

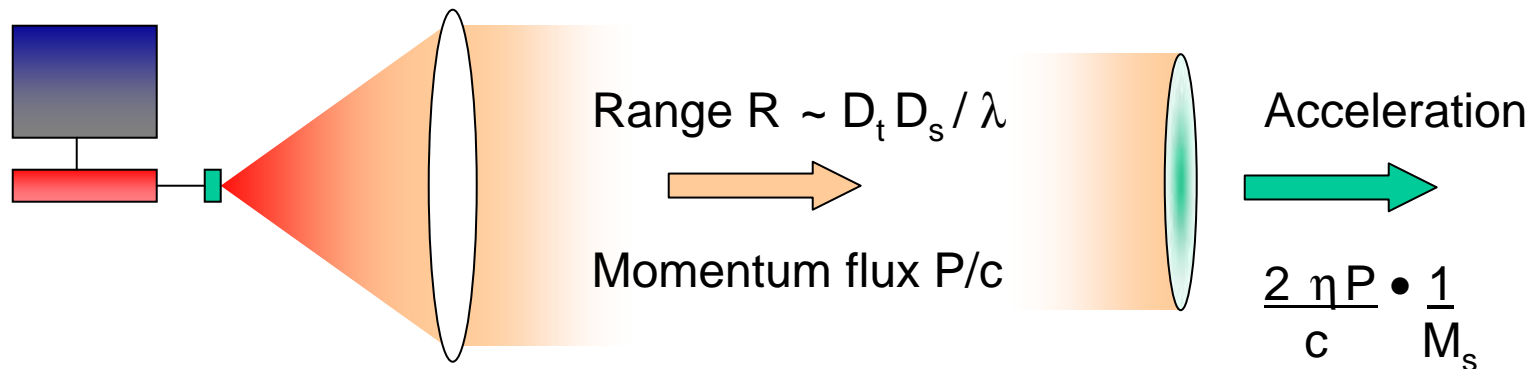
# ***SailBeam***

## ***Space Propulsion by Macroscopic Sail-type Projectiles***

**Presented at the  
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# Laser Sails: A Quick Review



Laser

"Lens"

Sail

power  $P$   
wavelength  $\lambda$

Area  $A_t$   
Diameter  $D_t$

Mass/area  $\sigma$   
Mass  $M_s$   
Area  $A_s$   
Diameter  $D_s$   
Reflectivity  $\eta$

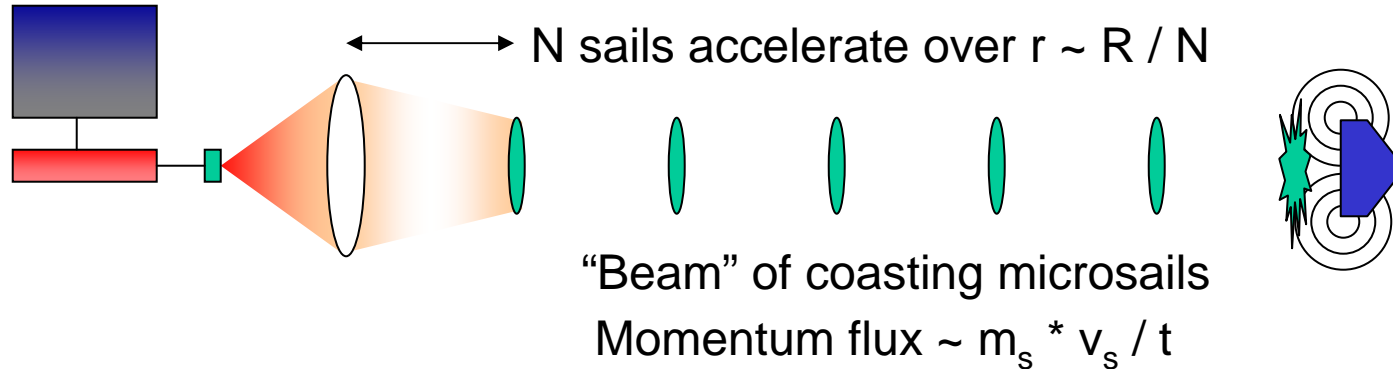
Acceleration  
time  $T$

- Infinite specific impulse
- Efficient thrust at relativistic velocities

**BUT**

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

# The SailBeam Concept



Laser

"Lens"

N microsails

power  $P$   
wavelength  $\lambda$

Area  $A_{tN} = A_t / N$   
Diameter  $D_{tN} = D_t / \sqrt{N}$

Mass/area  $\sigma$   
Mass  $m_s = M_s / N$   
Area  $a_s = A_s / N$   
Diameter  $d_s = D_s / \sqrt{N}$   
Reflectivity  $\eta$

Acceleration time:

Total time  $T$ Each sail  $t = T / N$ 

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

# 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

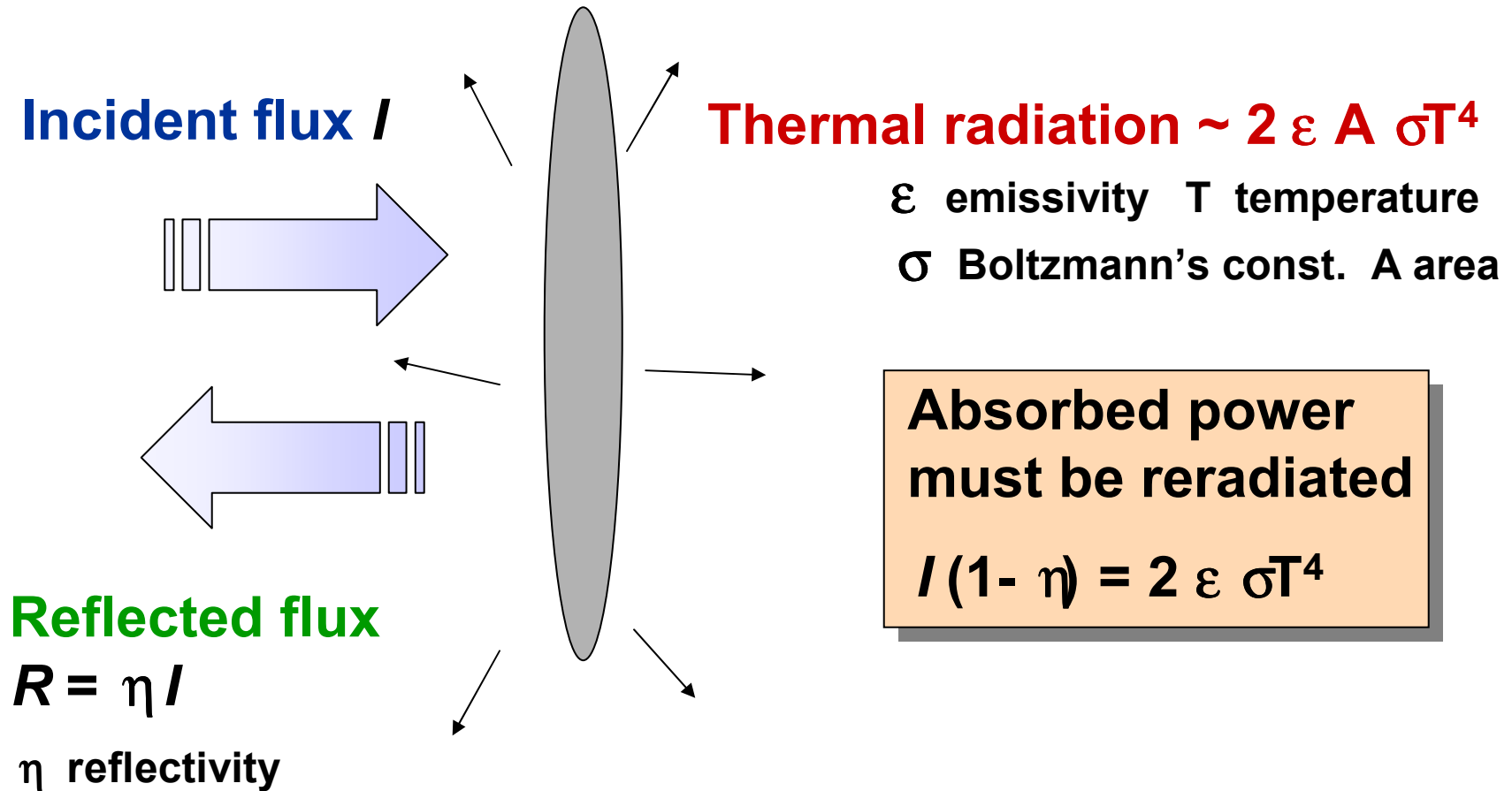
- Maximum sail velocity  $v_s = V_s * N^{1/4}$
- Payload mass is limited only by mission energy

