# Diode Laser Driven Microthruster Prototype

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IEPC-01-223

**The laser plasma thruster (LPT) is a new microthruster for small satellites. We report on development and testing of a prototype LPT. Some advantages of the LPT are: thruster voltage 4 V, mass less than 1 kg, power-to-thrust ratio 10 kW/newton and Isp up to 1000 seconds. Lifetime impulse is expected to be 500 N-s, and typical thrust level is 30 mN. The pre-prototype continuous thrust experiment includes the laser mount and heat sink, lens mounts, and focusing mechanism, which are coupled to the target material transport mechanism. The target material is applied to a transparent plastic tape, and the laser is focused on a series of tracks on the tape. The tape drive hardware and laser drive electronics, are described, as well as the control and diagnostic software. Design, construction, and calibration of the thrust stand are described. During continuous operation, the exhaust plume is deflected in the direction of the moving tape.**

## Introduction

The micro-Laser Plasma Thruster (μLPT) is a new 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 and 100% duty cycle to produce a repetitively-pulsed or continuous vapor or plasma jet on a surface in vacuum. The diode is a low-voltage device (4 V) 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 transparent tape without damaging it, the beam heats an absorbing coating on the opposite side of the tape to high temperature, producing a miniature ablation jet.

* Presented as paper IEPC-01-223 at the 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October, 2001.

The target fuel tape is 2.54 cm wide with 160 μm total thickness, including 60 μm of ablatant and 100 μm of transparent acetate backing. The minimum impulse bit is 1 nano N-s in a 100 μs pulse. Thrust-to-optical-power ratio ($C_m$) for the material is 60 μN/W, and specific impulse ($I_{sp}$) is 500 s. Typical thrust at 4 W optical power is 250 μN. Mass of the preprototype and associated electronics is 850 g. Prototype mass is expected to be 700 g, including 80 g of expendable ablation fuel. Lifetime impulse is expected to be 250 N-s. Nominal tape speed is 10 mm/s.

Previously, a series of single pulse material characterization tests were performed[1,2]. These tests identified the correct ablator material and the correct substrate material, based on the measured coupling coefficient and specific impulse. Our best results have come with black polyvinyl chloride (PVC) plastic ablator. All of these measurements were in single pulse mode. Before building a prototype, it was considered necessary to build a continuous thrust experiment to obtain thrust, $C_m$, and specific impulse measurements during continuous operation. The pre-prototype continuous thrust experiment is described in this paper.

## Experimental Setup

In order to get preliminary thrust, $C_m$, and $I_{sp}$ data in the continuous-burn mode prior to availability of the full reel-to-reel prototype device, we built a pre-prototype thruster. The preprototype uses a 50.5 cm continuous-loop tape 2.54 cm wide, and, at 10 mm/s with 100 μm track separation, offers 254 tracks and 3.56 hours of continuous operation. This capacity fully meets our requirements for the preliminary measurements, while providing early operational lifetime data as well.

**Fuel Tape Development**

Desirable properties for the transparent tape substrate material are high transparency in the near infrared and very high optical damage threshold to make burnthrough on the transparent side of the tape extremely unlikely.

Numerous polymer tapes were investigated for use as the fuel substrate. Requirements for the tape are that it must be no more than 127 μm thick, able to be coated with at least 55 μm of PVC fuel, and flexible enough to be rolled onto less than 6.35 mm diameter spool. Mylar was the prime candidate as a fuel substrate because of ruggedness and cost. There are over 100 different Mylar derivatives available commercially. Several different types were investigated. Although satisfactory, the Mylar poses two substantial detrimental traits. The best Mylar exhibits laser damage, and fuel coating adhesion is difficult. Even with advanced surface preparation compounds, adhesion to Mylar is marginal at best. After several weeks, the fuel coating would detach from the Mylar substrate. Surface preparations used in the automotive industry improved adhesion somewhat but the laser damage problem persisted.

