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GROUND-TO-ORBIT LASER PROPULSION ADVANCED APPLICATIONS

Jordin T. Kare

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GROUND-TO-ORBIT LASER PROPULSION — ADVANCED APPLICATIONS

Jordin T. Kare
Lawrence Livermore National Laboratory
Livermore, CA

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Laser propulsion uses a large fixed laser to supply energy to heat an inert propellant in a rocket thruster. Such a system has two potential advantages: extreme simplicity of the thruster, and potentially high performance -- particularly high exhaust velocity. By taking advantage of the simplicity of the thruster, it should be possible to launch small (10 - 1000 kg) payloads to orbit using roughly 1 MW of average laser power per kg of payload. The incremental cost of such launches would be of order $200/kg for the smallest systems, decreasing to essentially the cost of electricity to run the laser (a few times $10/kg) for large systems. Although the individual payload size would be small, a laser launch system would be inherently high-volume, with the capacity to launch tens of thousands of payloads per year. Also, with high exhaust velocity, a laser launch system could launch payloads to high velocities -- geosynchronous transfer, Earth escape, or beyond -- at a relatively small premium over launches to LEO.

In this paper, we briefly review the status of pulsed laser propulsion, including proposals for advanced vehicles. We then discuss qualitatively several unique applications appropriate to the early part of the next century, and perhaps valuable well into the next millenium: space habitat supply, deep space mission supply, nuclear waste disposal, and manned vehicle launching.

Space habitat supply depends primarily on the ability of the laser propulsion system to launch large total volumes at low cost, and with sufficient precision to avoid expensive rendezvous maneuvering. However, a key advantage is the laser system's ability to launch on short notice -- the ability to receive spare parts, emergency supplies, etc. on less than 24 hours notice could greatly simplify the logistics of space facilities. A crucial factor is the laser's cross-range capability, which allows a launch window of several hours per day to an inclined orbit.

Deep space mission supply requires the same properties as habitat supply, but also requires high specific impulse to reach Earth escape. Rendezvous with a deep-space mission could be aided by an on-board laser.

Nuclear waste disposal takes specific advantage of what is normally a disadvantage of laser propulsion -- small payload size. A laser launch system can demonstrate an almost arbitrarily low risk by launching a large number (100,000) of test payloads and allowing them to "crash" in various ways to verify emergency recovery systems. However, given that even a well-tested and reliable system can fail, the small payloads used would minimize the potential environmental damage from a failure. Very modest system performance would suffice for disposing of material on the Moon; a high-performance system could dispose of waste into deep space or into the sun.

Finally, launching manned vehicles requires relatively large payload capacity and places a premium on low acceleration. A gigawatt-scale laser propulsion system could provide the needed capacity, however, and could easily be designed and tested to provide the extrememly high level of safety needed for routine manned flight.

Introduction

Laser propulsion uses a large stationary laser to send energy to a small rocket vehicle. Pulsed laser propulsion uses high-energy laser pulses to ablate a solid (or liquid) propellant. With a suitable laser pulse cycle [1], specific impulses up to 1000 seconds can be attained with inert, storable propellants. Pulsed propulsion also makes possible very simple thrusters (potentially just a block of solid propellant) which may not require cooled (or indeed any) nozzles. Such thrusters provide two additional advantages: they can produce thrust at an angle to the incident laser beam, and they can be remotely steered by controlling the beam profile.

The SDIO Laser Propulsion Program, started in 1987, has focussed its efforts on using nozzleless solid-propellant thrusters to launch very small payloads into low Earth orbit (LEO) [2]. A laser launcher takes advantage of the thruster's ability to accelerate at an angle to the laser to launch vehicles directly into LEO without a ''kick motor''. Ground-based guidance eliminates the need for on-board guidance and control hardware, allowing very cheap disposable vehicles -- potentially less complex than a modern refrigerator. The vehicles would necessarily be mass-produced, and should thus be very inexpensive.