- In either case

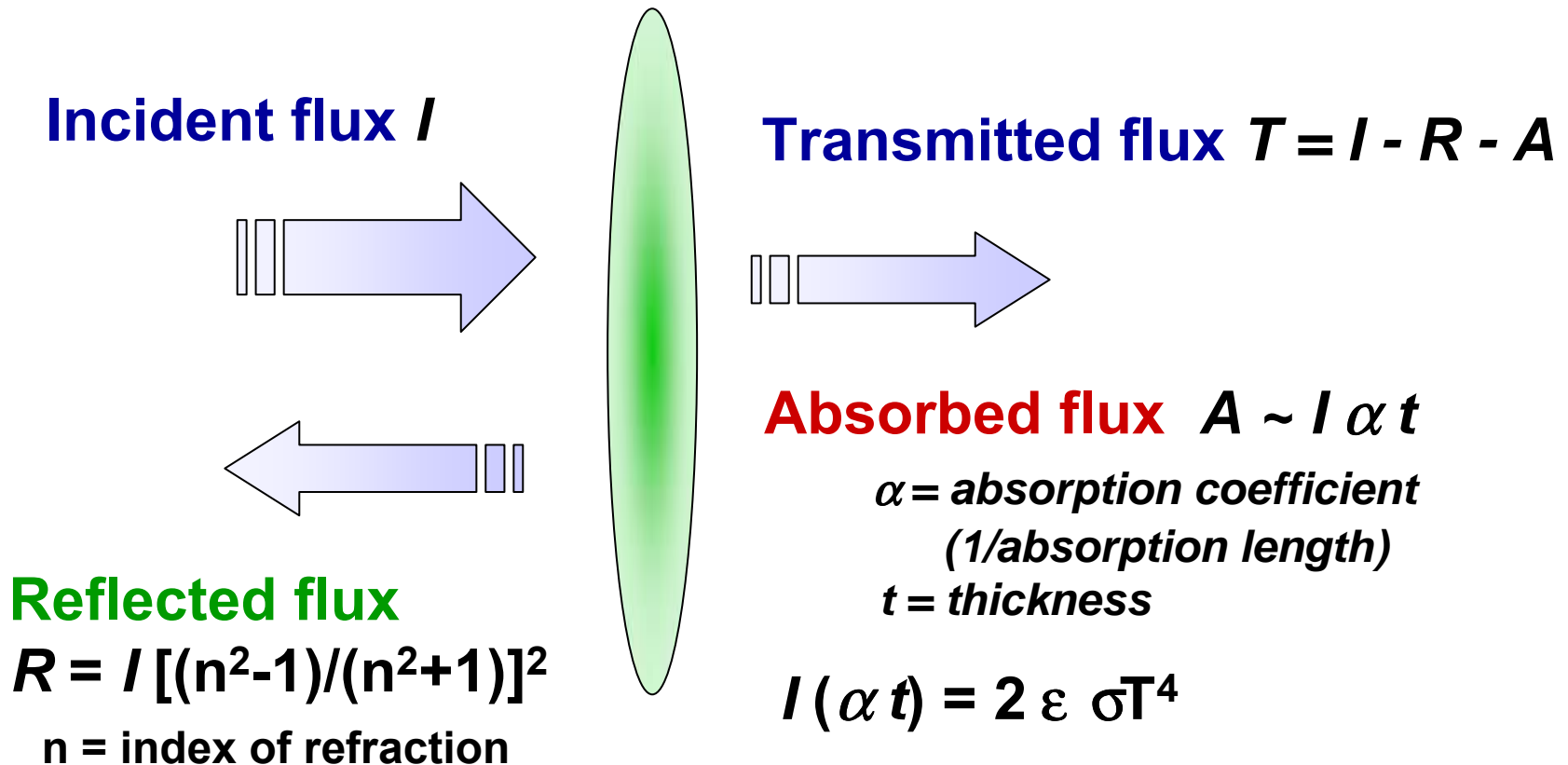
- High Flux at sail  $\phi_s(N) = \phi_s(1) * N$
- High Sail acceleration  $a_s = A_s * N$

\*Mission energy = laser power \* laser run time

# Metal Sails Are Flux Limited



# Dielectric Sails Beat the Flux Limit



**Absorption ( $\alpha t$ ) can be extremely small --  $10^{-12}$**

# Microsail Performance Can Be Impressive

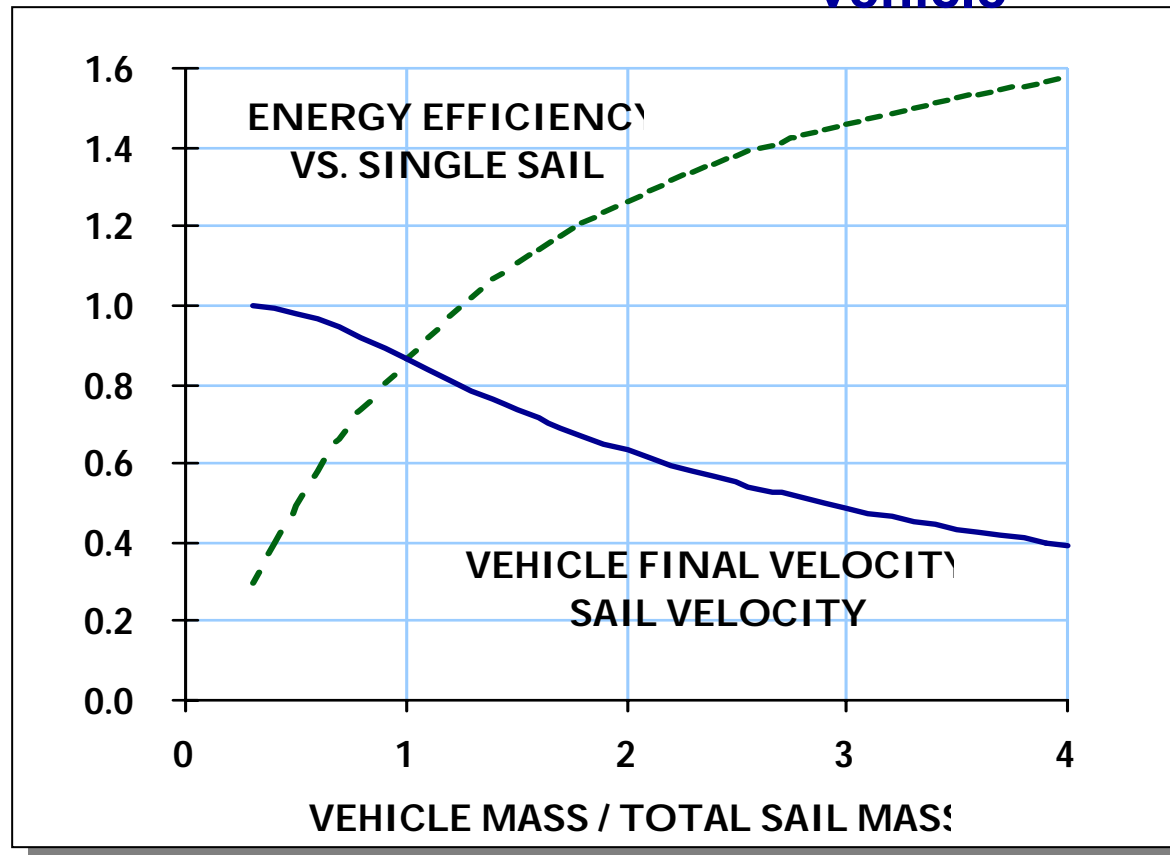
|                        |                            |
|------------------------|----------------------------|
| Wavelength             | 1 $\mu\text{m}$            |
| Index of refraction    | 1.6                        |
| Reflection coefficient | 0.19                       |
| Sail thickness         | 0.156 $\mu\text{m}$        |
| Density                | 2.6                        |
| Areal density          | 406 $\text{mg}/\text{m}^2$ |

