

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 30-08-2005		2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Performance Test Results for the Laser-Powered Microthruster (PREPRINT)				5a. CONTRACT NUMBER FA9300-04-M-3101	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Claude R. Phipps, James R. Luke (Photonics Assoc); Wesley Helgeson and Richard Johnson (NMT/IERA)				5d. PROJECT NUMBER BMSB	
				5e. TASK NUMBER R4MN	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Photonic Associates, LLC 200A Ojo de la Vaca Road Santa Fe, NM 87508				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-PR-ED-TP-2005-323	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRSS 1 Ara Road Edwards AFB CA 93524-7013				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S) AFRL-PR-ED-TP-2005-323	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the 4 th International Symposium on Beamed Energy Propulsion, Nara, Japan, 11-14 Nov 2005.					
14. ABSTRACT Microthrusters are useful for orienting and repositioning small craft above the atmosphere. We report technical results obtained during a successful 5-yearprogram 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 2.0mN/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 0.4kg and 40N-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 0.1-kg object with a 400-W laser beam having appropriate characteristics.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. William Hargus, Jr.
Unclassified	Unclassified	Unclassified	A	13	19b. TELEPHONE NUMBER (include area code) (661) 275-6796

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 2.0mN/W of incident laser power, giving a continuous thrust range from 50 μ N to 10mN. With our standard 30m x 8mm fuel tape, fueled thruster mass is 0.4kg and 40N-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 nanoparticles 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 0.1-kg object with a 400-W laser beam having appropriate characteristics.

NOMENCLATURE

C_m	= laser momentum coupling coefficient = $F/\langle P \rangle$	MIB	= minimum impulse bit
CPU	= central processing unit	NC	= nitrocellulose
CW	= “continuous wave”, continuous laser output rather than pulsed	$ns\mu LPT$	= ns-pulse micro laser plasma thruster
$DPSS$	= diode-pumped, solid state	μPPT	= micro pulsed plasma thruster
E	= short for “10 [^] ”	$\langle P \rangle$	= average incident laser optical power
f	= laser pulse repetition frequency	PVC	= polyvinylchloride
F	= thrust	PVN	= polyvinylnitrate
$FEEP$	= field emission electric propulsion	Q^*	= specific ablation energy = $W/\Delta m$
GAP	= glycidyl azide polymer	R	= range from target to optics (cm)
g_o	= acceleration of gravity at Earth’s surface	v_E	= exhaust velocity = $C_m Q^*$
I	= laser intensity on target	W	= total laser energy incident on target
I_{sp}	= specific impulse = v_E/g_o	w	= width of slit focus on target
L	= length of slit focus on target	Δm	= total ablated mass
$LISA$	= laser interferometer space antenna	η_{AB}	= ablation efficiency = $C_m I_{sp} g_o / 2 = C_m I_{sp} / 0.204$
$ms\mu LPT$	= ms-pulse micro laser plasma thruster	η_E	= laser optical power out/electrical power in
M	= optical magnification ratio	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- (≥ 10 kg), nano- (1-10kg) and even pico-craft (< 1 kg), this trend is reversing. For many applications, such as pointing and positioning microsatellites, a thrust of order 100 μ N 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 $ns\mu LPT$ is competitive with ion thrusters for some applications because of its low mass. The $ms\mu LPT$ 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 $ms\mu LPT$. 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

Table 1. Representative electric microthruster performance						
<u>Thruster</u>	<u>Thrust</u> (μN)	<u>I_{sp}</u> (s)	<u>Engine</u> <u>Mass</u> (kg)	<u>C_{ms}</u> (μN/W)	<u>MIB</u> (μN-s)	<u>Lifetime</u> <u>impulse</u> (N-s)*
Ion [1,2]	20,000	3,100	8	40	----	2.7E6 (N-star)
Hall [3]	30,000	1,300	1.1	60	----	----
FEED[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]	----	4,000		4.3	38	----
μ pulsed plasma thruster (μ PPT)[8,9]	30	1,000	1	20	2	320
ns- μ laser plasma thruster (ns μ LPT) [10]	100	3,000	0.8	40	4E-5	40
ms- μ laser plasma thruster (ms μ LPT)[11]	10,000	200	0.4	550	0.5	40

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

for precisely positioning satellites, and paramount in some system architectures such as LISA [12].

