Modular Laser Launch Architecture: Analysis and Beam Module Design

NIAC Phase I Fellows Meeting

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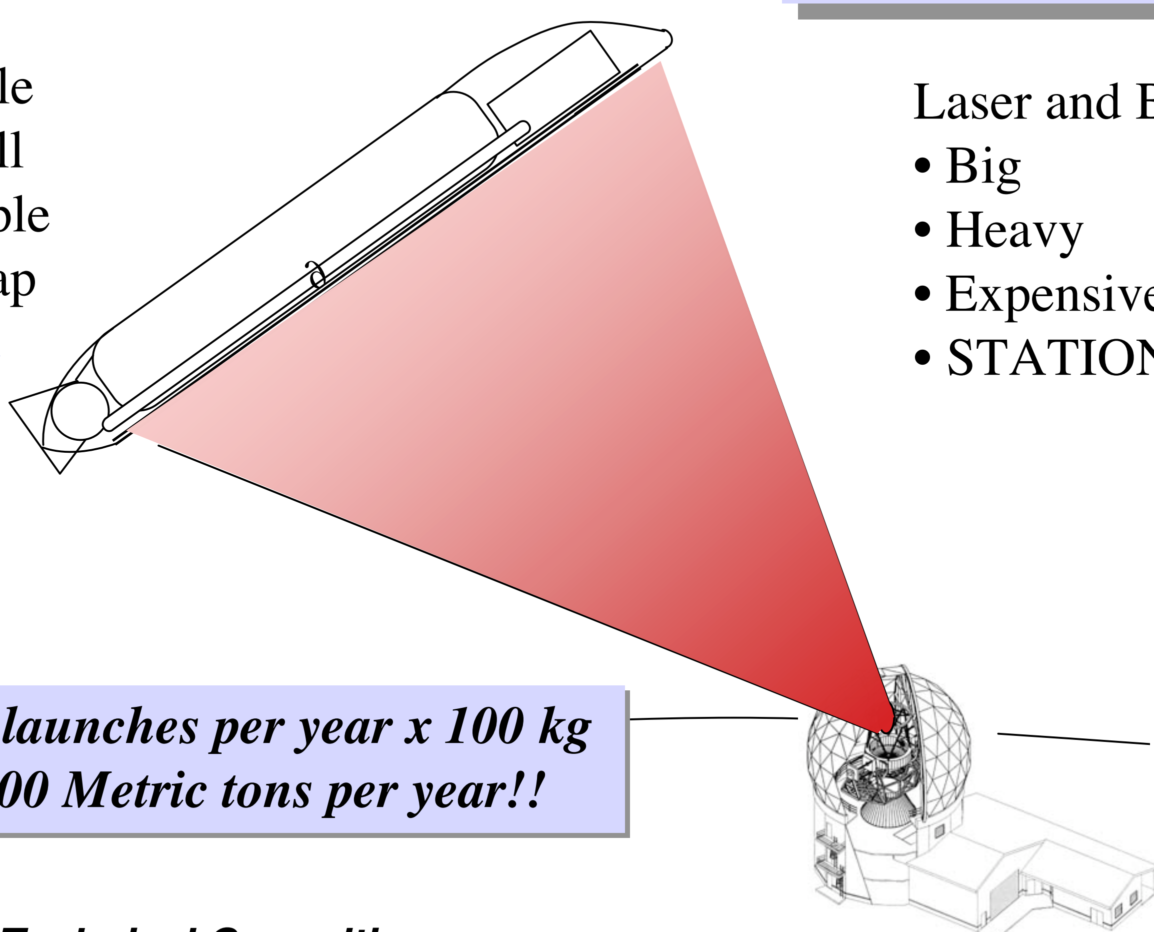
The Laser Launch Concept

Launch many small payloads
on demand -- up to 10 per hour

Leave The Hard Parts On The Ground!

Vehicle
- Small
- Simple
- Cheap
- Inert



Laser and Beam Projector
- Big
- Heavy
- Expensive
- STATIONARY

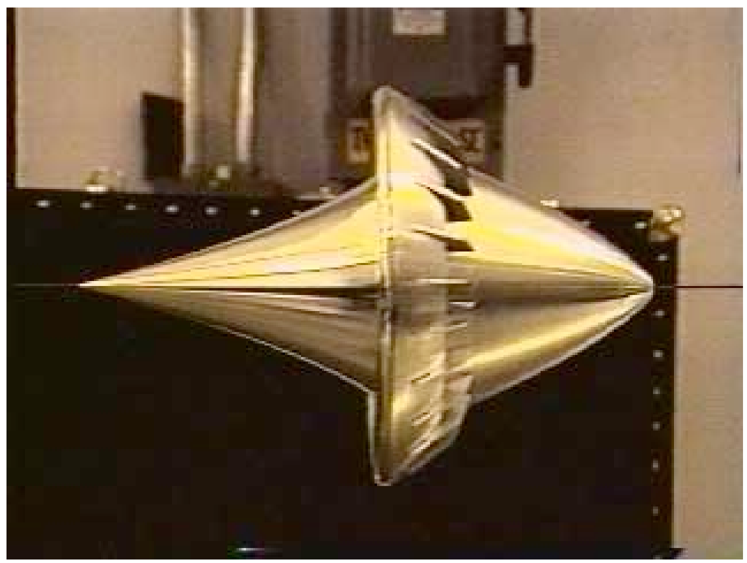
30,000 launches per year x 100 kg = 3000 Metric tons per year!!

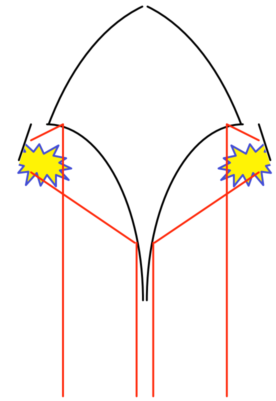
**Rule of Thumb:
1 kg of payload
per MWof laser**

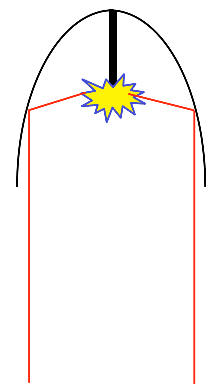
Why Laser Launch?

- **Massive launch capacity**
  - A 100-kg launcher can put **3000 tons per year** in LEO
- **Very low marginal cost to orbit**
  - Electricity, vehicle, and propellant easily **<$100/lb**
- **Potentially low total cost to orbit**
  - If the system is cheap enough to buy and run, and…
  - If there are enough payloads to launch
- **Maximum safety -- no stored energy on vehicles**
  - Enables all-azimuth launch from any site
- **High reliability, easy to maintain**
  - The hard parts stay on the ground
  - Vehicles are simple, mass-produced, and testable
- **Ultimate launch-on-demand -- FedEx to space**

Pulsed Laser Propulsion Works...