|                     |  |
|---------------------|--|
| Maximum laser flux  | $10^{14} \text{ W}/\text{m}^2$                           |
| Absorption          | 10-12  |
| Infrared emissivity | 0.01 (nominal)   |
| Radiated power      | $100 \text{ W}/\text{m}^2$                               |
| Operating temp.     | $\sim 684 \text{ K}$                                     |
| Maximum force       | $125 \text{ kN}/\text{m}^2$                              |
| <b>Acceleration</b> | <b><math>3.1 \times 10^8 \text{ m}/\text{s}^2</math></b> |

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

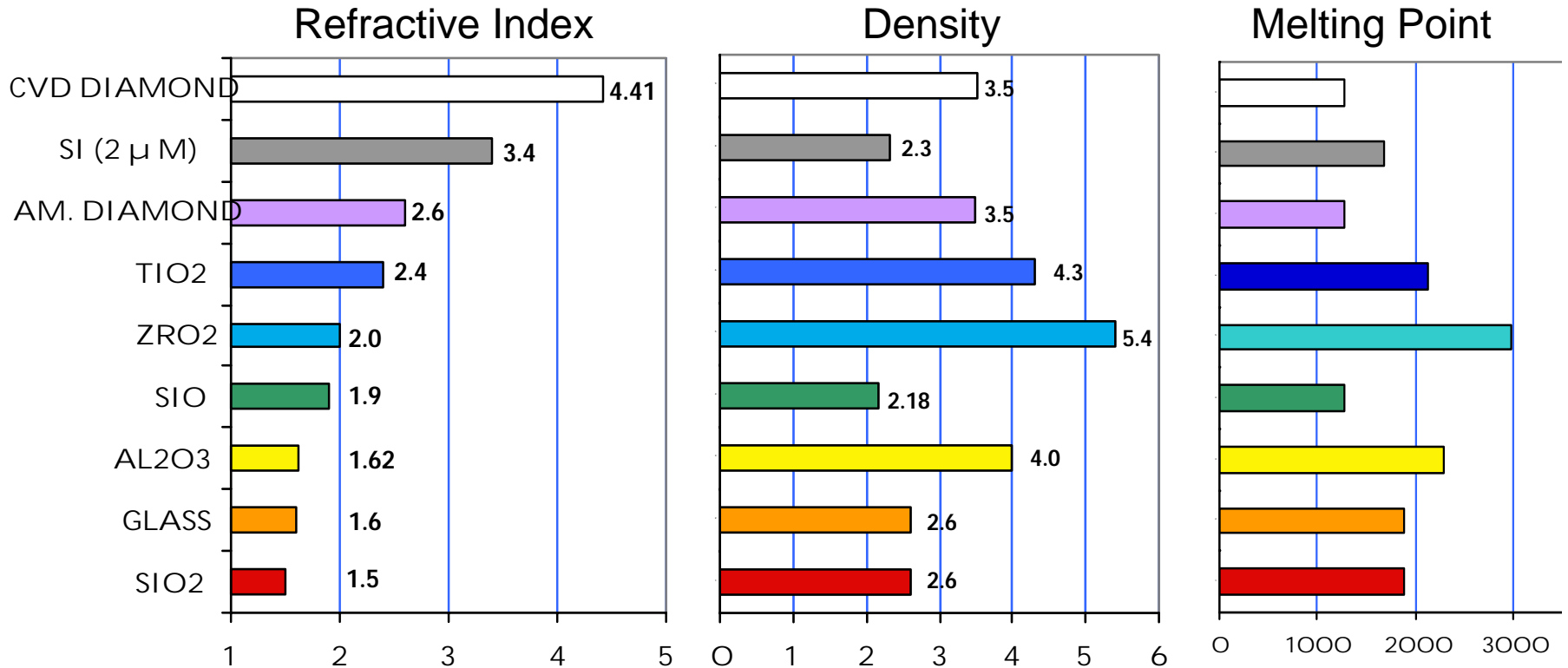
# Vehicle Velocity Limit

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





# Sail Material Options



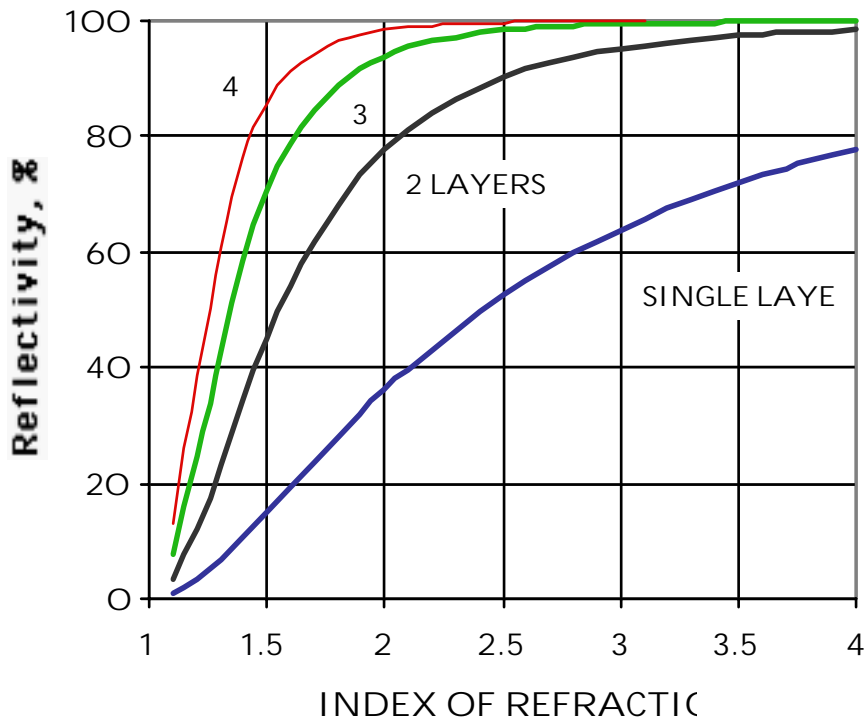
- **CVD Diamond has the highest performance**
- **SiO<sub>2</sub> and Si have the largest technology base (IC industry)**
- **Glass (doped SiO<sub>2</sub>) has the lowest bulk absorption (fiber optics)**
- **ZrO<sub>2</sub> (a common optical coating) is strong at high temperatures**