The components of a first-generation laser launch system are shown in figure 1. The estimated cost of building such a system is roughly $500 million; it would be capable of launching some 30,000 20 kg payloads into LEO each year, for a total launch capacity of 600 metric tons (MT) per year. A design and some applications for such a system are given in Kare [3].

This is, however, only a first-generation system, such as might be built in the next 5 to 10 years. Larger, more reliable, and higher performance systems are certainly possible. The next section discusses some possible directions for improvement, and the following sections discuss some possible applications for such second- and later-generation sysems. The key properties of laser propulsion to keep in mind are:

Simplicity (of the laser-driven thruster and vehicle)
- Low cost, highly reliable, economically scalable to very small size

High Performance
- High I_{sp} allows single-stage-to-anywhere
- Precision ground-based guidance

Safety
- Inert propellant means trajectory is always known; cannot go off course
- No explosion hazard -- during loading, at launch, or in flight
- Small vehicle -- worst crash is less destructive than a light plane crash

Low acceleration -- comparable to chemical rockets, not ''cannons''

BUT --

Limited payload size compared to chemical rockets
- No fundamental limit, but capital costs of large systems are high

Less flexible than some self-contained systems
- Diffraction- and horizon-limited range
- Fixed launch site (vs., for example, Pegasus or SSX flexibility)
- Subject to weather delays

Status of Pulsed Laser Propulsion Research

The double-pulse thrust cycle is illustrated in figure 2. A low-energy laser pulse evaporates a thin layer of solid propellant from a large block. This layer expands to of order atmospheric density, forming a gas layer millimeters to centimeters thick. A second, higher energy pulse forms a laser-supported detonation wave (LSD) wave at the solid surface -- a strong shock which heats the gas enough to create ionization that absorbs the laser beam. The laser beam energy in turn heats the gas behind the shock, maintaining the shock strength and keeping the wave going. When the shock has heated the entire gas layer, the laser turns off, leaving (ideally) a uniform gas layer at of order 10,000 K, which expands to produce thrust. Since the hot gas layer is very thin compared to the vehicle diameter, the expansion produces thrust efficiently without a nozzle.

Although the double pulse allows efficient heating of the gas to very high temperatures, the flat-plate nozzleless nature of the system remains even if only a single laser pulse is used. At low flux, a single pulse simply ablates the surface, creating a relatively cool, low velocity exhaust; this is an ablation-mode thruster.

Laser Propulsion Program research has consisted of computational modelling of the various phases of the thrust cycle, and of small-scale experiments using 1-100 Joule CO_2 lasers to generate single impulses on various propellant materials suspended in vacuum. These experiments generally measure the total impulse given to the target, and the mass lost by the target. These can be converted to a specific impulse (impulse/mass) and an efficiency (kinetic energy in the exhaust/laser pulse energy). The Program goal has been an efficiency of 40% at a specific impulse of 800 seconds (exhaust velocity of 8 km/s), but lower I_{sp}'s of 300 to 400 seconds (comparable to a liquid fuel rocket) are sufficient for launching payloads to LEO.

The four phases of the double pulse cycle are:

Evaporation
Plasma ignition
Propagation of Laser-supported detonation (LSD) wave
Expansion and recombination

These same phenomena occur with single laser pulses, but may overlap or change in importance -- in particular, an ablation-mode thruster may provide sufficient I_{sp} for LEO launches with little or no plasma formation, but would correspondingly make the evaporation and expansion phases more critical.

Some major double-pulse modelling results:

- Long pulses (>100 ns, preferably >1 μs) are desirable
- Propellant must be a strong absorber in solid state
  - Long absorption depth puts too much heat into remaining propellant
- Low-ionization-potential "seed" strongly helps LSD-wave formation
- Full recombination is unlikely in high-Isp thrusters

Major experimental results:

- Enhanced efficiency and I_{sp} with double pulses demonstrated
  - Strong dependence of impulse, mass loss on interpulse time
- 10x reduction of plasma ignition threshold with "invented" propellants
- Demonstrated 25 dyne-s/J (250 N/MW) coupling in air with "dimpled plates"
- Efficiencies (Exhaust kinetic energy/Laser pulse energy) demonstrated:
  - 8-10% at 600 - 800 s I_{sp}
  - 15% at 600 s I_{sp} with long pulses
  - 20-30% at 200 s I_{sp}

