, *op. cit.,* pp. 96-7
7. H. Horisawa and K. Sasaki, paper 207, *Proc. 29th International Electric Propulsion Conference,* published on CD (2005)
8. J. Mueller, *op. cit.,* pp. 102-3
9. D. Simon, B. Land, A. Nedungadi and B. Cybyk, "Instrumentation development for micro0 pulsed plasma thruster experiments," paper AIAA 2005-4264, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Tucson, 10-13 July 2005
10. C. Phipps, J. Luke and W. Helgeson, "3ks specific impulse with a ns-pulse laser microthruster," paper IEPC 319, 29th International Electric Propulsion Conference, Princeton, October 30-November 4, 2005
11. C. Phipps, J. Luke and W. Helgeson, "Giant momentum coupling coefficients from nanoscale laser-initiated exothermic compounds," paper AIAA 2005-3607, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Tucson, 10-13 July 2005
12. R. Leach, "Development of a μNewton Thruster for use with a Drag Free Control system and Formation Flying Satellites," *Proc. 1st International Symposium on Formation Flying Satellites*, Toulouse, October 2003
13. Lang, R., O'Brien, S.,. Schoenfelder, A., Hagberg, M., Demars, S. and Li, B., "High Power, High Brightness Diode Lasers", *1998 Diode Laser Technology Review,* U. S. Air Force Research Laboratory, AFRL/DELS, Kirtland AFB, NM (not paginated)
14. V. Rossin, E. Zuker, M. Peters, M. Everett, B. Acklin, "High-power, high-efficiency 910-980 nm broad area laser diodes," *Proc. SPIE* **5336** pp. 196-202 (2004)
15. C. Phipps, "Will your children ride a laser beam into orbit? Would you want them to?," *Proc. Third International Symposium on Beamed Energy Propulsion*, A. V. Pakhomov and L. N. Myrabo, eds., *AIP Conference Proceedings* **766**, pp.11-22 (2005)