# Multilayer Sails Are Usually Better

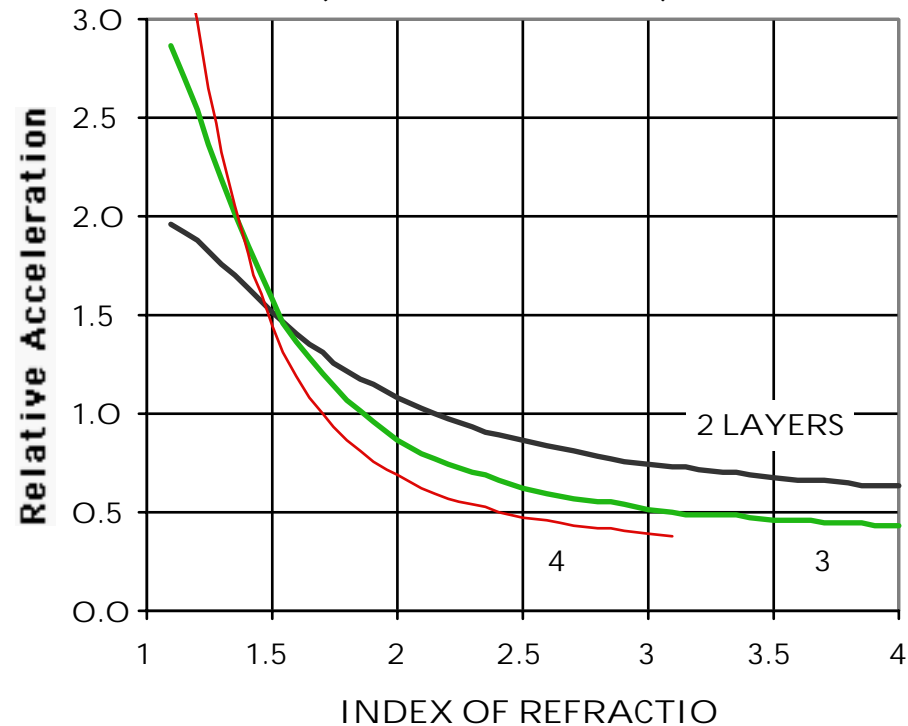
If they can be fabricated

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

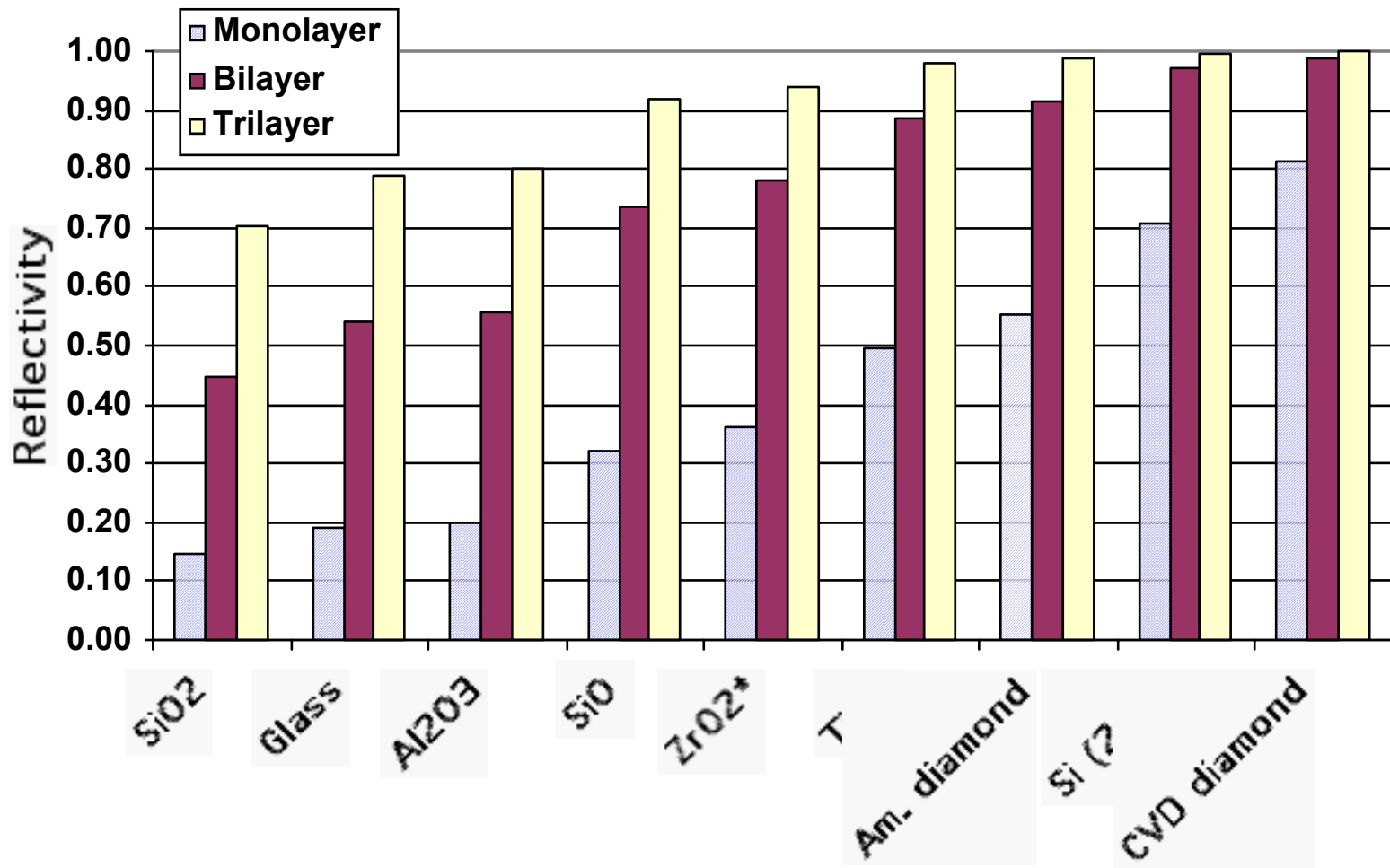
MULTILAYER REFLECTIVITY VS.



MULTILAYER SAIL ACCELERATION  
(VS. SINGLE LAYER)