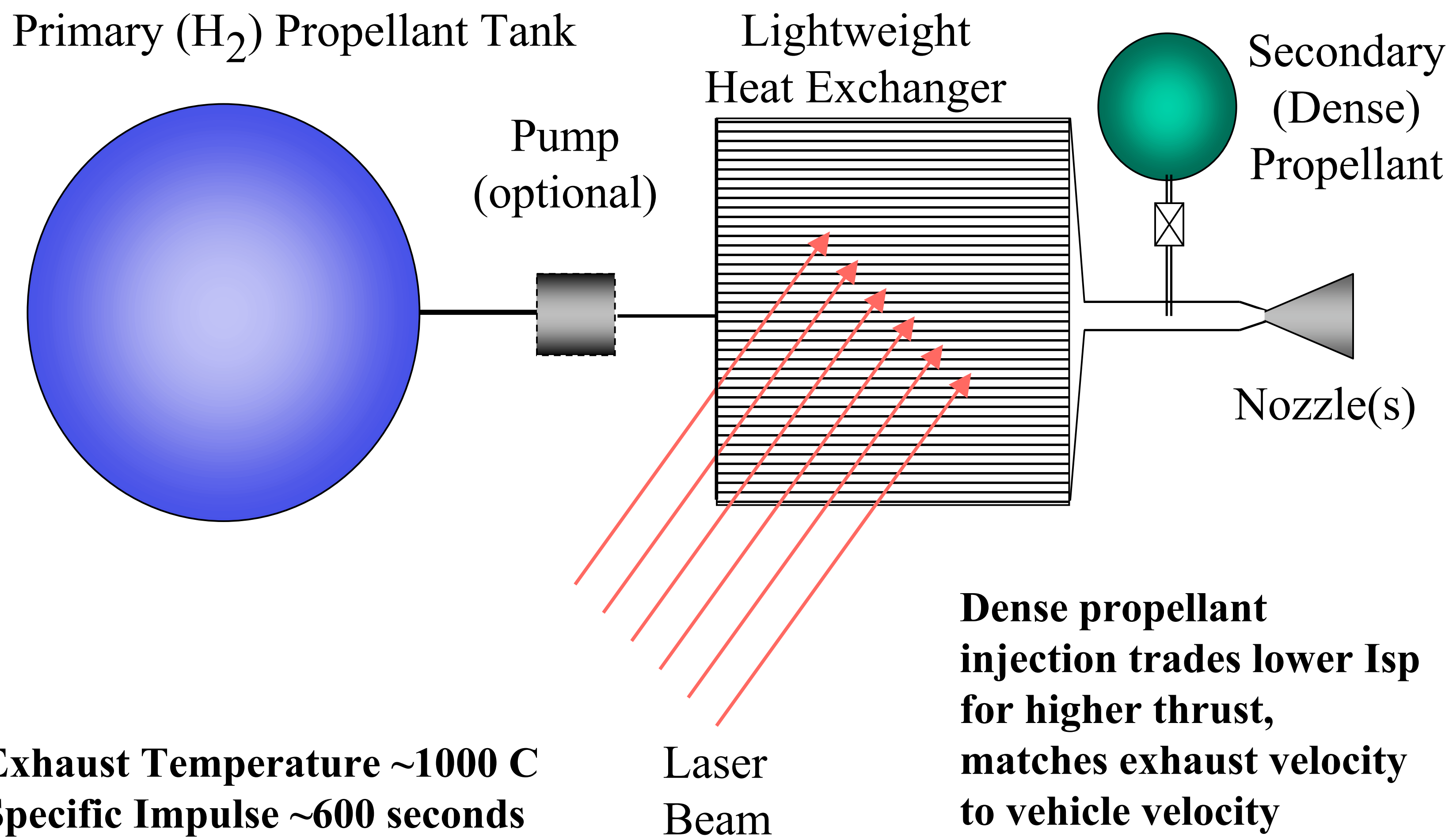




… But Has The Same Problems As Everything Else

- **Development cost**
  - Even at $10/watt, $1 Billion for 100 MW
- **Technical risk**
  - You don't know if it will work at all without spending $$$
    - In this case, for a multi-megawatt test laser
- **Programmatic risk**
  - You don't know what it will actually cost until you've built it
    - Big lasers have had cost/schedule/performance problems for 40 years!
  - Reality is always different from theory; operational systems are always different from prototypes

The Heat Exchanger Thruster



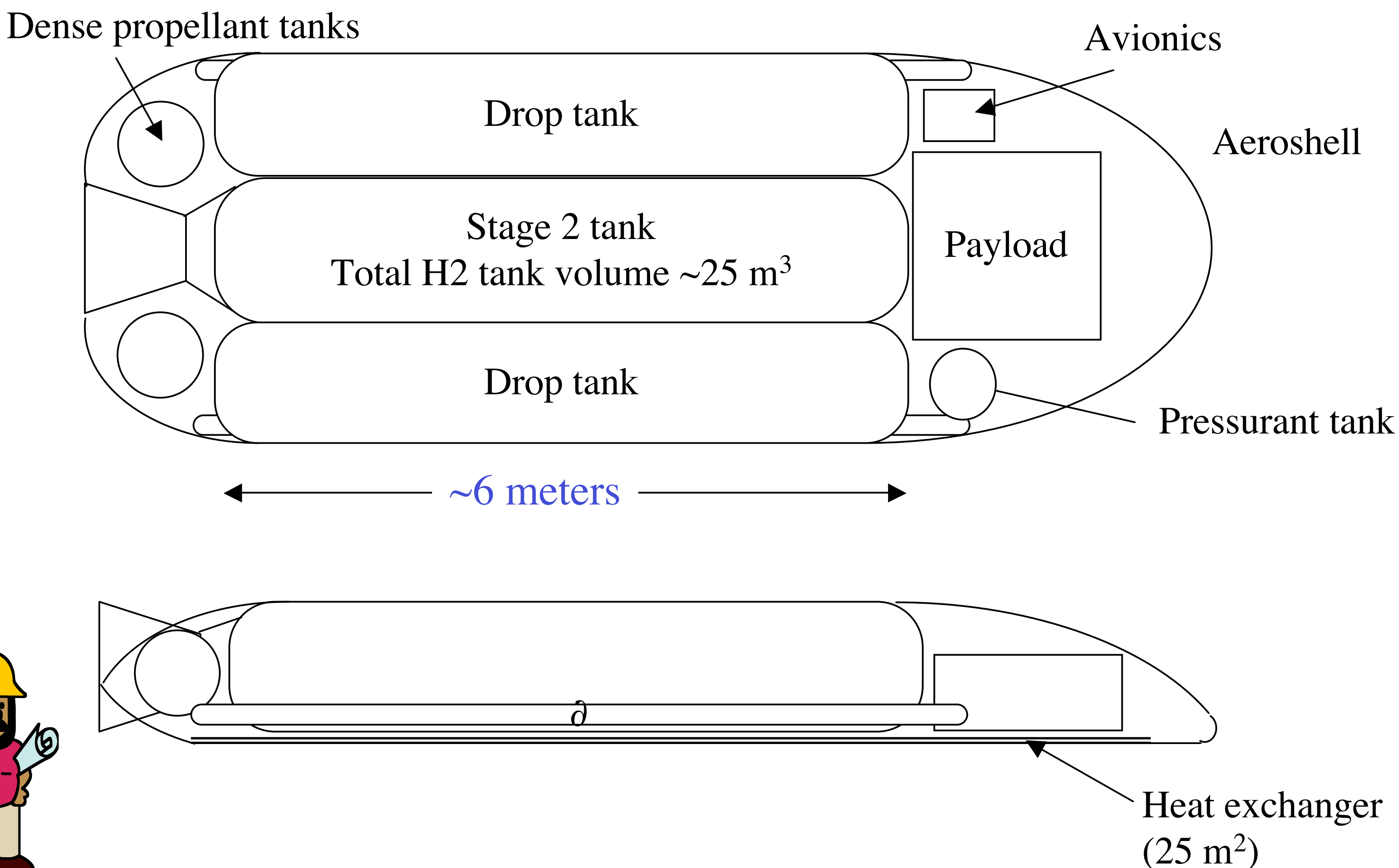
Dense propellant injection trades lower Isp for higher thrust, matches exhaust velocity to vehicle velocity

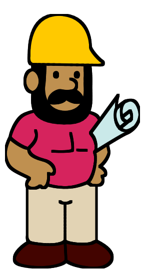
- **Exhaust Temperature ~1000 C**
- **Specific Impulse ~600 seconds**

Heat Exchanger Thruster Advantages

- **Works with <u>any</u> laser wavelength and pulse format**
- **Nearly 100% efficient**
  - high absorption, negligible reradiation
- **Simple to design**
  - Steady flow
  - Simple propellant properties (especially for H_2)
- **Simple to build**
  - Electroplating technique demonstrated at LLNL
  - Modular design scales easily to any area
- **<u>Simple to test</u>**
  - *Works with any radiant source; doesn't even need a laser*

Current 100 MW Vehicle Concept



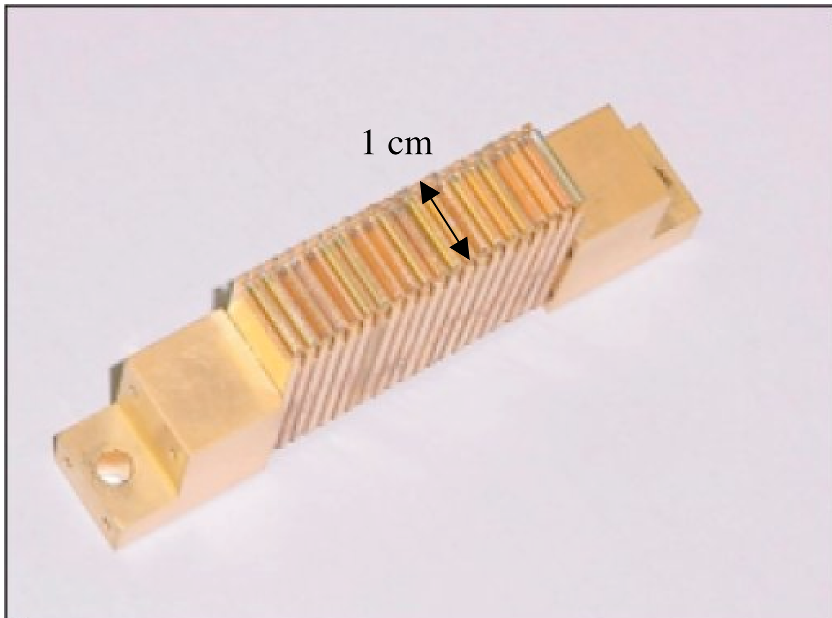


What Do We Do About The #%&@ Laser?

- **Lasers cost too much**
  - Absolute cheapest high power laser is $20-50/watt
    - CO2 electric discharge, with very poor beam quality
    - Should scale to 100 MW, but not easily or cheaply
  - Stay-on-all-day lasers above ~10 kW don't exist
    - AVLIS copper vapor lasers were 10 kW total, at a cost of >>$1000/watt
- **No one will pay to develop a large laser**
  - Too many bad memories: CO2, HF/DF, Excimer, FEL…
  - "There are liars, damn liars, and laser builders"

Laser Diode Arrays

- **>50% efficient DC to Light at ~800 nm**
- **10,000 hour lifetime (60,000 launches!) CW operation**
- **Run on DC current; water cooled**
- **Commercially available from multiple vendors**
  - **$4 - $10/watt NOW**
  - **$2/watt in a few years in 100 MW quantities**
  - **BUT -- not coherent; not high enough radiance to beam 500 km**



A 1200 Watt CW "stack" from Nuvonyx, Inc. -- a catalog item!

