

# High-Power Electric Propulsion Utilizing Laser-Driven Ponderomotive Fields

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George J. Williams, Jr.<sup>1</sup>  
*The Ohio Aerospace Institute, 22800 Cedar Point Rd., Brookpark, OH 44142*

**A new spacecraft propulsion scheme is proposed which leverages advances in high-energy particle acceleration via laser-plasma interactions. Ponderomotive forces associated with laser wake-fields have demonstrated the potential to accelerate electrons to near-relativistic energies. Different schemes are investigated which may generate efficient propulsion systems for deep-space and manned space missions. Ponderomotive propulsion which leverages its inherent capability to decouple the mass of the power system could revolutionize space travel by providing very high thrust at very high specific impulses.**

## I. □ Introduction

SEVERAL propulsion concepts are being developed to significantly enhance near-term space exploration capabilities. The most mature of these is solar electric propulsion (SEP). With specific impulses in the range of 2000 s to 10,000 s, it enables many solar system exploration missions which either deliver a larger payload or reduce mission time relative to chemical propulsion systems. Incorporation of nuclear (fission-based) electric power yielding nuclear electric propulsion (NEP) or nuclear thermal propulsion (NTP) will enhance this capability but not radically alter it. However, state of the art propulsion systems are inherently mass-limited. That is, either the mass of the propellant or the mass of the electrical power supply determines the size of the spacecraft delivered to its objective and/or the time required to deliver the spacecraft. This limitation precludes rapid transits and restricts exploration to infrequent, large-scale missions which are geared to compromise between various mission goals. The performance limits of the technology preclude the realization of a grander vision of exploration.

Several concepts have been explored in recent years which have the promise to overcome the limitations of NEP, NTP, and advanced chemical propulsion for deep space/interstellar applications. Figure 1 summarizes the findings of a recent investigation of several options.<sup>1</sup> Of those identified as best candidates, the Laser Light Sail concept warrants further discussion in the context of the present investigation. Laser Light sails are preferable to Solar Sails for deep space applications (the most demanding of which is used as a filter in the figure), because it enables a much higher photon density and therefore thrust.<sup>2</sup> A transmitter with 1000 km diameter optics ( $3 \cdot 10^6$  km<sup>2</sup> beam area) permits transmission of a 1  $\mu$ m-wavelength beam 40 light years. A comparable "sail" is required on the receiving end. For a  $10^{15}$  W laser, the mission lasts 84 years.<sup>1</sup> This is of interest not only because it represents one of the "best" options currently on the table for deep space exploration, but because it illustrates the belief that future developments in laser power and beam handling are deemed potentially possible if not yet feasible.

Previous studies into laser-accelerated propellant propulsion systems have relied on laser-induced ionization.<sup>3,4,5</sup> The laser either ionizes a gas or ablates a surface generating a plasma that is then accelerated by applied or self fields. Very high specific impulses are conceivable with some of these approaches, which use ponderomotive force to accelerate the induced plasma. A field is generated immediately following a laser pulse, and the field travels with the pulse through the plasma. The nature of the traveling field has led to being called a "wake field." However, the most promising for space propulsion are constrained by fundamental restrictions imposed by a tradeoff between laser power and laser spot size.<sup>3</sup> To date, the application of wake field acceleration has been

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<sup>1</sup> Senior Scientist, [george.williams@grc.nasa.gov](mailto:george.williams@grc.nasa.gov).

restricted to collinear acceleration of the plasma with the laser. The target, e.g. a dielectric tape or neutral gas, is ionized by the laser and the resulting plasma is accelerated in a wake-field. For spacecraft applications, this concept is limited by the laser spot size and the stability of the propellant as it is fed across the accelerator.

## II. □ Theory

The generation of large amplitude electric fields in plasmas by high-power lasers has been studied for several years in the context of high-energy particle acceleration.<sup>6</sup> The ponderomotive force is a non-linear force resulting from the time averaged motion of charged particles in a high frequency wave field. It acts on electrons by means of the oscillating electric and magnetic fields associated with a high-intensity electromagnetic wave. The electrons oscillate in the direction of the electric field of the wave, but the wave magnetic field distorts their orbits.<sup>7</sup> Although the force acts mainly on the electrons, the force is ultimately transmitted to the ions since it is a low-frequency effect. The details of the acceleration of the plasma will be discussed in detail in the next section.

Fields on the order of GeV/m are generated in the plasma wake of the laser by these forces. The laser fields generate longitudinal and transverse electron plasma waves with phase velocities close to the speed of light.<sup>8</sup> These fields and velocities offer the potential to revolutionize spacecraft propulsion and uniquely enable deep space transportation. If they can be coupled with a large plasma flux, rapid-transit manned missions are also possible.

There are several schemes to introduce large-amplitude plasma waves which can be grouped into three general categories. Laser wake-field accelerators (LWFA) introduce a single, short pulse from a single-frequency laser.<sup>6</sup> The pulse acts like a single negative macro particle moving through the plasma at the group velocity of the wave packet. Laser beat-wave accelerators (LBWA) introduce a high-frequency pulse by beating together two typically low-frequency laser beams.<sup>8</sup> This approach may lend itself to establishing a standing wave which will saturate the longitudinal field but maintain the radial field.<sup>9</sup> Conversely, a multistage configuration of the LWFA can suppress the radial field through the interference of the slightly different wave packets and yield longitudinal acceleration.<sup>10,11</sup>

For these two accelerator types, the maximum amplitude of the acceleration plasma wake-field is<sup>10</sup>

$$E^{\text{MAX}}[\text{GV/m}] = 2.8 \cdot 10^4 \left( \frac{\lambda_L}{r_L} \right)^2 \frac{P_L}{\lambda_p} \quad (1)$$

where  $\lambda_p$  is the equivalent plasma wavelength,  $c/\omega_p$ , in  $\mu\text{m}$ ,  $\lambda_L$  is the laser wavelength,  $P_L$  is the laser power in TW, and  $r_L$  is the radius of the laser spot size. This indicates that the field will be higher for longer wavelength lasers with tighter foci. It also suggests that the field will be higher for higher plasma densities. However, the condition that the self-field of the electrons being accelerated does not interfere with the wake-field structure limits the number of electrons being accelerated by a pulse to much less than  $4 \cdot 10^6 \lambda_p [\mu\text{m}]$ .<sup>10</sup> Limiting the spread in energy of the accelerated electrons also favors a lower plasma density. This tradeoff in plasma density will be investigated.

The third general scheme for generating an accelerating wake-field is the plasma wake field accelerator (PWFA).<sup>12</sup> In this scheme relativistic electrons are driven through the plasma in much the same way as the laser in the above examples. To first order, the waves induced by the electron beam can be treated in the same way as those generated by lasers.<sup>14</sup>

### A. Laser-Plasma Interaction

There are two possibilities for accelerating plasma via the ponderomotive force resulting from the interaction of high-intensity laser pulses with a plasma. One, typical of particle accelerators, is to accelerate the plasma parallel to the laser pulse. The other, which couples energy more diffusely,<sup>13</sup> structures the laser pulse to generate *radial* plasma waves. There are possibilities for structuring quasi-steady configurations for each approach.