# Reflectivity of Film Materials

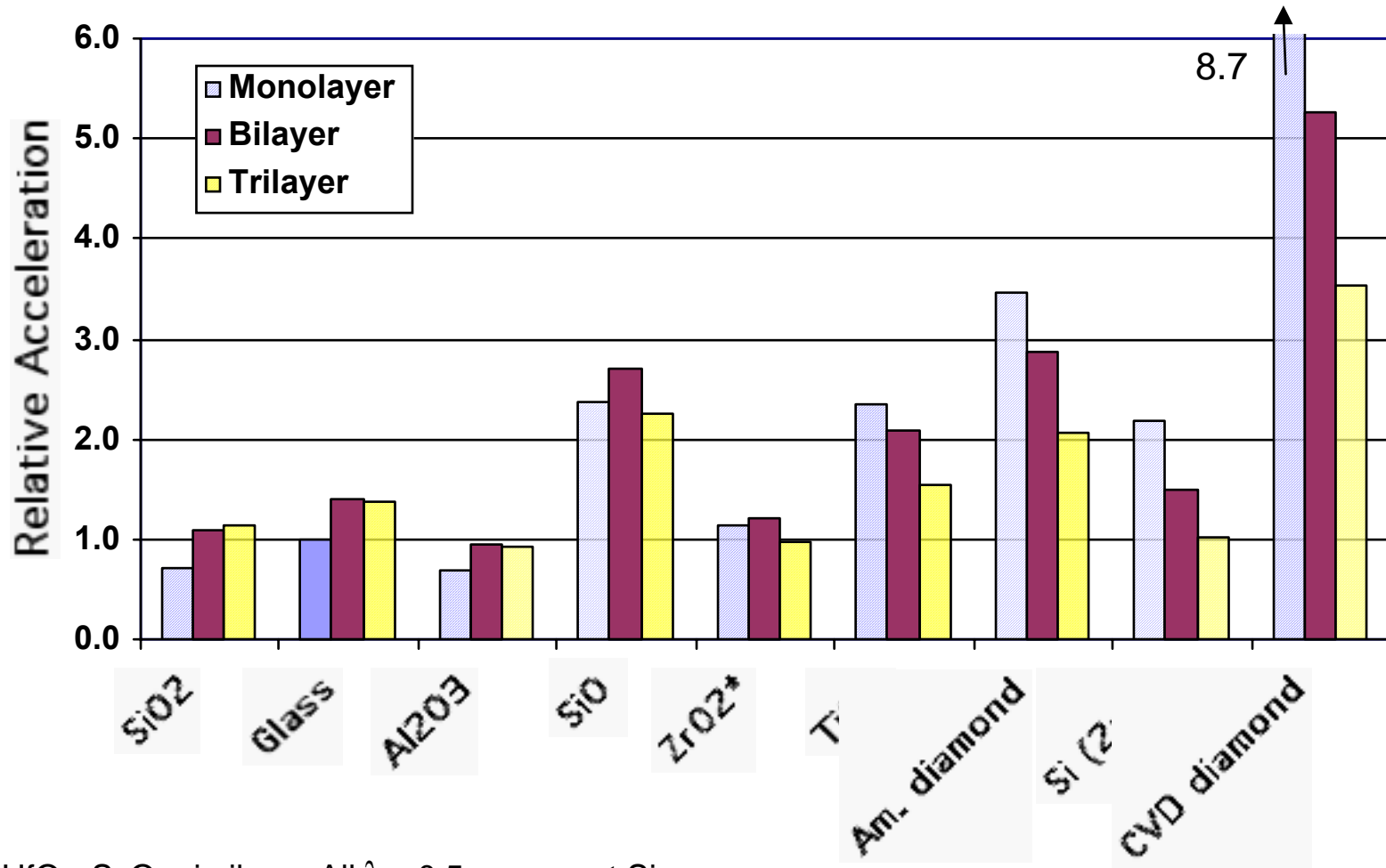


\*HfO<sub>2</sub>, ScO<sub>2</sub> similar

Am. diamond = Amorphous diamond film

# Relative Acceleration, Fixed Flux

- Reflectivity \* index \*  $\lambda$  / density determines acceleration (at fixed flux)

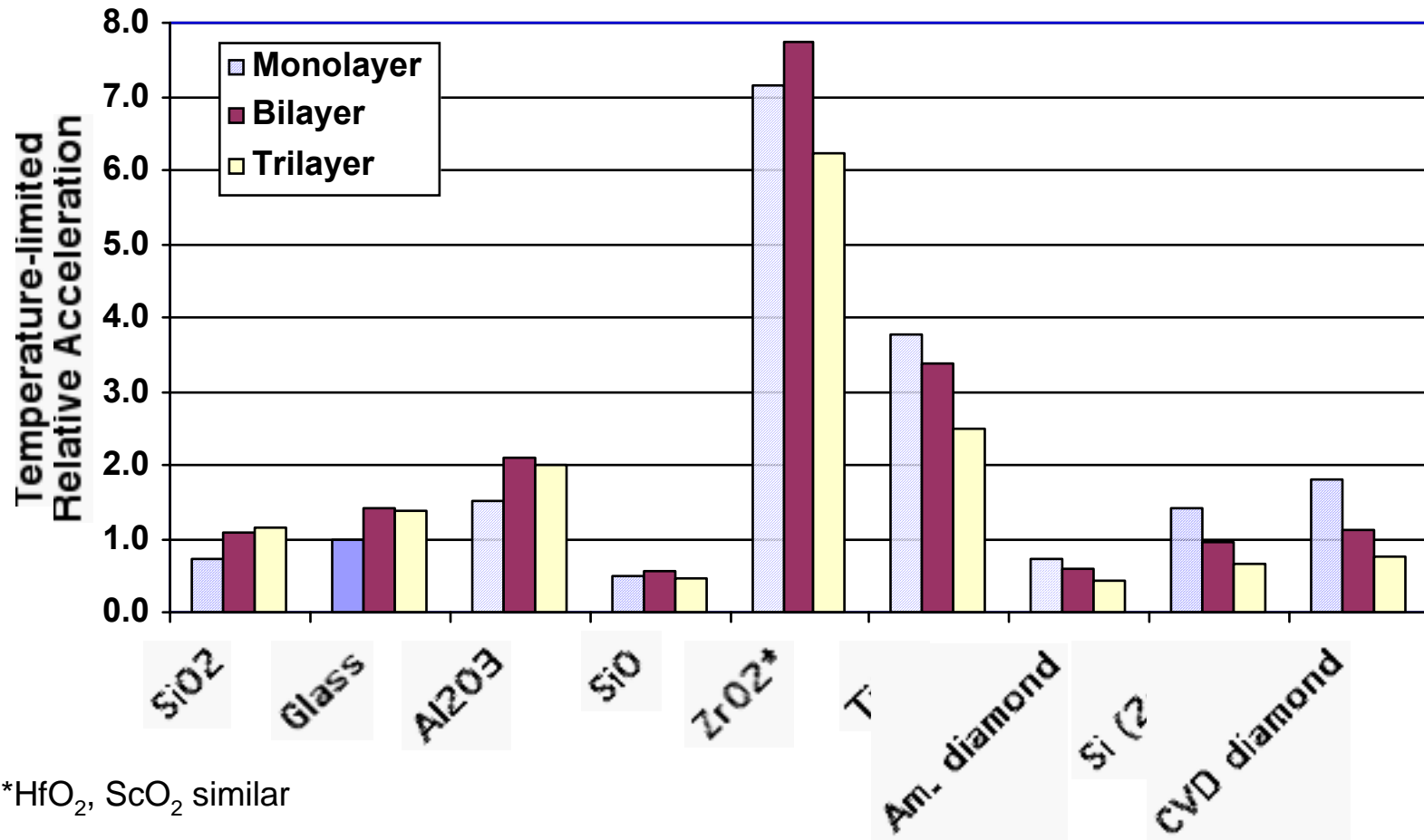


\*HfO<sub>2</sub>, ScO<sub>2</sub> similar All  $\lambda = 0.5\mu\text{m}$  except Si

# Relative Acceleration, Temperature Limited

A simple first cut:

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



\*HfO<sub>2</sub>, ScO<sub>2</sub> similar

# Sample Point Designs

|                        |                 |
|------------------------|-----------------|
| VEHICLE MASS, KG       | 1000            |
| VEHICLE VELOCITY, KM/S | $3 \times 10^7$ |
| ACCELERATION RANGE, KM | 65,000.0        |

|                                |                   |
|--------------------------------|-------------------|
| SAIL MASS, KG                  | 1000              |
| SAIL VELOCITY, KM/S            | $3.6 \times 10^7$ |
| SAIL ACCEL., KM/S <sup>2</sup> | 10,000            |
| SAIL ACCEL. TIME, S            | 3.6               |

| SAIL MATERIAL                    | DIAMOND  | SI 2 μ M | GLASS (SIO <sub>2</sub> ) | GLASS (SIO <sub>2</sub> ) |
|----------------------------------|----------|----------|---------------------------|---------------------------|
|                                  | 2 LAYERS | 2 LAYERS | 3 LAYERS                  | 1 LAYER                   |
| LASER WAVELENGTH, μ M            | 0.5      | 2        | 0.5                       | 0.5                       |
| LASER POWER, GW                  | 25       | 25       | 25                        | 100                       |
| DENSITY, G/CM <sup>3</sup>       | 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, μ M             | 0.04     | 0.21     | 0.08                      | 0.08                      |
| AREAL DENSITY, MG/M <sup>2</sup> | 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<sup>2</sup> 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- $\mu$ s laser pulses
    - Not directly applicable to single-layer microsails, CW laser
  - Bulk of recent data are on  $\text{SiO}_2$  and  $\text{HfO}_2$
- **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  $(\text{max flux})^{-1/2}$
  - $10^{-10}$  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**  $\sim [2(\text{sail diameter})/(\text{acceleration})]^{1/2}$ 
    - Typically  **$\sim 100 \mu\text{s}$**  (e.g., 0.1 m sail,  $2 \times 10^7 \text{ m/s}^2$  accel.)
    - $\ll$  Lightspeed feedback time to transmitter; can't do active stabilization
    - Spin rate must be  **$\sim 10,000 \text{ rps}$**
  - 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  $\ll 1$  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  $\Delta V$  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

