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Pulsed Laser Propulsion for Low Cost, High Volume Launch to Orbit

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ABSTRACT

Pulsed laser propulsion offers the prospect of delivering high thrust at high specific impulse (500 - 1000 seconds) from a very simple thruster, using the energy of a remote ground-based laser to heat an inert propellant. Current analyses indicate that payloads of approximately 1 kg per megawatt of average laser power can be launched at a rate of one payload every 15 minutes and a marginal cost of $20 to $200 per kg. A 20 MW entry-level launch system could be built using current technology at a cost of $500 million or less; it would be capable of placing 600 tons per year into LEO.

The SDIO Laser Propulsion Program has been developing the technology for such a launch system since 1987. The Program has conducted theoretical and experimental research on a particular class of laser-driven thruster, the planar double-pulse LSD-wave thruster, which could be used for a near-term launcher. The double-pulse thruster offers several advantages, including extreme simplicity, design flexibility, and the ability to guide a vehicle remotely by precise control of the laser beam. Small-scale experiments have demonstrated the operation of this thruster at a specific impulse of 600 seconds and 10% efficiency; larger experiments now under way are expected to increase this to at least 20% efficiency. Systems-level issues, from guidance and tracking to possible unique applications, have also been considered and will be briefly discussed. There appear to be no fundamental obstacles to creating, in the next five to ten years, a new low-cost "pipe-line to space".

Introduction

Most space power and space power transmission systems now being planned or discussed have power levels measured in kilowatts. We do not yet have space hardware that needs, or can handle, megawatts of electrical power; developing such hardware will require enormous technical development and capital investment. Yet very high powers and power densities are required for one space use: generating thrust for high acceleration, and particularly for launching payloads from Earth to orbit. Currently, these power levels can only be generated (with acceptable power-to-weight ratios) by chemical combustion: a modest solid rocket booster (10^6 newton thrust, 250 seconds I_{sp}) produces over 1 GW. Pulsed laser propulsion, unique among alternative thruster and power beaming technologies, can reach power levels and power densities comparable to chemical thrusters, with higher performance, and without requiring expensive flight hardware. A price is paid, of course, in complex hardware for generating and transmitting the laser beam, but that hardware can reside on the ground, indefinitely reusable and straightforward to build, test, and maintain.

Laser propulsion, as originally conceived by Kantrowitz [1], uses a large ground-based laser to supply energy to a small rocket vehicle. The laser beam heats an inert propellant, which is exhausted to provide thrust. Because the propellant exhaust velocity is not limited by its chemical energy content, specific impulses in excess of 1000 seconds can be achieved. Ground- or space-based CW lasers and space relay mirrors have been suggested as a way to power orbital maneuvering thrusters [2,3], but proposed CW-laser thruster designs have been relatively complex, using regeneratively-cooled nozzles and liquid hydrogen propellant. Such systems are competitive with other advanced orbital-maneuvering concepts such as solar-electric or solar-thermal, but are not suitable for a small-scale Earth-to-orbit launcher.

If a pulsed laser is used, a thruster the engineering temperature limits of conventional thrusters do not apply. High I_{sp} is thus available from propellants much heavier (on an atomic scale) than hydrogen. Also, with appropriate design, no nozzle is needed to produce efficient thrust, and ideally, a thruster can consist of only a block of suitably-formulated solid propellant.

Since the spring of 1987, the U.S. Strategic Defense Initiative Organization (SDIO) has sponsored a research Program on Laser Propulsion, managed through the Lawrence Livermore National Laboratory. The Program has focussed on a particular type of laser propulsion thruster, the double-pulse planar thruster [4]. This thruster uses a solid propellant block composed of one of several inert materials, such as plastic or water ice, seeded with additives to control its optical and chemical properties. An "evaporation" laser pulse ablates a few-micron-thick layer of propellant, forming a thin layer of gas which is allowed to expand to roughly atmospheric density. A second laser pulse then heats this gas layer to approximately 10,000 K. The hot gas layer expands rapidly, producing thrust. The entire process takes a few microseconds, and is repeated at 10^2–10^3 Hz rates. This process is illustrated in Figure 1.