For an unmagnetized, cold plasma of fluid electrons and immobile ions, the linearized equations describing the motion of the plasma electrons are<sup>14</sup>

$$m_e \frac{\partial \mathbf{v}}{\partial t} + m_e \mathbf{v}_{ei} \mathbf{v} = \nabla(\epsilon\phi + \phi_{\text{NL}}) \quad (2)$$

$$\frac{\partial n}{\partial t} + n_0 \nabla \mathbf{v} = 0 \quad (3)$$

$$\nabla^2 \phi = 4\pi en \quad (4)$$

where  $\mathbf{v}$  and  $n$  are the first order electron velocity and density perturbations,  $n_0$  is the unperturbed density,  $\nu_{ei}$  is the electron ion collision frequency,  $\phi$  is the electrostatic plasma potential, and  $\phi_{NL}$  is the ponderomotive potential. The ponderomotive potential can be expressed in terms of the normalized vector potential of the radiation field,  $a(r,z,t)$ :

$$\phi_{NL} = -\frac{m_e c^2}{2} a^2. \quad (5)$$

The density response and the electrostatic potential in plasma oscillation are given by forced oscillator equations:

$$\frac{\partial^2 n}{\partial t^2} + \nu_{ei} \frac{\partial n}{\partial t} + \omega_p^2 n = -\frac{\omega_p^2}{4\pi e^2} \nabla^2 \phi_{NL} \quad (6)$$

and

$$\frac{\partial^2 \phi}{\partial t^2} + \nu_{ei} \frac{\partial \phi}{\partial t} + \omega_p^2 \phi = -\frac{\omega_p^2}{e} \phi_{NL} \quad (7)$$

where  $\omega_p = \sqrt{\frac{ne^2}{m_e \epsilon_0}}$  is the plasma frequency. The axial and radial wake-fields are given by  $E_Z = -\frac{\partial \phi}{\partial z}$  and  $E_R = -\frac{\partial \phi}{\partial r}$ , respectively.

Assuming a collisionless plasma, the energy imparted to the ions is

$$E_i = \frac{a^2}{16\pi n_e} \frac{Z}{n(I)_{\min}} \left( \frac{1}{n(I)_{\min}} - 1 \right) \quad (8)$$

away from the axis of the beam.<sup>15</sup> This indicates that the accelerated plasma will be separated into groups of ions with like charge as is observed. However, this effect is lost at higher energies as the self-focusing becomes relativistic. In the classical case, the beam can be focused to its diffraction limit, roughly on the order of the wavelength. However, relativistic self-focusing results from the fact that the refractive index has a dependence on the laser intensity when the plasma frequency has a relativistic change due to relativistic mass increase of the electron motion. The relativistic plasma frequency becomes

$$\omega_p^2 = \frac{4\pi e^2 n_e}{m \epsilon_0} \left( 1 - \frac{v^2}{c^2} \right)^{1/2} = \frac{4\pi e^2 n_e}{m} \left[ \frac{1}{\left( 1 + 3.1 \frac{I}{I_r} \right)^{1/2}} \right] \quad (9)$$

where the relativistic threshold intensity is

$$I_r = \frac{3m^2 \omega_L^2 c^3}{8\pi e^2}, \quad (10)$$

where  $\omega_L$  is the angular frequency of the laser. Similarly, the cut-off density becomes

$$n_{ec} = \frac{\omega^2 m}{4\pi e^2} \left( 1 + 3.1 \frac{I}{I_r} \right). \quad (11)$$

Under these conditions, the laser can be focused to diameters less than 0.6 wavelengths.<sup>15</sup> The self-focusing stops when the plasma is depleted from the laser path.

As the beam propagates through the plasma, the wavefront deforms, leading to the self-focusing. From geometric considerations, the self-focusing length is<sup>15</sup>

$$L_{SF} = \left[ d_0 \left( \rho_0 + \frac{d_0}{4} \right) \right]^{\frac{1}{2}}, \quad (12)$$

where  $\rho_0$  and  $d_0$  are the geometric triangular projection and initial beam diameter respectively. The ratio of the self-focusing length to the initial beam diameter is

$$\frac{L_{SF}}{d_0} = 0.5 \left[ \frac{n(I_{max}) + n(I_{max}/2)}{n(I_{max}) - n(I_{max}/2)} \right]^{\frac{1}{2}}, \quad (13)$$

where the index of refraction varies with intensity for collisionless plasmas as

$$n(I) = \left( 1 - \frac{\omega_p^2(I)}{\omega_L^2} \right)^{\frac{1}{2}}. \quad (14)$$

Figures 2 and 3 compare the ratios of self-focusing length to initial beam diameter for various plasma densities and laser intensities for a 1  $\mu\text{m}$  and 10  $\mu\text{m}$  laser wavelength respectively. Note that for low plasma densities, the self-focusing lengths are quite long. This may be advantageous in designing a thruster.

In addition to forces on the plasma generated by self-focusing, intense laser pulses can introduce parametric instabilities that will also couple the laser energy into the plasma or scatter it. Inherent variations in the plasma density (in addition to those introduced by the laser itself) as well as variations in the local intensity within the laser spot induce instabilities. If the laser frequency is greater than the plasma frequency,  $F_{NL}$  moves ions from regions of higher to lower density. In the same sense, the laser can amplify ion acoustic waves. This is the parametric decay instability and results in both ion and electron waves which will propagate so that their pointing vectors sum to the laser's. If  $\omega_L \gg \omega_p$ , the parametric backscattering instability will occur. In this case an ion wave (stimulated Brillouin scattering) or electron wave (stimulated Raman scattering) will be generated along with a light wave moving in the opposite direction. If the laser frequency is less than the plasma frequency, the ponderomotive force,  $F_{NL}$ , will drive electrons from regions of low density to high density. The plasma density will increase in a pulse train following the laser pulse. This is the mechanism that typically drives wave-field accelerators when  $\omega_L \approx \omega_p$ . In the special case of  $\omega_L \approx 2\omega_p$ , the laser couples into plasma via two electron plasma waves. Lastly, independent of the plasma density, variations in the local intensity of the laser can "filament" the beam in what amounts to localized self-focusing.

Each of these instabilities can introduce significant loss mechanisms for plasma acceleration. Most of these can be avoided under the condition  $\omega_L \gg \omega_p$ . As stimulated Raman scattering cannot occur above  $\omega_L \approx 2\omega_p$ , this condition can be written quantitatively as  $\omega_L > 2\omega_p$ . In principle, ion acoustic waves could prove an effective means of coupling the laser power into plasma acceleration via Landau damping. This will be explored in greater detail below.

Another instability/loss is self-field ionization associated with the extremely high electric fields present as the tightly focused laser propagates through the plasma. Multiple-ionization of atoms by high-intensity beams occurs via tunneling and barrier suppression.<sup>16</sup> Experimental wake field data indicates that large atoms are multiply ionized, but not extensively so (a few electrons are removed inversely proportional to their ionization potentials).<sup>17</sup>

Indeed, there is some question whether a pre-ionized target gas is desirable. Inverse bremsstrahlung will couple the laser directly into electron thermal motion. This technique has been proposed to couple high-power lasers into fluid flows for enthalpy enhancement of the flow.<sup>18</sup>

The degree to which each of the instabilities is present depends on the intensity, wavelength and beam quality of the laser pulse and on the plasma composition, gradient lengths, and other plasma conditions. The characteristic transverse length,  $L$ , of the plasma has been correlated with experiment to provide a guide as to the prevalence of various processes.<sup>15</sup> If  $L$  is small, i.e.

$$\frac{L}{\lambda_L} \leq O(10)$$

then most of the coupling processes, including stimulated Brillouin scattering, are below threshold. If  $L$  is large,

$$\frac{L}{\lambda_L} \geq O(100)$$

then Brillouin, Raman scattering, filamentation, and even inverse bremsstrahlung become significant.  $L$ , the size of the laser-irradiated plasma, can be estimated as the minimum of  $c\tau/2$  or the focal spot radius (or characteristic dimension), where  $c$  is a typical plasma expansion velocity (ion sound speed) and  $\tau$  is the pulse length of the laser. Thus, one constraint placed on the design of an LDPP thruster is

$$\frac{L}{\lambda_L} \sim \frac{\min[c\tau, R(\mu\text{m})]}{\lambda_L(\mu\text{m})}. \quad (15)$$

As the laser pulse propagates from vacuum through the plasma, it will likely encounter significant density gradients. At the same time, it will likely be spatially expanding or collapsing. It is possible that the instabilities which will be avoided in the main chamber could become significant in these transition regions. This is of particular concern not so much as a performance loss of beam energy as it is as a source of rogue high-energy particles.