Although not as resilient and rugged, acetate has far better optical properties than the best Mylar tested. To date, optically clear acetate (similar to motion picture film) has proven to be the best substrate candidate. Acetate is as inexpensive as Mylar and far easier to coat. Modern acetate used for motion picture film has life expectancy of 50 years and over 1000 showings. Since the thruster fuel tape has a maximum of 100 passes, tape substrate life should not be a problem. This leaves only one serious consideration, vinyl fuel adhesion. Again, turning to the automotive paint experts, a surface preparation was acquired to enhance the PVC fuel adhesion. Using SEM Flexible Bonding Clear #39863, adhesion of the vinyl coating to the acetate was superb.

The adhesion mechanism is a chemical process and not strongly dependant on temperature or pressure. The most favored fuel at this time is Plasi-Kote® Ultra™ Vinyl #405. Several coated samples have been set aside to evaluate the effect of time, temperature, and environment on adhesion, flexibility, and stability. Preliminary tests show no difference in air cured or vacuum cured fuel tapes. Vacuum also shows no effect on adhesion properties. Vacuum life tests of spent and unused fuel tapes are underway to assess long term exposure to low pressures.

Joining the tapes into a continuous loop has proven to be difficult. The evolutionary design process used in the construction of the preprototype thruster has 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. Several tape joining methods have been tested, including self-adhesive splicing tapes and various glues. Mylar splicing tape forms a strong and flexible joint, but it is cut by the laser. One of the more successful glues is made by dissolving the acetate tape in acetone. This glue is painted on the ends of the tape and a lap joint is formed. However, even a well-made glue joint has not lasted more than several tape passes before failing. The failure invariably occurs next to the lap joint rather than in the joint itself. Kodak film cement is promising, but the tape joint remains an area for further study. The prototype thruster will not use a continuous tape, and will not require a joint to be made.

**Preprototype Thruster**

The design of the preprototype thruster has evolved into its present form as the requirements for the continuous burn thrust experiment developed. The preprototype experimental thruster consists of the optical assembly, the focusing mechanism, track selector mechanism, tape drive mechanism, and the tape guide rollers.

The optical assembly includes the laser, heat sink, and lens mounts. The laser is mounted to a copper heat sink, which also serves as the laser anode connection and the primary lens mount. A thermocouple is attached to the heat sink for rough indication of the laser temperature. The optical assembly, shown in Figures 1 and 2, is mounted adjacent to the target mounting stage. The aluminum target mounting stage is guided by two pairs of polished steel rods at right angles to each other. It is driven parallel to the optical axis by the focusing mechanism, and perpendicular to the optical axis by the track selector mechanism.

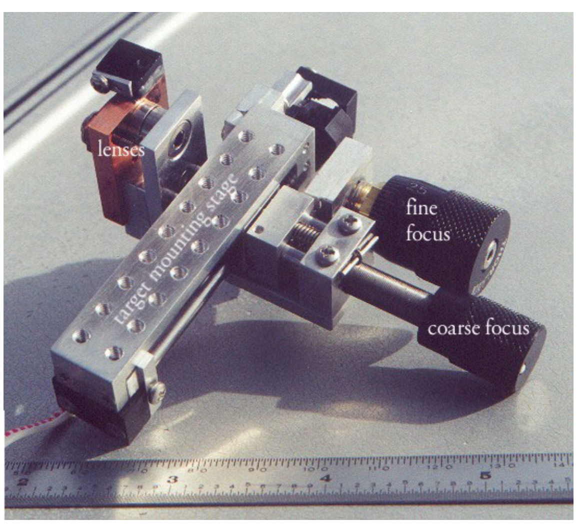


Figure 1. The optical assembly, target mounting stage, and focus mechanism.

