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LASER ACCELERATED HEAVY-ION PLASMA PROPULSION SYSTEM

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ABSTRACT

The Ultrafast "Laser Accelerated Plasma Propulsion System" LAPPS makes use of lasers with very short pulse lengths to accelerate charged particles to relativistic speeds. Recent experimental data reveal that high intensity lasers are capable of producing collimated, charge-neutral proton beams containing more than 6 x 10^{14} particles at a mean energy of 5 MeV with a total beam energy of 500J. If used in propulsion, these systems are capable of generating specific impulses of more than one million seconds albeit at very modest thrusts, and require a nuclear power system to drive them. A major research effort at the University of Michigan is directed at finding ways to enhance the thrust of LAPPS. One approach is to irradiate larger focal spots in solid targets, and the other is to accelerate heavier ions by first removing the moisture from targets then coating them with materials of larger mass numbers such as carbon or fluorine. In this paper we address these issues in light of a recently developed acceleration model.

NOMENCLATURE

C_s = Sound speed
d = diameter of focal spot
D = linear distance
E_i = ion energy
F = Thrust
g = Gravitational Acceleration
h = thickness of electron cloud
I = laser intensity
I_{sp} = specific impulse
λ = wave length
M_i = initial mass
M_f = final (dry) mass
R = radius of focal spot
S_f = distance to destination
t_f = travel time to destination
τ_{RT} = round trip travel time
V_e = exhaust velocity
V_f = final vehicle velocity
V_{max} = maximum ion velocity
Z = ion charge
η = conversion efficiency

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INTRODUCTION

In a recent publication [1] we examined the propulsion capability of a LAPPS system based on recently generated experimental data [2] in which a kelojoule laser of 1 micron wave length and a 500 fs pulse length was used to irradiate a focal spot of 9 µm in a gold foil. The power of such a laser was 10^{15} W giving rise to an intensity of 3×10^{20} w/cm^2 where it was noted that half of the energy (i.e. 500J) appeared in the proton beam that was ejected from the target. Using the often-cited model whereby the electrons from the blow-off plasma are accelerated by the laser, penetrate deeper in the target to set up an electrostatic potential. This positive potential accelerates ions and simultaneously slows down the electrons until the two species drift out of the target at the same (ambipolar) rate. Moreover, simple energy balance dictates that the energy imparted by the laser must appear in these electrons at some efficiency η. Since these electrons create the potential, then the electron energy must be 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 [3]

$$E_i \geq Z \sqrt{\eta I \lambda R} \qquad (1)$$

where I is the laser intensity Z the ion charge, λ the wave length and R the dimension of the focal spot. When I is expressed in 10^{18} w/cm^2 units and the lengths in microns Eq (1) yields the ion energy in Mev. When applied to the experiment alluded to earlier Eq (1) predicts an ion energy of 5.3 Mev although the experiments also showed a maximum ion energy of 58 Mev. Once again, an energy balance reveals that the number of ejected protons in the beam is 2×10^{14}. If viewed as a propulsion system the present-day LAPPS operating at a rep rate of 10^3 yields a specific impulse of $I_{sp} = 5 \times 10^6$ seconds and a thrust $F = 1.83 \times 10^{-2}$ N, a modest value indeed but requires one megawatt of electric power to drive it and, based on current estimates, a nuclear reactor system that can deliver such power will have a mass of 5 mT.[4] A measure of the effectiveness of present-day LAPPS as a propulsion system can be assessed by examining two missions: One for a robotic fly-by mission to the Oort cloud at a distance of 10,000 AU hence an interstellar mission and the other is a round trip to Mars using a constant thrust, accleration/decleration type of trajectory. For the first mission it can be readily shown using the standard rocket equation that

$$t_f = \frac{M_i - M_f}{F} V_e \qquad (2)$$

$$S_f = \frac{M_i V_e^2}{F} \left[1 - \frac{M_f}{M_i} + \frac{M_f}{M_i} \ln\left(\frac{M_f}{M_i} \right) \right] \qquad (3)$$

$$V_f = V_e \ln \left[1/\left(1 - \frac{F t_f}{M_i V_e} \right) \right] \qquad (4)$$

Where t_f is the travel time to destination whose distance S_f, M_i and M_f are respectively the initial and final masses of the vehicle, V_e the exhaust velocity, and V_f the final velocity at destination assuming starting from rest. For the second mission the round trip travel time τ_{RT} is given by[5]

$$\tau_{RT} = \frac{4D}{g I_{sp}} + 4 \sqrt{\frac{D M_f}{F}} \qquad (5)$$

where D is the linear distance to destination, and g the Earth's gravitational acceleration. In the case of the fly-by robotic interstellar mission using present-day LAPPS proton beam with $M_f = 5$ mT, the travel time for different thrust values are shown in Table 1.

Table 1
Fly by Mission to the Oort Cloud

Thrust (Newtons)	Travel time Years
0.031	698
25	26
100	13
500	7
1000	5

Note the significant drop in travel time even for modest increases in the thrust. For the round trip to Mars we choose the distance "D" to be 0.52 Astronomical units (AU), which is the closest distance of approach that occurs every 26 months when the Earth, the Sun and Mars are aligned. The solutions of

Eq (5) are displayed in Table 2, which gives the travel time for three different ions namely, protons, carbon and fluorine ions that have been shown to be accelerated by a present-day LAPPS to roughly the same average energy. Once again a dry mass of 5 mT was employed in the calculation along with the other propulsion parameters alluded to earlier. Although in the actual experiments the carbon and fluorine ions were accelerated to maximum energies of 5 MeV per nucleon (hence maximum energy of about 100 MeV) we employed Eq (1) to calculate the mean energy for each of these heavy ions.

Table 2
Mars Mission with heavy-ion plasma

Thrust	Travel time (days)		
(Newtons)	Protons	C^{12}	F^{19}
0.031	5193	2790	2487
25	186	100	89
100	92	49	44
500	41	22	20
1000	29	16	14

We see from Table 2 the substantial reduction in travel time as a result of accelerating heavier (than proton) ions such as Carbon and Flourine while effectively maintaining the same input laser parameters and those of the ejected beam. The increase in the thrust was assumed to result from increasing the size of the focal spot in the target. A thrust value of 25 N requires approximately 800 fold increase in the irradiated area from that of 0.03 N, and that simply means an approximate increase in the focal spot radius of 28 times. This in turn implies a focal spot roughly 270 µm radius which requires a corresponding increase in the laser power in order to maintain the same intensity as suggest by Eq (1).

There is however, a salutary effect that accrues from increasing the size of the focal spot. Recent theoretical models suggest that after the initial acceleration of the ions as implied by Eq (1) these ions and the corresponding electrons undergo expansion. If the expansion is assumed to be adiabatic (which occurs when the laser pulse length is shorter than the ion acceleration time)
Then these ions achieve a maximum velocity give by[6].

$$V_{max} = 2\sqrt{2}\,C_s \ln(d/h) \qquad (6)$$

where C_s is the ion sound speed and (d/h) is the aspect ratio (diameter to thickness) of the electron cloud formed when the laser strikes the target. We readily see that the ion acceleration is more efficient for larger focal spots which are also required to produce more particles in the ejected beam, hence higher thrust.

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