Caltech

LSC LIGO Scientific Collaboration

LIGO-G2301091

Radiative modeling and cryogenic design for LIGO Voyager prototype

R. Adhikari[a], S. Appert[a], K. Arai[a], **R. Bhatt[a]**, A. Brooks[a], B. Shapiro[b], C. Wipf[a]

[a]LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

[b]Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, USA

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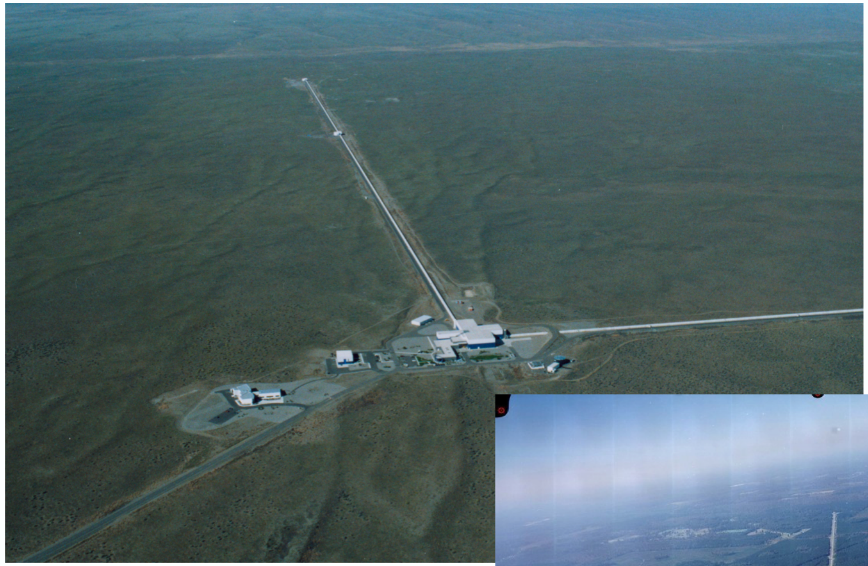
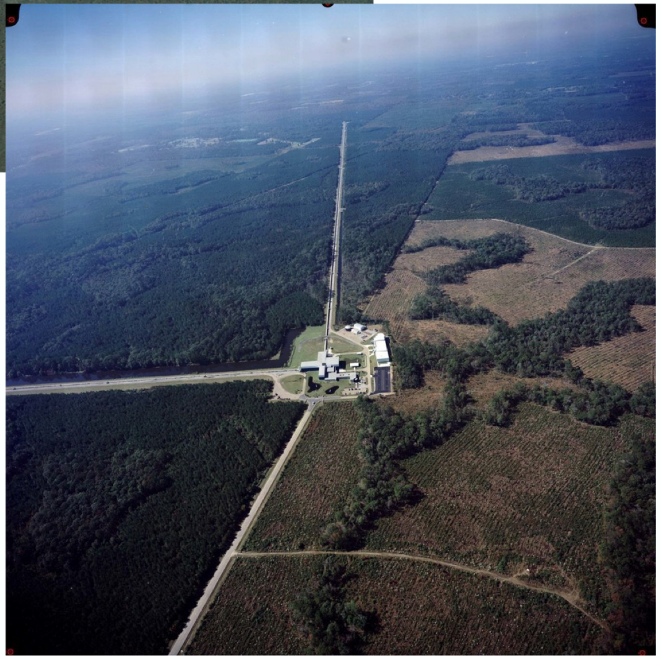
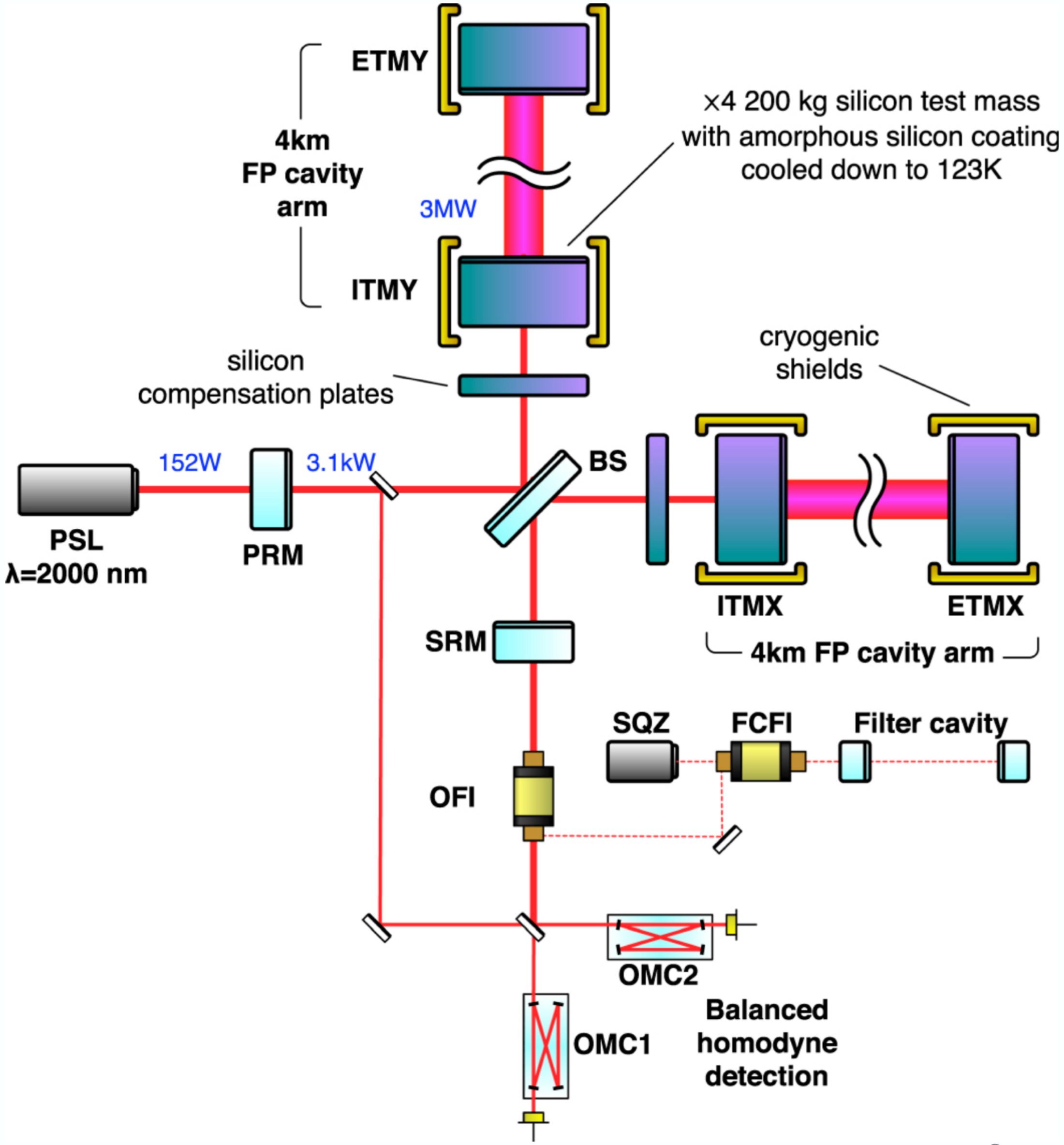
LIGO Voyager



LIGO Hanford Observatory



LIGO Livingston Observatory

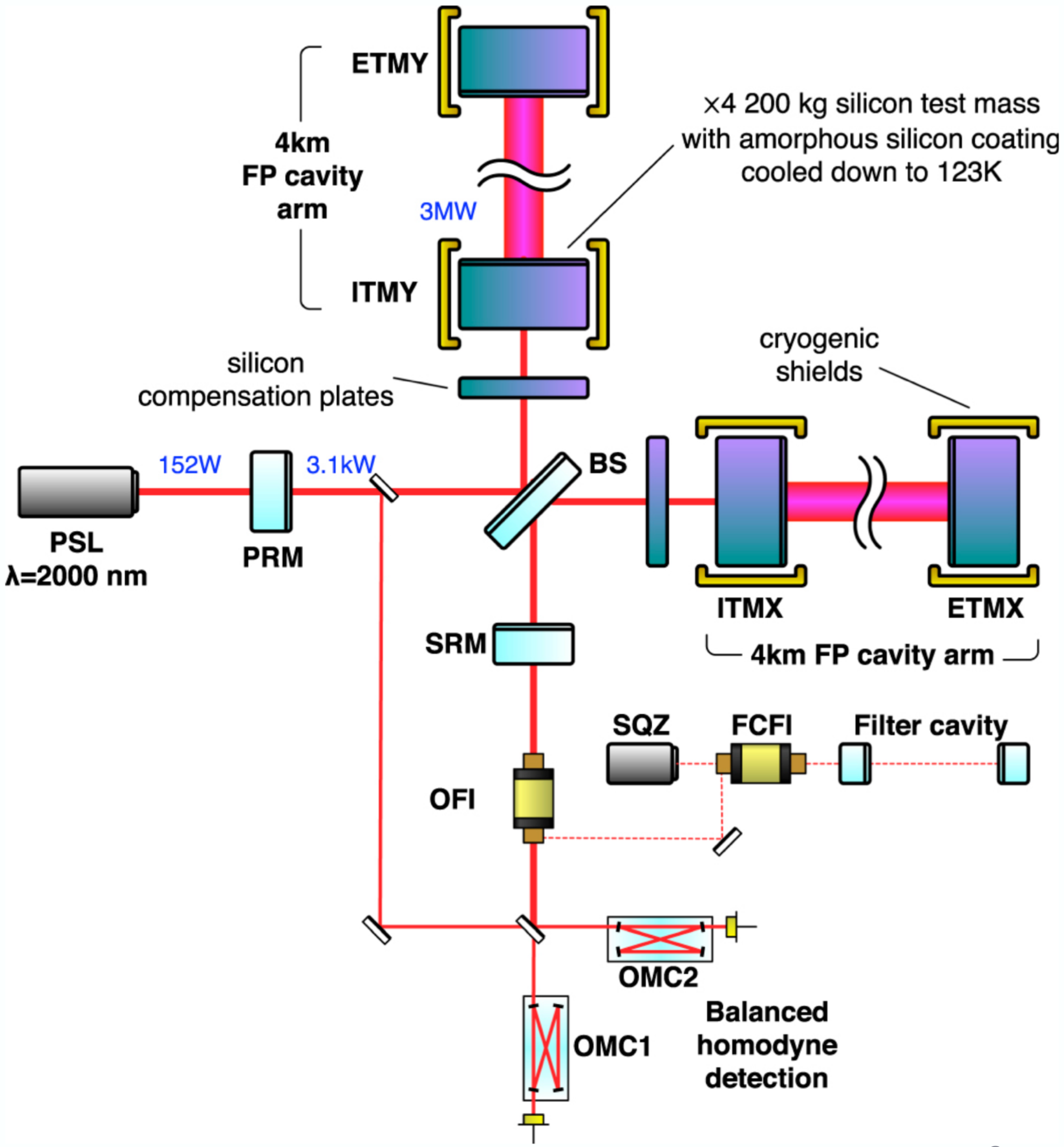


Voyager IFO schematic, from [Voyager White Paper]