## B. Pulse Propagation

Vacuum transmission of the laser pulses does not present a concern unless the laser is located some distance from the thruster itself. As discussed below, this may be an attractive mission configuration. An ideal Gaussian beam, i.e. one launched in a perfectly flat plane, will diverge over long distances and the shape of the pulse will be transformed. The length over which a beam can be considered collimated, the confocal parameter,  $b$ , is

$$b = \frac{2\pi w_0^2}{\lambda}, \quad (16)$$

where  $w_0$  is the diameter of the focus or of the beam at the emitting optic for a well-collimated beam. Beyond this distance, the beam will diverge linearly,<sup>19</sup>

$$w(z) = \frac{\lambda z}{\pi w_0}. \quad (17)$$

Thus, shorter wavelengths will provide better collimation and smaller spot sizes as will larger, less focused, beams.

Figure 4 compares the spot size of a 1  $\mu\text{m}$  wavelength beam as a function of initial beam diameter. In this sense, the confocal parameter is the collimated range of the beam. Note that the diffraction-limited collimated range for a 1 m diameter beam is 150 km. While this is adequate for transmission near a given body, it is significantly smaller than distances required for interplanetary missions. (Recall that the distance between earth and Mars varies from  $8.0 \cdot 10^7$  km to  $3.8 \cdot 10^8$  km.) A discussion of the implications of beam expansion will be discussed in the mission analysis below.

As a laser pulse traverses a plasma it is both attenuated and distorted by the above processes. After the pulse passes, electrons oscillate in and out of the pulse's wake. After several plasma periods,  $2\pi/\omega_p$ , the plasma is similar to its undisturbed state albeit with an increased electron temperature. If another laser pulse passes the same region before "equilibrium" is restored, a trough in the plasma is generated.

### III. □ Thruster Design

The detailed design of a laser-driven ponderomotive propulsion (LDPP) thruster is beyond the scope of this investigation. However, the general design, which incorporates the underlying physics and identifies critical design issues has been undertaken. This section presents the considerations and trades that were incorporated into a "thruster" which will support concept evaluation.

The vast majority of laser-plasma accelerators rely on 1) acceleration of the plasma in the direction of the laser propagation and 2) highly focused linear beams. This approach was explored for spacecraft propulsion in a previous investigation.<sup>20</sup> In this case, the laser was focused on a solid target and the propulsive acceleration was achieved by ponderomotive forces accelerating the "exploded" material downstream. This technique has as advantages the ability to achieve very high specific impulses ( $3.2 \cdot 10^6$  s) and almost perfect propellant utilization. However, it is severely limited to a beam area corresponding to the laser spot size and the constraint of a single pulse to generate and accelerate the plasma. Both result in a significant penalty in overall thruster efficiency—very high powers are required to generate significant thrust.

To overcome these two limitations, it is proposed to accelerate the plasma perpendicularly to a planar laser pulse. Analytic calculations have shown that a planar laser pulse in a plasma can produce the same lateral plasma acceleration as linear pulses which have been studied in the past. Figure 5 illustrates that increases in the wavelength of a driving laser can compensate for the decrease in intensity associated with the dispersion of the laser into a planar wave. However, there are two principal disadvantages to this approach. One is that the plasma will be accelerated bi-directionally. The other is that it is no longer practical to use a solid target.

A hybrid scheme which might lend itself to quasi-steady field generation is the resonator scheme shown in Fig. 6.<sup>14</sup> In this scheme a single pulse is introduced into the plasma in a manner analogous to the LWFA. As the pulse makes multiple passes, the wake-field amplitude grows to a standing wave if the resonator length is a multiple of the plasma wavelength. For a phase velocity of the plasma wave,  $v_p$ , and a thermal collision frequency,  $\nu_{ei}$ , the amplification factor is

$$\alpha = \frac{\nu_{ei}}{2v_p} \quad (18)$$

and the amplitude of the induced electric field will be  $E/\alpha L$ , where  $L$  is the cavity length and  $E$  is the field strength calculated from Eqs. 5 and 6.<sup>14</sup> If the beam in Fig. 6 is planar, then a field may be established in the plasma through which a large amount of plasma may be accelerated. Note that a well-focused planar wave will result in only a minor degradation in local intensity.

The simple, open resonator is nominally preferred as it minimizes beam-optics interactions which introduce losses in the beam. However, there are several advantages to the ring resonator. One is that the pulse enters the plasma in its least perturbed state. Another, related to the first, is that the path length of the resonator can be tailored to accommodate the relaxation time of the plasma to the primary pulse. The third advantage is that the pulse existing in the plasma will be reduced and potentially distorted due to its interaction with the plasma. While interaction with optics is to be minimized, the ring resonator might be tailored to "reform" the pulse to an optimal condition. It is also possible that the resonator could be configured to slightly "walk" the beam through the plasma in such a way as to minimize the pulse-to-pulse perturbation. However, quantifying these possibilities is beyond the scope of this investigation. Given the multiple possibilities, this investigation concentrates on the overall feasibility and benefit of the concept and assumes the pulses can be introduced into the plasma in a reasonable manner.

An issue common to both resonator configurations is the problem of the initial introduction of the pulse into the resonator. Unlike typical ring cavity lasers, the "light source" in this case is not generated by a separate pulse. In principle, the pulse could be coupled into the resonator and maintained therein by varying the polarization of the beam. This introduces additional beam losses unless this can be incorporated by the reflecting optics themselves. It is not clear if this can be done for such high-intensity laser pulses. More elaborate designs of the resonator mirrors

which rely on non-uniform beam shapes may also solve this issue. The ability to focus the beam to sub-diffraction-limited spot sizes would likely be prohibited by this approach, however. The best approach may simply be to introduce the first pulse off the axis of the resonator and allow the resonator optics to couple it into the resonator. However this issue is eventually resolved, the ring resonator will likely be the easiest path to resolve it.

Note that the resonator configuration does not impact the degree to which plasma is accelerated along the line of the laser pulse. Each pulse will carry with it some degree of axial acceleration which must be countered. In principle, the degree of axial acceleration will be minimized by avoiding induced Brillouin scattering and plasma wave generation by properly maintaining the laser frequency far from the plasma frequency. In addition, coupling the beam over a relatively long length will result in “breaking” of the axially accelerated plasma which will quickly mitigate very high energy ion and electron motion.<sup>28</sup>

Gradients in plasma acceleration in the transverse direction of the plane (i.e. perpendicular to the laser pulse but in its plane) are mitigated.<sup>14</sup> However, the variation in laser intensity as it propagates across the plasma will introduce a gradient in the direction of the laser pulse. In this sense, the open resonator configuration would be better. However, this variation can be minimized by tailoring both the plasma density gradient and the degree to which the laser is coupled to the plasma per pulse. Note that there is no efficiency loss associated with a high number of resonator pulses through the plasma except those encountered with the steering and focusing optics.

