ULTRAFAST-LASER DRIVEN PLASMA FOR SPACE PROPULSION

NIAC 00-02 Final Report

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Abstract

The rapid world-wide progress made recently in the use of ultrafast lasers to accelerate charged particles to relativistic energies brings into focus the potential utilization of such systems in space propulsion. Lasers with modest energies but with extremely short pulse lengths have been employed at the University of Michigan and several other laboratories in producing proton beams at mean energies of tens of megavolts. For example, the ten terrawatt laser at the University of Michigan, when focused on a spot of 5 μm in an aluminum foil, has produced a proton beam containing more than 10^{10} particles at a mean energy of more than 1 MeV, while the petawatt laser at the Lawerence Livermore National Laboratory has produced beams containing about 10^{14} particles at a maximum ion energy of 58 MeV and a mean energy of about 5 MeV. These results were sufficiently encouraging to warrant detailed examination of the underlying physics of the phenomena involved, and to assess potential application of these processes to propulsion systems that could open up the solar system and beyond.

In this phase I research, the physics of the interaction of a laser beam with an electron was addressed since the relativistic dynamics of such a particle in the electromagnetic fields of the laser plays a significant role in the eventual acceleration of the ions. The interaction of the laser radiation with the pre-formed plasma was also investigated especially in connection with the conditions for self-focusing; a condition deemed to be critical for propulsion applications. A conceptual design of how an ultrafast laser driven plasma propulsion system might look like, and how it might perform in this capacity, was proposed and analyzed. It was shown, for example, that the present day Livermore system can produce several million seconds of specific impulse albeit at a fraction of a Newton of thrust. With that capability, it can achieve a fly-by robotic mission to Mars in less than six years. But it was also shown that if the thrust can be increased to tens of Newtons at about the same energy, the Mars trip will be reduced to just a few weeks. In both instances, our analysis reveals that a magawatt nuclear power system would be required to drive the propulsion device. Moreover, we make note of the fact that encouraging research in space nuclear power and ultrafast laser technology can indeed make the development of such a propulsion system quite feasible in the NIAC time frame of 10-40 years. Finally, some of the critical experimental and analytical studies that must be carried out to make this a reality are introduced as the core of a phase II research proposal.

1.0 Introduction

1.1 Executive Summary

NASA's challenges of interplanetary manned missions sometime in this century along with robotic interstellar missions such as the so-called "precursor mission" to the Oort Cloud at 10,000 AU in less than 50 years, require propulsion systems that can produce specific impulses in the 10^5-10^6 seconds range and thrusts in the tens to hundreds of kilonewtons. This automatically eliminates from consideration conventional propulsion systems and even some of the advanced concepts such as nuclear thermal fission systems due to the small specific impulses they produce. With pure antimatter annihilation propulsion still very far into the future, fusion reactions with the next largest energy production per unit mass offer perhaps the next most promising approaches to this challenge. With these systems still, however, in the early stages of investigation for propulsion applications, there appears to be others which can produce very attractive propulsive capabilities that might indeed lend themselves to such applications in a much nearer time frame. One such system is "LAPPS", Laser Accelerated Plasma Propulsion System, which is currently at a critical juncture in its development and which is the subject of this phase I study.

Some very exciting research at the University of Michigan and a few other laboratories throughout the world have recently demonstrated that ultrafast lasers (with very short pulse length) can accelerate charged particles to relativistic energies. The 10 terrawatt laser at Michigan has produced proton beams containing more than 10^{10} particles at mean energies exceeding one Megavolt, while the petawatt system at the Lawrence Livermore National Laboratory has produced proton beams containing more than 10^{14} particles at mean energies of about 5 MeV. If utilized as propulsion devices, this study reveals that these present-day systems are capable of producing specific impulses exceeding millions of seconds albeit at very small thrusts. Experiments have, however, demonstrated that high duty-cycle capabilities are feasible with such systems yielding rep rates of kilohertz or higher, making them readily amenable to thrust enhancement. Moreover, this investigation has shown that the plasma, formed when the laser strikes the target, serves to focus the laser beam through the relativistic modification of the electron mass, and by a mechanism known as pondermotive channeling. The conceptual propulsion device that emerges from this study consists of a laser which can be fired a thousand times per second at targets that are fed into a chamber at the same rate producing a neutral charged particle beam which produces thrust as it emerges from the vehicle. The analysis further reveals that a nuclear power system would be required to drive such a propulsion system, and that its mass can be made of acceptable size through encouraging research in materials science and reactor design and development. The unique features of this concept with regard to space application in the NIAC time frame of interest can be summed up as follows:

