Update on LIGO Voyager Cryogenics at Stanford

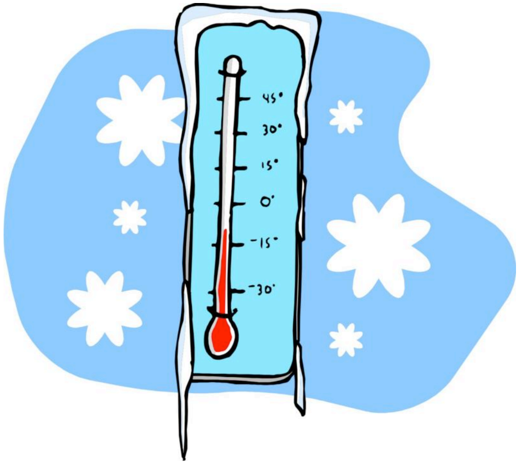
Brett Shapiro

Brian Lantz, Litawn Gan, Dan Fan, Sanditi Khandelwal,
Ian Gomez, Edgard Bonilla

LVC Glasgow – 30 August 2016

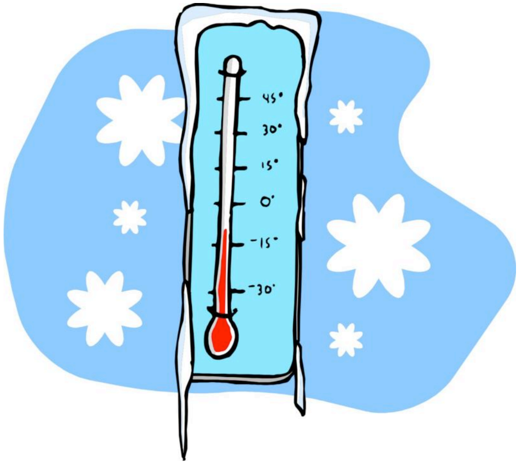
Experiment Goals

- Heat shield at about 80 K to radiatively keep the test mass at 123 K



Experiment Goals

- Heat shield at about 80 K to radiatively keep the test mass at 123 K

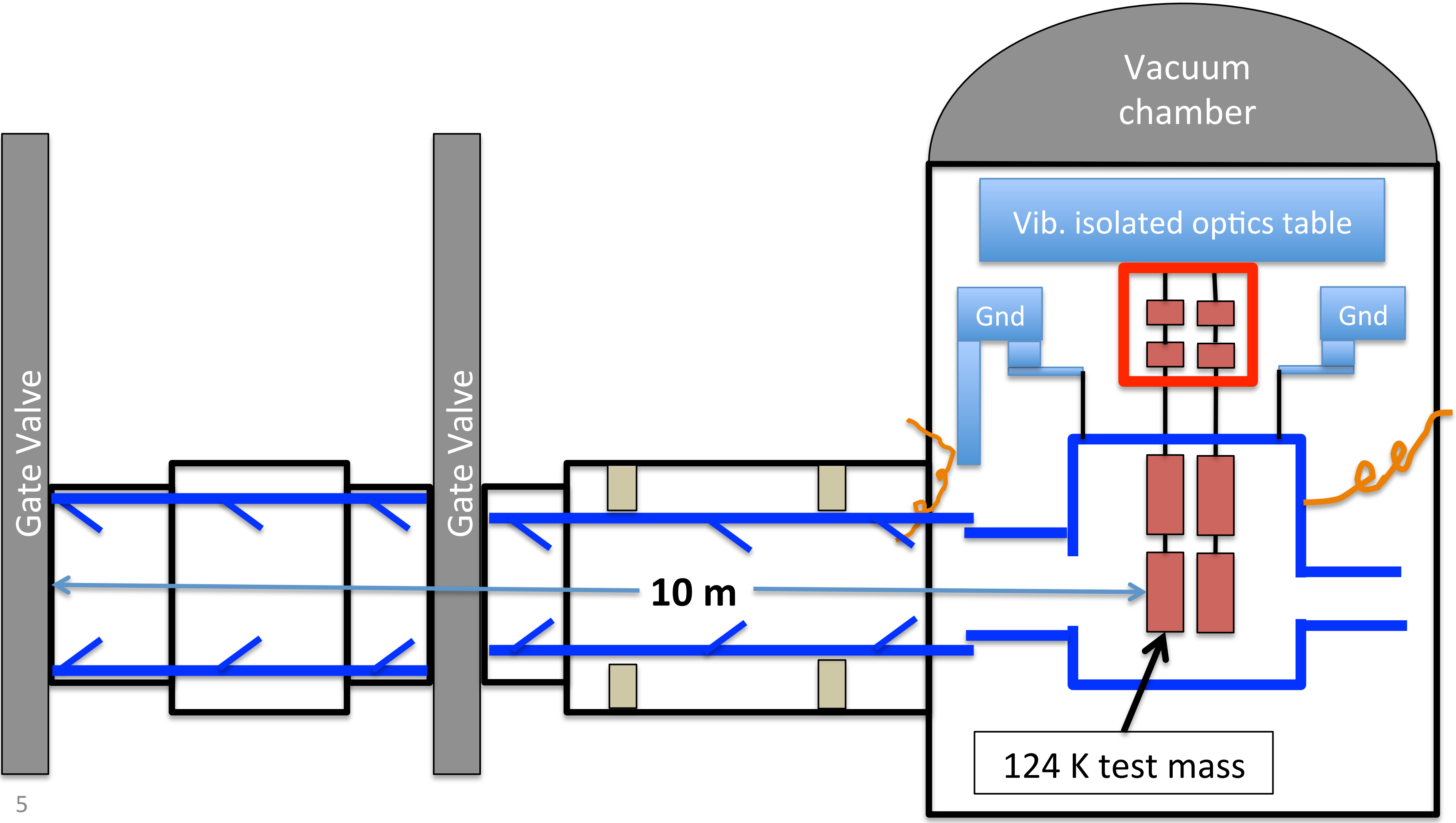


- Seismically isolated shield to avoid scattered light noise and possibly Newtonian noise

Contents

- Overview
- Measured thermal response
- Expected scattered light noise from cryo vibrations
- Expected Newtonian noise from cryo vibrations

Actively controlled shield (ETM)



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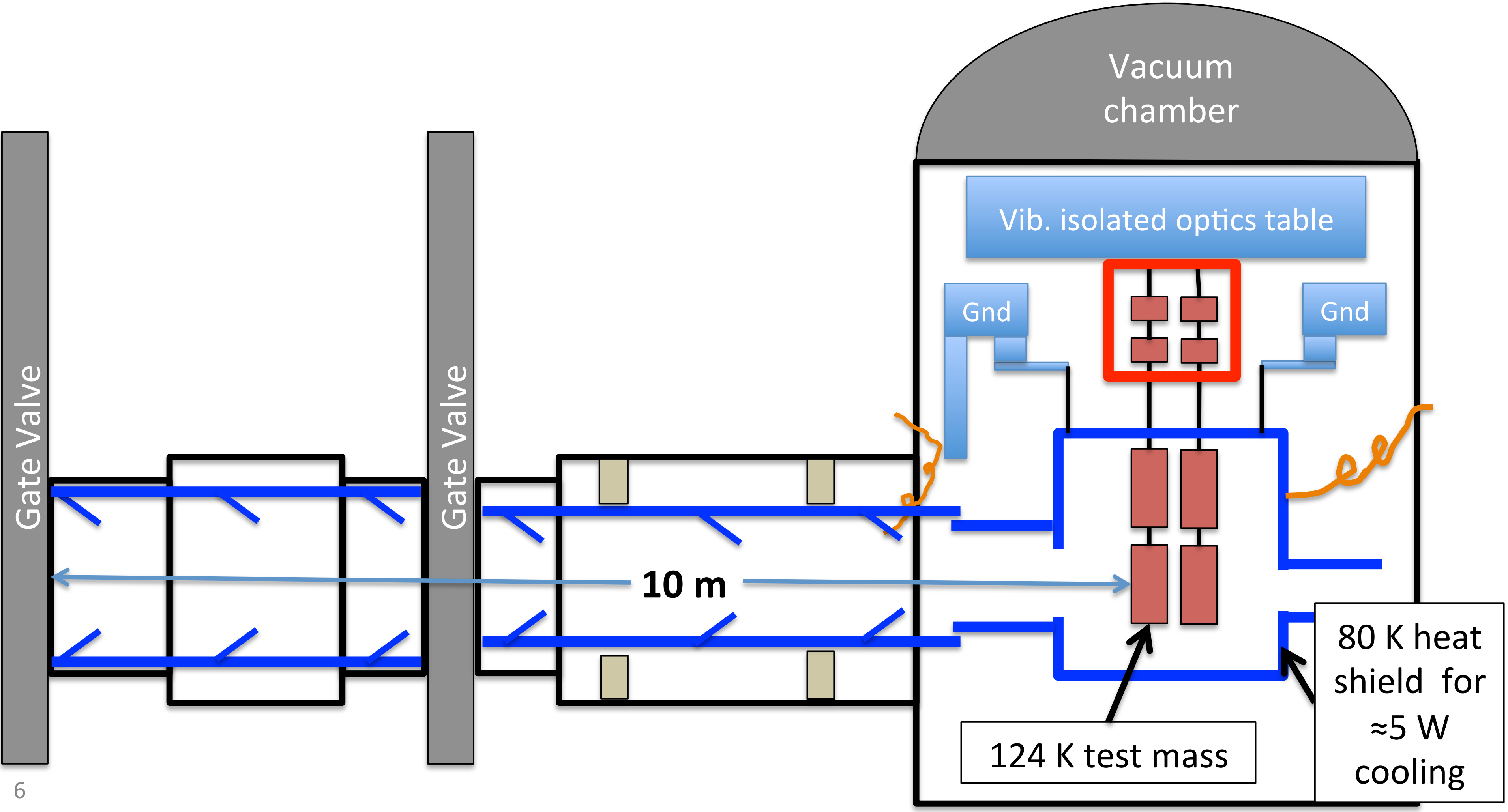

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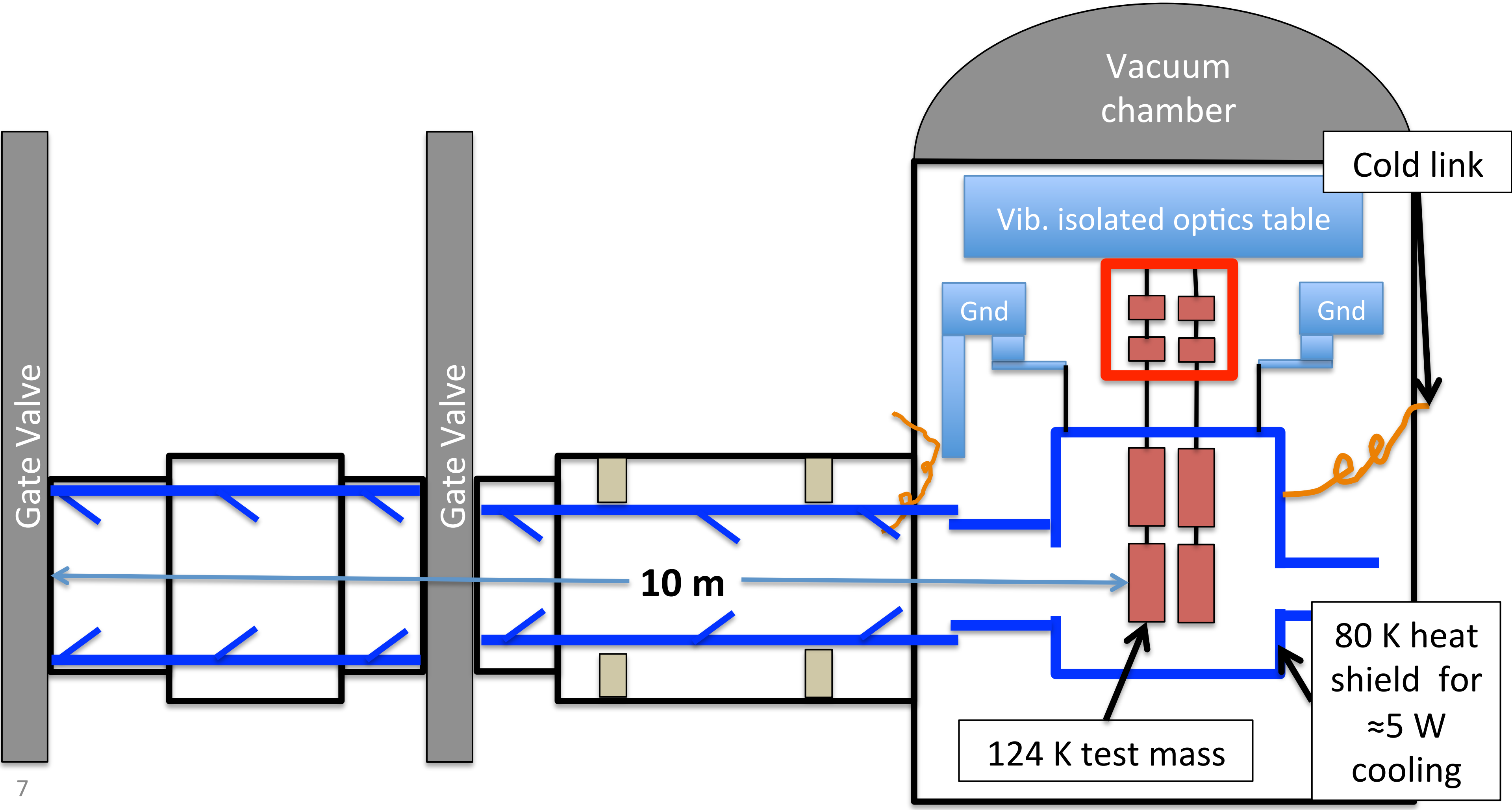

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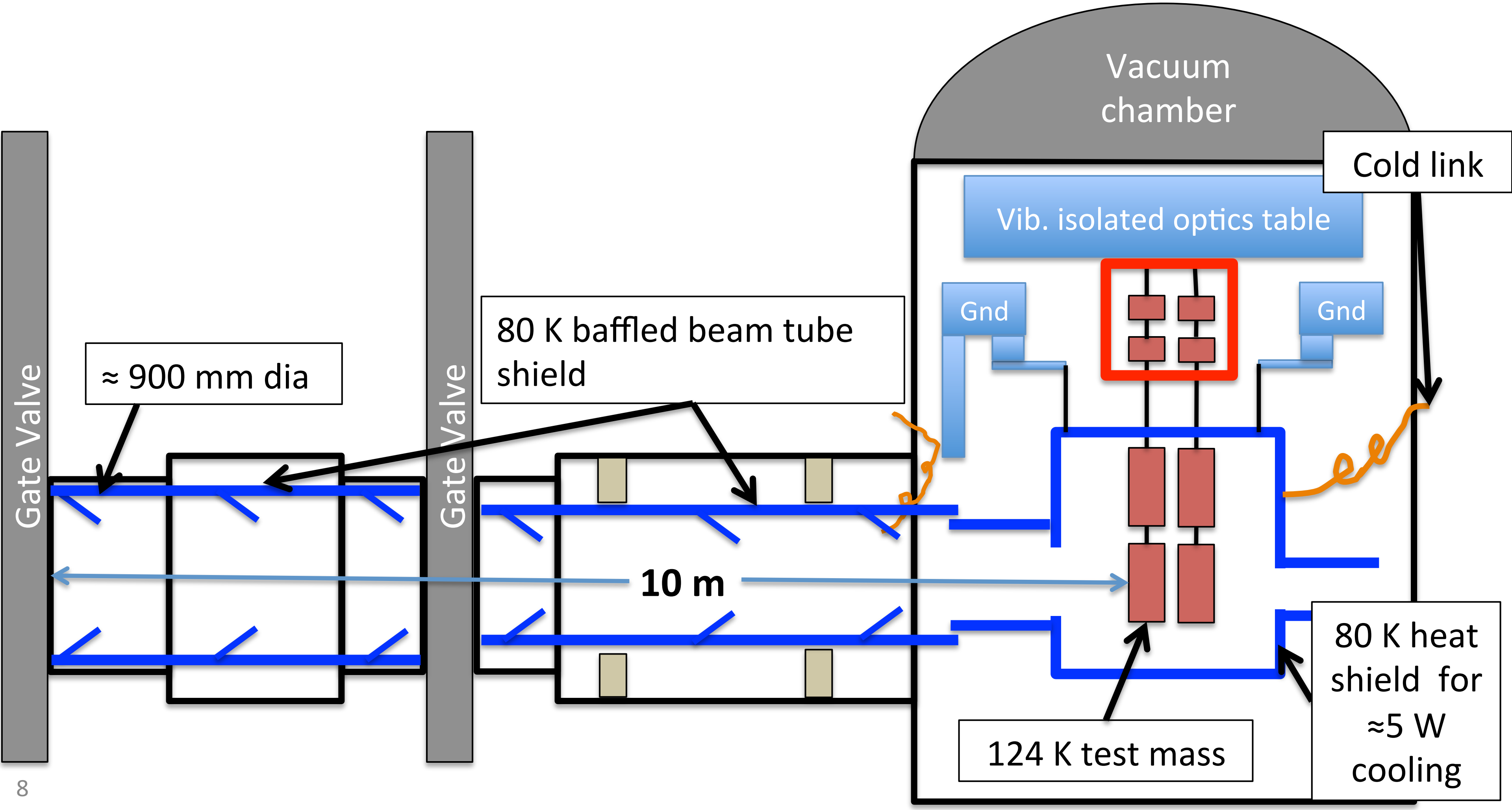