Because the hot gas layer is only a few millimeters thick, while a typical vehicle is two meters across, no nozzle is needed to confine the expanding gas. The expansion generates thrust uniformly across the flat base of the vehicle (hence the "planar" thruster). In addition to making the vehicle design extremely simple, this scheme has two other advantages. First, the thrust direction is independent of the laser beam direction; the vehicle can fly at an angle to the laser beam. Second, the thrust can varied across the base of the vehicle by controlling the beam profile. The vehicle can therefore be steered from the ground, and does not need its own guidance system.

Properties of a Ground to Orbit Launcher

Figure 2 illustrates the components of a minimum-size ground-to-orbit launch system which could be constructed in the next four to five years. The laser is a 20 MW average power electric-discharge CO_2 laser, producing 500 kJ, 2 microsecond pulses at 40 Hz. This would be a very large laser, but the technology for such large CO_2 lasers was well developed in the 1970's. Because of the physics of the double-pulse thruster itself, the 10 μm wavelegth is preferred over shorter wavelengths, although a laser propulsion system could operate at wavelengths as short as 1 μm. A high-power free electron laser (FEL) would be even better, offering higher electrical efficiency (20-25% vs. 15%) and possibly greater reliability. FEL technology is still new, however, and may not be available at competitive prices for several years. The laser requires roughly 150 MW of electricity, which can be obtained from the national power grid or produced locally, e.g., by diesel generators.

The laser beam is focussed by a 10 meter diameter beam projector telescope onto a two meter diameter vehicle. This combination gives a useful range of approximately 1000 km. The maximum payload mass is proportional to the system range (other factors being equal), but 1000 km approaches the maximum practical range, both because of limits on telescope and vehicle size, and because the vehicle must stay well above the laser's horizon during the launch. The telescope could be a variant of a conventional astronomical telescope, similar to the 10-meter Keck astronomical telescope now being built by Cal Tech and the University of California [5], or it could be a more specialized design, for example a phased array of smaller mirrors. An adaptive optics system is needed to correct for atmospheric turbulence and thermal blooming, but the combination of long wavelength and a cooperative vehicle (which can even telemeter back information about the beam profile) keeps the complexity of this system well within the state of the art. However, a mountaintop (3-km altitude) launch site is needed to reduce absorption of the laser beam by atmospheric water vapor and CO_2.

The vehicle consists of 120-150 kg of propellant, and 20 kg of payload, with a few kg of structural support, primarily a stiff baseplate to support the thin propellant block. A throwaway air-breathing stage improves performance by lifting the vehicle to 20 km or higher with a "laser pulse-jet". The vehicle then drops the air-breathing hardware and accelerates vertically to about 100 km, where it "turns over" and accelerates downrange to 400 - 500 km altitude and 1000 km range. At that point it runs out of propellant and enters a circular or elliptical orbit. The maximum acceleration is about 6 gees. The time from launch to entering orbit is 15 minutes or less.

Launcher Cost and Scaling

The cost of the 20-MW, 20-kg system described here is estimated at $450 million; this is roughly broken down in Table 1. The incremental cost of launching a single vehicle is simply the cost of the vehicle, propellant, and electricity; the electricity cost is some 30 to 40 thousand kWH or, at 4 cents/kWh, $1200 to $1600. Assuming a propellant cost of $10/kg and a vehicle cost of no more than $2000 (mostly sheet-metal structure, produced in quantity), the total incremental cost per launch could be below $5000; this would give a cost to orbit of $250/kg or less than $120/lb. However, the small payload size means the vehicle must remain cheap; even a few thousand dollars spent on, e.g., telemetry, could double the incremental costs.

The true cost to orbit requires amortizing the cost of the launcher itself, and its maintenance and manpower, and thus depends on how heavily the launcher is used. At one extreme, to reduce the true costs to $10,000/kg ($4500/lb, comparable to current expendable rockets) would require launching a minimum of 50,000 kg, or about 2500 launches, over the life of the system. At the other extreme, the launcher is capable of up to 100 launches per day, or more than 30,000 launches per year. That would put 600,000 kg, or more than 20 Space Shuttle loads, in orbit each year. This exceeds not only the capacity of the Shuttle fleet, but the total capacity of all existing US launch systems at current production rates [6]. Assuming a 5 year system life, and annual operating costs of 20% of the capital cost, the effective cost of the system would be $180 million per year, or $300 per kg launched. Including the incremental costs, the total launch cost would be approximately $550/kg, or $200/lb.

