SailBeam

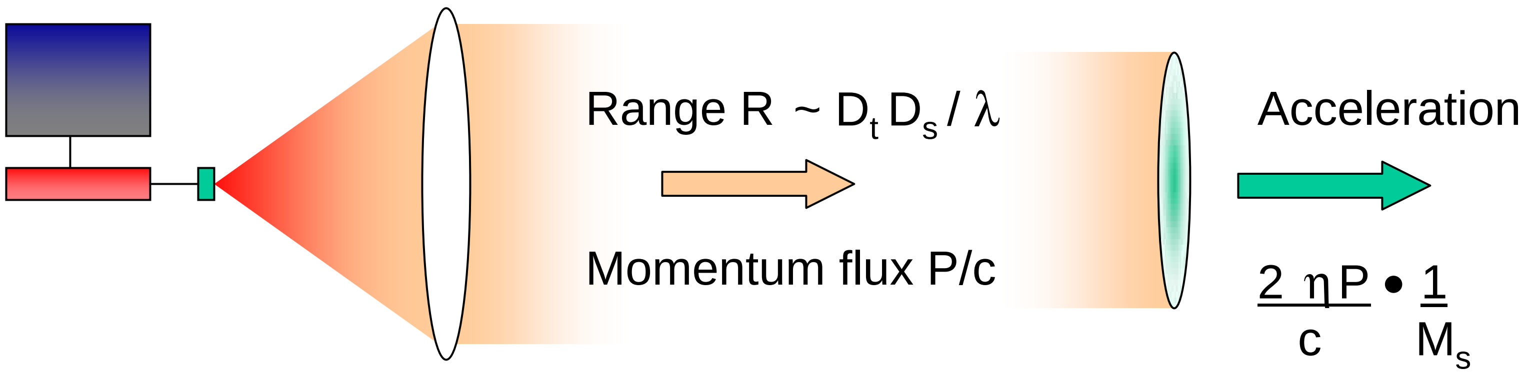
Space Propulsion by Macroscopic Sail-type Projectiles

Presented at the 2001 NIAC Workshop

Atlanta, GA
October 30 - 31, 2001

Dr. Jordin T.Kare
Kare Technical Consulting
222 Canyon Lakes Place
San Ramon, CA 94583
925-735-8012 jtkare@attglobal.net

Laser Sails: A Quick Review



Laser

power P
wavelength λ

"Lens"

Area A_t
Diameter D_t

Sail

Mass/area σ
Mass M_s
Area A_s
Diameter D_s
Reflectivity η

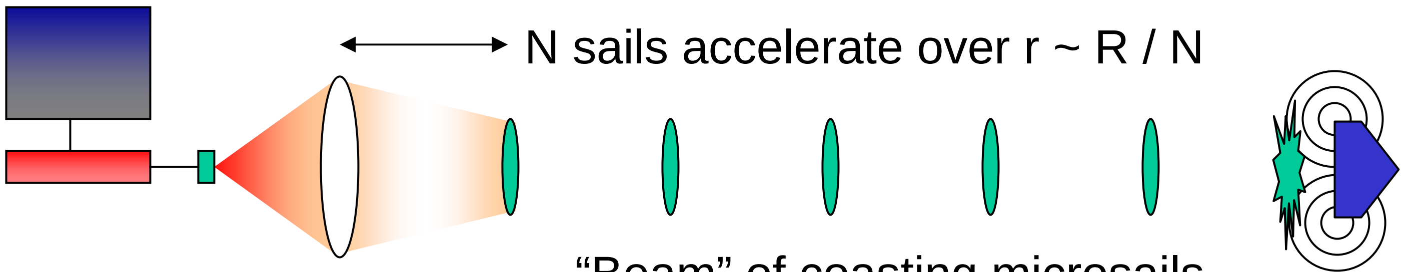
Acceleration time T

- Infinite specific impulse
- Efficient thrust at relativistic velocities

BUT

- Limited acceleration ➔ large R (10^{12} km)
- LARGE optics and sails - $D_t \bullet D_s \sim 10^9\ m^2$

The SailBeam Concept



Momentum flux ~ $m_s * v_s / t$

Laser		"Lens"		N microsails	
power	P	Area	$A_{tN} = A_t / N$	Mass/area	σ
wavelength	λ	Diameter	$D_{tN} = D_t / \sqrt{N}$	Mass	$m_s = M_s / N$
				Area	$a_s = A_s / N$
				Diameter	$d_s = D_s / \sqrt{N}$
				Reflectivity	η

- Vehicle accelerated by momentum transfer from microsails
  - Same total time
  - Same laser power, BUT
  - Much smaller transmitter lens
  - Much smaller sails

Acceleration time:

Total time T

Each sail $t = T / N$

SailBeam Scaling

- **For fixed sail velocity and mission energy***
  - Transmit aperture area $a_t = A_t / N$
  - Transmit aperture diameter $d_t = D_t / N^{1/2}$

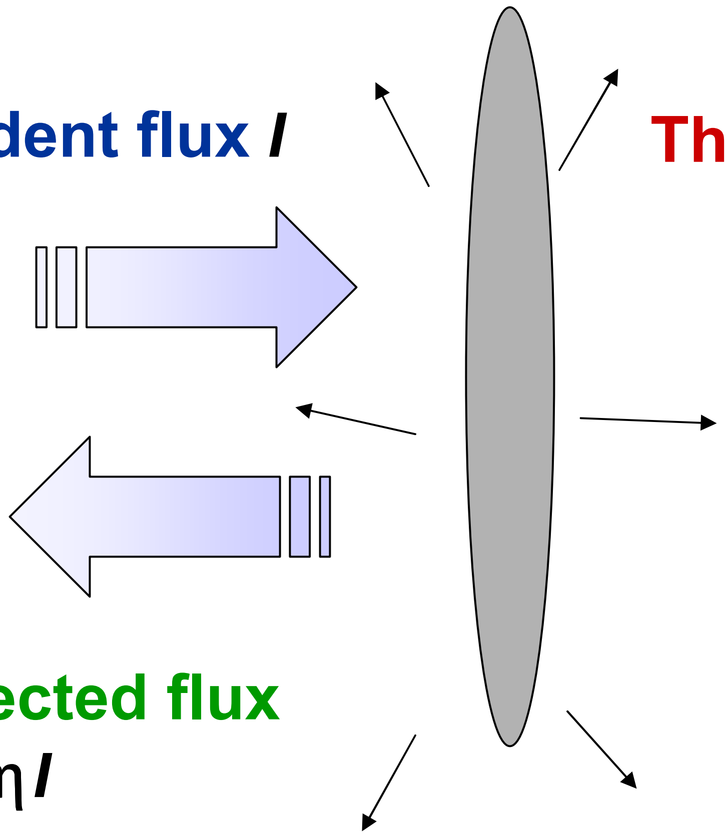
- **OR, For fixed laser power and aperture**
  - Maximum sail velocity $v_s = V_s * N^{1/4}$
  - Payload mass is limited only by mission energy

- **In either case**
  - High Flux at sail $\phi_s(N) = \phi_s(1) * N$
  - High Sail acceleration $a_s = A_s * N$

