Ultra-Fast Laser-Driven Plasma for Space Propulsion

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Demonstrating a technique that may lead to advances in certain forms of radiation therapy and electronics manufacturing, Livermore’s Petawatt, the world’s most powerful laser, impinges upon a target to generate 30 trillion protons from a tiny spot only 400 microns in size. Two other research groups, in Michigan and the United Kingdom, have demonstrated this technique with smaller-scale lasers.
Presentation Outline

1. Ultrafast lasers and charged particle acceleration
2. Underlying physics
3. Progress in Ultrafast laser research
4. Recent experimental results
5. The LAPPs propulsion concept
6. Phase II objectives
7. Accomplishments thus far
8. Nuclear Reactors for LAPPs
9. Conclusions and Future Investigations
– Recent Experiments at The University of Michigan and elsewhere have shown that Ultra-short Pulse [Ultrafast] Lasers can accelerate charged particles to relativistic speeds

– They have accelerated electrons and protons to more than 1 MeV

– They have accelerated Deuterons (in clusters) for Fusion Applications and for Nuclear Activation Applications such as $^8\text{B}^{10}(d,n)^{\text{C}}^{11}$. Also induced photon fission such as $^{197}\text{Au}^{\gamma,n}\text{Au}^{196}$

– Expect to accelerate protons to rest mass energies, i.e. to $v=0.866c$

Which would translate to $\text{Isp}=10^7 \text{ s}$
Ultra-High-Intensity Laser Labs

Circa 1988

Circa 2000
A ultrashort laser pulse with only 1 Joule of energy can accelerate an electron to an MeV in just a few microns.

\[
\frac{\text{energy}}{\text{time}} = \text{power}
\]

\[
\frac{1 \text{ joule}}{\text{sec}} = 1 \text{ watt}
\]

\[
\frac{1 \text{ joule}}{\text{picosecond}} = 1 \text{ terawatt}
\]

\[
\frac{\text{power}}{\text{area}} = \text{intensity}
\]

\[
\frac{1 \text{ terawatt}}{(10 \text{ micron})^2} = 10^{18} \text{ watt/cm}^2
\]

\[
\text{electric field (V/cm)} = (\text{intensity})^{1/2}
\]

\[
(10^9 \text{ V/cm}) \times (10 \text{ microns}) = 1 \text{ megavolt}
\]
Relativistic Electron Motion

\[ \mathbf{k} = k \hat{z}, \quad \mathbf{E} = E_0 \cos(kx - \omega t) \hat{x}, \quad \mathbf{B} = B_0 \cos(kx - \omega t) \hat{y} \]

\[ \frac{d \mathbf{p}}{dt} = \frac{d (\gamma m_0 \mathbf{v})}{dt} = q \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right), \]

\[ \gamma_\perp = \left( 1 - \left( \frac{v_\perp}{c} \right)^2 \right)^{-1/2} = \left( 1 + a_0^2 / 2 \right)^{1/2} \]

\[ a_0 = \frac{eA}{m_0 c^2} \]

\[ = 0.85 \times 10^{-9} \sqrt{I \left( \text{W/cm}^2 \right) \lambda (\mu \text{m})}. \]
Experimental Confirmation

A Beam of MeV Protons

- $a_0 = 3.0$
- Cone angle = 40°
- Always normal to the target
- Front side origin
- $2\pi$ mm-mrad
- $E \sim 10$ GeV/cm
- $N > 10^{10}$ p
- $J = 10^8$ A/cm$^2$

Mechanism for proton acceleration

Ion acquire an electrostatic energy:
\[ \varepsilon_i \approx Z e \phi \approx Z \varepsilon_e \]

Solving equation for energy balance and Coulomb energy we can estimate:

characteristic electron density
\[ n_e \approx n_c \left( a / 2\pi \right) \sqrt{\eta 2\lambda / R} \]

and electron energy
\[ \varepsilon_e \approx \pi a m c^2 \sqrt{\eta R / 2\lambda} \]

