Modular Laser Launch Architecture: Analysis and Beam Module Design

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Dr. Jordin T. Kare
Kare Technical Consulting
908 15th Ave. East jtkare@attglobal.net
Seattle, WA 98112 206-323-0795

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Executive Summary

A major obstacle to the development of revolutionary space launch systems is the combination of high cost and high technical risk. Systems ranging from rocket-based reusable launchers to air-breathing combined cycle engines to space elevators cannot be developed or realistically tested without investment of hundreds of millions to billions of dollars.

Laser launch uses a large ground-based laser system to power small rocket vehicles loaded with inert propellant. Laser launch has many potential advantages over other launch technologies in performance and cost. Its disadvantage is the need for a very large laser, with an output power of roughly one megawatt per kilogram of payload size -- tens to hundreds of megawatts for practical payloads. Developing such a laser and its associated large beam director has always involved costs and risks at least comparable to those of developing a new launch vehicle. Laser propulsion has therefore remained a laboratory curiosity, limited to tests with existing lasers at power levels of at most a few kilowatts.

However, laser launch has a unique and heretofore unappreciated advantage over other advanced launch technologies: modularity. The laser source does not need to be a single monolithic laser, but can consist of many relatively small lasers operating in parallel. A small laser (and associated beam director and other hardware) could potentially be developed at modest cost and relatively low risk, and then duplicated as needed to build an arbitrarily powerful launcher.

The purpose of this Phase 1 effort was to determine whether such a modular laser launch system is feasible, and if so, what the characteristics of each “beam module” might be; in particular, we sought to identify long poles where technology development is needed.

This effort focused on beam modules appropriate to the heat-exchanger (HX) thruster approach to laser launch, i.e., continuous (CW) lasers, although the beam module concept is applicable to pulsed laser propulsion systems as well.

The key results of his effort are as follows:

1. Recent developments (in some cases within the last year) in lasers and related technologies have made a modular laser system clearly feasible, and straightforward to develop. At least three laser technologies have been demonstrated that can provide sufficient power and beam quality for a practical beam module using otherwise-conventional technology, including glass optics.
    - 1a. Diode-pumped Ytterbium-doped fiber lasers have recently been demonstrated at 1 kW power levels and are projected to reach 10 kW in the near future. Fiber lasers are extremely efficient (>40% DC to light) and produce high-quality single-mode output. They are also robust and lend themselves to low-cost volume production; fiber lasers intended for industrial applications are already available commercially at power levels up to several hundred watts.
    - 1b. The diode-pumped alkali-vapor laser (DPAL), invented within the last year, may be competitive with fiber lasers in cost, and has the advantage of operating at a shorter wavelength (795 nm for Rb vapor, vs. 1080 nm), making it compatible with standard silicon and GaAs photovoltaic cells.
2. The cost of the relevant laser technologies is driven by the cost of laser diode arrays. Laser diode arrays are now a commodity product, with multiple competing manufacturers. Projecting current array prices to the quantities needed for a modular launch system yields prices of $2-3/watt for packaged arrays and $7-10/watt for complete lasers. Improvements in fabrication and packaging technology could potentially drop diode costs below $1/watt.
3. Low-cost optical fabrication technologies were thought to be required for a modular laser system, since the initial concept required of order 100,000 m^2 of optical aperture. No such technologies were identified, and some possibilities (e.g., electroformed optics) were effectively ruled out by analysis of the optical requirements. Fortunately, the required optical aperture area is inversely proportional to the laser beam quality and power (formally, the source radiance), and the laser options cited above require only of order 1000 m^2 of aperture, which can be fabricated at acceptable cost with standard techniques.

4. The beam module telescope can be a standard afocal Cassegrain telescope on a two-axis (alt-alt) mount. This very conventional optical configuration is made feasible in part by a significant breakthrough at the cutting edge of optical technology: photonic crystal fibers. These use regular patterns of holes running the length of the fiber to guide single-mode laser light at very high power with low loss. They allow the laser system to be mounted separately from the telescope without incurring the losses and alignment costs of traditional multiple-mirror beam paths.
5. The best telescope size currently appears to be close to 1 meter (0.9 – 1.2 meters, depending on manufacturing details), but using multiple small (30 – 50 cm) telescopes on a common mount warrants further consideration.
6. Other components of the beam module – beam pointing and tracking, power supplies, etc. – are well within the current state of the art, and a baseline configuration has been developed.
7. The largest open question for beam module design is whether adaptive optics to correct for atmospheric turbulence are worthwhile, and if so how to implement them. An active beacon on the vehicle is needed for tracking, and the beam power densities are low enough to avoid nonlinear effects such as turbulence-thermal blooming interaction, so adaptive optics would be technically straightforward, but might drive the design and cost of the optical system.
8. While primarily designed for laser launch, beam modules can transmit power for in-space propulsion, or more generally for laser power beaming. Their combination of low unit cost and large numbers enables many concepts involving distributed sources and multiple users. Ideally, beam module components can themselves be modular, allowing mixing and matching of lasers, telescopes, and tracking systems for different applications.

Based on these results, and somewhat surprisingly, it appears that further development of the beam module itself is an interesting but largely straightforward engineering problem. Although there is substantial room for improvement in specific technologies, such as fiber lasers and low-cost diode arrays, research on these technologies is being actively pursued for commercial and government purposes, so that the leverage available through NIAC-supported research is limited. Instead, the next steps in developing the modular launch architecture are to validate the thruster and vehicle concept, to improve system performance and cost estimates, and to understand the space-architecture implications of cheap high-volume, small-payload laser launch.

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Introduction: Laser Launch and the Beam Module Concept

Background: Laser Launch

Ground-to-orbit launch uses a ground-based laser to directly heat an inert propellant, which is exhausted to provide thrust to a small rocket vehicle. The concept was originally proposed by Kantrowitz [1] and has been investigated by a number of researchers; a convenient and extensive compilation of recent work and reviews of prior work can be found in [2]. Some of the features and benefits of laser launch in general are shown in Table 1.

TABLE 1: Features And Benefits Of Laser Launch

Feature	Details	Benefits
High performance	I_{sp} > chemical rockets, not limited by chemical energy storage. Thrust to weight similar to chemical rockets, >> other high-I_{sp} technologies	• Single stage to orbit with large margins
Simple vehicles; ground-based laser	Most hard parts stay on the ground; vehicle complexity ~ single-stage solid or pressure-fed liquid	• Low vehicle cost • High reliability, • Low maintenance cost
High launch rate	5-10 minutes per launch, as long as the laser runs	• Huge total launch capacity: >10,000 launches per year • Rapid response • Uniquely testable -- 1000 test launches in <1 month
Inert vehicles	No stored energy onboard; vehicle cannot fly off course due to guidance/control failure	• Greatly reduced range safety issues and costs
Nontoxic propellant	Primary propellants are liquid hydrogen and other common liquids (LN2, water)	• No handling or environmental issues

Projected costs for laser launch are heavily dependent on the launch system characteristics and the assumptions used. However, we estimate that with plausible assumptions, even the "full up" cost of laser launch, including vehicles, operations and maintenance, and capital amortization, can easily be below $220/kg ($100/lb), provided the launcher is used at a reasonable fraction of its full capacity.

The main obstacle to the development of laser launch has been the cost of laser. A rule of thumb for laser launchers is that the unit payload is 1 kg per MW of laser power. An operational laser with even 100 MW of output power would be very expensive -- over $1billion with the most optimistic estimates, and quite possibly several times as much. Such a laser (and its beam director) would also be a major step beyond demonstrated technology and therefore a large technical risk; the largest existing lasers have average power levels of order 1 MW, and the largest routinely-operating lasers are an order of magnitude smaller.

As with many advanced launch concepts, laser launch thus suffers from a “chicken and egg” problem: without a large laser, it is impossible to prove that laser launch is workable, much less cheap and reliable; without a proven launch technology, it is impossible to justify massive investment in new high-power lasers.

The Modular Laser Concept

In 1993, we proposed using non-coherent arrays of laser diodes to power a laser-launched vehicle. [3] The advantage of this approach was that diode arrays were compact, efficient (50% DC-light), infinitely scaleable, and potentially much cheaper than any other laser technology. The disadvantage was that a non-coherent source required a much larger optical aperture area than a coherent source to concentrate sufficient flux on a vehicle at long range.

For a diode array-based launcher to be remotely practical, this large aperture -- several thousand square meters -- could not be in the form of a single gigantic telescope or optical phased array. The key to making the diode array concept work was the realization that the optical aperture could instead be made up of many comparatively modest, low quality telescopes, which could be mass produced to keep their cost low.

This division of the laser source among many apertures was initially regarded only as a necessary evil, required by the low radiance of noncoherent arrays. However, we have recently realized that the fact that the laser and optical aperture can be subdivided into small independent beam modules is a fundamental advantage of laser propulsion over other advanced propulsion systems, and may well be the key to making laser launch the best option for a future launch architecture.

This key, and unique, advantage of laser propulsion is that it is possible to develop, test, and debug a very small element of a laser launcher -- perhaps as small as 1/10,000 of the full system -- and then simply replicate that element to launch a payload of any desired size. This is not possible with any other launch technology we are aware of: one cannot, for instance, build 100 small railguns or reusable launch vehicles (RLV’s) and stack them together to launch a large payload.[*]

A closely related advantage is that no single failure can result in loss of a significant part of the system, either during development or during operation. Again, this is certainly not true of most other launch systems (as, tragically, Columbia recently reminded us). RLV’s, with very high cost vehicles and tight margins, are particularly at risk, but so are radically different technologies such as gas guns and space elevators. Both of these have catastrophic failure modes which can destroy a large part of the system, and a very large investment, in a single event.

Other advantages of a modular laser launcher are:

- It enables the use of many types of lasers which cannot produce single very high power coherent beams, either because of fundamental limits or because of the practical problems of scaling them to large size.
- It reduces or eliminates problems inherent in a single high power laser and beam director. These include thermal blooming and coupled turbulence-blooming effects, which at best require high performance adaptive optics and at worst are uncorrectable, and scintillation.

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[*] It is possible in principle to build of order 100 small rocket engines or expendable rocket stages and stack them together to launch a large payload, but efforts to do so have not been notably successful: the Russian N-1 launcher, with many small engines, was a catastrophic failure, and the OTRAG parallel-staged vehicle was never completed. There is at least one ongoing effort of this type: the Scorpius launch vehicle being developed by Microcosm, Inc. However, the inherent structural overhead in such a modular rocket, and the inherent costs of expendable multistage rockets, limit the possible benefits.

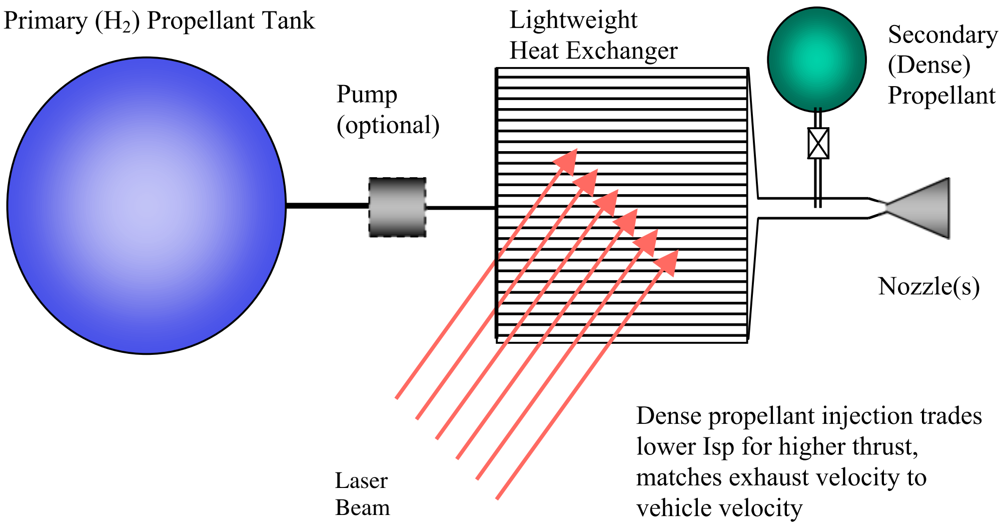

Figure 1: Heat Exchanger (HX) thruster concept

- New technologies (and new suppliers) can be incorporated at any time. For example, a higher-performance laser can be incorporated at any point in the development and production cycle of beam modules for a launcher, without interfering with the operation of already-produced modules. (By contrast, consider the difficulty of introducing a new turbine alloy or structural composite into a half-built SSTO).
- Development and testing of the of the overall launch system can start with the first beam module, and scale smoothly to a fully operational system. The only "subscale prototypes" required are inexpensive expendable vehicles.
- The launcher can be made arbitrarily reliable, simply by having more modules than are needed for operation; individual module failures have no effect on the overall system. A sufficient set of extra modules can also eliminate most system "down time," since modules can be rotated out of service for maintenance or repair as required without shutting down the system.

The Heat Exchanger Thruster and Vehicle

In principle, a modular laser launch architecture can encompass almost any kind of laser propulsion – pulsed or continuous-flow, air-breathing or pure rocket. In practice, the modular architecture, was invented in connection with the heat exchanger thruster, and is ideally matched to it.

The heat exchanger thruster [4] and vehicle concepts were invented by Kare as a CW-laser-compatible alternative to pulsed laser thrusters (e.g., [5], [6], [7]). In an HX thruster, liquid propellant is pressure- or pump-fed to a lightweight planar heat exchanger. For orbital launch, the propellant of choice is liquid hydrogen. H_2 provides a vacuum I_{sp} of 600 seconds, sufficient for a robust single-stage-to-orbit capability, at a heat exchanger temperature of only 1000 C (less than 2000 F). The heat exchanger can therefore be made of ordinary materials, rather than exotic high-temperature alloys, which allows building cheap expendable vehicles.[*] Figure 1 illustrates the basic HX concept.

The heat exchanger rocket has several advantages over other beamed-energy propulsion concepts. It is:

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[*] The alternative approach, using high temperature materials to reach 800 – 900 s Isp, is of interest for in-space propulsion, and for launch systems which can re-use vehicles or components; it may be competitive even for expendables if material and fabrication costs can be kept low. Further trade studies on heat exchanger options are certainly needed.

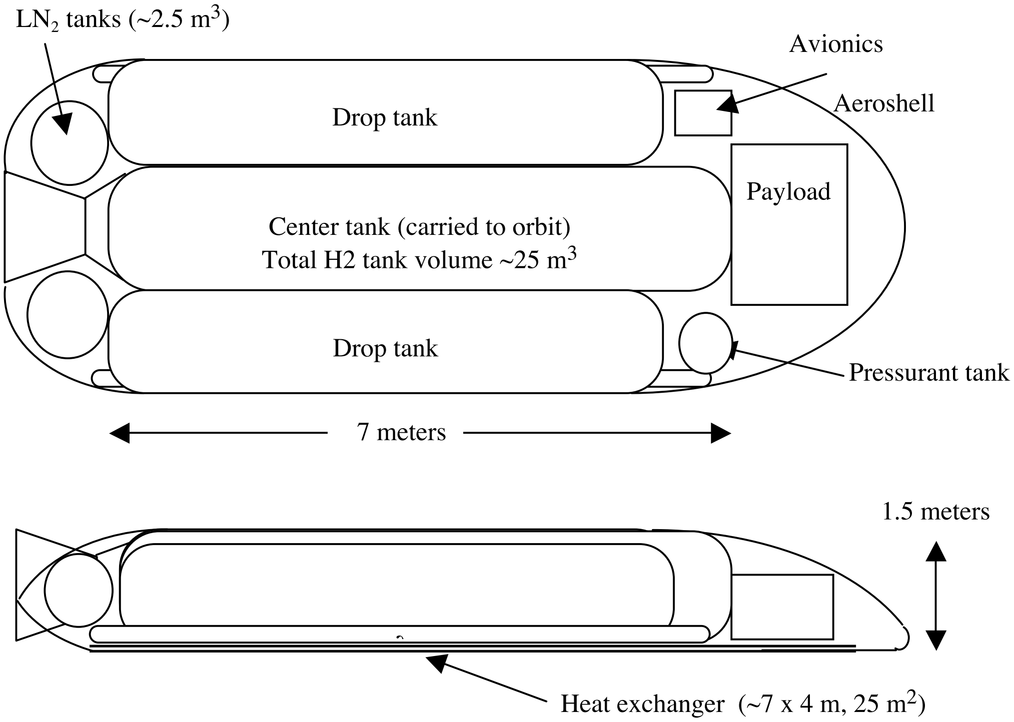

Figure 2: 100 MW HX vehicle concept. Dimensions are approximate.

- **Compatible with any laser**. The heat exchanger, as a simple solid absorber, works equally well with CW or pulsed lasers, and with lasers of any wavelength.
- **Highly efficient**. The low operating temperature minimizes reradiation losses, and moderate-temperature hydrogen is a nearly ideal propellant, so over 90% of the laser energy reaching the vehicle can be converted to useful exhaust kinetic energy, vs. 25% to 50% for pulsed laser thrusters. Also, the exhaust velocity can easily be varied by injecting dense propellant (e.g., liquid nitrogen) into the normal hydrogen flow. Maximum rocket efficiency is achieved when the exhaust velocity equals the vehicle velocity throughout the trajectory; the HX thruster can closely approximate this ideal case.
- **Flexible**. The thrust vector is independent of the heat exchanger orientation, so the heat exchanger can be sized and arranged to optimize the vehicle and system design; in particular, to minimize drag.. The heat exchanger requires no optics on the vehicle, and can accept a beam from any angle, allowing a much wider range of trajectories than "beam riding" vehicles that can only accelerate along the beam.
- **Easy to develop**. Except for the heat exchanger itself, all the components can be designed and tested using conventional aerospace techniques and facilities. The heat exchanger requires no exotic materials, and can be tested with any laser or with non-laser heat sources such as solar furnaces, arc lamps, or even electric heaters.
- **Easy to demonstrate**. Test vehicles can use water or liquid nitrogen rather than liquid hydrogen as propellant. The high thrust and high efficiency of the HX thruster means that even modest lasers can launch relatively heavy vehicles, and the large heat exchanger area minimizes requirements on beam quality and pointing.

The main reason the HX thruster and modular laser are a good match is the fundamentally CW nature of the HX thruster. As discussed below, the most promising technologies for low-cost modular lasers – fiber lasers, diode pumped alkali lasers, and diode arrays -- naturally produce a continuous beam. None can produce the high energy, limited-repetition-rate pulses needed for a large pulsed laser thruster. High-pulse-energy pulsed lasers are likely to always be significantly more expensive than CW lasers, because of the need for both a large volume of energy-storing lasing medium (a 1-kW fiber laser has only a fraction of a cubic centimeter of lasing medium) and high-peak-power optics.

Another factor derives from the structural flexibility of the HX thruster; a side-facing heat exchanger can be larger than the front- or rear-facing collecting surface required by most pulsed thruster designs, without producing excessive drag. This minimizes the optical performance required of the beam modules: the size and figure accuracy of the primary optic and the pointing accuracy of the tracking system can be lower than with other approaches.

The current baseline HX vehicle concept is shown in Figure 2. The dimensions shown are for a 100 MW (collected power) vehicle, with a nominal payload of 100 kg.

The mass and performance characteristics of this vehicle have been modeled to a first-order physics-based level, and the design appears to close with reasonable mass margins and other assumptions. The actual payload depends on various factors, including the altitude and velocity at which the vehicle starts, the exact trajectory flown, and whether or not the vehicle drops some mass (empty tanks and aeroshell) once above the atmosphere. There is still extensive room to optimize the vehicle and trajectory design, especially the use of dense propellant injection to control I_{sp}, so the estimated mass to orbit is conservative. Details of this modeling are given in a recent paper [8].

NIAC Phase I Objectives

Three main tasks were identified in the Phase I proposal:

1) Define source requirements and scaling relationships for modular laser launch systems

2) Develop beam module options and baseline designs

    2a) Review relevant technologies, including laser technologies (diode arrays, fiber lasers, gas-discharge lasers, and others as appropriate), optical fabrication techniques for low-cost large optics, and adaptive optics

    2b) Define characteristics (power, aperture size, etc.) for possible beam modules using various laser technologies

    2c) Select one or more baseline beam modules from possible options (based on projected cost and feasibility) and prepare preliminary module designs

    2d) Prepare beam module technology roadmap; identify key development issues and possible high-leverage technology improvements leading to low-cost, highly manufacturable beam modules

3) Update system concept and develop architecture roadmaps

    3a) Define system characteristics, especially number of beam modules, for various classes of developmental and operational laser launch systems, from sounding-rocket tests through large-scale cargo and human launches

    3b) Identify and, where possible, quantify other system characteristics and requirements associated with these systems, such as power requirements, launch site and other infrastructure requirements, and safety and environmental issues

    3c) Prepare an overall roadmap for development of an operational modular HX launch system and transition from current launch technologies to a mixed laser/conventional launch and eventually to either primarily laser launch or a mixed launch architecture of laser launch and advanced reusable vehicles

Phase I Results

Task I: Source Requirements and Scaling Relationships

Vehicle Dependent: Power, Range, Run time

There are two constraints on the laser power needed to launch a payload from the ground to orbit:

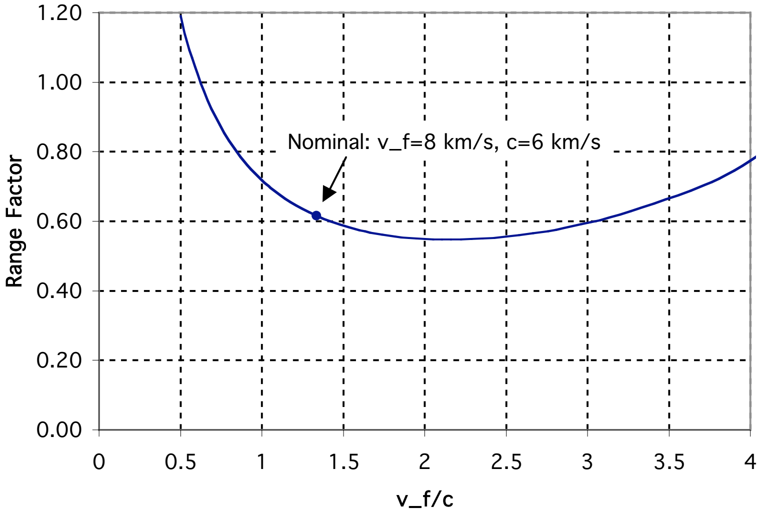

Figure 3: Acceleration range vs. β = *final velocity/exhaust velocity*

range and minimum acceleration.

