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Liquid-fueled, Laser-powered, N-class thrust Space Engine with Variable Specific Impulse

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Abstract. We discuss the requirements for developing a lightweight laser-powered space engine with specific impulse range $200 < I_{sp} < 3{,}600$ seconds and 6N maximum thrust. Operating parameters which can achieve this have been demonstrated separately in the laboratory. We review earlier solid fuel data. Such an engine can put small satellites through demanding maneuvers in short times, while generating the optimum specific impulse for each mission segment.

We will address specific problems which have been solved. The first of these is fuel delivery to the laser focus. A pulsed laser format is required for reasons we will discuss. Solid-fuel configurations (such as the fuel tapes used in the Photonic Associates μLPT microthruster) are not amenable to the range of mass delivery rates (μg/s to mg/s) necessary for such an engine. Liquid fuels are suggested. However, liquids with ordinary viscosities splash under pulsed laser illumination, ruining engine performance by causing the majority of fuel mass to be ejected at low I_{sp}. We have shown that I_{sp} = 680 seconds can be achieved by a viscous fuel based on glycidyl azide polymer and an IR-dye laser absorber. The second problem is optics clouding from ablated material. This can be handled actively by a flowing gas system. The final problem is mass: we will present an engine design which fits within a 10-kg "dry mass" budget.

The engine, 80kg mass with fuel, is designed to fit within a 180-kg spacecraft, and use up 3kW of prime power to deliver a Δv of 17.5 km/s to the spacecraft in sixteen months.

Keywords: laser momentum coupling, laser propulsion, specific impulse, space propulsion
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NOMENCLATURE

C_m	=	$F/\langle P \rangle$
C_{ms}	=	system $C_m = F/P_e$
E	=	short for “10^”
f	=	laser pulse repetition frequency
F	=	thrust
GAP	=	glycidyl azide polymer
GLYN	=	polyglycidylnitrate
g_o	=	acceleration of gravity at Earth’s surface
I	=	peak laser intensity on target
I_{sp}	=	specific impulse = v_E/g_o
μLPT	=	micro laser plasma thruster
PVA/PEG	=	polyvinyl alcohol/polyethylene glycol copolymer
PVC	=	polyvinylchloride
PVN	=	polyvinylnitrate
P_{opt}	=	time average optical power on target
P_e	=	electrical power input
$Q*$	=	specific ablation energy = $W/\Delta m$
v_E	=	exhaust velocity = $C_m Q*$
W	=	optical energy on target
Δm	=	total ablated mass
η_{AB}	=	ablation efficiency = $C_m I_{sp} g_o/2 = C_m I_{sp}/0.204$
η_{eo}	=	P_{opt}/P_e
η_t	=	thrust efficiency = $\eta_{AB}\eta_{eo}$
τ	=	laser pulse duration

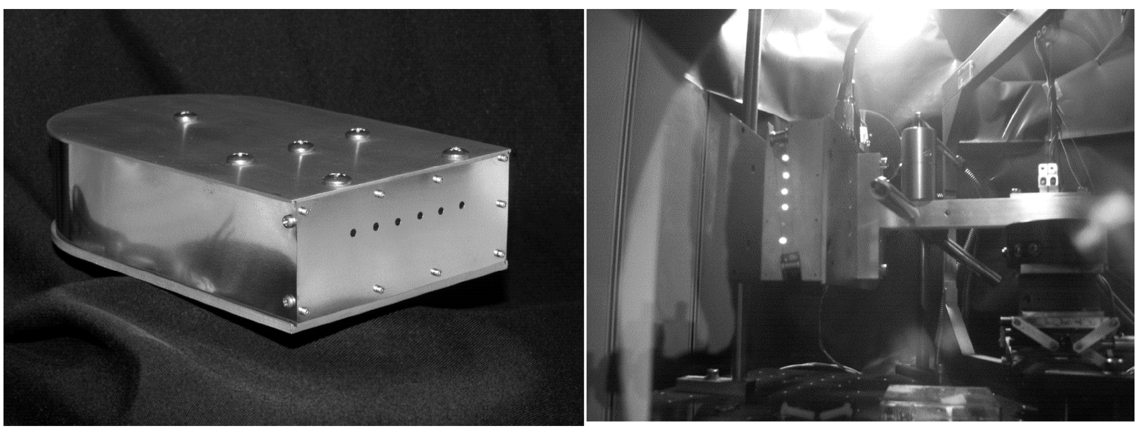


Figure 1. The μLPT is a working example of laser propulsion. This 20W, laser-powered thruster weighs 0.5kg and generates 10mN thrust. At right is the thruster in operation in our 50μtorr chamber.