Then characteristic ion energy is
\[ \varepsilon_i \geq Z \sqrt{\eta IR\lambda} \]
## Comparison of Recent Results

<table>
<thead>
<tr>
<th>Institute</th>
<th>Energy (MeV)</th>
<th>Yield (W/cm², J, ps)</th>
<th>Laser (W/cm², J, ps)</th>
<th>Target</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>U of Michigan</td>
<td>1</td>
<td>10⁸</td>
<td>3 × 10¹⁸, 4</td>
<td>0.4</td>
<td>He</td>
</tr>
<tr>
<td>Rutherford</td>
<td>6</td>
<td></td>
<td></td>
<td>Ne</td>
<td>PRL 83 737 (1999)</td>
</tr>
<tr>
<td>Rutherford</td>
<td>20</td>
<td>10¹²</td>
<td>5 × 10¹⁹, 50</td>
<td>1.0</td>
<td>Al</td>
</tr>
<tr>
<td></td>
<td>420</td>
<td></td>
<td></td>
<td>Pb</td>
<td>PRL 85, 1654 (2000)</td>
</tr>
<tr>
<td>U of Michigan</td>
<td>1.5 (2ω)</td>
<td>10¹⁰</td>
<td>3 × 10¹⁸, 1</td>
<td>0.4</td>
<td>Al</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10¹⁰</td>
<td>6 × 10¹⁸, 4</td>
<td>0.4</td>
<td>CD</td>
</tr>
<tr>
<td>LLNL petawatt</td>
<td>50</td>
<td>10¹⁰</td>
<td>1 × 10²⁰, 60</td>
<td>0.4</td>
<td>CH &amp; Au</td>
</tr>
<tr>
<td>LLNL JanUsp</td>
<td>20</td>
<td></td>
<td>1 × 10²¹, 5</td>
<td>0.05</td>
<td>APS-DPP (2000)</td>
</tr>
</tbody>
</table>
- **Relativistic Self-Focusing**

For a focused laser beam with higher intensity on axis and lower intensity off axis in a plasma, the *Index of Refraction*, \( n \)

\[
n = \sqrt{1 - \frac{w_P^2(\gamma)}{w_0^2}} = \sqrt{1 - \frac{w_{P0}^2}{\gamma w_0^2}}
\]

Where \( w_{P0} = \frac{4\pi n_e e^2}{m_e} \) = plasma frequency

\( \omega_0 \) = Laser Frequency

Will be higher on axis and lower off axis and plasma acts like a “lens”. Hence what is known as “Relativistic Self-Focusing”

- **Ponderomotive Self-Channeling**

For a focused laser pulse with transverse laser *intensity gradient*, the transverse Ponderomotive force will push electrons outward and that results in a depression in electron density on axis. This makes *Index of Refraction*, \( n \), higher on axis and once again the plasma acts like a positive lense and leads to self-focusing of the laser pulse. This is referred to as “Ponderomotive Self-Channeling”
Relativistic Mass Shift Affects Light Propagation in Plasma

Plasma frequency: \( \omega_p = \sqrt{\frac{4\pi n_e e^2}{m_0}} \)

Index of refraction for light waves: \( \eta \approx \sqrt{1 - \frac{\omega_p^2}{\gamma \omega_0^2}} \approx 1 + \frac{1}{2} \frac{\omega_p^2 \langle a^2 \rangle}{\omega_0^2} \)

\( \Rightarrow \) Phase velocity, \( v_\phi = c\eta^{-1} \propto I \)

Relativistic self-focusing:

\( P_c = 17 \left( \frac{\omega_0^2}{\omega_p^2} \right) \text{ GW} \)
Experimental Evidence of Relativistic Self-Guiding

Axial-imaging

Side-imaging of Thomson scattered light

Exit Gas Jet Entrance

2.5 TW
2.0 TW
1.5 TW
1.0 TW ≈ P_c
0.5 TW

Maximum Proton Energy Scales Linearly with Laser Intensity

@ 1.053 μm

Maximum proton Energy (MeV)

Laser Intensity (W/cm²)
Scaling of maximum proton energy vs. laser intensity

When the laser intensity is higher than $10^{19}$ W/cm$^2$ the maximum proton energy grows as $I^{0.5}$.