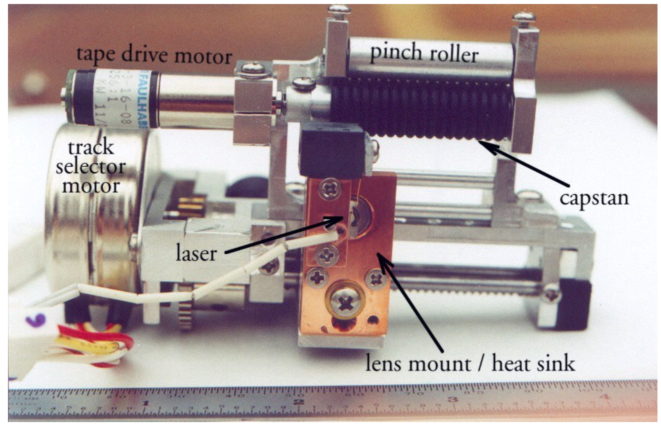


Figure 2. Selected parts of the preprototype thruster, looking in the direction of the laser propagation.

The focusing mechanism (Figure 1) acts directly on the target mounting stage, against a return spring. The coarse focus knob has a 0.318 mm thread pitch, and the fine focus knob has a 0.254 mm thread pitch and acts through a 10:1 lever. The fine focus knob is marked with 50 divisions around its circumference. Each division corresponds to approximately 0.5 µm of travel of the target mounting stage relative to the optical assembly.

The track selector mechanism drives the target mounting stage perpendicular to the laser beam axis with a stepper motor, which turns a small brass jackscrew through a 3:1 reduction gear. The jackscrew has a 1.5 mm thread pitch and runs in acetal (self-lubricating plastic) bearings. In half-stepping mode, the motor can move the target mounting stage in steps as small as 5 µm. The track selector mechanism can be seen in Figures 2 and 3.

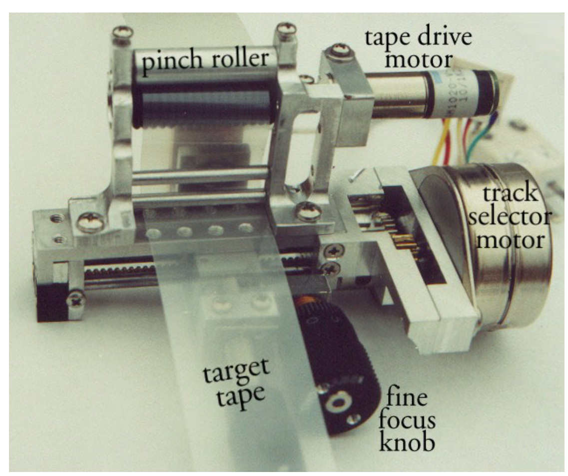


Figure 3. The optical assembly and focusing, track selector and tape drive mechanisms.

The tape drive mechanism is mounted on the target mounting stage. In Figures 2 and 3 (Fig. 3 shows an uncoated fuel tape), the motor drives the tape vertically through the laser focus. The capstan is attached directly to the motor shaft, and is covered with viton O-rings which provide traction to grip the tape. The tape is held to the capstan by a pinch roller. The tape drive mechanism weighs 35 g, including the motor and mounting hardware. The entire subassembly shown in Figures 2 and 3 weighs 250 g, including the 120 g track selector motor.

Although the track selector motor was not specifically designed for operation in vacuum, it has operated flawlessly. The tape drive motor is a MicroMo Electronics AM1020 stepping motor with an attached 256:1 planetary gearhead. Both the motor and gearhead were specially ordered with ball bearings and vacuum-compatible lubricants. Combined, the motor and gearhead form a cylinder 10 mm in diameter and 36 mm long, weighing 15 g. This motor is capable of driving the tape while running 20% faster than the manufacturer's listed maximum speed. A smaller motor is available from the same company, which weighs only 9 g. Using two of these small motors for the tape drive and track selector functions, it is possible to reduce the total motor mass from 135 g to only 18 g.

The tape guide rollers and frame are shown in Figure 4 (with an uncoated fuel tape). The guide rollers are thin wall aluminum tubes. Some of the rollers are mounted in miniature ball bearings, while others have Teflon sleeve bearings. The dial indicator shown in Figure 4 is used for focusing and is removed before mounting the preprototype thruster on the thrust stand. At the right side of the tape guide roller frame is a spring-loaded tape tensioning arm. This arm accommodates variations in the tape length. The tape guide rollers and frame weigh 170 g, and the complete thruster weighs 420 g (not including the dial indicator shown in Figure 4).