INTRODUCTION

Photonic Associates’ 10-mN μLPT [Figure 1, refs. 1-4] used laser diodes in “transmission mode” with a double-layer fuel tape using laser-absorber-doped glycidyl azide polymer (an exothermic) on the external face. This arrangement was convenient and simple to implement, and was necessary to protect laser optics from exhaust deposits, because the low beam quality of the laser diodes used in that device required the final focusing optic to be very close to the ablation fuel to achieve the required intensity. The tape arrangement is now significantly out of date, and will not be used with liquid fuels. Table 1 summarizes the advantages we see for the LPT’s compared to other thruster technologies.

Table 1. Comparative advantages of the Laser Plasma Thruster Engine

Thruster	Thrust(N)	I_{sp} (s)	kW/kg	Thrust Density (N/m^2)	Engine Mass (kg)	Thrust Efficiency η_T	System C_{ms} (N/MW)	Cons	Pros
Ion (NSTAR)	0.5	6,000	0.28	1.3	8	68%	40	Erosion, electrical isolation	Efficiency, long history
Hall * (HIV-HAC)	0.48	3,650	0.18	18	17	55%	160	Erosion, electrical isolation	Efficiency, long history
MPD	100	3,500	0.12	50,000	50	30%	100	MW, not kW device	Thrust density
New LPT	max 6.5	120–3,600 **	0.32	**max 4,000**	**9.5**	**34-123%**	**max 2160**	40-60% Laser E-O Efficiency	**Non-toxic fuel and exhaust, no high-pressure tanks**

* Data from NASA “HIVHAC” Hall Effect Thruster (HET). [Ref. 5]
** Demonstrated. We believe 10ks is possible.

A separate development path [ref. 6] produced a research device using ns-duration pulses which produced I_{sp} = 3600 seconds, C_{ms} = 53μN/W and η_{AB} = 95%. The only essential difference between these devices is laser intensity on target.

SUMMARY OF EARLIER DATA

In the nine-year period from 1998-2007, we executed five “Phase I” and two “Phase II” R&D programs in support of the μLPT development. Table 2 summarizes the data we obtained in those programs on a number of solid fuel materials with pulsewidths ranging from ns to ms and wavelengths 920nm<λ<1060 nm [7-23].Ablation efficiency η_{AB}>1 is possible because of the exothermic fuel’s chemical energy contribution, of order 2500 kJ/kg, in the low-I_{sp} regime.

A NEW ENGINE CONCEPT

We recently became interested in building a 1N-levethrust engine which would combine the best features of the μLPT’s at a larger scale appropriate for propelling a whole spacecraft. For such applications, power-to-weight and thrust-to-weight ratios become critically important to performance. To meet demanding new requirements for these parameters, it was necessary to visualize a high power, low mass, diffraction-limited laser source, and an entirely new way of efficiently storing and delivering ablation fuel to the laser focus. It was apparent that liquid ablation fuels, rather than solid fuel tapes, are the only reasonable approach to delivering kg-level amounts of

Table 2. Solid fuel data summary									
Ablator	Gold	GAP:C	GAP:dye	PVC:C	PVN:C	GLYN:C	PVA/PEG:C	Liquid GAP:dye	Epson black ink
Pulsewidth	5ns	2ms	2ms	10ms	1ms	2ms	20ms	5ns	0.25ms
I_{sp} (s)	3660	137	218	1530	64	116	330	680	1820
C_m (N/MW)	53	3050	1050	35	86	1280	423	73	12.5
η_{AB}(%)	95	205	112	26	2.7	73	68	24	11
Fluence (J/cm^2)	64	127	753	5840	55	127	5.7E4	1420	753

fuel to a kW-level laser propulsion engine at μg/s to mg/s rates. Three problems were solved in order to develop this concept.

The first problem was identifying sub-kg laser technology capable of delivering both ns- and ms-pulses in a kW-level, diffraction limited beam. It was apparent that diode pumped fiber laser oscillators already exist which are capable of delivering 100W in a diffraction-limited beam [refs. 24 & 25]. Fiber lasers using diode-pumped photonic crystal fibers with core diameters on the order of 40μm and lengths of 5–10m continuously deliver 50W average power in a 10kHz train of nanosecond pulses. By turning off the modelocker and pulsing the pump diodes, the same laser can deliver the same average power in free-running ms-duration pulses. Despite the number of energy transfer steps, overall wallplug electrical efficiency of the laser is still of order 40%.