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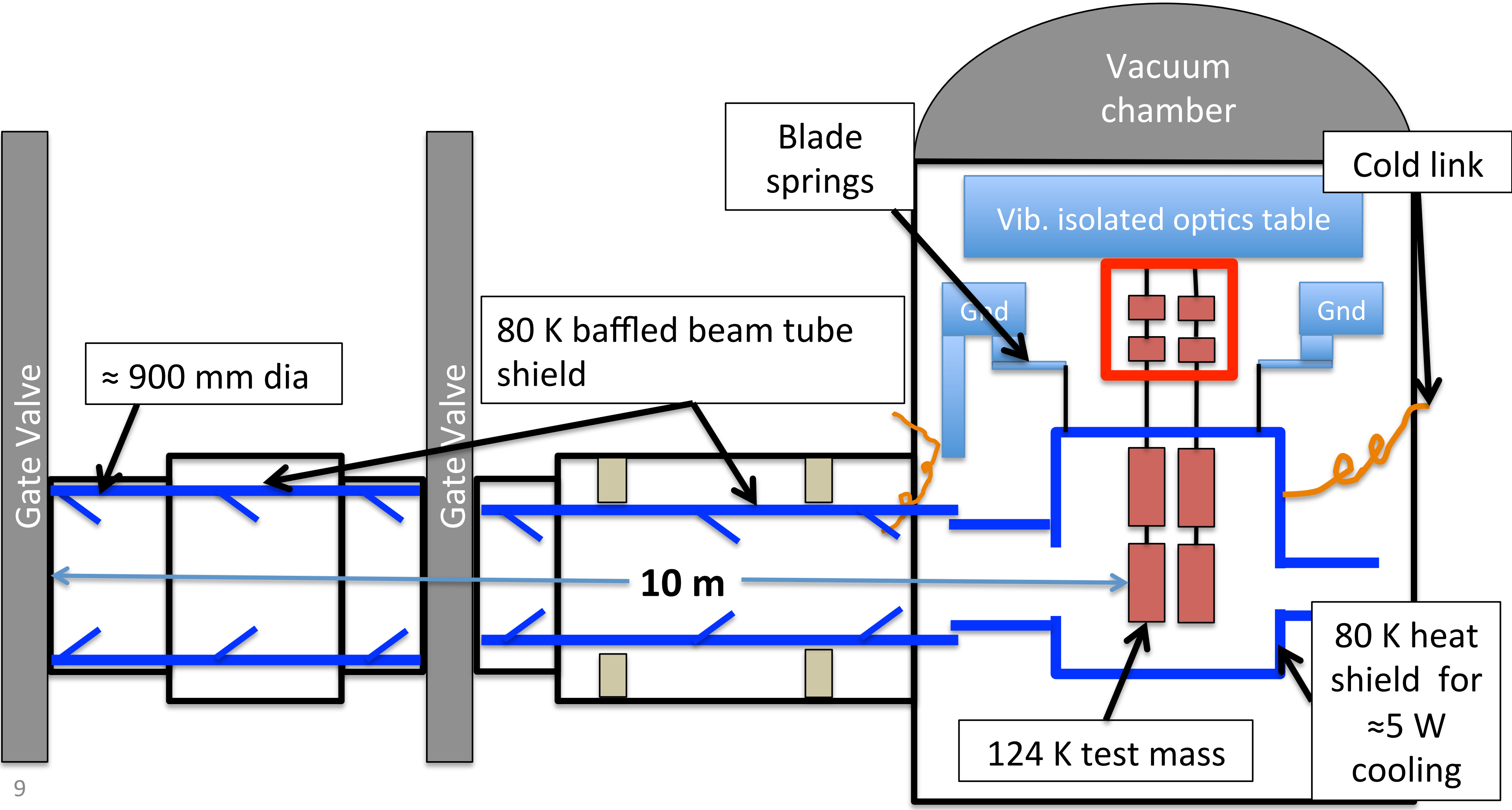

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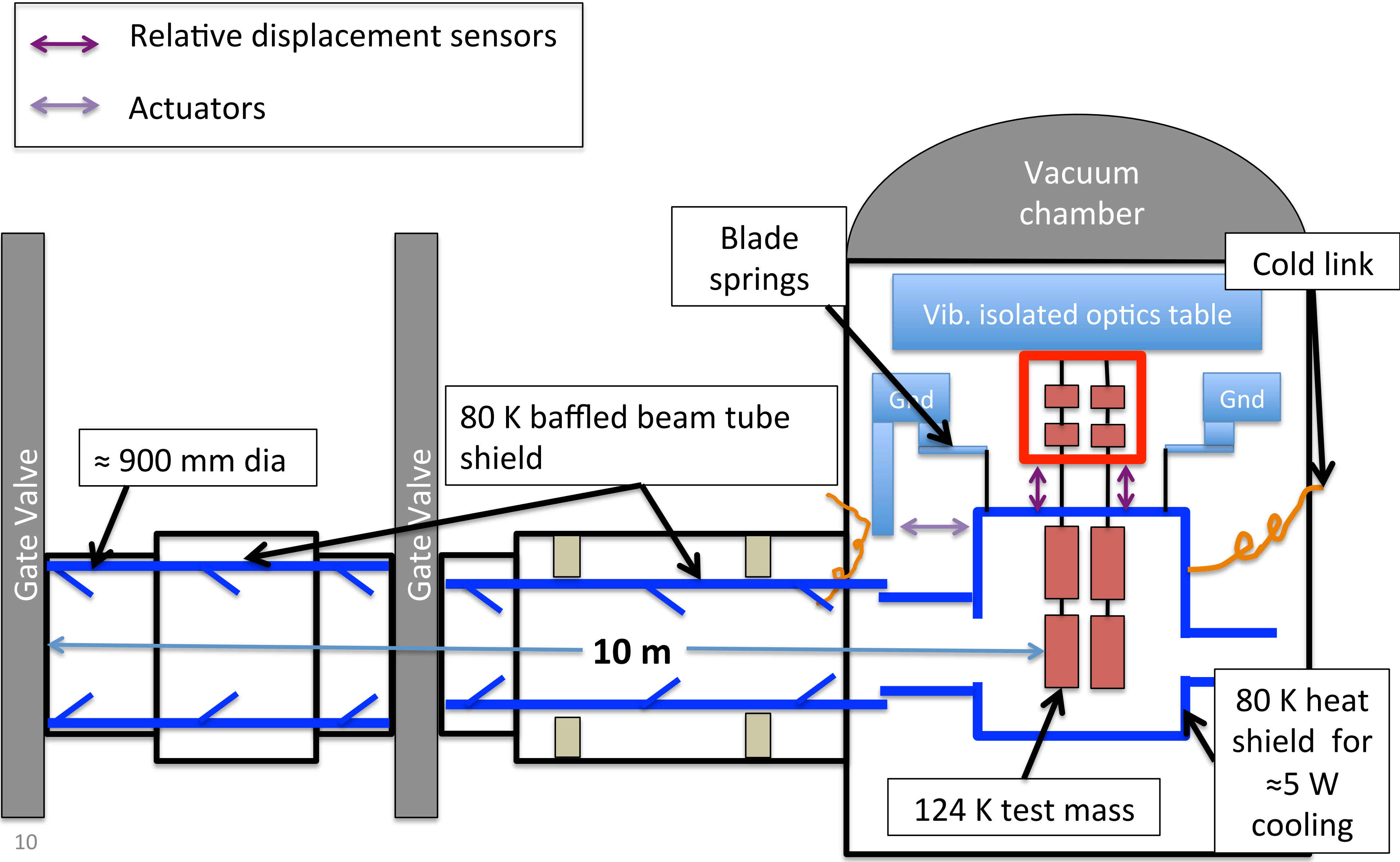
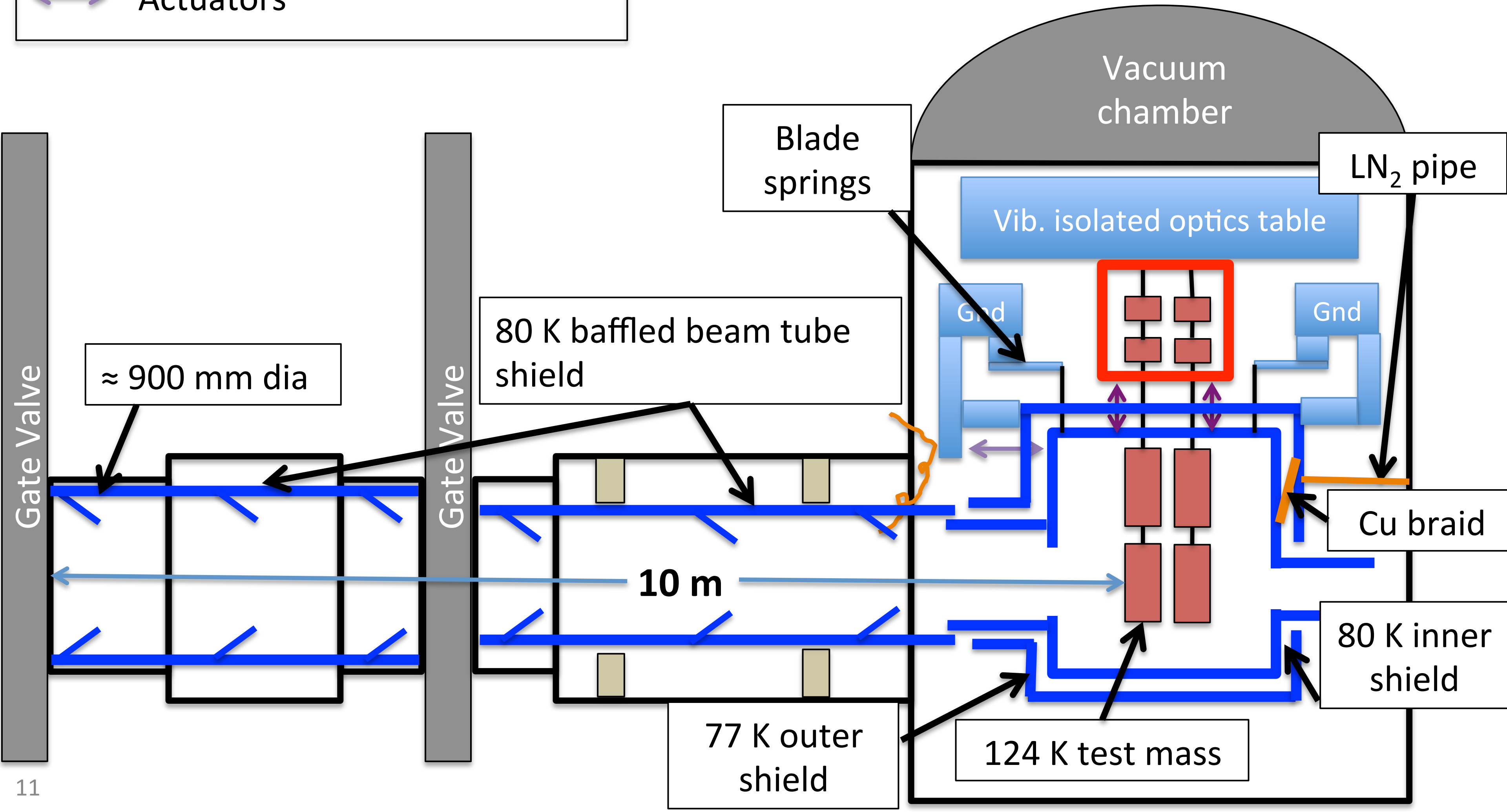


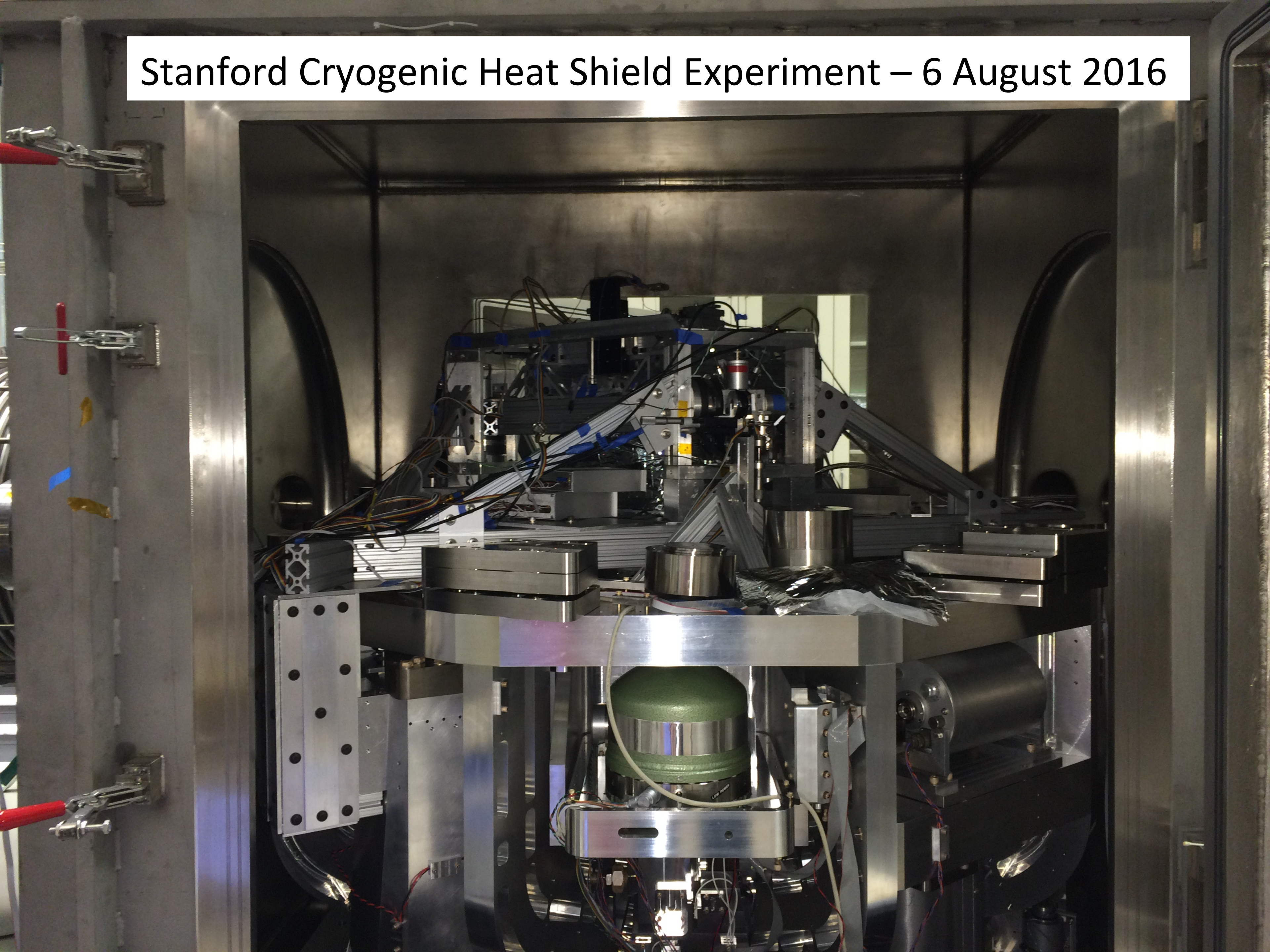
Actively controlled shield (ETM)