Near future plans:

- 1 kJ, 1 μs pulse experiments
  - Goal is 20% efficiency at 600 s Isp and 40% at 300 s
- Ablation-mode tests
- Modelling and experiments at 1.06 μm for compatibility with SDIO FELs
- Rep-pulse experiments at substantial average power in 1991-92

Directions For Growth -- Laser Propulsion in the 2000's

Laser propulsion has the nice property of growing essentially linearly from an initial system launching 20 kg payloads to gigawatt-scale systems launching multiton payloads. However, there are many ways to improve the basic system other than simply building a bigger one:

Advanced vehicles

- Primarily work of Myrabo -- Apollo Lightcraft [4] and Technology Demonstrator [5]
  - High mach number air-breathing performance
  - Efficient integrated structures
- Emphasize performance rather than lowest vehicle cost
- Great potential for 2nd and later generations
  - Vehicles must be re-usable; probably must be large(r) to be economic
  - Designs require lasers and/or relay mirrors in orbit

Advances in lasers/optics

- Free Electron Lasers
  - Short wavelength, tunable for maximum transmission
  - Potentially 25% efficient or better
- Diode and diode-pumped lasers
  - Potentially as cheap as power semiconductors -- pennies per watt
  - Short wavelength, highly reliable (''no moving parts'')
  - Potentially very efficient -- 50%? -- reduces power cost
- Large, low cost beam directors via segmented active optics
  - >>10 meter diameters are possible

Space-based relay mirrors increase flexibility, performance

- Extend range over the laser's horizon
  - Much greater ''reach'' for orbital maneuvering
- Increase launch windows to inclined orbits
- Large mirrors (potentially easy in space) can give very long range
  - Range = $D_1 D_2/\lambda$
  - 100 meter mirror directly drives vehicles in GEO
  - 100 m mirror and 100-1000 m collector reaches Mars

Space-based lasers eventually do the same

- May be necessary at short wavelengths to avoid atmospheric limits
- Can be direct solar or solar-electric powered

Application 1: Habitat Supply

Beginning with Space Station Freedom (or even with the Soviet Mir), more or less permanent habitats will exist in cislunar space. These will need many kinds of supplies, primarily transported (at least at first) from the Earth.

1. Routine (re)supply

    Consumables: Food, water, air, fuel/reaction mass (which could be water)
    Raw materials for space industrial products -- silicon, metals
    Miscellaneous small items: parts, lubricants, laboratory supplies
    Construction materials

2. Priority supplies

    Replacement parts/tools
    Specialized tools and hardware
    Perishable samples or reagents -- even radioisotopes
    Medical supplies

Routine resupply can be minimized through recycling, but highly efficient recycling will be complex and costly. Many items, notably raw materials for export products and fuel, cannot be recycled. Some items could be supplied from the Moon or other space sources: oxygen, possibly water, reaction mass, and even some raw materials and construction materials. But many items will come only from Earth until an extensive space mining and manufacturing economy develops. Laser propulsion offers:

1. Low-cost routine supply -- incremental launch costs of $10 - $100 per pound

    Moderate handling costs
        Minimal ground "payload integration" costs & delays
        Space payload handling must be automated via small self-contained ''retrievers''
            Can't have an astronaut out collecting every 100 kg parcel

    Respectable total capacity
        Inclined orbits: ~10 launches per day
        Equatorial orbits: ~100 launches per day

2. Efficient launch to GEO, L4/L5, etc.

    Ideal for laser launch -- trajectories stay above horizon; high I_{sp} is well-matched

    Modest laser on habitat (10% of GBL size) useful for apogee burn

3. Launch on demand; at most 24 hour delay, usually less

    But requires at least 2 launch sites to allow for weather, equipment failures, maintenance
    Also require very reliable hardware at the habitat if vehicles need help to rendezvous
        Keep one ''ready'' rocket for extreme-emergency situations

NO conventional system offers priority supply (unless traffic is so heavy there is ~1 launch per day in any case). The cost is exorbitant even for the most optimistically-priced vehicles, such as the SSX, with a per-launch cost of $1 million. Yet priority suppy can drastically simplify logistics: if spares and emergency supplies can come from the ground, you don't have to carry everything you might ever need in a hurry.

