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Laser Accelerated Plasma Propulsion System (LAPPS)

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Abstract

Recently conducted experiments at the University of Michigan and elsewhere have shown that ultrashort pulse (ultrafast) lasers could accelerate charged particles to relativistic speeds. For example a picosecond laser pulse with only one joule of energy can accelerate an electron to MeV energy in just a few microns distance. This takes place through the high gradient potential that manifests itself in an electric field of a gigavolt per cm which in turn accelerates the electron to a megavolt energy over a distance of 10 microns. Current achievable laser peak power of 10^{15} watts has been utilized in the study of relativistic non-linear optics in plasmas, and it is expected that laser power values will be reached in the near future that will accelerate protons to energies equal to their rest mass energy. That readily means that when such particles are ejected from a system at 0.866 the speed of light they will produce a specific impulse of 26 million seconds. Current experiments have also demonstrated that a beam of one MeV protons containing more than 10^{10} particles has been accelerated by an electric field of 10 GeV/cm corresponding to a laser power of about 100 TW. On the basis of these accomplishments it is reasonable to project that accelerating 100 MeV proton beams containing 10^{18} particles will be quite achievable in the near future. If utilized as a propulsion device such a system will make distant planets in the solar system and some interstellar missions reachable in relatively short times.

Nomenclature

a_0 = Normalized vector potential
A = Vector potential of an electromagnetic field
B = Magnetic field
c = Speed of light
D = Linear distance
E = Electric field
e = Electronic charge
F = Thrust
g = Gravitational acceleration
γ = Relativistic parameter
I = Laser intensity
I_{sp} = Specific Impulse
k = Wave number
λ = Laser wavelength
m_0 = Rest mass
m_e = Electron mass
m_f = Final (dry) mass
m_i = Initial mass
n = Index of refraction
n_e = Electron density
p = Momentum
q = Electric charge
S_f = Mission distance
t = Time
t_f = Mission time
u_e = Exhaust velocity
u_f = Mission final velocity
v = Velocity
w_0 = Laser frequency
w_p = Plasma frequency

Introduction

A propulsion system that can open up the solar system and beyond could evolve from some current research dealing with laser accelerated plasmas. Recently conducted experiments at the University of Michigan and elsewhere have dramatically shown that ultrashort pulse (ultrafast) lasers can accelerate charged particles to relativistic speeds. For example, a picosecond laser pulse with only one joule of energy can accelerate an electron to MeV energy in the short space of a few microns. This takes place through the laser-generated high gradient potential that manifests itself in an electric field of a gigavolt per cm, which in turn accelerates the electron to a megavolt energy over a distance of 10 microns. As shown in Fig. 1, current achievable laser peak power of about 10^{15} Watts has been utilized in the study of relativistic non-linear optics(1), and it is expected that laser power values will be reached that will accelerate protons to energies equal to their rest mass energy. Fig. 2 shows the progress made in this area where it can be seen that proton energies approaching 100 MeV are within striking distance. In fact, a beam of protons containing more than 10^{10} protons was recently(2) accelerated by an electric field of 10 GeV/cm corresponding to a laser power of about 100 TW. Many of these achievements have been the result of developing interest in ion acceleration by compact, high intensity subpecosecond lasers with potential applications to the initiation of nuclear reactions on a tabletop.

Because of the unique properties of these laser accelerated plasmas, it should come as no surprise that we propose their utilization in space propulsion. If protons at rest mass energies can be ejected from such a system they will emerge at 0.866 speed of light and generate a specific impulse of 26 million seconds. If also a reasonable number of them, say 10^{15}-10^{20} can be accelerated by this method at a repetition rate of 10-10^{3} (also deemed feasible by current thinking) then such a system will possess the propulsive capability that will make distant planets in the solar system reachable in 100's of days and some interstellar missions achievable in the 10's of years. Not to be overlooked in this regard is the relative simplicity of such a system since the particles will be accelerated in the direction of the laser beam obviating the need for guiding systems such as magnetic nozzles often cited in connection with fusion-driven propulsion devices.

Physics of Laser Acceleration

In spite of the absence of a self-consistent theory of high-energy electron and ion generation in the laser-solid target interactions we can present a heuristic, plausible explanation that allows us to obtain qualitative estimates. We consider the interaction of a high-contrast laser pulse with an intensity that exceeds 10^{18} W/cm^2 at normal incidence to a target in which high-energy electrons with velocities near the speed of light are produced. We stipulate that when such a high-intensity, high-contrast laser terminates at the target surface it produces a plasma with a size of about half the laser wavelength(3) due to the longitudinal electron oscillations resulting from the oscillating Lorentz force. Near the target-vacuum surface the electrons are pushed in and out by the oscillating component of the ponderomotive force. Inside the target this force sharply vanishes. Twice in a laser period electrons re-enter the target.

