A Diode-Laser-Driven Microthruster

Claude R. Phipps
Photonic Associates
200A Ojo de la Vaca Road
Santa Fe NM 87508
505-466-3877
crhipps@aol.com

James R. Luke
UNM/New Mexico Engineering Research Institute
901 University Blvd. SE
Albuquerque, NM 87106-4339
505-272-7275
luke@nmeri.unm.edu

G. Glen McDuff
UNM/New Mexico Engineering Research Institute
901 University Blvd. SE
Albuquerque, NM 87106-4339
505-272-7240
mcduff@nmeri.unm.edu

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Abstract

We developed a new type of orientation thruster for micro- and nanosatellites. The Micro Laser Plasma Thruster (µLPT) is based on the commercial availability of diode lasers with sufficient brightness and 100% duty cycle to produce a repetitively-pulsed or continuous plasma jet on a surface in vacuum. A low-voltage semiconductor switch drives the laser. A lens focuses the laser diode output on the ablation target, producing a miniature jet that provides the thrust. Single impulse dynamic range is 5 orders of magnitude, and minimum impulse bit is 1 nano N-s in a 100µs pulse. With diffraction-limited focusing optics, 0.5W optical power can produce thrust from selected ablator materials. Thrust-to-power ratio (C_m) is 50 to 100 µN/W and specific impulse (I_sp) is 200-500 seconds with a 1-W laser, depending partially on the illumination mode. Transmission (T) and reflection (R) illumination modes are discussed. R mode gives about 50% better I_sp and 2 times better C_m. Improved results are anticipated from higher laser power in the reflection mode. The prototype engine we are developing is intended to provide lifetime on-orbit steering for a 5kg satellite.

Introduction

The micro-Laser Plasma Thruster (µLPT) is a new sub-kg micropropulsion option which is potentially competitive with the micro-Pulsed Plasma Thruster on TechSat21 and similar microsatellite platforms. It takes advantage of the recent commercial availability of 4-watt diode lasers with sufficient brightness to produce a repetitively-pulsed or continuous plasma jet on a surface in vacuum. The diode is a low-voltage device with electrical efficiency in excess of 50%.

A lens focuses the laser diode output on a 100-µm diameter spot on the transparent side of a specially-prepared fuel tape. Passing through the acetate-base tape without damaging it, the beam heats a specially prepared absorbing coating on the opposite side of the tape to high temperature, producing a miniature ablation jet [Figure 1].

The target fuel tape is 1 inch wide with 160µm total thickness, including 60µm of ablatant and 100µm of transparent acetate backing. Laser coupling coefficient for the material C_m=60 µN/W, and specific impulse I_sp=500 seconds. Typical thrust at 4W optical power is 250µN. Prototype mass is expected to be 700g, including 80g of expendable ablation fuel. Lifetime impulse is expected to be 250 N-s. Normal tape speed is 1cm/s.

Transmission-mode geometry is illustrated in Figure 1. We are also studying Reflection-mode, [Figure 2] in which the jet and the laser are located on the same side of the target. R-mode gives about 2 times better $I_{sp}$ and 50% better $C_m$, but offers significant design challenges to prevent contamination of the illumination optics.

Earlier work demonstrated feasibility of the µLPT [1]. It is expected to show good performance in system specific impulse $I_{ssp}$, defined as [2]:

$$I_{ssp} = I_{sp}(1+k) \quad (1)$$

Where $$k = \frac{M_{dry}}{M_{fuel}}. \quad (2)$$

because $k \sim 4$ for this thruster. Dry mass consists of the package, a laser diode, two tiny lenses, an electronics board and two tiny motors to move the fuel tape past the laser diode focus and change tracks. The µLPT requires no neutralizers, heaters, high voltage supply, high voltage switches, magnetic fields, nozzle, gas, tanks, or valves. It is also free of mysterious small-scale physics. Most importantly, nothing erodes during operation except the ablation fuel. The µLPT can operate pulsed or CW, and power density on target is optically variable in an instant, so $I_{sp}$ can be adjusted on the fly to match mission requirements. The present application uses a continuous (CW) laser.
The prototype engine we are developing is intended to provide lifetime on-orbit steering for a 5-kg satellite.