- $\text{Al}_2\text{O}_3$             0.25 GPa (1 GPa ~150,000 psi)
- Si                    1 GPa
- $\text{SiO}_2$               2 GPa
- CVD diamond      3.5 GPa

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

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

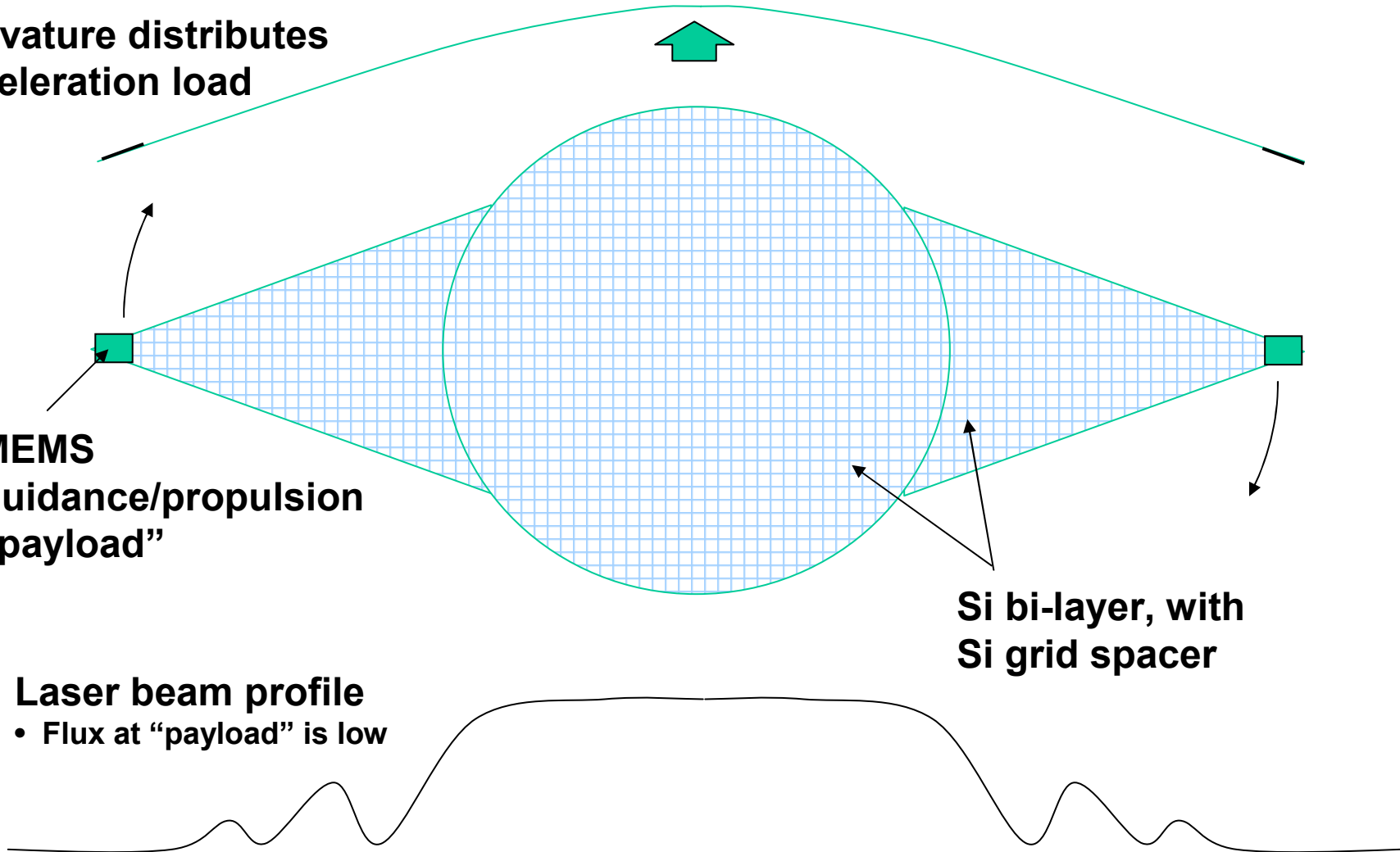
# Microsail Conceptual Design

Curvature distributes acceleration load

MEMS guidance/propulsion "payload"

Si bi-layer, with Si grid spacer

Laser beam profile  
• Flux at "payload" is low



# 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  $\ll$  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

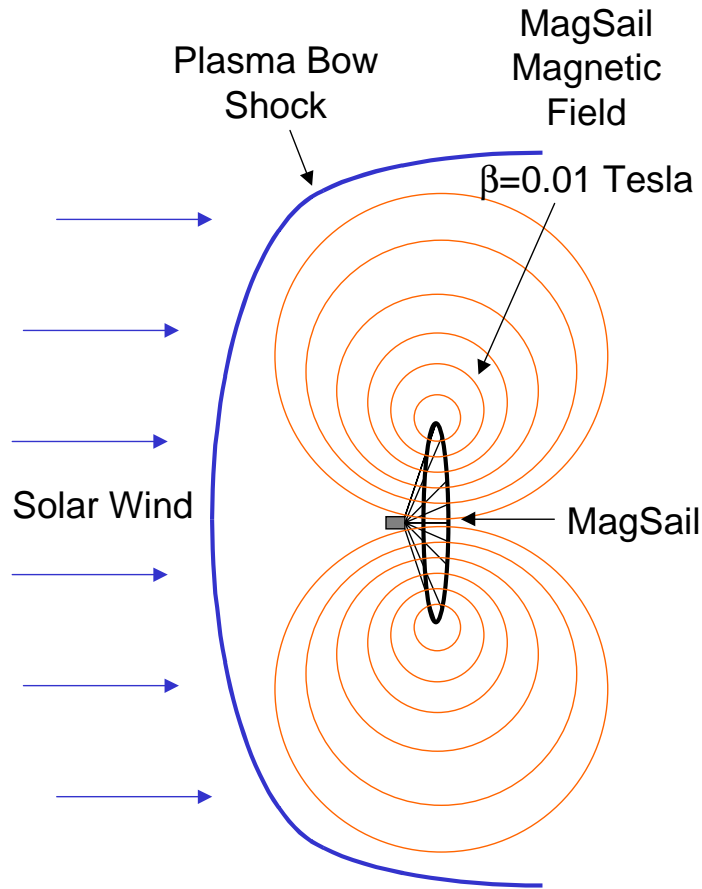
- **Laser**

- 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

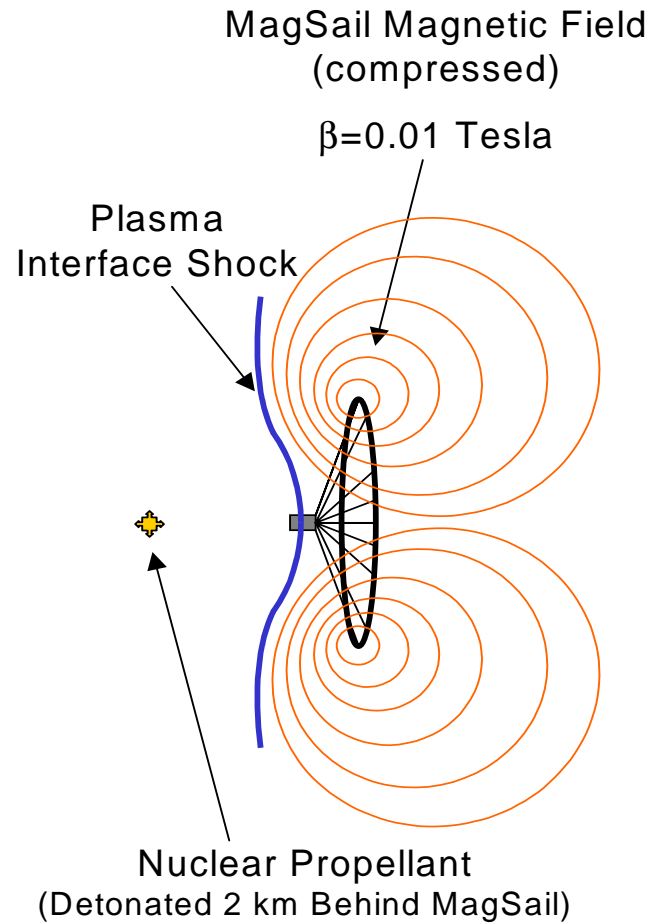
- **Impact** -- proposed by Singer in original 1980 particle-beam paper