Application 2: Deep-Space Mission Supply

This topic is discussed in some detail in an earlier paper [6]. Laser propulsion is of limited direct use in driving deep space missions, because diffraction spreads the laser beam to an unusably large diameter over interplanetary distances -- although eventually, as the scale size of the laser transmitter and the receiving vehicle grow, the useful range can be interplanetary or even interstellar [7]. The most immediate use of laser propulsion is simply as a low-cost way to place mission components (fuel, structural mass, etc.) in Earth orbit.

However, laser propulsion can have more direct applications. Microspacecraft have been proposed [8] to preceed deep space missions and perform such preliminary tasks as selecting a landing site and sampling local conditions. A high-I_{sp} laser launch system is ideal for launching such precursor probes.

A laser launcher could send out supply packages to rendezvous with a deep space mission, either en route or at its destination. However, the rendezvous velocity would be high for most trajectories, and even a very small error (or deliberate change) in the trajectory of the main mission would cause supplies to miss their target. Putting thrusters and guidance hardware on the supply packages would make them expensive -- essentially spacecraft in their own right -- and thus probably uneconomical.

The situation is different if the mission vehicle is large enough to carry a laser of respectable size -- at least megawatt-scale. It can then "reach out and grab" incoming supply packages over a large volume of space and a substantial range of relative velocities. For this application, the inert, storable nature of the laser propulsion propellant is critical -- a small supply package could not store cryogenic propellants.

The reach of the mission vehicle can be extended even further if the supply packages carry lightweight concentrators to collect the incident laser light. Since the laser can deliver power to such a concentrator for a longer time than to a thruster directly, the required size of the on-board laser is also reduced.

Although prompt supply is not possible even with a laser propulsion system over interplanetary distances, the ability to do a high delta-V launch (and to some extent, a high delta-V capture maneuver) means that a laser system could launch supply packages on much faster trajectories than those likely for chemical propellant systems. This could allow, e.g., getting specialized research tools to a Mars mission before it leaves the planet, when the need is only discovered after the mission arrives.

A major limitation is that any such deep-space mission support requires very high confidence in the on-board laser -- or limits supply packages to non-mission-critical items.

Application 3: Nuclear waste disposal

Kantrowitz [9] has suggested using a laser propulsion system to dispose of high-level radioactive waste in space. The problem of finding an environmentally acceptable waste disposal site has consumed billions of dollars and met with enormous political complications of the 'NIMBY' (Not In MY Back Yard) variety. Disposal of waste in space has been studied fairly extensively [10], but conventional launchers (in addition to being very expensive) always present the spectre of a catastrophic accident releasing the radioactive payload into the environment. No amount of engineering design can eliminate that risk, and no reasonable test program using conventional launchers can demonstrate safety. The problem is compounded by the need to launch, at the very least, to the Moon.

Laser Propulsion offers safe, cheap disposal:

- Arbitrarily high *demonstrated* reliability:
  - Laser system can be modular and heavily "overbuilt" -- even duplicated
    - Single-stage launch -- no failures in LEO
  - Very many (e.g., 10^5) vehicles can be test-launched
  - Emergency re-entry/recovery systems can be tested 10^5 times too
    - Catastrophic failure probability less than one-in-a-billion
- Inherent safety even in disaster
  - Small payload size means even a worst-case accident is limited
    - Easy to crash-proof (mouse vs. elephant)
  - Inert vehicle -- can't explode, can't go "off course"
  - Of course, you do need to *find* a payload that crash lands in Mongolia...

