Cryogenic Considerations for LIGO Voyager

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for the Voyager Team

GWADW 2016 in Elba

Outline

- Design concept and sensitivity goal
- Crystalline silicon test masses
- Cooling to 123 K
- Suspensions

Voyager Design Concept

- Crystalline silicon test masses at 123 K
  - Low mechanical loss + vanishing thermal expansion => improved thermal noise
  - High thermal conductivity + vanishing thermal expansion => reduced thermal lensing (and improved shot noise)
  - Efficient radiative cooling (with special coatings) => relaxed constraints on optical power & suspensions
  - Large enough substrates available (45 cm, 140-200 kg)

- Checking the details
  - Verify silicon optical properties & noise
  - High emissivity coatings => thermal noise
  - Heat shield vibrational couplings (scattered light, Newtonian?)

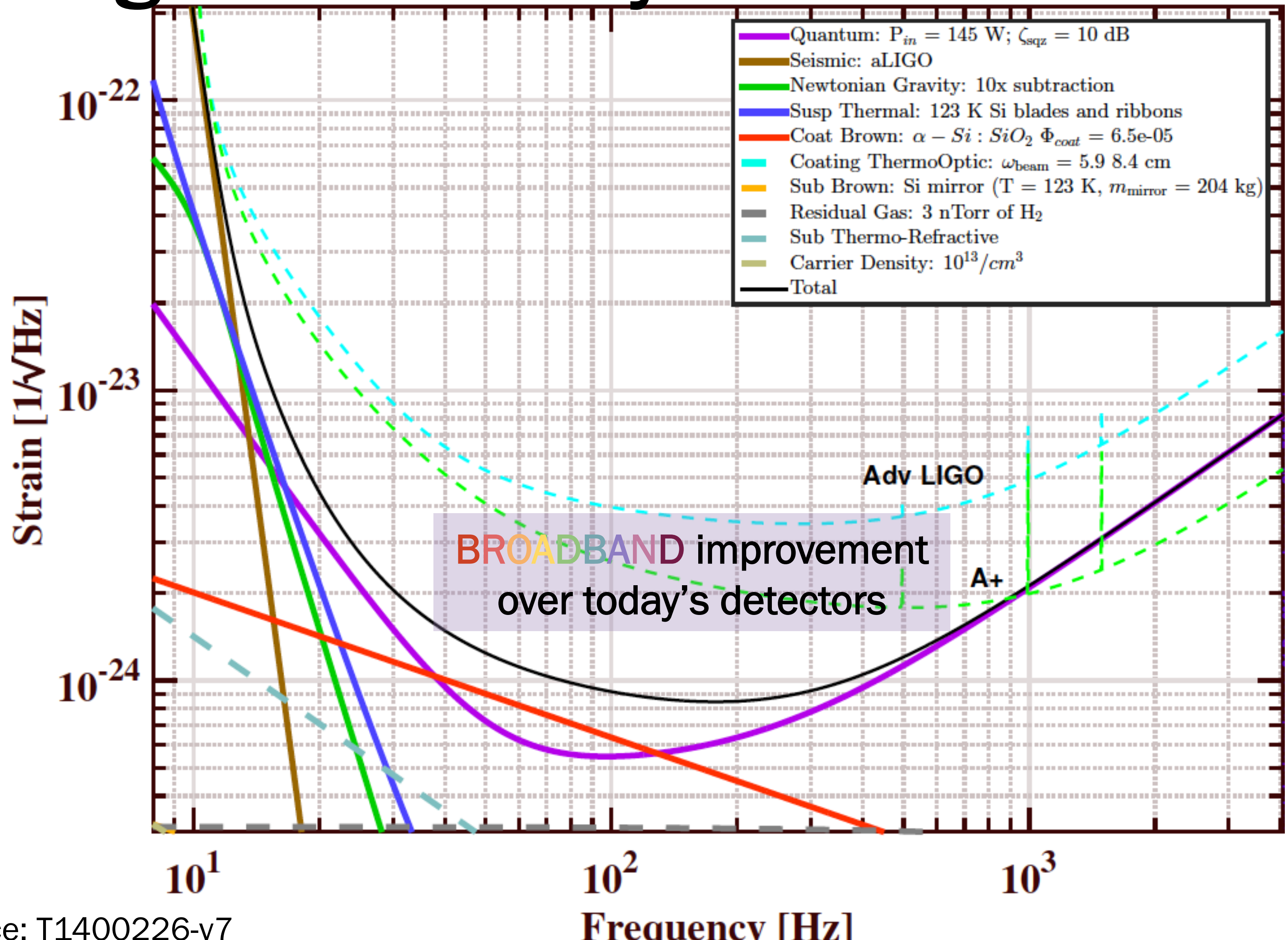
Voyager Design Concept

- Optical technologies: lasers, detectors, coatings, squeezers
  - New wavelength (1.5-2 μm)
  - Coating absorption important for heat budget

- Suspensions
  - aLIGO levels of isolation and thermal noise considered sufficient
  - What's new? Heavier silicon test masses & thermal gradient
  - Monolithic cold silicon ribbons vs. "hybrid" silica fibers

- Vacuum envelope, seismic isolation unchanged from aLIGO

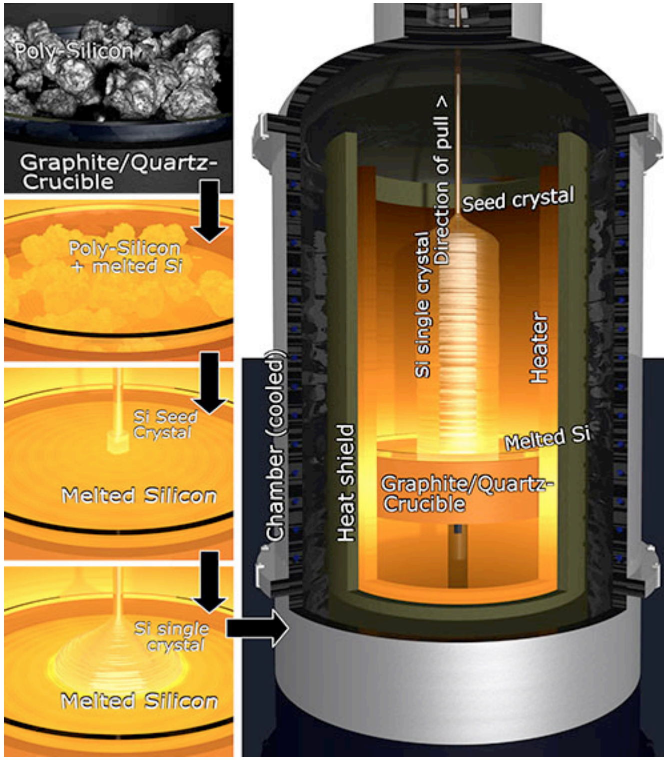
Target Sensitivity



Source: T1400226-v7

Growing Crystalline Silicon

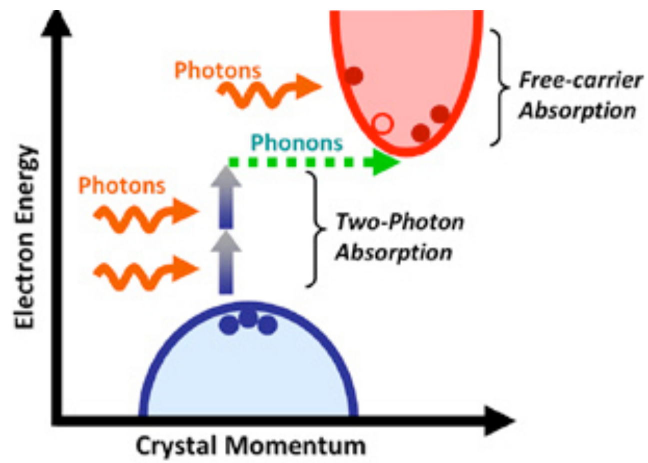
- 48 cm ingots commercially grown via Czochralski process
- Main impurity is oxygen (from silica crucible, $3\text{x}10^{17}/\text{cm}^3$)
- B field during growth to suppress convection, limit oxygen transport
- Radial & axial gradients in composition
- Resistivity up to several kΩ cm



