Advanced Space Propulsion with Ultra-Fast Lasers

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Abstract. A novel propulsion system that is expected to evolve from promising worldwide research in which ultrafast lasers [with very short pulse length] are used to accelerate charged particles to relativistic speeds is presented. The LAPPS [Laser Accelerated Plasma Propulsion System] concept makes use of high power lasers with femtoseconds pulse lengths that are made to strike micron size focal spots in very thin targets giving rise to nearly collimated, charge neutral, proton beams with mean energies of several MeV. When utilized in a propulsion device these beams produce specific impulses of several million seconds albeit at very modest thrusts, and require nuclear power systems to drive them. In this paper we examine the underlying physics issues and the technological problems that must be addressed to make LAPPS a viable propulsion device that could open up interplanetary and interstellar space to human and robotic missions in the not too distant future.

INTRODUCTION

One of the remarkable scientific developments of recent years is the demonstration, in table top experiments, that ultrafast (very short pulse length) lasers can accelerate charged particles to relativistic speeds. The University of Michigan and the Lawrence Livermore National Laboratory, among others, have produced, by this method, proton beams containing more than 10^{12} particles at mean energies of tens of MeV. In fact progress is being made so rapidly in laser technology that peak powers will soon be reached that can accelerate protons to rest mass energies. This means that these particles, when ejected form a propulsion device, will travel at 0.866 of the speed of light, and that translates to specific impulses of well over 10 million seconds. The implication of these facts for space propulsion are truly staggering especially when coupled to the fact that rep rates of kilohertz have also been achieved for high intensity lasers.

The underlying physics of the acceleration process is currently without an exact theory. Nevertheless a plausible, heuristic analysis consistent with sound physics principles can indeed be made to generate a mathematical expression that can predict experimental results with some measure of accuracy, consistency and reliability. When a high-intensity laser strikes a target, it produces at the surface a plasma with a size of about half a laser wavelength[1] due to the longitudinal electron oscillations resulting from the oscillating Lorentz force. In fact a free, stationary electron will

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size of about half a laser wavelength[1] due to the longitudinal electron oscillations resulting from the oscillating Lorentz force. In fact a free, stationary electron will execute a "quivering" motion in the form of figure 8 when subjected to the electric and magnetic fields of the laser, and the spatial extent of the "quiver" is determined by the modified vector potential
"a_o" give by[2]

$$a_o = \frac{eA}{m_o c^2} \quad (1)$$

$$= 0.85 \times 10^{-9} \sqrt{I(w/cm^2)} \quad \lambda\,(\mu m) \qquad (2)$$

where e is the electron charge, A the standard vector potential, m_o the rest mass of the electron, c the speed of light, I the laser intensity and λ the laser wave length. It should be noted that a_o is related to the relativistic parameters "γ" through

$$\gamma = \left(1 - v^2/c^2\right)^{-1/2} = \left(1 + \frac{a_o^2}{2}\right)^{1/2} \qquad (3)$$

hence the connection between the laser parameters and the velocity (or acceleration) of the electron with which it interacts. Twice in a laser period the electrons of the plasma re-enter the target while the ions remain virtually immobile due to their large mass. Returning electrons are accelerated by the "vacuum" electric field and subsequently deposit their energy inside the target. The electrons of the plasma become strongly heated by the laser light, penetrate deeper inside the solid target with relativistic speeds, and form a low-density, high-energy component of the entire electron population. These high-energy electrons create an electrostatic field, which accelerates ions in the forward direction while decelerating the electrons until both species drift out at the same rate. An electrostatic field near the target surface has a bipolar structure with the more pronounced component accelerating ions in the forward direction. If the laser pulse duration is longer than the ion acceleration time in the layer then the ions would acquire an energy equal to the electrostatic energy. Since this "ambipolar " potential causes both the electrons and ions to proceed at the same rate, they emerge from the back surface of the target in a perpendicular direction in a "neutral", nearly collimated beam form as shown in Fig 1. This emerging beam of charged particles is what provides the thrust in a propulsion device.