For a launch system, the range limit may be set by the vehicle going over the laser's horizon, or (for a ground-based laser) by the vehicle getting too close to the laser's horizon, resulting in the beam being absorbed in the atmosphere. Of more interest for this effort, however, is the fact that the laser beam divergence will cause the beam to grow with distance, eventually becoming larger than the vehicle's heat exchanger (or other beam-collecting surface) so that the transmission efficiency η_{trans} from the laser to the vehicle falls off, eventually as $1/R^2$. The useful range of the laser system therefore depends on the beam divergence (and the vehicle dimensions), or, conversely, a range requirement can be used to define the beam divergence, and therefore the laser and optical system requirements.

We can calculate a maximum mass vs. range by ignoring gravity and drag effects, and considering a simple free-space acceleration with a thruster exhaust power $P_{thr} = P_{laser}\,\eta_{trans}\,\eta_{thr}$. We consider two more-or-less limiting cases: conventional constant-specific impulse operation with constant exhaust velocity $c = g\,I_{sp}$, and matched-velocity operation where the exhaust velocity equals a fixed multiple of the vehicle velocity $c(t) = c_0\,v(t)$. (In the latter case, some care is needed to choose the correct frame of reference; the correct frame is generally the one in which the vehicle was originally at rest.) For simplicity, we initially assume a constant thruster power (i.e., constant transmission losses and thruster efficiency).

For the constant-I_{sp} case,

$$\frac{dm}{dt} = -2P_{exh}/c^2 = 2P_{laser}\eta_{trans}\eta_{thr}/c^2 \qquad (1)$$

$$\frac{m(v)}{m_i} = e^{-v/c} \text{ (the rocket equation)} \qquad (2)$$

From these, we can calculate the distance L the vehicle travels going from v=0 to a final velocity v_f. Defining for convenience $\beta = v_f / c$,

$$L = \frac{m_f v_f^3}{2P_{exh}} \left(\beta^{-3}\right)\left(e^{\beta} - \beta - 1\right) \tag{3}$$

Thus, we can directly calculate the mass we can get to orbital velocity for a given acceleration range and power. The expression $\beta^{-3}\left(e^{\beta} - \beta - 1\right)$ is plotted in Figure 3, and has a minimum of 0.55 near β =2:

$$m_f = \frac{2P_{exh}L}{v_f^3}\left(\frac{\beta^3}{e^{\beta} - \beta - 1}\right) \le 3.64\,\frac{P_{exh}\,L}{v_f^3} \tag{4}$$

Quantitatively, for v_f = 8000 m/s and *c* = 5900 m/s (~600 s I_{sp}), m_f = 6.39 kg/MW(exh) x (L/1000 km).

For the matched-velocity case,

$$\frac{dm}{dt} = \frac{-2P_{exh}}{\left(c_0 v\right)^2} \tag{5}$$

$$m\frac{dv}{dt} = \frac{2P_{exh}}{c_0 v} \tag{6}$$

$$c_0\frac{dm}{m} = -\frac{dv}{v} \tag{7}$$

$$\left(\frac{m}{m_i}\right)^{c_0} = \frac{v_i}{v} \tag{8}$$

Note that this diverges for zero initial velocity (and zero exhaust velocity), so a real system will have a minimum exhaust velocity c_{min}; for $c_0 v < c_{min}$ the rocket equation will apply.

The matched-velocity case is particularly simple for $c_0 = 1$: $mv = m_i v_i = m_f v_f$, and $dv/dt = a = 2P_{exh}/m_f v_f$, so the vehicle has a constant acceleration *a* and (with a small error due to the initial acceleration from rest up to v_i),

$$L = \frac{v_f^2}{2a} + L_i \tag{9}$$

$$m_f \approx \frac{4P_{exh}}{v_f^3}L \tag{10}$$

The energy efficiency of the matched-velocity case is significantly higher than the constant-thrust case (ideally, 100% at $c_0 = 1$ vs. approximately 65% at at $\beta \sim 1.6$).

A real launch system will, of course, have varying exhaust power over its trajectory, due to varying transmission losses, and therefore will have some longer range for a given final mass and maximum power. A drop in power and acceleration at the beginning of the trajectory, when velocity is low, will have less effect on *L* than one at the end of the trajectory, suggesting that the laser should be sited to maximize power received at the end of the trajectory.

Quantitatively, for v_f = 8000 m/s, m_f = 7.8 kg/MW(exh) x (L/1000 km).

For a true ground-launched vehicle, the lower acceleration limit is 1 g -- 9.8 m/s^2 – since the vehicle must be able to lift itself off the ground. Even if the vehicle gets some initial velocity, as from a catapult or carrier aircraft, an initial thrust/weight of close to 1 g is needed to maintain vertical velocity and accelerate horizontally before falling back to Earth.

For conventional rockets, it is common to approximately account for gravity and drag losses by defining an effective mission velocity v_{eff} somewhat greater than orbital velocity, typically between 9 and 10 km/s; the value will also depend somewhat on the initial acceleration, but not strongly. This allows us to set a maximum on m_f for the constant-I$_{sp}$ case:

$$m_f = e^{-v_{eff}/c} m_i \le \frac{2P_{exh}}{a_i c} e^{-v_{eff}/c} \tag{11}$$

which has a maximum at $c = v_{eff}$, but falls off slowly for c within roughly a factor of 2 of the optimum. Combining this with the range calculation above, ***if*** the exhaust power is constant from launch to orbit, we get

$$m_f = \frac{2P_{exh}L}{{v_f}^3}\left(\frac{\beta^3}{e^\beta - \beta - 1}\right) \le \frac{2P_{exh}}{a_i c} e^{-v_{eff}/c} \tag{12}$$

$$L \le \frac{{v_f}^2}{a_i}\left(\frac{e^\beta - \beta - 1}{\beta^2}\right) e^{-v_{eff}/c} \tag{13}$$

Quantitatively, for v_{eff}=10 km/s and a_i=9.8 m/s^2, m_f is between 6.4 and 7.5 kg/MW(exh) for I$_{sp}$ between 600 and 1000 seconds, and *L* is between approximately 1000 and 1600 km.

(The acceleration time is just

$$t_f = \frac{\left(m_i - m_f\right)}{-dm/dt} = \frac{c}{a_i}(1 - e^{-v_{eff}/c}) \tag{14}$$

or slightly less than the specific impulse divided by the initial acceleration (in units of g).

For the matched-velocity case, we assumed a 1/*e* mass ratio in accelerating from 0 to $v = c_{min}$, which gives

$$m_f = e^{-1} m_i \frac{c_{\min}}{v_{eff}} \le \frac{2P_{exh}}{a_i v_{eff}} e^{-1} \tag{15}$$

which is approximately 7.5 kg/MW; the corresponding range is approximately 960 km.

Trajectory simulations give results somewhat different from these in numerical values, but with similar scaling. In particular, m_f in simulations is somewhat smaller than calculated here for launches from the ground, even allowing for transmission losses, in part because the thruster efficiency is lower in the atmosphere than in vacuum, even with an ideal nozzle. The analytical values are more typical of air-launched vehicles starting at high altitude, or ground-launched vehicles given a sizeable (300 m/s) initial velocity.

Typical simulated trajectories give total mass to orbit of 4-5 kg/MW(laser), and involve nominal powered trajectories of 600-800 km – the actual powered flight distance is often considerably longer, but with power dropping off rapidly beyond the nominal distance.

The actual laser-to-vehicle range, which is what drives the beam module characteristics, is of course not the same as the trajectory length *L*. The laser range will be longer than L due to the slope of the laser beam, but can be shorter if the laser is located in the middle of the trajectory rather than at the vehicle launch site.

As a nominal design baseline, we assume the vehicle is launched approximately 200 km uprange of the laser array, and is powered to a nominal range of 400 km downrange at an altitude of 300 km. The final vehicle mass to orbit is between 4 and 5 kg/MW(laser).

The actual payload to orbit, of course, depends not only on the total mass to orbit but on how much of that mass is payload, as opposed to vehicle components. Vehicle design was outside the scope of this project, except for some nominal heat-exchanger sizing discussed in the next section, but a ground-launched vehicle appears to require 3-5 kg of heat exchanger, tanks, structure, etc. per MW. Obviously the upper end of that range implies no payload to orbit; in that case, the system becomes dependent on less-than-ideal compromises such as partial staging (dropping empty propellant tanks) or aggressive launch assists such as air drops or catapults. A considerably more detailed vehicle design is needed to determine the "true" payload per MW; for the purposes of this study we continue to use a nominal value of 1 kg/MW(laser).

Pulsed propulsion concepts can have substantially lower non-payload vehicle mass – zero, in the limit of the planar double-pulse thruster, in which the entire propulsion system is a simple block of solid propellant. However, pulsed thrusters have lower (and as yet poorly-known) thruster efficiencies, probably between 25% and 50% for I_{sp}s in the optimum range for low-orbit launch. Higher efficiencies may be possible at substantially higher specific impulse, but that leads to decreasing mass to orbit and increasing range requirements; e.g., at 4000 s fixed I_{sp} (c = 3920 km/s), $m_f = 4.0$ kg/MW(exh), and $L \sim 2700$ km.

Flux and Heat Exchanger Requirements

Power to weight is the most rigid constraint on a launch vehicle heat exchanger, since the heat exchanger mass is carried to orbit and every additional kilogram of heat exchanger reduces the payload to orbit. Heat exchanger mass mass must be less than ~2 kg/MW(exh) (specific power S of >0.5 MW/kg,) to allow a reasonable overall vehicle mass budget.

The flux (laser power per unit area) at the vehicle is constrained by several factors. For full-scale vehicles, the heat exchanger (or other collector) area is constrained by plausible vehicle dimensions, air drag, and structural support mass requirements; a 100 MW, 500 kg-dry-mass vehicle could not readily support a 10 x 10 meter heat exchanger operating at a mean flux $<\phi_{vehicle}>$ of 1 MW/m^2. (The square-cube relationship between surface area and mass, and similar scaling for, e.g., buckling of structural members, means that the benefits of high flux are greater for larger vehicles; conversely, small test vehicles can fly at lower flux). The power/weight constraint also means that a low flux heat exchanger must be extremely flimsy; areal density $\sigma = <\phi_{vehicle}>/S$. At 1 MW/kg and 1 MW/m^2, the entire heat exchanger structure would need to mass 1 kg/m^2; for a metallic heat exchanger (density $\rho \sim 9$ Mg/m^3) the heat exchanger could have an average solid material thickness of only 0.11 mm.

The baseline 100 MW vehicle has a 4 x 7 m heat exchanger which operates at $<\phi_{vehicle}>$ ~3.6 MW/m^2. The baseline design assumes a heat exchanger mass mass of 128 kg (1 kg/MW + 1 kg/m^2 to allow for manifolds and support structure) and thus a mean areal density for the actual heat exchanger of 3.6 kg/m^2. The actual heat exchanger will probably vary in areal density, with the highest-temperature sections being the heaviest, but 3.6 kg/m^2 appears to be (just) achievable with a metallic heat exchanger, and fairly easy to achieve with a graphite- or ceramic-based heat exchanger.

Minimum operating flux for a flat-plate absorber is also constrained by reradiation. At a surface temperature Ts, a black surface will radiate power according to the familiar Stefan-Boltzmann formula

$$\phi_{reradiated} = \sigma_{sb} T_s{}^4 \tag{16}$$

where $\sigma_{sb} = 5.67 \times 10^{-8}$ J K^{-4} m^{-2} s^{-1}

This leads to a loss of power from the hottest part of the heat exchanger that is shown in Figure 4. Clearly, a 100% loss is unacceptable; the 100% loss curve represents the asymptotic limit of the temperature the heat exchanger can reach. Given that laser power is expensive, it is highly desirable to operate above at least the 30% loss curve. (Note that, averaged over the whole heat exchanger, the loss will

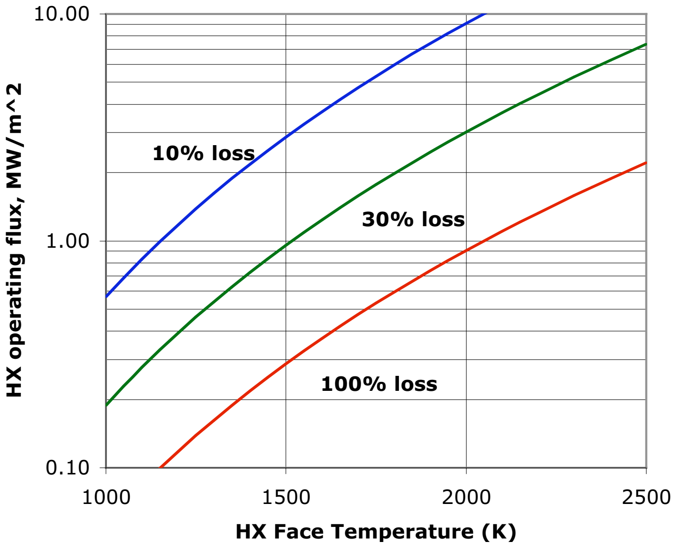

Figure 4: Reradiation loss as a function of heat exchanger temperature and flux

be much lower.) Thus, a flat heat exchanger operating at Ts = 1500 K must operate at at least 1 MW/m^2, and preferably several times higher; at Ts = 2000 K the minimum is roughly 3 MW/m^2

The maximum flux on the heat exchanger is driven by the thermal conductivity of the heat exchanger material, and the heat transfer coefficient from the solid heat exchanger into the propellant gas. Thermal conductivities for materials of interest range from ~40 W/m-K (silicon carbide) to several hundred W/m-K (copper, graphite); at 100 W/m-K conductivity and $\phi = 10$ MW/m^2, the temperature gradient is 10^5 K/m, or 100 K per millimeter. The temperature drop from the heat exchanger inner wall to the propellant gas depends on the heat exchanger design, but is also proportional to the incident flux. In the baseline heat exchanger design, the total temperature drop from surface to gas is roughly 100 K at 3.6 MW/m^2.

The maximum-flux limit is of interest mainly because it limits how uniformly the heat exchanger is illuminated. The baseline heat exchanger is designed to accept a peak flux of 5 MW/m^2 on the hottest part of the heat exchanger. A 2:1 variation in flux across the heat exchanger will generally be acceptable; a 10:1 peak in flux, lasting more than a few milliseconds, would certainly destroy the baseline heat exchanger.

Concentrators

We can increase the collection area (and potentially reduce the mass) of a heat exchanger by using optical concentration, as in concentrator-type solar arrays. All concentrators have the disadvantage of reducing the acceptance angle for the laser beam; i.e., the concentrator needs to maintain a specific orientation relative to the beam, and the higher the concentration the narrower the range of orientations allowed.

Concentrators also add drag and mass to a vehicle. Drag effects can be avoided if the concentrator is deployable, and is not deployed until the vehicle is above the atmosphere. Mass can be kept low if thin, lightweight structures can be used for the concentrator. Both of these factors mitigate against using high concentration ratio concentrators which need precise shaping and alignment.

A simple deployable concentrator scheme which doubles the effective collection area (and thus halves the flux requirement) for a flat-plate heat exchanger is sketched in Figure 5.

An option for using concentrators is to start the vehicle at high altitude, above enough of the atmosphere to allow the vehicle to use a concentrator over its entire powered trajectory. A balloon or aerostat launch platform [9] could carry vehicles with fixed concentrators; a volume-limited launch

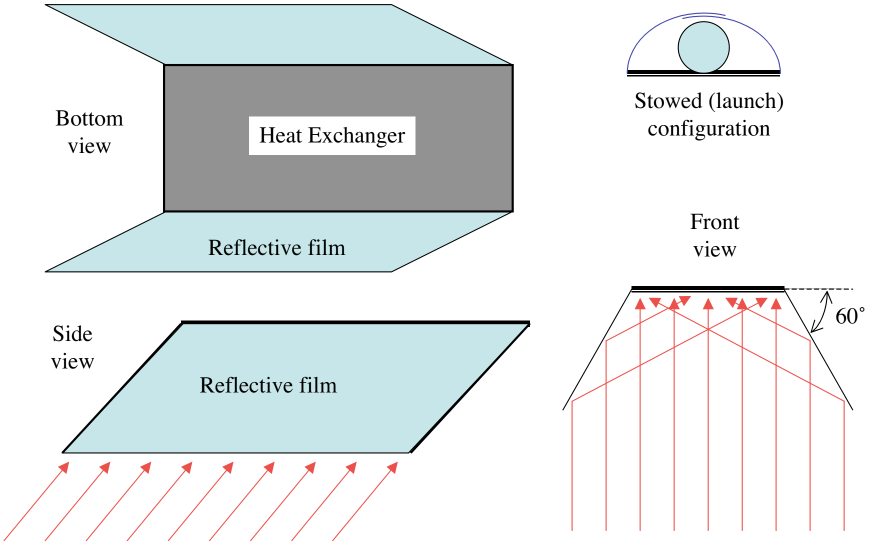

Figure 5: 2:1 deployable concentrator for HX vehicle

platform such as DARPA's RASCAL carrier vehicle [10] would still require the reflector to deploy, but could use geometries such as that sketched in Figure 6. This appears to be the best option for small (<<100 MW) vehicles. For example, a 10 MW vehicle (~50 kg dry mass), operating at 5 MW/m^2 flux, would have a heat exchanger area of only 2 m^2, requiring a very narrow beam. Using a 0.1 mm (~ .004 inch) curved or holographic film concentrator, the same vehicle could plausibly support a 20 m^2 collection area, comparable to the baseline 100 MW vehicle, with a collector mass of order 6 kg (0.15 kg/m^2 for the film, plus support structure)

Most non-HX laser propulsion approaches require on-vehicle concentrators with high concentration ratios, which is a major reason for preferring the HX thruster.

Aperture Requirement and Radiance/Aperture Trade

Before considering specific technologies for beam modules, it is necessary to know at least roughly the number of modules of interest and the scale of the optics and lasers involved. The first constraint is the total aperture area, which is a function of the required range R and ϕ_{vehicle} – or, equivalently, the required source brightness (watts per steradian).

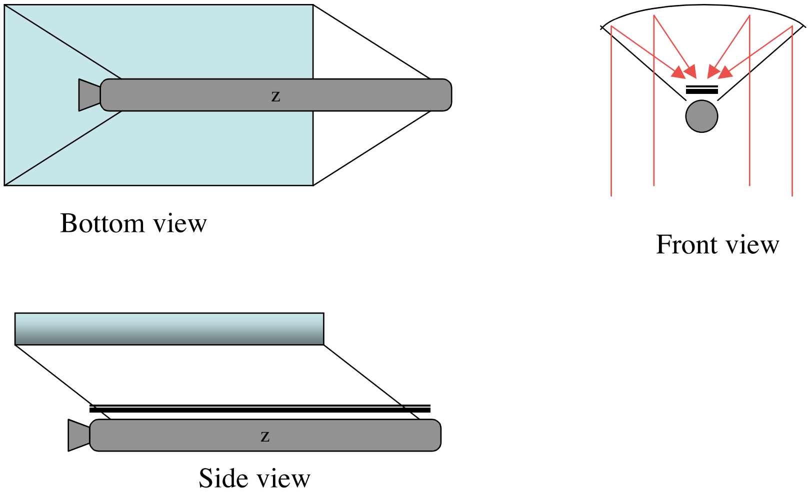

Figure 6: Concentrator configuration for small vehicles.

$$B_{source} = \phi_{vehicle} R^2 = A_{source} \Re_{source} \tag{17}$$

where $\Re_{source}$ is the source radiance. Radiance is measured in watts per square meter per steradian (W/m^2-sr). Radiance is a convenient parameter because it is characteristic of an optical source, and is conserved (aside from losses) through optical transformations.

For a coherent beam with power P, radiance on axis is given by

$$\Re = P / (\lambda^2 M^2_x M^2_y) \tag{18}$$

where $M^2_{[x,y]}$ is the beam quality factor for the [x, y] axis [11].

For a noncoherent extended source, such as an array of laser diodes, the radiance is given by

$$\Re = P / A_{source} \Omega_{source} = P / l_x l_y \theta_x \theta_y \tag{19}$$

where l_x and l_y are the source dimensions (for a rectangular array) and θ_x and θ_y are the source divergence angles. Note that this is independent of wavelength, and independent of power to the extent that the array has a fixed power per unit area (e.g., current diode array stacks produce ~500 W/cm^2, for power levels from 100 W to many kilowatts). It is not difficult to show that for an extended source made up of many small coherent sources, the best possible radiance achievable, for instance by adding microlenses in front of each source, or squeezing the sources closer together, equals the radiance of a single source – e.g., one laser diode in a laser diode array.

(The radiance for a blackbody source at temperature T is just $\sigma T^4 / \pi$, where σ is the Stefan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}.)

For the baseline vehicle, the required flux is $\phi_{vehicle} \times 1/\cos(\theta)$ where θ is the angle between the heat exchanger normal and the beam. For a nominal angle of 45 degrees, this is 3.6 MW/m^2 x 1.41 ≈ 5 MW/m^2. The range depends on the trajectory and laser placement (e.g., whether the laser is located near the launch site, or near the midpoint of the trajectory) but for our baseline trajectory the maximum range from the laser to the vehicle is 500 km. we require $B = A\ \Re = 1.25 \times 10^{18}$. Other laser launch systems tend to have somewhat higher flux requirements and/or longer ranges, so this is near the minimum value for a practical launcher.