**Physical Principles**

Laser ablation [3] is the process by which a laser heats a solid surface sufficiently to eject atoms from the surface. This process is complex, covers a wide range of parameters, and can involve phase explosion [4] as well as plasma formation in the vapor immediately above the surface.

Laser impulse production by laser-induced ablation in vacuum is well understood [5, 6]. The maximum momentum per joule of incident laser light is produced at a fluence $\Phi_{\text{opt}}$ which is close to the threshold for plasma formation since, above this level, plasma inhibits coupling. Even with laser spot size $d_s$ as small as 5 $\mu m$, impulse coupling efficiency $C_m$ and $\Phi_{\text{opt}}$ are well-predicted. Apart from slowly varying factors related to dimensionality of the expansion and the ratio of $d_s$ to thermal penetration depth during the pulse, estimates based on the existing literature apply. With continuous laser illumination and a moving target tape, the interaction at a particular spot on the tape is still impulsive in nature.

In order to estimate the fluence required to produce plasma jets on a surface, we surveyed the literature in which the fluence for optimum coupling and plasma formation were reported. Our results are summarized in [1].

The reference predicts that 1-W diodes with pulse durations at least 0.2 to 1 ms will be able to produce plasma jets. From 2-20 times greater laser power will be required to compensate thermal conductance with very small spots and long pulses when highly thermally conductive materials are used. With 1 to 4 W CW laser power in our research setup, it has been necessary to use ablants with low thermal conductivity such as PVC. As expected, we were not able to produce a spark on aluminum. Table 1 discusses the figure of merit we chose for target materials.

The momentum coupling coefficient $C_m$ is defined as the ratio of target momentum $m \Delta v$ produced to incident laser pulse energy $W$ during the ejection of laser-ablated material (the photoablation process).

For continuous lasers, it is the ratio of thrust $F$ to incident power $P$:

$$C_m = \frac{m \Delta v}{W} = \frac{F}{P}.$$  \hspace{1cm} (3)

In the ablation process, $Q^*$ is the ratio of incident laser energy $W$ to the target ablated mass $\Delta m$ (the asterisk is customary notation; $Q^*$ is not a complex number):

$$Q^* = \frac{W}{\Delta m}.$$  \hspace{1cm} (4)

For the sake of discussion, we will consider a monoenergetic exhaust stream with velocity $v_E$. Momentum conservation requires

$$m \Delta v = \Delta m v_E,$$  \hspace{1cm} (5)

so the product of $C_m$ and $Q^*$ is the effective exhaust velocity $v_E$ of the laser rocket, independent of the efficiency with which laser energy is absorbed. This can be seen by writing:

$$C_m Q^* = \frac{(N-s)(J)}{(J)(kg)} = \frac{(kg)(m)}{(kg)(s)} = m/s.$$  \hspace{1cm} (6)

If for example, a significant amount of the incident energy is absorbed as heat in the target substrate rather than producing material ejection, $Q^*$ will be higher and $C_m$ will be proportionately lower, giving the same velocity in the end.

While it is understood that real exhaust streams have velocity distributions, we have shown [6] that the monoenergetic stream approximation will not introduce large errors $< v^2 > / < v >^2 < 1.15$ for laser-produced plasmas, and the principal points we want to make will be easier to understand using that assumption.

**Table 1.** A figure of merit for selecting target materials is the ratio $x_{th}/d_s$ of thermal diffusion distance to laser spot size $d_s = 5 \mu m$. The figure of merit is shown for several materials [7, 8].