- Availability of ample data based on current research to warrant serious consideration for propulsion utilization
- Relative simplicity, and the absence of technological complexities that characterize other advanced propulsion concepts
- Very encouraging research in the development of high intensity lasers that could lead to the accelerating of protons to rest mass energies
- The capability to produce specific impulses that far exceed those projected to be produced by competing processes such as fusion or antiproton-catalyzed fusion concepts
- Currently demonstrated high duty cycle capability as reflected in kilohertz rep rate operation of ultrafast lasers
- Absence of any discernible laser-plasma phenomena that can detract from its ability to function as a propulsion system
- Continued and rapid progress in technologies that are critical to its development for the application it is suggested for.

While present-day systems are perfectly capable of producing specific impulses that can meet or exceed the needs of interplanetary or even some interstellar robotic missions the fact remains that they produce much too small of a thrust to make them suitable for manned missions. With thrust being the product of the rep rate, the mass, number, and velocity of the ejected particles, it is clear that some mechanisms must be found to enhance any or all of these parameters in laser accelerated plasmas. Addressing these issues and validating them experimentally lies at the heart of the phase II proposal. Specifically, we plan to consider:

- Increasing the rep rate on the target side to match the kilohertz rep rate on the laser side which has already been accomplished. This can be achieved by using "jets" in place of solid targets
- Increasing the particle density in the ejected proton beam. This can be accomplished by increasing the area of the focal spot since, for a fixed thickness of the target, the number increases with the area.
- Increasing the particle velocity by increasing the energy of the ejected particles. This requires increasing the laser power so as to increase the intensity since the particle energy scales directly with intensity for a fixed wavelength.
- Addressing under these circumstances the laser-plasma phenomena such as focusing effects that may impact the efficiencies of energy transfer from laser to protons
- Addressing, in cooperation with NASA Marshall and NASA Glen, nuclear reactor and thermal power conversion designs based on latest developments in this field that would allow a LAPPS propulsion system to become a reality in the next several decades.

1.2 Background and Rational

In recent years, NASA has set a number of challenging and ambitious mission goals for space exploration in this century. These include manned missions to Mars in several months instead of several years, and some robotic missions to 10,000 AU in less than 50 years. As pointed out earlier, most of these interplanetary and interstellar missions require propulsion systems that can deliver specific impulses in the range of 10^5-10^6 seconds and tens to hundreds of kilonewtons of thrust. To appreciate the importance of these two parameters, we focus on the example of a simple trajectory consisting of a continuous burn acceleration/deceleration at a constant thrust for such missions. It can readily be shown from the standard non-relativistic rocket equation that the round trip time, τ_{RT}, between two points separated by the linear distance D can be written as[1]

$$\tau_{RT} = \frac{4D}{gI_{sp}} + 4\sqrt{\frac{Dm_f}{F}}\,, \tag{1}$$

where g is the earth's gravitational acceleration, I_{sp} the specific impulse, m_f the dry mass of the vehicle, and F the thrust. The inverse dependence of travel time on I_{sp} and F reveals dramatically the desirability of having both of these parameters as large as possible and feasible. Equation (1) also reveals that for an optimum travel time, the two terms on the right-hand side should be comparable to one another. For interplanetary missions, for example, it can be shown that very large I_{sp} at very small F does not result in rapid transit time, while for robotic intersteller missions with very large D and modest m_f, the travel time can be shortened significantly if I_{sp} is particularly large. As noted earlier, present-day ultrafast laser accelerated plasma propulsion systems embodied in LAPPS are capable of producing very large I_{sp}'s albeit at a very modest F, hence they may be particularly suitable for the robotic interstellar missions while inadequate for manned missions within the solar system. To accommodate the latter missions, research must be aimed at means by which large thrusts can be generated by LAPPS, and this research has identified those mechanisms by which this can be accomplished.