The 20-MW, 20-kg system described here is probably near the smallest size that can be built cost-effectively. This results from tradeoffs among vehicle size and structural mass, beam projector size, and laser properties. There is, however, no obvious limit to increasing the system size, and larger systems gain at least linearly in payload size vs. laser power, and considerably better than linearly in payload size vs. system cost.

Table 1: Approximate system cost breakdown

Laser:	$185 M	(approx. $8/watt + $25 M design cost)
Telescope:	$100 M	(based on Keck 10 meter astronomical telescope cost)
Adaptive Optics:	$ 15 M	
Tracking:	$ 50 M	
Power plant:	$ 50 M	(Diesel generators)
Structure:	$ 50 M	(roads, buildings, etc.)
Total	$450 M	

Applications

There is no fundamental upper limit to the size of payloads that could be launched with a laser. However, economic limits will restrict lasers to small payloads in the near future — a 1-GW laser could be built for perhaps $10 billion, much less than the amount that has been spent on the Space Shuttle, but at present there is literally no use for the 50,000 tons of payload that it could launch each year.

Even at 20 to 100 kg payload size, however, there are many possible payloads. So-called "lightsats" have been proposed for communications, remote sensing, and scientific applications; while these are usually thought of as weighing 100 to 1000 kg, some lighter satellites ("microsats") have already been flown [7]. Most of these satellites would be needed in small quantities, but cumulatively they could represent a market for several hundred launches per year. Some uses, such as packet-switching low-orbit communications networks, could involve hundreds or thousands of microsats. Obviously, there are also possible strategic defense applications, particularly in connection with recent suggestions for swarms of small space-based interceptors ("Brilliant Pebbles").

The number of applications grows enormously if some form of assembly in space is possible. It is currently impractical to assemble anything in space from 20-kg modules using either human or robotic labor; there is not even a practical way to collect such pieces and bring them together. However, the technology needed to build small autonomous spacecraft capable of rendezvous and docking maneuvers is rapidly being developed. At the simplest level, satellites of moderate size could be launched as modules, starting with a maneuverable guidance and command unit. This unit could, over several days, collect and join together independent modules (power, communications, scientific experiment, booster) to form, for example, an interplanetary probe.

A larger-scale application of this concept would be efficient resupply of Space Station Freedom. Supplies (food, water, tools, spare parts, etc.) could be delivered to orbit perhaps 100 km from the Space Station (to keep the Station safe from both laser beams and packages at high relative velocity) A very small (<100 kg) retriever vehicle would collect these supply packages and return them to a suitable airlock on the Station. Astronaut time would be needed only to unpack and store the supplies, and perhaps to monitor the final approach of the retriever to the Station. Even chemical fuels, oxygen, and batteries could be delivered — a particularly direct way of "beaming" power, and one which could be used over arbitrary distances, since the laser can easily launch payloads to escape velocity.

The laser system cannot launch to a given non-equatorial orbit at any time; the laser is precisely in the orbital plane only twice a day. However, the laser has some crossrange capability — the vehicle can be steered in a "dogleg" trajectory which results in an orbit that does not pass over the laser. Even a 100 kilometer crossrange capability (out of a laser range of 1000 km or more) could allow at least eight payloads per day to reach the Space Station. Eight payloads per day would be over 50 tons — two Shuttle loads — per year. The limited size of each payload would be somewhat offset by the promptness of delivery; a tool or spare part could be delivered to the Station with, in many cases, less than a day's delay. As Federal Express has demonstrated, overnight delivery frequently commands a premium price, and is sometimes truly invaluable.

Uses for a Sub-Scale Laser Facility

Although a true launch-to-orbit system requires a 20-MW system, there are some propulsion applications for considerably smaller lasers. Perhaps the most important of these is orbital maneuvering propulsion. A laser as small as 1 to 2 MW can give considerable impulse to a satellite passing overhead. To keep the beam projector size and cost within reason, the satellite must deploy a crude reflector (essentially a beach umbrella of aluminized Mylar) to concentrate the laser beam. However, with such a concentrator, the satellite can get thrust with triple the specific impulse of solid rockets, or twice that of H_2/O_2 rockets, from a completely safe and stable block of inert propellant.

The laser can only track a given satellite in low orbit for a few minutes each day; exactly how much time depends on the details of the satellite's orbit and the laser range. (Orbiting mirrors would greatly increase this, but would cost much more than the laser system). That is sufficient to allow a 2-MW laser to maintain or raise the orbit an object as large as a Space Shuttle External Tank. It is also sufficient to push ton-sized satellites from low orbit to geosynchronous transfer orbit on time scales of weeks, while saving half to two thirds of the mass of a standard liquid or solid fuelled upper stage.