This can be converted directly into a total telescope area given the source radiance. To give a feel for this, Table 2 gives some of the parameters for hypothetical sources:

Table 2: Radiances And Aperture Requirements For Some Typical Sources

Source	Radiance, (W/m^2-sr)	Solid angle subtended for 5 MW/m^2 flux (steradians)	Mirror area for 5 MW/m^2 at 500 km
Incandescent light (3000 K blackbody)	1.5×10^6	Can't do it; 2π source is only 4.5 MW/m^2	
Sunlight (6000 K blackbody)	2.3×10^7	0.21	53,000 km^2
"Raw" laser diode array (no microlenses) (500 W/cm^2, 1 x 0.1 radian divergence)	5×10^7	0.1	25,000 km^2
Ideal laser diode array (1 W diodes with M^2 ~ 100, 0.8 um)	1.6×10^{10}	3×10^{-4}	75 km^2
1 kW single-mode laser, 1 um	1×10^{15}	5×10^{-9}	1,250 m^2

Note that these values are independent of the actual power of the system; the same mirror area is required whether the power delivered is one kilowatt or one gigawatt; only the illuminated area (spot size) at the vehicle changes. However, as discussed further in the next section, the minimum unit mirror size does depend on the power level, since diffraction limits how small the illuminated area can be; in the extreme case, getting 5 MW/m^2 at 500 km out of a single 1 kW laser would require the entire 1,250 m^2 aperture to be coherent.

Beam Divergence and Beam Profile

The beam profile at the vehicle is the result of convolving several factors. The profile of an individual sub-beam (i.e., light from one fiber laser) will be broadened by diffraction and wavefront error. The output of an entire beam module will be further broadened by the physical extent of the source, by alignment and mirror figure errors (which may vary with the telescope orientation) and atmospheric turbulence.

In addition, the collective array will have a beam profile (flux distribution) that is the incoherent sum of the individual module outputs. This collective profile will include deliberate distribution of the flux across the vehicle, and a random component due to beam module pointing errors.

The single-module beam profile can be modeled as a convolution of Gaussian distributions. For simplicity, we will make an assumption about how the beam module optics are configured: we will use parallel sub-beams and subapertures, rather than converging sub-beams that fill the module aperture. The difference is illustrated for two sub-beams in Figure 7. Using subapertures increases the beam divergence due to diffraction, but eliminates geometric divergence. In principle, the two approaches give equivalent results; they effectively swap the near-field and far-field beam behaviors. In practice, using subapertures with real (typically Gaussian) beams will give a smoother and more centrally-peaked beam profile in the far field. For modeling purposes, the subaperture approach, when combined with well-behaved lasers (i.e., single spatial mode and Gaussian beam profile, or nearly so), gives an easy-to-calculate set of Gaussian beam properties.

The standard definition of a Gaussian beam is:

$$\phi(r) = \frac{2}{\pi}\frac{P}{w^2}\exp(-2r^2/w^2) \tag{20}$$

or, since a Gaussian is conveniently separable,

$$\phi(x,y) = \frac{2}{\pi}\frac{P}{w_x w_y}\exp(-2x^2/w_x{}^2)\exp(-2y^2/w_y{}^2) \tag{21}$$

where w is the radius, or half-width, to the $1/e^2$ flux level. There is no outer limit to a Gaussian beam; the fraction of the total power within a given radius r is $1 - \exp(-2\,r^2/w^2)$. Generally an aperture with diameter $d = 2r > \sim 3w$ is considered big enough to pass a Gaussian of width w, since it will block less than $e^{-4.5} \sim 1.1\%$ of the beam power.

The diffraction-limited Gaussian beamwidth at a distance z from a source with beamwidth w_s is

$$w_{diffraction}(z) = \frac{\lambda z}{\pi\, w_s} \tag{22}$$

(In general, neither $w(z)$ nor w_s represents the beam waist, or minimum width; if the beam waist is at the source, the beam width is given by

$$w(z) = w_s\left(1+\left(\frac{\lambda z}{\pi\, w_s{}^2}\right)^2\right)^{1/2} \tag{23}$$

which approaches the diffraction limit for large z.)

Illuminating an aperture of diameter d_s with a Gaussian with $w_s = d_s/\pi$ will produce a Gaussian spot with 87% of the energy within a diameter $d(z) = 2\,w(z) = 2\,\lambda\,z\,/\,d_s$. By comparison, a uniformly illuminated circular aperture of diameter d_s produces a central Airy peak containing 83% of the beam energy of

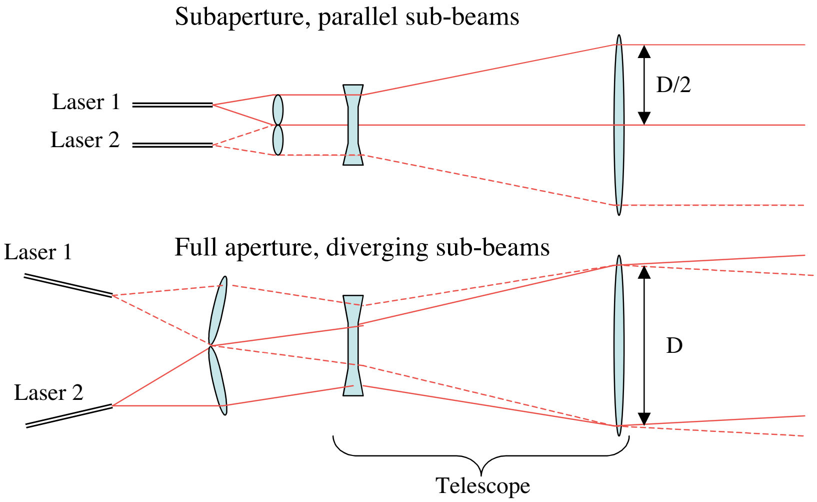

Figure 7: Subaperture vs. full aperture sub-beams. Both have equivalent far-field radiance.

diameter $d(z) = 2.44\,\lambda\, z \,/\, d_s$. The Gaussian illumination produces a significantly smaller spot, although a lower flux on-axis. (The ideal source profile for maximum "power in the bucket" due to diffraction is actually a truncated Airy or sin(x)/x profile, for circular or rectangular buckets respectively, but a Gaussian is a reasonable approximation. and much better than a uniform source.)

Atmospheric turbulence can be approximately characterized by the Fried parameter r_0, which is defined such that the time-averaged power of a beam passing through the atmosphere will be distributed over a Gaussian of width

$$w_{atm}(z) \sim \frac{\lambda z}{c_F r_0} \tag{24}$$

where c_F is a constant, approximately 2.

(Atmospheric turbulence has been extensively studied, and extensive and detailed calculations are available, but since the atmosphere itself is highly variable and rarely well-characterized, this is a sufficiently accurate estimate. A slightly better estimate, using equations from Tyson and Ulrich [12], gives

$$w_{atm}(z) \sim \frac{1.45}{\pi} \lambda\, z\, r_0^{-5/6} w_s^{-1/6} \tag{25}$$

This gives a larger value for w_{atm} than the nominal equation if $w_s << r_0$, but in that case the overall beam width is dominated by diffraction anyway.)

r_0 varies as $\lambda^{6/5}$, and depends on atmospheric conditions (specifically the refractive index structure constant C_n^2) integrated over the atmospheric path length. For moderate zenith angles, r_0 is proportional to $\cos(\theta_{zenith})$.

Surface figure errors in the beam module optics will both broaden individual sub-beams and cause the beams to be imperfectly aligned. A root-mean-square (RMS) single-axis mirror surface slope error σ_{slope} will produce a Gaussian spot width of $w_{figure}(z) \sim 2\sqrt{2}\,\sigma_{slope}\, z$.

Finally, mechanical jitter will widen the beam. Jitter can come from many sources, including the mount drive mechanism, cooling water flow (if there are high-power components mounted on the telescope), excitation of structural modes by moving parts (such as a beam-steering mirror), wind loads, and even transmitted ground vibration. Assuming a single-axis RMS jitter angle of σ_{jitter}, the jitter-produced Gaussian width will be $w_{jitter}(z) \sim \sqrt{2}\,\sigma_{jitter}\, z$.

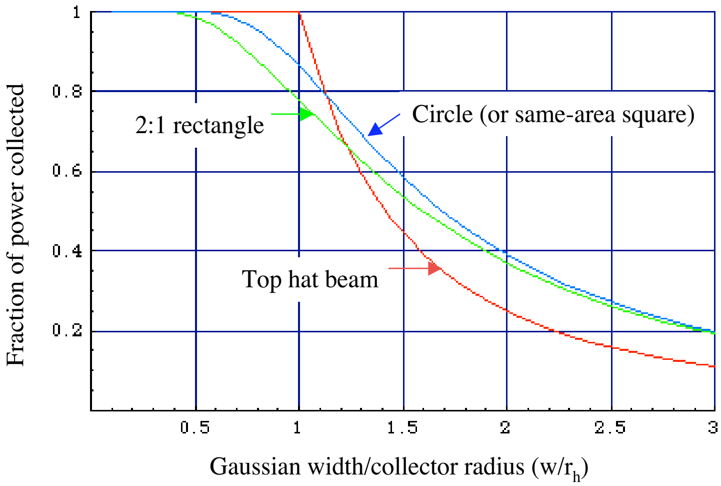

Figure 8: Power collected vs. Gaussian beam width

The convolution of two Gaussian distributions of widths w1 and w2 is just $w_{total} = \sqrt{w_1{}^2 + w_2{}^2}$, so we can combine the various contributions into an overall single-module beam width:

$$w_{module} = \sqrt{w_{diffraction}{}^2 + w_{atm}{}^2 + w_{figure}{}^2 + w_{jitter}{}^2} \tag{26}$$

$$= z\sqrt{(\lambda/d_s)^2 + (\lambda/c_F r_0)^2 + 8\sigma_{slope}{}^2 + 2\sigma_{jitter}{}^2}$$

Finally, if all the modules in an array are aimed at the center of a heat exchanger, the overall beam profile will include a term due to the random pointing errors of the beam modules. For a single-axis RMS pointing error $\sigma_{pointing}$,

$$w_{beam} = \sqrt{w_{diffraction}{}^2 + w_{atm}{}^2 + w_{figure}{}^2 + w_{jitter}{}^2 + w_{pointing}{}^2} \tag{27}$$

$$= z\sqrt{(\lambda/d_s)^2 + (\lambda/c_F r_0)^2 + 8\sigma_{slope}{}^2 + 2\sigma_{jitter}{}^2 + 2\sigma_{pointing}{}^2}$$

Since it is awkward keeping track of *z*, we can express this in terms of a beam divergence angle $\theta_{beam} = 2w_{beam}(z)/z$

$$\theta_{beam} = \sqrt{\theta_{diffraction}{}^2 + \theta_{atm}{}^2 + \theta_{figure}{}^2 + \theta_{jitter}{}^2 + \theta_{pointing}{}^2} \tag{28}$$

$$= 2\sqrt{(\lambda/d_s)^2 + (\lambda/c_F r_0)^2 + 8\sigma_{slope}{}^2 + 2\sigma_{jitter}{}^2 + 2\sigma_{pointing}{}^2}$$

(We do need to keep track of that factor of 2 out front, however, since the individual terms were defined in terms of half-angle rather than full-angle divergence)

Power received

For a simple Gaussian, the power received on a circular heat exchanger of radius r_h is just

$$P_{rec} = \frac{2P}{\pi w^2}\int_0^{r_h} 2\pi r \exp\left(-2r^2/w^2\right) dr = P\left[1 - \exp\left(-2(r_h)^2/w^2\right)\right] \tag{29}$$

This is plotted in Figure 8 as a function of w/r_h. The usual definition of diffraction range corresponds to $w/r_h = 1$, at which point $\eta_{rec} = P_{rec}/P = 0.865$. However, the falloff in power with increasing *w* (and thus increasing range) is fairly slow, and η_{rec} doesn't drop below 0.5 until $w/r_h = 1.70$.

By contrast, a uniform flux ("top hat") circular beam of radius w has $\eta_{rec} = 1$ for $w/r_h < 1$, but $\eta_{rec} = (w/r_h)^{-2}$ for $w/r_h > 1$, which is only 0.35 at $w/r_h = 1.70$.

A square heat exchanger with the same area (and therefore a side length of $\sqrt{\pi}\ r_h$) has almost exactly the same efficiency as the circular heat exchanger; the greatest difference in η_{rec} is just over 1%. Even a rectangular heat exchanger is only slightly less effective, as shown by the red curve in Fig. 8, which corresponds to a 2:1 aspect ratio rectangle, again with the same total area.

At this point, calculation of the actual energy delivered to a vehicle as a function of range requires a numerical integration, and should include several factors, including the variation in Gaussian beam width and atmospheric absorption as a function of zenith angle, and the variation in the projected heat exchanger area with vehicle-to-beam orientation. To estimate the requirements for a beam module, however, we will simply assume that the useful range for a beam module is the range at which $w_{beam}(z) = 1.7\, r_h$ for a circular heat exchanger, or (slightly more optimistically) $\sqrt{l_h\, w_h}$ for a rectangle of length l_h and width w_h.

Figure 9 illustrates the relative flux vs. radius for three values of w, where a flux of 1 corresponds to a uniform top-hat beam just filling the heat exchanger area. Obviously, at short and even intermediate ranges, the overall beam profile must be spread out over the heat exchanger area to keep the peak flux within reason (and to produce something approaching a uniform degree of heating for gas flowing through different parts of the heat exchanger).

Fortunately, the modular laser system can spread the beam in an arbitrary but controlled fashion simply by offsetting the aim-points of each module relative to the nominal center of the heat exchanger. This is another significant advantage of a modular laser system; with a monolithic system, changing the beam width is possible by defocusing the telescope, but any finer control over the beam profile (including uniformly illuminating a square or rectangular target) requires complex beam-shaping optics.

Note that spreading beams out to reduce the peak flux necessarily increases losses around the edge of the heat exchanger; this will be a trade for any particular heat exchanger and system design. The allowable peak-to-average flux ratio can be increased considerably if the heat exchanger is designed such that the hot end (which is most subject to damage by excess flux) is on an edge of the heat exchanger and not near the center where peak flux is expected.

Thermal Blooming and Scintillation

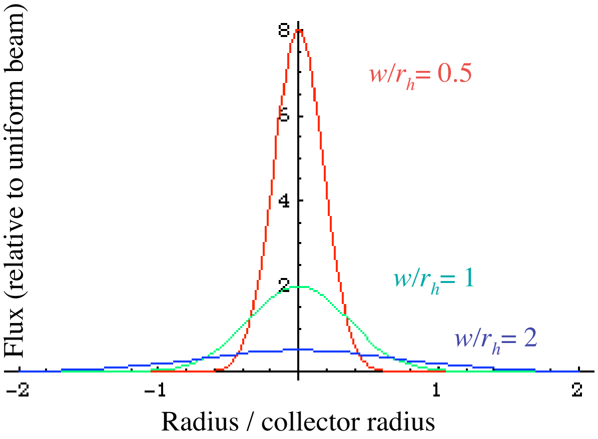

Figure 9: Gaussian flux vs. radius for various beam widths

The beam module array will be nearly free of scintillation (at least on the time scales of interest for the heat exchanger thruster) because the flux at the vehicle will be the sum of many uncorrelated and incoherently-summed speckle patterns at any point.

We did not have time to calculate thermal blooming effects. With the original beam module concept, using relatively low-radiance sources, we expected to be far below the threshold for significant thermal blooming. With the baseline described below, the individual module beam fluxes are high enough that thermal blooming may be an issue, and will need to be addressed in future studies.

Quantitative Requirements

For our nominal 100 MW vehicle, the heat exchanger is approximately 4 x 7 meters. The baseline trajectory endpoint puts the vehicle at 300 km altitude, 400 km downrange of the laser array, for a range R of 500 km (neglecting the curvature of the Earth) and a laser zenith angle of 53 degrees. The heat exchanger is tilted roughly 45 degrees to the laser beam (allowing for a few degrees of downward tilt by the vehicle) so the projected heat exchanger is close to a 4-meter square. This gives a nominal requirement of $w(R)/R = 8 \times 10^{-6}$, or $\theta_{beam} = 16$ microradians.

The divergence component over which we have least control is atmospheric turbulence. If we allocate the entire divergence to turbulence, we get

$$w(z)/z = \lambda / c_F\, r_0 \tag{30}$$

$$r_0 = \lambda\, z / c_F w(z) \approx 6.25 \times 10^4\, \lambda \tag{31}$$

For $\lambda \sim 1$ µm (the middle of the wavelength range of most interest), we therefore need $r_0 > \sim 6.3$ cm. Allowing for $\cos(\theta_{zenith}) = 0.6$, the corresponding zenith value of r_0 is ~10 cm. r_0 varies as $\lambda^{6/5}$, so this corresponds to a visible-wavelength (0.5 µm) zenith r_0 of 5 cm. This is acceptably small but not comfortable; 5 cm is a typical daytime value for r_0 (and is used as the nominal value in a commonly-used atmospheric turbulence model, the Hufnagel-Valley [HV] 5/7 model [13]) but this leaves no margin for other beam-spreading factors.

However, a large fraction of the overall atmospheric turbulence is large-scale (relative to our apertures) and thus appears as an overall wavefront tilt, which can be removed by an active tracking system with sufficiently fast tip-tilt correction. Tilt (on two axes) comprises 85-90% of the total mean square wavefront error given by,

$$\left\langle \phi^2 \right\rangle = 1.03 \left(D / r_0 \right)^{5/3} \tag{32}$$

for an aperture of diameter D. [14] Correcting 2-axis tilt is therefore comparable to increasing r_0 by a factor of $(0.1 - 0.15)^{-3/5}$, or roughly 3 to 4; this gives a comfortable margin in r_0. (Actively correcting focus would reduce the mean square wavefront error another 25%.)[*]

If we assume an actual r_0 (0.5 µm, zenith, daytime) value of 5 cm, and a factor of 3 improvement in turbulence-related beamwidth due to tip-tilt correction, the net contribution of the atmosphere to beamwidth is

$$r_0 = (5\, cm) \left(\frac{1\, \mu m}{0.5\, \mu m} \right)^{6/5} (0.6) \approx 6.9\, cm \tag{33}$$

$$\theta_{atm} = \frac{1}{3} \times \frac{2\lambda}{c_F r_0} \approx 4.8 \times 10^{-6} \text{radians} \tag{34}$$

Given the large uncertainties in this, we allow a factor of almost 2 margin for θ_{atm} and allocate 9 µrad. This still leaves $(16^2 - 9^2)^{1/2} \approx 13.2$ µrad to allocate to other sources of beamwidth.

If we allocate 6 µrad to diffraction, the minimum mirror diameter is

$$d_s = \frac{2\lambda}{\theta_{diffraction}} \approx 0.33 \text{ m} \tag{35}$$

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[*] This calculation may be optimistic in estimating the reduction in divergence due to tip-tilt correction; the author would welcome comments or corrections.

which is certainly practical. Note that this is the diameter per spatially-coherent sub-beam.

We allocate 6 μrad to mirror slope (figure) errors, which requires an actual RMS slope error of (6 / 4√2) ~ 1.0 μrad, or about 1 wave per meter for 1 μm wavelength. Over a 33 cm aperture, the RMS figure error can be 1/3 wave, which is very modest for conventional optics (i.e., typical of consumer-grade amateur telescopes); professional telescope optics are typically figured to 1/10 or 1/20 wave.

Finally, we allocate 6 μrad each to pointing error and jitter; the corresponding 1σ RMS errors, per axis, are (6 / 2√2) ~ 2.0 μrad. These values are achievable with some difficulty in conventional telescopes, although usually not at the slew rates needed here. However, with an active tracking system and suitable calibration, these values should be achievable.

With these allocations, the remaining margin is small (5.6 μrad), suggesting that we may be optimistic in this baseline design. Fortunately, we have an ace in the hole, in the form of deployable reflectors, as sketched in Figure 5 above. Doubling the effective heat exchanger area (even if done asymmetrically, so the collection area is rectangular) would allow the beam divergence to increase by nearly √2. This would allow either an across-the-board increase of roughly 4/3 (to 12/8/8/8/8 μrad) or, e.g., holding the line on θ_{atm}, $\theta_{diffraction}$, and θ_{slope} and doubling the allowance for pointing error and jitter.

However, unless we resort to high-ratio concentrators, as in Figure 6, the tentative conclusion is that the baseline system is near the limit of performance for beam modules without adaptive optics. A substantially lower-power system would be severely range-limited, causing the mass launched to orbit to scale as approximately $P_{\text{laser}}^{3/2}$. Conversely, a substantially higher-power system is likely to be limited by liftoff mass or other factors, not by laser range.

Adaptive Optics

If beam divergence ends up driving the payload to orbit, either because we have underestimated the effects of turbulence or because we want to launch smaller vehicles, we have the option of adding adaptive optics to the beam modules. As discussed below, vehicles will probably carry beacons, either active lasers or retroreflectors, which eliminates the main problem in most adaptive optics systems.

If the beacon can be extended some distance ahead of the vehicle, the pointahead problem can also be resolved. (Pointahead occurs because of the finite speed of light; if the atmosphere is sampled by a downward-propagating beacon, and a corrected return beam is aimed exactly back along the beacon path, the correction will be accurate but the vehicle will have moved a perpendicular distance $d = 2 R v_\perp / c$, where R is the range, $v_\perp$ is the vehicle velocity perpendicular to the beam, and c here is the speed of light. Aiming the return beam ahead of the beacon beam by an angle $2 v_\perp / c$ will compensate for the vehicle motion, but the return beam will pass through a slightly different section of the atmosphere and the correction will be imperfect. For $v_\perp$ = 6 km/s and 500 km range, the vehicle transverse motion (and therefore the optimum beacon offset) is ~20 meters. A 20-meter boom is awkward but not unreasonable to add to the baseline vehicle, as it is needed only toward the end of the trajectory (i.e., in vacuum) and can be quite flexible: the beacon position can be in error by 1 meter or more without serious impact.