Independent of resonator design, the bi-directionality of the acceleration remains the single greatest issue. If the plasma is exposed to vacuum in both directions, this will exactly nullify the thrust produced. If enclosed except in the direction of thrust, as a typical thruster would be, the high-energy plasma ejected in the upstream direction would either destroy the upstream enclosure or, if this were avoided, represent a fifty percent efficiency hit. Therefore, not only must the plasma accelerated upstream not be allowed to hit the upstream surface, it must be converted into thrust. Since the plasma is accelerated in bulk as a result of an effective pressure rather than via wave coupling, using density gradients to reflect the wave so that the momentum will be coupled in a single direction is not possible. Previous advanced propulsion techniques which suffered from this same issue have proposed reflecting the plasma with a very strong magnetic field.<sup>21</sup> It is not clear that this can be achieved without a significant power loss via superconducting magnets.

Perhaps the best way to achieve mono-directional acceleration is to guide the accelerated plasma rather than reflecting it. In this regard, a strong magnetic field would redirect the accelerated plasma gradually over a length tailored to the geometry of the thruster and the energies of the accelerated ions. A significant variation in ion energy in the pulse direction would complicate this, another reason to design for a large number of resonator passes. Figure 7 provides a schematic of the proposed thruster configuration. At this stage, the relative dimensions are for illustrative purposes only. The following section will quantify many of them for some applications. However, first, some consideration must be given to the propellant.

In principle, any propellant can be used with this proposed propulsion system. The laser will ionize to some degree atomic or molecular species and dissociate the latter as well. A trade study indicated that readily-ionized heavier ions enabled higher thrust to power ratios. In addition to the expected decrease in specific impulse, there is also an increase in efficiency due to an increase in charge state with minimal loss to the ionization itself. This is consistent with laboratory studies with different inert gas and hydrogen accelerants.<sup>13</sup> While xenon indicated superior performance, krypton was selected as the nominal propellant for the following performance characterizations. Its abundance and relative ease in handling make it a benign choice. In the end, mission requirements will establish the mass and trip time requirements which will result in a trade study to determine the propellant. A separate question to be considered at this point is whether the confinement of the propellant in the proposed thruster configuration require it to be pre-ionized. Ideally, the propellant would be limited to the region of interrogation of the laser and the density would vary inversely with the laser intensity to facilitate relatively uniform thrust. While a fully ionized plasma could be configured to exactly meet these requirements, the magnetic field required to do so would likely be prohibitively intrusive. A neutral gas (or liquid) jet could be configured to meet the volumetric requirement, but it would result in significant gradients and even more significant issues regarding propellant recirculation. The best approach appears to be to have a pre-ionized gas which could be generated via rf source and maintained via a relatively weak magnetic field. This is a configuration comparable to existing rf-ion thrusters used for spacecraft propulsion. The details of this configuration are left to the next phase of thruster design.

#### IV. □ Performance Model

In order to evaluate the impact of a ponderomotive propulsion system on mission architectures, a conceptual model of a thruster was incorporated with the plasma model. A uniform plasma is assumed to be magnetically confined such that the laser plane passes through it and that five percent of the particles are lost to space at a uniform rate. (The latter reflects the presence of neutrals or imperfect confinement. For example  $5 \cdot 10^{16}$  particles will be lost per  $\text{cm}^3$  for a plasma with a density of  $1 \cdot 10^{18} \text{ cm}^{-3}$ .) A power source is assumed which can arbitrarily couple 10 MW into one or more laser pulses per second. The intensity of the laser pulse was assumed to be constant for each pass in the resonator and was determined by pulse duration, focal width, and total power in the pulse. The last was decreased per pulse by an absorption coefficient which was a function of laser intensity, plasma density, and degree of resonance between the laser and plasma frequencies. Once coupled into the plasma, each pass results in a wave of particles which will have less total energy than that from the previous pass. The thrust of the rocket is calculated by integrating the total efflux of particles over the duration the pulse resonates in the cavity (from a picosecond to several nanoseconds). The specific impulse of the rocket takes into account the five percent loss over a full second before the next laser pulse. Ten percent of the laser power is assumed to be lost to the mirrors, to ionization, or to thermalization of the plasma which does not result in useful thrust.

The dimensions of the acceleration region is arbitrary. Typical characteristic lengths of fusion and previous propulsion concepts which incorporate ponderomotive acceleration are on the order of a few wavelengths. In theory, that same dimension could be incorporated in this initial design, but that fails to take advantage of the planar characteristic which we wish to exploit. Indeed, the advantage is primarily in the minimizing of the dimension in which the beam is flattened. For this investigation, a thruster with cross-sectional dimensions in cm is selected: nominally 20 cm wide and 5 cm high. This still very small in terms of MW space propulsion, but huge in comparison to typical ponderomotive active areas (including those associated with propulsion):  $10^{-2} \text{ m}^2$  versus  $8 \cdot 10^9 \text{ m}^2$ . A minimum beam waist of  $0.5\lambda$  for the laser is assumed. The initial focus size of the beam (i.e. at the beginning of its pass through the plasma is assumed to be  $1.5\lambda$ ). A working length of 20 cm requires an  $L_{\text{SF}}/d_0$  on the order of 4000 for a  $50 \text{ }\mu\text{m}$  initial beam waist. This restricts the plasma density to below  $10^{16} \text{ cm}^{-3}$  for a  $100 \text{ }\mu\text{m}$  laser. In terms of propellant efficiency, beam uniformity, and discharge efficiency, lower plasma density is better.

Figure 8 shows the calculated thrust for a 10 MW ponderomotive rocket as a function of specific impulse. As the specific impulse approaches  $10^7 \text{ s}$ , the ions become relativistic. Energy is then coupled into the “mass” of the propellant as well as the velocity yielding higher thrust to specific impulse ratios than would be expected classically. The input power is assumed to be constant across this range of specific impulses. The laser wavelength and pulse characteristics, plasma density and volume, and initial intensity are varied to achieve 90 percent beam absorption in a manner consistent with the constraints discussed above. However, over a segment of the range, e.g.  $10^4 \text{ s}$  to  $10^5 \text{ s}$ , only the plasma density and laser pulse characteristics need to vary. The plasma density is readily controlled. The laser intensity can be varied by changing its focal diameter via active optics. In the ring resonator design, this might be accomplished by modifying the ring geometry. Therefore, a significant range in specific impulse would be available for a given thruster/laser configuration.

To better illustrate the acceleration process, two example cases are presented. These are summarized in Table 1. The first is a  $10^7 \text{ s}$  specific impulse case that emphasizes the high-energy which can be imparted to the ions. It is representative of the vast majority of cases modeled. Figure 9 shows the evolution in average beam ion energy per pass of the laser pulse through the plasma. The absorption of the laser power as a function of distance through the plasma is taken from empirical data.<sup>14</sup> It is proportional to the local plasma density, the laser intensity, and the ratio of the plasma and laser frequencies. The intensity is selected to generate ions in a particular energy range. The density is then selected to ensure large self-focusing lengths. The laser frequency is generally a compromise between coupling length and divergence. However, for this particular case, a visible wavelength was selected based almost entirely on focusing requirements—it enables a much tighter focus and therefore intensity. The density was forced low enough to facilitate the coupling at the expense of a large number of passes. The fidelity of the model does not allow for evaluation of whether this trade is reasonable in terms of laser-optics losses.