LIGO Voyager

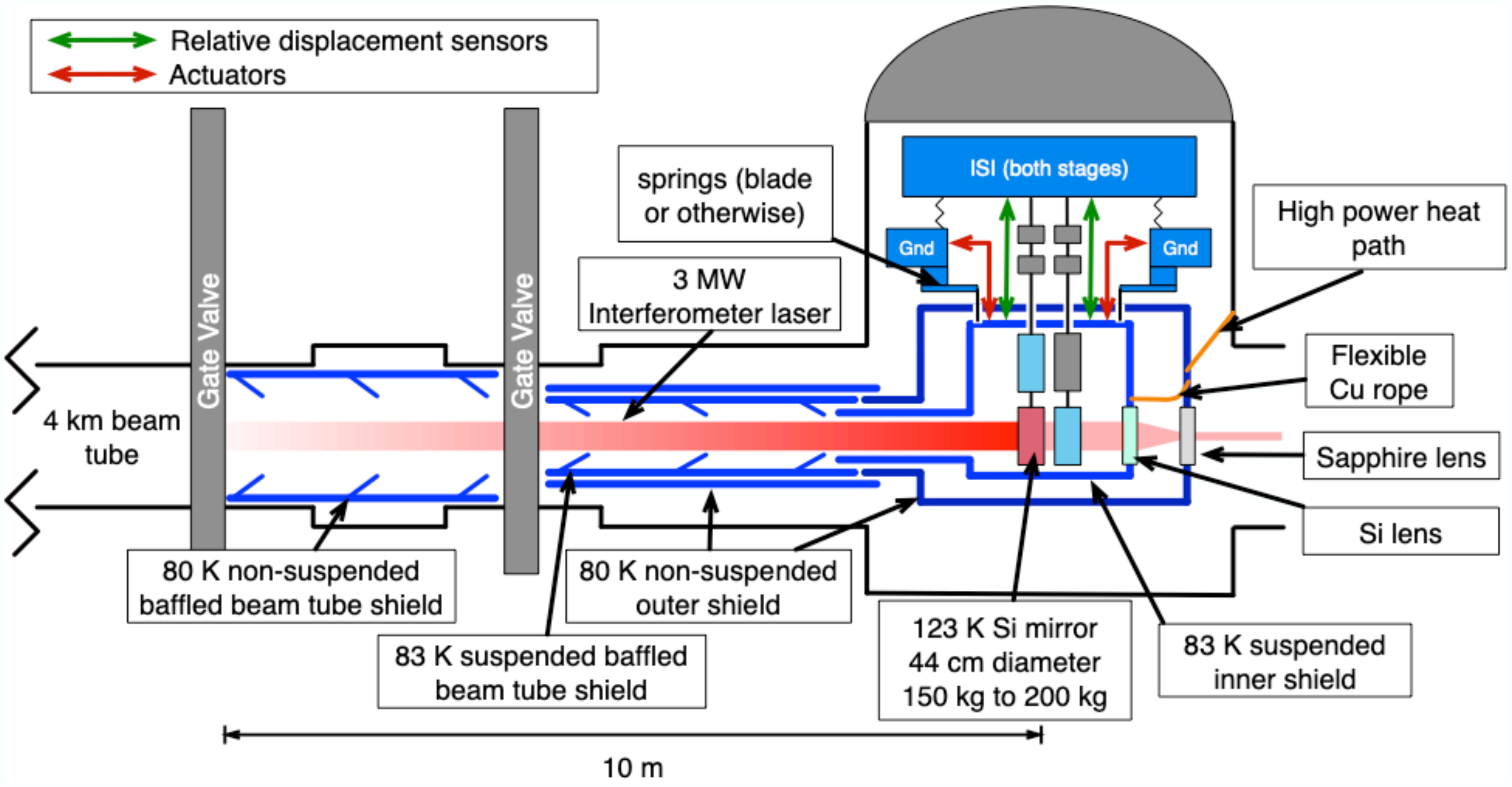
CAD drawing of LIGO India

LIGO Livingston Observatory



Voyager IFO schematic, from Voyager White Paper

Voyager Cryogenics

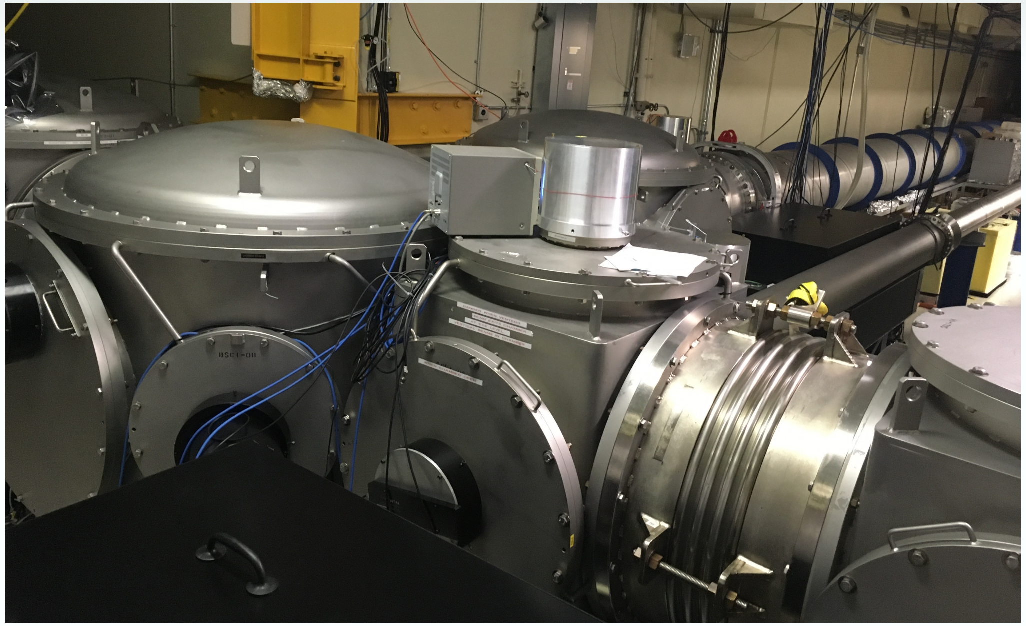


Voyager ETM chamber design, from [Voyager White Paper]

- Si mirrors
- 2 layers of radiative shielding
- Conductively cooled via heat extraction path
- Shields extend into beam tube
- Radiative cooling of test mass (TM) from inner shield (IS)
- Quasi-monolithic suspension: cold Si blade springs and Si ribbons

Mariner

- Voyager-like upgrade to Caltech 40m Lab
- Demonstration of 2-µm cryogenic silicon suspended mirror interferometry
    - ~6 kg Si optics
    - 123 K operation
    - 2050 nm pre-stabilized laser (PSL)



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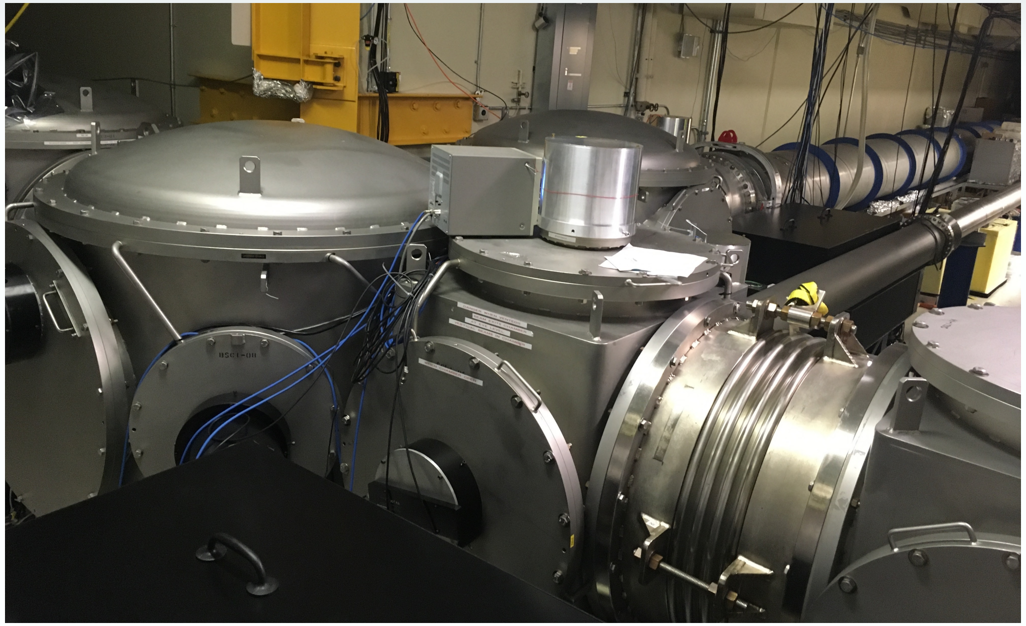

Phase I	Phase II
Warm PUM (SiO_2)	Cold PUM (Si)
2-stage metal wire suspension	Si springs + ribbons (monolithic)
SiO_2/Ta_2O_3 coating	a-Si coating
FPMI configuration	DRFPMI configuration

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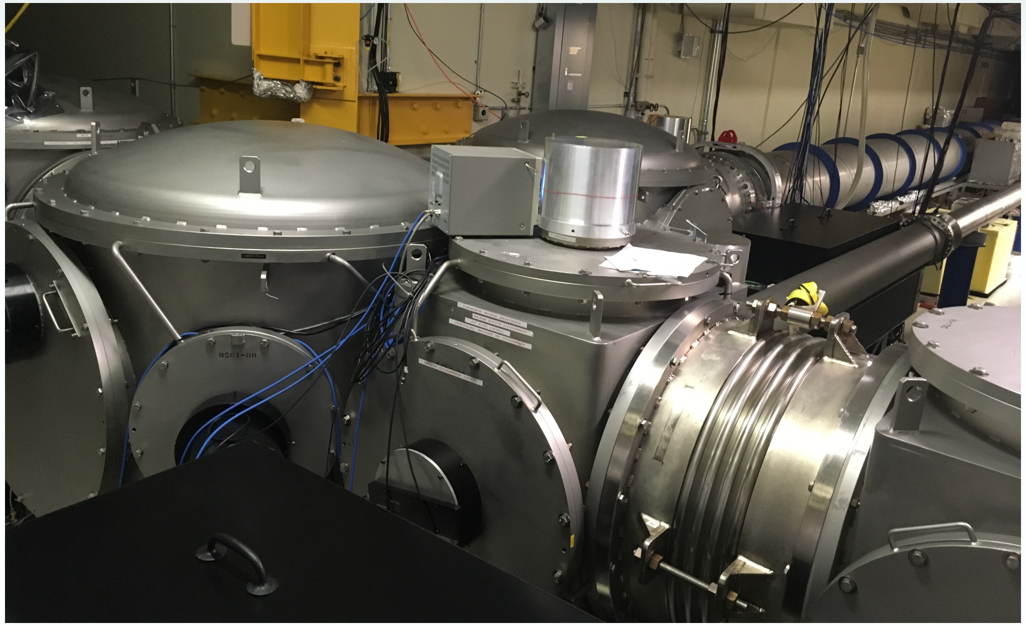

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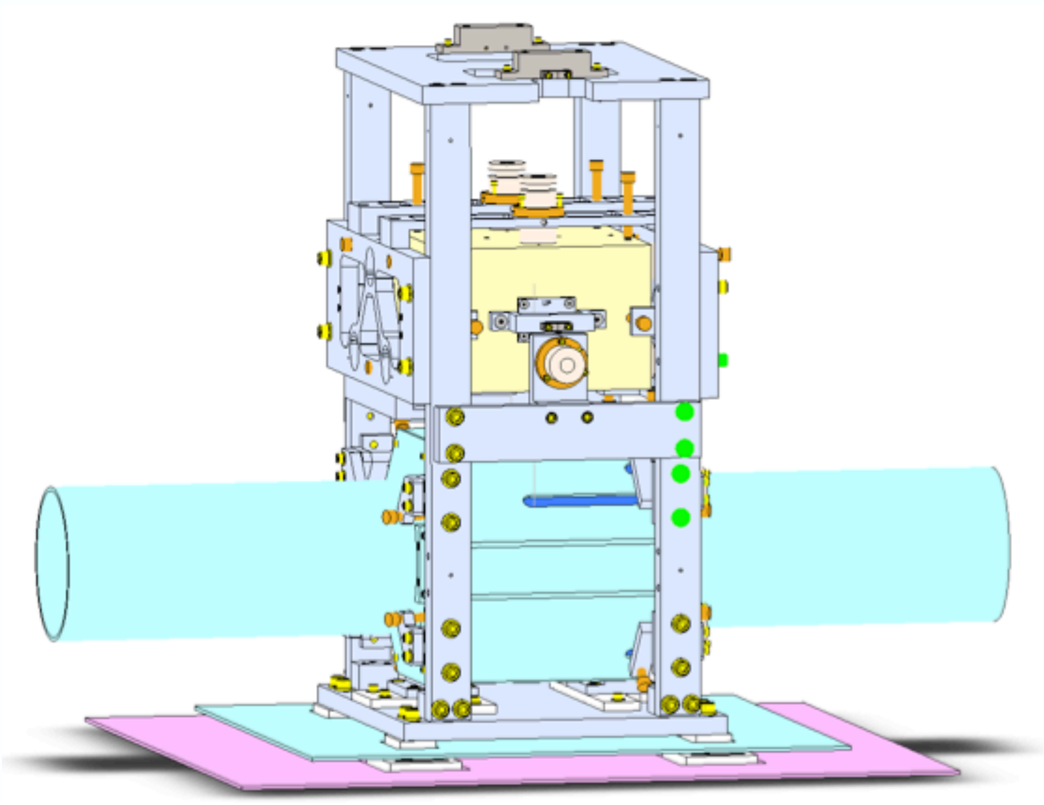
Warm PUM (SiO_2)	Cold PUM (Si)
2-stage metal wire suspension	Si springs + ribbons (monolithic)
SiO_2/Ta_2O_3 coating	a-Si coating
FPMI configuration	DRFPMI configuration

Why 2 phases?