ShinEtsu

Absorption in the Test Mass

- Input test mass thermal budget: want 20 ppm/cm or better
- Impurities can contribute free carriers => absorption
  - Numerous theoretical models, Drude being the simplest
  - Drude free carrier absorption scales as: λ^2 (n / μ) (where n = carrier density, μ = carrier mobility)
  - Resistivity scales as: $1 / (n \mu)$
- Effect of oxygen depends on how it is incorporated
  - Interstitial oxygen does not change the resistivity
  - Electron "donor" states of oxygen are also possible
  - Donors are created and annihilated via heat treatment (which can also precipitate SiO_2)
- Scaling from previous measurements, expect few kΩ cm resistivity is OK



Jalali et al, OPN June 2009

Experiments on Czochralski Silicon

- Procured silicon “slugs” for testing
  - Disks 10 mm thick x 200 mm diameter, cut from magnetic-Czochralski grown ingots
  - Undoped and high resistivity ~4 kΩ cm
- Many properties to be investigated
  - Absorption
  - Scattering
  - Birefringence
  - Mechanical loss
  - Impurity concentration
- Check dependence on T, λ, location in ingot, heat treatment…

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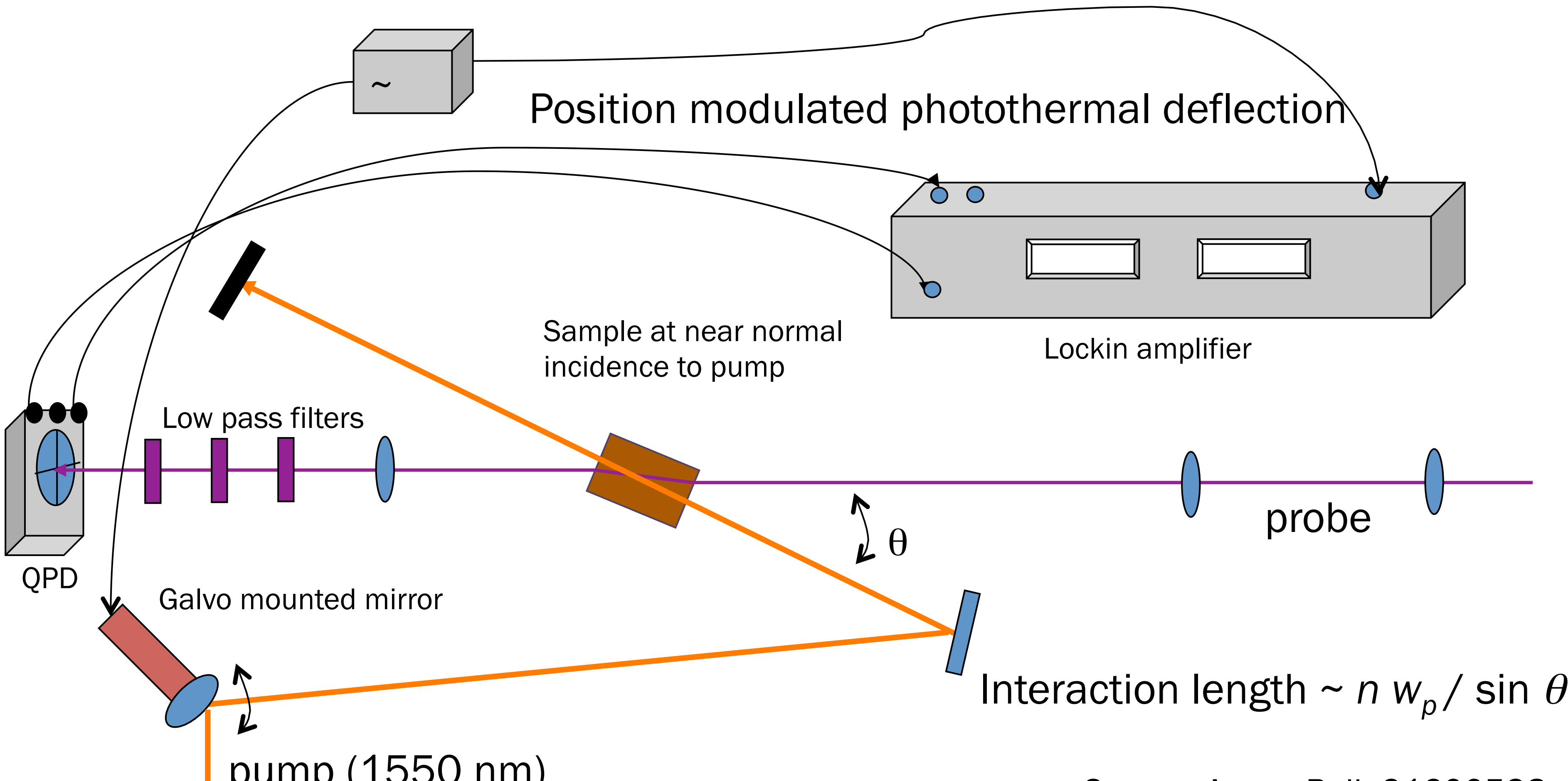
Absorption: Experimental Setup