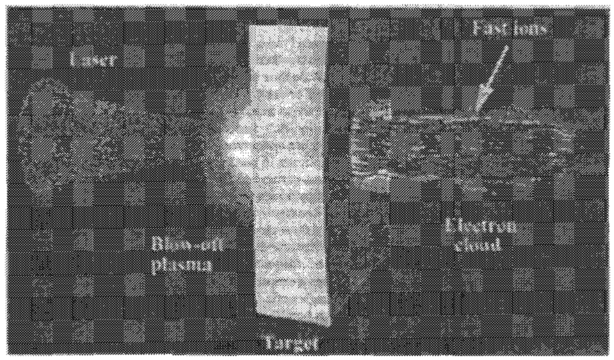

Figure 1. Ultrafast laser impinging upon target to produce fast ions.
(Courtesy of Scott C. Wilkes).

The electrons that are initially accelerated by the laser must overcome the Coulomb energy in the pre-formed plasma in order to penetrate the target to set up the electrostatic potential. Moreover, simple energy balance dictates that the energy imparted by the laser must appear in these electrons at some efficiency. Since these electrons create the potential, the electron energy must, therefore, equal that of the potential energy, and that in turn must equal that of the ions acted upon by this potential. When all these facts are put together, the energy of the ejected ions can be expressed by[3]

$$E_i = Z\sqrt{\eta I R \lambda} \qquad (4)$$

where Z is the ion charge, η the efficiency of the energy conversion, R the size of the focal spot, and λ the wavelength of the laser. When the laser intensity is given in W/cm^2 and the spatial dimensions in microns, Eq (4) gives the ion energy in MeV. The above equation predicted reasonably accurately the one MeV ions accelerated by the 10 TW laser in the University of Michigan experiments [4], and the 5.3 MeV (mean) energy ions produced by the Livermore petawatt laser[5,6]. Clearly, several MeV ions produce specific impulses of several million seconds, more than required for almost all missions envisaged in the solar system and beyond. But, as we shall note shortly, it is the thrust which these present-day experiments can produce that is not adequate for most missions of interest. The thrust can be written in the form

$$F = \omega N_i M_i v_i \qquad (5)$$

where ω is the rep rate, N_i the number of ions in the ejected beam, M_i the ion mass, and v_i the ion velocity. With the exception of the mass, the remaining parameters in Eq (5) lend themselves to change (increase or decrease as the situation may dictate) and present-day experiments are being analyzed and modified to address these changes[7].

THE LAPPS PROPULSION CONCEPT

The propulsion system addressed here is illustrated in Fig 2. It consists of a power supply which will most likely be nuclear, and the laser it drives which will be used to accelerate a beam of protons to relativistic speeds. These protons emerge, as noted earlier, in a nearly collimated form along with an equal number of electrons so that the beam is electrically neutral when it leaves the vehicle to provide the thrust. This is particularly significant since no space-charge effects will arise that might adversely influence the performance of the vehicle. Even present-day experimental data, if viewed from the standpoint of a propulsion system, will indicate a specific impulse of several million seconds which is significantly larger than any projected to be produced by "competing" advanced propulsion concepts such as those driven by fusion energy. Although a current Laser Accelerated Plasma Propulsion System [LAPPS] is capable of producing a very large specific impulse (I_{sp}), it does not produce large enough thrust (F) to make it suitable for, say, a manned interplanetary mission where a measure of balance between I_{sp} and F must be attained to result in an optimum travel time. This can be seen from the expression for the round trip time, τ_{RT} between two points separated the linear distance D, namely[8]