Returning electrons are accelerated by the "vacuum" electric field and then deposit their energy inside the target. The electrons of this plasma are strongly heated by the laser light, penetrate deeper inside the solid target with relativistic velocities, and constitute 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, and in turn they themselves are decelerated by the same field. An electrostatic field near the target surface has a bipolar structure with the more pronounced component accelerating ions in a forward direction. If the laser pulse duration is longer than the ion acceleration time in the layer the ions acquire an energy equal to the electrostatic energy.

These processes can be further understood with the aid of the equations that describe the dynamics of charged particles in electromagnetic fields. We consider a laser beam propagating in the z-direction i.e. its wave vector is give by k=k$\hat{\underline{z}}$, and its electric and magnetic field vectors given by

$$\underline{E} = E_0 \cos(kx - \omega_0 t)\hat{\underline{x}} \qquad (1)$$

$$\underline{B} = B_0 \cos(kx - \omega_0 t)\hat{\underline{y}} \qquad (2)$$

where ω_0 is the frequency, and $\hat{\underline{x}}, \hat{\underline{y}}, \hat{\underline{z}}$ are the unit vectors in the x,y,z directions respectively. If a charged particle of rest mass m_0, and charge q is acted on by the fields of the beam then its motion is governed by the familiar Lorentz equation$^{(4)}$ i.e.

$$\frac{d\underline{P}}{dt} = \frac{d}{dt}(\gamma m_0 \underline{v}) = q\underline{(\underline{E} + \underline{v}x\underline{B})} \qquad (3)$$

where $\underline{P}$ is the momentum vector and $\gamma = (1 - v^2/c^2)^{-1/2}$ the familiar relativistic parameter. It is possible to relate this parameter to the intensity of the beam by first introducing the normalized vector potential "a_0" defined in terms of the standard vector potential of the electro-magnetic fields "A" through

$$a_0 = \frac{eA}{m_0 c^2} \qquad (4)$$

which leads to the desired relations$^{(5)}$, namely

$$\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}} = \left(1 + \frac{a_0^2}{2}\right)^{1/2} \qquad (5)$$

and

$$a_0 = 8.5 * 10^{-10}\sqrt{I(w/cm^2)}\lambda(\mu m) \qquad (6)$$

Here I denotes the intensity of the laser beam, and λ its wavelength. It is straight forward, but lengthy, to demonstrate that an electron moving under the influence of the electromagnetic fields of the beam will drift in the direction of the propagation of the beam (i.e. z-direction) while it quivers in x-z plane producing a figure "8" trajectory in that plane. It should be noted that the velocity of the electron quiver motion approaches the vacuum speed of light when the laser field is very intense as in the case under consideration in this paper. A measure of the effectiveness of charged particle acceleration by such intense (ultrafast) laser pulse is the example of electron acceleration by a one-joule laser with a picosecond (10^{-12}) pulse length. The power delivered by this laser would be a terawatt, and if the radius of the focal spot were 10μm then the intensity would be about 10^{18} W/cm^2. Noting that the accelerating electric field is related to the intensity by

$$E(V/cm) \cong \sqrt{I(W/cm^2)} \qquad (7)$$

we see readily that an electron would acquire an MeV energy over a distance of 10 μm in accordance with

$$(10^9\, V/cm)(10\mu m) = 1MeV \qquad (8)$$

Another effect of the relativistic laser intensity is that it changes the plasma frequency and thus the index of refraction of the plasma. The refractive index of a plasma is given by

$$n = \sqrt{1 - \frac{\omega_p^2(\gamma)}{\omega_0^2}} \qquad (9)$$

where ω_0 is the laser frequency and

$$\omega_p(\gamma) = \omega_{P_0} / \sqrt{\gamma} \qquad (10)$$

is the relativistic plasma frequency in which

$$\begin{aligned} \omega_{P_0} &= \sqrt{4\pi n_e e^2 / m_e} \\ &= 5.64 * 10^4 n_e^{1/2}(cm^{-3})\, rad/s \quad (11) \end{aligned}$$

is the non-relativistic plasma frequency which is determined by the electron density n_e only, and