THE ms μ LPT

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 50 μ N/W. Overall thrust range is five orders of magnitude, from 10mN to 1 μ N. The minimum impulse bit is 0.5 μ N-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 ns μ LPT and the ms μ LPT 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

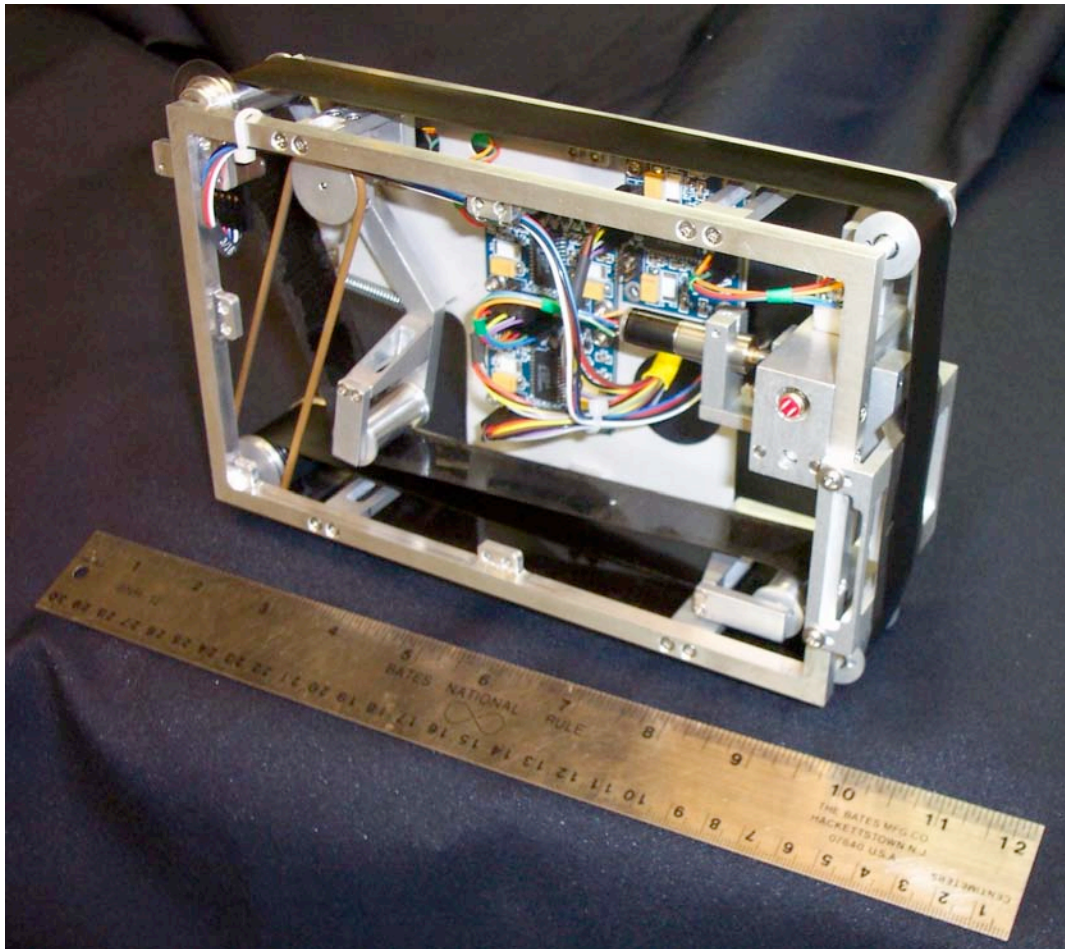


Figure 1. Laboratory test model of the mspLPT. The fuel tape in this version is 2.54cm x 100cm, and can run for 5 hours at nominal 100 μ N thrust.

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 100 μ m x 1 μ m 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].