Note that laser guide stars and other beacons not actually attached to the vehicle will not be usable with a modular laser system, due to the physical extent of the module array. Each beam module would require its own guide star; even adjacent modules would see an unacceptable difference in angle between a guide star and the vehicle for laser guide star altitudes of 20 – 90 km.

Even with an ideal beacon, the finite size of the heat exchanger will result in some adaptive correction error. Good correction is obtained only within the so-called isoplanatic angle. Fortunately, the isoplanatic angle is of order r_0 / h, where h is the scale height of the atmospheric turbulence, ~10 km for most conditions, and a typical value (again, as used in the HV 5/7 model) is 7 μrad, which is 3.5 m at 500 km.

The approximate number of discrete actuators needed for adaptive optics compensation is $\left(d_s / r_0\right)^2$ per sub-beam or, for a whole beam module array with total source aperture A, $4A / \pi r_0^2$ [15]. Unfortunately, beyond the lowest-order (tip-tilt and possibly focus) corrections, partially correcting for turbulence does not reduce the overall beam width, but superimposes a diffraction-limited peak containing part of the beam energy on the wider background beam, so there is limited value in providing low-order correction with significantly fewer than this number of actuators (as opposed to astronomy, where a high-resolution component superimposed on a low-resolution background may be sufficient to resolve an object of interest.)

Because the vehicle moves fairly quickly, the adaptive optics bandwidth required is somewhat higher than that required for astronomy, but presumably comparable to the requirements for imaging or transmitting laser beams to low-Earth-orbit satellites.

A variety of designs for suitable wavefront sensors and deformable mirrors exist, and each beam module will have an independent adaptive system, so there are no scaling issues relating to large numbers of sensors or actuators. The main issue for adding adaptive optics to beam modules will be cost. The total system aperture A depends on the laser source radiance $\Re$, so the total number of actuators needed will vary inversely with $\Re$.

Field of Access and Slew Rate

Field of access (i.e., where the beam modules are able to point) depends on the overall system geometry and the intended flexibility of launch azimuth.

At one extreme, a launcher located on or very near the equator might be designed for purely equatorial launches. Such an arrangement maximizes access to an equatorial LEO station (for satellite assembly or fuel depot) and is ideal for payloads destined for GEO. In this case, the beam module may track along essentially a single axis, with only small crosstrack deviations.

In general, however, we would expect a launch system to have more flexibility, ideally being able to launch to any azimuth. This requires the beam modules to cover essentially the entire sky above some minimum elevation; the minimum elevation is generally set either by atmospheric absorption or by the degradation of the beam due to turbulence, both of which vary as $1/\cos(\theta_{zenith})$. Astronomers and other atmospheric-transmission connoisseurs prefer a maximum zenith angle of 45 degrees, but typical laser propulsion trajectories still get significant benefit from zenith angles as large as 65 – 70 degrees, even if, as in our baseline trajectory, the nominal "maximum range" design point occurs at a lower zenith angel..

In addition, it is desirable to have the beam module be able to point all the way to the horizon over at least a limited range of azimuths, for two reasons: initial boost, and testing. Initial boost refers to the need to "pick up" a vehicle at low altitude and short enough range that atmospheric absorption and turbulence are not issues. For testing, it is useful to be able to aim each beam module individually at a near-ground-level target, to measure beam quality, align optics, etc.

The required slew rate may be determined by either end of the trajectory. The straightforward limit is near the end of the trajectory, when the vehicle velocity is close to 8 km/s relative to the laser site. The corresponding angular velocity depends on the vehicle range and the angle between the beam and velocity vectors, but typical values are 500 km and 45 degrees, giving a slew rate of (8 sin(45 degrees) / 500) ~ 0.011 radians/second or 0.65 degrees/second; a conservative design thus requires a slew capability, while pointing the laser beam, of at least 1 degree/second. The required angular acceleration (and therefore the drive mechanism torque) in this case is low; the vehicle changes range, velocity, and vector slowly. For example, an 8-g acceleration changes the vehicle velocity by 1%/second. Slew acceleration of 0.02 degrees/s^2 is generally sufficient, and lower values may be acceptable.

If, however, the vehicle is launched close to the laser with even modest velocity, slew may be dominated by the start of the trajectory. A limiting case is probably a near-sonic vehicle (300 m/s) launched from a site 10 km from the laser site, and still at low altitude (i.e., flying nearly perpendicular to the beam) The slew rate in this case is 0.3/10 ~ 0.03 radians/s or 1.7 degrees/s, requiring a beam module capability of at least 2 degrees/s. The corresponding acceleration is even higher; a vehicle accelerating at 20 m/s (2 g) would change slew rate by .002 radians/s^2, or over 0.1 degree/s^2 – 5 times higher. This acceleration will be a significant constraint on beam module design.

Task II: Beam Module Options and Baseline Designs

Laser Technologies: Best Prospects

The most promising options for beam module lasers are all based on high power laser diode arrays or "stacks". Laser diode arrays are compact, efficient (typically 50% DC-light) and require only low-voltage DC power and water cooling. The lifetime of high power arrays is increasing, but current arrays are capable of 5000 hour life with 95% reliability[*] which is sufficient for upwards of 30000 launches. (Many industrial applications actually have greater reliability requirements, since industrial lasers often operate 24 hours a day and a laser failure requires an expensive production line shutdown; inherent in the modular laser concept is the ability to shut down and repair individual modules without interrupting launch system operation). A typical commercial diode array stack is shown in Figure 10.

Unfortunately, the radiance of diode arrays is insufficient for a laser launcher. Common diode bars use broad area diodes which operate in high-order multimodes in the along-bar (x) direction, with $M^2 \sim 100$, although they are nearly single mode in the perpendicular (y) direction. Individual diode power is typically 0.5 - 1 watt, giving a diode radiance (for common 808 nm diode wavelength) of ~ 1 W / $(.808\ \mu\text{m})^2 \times 100 \approx 10^{10}$ W/m^2-sr. This radiance can be approached for diode array stacks using two-dimensional microlens arrays which collimate the beams from individual diodes; using one-dimensional (cylindrical) microlenses limits the radiance to roughly half this value due to the spaces between the lasing regions along the bar.

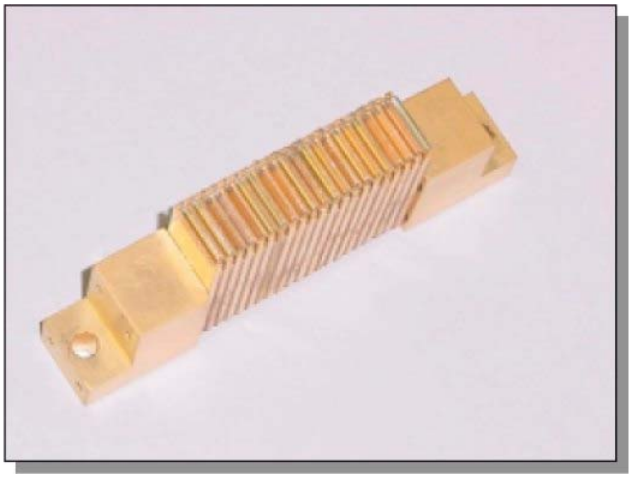

Figure 10: 1.2 kW CW laser diode array "stack"
(Courtesy Nuvonyx, Inc.)

Most diode array stack designs have concentrated on spacing bars as close together as possible (high power per unit face area) for efficient proximity coupling, but that the array radiance is independent of the bar spacing if suitable lenses are used – the maximum y-direction lens aperture is proportional to the bar spacing, so the diffraction-limited beam divergence decreases as the spacing increases.

Bars made with single mode diode lasers are available but with significantly lower power (~10 W/bar, 100 mW/diode); using 2-D microlenses, these arrays have a radiance of up to $\sim 10^{11}$ W/m^2-sr. There are reasonable prospects for developing higher power single mode diodes (e.g., using tapered structures [16]) which could approach 10^{13} W/m^2-sr, but the cost and electrical efficiency of these arrays is as yet unknown.

There are several ways to increase the radiance of diode arrays, either directly, by combining the diode outputs, or indirectly, by using the diode arrays to pump a converter. In either case, the resulting device can be characterized by its conversion efficiency η_{conv} = output power / raw diode power and its radiance. Current possibilities are summarized in Table 3 and discussed below.

Wavelength stacking

The original concept for raising the radiance of diode arrays [17] took advantage of the ability to manufacture diode bars over a significant range of wavelengths. Using a diffraction grating, the light from a stack of diode bars could be made to appear to come from a single bar, as shown in Figure 11. (This

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[*] Typical manufacturer's specifications are 3% degradation in power output per 1000 hours of operation, with no actual specification on lifetime or mean time to failure.

process does not violate conservation of radiance; it essentially adds an extra phase space dimension – wavelength – to the classical radiance factors of beam width and beam divergence).

Table 3: Laser Conversion Efficiency And Radiance

Laser type	Converter	η_{conv}	Output power, W	Output beam quality (M^2_x xM^2_y)	λ, um	Approximate Radiance W/m^2-sr
Multimode diodes	good microlens	~1	1	100 x 1.5	0.808	1 x 10^{10}
Single mode diode bars	none	1	0.1	1.5 x 1.5	0.808	5 x 10^{10}
Wavelength stacking	External diffraction grating	0.8	80	100 x 1	0.808	1 x 10^{12}
Spectral Beam Combining	Intracavity diffraction grating	0.45 *0.6*	25 *500*	4.5 x 3 *3 x 2*	0.808	2 x 10^{12} *1 x* 10^{14}
Fiber laser	Yb double-core fiber	0.8	1,000 *10,000*	1.2 x 1.2 *1.5 x 1.5*	1.08	6 x 10^{14} *4 x* 10^{15}
DPAL	Rubidium vapor in He gas cell	0.5 – 0.8	*10,000*	*1.5 x 1.5*	0.795	*6 x* 10^{15}

Italics indicate near-term (1-2 year) goals

Unfortunately, such wavelength stacking is limited to a stacking factor S ~ (dλ / Δλ) where dλ is the spectral width of the individual diode output and Δλ is the range of wavelengths over which suitable bars can be fabricated. Optimistically, S ~100. An extra factor of 2 is available by combining two beams of orthogonal polarization. Using conventional low-cost multimode diode bars, the resulting beam radiance would be roughly 10^{12} W/m^2-sr, which is still impractically low for a launch system; the corresponding baseline system mirror area would be 1.25 x 10^6 m^2, or over a square kilometer of mirrors. Using simple wavelength combining, therefore, it was necessary to assume that significant progress would be made in improving single-mode diode bars. (A radiance of 10^{12} W/m^2-sr is, however, sufficient for laser propulsion at short range, perhaps to 20-50 km, or for many power beaming applications.)

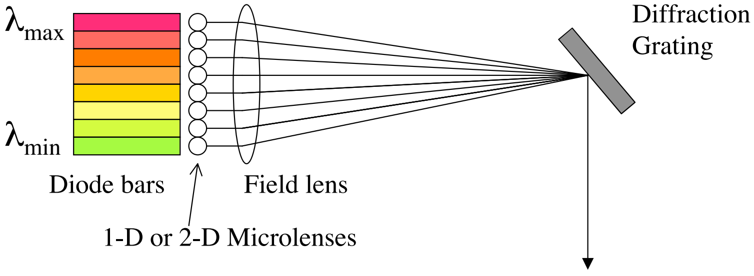

Figure 11: Wavelength stacking of diode arrays

Wavelength stacking also presented a problem in configuring sources, in that the resulting beam was radically asymmetric, with an M^2 close to 1 in the y direction and of order 10^4 in the x direction (10^2 for single-mode diode bars) making it difficult to form a roughly circular or rectangular beam or to couple efficiently into optical fibers.

Spectral Beam Combining

A more sophisticated approach to trading spectral width for radiance has been demonstrated recently by Aculight Corporation (Hamilton et al. [18]). Their approach, referred to as Spectral Beam Combining (SBC) places diode bars in an external cavity which includes the diffraction grating or other dispersive element, as illustrated conceptually in Figure 12. With this configuration, individual diodes automatically oscillate at the correct wavelength to combine their outputs into a single beam. By using a wide field-of-view optical configuration (Schmidt reflector), Aculight has been able to generate a reasonably high quality beam ($M^2_x = 4.5$, $M^2_y = 3$) from seven single-mode diode bars (of order 1400 individual diodes), easily exceeding the radiance gain expected from simple open-loop wavelength stacking.

The power output from the SBC assembly is significantly lower than that from the uncombined bars; the "SBC efficiency" is given as approximately 50%. It is likely that the SBC efficiency can be increased by improving the alignment of the diodes and microlenses and, at the expense of beam quality, by widening or removing the exit slit that defines the x-direction beam width , but the achievable value is unknown.

SBC also requires precise alignment of the individual diode arrays and correction of smile (curvature of the diode bars, resulting in varying diode offset in the y direction).

Another limit on SBC is the need to keep the operating wavelength of each diode within the diode's gain bandwidth. For the demonstration, this required a temperature gradient from one end of the row of modules to the other. In high volume production, however, diode bars could be manufactured with an appropriate range of nominal center wavelengths, eliminating the need for temperature gradients.

Provided SBC can be applied to broad-area diode bars, a reasonable near-term goal for SBC array performance would be a power level of 240 to 500 watts (8 bars, 60 – 100 W/bar, SBC efficiency 50 – 63%) with a beam quality of 6X diffraction limited ($M^2_x \sim 3$, $M^2_y \sim 2$), for a radiance of up to (500 W/$(0.808\ \mu m)^2$ x 6) $\approx 1.2 \times 10^{14}$.

Fiber Lasers

High power fiber lasers using double-core fibers have recently become a very active research topic. Since the first demonstrations of >100 W from a fiber laser [19] several groups have produced Yb-doped fiber lasers with power levels of 100 watts or more, and single fiber lasers up to several hundred watts are available commercially [20]. Most of these lasers are pumped with discrete broad-area diode lasers. However, SPI Photonics has demonstrated a diode-bar-pumped fiber laser with power output of over 1 kW with fair beam quality ($M^2 \sim 2$) and over 600 W with nearly diffraction limited beam quality, using the configuration shown in Figure 13 [21]. At the fiber laser wavelength of 1.08 nm, these correspond to radiances of 2.2×10^{14} W/m^2-sr and 4×10^{14} W/m^2-sr respectively.

Fiber lasers are extremely efficient at converting diode light to fiber light. It is somewhat difficult to compare efficiencies since several different definitions of efficiency are used, but in terms of (fiber output / diode output), efficiencies of 75% to 90% are reported. Current commercial fiber lasers have a wallplug efficiency (AC line power to light) of 20-25%, and efficiencies of 40% should be achievable.

Higher power fiber lasers appear to be possible, with a near term goal of 10 kW from a single fiber [22]. Spectral combining of fiber lasers, either using the SBC approach of multiple fibers in an external cavity, or using simple wavelength combining, is also a route to higher radiance with fiber lasers, at the likely expense of some loss in efficiency.

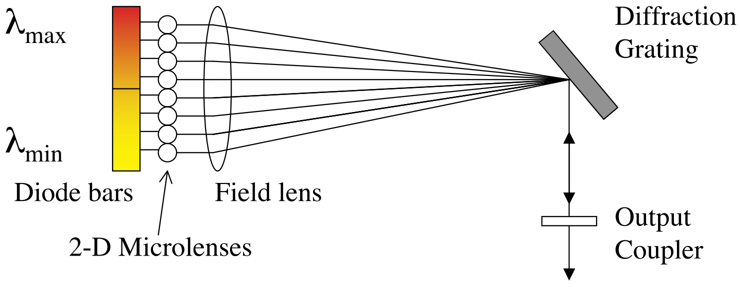

Figure 12: Spectral beam combining

Erbium-doped fibers can be used with longer-wavelength laser diodes to produce somewhat lower powers at eye-safe wavelengths (1550 nm); if these lasers continue to improve, they might eventually be preferable to the shorter wavelength lasers simply because they have fewer safety issues.

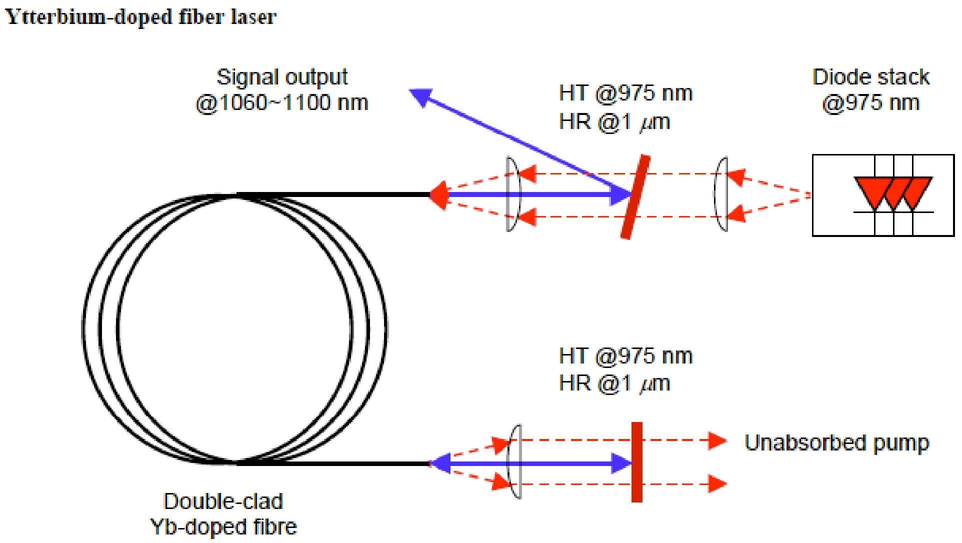

Figure 13: 1-kW end-pumped fiber laser using diode bar pump (courtesy SPI Photonics, Inc.)

Diode Pumped Alkali Laser

A new laser concept has been developed by Krupke et al [23, 24]. The diode-pumped alkali laser uses alkali metal vapor (Cs, Rb) in a helium buffer gas. A DPAL has been demonstrated at modest power (30 W), but with an extremely good match between predicted and observed characteristics, which gives confidence that substantially higher laser powers with good beam quality can be built. A possible 100 kW DPAL configuration is illustrated in Figure 14.

DPAL efficiency depends on the details of the DPAL design, but efficiencies in the range of 50 – 80% appear to be feasible.

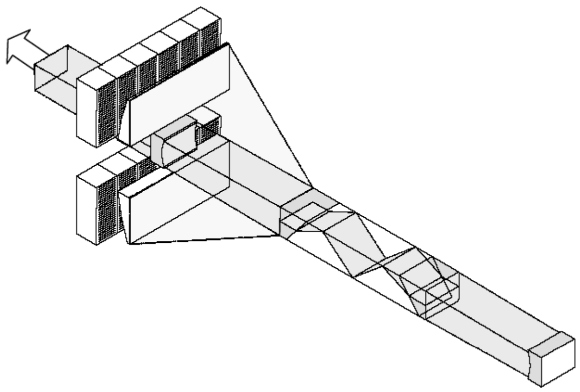

Figure 14: 100 kW Diode Pumped Alkali-vapor Laser (DPAL) concept (courtesy of W. Krupke)

Coupling diode arrays to the alkali vapor cell is comparatively simple, allowing the use of minimum-cost diode array stacks, such as those under development for pumping glass lasers. However, the narrow width of the (collisionally-broadened) alkali vapor absorption line will require diode arrays with narrow linewidths and tight wavelength control.

DPALs are even newer than fiber lasers, and the relative costs of DPALs and fiber lasers are unknown, but the DPAL requires considerably more hardware (cavity optics, gas handling, temperature control) and may thus be somewhat more expensive than an equal-power fiber laser, but DPALs may be scaleable to higher unit power.

The choice between DPALs and fiber lasers may be based on other factors, including beam quality, complexity, and reliability. The shorter DPAL wavelength (which makes DPALs compatible with standard Si and GaAs photovoltaic cells and Si detectors) could be a significant advantage.

Laser Alternatives

There are, of course, many other lasers which meet the minimum requirements of low atmospheric absorption and adequate radiance for a launch system, but none appear likely to match the capital and operating costs of the diode-based options described above. We note a few specific cases of interest:

Diode Pumped Solid State Laser (DPSSL)

DPSSLs are the most widely developed class of diode-pumped lasers, but appear to have no clear advantages, and several disadvantages, relative to fiber lasers in the 1-10 kW power range. In particular, they have lower conversion efficiency (25-50%), require more complex optics, and are harder to cool. New configurations, such as the disk laser may keep DPSSLs competitive with fiber lasers.

CO_2 Lasers

High power CO_2 lasers have generally had poor beam quality, but assuming a diffraction limited beam, a CO_2 laser module would still need 100 times the power of a near-IR laser to provide the same radiance. The long wavelength also means that the minimum diffraction-limited mirror size is 2 – 3 meters. A CO_2 beam module with a few-hundred-kilowatt laser and 2-meter aperture remains a possibility, but a distant one.

Gas-dynamic lasers

Open-cycle gas-dynamic lasers have been a leading choice for military lasers (MIRACL, AirBorne Laser (ABL)) with modest run times, but are likely to be too expensive to operate for a launch system. However, laser propulsion tests can be done with these lasers, including possible launches of small payloads to orbit using ABL.

Closed-cycle COIL lasers are under development for industrial applications, but do not appear likely to compete with diode-based lasers.

Free Electron Lasers (FELs)

FELs are serious contenders for large monolithic lasers, but have so far proven expensive to build; the DOE Jefferson Laboratory FEL is a mid-IR laser (6-10 μm) with a power output of >10 kW (20 kW goal), built at a cost of over $30 million. [25] Since FELs have few alternate applications, the prospects are poor for reducing costs at a scale appropriate to beam modules.

Pulsed laser capabilities

Most of the main laser options are primarily CW lasers, with limited pulse energy capability. With current technology, diode lasers cannot produce much more peak power than they can average power, given suitable cooling; the dominant limit is the damage threshold of the output facet. Characteristic damage thresholds are 10^{11} W/m^2, and the output facet area for broad-stripe diodes is of order 100 um^2, giving thresholds of a few watts. Facets will survive very short pulses at higher power, but the total energy in short pulses is then limited by the finite current-carrying capacity of the diode junction.

