Advancing the Utility of Small Satellites with the Development of a Hybrid Electric-Laser Propulsion (HELP) System

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ABSTRACT. Some of the major space operational capabilities desired for modernizing and transforming our existing space infrastructure include: 1) in-space robotic assembly of modular structures, 2) routine spacecraft repositioning and rescue services, 3) use of formations of satellites that can perform functions not possible with traditional single large structures. All of these applications can make use of a new generation of highly capable micro-satellites. Advantages inherent with the use of small satellite formations include: - enhanced launch flexibility; on-orbit adaptability and reconfigurability; multi-mission capability; and mission longevity. **These characteristics equate to greater responsiveness and increased performance requirements at lower costs.** Specific applications well suited to small satellites include; space-based navigation and guidance for precision target tracking; high-bandwidth global communications for military forces utilizing space-to-space or space-to-ground laser communications; detection, and precise positional knowledge of enemy weapons of mass destruction (geolocation) using formation flying detector systems; formation satellite support of synthetic aperture radars; and precision proximity operations, to name but a few. **Mobilizing these micro-satellites will require revolutionary propulsion systems designed for critical performance needs such as long-term maneuvers and precision control. The operational metrics to consider include reliability, safety, simplicity, and weight-constraints.**

The Hybrid Electric-Laser Propulsion (HELP) system responds to these needs. Modularity, compactness, use of a chemically-benign propellant, and the absence of pressurized tanks, valves, and high voltage supplies, make it an operationally preferable companion to small satellites for a wide range of *on-orbit applications*. The objective of our work is to demonstrate the feasibility of a HELP system combining features from current state-of-the-art electric and laser thruster technology with several new features developed by Design_Net Engineering. Short pulse-width Q-switched lasers have the ability to create super hot plasmas from a readily available, inexpensive, and environmentally benign propellant. The resulting plasma is contained and directed to provide uniquely high and scalable specific impulse and variable thrust. It also enables superior minimum impulse bit (MIB) and noise levels. The HELP system feeds propellant using a patent-pending system that ensures repeatability and efficient propellant usage. A simple "plug-in" interface to the host spacecraft bus can be easily integrated and robotically serviced on-orbit. These features provide modularity, serviceability, and flexibility. The production of the HELP system will fill the current shortfall of cost effective enabling propulsion technologies for small satellite applications. Although some technological hurdles exist, they do not collectively appear to be "show stoppers".

This paper provides an overview of the status of current micro-propulsion systems, discusses associated problems and limitations of these systems in terms of key performance metrics and finally describes the HELP system, which is currently under development with support from DARPA.

INTRODUCTION

A key enabling technology that has seen limited advancement is precision micro-propulsion needed for close-proximity space object inspectors, synthetic aperture radar (SAR) systems, precision geolocation, high resolution imaging, and ground moving target indicator (GMTI) missions. Such applications impose tremendous demands and challenges on the attitude control and propulsion systems that far exceed the capabilities of current propulsion technologies.[4, 5, 9] Major limiting factors in current micro-thrusters are repeatability, inefficiency in propellant and power usage, low specific impulse (I_{sp}), high noise, contamination, and the inability to provide a continuous operating mode. Thus the development of high efficiency, high I_{sp}, low minimum impulse bit (MIB), low-cost propulsion suited to micro/mini-satellite's need for orbit change, station keeping, precision positioning or attitude control is an essential prerequisite. Due to the nature of the small satellite, the components of this system need to be low cost, compact, efficient, and provide the long life and high

ΔV performance needed to dramatically enhance the mission capability. This paper discusses key performance metrics for micro-propulsion and their impact on mission performance. It also describes a superior micro-thruster, the Hybrid Electric-Laser Propulsion (HELP) System, which is under development by Design_Net Engineering (DNet) and which meets the requirements described above.

MICRO-PROPULSION

Micro-Propulsion System Requirements

From a propulsion standpoint, formation missions will require multiple precision thruster systems that can deliver both high thrust and/or high I_{sp}. Today, many of even the simplest missions require multiple propulsion subsystems to perform its tasks, leading to increased mass, power and volume as well as increased system complexity. This is because no single technology can provide for the needs of high ΔV, low MIB, low noise, high efficiency, variable thrust etc. Thus, there is

clearly a need for an enabling propulsion system that through its configurability can meet a wide range of challenging performance metrics.

This single configurable propulsion system would have a broad performance range and could be adjusted on-orbit to suit the varying needs of a mission. This design consideration is very attractive, because such a propulsion system would simplify the spacecraft architecture (eliminating the need for multiple systems), minimize the spacecraft bus requirements and reduce its dry weight, complexity and cost, all of which are of particular importance for application to small-sats. Table 1, contains a selection of likely operation tasks that pertain to military and/or science missions. As can be seen, this small collection already translates to a wide range of thruster performance metrics, reinforcing the postulate that a configurable and 'tunable' (can provide high I_{sp} with variable thrust) thruster system is the key to providing the best performance and the most operational flexibility.

Table 1: Sample of typical Mission Tasks and Propulsion System Performance Requirements

Mission Operation Task / Comment	Requirement	Value [4, 5, 9]
Robotic service work done with proximity operations (<1m separation) and done over a long period of time	High ΔV, Precise Control of position	T< 1 μN with ms response time plus high I_{sp}
Provide full 3-axis control & fine position control for constellation configuration maintenance	Precision thrust	T< 10 μN
High positional accuracy - Spacecraft control to fractions of a wavelength	Precision thrust control	MIB< 10 μN·s ± 0.1 μN·s, High BW
Oppose drag & enable orbit raising (dependent on drag assumptions & maneuvering periods) Spacecraft rearrangements in constellation	Coarse thrust and high Isp	T> 0.1 mN I_{sp} > 5000 s
Spacecraft tip-off recovery	Coarse thrust range & control	T=25 – 100 μN $T_{control}$ ± 1 μN
Example 1 yr ΔV Straw-man mission for 100kg S/C 600Km orbit		
1 yr mission lifetime ΔV budget	Mission ΔV budget	Total= 270 m/s
Formation initialization over a 30 day maneuver period	Formation maneuver ΔV	~ 30 m/s
Over 1 yr life in ~ 600 Km orbit	Stationkeeping/drag ΔV	~ 40 m/s
Nominal 30 day maneuver period (depends on altitude change)	Orbit adjustment ΔV	~ 50 m/s
Deorbit at end of mission (dependent on orbit altitude)	Deorbit ΔV	~ 150 m/s

Micro-Propulsion State of Practice

There are several distinct thruster technologies (i.e. MEMS, cold-gas, electric, and laser systems) under continual development with the hope of filling the technology needs of the future. Dr. Leach examined the state-of-the-art micro-propulsion systems[1, 2] and concluded that no single existing micro-propulsion system is superior and suitable for arbitrary small satellite mission requirements. The research also showed that simply scaling existing micro-propulsion technology has its limitations. For example, chemical

reactions have limited I_{sp}; electric acceleration is limited by field strength and gas density etc.

Factors limiting the application of current low power laser and electric micro-thrusters (micro-PPTs, FEEPs, Colloids, etc.) include: poor repeatability, i.e. high noise level at minimum impulse bit; inefficiency in propellant and power usage; low I_{sp} that isn't much better than chemical propulsion; poor component lifetimes (i.e. accelerating grids, spark plugs); the inability to operate in a continuous (i.e. low mechanical noise) operating mode because pulse repetition

frequency (PRF) is too low; slow operation or PRF limits control bandwidth to <10Hz; use of high voltage systems decrease reliability.