If a high enough laser flux can be achieved in orbit, the laser could also clear away space junk. Small bits of debris would be evaporated. The surface of larger pieces would ablate, producing enough thrust (at low specific impulse) to deflect the junk into orbits that re-enter the atmosphere.

A megawatt-scale laser facility is also a necessary step in developing a laser launcher. While not capable of putting anything in orbit, it could launch small "sounding rockets" to several hundred km altitudes, and provide detailed information on atmospheric absorption, turbulence, and blooming. It could also aid other space experiments, by providing very high levels of burst power to satellites passing overhead (although this function might be better served by a short wavelength laser whose light could be efficiently converted to electricity by ordinary solar cells).

Status of Laser Propulsion Research

The SDIO Laser Propulsion Program has conducted experiments at several industry and Federal laboratories, and both industry and university groups have done theoretical analysis and computer modelling of the double-pulse planar thruster and related schemes. We have demonstrated experimentally that the double pulse thruster concept works, producing higher thrust efficiency (exhaust kinetic energy/laser pulse energy) and higher specific impulse than can be achieved with single laser pulses under similar conditions. This was done with single pairs of CO_2 laser pulses, with pulse energies of a few Joules and pulse widths of 50 to 100 ns. Specific impulses of 700 to 800 seconds have been demonstrated using both single and double pulses.

The actual thrust efficiencies achieved with double pulses are only about 10%, while the launch system specifications cited above assume an efficiency of 40%. However, theory and computer modelling suggest that substantially higher efficiencies will be obtainable with longer pulses. Several energy loss mechanisms involve characteristic time or distance scales comparable to the scale of the current experiments, and will be much reduced at larger scales. We are currently preparing for experiments using a 2 kJ, 1 μs laser at Avco Research Laboratory, in which we hope to demonstrate efficiencies of 20% or more. Note that varying the efficiency changes only the size of the laser needed to lift a given payload; even at 20% efficiency all of the applications described above are practical, although the launch system cost would be somewhat higher.

We have identified several promising propellant candidates, including lithium hydride and other light hydrides, water ice, and certain C-H-O plastics, notably polyacetals (trade names Delrin and Celcon). More important, we now understand many of the properties required of a good propellant, such as short optical absorption depth in the solid (for efficient evaporation during the first laser pulse) and at least one component with a low ionization potential (for efficient absorption of the second pulse, which is absorbed by electron-ion and electron-neutral interactions). We have demonstrated our ability to modify propellants to achieve desired properties, for exampe by mixing wavelength-sized metal flakes into a plastic propellant to serve as plasma ignition sites; these lower the flux needed to achieve efficient heating during the second laser pulse.

Finally, we have analyzed many of the critical systems-level problems involved in building an actual launcher. We have, for example, calculated the control-loop response involved in guiding a laser-driven vehicle from the ground, and demonstrated that such ground-based guidance is stable over a wide range of conditions.

If the planned tests with single pulse pairs at 2 kJ are successful, the Laser Propulsion Program will be ready to proceed to tests with a repetitively pulsed laser of significant average power. Unfortunately, few such lasers are available, and none provide our desired pulse format. The Program currently plans to modify the Humdinger CO_2 laser at Avco Research Laboratory, but we are still seeking other options. The Program will also begin work on tests using Nd:glass lasers at 1.06 μm, both to determine the wavelength scaling properties of the double-pulse thruster, and specifically to see how laser propulsion could be adapted to use the large 1.06 μm FEL's now under develoment by the SDIO.

Program for Laser Propulsion

There are several possible routes to a working laser launch system. Assuming continued development of large lasers by the SDIO, it is likely that lasers (and optics) sufficient for launch-to-orbit will be built in the next decade. If these can be adapted (primarily through extended run times and improved durability) to routine use, laser launching may be a major peacetime application of strategic defense technology.

Alternatively, a dedicated laser launcher using CO_2 technology could be built. This would require a modest expansion of the current research efforts to demonstrate higher efficiencies, select and optimize a propellant, and demonstrate sustained performance with repetitive pulses. This would be followed by the design and construction of a sub-scale launch facility with 1-2 MW average power and a 4-meter-class telescope; the laser in particular could serve as a prototype module for a larger modular laser. As noted above, this sub-scale system could find immediate practical applications in satellite maneuvering. It would also answer essentially all questions about the viability of a larger system, particularly with respect to transmitting a beam through the atmosphere.