The Beam Module Concept

- **DON'T build one big laser and beam director**
- **Build MANY small "Beam Modules"**
  - Completely independent laser and beam director
  - Minimal common services, ideally only power and water

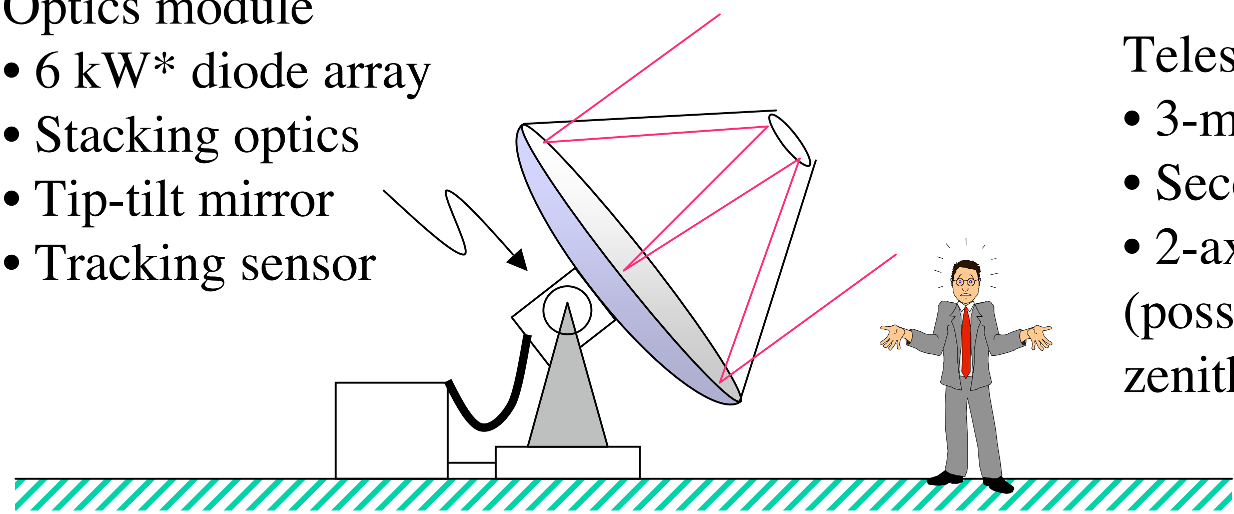
"This division of the laser source among many apertures was initially regarded only as a necessary evil, required by the low radiance of noncoherent [laser diode] arrays. However, we have recently realized that the fact that the laser and optical aperture can be subdivided into small independent "beam 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"
-- J. Kare 7/03

Advantages of Beam Modules

- **Scalability**
  - System grows smoothly by adding beam modules
- **Reliability and maintainability**
  - Failed modules have no effect on launch (even in progress)
  - Beam modules can be replaced as units
- **Cost**
  - Everything in the system is mass-produced
  - Plausible cost goal: comparable to a modern automobile (excluding laser)
- **Development**
  - All the technical risk is in the first few units: $M, not $B
  - No failure costs very much -- you can't "crash the prototype"

Conceptual Beam Module (as of last year)

Optics module
• 6 kW* diode array
• Stacking optics
• Tip-tilt mirror
• Tracking sensor



Telescope
• 3-m replica primary
• Secondary
• 2-axis alt-az mount (possibly alt-alt to avoid zenith singularity)

Support module
• Diode power supply (16 kW* DC)
• Diode temperature controller
• Cooling water pump/regulator
• Tracking sensor controller
• Mount controller and drivers
• Tip/tilt controller and drivers

A 100 MW launch system might have ~20,000 of these* -- But you can build ONE to start with

*Based on 2×10^{13} radiance and 500 km range; better radiance or shorter range would increase unit power and decrease number required

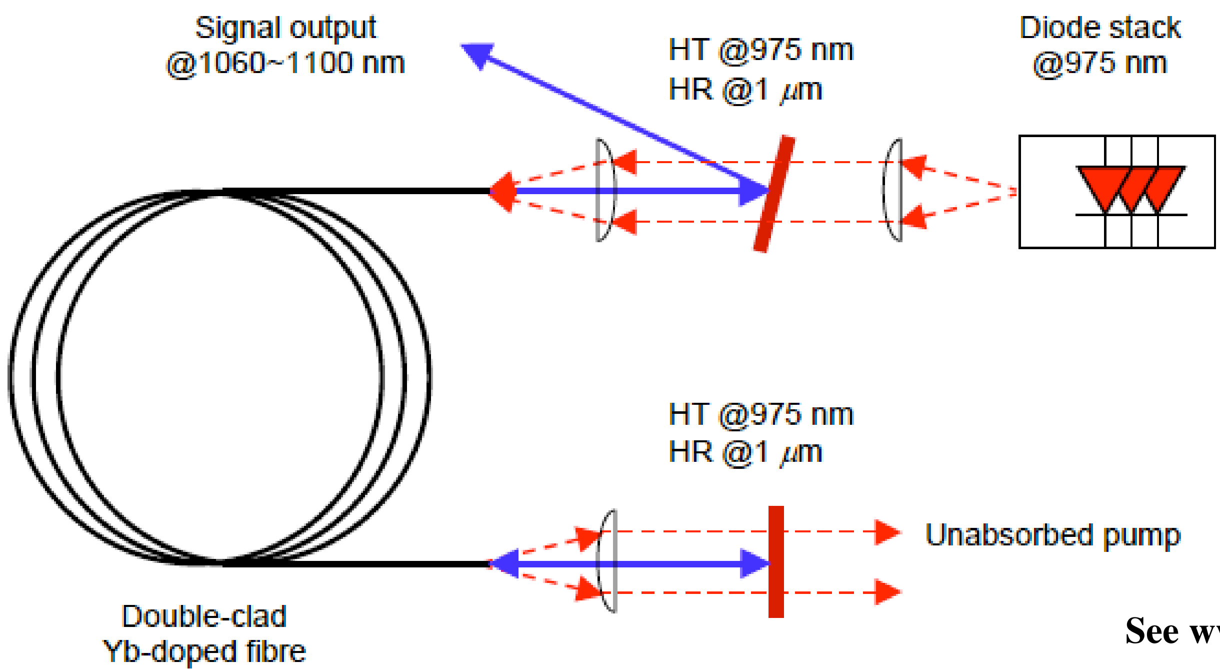
At Least Three Solutions

- **Fiber Lasers**
- **Spectral Beam Combining**
- **Diode Pumped Alkali Laser (DPAL)**

All made breakthroughs within the last year!

Fiber Lasers

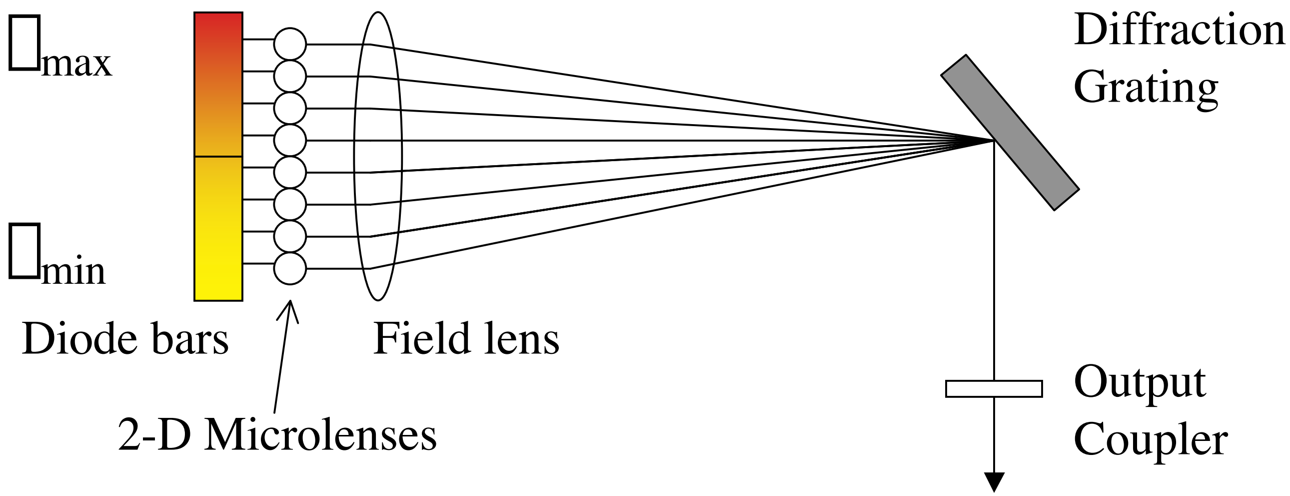
Ytterbium-doped fiber laser



See www.spiphotonics.com

- **Converts non-coherent diode array light to single-mode laser output with up to 90% efficiency; 75% is routine**
- **Demonstrated at 1 kW; 10 kW projected within 1-2 years**
- **Simple and mass-produceable; already in commercial production**