**Thruster Control Electronics**

The preprototype electronics breadboard is large; the entire electronics package weighs 430 g. Figure 5 shows the preprototype thruster and electronics boards mounted on the thrust stand inside our vacuum chamber. A design effort is underway to reduce the mass of the electronics.

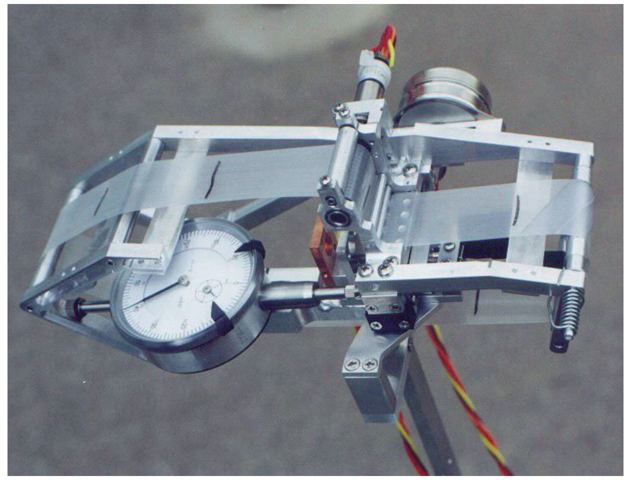

Figure 4. The complete preprototype thruster.

Thruster control is divided into three major sections, laser power control, motor speed control, and communications and diagnostics. The heart of the controller is a Texas Instruments (TI) MSP430 microcontroller. The MSP430 was chosen for its ultra low power, only 7 mW at full computing speed and only 5 µW in standby. The MSP430 has a 105 $mm^2$ footprint in its plastic quad flatpack (PQF) package and a mass of only 1.2 g (unmounted). 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, in prototype form, is estimated at 2.2 g.

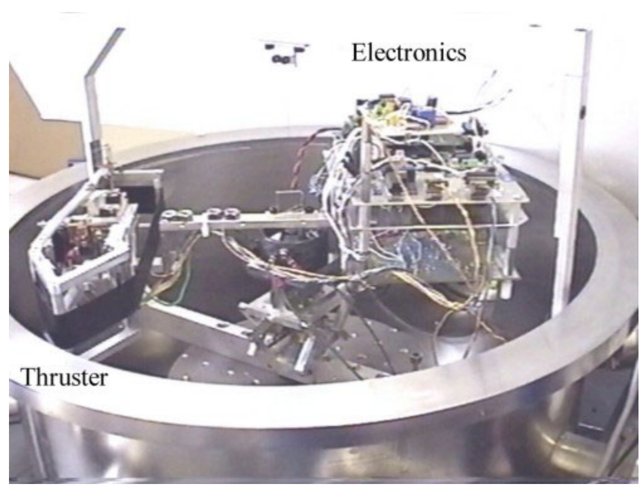


Figure 5. The thruster and electronics mounted on the force test stand inside our vacuum chamber.

The laser current is set by the user and input to the MPS430. The MPS430 commands an LTC1624 Switching Regulator to adjust the drive to an external MOSFET that acts as a current source. Feedback to the LTC1624 provided by a current sensor maintains the current to less than one percent. The LTC1624 is a commonly used regulator in cell phones, PDAs, and laptop computers as a battery charge controller. It too is available in surface mount (SO8 package) with mass of less than a gram. The IRF9Z34 MOSFET is one of the heavier components weighing in at 1.9 g. The total mass for the final design laser current source is projected to be less than 5 g.

Both the tape drive motor and track selector motor are driven by similar circuits. A Motorola MC3479 Stepper Motor Controller is used in both circuits. The motor controllers are directly driven from the microcontroller, with no amplifier stages.