Microthruster Illumination Summary

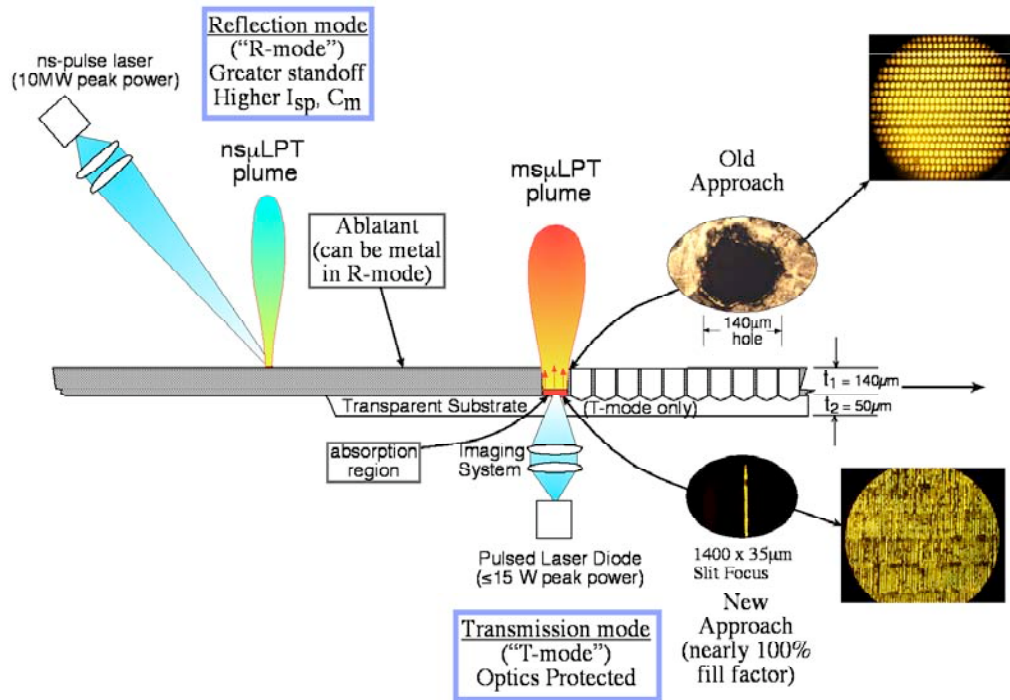


Figure 2. Illumination designs in R-mode (for ns pulses) and T-mode (for ms pulses).

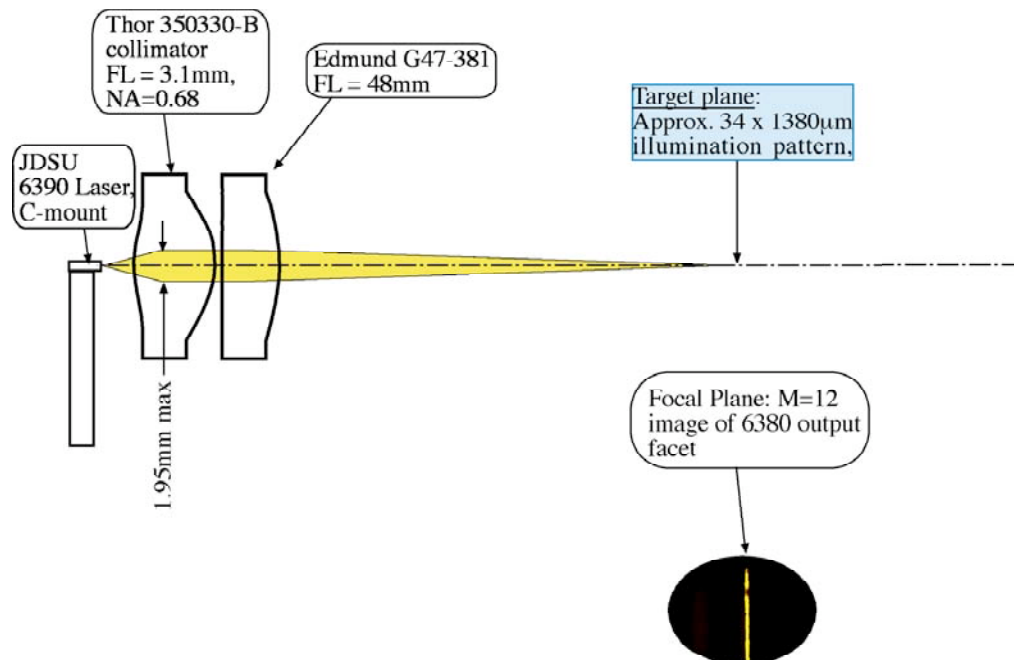


Figure 3. Target focusing optics create a magnified image of the laser output facet on the target, preserving its brightness.