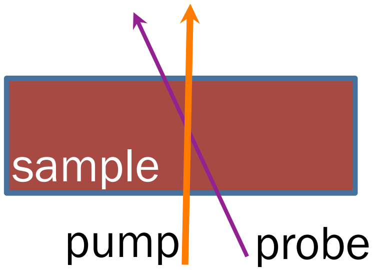
A. Markosyan, A. Bell

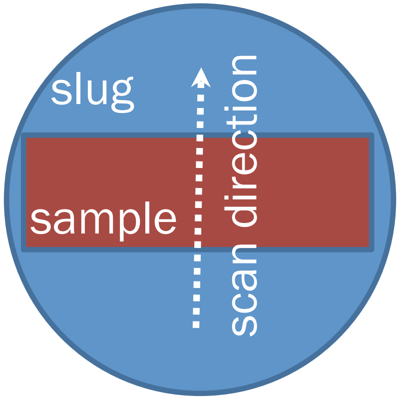


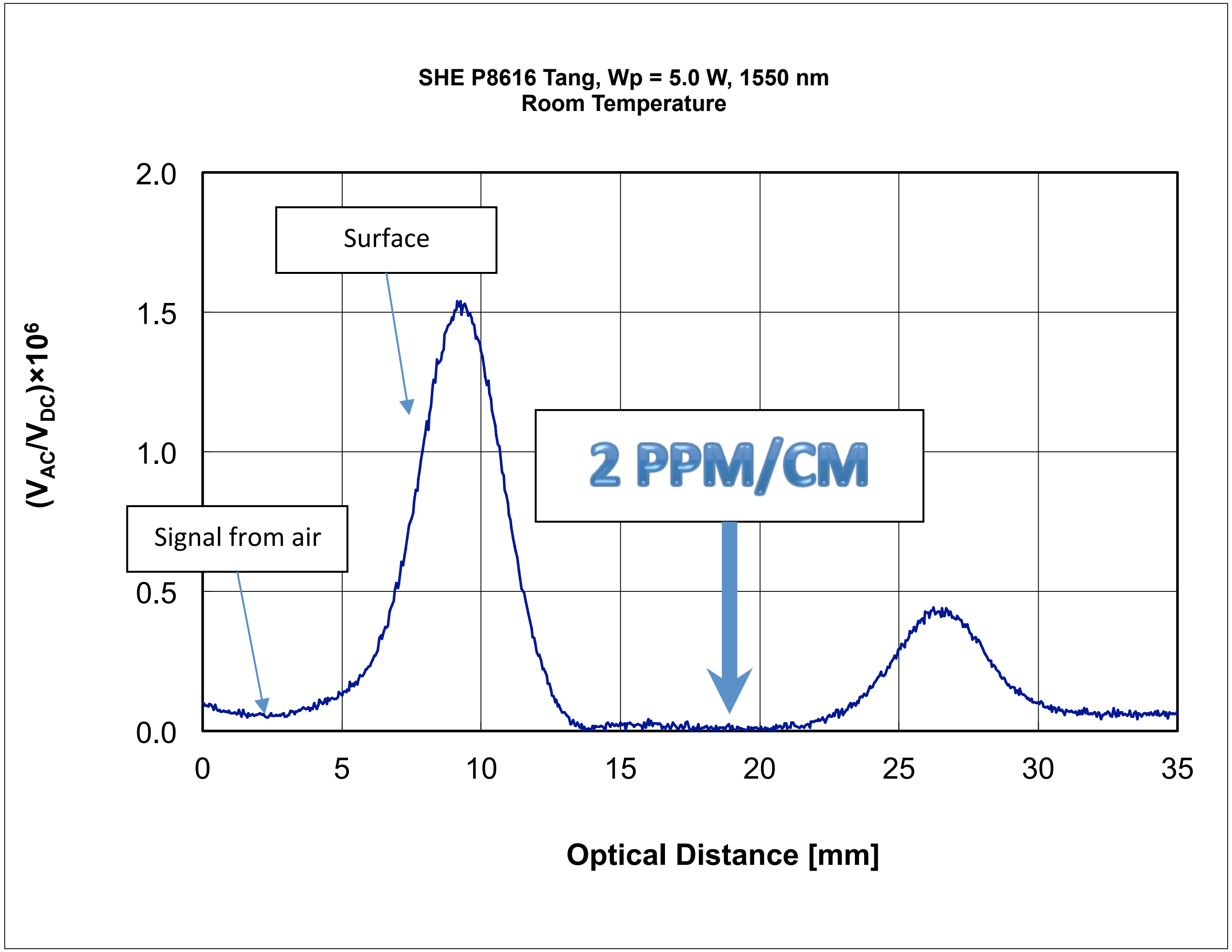
Source: Angus Bell, G1600538

Very Low Absorption in Czochralski Silicon

A. Markosyan, A. Bell







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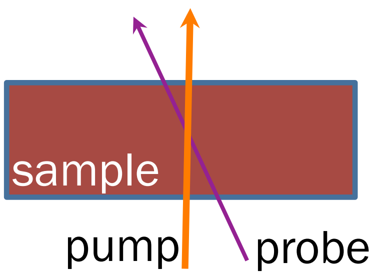
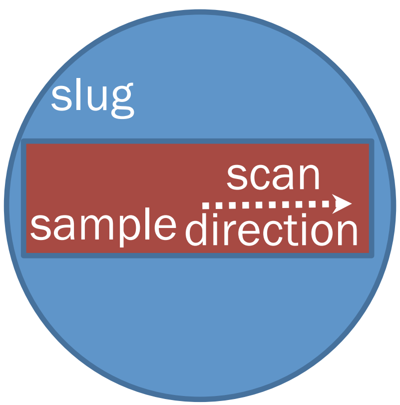
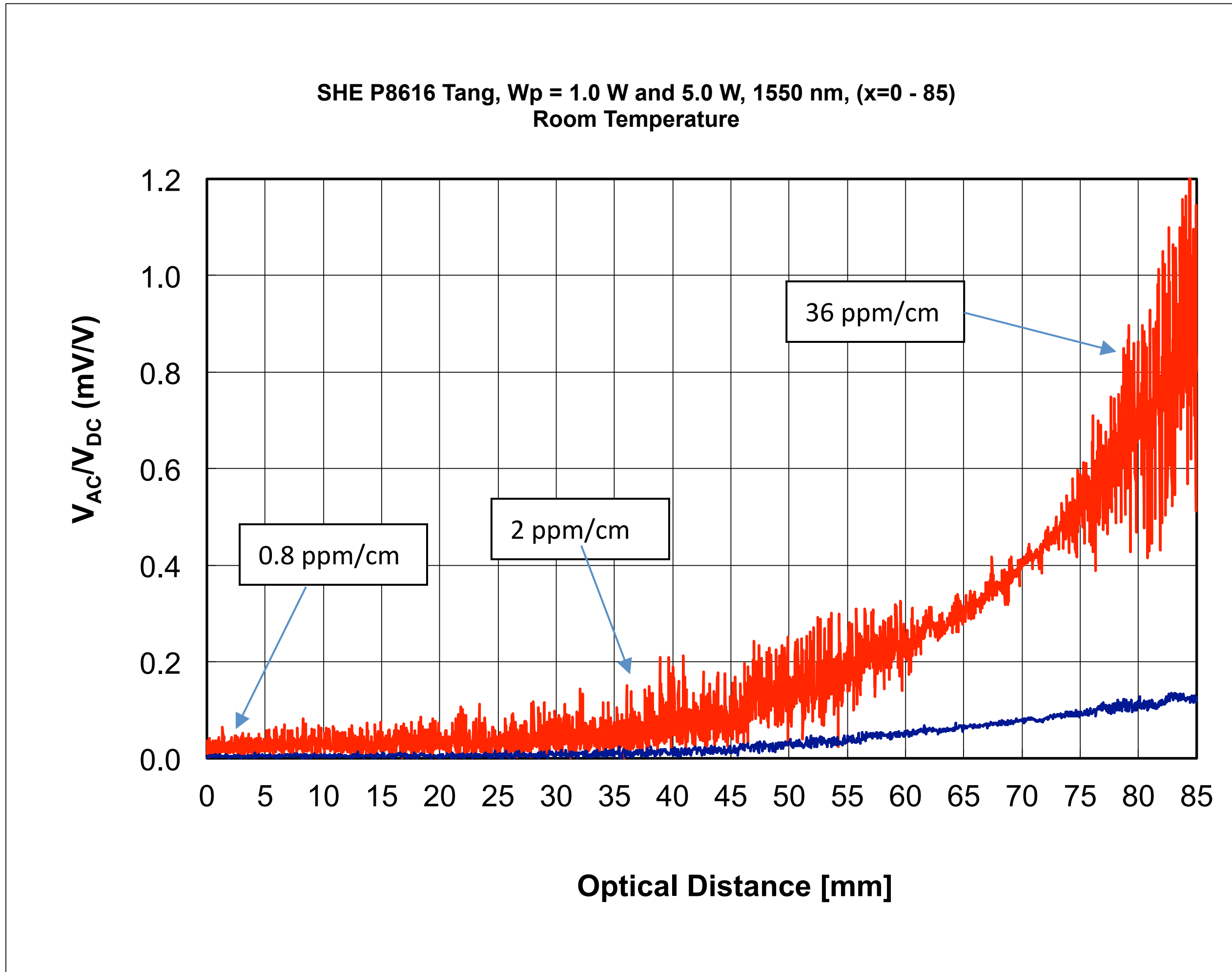




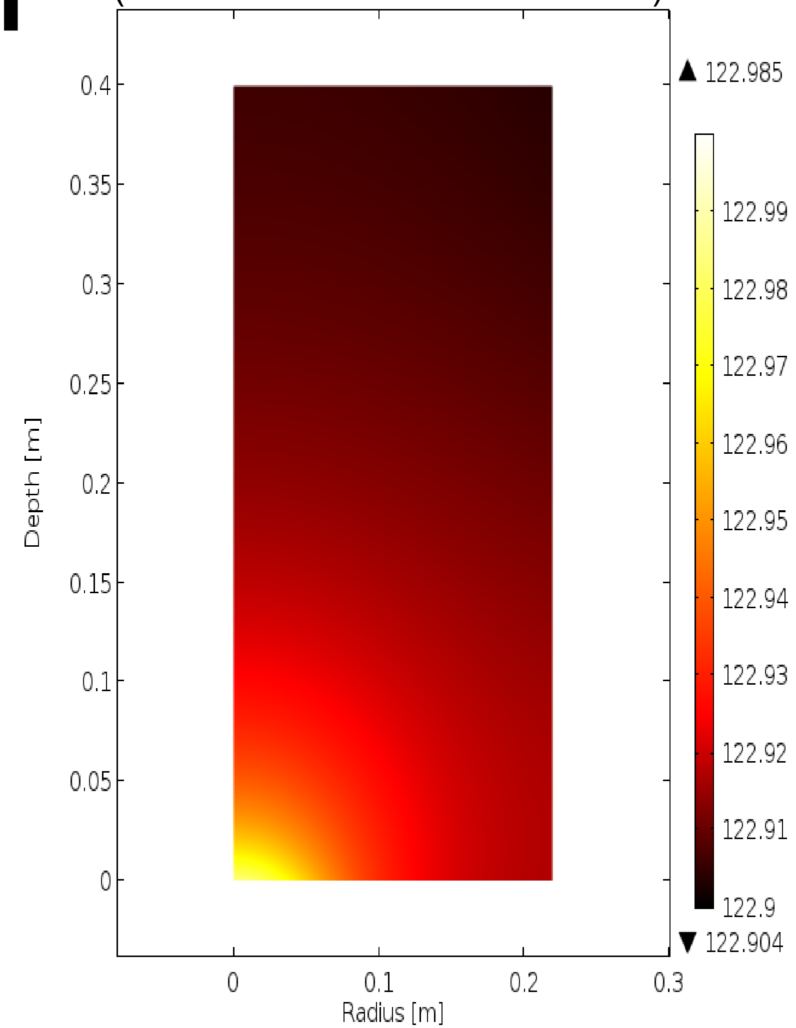


Thermal Equilibrium

- Heat In
  - Coating absorption
    3 W (3 MW x 1 ppm)
  - Substrate absorption
    5 W (6 kW x 20 ppm/cm x 40 cm)
  - Conduction through fibers
    (warm PUM) negligible
  - Radiation from beam tube
    negligible