LLNL: PRL 85, 2945 (2000)
RAL: PRL 84, 670 (2000)
The intensity dependence of the maximum energy of protons (black dots) in comparison with the experimental data (squares): CUOS – [5], RAL – [13], and LLNL – [3], and simulations without preplasma (open circles).
Higher Duty-Cycle Terawatt Lasers: Better Signal Averaging

- **Diode-Pumping**
  - France

- **Stanford (Ti:Sapphire)**

- **U. Rochester (Glass)**

- **NOVA (Glass)**

Repetition Rate (Hz)

10^3

1

10^-3

10^-6

Year

1985

1990

1995

2000
Laser Accelerated Plasma Propulsion System (LAPPS)


Laser Beam
\[ \lambda = 1.0 \mu m \]
\[ \tau = 500 \text{ fs} \]
\[ I = 3 \times 10^{20} \text{ W/cm}^2 \]
\[ \varepsilon = 1 \text{ kJ} \]
\[ P = 10^{15} \text{ W} \]

Proton Beam
\[ N = 2 \times 10^{14} \]
\[ \varepsilon_{\text{max}} = 58 \text{ MeV} \]
\[ \varepsilon_{\text{ave}} = 5.3 \text{ MeV} \]
\[ \text{Energy} = 500 \text{ J} \]

LAPPS Propulsion System
Rep Rate \( \omega = 10^3 \)
\[ I_{sp} = 5 \times 10^6 \]

Thrust \( F = 1.83 \times 10^{-2} \text{ N} \)
Driver = Nuclear Reactor \( \sim 1 \text{ Mw}_e \)
\[ M_f = 5 \times 10^3 \text{ kg} \]
Laser-Accelerated Plasma Propulsion System (LAPPS)
Design of 160 MW<sub>e</sub> Nuclear Power System (Brayton)

(Lee Mason, NASA GRC)

Masses in kg

<table>
<thead>
<tr>
<th>System Sizing</th>
<th>Near Term</th>
<th>Mid Term</th>
<th>Far Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor/Shielding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Reactor</td>
<td>115307</td>
<td>96163</td>
<td>74399</td>
</tr>
<tr>
<td>(1) Inst. Shield</td>
<td>4923</td>
<td>4386</td>
<td>3694</td>
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<tr>
<td>(0) Crew Shield</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(1) PHTs</td>
<td>1748</td>
<td>1591</td>
<td>1500</td>
</tr>
<tr>
<td>Power Conversion</td>
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<td>17433</td>
<td>15513</td>
</tr>
<tr>
<td>(10) TAC/Ducts</td>
<td>182</td>
<td>182</td>
<td>181</td>
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<tr>
<td>(10) Recuperators</td>
<td>916</td>
<td>805</td>
<td>775</td>
</tr>
<tr>
<td>(10) Coolers</td>
<td>487</td>
<td>424</td>
<td>384</td>
</tr>
<tr>
<td>(10) Structures</td>
<td>158</td>
<td>141</td>
<td>134</td>
</tr>
<tr>
<td>Heat Rejection</td>
<td></td>
<td>110756</td>
<td>42080</td>
</tr>
<tr>
<td>(1) Radiator</td>
<td>110756</td>
<td>42080</td>
<td>8810</td>
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<tr>
<td>(1) Aux. Equip</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Power MGMT &amp; Dist.</td>
<td></td>
<td>534155</td>
<td>161079</td>
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<tr>
<td>(1) Electronics</td>
<td>234756</td>
<td>92061</td>
<td>34709</td>
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<tr>
<td>(1) Radiator</td>
<td>83137</td>
<td>28696</td>
<td>25592</td>
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<tr>
<td>(1) PL Rad.</td>
<td>57905</td>
<td>28953</td>
<td>14476</td>
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<tr>
<td>(1) Cabling</td>
<td>158357</td>
<td>11370</td>
<td>2379</td>
</tr>
<tr>
<td>Total</td>
<td>784322</td>
<td>320813</td>
<td>180309</td>
</tr>
<tr>
<td>Ratio</td>
<td>4.9 kg/kW&lt;sub&gt;e&lt;/sub&gt; =</td>
<td>2.0 kg/kW&lt;sub&gt;e&lt;/sub&gt; =</td>
<td>1.1 kg/kW&lt;sub&gt;e&lt;/sub&gt; =</td>
</tr>
<tr>
<td></td>
<td>4.9 mT/MW&lt;sub&gt;e&lt;/sub&gt; =</td>
<td>mT/MW&lt;sub&gt;e&lt;/sub&gt; =</td>
<td>mT/MW&lt;sub&gt;e&lt;/sub&gt; =</td>
</tr>
</tbody>
</table>
EXAMPLES OF TWO MISSION