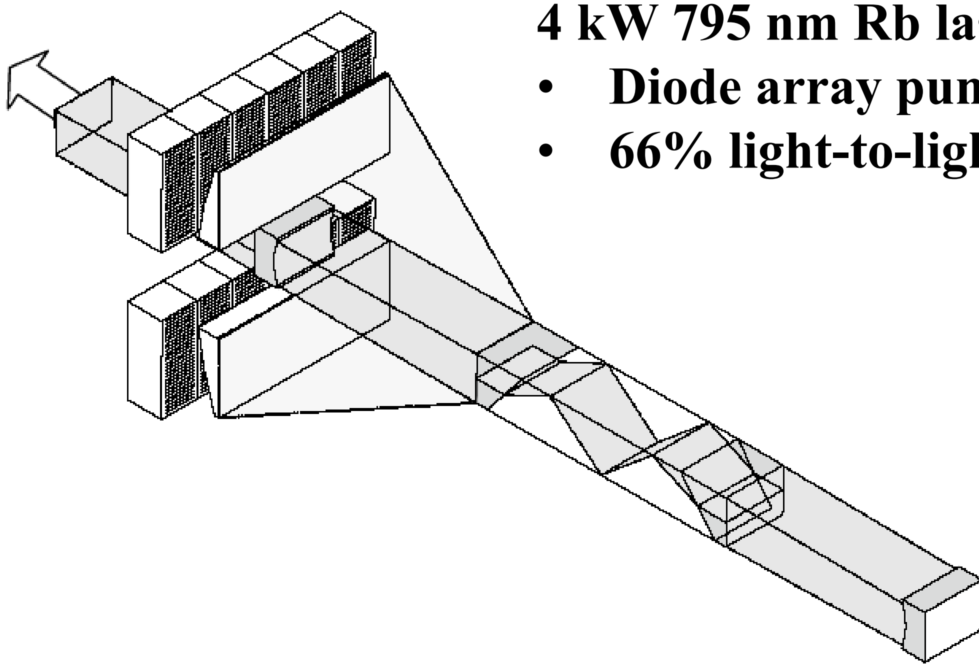
Spectral Beam Combining (SBC)



- **Diodes operate independently in external cavity**
  - Antireflection coating on laser diode output facets
  - Each diode automatically operates at the “correct” wavelength
- **Demonstrated* with ~700 diodes in 7 bars (26 watt output)**
  - >1000-fold stacking should be feasible
- **SBC efficiency ~50% (power out compared to raw diode bars)**

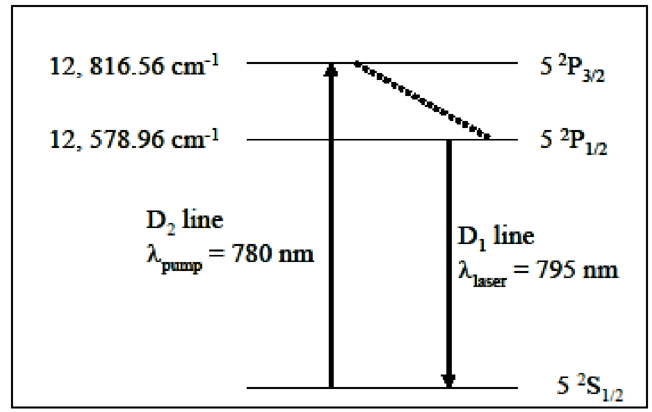
•AcuLight, Inc., Bothell, WA, 2004

Diode Pumped Alkali Laser (DPAL)



4 kW 795 nm Rb laser concept

- **Diode array pump 6.08 kW @ 780 nm**
- **66% light-to-light efficiency**

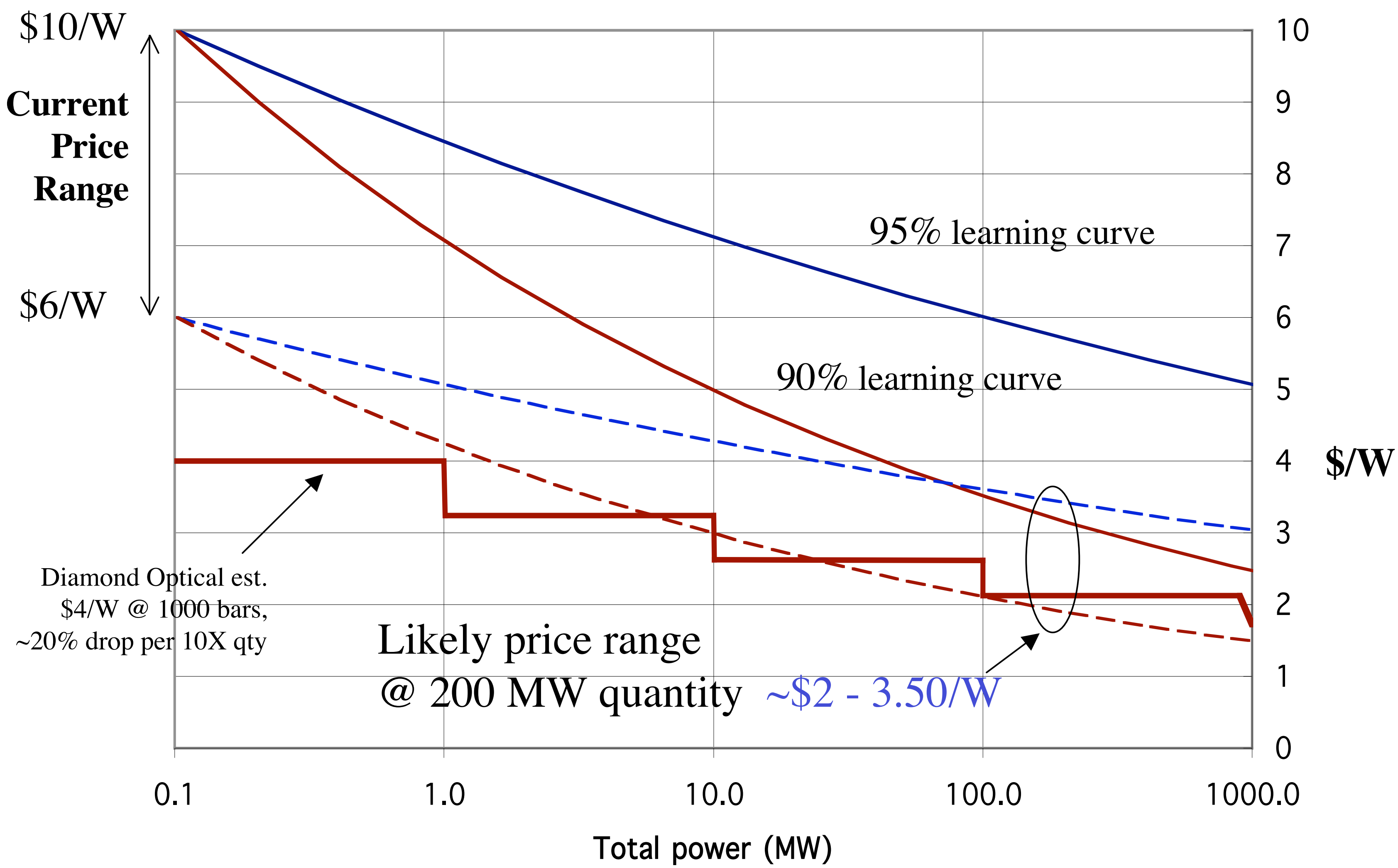


- **New concept (2003) developed by W. Krupke et al. (ex-LLNL)**
- **Rb (785 nm) or Cs (895 nm) vapor in He buffer gas**
  - Absorption line pressure-broadened to match diode linewidth
  - High efficiency requires tight control of diode wavelength, spectrum
- **Demonstrated at ~30 W level**
  - Performance predicted accurately with no free parameters

Laser Subsystem: Alternatives

	Baseline Fiber Laser	SBC Diodes	DPAL
Lasing medium	Yb-doped double-core fiber	8 x 125 W diode bars	Rubidium vapor cell
Wavelength	1.08 μm	805 - 810 nm	795 nm
Module output power	50 kW	10 kW	50 kW
Unit laser power	10 kW	600 W	10 kW
# of lasers/module	6	20	6
Beam quality (M^2)	1.5	2	1.2
Radiance ($P / \lambda^2 (M^2)^2$)	3.8×10^{15} W/m^2-sr	2.3×10^{14}	1.1×10^{16}
Laser Efficiency (P_{out} / P_{diode})	80%	60% SBC eff.	54%
Pump Power per laser	12.5 kW	1000 W	18.5 kW
Diode Efficiency	50%	50%	50%
DC efficiency (P_{out} / P_{DC})	40%	30%	27%
DC Power (module)	150 kW	40 kW	222 kW
Cooling Requirement	90 kW	28 kW	162 kW
Water flow	~100 liter/min	~50 liter/min*	~300 liter/min*