*Mission energy = laser power * laser run time

Metal Sails Are Flux Limited

Incident flux I



Thermal radiation ~ $2\,\varepsilon\, A\, \sigma T^4$

ε **emissivity** T **temperature**

σ **Boltzmann's const.** A **area**

Absorbed power must be reradiated

$$I\,(1-\eta) = 2\,\varepsilon\,\sigma T^4$$

Reflected flux

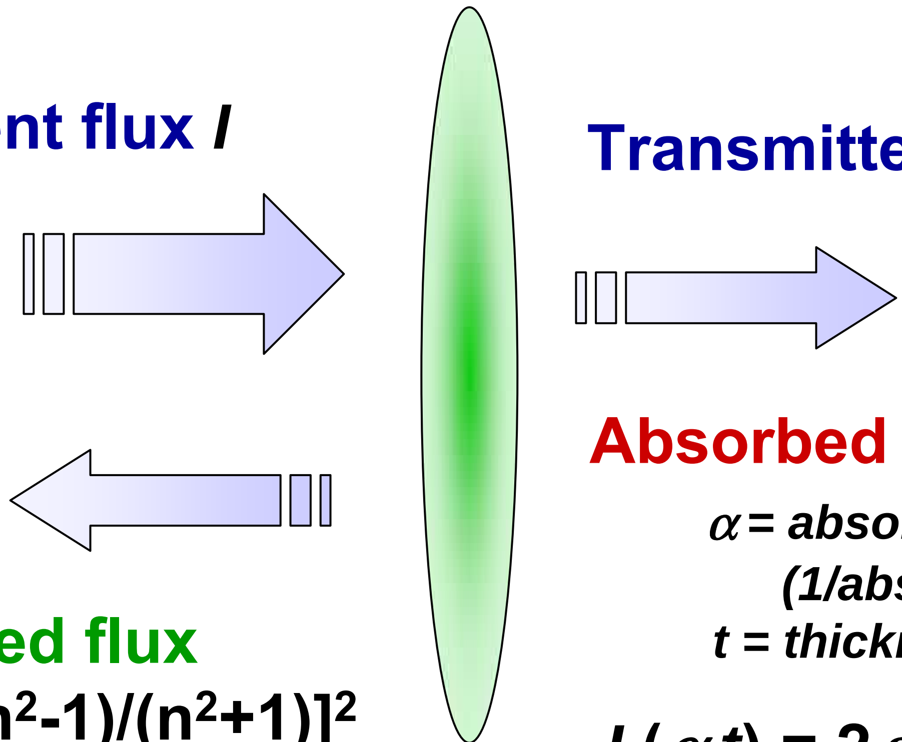
$$R = \eta I$$

η **reflectivity**

Absorption $(1-\eta)$ **is ~1% at best**

Dielectric Sails Beat the Flux Limit

Incident flux *I*



Transmitted flux $T = I - R - A$

Absorbed flux $A \sim I\,\alpha\,t$

α = absorption coefficient (1/absorption length)

t = thickness

$$I\,(\alpha t) = 2\,\varepsilon\,\sigma T^4$$

Reflected flux

$$R = I\,[(n^2-1)/(n^2+1)]^2$$

n = index of refraction

Absorption (αt) can be extremely small -- 10^{-12}

Microsail Performance Can Be Impressive

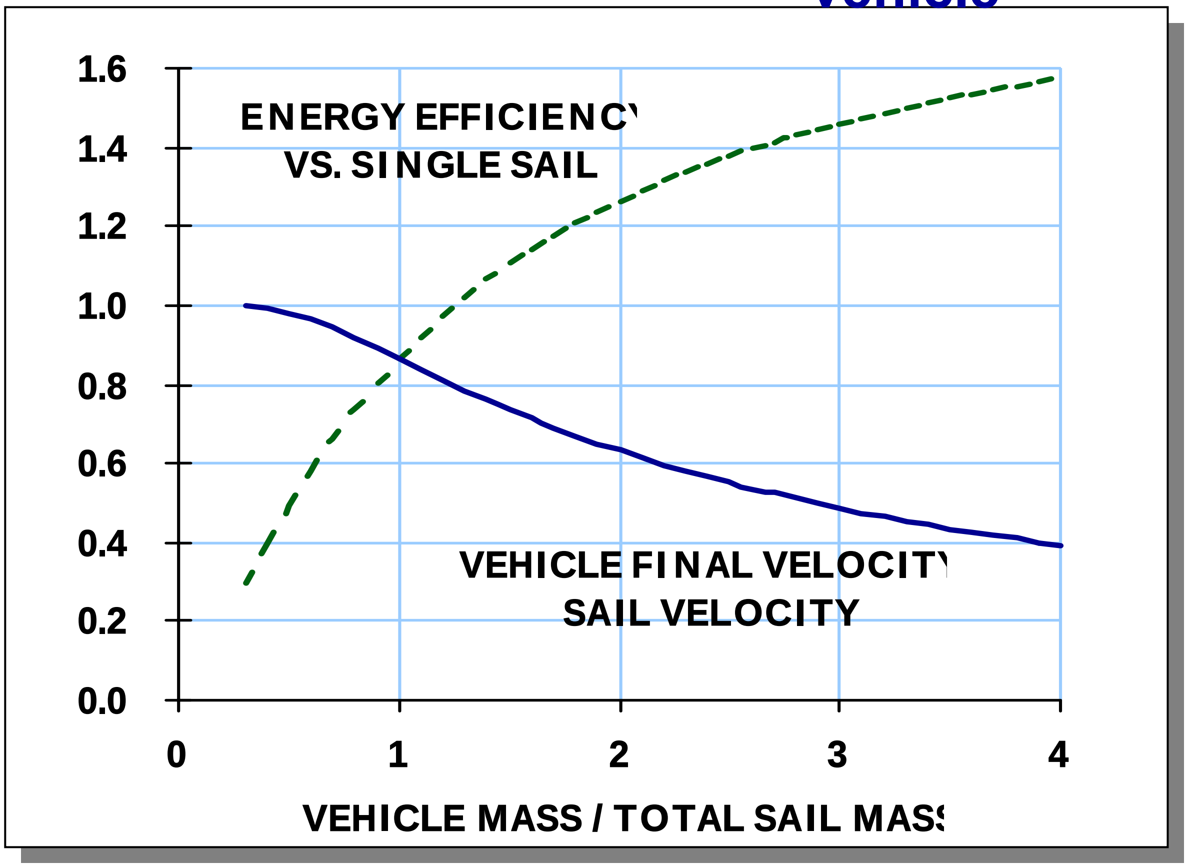
Wavelength	1 μm
Index of refraction	1.6
Reflection coefficient	0.19
Sail thickness	0.156 μm
Density	2.6
Areal density	406 mg/m^2

Maximum laser flux	10^{14} W/m^2
Absorption	10^{-12}
Infrared emissivity	0.01 (nominal)
Radiated power	100 W/m^2
Operating temp.	~684 K
Maximum force	125 kN/m^2
Acceleration	3.1×10^8 m/s^2

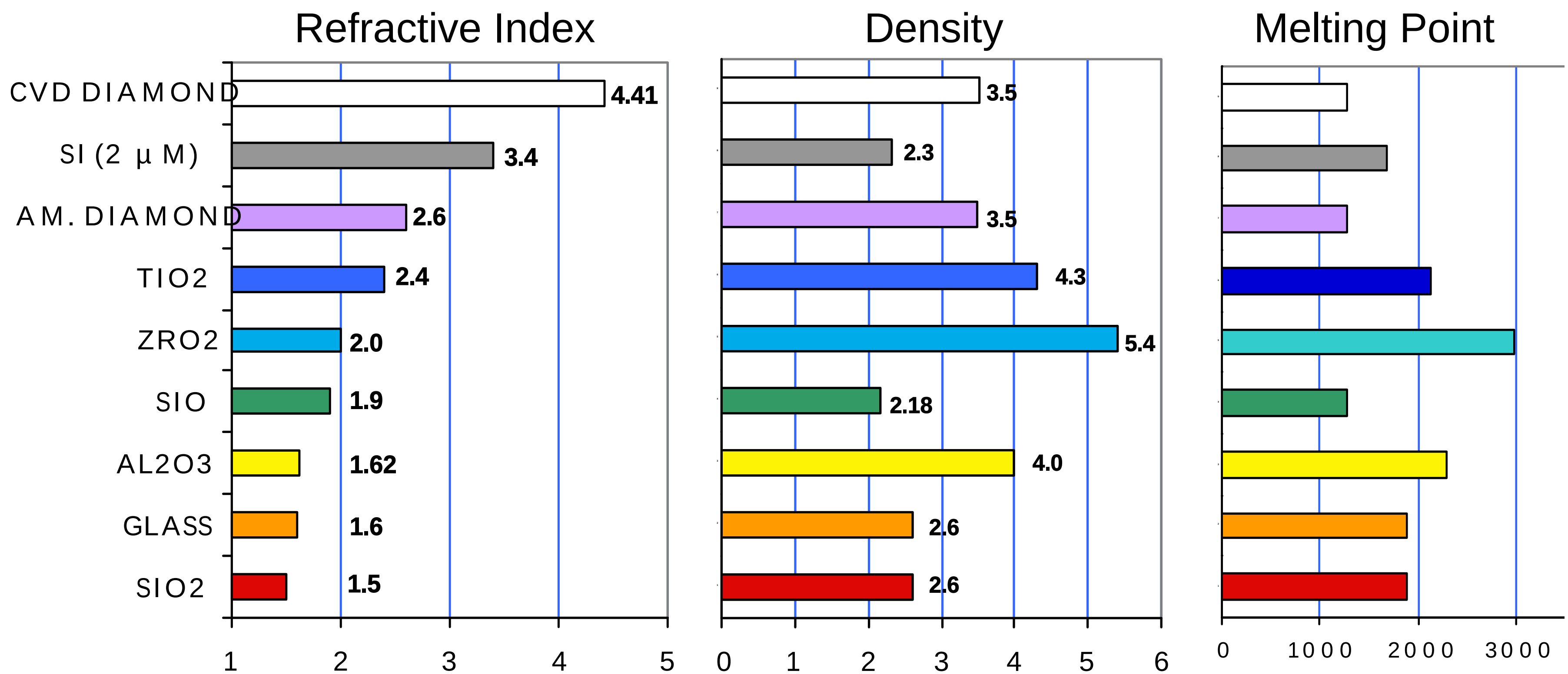
That's 32 MILLION G's
"Zero to lightspeed in 0.97 seconds"