2.0 Advanced Concept Description

2.1 Major Attributes of LAPPS

Unlike other systems considered for potential propulsion applications, such as inertial confinement fusion where large energy (on the order of magajoules) lasers are required, LAPPS requires lasers with modest energies because of the extremely short pulse lengths that have been achieved. For LAPPS, it is the large laser power and intensity that are needed to accelerate protons to very high energies. The developments in these two areas have been remarkable and rapid. In fact, petawatt lasers have now been achieved, and laser powers that would accelerate protons to rest mass energies are within reach. As will be seen later, it is the laser intensity that figures prominently in the acceleration mechanism(2), and intensities exceeding 10^{20} W/cm^2 have already been utilized(3) in producing protons with maximum energies of about 60 MeV. Experiments at various laboratories seem to also verify numerical simulations that predict that intensities of about 10^{21} W/cm^2 which will produce protons at energies of about 100 MeV are indeed achievable. Hence, the groundwork for the utilization of LAPPS as a propulsion system has already been established and what remains is effectively finding ways with which these capabilities can be cultivated to produce more particles at the desirable energies. These unique attributes of LAPPS are not likely to be matched by other concepts currently envisaged as propulsion systems of the near future.

2.2 Physics Basics of LAPPS

Although no self-consistent theory of high-energy electron and ion generation in laser-solid target interactions currently exists, we can present a plausible explanation based on sound physics principles that would allow us to predict with some degree of reliability the performance of a LAPPS propulsion system. We begin by noting that when a high-intensity laser terminates at the target surface, it produces a plasma with a size of about half a laser wavelength(4) 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 "pondermotive" force. Inside the target this force sharply vanishes. Twice in a laser period electrons reenter the target. Returning electrons are accelerated by the "vacuum" electric field and then 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 velocities, 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, 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 that the ion acceleration time in the layer, the ions acquire an energy equal to the electrostatic energy. Since this electrostatic field accelerates the ions while decelerating the electrons, an equilibrium is eventually reached whereby both of these species drift at the same rate and give rise to a neutral charged particle beam that emerges in a perpendicular direction to the back surface in nearly a collimated form. Such a beam is the one that provides the thrust to the vehicle.

With this qualitative description in mind, we proceed now to deduce the mathematical expressions that allow us to assign quantitative values to the parameters of interest. Since the laser-electron interaction lies at the heart of the acceleration process, we begin by examining the dynamics of this particle in the fields of the high-intensity laser. The starting point is the relativistic Lorentz equation given by[5] (in mks system):

$$\frac{d}{dt}(\vec{p}) = \frac{d}{dt}(\gamma m_o \vec{v}) = q(\vec{E} + \vec{v} \times \vec{B}), \tag{2}$$

where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the familiar relativistic parameter, m_o the rest mass of the electron, q the electron charge, $\vec{v}$ its velocity, and $\vec{E}$ and $\vec{B}$ the electric and magnetic field of the incident radiation respectively. For a linearly polarized electromagnetic wave propagating in the z-direction, and the axis of laser polarization along the x-direction, the fields can be expressed by

$$\vec{E} = \hat{x} E_o \sin(k_o z - \omega_o t) \tag{3}$$

$$\vec{B} = \hat{y} E_o \sin(k_o z - \omega_o t), \tag{4}$$

where $\hat{x}, \hat{y}$ are unit vectors in these directions, k_o the wave number, and ω_o the frequency of the wave. Upon substitution of (3) and (4) into (2), and expressing the fields in terms of the vector potential $\vec{A}$, a solution can be obtained[6] that reveals that the electron will execute a figure-of-eight trajectory as shown in Fig. 1, and an average drift motion along the direction of laser propagation. Physically, the drift motion is a result of the laser longitudinal pondermotive force, F_p, which can be written as[7]

$$\vec{F}_p = -\frac{m_o c^2}{8\pi} \frac{\nabla a_o^2}{\sqrt{1 + \frac{a_o^2}{2}}} \left[\left(\frac{2}{a_o^2} + 1 \right) E_t(2\pi, K) - \frac{2}{a_o^2} F_t(2\pi, K) \right], \tag{5}$$

where, we recall, that m_o is the rest mass of the electron, c the speed of light, F_t and E_t the elliptic integrals of the first and second kind respectively, and the argument K is given by