Several improvements are planned for the thruster control circuitry. Most of these are aimed at mass and parts count reduction. For example, the laser temperature monitoring circuitry now composed of three integrated circuits will be replaced with a single chip, resulting in a component mass reduction of about 5 g and equal reduction in circuit board mass. Along with the mass reduction, the new circuitry will require about one square inch less circuit board area. Reduction of the circuit board mass is critical as it contributes about half the total mass of the electronics. Use of alternate circuit board materials will be investigated as part of the final mass reduction exercise.

**Control System Software**

Control software for the thruster development was written to expedite development and data acquisition. The development software is constantly updated and modified to perform new tasks as the development process advances.

The embedded code was written in C and compiled with the TI compiler supplied with the microcontroller. Two interface programs were written to control the thruster. One is text based and the other is written in National Instruments LabView. Both perform the same functions but the latter is far more user friendly and has data display features.

**Thrust Stand**

A torsion pendulum thrust stand was designed and built. The torsion pendulum is supported by an aluminum frame which is mounted in the vacuum chamber (Figure 5). The pendulum crossbar hangs from a single high-tensile steel wire. A mirror is attached to the center of the crossbar, and with a laser beam forms an optical lever. Laser beam deflection is twice the pendulum deflection. The preprototype thruster and the electronics boards are mounted on opposite ends of the pendulum crossbar. Because of the small forces that we need to measure, it was important to ensure that no wires go to the thruster or the electronics. Therefore the thruster is controlled via an optical data link that is part of the electronics board. Through this link, command signals are sent to the thruster from a computer, and diagnostic information is sent back from the electronics board.

Table 2. Pendulum parameters.

| Parameter | Symbol | Value |
|---|---|---|
| Support wire length | $L$ | 10 cm |
| Support wire diameter | $d$ | 0.0254 cm |
| Thrust axis radius | $R$ | 16 cm |
| Arm to C.G. thruster | $R_1$ | 13 cm |
| Arm to C.G. circuit board | $R_2$ | 10 cm |
| Thruster mass | $m_1$ | 420 g |
| Circuit board mass | $m_2$ | 430 g |
| Counterweight mass | $m_2'$ | 43 g |
| Force response | $F/\theta$ | 2.54 mN/rad |
| Impulse response | $p/\theta$ | 15.4 mN-s/rad |
| Calculated resonant period | $T_c$ | 37.6 s |
| Observed resonant period | $T_m$ | 38 s |
| Resolution at 25% accuracy | ---- | 20 μN |
| Laser deflection @ 100 μN | $\theta_b(100)$ | 78.8 mrad |

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. The mercury cup is mounted on a lifting platform which can be operated from outside the vacuum chamber and serves as a pendulum support. During thrust measurements, the cup is lowered until the contact pins are just barely in contact with the mercury.

**Laser Qualification**

In our Phase I effort, we exclusively used a single-transverse mode diode laser with diffraction-limited beam quality, capable of 5.2 µm spot diameter with f/2 (numerical aperture = 0.47) optics. Early in the Phase II planning, based on the Phase I data, we realized that very fast (large numerical aperture) optics would still permit us to produce an adequately small focal spot (and adequately high intensity) on the target tape using much less costly multi-mode lasers.

The lasers are SDL, Inc. 2 W and 4 W models 6370-A-970-10-2.0 and 6380-A-970-10-4.0 lasers costing \$850 and \$1250 each, respectively. We have been extremely pleased with their performance and durability throughout the remainder of the program. Both lasers have 100x1-µm output facets.

A life test was performed on one of the 2 W lasers. Although the laser was damaged by three power outages, prior to the power outages the laser operated for over 1000 hours at 40$^{o}$C (case temperature) and 1.5 W output in vacuum.

## Results

Figure 6 shows a typical continuous burn track on the fuel tape. It is extremely uniform in width and depth. The bottom of the track is slightly smaller than 100 µm, permitting us to stack tracks at 10 tracks/mm, or 250 tracks per tape.