Unlike weight- and volume-limited conventional systems, a laser launcher could potentially handle unprocessed or minimally-processed waste. This minimizes both radiation and toxic chemical hazards on the ground, and is therefore crucial to an economical system. A laser system could even be cheaper than geological disposal, because there would be less handling (separation, glassification) of waste.

Lasers can launch waste directly to any desirable disposal site -- the Lunar surface, interplanetary space, or deep space (solar escape). The required delta-V's are roughly 11 to 15 km/s, beyond the capability of any single-stage chemical rocket or proposed cannon launcher. Laser propulsion could even launch payloads directly into the Sun, at 30 km/s delta-V. The precision guidance and flexible launch direction of a laser system could allow dumping payloads into, e.g., a selected lunar crater, for future recovery if desired.

Very small laser propulsion payloads could present problems of shielding (to protect both launch-site workers and possible crash site bystanders) and safe any-angle reentry [11]. However, some problems of laser propulsion, such as launch delays due to weather, are not important as long as the total mass launched is constant and the reliability is high.

Application 4: Manned Launch

In the long run, the most valuable payload is always Man. Laser propulsion, because of its inherent safety, is a nearly ideal launcher for people, provided the basic requirements of a man-rated launcher can be met.

Requirements:

- Excellent safety -- but actually less than for nuclear disposal
  - Accident consequences are smaller; hysteria is less
- Sufficient payload capacity
- Low peak acceleration
  - Apollo was ~5 G's; Shuttle is ~3 G's
  - Good shock absorber required (<1 G vibration?)
    - Easy to do in a large vehicle with a high pulse rate

Payload capacity needed is clearly less than 1 ton (a Mercury capsule):

- Better structures, electronics available
- Minimal life-support needed
  - Normal dock-or-reenter in ~2 hrs (1 orbit)
    - Assumes synchronized launch; 2-4 ''windows'' per day
  - Worst-case dock-or-reenter in ~24 hours
- Minimal guidance system (Must have some, to prevent tumble)
- Baggage goes up first! (Limit 1 carryon, must fit under your seat)
- Potentially ~300 kg, but must include:
  - Person (up to 100 kg)
  - Couch
  - Air/water/power
  - Pressure shell
  - Emergency reentry system (pared to minimum mass via extensive tests)

G-limit:

- Drives system to long range, high I_{sp}
- 1000 km range gives 5-6 G's for last few seconds @ 800 s I_{sp}
  - ~12 G's at 400 s
- Thrust is constant, so acceleration peaks sharply at end of launch
  - Trivial to throttle system -- just reduce laser pulse rate
  - But good shock absorbers will be a necessity

Acknowledgements

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[11] The shielding requirement was pointed out at the Vision-21 Symposium by both Theodore Taylor and Frank Rom; the waste/shielding mass ratio is a function of the total mass, and is lowest (worst) for masses of 10's of kg.