$$K = \frac{a_o^2/2}{1 + a_o^2/2}. \tag{6}$$

The quantity a_o is known as the normalized vector potential of the laser field and is defined by

$$a_o = \frac{qA}{m_o c^2} = 8.5 \times 10^{-10} I^{1/2} \left(W/cm^2\right) \lambda(\mu m), \tag{7}$$

where I is the intensity of the laser beam whose wavelength is designated by λ. It may be noted that in the low intensity limit of $a_o^2 << 1$ the pondermotive force reduces to

$$\vec{F}_p = -\frac{m_o c^2}{4} \nabla a_o^2, \tag{8}$$

revealing that it is roughly proportional to the gradient of the intensity. The electron motion depicted in Fig. 1 has been confirmed experimentally[8] at the University of Michigan and featured on the cover of Nature magazine as the first major effort in the study of relativistic non-linear optics especially as it applies to the non-linear "Thomson Scattering" phenomenon. The figure also confirms the electron "quiver" motion that takes place when the laser beam interacts with the pre-formed plasma as alluded to earlier.

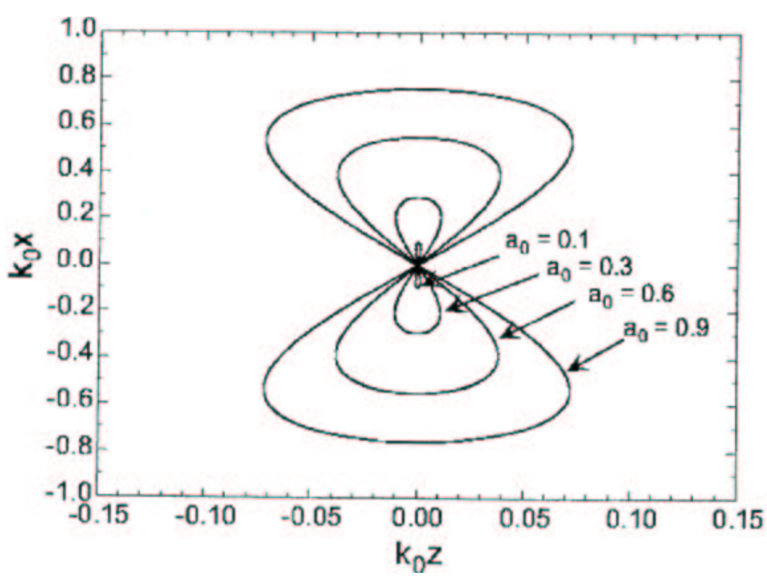

Figure 1. Trajectory of an electron in a linearly polarized laser field as a function of laser intensity

The next issue of importance is whether the incident laser beam remains focused as it propagates through the pre-formed plasma to further accelerate that segment of the electron population that penetrates the target to create the electrostatic potential. It is critical, therefore, that the laser beam remains focused to achieve maximum efficiency of energy transfer. One of the effects of a "relativistic" laser intensity is that it changes the frequency of the plasma it interacts with and correspondingly modifies its index of refraction. The refractive index is given by

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

where, once again, ω_o is the laser frequency, and

$$\omega_p(\gamma) = \frac{\omega_{p_o}}{\gamma} \qquad (10)$$

is the relativistic plasma frequency in which

$$\omega_{p_o} = \sqrt{\frac{4\pi n_e e^2}{m_o}} = 5.64 \times 10^4\, n_e^{1/2}\left(\text{cm}^{-3}\right)\text{rad/sec} \qquad (11)$$

is the non-relativistic plasma frequency which is determined by the electron density, n_e, only. It is convenient, for the purposes of this discussion, to relate γ to the laser intensity, I, which can be shown to take the form

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

with a_o having been introduced in Eq. (7). We note readily that the index of refraction of a plasma depends on the local laser intensity. As a result, a laser beam with spatially and temporally dependent laser 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 intensity off axis in a plasma, the index of refraction of the plasma is higher on axis and lower off axis. This process is referred to as relativistic self-focusing(9).