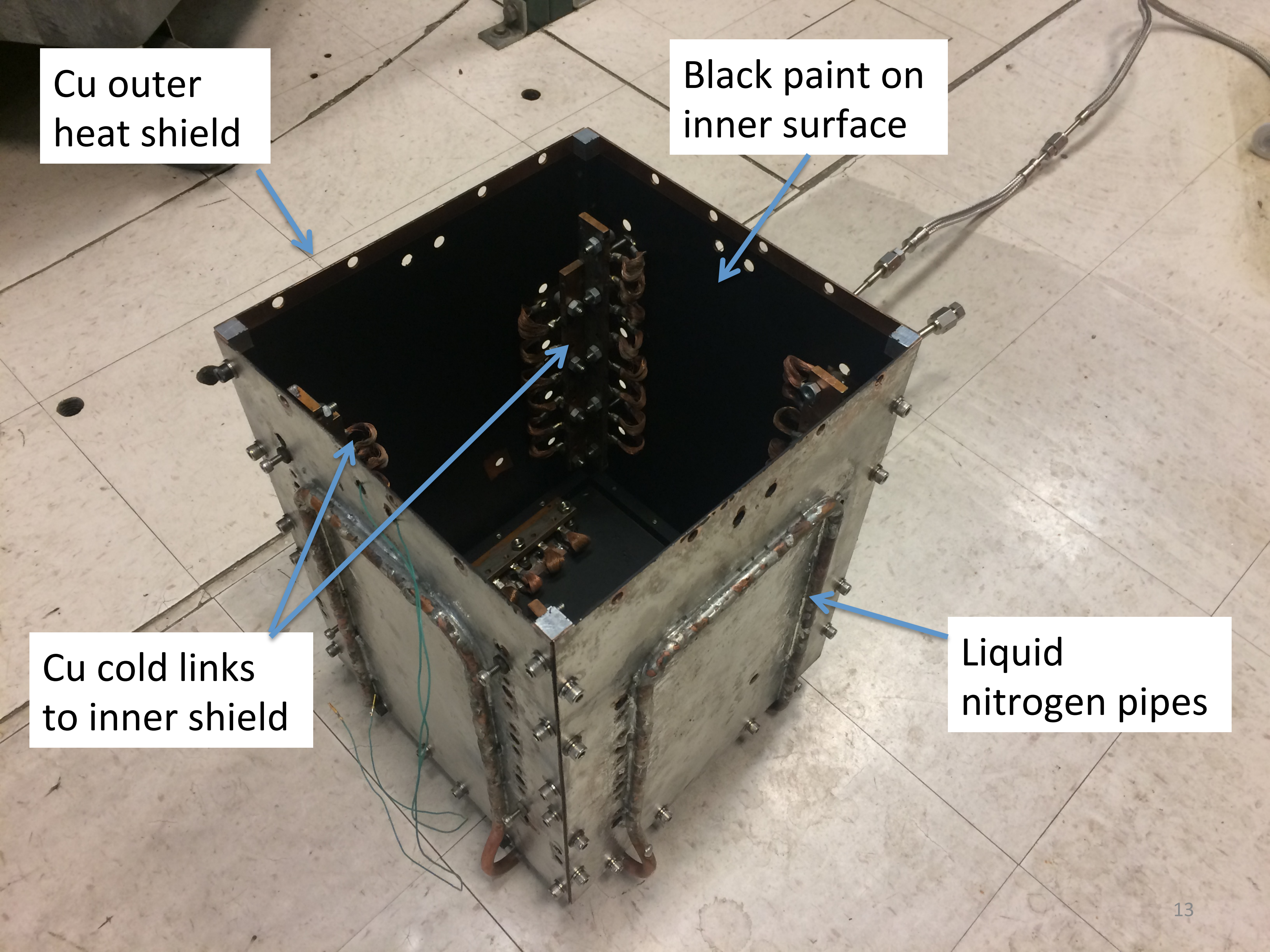
⟷ Relative displacement sensors

⟷ Actuators



Stanford Cryogenic Heat Shield Experiment – 6 August 2016



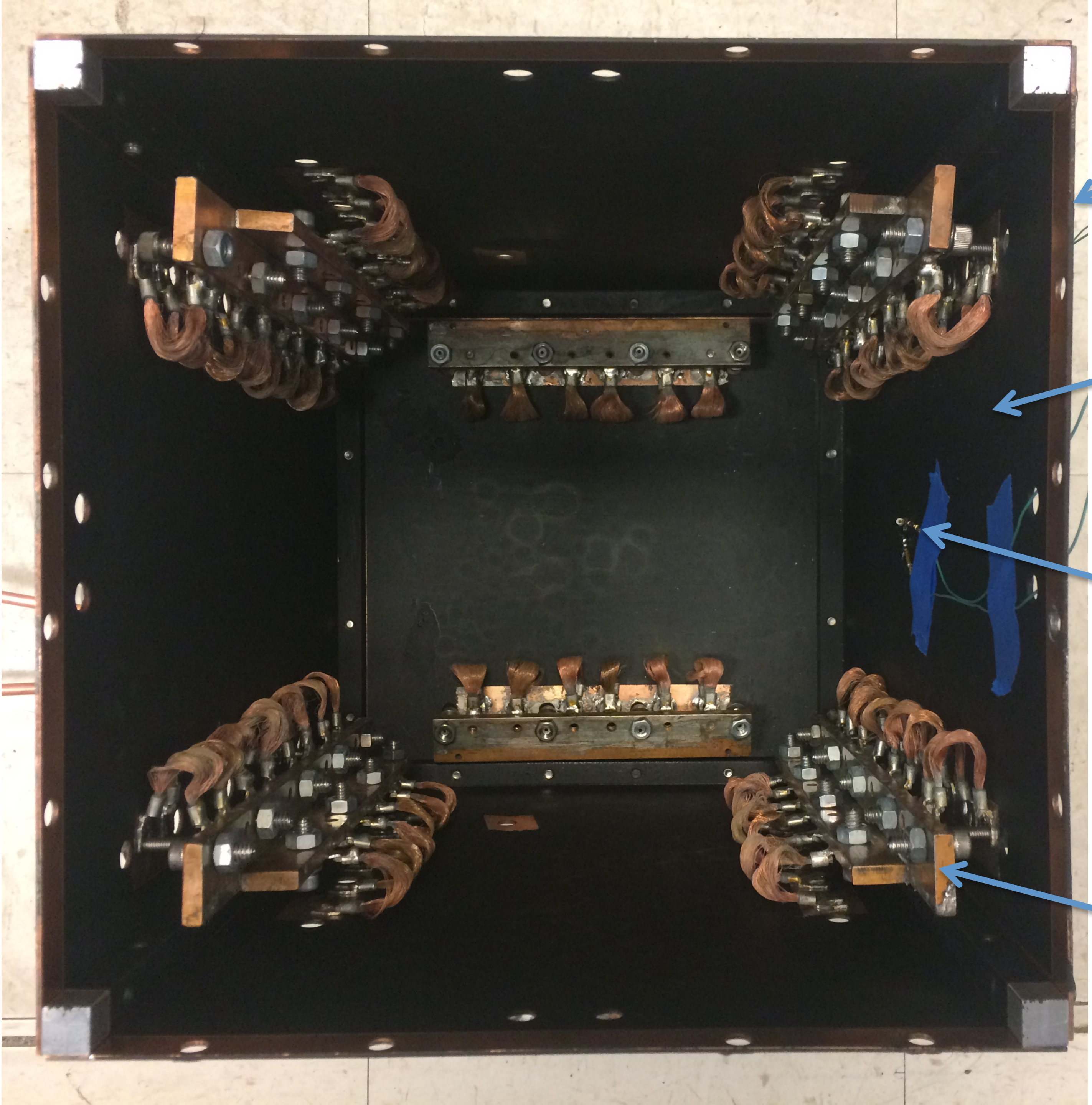


Cu outer heat shield

Black paint on inner surface

Cu cold links to inner shield

Liquid nitrogen pipes

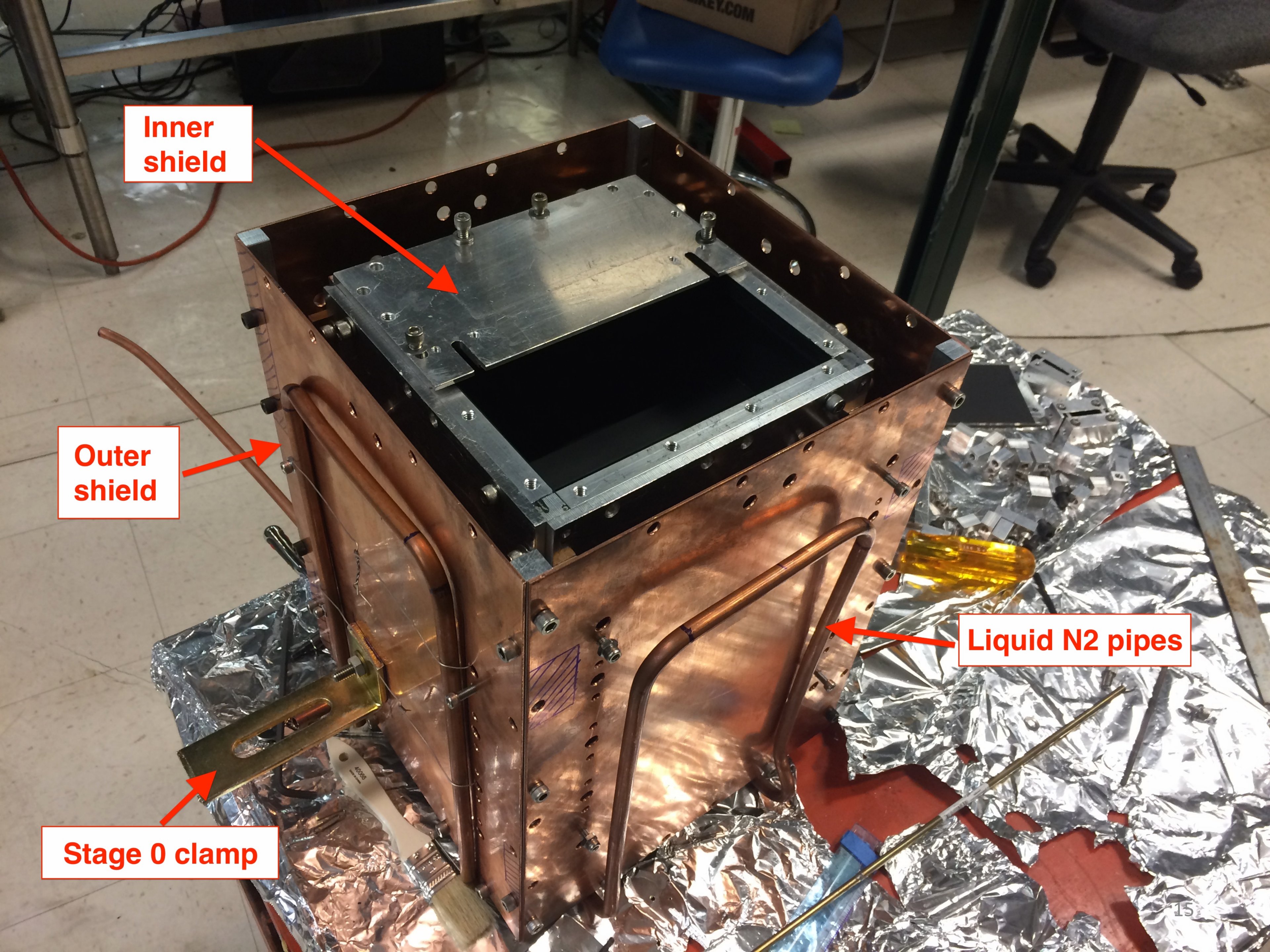


Cu outer heat shield

Black paint on inner surface

Temperature sensor

Cu cold links to inner shield



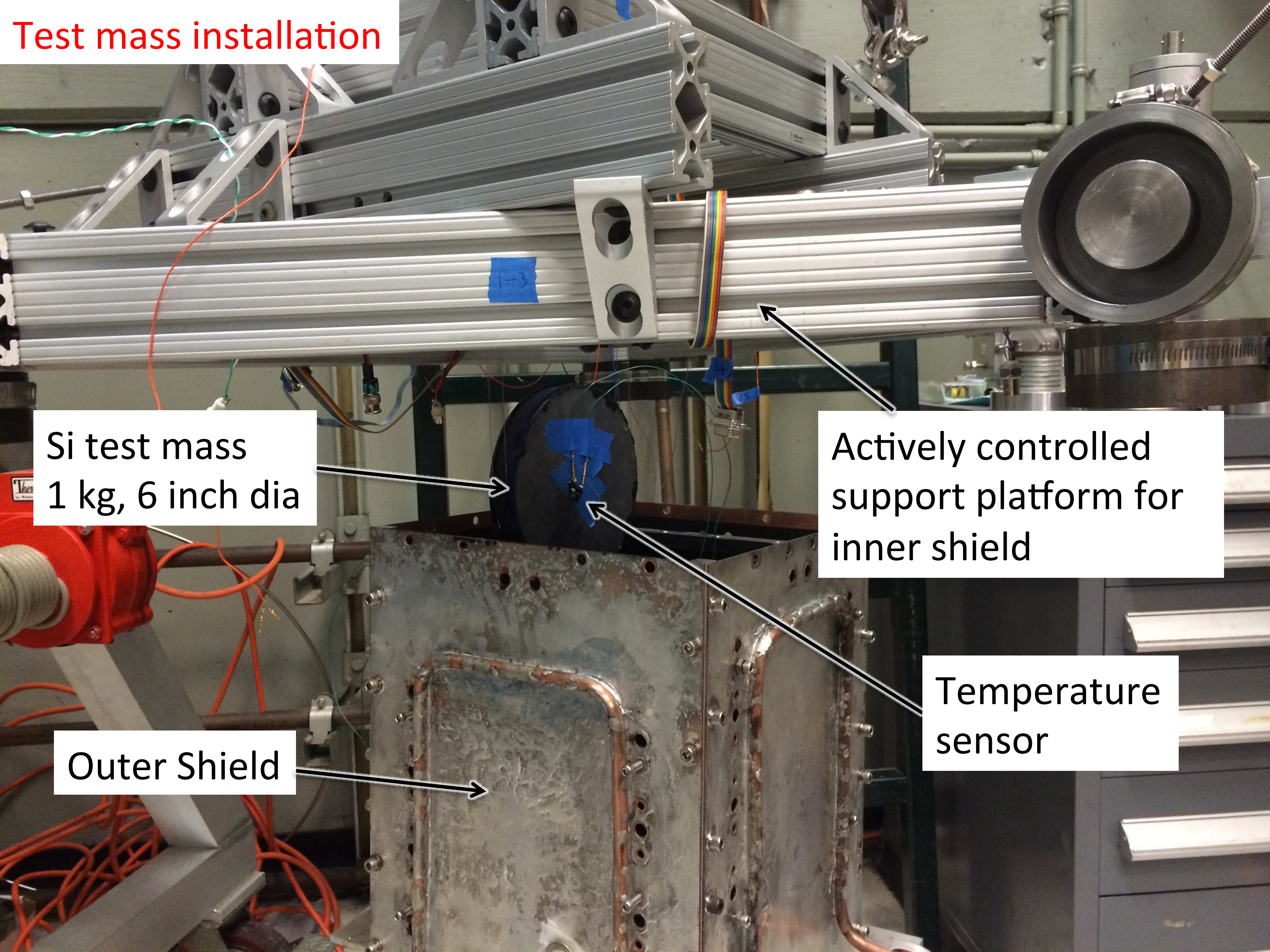
Inner shield

Outer shield

Liquid N2 pipes

Stage 0 clamp

Test mass installation

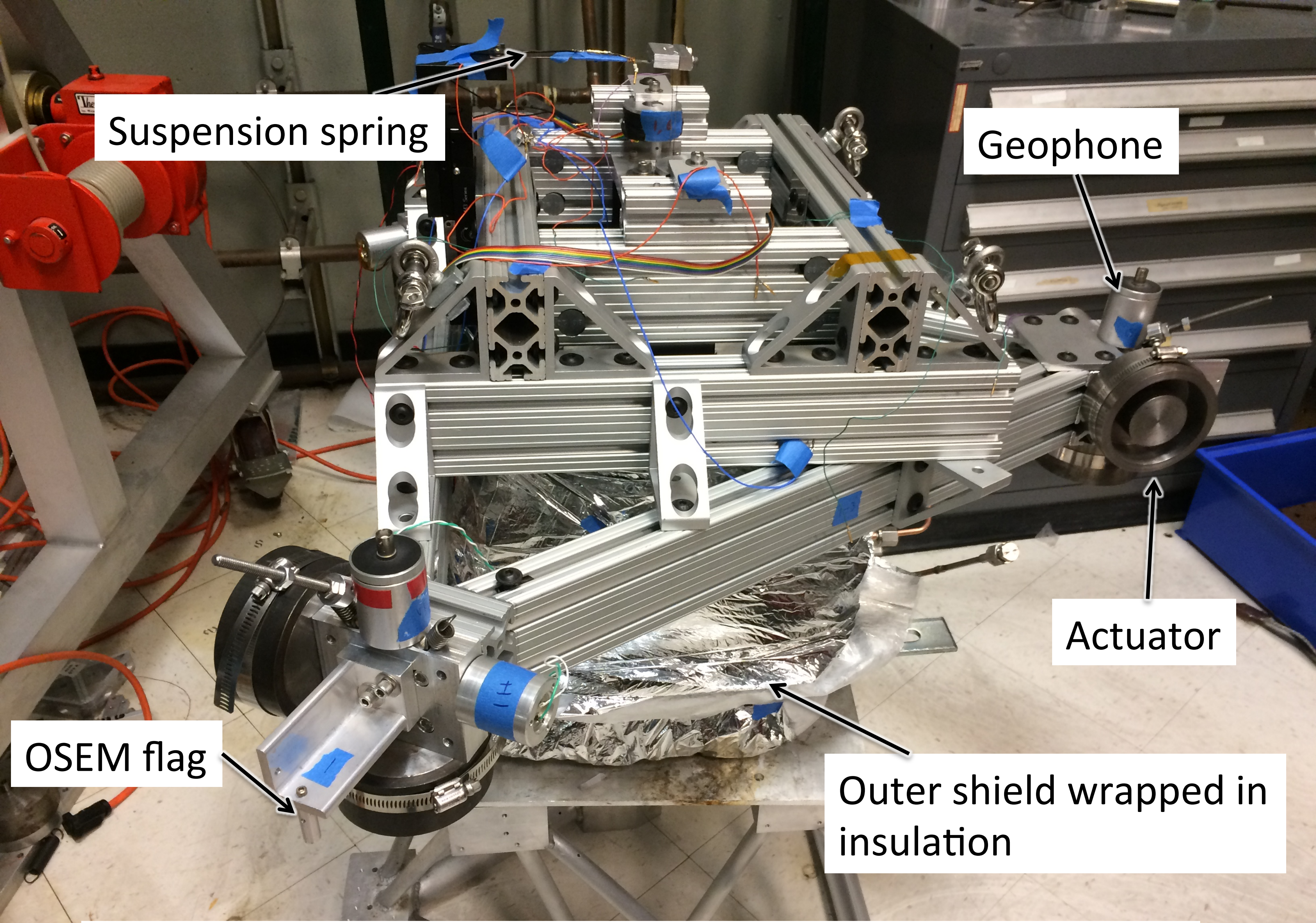


Si test mass
1 kg, 6 inch dia

Actively controlled support platform for inner shield

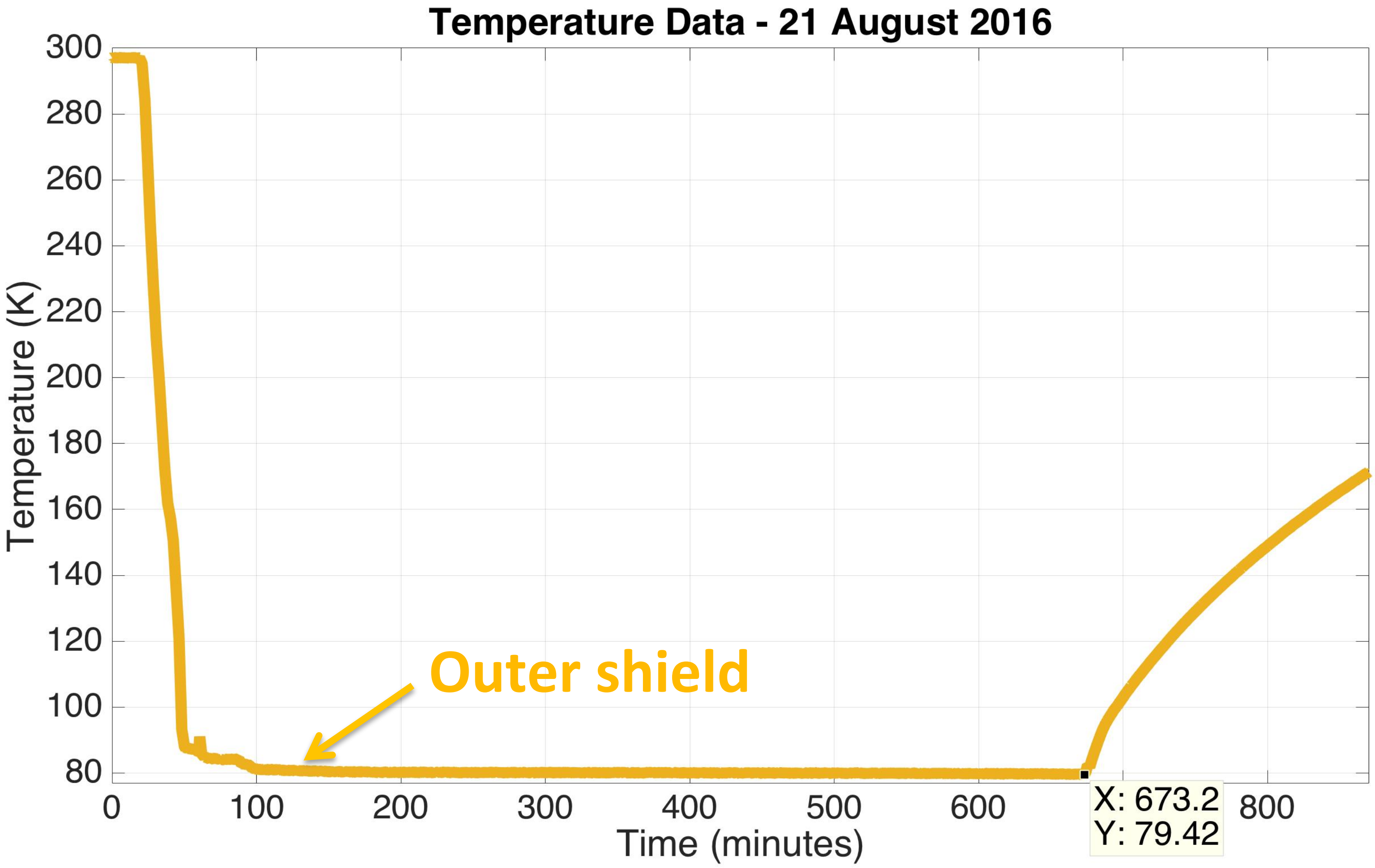
Temperature sensor

Outer Shield



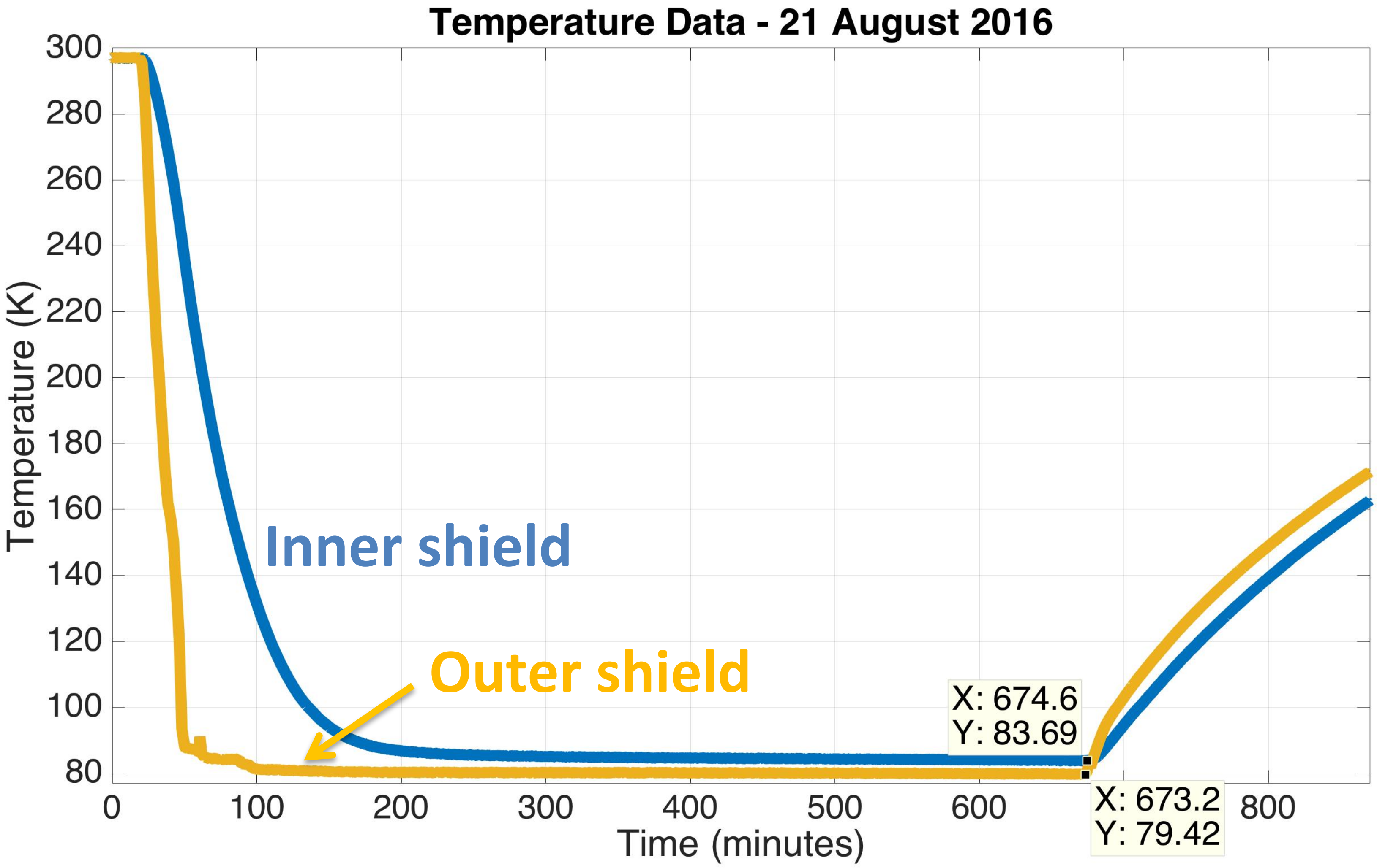
Assembled cryo experiment before installation into chamber