Each system has different inherent limitations. Additionally, many of the current technologies have unacceptably high overhead mass; must deal with valve wear and leakage; and use propellants which are toxic or provide on-orbit contamination. Most of the current systems require complex subsystem components that are difficult to integrate into a small bus structure and none are on-orbit replaceable at this current time. Historically, most current systems have been designed for a specific application and tend to be the leader for that particular niche, having key advantages over the others, but as such, have finite performance metrics, eliminating their wide appeal and use. Most have also reached mature states and thus are nearing their maximum potential. Consequently, they will not see significant future improvement. Greater performance leaps can only be attained through technology jumps. Consequently, the availability of an alternative enabling, configurable, high-precision micro-propulsion technology is essential.

A design with the thrust-to-power ratio of a colloid, an I_{sp} greater than or equal to that of a Field Emission Electric Propulsion (FEEP), the ease of integration of a Pulsed Plasma Thruster (PPT), the non-contaminating characteristics of a cold gas thruster and in addition, the 'tunable' nature as discussed above to meet the numerous and varying needs of a mission would prove ideal. The Hybrid Electric-Laser Propulsion (HELP) system is being designed to fulfill this ideology.

Key Performance Metrics

Depending upon the specific mission requirements and objectives, a spacecraft can employ any number of thruster units to be able to satisfy its needs, depending on the type of thrusters available and their capability. The decision of which propulsion system to use for a mission is very important matter that can have both immediate and long-term repercussions. Common selection criteria can include design features, interfaces, physical characteristics (system size and mass), power requirements, safety criteria and sometimes more importantly the system's performance. Key performance metrics to consider when performing trade studies comparing micro-propulsion options are: *specific impulse* I_{sp}, precision–*minimum impulse bit* MIB, *thrust noise* f_n, *thrust* T and *integral velocity change* ΔV. The significance and implication of these metrics can be seen from Figures 1, 2, 3 & 4, respectively, and are discussed below.

Specific Impulse

*Specific impulse* I_{sp}, is defined as the total impulse per unit weight of propellant and is given by

$$I_{sp} = \frac{\int_0^t F \cdot dt}{g_0 \int \dot{m} \cdot dt} , \qquad (1)$$

Where F is the thrust force integrated over the burning time t, $\dot{m}$ is the total mass flow rate of propellant and g_0 is the acceleration due to gravity. Specifically, I_{sp} is a measure of the energy content of a propellant and the efficiency with which it can be converted into thrust. It is an important figure of merit of the performance of a thruster system, the higher the value the better the performance of the thruster. The significance of a high I_{sp} thruster system is a lower associated propellant budget providing benefits of reduced launch costs (each Kg saving of a satellite mass translates to a saving of approximately \$10,000 to \$30,000 in launch costs) or alternatively, the resultant available mass budget can be used for extra payload or power. Then again, if the allocated propellant budget was maintained then the additional/spare propellant that would result would increase the operational lifetime. As a result of these benefits, high I_{sp} thruster systems are preferable options for performing stationkeeping, orbit maintenance, attitude control, and precision pointing and positioning. Figure 1 shows the dependence of the required propellant mass on the specific impulse for a selection of micro-propulsion systems. The data were deduced for the example one-year ΔV Straw-man mission (100kg spacecraft; 600Km orbit; Mission ΔV budget of 270 m/s) given in Table 1. As can be seen from Figure 1, only a few of the propulsion options are practical for use on small spacecraft, that is their use will require minimal propellant mass to support the mission ΔV budget and still ensure sufficient mass availability for a payload. Typically, propellant budgets are no greater than 25% of the spacecraft dry weight[3], assuming a 100kg spacecraft the available propellant mass would be 25kg considering this, it can be seen that only the FEEP and HELP micro-propulsion systems meet this criterion/standard.

Minimum Impulse Bit

Minimum Impulse Bit MIB, relates to the operational precision of a thruster system, specifically it is the minimum impulse that a thruster can achieve and is defined as the integral of the thrust force over the minimum time the thruster is turned on for acceptably repeatable pulses. MIB is given by

$$MIB = \int_0^{t\,min} F \cdot dt , \qquad (2)$$
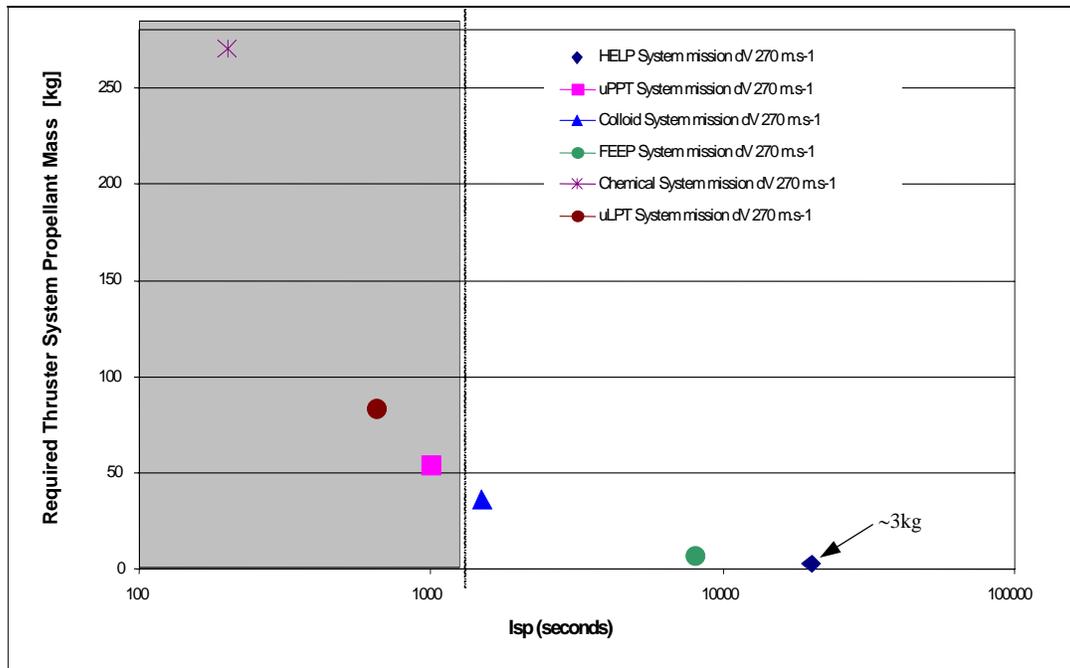
Figure 1. Propellant mass as a function of I_{sp}

Where *F* is the thrust force integrated over the minimum burn/operation time t_{min} required for repeatable pulses. It is another important figure of merit of the performance of a thruster system, the smaller the value the better the performance of the thruster. The significance of a small MIB thruster system is better thrust response control and therefore enhanced controllability of precision maneuvers and increased stability. Consequently, fine MIB thruster systems are preferable options when precision positional (transitional) and pointing (rotational) control are necessary since fine MIB translates to reduced spacecraft drift and pointing error, which in turn results in a reduced ΔV requirement to combat the drift. This advantage is especially important to Interferometry type formation flying missions and grand orbital telescope systems. Examples of which include gravitational waves missions like LISA (Laser Interferometer Space Antenna), X-ray Interferometry telescope observatory missions like MAXIM (Micro-Arcsecond X-ray Imaging Mission), and terrestrial planet searching missions like SIM (Space Interferometry Mission) and TPF (Terrestrial Planet Finder), as well as NGST (Next Generation Space Telescope).

Figure 2 shows the dependence of spacecraft drift on the minimum impulse bit for a selection of micro-propulsion systems. Again, the data were deduced for the example one-year ΔV Straw-man mission (100kg spacecraft; 600Km orbit; Mission ΔV budget of 270 m/s) given in Table 1. Typical control requirements of interferometry type formation flying missions range from nano-meter positional control to milli- and micro-arcsecond pointing control. [4, 5] As can be seen from Figure 2, only a few of the micro-propulsion options can support this requirement, namely the Colloid, FEEP and HELP systems.