$$\gamma = \sqrt{1 + \frac{a_0^2}{2}} \qquad (12)$$

is the relativistic factor associated with the average transverse quivering velocity of an electron in a laser field. In other words, the index of refraction of a plasma depends on the local laser intensity. As a result, a laser beam with spatially and temporally dependent intensity distribution I(r,t) experiences spatially and temporally varying index of refraction n(r,t) leading to change in its characteristics and propagation. For a focused laser beam with higher intensity on axis and lower off axis in a plasma, the index of refraction is higher on axis and lower off axis. Therefore the plasma acts like a positive lens resulting in a self-focusing of the laser beam. This process is referred to as relativistic self-focusing(6) . Moreover, because of the transverse intensity gradient of such a laser associated with the pressure it exerts on the plasma, the corresponding ponderomotive force will push electrons outward until it is balanced by the electron-ion Coulomb force. This results in a depression of electron density on axis and, as can be seen from eq. (9), the index of refraction is higher for lower electron density. Such an electron density distribution acts, once again like a positive lens and leads to self-focusing often referred to as "ponderomotive" self-channeling(7).

In summary we see that when an intense, focused laser beam interacts with a solid target, a plasma is formed which interestingly enough serves to sustain the focusing due to the relativistic mass modification of its electrons, and a reduction in the electron density on axis. The energetic electrons ablated from the target surface are eventually pushed back into target and accelerated to relativistic speeds by the "vacuum" laser fields giving rise to an electrostatic potential which in turn accelerates the ions to high energies.

The "LAPPS" Propulsion Concept

We noted earlier that a beam of one MeV protons containing more than 10^{10} particles has been successfully accelerated by a 100 TW laser beam with a one micron wavelength impinging on an aluminum foil of about one micron thickness(2). The laser focal spot had a radius of 5 μm, and the accelerating electric field was found to be about 10 GeV/cm. We note from Fig. 2 that proton energies nearing 70 MeV had been achieved with lasers of intensity near 10^{19} W/cm^2 (8). It is clear that in order to produce propulsive capabilities commensurate with interplanetary and other potential manned space missions from this scheme, proton beams containing 10^{18} particles at about 100 MeV energy would be highly desirable. At a rep rate of one kilohertz (which also appears to be close at hand) this propulsion device will produce about $0.2*10^3$ Newtons of thrust and a specific impulse of about $13*10^6$ seconds. Such a system, illustrated in Fig. 3, will consist of an ultrafast laser that can be fired 10^3 times per second at an appropriate solid target such as aluminum foils that are fed into a reaction chamber at the same rate. To get a sense of how near-term such systems might be we turn to some recently-generated experimental results(9) and asses their merit as a foundation for a propulsion system. The experiments in question have produced proton beams at about 58 MeV energy using a one petawatt (10^{15}) laser system of 500 fs pulse duration. Simple energy conservation shows that such 500J lasers will accelerate $5*10^{14}$ protons, and from the familiar expression of the relativistic kinetic energy, namely

$$KE = m_0 c^2 [\gamma - 1] \qquad (13)$$

we see that a 58 MeV proton will have a γ of 1.0618 resulting in a velocity of 0.3363 the speed of light, and a specific impulse of about 107 seconds. From Eq. 12, we find that a_o=0.505 which when substituted in eq(6) yields $\lambda^2 I=0.36*10^{18}$. A peak intensity of $I=3*10^2$ W/cm^2 in a focal spot of 9 μm was employed in the experiments and with such intensity it is reasonable to conclude that the laser wavelength, λ, is on the order if 0.034 μm. It should be noted at this point that Eq. (13) coupled with Eq (12), often employed in the description of a laser-ion acceleration in gas targets(10), predicts an ion energy which is an order of magnitude lower than those observed in the solid-target experiments(2). Hence the results presented here may be viewed as conservative.

As a propulsive, device the system in question will produce, at a kilohertz rep rate, a thrust, F of $84*10^{-3}$ N which, as we shall note shortly, is too small for many missions of interest in spite of the spectacular specific impulse it produces. Nevertheless it can provide a capability that makes it suitable for other missions where no large payloads are needed. To estimate the dry mass, m_f, of this propulsion system we assume, that a kilojoule laser that transfers ½ of its energy (500J) to the accelerated protons is employed. At the kilohertz firing rate, noted earlier, an energy source that delivers 1 MW of power to the laser would be required. Such a large power source would most likely be a nuclear reactor, and the mass of such a reactor might be estimated (11) to be 8 mT or $8*10^3$ kg assuming, of course, a high laser efficiency.