Measured Temperature Response

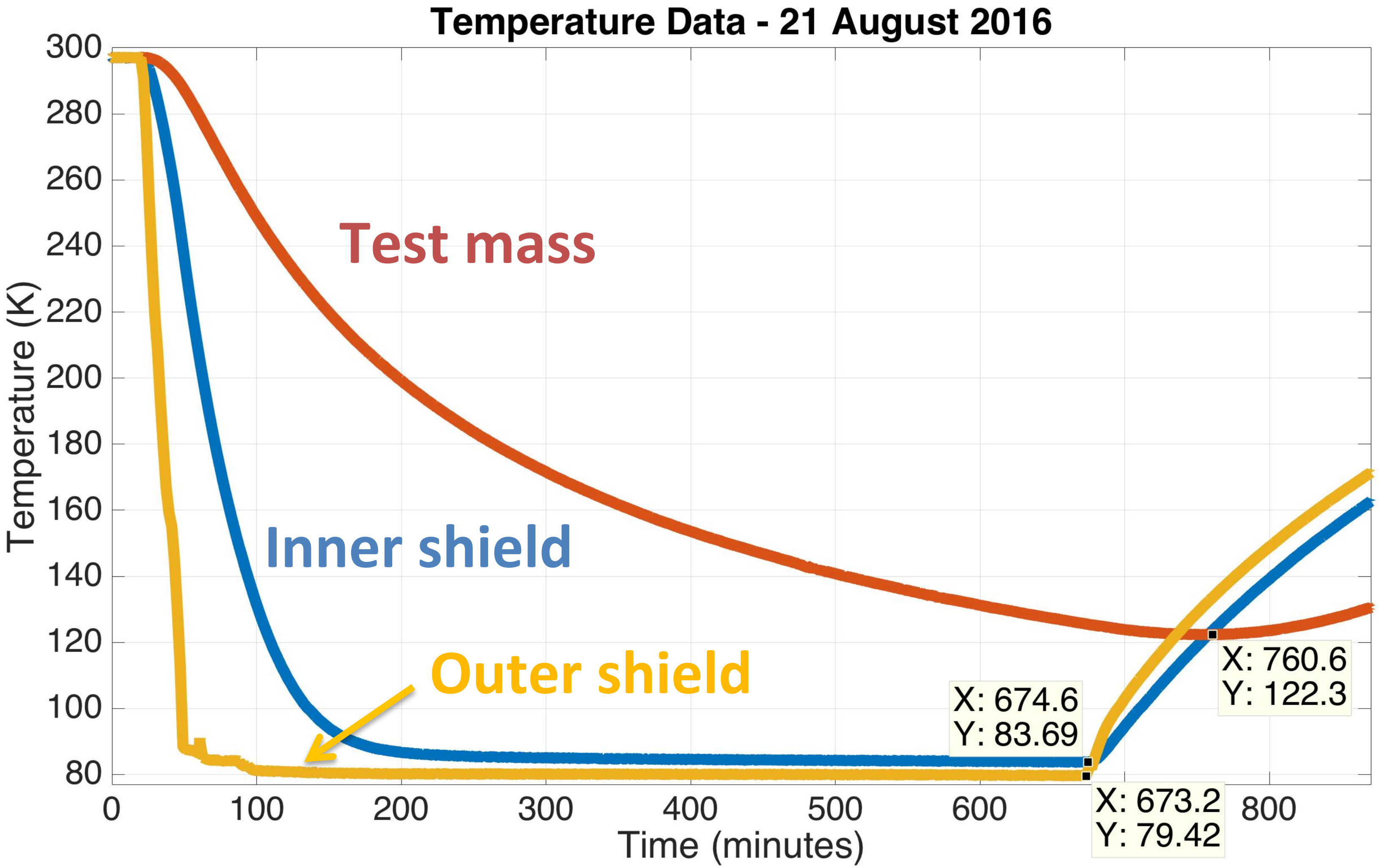


Outer shield

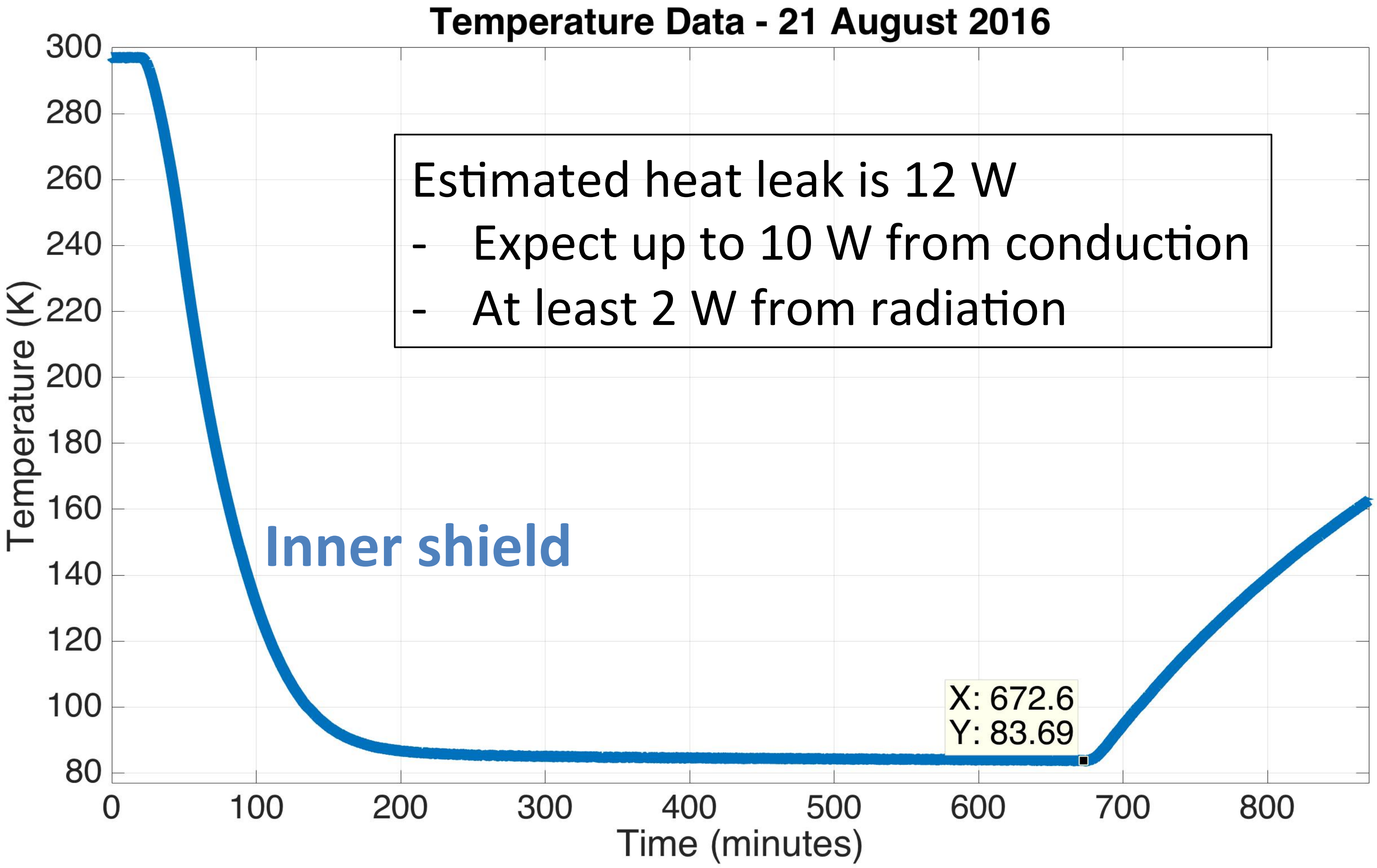
Measured Temperature Response



Measured Temperature Response



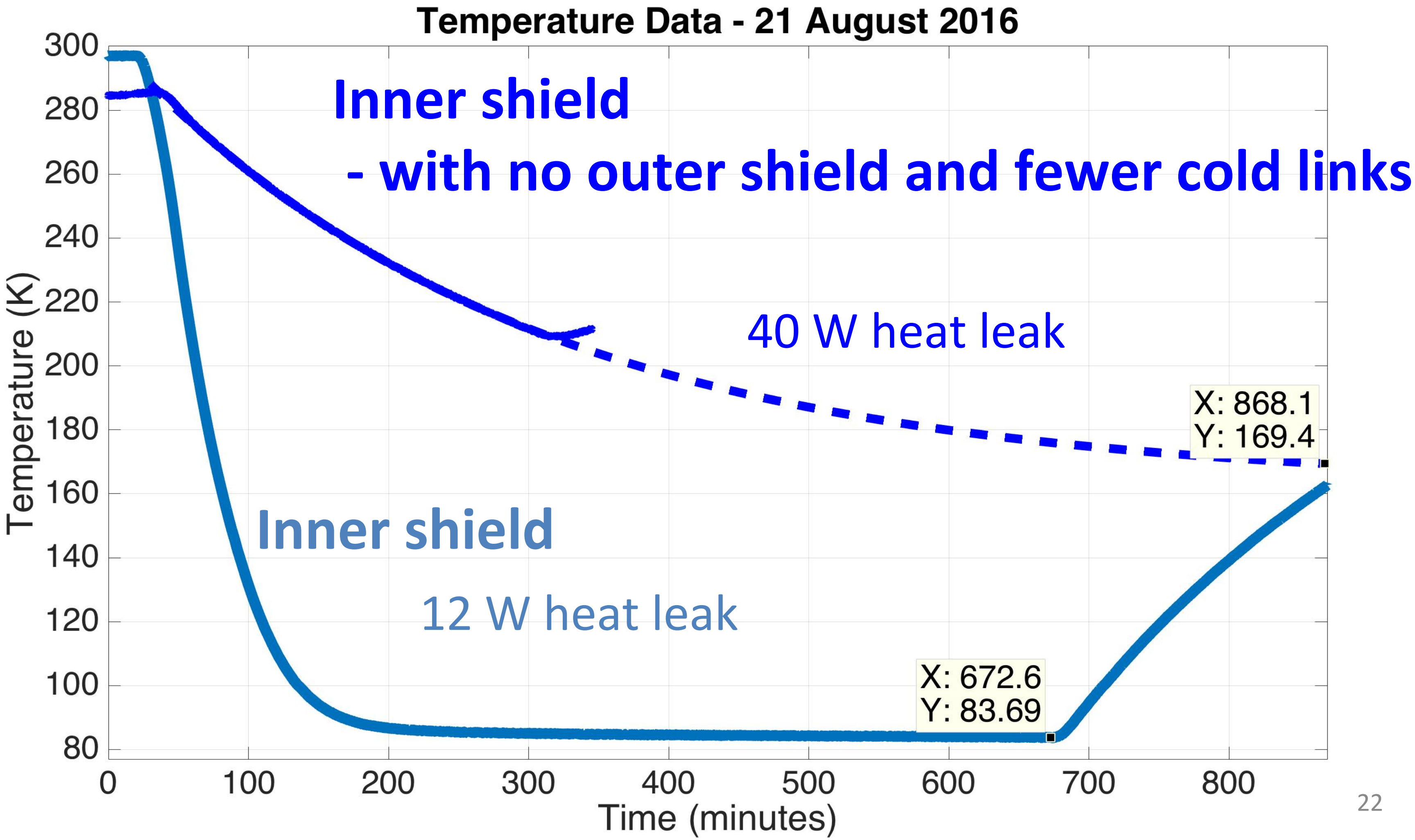
Measured Temperature Response



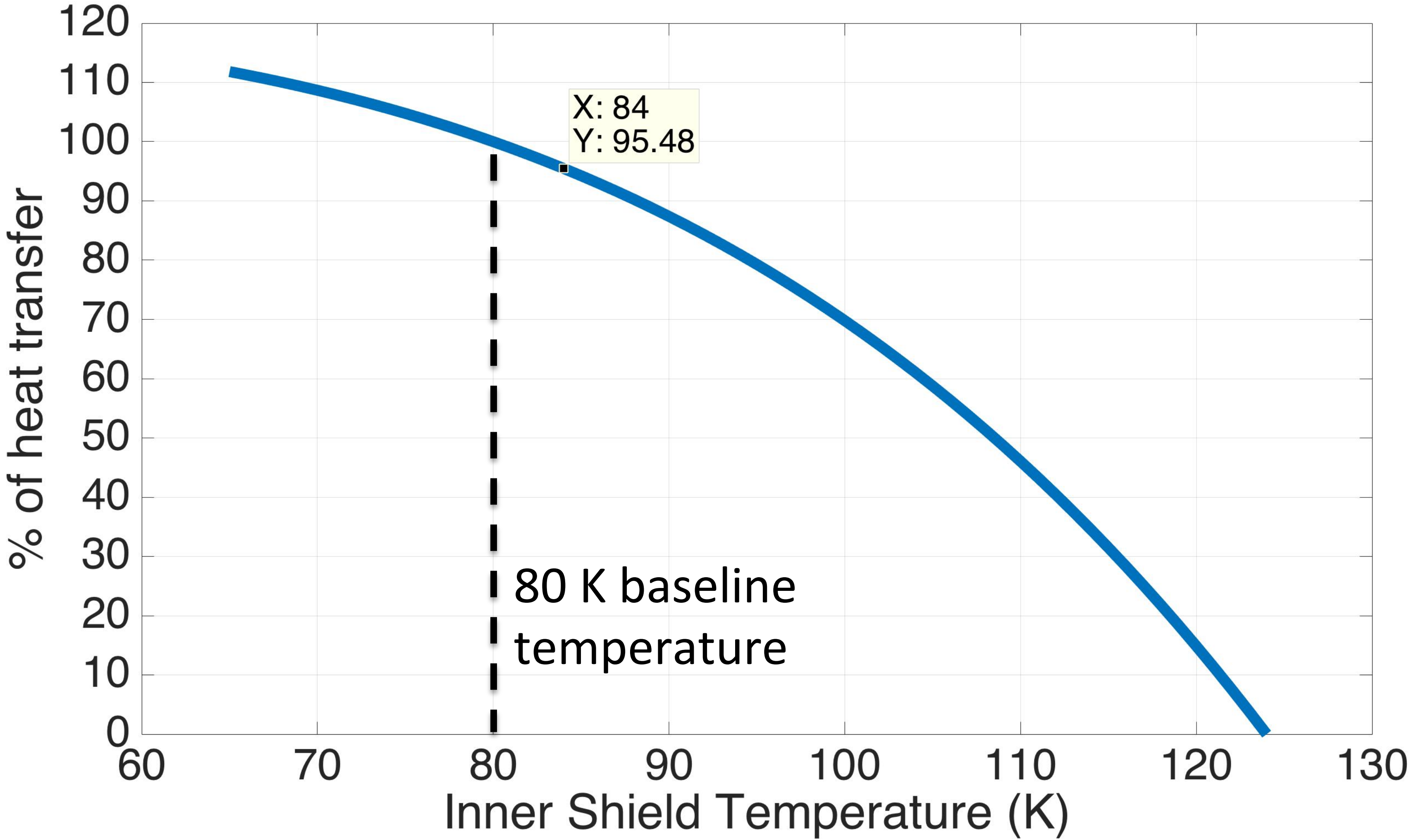
Estimated heat leak is 12 W

- Expect up to 10 W from conduction
- At least 2 W from radiation

Measured Temperature Response

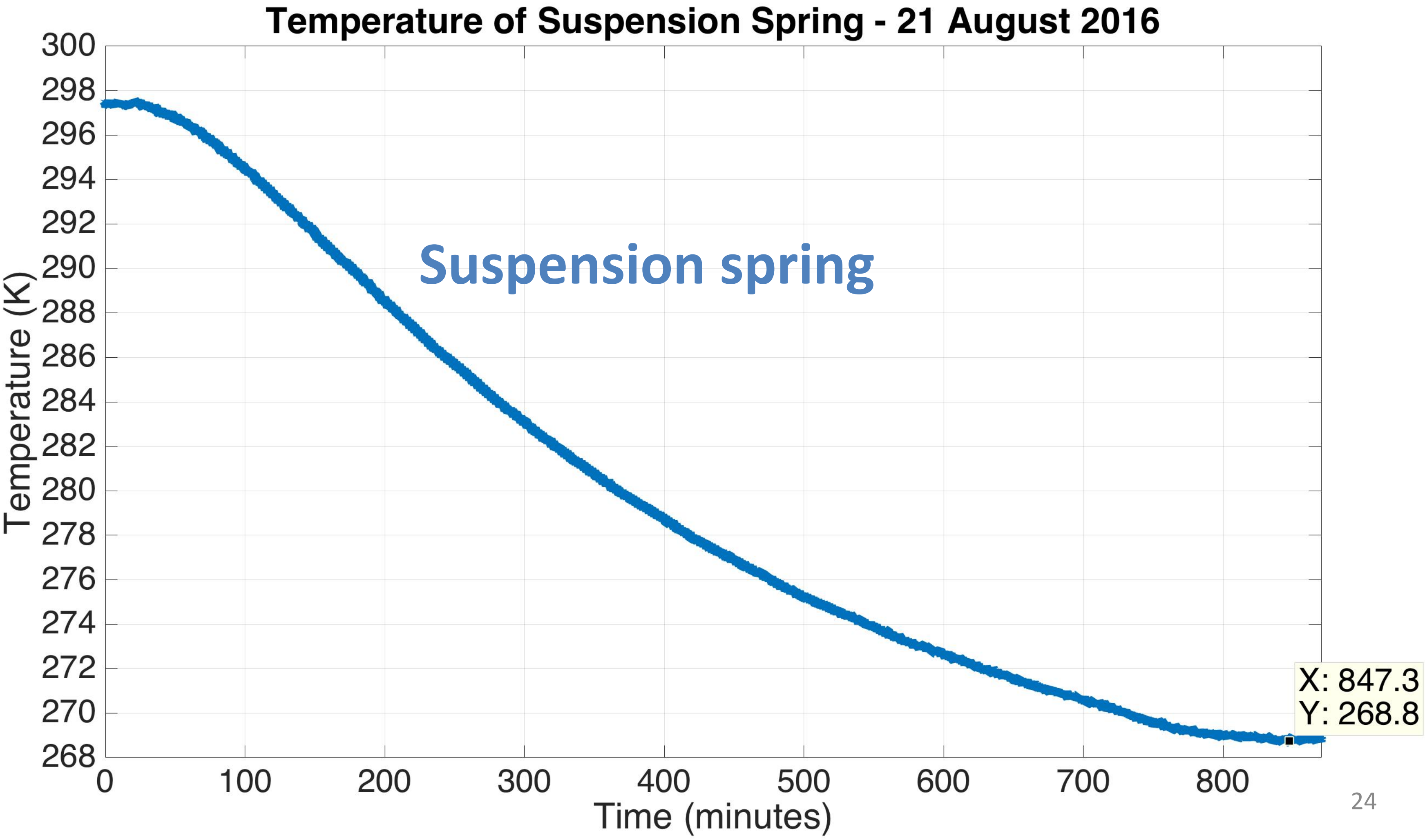


Test Mass Heat Transfer vs Shield Temp



80 K baseline temperature

Measured Temperature Response

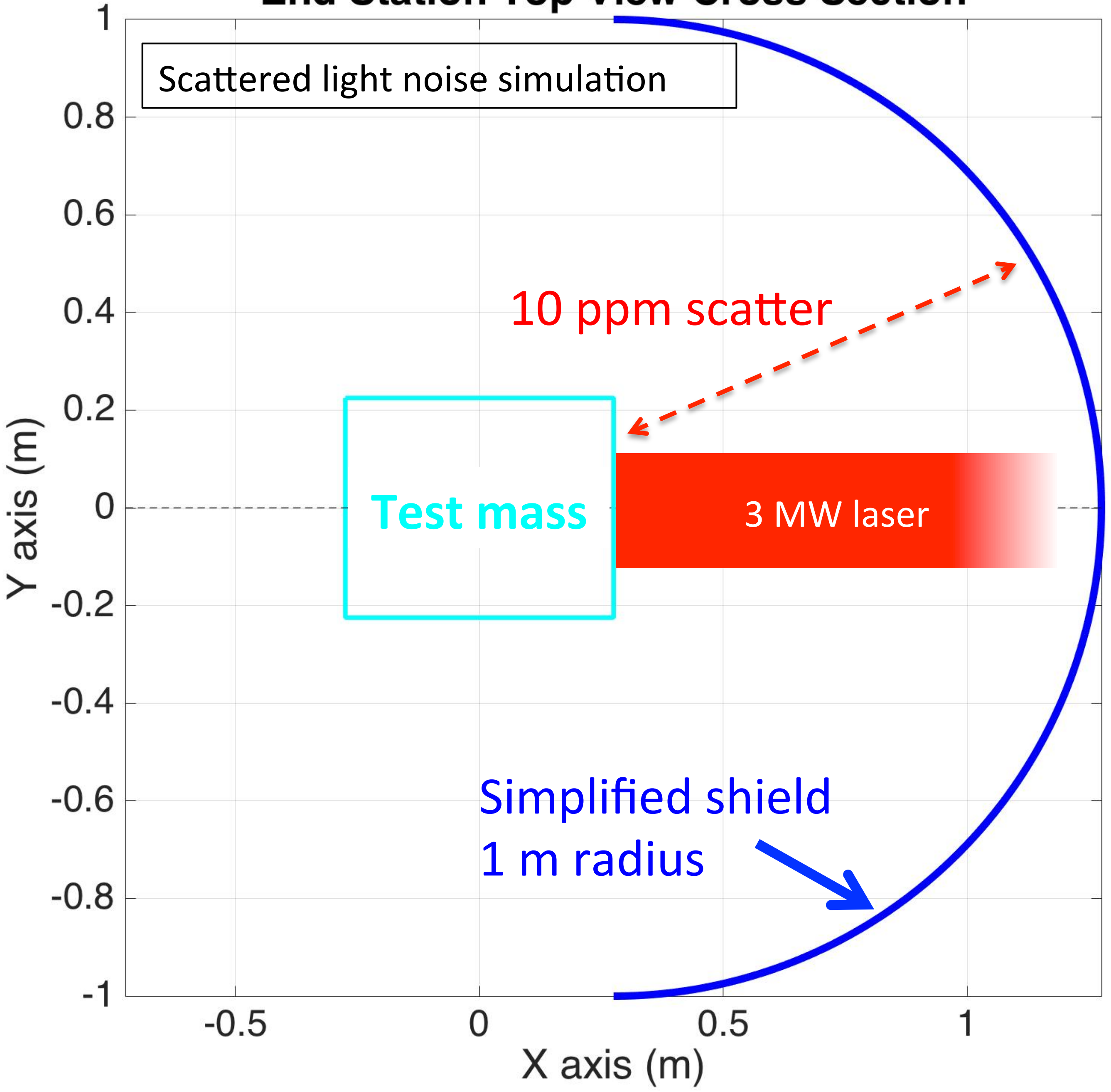


Temperature of Suspension Spring - 21 August 2016