Thrust Noise

Thrust Noise f_n (thrust variation), also relates to the operation precision of a thruster system. Specifically, it is defined as the variation/error in the output thrust force of a thruster system that is generated in response to a commanded thrust force level (i.e. the error induced owing to the generated thrust force value varying slightly from the thrust force value commanded). It is another important figure of merit of the performance of a thruster system, the smaller the value the better the performance of the thruster. The significance of a low noise thruster system is better thrust response control and therefore enhanced controllability of precision maneuvers and increased stability, also noise sources can interfere with and even prevent sensitive science measurements being made.

This is particularly important for gravitational wave missions, where they are trying to measure gravitational strain levels on the order of $h \leq 10^{-23}$, where h is the dimensionless amplitude of a gravitational wave (strain).
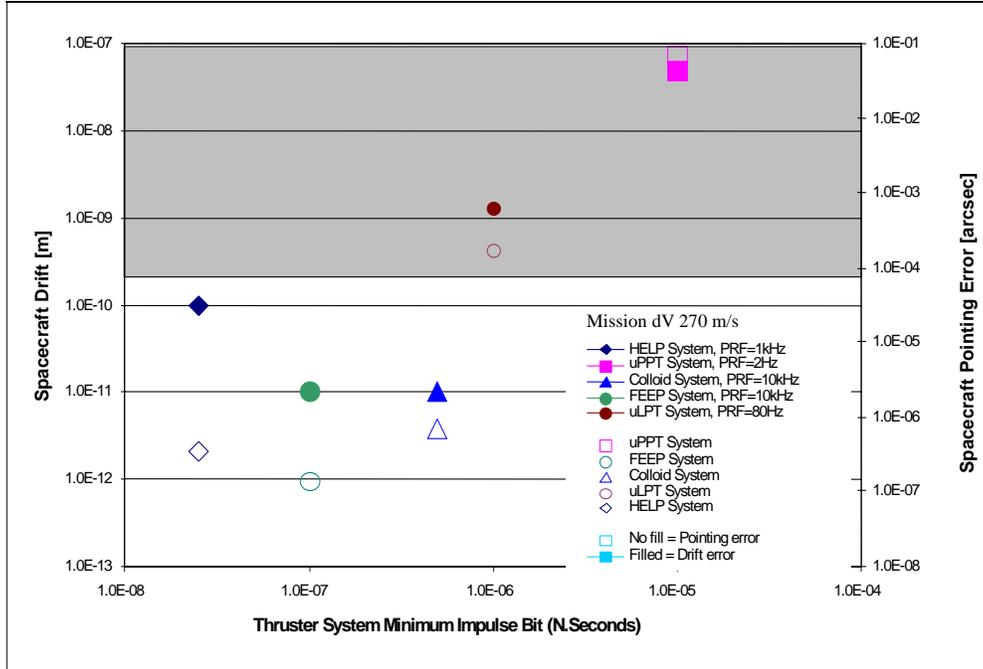
Figure 2. S/C Drift (translational control) & Pointing error (rotational control) as a function of MIB

In order to be able to achieve this, they utilize drag-free control systems/disturbance reduction systems to minimize the "spurious" (non-gravitational) accelerations that can result from competing effects of other fluctuating forces present such as external forces—solar radiation pressure fluctuations and thruster noise, since they can dominate and mask signals due to gravitational waves. Typically, the acceleration budgets and the subsequent source noise budgets that are necessary to achieve the science objectives are identified. For example, for the LISA mission the assigned acceleration budget and thruster noise budget are[4]

$$S_a^{1/2} \approx 10^{-15} \left[1 + \left(\frac{f}{3 \times 10^{-3}} \right)^2 \right] \left[\frac{10^{-4}}{f} \right]^{1/3} \text{ m·s}^{-2} \cdot \text{Hz}^{-0.5}, \text{ over the}$$

measurement bandwidth (MBW) of 10^{-4} Hz to 10^{-1}, which corresponds approximately to a root mean square (rms) acceleration of 1×10^{-15} m·s^{-2} and < 0.1 μN/Hz$^{-0.5}$, respectively.

Figure 3 shows a plot of the rms of acceleration for an example drag-free (DF) 100kg spacecraft (S/C) that was achieved over the LISA MBW as a function of thruster noise level (f_n). Figure 3 also presents the noise values for a selection of current state-of-the art micro-propulsion systems. As can be seen, a lower rms acceleration can be achieved with a better (lower)

thruster noise level. In fact, the simulations associated with this trade study (assessment of DF system's subsystems—accelerometer and thruster, noise levels and their impact on the achievable DF performance) demonstrated that it is the thruster noise that is the limiting factor as little improvement was observed with the reduction of the accelerometer noise x_n. [6]

Thrust

Thrust T, is defined as the force produced by a propulsion system acting upon a vehicle, or more simply it is the reaction experienced by a vehicle due to the ejection of matter at a high velocity. It is another important figure of merit of the performance of a thruster system. In this instance though, the higher the value does not necessarily mean a better performance of the thruster is achieved. It is more subjective to the user and their needs. The other primary metric that goes hand-in-hand with *thrust* when measuring/evaluating the performance of a propulsion system is the *velocity change* that the system can produce ΔV. ΔV is defined as the amount of a*pplied incremental velocity* that is required to perform a maneuver/task or that can be provided from a specified mass of propellant. The relationship of ΔV to I_{sp} and propellant mass m_p is given by

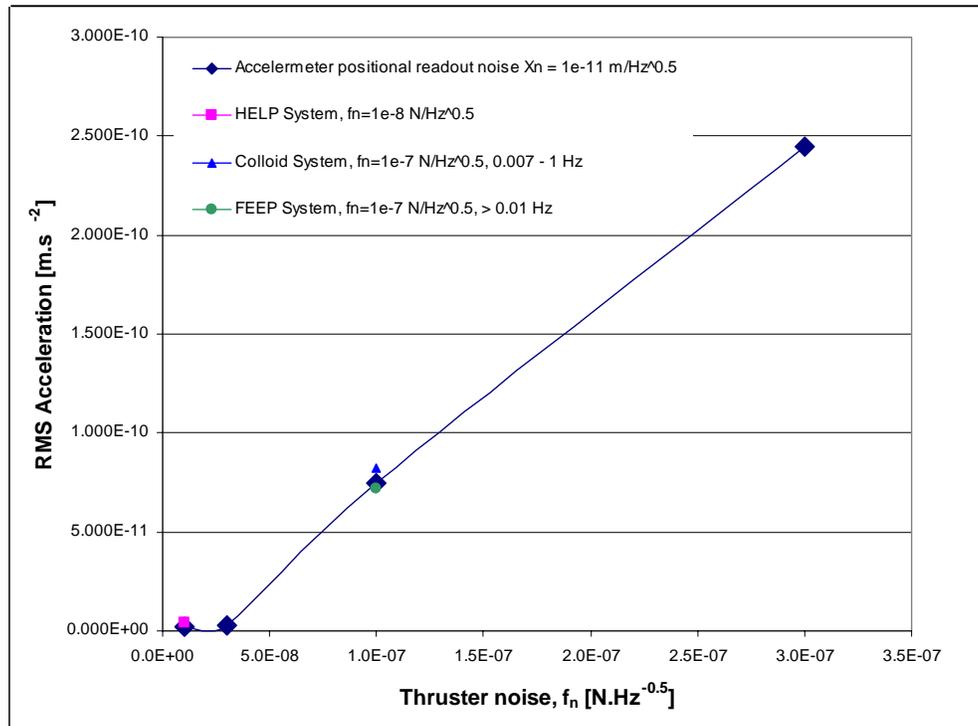$$\Delta V = \frac{g_0 \cdot I_{sp} \cdot \Delta m_p}{m_T}, \tag{3}$$

Figure 3. Plot of the RMS of acceleration for an Example DF 100kg S/C achieved over the LISA MBW as a function of f_n

Where I_{sp} is the specific impulse, Δm_p is the mass of propellant consumed, m_T is the total initial vehicle mass (total mass = mass s/c ($m_{s/c}$) + initial propellant mass (m_p)) and g_0 is the acceleration due to gravity.