- 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  $\gg m_{\text{sail}}$

# MagSail Concept



Solar-wind-driven MagSail



Nuclear-pulse-driven MagOrion



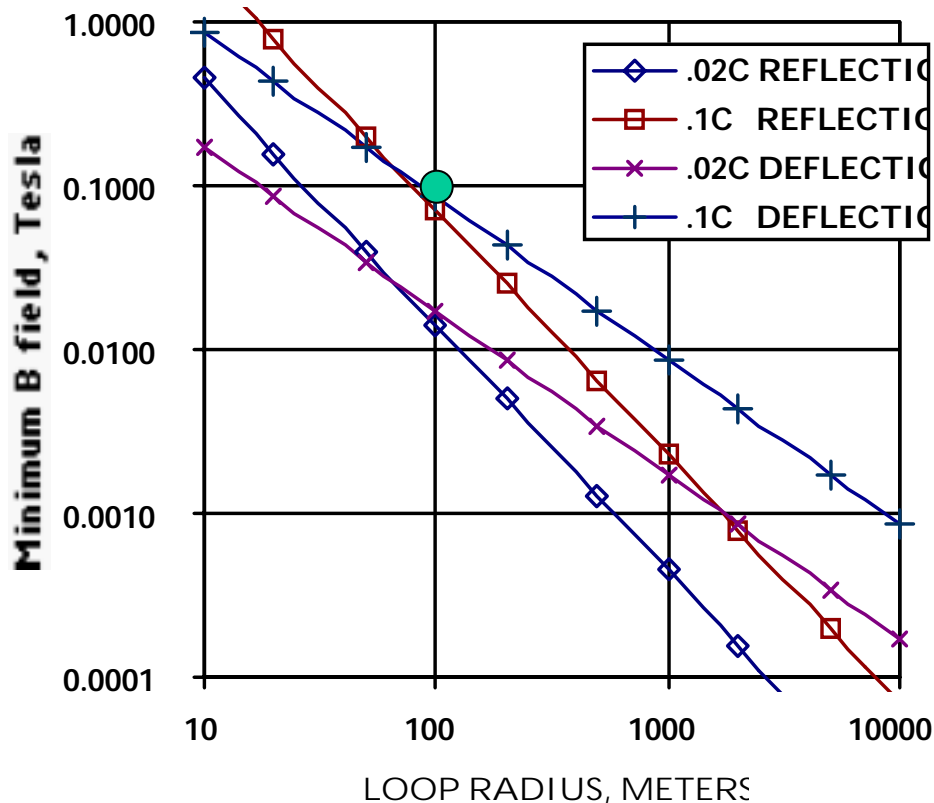
# Estimating MagSail Requirements

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

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

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

$$m_{\text{ion}} V_{\text{rel}} / q B \ll r_{\text{loop}}$$



## ● Nominal design point

- 100 m loop radius
- 16 MA loop current
- 1000 kg loop mass
- $1 \times 10^7$  Amp-m / kg superconductor performance

## MagSail Drag

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

**$N_i$  = Number density of ions**

**(nominally  $10^5 \text{ m}^{-3}$ , or  $0.1/\text{cm}^3$ )**

**$m_i$  = Average ion mass (1 amu)**

**$\mu_0 = 4\pi \times 10^{-7}$**

**$I$  = Loop current**

**$r$  = Loop radius**

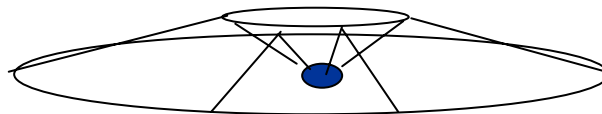
**$V$  = Vehicle velocity**

**For  $V=0.1c$ ,  $r=100\text{m}$ ,  $I=16 \text{ MA}$**

**•  $F_{\text{drag}} = 34 \text{ N}$ ; Thrust  $\sim 8 \text{ N}$**

# Suppressing Drag During Acceleration

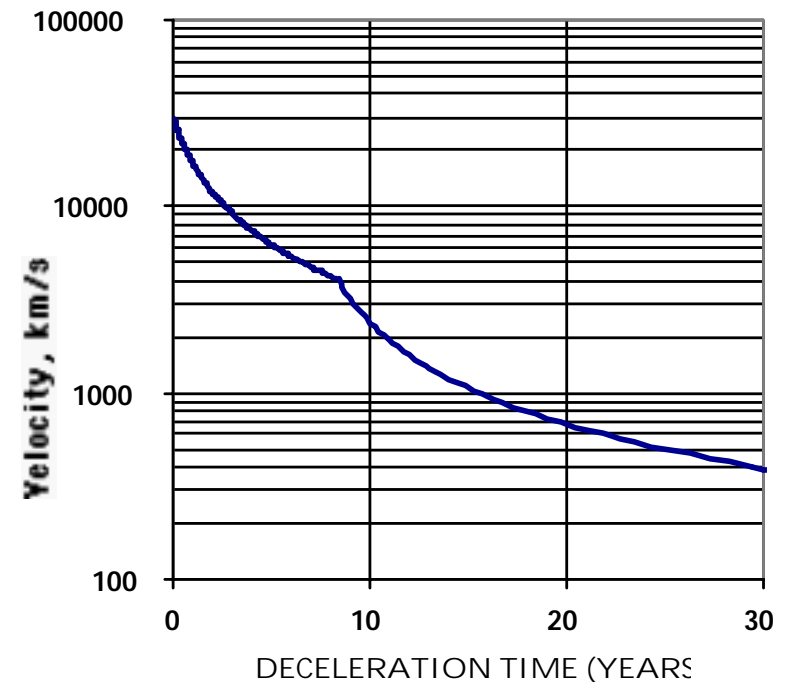
- Drag is dominated by low-field region far from loop
- 2nd larger loop with opposite dipole cancels field
  - For constant dipole moment, current  $I$  varies as  $1/r^2$
  - Central field proportional to  $I/r$ , varies as  $1/r^3$ 
    - Outer loop doesn't affect propulsive MagSail
  - Mass is proportional 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 <sup>3</sup> | 10 <sup>5</sup>        | 0.1 ion/cm <sup>3</sup> |
| Initial dynamic pressure, N/m <sup>2</sup> | 7.7 x 10 <sup>-8</sup> |                         |
| Brake loop radius, km                      | 28                     |                         |
| Brake loop current, kA                     | 55                     |                         |
| Magnetic field pressure, N/m <sup>2</sup>  | 6.1 x 10 <sup>-7</sup> | B <sup>2</sup> /2μ      |
| Superconductor J/rho, A-m/kg               | 10 <sup>7</sup>        |                         |
| Brake loop mass, kg                        | 968                    |                         |
| Initial drag force, N                      | 1405                   |                         |