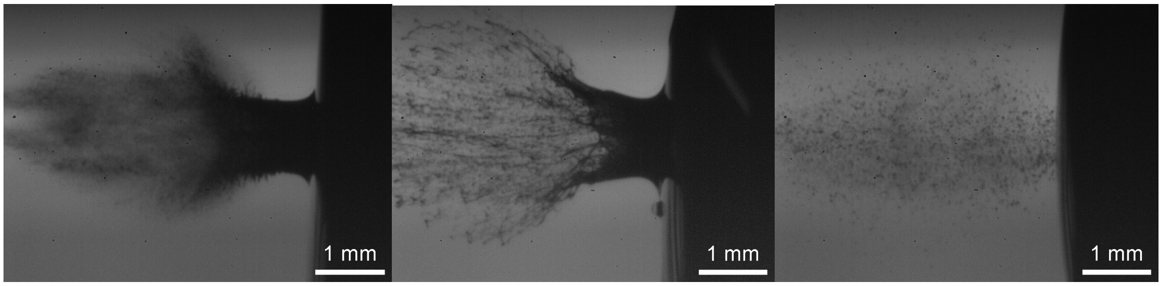
Second problem: Liquids with ordinary viscosities splash under pulsed laser illumination, even with ns-duration pulses, ruining engine performance by causing the majority of fuel mass to be ejected at low I_{sp}. All previous work with liquid ablation fuels has shown very disappointing I_{sp}.

However, in recent measurements in work for NASA [ref. 8], we demonstrated that I_{sp} = 680 seconds can be achieved by a viscous liquid fuel based on glycidyl azide polymer (GAP) and an IR-dye laser absorber. Figure 2, using data provided by Dr. Lukas Urech of the Lippert group, illustrates the solution.

To obtain the results quoted, we used a viscosity of about 200Pa-s in partially polymerized GAP with Epolin 2057 IR dye as the laser absorber [Figure 3]. In the Figure, the input beam can be either ns or ms-duration laser pulses. A motorized translation stage scans the focal point across the disk. The dimple created in the liquid by irradiation can be clearly seen.

We see no reason why the I_{sp} we achieved on gold [Table 2] cannot be achieved on a viscous liquid polymer, after fine-tuning the operating parameters. Ultimately, we expect to demonstrate I_{sp} = 10,000 seconds from liquid fuels. This can be done because theory [refs. 10-12] shows that I_{sp} in high power laser ablation is just a matter of laser intensity, following the relationship given in Eq. (1) [ref. 26]:

$$I_{sp} = 442 \quad \frac{A^{1/8}}{\Psi^{9/16}} (I \lambda \sqrt{\tau})^{1/4} \tag{1}$$



(a) (b) (c)

Figure 2. Shadowgraph Data from the Lippert Group [ref. 27] show that spray in liquid fuels is inhibited by viscosity. Inhibition of spray is crucial because it will dramatically lower I_{sp} by partitioning laser energy into slow-moving droplets instead of high-velocity plasma. All pictures are for $\Delta t = 10\mu s$ after the laser shot. The liquid fuel is GAP doped with 0.7-1% nanocarbon in each case. The solvent is ethyl acetate. The concentration of GAP varies according to (a): 0.7%, (b): 50%, (c): 70%. These results show the inhibition of splashing as the concentration of GAP (a viscous liquid) increases relative to the ethyl acetate. Of course, we could also make liquid fuels which are as viscous as necessary to generate high I_{sp} by partially polymerizing the GAP or dissolving it in ionic liquids. These alternatives have very low or vanishing vapor pressure.

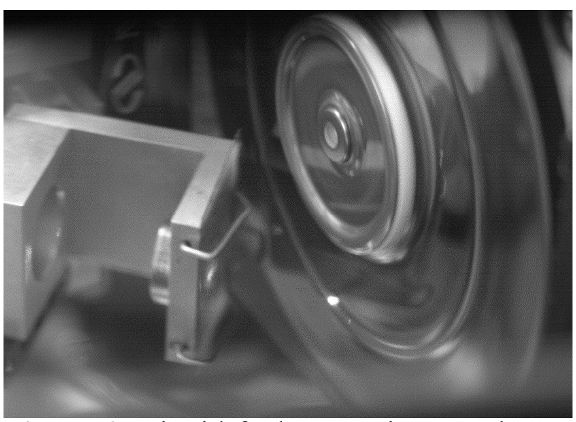


Figure 3. Liquid fuels are spin coated onto an IBM 2.5 inch diameter hard drive disk rotating at about 1 rps in vacuum. The disk is removed and weighed before and after irradiation to determine ablation mass loss δm which, in combination with total delivered impulse δJ gives $I_{sp} = \delta J/(\delta m g_o)$.