The second case illustrates the concept’s ability to efficiently generate relatively low specific impulse. To achieve the low laser intensities necessary ( $\sim 10^{16} \text{ W/cm}^2$ ) for a specific impulse of  $7000 \text{ s}$ , the beam spot can be increased, the pulse duration can be extended, and/or the power per pulse can be reduced. The laser interrogation volume can most readily be expanded by increasing the cross-section of the planar beam. Thus, the beam remains tightly focused, but the power is more distributed. In addition, increasing the repetition rate of the laser so that the power per pulse is reduced significantly reduces the laser intensity. Figure 10 shows the variation in ion energy in a LDPP thruster over a single laser pulse. 10 MW is maintained for a laser pulse rate 100 Hz. The trend in Fig. 10 is



repeated 100 times per second as opposed to once as in the previous case. Because the total duration of the “laser-on” time is still a very small fraction of the “plasma-on” time, there is no change in propellant loss rate. Generally changing the switching frequency of a laser is not as complicated as changing the focal spot size, so this may be the most attractive means of throttling a given engine over a very large range of specific impulses for a given total power.

#### V. □ Mission Implications

Table 2 provides nominal specific impulse requirements for a variety of missions.<sup>22</sup> This section assesses the potential impact the LDPP system could have given these general guidelines. The potential to efficiently achieve very high specific impulses suggests that it might be geared for interstellar or interstellar type missions. This will be discussed followed by a discussion of planetary applications.

High-power solid state lasers with efficiencies greater than 50 percent are reasonable expectations in the coming decades.<sup>23</sup> This is of particular importance if the laser is part of the spacecraft. As discussed below, the enabling capability of LDPP is primarily realized when the laser is decoupled from the spacecraft and is part of a power delivery system which is either on a separate, relatively stationary craft or base. If the laser is incorporated along with the power supply on a single spacecraft, the power conversion efficiency will also be at best 50% in the near future and this will likely make the LDPP system prohibitively massive except for a dedicated mission for which it is uniquely enabling. Such a mission has not yet been identified.

As shown in the high-energy example above, very high, relativistic, plasma acceleration is possible. Thrust density and thruster efficiency are much higher than most alternative concepts such as light sails or other laser-driven propulsion.<sup>1</sup> Mass estimates are based on a survey of recent literature and reflect near-term and long-term potential developments in reactor technology. For this case, the trip time is on the order of few hundred years. This is an improvement over other systems, but not a revolutionary one. It does, however, enter conventional nuclear power into the mix for these types of missions.

One path that might be open to the interstellar regime is to emphasize the relativistic speeds of the propellant. Increasing the intensity of the laser will couple more energy into the relativistic mass of the propellant so that the travel time might be significantly reduced. In addition to using light (H) propellant (potentially in situ), there exists the possibility of decoupling the nuclear power supply from the spacecraft. In this respect, the propulsion system would become a hybrid of a laser sail and what might otherwise amount to a sophisticated nuclear electric rocket. Several issues do arise in this configuration. First, correcting the bi-directionality of the accelerated plasma in the thruster itself will be problematic for relativistic plasma beams. Second, the size of the laser collector/emitter might be on the order of kilometers. Third, pointing stability over the vast distances might prove prohibitive. However, if these were overcome, the capability of the system might be attractive.

The same configuration could be explored for interstellar-precursor class missions. The principal advantage of this type of mission over a true interstellar mission is that there is no need to decelerate the craft once on station.<sup>2</sup> If the laser power is decoupled from the craft, very rapid transits (years) are possible. It should be noted at this point that decoupling the power supply from the spacecraft by power beaming or even direct laser coupling is not a new concept.<sup>24</sup> Laser power delivery to wavelength optimized “solar” panels has the promise of very-high efficiency power transfer (~0.8).<sup>25</sup> Coupled with electric propulsion, this could be a very promising propulsion architecture and much of what is said below about interplanetary applications of the LDPP could be undertaken by that configuration. However, the LDPP retains some significant advantages including no independent limit on laser power density which will significantly reduce spacecraft mass for high powers and the ability to directly convert the beam power into thrust. It remains to be seen if the laser handling and beam steering hardware on the LDPP spacecraft is in fact less massive than the power conversion and processing hardware on the conventional craft.

In terms of interplanetary and near-earth missions, the LDPP concept does not offer advantages over other systems if the power supply is not decoupled. It would essentially be a complex nuclear electric propulsion system. While it might have a significantly broader range in specific impulse for a given engine, it is not clear if that would be of any value for so massive a craft. Indeed, the LDPP is likely inherently heavier and more complex than an electric propulsion device. However, there are several advantages to an LDPP system with a decoupled power supply over an NEP explorer.

For example, consider a mission to explore the Jovian moons as typified by the recent Prometheus I mission.<sup>26</sup> An NEP craft could perform this mission;<sup>27</sup> however, it is significantly limited by the necessity to relatively rapidly transit through regions of the Jovian magnetosphere which would subject the craft to very strong radiation. By

decoupling the power supply (and its shielding and thermal management system) from the spacecraft and using beamed power, the spacecraft could complete these transits in less than 20 % of the time.

There are several potential configurations for separating the spacecraft from the laser source. One of these would be to have the laser on board a platform that was itself in transit to Jupiter. Power could be divided between its own propulsion system and power delivered to the exploring craft. This would minimize pointing uncertainties and allow significant flexibility in how the mission might unfold once the exploring craft were on station. (Because of their significantly lighter mass, they would likely arrive years before the power platform itself, but they would have access to the beamed power throughout their flight.) Indeed, a single power platform could enable several exploring craft. This is especially true once the latter are in orbit about moons with time of occulting used to power other craft.

The same general principle can be applied to Earth-Mars transfer. The power platform could be placed in orbit between Earth and Mars and used to power craft from one to the other. As an example, a 100 MW laser could enable a 30 day transit from low earth orbit to low Mars orbit with a 7mT payload. This is a significant advancement over any propulsion system dedicated to a single craft.

## VI. □ Conclusion

Plasma acceleration by means of ponderomotive forces introduced in the wake of laser pulses appears to offer significant potential for spacecraft propulsion. Specific impulses greater than 1 Ms are possible using these schemes. This is a three order of magnitude increase over current electric propulsion capabilities. Laser efficiencies have increased significantly in the last ten years and further increases are expected.<sup>28</sup> Coupled with increases in specific power resulting principally from the use of beamed power to decouple the mass of the power supply and the laser itself, the ponderomotive propulsion system might revolutionize space travel by providing high-power high-specific impulse capabilities in excess of projected evolution of electric propulsion capabilities.

Missions enabled by the potentially huge performance enhancements include interplanetary and interstellar precursor type missions. For interplanetary missions, specific impulses comparable to existing electric propulsion capabilities (~ 5000 s) may be most consistent with the evolution in nuclear space power. Thus lower field strengths generated in high-density plasmas which can be achieved through proper beam conditioning (improper in the context of particle accelerators!) may be optimal. The most attractive means of achieving lower specific impulses is to increase the repetition rate of the laser and thereby decrease the energy per pulse without decreasing overall efficiency of the power conversion.