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

$$I = B\tau^{0.5} \quad (1)$$

where $B = 480 \text{ MW/m}^2$ [15].

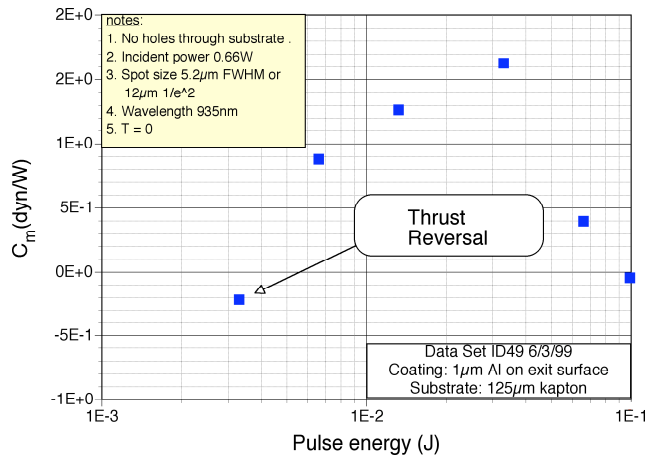


Figure 4. Measurements showing the possibility of T-mode illumination were noted as “reversal” in early measurements of R-mode thrust using an aluminized kapton surface. These measurements were done with a diffraction-limited laser diode.

ablating front surface at low fluence, despite its being only $0.5\mu\text{m}$ 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.

With $\tau=2\text{ms}$ and slit dimensions w and L , Eq. (1) gives for the required peak laser power $P = BwL\tau^{0.5} = 1.2\text{W}$ to reach ignition threshold. In practice, we have found $P = 5\text{W}$ 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 Layer

At $\tau=2\text{ms}$, 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 $C_m = 60\mu\text{N/W}$ and $I_{sp} = 750\text{s}$ and $\eta_{AB} = 20\%$. Because we wanted maximum C_m to be the leading feature in the ms μ LPT (maximum I_{sp} is the leading feature of the ns μ LPT) 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 formulation.

Table 2. Representative performance of various ablating layer compositions				
Ablatant	Absorber	C_m ($\mu\text{N/W}$)	I_{sp} (s)	η_{AB} (%)
PVC	5% nanocarbon	60	750	20
PVN	5% nanocarbon	300	140	20
NC	2% nanocarbon	500	145	35
GAP	Epolin 2057 IR dye	1300	200	125
GAP	1% nanocarbon	2200	160	175

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 $C_m = 2.2\text{mN/W}$ shown in Table2 is sufficient to levitate a 0.1-kg object with a suitably configured 400-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 μ LPT, since otherwise they would have to come from the host platform. If these high currents were not internal to the uPT, then