where τ is laser pulse duration, λ laser wavelength, I laser intensity (W/cm^2), $\Psi = A/2[Z^2(Z+1)]^{1/3}$, A is average atomic mass and Z is mean ionic charge in the jet. Plasma temperature is proportional to $(I\lambda\sqrt{\tau})^{1/2}$. Our experimental data supporting this idea is shown in Figure 5. In the figure, data we have obtained from actual thrust tests over periods of minutes to hours (Table 2) is augmented by single-shot data we obtained in other programs on aluminum targets. Together, the data shows that 3,660 seconds has already been obtained on solids, and that laser fluence of order 5kJ/cm^2 at 1.06μm, 10ns should produce 10,000 seconds. Such fluence on a 10μm spot is provided by 4 mJ energy pulses.

<u>The third problem</u> was how to eliminate optics clouding due to exhaust deposits in a 100W-class target illumination system. The solution which occurred to us has been used in laser welding for decades [Figure 4]. Gas flow through an illumination head in which the mean free path for a backscattered particle is less then the distance to the optics solves the problem. Calculations show that, in space, the

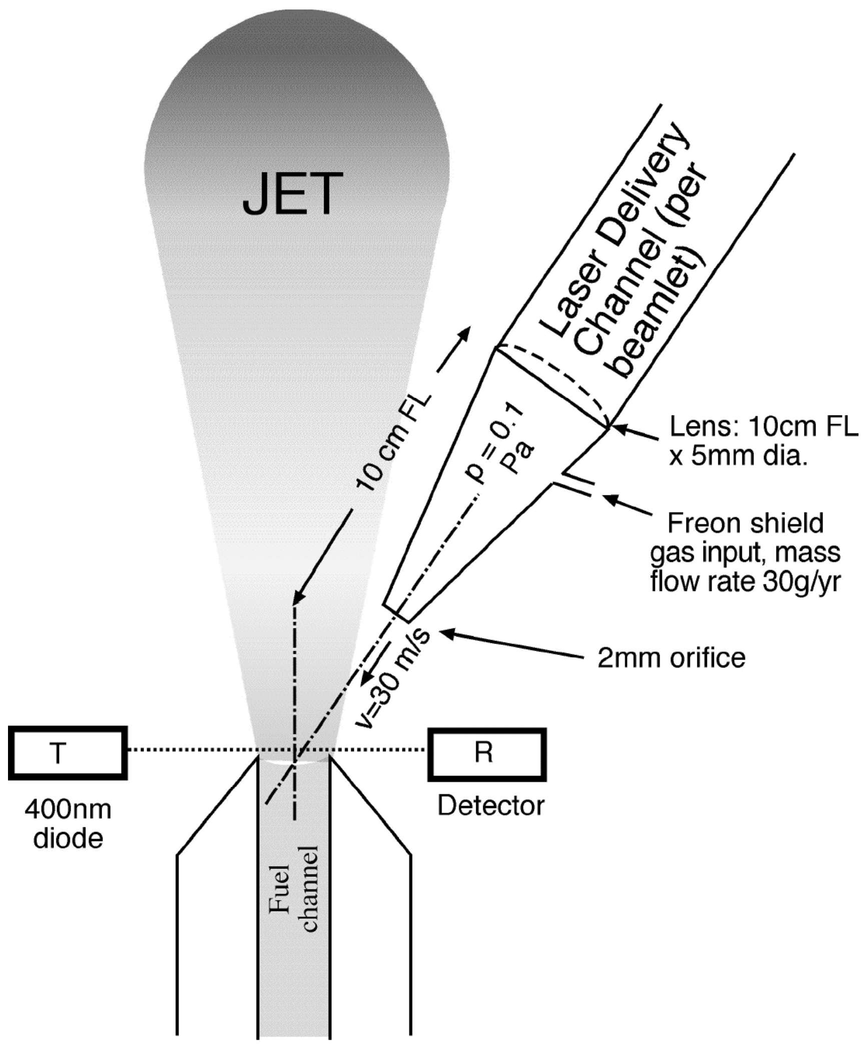


Figure 4. Beam delivery system. High intensity laser energy with ms or ns pulse durations makes a variable I_{sp} jet on a liquid target. A diode transmit/receive pair may be necessary to provide a control signal for the fuel pump.

flow required to provide this protection is only 30 grams per year of operation. Two lasers will address two fuel orifices.

Table 3 summarizes the performance we expect from the new liquid-fueled thruster we hope to develop.