Fiber laser end facets can withstand considerably higher fluxes, but pulsed lasers driven by CW pumps (including continuous-flow chemical lasers, diode pumped solid state lasers, etc.) require that the pulse energy be accumulated between pulses and stored in the lasing medium. The lasing medium can store only a certain number of joules per liter or per gram, and fiber lasers (and probably DPALs) simply don't have very much lasing medium. For example, a 1-kW fiber laser using 10 meters of fiber with a 30 um core has less than 0.01 cubic centimeters of actual lasing volume, where a 1-kW diode-pumped solid state laser (which can be operated as a high-energy pulsed laser) might have several cubic centimeters of similarly-doped lasing medium. (The fiber laser length is limited by nonlinear effects in the laser core, so even if the cost were low, it would not be feasible to use kilometers of fiber in a pulsed fiber laser.)

Thus, typical current pulsed fiber lasers produce sub-millijoule pulses at kHz rates, with pulse widths ranging from microseconds to less than 1 picosecond. It is possible to make microthrusters which use such fiber lasers, e.g. [26]; it is scaling such thrusters to useful size for a launch vehicle that is problematic. Fiber laser systems can be scaled to substantial power (e.g., [27]) but only with considerably more complexity and lower efficiency than for CW operation. Simply raising the pulse rate to extract more power from a fiber is problematic for propulsion, because there is a minimum inter-pulse time needed to allow the exhaust from one pulse to clear (both in the sense of becoming transparent, and in the sense of getting out of the way) before the next pulse arrives. This time is generally of the order of D/c, where c is the exhaust velocity and D is the characteristic size of the thruster – at least centimeters, and typically of order a meter, for launch vehicles. Thus, for $c = 10^4$ m/s, pulse rates much above 10^4 Hz will not work.)

A minor factor for pulsed beam modules is the need to synchronize pulses, including both the timing of the laser pulsing and the module-to-module variation in speed-of-light delay to the vehicle. Some pulsed lasers have significant timing jitter from pulse to pulse. For microsecond-length pulses, accurate synchronization of many lasers is probably straightforward. For nanosecond-length pulses, as used by Pakhomov [28] synchronization may be difficult, especially since the relative speed-of-light delay between modules varies over the trajectory. Effectively, for nanosecond or shorter pulses, the synchronization problem is comparable to the problem of phasing a true-time-delay microwave phased array array with a similar extent and number of modules.

If a pulsed thruster is optimum for a future launch system (which is certainly possible, e.g., for a nuclear waste disposal system, which requires ~15 km/s delta-V) then pulsed-laser beam modules can certainly be built. For the near term, however, CW beam modules appear likely to be substantially cheaper.

Microwave Arrays

Microwaves are an alternative to lasers for any beamed power application. Microwave sources have been much cheaper and more efficient than lasers, although the gap has greatly narrowed with the advent of laser diode arrays. The main disadvantage of microwaves is their long wavelength, which means that they require much larger coherent apertures than lasers. A modular microwave power beaming system, similar in principle to the modular laser, was proposed by Benford and Dickinson in 1995 [29], but was not well-suited to launch applications until it reached very high power levels (several GW).

With microwave frequencies (2.45 to perhaps 30 GHz) there was also a significant problem of breakdown in the upper atmosphere at the megawatt per square meter fluxes required for a conventional launch vehicle.

Recently, there has been an analysis by Parkin et al. of a microwave-driven heat exchanger rocket using millimeter waves (140 GHz) and an efficient planar heat exchanger thruster [30, 31]. The design assumes a shorter transmitter range (~150 km) and trajectory length (~200 km horizontal distance) thus keeping the microwave antenna area within reason, at the expense of requiring P_{exh}=275 MW for a 100 kg payload.

We continue to believe the laser approach is preferable, for several reasons:

- Millimeter wave sources are not significantly cheaper than likely laser sources, considering the smaller payload per megawatt, and their trend is less favorable. Parkin estimates that high power millimeter-wave sources cost ~$2/watt with power supplies (but without antennas or control circuits); at 3 MW/kg payload, a 100-kg launcher would require ~$600 million worth of microwave tubes and power supplies alone. The rate of improvement in microwave tubes is slower than for diode lasers (in part because the field is much more mature), and other prospective markets are limited.
- Phased arrays of dish antennas have significant sidelobe losses, especially if they are required to track over large angles. This may create hazards to other satellites, aircraft, etc.; it certainly raises the system power requirement. As little as a 3 dB loss (which would be difficult to achieve) would double the microwave system cost.
- Even at 140 GHz and 150 km range, the microwave antenna aperture is large enough to be at least as expensive as the modular laser system optics: for a 3-m heat exchanger (Parkin's

baseline) the required (filled) aperture diameter is ~2 $\lambda R / d_{hx} \approx 200$ m; a typical transmitter would use ~600 8-meter dishes in a dense hexagonal array.

- The microwave system requires phase locking of several hundred modules, with rapid phase adjustments for vehicle tracking; this has not been demonstrated for millimeter wave systems, and will be a substantial technical problem.

Primary Optics

As originally conceived, using wavelength-stacked diode arrays ($\Re \sim 10^{13}$ W/m^2-sr), a beam module array for a laser launcher would require a total optical aperture of order 10^5 square meters. This implied a need to build complete beam-director telescopes at a cost of no more than \$$10^4$/m^2, and preferably significantly less – between one and two orders of magnitude cheaper than current astronomical telescopes, and over two orders of magnitude cheaper than specialty telescopes such as the 3.5 meter adaptive-optics telescope at the Starfire Optical Range, which cost \$27 million, or \$2.8 million per square meter [32] (although that figure does include extensive research facilities). Such cheap optics would require a radical approach to optical fabrication and mounting, and represented a possible show-stopping obstacle to the beam module concept.

With near-diffraction-limited high power lasers (fiber lasers, and probably DPALs) available, at prices only moderately higher than wavelength-stacked arrays, we can assume $\Re > 10^{15}$ W/m^2-sr, and therefore optical apertures of order 1000 m^2. This implies that costs as high as several x \$$10^5$ /m^2 are readily acceptable for a 100 MW class system. As we discuss below, this is still not trivial to achieve, but it can be done with conventional polished-glass reflective optics. We therefore did substantially less investigating of radical optics approaches than we intended at the time this effort was proposed.

However, since optics will be a significant cost (saving \$100 million is not insignificant, even in a system which costs \$1.5 billion) it is worth noting the alternatives which were considered, however briefly, so that they can be reviewed in more detail in the future.

Primary Mirror Fabrication: Baseline

The baseline for primary mirrors is more-or-less traditional machine grinding and and polishing, with iterative testing to correct errors. The main issue for this process is the material and type of blank used.

Most professional telescopes use one of two types of zero-expansion glass: Zerodur (Schott Glass) or ULE (Corning). Both are expensive and produced (poured) in limited quantities. ULE is formed in boules 1.5 m in diameter and several centimeters thick, so conventional blanks can be produced up to 1.4 meters in diameter; larger blanks would imply a large investment in production facilities. (ULE is widely used for precision masks for integrated circuit fabrication and other ultra-precise tooling, so the volume needed for ~1000 m^2 of mirror would not greatly impact the total production.)

Given the relaxed wavefront characteristics needed for a beam module relative to an astronomical telescope, borosilicate glass (Pyrex and various other brand names) may be cheaper than ULE or Zerodur. The raw glass is certainly several-fold cheaper, and available in quantity. Borosilicate glass has been used extensively in spin-casting of large mirrors with integral lightweighting cavities, a technique developed by J. R. P. Angel at the University of Arizona [33]. Either borosilicate or ULE can be used to make fused honeycomb mirrors. Honeycomb mirror components are normally made by waterjet cutting glass sheets; the components are then fused together at high temperature.

Assuming the final optical performance is satisfactory, the main issue with using borosilicate is the difficulty of testing it during polishing, since it must be at a uniform and stable temperature during testing. ULE/Zerodur can be tested without delays for temperature settling and with minimal temperature controls. This may not be an issue in a volume-production situation with dedicated production and test facilities; with several mirrors in a given fabrication stage at one time, one or more mirrors can be equilibrating for test while others are being polished.

(There may be intermediate cost/performance options between borosilicate glass and ULE/Zerodur, including Russian-produced Zerodur equivalents. Both ULE and Zerodur come in various grades as well.)

Mr. Don Avritt of Optical Surface Technologies (Albuquerque, NM) was kind enough to investigate some options for glass blanks and provide a preliminary cost estimate for production of 1000 1-meter-class mirrors. He proposed using 34-inch borosilicate blanks (the limit for his supplier), slumped to near net shape and conventionally fine-ground and polished. He estimated [34] that his company could deliver these mirrors (0.7 m^2 area) for $22,000 each, with a production rate of between 3 and 5 per week using their existing facilities. The capital cost to double this production rate was estimated at $1 million. We note, however, that another telescope expert expressed some skepticism about the feasibility of quickly reaching high production rates, since large optics fabrication remains something of an art, and there is a very limited supply of skilled optics workers. Training a substantial number of new workers could be both time consuming and expensive. Such an investment is more likely to be made by the optics industry if the growth of the launch system, and therefore the production of beam modules, is planned to continue for many years (which we would expect) rather than stopping after the production of a fixed number of units.

The Thirty Meter Telescope project (formerly CELT, the California Extremely Large Telescope) [35] provides a rough cross-check on the feasibility of building thousand-unit quantities of meter-scale optics. The TMT project has done design studies, including initial cost studies, for a 30-meter-diameter astronomical telescope with a primary composed of 1080 hexagonal segments, each 0.5 meters on an edge (1.0 meter corner-to-corner diameter) and 45 mm thick. No cost estimates have been published, but we would expect the telescope cost to be similar to that of previous world-class observatories, of order $100 million, or ~$140,000 per square meter. Extrapolating from published information, the Zerodur segments are probably expected to cost of order $10,000, including stressed-lap polishing and ion figuring, which would be comparable to Optical Surface Technologies' estimate, but for higher quality mirrors.

Alternative fabrication techniques and approaches

We looked briefly at several alternate approaches for making primary mirrors, but found no vendors willing to offer acceptable performance at low cost. Very briefly, the alternatives are:

- Replica optics -- glass or other blanks are slumped, ground, or otherwise formed to approximate shape and coated with a thin layer of epoxy. Blanks are then pressed onto a precision-polished convex master, and the epoxy layer replicates the surface of the master. Replication is an established technique for mass producing optics, but is not generally used for this quality or size (assuming 1 meter) mirrors. The conventional use is to produce relatively small aspheric surfaces which would otherwise require complex polishing of each piece; the cost of an expensive aspherical master can be spread over many parts. Replication is the most likely alternative to conventional optical fabrication, and should be considered in future studies.

- Electroformed optics – a metal, usually nickel, is electrochemically deposited on a convex master with sufficient thickness to be self-supporting when removed. Electroformed optics are commonly used as concentrators or reflectors for precise illumination; they are easily made in deep curves, and are intermediate in cost and performance between cheap polished-metal or plate-glass mirrors and conventional optics. Because metals have high thermal expansion and only moderate stiffness, electroformed optics do not appear to be able to meet the quality requirements for a beam module (<< 1/2 wave surface figure error over 10 cm).

- Diffractive optics -- both micro- and large-scale optics are increasingly being fabricated using the precision masking and etching processes developed by the semiconductor industry. By fashioning binary steps of 1/2, 1/4, 1/8… wavelength delay in appropriate patterns, highly-efficient single-order diffraction gratings, zone plates, and similar diffractive optics can be made, or (of more interest) masters can be etched and then replicated on cheap flat material. Very lightweight Galilean telescopes could be made with thin diffractive optics. Diffractive optics have severe chromatic aberration, but that is not a serious issue for monochromatic sources; it would be problematic for SBC or wavelength-stacked sources.

  Unfortunately, diffractive optics currently seem to bypass the size and quality range of interest; there are high-precision micro-optics, low-precision Fresnel optics up to ~1 meter (in many cases developed for high-end television projection screens) and very large (25 m diameter, multi-km focal length) space optical system designs.

- SiC and other alternate materials -- Silicon, silicon carbide, and some other materials are finding application in specialty optical systems, including satellite optics; SiC in particular is exceptionally stiff, can be fabricated in a variety of ways (so that mirrors and telescope structures can both be made of SiC and thus have matched thermal expansion) and has been demonstrated to be polishable to a very good surface. However, it is not cheap, and does not seem to have large advantages over glass for non-weight-limited terrestrial applications.

Primary Mirror Coating

Conventional telescope optics are generally vacuum-coated with aluminum or "protected silver" (silver plus a transparent layer; bare silver tarnishes quickly) The best standard coatings absorb ~2% of the incident beam at near-infrared wavelengths. This is acceptable (though obviously undesirable) from the standpoint of efficiency, provided only a few such surfaces are encountered. It is problematic for high radiance beam modules because the absorbed power would heat both the primary mirror and the air above it. 2% of a 100 kW/m^2 beam is 2 kW/m^2 – more heat than a black surface absorbs in direct noon sunlight. Sustaining such a heat flux would definitely force the mirror to be made from ultralow-expansion material, and probably require active cooling of the mirror (e.g., by flowing cool air through a honeycomb backing).

Laser mirrors, including beam directors, typically solve this problem with multilayer dielectric coatings. Such coatings can be made with reflectivities of 99.9% or more, which would reduce the absorbed power to <80 W/m^2. However, such coatings are costly to apply to large surfaces (especially fast optics with highly curved surfaces), often fragile, and difficult to clean. They are also not generally strippable, meaning that if the coating is imperfect when applied, it cannot be removed from the underlying glass and replaced; the glass must be reground and repolished. This is probably less of an issue for a large production run of mirrors than for single optics, since coating processes are highly repeatable once a successful coating is made. A valuable, but not urgent, R&D effort would be to review the technology for large multilayer-coated optics and identify ways to reduce life cycle costs for large numbers of optics, e.g., by making coatings hard enough to be cleanable or soft enough to be strippable.

Telescope Optical Configuration

Figure 15 illustrates the main telescope configurations considered.

The conventional on-axis Cassegrain configuration has no significant problems other than a small loss due to the obscuration of part of the aperture by the secondary mirror and support struts, and is almost certainly the lowest cost configuration; it is therefore our baseline choice. Multiple small telescopes – one per laser – on a common mount may be competitive; the trade would be between the cost of optics and the cost of tip-tilt correction (required for each telescope).

With low-power, relatively low-radiance diode-array lasers, it would be feasible to mount the laser directly on the telescope. As the laser power increases, this becomes less practical both because of the size and mass of the laser assembly itself, and because high-volume cooling-water flows will cause vibration; also, at least some laser configurations involve precise alignments that are easier to maintain if the laser stays stationary.

The two traditional choices for coupling a stationary instrument to a pointable beam are a Coude beam train (multiple mirrors to transfer the beam through two rotating joints) or a fixed telescope with one or more rotating flat reflectors. A Coude beam train is lossy, unless large, expensively-coated mirrors are used, and very difficult to align, while a fixed telescope/steering flat arrangement adds one or two full-aperture optics, at considerable cost – a large flat is not significantly less expensive than a curved mirror of similar size. However, courtesy of new optical technology, we can avoid both these choices.

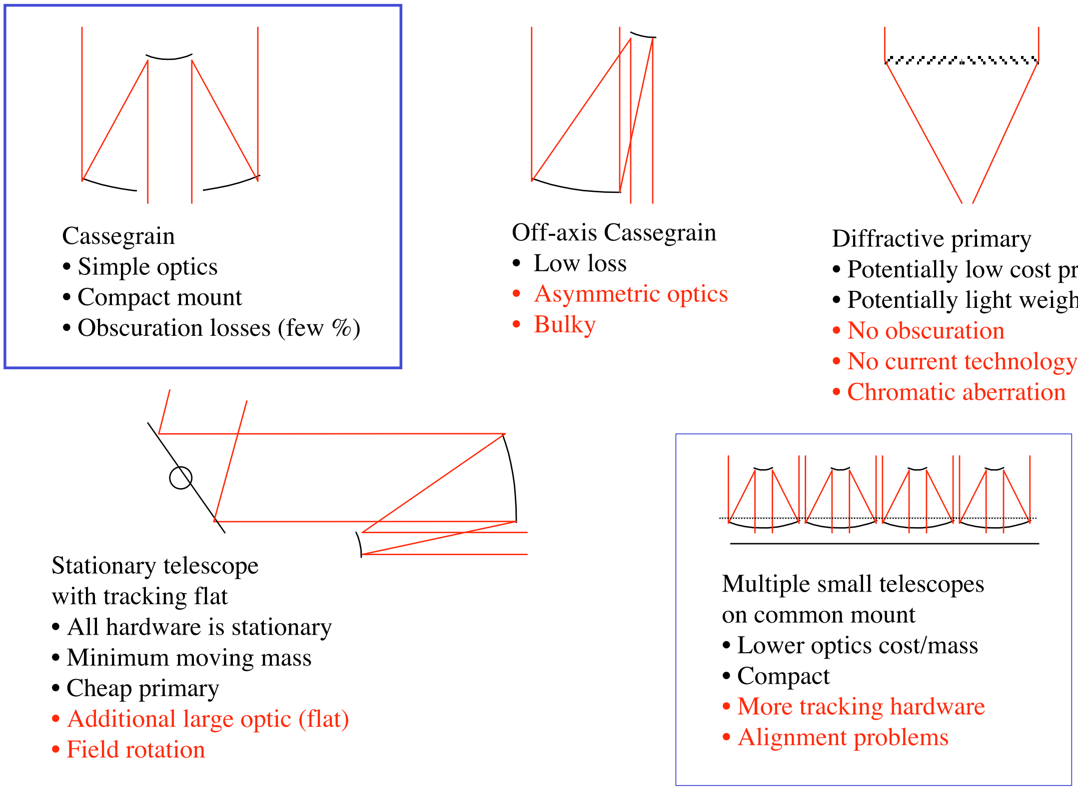

Figure 15: Possible beam module telescope configurations

<u>Photonic Crystal Fiber Feed</u>

Instead, we propose to use flexible single-mode optical fibers to deliver the beam energy from the laser directly to the telescope focal plane. Until recently, the limited power-handling capability of single-mode fibers would have made this difficult, but the same developments that allow a fiber laser to operate at kilowatt and higher power levels also allow passive fibers to transmit similar power levels without damage.

Of most interest are photonic crystal fibers, an example of which is shown in Figure 16. PC fibers have a regular array of holes – actual empty spaces – running the length of the fiber. By choosing the hole size and spacing, it is possible to define a matrix which will allow the propagation of a single transverse optical mode along the axis, but will not propagate any higher modes. The allowed mode occupies a substantial part of the PC hole array, so most of the energy is actually propagating in the holes, not in the solid fiber, which minimizes both absorption and nonlinear effects.

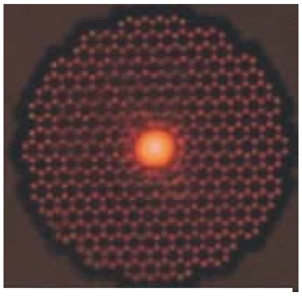

Figure 16: Single-mode photonic crystal fiber cross-section (Courtesy Blaze Photonics)

PC fibers are already commercially available from several sources, and are a rapidly-evolving technology; we anticipate that fibers capable of carrying a 10 kW single mode beam over several meters with <1 dB loss (<10% power loss) will be available within the next two years.

Assuming suitable connectors are available, the PC fiber approach also allows individual lasers to be disconnected from and reconnected to the telescope as needed, with a minimum of realignment required. Highly precise. low-loss fiber connection technology is another product of the communications fiber optic industry that can be applied to beam modules.

The pointing and tracking subsystem will probably be mounted on the telescope, because it requires a relatively large field of view.

Optimum Telescope Size

Figure 17 shows qualitatively the variation in cost per unit area as a function of mirror size. In general, telescope cost per unit area increases with telescope size, but at some point in reducing the telescope size, the fixed costs of the pointing and tracking system, and possibly other components such as drive motors, will outweigh any further savings in optics costs. We have somewhat arbitrarily chosen a 1-meter diameter baseline, but would consider any size between ~33 cm (the diffraction limited minimum) and ~2 m as a reasonable possibility.

Other Telescope Subsystems

Secondary and Steering mirror

The secondary (and any other fixed optics, such as fold mirrors) can be conventional Zerodur optics with multilayer coatings. The minimum secondary size is limited by field of view requirements (not by f/number, since the telescope is afocal) or by heating or coating flux limits; neither is likely to be a problem down to ~10 cm.

The secondary may be used as the fast steering mirror, or a separate flat mirror can be used. Complete 2-axis mirror assemblies are catalog items, with a small-quantity cost of a few thousand dollars (5 cm mirror).

Focus

Telescope focus can be fixed, active (automatically adjusted with a bandwidth of order 1 Hz to correct for thermal or gravitational changes) or adaptive (adjusted with a bandwidth of order 100 Hz or higher to correct for the second order term in atmospheric aberration.) Fixed focus requires a highly thermally-stable truss or barrel to support the secondary. It is problematic for beam modules both because of the cost of such a truss (DFM Engineering, a well-regarded manufacturer of meter-sized professional telescopes, uses invar trusses) and because the ranges involved are short enough that some refocusing may be required over the course of a launch. (If a single large telescope were used, such refocusing would be mandatory, since the beam diameter would need to be matched to the apparent vehicle size.) We therefore assume that the secondary has an active focus mechanism.

The extra beam quality obtained from adaptive focus correction is small, but may be available essentially for free if the secondary is used as the fast steering mirror.