The significance of a higher thrust is a reduction in maneuver time i.e. response time/maneuverability of the spacecraft to a commanded thrust would be faster than that for a lower thrust system this effect can be seen from Figure 4. Figure 4 shows the dependence of spacecraft maneuver time on thrust (or integral velocity change ΔV). Fast maneuver times are important for reconnaissance missions but may not be for de-orbiting. On the other hand, high thrust propulsion systems would not be desirable for precision maneuvering missions as the controllability will be inferior resulting in a greater ΔV requirement to combat the over-compensation. Therefore, high thrust propulsion systems are preferable options for performing orbit transfers, plane changes, rendezvous or relocation maneuvers, where as low thrust but high ΔV systems are preferable for performing stationkeeping, orbit maintenance, attitude control, and precision pointing and positioning.

Design Conclusions

In view of the previous section, that discussed the pros and cons associated with key performance metrics and the discrimination role they can play in the selection process of a thruster system for a given mission application, the following is concluded. The previous analysis highlights the trades between high thrust and specific impulse that current thruster systems incur, for example, higher impulse generally requires a thruster system sacrifice the magnitude of thrust which leads to longer maneuver times, where as higher thrust results in the relinquishment of high impulse leading to higher propellant mass requirements. Subsequently, it implies that a propulsion system that could capitalize on all of the benefits associated with each of these key performance metrics would be the optimum choice. Unfortunately, to date no system does or can. **A system that is 'tunable' (can provide high I_{sp} with variable thrust) is needed and as such will provide the best performance and the most operational flexibility**.

A propulsion module called the Hybrid Electric-Laser Propulsion (HELP) system is projected to be able to realize the tunability required to allow maximum use of fuel and the best overall system efficiency, details of this design are presented in the following sections.
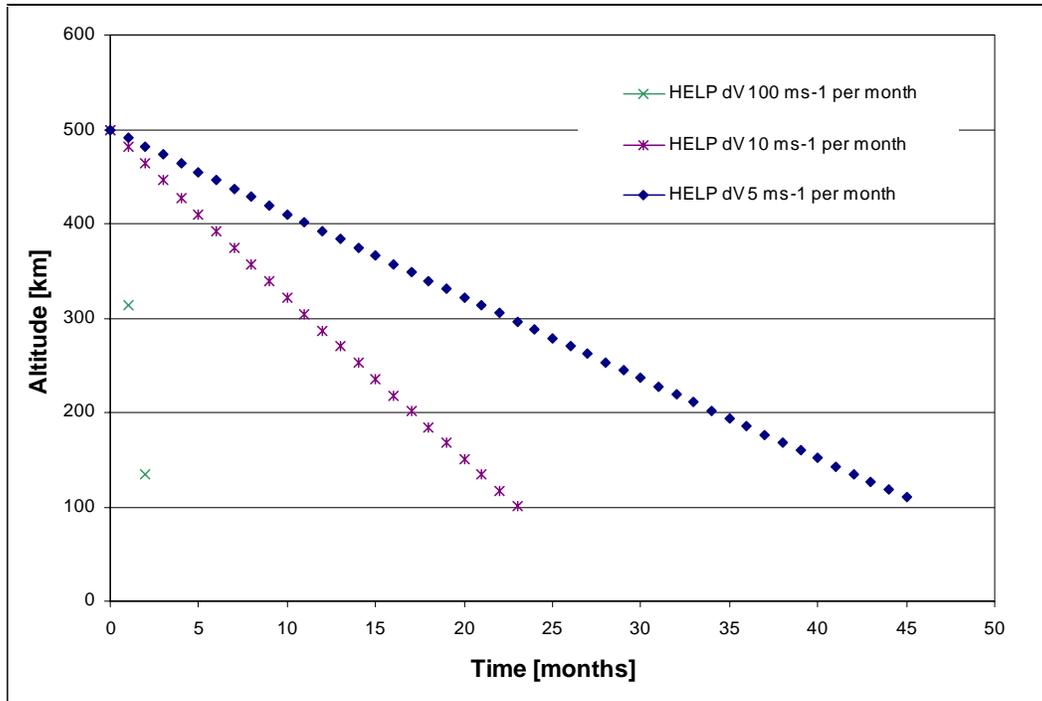
Figure 4. Spacecraft maneuver time (e.g. orbit altitude change) as a function of Thrust (T)

INNOVATIVE THRUSTER SOLUTION

Hybrid Electric-Laser Propulsion (HELP) an alternative Propulsion Solution

Laser plasma thrusters have been discussed in the past[7,] [8] and show good potential, but current designs still have many drawbacks. The use of low-power lasers limits the energy realm of operation and the resultant $I_{sp.}$ Current designs do not provide a good method for thrust control. Prior to the HELP design, the use of lasers to produce thrust by ablation have encountered repeatability problems. Dramatic surface morphology changes occur as the laser "bores into" the surface [9]. This influences the characteristics of the plasma expelled and thus the thrust produced. Last of all, the current system designs do not lend themselves to providing high-value ΔV, and are not easy to integrate with a small spacecraft.

Despite these technological problems, DNet, having a familiarity with laser ablation, plasma physics AND small spacecraft integration, believes that lasers may indeed provide the "break-through" technology needed—but in a different way than is currently being explored. The HELP research conducted to date has focused on three key aspects of laser propulsion—1) how to improve the I_{sp} and control the thrust characteristics of laser ablation; 2) how to make good repeatable thrust systems that do not use mechanical feeds and minimize contamination; and 3) how to systems engineer a propulsion module that is geared towards integration and operational simplicity.

Process of Laser Ablation

The process of laser ablation (i.e. material removal via laser-light) is complex, involving different processes depending on how the laser-light interacts with the target matter (see Figure 5, an overview of the various parameter regimes in laser ablation).