When a laser pulse is focused and propagates inside a plasma, because of the transverse laser intensity gradient, the transverse pondermotive 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. Since the index of refraction of a plasma is higher for lower electron density (see Eq. (9)), such an electron density distribution acts like a positive lens, and leads to self-focusing of the laser pulse. This is referred to as pondermotive self-channeling. We conclude from the above discussion that when a laser pulse propagates in a plasma it can undergo self-guiding when the effects of relativistic self-focusing and pondermotive self-channeling overcome the natural diffraction of the laser beam. This occurs when the laser power, P, is higher than a critical power, P_{cr}, given by[10, 11]

$$P_{cr} \cong 17\left(\omega_o^2 \big/ \omega_{p_o}^2\right) GW . \tag{13}$$

Usually, in a self-guided channel, the radius of the laser oscillates about some fixed value as the laser propagates. However, the exact behavior depends on the condition of the experiment, such as the wave front, the laser pulse shape, the laser intensity, etc[12, 13]. In addition, the threshold for self-guiding can increase for various reasons. For instance, the need to overcome additional defocusing forces, such as that due to ionization defocusing, results in a higher threshold. Furthermore, plasma heating can suppress self-guiding of a laser pulse due to a loss of energy caused by side scattering and reduction in the effective quiver velocity resulting from intense plasma heating[14].

The third phase of this analysis consists of deducing mathematical expressions that relate the parameters that characterize the laser on the one hand, to those that characterize the target and the ejected particles on the other. We recall that the mechanism for generating high energy protons consists of shining a high intensity laser on a target whose thickness is on the order of the wavelength of the laser, and whose focal spot is on the order of several wavelengths. When such a laser with intensity I, and wave length λ, strikes a target with a focal spot of radius R and thickness l, a plasma is formed at that instant whose electrons will "quiver" in the fields of the laser. Some of these electrons will be accelerated and pushed by the laser deep in the target giving rise to an electrostatic potential which causes the ions (protons) to be ejected primarily from the back end of the target. The electrons that are accelerated by the laser must overcome the Coulomb energy in order to penetrate the target to set up the potential. This Coulomb energy can be calculated from the standard expression[15]:

$$E_c = \int_{\vec{r}} \int_{\vec{r}'} \frac{\rho(\vec{r})\rho(\vec{r}')}{|\vec{r}-\vec{r}'|} d^3r d^3r' , \tag{14}$$

where ρ is the charge density and $|\vec{r}-\vec{r}'|$ = R is the separation between the charges taken here to be the same as the radius of the focal spot. Since the plasma region of interest is quite small, it is reasonable to assume that the charge distribution would be spatially uniform so that we can write

$$\rho = en_e \text{, and} \tag{15}$$

$$\rho d^3r = en_e V = eN_e , \tag{16}$$

where e denotes the electronic charge, n_e the electron density, V the volume, and N_e the total number of electrons in the plasma. In view of these assumptions, Eq. (14) reduces to

$$E_c = \frac{(eN_e)^2}{R} . \tag{17}$$

Clearly, the electron energy, E_e, must exceed the Coulomb energy in order to penetrate the target, hence

$$N_e E_e \geq \frac{(eN_e)^2}{R} \tag{18}$$

so that

$$E_e \geq \frac{e^2 N_e}{R} . \tag{19}$$

If the efficiency of converting the incident laser energy into charged particle energy is designated by η, then a simple energy balance yields

$$n_e E_e c = \eta I , \tag{20}$$

where c is the speed of light. Noting that the total number of electrons in the plasma, N_e, can be expressed by

$$N_e = \pi R^2 l n_e \tag{21}$$

with l being the thickness of the target. Substituting this in Eq. (19) and combining with Eq. (20) we obtain

$$E_e \geq \sqrt{\frac{\pi e^2}{c} IR\eta} . \tag{22}$$

This energy is equal to the potential energy eΦ, where Φ is the electrostatic potential set up by the penetrating electrons that causes the ejection of ions with charge number Z. With E_i denoting the ion energy, we can readily write

$$E_i \geq Ze\Phi = ZE_e , \tag{23}$$

which upon utilization of Eq. (22) becomes

$$E_i \geq Ze\sqrt{\frac{\pi}{c} I\eta R\lambda} , \tag{24}$$

where we have replaced the target thickness "l" by the laser wavelength, λ, since they are typically of the same order of magnitude. Although not addressed in this analysis, it should be kept in mind that for consistency the intensity I in Eq. (24) should be in units of W/cm^2, and the spatial dimensions, R and λ, in microns so that the above equation can be replaced by