1. Fly-By Mission

\[ t_f = \frac{M_i - M_f}{F} v_e \]

- \( t_f \) = travel time to destination
- \( M_i \) = Initial Mass
- \( M_f \) = final Mass (Dry Mass)
- \( F \) = Thrust
- \( v_e \) = exhaust velocity

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

- \( S_f \) = distance to destination

\[ V_f = v_e \ln \left[ \frac{1}{1 - \frac{F t_f}{M_i v_e}} \right] \]

- \( V_f \) = final velocity at destination
  Assuming starting from rest
Final Mass = 5000 kg:

<table>
<thead>
<tr>
<th>Thrust (Newtons)</th>
<th>Travel Time (years)</th>
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<tbody>
<tr>
<td>0.031</td>
<td>698.4</td>
</tr>
<tr>
<td>25</td>
<td>25.6</td>
</tr>
<tr>
<td>100</td>
<td>13.3</td>
</tr>
<tr>
<td>500</td>
<td>6.5</td>
</tr>
<tr>
<td>1000</td>
<td>4.9</td>
</tr>
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</table>

Final Mass = 1000 kg:

<table>
<thead>
<tr>
<th>Thrust (Newtons)</th>
<th>Travel Time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.031</td>
<td>312.97</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>100</td>
<td>5.5</td>
</tr>
<tr>
<td>500</td>
<td>3.4</td>
</tr>
<tr>
<td>1000</td>
<td>2.8</td>
</tr>
</tbody>
</table>
2. **Constant Thrust, Continuous Burn Acceleration/Deceleration Type of Trajectory**

\[
\tau_{RT} = \frac{4D}{gI_{sp}} + 4\sqrt{\frac{DM_t}{F}}
\]

\[
\tau_{RT} = \text{Round Trip time}
\]

\[
D = \text{linear distance to destination}
\]

\[
g = \text{Earth’s gravitational Acceleration}
\]

\[
I_{sp} = \text{Specific Impulse}
\]

\[
M_t = \text{Dry Mass}
\]

\[
F = \text{Thrust}
\]

Note the additive effects of the two terms on the right-hand side of Equation

For Optimum \(\tau_{RT}\), the two terms must be somewhat comparable!
**Final Mass = 5000 kg:**

<table>
<thead>
<tr>
<th>Thrust (Newtons)</th>
<th>Travel Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.031</td>
<td>5193</td>
</tr>
<tr>
<td>25</td>
<td>186</td>
</tr>
<tr>
<td>100</td>
<td>91.5</td>
</tr>
<tr>
<td>500</td>
<td>41</td>
</tr>
<tr>
<td>1000</td>
<td>29</td>
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</tbody>
</table>