Suspension spring

Scattered Light Noise

End Station Top View Cross Section



Scattered light noise simulation

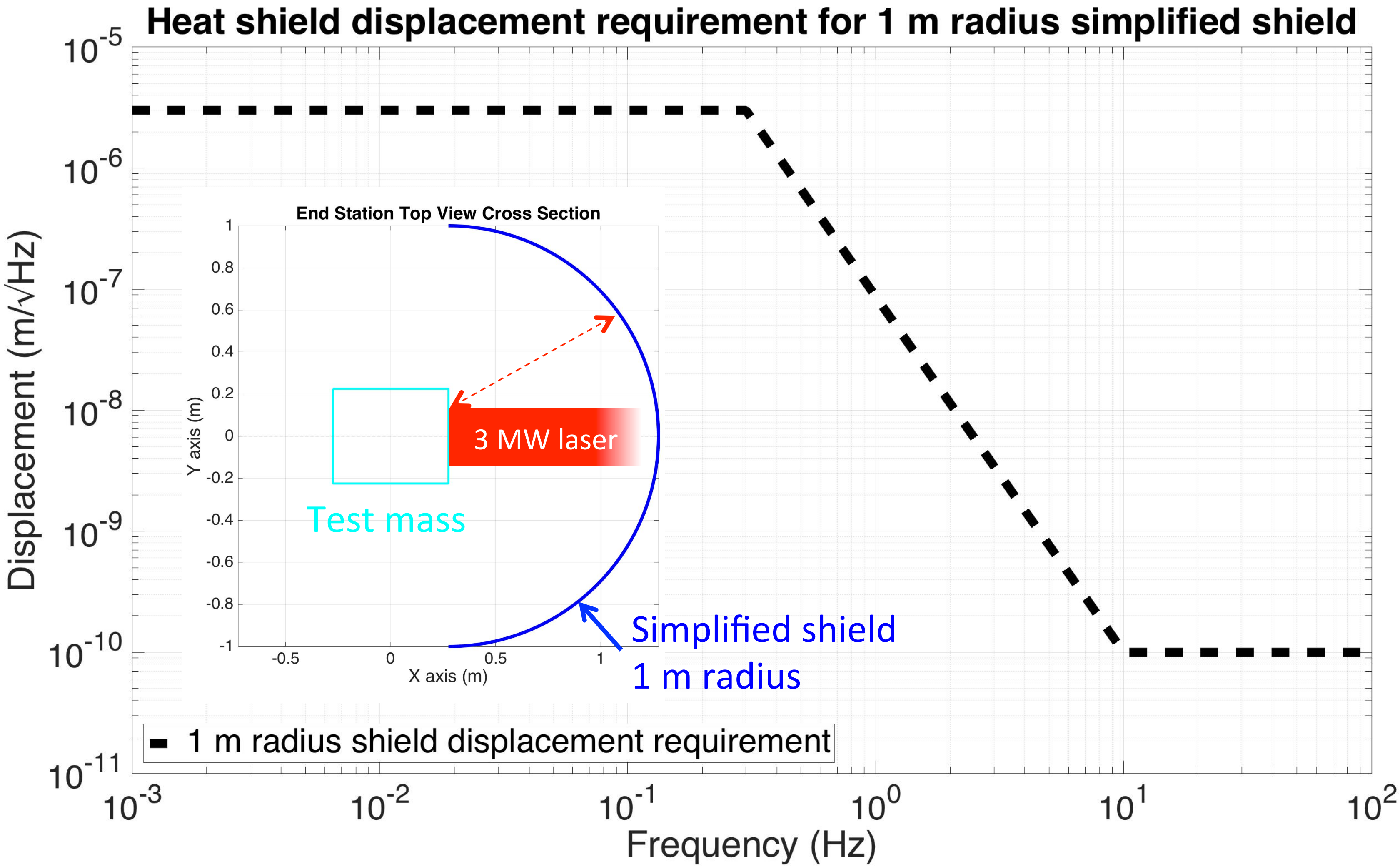
10 ppm scatter

Test mass

3 MW laser

Simplified shield
1 m radius

Scattered light noise simulation



Heat shield displacement requirement for 1 m radius simplified shield

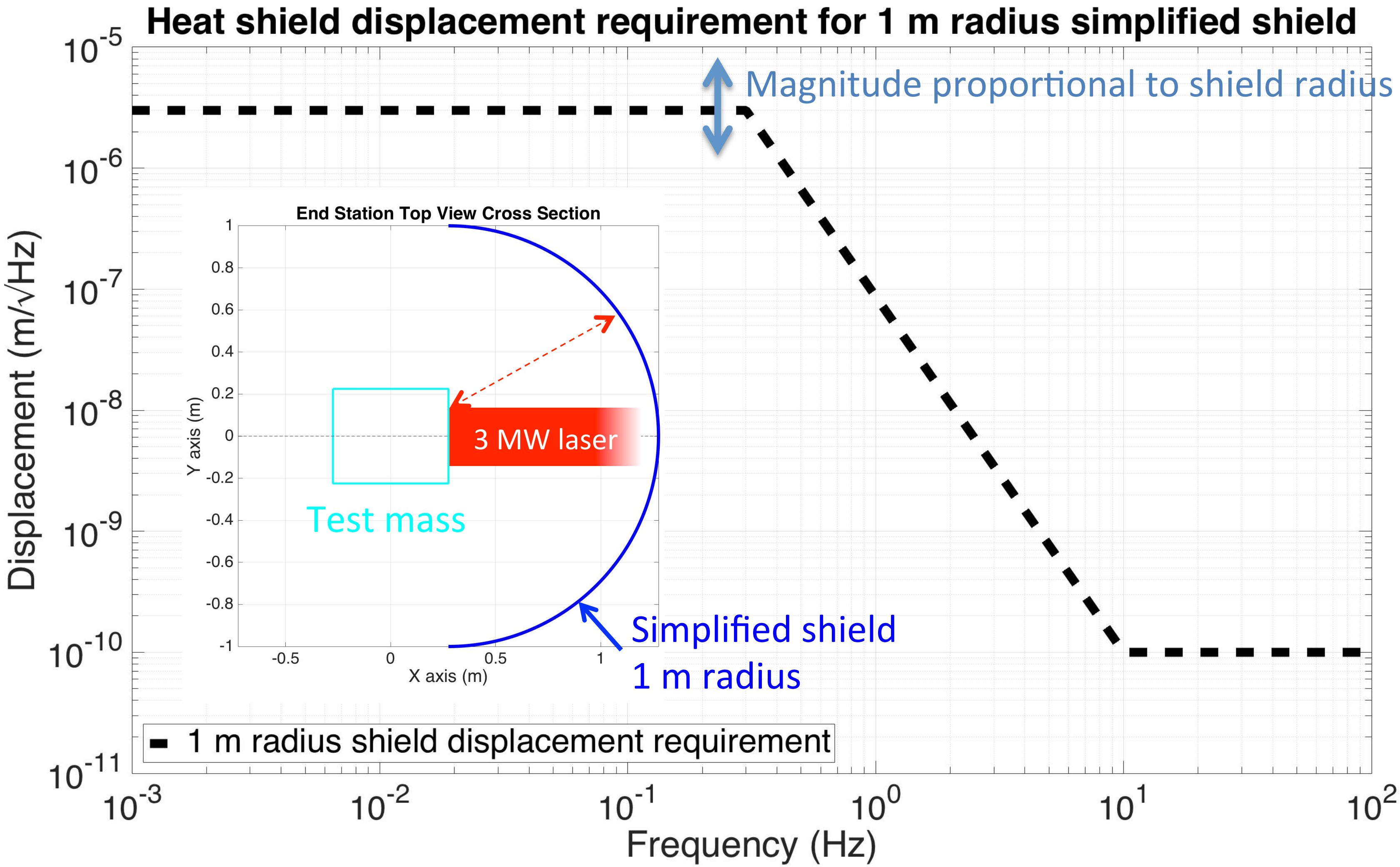
End Station Top View Cross Section

3 MW laser

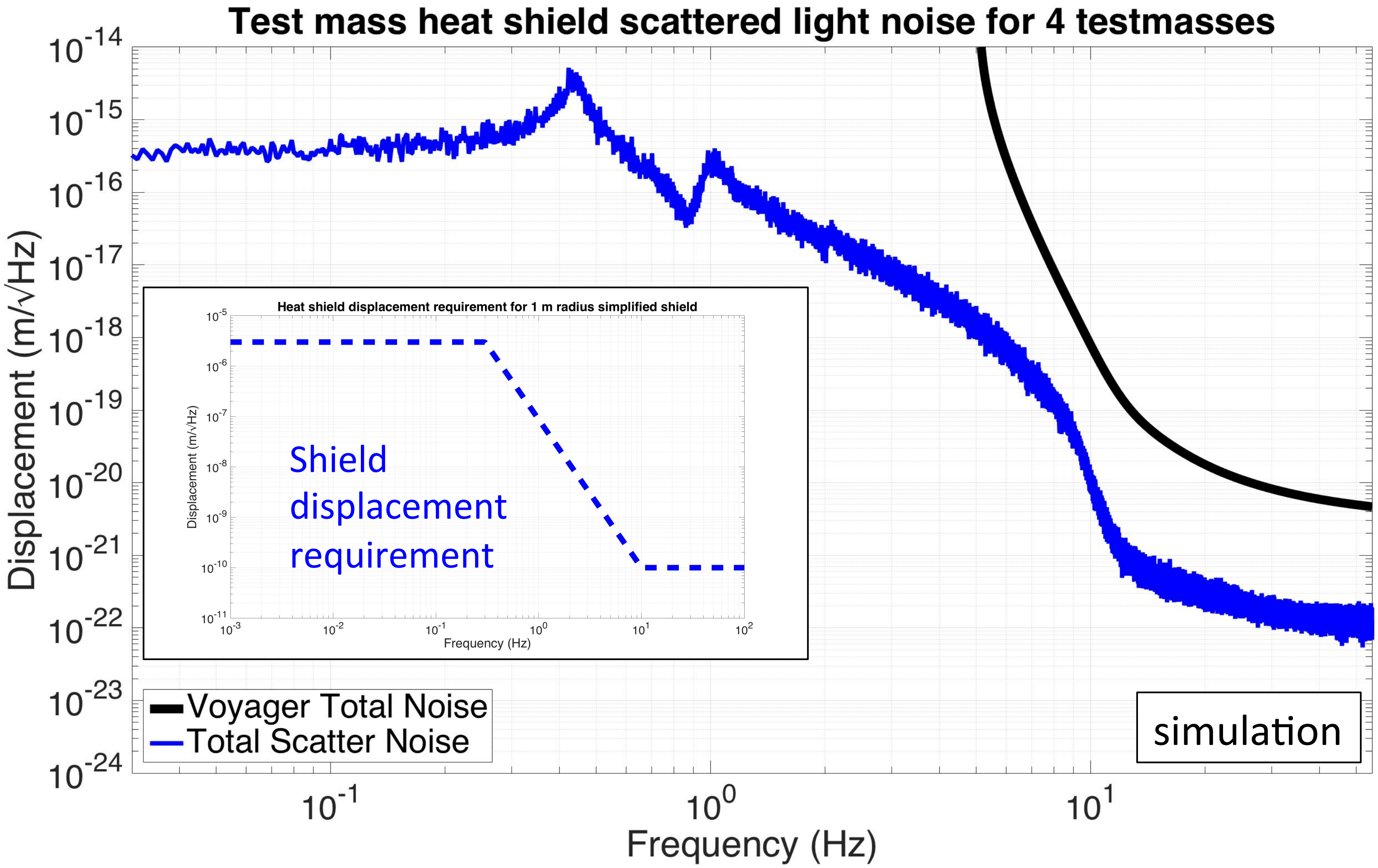
Test mass

Simplified shield
1 m radius

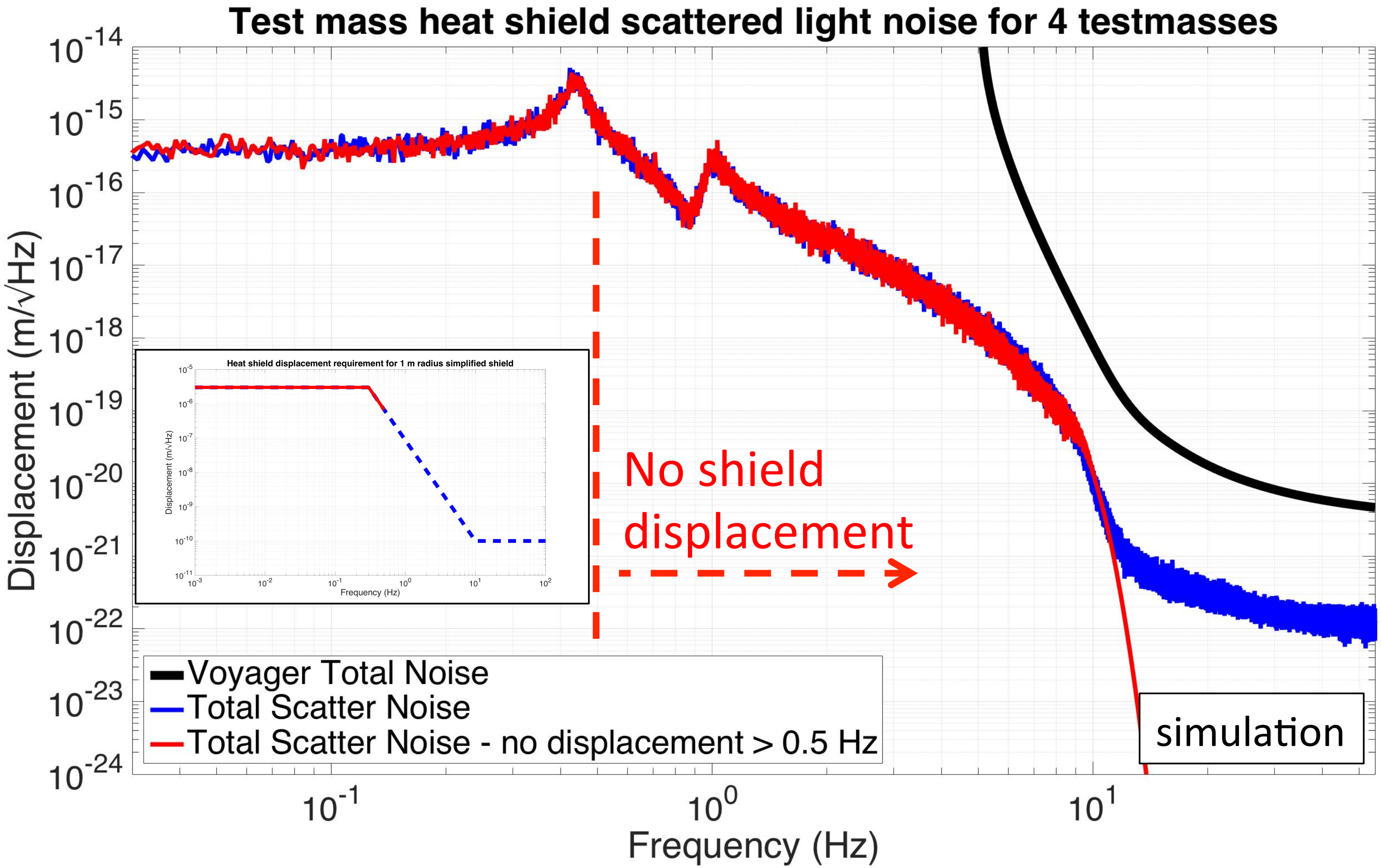
Scattered light noise simulation



Scattered light noise simulation



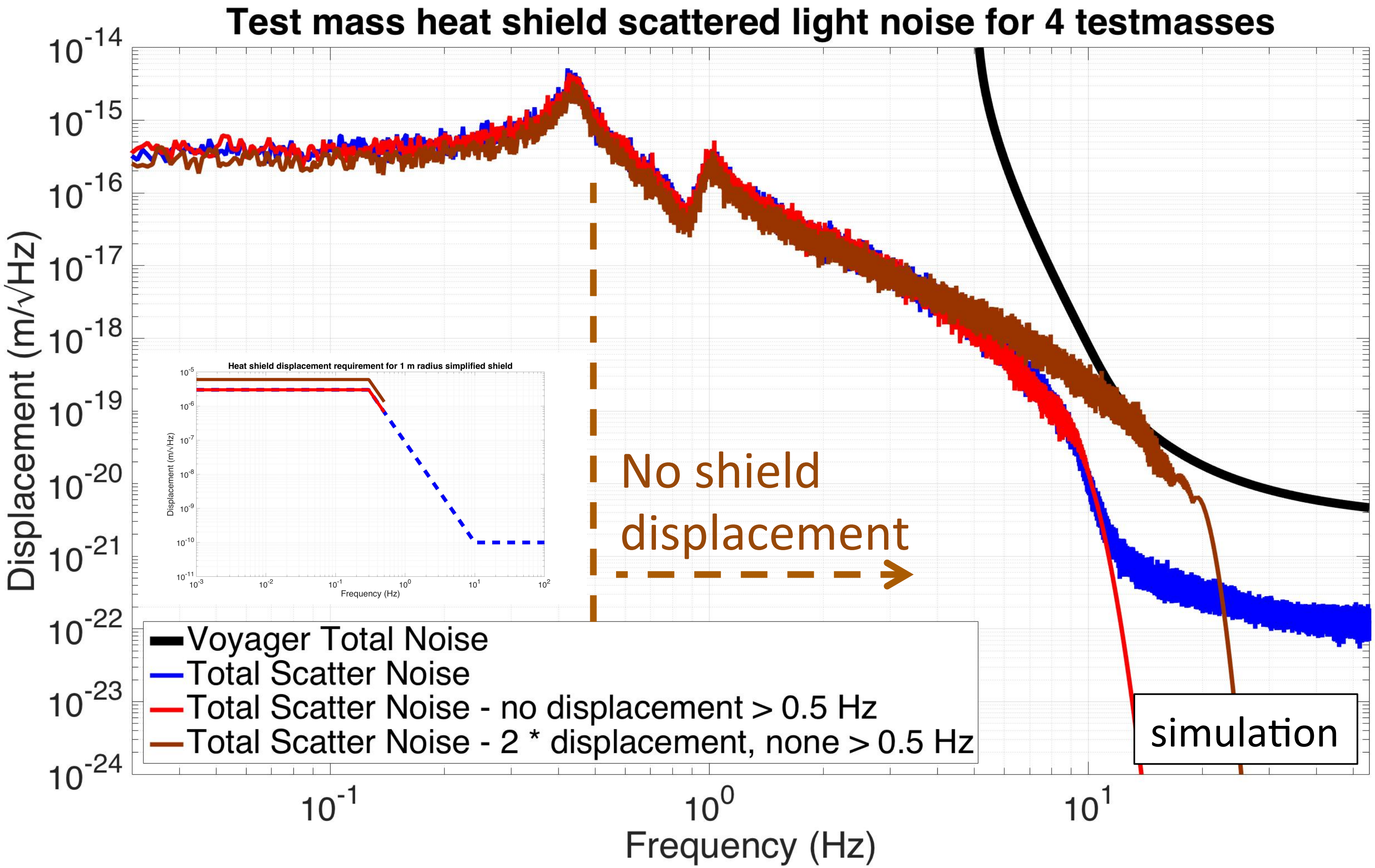
Scattered light - upconversion