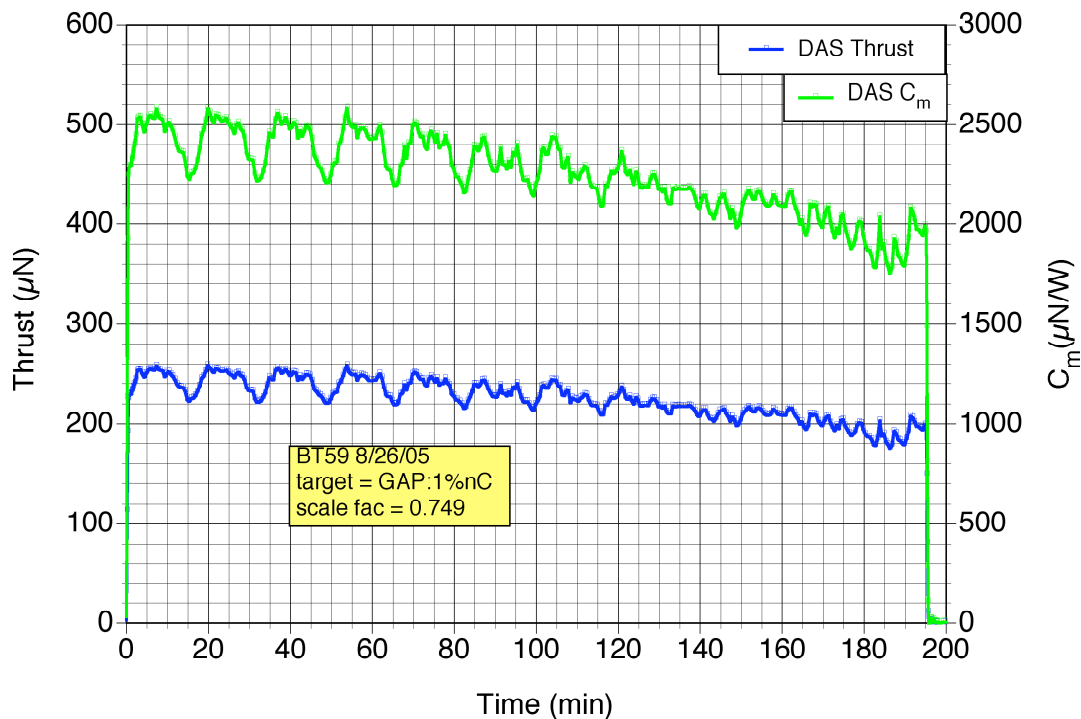


Figure 5. Performance of the test model μ LPT. The fuel tape in this version is 2.54cm x 100cm. Thrust variations are due to ablation coating thickness variations. Standard deviation relative to the mean is 9.6% for both in this case. Mean C_m in this 3h, 30 min. run was 2240 μ N/W. The test was deliberately terminated and did not end in failure of any component. “DAS” refers to our digital acquisition system.

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 design that will accept a wide input voltage while precisely controlling diode currents

Table 3. Prototype predicted performance	
At normal thrust level:	100 μ N
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 $C_m(\mu\text{N/W})$	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 $C_m(\mu\text{N/W})$	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 $C_m(\mu\text{N/W})$	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

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 ms μ LPT 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.

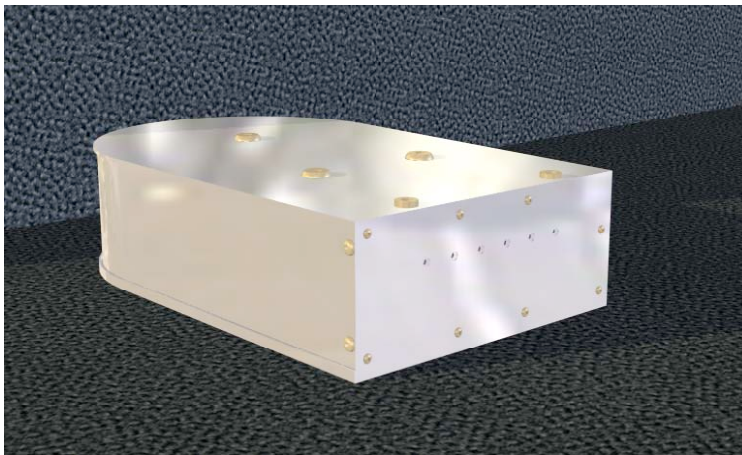


Figure 6. The ms μ LPT prototype. The six output ports on the front face are fired in balanced pairs to maintain a centered thrust axis.

The ms μ LPT has demonstrated $C_m = 2200\mu\text{N/W}$ at $P = 5\text{W}$, $\tau = 2\text{ms}$, allowing a design which can generate $550\mu\text{N}$ 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 0.4kg and minimum impulse bit is 500nN-s. The demonstrated momentum coupling coefficient is sufficient to levitate a 0.1-kg object with a 400-W laser beam having appropriate characteristics. A ms μ LPT with 0.5kg of fuel could re-enter a 10-kg microsatellite from low Earth orbit.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support provided by the Small Business Innovative Research Program for this work through several contracts, including F49620-00-C-0005, F49620-02-M-0025 and FA9300-04-C-0030. We also acknowledge the excellent guidance provided by Dr. William Hargus at the Air Force Research Laboratory, Edwards Air Force Base, and by Dr. Gregory Spanjers, formerly of Edwards and now PowerSail program manager at AFRL Kirtland. On the materials science side, we benefited in a major way from ideas for, and samples of, new fuel materials that were provided by Drs. Darren Naud and Mike Hiskey of Los Alamos National Laboratory and by the group of Dr. Thomas Lippert at the Paul Scherer Institut, Villigen, Switzerland throughout this program.

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