Interstellar Missions with LAPPS

As a measure of the effectiveness of this present-day LAPPS propulsion device presented above we consider two types of missions: one which consists of a round trip between two points separated by a linear distance, D, using a constant thrust, acceleration/deceleration type of trajectory. For this mission the travel time, τ_{RT} is given by$^{(12)}$

$$\tau_{RT} = \frac{4D}{gI_{SP}} + 4\sqrt{\frac{Dm_f}{F}} \qquad (14)$$

where g is the earth's gravitational acceleration (~10m/s^2), and I_{SP} the specific impulse. We readily note that the LAPPS under consideration is not suitable for such missions in spite of the very large I_{SP} because of the very small thrust (F) it generates.

The other mission for which this propulsion device might be suitable is an interstellar robotic fly-by mission to the Oort cloud at a distance of 10,00 astronomical units (AU). If we denote by S_f the distance to the destination, and by t_f the time it takes to reach it, then from the standard non-relativistic rocket equation we can write for the fly-by mission $^{(13)}$:

$$t_f = \left[{(m_i - m_f)}/{F}\right] u_e \qquad (15)$$

$$S_f = \frac{m_i u_e^2}{F}\left[1 - \frac{m_f}{m_i} + \frac{m_f}{m_i}\ln\left(\frac{m_f}{m_i}\right)\right] \qquad (16)$$

$$u_f = u_e \ln\left[1 \Big/ \left(1 - \frac{Ft_f}{m_i u_e}\right)\right] \qquad (17)$$

where u_e is the exhaust velocity, m_i the initial vehicle mass, and u_f the velocity of the vehicle when it reaches its destination, assuming it started from rest. For the interstellar mission to the Oort cloud in which S_f is 10,000 AU ($\approx 1.5*10^{15}$ m) the above equations yield a time (t_f) of about 46 years. This is considered a very acceptable mission time since it can be carried out in a researcher's lifetime. It falls well within the 10,000 AU – 50year objective once specified by NASA for interstellar precursor missions.

Conclusions

We have presented in this paper a novel propulsion concept in which laser accelerated plasma provides the propulsive capability. It is based on well established and documented research that has conclusively demonstrated the acceleration of charged particles to relativistic speeds by ultrafast lasers. By focusing on recently-generated experimental results, we have shown that even present day systems can serve as propulsion devices that can meet the needs of fast, robotic interstellar fly-by missions. This attests to the fact that LAPPS can be truly viewed as a near-term concept.

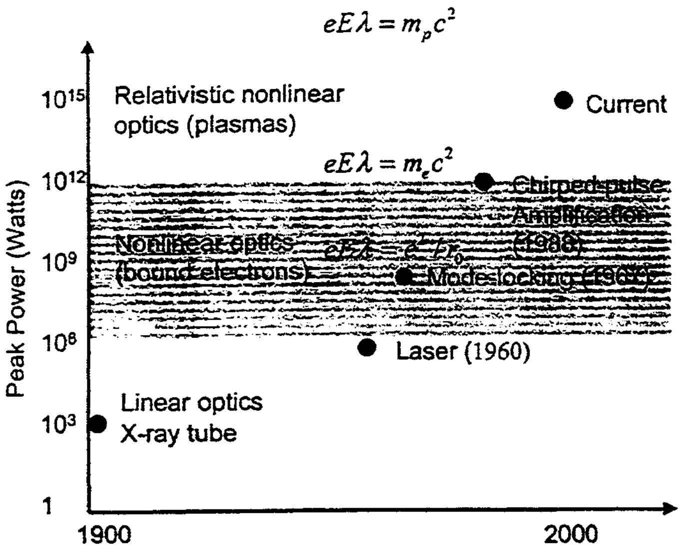
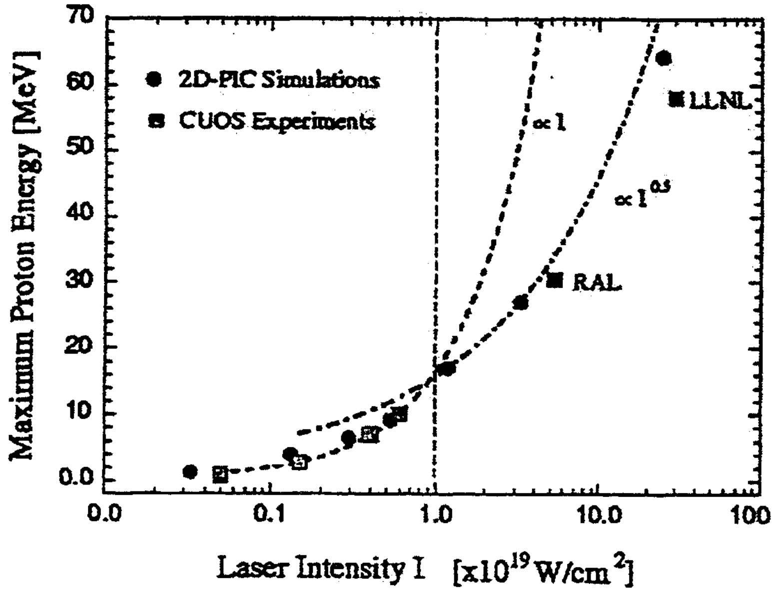