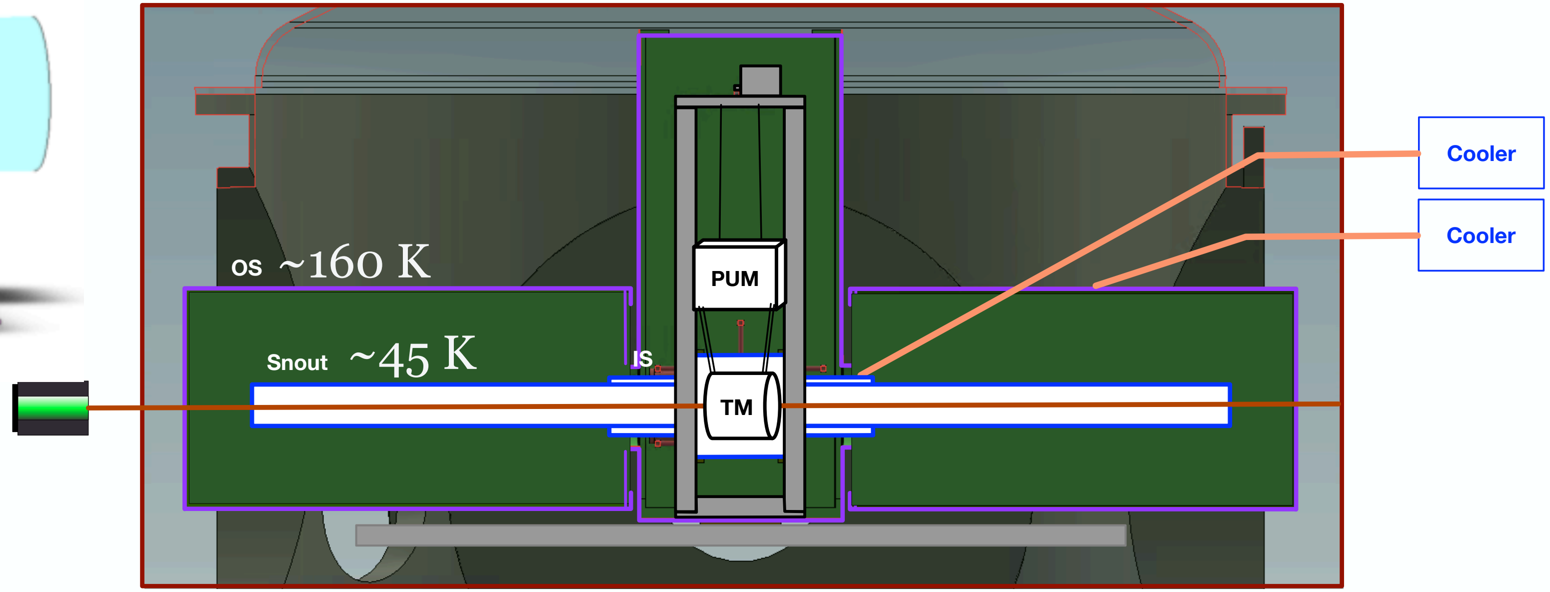
- Despite best efforts, unexpected challenges can arise with new technologies
    - We don't need DRFPMI to learn things
    - Ex: phase noise in Si substrate
- Integrate Phase I lessons into Phase II → optimize for low noise

Phase I

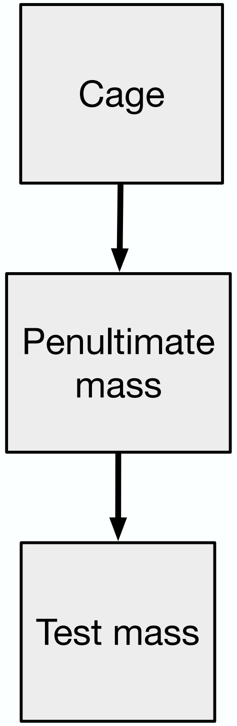
Phase I
Warm PUM (SiO_2)
2-stage metal wire suspension
SiO_2/Ta_2O_3 coating
FPMI configuration