$$E_i \geq Z\sqrt{\frac{\pi}{c} I\eta R\lambda} \quad \text{eV} \tag{25}$$

to yield the ion energy directly in electron volts. As a test of the accuracy of the above results, we apply it to some recent experimental results[16] in which a kilojoule laser with petawatt power was focused on a target with a focal radius R = 10 μm, and λ = 1 μm, giving rise to an intensity of $I = 6 \times 10^{20}\ W/cm^2$. The data suggest that 50% of the laser energy appeared in the particle beam yielding an efficiency η = 0.50, and with these values Eq. (25) predicts a particle energy of about 5.5 MeV. In Ref. 16, an expression for the cycle-averaged electron energy was presented as

$$E_e = m_o c^2 \left[1 + \frac{2V_p}{m_o c^2}\right]^{1/2}, \tag{26}$$

where $V_p = 9.33 \times 10^{-14}\, I\left(W/cm^2\right)\lambda^2(\mu m)$ is the non-relativistic pondermotive potential. If we substitute in this expression the above-noted parameters we find that E_e is also about 5.5 MeV which by our analysis is also equal to the ion (proton) energy.

Equation (25) seems also to predict reasonably accurately the energy of the protons produced in the University of Michigan experiments[17] utilizing a 10 TW laser that delivered about 4 J of energy in 400 fs pulse at a wavelength of about 1 μm to a thin aluminum foil. The thickness of the target l was taken to be about one λ, i.e., 1 μm and the radius of the focal spot (R >> l) with a value of R = 5 μm. A laser intensity $I = 3 \times 10^{18}\ W/cm^2$, and η = 10% were employed, and with that an ion energy of about 1 MeV was predicted by Eq. (25) and confirmed by the experiment. An estimate of the proton energy based on the pondermotive potential as represented by Eq. (26) appears to yield a value which is an order of magnitude lower than observed in the experiment. This discrepency is often attributed to the fact that Eq. (26) is more applicable to ion acceleration in gas targets than in solid targets[18, 19].

3.0 LAPPS as a Propulsion Device

The above analysis, along with an abundance of experimental data suggest that a near-term propulsion system based on the LAPPS concept is quite feasible. We envisage such a system to consist primarily of an ultra-fast laser driven by some kind of a power supply where in the laser is fired at a kilohertz rate at a target that is fed into a chamber at the same rate as illustrated in Fig. 2. The charged particles that are ejected from the target at sufficiently high energy and in sufficiently large numbers will provide the thrust to the vehicle. To assess the propulsive capabilities of such a system, we turn to some recent experiments conducted at the Lawerence Livermore National Laboratory[3, 16] and assume that the data produced do indeed typify a present-day propulsion device. In these experiments, a kilojoule laser with a 500 femtoseconds pulse length was fired at a focal spot of 9 μm radius in a gold foil of 125 μm thickness. An intense collimated beam of high-energy protons was emitted normal to the rear surface of the target when a peak intensity of 3 x 10^{20} W/cm^2 was reached. The energy spectrum of the emitted protons displayed a high energy cutoff as high as 58 MeV on the axis of the beam. Inferred from the results is the fact that half of the laser energy appeared in the emitted protons thus yielding $\eta = 0.5$, and laser power on target of a petawatt. Assuming the typical one micron wave length for these lasers, and substituting the various parameters in Eq. (25), we find that the mean energy of the emitted protons is about 5.3 MeV. This yields a particle velocity of about 3.2 x 10^7 m/sec which translates to about 3.2 x 10^6 sec for a specific impulse. With half of the laser energy appearing in the emitted proton beam, simple energy balance indicates that the number of protons in the beam is about 6 x 10^{14}. We noted earlier that kilohertz rep rates have been achieved on the laser side in experiments in France, and if we assume that the same rep rate can be accomplished on