**Final Mass = 1000 kg:**

<table>
<thead>
<tr>
<th>Thrust (Newtons)</th>
<th>Travel Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.031</td>
<td>2322.5</td>
</tr>
<tr>
<td>25</td>
<td>82</td>
</tr>
<tr>
<td>100</td>
<td>41</td>
</tr>
<tr>
<td>500</td>
<td>18.5</td>
</tr>
<tr>
<td>1000</td>
<td>13</td>
</tr>
</tbody>
</table>
Objectives of Phase II

i) Experimentally validate the formula

\[ E_i \approx Z_i \sqrt{\eta I_R \lambda} \]

ii) Thrust Enhancement Approaches

\[ F = W N M V \]
\[ F = \text{Thrust} \]
\[ W = \text{Rep Rate} \]
\[ N = \text{Number of ions in proton Beam} \]
\[ M = \text{mass of proton} \]
\[ V = \text{velocity of proton} \]

Focus on \( N = \Pi R^2 t \)
Specifically on \( N \sim R^2 \)
Experimentally Investigate variation of “N” with “R”

iii) Enhance Rep Rate “w” on target side to match that on Laser side
a. solid target – film spool
b. liquid jet target – approach steady state

iv) Address issues related to laser-plasma interactions e.g. relativistic focusing and Filamentation Instability

v) Conceptual design of Nuclear reactor for use in LAPPs
Accomplishments Thus Far

i) Experimentally verified $E_i \sim \sqrt{I}$ at high Intensities as would be the case in a propulsion system.

ii) Experimentally verified $E_i \sim \sqrt{\lambda}$, optimum target thickness $t \approx 10 \lambda$.

iii) Experimentally established condition for filamentation Instability.

$$P = 5 \ P_c = 5 \left[ 17 \left( \frac{\omega_o}{\omega_p} \right)^2 \ G \ W \right]$$

$$\frac{4 \Pi c}{\omega_o \ a_o} \leq 2 \ r_o$$

c = speed of light

$a_o = 8.5 \times 10^{-10} \ \mu \ m \ \lambda^{\frac{1}{2}} \ \text{[W/cm}^2\text{]}$

$\omega_p = \text{plasma frequency}$

$r_o = \text{radius of focal spot}$

iv) Preliminary Conceptual design of space Nuclear Reactor for use in LAPPS. Likely fuel is cermet fuel with Am (242m) as fissile material due to its large thermal neutron cross section.
Proton Energy vs. Target Thickness

- Mylar Target @ 1.053um
- Mylar dE/dx corrected
- Al Taget @ 532 nm
- Al dE/dx corrected

Max. Proton Energy (MeV)

Target Thickness (microns)
FIG. 1. (a) Energy transmission as a function of incident laser power. The solid line corresponds to 100% transmission. (b) Energy transmission as a function of plasma density for an incident laser power of 6 TW.
REPRESENTATIVE CERMET GAS COOLED CORE (OPEN OR CLOSED CYCLE)
TYPICAL CERMET FUEL ELEMENT SHOWING THE WRAPPER, COOLANT FLOW TUBES, & CERMET MATRIX MADE OF REFRACTORY METAL & FISSILE BEARING CERAMIC.
CERMET REACTOR SYSTEM FEATURES