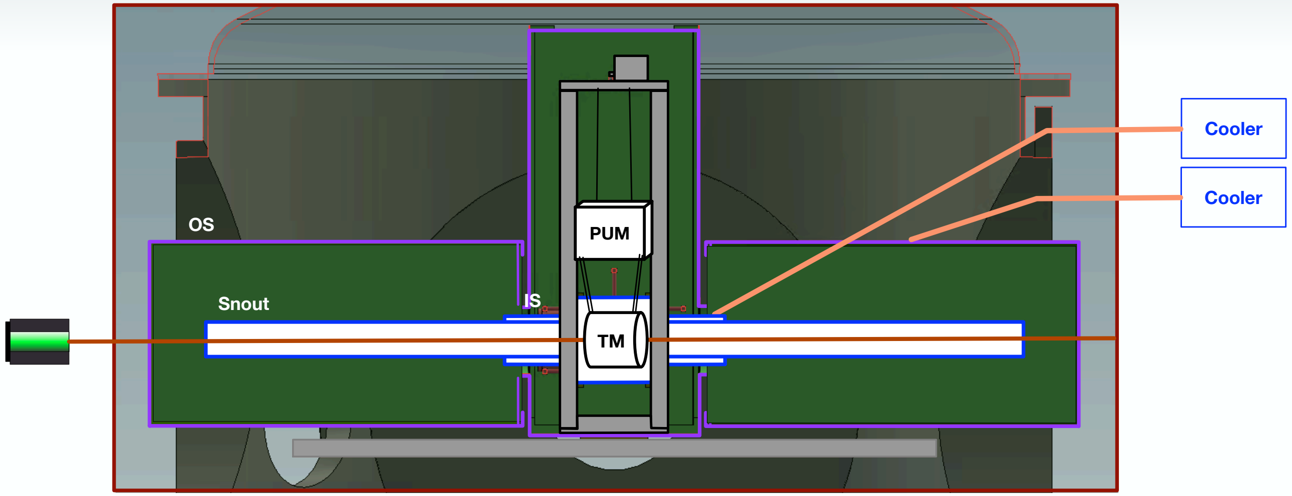


K. Arai



Thermal Modeling



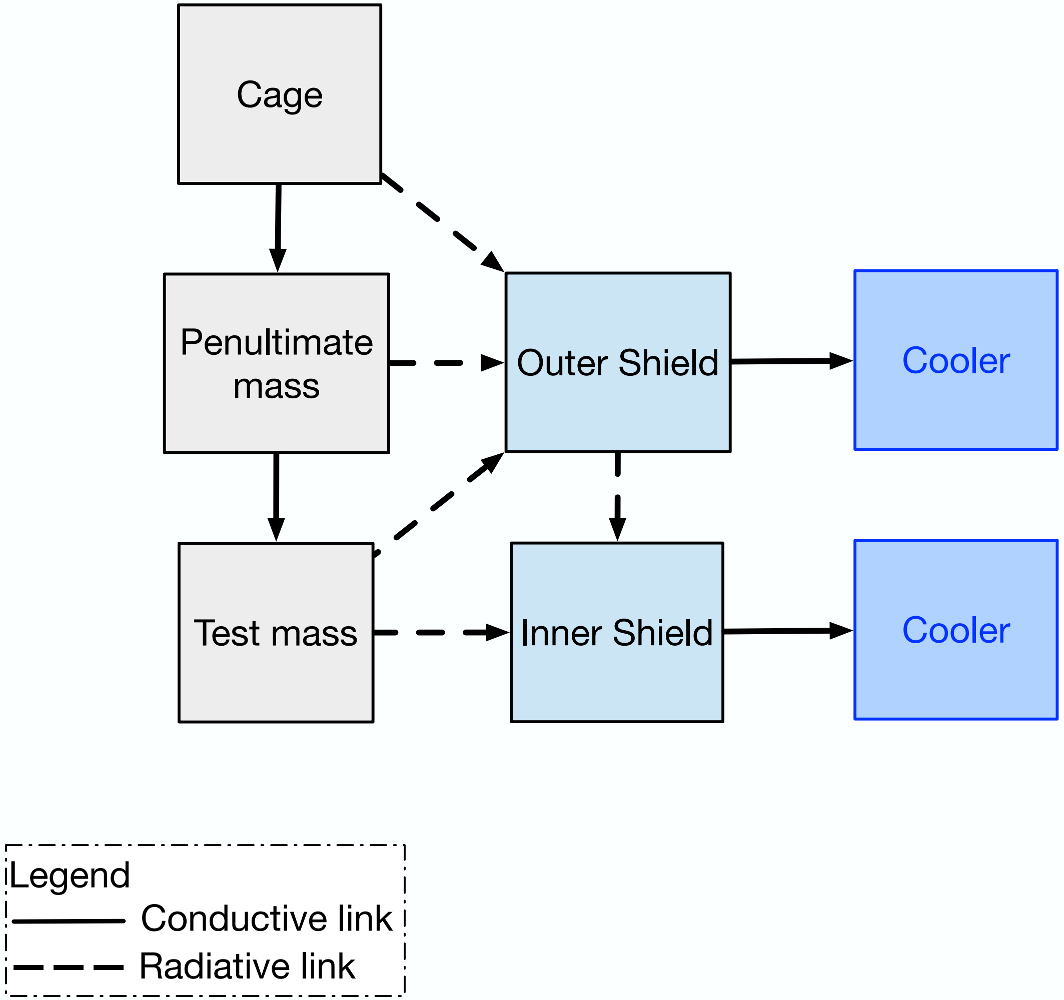


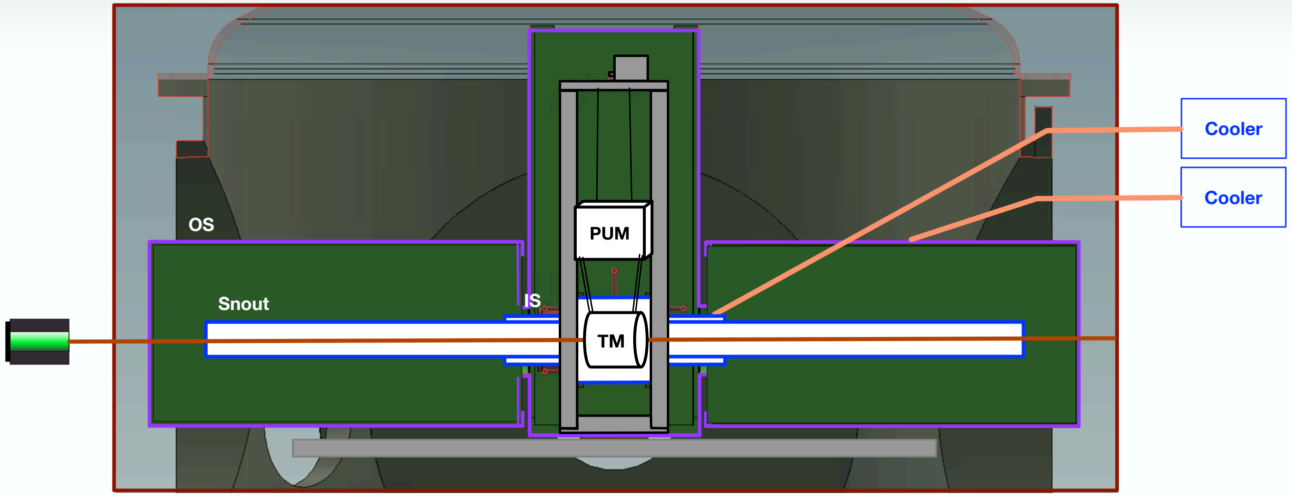
Suspension

- **Heat flow along wires to PUM and TM**

Legend
——— Conductive link
– – – Radiative link

Thermal Modeling





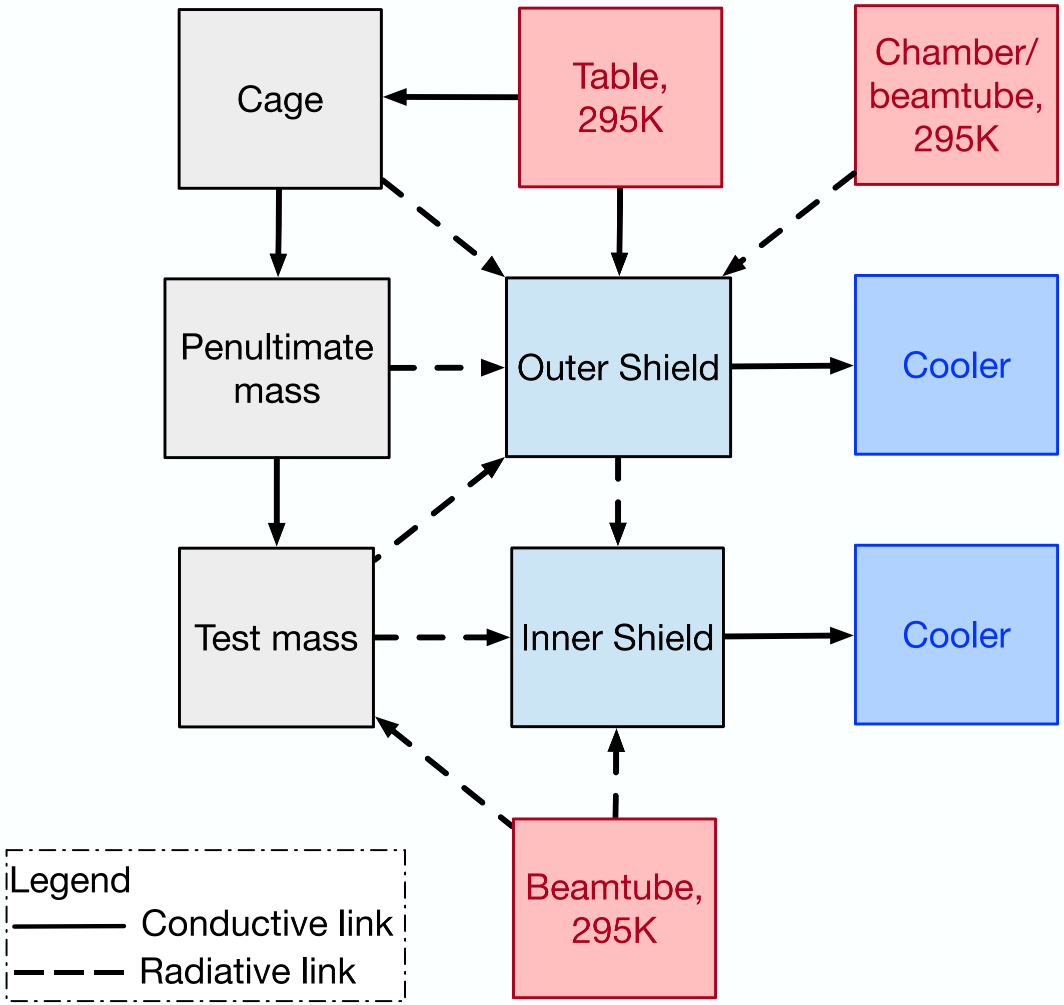
Suspension

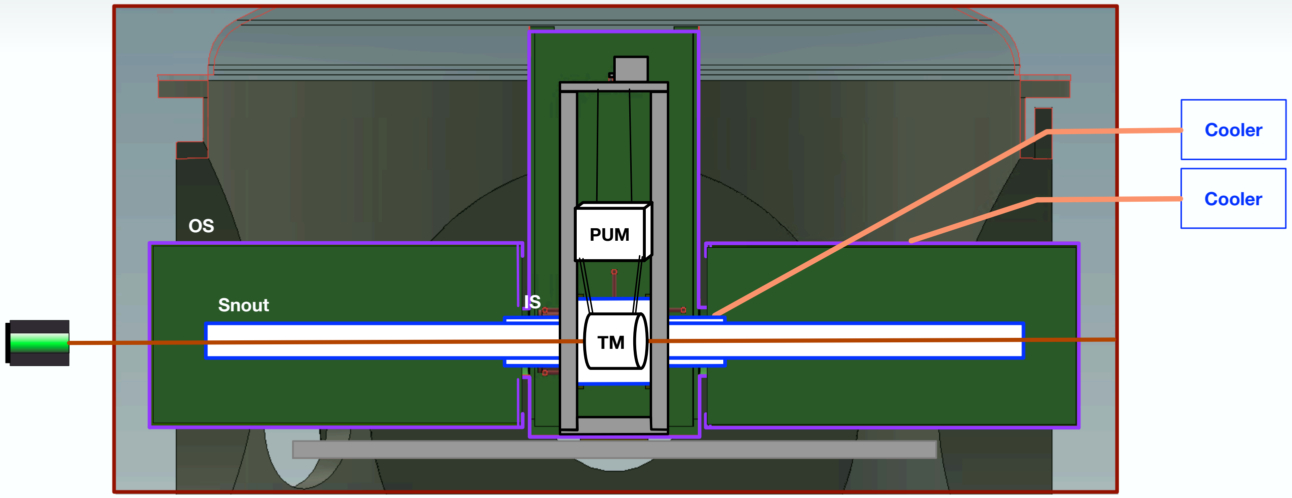
- Heat flow along wires to PUM and TM

Cooling

- **IS/OS cooled by separate coolers**
- **TM cooled radiatively by IS**
- **View factor from OS to TM via holes in IS**

Thermal Modeling





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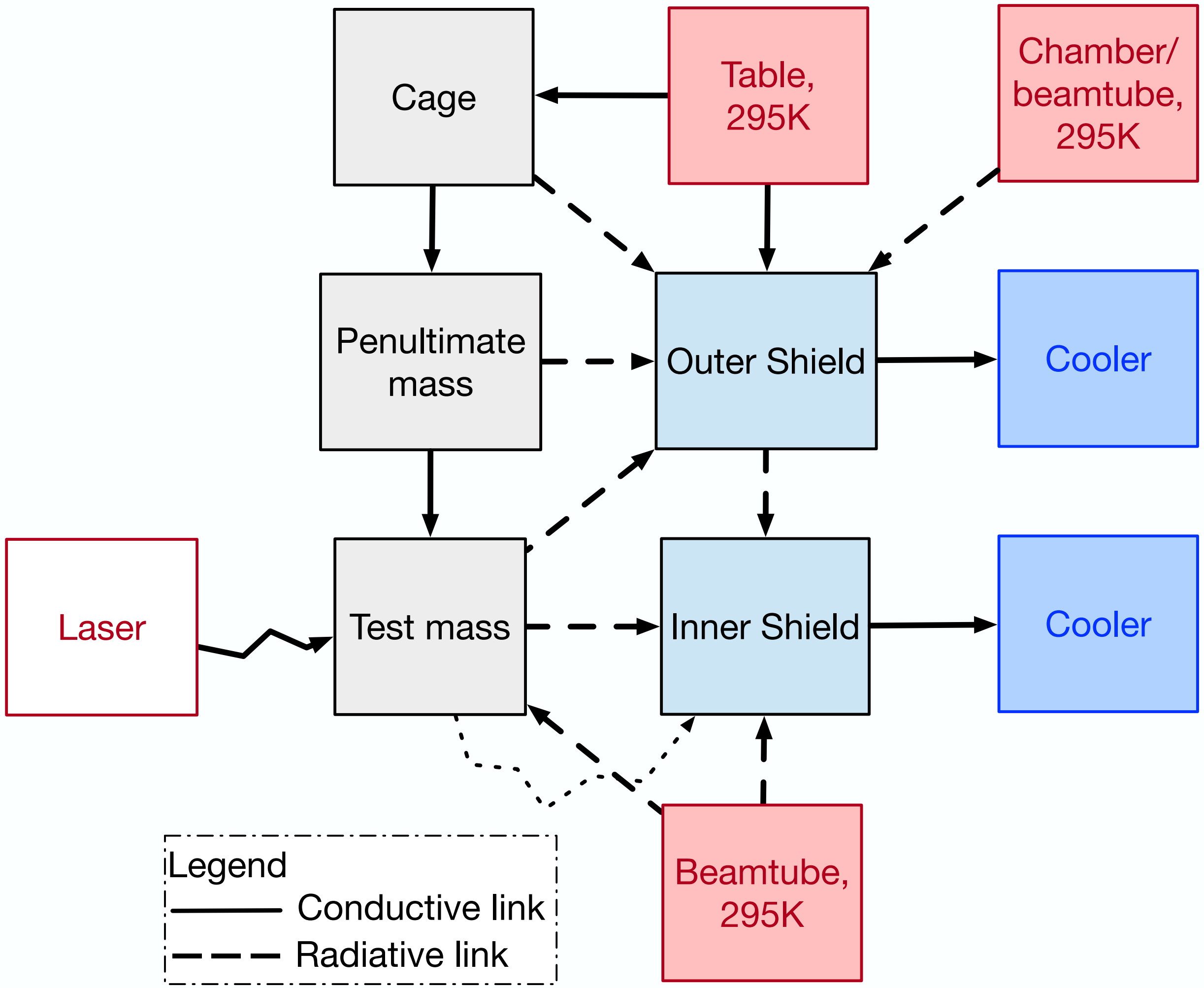
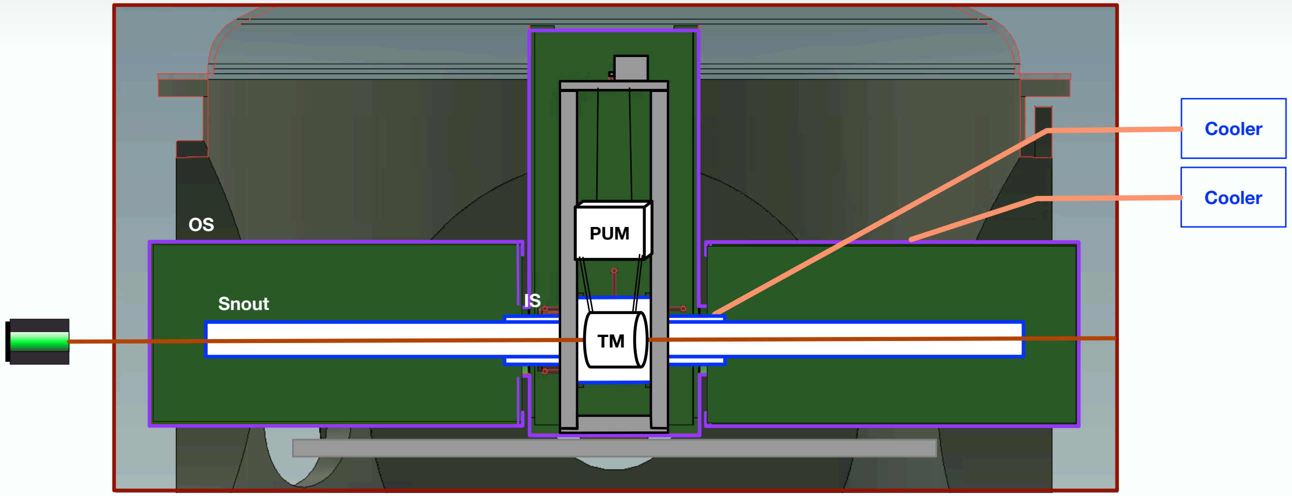
Heating

- **Chamber and beam tube heat OS/IS**
- **View factor from beam tube to TM through IS snout**