Despite this promising potential, several issues remain to be resolved:

- Efficient, lightweight steering of the accelerated plasma is required. This is most problematic for relativistic acceleration of the plasma, but is also a concern even for relatively low energies.
- The plasma wake of the pulses through the plasma may not have time to dampen to a relatively quiescent state. The technique makes use of a resonator scheme to efficiency couple the laser power into propulsive force via many passes of a laser pulse through the plasma. If the plasma is significantly out of equilibrium, the onset of other modes of laser coupling will ensue and the thruster will not perform well. The object-oriented particle-in-cell (OOPIC) code has been used in the past to model plasma and laser wake fields.<sup>29,30</sup> OOPIC modeling will be incorporated in future stages of this analysis to provide a higher degree of confidence in particular trends identified through the more basic calculations. In particular, OOPIC would address the temporal evolution of the plasma in the wakefield. OOPIC is not optimal for LWFA calculations and will be replaced by more sophisticated codes developed to support LWFA (e.g. VORPAL or QUICKPIC<sup>31</sup>) if the Phase 1 results are sufficiently promising.
- Even if the plasma returns to a quiescent state, the various modes of laser coupling must be handled in greater detail. Especially in boundary regions, the introduction of other modes could preclude efficient or long duration operation.
- Detailed mission analysis is required to quantify the benefits of having a laser-based power delivery system in space to assist exploration. While it is clear that such a system could revolutionize the nature of exploration, it is not clear that it is cost effective or realizable in the near term.

Finally, a more detailed modeling of the pulse coupling to the plasma is merited. The self-focusing, especially in the relativistic limits, requires a detailed modeling which was beyond the scope of this investigation.

## Acknowledgment

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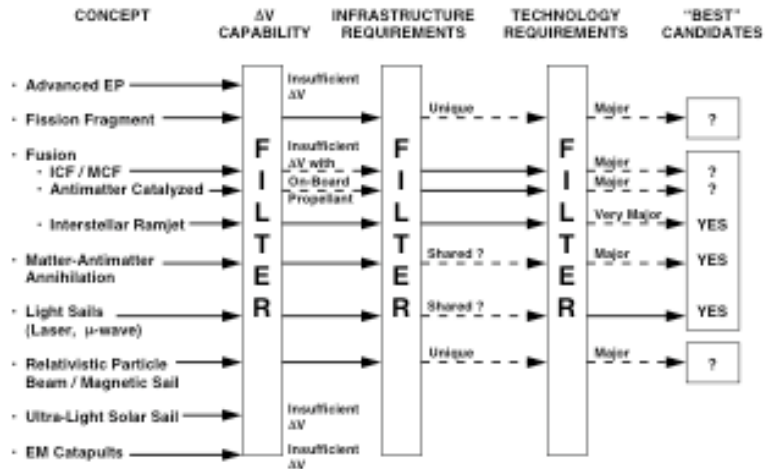
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**Table 1 Details of illustrative cases**

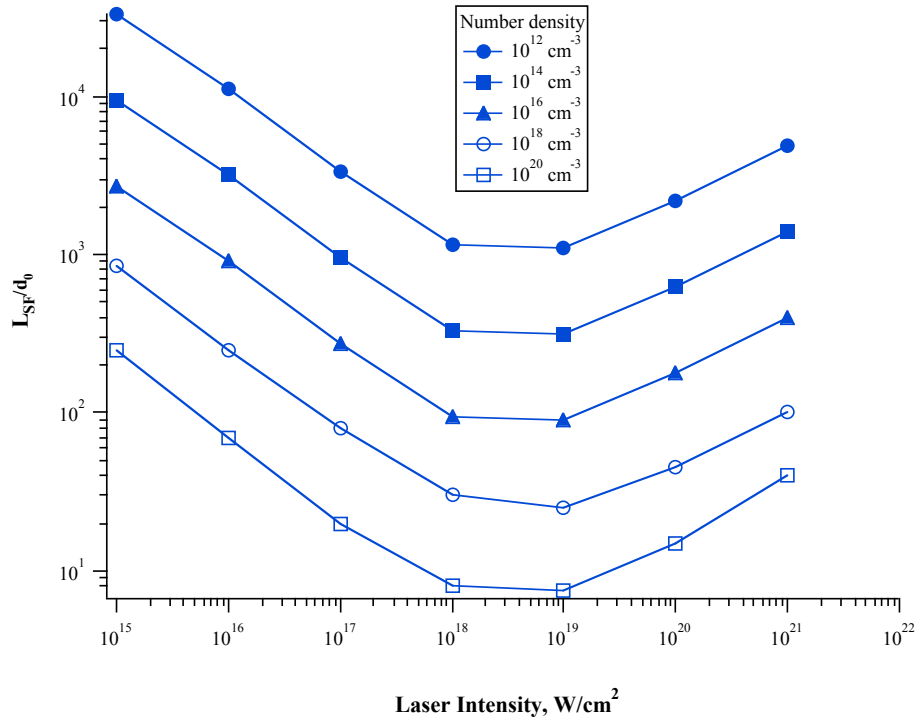
	Configuration 1	Configuration 2
Input Power, MW	10	10
Specific Impulse, s	10,000,000	7000
Thrust, N	1.0	400
Peak laser intensity, W	$6.0 \cdot 10^{25}$	$1.0 \cdot 10^{17}$
Laser pulse length, ps	0.1	1.0
Pulse rate, Hz	1.0	100
Initial planar focal width, $\mu\text{m}$	0.25	100
Chamber length, m	0.2	0.5
Chamber width, m	0.001	0.5
Propellant	Kr	Xe
Propellant density, $\text{cm}^{-3}$	$1.0 \cdot 10^{14}$	$5.0 \cdot 10^{16}$
Power coupling efficiency	0.93	0.90

**Table 2 Specific impulse requirements for various missions.**

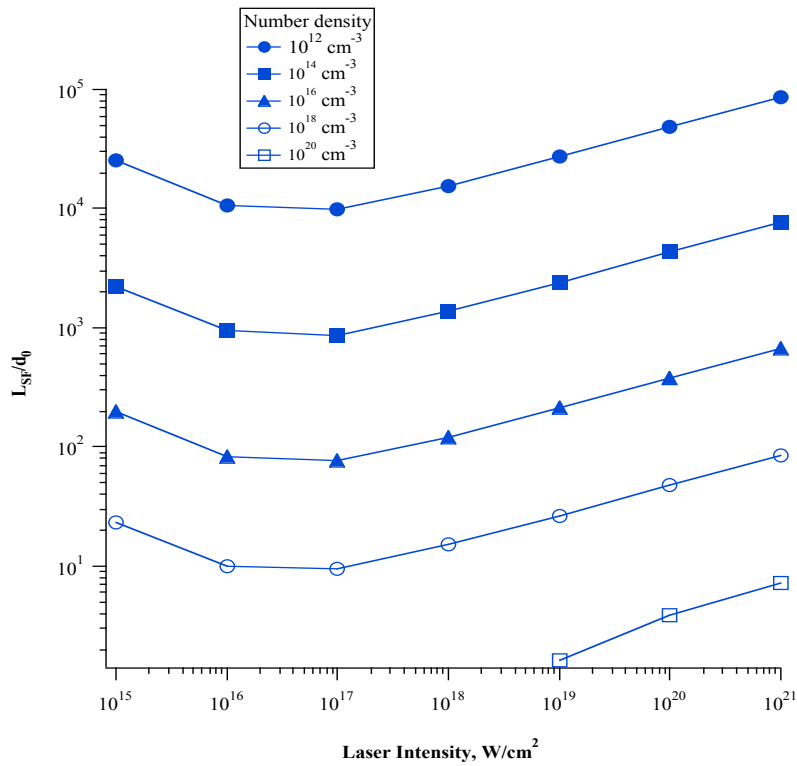
Mission	$\Delta v$ , km/s	$I_{sp}$ , s	Level of current capability
<b>Interstellar</b>	$10^4$	$>10^6$	None
<b>10000 AU</b>	$10^3$	$10^5$	None
<b>100-1000 AU</b>	$10^2$	$10^4$	Poor
<b>Outer planets</b>	$10^1$	$10^3$	Moderate
<b>Inner planets</b>	$10^0$	$10^3$	High