How Much Will They Cost? Diode Arrays



Laser Diode Cost Trends

- Substantial reductions in bar cost
  - $100/bar, 100 W bars in 1-2 years (F. Way, Diamond Optical)
  - $10/bar (50 W bars?) "to stay competitive" (a major manufacturer)
- Substantial reductions in packaging cost
  - LLNL, Oriel, others developing low-cost packaging
    - Oriel "TO-220" package aimed at 50% of late-'03 price; available in mid 2004
  - Diamond Optical willing to quote ~50 cents/watt
- Unpredictable gains in performance
  - Bars have been stuck at 60 W for several years (100 W Real Soon Now)
  - Major improvement may require radical approach (e.g., VCSEL arrays)
- But...Current market does not support large investments in improved processing/packaging
  - ~$100M/year for all high power arrays, vs. $4B/year for discrete diodes at peak of telecomm market
  - ~$1B market for launch system would drive industry

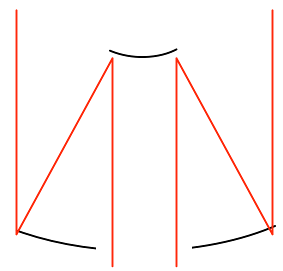
How Much Will They Cost? Complete Lasers

- **Current commercial fiber lasers are $500/watt* -- Too Much. BUT**
  - Relatively low unit power: 100 W
  - Based on discrete packaged diodes @ $100 - 150/watt, not bars
  - Semi-custom production: typically ~10 units
- **Best prediction for high-volume, multi-kW lasers: $7 - 10/W**
  - 3 - 4X diode cost
  - Best estimate of component cost in quantity
  - Consistent with projected cost of fiber ($2K / 1 kW)
  - Consistent with ~85% learning curve for complex assemblies
- **Other laser options in same range**

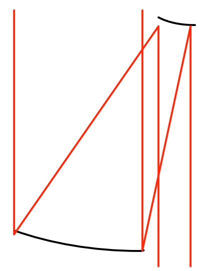
Telescope Requirements

- **Total Area**
  - Set by laser radiance (W/m^2-sr) and vehicle flux requirement
    - e.g., fiber laser @ 3.8×10^{15} W/m^2 sr requires ~330 m^2 of optics
  - Secondary limits from mirror heating, thermal blooming
    - Still need to double check blooming
- **Mirror size and quality**
  - Diffraction: $D_{mirror} > f$ □ R / d
    - $R / d \sim 10^5$ (500 km / 5 m) $f \sim 2$ (2.44 for classical limit)
    - ~ 16 cm @ 0.8 □m, 22 cm @ 1.08 □m
  - Wavefront error: Slope < 0.5×10^{-6}
    - ~5 waves per meter (vs. 1/10 wave for astronomical telescope)
- **Pointing and tracking**
  - Pointing range (nominal) +/- 80° along track, +/- 45° crosstrack
  - Closed loop tracking to <<10 □rad; open loop pointing to ~1 mrad

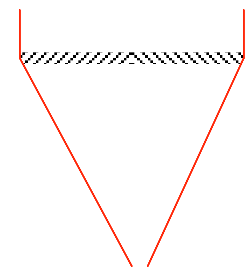
Optics Options



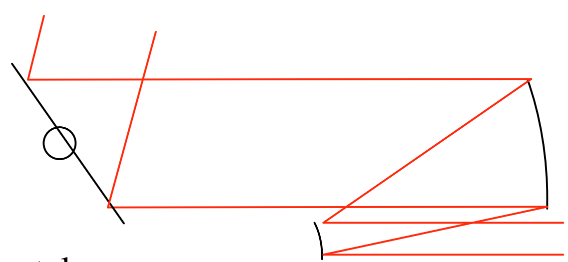
Cassegrain
- Simple optics
- Compact mount
- Obscuration losses (few %)



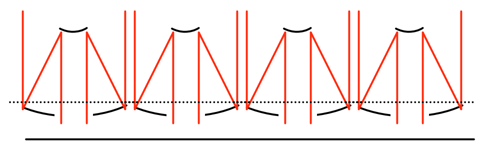
Off-axis Cassegrain
- Low loss
- Asymmetric optics
- Bulky



Diffractive primary
- Potentially low cost primary
- Potentially light weight
- No obscuration
- No current technology
- Chromatic aberration

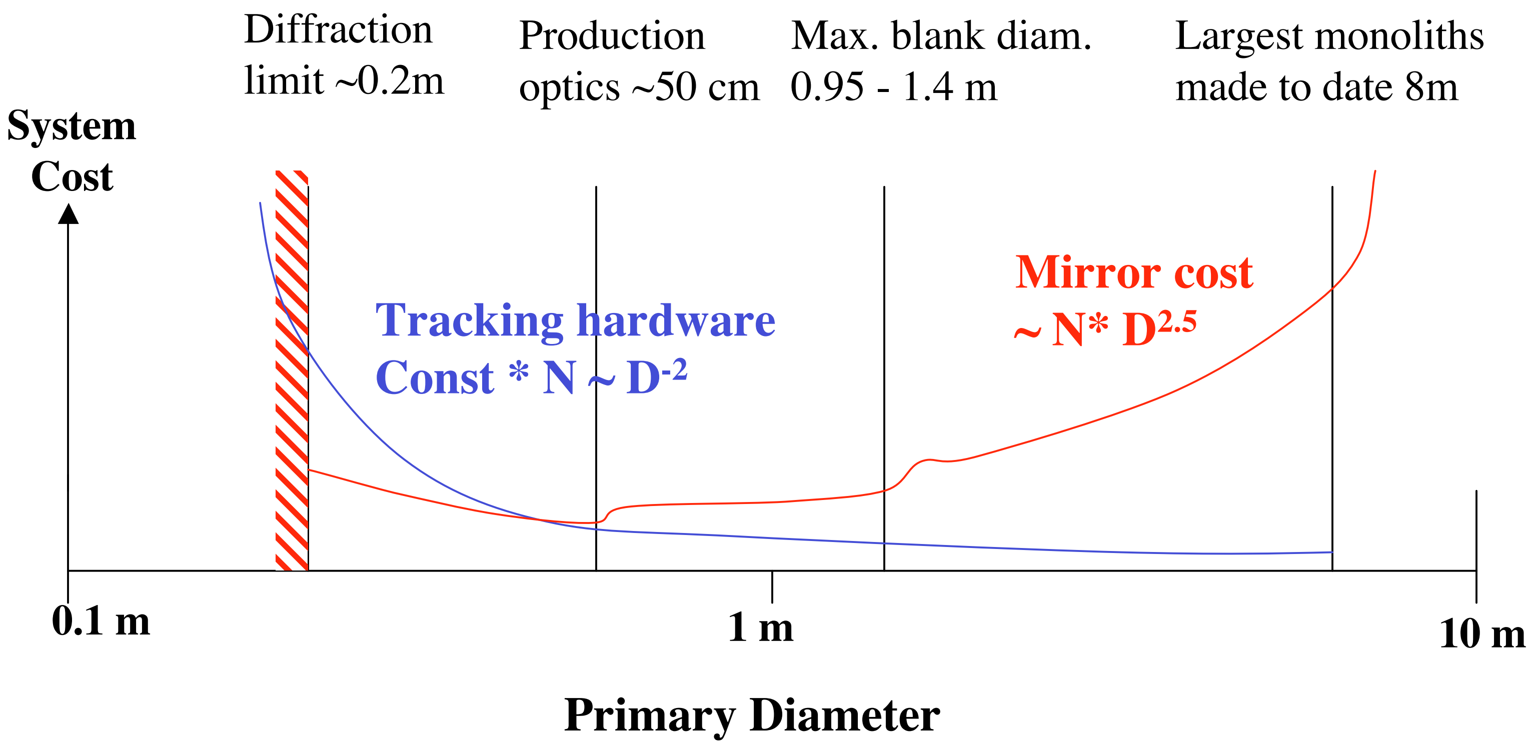


Stationary telescope
with tracking flat
- All hardware is stationary
- Minimum moving mass
- Cheap primary
- Additional large optic (flat)
- Field rotation



Multiple small telescopes
on common mount
- Lower optics cost/mass
- Compact
- More tracking hardware
- Alignment problems

Optimum Primary Diameter



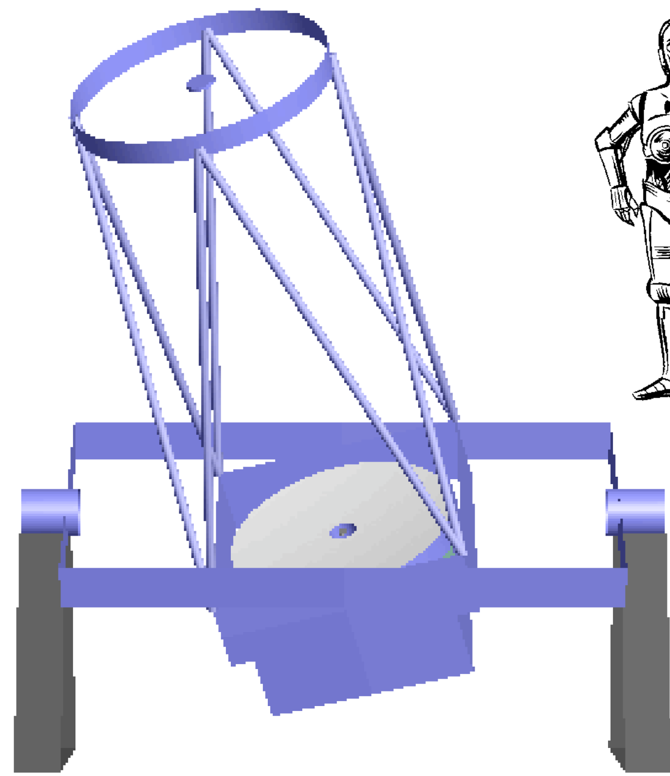
- Minimum size set by tracking hardware cost or diffraction
- Maximum set by rapid increase in mirror cost with size
- Small jumps at limits of various "standard" supplier capabilities