Vehicle Velocity Limit

- **Treat sail beam as continuous momentum flow**
  - *d*m/*d*t * v in laser frame
  - *d*m/*d*t * (v - $v_{vehicle}$) in vehicle frame
- **For vehicle mass = sail mass, $v_{vehicle} = 0.86\ v_{sail}$**



Sail Material Options

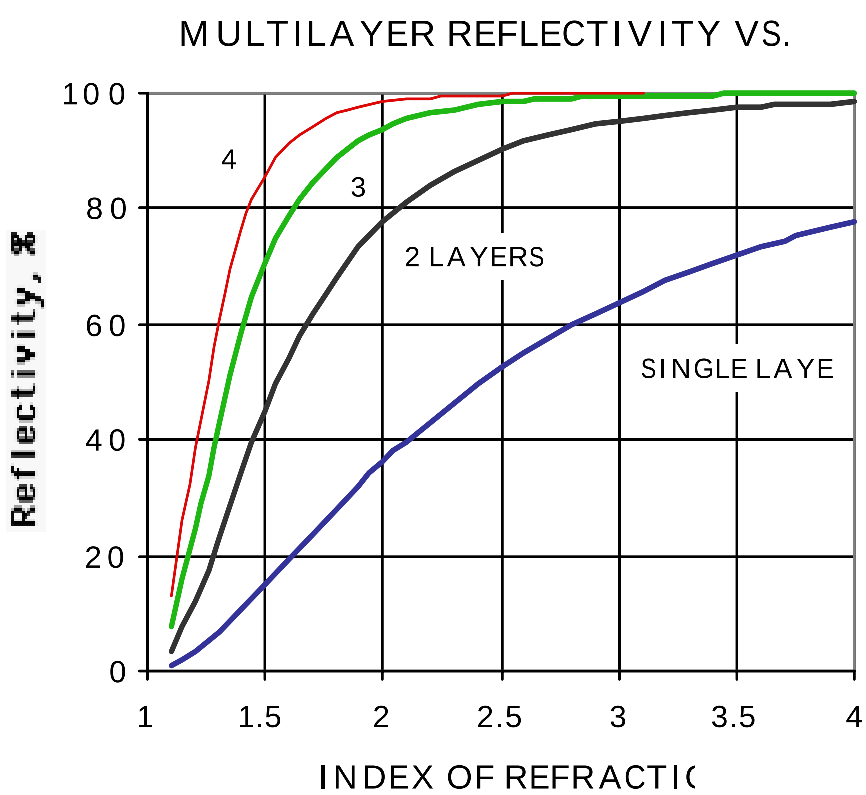


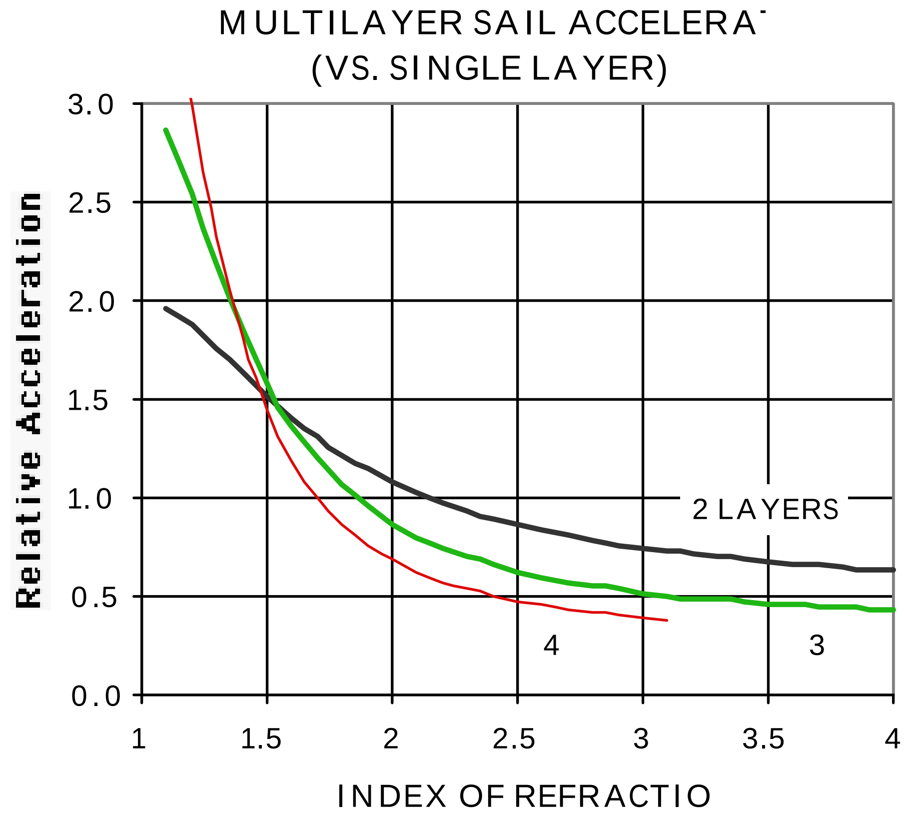
- **CVD Diamond has the highest performance**
- **SiO_2 and Si have the largest technology base (IC industry)**
- **Glass (doped SiO_2) has the lowest bulk absorption (fiber optics)**
- **ZrO_2 (a common optical coating) is strong at high temperatures**