<table>
<thead>
<tr>
<th>Material</th>
<th>$x_{th}(100\mu s)$</th>
<th>$x_{th}/d_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>1.1 $\mu m$</td>
<td>0.22</td>
</tr>
<tr>
<td>PVC</td>
<td>3.1 $\mu m$</td>
<td>0.62</td>
</tr>
<tr>
<td>Silica</td>
<td>9.2 $\mu m$</td>
<td>1.7</td>
</tr>
<tr>
<td>Nylon</td>
<td>29 $\mu m$</td>
<td>5.6</td>
</tr>
<tr>
<td>Carbon Phenolic</td>
<td>40 $\mu m$</td>
<td>8.0</td>
</tr>
<tr>
<td>Tungsten Carbide</td>
<td>50 $\mu m$</td>
<td>9.9</td>
</tr>
<tr>
<td>Aluminum</td>
<td>88 $\mu m$</td>
<td>1.7</td>
</tr>
<tr>
<td>Copper</td>
<td>110 $\mu m$</td>
<td>21</td>
</tr>
<tr>
<td>Graphite</td>
<td>130 $\mu m$</td>
<td>25</td>
</tr>
</tbody>
</table>
The specific impulse $I_{sp}$ is simply related to the velocity $v_E$ by the acceleration of gravity:

$$C_m Q^* = v_E = gI_{sp} \quad (7)$$

Energy conservation prevents $C_m$ and $Q^*$ from being arbitrary. Increasing one decreases the other.

From Eqs. (3) and (4), energy conservation requires that several constant product relationships exist:

$$2\eta_{AB} = \Delta m v_E^2 / W = C_m^2 Q^* = g C_m I_{sp} = C_m v_E. \quad (8)$$

In Eq. (6), the ablation efficiency parameter $\eta_{AB} < 1$ is the efficiency with which laser energy $W$ is converted into exhaust kinetic energy. Choosing combinations of $C_m$ and $v_E$ that exceed 2 violates physics, since $\eta_{AB}$ must be less than 1.

Ablation efficiency can approach 100%, as direct measurements with other types of lasers on cellulose nitrate in vacuum verify [6], but a value of 50% or less is likely. The impact of $\eta_{AB} < 1$ is that the $C_m$ value deduced from a given $v_E$ may be less than the maximum permitted by conservation of energy. Exit velocity $v_E$ is the fundamental quantity. Eq. (7) emphasizes the crucial importance of $I_{sp}$ in determining ablator lifetime $\tau_{AB}$:

$$\tau_{AB} = \frac{M}{m} = \frac{M g I_{sp}}{F} \quad (9)$$

where $M$ is the initial ablant mass and $m$ is mass ablation rate.

Since the maximum specific impulse of ordinary chemical rockets is about 500s, limited by the temperatures available in chemical reactions, exit velocity $v_E > 5$ km/s ($I_{sp} > 500$s) is accessible only by laser ablation or some other non-chemical process such as ion drives.

**Laser Diode Capabilities**

Recently, high-brightness diode lasers [9] have become available with optical power up to 4W from a single 100µm x 1µm facet, electrical efficiency in excess of 50%, 100% duty cycle, and operating case temperature up to 95°C. Mean time between failures (MTBF) is 100,000 hours at 40°C [10].

Diffraction-limited, 1W flare-type single-transverse-mode diodes at 935 nm wavelength have a theoretical brightness $B = P/\lambda^2 = 1$TWm$^{-2}$ sterrad$^{-1}$. In practice, they can easily be focused to 5-µm diameter spots with f/2 optics to produce 50 GW/m$^2$ intensity on target. These are very expensive.

Fortunately, less costly multi-transverse-mode diodes with emitter effective area $A = 100$ µm$^2$ [100µm long x one wavelength effective width] typically emit 80% of their output into $\Omega = 0.07$ sterradians, giving $B = 0.8P/(A\Omega)\sim 0.5$TW m$^{-2}$ sterrad$^{-1}$ for the 4-W model 6380-A device [10]. In practice, these can readily be focused with 0.65 NA (numerical aperture) commercial optics to produce a 400 to 500-µm$^2$ spot, giving 10GW/m$^2$ on target.

As we will show, these intensities are sufficient to form plasma on absorbing materials.

Diodes are constant-power (non-storage) lasers.