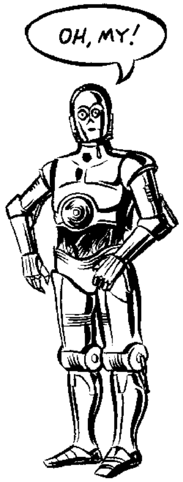
TANSTAACT(TAG)

- **There Ain't No Such Thing As A Cheap Telescope (That's Any Good)**
  - Many advanced technologies not necessary (or cheap)
    - Non-glass substrates (SiC, Graphite Epoxy)
    - Advanced polishing techniques (magnetorheological polishing)
    - Active/Adaptive primary (PAMELA)
  - Several possibilities still to look at
    - Replica optics
    - Electrodeposited metal optics
    - Lightweight mount (up to half the cost of a telescope)
- **Shifts optimum toward fewer, smaller telescopes than original concept**
  - "Only" 1000 - 2000 x 1 m, vs. 10,000 x 2 - 3 m
  - Allowed by improved (higher radiance) laser options

Telescope Baseline

- **~1 meter f/2.5 Cassegrain**
  - Afocal (technically a Mersenne)
  - Borosilicate (Pyrex) primary
    - "Few-wave" accuracy
  - Multilayer coated for low absorption
- **Small (10 cm) secondary**
  - Minimize obscuration
  - Limited field of view is OK
- **Alt-Alt mount**
  - Tracks smoothly through zenith





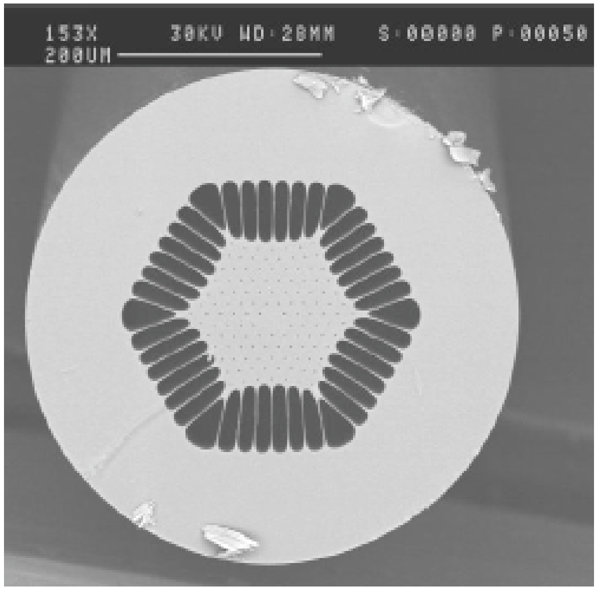
~$100K each @ 1000 units ($22K for primary)
$2 - 5M investment to be able to make 1/day

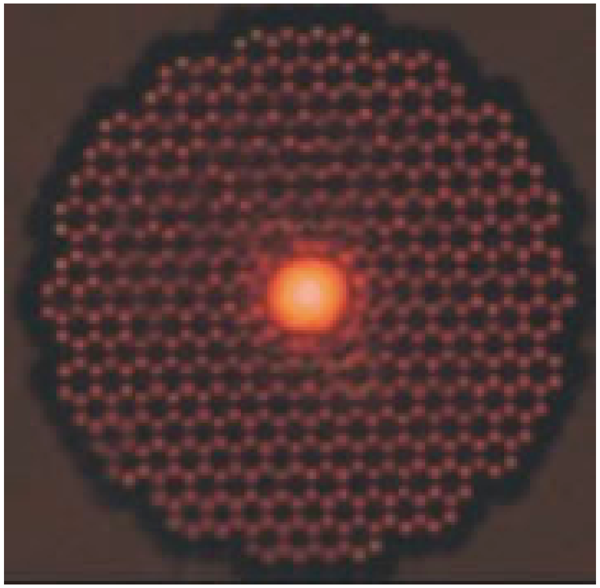
Photonic Crystal Fibers

Left:
"Air-clad" double core fiber

Right:
Visible-wavelength high power single-mode guiding

J. Limpert, et al. "Thermo-optical properties of air-clad photonic crystal fiber lasers in high power operation," Opt. Express 11, 2982-2990 (2003)



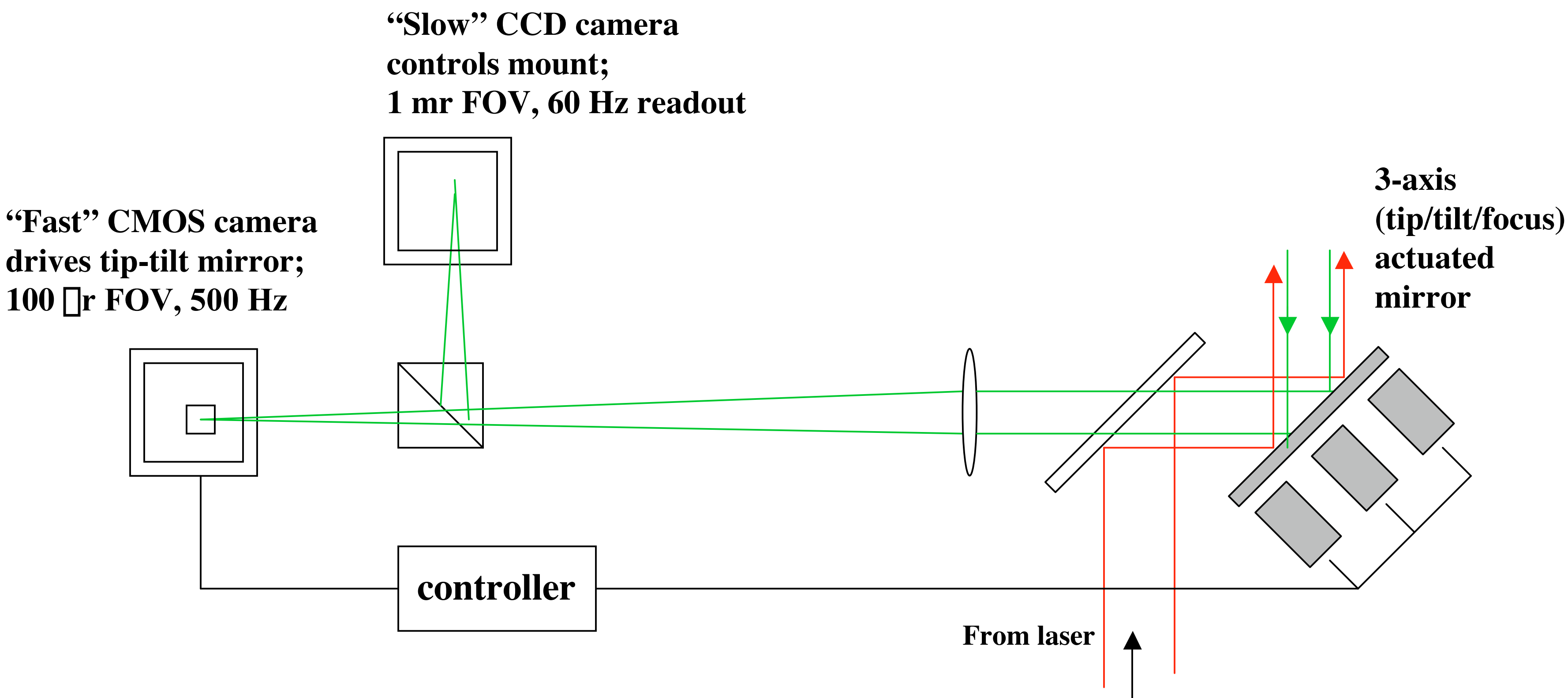


www.blazephotonics.com

- **Transport kW power with low loss (<<1 dB/meter)**
  - "Holey" fiber region guides single mode; forbids higher modes
  - Most power is transported in void space; avoids nonlinear effects
- **Enabling for low cost beam projectors**
  - Eliminates multiple mirrors in beam path
    - Lossy, difficult to align, difficult to clean
  - Isolates laser from telescope motion, dust, etc....