The principal processes that are responsible for the onset of ablation are 'photochemical', 'photothermal' and 'photophysical'. Figure 6 shows a flowchart illustrating some of the different interaction and feedback mechanisms involved in laser ablation. Ablation via the photochemical process involves the breakdown of the chemical bonds in the molecule while photoablation simply involves heating of the material and photophysical refers to a combination of both photochemical and photothermal processes. The interaction mechanism between the laser-light and the target material is dependent on both the parameters of the laser beam (i.e. pulse width, fluence, wavelength of laser-light, intensity, and width of laser focus etc.) as well as the physical and chemical properties of the target material (i.e. bulk elemental composition, melting- and boiling-points, reflectivity, and particle size etc.).
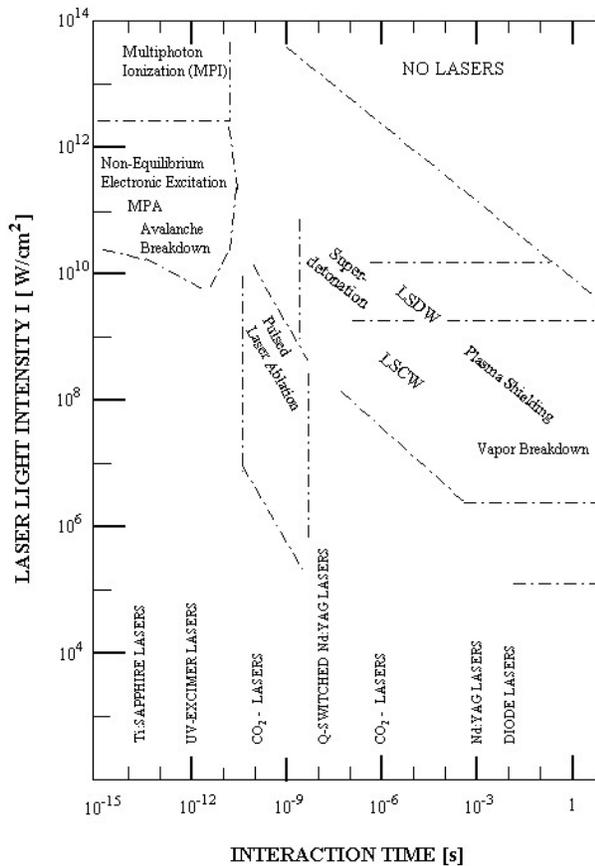
Figure 5. Overview of the various parameter regimes in laser processing [Figure reproduced from [10]]
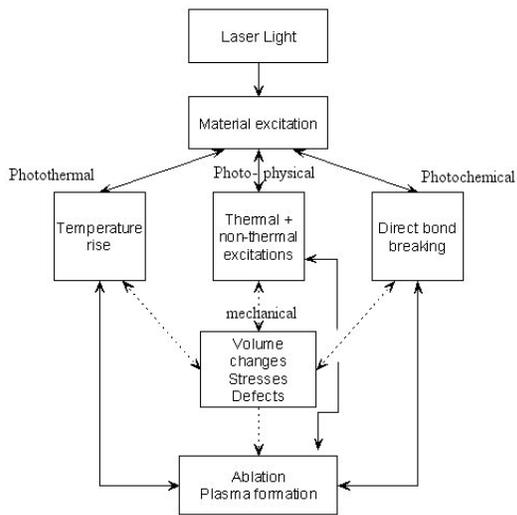
Key

→ Solid arrows indicate direct paths resulting in ablation
⋯▸ Dashed arrows indicate indirect paths resulting in ablation
↔ Double-headed arrows indicates coupling between processes

Figure 6. Flowchart illustrating some of the different interaction & feedback mechanisms that can be involved in laser ablation [Figure reproduced from [10]]

Typically the excitation energy from the laser-light is dissipated into heat and so photothermal is assumed to be the dominant process causing ablation. The dominant effects that result from laser exposure include laser-induced 'melting', 'vaporization' and 'plasma formation', and are defined by the laser-light intensity (see Figures 7 and 5).
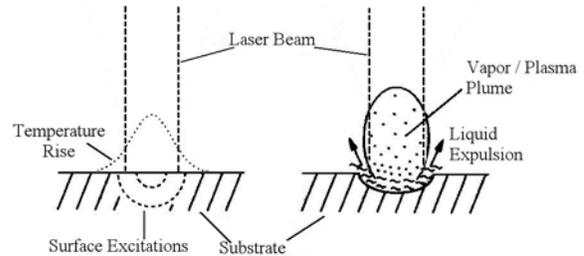

Figure 7. Illustration depicting the dominant effects that result from laser exposure i.e. laser-induced *melting*, *vaporization* and *plasma formation* [Figure reproduced from [10]]

With regard to the application of laser ablation in the HELP thruster system, the creation of high-energy plasma formation is of more interest, as material removed in this form has absorbed more energy, is released at much higher velocities, and produces significantly higher specific impulses I_{sp} than material released in other states. There are three energy realms associated with plasma formation; 'laser-supported combustion waves (LSCW)', 'laser-supported detonation waves (LSDW)' and 'superdetonation' [10], all of which are dependent upon the laser-light intensity. The wavelength of the laser-light can also impact how a laser interacts with a material. For example, if the laser-light intensity reaches a critical value, typically 10^7 W/cm^2 < I_{cr} < 10^{10} W/cm^2, and depending on the laser-light wavelength, plasma shielding (see Figure 8) can also arise; that is, the laser-light does not reach the substrate but instead is completely absorbed by the plasma, resulting in weak coupling between the plasma and the substrate and inhibiting energy transfer (i.e., laser-induced material vaporization stops). The first regime is that where LSCWs occur, specifically the laser-light intensity I, is high enough to cause optical breakdown within the gas/vapor in front of the substrate, but is too low to cause a detonation wave (i.e. $I_p \leq I \leq I_d$)[10, 11] (see Figure 9).
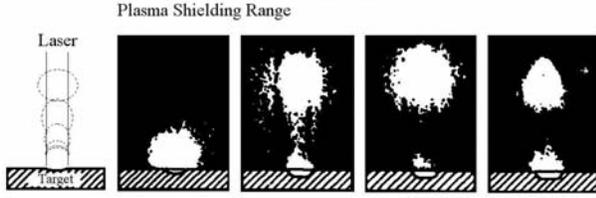
Figure 8. Critical laser-light intensity range where Plasma shielding arises [Figure reproduced from [10]]
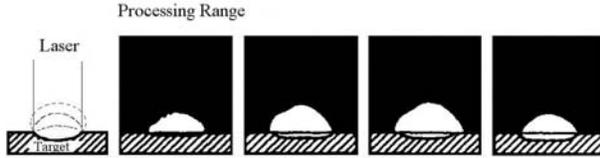
Figure 9. LSCW regime where the laser-light intensity is high enough to create a stationary plasma in front of the substrate, which is confined to region near the surface [Figure reproduced from [10]]

The second regime involves higher laser-light intensities, specifically $I \geq I_d$, where $I_d > 10^8$ W/cm[10, 11], and results in the ablated material propagating away with supersonic speeds which in turn causes a shock wave to be driven into both the ambient medium and the substrate. In this case the velocity of the shock wave in the ambient is approximately equal to that of the ionization front. The propagation velocity v_{dw}, of a LSDW can be approximated by[10]

$$v_{dw} \approx \left(2(\gamma^2 - 1) \frac{I}{\rho_g} \right)^{1/3} \propto I^{1/3}, \tag{4}$$

where γ is the adiabatic coefficient $\approx 5/3$, and ρ_g is the density of the ambient medium. The third regime involves very high laser-light intensities, typically $I \geq 10^9$ W/cm^2, and is where superdetonation arises. Under this circumstance the ionization front propagates in front of the shock wave. The propagation velocity v_{sd}, of superdetonated ionization waves can be described by[10, 12]

$$v_{sd} \propto I^n, \tag{5}$$

where $n > 1$ [12], and values for v_{sd} have been shown to reach values on the order of 10^9 cm/s meaning I_{sp}'s potentially up to 1,000,000 seconds can be achieved.

