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Ultrafast-Laser Accelerated Plasma Propulsion System for Space Exploration

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Abstract

A near-term plasma propulsion system that could open up the solar system and beyond to human exploration is presented. It is based on some recent experimental research at the University of Michigan and several other laboratories throughout the world in which it was shown that ultrafast (with very short pulse length) lasers can accelerate charged particles to relativistic speeds. Those experiments have demonstrated dramatically the production of nearly collimated beams of protons at mean energies of several MeV when lasers with intensities of $\geq 10^{18}$ W/cm^2 were made to impinge on small focal spots in solid targets with a few microns thickness. When viewed from a propulsion standpoint these present- day systems can be considered as the precursors of devices that are capable of producing specific impulse of millions of second albeit at modest thrusts. If employed as propulsion systems, they can achieve interstellar fly-by missions in a scientist's lifetime but require significant enhancement in thrust to make then suitable for, say, manned mission in the solar system. In this paper we examine the underlying physics of the concept and indicate the steps required for its evolution into an effective near-term robust propulsion device.

Nomenclature

a_o = Normalized vector potential

c = Speed of light

D = Linear distance

E_i = ion energy

F = Thrust

g = Gravitational acceleration

γ = Relativistic parameter

I = Laser intensity

I_{sp} = Specific Impulse

λ = Laser wavelength

M_i = ion mass

N_i = number on ions

v_i = ion velocity

ω = rep rate

Z = ion charge

η = conversion efficiency

Introduction

One of the remarkable scientific developments of recent years is the demonstration, in tabletop experiments, that ultrafast (very short pulse length) lasers can accelerate charged particles to relativistic energies. As can be noted in Table 1 and Fig. 1, the University of Michigan and the Lawrence Livermore National Laboratory (LLNL), 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 their rest mass energies. This means that these particles will be ejected at 0.866 of the speed of light and that translates to specific impulses of about 10 million seconds. The implication of these facts for space propulsion are truly staggering especially when coupled with the fact that rep rates of kilohertz have also been achieved for high intensity lasers.

Table 1
Recent Results of Proton Acceleration

Institution	Proton		Laser			Target	Reference*
	Energy MeV	Yield	Intensity W/cm^2	Energy J	Pulse Length fs		
U of Mich	1	10^8	3 x 10^{18}	4	0.4	He	PRE 56, 7042 (1999)
Rutherford Lab	6		5 x 10^{19}	50	0.9	Ne	PRL 83,737 (1999)
Rutherford Lab	20	10^{12}	5 x 10^{19}	50	1.0	A1	PRL 84,670 (2000)
	420		5 x 10^{19}	50	1.0	Pb	PRL 85,1654 (2000)
U of Mich	1.5	10^{10}	3 x 10^{16}	1	0.4	A1	PRL 84,4106 (2000)
	10		6 x 10^{18}	4	0.4	Cd	APS-DPP (2000)
LLNL	50	10^{10}	1 x 10^{20}	60	0.4	CH& Au	PRL 85, 2945 (2000)
LLNL	20		5 x 10^{19}	5	0.05		APS-DPP (2000)

* PRE = Physical Review E
PRL = Physical Review Letters
APS = American Physical Society
DPP = Division of Plasma Physics (Bulletin, Vol. 45, No. 7)

The propulsion system proposed here is illustrated in Fig. 2. It consists of a power supply which (as will be noted shortly) will most likely be nuclear, and a laser that it drives that will be used to accelerate a beam of protons to relativistic speeds. These protons emerge in a nearly collimated form along with an equal number of electrons so that the emitted beam is electrically neutral when it leaves the vehicle to provide the thrust. Even present-day experimental data, if viewed from the standpoint of a propulsion system, will indicate a specific impulse (I_{sp}) of about a 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 I_{sp}, it does not produce high 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 optimum travel time. This can be seen from the expression for the round trip travel time, τ_{rt}, between two points separated by the linear distance, D, namely[1]

$$\tau_{rt} = \frac{4D}{gI_{sp}} + 4\sqrt{\frac{Dm_f}{F}}, \qquad (1)$$

where g is the earth's gravitational acceleration, and m_f the drymass 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 must be somewhat comparable in order to produce an optimum $\tau_{rt.}$ Eq. (1) 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[2] 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[3,4] and analyzed in detail elsewhere[5]. A summary of the experimental data, along with the characteristics of a propulsion system it may evolve into, is given in Table 2.