- Heat Out
  - Radiative coupling to 80 K shield
    10 W
  - Conduction through fibers
    (cold PUM) negligible

Temperature in Si ETM
(10 W absorbed at surface)



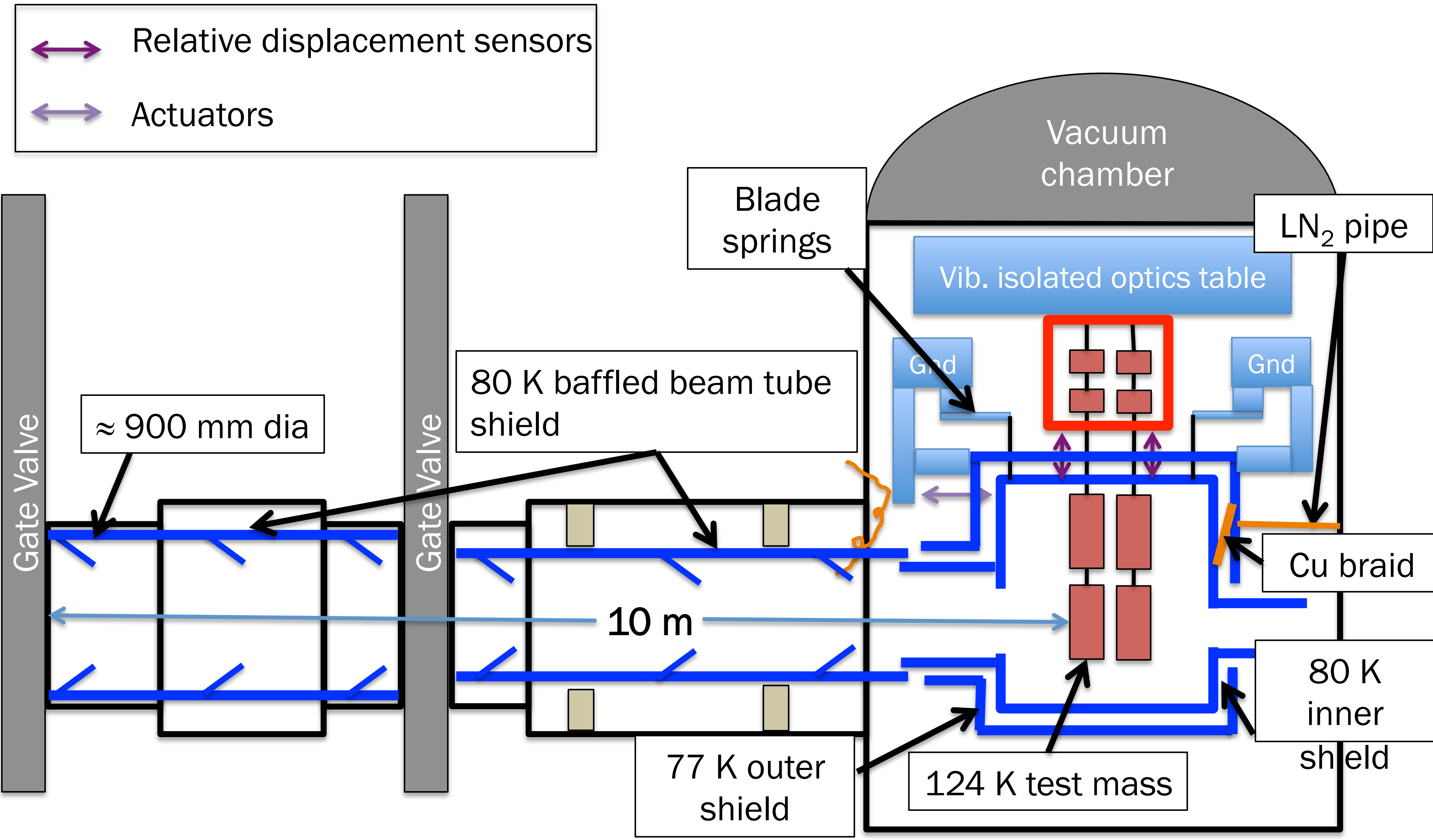
$e_{barrel} = 0.95$ $e_{HR}, e_{AR} = 0.75$