Tracking Subsystem

- **Requirement: point beam to ~5 μradians**
  - Track vehicle (control mount) 500 μr @ <10 Hz
  - Compensate atmosphere <100 μr @ ~100 Hz



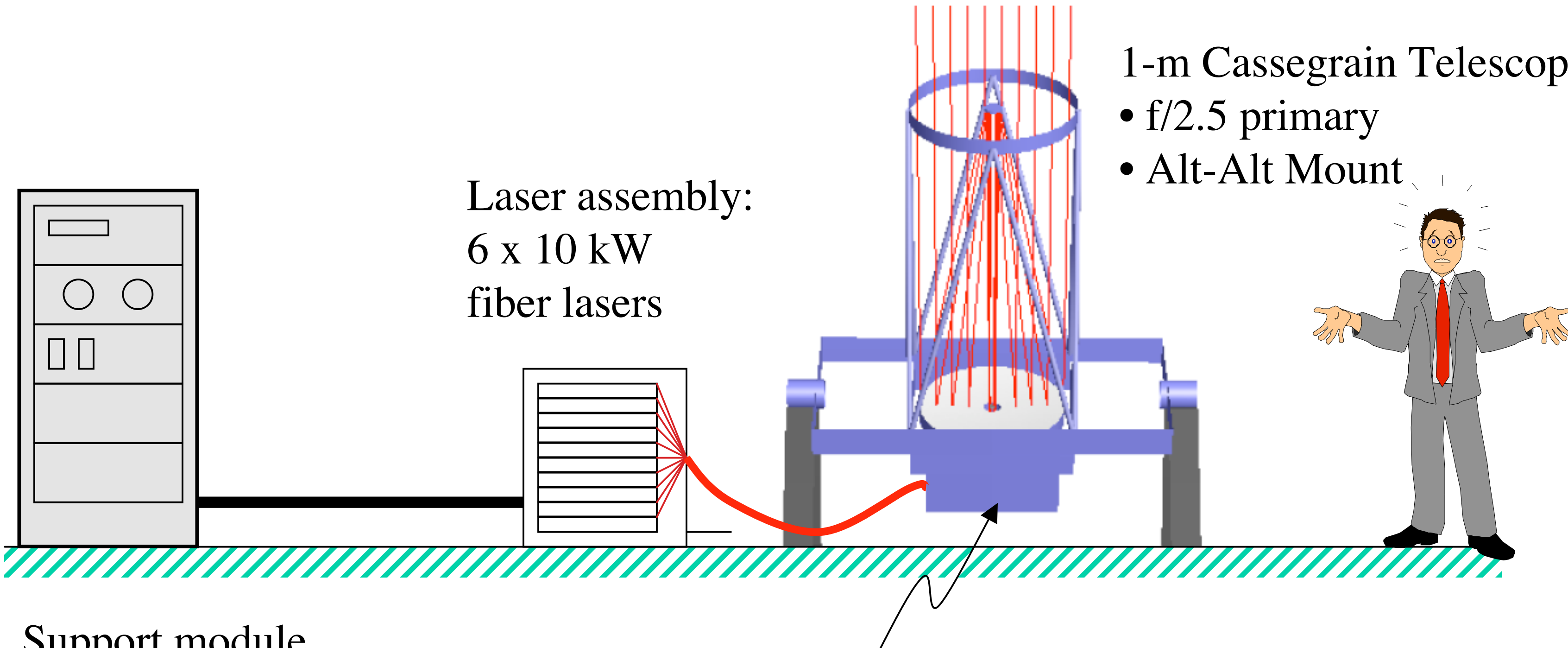
Beacon Options

- **Reflected laser light**
  - Too much local scattered light
- **Thermal radiation from hot heat exchanger**
  - Start/restart problem
  - No pointahead for atmospheric correction
- **Ground-based laser with retroreflector**
  - Possible, but requires high power (kW), good tracking
- **Beacon on vehicle**
  - Narrow-angle with pointing mechanism
  - Wide-angle -- simplest possible system
    - A laser diode and a pingpong ball

Baseline Beam Module

1-m Cassegrain Telescope
- f/2.5 primary
- Alt-Alt Mount

Laser assembly:
6 x 10 kW
fiber lasers



Support module
- Diode power supply (250 kW DC)
- Cooling water pump/regulator
- Tracking sensor controller
- Mount controller and drivers
- Tip/tilt controller and drivers

Optics module
- Fiber output optics
- Tip-tilt mirror
- Tracking sensor

- Allows for 20% losses in optics, 10% loss in transmission, and 10% of modules offline for maintenance/repair

100 MW System Capital Cost

• **Laser**		**1020**
– 120 MW Fiber lasers @ $8/watt	960	
– 300 MW DC supply @ $.20/watt	60	
• **Optics**		**144**
– 2000 Primary mirrors @ $22 K	44	
– Other optics, pointing, tracking @ $25 K	50	
– Mount and pad @ $25 K	50	
• **Facilities**		**161 - 350**
– H2 plant (1000 - 30,000 launches/year)	2 - 60	
– Power buffer	15	
– Power line	11-48	
– Launch stand	30	
– Physical plant	100 - 195	
• **TOTAL**		**1325 - 1514**

My long-standing Rule Of Thumb estimate: ~$2 Billion

What Happens To Space?
Architectural Implications 1

- **Cheap small payloads (common to all laser launch)**
  1. Microsats/Nanosats: any mission that can be done in 100 kg pieces will be cheapest that way
     - But that will only account for a few % of launch capacity
  2. Modular satellites/Constellations: Divide up functionality into 100 kg co-orbiting blocks (cf. NIAC work on constellations)
  3. On-orbit fueling/refueling/resupply
     - Stimulates development of autonomous microspacecraft rendezvous and docking, "tug" spacecraft
     - Opens up high-mass-ratio mission space: Moon/Mars with storable propellants
  4. On-orbit assembly: large structures constructed on orbit
  5. True space industry?

What Happens To Space Industry? Architectural Implications 2

- **Routine, on-demand launch; very high reliability**
  - Shift in spacecraft reliability criteria; “ground spares” OK

- **A change in space industry**
  - Large aerospace company resources are not required
    - To build vehicles
    - To build beam modules
    - To build payloads
  - “Learning curve” for participation is <u>much</u> less costly

– **A change in space politics**
  - More countries can have their own launchers, or “rent time” on larger launchers and provide vehicles or payloads

What Happens To Human Space?
Architectural Implications 3

- **Immediate shift in logistics for human LEO missions**
  - Missing/broken widgets replaceable by Next Day Space

- **Scaling <u>and reliability</u> enable growing human presence**
  - Laser launch is <u>uniquely</u> testable to ~ 10^{-8} failure probability
    - e.g., 10^4 launches AND 10^4 abort/recoveries before flying a person
  - Initial human launch capability at TBD payload/laser power
    - Mercury capsule was ~1500 kg; surely we could do better?
    - Potential driver for launch system growth to ~1 GW
  - Growth to 2 or more person vehicle opens up passenger launch -- to thousands or 10's of thousands per year

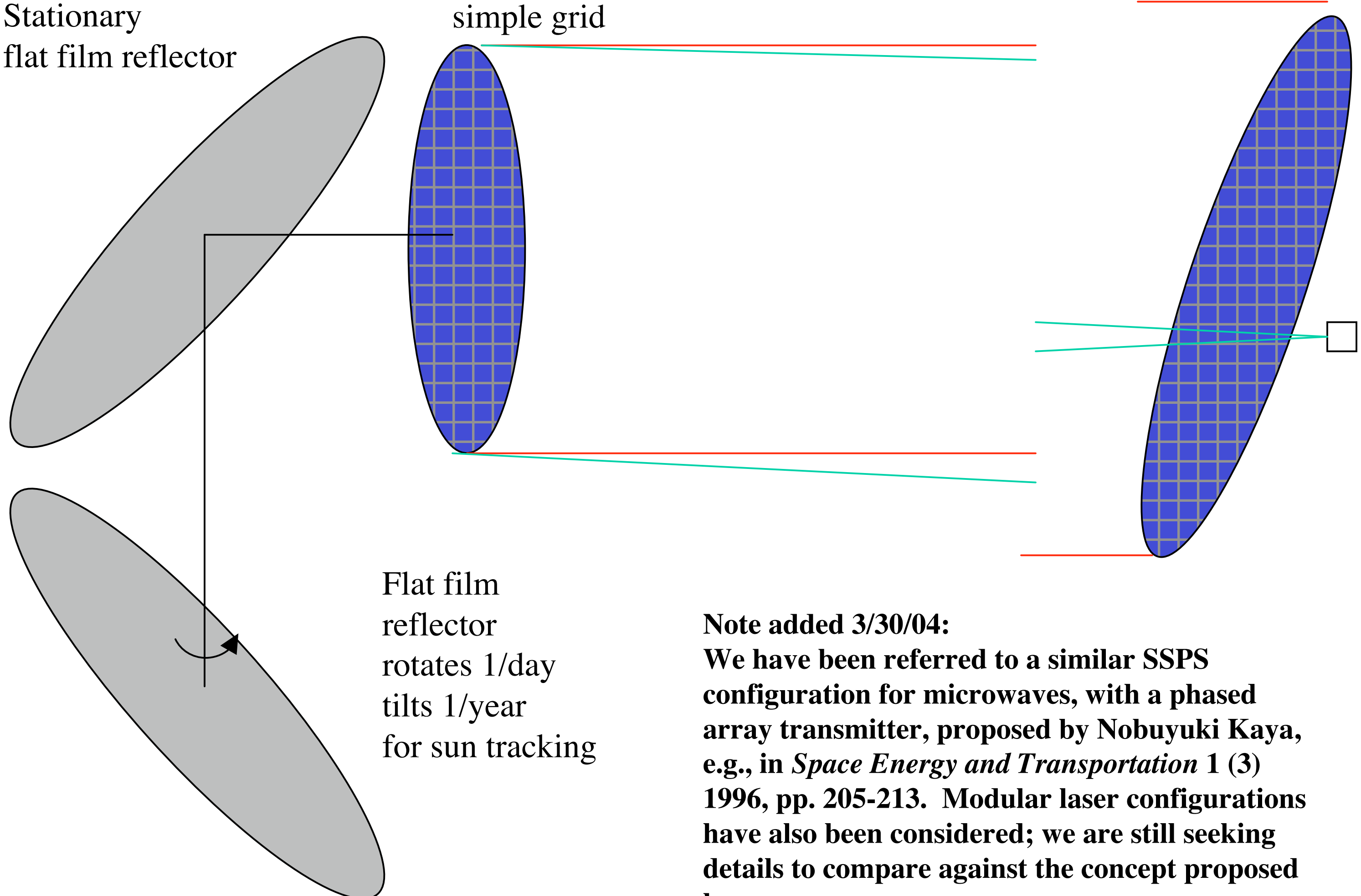
In-Space Power and Propulsion Architectural Implications 4