Multilayer Sails Are Usually Better

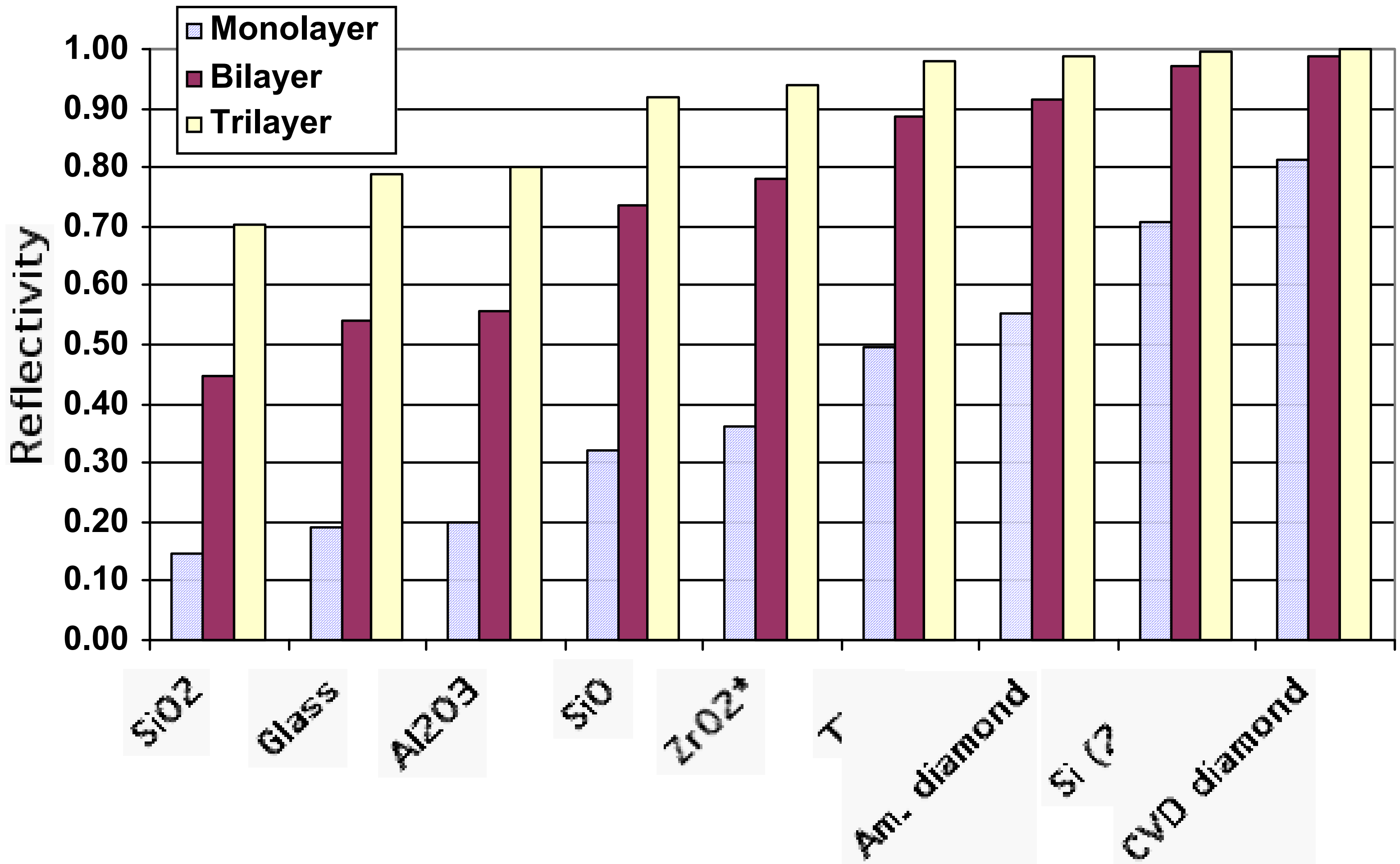
If they can be fabricated

- **$R = (n^{2N} - 1 / n^{2N} + 1)^2$**
  - **N quarter-wave layers spaced by quarter-wave vacuum**





Reflectivity of Film Materials

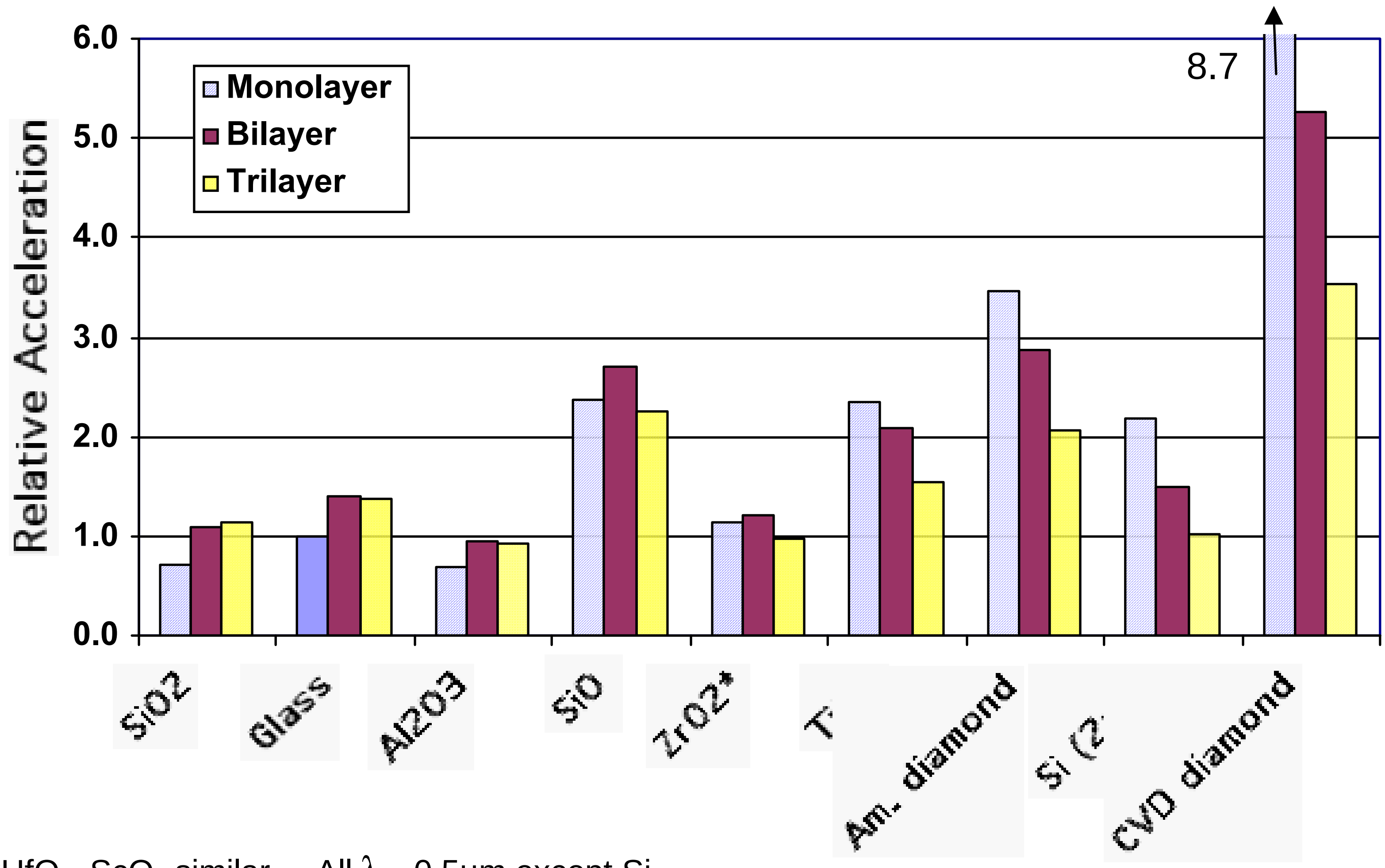


*HfO_2, ScO_2 similar

Am. diamond = Amorphous diamond film

Relative Acceleration, Fixed Flux

- Reflectivity * index * λ / density determines acceleration (at fixed flux)

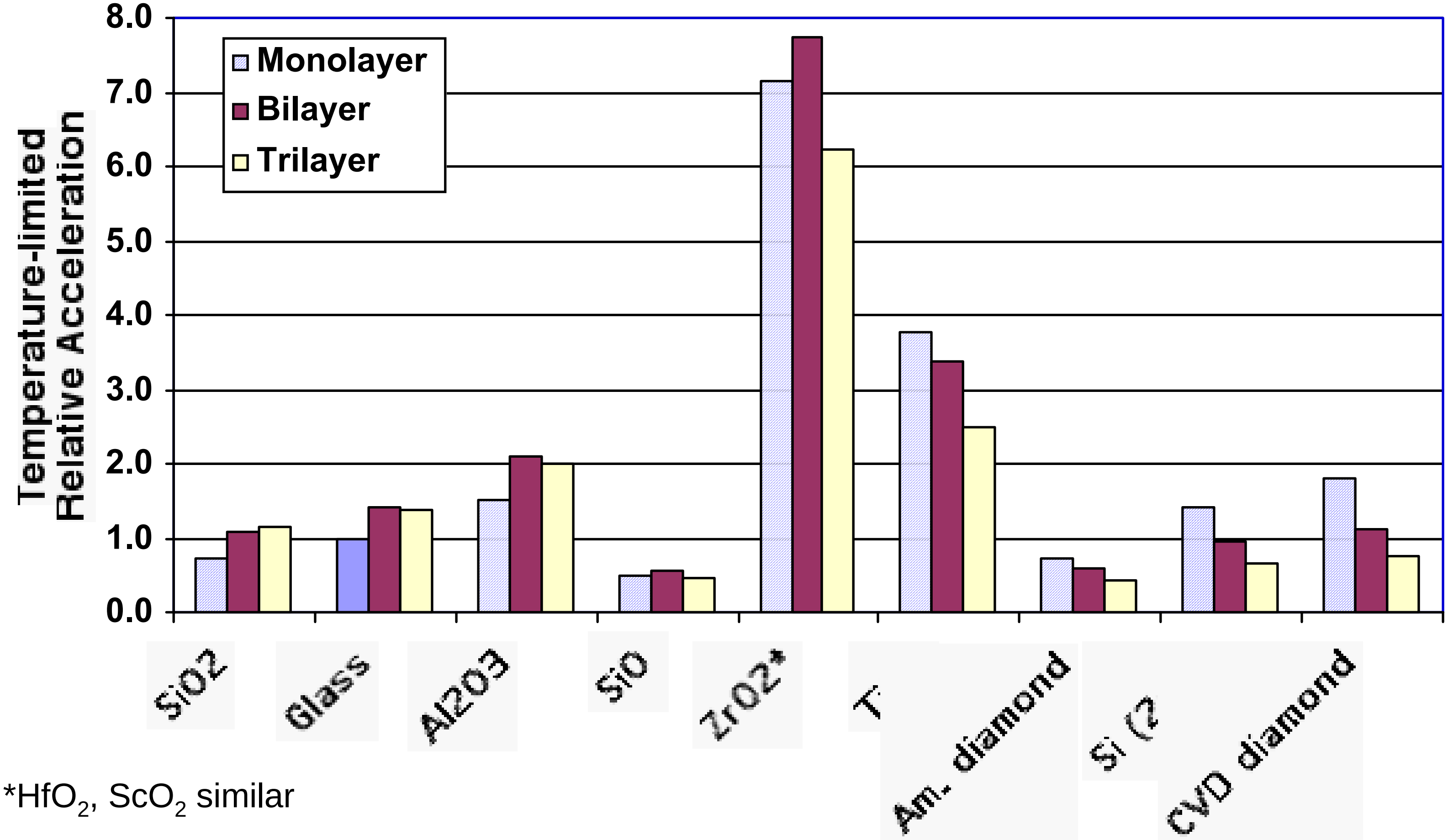


*HfO$_2$, ScO$_2$ similar All λ = 0.5µm except Si

Relative Acceleration, Temperature Limited

A simple first cut:

- Assumes constant absorption and emittance, flux $\propto T^4$
- Uses melting/decomposition temperature for T



*HfO_2, ScO_2 similar

Sample Point Designs

VEHICLE MASS, KG	1000
VEHICLE VELOCITY, KM/S	3×10^7
ACCELERATION RANGE, KM	65,000.0

SAIL MASS, KG	1000
SAIL VELOCITY, KM/S	3.6×10^7
SAIL ACCEL., KM/S^2	10,000
SAIL ACCEL. TIME, S	3.6

SAIL MATERIAL	DIAMOND	SI 2 µM	GLASS (SIO2)	GLASS (SIO2)
	2 LAYERS	2 LAYERS	3 LAYERS	1 LAYER
LASER WAVELENGTH, µM	0.5	2	0.5	0.5
LASER POWER, GW	25	25	25	100
DENSITY, G/CM^3	**4.4**	**3.4**	**2.6**	**2.6**
REFRACTIVE INDEX	**7.0**	**4.7**	**3.2**	**3.2**
SAIL REFLECTIVITY	**0.97**	**0.87**	**0.79**	**0.19**
LAYER THICKNESS, µM	**0.04**	**0.21**	**0.08**	**0.08**
AREAL DENSITY, MG/M^2	**314**	**1459**	**609**	**203**
SAIL DIAMETER, M	0.26	0.11	0.16	0.28
TELESCOPE DIA., M	310	2820	480	280
SAIL MASS, MG	**16**	**14**	**13**	**13**
OF SAILS, MILLIONS	**62**	**69**	**77**	**79**
TOTAL ACCEL. TIME, YEARS	7.1	7.9	8.8	9.0

Blue = derived value

Potential Limits on Microsails

- **Absorption**
- **Mechanical strength / beam uniformity**
- **Stability and beam tracking**
- **Sail structure and attachments**
  - **Nothing *but* a dielectric film can survive 100 MW/cm^2 for long**
- **Sail guidance**
  - **How to hit the vehicle's "sweet spot" over a light-year?**
- **Momentum transfer**
  - **How to do it?**
  - **Impact limits -- even 0.0001 kg packs a large punch at 0.1 c**
  - **Inelasticity -- how much energy ends up in the vehicle?**

Thin Layer Absorption / Damage

- **Damage thresholds not well known**
  - **Most data are from multilayer reflectors and sub-μs laser pulses**
    - **Not directly applicable to single-layer microsails, CW laser**
  - **Bulk of recent data are on SiO_2 and HfO_2**
- **Film absorption is typically 10^{-6} or higher**
  - **Several orders of magnitude higher than bulk absorption**
  - **Heavily dependent on fabrication method**
    - **Usual methods (sputtering, vapor deposition) deposit porous layers, varying amounts of impurities**
    - **Low absorption was rarely the main goal of process development**
  - **Bulk absorption appears to dominate, but surface absorption is significant**
    - **Measurements are indirect and quite difficult**

Thin Layer Absorption / Damage (2)

- **SailBeam allowable absorption is design-dependent**
  - Flux limit depends on material emissivity and temperature limits
  - Transmitter aperture diameter varies as (max flux)$^{-1/2}$
  - 10^{-10} absorption probably acceptable; >10^{-8} presents problems

- **Conclusion: R&D needed**
  - Experimental measurement of limiting flux
    - Long pulses (~millisecond) and single-layer films
  - Process development and/or "new" processes to reduce absorption, e.g.,
    - Pulling of bulk material (flat version of fiber optic fabrication)
    - Doping and etching of thick wafers

    (Processes used to make thin structures in other fields, but not usually used for optical films))

Spin Stabilization

- **Microsail must be stable in beam**
  - **Characteristic time scale ~ [2(sail diameter)/(acceleration)]$^{1/2}$**
    - **Typically ~100 μs (e.g., 0.1 m sail, 2 x 10^7 m/s^2 accel.)**
    - **<< Lightspeed feedback time to transmitter; can't do active stabilization**
    - **Spin rate must be ~10,000 rps**
  - **Spin provides at least neutral stability**
    - **Other projects are investigating stability for other beam-driven systems (e.g., Benford et al., microwave sails)**
  - **Active damping of oscillations is possible**
    - **On-sail guidance components, or**
    - **Platforms spaced along sail acceleration path**

- **Spin keeps sail in tension**
  - **Prevents collapse or wrinkling due to nonuniform beam / loads**

Guiding Microsails

- **Sails will need some course correction capability**
  - **Finite velocity error at launch: 1 nrad error => 1 km miss at 0.1 l.y.**
  - **Sail will be perturbed in flight, e.g., by dust impacts**
  - **Main laser is too diffuse to apply corrections even 1 light-day out**
- **At least two options:**
  - **"Guidance stations" along path to ~1 light day**
    - **Can measure course to <<1 nrad and correct with laser pulses**
      - **Measuring sail-to-sail relative errors is sufficient**
    - **Corrections extend beyond most solar-system perturbations**
    - **No requirements on sails, but may not be accurate enough**
  - **MEMS micropropulsion on sails**
    - **Few m/s ΔV is sufficient, and feasible even at very small scales**
    - **Vehicle can provide a "homing beacon" laser**
    - **Sail sensors and control system are simple, but not trivial**

Much Work Remains To Be Done

Tensile Strength

- **Tensile loads are comparable to force on sail**
  - Centrifugal load due to spin stabilization
  - Acceleration loads on "payload" or low-illumination area
- **Tensile strengths of freestanding thin films are poorly known**
  - Highly variable, depending on film fabrication details