Thermal Modeling





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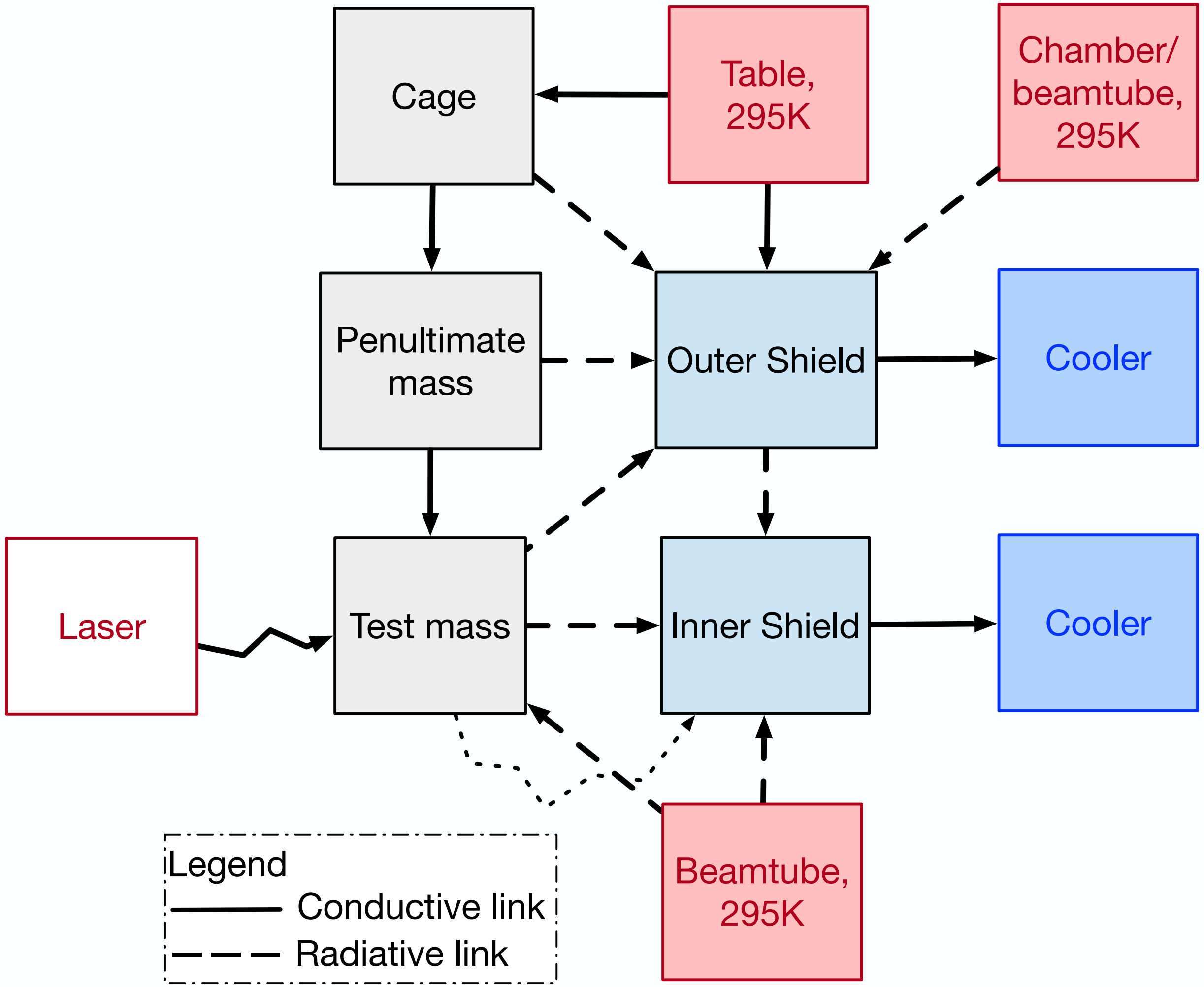
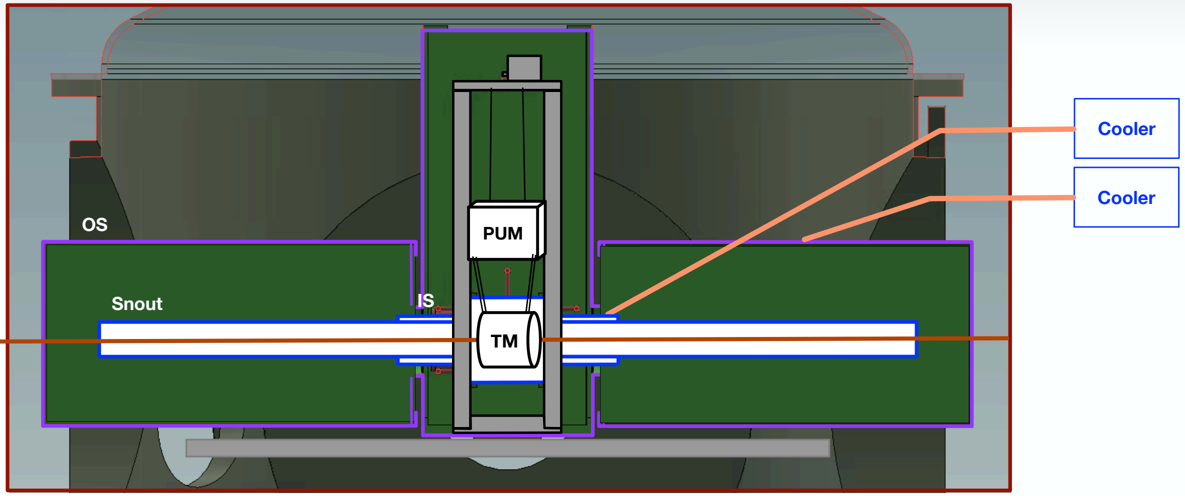
Laser heating

- **100 mW TM absorption**
- **10 ppm scattering off of TM to IS**

Thermal Modeling





Main heat loads on test mass: **beam tube, laser**

- Snout extensions of rad shields buffer RT radiation from beam tube
  - Tradeoff: longer = better RT shielding; shorter = less thermal mass to cool
  - Shield end-to-end length: 1 m
- Can cool with laser off

What cooler do we select?
→ Consider **cooling and vibration requirements**

What's the best we can do?

- Radiative cooling limit:
  - ε=1
  - 0 K environment fully enclosing sample

$$mC_p \frac{dT}{dt} = -\sigma A T^4$$

T = temperature (K)
A = area (m^2)
m = mass (kg)
C_p = heat capacity ($^J/_{kg\ K}$)
σ = Stefan-Boltzmann constant ($^W/_{m^2 K}$)

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- Mariner time to 123 K: ~20 h
- Voyager time to 123 K ~68 h (< 3 days)

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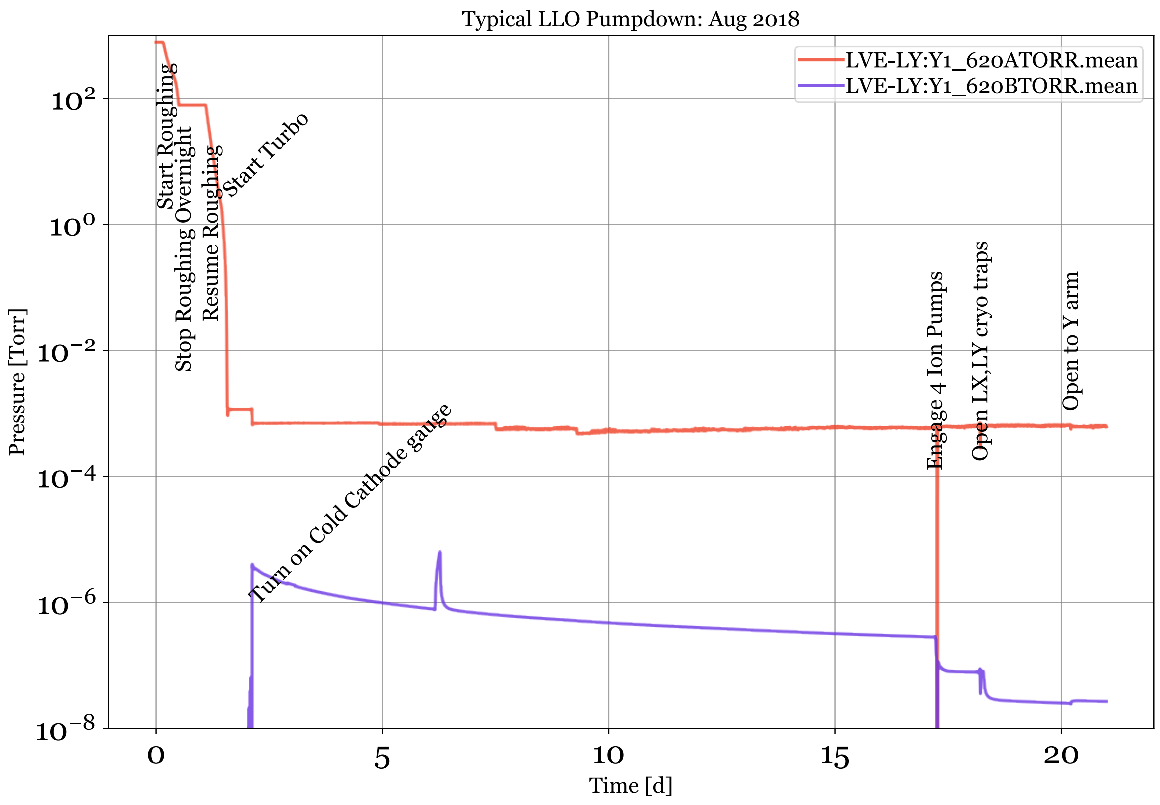
LLO pumpdown: ~18 days



Typical LLO Pump down, from Voyager White Paper

Cooling Requirements

1. Time to cool Si optic to 123 K should be comparable to vacuum pump down time

Mariner Goals

Goal #1	$\tau_{123K} \sim 24$ h

Cooling Requirements

1. Time to cool Si optic to 123 K should be comparable to 40m vacuum pump down time

➢ Need excess cooling power at 123 K to offset TM heat loads

2. Cooling power delivered to TM should be ~2x the heating power at 123 K

Mariner Goals

Goal #1	$\tau_{123K} \sim 24$ h
Goal #2	$P_{cool,\ 123K} \geq 0.7$ W

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Voyager Goals

Goal #1	$\tau_{123\mathrm{K}} \sim 18$ d
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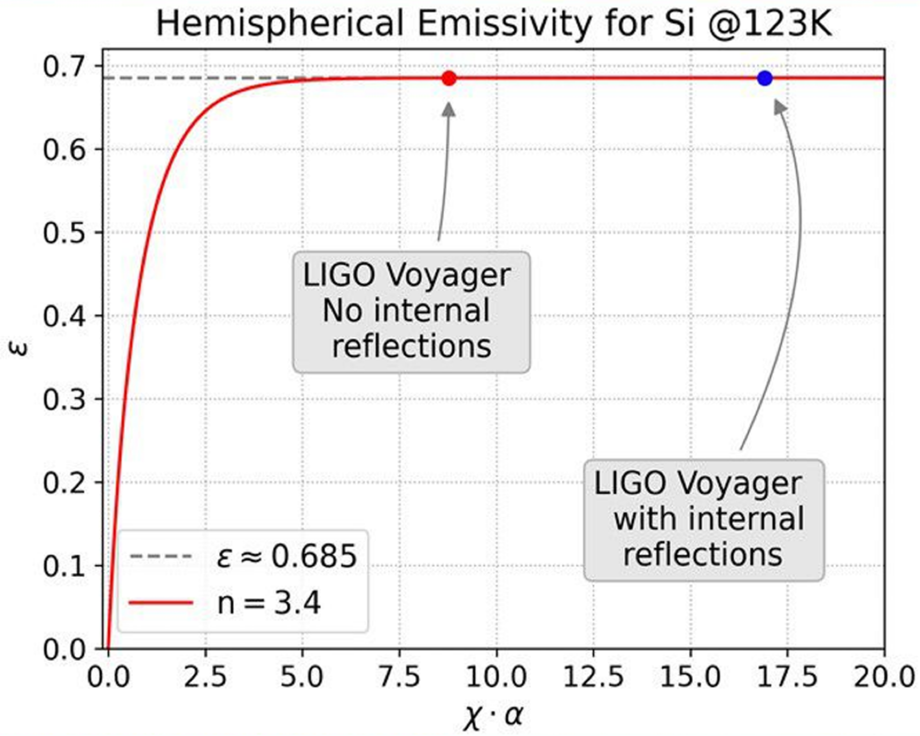
→ Dependent on TM barrel emissivity