Pointing and Tracking

Figure 18 shows a conceptual design for a pointing and tracking subsystem. Coarse pointing is done open loop (in the sense of not needing a signal from the vehicle), using encoders on the telescope mount axles. This may be sufficient to bring the vehicle into the field of view of a coarse tracking sensor on the telescope. If not, a small “finder” telescope and imaging sensor (CCD or CMOS camera) with a larger

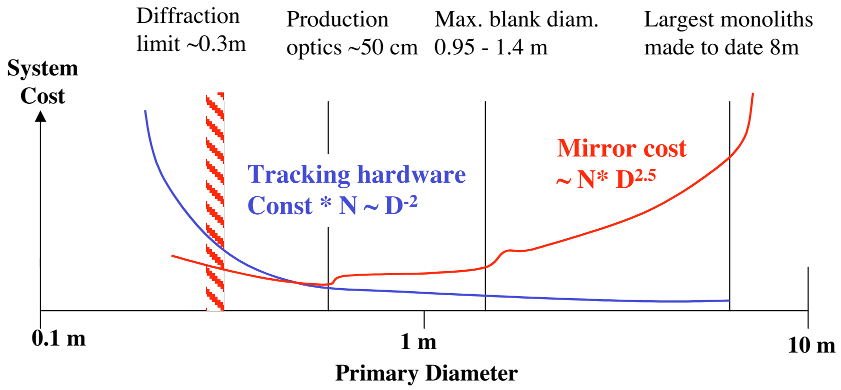

Figure 17: Variation in telescope cost with aperture

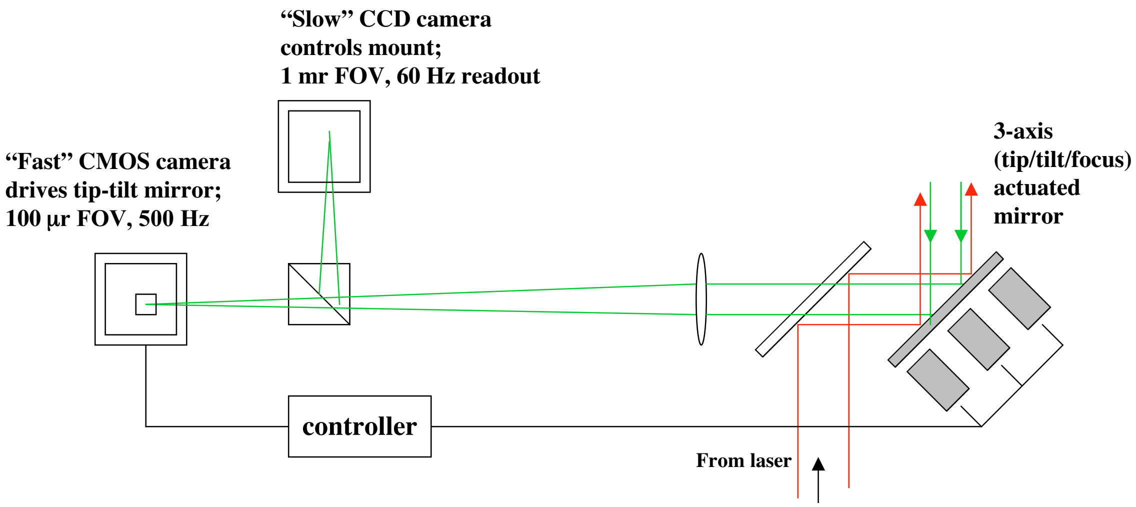

Figure 18: Pointing and tracking subsystem

(nominally 1 degree) field of view may be attached to the main telescope and used to guide the telescope to the target. (There will be a cost trade between precise encoders and/or increased tracking sensor field of view and a finder telescope, but the requirements for the finder telescope are at most comparable to those of amateur-astronomy telescopes and CCD cameras.)

The coarse tracking sensor and its controller will drive the telescope mount to keep the vehicle near the center of the telescope field of view, and thus keep the fast steering mirror centered in its range of motion. The sensor is a standard industrial monochrome CCD camera, nominally 1024 x 1024 pixels operated at its normal 60 Hz field rate, with a pixel instantaneous field of view (IFOV) of (typically) 10 uradians, and a full field of 10 mrad, or about half a degree, which probably exceeds the usable telescope field.

One way to reduce the beam module cost is to relax the precision requirements for the mount and drive mechanisms. Astronomical telescopes typically have extremely smooth, precise, slip- and backlash-free drives, using either gear/worm drive or disk/roller drive mechanisms with DC servo or stepper motors; even if an automatic guiding mechanism is used the drive system is expected to maintain sub-arc-second pointing over many seconds Large military laser beam directors relax the open-loop precision requirement but add fast slewing and rapid settling to acquire and track hostile targets. Beam modules require neither: the tracking system necessarily compensates for errors in mechanical pointing, including vibrations up to its bandwidth limit, while vehicle trajectories are predictable. We assume a comparatively lightweight mount, probably cast aluminum or composite, and simple cable or belt drives with standard industrial bearing

The fast pointing sensor controls the fast steering mirror and the active or adaptive focus. A key to making the modular laser system work is that the pointing system can be commanded to hold the beacon spot anywhere on the sensor, so that the beam can be offset from the beacon by a commandable amount. This allows varying pointahead with vehicle velocity and orientation, and also lets beams be distributed across the heat exchanger area for uniform (or nonuniform, if desired) flux. The sensor is a CMOS-type sensor which allows selective readout of individual pixels or regions, so that sub-frames can be read out at up to several hundred Hz.

Beacon

We briefly evaluated several options for tracking the vehicle:

Simple imaging

Simply imaging the vehicle in reflected sunlight (through a filter blocking scattered laser light) is not feasible; most of the vehicle is (necessarily) black. Of course, it also limits the system to daytime operation.

SWIR imaging

Tracking the vehicle in the near infrared certainly possible; the heat exchanger hot end will be a near-black-body source at close to 1500 K (peak wavelength near 2 microns) against a cold sky background. However, this solution suffers from the "bootstrap problem" – if the heat exchanger is cold, it can't be found to point the laser at it to heat it. This might be bypassed at launch (for instance, by pre-heating the heat exchanger) but would prevent re-starting the thruster after a shutdown. Also, although IR cameras are readily available, the camera and optics are significantly more expensive than equivalents for near-IR and visible light.

Scattered or reflected main laser light

Even with a high-quality absorbing coating on the heat exchanger, the vehicle will be an enormously powerful light source – probably over a megawatt -- at the main laser wavelength, due to imperfect absorption and due to the edges of the beam scattering from (presumably white or shiny) bits of vehicle exposed around the heat exchanger. However, any tracking system based on using the main laser wavelength will need to contend with scattering within the beam module. While there are possible ways to work around this (e.g., pulsing the laser in any given beam module off for a few microseconds at a time, and tracking during this "blink") this adds significant complexity to the system.

The following options use a dedicated beacon. The beacon power depends on the required signal at the tracking and (primarily) the fast pointing sensors. We can estimate the required beacon flux ϕ_{beacon} as follows (this is an order-of-magnitude discussion; values should not be considered precise):

$$\mathrm{SNR} = N_{signal} / N_{noise} > 10 \tag{36}$$

(enough for reliable detection and centroiding to ~1/10 pixel)

$$N_{signal} = \phi_{beacon}\, \tau_{frame}\, A_{telesc}\, \eta_{optics}\, \eta_{\mathrm{det}}\, \lambda / hc \tag{37}$$

$$N_{noise} = \sqrt{(N_{signal} + N_{dark} + N_{sky} + N^{2}_{readout})} \tag{38}$$

Where τ_{frame} is the sensor frame integration time, η_{optics} is the transmission efficiency of the optics, η_{det} is the detector quantum efficiency, and λ / hc is the photon energy.

N_{dark} is the detector dark charge (dark current x τ_{frame}), which for video sensors is of order 10^4 at normal 1/60 second frame rates, and thus of order 10^3 for the 1000-Hz fast pointing sensor.

N_{sky} is the sky background:

$$N_{sky} = Rs_{sky}\, \tau_{frame}\, A_{telesc}\, \Omega_{pixel}\, \eta_{optics}\, \eta_{\mathrm{det}}\, \Delta\lambda_{filter}\, \lambda / hc \tag{39}$$

where Rs_{sky} is the spectral radiance (W/m^2-sr-um) of the sky, Ω_{pixel} is the pixel (detector) solid angle, and $\Delta\lambda_{filter}$ is the filter bandwidth.

Rs_{sky} depends on the local atmosphere and sun angle, but (assuming the vehicle isn't flying too close to the sun) a conservative value is 10^{-5} of the solar disk spectral radiance, which in turn is of order 10^7 W/m^2-sr-um in the visible and near IR. η_{optics} is typically 0.25 (recalling that the incoming light is split between at least two sensors, and is not at the design wavelength of the mirror coatings). A high quality scientific CCD might have η_{det} ~ 0.9, but we will assume a cheap industrial sensor with $\eta_{det} = 0.4$. Assuming a 1 m^2 telescope, a 10 µradian square pixel field of view (10^{-10} sr), and a 1 nm filter, $N_{sky} \sim 10^{-15}$ J/(photon energy) ~ 4 x 10^3 photons.

Again, for a high-quality detector, $N_{readout}$ could be as low as a few electrons, but for a low cost sensor, $N_{readout}$ could be up to ~100. Conservatively, we can therefore estimate

$$N_{noise} \approx \sqrt{N_{signal} + 1000 + 2000 + 4000 + 10{,}000} \approx \sqrt{2 \times 10^{4}} \approx 140 \tag{40}$$

Working backwards through Eq. 37, $\phi_{beacon} > 1.4 \times 10^6$ photons/s-m^2 ~ 2×10^{-13} W/m^2

Ground laser with retroreflector

A ground-based beacon laser in the middle of the beam module array can illuminate one or more retroreflectors on the vehicle, which return light to the array for tracking. Using a wavelength far from that of the main laser (e.g., 532 nm) would make the beacon laser signal easy to detect. One problem with this approach is that, unlike typical retroreflector applications with a single receiver, this application requires that the returned beam cover a large area even at the minimum range (which could be as short as a few 10's of km), so the retroreflector must produce an appropriate beam divergence. There is a possible bootstrap problem, in that if the beacon laser loses its own tracking, there is no easy way to reacquire the vehicle; this can be addressed by making the beacon laser divergence wide enough (and its mount precise enough) to follow the vehicle "open loop" through any momentary tracking failures. There is also a potential problem with scintillation; the outgoing beam will be deflected by atmospheric turbulence, and the beam flux at the retroreflector will therefore vary randomly, including dropping to zero for of order the atmospheric correlation time.

A minor problem is that a large broadband retroreflector could return an unsafe amount of main laser power to the ground; the retroreflectors would need to be designed to specularly reflect only the beacon wavelength, and diffusely reflect or absorb the main laser wavelength.

The beacon laser power is reasonable: assuming the beacon laser has a divergence of 100 μrad, the beacon spot at the vehicle at 500 km will be 50 m in diameter. The retroreflector cannot be too large; if we assume an effective size equal to a 5 cm diameter circle, the retroreflector will capture and return 10^{-6} of the laser power. Assuming this is distributed over 10 km^2, the returned flux will be 10^{-13} P_{beacon} per m^2, and the beacon laser could be as small as 2 watts. Even a few-hundred-watt beacon laser would not strain the resources of a launch system, so there is considerable margin. Using several beacon lasers would reduce the probability of both scintillation dropouts and tracking failures.

A beacon laser may be desirable even if is not retroreflected for tracking; the beacon beam would provide a precise 2-axis attitude reference for the vehicle and could be used for a communications uplink.

Onboard laser

The final, and recommended, beacon option is an active laser beacon on the vehicle itself. Assuming a perfectly omnidirectional beacon at 500 km range, supplying 2×10^{-13} W on the ground requires $2 \times 10^{-13} \times 4\pi \times (5 \times 10^5)^2 \sim 0.63$ watts. The beacon could thus be as simple as a pair of laser diodes with hemispherical diffusers, even assuming full 4π coverage was desired.

Using an onboard beacon eliminates any issues in locking on to the vehicle. The beacon can also be modulated to provide a data downlink from the vehicle; provided the modulation rate is substantially higher than the fast pointing sensor frame rate, the pointing sensor will see only the average beacon power. (High data rate modulation can be detected with a photodiode in each beam module. The signal-to-noise for each individual beam module would be poor, but by summing the outputs from all beam modules, data rates of several kilobits/second should be easily supported.)

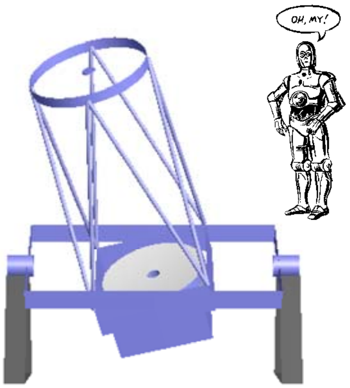

Figure 19: Concept for 1-m f/2.5 Cassegrain telescope and mount

A final advantage of the onboard laser beacon is that, given the small size and weight of the beacon itself, it can easily be put on a boom or spike extending in front of the vehicle. to provide pointahead for the fast pointing subsystem and adaptive optics, if any. The pointahead can be adjusted by physically moving the beacon (retracting or extending the boom) or by simply switching among several beacons as required. (Pointahead can, and should, be provided with a retroreflector/ground beacon laser system as well, by putting the retroreflector on a similar boom, but this will tend to drive the size of the retroreflector down, and therefore the beacon laser power up, substantially)

Baseline Telescope and Beam Module Design

Figure 19 shows a preliminary CAD model of the beam module telescope and 2-axis mount. This is a 1-meter diameter f/2.5 telescope, with a 10-cm afocal secondary (10X magnification) Note that the mount has both axes horizontal (an altitude-altitude or elevation-elevation mount) rather than the common altitude-azimuth mount used for cannons and many modern telescopes and beam directors. This is because the standard mount has a singularity at the zenith, where the azimuth axis has to move up to 180 degrees for an arbitrarily small change in target position. Since laser launched projectiles will go nearly overhead routinely, this is undesirable; the alt-alt mount moves the singularity to the horizon.

Figure 20 (insert) shows schematically the complete baseline beam director, combining the telescope, 60 kW fiber laser assembly (for a transmitted power of 50 kW), and power supplies.

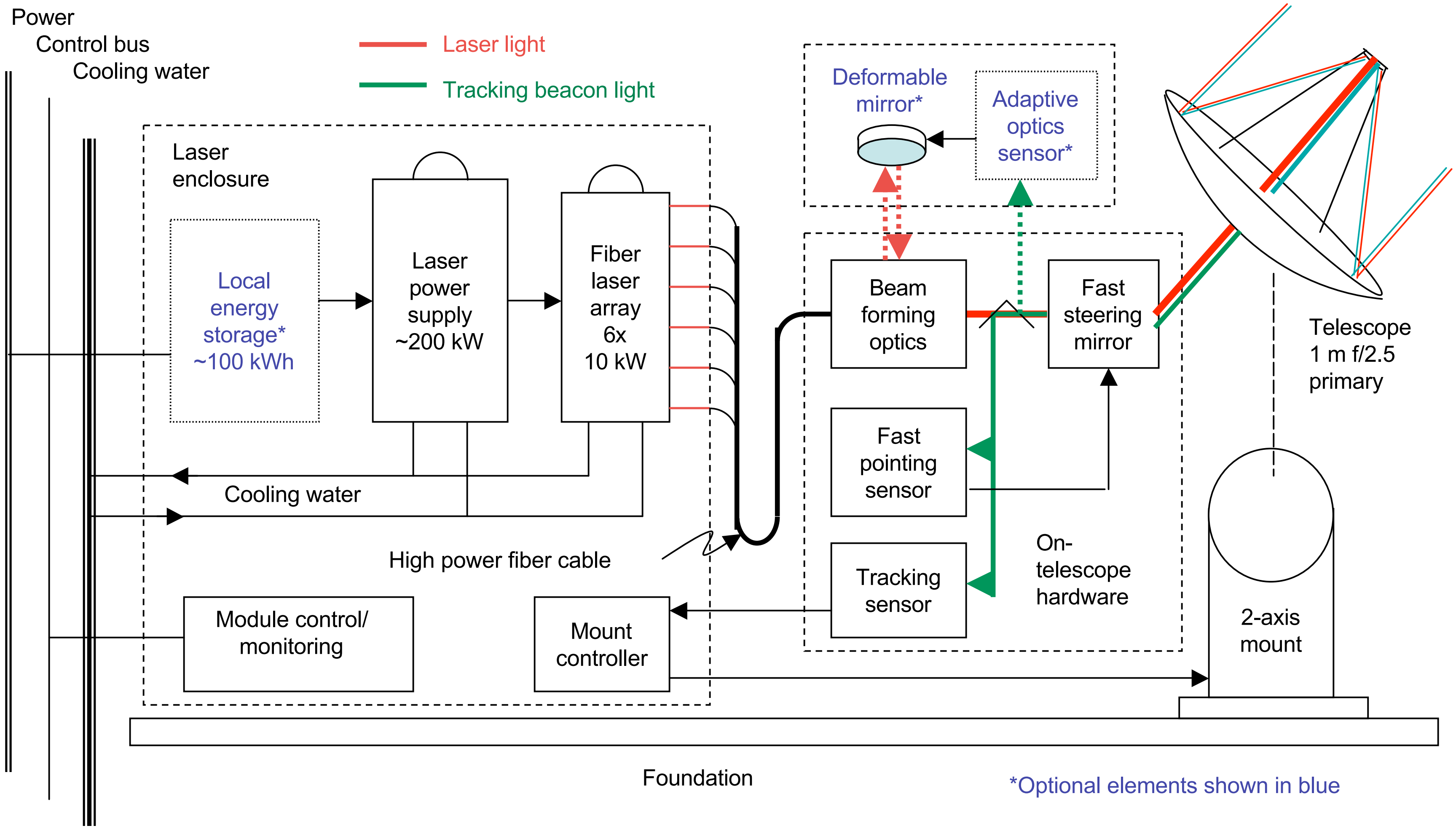

Figure 20: Baseline beam module

Task III: Architecture and Technology Roadmap

System Cost

The capital cost of a modular laser launch system is nominally the cost of beam modules themselves, plus the cost of the supporting facilities: power, cooling, roads, land, etc. Not all of the support facilities are associated with the beam module array; there are also costs for vehicle storage and integration facilities, propellant production and storage, and catapults or other non-laser-related launch site hardware. Some of these support facility costs will depend on how heavily used the system is, while others are roughly fixed.

For the current baseline system, and for higher-power beam modules, we expect the beam module cost to be dominated by the cost of the laser, so we consider the laser cost first. All of the leading laser options use diode laser arrays as a major component, so we need to estimate the future cost of laser diode arrays.

The current cost of laser diode stacks varies among manufacturers, and depends on both quantity and type. Without seeking formal quotes, we discussed diode bar and stack prices with representatives of several manufacturers, including Decade Optical, Coherent, Oriel, Quintessence Photonics, and Cutting Edge Optronics.

Current prices for raw (unmounted) diode bars operating at 808 nm are \$100 - 150 per 60-watt bar (the current standard) in 100-kW quantities. Currently, most diode bars are fabricated to order, using general-purpose fab lines also used for discrete laser diodes, microwave integrated circuits and other specialty (i.e., non-silicon) devices. Raw bars can be expected to drop significantly in price when production volumes are large enough (MW/year for a single manufacturer) to warrant a dedicated fab line. One engineer from a major manufacturer noted that his company expected the price of diode bars to drop to \$10 each (less than 17 cents/watt) in the near future.

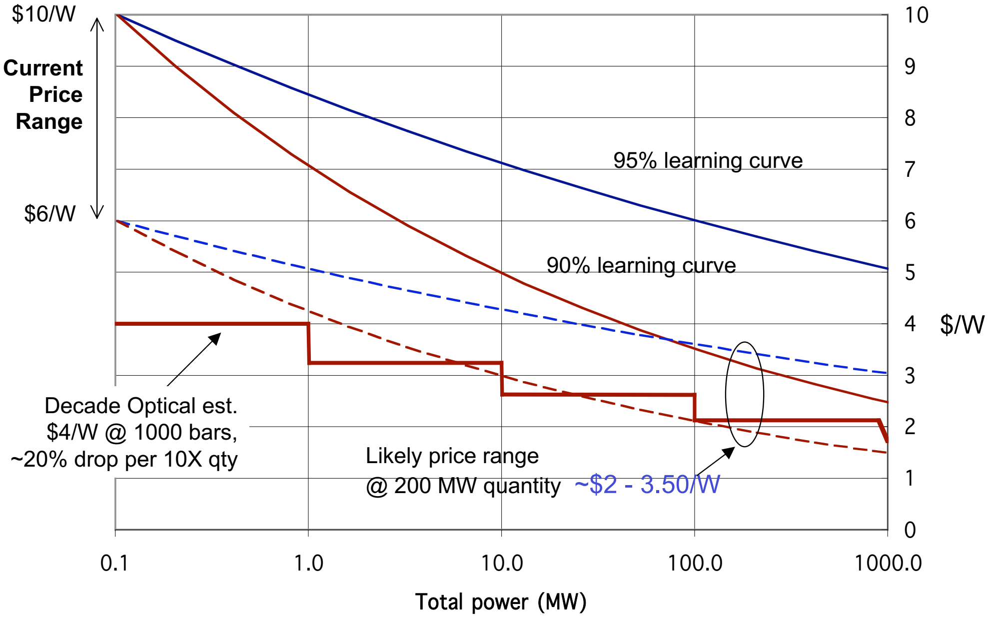

Figure 21: Projected price of laser diode arrays vs. quantity, assuming no performance gains

Much of the manufacturer-to-manufacturer variation in diode array stack costs comes from differences in mounting and cooling arrangements and in mounting and aligning microlenses. Most manufacturers cited costs of $6 to $10 per watt for assembled CW stacks in 100 kW quantities, including cylindrical microlenses. Decade Optical (which supplies primarily military customers of high-power arrays) estimated $4/watt for a 1000-bar array, and $3.20/watt for 10,000 bars. Decade uses simple cylindrical microlenses (actually optical fibers stripped of cladding) which yield considerably less than diffraction-limited beam quality; this may be adequate for pumping fiber or alkali-vapor lasers, but for systems that use the diode output directly, aspheric 2-D microlens arrays would probably be required, at somewhat higher cost.