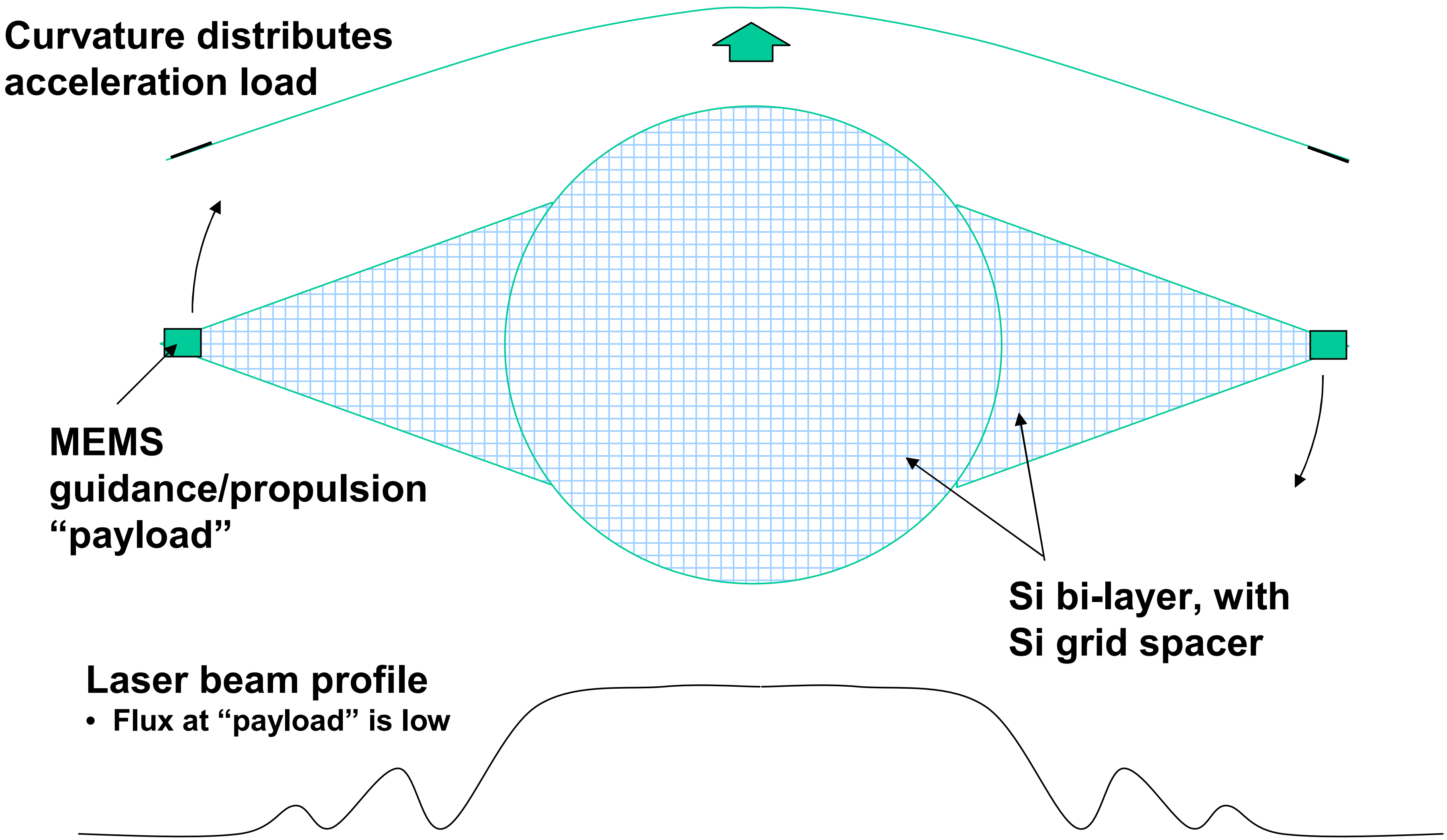
But some typical values are

- Al_2O_3 — 0.25 GPa (1 GPa ~150,000 psi)
- Si — 1 GPa
- SiO_2 — 2 GPa
- CVD diamond — 3.5 GPa

- **Nominal requirement is** $\sigma_{sail} \sim m_{sail}\, a_{sail} / (d_{sail}\, t_{sail})$
  - t_{sail} is the sail thickness, nominally $\lambda/4n$
  - Typical values are 3 - 10 GPa (for 10^7 m/s^2 acceleration)

Tensile strength looks OK, but only barely -- may drive many aspects of sail and system design

Microsail Conceptual Design



Coupling Microsails To Macroscopic Vehicles

1. Magnetic Coupling

- **Turn microsail into plasma**
  - Use a laser on the vehicle (at a wavelength absorbed by sail), or
  - Run it into something
    - Plasma cloud (Landis shield)
    - Gas/dust cloud (residue of previous sail?)
    - Solid film or mesh (mass << sail)
- **Transfer momentum to vehicle**
  - Bounce plasma off a magnetic field (MagOrion concept)
    - Elastic; low energy absorption

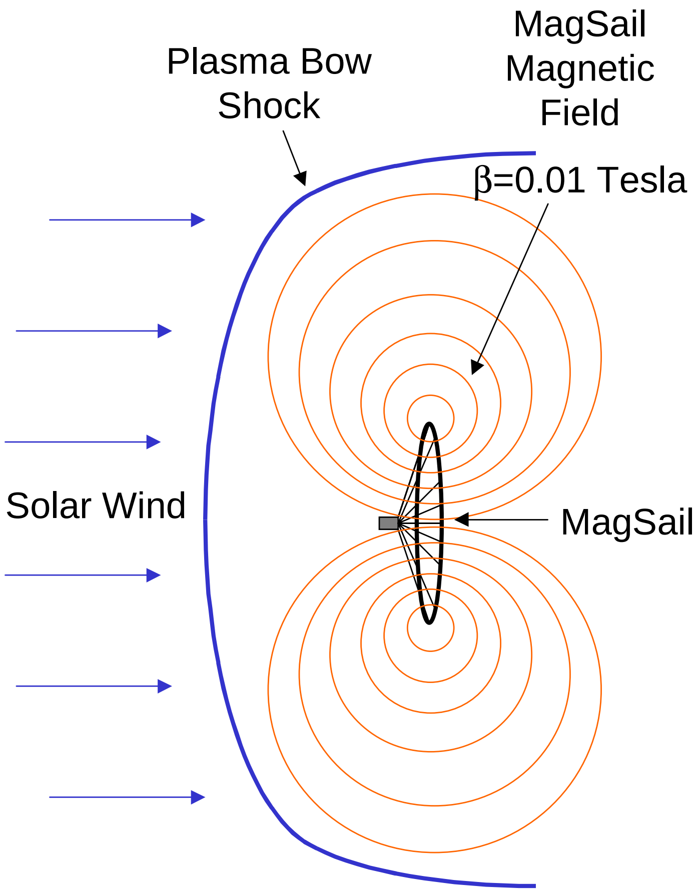
2. Or emulate ORION

- Let solid (or perhaps vaporized) sail hit something
  - A solid pusher plate
  - A confined gas or plasma
- Reject impact energy via ablated mass or radiation

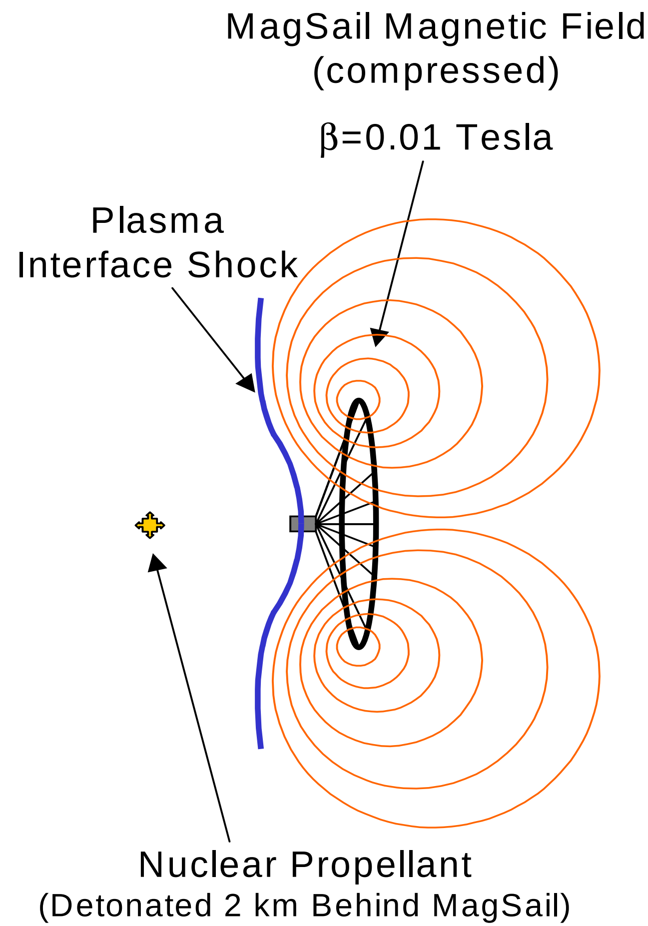
Ionizing Microsails

- **Laser**
  - Use wavelength absorbed by sail, probably UV
  - Thin sail is easy for laser to ablate (vs., e.g., spherical particle)
  - Requires ~50 - 100 MJ / kg -- <1 kJ for typical microsail
    - 3 - 10 kJ needed for safety margin, pointing error, etc.
  - Sail expands into spherical plasma at ~10 km/s
    - Must hit sail 0.01 - 0.1 s before impact at 10's to 100's of km
    - Must track sail with ~0.1 m accuracy at 10^5 m
- **Impact** -- proposed by Singer in original 1980 particle-beam paper
  - Let microsail strike something -- solid, particle cloud, gas, plasma
    - High-velocity impact produces X-ray temperatures
  - Low energy requirement, but possibly complex hardware
  - Vehicle must carry sacrificial mass
    - Specific impulse is no longer infinite
    - Cleverness needed to "hit" sail without tossing away $>>m_{sail}$