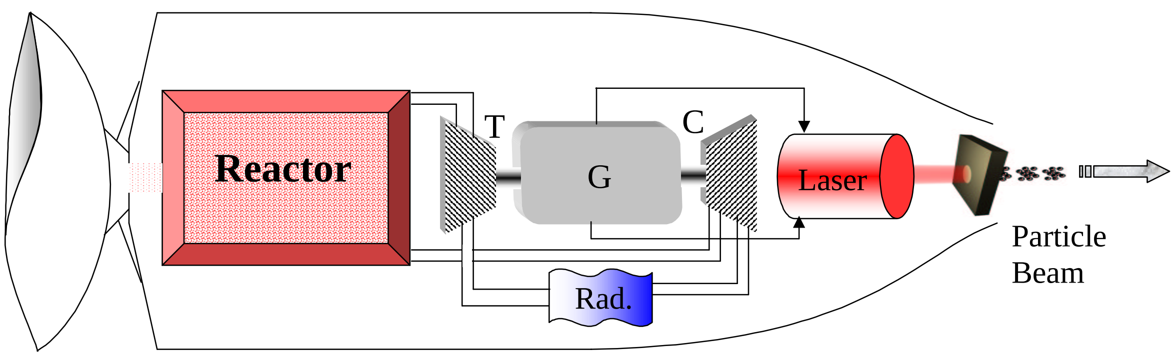

Figure 2. Laser-Accelerated Plasma Propulsion System (LAPPS).

the target side (to be addressed in phase II research) then 500 kW of jet power can be expected from this propulsion device. Moreover, it is quite clear that a MW power source will be needed to drive the laser, and that simply implies that a nuclear power system would be required as illustrated in Fig. 2. Current design of such systems suggest[20] a ratio of 5 mT/MW for the specific mass, and if we assume that the mass of the power system is effectively the mass of the vehicle, then the dry mass of the about LAPPS would be 5 x 10^3 kg. Research in the area of power conversion, radiator material and design, etc., also suggest that the specific mass may also by improved significantly in the near future. A summary of the characteristics of a present-day LAPPS is given in table 1.

If we apply these results to three fly-by missions[21]: Pluto, Jupiter, and Mars, we find that these journeys will take 56 years, 19 years, and 6 years respectively. These journeys may be viewed as long and that is a consequence of the very small thrust projected to be produced by present-day LAPPS. As we noted earlier, improvement in this propulsion characteristic is critical if interplanetary travel is to be achieved in relatively short times. For example, a round trip to Mars, using the scenario prescribed by Eq. (1), can be accomplished in 6 months if the thrust of LAPPS can be improved to 25 N only. This can be done by ejecting more protons at the same energy, and that can be done by focusing the laser on a focal spot with a radius which is about 28 times larger than the first one. In order to maintain the same energy for the protons, the intensity (and the wave length) must be kept the same, hence the power of the laser must be increased accordingly. In this example, a laser power of about 600 petawatts would be needed and the rapid progress that is being made in this field will make this also achievable in the near future. In fact, for the same laser energy, a reduction in the pulse length from 500 fs to about one fs would almost achieve this goal.

Table 1
Present Day LAPPS Parameters

1. Proton Beam			
	i) Particle Population	=	6×10^{14}
	ii) Mean Energy	=	5.3 MeV
	iii) Beam Energy	=	500 J
	iv) Associated Electric Field	=	17 GeV/cm
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	=	3.2×10^6 s
	iii) Thrust	=	3.1×10^{-2} N
	iv) Nuclear System	=	1 MW_e
	v) Vehicle Dry Mass	=	5×10^3 kg

4.0 Conclusion

We have demonstrated in this study that a propulsion system can indeed evolve from a world-wide research activity which shows that ultrafast lasers can accelerate charged particles to relativistic energies. By examining the underlying physics of the acceleration mechanism, we have deduced the mathematical expressions that allow us to assess the propulsive capabilities of such systems in terms of the important parameters of thrust and specific impulse. We find that systems based on present-day experimental data are capable of producing specific impulses of millions of seconds albeit at a very modest thrust. Although a propulsion system with these capabilities may be suitable for interstellar fly-by missions, it is not suited for manned interplanetary missions due to the smallness of the thrust it generates. We have proposed schemes by which the thrust can be enhanced, and identified the technological issues that have to be addressed in order to make this concept a viable propulsion system in the near future.

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