Table 2
Present Day LAPPS Parameters

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

In these experiments, a high energy conversion efficiency was observed in that half of the laser energy (500 J) appeared in the ejected beams, and at an assumed rep rate of one kilohertz, this gives to a 500 kW jet power. At this rep rate, a power source that delivers a megawatt of electric power to the laser would be needed, and based on present-day conversion components, a mass to power ratio of 5 mT per megawatt is considered reasonable[6]. It is anticipated, however, on the basis of the progress being made in the various 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 2 is found to be adequate for robotic interstellar missions[7], it is not 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 ways of enhancing the thrust.

Technical Background

We have carried preliminary studies in order to understand the mechanisms involved in the acceleration of charged particles by intense lasers. Since no exact theory exists, our attempt was focused on developing a plausible theory, perhaps heuristic, that would allow us to derive mathematical expressions with which we can assess the performance of a LAPPS propulsion device. Such an analysis would also allow us to identify the technical issues that might stand in the way of achieving these objectives. Drawing on much experimental information, we formulated a meaningful scenario of the acceleration mechanism which we believe to be realistic and consistent with sound physics principles.

When a high-intensity laser strikes a target, it produces at the surface a plasma with a size of about half a laser wavelength[8] due to the longitudinal electron oscillations resulting from the oscillating Lorentz force. 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 this 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. This emerging beam of charged particles is what provides thrust in a propulsion vehicle.

The electrons that are 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, then the electron energy must 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 ion can be expressed by[5]

$$E_i \geq Z\sqrt{\frac{\pi}{c} I \eta r \lambda} \qquad \text{eV}, \qquad (2)$$

where Z is the ion charge number, c the speed of light, η the efficiency of the energy conversion, r the radius of the focal spot, and λ the wavelength of the laser. For the energy in the units shown, the laser intensity must be in W/cm^2 and the spatial parameters in microns. The above equation predicted reasonably accurately the one MeV ions accelerated by the 10 TW laser in the University of Michigan experiments[9], and the 5.3 MeV (mean) energy ions produced by the Livermore petawatt laser[3,4]. Clearly, several MeV ions produce specific impulses of several millions seconds, more than required for almost all missions currently envisaged in the solar system and beyond. But, as we noted earlier, it is the thrust which present-day LAPPS can produce that is not adequate for most of these missions. It can be written as

$$F = \omega \, N_i M_i v_{i,} \qquad (3)$$

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 of the proton, the remaining terms in the above equation lend themselves to change and, as such, constitute the target of future investigations.

The LAPPS Development Plan

The development of LAPPS into the desirable propulsion system, that it can be, hinges critically on its ability to produce sizable thrust. As noted above, thrust enhancement can be accomplished by i) increasing the number of the particles (protons) in the emitted beam, and/or ii) increasing the rep rate, and/or iii) increasing the velocity of the ejected particles. Increasing the velocity beyond what is currently available may not be the first priority since that leads to an increase in the specific impulse, which, for many missions of interest, may be inimical. Increasing the beam population should perhaps receive the most immediate attention since it may be the most readily achievable approach without introducing any serious undesirable effects. In the University of Michigan experiments, a one MeV proton beam containing about 10^{10} particles was generated when the 10 TW hybrid Ti:sapphire/Nd:phosphate chirped pulse amplification laser was shined on a 5 μm spot in a thin A1 foil. The focused intensity was about 3 x 10^{18} W/cm^2 giving rise to an accelerating electric field of about 10 GeV/cm. In the case of the Livermore experiment, an intensity of about 3 x 10^{20} W/cm^2 was focused on a spot of 9 μm radius giving rise to an estimated 6 x 10^{14} particles as was shown in Table 2. The corresponding computed thrust was about 3 x 10^{-2} Newtons for a mean proton energy of about 5.3 MeV. If we use, as an example, a 6 month round trip to Mars using present-day Livermore LAPPS, on a trajectory as prescribed by Eq. (1), we find that a thrust of 25 N would be required, an 800 times enhancement over the current capability. If we wish to maintain the same intensity, then a focal spot of radius equal to $\sqrt{800}$ times the original radius must be used in order to produce the desired thrust. This is so because the number of ejected particles should scale with the area of the focal spot for a fixed thickness of the target. Maintaining the same intensity implies maintaining the same energy of the ejected particles as may be noted from the relation[(10)]