**Single-Pulse Target Materials Survey**

The purpose of this research program was to determine what materials give good $I_{sp}$ and suitable $C_m$ for a microthruster. Measurements were carried out with single pulses from the single-mode 1W diode laser. All measurements were done in vacuum, typically 0.1 millitorr.

![Figure 3. Torsion pendulum, showing normal operation as well as calibration setup.](image-url)
**Torsion Balance**

In order to measure impulses 5 orders of magnitude upwards from nano N-s, we constructed a highly sensitive torsion pendulum [Figure 3 and reference 1]. Although this fact is not specifically relevant to our measurement program, the sensitivity of the pendulum is illustrated by the fact that it readily responded to the pressure (not ablation pressure) of 1W of laser light.

The pendulum deflection $\theta$ is evaluated by reflecting a probe laser off a micromirror mounted to the center of the torsion mechanism [Figure 3], and pendulum rotation

$$\theta = \theta_b/2$$  \hspace{1cm} (10)

is half the probe beam deflection. Torque $M$ defines the constant $k$:

$$M = FR = k\theta$$  \hspace{1cm} (11)

and

$$k = GJ/L,$$  \hspace{1cm} (12)

where $L$ is effective length

$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2},$$  \hspace{1cm} (13)

$G$ is the torsion modulus of the fiber

and

$$J = \frac{\pi d^4}{32}.$$  \hspace{1cm} (14)

Equating kinetic and stored energy,

$$W = \frac{k \theta_o^2}{2} = \frac{p^2}{2m} = \frac{I \omega_o^2 \theta_o^2}{2}$$  \hspace{1cm} (15)

gives the resonant frequency,

$$\omega_o = \sqrt{\frac{k}{I}}.$$  \hspace{1cm} (16)

In the above,

$$I = mR^2$$  \hspace{1cm} (17)

$\theta_o$ is peak deflection in response to impulse $p$.

From Eq. (15), the impulse response of the pendulum is:

$$\frac{p}{\theta_o} = \sqrt{k m} = \sqrt{\frac{GJ m}{L}} = \sqrt{\frac{\pi Gm}{32 L d^2}}$$  \hspace{1cm} (18)

and the force response

$$\frac{F}{\theta} = \frac{GJ}{LR} = \frac{\pi G}{32 LRd^4}.$$  \hspace{1cm} (19)

The fiber was 78-$\mu$m diameter fused silica.

**Torsion Balance Calibration**

We found that force calibration rather than impulse calibration gave by far the most precise result. Figure 3 illustrates the method employed.

With impulse calibration, accurately measuring the recoil was difficult, and finding materials with the correct coefficient of restitution for zero recoil of the test mass was more difficult. With force calibration, the measured variables were simple and static, giving a measurement accuracy better than 5%.

It was necessary to take account of the fact that both pendula move when the test pendulum is advanced a distance $x$ via a micrometer stage. It is not necessary to measure the angle $\psi$. Where $F_1$ and $F_2$ are, respectively, the force produced by the torsion and test pendula, we measure

$$x = x_1 + x_2$$  \hspace{1cm} (20)

Since

$$F_1 = \frac{GJ \theta \cos \theta}{LR} = \frac{GJ x_1}{LR^2},$$  \hspace{1cm} (21)

$$x_1 = \frac{LR^2}{GJ} F_1$$  \hspace{1cm} (22)

while

$$x_2 = \frac{L_t}{m_{eff} g} F_2.$$  \hspace{1cm} (23)

Now of course $F_1 = F_2 = F$

So

$$x_2 \approx \frac{L_t GJ}{m_{eff} g LR^2} x_1$$  \hspace{1cm} (25)

$$x = x_1 \left(1 + \frac{x_2}{x_1}\right) \approx x_1 \left(1 + \frac{L_t GJ}{m_{eff} g LR^2}\right)$$  \hspace{1cm} (26)

and

$$x \approx \frac{F}{\theta} \left[\frac{LR^2}{GJ} + \frac{L_t}{m_{eff} g}\right].$$  \hspace{1cm} (27)
The approximation in Eq. (26) is accounted for by using small displacements. Friction hysteresis was accounted for by comparing measurement series with \( x \) increasing vs. \( x \) decreasing and eliminating displacements large enough to cause hysteresis outside the desired measurement accuracy.