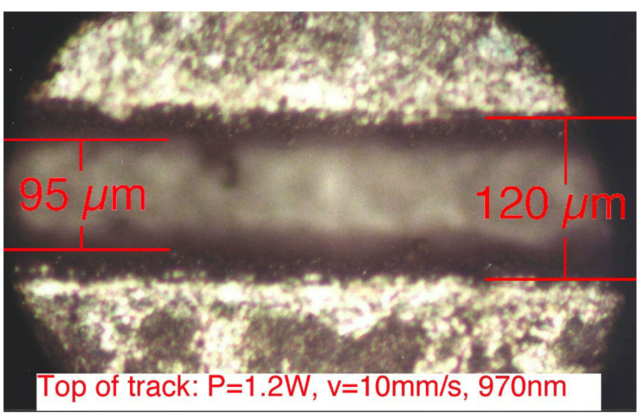


Figure 6. Photomicrograph of continuous burn track.

Figure 7 shows two views of the thruster in operation. The exhaust plume typically has a bright white spot right at the laser focus, and a cone of ejecta. The cone is usually orange in color, and is difficult to photograph because it is much less bright than the central spot. Often the plume includes several bright sparks. The bright sparks appear to be chunks of hot material; Figure 8 shows one of the sparks being reflected off a tape guide roller.

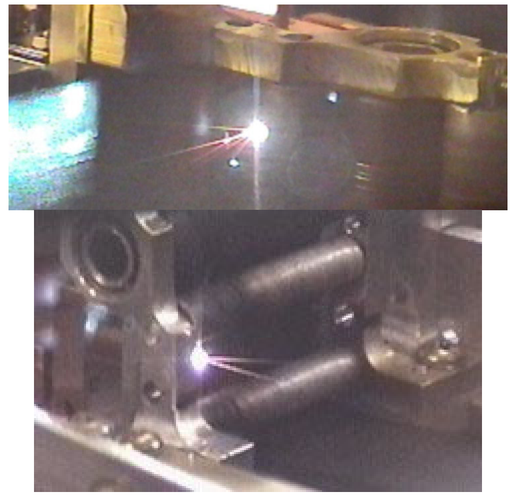

Figure 7. Two views of the thruster in operation.

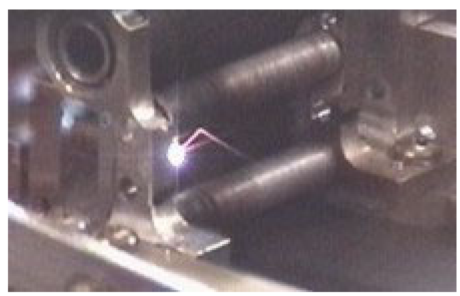

Figure 8. Ejected material reflecting off a guide roller.

An unexpected result of continuous operation with the moving target tape is that the exhaust plume (and therefore the thrust vector) is not perpendicular to the tape. When this plume steering phenomena was observed, an attempt was made to measure the angle of the exhaust plume. This was done both visually and by observing the deposits on a witness plate placed in the exhaust plume. A video camera was set up to view the plume. Analysis of the resulting images showed that the plume was tilted approximately 46$^{o}$ in the direction of tape motion. Figure 9 shows one such image, in which the tape is moving horizontally to the right. The plume tilted to the right, in the direction of the tape motion.

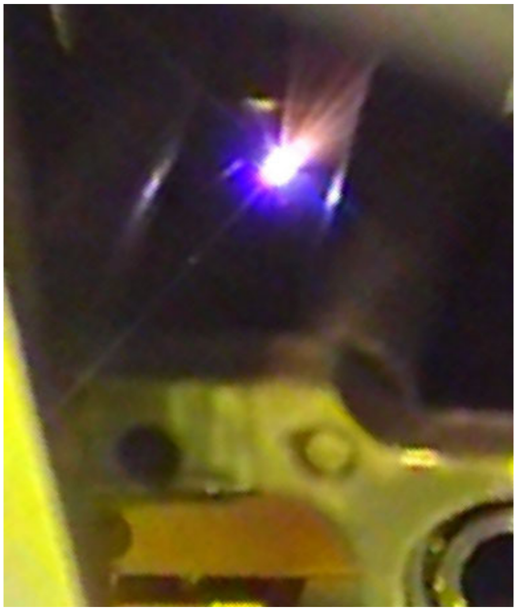

Figure 9. The exhaust plume, tilted in the direction of tape motion.