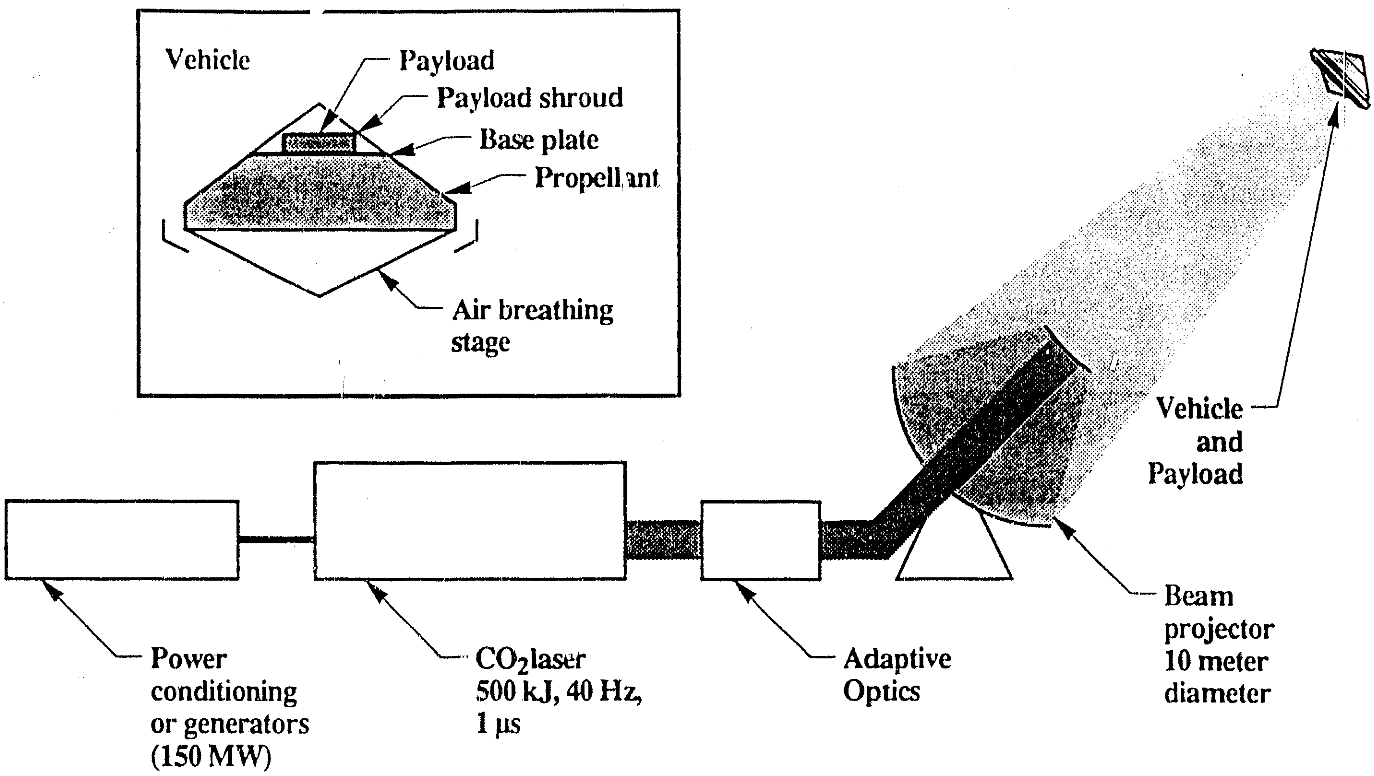

Figure 1: Components of a 20 MW/20 kg Laser Launch System

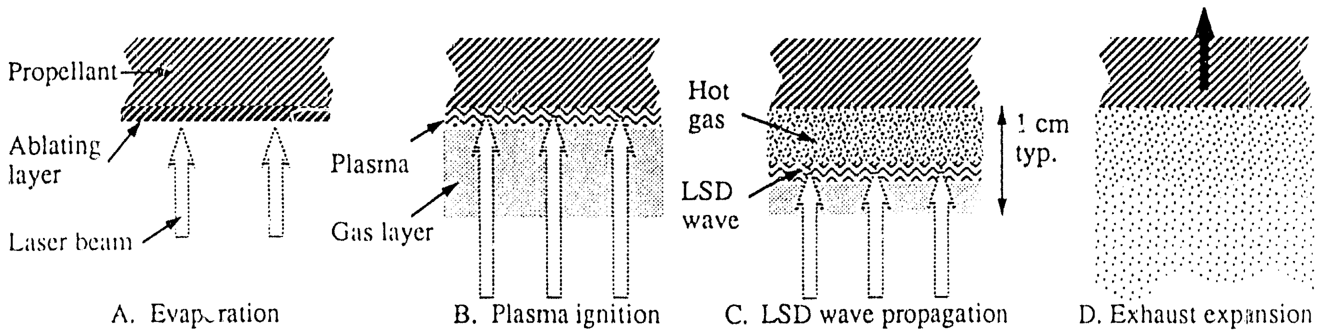

Figure 2: Double-Pulse Thrust Cycle

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