$T_{shield} = 80$ K $P_{abs} = 10$ W

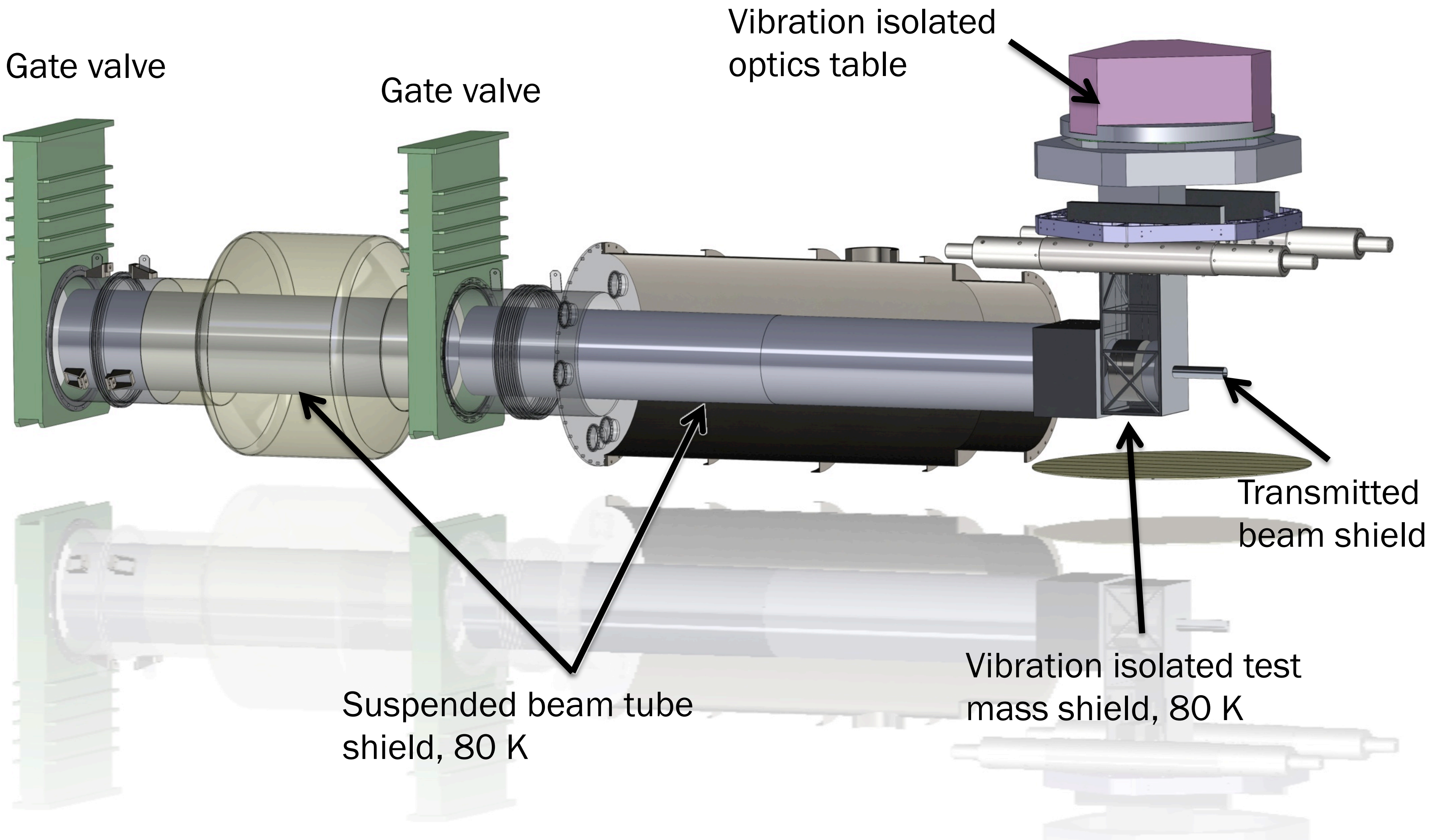
$w_{beam} = 8$ cm

Source: T1400226-v7

Cryogenics for Voyager

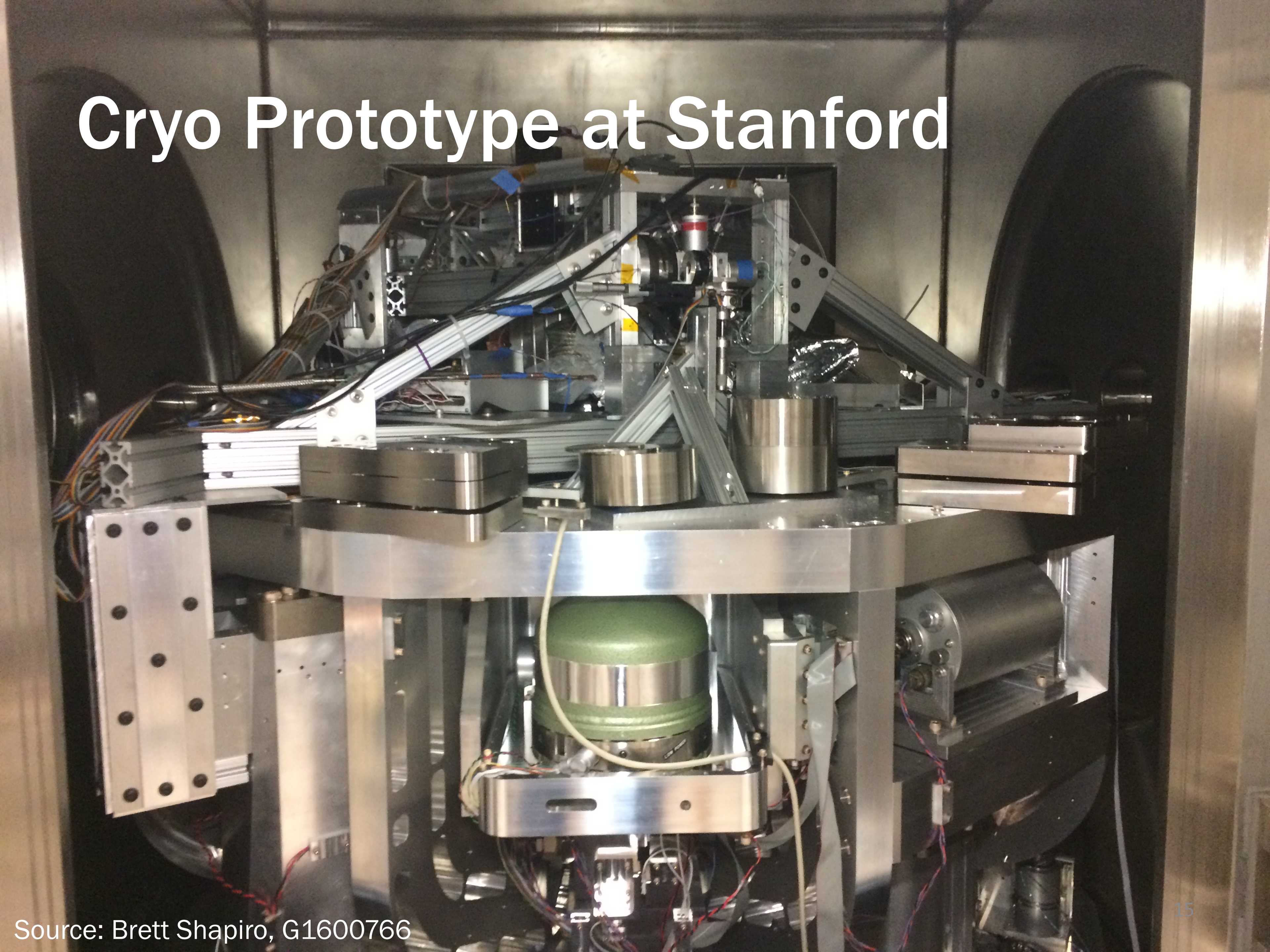


Cryogenics for Voyager



Source: Brett Shapiro, G1600766

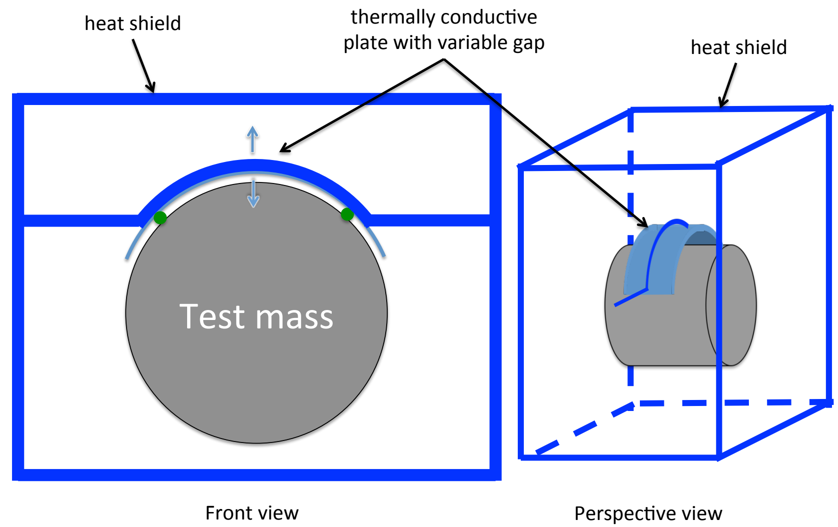
Cryo Prototype at Stanford

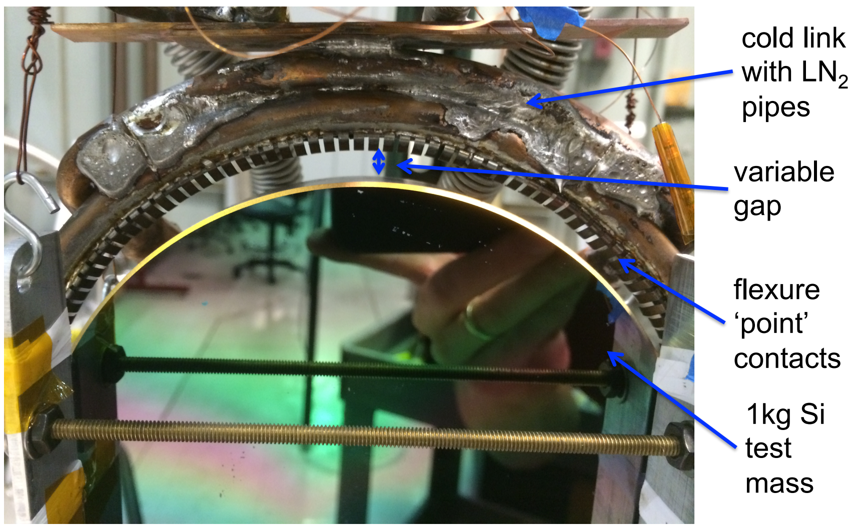


Source: Brett Shapiro, G1600766

Heat Switch for Rapid Cooldown

- Could we use a nearby cold plate and a little exchange gas to reach 123 K in a day?
- Controllable gap and gas pressure set the strength of the thermal link