- HELIUM-COOLED CLOSED CYCLE REFRACTORY CERMET FUELED SYSTEM
- BRAYTON CYCLE KNOWN TO PROVIDE 40% OR BETTER THERMAL EFFICIENCIES
- HELIUM IS A PROVEN WORKING FLUID WITH EXCELLENT HEAT TRANSFER AND MATERIAL (INERT) CHARACTERISTICS
- CERMET SYSTEMS PROVIDE EXCELLENT SAFETY AND PERFORMANCE FEATURES
- LARGE MARGIN OF SAFETY DEMONSTRATED FOR LAUNCH, REENTRY, AND TRANSIENT CONDITIONS
- RUGGED SYSTEM
- ALLOW EXTREME OPERATING TEMPERATURES (Hence great efficiencies)
- EXCELLENT FISSION PRODUCT RETENTION
- PROMISE OF MANY (10’s) YEARS OF OPERATION AT TENS OF MEGAWATTS & AT OVER 70% AVAILABILITY.
<table>
<thead>
<tr>
<th>Matrix / Clad</th>
<th>Fuel candidates Compatible to Matrix</th>
<th>Performance Characteristics</th>
<th>Peak Coolant Temperature</th>
<th>Basic Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/W – Re</td>
<td>$UO_2$ or $PuO_2$ or $Am^{242m}O_2$</td>
<td>High Temperature compatibility to 2500K</td>
<td>2250K</td>
<td>Subcritical when immersed in water Or buried. BeO radial reflectors recommended</td>
</tr>
<tr>
<td>Mo/Mo – Re</td>
<td>$UO_2$ or $PuO_2$ or $Am^{242m}O_2$</td>
<td>High Temperature compatibility to 2250K</td>
<td>2000K</td>
<td>Subcritical when immersed in water Or buried. Be radial reflectors recommended.</td>
</tr>
<tr>
<td>Mo/Mo – Re</td>
<td>UN</td>
<td>High Temperature compatibility to 1900K</td>
<td>1650K</td>
<td>Subcritical when immersed in water Or buried. Be radial reflectors recommended.</td>
</tr>
</tbody>
</table>
### REPRESENTATIVE DIMENSIONS AND MASSES OF POTENTIAL CREMET REACTOR SUB-SYSTEMS

<table>
<thead>
<tr>
<th>ACTIVE CORE MATERIALS</th>
<th>FUEL CERAMIC At (85-92) %td</th>
<th>ACTIVE CORE</th>
<th>REFLECTOR (Be or BeO) shell at 80%td</th>
<th>VESSEL H and D</th>
<th>OVERALL MASS (EST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo or W based</td>
<td>$^{239}$PuO₂ (95% Pu-239)</td>
<td>H=D</td>
<td>(10-12) cm</td>
<td>H=65 cm</td>
<td>850 Kg for W and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=(29-30) cm</td>
<td></td>
<td>D=50-55 cm</td>
<td>730 Kg for Mo</td>
</tr>
<tr>
<td>Mo or W based</td>
<td>$^{242m}$AmO₂</td>
<td>H=D</td>
<td>(10 -12) cm</td>
<td>H=40-45 cm</td>
<td>410 Kg for W and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=(19-20) cm</td>
<td></td>
<td>D=40-45 cm</td>
<td>320 Kg for Mo</td>
</tr>
</tbody>
</table>
Conclusions and Future Investigations

1. Ultrafast Lasers have been used effectively to accelerate charged particles to relativistic speeds.

2. Experiments at University of Michigan and elsewhere have produced proton beams continuing more than $10^{14}$ particles at mean energies of several MeV.

3. Laser powers will be reached soon that will accelerate protons to rest mass energies. That translates to a specific impulse, $I_{sp}$, of about 26 million seconds.

4. A LAPPSS (Laser Accelerated Plasma Propulsion System) device based on present day experimental data will produce an $I_{sp} \approx 3 \times 10^5$ seconds albeit at a thrust, $F$, of $3 \times 10^3$ Newtons. It will require a one MWe nuclear power system to drive it at an approximate mass of 5 mT.

5. If thrust can be enhanced to just 25 Newtons such LAPPSS will make a fly-by robotic interstellar mission to 10,000 AU in about 26 years and a round trip to Mars in about 6 months.

6. Increase in thrust can be achieved using larger focal spots. Increase in Laser power will allow this if intensity (and correspondingly proton energy and specific impulse) is to be maintained.

7. For some missions large $I_{sp}$ may not be required if sizable thrust can be produced. Hence, larger focal spots at lower laser power (hence lower in intensity) may be more desirable.

8. Large Rep Rates (~1 KHz) may be necessary. Achieving such rates at the target side may require liquid jet targets or fast moving solid targets.

9. A Nuclear Fission Reactor will be needed to drive a LAPPSS propulsion system. A reactor using cermet fuel containing Am (242m) with a half life of 141 years is being considered due to its relatively small size, small mass and safety features.

10. Future investigations will address thrust enhancement approaches, fast moving targets, and nuclear reactor and power conversion systems for use in LAPPSS.