TM Barrel Emissivity

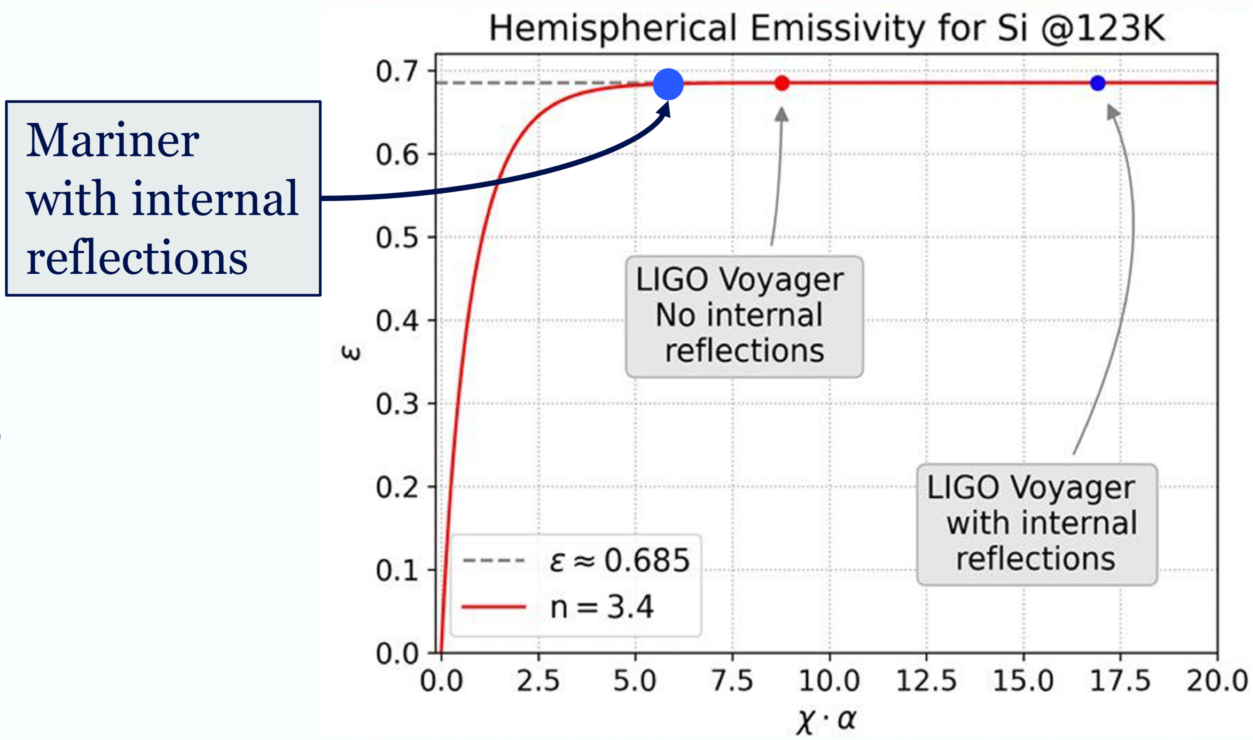
- Is bare Si enough?
  - Voyager TM effective emissivity: $\varepsilon \approx 0.685$



J. Reis, O. Aguiar [G2101151]

TM Barrel Emissivity

- Is bare Si enough?
  - Voyager TM effective emissivity: $\varepsilon \approx 0.685$
  - Mariner TM effective emissivity: $\varepsilon \approx 0.685$



J. Reis, O. Aguiar [G2101151]

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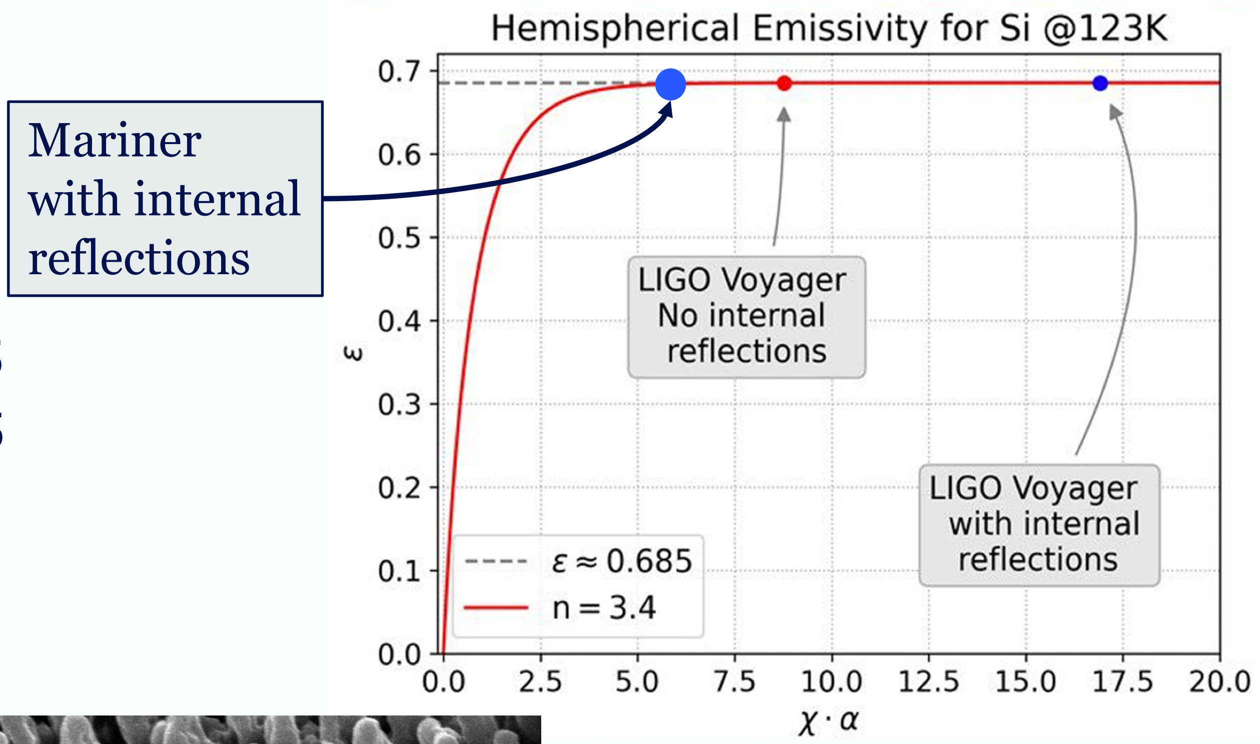
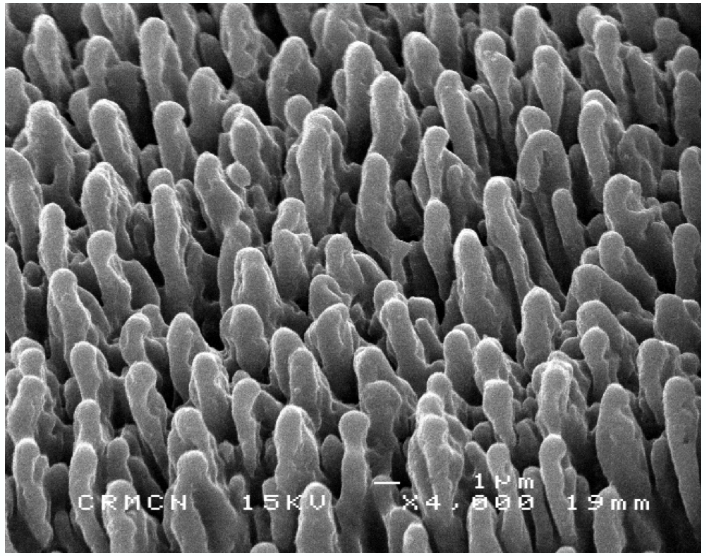
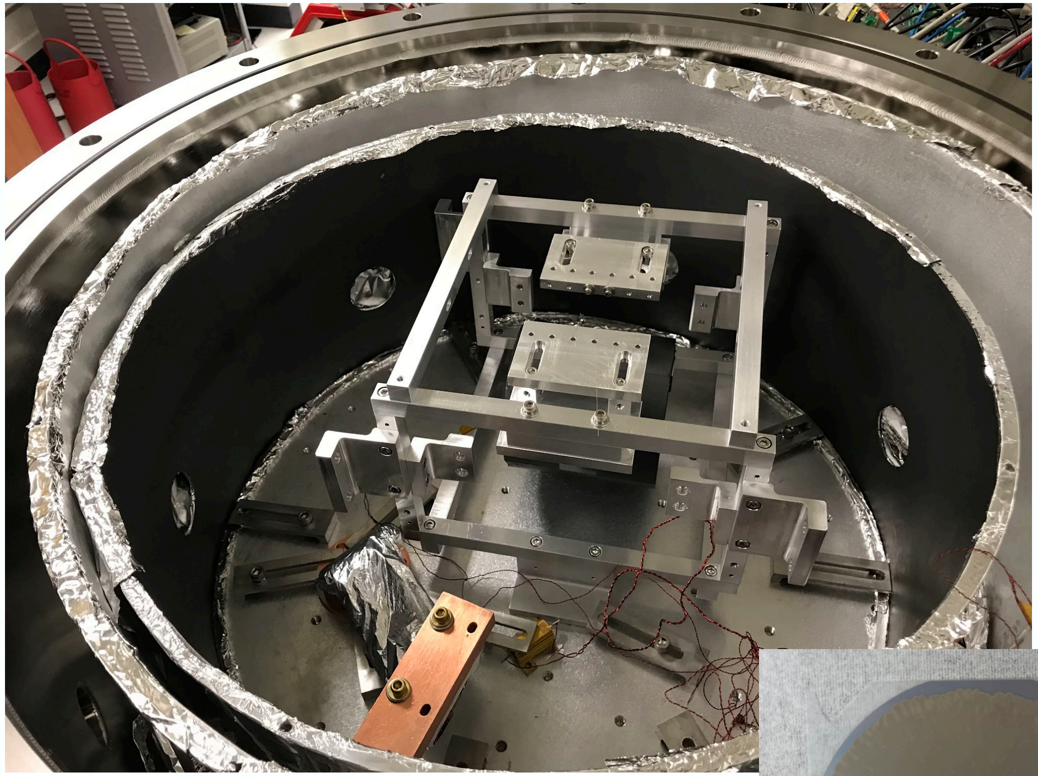


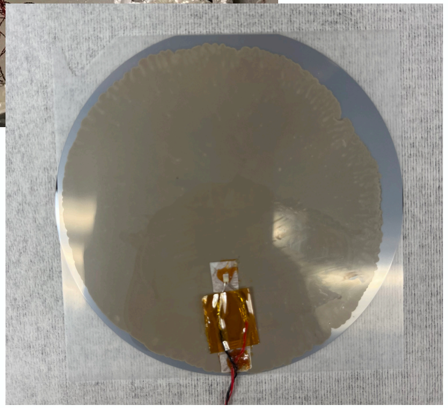
J. Reis, O. Aguiar G2101151

- High emissivity barrel coating
- → maximizes radiative coupling between TM and cold shielding
- Black Si
  - Surface modification of Si – creates needle-shaped structure
  - ε~0.8



Cooling Tests

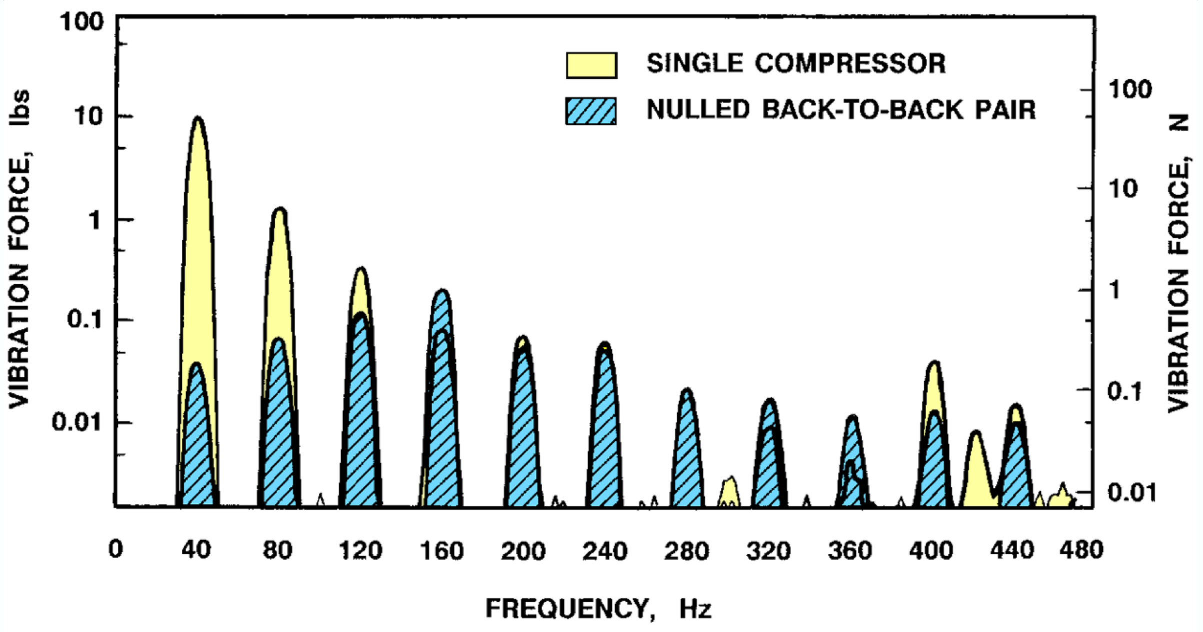




- Cool Si samples in tabletop cryostat
  - Extract cooldown times to 123 K
- Estimate emissivities
- Test bonding methods