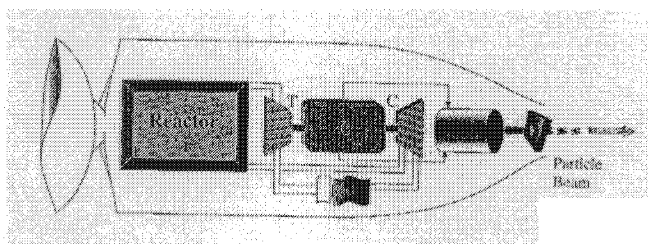

FIGURE 2. Laser-accelerated plasma propulsion system (LAPPS).

$$\tau_{RT} = \frac{4D}{gIsp} + 4\sqrt{\frac{D m_f}{F}} \qquad (6)$$

where g is the earth's gravitational acceleration, and m_f the dry mass of the vehicle. The above equation is based on a constant thrust, acceleration/deceleration type of trajectory where it can be seen that the contribution of the two terms on the right-hand side are additive and must therefore be somewhat comparable in order to produce a reasonably optimum τ_{RT}. Eq (6) also reveals the need for large I_{sp} and F to obtain a small travel time but within the framework of the balance just alluded to. If a fly-by robotic mission[9] to an interstellar destination such as the Oort Cloud (10,000 AU) is contemplated then it can be shown that present-day LAPPS can accomplish such a mission in an acceptably short time. To put these predictions in proper perspective, we focus on some recent results produced at Livermore[5,6] and analyzed in detail elsewhere [3]. A summary of the experimental data, along with the characteristics of the propulsion system it may evolve into, is given in Table 1. In these experiments, a high energy conversion efficiency was observed in that half of the laser energy (500J) appeared in the ejected beam and at an assumed rep rate of one kilohertz this results in a 500 kW jet power. At this rep rate, a power source that delivers at least a megawatt of electric power would be needed, and based on present-day power conversion analyses, a mass to power ratio of 5 mT per megawatt electric is considered reasonable[10]. It is anticipated, however, on the basis of the progress made in the various

1. Proton Beam			
	i) Particle Population	=	6×10^{14}
	ii) Mean Energy	=	5.3 MeV
	iii) Beam Energy	=	500 J
2. Laser Beam			
	i) Wavelength	≈	1 μm
	ii) Pulse Length	=	500 fs
	iii) Intensity	=	3×10^{20} W/cm^2
	iv) Energy	=	1 kJ
	v) Power	=	1 Petawatt
3. Target			
	i) Material	=	Gold Foil
	ii) Thickness	=	125 μm
	iii) Focal Spot Radius	=	9 μm
4. LAPPS Propulsion System			
	i) Rep Rate	=	1 kHz
	ii) Specific Impulse	=	3.2×10^6s
	iii) Thrust	=	3.1×10^{-2}N
	iv) Nuclear System	=	1MW
	v) Vehicle Dry Mass	=	5×10^3 kg

TABLE 1. Present-day LAPPS Parameters

components of the power supply that a five fold improvement in the specific mass can be achieved in the near future. Since the LAPPS propulsion system described in Table 1 may be judged to be adequate for robotic interstellar missions[11], it is not particularly suited for manned interplanetary missions due to the smallness of the thrust as discussed earlier. For this reason, much of the research that should be done in the area of developing present-day laser accelerated plasmas into viable propulsion devices that could meet the challenges of missions within the solar system must focus on means of enhancing the thrust.

SOME MISSIONS WITH LAPPS

As a measure of the propulsive capability of present-day LAPPS we consider two missions, a fly-by interstellar mission to the Oort cloud, and a round trip journey to Mars. For the first case the equation of interest are[9]:

$$t_f = \frac{m_i - m_f}{F} v_e \qquad (7)$$

$$S_f = \frac{m_i v_e^2}{F}\left[1 - \frac{m_f}{m_i} + \frac{m_f}{m_i}\ln\left(\frac{m_f}{m_i}\right)\right] \tag{8}$$