In addition to the visual analysis, the density of the deposits on the witness plate were measured. The plume deposit density parallel to the direction of tape motion is shown in Figure 10. This plot was produced by scanning the witness plate, and the vertical axis in the graph corresponds to the darkness of the (originally white) plate. Analysis of Figure 10 indicates that the peak of the exhaust deposits occurs at an angle of 37° from the normal. The sharp drop in plume deposits at 40.5° is the shadow of one of the tape guide rollers. The location of the roller in relation to the laser and exhaust plume is shown in Figure 11. The roller appears to intercept about half of the exhaust plume (therefore about half of the available thrust). An immediate item of future work is to redesign the tape path to eliminate the top roller.

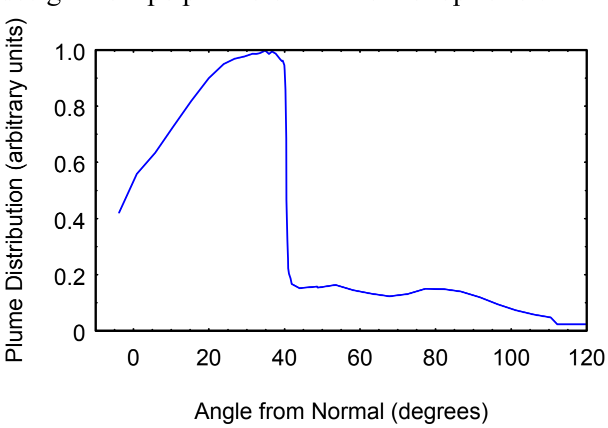


Figure 10. Angular distribution of the plume, parallel to the tape direction.

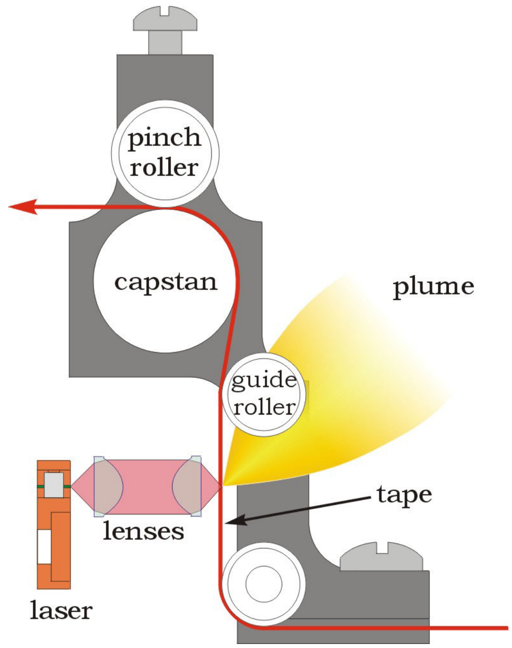


Figure 11. The location of the tape guide rollers, optical components, and exhaust plume.

The steering of the plume in the direction of the tape motion is not a result of the moving tape imparting a velocity component to the exhaust. The speed of the particles in the exhaust is related to their temperature as

$$\frac{1}{2}mv^2 = kT \tag{1}$$

where $m$ is the mass of the particles, $v$ is their speed, $T$ is their temperature, and $k$ is Boltzmann's constant. Assuming that the exhaust is made up of molecules of PVC and estimating their molecular weight at 1E6 amu, and estimating the temperature (based on the color of the exhaust) at 1200 K, the speed of the exhaust particles is about 14 m/s. The tape speed is 0.01 m/s. Computing the resultant of these two vectors, we find that the angle of the jet should be 0.04° to the normal. Using these conservative numbers, it is clear that tape motion alone cannot account for the observed plume steering.