No shield displacement

simulation

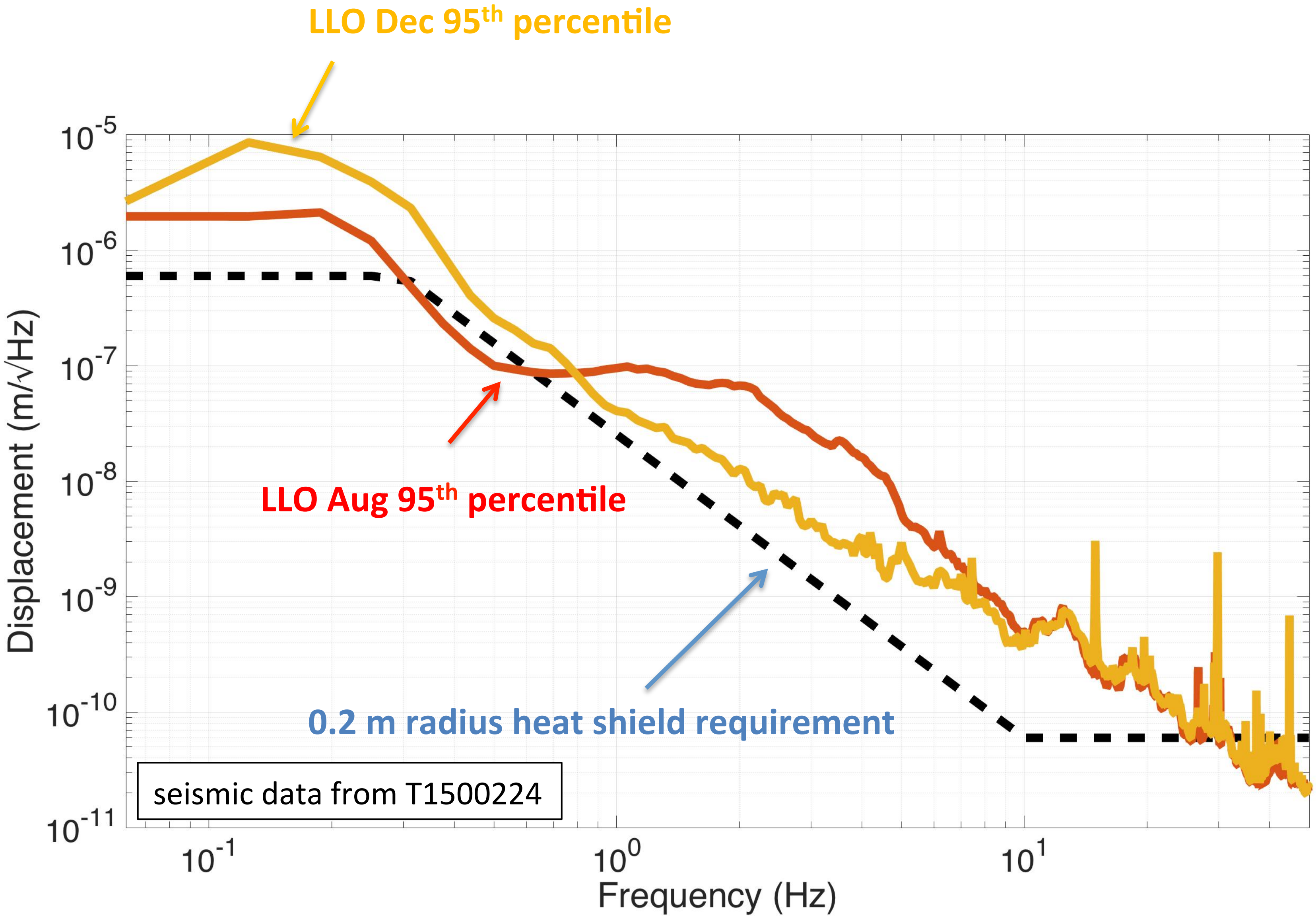
Scattered light - upconversion



No shield displacement

simulation

Shield Seismic Isolation



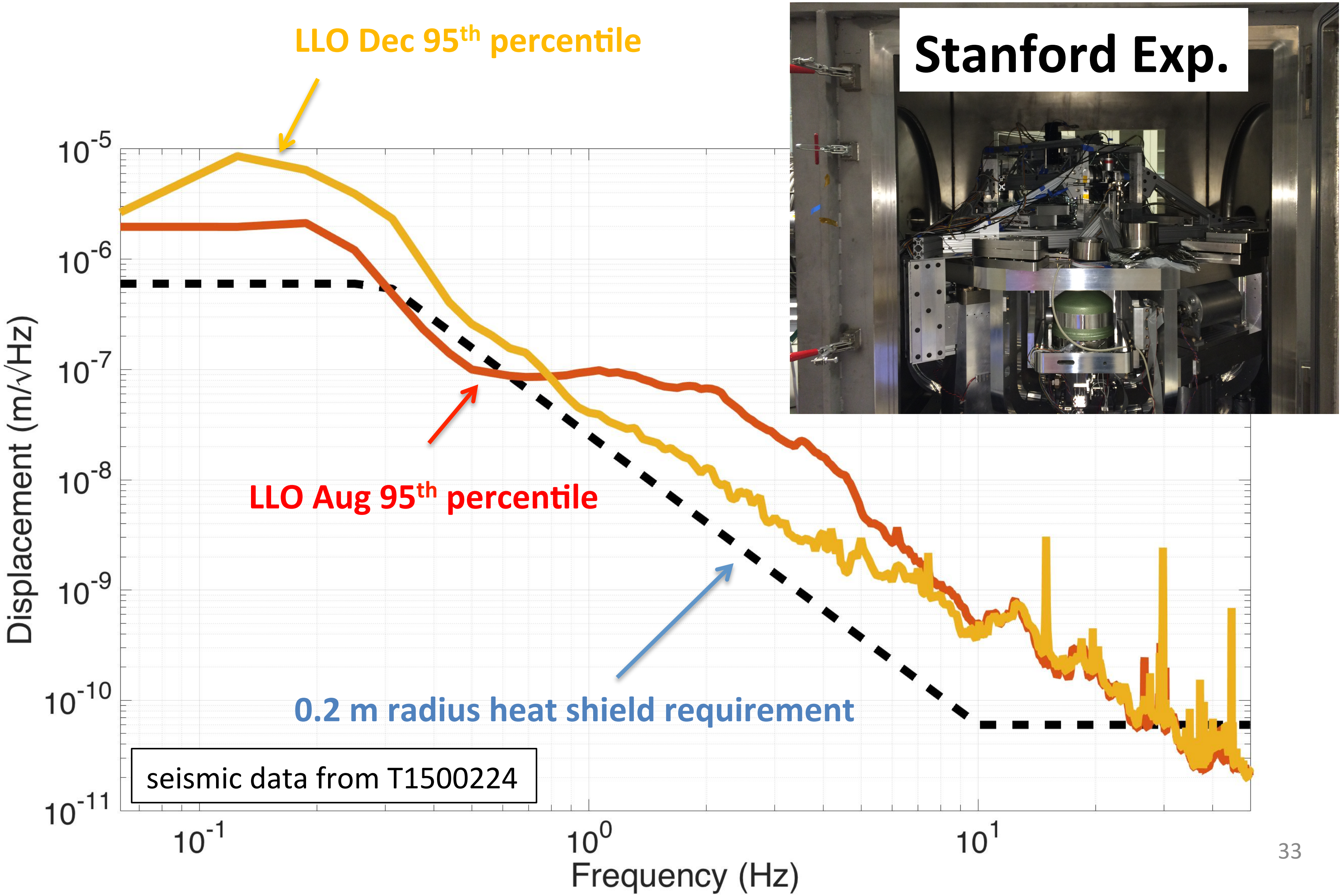
LLO Dec 95th percentile

LLO Aug 95th percentile

0.2 m radius heat shield requirement

seismic data from T1500224

Shield Seismic Isolation



LLO Dec 95th percentile

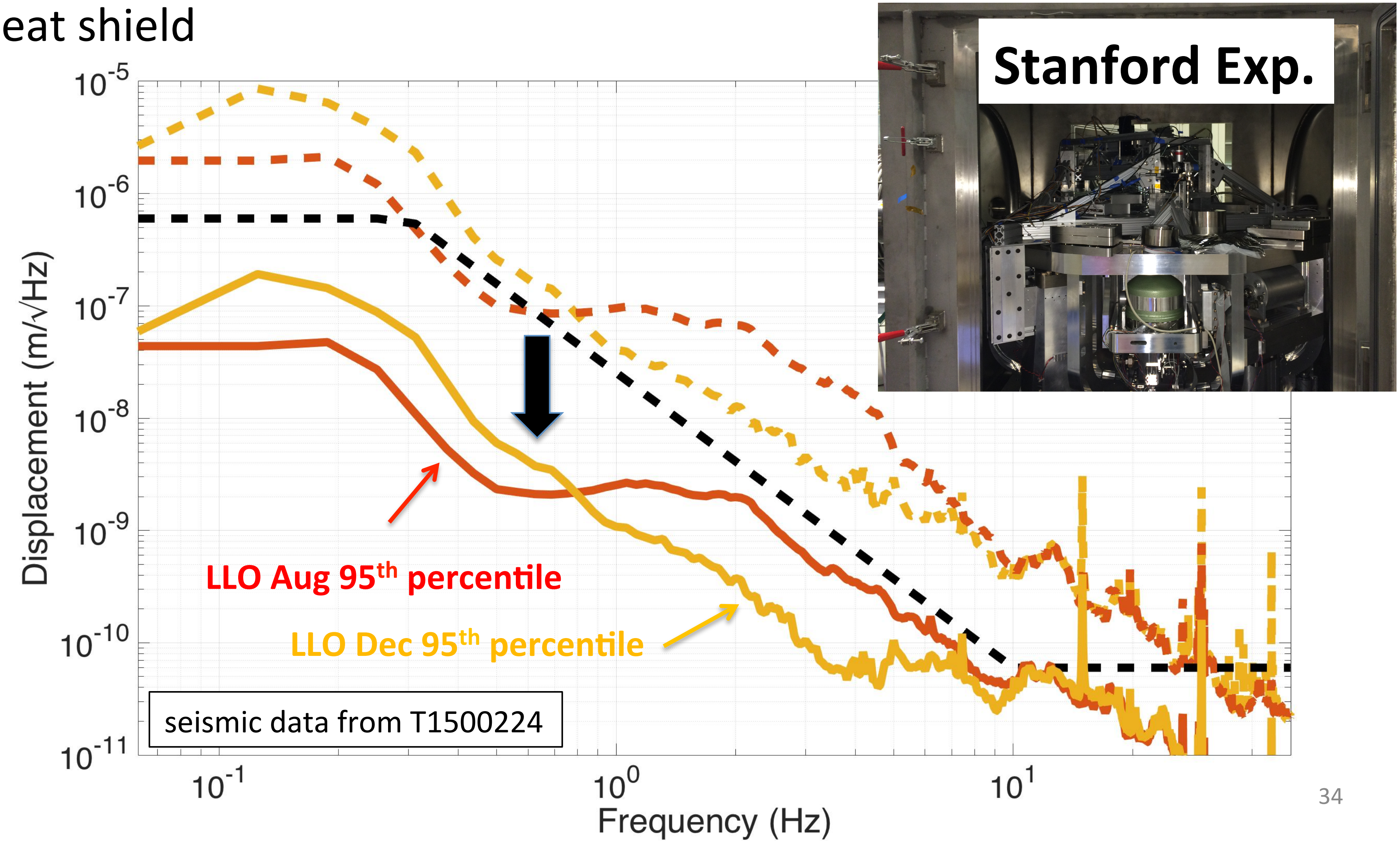
LLO Aug 95th percentile

0.2 m radius heat shield requirement

seismic data from T1500224

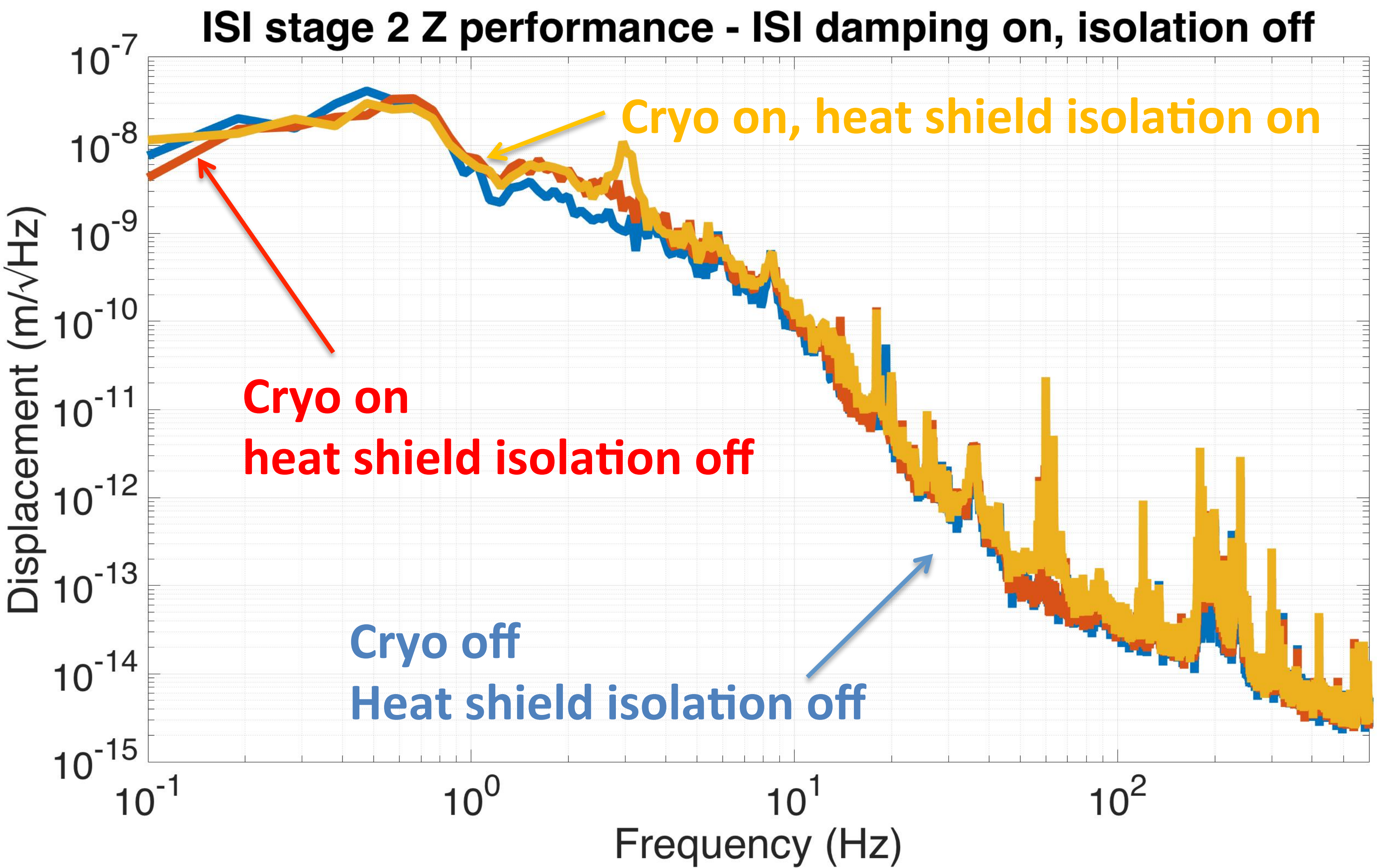
Shield Seismic Isolation

Simulated performance with isolation loops designed for Stanford heat shield



seismic data from T1500224