Short-Pulse Laser Ablation

With the development of a new generation of lasers that can provide joules to kilojoules of energy within ultra-

short pulse widths ($\tau \leq$ hundred picoseconds) new laser interaction processes and effects preside. Previous research[13] in this area has shown that continuous-wave (microsecond and longer pulse-width lengths) irradiation leads to momentum transfer via compression waves in laser-sustained plasma, as discussed above, while high-energy short pulse-width ($\tau \leq 10^{-10}$s) irradiation leads to momentum transfer through direct ablation of material. This later process has also been shown[13] to be the more energy efficient process—more efficient manner by which momentum transfer is instigated, providing better I_{sp}'s and mass power ratios than continuous wave irradiation. Subsequently, the use of short-pulse high-energy lasers are proposed for the HELP system—as mentioned previously, high intensity is also ideal to maximize the I_{sp} and thus the mission ΔV capability, since plasma velocity is proportional (though not linearly) to the laser-light intensity. The I_{sp} imparted by such short-pulse ablation dominated momentum transfer induced processes is given by[14, 15]

$$I_{sp} \equiv \frac{1}{W} \int_{t_0}^{t_f} F(t)\, dt = \frac{1}{W} \int_{t_0}^{t_f} \frac{dP(t)}{dt}\, dt$$

$$= \frac{P}{W} = \frac{m_{ex} v_{ex}}{m_{ex} g_o} = \frac{v_{ex}}{g_o}, \tag{6}$$

where W is the weight of the ablated propellant and $F(t)$ is the thrust as a function of time t. The integral presents an impulse applied to the target and the time interval (t_0, t_f) over which the integration takes place is defined by the duration of the ablation (duration of mass-removal from the target). This interval is typically incomparably longer than the pulse width of the irradiating laser and is about equal to the plasma lifetime. v_{ex} is the mean propellant velocity, m_{ex} is the mass of the ablated propellant, g_o is the acceleration due to gravity and P is the acquired momentum per pulse. Therefore, assuming the ablated propellant has the same mean velocity in accordance with the above equation one should be able to deduce the I_{sp} from the speed of the ablated ions. Prior research[14] has observed I_{sp}'s of $\sim$ 20,000s for a target of graphite (when using a Nd:YAG laser, irradiance of 3×10^{13} W/cm^2, and τ of 100ps at λ of 532 nm)—a significant improvement over achieved I_{sp} levels of current micro-propulsion technology. This research also noted a strong dependence of the gained I_{sp} to the target material used––I_{sp} decreased with increasing atomic mass. Thus, the choice of propellant, contingent on application and therefore required performance, is an important design and implementation choice.

The required length of a laser pulse τ to make ablation the dominant mechanism of momentum transfer relates to the plasma's critical electron density, N_{ec}. Specifically, the upper limit of τ is set by the time that it takes to develop a high-density plasma that becomes opaque to further transmission of the laser-light's energy. This phenomena (total reflection of laser-light) occurs when the plasma's complex refractive index becomes purely imaginary and its frequency exceeds a critical value $v_{cr} = v$, the frequency of the incident laser-light. Under such circumstances the corresponding critical electron density N_{ce} is given by[14]

$$N_{ce} = \frac{m_e \varepsilon_0 v_{cr}^2}{e^2}, \qquad (7)$$

where m_e is electron mass, ε_0 is the permittivity of free space, v_{cr} is the critical plasma frequency, and e is electron charge. In the case of the HELP system, we anticipate the use of a short pulse-width Q-switched laser with a 1.06μm output wavelength. As such the corresponding critical electron density would be N_{ce} $\sim 2.5 \times 10^{25}$ m^{-3}. Now assuming impact ionization is the predominant mechanism of electron density growth, therefore disregard multiphoton ionization, and any loss mechanisms since the timescales are so small then the following equation results[14]

$$\frac{dN_{ce}}{dt} = r_i \cdot N_{ce}, \Rightarrow t_{cr} = \ln(N_{ce})/r_i, \qquad (8)$$

where t_{cr} is the approximate upper limit on the critical time (i.e. required length of a laser pulse τ to make ablation the dominant mechanism of momentum transfer) and r_i is the ionization rate. Taking $r_i \sim 6e^{11}$ s^{-1} then gives an upper limit on τ of ~100ps.

Short pulse widths are also desirable because they reduce thermal-transfer to the bulk material and therefore the heat-affected zone, which in turn reduces the collateral damage that results on the target propellant. This is important, as it eases the task of replenishing the target area to ensure repeatability. As mentioned previously, dramatic surface morphology changes occur with repeated exposure to a laser—often it results in a rough trough being burned into the target material after a period of time.[9] Figure 10 shows a picture of NaCl surface that has been irradiated by 16ns pulse 248nm KrF-laser and the crater and cracks that resulted.
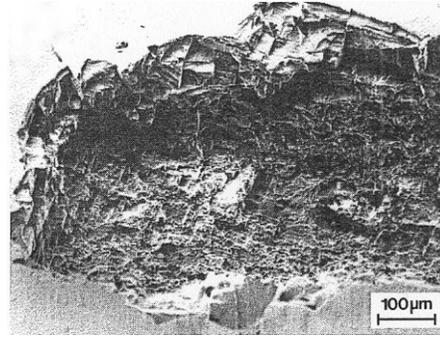
Figure 10. Example of how a materials surface structure is impacted after being ablated by laser radiation [Figure reproduced from [10]]

Such effects influences the characteristics of the plasma expelled and thus the thrust or I$_{sp}$ produced. Consequently, it seems critical to avoid re-exposure of the target propellant's surface in order to ensure repeatability in a thruster system that is based on a laser ablation concept. This matter has been researched and a design solution proposed to address it, incorporated within the HELP system.

Note not all of the increase in laser peak power (that comes from the use of high-energy short-pulse lasers) is realized directly as an increase in the velocity of the ablated material and therefore an increase in the I$_{sp}$. This is the crux of the scaling laws that we seek to establish—*how can we control the intensity and pulse width to vary the I$_{sp}$ and the thrust*. Obviously, some applications require higher thrust but do not need super high I$_{sp}$, other applications require the opposite—as pointed out in the section "*Key Performance Metrics*". For the case where a higher thrust is more desirable than a high I$_{sp}$, and mission ΔV capability, such high laser intensities are not ideal because above a certain intensity the efficiency of the interaction decreases dramatically as a progressively larger fraction of the incident light is used to heat and accelerate the plasma rather than to heat and **ablate** the target. Design configuration and operation decision details of the HELP system are discussed in the following sections.

HELP MICRO-PROPULSION DESIGN

HELP System Description

HELP is based on recent advances in the science of short pulse-width high-power laser ablation, high temperature plasma containment, and electromagnetic collimation techniques. Additionally, a novel propellant feed system design ensures repeatability and efficient propellant usage. A block diagram of the HELP system showing its components and subsystems is shown in Figure 11.
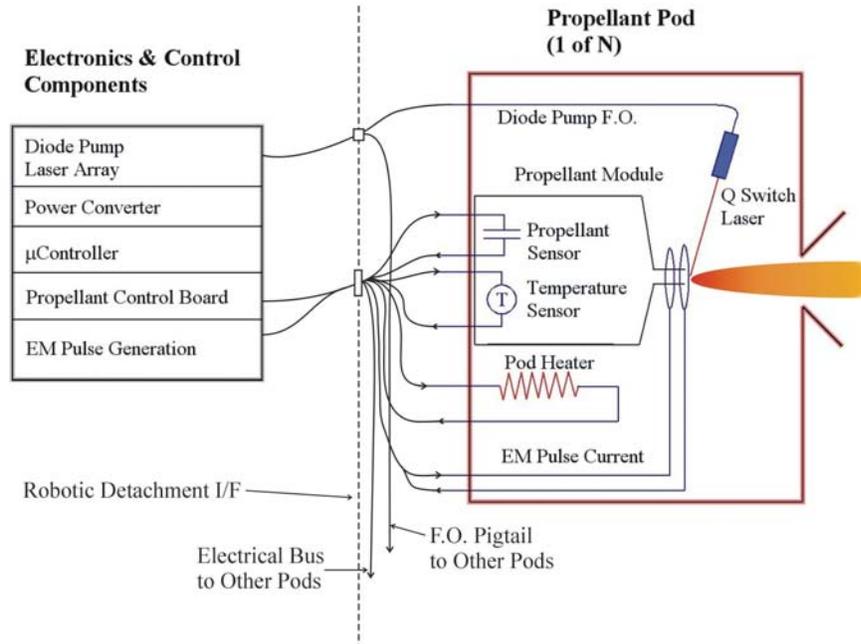
Figure 11. Block Diagram of Hybrid Electric-Laser Propulsion (HELP) System Components"

The principal functional subsystems of the HELP thruster subsystem are: 1) *laser ablation subsystem*, 2) *plasma collimation subsystem*, 3) *propellant feed subsystem*, and 4) *control and power conversion subsystem*. These four functional components are housed in two discrete and easily connected (to enable robotic servicing) physical units: the electronics & control unit, and the modular propellant pod.