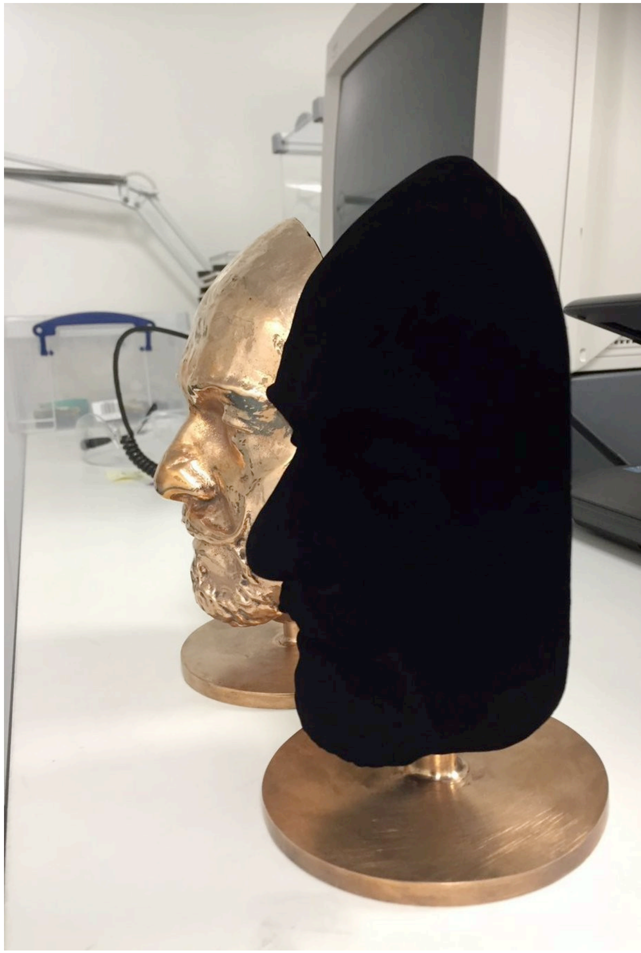




Source: T1400226-v7

Black Barrel Coatings

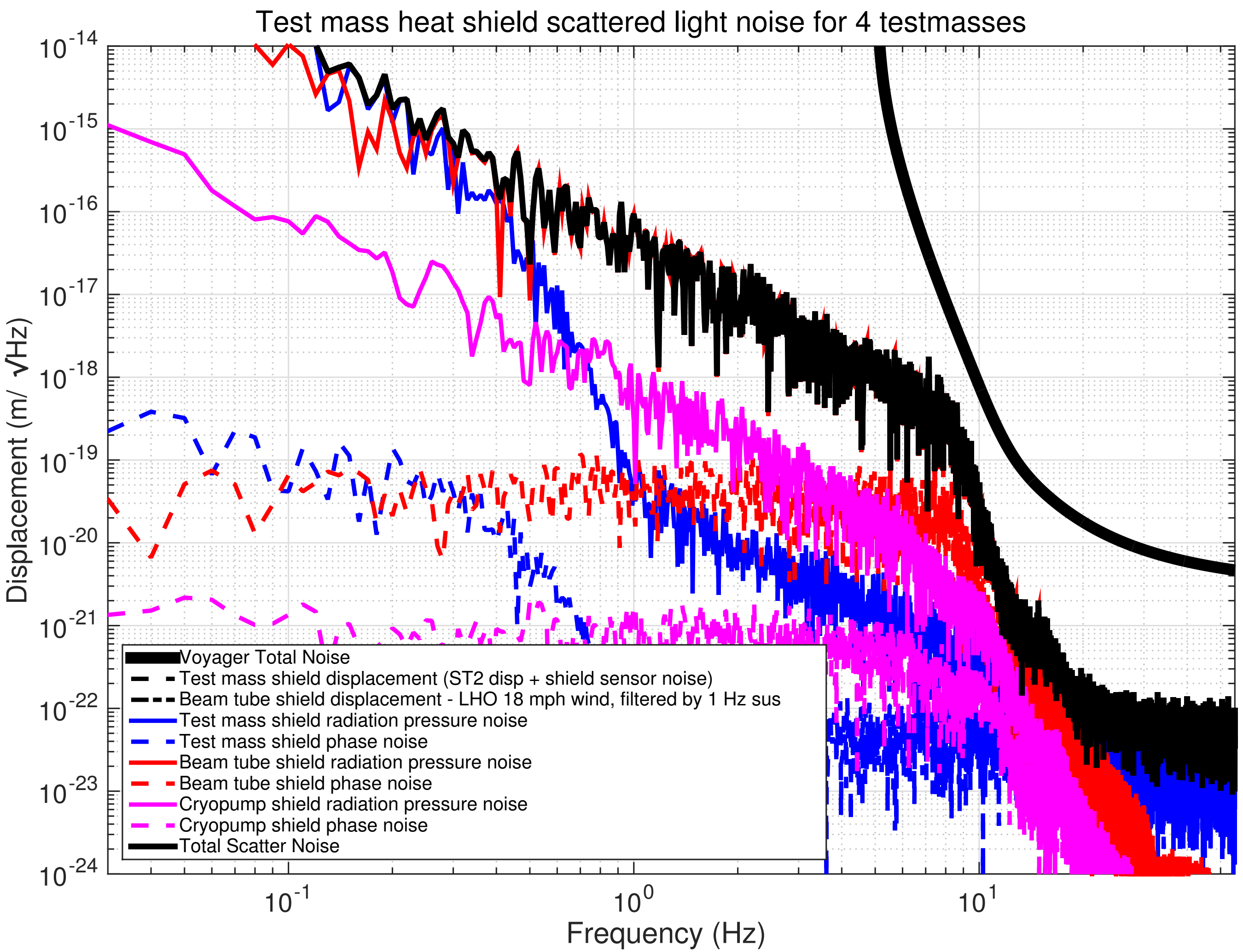
- Bare silicon emissivity ~0.1 => 0.95 with Acktar Black
- Negligible thermal noise
  $\varphi_{\mathrm{Acktar}} \approx 2\mathrm{x}10^{-3}$
  $Y_{\mathrm{Acktar}} \approx 10$ GPa
- Would allow ~10 W heat extraction at 123K
- Alternatives: Vantablack, GSFC "Blacker Than Black" nanotube coatings



surrey nanosystems

Source: Matt Abernathy et al, P1500242

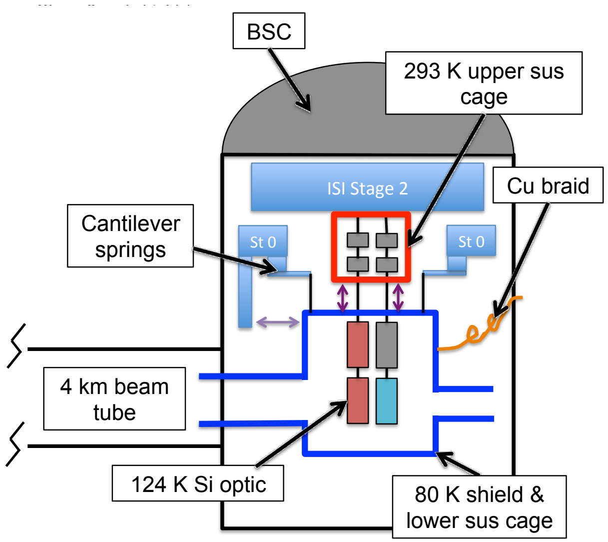
Heat Shield Scatter Estimation

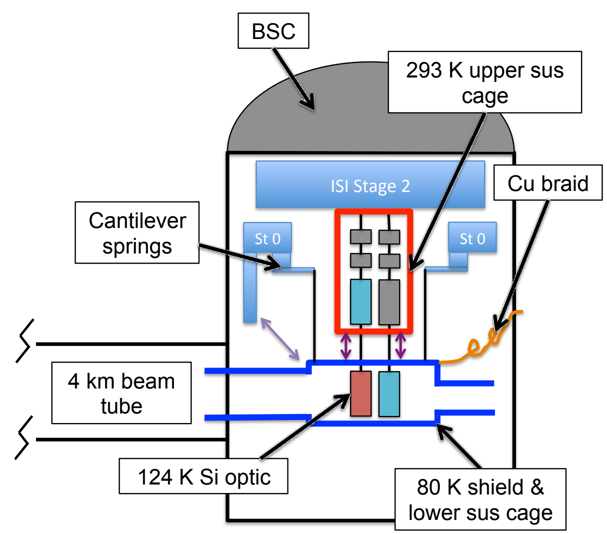


Source: T1400226-v7

Suspensions

- Cold silicon ribbons?
  - Better thermal noise
  - Fabrication challenge?
  - Variable tensile strength/loss/surface quality
- “Hybrid” silica fibers
  - Incomplete thermoelastic cancellation
  - Thermal gradient in fiber
  - Have to bond with silicon