Cryo induced vibrations on ISI



Cryo on, heat shield isolation on

Cryo on
heat shield isolation off

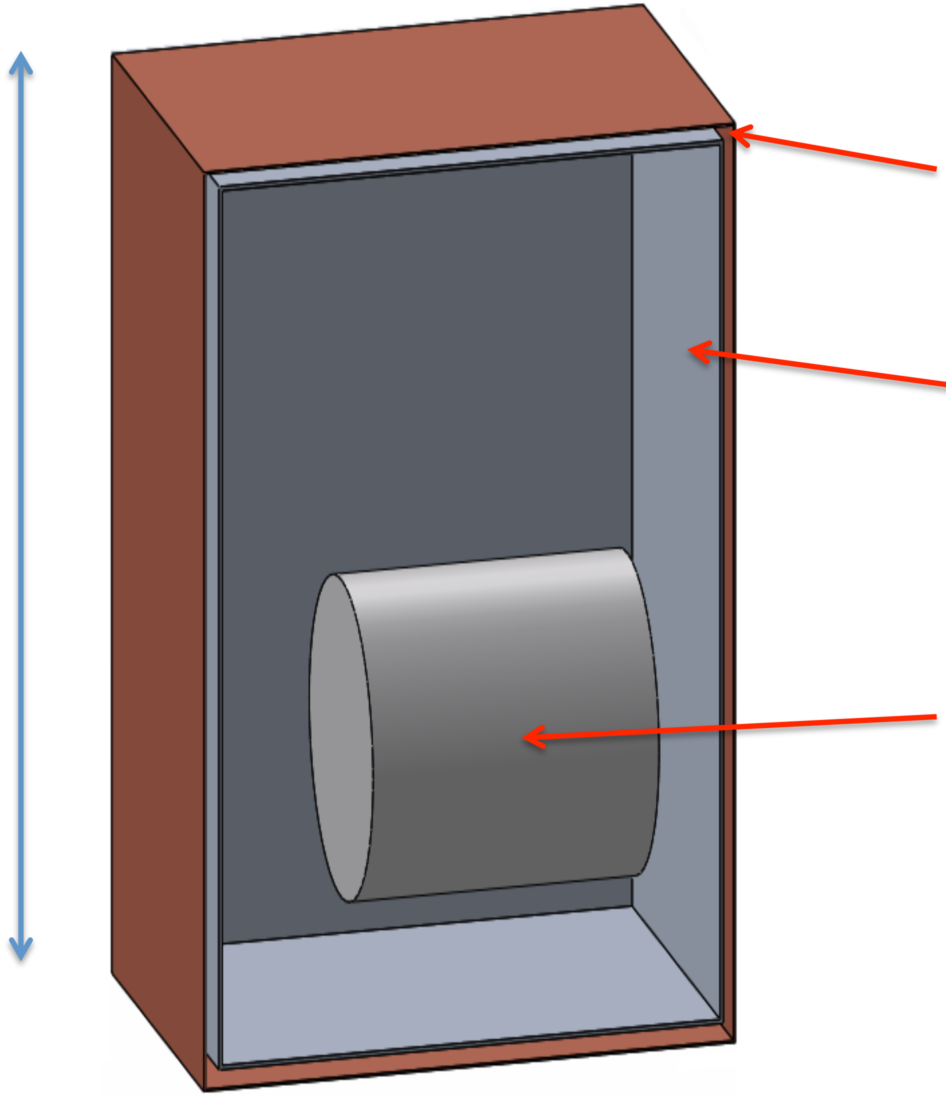
Cryo off
Heat shield isolation off

Newtonian Noise

Courtesy of Edgard Bonilla

Simulations based on Nick Lockerbie's G1200625

Shield Newtonian Noise Simulation



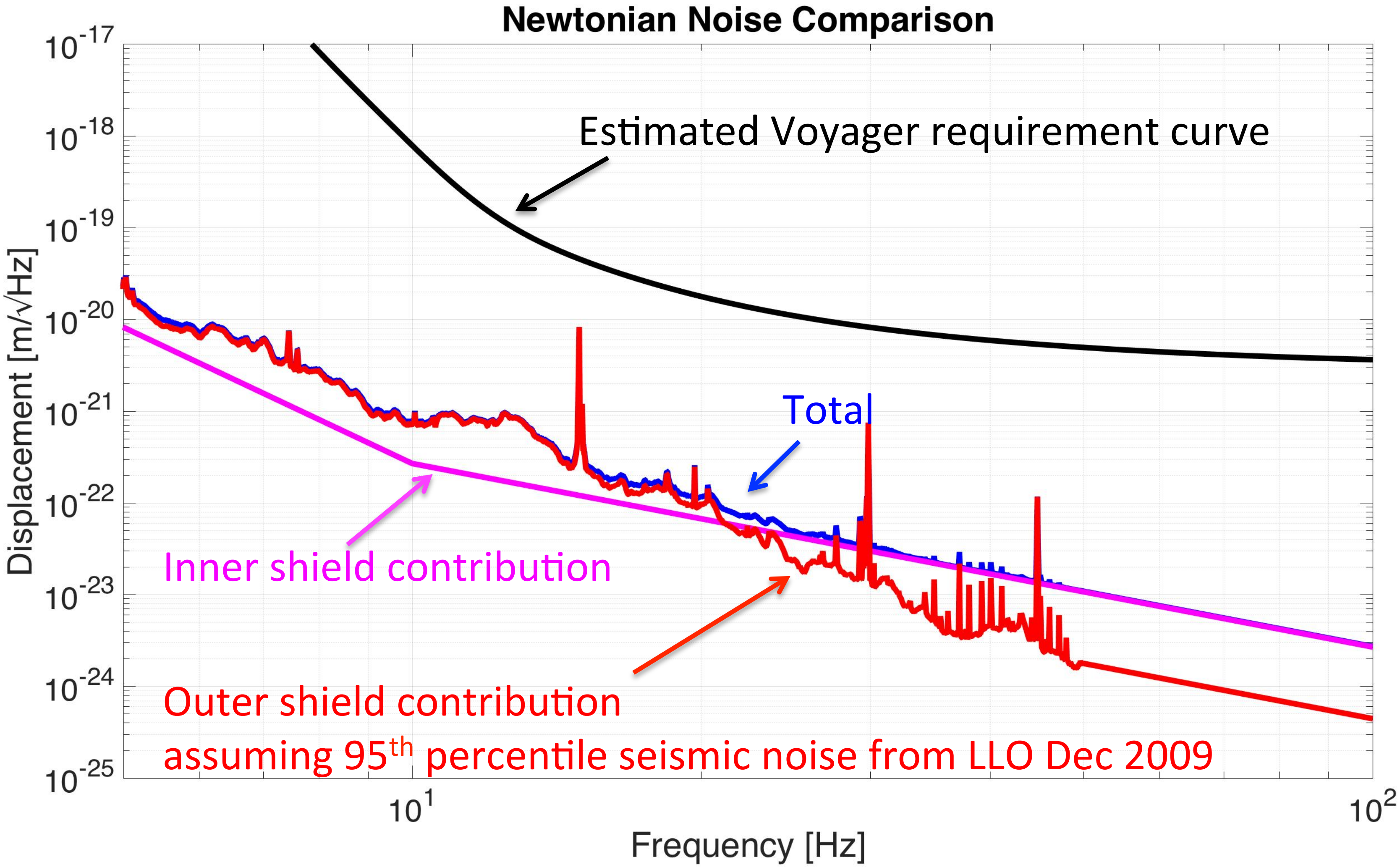
1.25 m

Outer shield
180 kg of Cu

Inner shield
100 kg of Al

Silicon Test Mass
- 45 cm diameter
- 54 cm length
- 200 kg

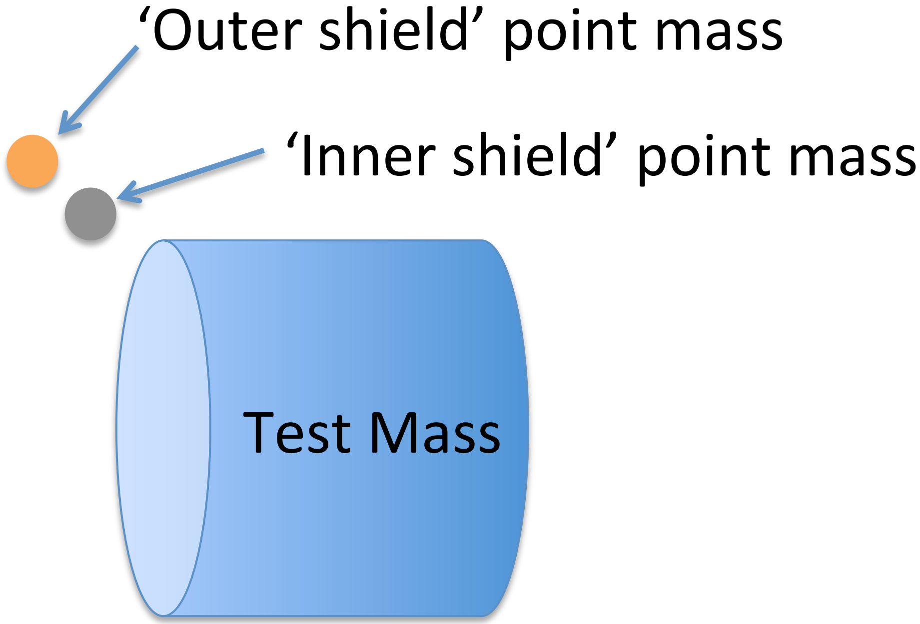
Shield Newtonian Noise Simulation

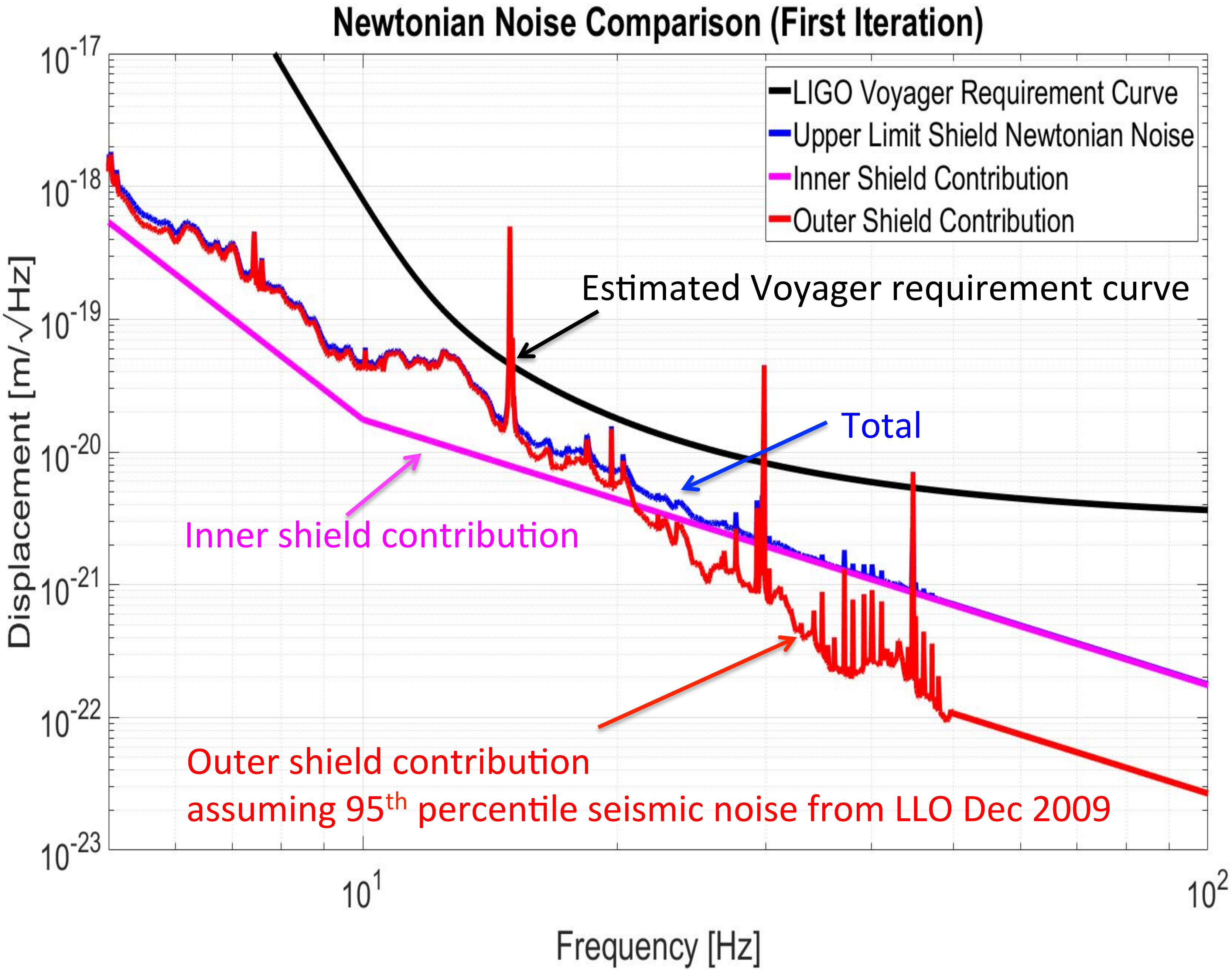


Outer shield contribution
assuming 95th percentile seismic noise from LLO Dec 2009