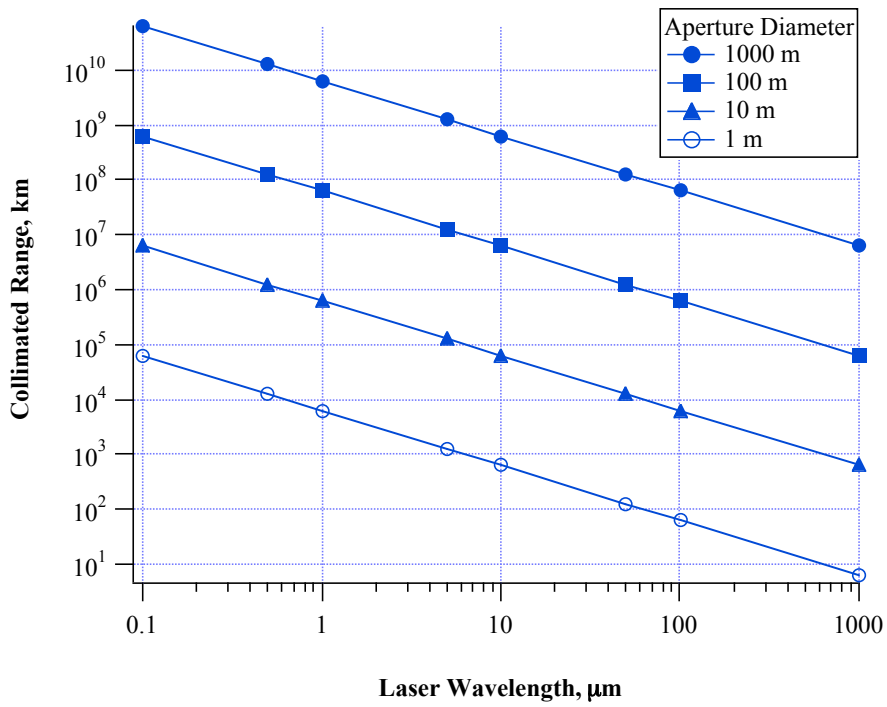
**Figure 1 Interstellar rendezvous mission propulsion option screening process.<sup>1</sup>**



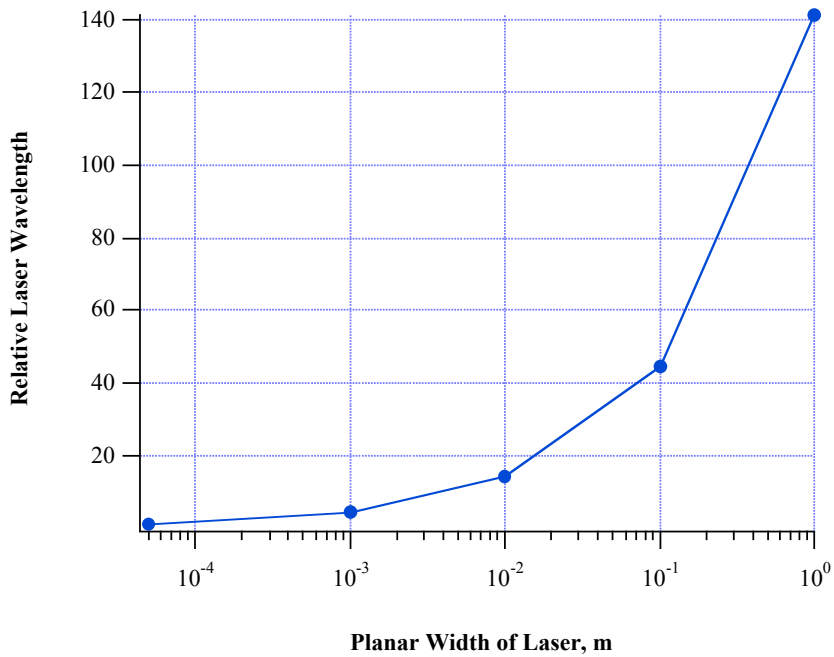
**Figure 2** The ratio of the self-field length to initial beam diameter for a 1 μm laser.



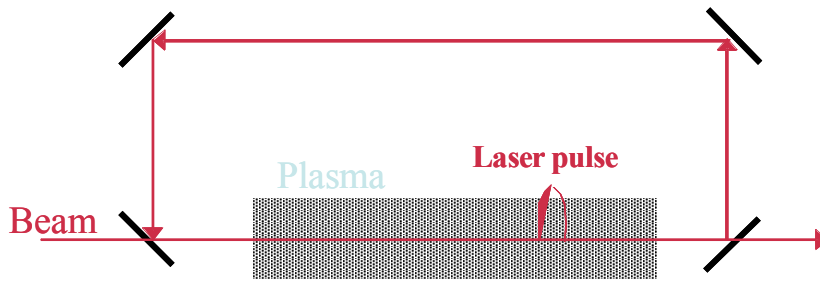
**Figure 3** The ratio of the self-field length to initial beam diameter for a 10 μm laser.



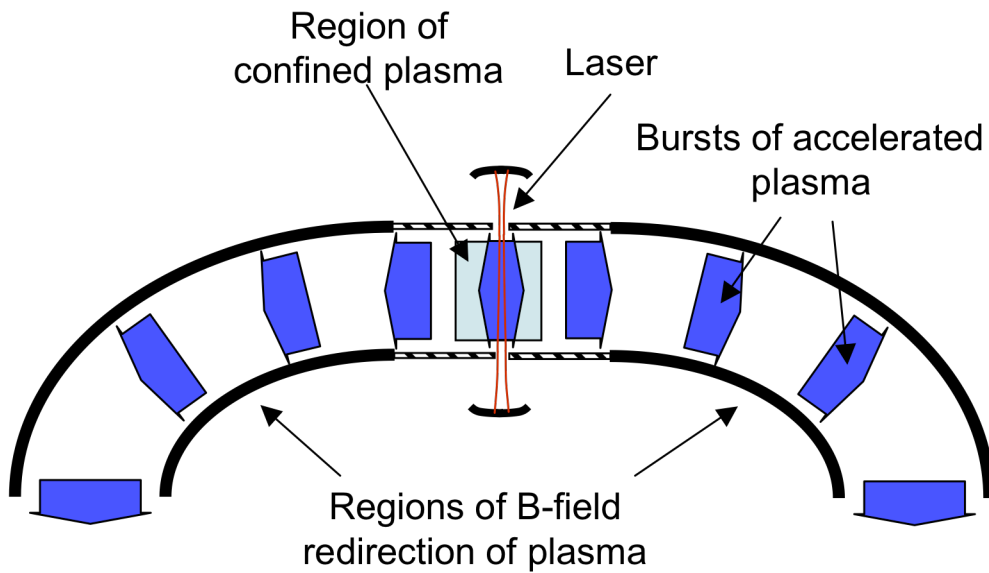
**Figure 4 Increase in laser wavelength required to maintain the same electric field as the planar width of the laser beam is increased.**