Like most industrial products, laser diode arrays may be expected to drop in price with increasing production quantities, even if there are no major improvements in technology. Standard models for such price drops assume a fixed percentage price change (learning curve factor) for each doubling in production volume. Electronic components typically have a 95% learning curve while "assemblies" have 85-90% learning curves [36]; diode array stacks are probably in between. Figure 21 shows projected diode array costs for 90% and 95% learning curves (as well as an extrapolation of Decade Optical's estimates) to >100 MW quantities; the projected array prices are $2-3/watt.

Assembly and alignment of diode array stacks and microlenses is still moderately labor-intensive; we note that one of the major diode-array related efforts at LLNL is developing self-aligning "snap together" arrays.

Increasing the power per diode bar would automatically reduce the cost per watt of assembling stacks. At least some current 60 watt bars can be operated at 75 watts, with some loss of lifetime and reliability. 100 watt "standard" bars have been claimed as imminent for several years, and presumably will arrive eventually. Alternatively, a commercial manufacturer, Oriel, is offering 30-watt diode bars in a high-volume commercial package resembling the common TO-220 transistor package, with the stated goal of reducing the price per watt to half that of prior packaged arrays.

Overall, we therefore predict that within 5 years, microlensed, cooled CW diode arrays will be available in 100-MW quantities for no more than $2.40/watt, and probably less than $2/watt. There is a significant chance that the price will drop below $1/watt.

The cost per watt of assembled lasers must include a multiple of the cost of diode arrays to allow for conversion efficiency and coupling losses, plus the cost of other components, housings, assembly and testing, and a reasonable profit for the manufacturer – although profit margins should be significantly lower for a high-volume production item with a continuing demand and multiple suppliers than for typical aerospace hardware. (We note again that typical aerospace (and military) requirements for testing and documentation, which drive the cost of space hardware, should be largely irrelevant, since individual laser failures are unimportant. The only laser requirement that may force significant testing and documentation is lifetime, since widespread premature failure of lasers would be expensive.)

Fiber lasers may be considered a reasonable baseline. Current fiber lasers cost approximately $500/watt[*] but this price is based on fibers pumped by comparatively expensive discrete diodes ($75-150/watt) and sold in very low quantities. Dual-core fiber for high-power fiber lasers is also still a specialty product with a heavily volume-dependent price. A rough estimate from a major specialty-fiber manufacturer was that fiber for a 1 kW fiber laser (a few meters of fiber) costs of order $10,000 today, but could easily drop to $2000 in quantities of 10's of kilometers. We would also expect fiber cost to be relatively insensitive to laser power, within a given fiber technology (i.e., photonic crystal fibers may be more or less expensive than conventional fibers). Assembly and test costs should also be relatively insensitive to laser power.

A rough guess at the cost breakdown for current and future lasers is shown in Table 4. Note that "other hardware" includes DC power supply costs.

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[*] List price of an SPI 100W fiber laser was $70,000 as of Feb. 2004, but prices are falling and most purchasers receive some discounts.

Table 4: Estimated Costs for High Power Fiber Lasers

Item	Current 100 W	1 kW, Qty 1	1 kW, Qty 10^5	10 kW, Qty 1	10 kW, Qty 10^4
Laser diodes	15,000 @100/W	15,000 @10/W	3,000 @2 /W	90,000 @ 6/W	30,000 @ 2/W
Fiber	5,000	10,000	2,000	30,000	6,000
Other hardware	5,000	10,000	2,000	30,000	10,000
Ass'y & Test	5,000	15,000	2,000	30,000	10,000
Total cost	30,000	50,000	9,000	180,000	56,000
Markup	67%	100%	40%	100%	40%
Price	50,000	100,000	13,600	360,000	78,000
Price/watt	500	100	13.60	36	7.80

Table 5 gives a breakdown of the expected cost of a baseline beam module and modular launch system, circa 2010. We assume a total of 2200 beam modules, to allow for beam transmission losses and for spare modules. The projected module cost is about $640K, with the majority of the cost, as expected, in the lasers themselves. The system cost is just over $1.5 billion. Realistically, we need to allow a sizeable margin on this cost, but even allowing a 30% margin, the total system cost would be just under $2 billion, which is consistent with our past estimates of overall system cost.

Table 5: Cost Breakdown For Beam Module and Launch System

			Per module $K		Full array $M
Lasers					(2200 modules)
Fiber lasers	6 x 10 kW	$7.50/watt	450		
Power supply	200 kW	$0.20/watt	40		
				490	1078
Optics					
Primary			25		
Other optics			25		
Mount			25		
Pointing & tracking			25		
				100	220
Physical plant (buildings, power, cooling)				50	110
				640	1408
Launch site (usage dependent)					100
Launch System Total					1508

Operating and Maintenance Costs

It is difficult to estimate operating costs for radically new systems. Operating costs for a modular laser launch system will probably be dominated by launch site activities; the manpower needed to actually run the laser system should be minimal, approaching the limit of one operator and one dog.* Maintenance, however, will be a significant cost, roughly proportional to the amount the launch system is used.

If we assume a mean service life for the beam module lasers of H operating hours, after which the entire laser is replaced (as opposed to, e.g,, replacing individual laser diode arrays), the maintenance cost per launch depends strongly on H. For current diode arrays, a typical rated lifetime is 5000 hours; assuming a 10-minute laser run time per launch, the cost would be of order ($1 billion / (5000 hours x 10 launches per hour) ~ $20,000 per launch for the baseline system, or $200/kg for a 100 kg payload.

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* The traditional staff for a fully-automated factory: the operator is there to feed the dog, and the dog is there to bite the operator if he tries to touch any of the machinery.

However, the nominal array lifetime is based on applications where loss of any substantial fraction of the array power causes the whole laser system to shut down. By contrast, there will be little or no cost to letting individual lasers or beam modules "run down" to low power while still in service. For example, in a conventional industrial application with a single fiber laser doing a task (such as welding), a drop of 10% in output power may require taking the laser out of service for repair or replacement. In a large beam module array, if N beam modules drop 10% in output power, the "repair" can be to install N/10 new beam modules, leaving the original N still in service. This can continue until the original modules drop to a very low power level, or fail completely, at which point their lasers can be replaced. The correct value for H is therefore close to the mean time to failure for lasers, rather than the rated lifetime based on some (generally small) probability of failure. The mean time to failure for diode arrays is already of order 10,000 hours, and can probably be extended to >20,000 hours through continuing improvements in processing and packaging; the MTBF for single hermetically-packaged diode lasers for communications is in excess of 200,000 hours.

Most other beam module components should have typical electronic and (for the telescope mount) mechanical system reliability; maintenance and repair costs of order 10% of capital cost per year are appropriate.

One issue of concern when considering low-radiance lasers is of less importance with high-radiance lasers: cleaning and protecting telescope mirrors. Dust will accumulate on exposed mirrors even under ideal conditions, and there is always some chance of gross contamination, for instance due to an unexpected rainfall. With very low-cost optics ($1000/m^2) even minimal cleaning or handling by skilled technicians could easily cost as much per year as the original optics. With the current baseline of ~2000 1-meter telescopes and a primary-mirror cost of $22,000, regular dusting and periodic (perhaps every 2 years) re-coating or even replacement of primary optics would add only of order $30M/year to the system maintenance cost.

Site and Infrastructure Requirements

We have not begun to search for a specific launch site. In general, the requirements for the site will be that it have clear air with minimal cloud cover, and that the "seeing" is reasonable. An astronomical-observatory quality site is not required (which is fortunate, since such sites tend to be inaccessible, and are often ecologically fragile and protected) but sites with strong turbulent winds would be avoided. An isolated location with good road access is desirable, although probably more important for the vehicle launch site than for the laser site. Moderate to high altitude is a benefit, both for reduced atmospheric absorption and to give better visibility close to the horizon (no obstructions); ideally, there should be a line of sight between the vehicle launch facility and the laser site, but in most cases the separation will be too great. We expect that the most likely U.S. sites will be in the southwestern desert, perhaps at White Sands or China Lake.

(This assumes laser launch will be able to avoid range safety requirements that force chemical launchers to launch over water. This is probably the case, but will require much negotiation and quite possibly special legislation – i.e. substantial amounts of time and effort.)

A benefit of high-radiance lasers and the associated reduction in optical aperture is that the ground footprint of the modular laser system becomes small, although not negligible.

The baseline beam module requires roughly a 5 x 5 x 5 meter "keep out" area, but can park in a somewhat smaller volume, probably with a sliding cover for rain protection; a classical telescope dome is probably neither required nor desirable. The physical size of the laser depends on the technology used, but is likely to be modest; even with current fiber lasers, several kilowatts of laser can fit in a standard 19-inch rack. Adding controls, cooling hardware (even assuming a centralized cooling tower and water supply, there will need to be valves, drains, etc.) might require several meters of rack space.

With malice aforethought, we should be able to design the parked telescope and the laser and other support equipment to fit in a 12 x 2.3 x 2.6 meter volume. This corresponds to the interior volume of a standard 40 foot "hi-cube" shipping container, which is the largest commonly-used container. Ideally, the outer housing of the beam module would <u>be</u> a shipping container, so that the assembled module could be transported and delivered as a unit, and simply anchored in place on a suitable slab. A less aggressive packaging approach would have a telescope pallet and one or two equipment pallets which could be unloaded from a container and installed in a prefabricated building. In either case, the intent would be to require little or no precision workmanship on site.

To avoid line-of-sight obstructions and ensure adequate access for vehicles, power, and cooling, beam modules would need to be spaced some distance apart. A "lot size" of 10 x 30 meters would accommodate both side and end access to the module with container-carrying vehicles. A 2000 module array would then occupy 600,000 m^2 – about a quarter of a square mile. The site would not need to be a single contiguous area, but for a variety of reasons – security, utility costs, etc. – it should probably be reasonably compact. However, a good site would also provide expansion up to at least gigawatt scale – two to three square miles.

The laser site will need power and cooling water, but the actual requirements will depend on the planned level of use: a 100 MW launcher (~120 MW of beam power) will require roughly 400 MW of power and 250-300 MW of cooling during a launch, but the daily average will probably be much lower, at least initially. We have not investigated power options in detail, but we estimate, very roughly, that diesel or gas turbine generators will cost of order $1/watt, while power storage for a few launches (15-30 minutes) can be provided cheaply, though not elegantly, with lead acid batteries at a cost of order 10 cents/watt (12 volt, 200 A-hr truck batteries operated at 100 A discharge current), although with limited cycle life. Thus, the launch site can be self-powered for a capital cost between roughly $80 and $400 million (for 10% to 100% utilization). Access to grid power would be preferable, but local storage will still be needed to avoid large unsteady loads on the grid.

Evaporative cooling provides of order 2 MJ/kg of cooling, so each launch would evaporate a few hundred kg of water. However, very large volumes of water will need to circulate through the launch site to keep laser diodes at a stable temperature: assuming a 10 C allowed temperature rise (approximately 50 kJ/kg), the launch site would need to circulate several thousand liters of cooling water per second, and have a cooling water reserve of several million liters. Local cooling to air at each beam module is almost certainly undesirable due to the effect on atmospheric turbulence of large heat sources, although a low-duty-cycle system might store heat locally (e.g., in a few thousand liter water tank, with local circulation) at each module and discharge it more slowly into the main cooling system.

Laser Site Configuration

One key factor for overall launch system performance is where the laser array is located relative to the vehicle launch site. Placing the laser array very close to the launch site allows the laser to "see" the vehicle starting at a very low altitude, perhaps even while the vehicle is still on a launch tower, and minimizes atmospheric absorption at liftoff. It also allows launches to almost any azimuth. However, it limits the overall trajectory length to half the maximum length the laser could power.

Conversely, placing the laser near the midpoint of the trajectory gives the maximum possible laser range, but requires the vehicle to somehow climb to nearly its final orbital altitude before the laser can acquire it. Even in this case, a single launch site can launch vehicles into a fairly wide range of trajectories – nominally +/- 15 degrees in azimuth or +/-100 km in transverse position -- at very little cost in delta-V, but multiple launch sites are required if launches to both polar and low-inclination orbits are required.

A compromise places the laser 100 – 200 km downrange of the launch site, and assumes that a line of sight can be established close to the horizon without an impractical amount of absorption. In this case, a catapult, aircraft launch, or some similar mechanism is needed to get the vehicle to perhaps 10 km altitude. A single launch site can accommodate more than 90 degrees of azimuth (polar to equatorial).

It is possible to split the laser system, and place some fraction of the power near the launch site for takeoff, and the rest downrange in one or more clusters. This is clearly advantageous if the overall system is range-limited, rather than liftoff-mass limited – the system has roughly three times the range of a system with a single laser at the launch site, so even with half the laser power at any one time, it will put significantly more mass in orbit. More that two sites are probably not worthwhile, and would allow access to only a narrow range of azimuths.

(A modular launch system could in principle distribute modules over a large area, for instance in a line along a trajectory, but we haven't identified any advantages to doing so, and there would be significant practical disadvantages in terms of, e.g., distributing power and cooling.)

Finally, and of most interest, the modular laser can be not only split, but diversified. For example, suppose wavelength-stacked diode arrays may provide only 1% of the radiance of fiber lasers, but at half the cost per watt. Beam modules using wavelength-stacked arrays and cheap replica optics could be used at the launch site to power the vehicle from launch to 50 - 100 km altitude, where it could pick up the main laser beam at somewhat reduced power; both beam module arrays would provide power for a time, until the vehicle passed completely out of effective range of the launch-site array.

Optimizing the system is still more complicated if alternate propulsion schemes are used (for example, any type of air-breathing propulsion at low altitude). A strong possibility would be to use dual laser sites for the fully operational system, but complete the main laser array first and do testing and initial operations with air-launched or solid-rocket-boosted vehicles.

Environmental, Safety, and Other Issues

The largest obstacle to rapid construction of a modular laser launch system is probably not technology or cost, but regulation.

The modular laser system is largely environmentally benign, except for the hazard to birds flying through the beams; with infrared lasers, it will not even be a visual disturbance. The bird hazard is not negligible, but is comparable to that produced by electricity-generating windmill farms. It may be necessary to employ bird-discouraging techniques similar to those used at some airports – noisemakers, simulated predators, etc. – to minimize the hazard.

The power system may pose some environmental issues: generator exhaust, battery disposal if lead-acid or nickel-cadmium batteries are used for power storage.

Nonetheless, any facility on this scale will require extensive environmental review, especially if (as is likely) the preferred site is in an environmentally sensitive area. Our nominal schedule allows 4 years for environmental review before beginning permanent building at the launch site, but this may not be adequate.

Aircraft safety will require a combination of a "no fly" zone and active safety measures, including both general area-scan radar and last-resort "along the beam" radar, interlocked to shut down the laser array if an airplane approaches the beam. The size of the no-fly zone will depend on the laser field of access, but a typical value would be a 50 km radius around the launch site for commercial aircraft (i.e. vehicles flying up to 15 km altitude) since a typical minimum beam height at 50 km would be >20 km. Low altitude flight (e.g., into and out of a nearby airport) could be allowed at closer range; conversely, a corridor from the vehicle launch site to the laser site might be completely blocked, both to avoid the laser beam (if the beam tracks relatively close to the horizon to pick up vehicles at low altitude) and to ensure that aircraft are not at risk of being hit by a falling vehicle if a launch is aborted.

Individual eye safety will be an issue near the laser site, due to scattered light, but we have not investigated the likely requirements. The vehicle will need to be designed to ensure that there are no specular surfaces that could reflect a significant laser flux to the ground; this mainly means that there can be no flat, shiny surfaces on the vehicle, including the heat exchanger surface. At vehicle-to-ground ranges of 10's of kilometers, even a few-degree beam spread would lower the worst-case flux on the ground to <<100 W/m^2, which is acceptable for naked-eye safety; more severe requirements (e.g., "binocular safe" and "telescope safe,") may be appropriate since vehicles in flight will be an obvious attraction for observers.

The last major safety issue we are aware of is satellite safety. We have not researched satellite safety thresholds, and such information may not be publicly available, but the general rule for laser illumination of satellites is "Don't." The modular laser system poses a lower hazard level than a monolithic laser because whatever energy misses the vehicle is spread over a cone of order 1 milliradian wide, but for the same reason the probability of a satellite passing through the beam, and the likely exposure duration, are increased. At a minimum, careful coordination of laser launch schedules with satellite passes will be required.

Other Architecture Issues

Launch missions

Most of the mission and overall space architecture issues for the modular laser launch system are similar to those for other laser launch concepts: how to integrate a system which can cheaply launch very large numbers of small payloads with rocket-based systems that launch relatively few much larger payloads. Exploring the mission options for laser launch in general was beyond the scope of this effort, but we summarize some possibilities below.

The modular laser launcher does have two unique aspects: continuous scaling and extreme reliability. Continuous scaling presents both problems and opportunities for mission planners and architecture designers. For the mission designer, launch mass can be traded for schedule; a spacecraft slightly too heavy to launch at a given time may be within the mass limits a few months later. For the architecture designer, infrastructure must be designed to accommodate a range of payload sizes, or risk making inefficient use of the launcher (or not being able to use it at all until some minimum payload size is reached).

High reliability, on the other hand, is an inarguable benefit. Laser launch systems in general offer the possibility of achieving and demonstrating high reliability, simply because the marginal cost of launches is very low: an enormous number of launches (by expendable rocket standards) can be dedicated to debugging and "burning in" the launch system before high-value payloads are launched. Laser launches also keep most of the launch system complexity on the ground, where margins can be arbitrarily large and maintenance is straightforward.

The modular laser system further improves reliability by eliminating most of the possible catastrophic failure mechanisms for the laser. With fairly simple measures, such as distributed power storage, the probability of a laser failure bad enough to cause a launch failure can be reduced to essentially the probability of large-scale catastrophe – a major earthquake, for example. With robust vehicle margins, the overall reliability of laser launch can easily exceed 0.9999. With an emergency re-entry system, the probability of loss of payload could be reduced even farther, to levels comparable to those of commercial aviation.

The following mission classes are discussed in roughly increasing order of difficulty, not particularly in terms of the launcher but in terms of the degree of change required in how things are done in space. For each class we suggest the rough scale of number of laser launches that might plausibly be involved.

- Microsatellite launch (10-100 launches/year)

Some fraction of space missions can be done by independent small satellites, especially if the objectives of each individual mission are limited. Progress in electronics, and increasingly in microelectromechanical devices (MEMS) has increased the capability that can be packed into 100-kg-class spacecraft, and lowered the mass and cost of support elements such as attitude control systems. Low cost launches might open up a market for small satellites built by universities or companies for specific purposes. However, past opportunities for low-cost small launches (e.g., as secondary payloads on expendables, or Shuttle Getaway Specials) have not been oversubscribed, suggesting that the market for such launches may be modest.

- Homogeneous constellations (100 –1000 launches/year)

Many missions can be done with arrays of modest-sized satellites. The most prominent examples have been low-Earth-orbit communications networks (Iridium, Teledesic, Orbcomm), but applications involving close formation-flying arrays have been proposed, including space-based radars and interferometric or segmented-aperture telescopes. Laser launch is particularly well suited to such applications since replacement elements can be launched on demand, reducing the need for on-orbit spares.

- Heterogeneous constellations/modular satellites (TBD)

It is possible to subdivide the functions of a traditional single satellite into several pieces, which can fly in formation. For example, an earth-sensing mission could consist of one or more sensors, a memory and processing unit, and a communications unit, each it its own satellite, with short-range RF or laser interconnections. There are clear advantages to such an arrangement in terms of optimizing each platform (for agility, low vibration, lines of sight, thermal loads, etc.) and in terms of allowing components to be upgraded or replaced. In the past, the additional overhead mass and complexity made such solutions uncompetitive with single integrated satellites, but the combination of miniature support subsystems and low-cost launch for satellites below a limiting size might make such modular satellites preferable for many missions.

- Propellant and supplies

A large fraction of all mass launched into LEO is propellant. Liquid propellant, and other liquid supplies including water and oxygen, are obvious candidates for laser launch, provided spacecraft can be fueled on orbit. This could be done directly, with laser-launched propellant or supply containers docking with individual spacecraft; this would require each laser launched vehicle (or payload) to have independent rendezvous-and-dock capability.

A more satisfactory, but more capital intensive, option would be to create fuel depots in low Earth orbit, equipped to collect laser-launched small payloads, perhaps using small tethered or free-flying retriever vehicles to capture the payloads and maneuver them into position. The optimum number and distribution of such depots is an interesting question for further research.

If chemical propellants are available cheaply in LEO, the need for advanced in-space propulsion systems is greatly reduced. Most inner-Solar-system missions, including manned Mars missions, could reasonably be done with chemical propulsion if the cost per kilogram of propellant in LEO were reduced 10- to 100-fold.

Currently, there is little market for non-propellant supplies in LEO, except for some Space Station supplies. However, the logistics of human operations in LEO would be greatly simplified if deliveries of supplies, spare parts, tools, etc. could be made as needed, generally on a day's notice, instead of being planned months or years ahead of time.

- On-orbit assembly

Given rendezvous and docking capability, either built in to individual vehicles/payloads or via an on-orbit infrastructure, it becomes plausible to actually assemble large spacecraft on orbit from arbitrary-sized pieces. The range of options for on orbit assembly is enormous, ranging from fully-autonomous robotic assembly to teleoperation to direct human assembly, and from the simplest process of latching together two or three modules to welding, machining, and electronics test-and-repair. The economics of on-orbit assembly may change if maintaining humans in orbit becomes both routine and much less expensive; a significant part of spacecraft cost and mass comes from the need to assemble and test satellites in a 1-gee environment, and then have them survive launch, even though they will only operate in zero-gee. A manned final-assembly shop in low Earth orbit, with test and repair facilities, could substantially change the way satellites are designed and built.

- Human launch

For the modular laser launcher, launching people requires very little other than sufficient payload capability, and an appropriate destination. The system reliability will almost automatically far exceed that of current "man-rated" launch systems, even without an emergency recovery system, but we assume that any man-rated laser launch vehicle would have re-entry capability for the crew.