MagSail Concept



Solar-wind-driven MagSail



Nuclear-pulse-driven MagOrion

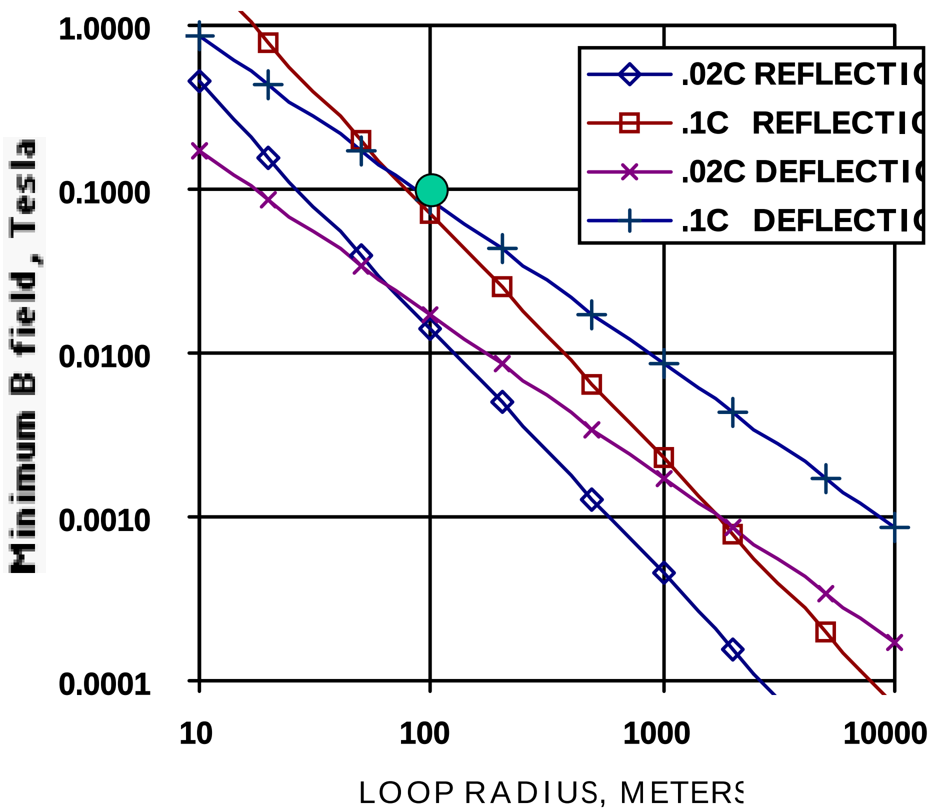
Estimating MagSail Requirements

- **Collective plasma reflection (Dynamic pressure)**

$$B^2 / 2\mu_0 >> m_{sail} V_{rel}^2 / \pi r_{loop}^3$$

- **Individual ion deflection (Larmor radius)**

$$m_{ion} V_{rel} / q B << r_{loop}$$



- **Nominal design point**
  - 100 m loop radius
  - 16 MA loop current
  - 1000 kg loop mass
  - 1 x 10^7 Amp-m / kg superconductor performance

MagSail Drag

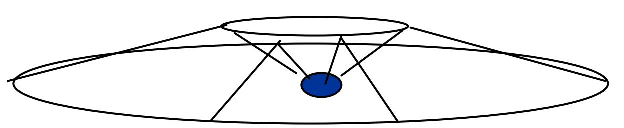
$$F_{drag} = 1.175\pi (N_i\, m_i\, \mu_0^{1/2}\, I\, r^2\, V^2)^{2/3}$$

N_i = Number density of ions
(nominally $10^5\ m^{-3}$, or $0.1/cm^3$)
m_i = Average ion mass (1 amu)
μ_0 = $4\pi \times 10^{-7}$
I = Loop current
r = Loop radius
V = Vehicle velocity

For V=0.1c, r=100m, I=16 MA
- **F_{drag} = 34 N; Thrust ~ 8 N**

Suppressing Drag During Acceleration

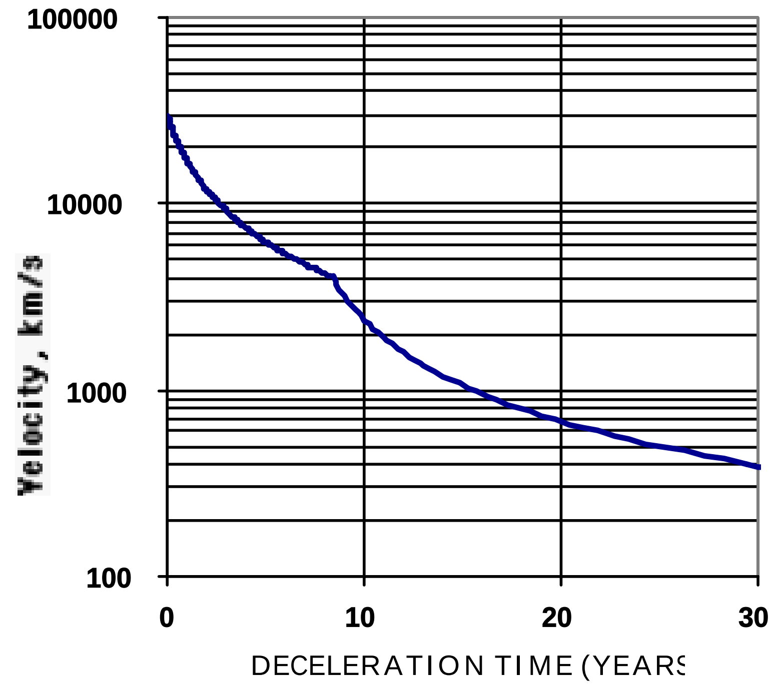
- Drag is dominated by low-field region far from loop
- 2nd larger loop with opposite dipole cancels field
  - For constant dipole moment, current I varies as $1/r^2$
  - Central field proportional to I/r, varies as $1/r^3$
    - Outer loop doesn't affect propulsive MagSail
  - Mass is proportional to I r, so varies as 1/r.
- Expect drag < 1 N at 0.1c
  - Nominally 100m inner and 1 km outer loop radii
  - Modeling and optimization needed



How To Stop When You Get There

- **Redeploy MagSail conductor into drag brake**
  - Very large, low-current loop
  - B field pressure ~ dynamic pressure of interstellar medium
  - Ideally, continue to expand loop as velocity falls
  - Brake to rest against stellar wind once velocity is <500 km/s

Parameter	Value	Comment
Vehicle mass, kg	1000	excluding brake loop
Initial velocity, km/s	30,000	0.1 c
Interstellar ion density, #/m^3	10^5	0.1 ion/cm^3
Initial dynamic pressure, N/m^2	7.7×10^{-8}	
Brake loop radius, km	28	
Brake loop current, kA	55	
Magnetic field pressure, N/m^2	6.1×10^{-7}	$B^2/2\mu$
Superconductor J/rho, A-m/kg	10^7	
Brake loop mass, kg	968	
Initial drag force, N	1405	