$$\gamma = \left(1 - v^2/c^2\right)^{-1/2} = \left[1 + \frac{a_0^2}{2}\right]^{1/2}, \qquad (4)$$

where γ is the familiar relativistic parameter, and

$$a_o = 8.5x10^{-10} \, I^{1/2}\left(W/cm^2\right)\lambda(\mu m) \qquad (5)$$

with I and λ denoting respectively the intensity and wavelength of the laser. Of course, ejecting more particles at a lower energy may also be achieved by lowering the intensity which for a fixed focal spot area means lower laser power. The other approach to thrust enhancement lies in the rep rate at which the system operates. We have already noted that kilohertz rep rates on the laser side have already been achieved and they are quite adequate for a propulsion system as was suggested in the LAPPS of Table 2. The remaining parameters, however, were based on solid targets and it is not clear whether such targets can be fed into a reaction chamber at such a rate. This may be achievable and if so, we can raise the rate further while securing the collimation, brightness, etc., of the emerging particle beam. Since laser produced and accelerated plasma lies at the heart of this propulsion approach (due to its relatively low cost), it is somewhat limited by the emission of debris(13) which may damage sensitive components positioned close to the source. It has been suggested that this debris emission can be lowered several orders of magnitude(14), or even eliminated(15) with a microscopic liquid-droplet target system. It has also been pointed out such a target features high flux and brightness; allows long time operation without interruption; and provides fresh target material at high rates, thus allowing the use of high-repetition-rate lasers.

Conclusion

We have presented in this paper a novel propulsion system based on recent successful experiments showing the effective utilization of ultrafast lasers in accelerating charged particles to relativistic speeds. A LAPPS device based on present-day experiments is found to be capable of producing specific impulses of several million seconds albeit at moderate thrusts. It can, nonetheless, perform interstellar, robotic fly—by missions in a human's lifetime, but requires sizable enhancement of thrust to carry out fast manned missions within the solar system. It will however, require a nuclear power system in the megawatt range to drive it, but such space reactors could well be developed in the near future given NASA's new space nuclear power initiative. Ways of increasing thrust in LAPPS have also been suggested and they include, among other things, the use of liquid droplet jet targets, which could in principle, allow for near steady state operation of this propulsion system.

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References

1. T. Kammash, **Fusion Energy in Space Propulsion**, AIAA Progress in Astronautics and Aeronautics, Vol. 67, Washington, D.C. (1995), p. 69.
2. T. Kammash, J. Propulsion and Power, **16**, 1100 (2000).
3. R.A. Snavely, et al, Phys. Rev. Letters, **85**, 2945 (2000).
4. M. Roth, et al, Proc. 1st Int. Conf. On Inertial Fusion Sciences and Applications, Bordeaux, France, Sept. 12-17 (19999), also UCRL-JC-135735, Sept. 16 (1999).
5. T. Kammash, NIAC 01-01 Final Report, Dec. (2001).
6. L. Mason, NASA Glenn Res. Center, private communication (2001).
7. T. Kammash, K. Flippo, and D. Umstadter, AIAA 37th Joint Propulsion Conference, paper 2001-3810, Salt Lake City, July 8-11 (2001).
8. W. Yu, et al, Phys. Rev. E, **58**, 2456 (1999).
9. A. Maksimchuk, S. Gu, K. Flippo, and D. Umstadter, Phys. Rev. Letters, **84**, 4108 (2000).
10. E.S. Sarachik and G. T. Schappert, Physical Review D, **1**, 2738 (1970).
11. G.Z. Sun, et al, Phys. Fluids, **30**, 526 (1987).
12. A.B. Borisov, et al, Phys. Rev. A, **45**, 5830 (1992).
13. M. Richardson et al, Appl. Opt., **32**, 6901 (1993).
14. L. Rymell and H.M. Hertz, Opt. Commun., **103**, 105 (1993).
15. L. Rymell, et al, Appl. Phys. Letters, **66**, 2625 (1995).
16. L. Rymell, Lund Reports on Atomic Physics LRAP-170, Lund, Sweden (1995).