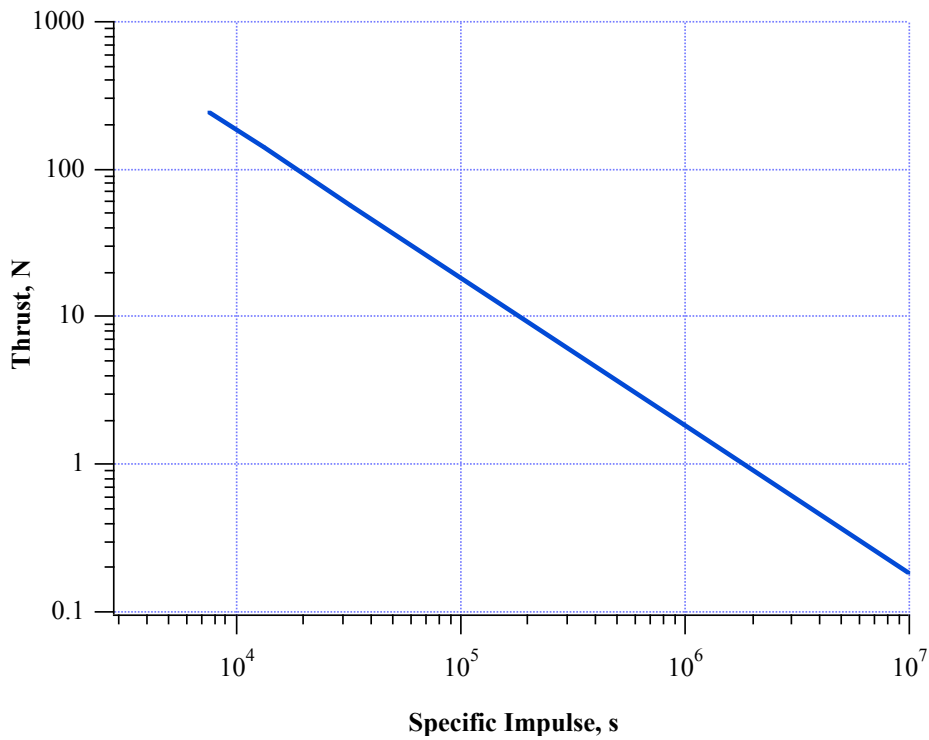
**Figure 5 Increase in laser wavelength required to maintain the same electric field as the planar width of the laser beam is increased.**



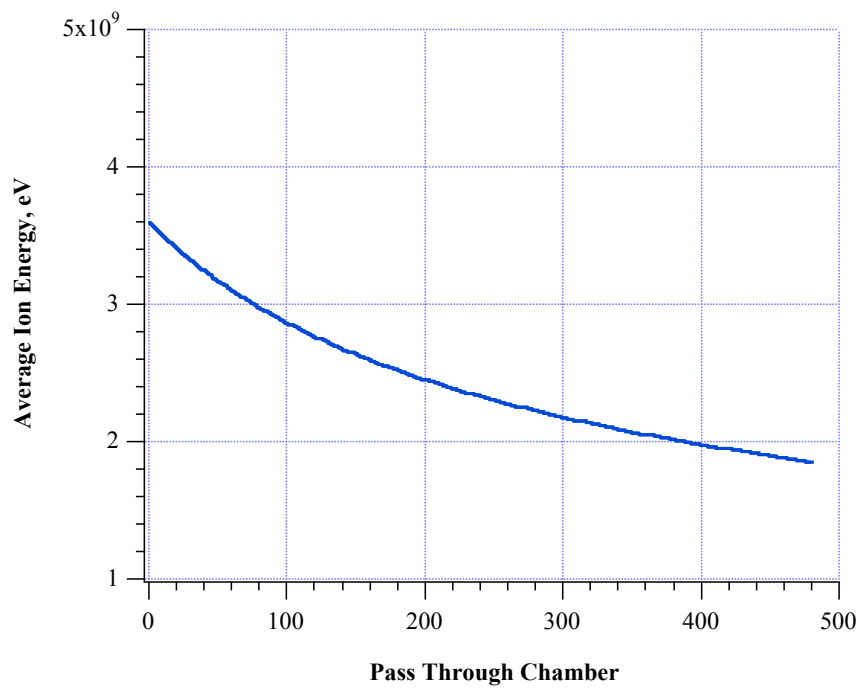
**Figure 6 Schematic of ring cavity for coupling laser power into the plasma.**



**Figure 7 Schematic of the LDPP thruster.**



**Figure 8 Thrust as a function of specific impulse for a 10 MW system.**



**Figure 9 Average ion energy as a function of pass number for a resonator configuration that yields a specific impulse of  $10^7$  s.**



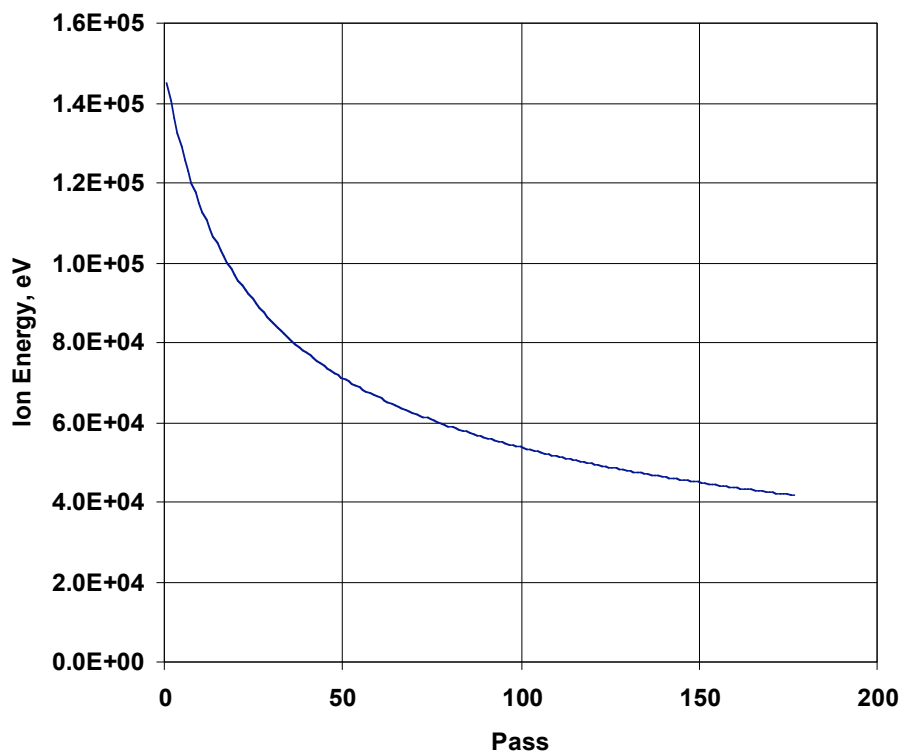


Figure 10 Average ion energy as a function of pass number for a resonator configuration that yields a specific impulse of  $7 \cdot 10^3$  s.