$$v_f = v_e \ln\left[\frac{1}{1 - \frac{F t_f}{m_i v_e}}\right] \tag{9}$$

where t_f is the one-way travel time to destination, m_i the initial mass of the vehicle v_e the exhaust velocity, S_f the one-way distance to destination, and v_f the final vehicle velocity at destination assuming it started from rest. We apply these equations to a robotic mission to the Oort cloud for which S_f = 10,000 AU and the results are shown in Fig 3 where travel time is plotted against thrust for two values of m_f, namely 5000 kg and 1000 kg. The first mass is that which is given in table 1 which is based on present-day nuclear power designs and the scaling of 5 mT per MWe. The second takes into account research progress that is expected to take place in reactor design, radiator materials and design etc which will lead to a value of 1 mT per MWe. We note that present-day LAPPS at an m_f = 5mT will accomplish this mission in about 700 years, but if its thrust can be increased to 25 Newtons the same journey will take about 26 years, well within a scientist's lifetime. We note, further, that at the reduced mass of 1 mT, present-day LAPPS will accomplish the same mission in about 313 years, and at 25N thrust the travel time is reduced to about 12 years.

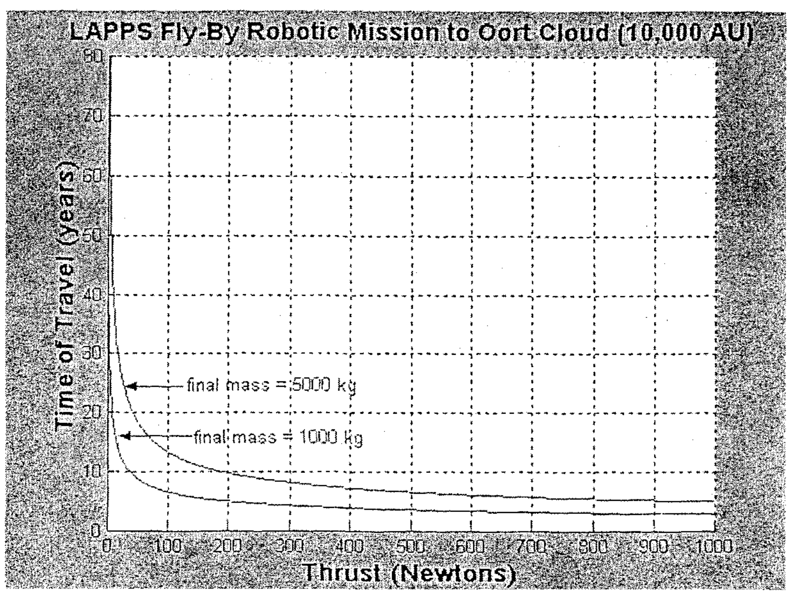

FIGURE 3. LAPPS Fly-By Robotic Mission to Oort Cloud (10,000 AU)

For the round trip to Mars we revert back to Eq (6) which can be cast in the following form

$$\tau_{RT} = 4\left[\sqrt{\frac{Dg\,I_{sp}}{f\alpha}} - \frac{D}{g\,I_{sp}}\right] \tag{10}$$

where we have introduced the mass ratio

$$f = \frac{m_f}{m_i} \tag{11}$$

and

$$\alpha = \frac{P_j}{m_f} = \frac{Fg\,I_{sp}}{m_f} \tag{12}$$

which is the ratio of the jet power to the final (dry) mass of the vehicle. It can be shown(11) that the trip time can be optimized at f =1/4 independent of the values of D and α. Although the travel time is minimum at this mass ratio, it is far from being economic since the propellant mass will be 3 times the dry mass, which in the case of LAPPS is 15 mT. For present-day LAPPS α= 1/10, and at this value the optimum round trip to Mars will be about 350 days but at prohibitively large cost due to the large amount of propellant required. Going back to the un-optimized travel time, as given by Eq (6) and shown in Fig. 4 we find that the travel time by present-day LAPPS is 5193 days, which readily improves to 186 days upon increasing the thrust to 25 N. At the lower mass of 1 mT, the round trip time for current LAPPS goes down to 2323 days while at 25N that time is reduced to a mere 82 days-a very encouraging result indeed!