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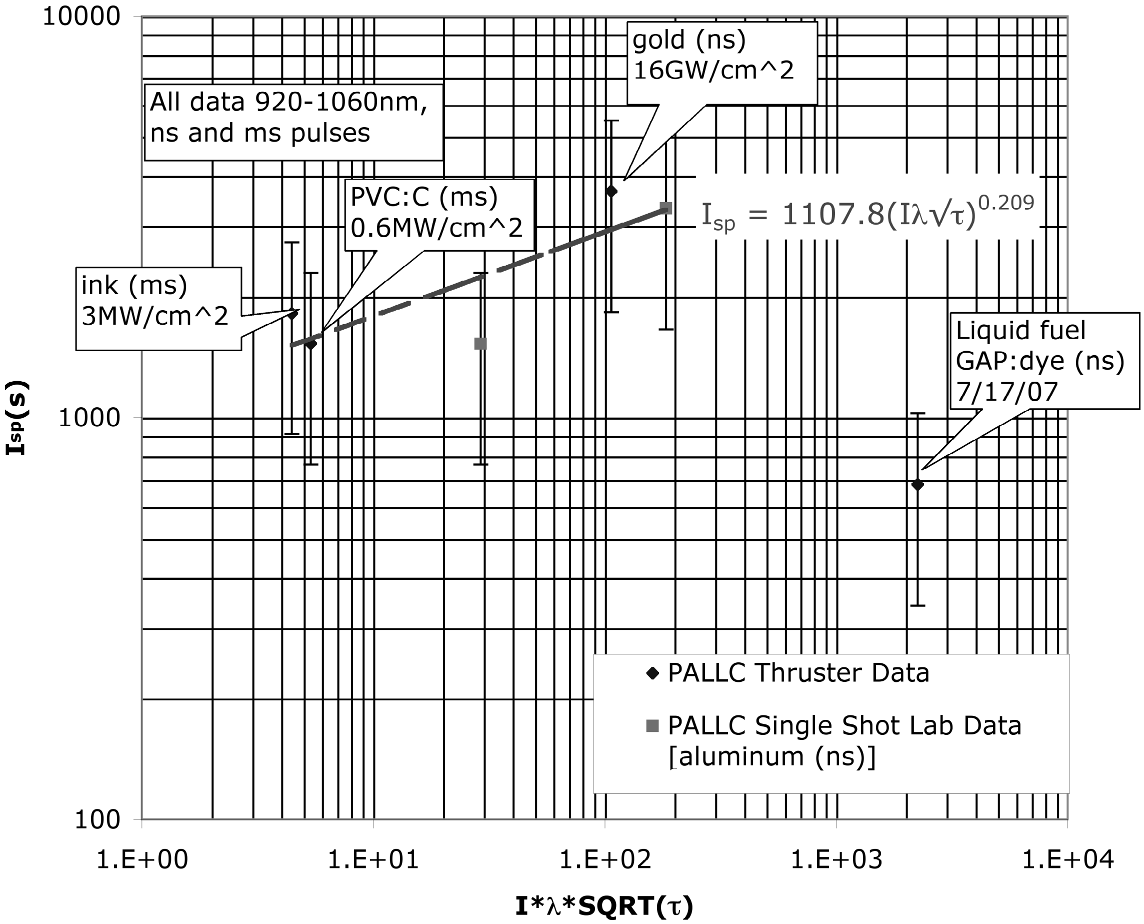

Figure 5. Experimental data shows that I_{sp} is just a matter of intensity. In the Figure, the units of I and λ are W/cm^2 and cm, respectively. The coefficient for the power law fit is a factor of two different from that in Eq. (1), which is calculated from first principles.

Table 3. Anticipated Engine Performance

Engine Parameters		
Motor Mass	10.5kg	
Fuel Mass	69.5kg	
Fuel Type	Energetic Liquid Polymer	
No. of Fiber Lasers	18 (100W max optical each)	
	High I_{sp} mode	**Low I_{sp} mode**
I_{sp}	3,660	116
Thrust at 3kWe input	57 mN	6.48 N
RMS Thrust Noise	1%	1%
Electrical/Optical Efficiency	40%	60%
Mass Usage Rate	1.6mg/s	5.7g/s
Lifetime Impulse	2.5MN-s	79kN-s
System C_m	19μN/W	2.2mN/W
Thrust Efficiency	34%	123%
P_{in} (electrical)	3kW	3kW
Δv for 180kg spacecraft	17.5 km/s	555m/s
Fiber Laser Amplifiers:		
Time-average Optical Power	1800W	1200W
P_{peak} (optical), EA	1MW	670W
Pulse Duration	10ns	1ms
Pulse Energy, EA laser	1mJ	670mJ
Pulse Repetition Rate	10kHz	100Hz

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