- **Providing electric power shifts module design goals, but "power" modules can also be used for launch**
  – PV-compatible wavelength preferred (nominally 700 - 900 nm)*
  – Higher beam quality (adaptive optics) may be desired
  – However, dedicated pulsed lasers may be preferred for high-Isp pulsed propulsion
- **Low cost modules open design space for space power**
  – For GEO power, each satellite can have a dedicated source
  – For LEO/MEO power, modules can be distributed to many sites worldwide
- **Launcher site can provide 100-MW power levels anywhere out to GEO**
  – Relay architectures to be explored

Beam Module Satellite Solar Power System

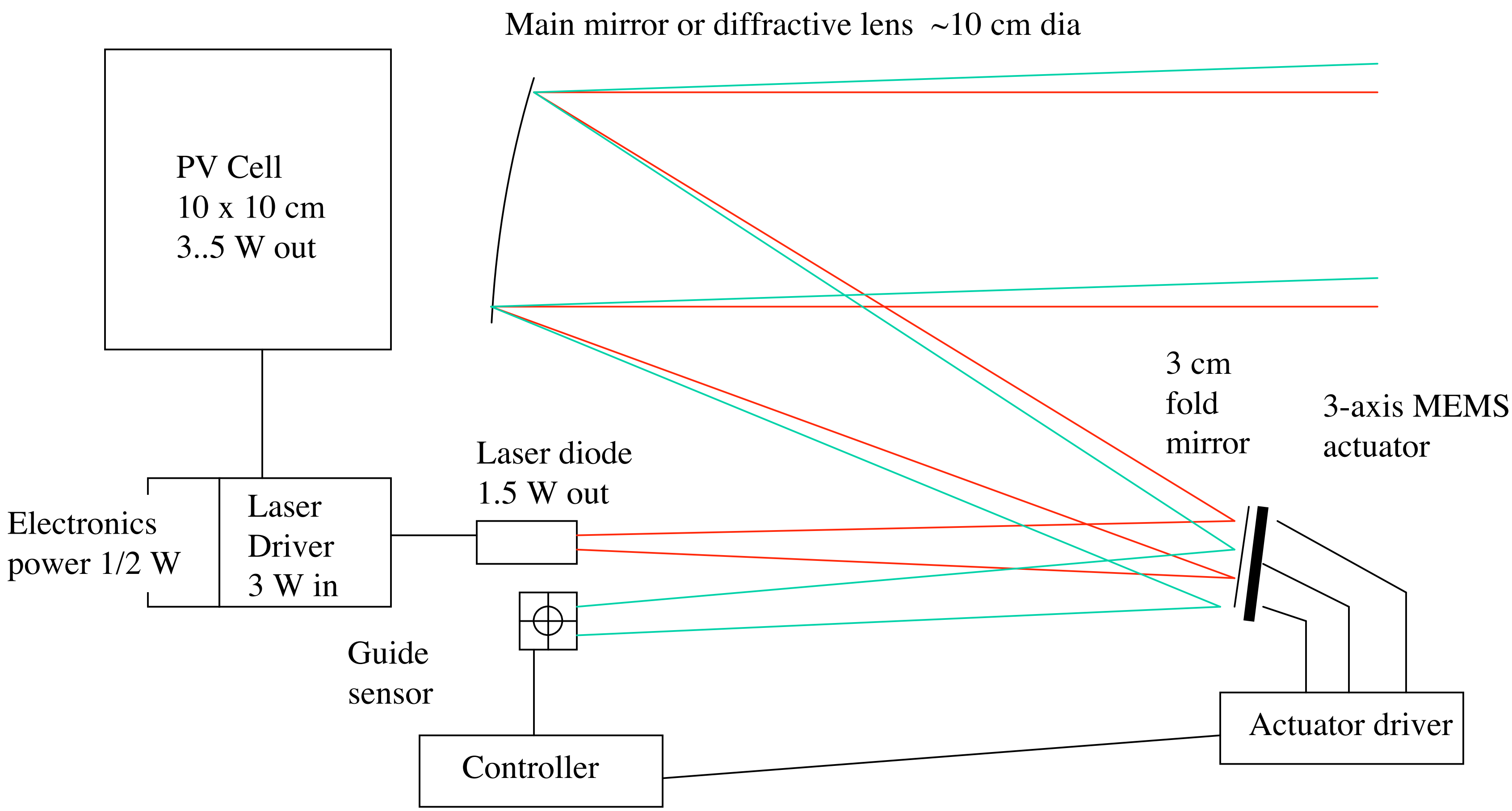
- **Small (10 cm) optics in GEO generate practical (<1 km) spot size on Earth**
  - Ideal application for diffractive optics?
- **Optics-sized solar panel produces a convenient amount of power: ~3 W for 100 cm^2**
- **SO... build self-contained ~10x10x10 cm beam modules and simply stack them up to make a powersat**
  - No high power cables
  - No phase locking;
    - No minimum satellite size to deliver power
    - Power can be shared among any number of receivers
  - Modules simply clip to a frame

Beam Module SSPS



Note added 3/30/04:
We have been referred to a similar SSPS configuration for microwaves, with a phased array transmitter, proposed by Nobuyuki Kaya, e.g., in *Space Energy and Transportation* 1 (3) 1996, pp. 205-213. Modular laser configurations have also been considered; we are still seeking details to compare against the concept proposed here.

Solar Power Satellite Beam Module



Conclusions 1: Technology Is Ready

- **<u>Lasers crossed the threshold within the last year</u>**
  - Performance is sufficient, and nearly certain to improve
  - Costs are still high, but not inherently so
    - Costs will drop with volume and time
- **Current optics technology is dull, but adequate**
  - Modern glass optics are cheap enough with high-radiance lasers
    - Optimum primary size is ~1 meter or less
  - Innovative but unproven technologies are waiting in the wings
- **No show-stoppers elsewhere in the system**
  - Mounts, pointing and tracking, etc. are straightforward
    - On-vehicle "omni" beacon looks best for pointing/tracking and makes adding adaptive optics straightforward if required
  - Power storage is ripe for innovative tech (advanced batteries, flywheels) but not a system driver

Conclusions 2:
Architecture Implications Are Profound

- **Laser launch in general shifts paradigms**
  - Small unit payloads, routine prompt access => <u>on orbit industry</u>
- **Modular launcher technology changes industry**
  - Small companies can play -- modules can come from many sources
  - Small countries can play -- buy their space launch "by the yard"
- **Crewed flight is a new game**
  - Continuous scaling from support (100 kg payloads) to solo launches (~1000 kg) to taxi (tour bus?) service
  - Inherently high reliability, inherently testable -- tourist friendly!
- **Significant effects on in-space power and propulsion**
  - Requirements are different, but overlapping
  - Low-enough unit costs open new options, e.g., laser-per-satellite power systems, distributed power belt for orbit raising
- **Spinoffs: powersats, power beaming, industrial lasers...**

Where to go?

- **Technology development -- only small niches**
  - Most technology is being driven by other uses
  - Some leverage in low-cost optics, SBC lasers
- **Technology integration and demonstration**
  - Integrated subscale module
    - COTS fiber laser(s) or SBC laser array (~100 W)
      - Upgradeable to higher power as lasers become available
    - Optics TBD: at least half-scale; full-scale if possible
    - Full tracking system
  - Full scale beam module is a bit much to bite off: ~$10-20 M
    - Higher power-per-module than originally conceived
- **System integration and architecture studies**
  - Many, many issues barely touched: siting, markets, safety...

Laser Launch Architecture With Modular Ground-Based Laser Array