Physically the system is arranged so that the propellant pod is detachable. Approximately 80% of the propellant pod mass consists of propellant and approximately 90 to 95% of that propellant is usable with the novel feed system design. The propellant pod is attached to the outside of the spacecraft (or could be boom mounted) with an optional robotically serviceable interface. Only low voltage and optical signals exist at the propellant pod to spacecraft interface. The control and power conversion subsystem unit is contained within the spacecraft bus and has typical serial digital and power interfaces.

The entire propellant pod/Q-switched laser sub-assembly (consisting of an arbitrary number of individual "pods") can be "plugged into" the spacecraft via two connectors, one a fiber optic connector, the other a simple low-voltage electrical connector. The electrical connector connects the pod heaters, temperature sensors, capacitive sensors, and EM pulse coils to the control system and the fiber optic connector connects the pump lasers to the Q-switched micro-chips.

Laser Choice

The utilization of Q-switched lasers in commercial applications is becoming increasingly popular due to their excellent beam quality and increased peak pulse power over traditional gas lasers. These same qualities are also very desirable to a laser thruster system, since more energy per pulse can be transferred to the propellant resulting in increased plasma velocity, which translates to increased I_{sp} and mission ΔV capability. Q-switching involves the use of a saturable absorber within the laser cavity to delay the onset of lasing (see Figure 12).

The laser pump energy is accumulated within the absorber material until it reaches the materials saturation point (most of the atoms/molecules are in a high-energy state), at which point the absorber material becomes bleached and transparent to the incident light and then emits a short high-energy laser pulse. These short, extremely repeatable pulses allow a very low and very precise MIB.
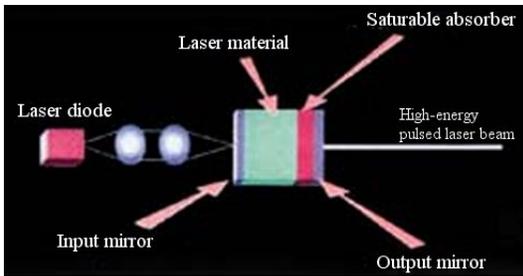
Figure 12. Basic Configuration of a Passively Q-switched Laser

The design of such lasers is simplistic in principal (although extremely complex in development) and is also inherently robust and reliable; they may also be packaged into very small volumes. Other features of such lasers include reported electrical efficiency ($\geq$ 35%)[16] and *projected* high mean-time-between-failure (MTBF) of 1 million hours (~114 years). [16]

An example embodiment of a HELP thruster system could comprise of a low power diode-pumped solid-state laser beam (contained within the electronics chassis) and carried through an optical fiber to a Q-switch/microchip laser. Where the microchip consists of a monolithic block of laser material coupled with a saturable absorber. Hence, the pump could excite the laser material atoms causing them to lase, providing an intense high repetition rate laser beam output. This output could then be focused onto a regenerative ablation target surface producing a plasma jet, which provides the thrust. Ion engines have 20-30% ionization efficiency but the HELP system will achieve *near total ionization*. Unlike previous laser systems, use of a short-pulse "rapid-fire" Q-switched laser, for example, in the HELP system could produce very high ion temperatures giving much higher I_{sp}'s. Configurability of the I_{sp} is achieved by the degree of focus of the laser and the resultant beam intensity on the target and pulse length of the irradiating laser. Additionally, gating the pump laser at pulse trains as low as 0.1ms allows very fine MIB control.

Plasma Collimation

In addition to employing a laser to ablate the target propellant and form a highly ionized plasma the HELP subsystem has the option to use an electromagnetic (EM) field to contain the initial plasma ball until it leaves the nozzle, helping to provide a more efficient and directed momentum transfer and dramatically reduce contamination.

The shape and manner in which the plasma plume is ejected and propagates is of interest because it directly impacts the generated thrust level and thrust efficiency

of the system (lower kinetic temperature losses). The ion beam profiles of current "ion type" (i.e. electric and laser) thrusters have recorded divergence angles varying between approximately ±13 and ±50 degrees[8, 16, 17, 18] (see Figures 13 and 14), which corresponds to a performance reduction of as much as 36%.
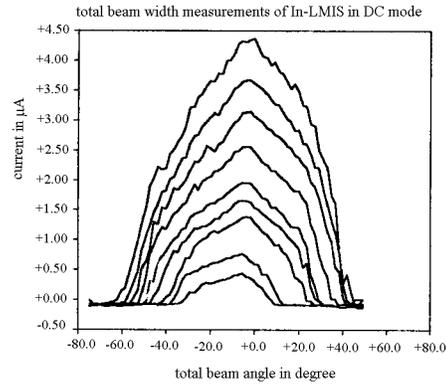
Figure 13. Ion beam divergence profile of Indium-LMIS [Figure reproduced from [17]]
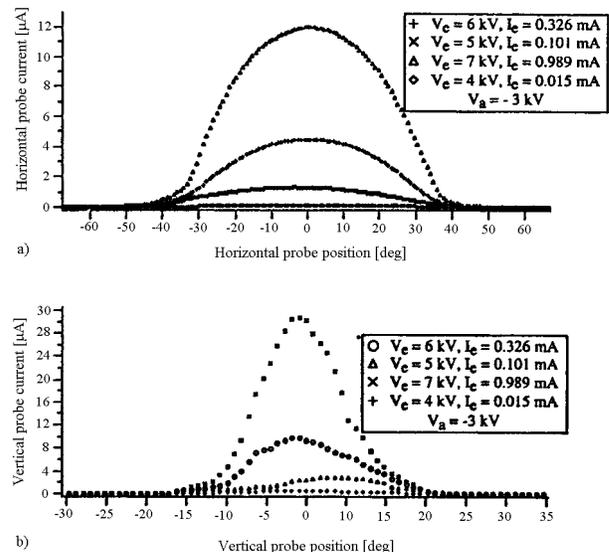
Figure 14 Ion beam divergence profiles a) horizontal and b) vertical probes of Cesium-FEEP [Figure reproduced from [18]]

Consequently, our option of an EM field for controlling and collimating the trajectory of the ions expelled from the target propellant is available. This option will focus and narrow the velocity distribution function of the plasma and thus improve the achievable I_{sp}, thrust, and system performance, as well as minimize contamination and cross-coupling effects.

To understand the principle of this containment, it is critical to appreciate two fundamental principles of this

hot plasma. The first is related to its creation and the second is related to its density and temperature. In the creation of a plasma in the "superdetonation" regime, the target is heated so intensely and so quickly that the individual atoms reach ionization temperature and quickly shed their electrons. The electrons, because they are lighter than the ions "rush" away from the surface and a strong electric field is created which, in turn, accelerates the ions away from the surface. The complex and rapid plasma interaction that takes place is "helped along" by a short EM pulse that serves to momentarily confine the electrons to a focused column and concentrate the electric field. The combination of these effects forces the plasma jet to move rapidly away from the surface creating the maximum momentum coupling for the mass and velocity available and minimizing the commensurate contamination. The control system operating the laser also administers the EM pulse. The exact timing, shaping, and magnitude of this pulse is under research.