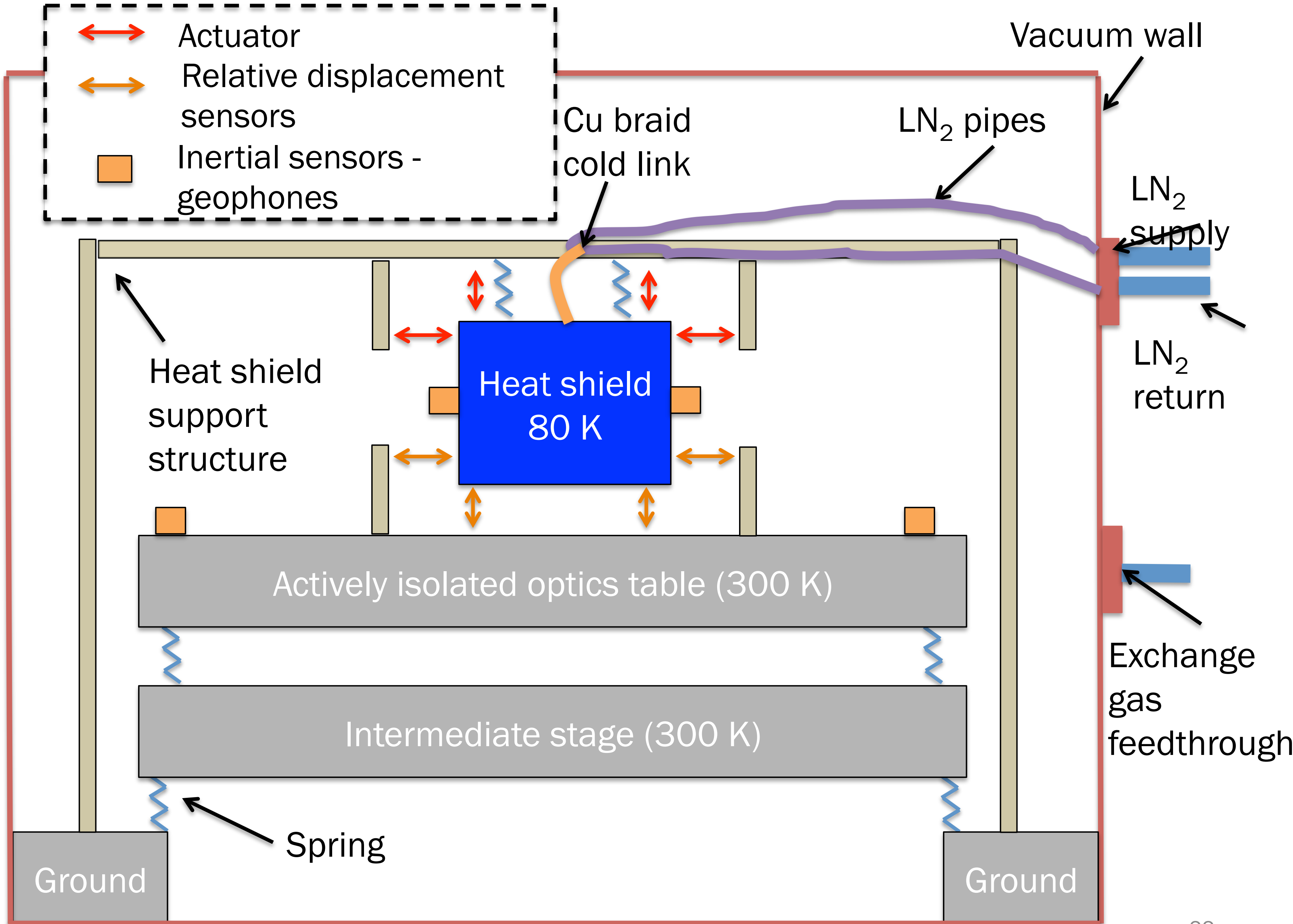




Summary

- 123 K silicon offers a broadband sensitivity enhancement within today's facilities
- Very low absorption is available in large silicon crystals
- Thermal noise/scatter from cryo system should be tolerably small
- Monolithic suspension, or "hybrid"?

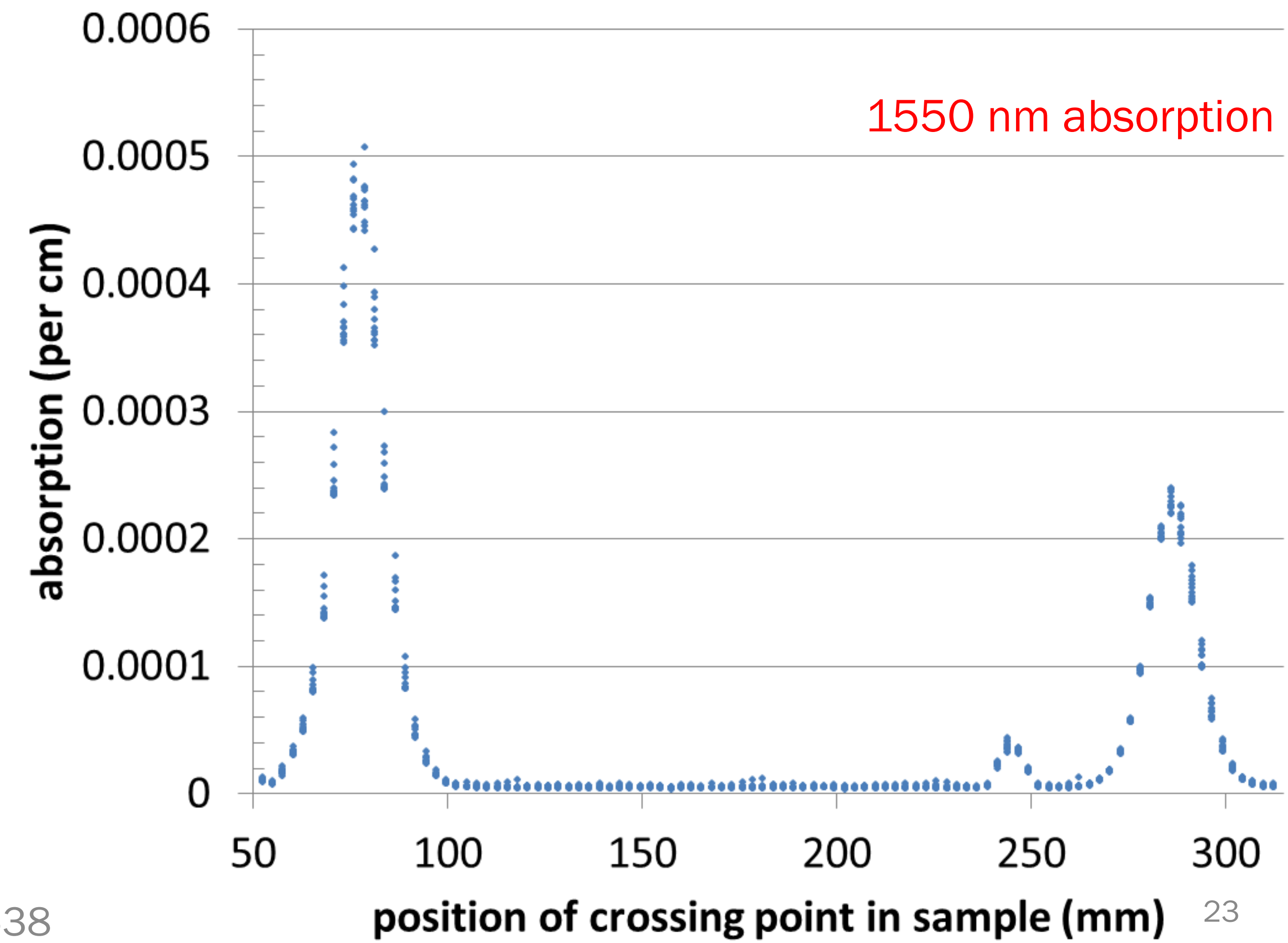

BON VOYAGE
SSPERK



Actuator
Relative displacement sensors
Inertial sensors - geophones
Vacuum wall
Cu braid cold link
LN_2 pipes
LN_2 supply
LN_2 return
Heat shield support structure
Heat shield 80 K
Actively isolated optics table (300 K)
Intermediate stage (300 K)
Exchange gas feedthrough
Spring
Ground
Ground