→ Cryostat upgrades in progress to simplify thermal modeling and increase cooling efficiency

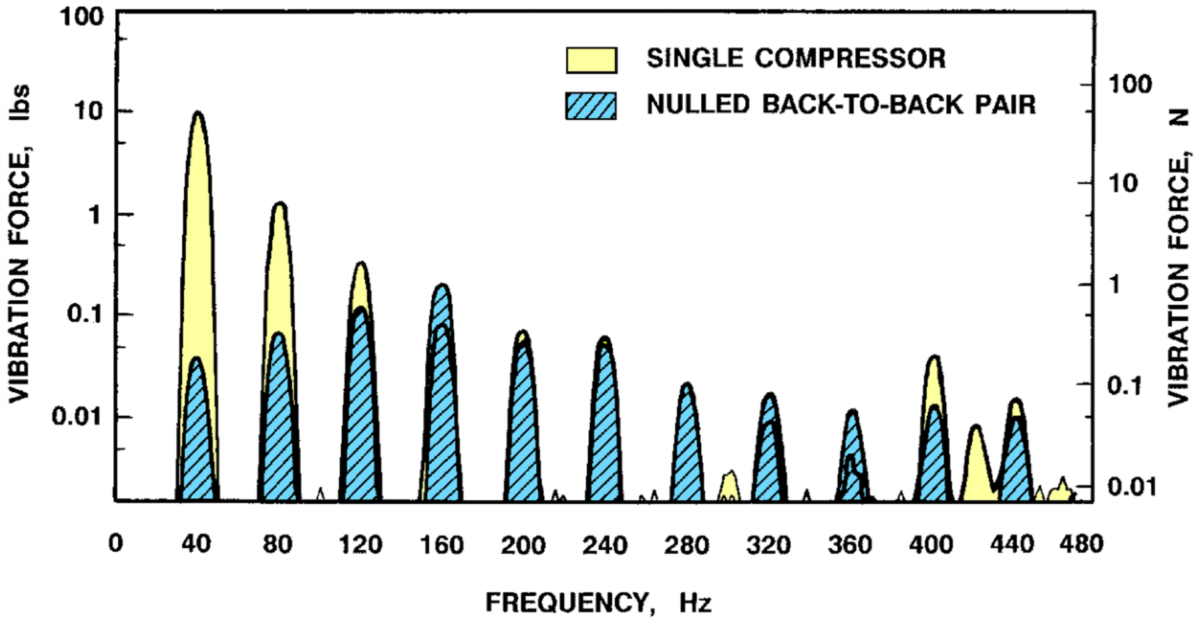
Vibration Considerations



Vibration spectrum generated by a BAe 80K Oxford-style, linear-drive compressor with a 40-Hz drive frequency.

R. Ross, [Vibration suppression of advanced space cryocoolers]

Vibration Considerations



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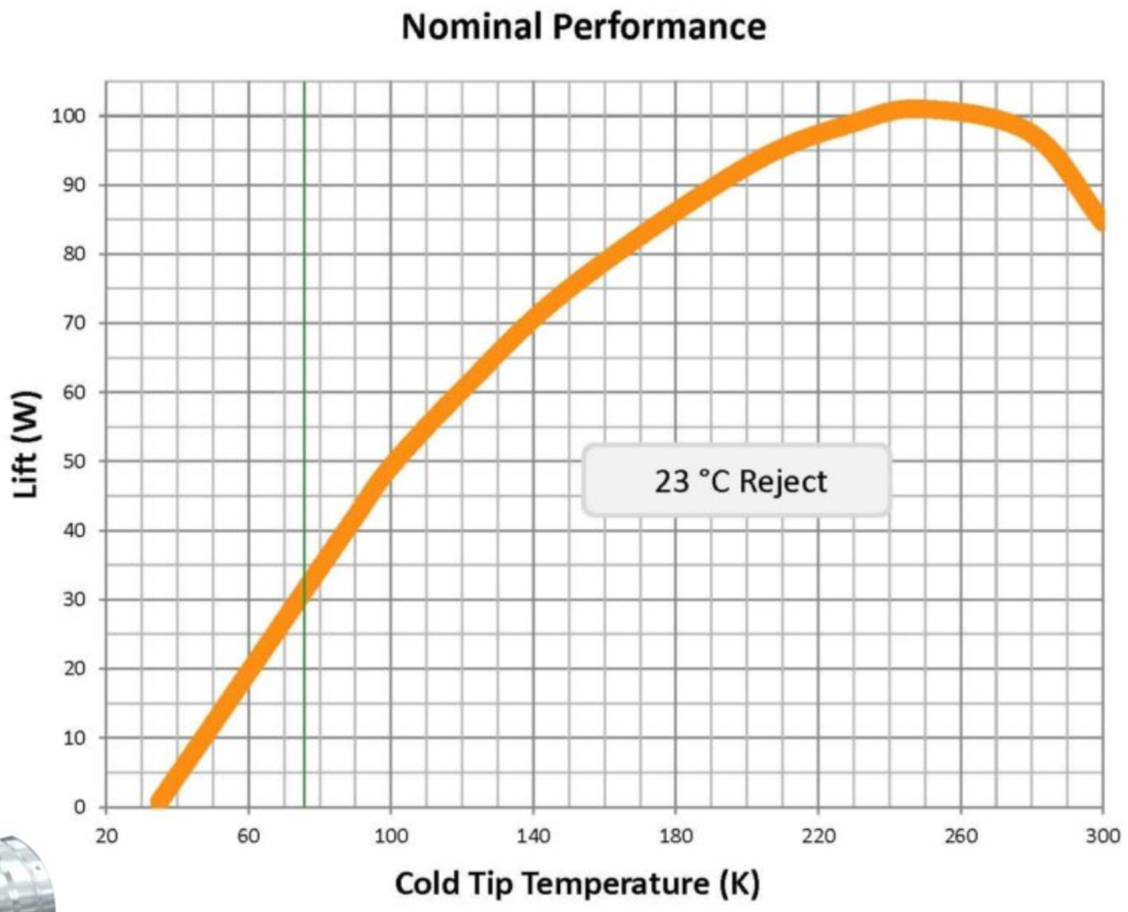
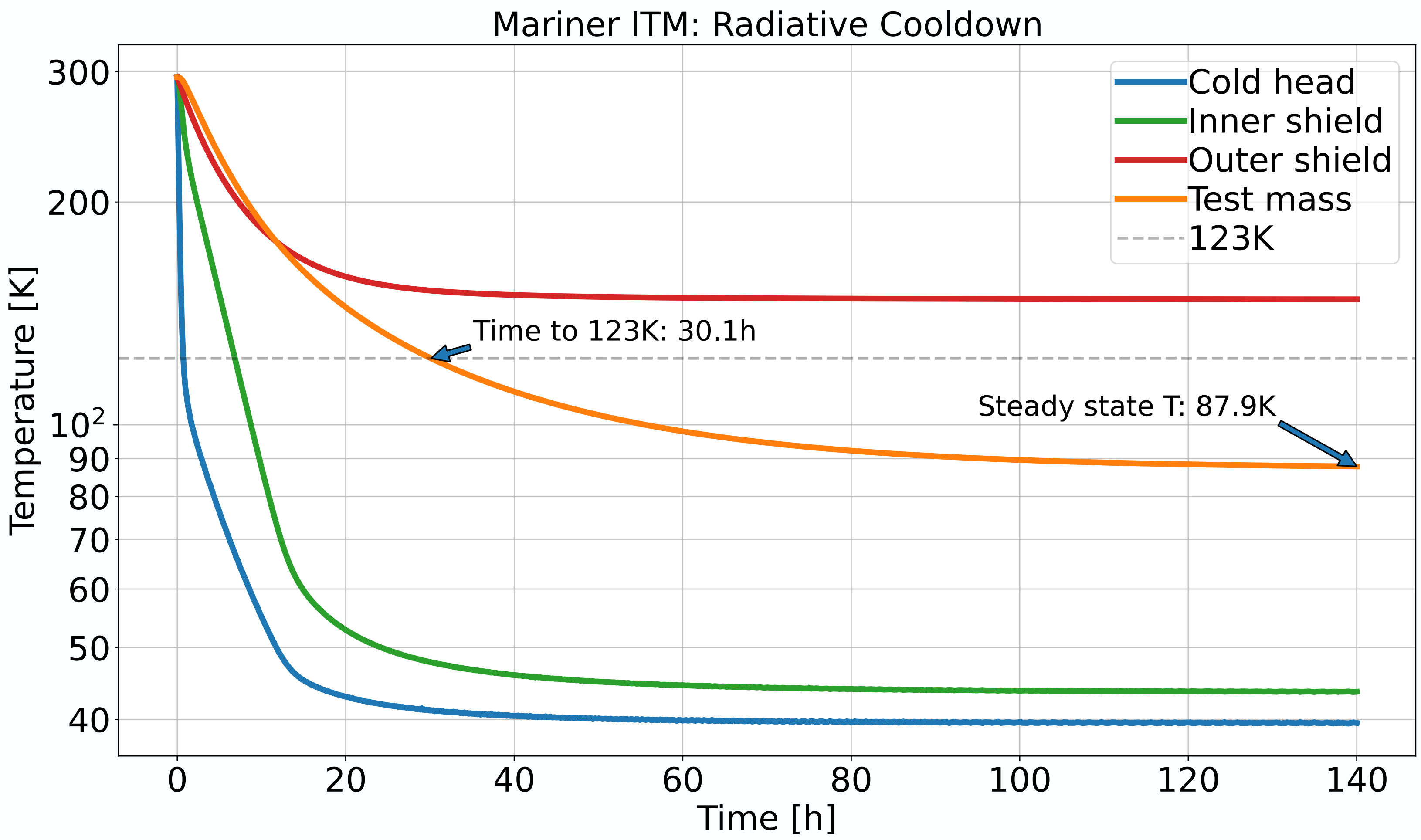
Sunpower CryoTel DS 30



[Sunpower Inc.]

Mariner Cooldown

Goal #1	$\tau_{123K} <\sim 24$ h
Goal #2	$P_{cool,\,123K} \geq 0.7$ W



- Sunpower DS 30 (Stirling) cryocooler
- High emissivity (0.9) coating on Si barrel
- High emissivity (0.9) coating on inner shield (inner surface)
- Laser off during cooldown
- $\tau_{123K} \sim 30$ h
- $P_{cool,\,123K} = 1$ W

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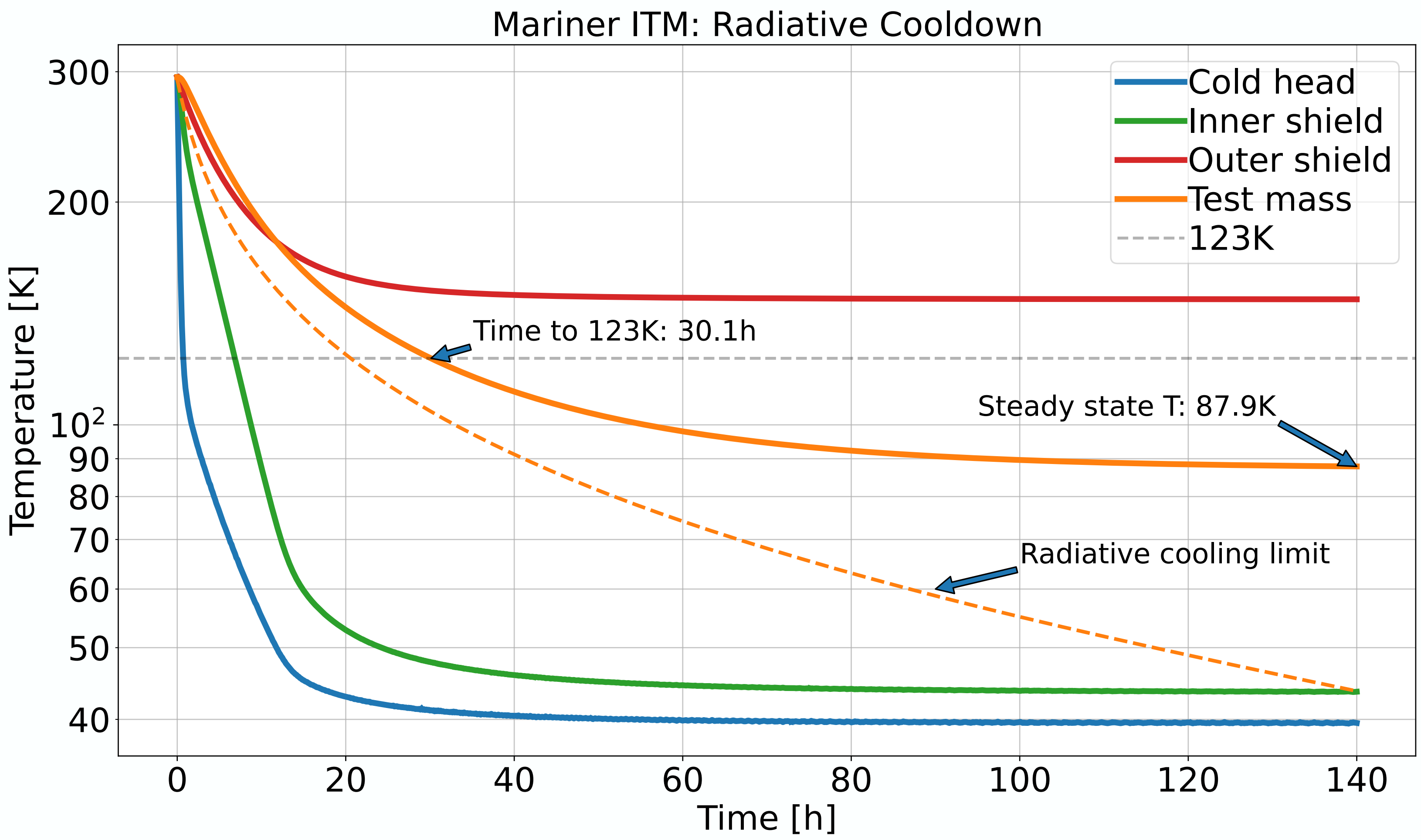