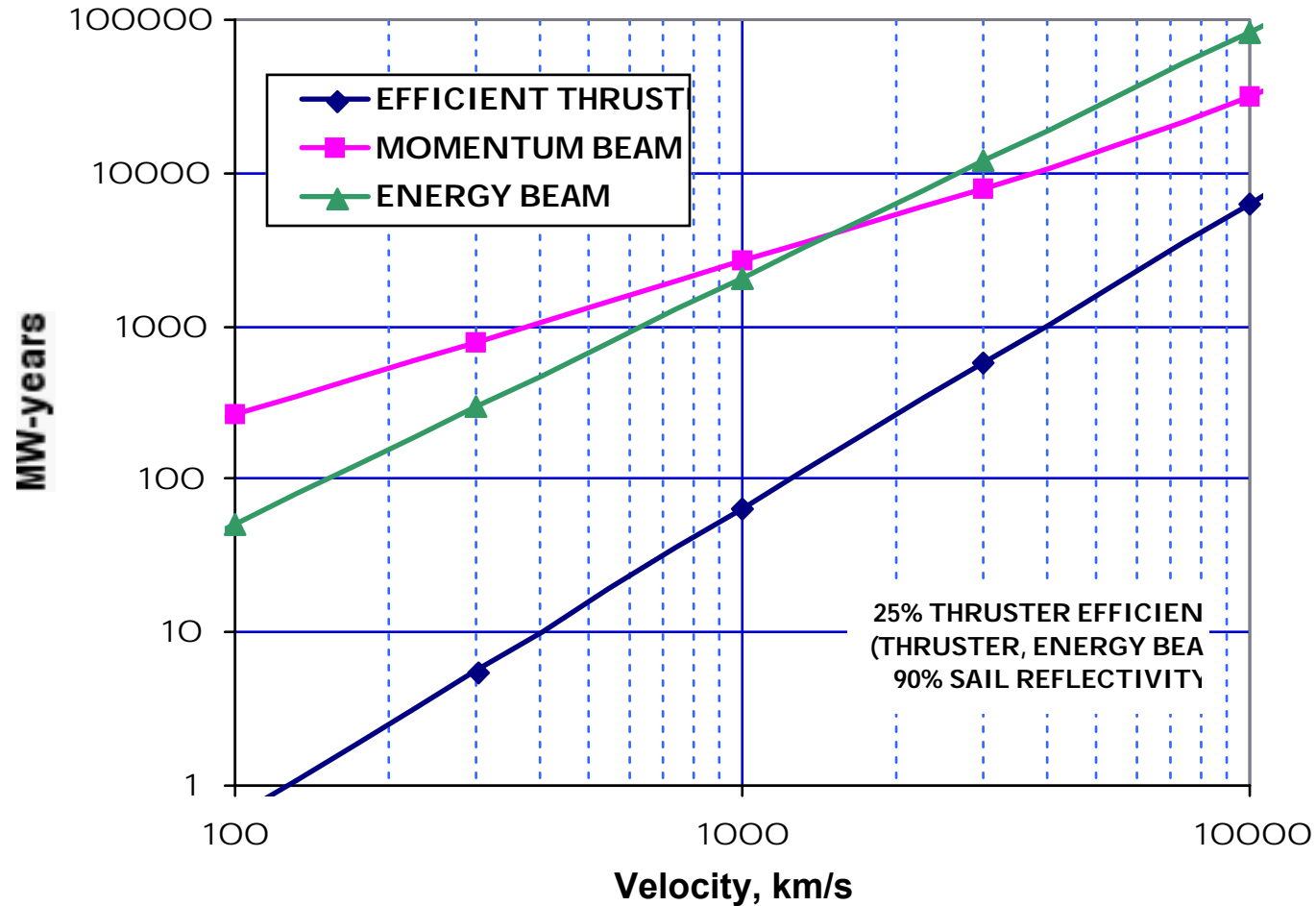


# Precursor Missions

- **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  $0.01 c = 3000 \text{ km/s}$
- **...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

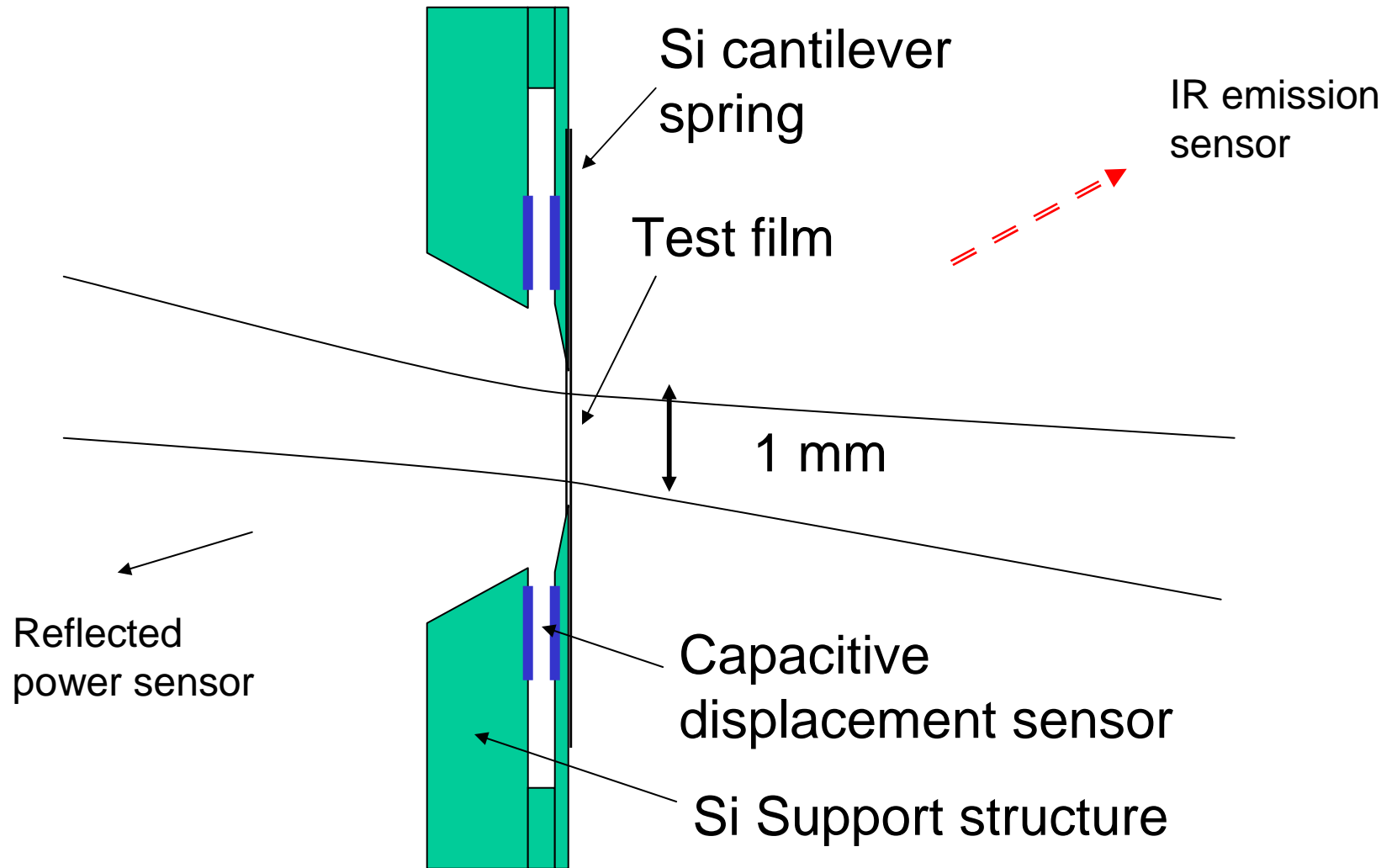
- **“Sail” diameters ~1 mm or less**
  - Still a thin film:  $\gg 1000:1$  width:thickness
  - Variety of materials and fabrication processes available
- **Laser pulse power ~1 MW**
  - 1 MW of laser power yields ~1 million G acceleration
- **Laser pulse lengths ~ 1 msec**
  - Final velocities of 10 - 30 km/s
  - Sufficient 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**