Finally, using the engineering experience and proof-of-principle results from the sub-scale launcher, a full 20-MW launcher could be designed and built. The time required to do this depends on the priority given to the project, but an overall time scale of 5 years appears feasible.

Conclusions

A working ground-to-orbit laser launch system could be built by the middle of the coming decade. Such a launcher would be capable of launching tens of thousands of small (20 kg) payloads into low Earth orbit every year, at an incremental cost approaching $100/lb. The capital cost of the system, including development costs, would be approximately a half-billion dollars — comparable to the cost of a handful of Shuttle or expendable rocket launches, whose total payload the laser could launch in a few months.

Such a laser system could significantly lower the cost of many space operations, from Space Station resupply to launching of small communications satellites. It would also provide unique capabilities for prompt launch of, for example, emergency spares or small sensor satellites. Even a sub-scale laser system, costing roughly 1/10 as much, could provide new capabilities, notably for maneuvering satellites using thrusters with two to three times the specific impulse of chemical rockets.

The basic operation of a laser propulsion thruster has been demonstrated in the laboratory; larger scale tests which should demonstrate realistic thruster efficiencies are planned for the next few months. Although there is considerable development work to be done, no major advances in physics or technology are needed to build a launch system using CO_2 lasers; large FEL's offer even more possibilities in a slightly longer term. In either case, beamed laser energy and the uniquely simple flat-plate thruster offer the first real near-term competition to rockets for getting into space.

Acknowledgements

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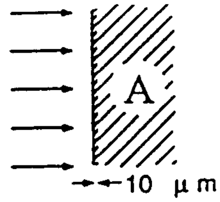
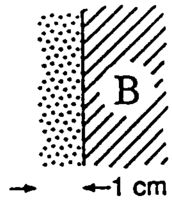
Figure 1: Double-Pulse LSD-Wave* Thrust Cycle

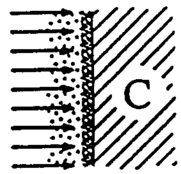
A) "Metering" pulse evaporates a thin layer of propellant
$\tau_1 = 2 - 5\ \mu s$



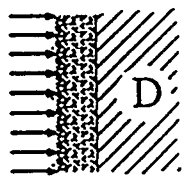
B) Gas expands to the desired density
$\tau_{1\text{-}2} = 0 - 5\ \mu s$



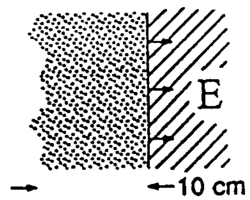
C) Main pulse passes through gas,
forms plasma at surface τ_{ign} = few ns



D) Plasma absorbs beam by inverse brems-strahlung; absorbing layer (LSD wave) propagates through gas $\tau_2 = 1\ \mu s$



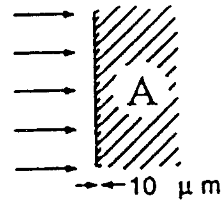
E) Uniformly hot gas expands in 1-D,
producing thrust $\tau_{exp} = 3 - 10\ \mu s$



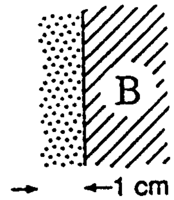
F) Exhaust dissipates; cycle repeats at 100 Hz - few kHz

Figure 1: Double-Pulse LSD-Wave* Thrust Cycle

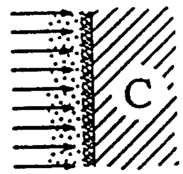
A) "Metering" pulse evaporates a thin layer of propellant
$\tau_1 = 2 - 5\ \mu s$



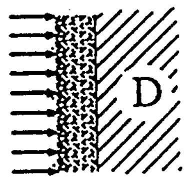
B) Gas expands to the desired density
$\tau_{1\text{-}2} = 0 - 5 \mu s$



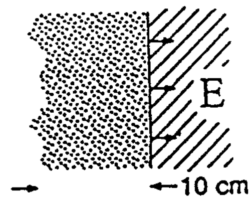
C) Main pulse passes through gas,
forms plasma at surface τ_{ign} = few ns