The cause of the deflection of the exhaust plume is probably that as the laser ablates the fuel material, the edge of the trench forms a plume-steering surface, as illustrated in Figure 12. The thin edge of this surface could break off, resulting in the observed hot chunks of material in the plume.

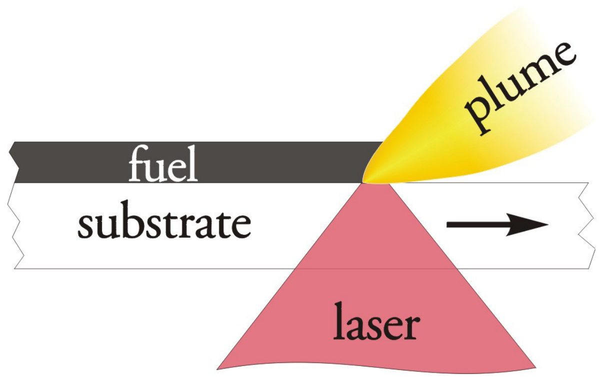


Figure 12. Plume steering by the edge of the ablated fuel material.

Figure 13 shows the angular distribution of the plume deposits on the witness plate in a plane perpendicular to the tape direction. The plume is fairly narrow, with approximately 93% of the deposits falling within ± 25° of the center line. This should minimize plume deposits on the spacecraft.

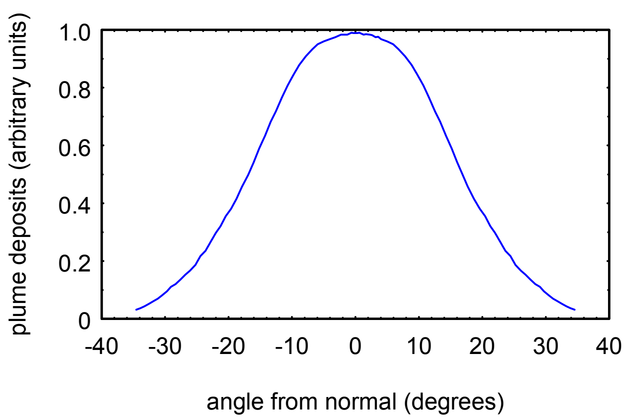


Figure 13. The angular distribution of the plume in a plane perpendicular to the tape direction.

## Conclusions

A preprototype micro laser plasma thruster has been designed and constructed, and tested on a torsion pendulum thrust stand. After testing numerous materials, black PVC on a clear acetate tape was determined to have the best performance. The tape is formed into a continuous loop, but the joints typically fail before the fuel is used up. The prototype design will not use continuous loop tapes, so this is not a major concern.

It was observed that the exhaust plume was not perpendicular to the target tape, but that the center of the plume is deflected by about 40° in the direction of the tape motion. This plume steering is apparently due to the shape that forms at the edge of the fuel as it is ablated. Approximately half of the plume is intercepted by one of the tape guide rollers, which reduces the available thrust by a factor of two. The measured thrust is further reduced because the thrust vector is not perpendicular to the pendulum crossbar.

The most pressing item of future work is to reengineer the tape path in order to remove the guide roller that is intercepting the exhaust plume. Subsequently, the preprototype thruster will be re-oriented so that the thrust vector is perpendicular to the crossbar of the torsion pendulum, so that accurate thrust measurements can be made. Using these results, the prototype thruster design can be completed. The mass of the electronics can be significantly reduced with carefully laid out surface mount components.

The μLPT concept is extensible to operation with continuously repetitive ns-duration pulses, in which regime $I_{sp}$ as high as 7000 s has been observed[3]. Appropriate lasers now exist with 15 g mass, 100 mW average power and 1 ns pulse duration. Development of these to the 1 W average power level is expected within a year[4]. This avenue should be aggressively pursued.

## References

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