Control Electronics

Operationally, the HELP system is controlled by the fourth of the key subsystems, the control and power conversion subsystem. This subsystem provides power conversion, a bank of pump lasers, a CPU with the software to interface to spacecraft commands, and feedback to the spacecraft system on HELP health and status. This system converts spacecraft commands such as "provide x thrust" or "provide x thrust at y I_{sp}" into the actual control system signals to the one or more thruster pods under its control. A pseudo-steady-state continuous mode can be achieved by operating the laser at a very high repetition rate compared to the system response resonances.

Design and Operation Details

The core functional capabilities of the HELP system can be summarized by three sub-processes which are associated with its three principal sub-systems namely; the '*propellant feed*', '*laser ablation*', and the '*plasma collimation*' sub-systems. The first sub-process entails maintaining the viscosity of the propellant to allow feed to the target ablation area, while the latter two sub-processes involve operating and controlling the lasers and collimating electromagnetic field respectively.

Thus far, this paper has principally focused on design features that enable the generation of high I_{sp}, the benefits of this metric are important, as discussed in the section "*Key Performance Metrics*". But as mentioned briefly earlier, other metrics may have precedence depending on the mission needs although, more and more applications are becoming progressively more

complex and thus require a more flexible propulsion system that can provide a wide range of challenging performance metrics—a 'tunable' system able to provide high I_{sp} with variable thrust would provide the best performance and most operational flexibility and therefore have the widest appeal and application. Hence, this aspect was accounted for in the HELP system design—the propellant pods are designed in a modular "honeycomb" fashion (six sided pods can be ganged together, see Figure 15) so that the size of the total pod is configurable and scaleable for the application.

Figure 15. HELP System Straw-man Flight Pod Cluster

Each individual pod in the group may also have differing I_{sp} capability and different thrust ranges making the entire "gang" on-orbit variable for a wide range of applications. Each gang is separately controlled by the electronics and each can have a unique functional capability whether that includes orbit raising, precision attitude control, or precision positioning. This feature is achieved by using a selection of propellants (with varying atomic masses) and lasers (with different operation characteristics – power, intensity, pulse-width, wavelength and beam diameter etc.), and if needed, the use of multiple lasers per pod. Figure 16 shows an illustration of an example configuration for a 'tunable' HELP system.

High atomic mass
propellant

Low atomic mass
propellant
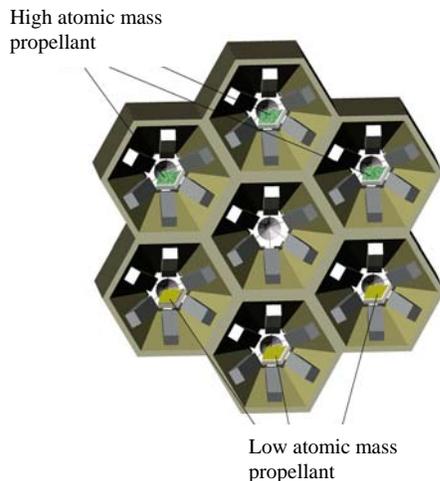
Figure 16. Example of a 'tunable' Multi-thruster HELP system configuration utilizing a selection of propellants

Also if the chosen application/mission is not sensitive to electromagnetic interference then the plasma collimation field option can be used as well to further improve the efficiency and performance of the HELP system.

CONCLUSIONS

This paper gives an overview of the status of currently available thruster technology including some of the problems and limitations associated with these designs with respect to their applicability to small satellites. It also discussed various propulsion design trades, and presents details of a propulsion module called the Hybrid Electric-Laser Propulsion (HELP) system which is projected to be able to realize the tunability required to allow maximum use of fuel and the best overall system efficiency.

This paper also emphasizes the fact that revolutionary, NOT evolutionary, approaches are now needed to develop the core technologies, that will raise the utility of small satellites and allow them to realize their full promise and as such meet the demands of future missions.

In summary, we believe the production of the HELP system will fill the current shortfall of cost effective enabling propulsion technologies existing within small satellite applications to support formation-flying and precision attitude control functions. The HELP system also promises to achieve significant cost reductions. The projected advantages of the system over other micro-propulsion technologies include:

1. The potential of achieving extremely high specific impulses (related to the exhaust velocity), much larger than competing systems because of the very high resultant temperatures that can be attained from the application of short-pulse high energy lasers.
2. Very large operating range (generated I_{sp} and thrust) compared to any other thruster design as a result of the systems high operational efficiency and its modular, scalable and very flexible 'plug-and-play' design and construction.
3. Very small minimum impulse bit (MIB) values compared with other thruster systems.
4. Potential of achieving the least associated noise of any thruster system due to the system having no moving parts but comprising of electric parts only and having the ability to be operated in a pseudo-continuous mode at relatively high frequency.
5. System lifetime surpassing any other system as a result of the phenomenal mean-time-between-failure (MTBF) values recorded for the principal system components (i.e. lasers having MTBF $\geq$ 1 million hrs) and the added benefit of having close to 100% propellant usage.
6. Potential compactness and minimal mass of system arising from the minuteness and simplicity of the operating parts of the thruster.

Other anticipated benefits of the HELP system are a scalable modular micro-thruster that has significant system and performance enhancements including improved thrust-to-weight ratio, increased mission lifetime, close to total use of propellant, reduced weight, higher total impulse and a very simple spacecraft interface enabling on-orbit robotic servicing.

Further investigations are underway in this field to ensure the production of this unique high performance thruster is available to the small satellite community in the near future.

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BIOGRAPHY

Rachel Leach graduated from Leicester University in 1997, and completed her Ph.D. in July 2001 at the University of Birmingham in Physics and Astronomy. Her Ph.D. research was primarily focused on the development of hardware for future space-borne gravitational wave missions. In particular, her work concentrated on modeling responses of dynamic systems, which require extremely low drag (pico-g satellites) and formation flying satellites, which require high precision position control. She is currently working for Design_Net Engineering LLC in Lakewood, Colorado as the senior staff scientist leading and directing DNet's internal research and development (IR&D) program. Her current research efforts are focused on the design and development of a new class of micro-Newton thrusters. She is also the assistant project manager of software and electronics development for the Low Temperature Micro-Gravity Physics Experiment Facility, which will be flown as a facility class experiment on the ISS.

Thomas S. Adams has been employed in the aerospace business for 25 years including stints with the Boeing Company as a system assembly and checkout liaison engineer for the Minuteman Force modification program from 1977 to 1981, and in a Project Management/Systems Engineering role with the Lockheed Martin Corporation from 1981 to 1999 on programs such as the Peacekeeper ICBM Assembly Test and Checkout (AT&SS) program, Small ICBM, Super Conducting Super Collider, and the Titan IV, Titan II, Atlas, and Athena launch vehicle programs. The time spent at Lockheed Martin offered Mr. Adams the opportunity to function in numerous discipline areas, including Nuclear Hardness and Survivability, Electromagnetic Compatibility, High Energy Physics Detector Design, Payload Integration, and project management. He is currently employed by DNet as Chief Operations Officer, Senior Systems Engineer, and Project Manager of the Electronics and Software Subsystem development Contract for the NASA/JPL Low Temperature Microgravity Physics Facility (LTMPF) Experiment, which is to be deployed on the International Space Station.

Gerald B. Murphy began his career in the "space business" at the University of Iowa in 1974 working data analysis on an explorer mission. He has a B.S. in Math and Physics from the Iowa State University. Gerry also has a M.S. in Astrophysics and M.S. in Electrical Engineering from the University of Iowa. Gerry Murphy has written over 20 papers published in referred journals and holds 4 patents. His critical skill

areas include space hardware design, development and test, and high-risk program management.

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