Results are given in Table 2, which shows computed impulse response along with measured force response for two pendula of different mass.

**Table 2. Single-pulse test pendulum parameters**

<table>
<thead>
<tr>
<th>Pendulum</th>
<th>Light</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant freq. (Hz)</td>
<td>1.73</td>
<td>0.33</td>
</tr>
<tr>
<td>Effective mass (mg)</td>
<td>17.3</td>
<td>580</td>
</tr>
<tr>
<td>( L_1 ) (m)</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>( L_2 ) (m)</td>
<td>0.070</td>
<td>0.10</td>
</tr>
<tr>
<td>( R ) (m)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>( p/\theta_0 ) (( \mu \text{N-s}/\text{rad} ))</td>
<td>6.81±4%</td>
<td>35.8±4%</td>
</tr>
<tr>
<td>( F/\theta ) (( \mu \text{N}/\text{rad} ))</td>
<td>134±4%</td>
<td>110±4%</td>
</tr>
<tr>
<td>Resolution (( \mu \text{N-s} ))</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>Capacity (( \mu \text{N-s} ))</td>
<td>4.0±4%</td>
<td>20±4%</td>
</tr>
</tbody>
</table>

The majority of our single-pulse data was taken with PVC films. Reference [1] shows the data we obtained. Errors are discussed in the following section.

Table 3 summarizes data for these and some additional materials. Perhaps most promising among these is the triazene designer polymer being developed for us by polymer chemists at the Paul Scherrer Institut [11].

**Table 3. Single-pulse data summary**

<table>
<thead>
<tr>
<th>Ablatant (Substrate)</th>
<th>Mode</th>
<th>Peak Best-fit ( C_m (\mu \text{N/W}) )</th>
<th>Peak Best-fit ( I_{sp} ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>R</td>
<td>120</td>
<td>650</td>
</tr>
<tr>
<td>Printers ink (Paper)</td>
<td>R</td>
<td>32</td>
<td>200</td>
</tr>
<tr>
<td>PVC (acetate)</td>
<td>T</td>
<td>65</td>
<td>300</td>
</tr>
<tr>
<td>Scherrer Triazene Polymer (PET)</td>
<td>T</td>
<td>50</td>
<td>200</td>
</tr>
</tbody>
</table>

The smallest impulse we measured was 0.4 nN-s, and the largest 16 \( \mu \text{N-s} \), giving a range of nearly 5 orders of magnitude.

**Measurement Errors**

Standard errors in measuring \( C_m \) were ±10% and, in measuring \( I_{sp} \), ±25%. For \( C_m \), these come from the combined uncertainty of measuring pulse energy and pendulum deflection, and pendulum calibration error. The latter is ±4% (Table 2) and pendulum deflection error in the range of data reproduced here is ±2%. The remainder of the error is due to uncertainties in the laser calorimeter response. For \( I_{sp} \), determined from the product \( C_m Q^* \), measurement uncertainties are those of \( C_m \) augmented by the larger uncertainties inherent in our measurement of excavated mass leading to \( Q^* \).

In all the single-pulse measurements, ablated mass was on the order of nanograms, so it was impossible to determine it by weighing the targets. Instead, it was necessary to determine \( Q^* \) by direct microscopic measurement of the excavated volume. Though we avoided assigning \( Q^* \) values when the character of the target ablation did not involve clean craters, some uncertainty in the results derives from qualitative judgment factors.
Preprototype Development and Testing

In order to get preliminary thrust, $Q^*$ and $I_{sp}$ data in the continuous-burn mode prior to availability of the full reel-to-reel prototype device [see following section], we built a preprototype thruster. Additional purposes are to identify operational problems, determine methods of creating the target tapes, and to identify physics problems associated with continuous tape motion that were not evident in single-pulse measurements.