Silicon absorption measurements

- Ingots polished with diamond slurry and pitch lap
- Consistently gives ~0.1% absorption at the surface
- Polishers uses it as it more easily gives good flatness over 4” diameter



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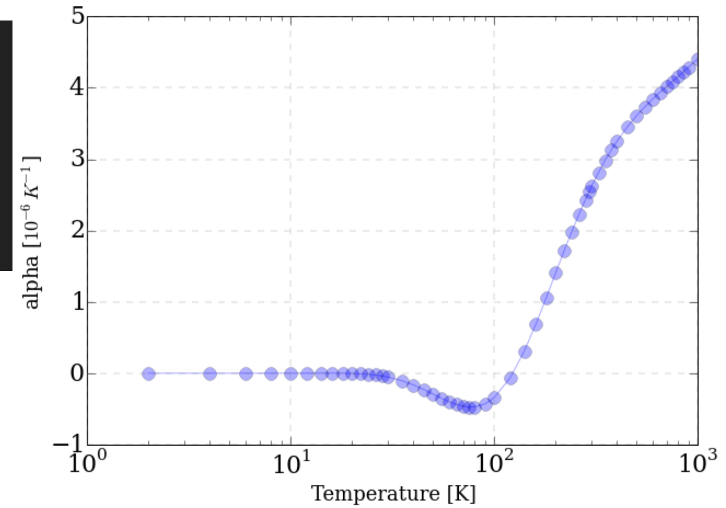
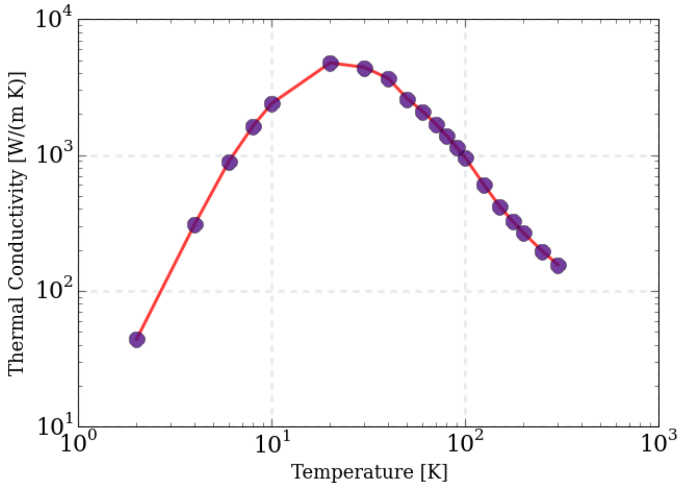
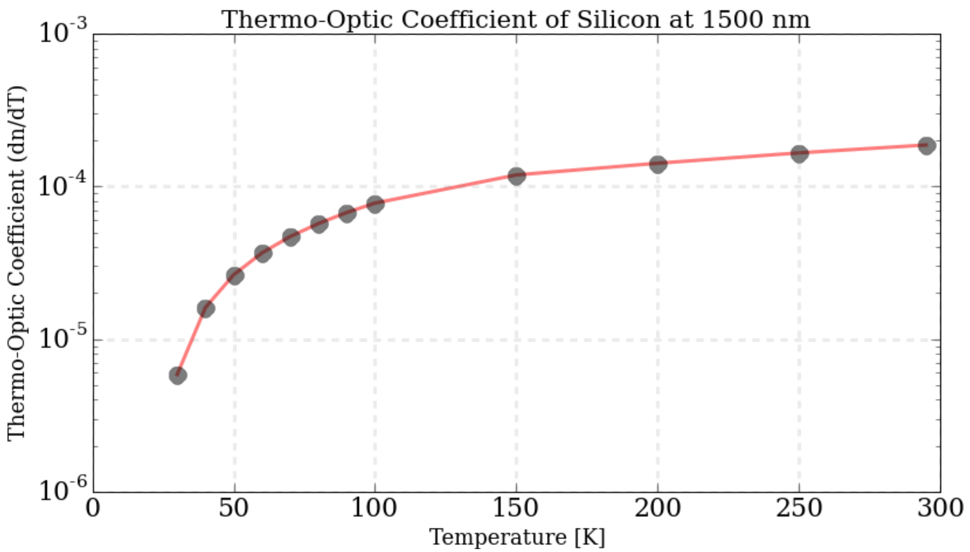
Some Plots



alpha [10^{-6} K^{-1}]
5
4
3
2
1
0
−1
10^0
10^1
10^2
10^3
Temperature [K]



Thermal Conductivity [W/(m K)]
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
Temperature [K]



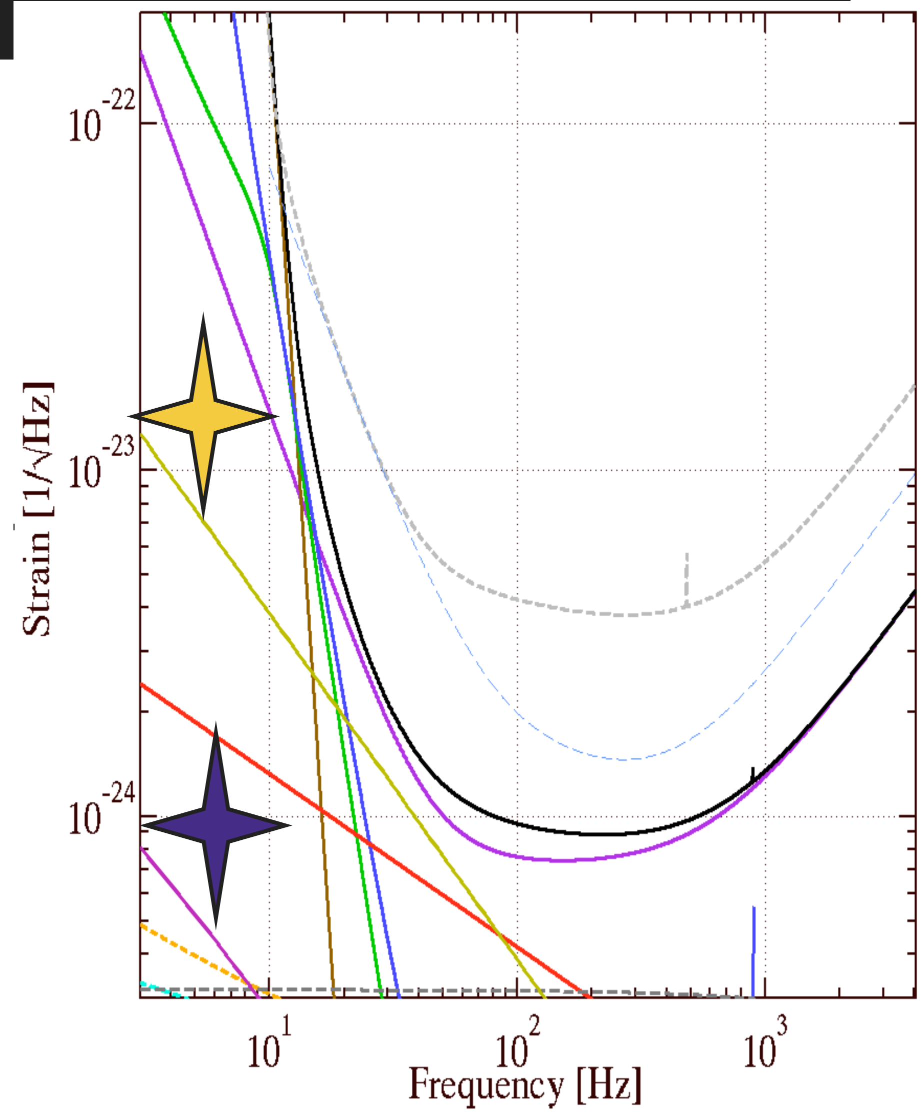
Thermo-Optic Coefficient of Silicon at 1500 nm
Thermo-Optic Coefficient (dn/dT)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
50
100
150
200
250
300
Temperature [K]

Carrier density noise

Visit in Oct 2014 by D. Heinert (Jena)

noise was determined to be insignificant contribution to noise

Thermorefractive noise in ITM is close, but not dominant



Suspensions

- Isolation: mass distribution, blades
- Thermal noise: fiber vs. ribbon
- Where to put the temperature gradient
- Fabrication material, aspect ratio