D) Plasma absorbs beam by inverse bremsstrahlung; absorbing layer (LSD wave) propagates through gas $\tau_2 = 1 \mu s$



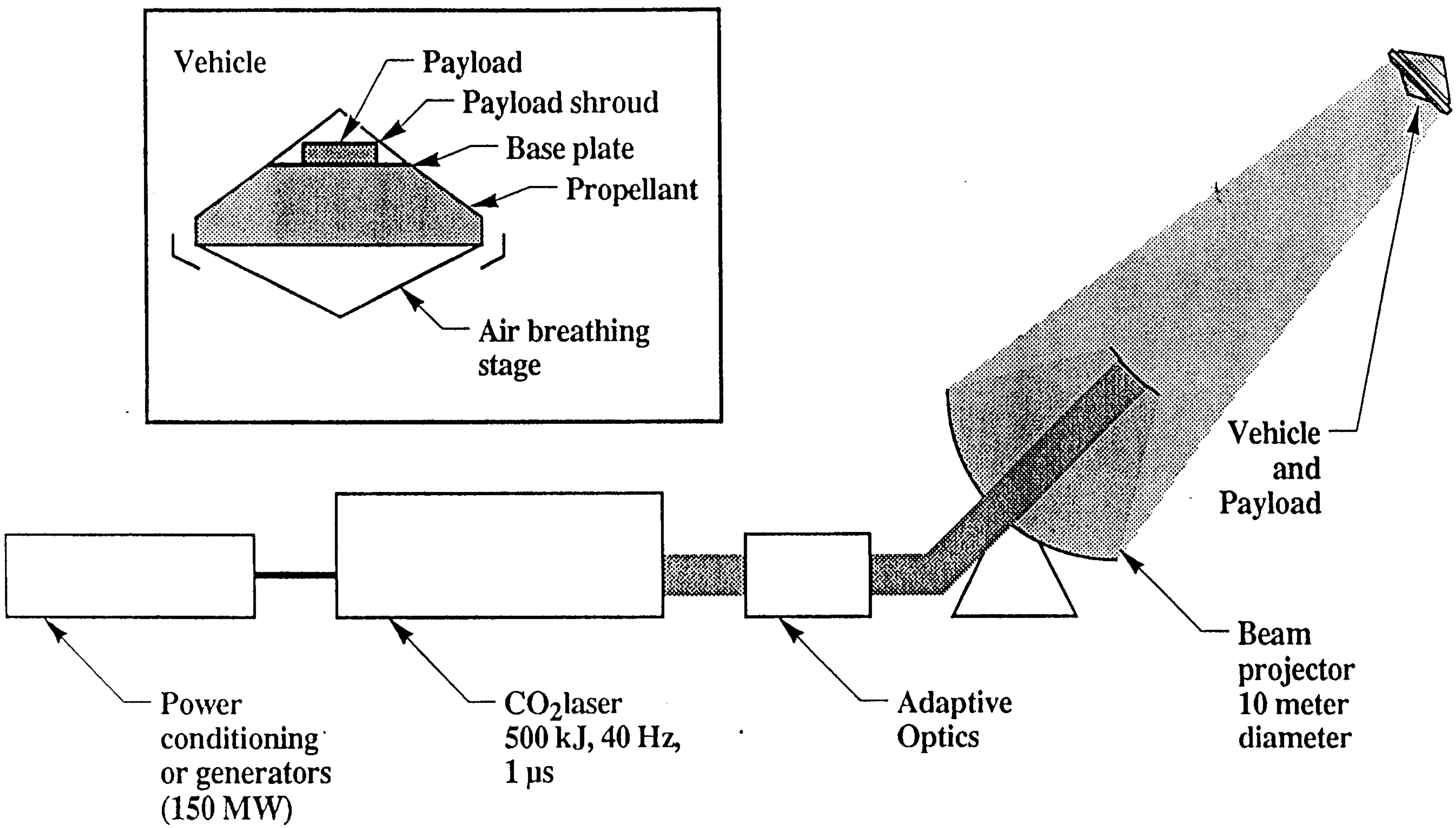
E) Uniformly hot gas expands in 1-D,
producing thrust $\tau_{exp} = 3 - 10 \mu s$



F) Exhaust dissipates; cycle repeats at 100 Hz - few kHz

Figure 2:
Components of a 20 MW/20 kg Laser Launch System

SDIO Laser Propulsion Program



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