It uses a 0.505-m continuous-loop tape 1 inch wide, and, at 0.01 m/s with 100-$\mu$m track separation, offers 254 tracks and 3.56 hours of continuous operation. This capacity fully meets our requirements for preliminary measurements, and provides early operational lifetime data as well.

Figures 4 and 5 show the preprototype and some of its components. Details of the preprototype design are provided in [12].

We used the continuous beam from the multi-mode 4W diode laser for these measurements, which were done in vacum, typically 0.1 millitorr.

The prototype thruster will use a reel-to-reel tape, and so will not require a joint to be made.

However, joining the tapes into a continuous loop in the preprototype has proven to be difficult. The design process used in the construction of the preprototype resulted in the requirement for several small-radius bends in the tape path. As a result, the tape joint must be very flexible, as well as being very thin and under significant stress to keep the tape registered properly with the laser. Several tape joining methods have been tested, including self-adhesive splicing tapes and various glues. Tape joints have lasted for hours of operation.

The dial indicator shown in Figure 4 is used for focusing and is removed before mounting the thruster on the force test stand.

![Figure 4. Complete preprototype thruster](image-url)
Figure 5. Selected parts of the preprototype thruster, looking in the direction of laser propagation

Figure 6. The thruster and electronics mounted on the force test stand
Prototype Thrust Stand

Here as well, a torsion balance provides an excellent technique for measuring the 10 to 100 μN range of thrust generated by the microthruster. Instead of a 78-μm glass fiber, we used a 0.010-inch high-tensile strength steel wire to create the thrust stand shown in Figure 6. Eqs. 10-27 apply equally well to this case, with the results shown in Table 4. The deflection of the torsion balance we designed is 39 mrad under 100 μN applied force, whereas a standard pendulum of the same length (20 cm) as the span of the torsion balance and supporting 0.8 kg mass would deflect just 13μrad, about 3,000 times less.

The leading alternative technique is the swinging gate type of thruster stand, which requires relatively costly, specialized flexure bearings and also has a force sensitivity at 25% accuracy of 20 μN [13, 14].

Table 4. Thrust stand pendulum parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant freq. (Hz)</td>
<td>0.027</td>
</tr>
<tr>
<td>Resonant period (s)</td>
<td>38</td>
</tr>
<tr>
<td>L (m)</td>
<td>0.10</td>
</tr>
<tr>
<td>R1 (m)</td>
<td>0.13</td>
</tr>
<tr>
<td>R2 (m)</td>
<td>0.10</td>
</tr>
<tr>
<td>m1 (kg)</td>
<td>0.42</td>
</tr>
<tr>
<td>m2 (kg)</td>
<td>0.43</td>
</tr>
<tr>
<td>Preprototype total mass (kg)</td>
<td>0.85</td>
</tr>
<tr>
<td>p/θ0 (μN-s/rad)</td>
<td>15 ±5%</td>
</tr>
<tr>
<td>F/θ (mN/rad)</td>
<td>2.5 ±5%</td>
</tr>
<tr>
<td>Resolution (μN) @ 25% accuracy</td>
<td>20</td>
</tr>
<tr>
<td>Capacity (mN)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Electronics

Power is supplied to the thruster through contacts immersed in mercury. This provides electrical connections that are free of static friction, and the small viscous forces due to the contacts moving in the liquid mercury serve to damp the pendulum oscillations. By varying the depth to which the contacts extend into the mercury, the Q of the pendulum can be varied from about 3 to about 25.

The MSP430 was chosen for the preprototype microcontroller for its ultra low power, only 7 mW at full computing speed and only 5uW in standby. In/out functions of the MPS430 include six pulse width modulated channels for motor and laser control, an eight channel 12 bit analog-to-digital converter, two universal asynchronous receiver transmitter channels for communications and non-volatile memory, and several discrete I/O ports. Total mass for the microcontroller and ancillary electronics is estimated at 2.2 grams. Details of the control system design and operation are provided in [12].

A 2400 baud optical data link allows transmits commands and data between the electronics control system board and a desktop computer.