Figure 1. Peak Power History



Sentuko *et al.* (2000).

Figure 2. Scaling of maximum proton energy with laser intensity λ=1μm

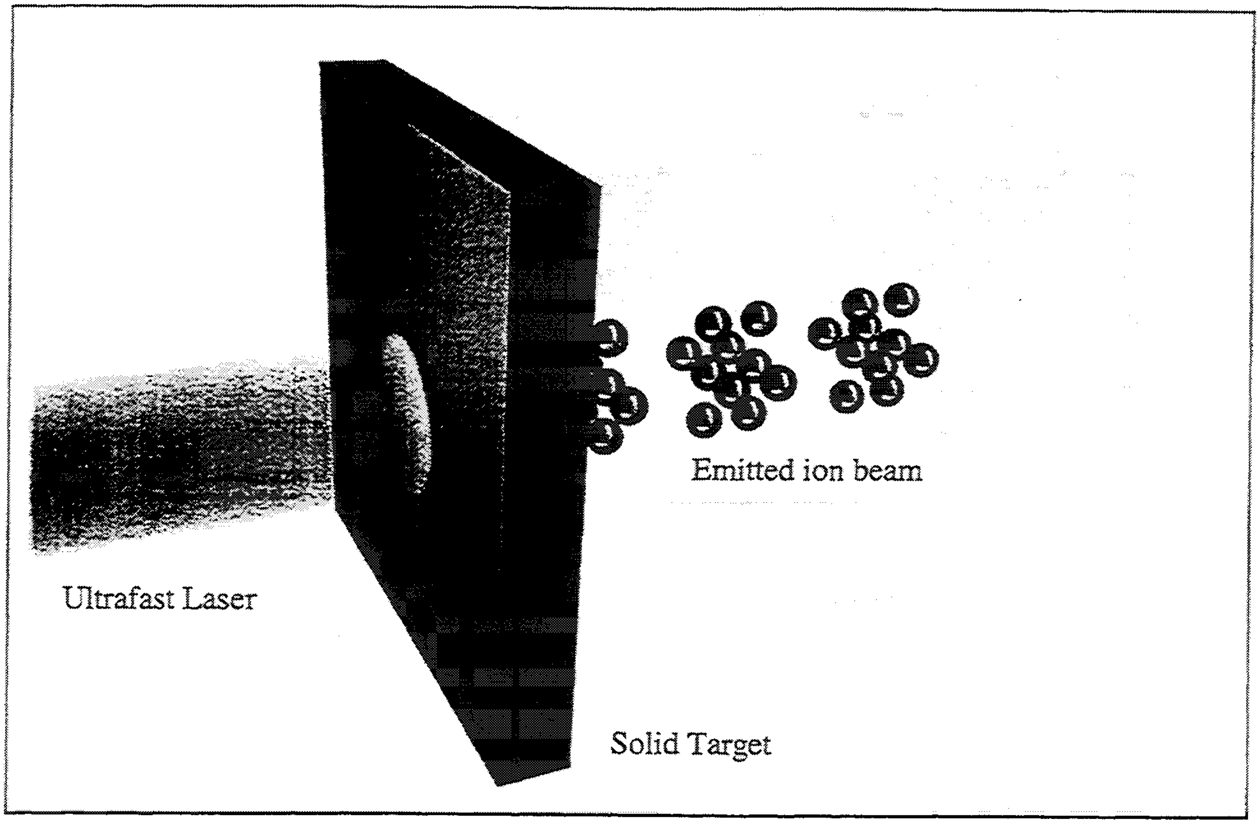


Figure 3. A schematic of LAPPS propulsion concept

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