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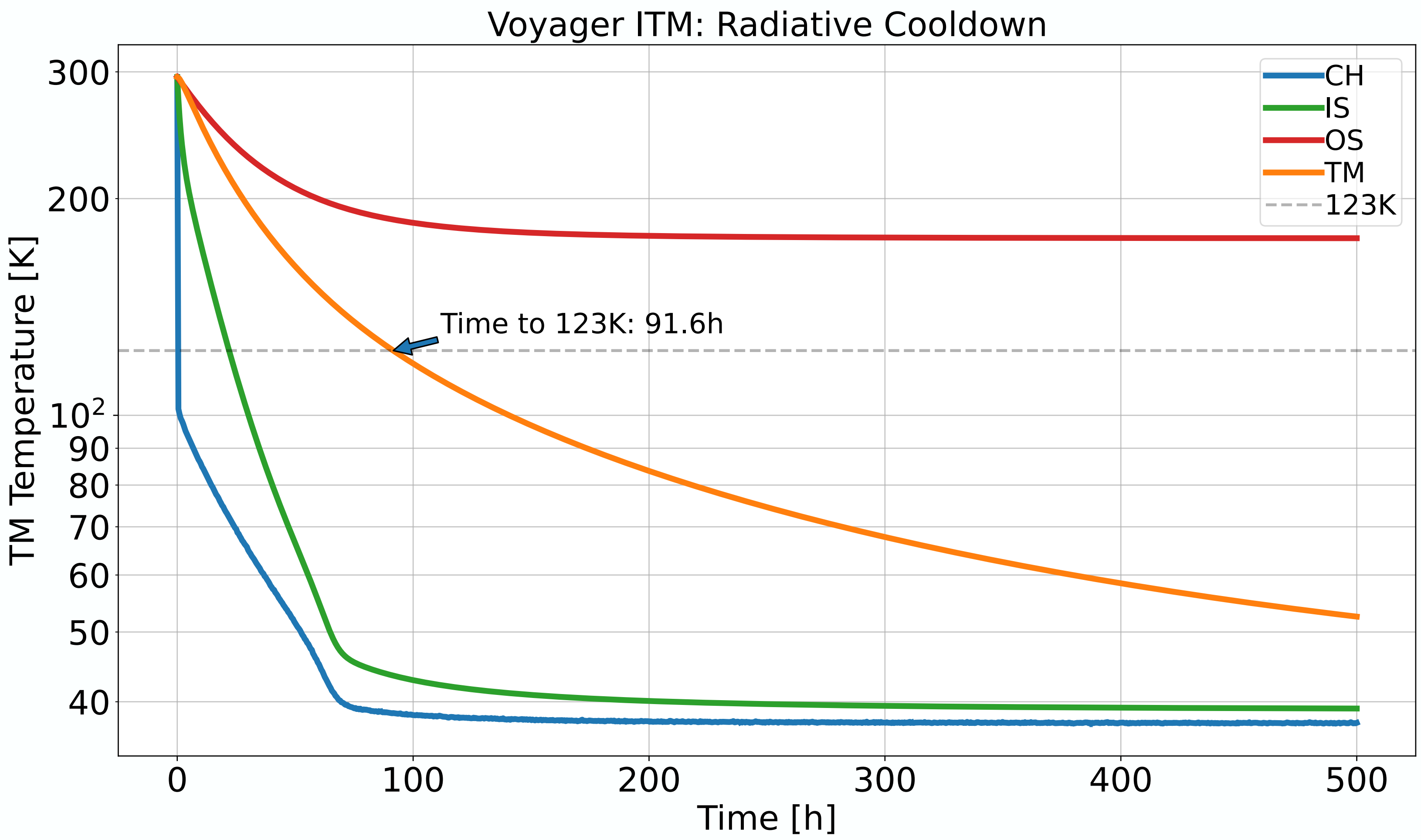
Voyager Cooldown

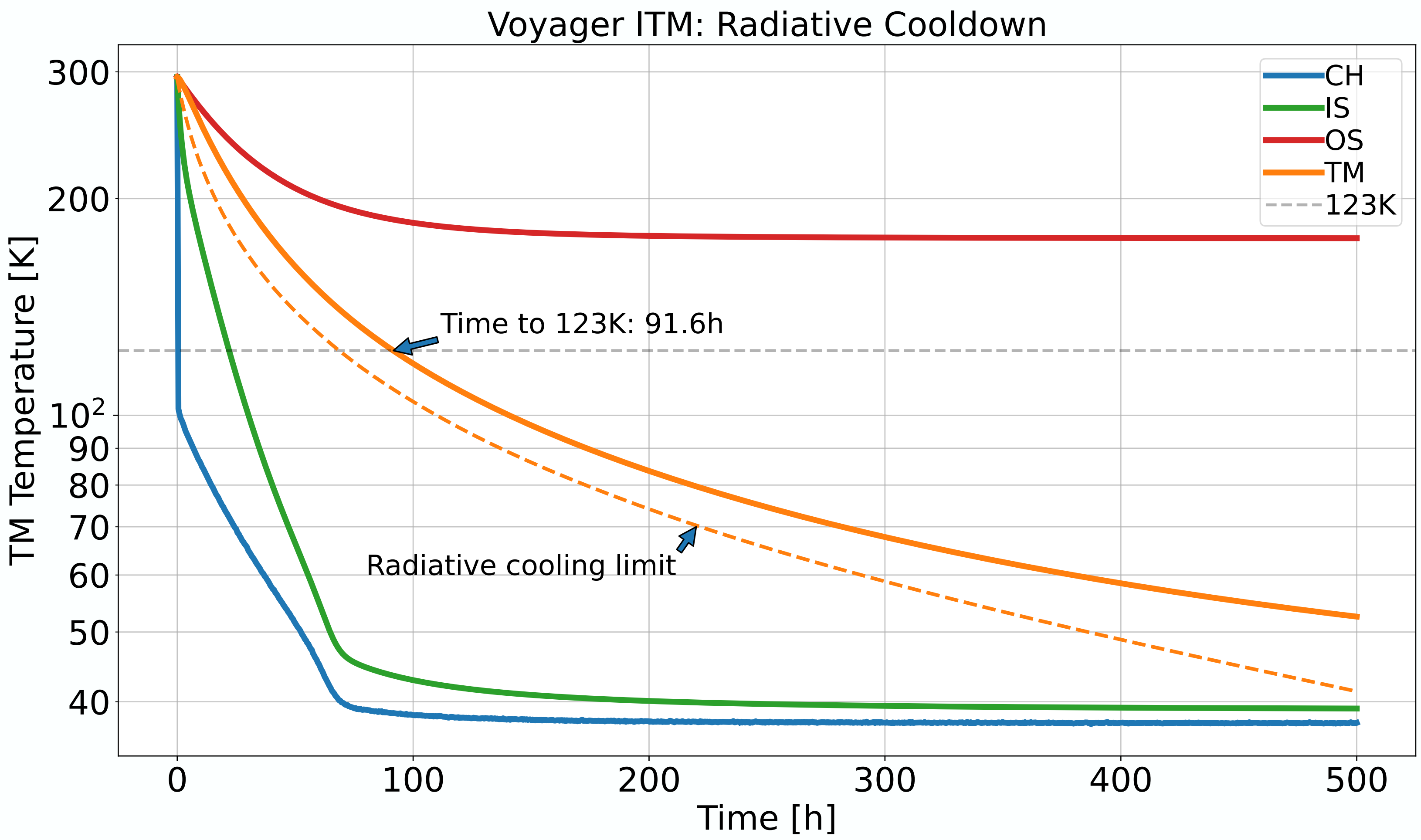
Goal #1	$\tau_{123K} <\sim 18$ d
Goal #2	$P_{cool,\ 123K} \geq 10$ W



- Need ~1 kW cooling power at 123 K
  - Multiple coolers?
  - LN2?
- High emissivity (0.9) coating on Si barrel
- High emissivity (0.9) coating on inner shield (inner surface)
- Laser off during cooldown
- $\tau_{123K} \sim 92$ h
- $P_{cool,\ 123K} = 11$ W

Voyager Cooldown

Goal #1	τ_{123K} <~ 18 d
Goal #2	$P_{cool,\ 123K} \geq 10$ W



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Future Work

- Thermal modeling in COMSOL
- Testing of more high-emissivity coatings necessary for optimal cooldown of Mariner/Voyager TMs
- Mariner Phase I/II will inform Voyager cryogenic design

Backup Slides

Si Properties

Property	Silicon at 123 K	Silicon at 295 K	Fused silica at 295 K
Thermal expansion (1/K)	1×10^{-9}	2.6×10^{-6}	3.9×10^{-7}
Specific heat (J/kg/K)	300	700	739
Thermal conductivity (W/m/K)	700	130	1.38
Refractive index	3.5	3.45	1.438
dn/dT	1×10^{-4}	1.78×10^{-4}	1.1×10^{-5}

Voyager White Paper

Voyager SUS Parameters

Parameters	aLIGO	150 kg test mass	200 kg test mass
P, Main chain payload (kg)	124	470	470
m_1 (kg)	22	148.8	116.5
m_2 (kg)	22	101.7	87.6
m_3 (kg)	40	69.5	65.9
m_4 (kg)	40	150	200
Total length to optic center (mm)	1642	1642	1642
L_1 (mm)	422	410.5	410.5
L_2 (mm)	277	410.5	410.5
L_3 (mm)	341	410.5	410.5
L_4 (mm)	602	410.5	410.5
fiber/ribbon material	silica fiber	silicon ribbon	silicon ribbon
σ_4, fiber/ribbon stress (MPa)	774	150	150
PUM springs	no	yes	yes
10 Hz seismic noise (m/$\sqrt{\text{Hz}}$)	1.7e-19	8.8e-20	1.9e-19
10 Hz long. thermal noise (m/$\sqrt{\text{Hz}}$)	6.5e-19	1.4e-19	1.6e-19
10 Hz damping noise est (m/$\sqrt{\text{Hz}}$)	1.7e-20	5.1e-21	1.7e-20

Voyager White Paper

Thermal Modeling

Radiation:

$$P_{ij} = \frac{\sigma\left(T_i^4 - T_j^4\right)}{\frac{1-\varepsilon_i}{A_i\varepsilon_i} + \frac{1-\varepsilon_j}{A_j\varepsilon_j} + \frac{1}{A_iF_{ij}}}$$

Conduction:

$$P_{ij} = \frac{\kappa A}{l}\,(T_i - T_j)$$

P = power (W)
T = temperature (K)
ε = emissivity
A = area (m^2)
l = length (m)
F = geometric view factor
κ = thermal conductivity (W/mK)

Current thermal model (python) integrates a system of ODEs to model temperature vs. time of major chamber components

- Estimates radiative view factors
- Temperature-dependent heat capacity, thermal conductivity