In this way, functions such as current to the laser, operating time and pulsed mode operation (if desired) can be controlled. Data outputs include laser heatsink temperature, current, and voltage.

Preprototype Operation

Figure 7 shows a photomicrograph of a continuous target tape burn. The track is 95μm wide near the substrate, and 120μm wide at the top of the ablative coating.

Figure 7. Photomicrograph of continuous target burn.

Figure 8 shows the preprototype in operation, and also demonstrates ablation plume rotation, discussed in the following section.

Preliminary Thrust Measurement

At this writing, a very preliminary thrust measurement of 20μN – 50% has been obtained at tape speed v = 0.01 m/s and laser optical power 1.75W. These figures correspond to a coupling coefficient Cm of 11 μN/W.

This is a substantially smaller value than shown in Table 3. However, (see [12]), some unexpected features of T-mode operation with a moving tape indicate this result is about 4 times less than the actual thrust being generated.
Figure 8. Preprototype in operation

Figure 9 illustrates our reasons for this statement. Plume rotation occurs with a moving tape because the time-dependent burn sequence results in a steady-state concavity in the ablatant that steers the plume in the direction of tape motion.

Figure 9. Plume rotation with moving tape (T-mode)

The plume rotation angle $\theta$ in the current configuration is about $60^\circ$. For this reason, since $\sin \theta = 0.5$, only 50% of the thrust generated is parallel to the measurement axis of the thrust stand. The second factor is that about 50% of the generated thrust is absorbed by the roller shown.

Taking these factors together, we estimate the true thrust at $44\mu$N/W or $80\mu$N.

Both these factors will be corrected in the near future through redesign of the preprototype target advance mechanism.

R-mode Illumination

These new results also indicate that R-mode illumination may have an unanticipated advantage [Figure 10].

Figure 10. Plume rotation in R-mode

The most encouraging results in the literature [14] for forward-peaked ablation plumes in R-mode have given a polar distribution $\propto \cos^{10}\theta$. This indicates we may be able to use the R-mode as indicated in Figure 10 for few-hour intervals, since plume rotation will tend to protect laser optics. A better way to take advantage of R-mode is indicated in Figure 11. In this design (which we will implement), we have rotated the laser incidence angle to very near $90^\circ$, so that the optics are as far from the plume in angle space as possible - and also about 40 times more distant. The combination, according to the formula in the Figure, which is based on our deposition data, should give up to 95 hours of operation before the protective shield has to be replaced.

Prototype

A robust prototype design must take full account of optics contamination. Subject to the results of the R-mode research program, the baseline prototype concept is still a T-mode design at this time (Figure 12).

The T-mode prototype has been designed to take full advantage of what we have learned with the preprototype. The design is summarized in Figure 12. It features a reel-to-reel tape advance using a single motor, with a spring-type tape tensioner.

Table 5. Prototype Specifications

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>14x12x7 cm</td>
</tr>
<tr>
<td>Wet mass</td>
<td>0.75 kg</td>
</tr>
<tr>
<td>Dry mass</td>
<td>0.55 kg</td>
</tr>
<tr>
<td>Lifetime</td>
<td>277 hours</td>
</tr>
<tr>
<td>Lifetime impulse</td>
<td>180 N-s</td>
</tr>
<tr>
<td>Specific impulse</td>
<td>440 s</td>
</tr>
</tbody>
</table>
Figure 11. R-mode illumination system
Figure 12. Prototype Functional Design

39.4 m (129 ft.) of 1” x 160μm tape (total) 207 grams

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Conclusions

The micro-LPT is potentially competitive with the micro-Pulsed Plasma Thruster [micro-PPT] on TechSat21 and similar microsatellite platforms. ACS propulsion system requirements for the TechSat 21 mission include 4 axis thrust, 0-75 N thrust per axis, 100 N-s impulse per axis, 320N-s total impulse, 2mN-s minimum impulse bit, less than 20W electrical power input and less than 1kg system mass. We see no reason why the micro-LPT we are developing cannot meet each one of these requirements.

References