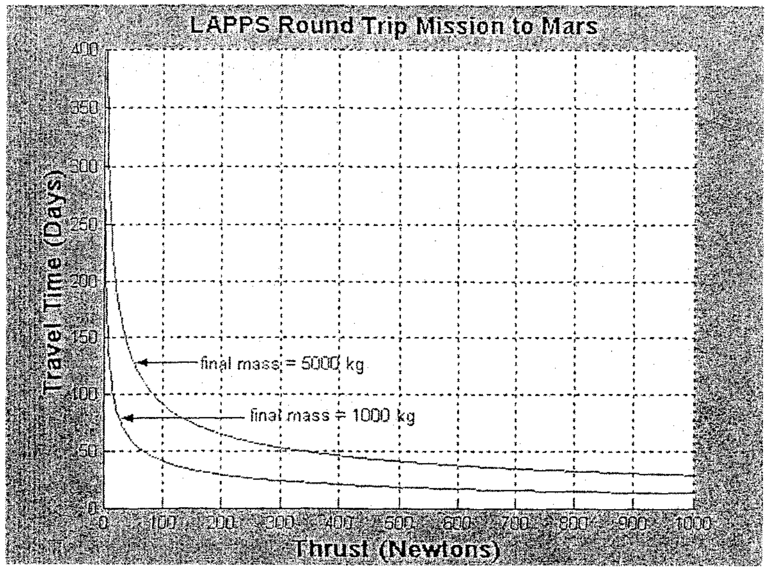

FIGURE 4. LAPPS Round Trip Mission to Mars

CONCLUSION

We have presented in this paper an advanced propulsion concept based on recent successful experiments in which ultrafast lasers were utilized in accelerating protons to relativistic speeds. We have shown that a LAPPS device based on present-day data is capable of producing several million seconds of specific impulse, albeit at modest thursts, and requires a nuclear power system to drive it. Our analysis also reveals that a modest increase in the thrust will allow such a vehicle to make a fly-by interstellar mission to the Oort cloud in a human's lifetime, and a round trip journey to Mars in about six months.

ACKNOWLEDGMENTS

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REFERENCES

1. Yu,W. et al, Phys. Rev. E **58**, 2456 (1999).
2. Sarachik E.S. and Schappert, G.T., Physical Review D, **1**, 2738 (1970).
3. Kammash, T. NIAC 01-01 Final Report, Dec (2001).
4. Maksimchuk, A. Gu, S. Flippo, K., and Umstadter D., Phys. Rev. Letters, **84**, 4108 (2000).
5. Snavely, R.A. et al, Phys. Rev. Letters, **85**, 2945 (2000).
6. Roth, M. et al, *High-Energy Electron, Position, Ton and Nuclear Spectrocopy in Ultra-Intense Laser-Solid Experiments on the Petawatt,* Proc. 1st Int. Conf. On Inertial Fusion Sciences and Applications, Bordeaux, France, Sept. 12-17 (1999), also UCRL-JC-135735, Sept. 16 (1999).
7. Kammash, T. Flippo K. and Umstadter D., 38th AIAA Joint Propulsion Conference, Indianapolis, IN July 7-10 (2002) paper AIAA 2002-4090.
8. Kammash, T. *Fusion Energy In Space Propulsion* AIAA progress in Astronautics and Aeronautics, vol. 167, Washington, D.C. (1995) p.69.
9. Kammash, T. J. Propulsion and Power **16**, 1100 (2000).
10. Mason, L. NASA Glenn. Res. Center, Private Communicate (2001).
11. Emrich Jr., W.J. 38th AIAA Joint Propulsion Conference, Indianapolis, IN, July 7-10 (2002) paper AIAA 2002-3931.