Crewed launches can be divided based on the minimum practical vehicle size. "Astronauts" (trained personnel, although not necessarily trained to the levels of today's astronauts) can be launched (and reenter) in single-person capsules. A Mercury capsule weighed 1355 kg (excluding escape tower) [37] but a corresponding current-technology capsule would be lighter. It might be possible to make a person-carrying laser launched vehicle with as little as 500 MW of laser power, but the threshold is more likely to be 800 – 1000 MW.

Wider access to space for science and industry will require the ability to launch relatively untrained passengers, and to do flight training. Because of the cost of life support and other equipment, and the inherent need to have re-entry and landing capability, it is likely that crew-carrying laser-launched vehicles would be at least partly reusable. A two- or three-person vehicle with modest aerodynamic maneuverability and either horizontal or vertical landing capability would meet most requirements, but the likely mass and laser requirements for such a vehicle are yet to be determined.

Larger vehicles would be needed for large-scale space tourism, but the practical threshold is unknown. With frequent launches, it may not be necessary to have very large vehicles; a capacity of four to six passengers plus a pilot/attendant might be sufficient. (Luggage could be launched separately, jokes about lost-in-space baggage notwithstanding.) The trade between laser launch and reusable chemical launch vehicles for launching large numbers of people may depend as much on safety and comfort as on cost.

Non-launch Applications

Non-launch applications can be divided into applications for beam modules themselves, and applications for beam-module derived technologies. In the latter category, the greatest impact of a modular launch system may be simply in providing a large market for high-power fiber lasers and diode arrays, and thereby dropping the price of lasers substantially.

Space-related applications divide into two overlapping categories: power beaming and propulsion.

Power beaming

There are many concepts for laser power beaming, including Earth to spacecraft, Earth to moon, point to point in space, and space to Earth (solar power satellites). Most of these involve modest laser power levels compared to laser launch, from a few kilowatts (GEO satellite eclipse power) to a few megawatts (lunar base power [38]). They also tend to involve modest receiver fluxes, limited by the thermal design of photovoltaic receivers to a few kW/m^2.

Beam modules are unlikely to be useful directly for most space power beaming applications, because the required ranges are too great and the power levels too low. A single baseline beam module (50 kW, 20 ur beam divergence including atmospheric effects, no adaptive optics) would produce a flux of xxx W/m^2 with a nominal 800 meter spot width at GEO (40,000 km slant range). This is probably too low to be of practical use. However, a full launch array can produce a useful flux, ~500 W/m^2 at the spot center for a 100 MW array, over the same range. This would give nearly sunlight-equivalent output from solar panels, assuming a laser wavelength near the panel response peak. This would allow a launch array to be used (for roughly an hour at a time, a handful of times per year) to power a GEO satellite with failed batteries through eclipse. Since saving even a GEO satellite could be worth tens to hundreds of millions of dollars, it may be worth incremental modifications of a launch array design to allow such uses, but not, for example, using a different laser type at 50% higher cost.

More practically, beam module lasers and somewhat-improved telescopes could be combined with adaptive optics to provide lower-divergence beams.

Using multiple beam modules, rather than a single laser and telescope, may be advantageous even if the resulting system wastes some power. The modular system has greater redundancy and (if the modules are distributed over a wide area) greater immunity to weather. Modules can be switched between customers as required, providing incrementally higher or lower power levels to meet varying demand. If components (especially lasers) can be adapted from a launch system, both development and production costs would be reduced compared to a custom design.

The most common photovoltaic (PV) materials, Si and GaAs, have peak efficiencies between 0.7 and 0.9 um, with rapid falloff in efficiency at longer wavelengths. Laser power beaming to existing single-layer PV arrays, or arrays designed for both solar and laser conversion, will therefore require one of the shorter-wavelength laser options: DPALs, wavelength-stacked diode arrays, etc. Dedicated laser-driven arrays might be made with lower band-gap materials and work with Yb fiber lasers, but there would be a significant development cost for such arrays.

Modern multilayer PV cells present a problem for laser power beaming to arrays designed for solar conversion (e.g., to power GEO satellites through eclipses); these cells involve two or three series-connected layers which are optimized to produce approximately equal currents when illuminated with a solar spectrum, and will not work with monochromatic light that drives primarily one layer. Beam modules naturally solve this problem by using two or three module types with different laser wavelengths to illuminate the multilayer arrays. Of course, this is beneficial mainly if the application requires multiple beam modules anyway; otherwise combining several discrete laser wavelengths into a single beam is probably more cost effective.

For space-to-space power beaming over relatively short range, laser mass and power consumption will be critical. Wavelength-stacked or SBC diode arrays appear to be ideally suited to such applications, with fiber lasers a strong alternative if efficient wavelength-matched photovoltaics are available. However, packaging and cooling are likely to be sufficiently different for space applications that we would expect only modest synergy between ground-based beam modules and space-based power beaming systems.

In-space propulsion

A beam module array can obviously drive a thruster in space, provided the vehicle is within line-of-sight of the array. Heat exchanger thrusters should be throttleable over a wide range, including operating on residual pressurant gas in the propellant tanks. It should be possible, therefore, to use either a launch array, or smaller arrays of beam modules, to power orbit-raising or circularization maneuvers, rendezvous maneuvering, etc. for laser-launched vehicles. However, the need to be within a few hundred km of a module array for maneuvering will add complexity to such operations. Eventually, small beam module arrays could be distributed around the world, allowing any given spacecraft access to maneuvering power many times per day, but this introduces enough other problems (e.g., environmental and aircraft safety issues) that it may not be the best solution for in-space maneuvering.

There are, however, many alternative system configurations that should be investigated. As a few examples:

- “Flying beam modules” on aircraft or aerostats could provide relatively modest power levels at somewhat longer ranges than ground-based modules; aerostats in particular can fly high enough to be above most atmospheric absorption and turbulence. Hardware could be very similar to ground-based modules, except for light-weighting. Depending on the power level and the amount of time such modules were used, they could be powered conventionally with onboard generators, or by microwave or laser power beaming from the ground.
- Space-based beam modules located near stations or propellant depots could supply maneuvering power to arriving vehicles and orbit-raising power (within limits) to departing ones.
- As with power beaming, laser systems with substantially lower beam divergence could be used over long ranges, with airborne or orbiting relay mirrors. Portions of the hardware for such systems could be derived from beam modules, but the overall laser and optics parameters would be quite different.

The CW laser/heat exchanger thruster combination is, however, inherently less than optimum for in-space propulsion. Pulsed laser propulsion can provide higher I_{sp} and can use much denser, easily storable solid or liquid propellant. The relatively high cost of pulsed lasers, and the high flux requirements (and implied need for focusing optics on the vehicle) for pulsed thrusters are much less of a problem in space than for launch; thrust levels can be much lower and lightweight thin-film reflective or diffractive optics can be easily deployed. Thus, we would expect the long-term solution for in-space laser propulsion to be based on pulsed lasers and largely separate from the modular launch system, even if the lasers are ground-based.

Technology Roadmap

Figure 22 shows the overall roadmap and timescale for building and deploying a modular laser launch system. Figure 23 shows the main elements of the development process for the beam modules themselves.

Because there appear to be few or no actual new technologies needed, most of the work required is system integration and cost reduction. We show a nominal 2-year effort to pull together the pieces and design and build a "testbed" or "breadboard" beam module, with modest total laser power (a few hundred watts) and a nominally half-sized telescope (0.5 meter diameter), which is near the largest size that can be bought essentially "off the shelf" from research telescope makers. This testbed would be used to develop experience with fiber lasers, photonic crystal "beam transfer" fibers, and other relevant components, and to experiment with pointing and tracking hardware and algorithms, but would break no new technical ground relative to existing (mainly military-sponsored) laser and beam director systems. At a rough estimate, this effort might cost $3-5 million, including $300,000 for lasers (at current prices) and a similar amount for optics.

Given experience with the testbed, and another 2-3 years of progress in fiber lasers and diode arrays, NASA would be in a position to develop specifications for a prototype beam module, with full-size optics and a reasonable fraction of full laser power. At this stage, it would be appropriate to emphasize innovation and wide competiton, so we suggest a broad development program with several teams funded – and specifications written as broadly as possible. Because a significant point of the prototyping effort would be to develop mass-producible hardware, we also suggest that at least two teams be funded to produce multiple sets of hardware. We show this as a dual effort, with separate telescope/optics and laser development, because the two technology areas are different and could well be addressed by different companies. Ideally, lasers and telescopes would be interchangeable, and the process of integrating them as simple as attaching a fiber optic cable. In reality, however, integration will take significant effort and

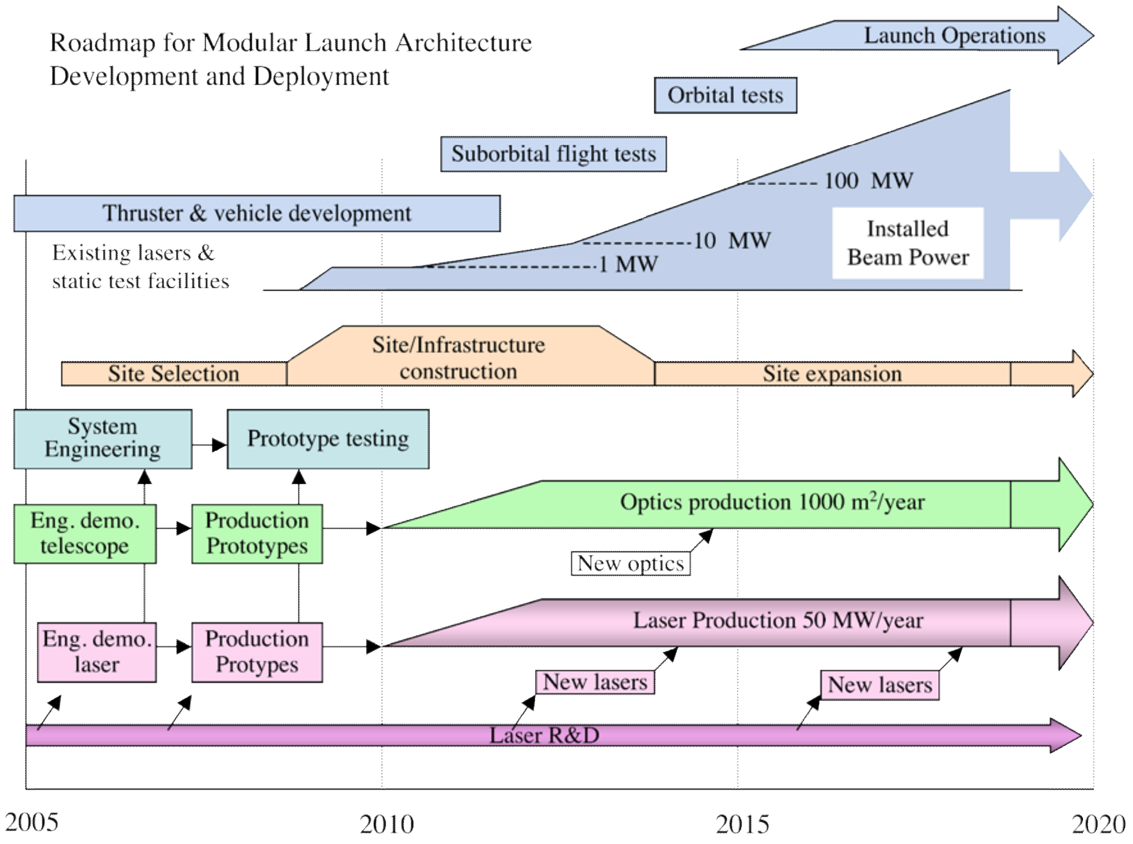

Figure 22: Roadmap for the modular laser launch architecture

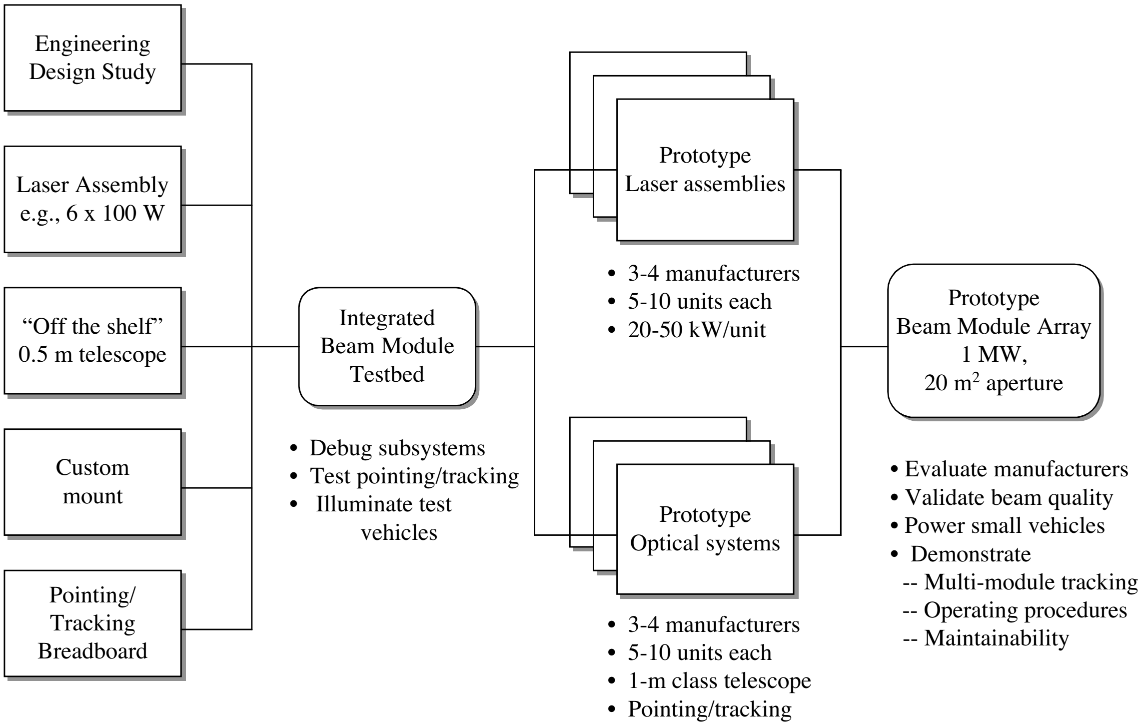

Figure 23: Technology development process for beam modules

planning, and it may be preferable to have teams develop complete beam modules, perhaps with separate technology-development efforts for innovative laser or optics approaches.

Assuming a drop in laser prices to ~$50/watt (which we would expect once fiber lasers are routinely using diode bars rather than single diodes), a 1-meter, 20-kW beam module (to take the nominal size) might cost $3 million, and each development effort $20-30 million, so this would be a $100 million-class project, comparable to a small satellite program, but still inexpensive by launch vehicle standards. Funding fewer teams or requiring less hardware would, of course, reduce the short term cost, but (as always in such trades) increase the longer-term cost and risk.

The output of the prototype module program would be a small, and diverse, beam module array with a total power output of perhaps 1 MW – sufficient to flight-test small sounding rockets or deliver useful propulsive power to a concentrator-equipped satellite. The prototypes would be installed at the beginnings of a launch site – we hope that 4 years would be long enough to select a site and perform enough of the necessary environmental and other studies to start site construction, but if necessary the prototype array could be located at a temporary site.

We allow a year for testing of the prototype modules; we assume a decision is made to begin producing laser modules in 2010, and that production ramps up over 2-3 years, with the first operational modules delivered in 2012 and operational in 2013, and 100 MW of modules (quite possibly from two different vendors) delivered in 2014 and operational in 2015. A year of debugging and test launches would lead to the first operational launch (or paying customer, if the system is commercially owned and operated) in 2016, with a nominal payload size of 100 kg.

We show the module production lines remaining open indefinitely. Some production rate would be needed to replace failed components, but we would hope the full capacity would be kept running. Assuming 10% of the installed base needs replacing per year, the growth of the system is shown in Figure 24; the system would double its initial payload capacity sometime in 2018, and approach a steady-state limit of 500 MW in the 2030's. Alternatively, with some combination of technology improvements and continued investment in production facilities, the system could grow more quickly, and to arbitrarily large size, as shown in Figure 25: a linear gain of 10 MW/year in module production capacity yields 1 GW in 2027 and 2 GW – enough to launch anyone who wants to go to space -- in 2038.

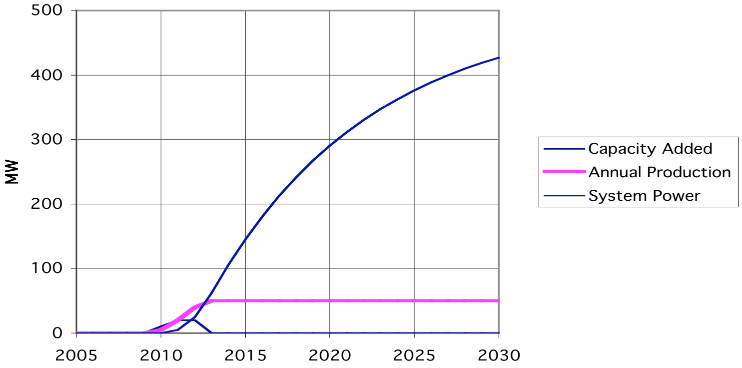

Figure 24: Module production and system power for fixed technology and limited investment in production facilities

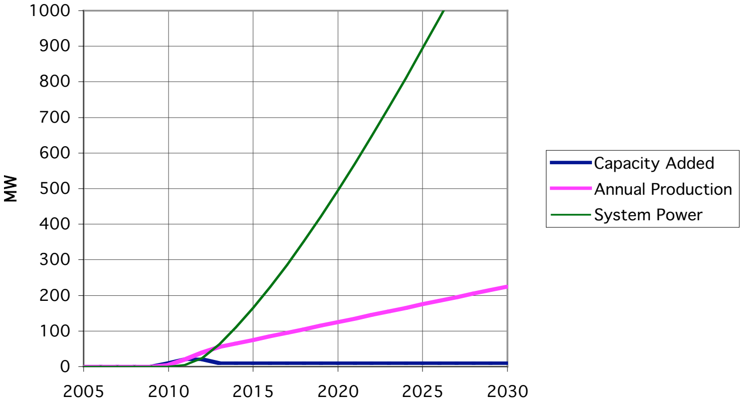

Figure 25: Module production and system power for fixed technology, but continuing investment in production facilities

Conclusions

When it's steamboat time, you steam. – Mark Twain

In this study, we found several surprises:

First, it is hard not to be impressed by the near-simultaneous appearance of several independent solutions to the problem of combining the power of large numbers of diode lasers. High power fiber lasers in particular are as close to an ideal device as one is likely to encounter: simple, compact, and extremely efficient. They have already demonstrated sufficient performance for a modular launch system, and the consensus of researchers is clearly that there will be swift improvement in fiber laser power up to at least several kW. The only potential flaw in fiber lasers is their cost, and it seems very unlikely that mass production will not lower the cost substantially – possibly not to $5/watt, but certainly to less than $20/watt.

A useful comparison may be inkjet printers. Like fiber lasers and diode pumped solid state lasers, inkjet printers shared some components with other printing technologies. Inkjets existed alongside other printers for many years, but had serious limitations in speed and print quality, as fiber lasers did in power, and were limited to specialty applications. The first general-purpose inkjets were comparable in cost to other printers with similar performance – several hundred dollars per page-per-minute. But inkjets were inherently simple and mass-produceable, once sufficient ingenuity and sheer effort were applied to their design – there is an enormous amount of engineering development in an inkjet printhead. Inkjets now cost so little that they are literally given away with new computers, and they cost well under $10 per page-per-minute. (Some of this results from subsidizing printer prices with ink sales, but even at a fair price, inkjets are by far the cheapest printing technology available.) Given a several-hundred-million dollar market, <u>and the opportunity for many vendors to compete continuously for that market with improved designs over several design generations</u>, radically lower fiber laser prices are nearly inevitable.

Second, optics have not made similar breakthroughs that we were able to find. Given the lively progress in large astronomical telescopes, lightweight and "gossamer" space optics, and sophisticated optical fabrication techniques like magnetorheological polishing and ion milling, we expected to find a range of technologies for, and producers of, low cost meter-scale optics. Instead, while there certainly have been improvements in optical fabrication, the number of large optics producers remains tiny, and the options for cost savings limited. Combined with the tighter-than-anticipated (though still far from state-of-the-art) surface accuracy requirements of beam modules, we cannot yet project costs for beam module optical aperture below $100,000 per square meter with any confidence.

Fortunately, these two surprising results cancel each other out. The higher-than-expected radiance available from fiber lasers, and probably from DPALs, means that $100,000 per square meter is an entirely acceptable cost for beam modules.

Third, we were not surprised to find that high-power diode arrays – vital to all of the most promising beam module laser options -- have continued to drop in price, although the lack of improvement in performance (bar power, lifetime, beam quality) over the last few years is disappointing. What was a surprise is that high power bars and arrays have become a commodity, with major manufacturers competing to introduce new features and lower costs. Radical price drops or performance increments are therefore much more likely in the future, at least until the next major upturn in the communications industry again absorbs the attention of researchers and manufacturers.

Finally, we anticipated when proposing this project that we would identify some key technology for beam modules that could be further explored, developed, or demonstrated in Phase II – for example, wavelength stacking of diode arrays, or low-cost replica optics. Instead, our Phase I bottom line is that the technologies needed for beam modules either already exists, or else are advancing so rapidly (and with so large an investment) that the leverage of additional research on the scale of a NIAC Phase II project would be small. There is certainly interesting engineering to be done, and there are topics, such as cheap large optics fabrication, which could benefit from NIAC-quality innovation, but the next logical step in beam module development is a straightforward engineering design study, followed by construction of prototypes.

The key technical issues for the modular laser launch architecture, therefore, are now those of the thruster and vehicle. Assuming those issues are resolved, the key issues for the architecture as a whole are those of missions and economics: how much will it cost to build a pipeline to space, and what will we do with it?

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