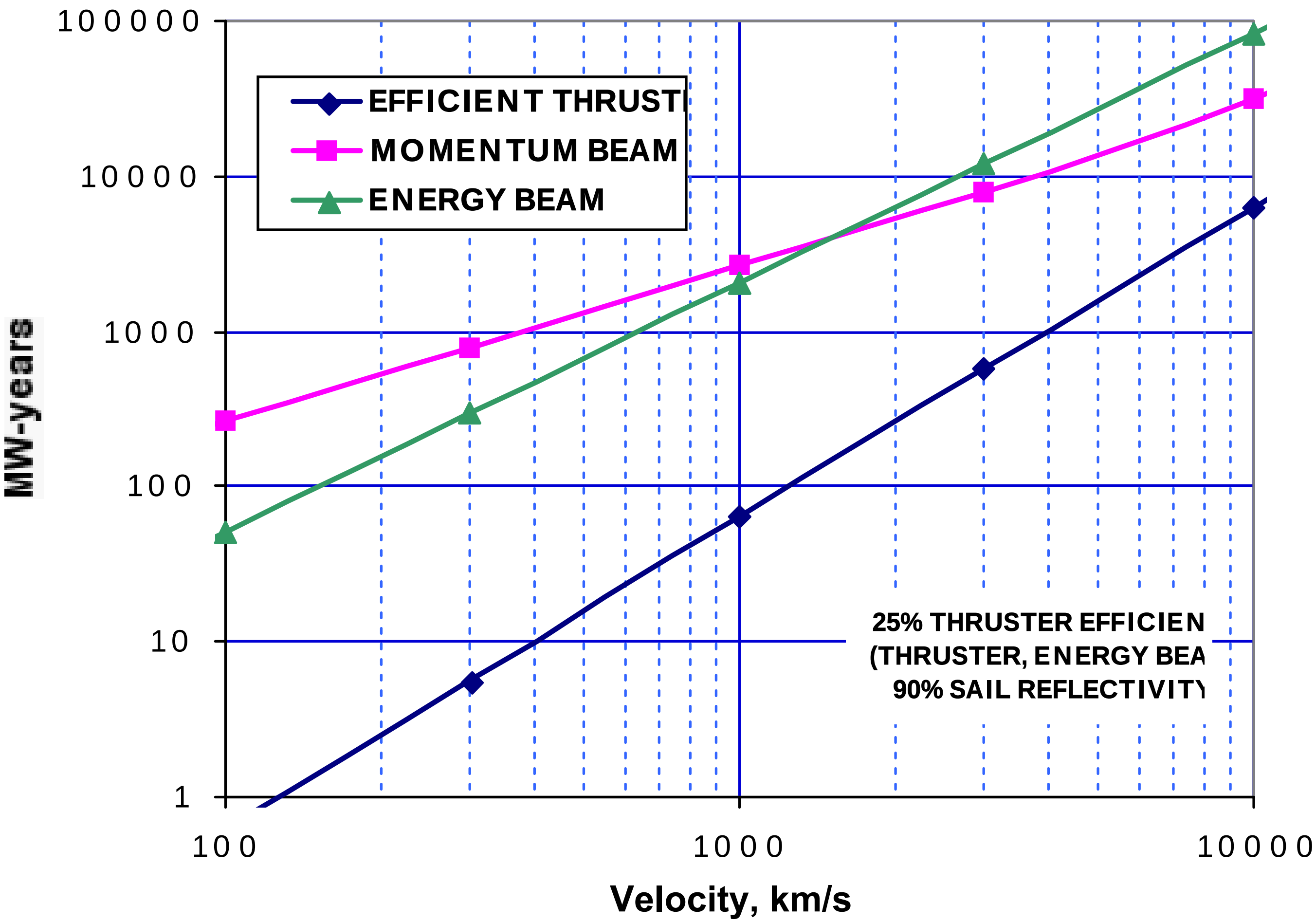


Precursor Missions

- **Microsails can transmit energy as well as momentum**
  – **Thrust can be generated in any direction**
    - **Allows rendezvous and return missions**
  – **Requires energy conversion to drive thruster**
    - **Direct, e.g., run sail into a contained plasma**
    - **Indirect, e.g., compress magnetic field to produce current to drive a plasma thruster**
- **Efficiency is low compared to alternatives...**
  – **Efficiency is at best sail velocity/c; can't scale down sail velocity (and therefore laser/optics size) by much**
  – **Probably not competitive below 0.01 c = 3000 km/s**
- **...But a prime alternative is laser propulsion**
  – **Laser-thermal (pulsed ablation) or laser-electric**
  – **Suitable for missions up to perhaps 0.02 c**
  – **Direct technology precursors (lasers, optics) for SailBeam**

Comparing Energy Requirements

to accelerate 1000 kg to various velocities



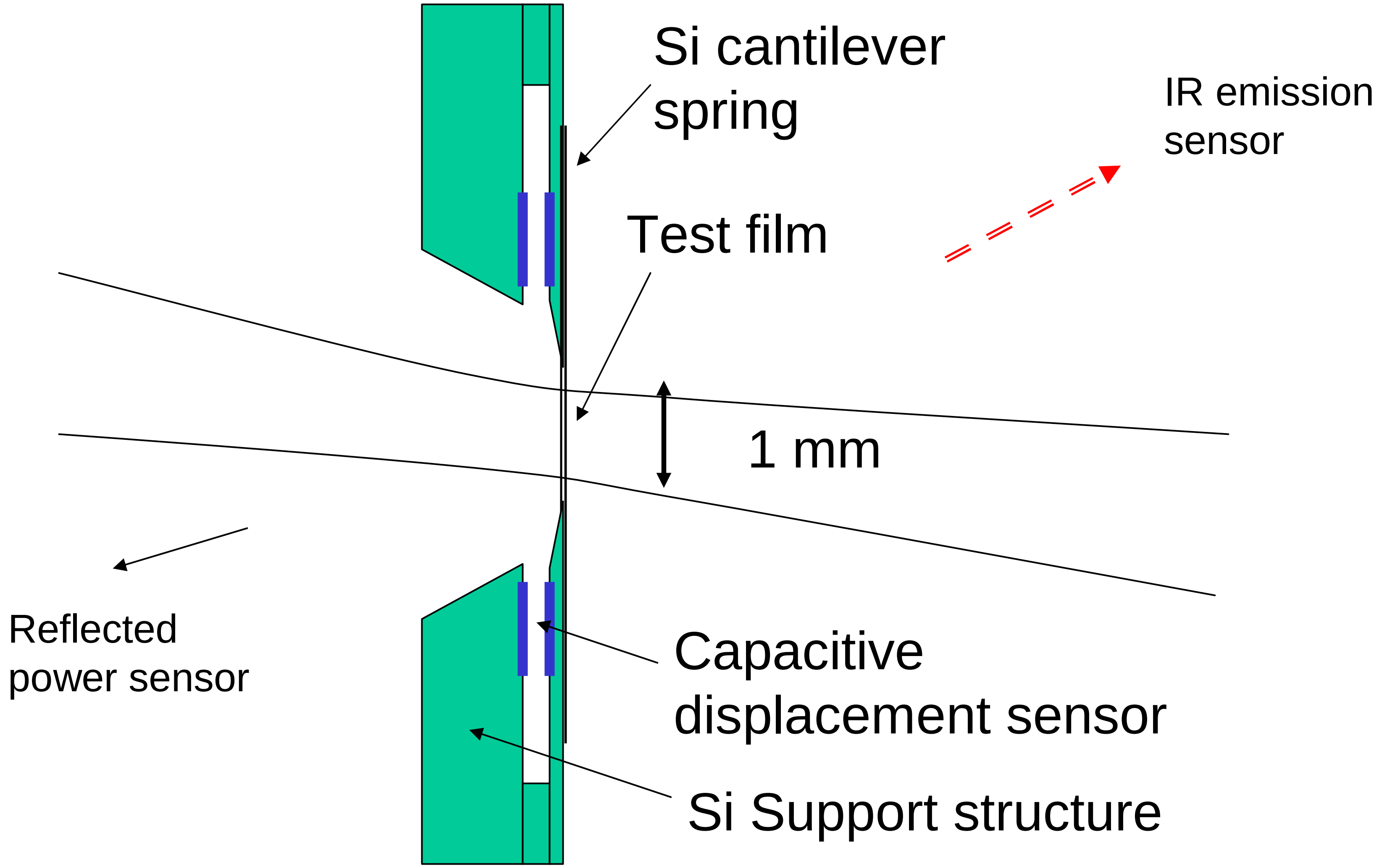
Near Term Experiments

- "Sail" diameters ~1 mm or less
  - Still a thin film: >>1000:1 width:thickness
  - Variety of materials and fabrication processes available
- Laser pulse power ~1 MW
  - 1 MW of laser power yields ~1 million G acceleration
- Laser pulse lengths ~ 1 msec
  - Final velocities of 10 - 30 km/s
  - Suffiicient to demonstrate stable acceleration
- Existing facilities meet requirements
  - E.g., LHMEL (Air Force Wright-Patterson)
    - 1 kJ Nd-Glass flashlamp-pumped laser
    - ~1 msec "dump" mode
  - Experiments fit in a 5 - 50 meter long vacuum pipe

Near Term (Phase 2) Experiment Goals

- **Measure damage/failure flux for films**
  - Test likely materials under CW conditions
  - Develop and test alternate film fabrication methods
- **Demonstrate “static thrust”**
  - MEMS force gauges integrated with film
- **Demonstrate enhanced thrust with multilayers**
- **Measure film absorption and thermal balance**
  - Difficult but not unprecedented measurements
  - Use photoacoustic or photoelastic techniques plus IR radiometry
- **Demonstrate “free flight” acceleration to >10 km/s**

Force Measurement Concept



Conclusions

- **Real interstellar probes are possible**
  - **0.1 c or faster; Alpha Centauri in 10 years?**
  - **Multi-kg (or even multi-ton) payloads**
- **System requirements are (relatively) modest**
  - **~0.2 GW-year of laser output per kg to 0.1 c**
  - **Sub - kilometer scale optics**
  - **Sub-meter scale thin film sails**
- **Development can be done soon**
  - **Development path overlaps with laser propulsion/beamed energy**
  - **Key aspects are small scale, e.g., thin film absorption**

- **Real experiments can start right away**