Shield Newtonian Noise Simulation

Newtonian upper limit estimation
- Assume all shield mass concentrated into a single point





Estimated Voyager requirement curve

Total

Inner shield contribution

Outer shield contribution
assuming 95th percentile seismic noise from LLO Dec 2009

Conclusions – what's good

- 80 K heat shield and seismically isolated optics are not mutually exclusive in a LIGO-like environment.
- Scattered light appears to be manageable with reasonable amounts of vibration isolation
  - Can be further helped with clever light absorbing geometries and sufficiently black paint
- Newtonian noise appears to not be a concern

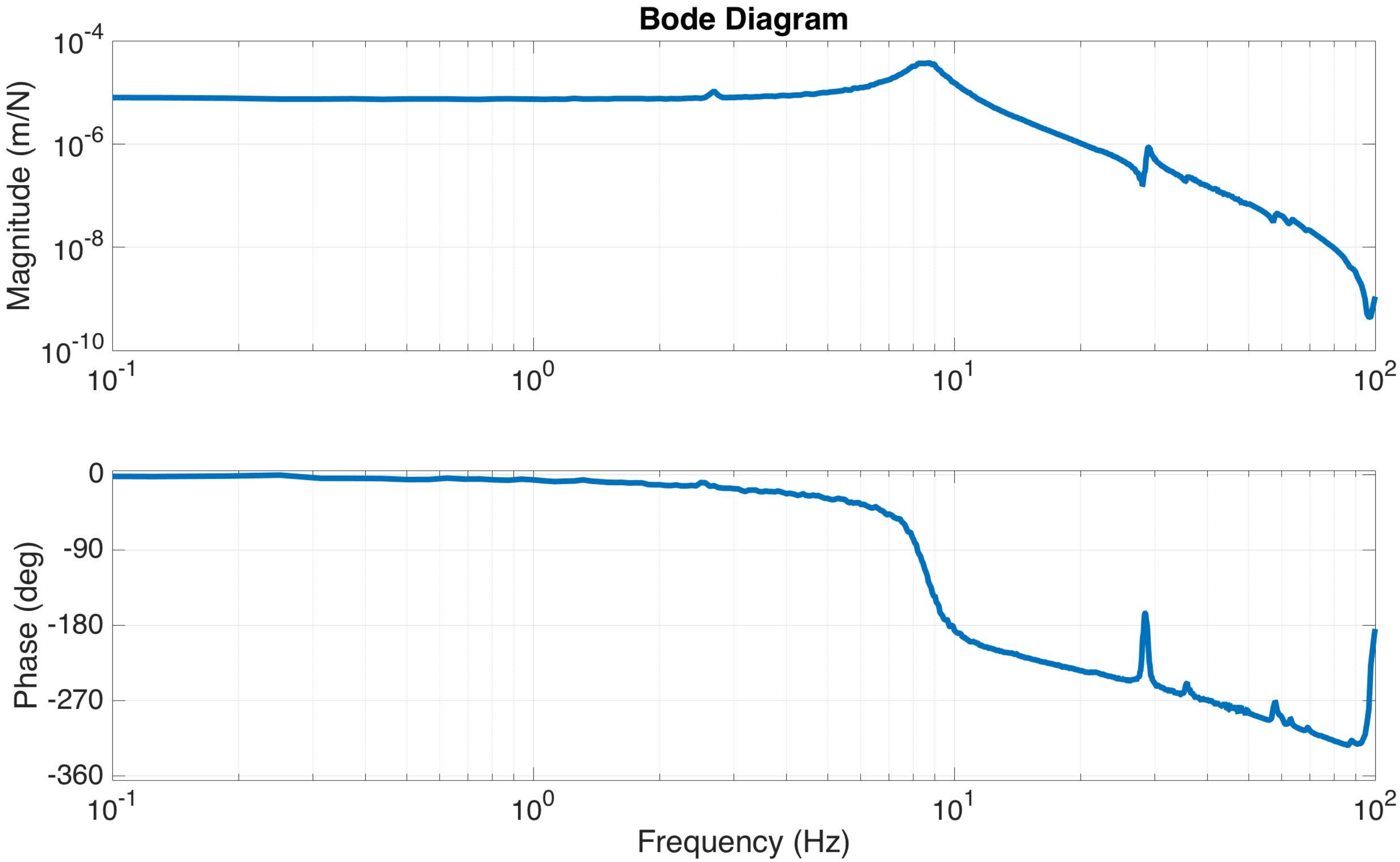
Conclusions – what needs more work

- More work needed on the initial test mass cooling. In contact with Charlie Danaher at HPD.

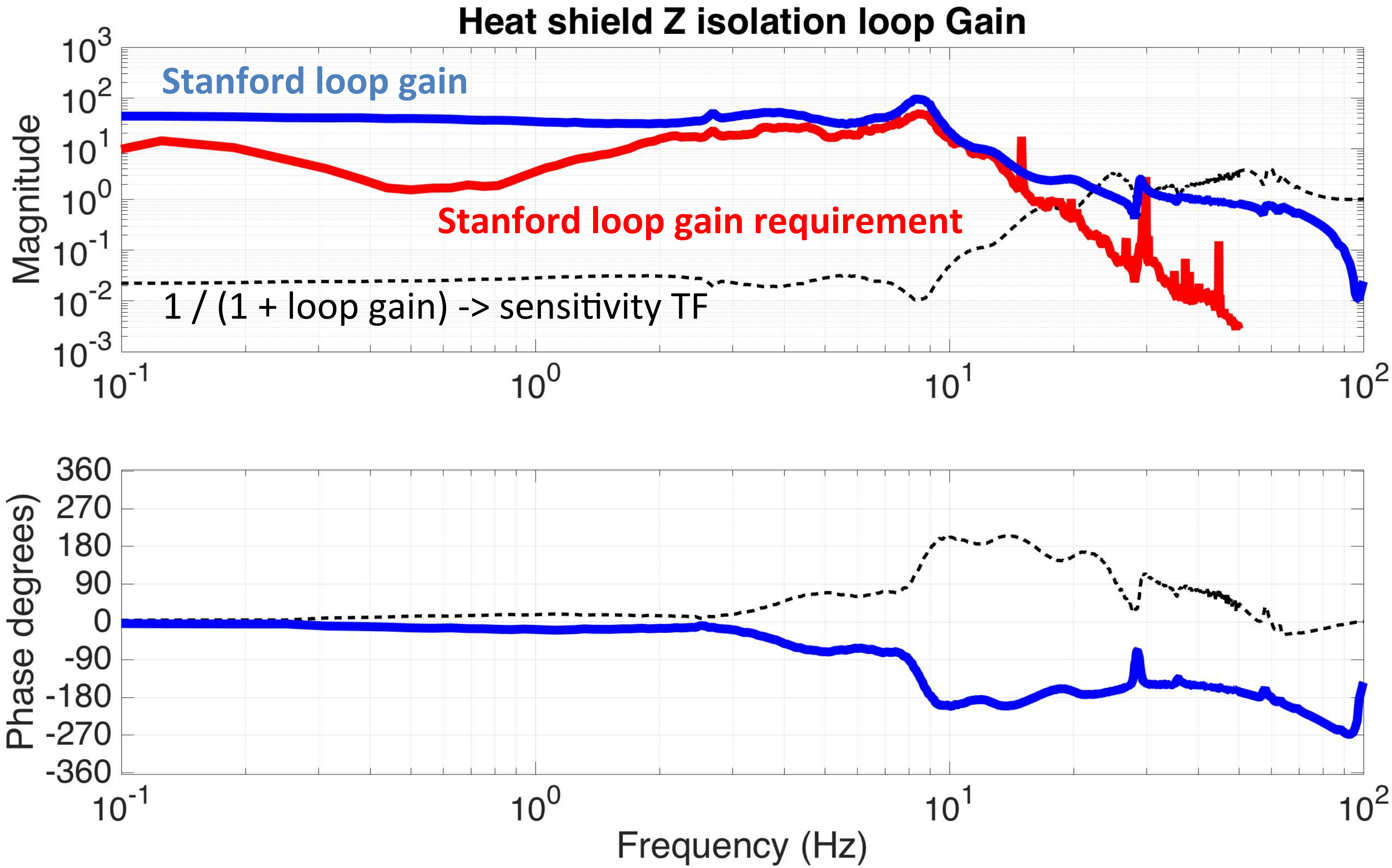
- Suspension springs likely needed thermal control

Extra Slides

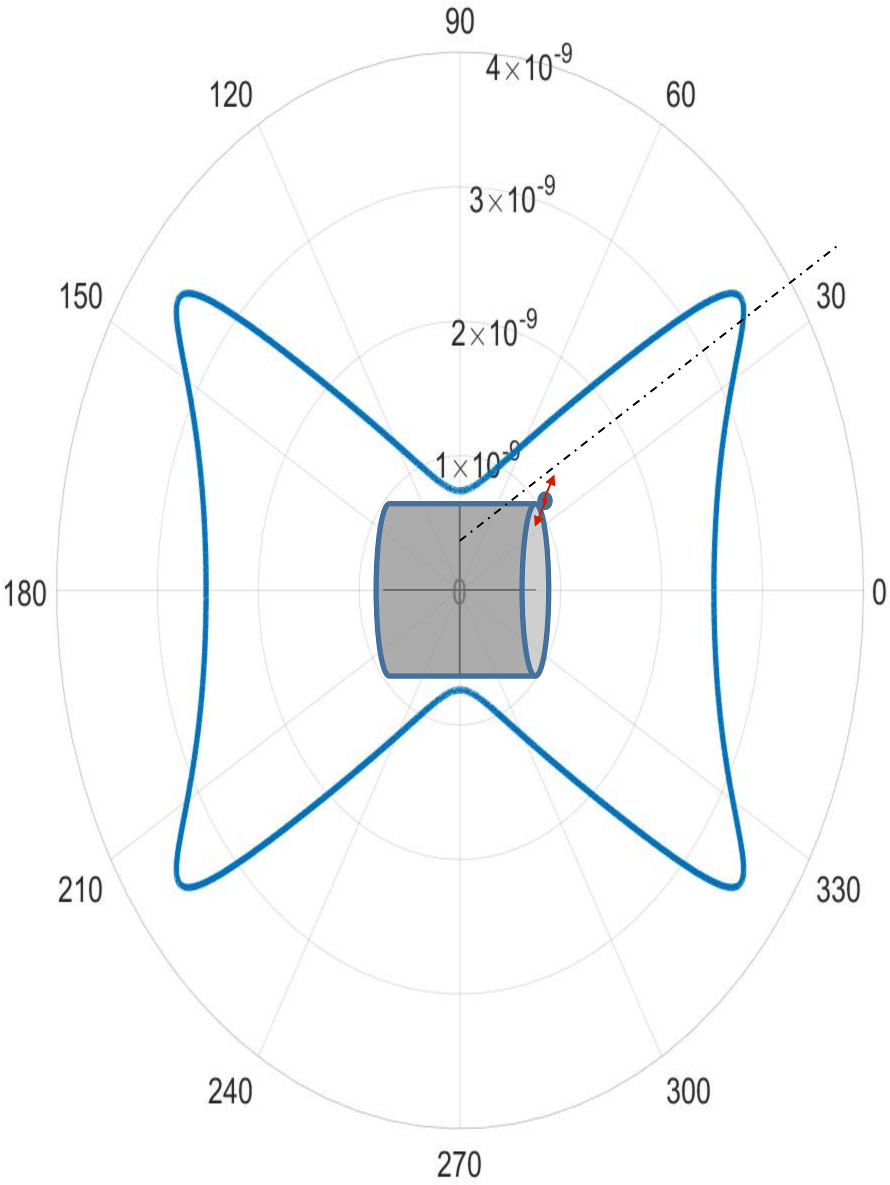
Inner Shield Vertical Plant

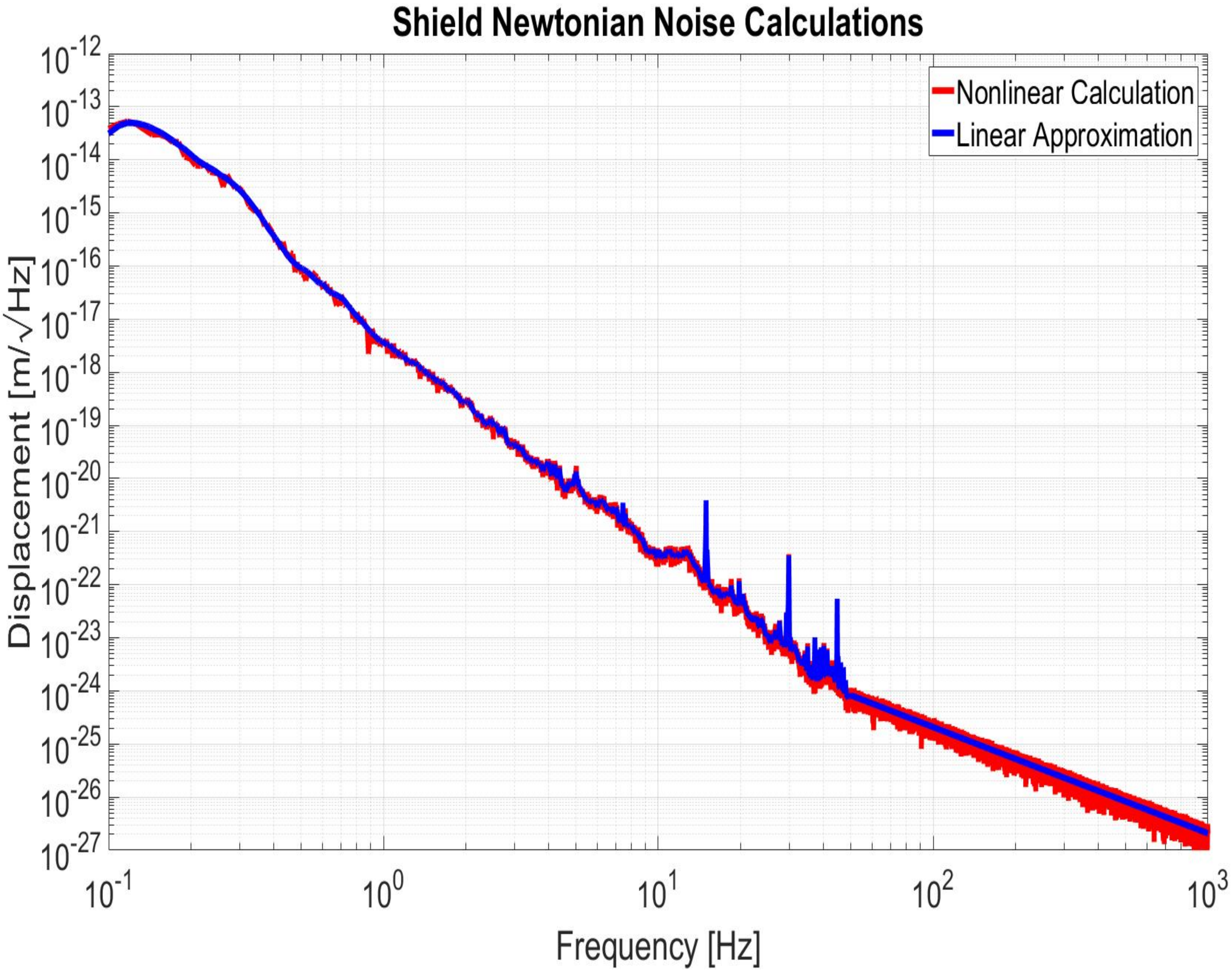


Shield Seismic Isolation



Axial Force Gradient Amplitude




Shield Newtonian Noise Calculations
Nonlinear Calculation
Linear Approximation
Displacement [m/√Hz]
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^-26
10^-27
10^-1
10^0
10^1
10^2
10^3
Frequency [Hz]

$$\boldsymbol{F}_{\mathrm{axial}} = \boldsymbol{G}\,\mathrm{M}\sum_{n=0}^{\infty}\left\{\frac{(2n+1)\,\mathrm{P}_{2n+1}(\cos(\theta))}{R_0^{(2n+2)}}\sum_{p=0}^{n}\left(\frac{(-1)^{p}(2n)!\,\ell^{2[n-p]}\,b^{2p}}{2^{2p}\,p!\,(p+1)!\,(2[n-p]+1)!}\right)\right\}.$$

(Unit source-mass.)

n = 0: Monopole.

n = 1: Quadrupole.

n = 2: Hexadecapole.

n = 3: 64-pole, etc.

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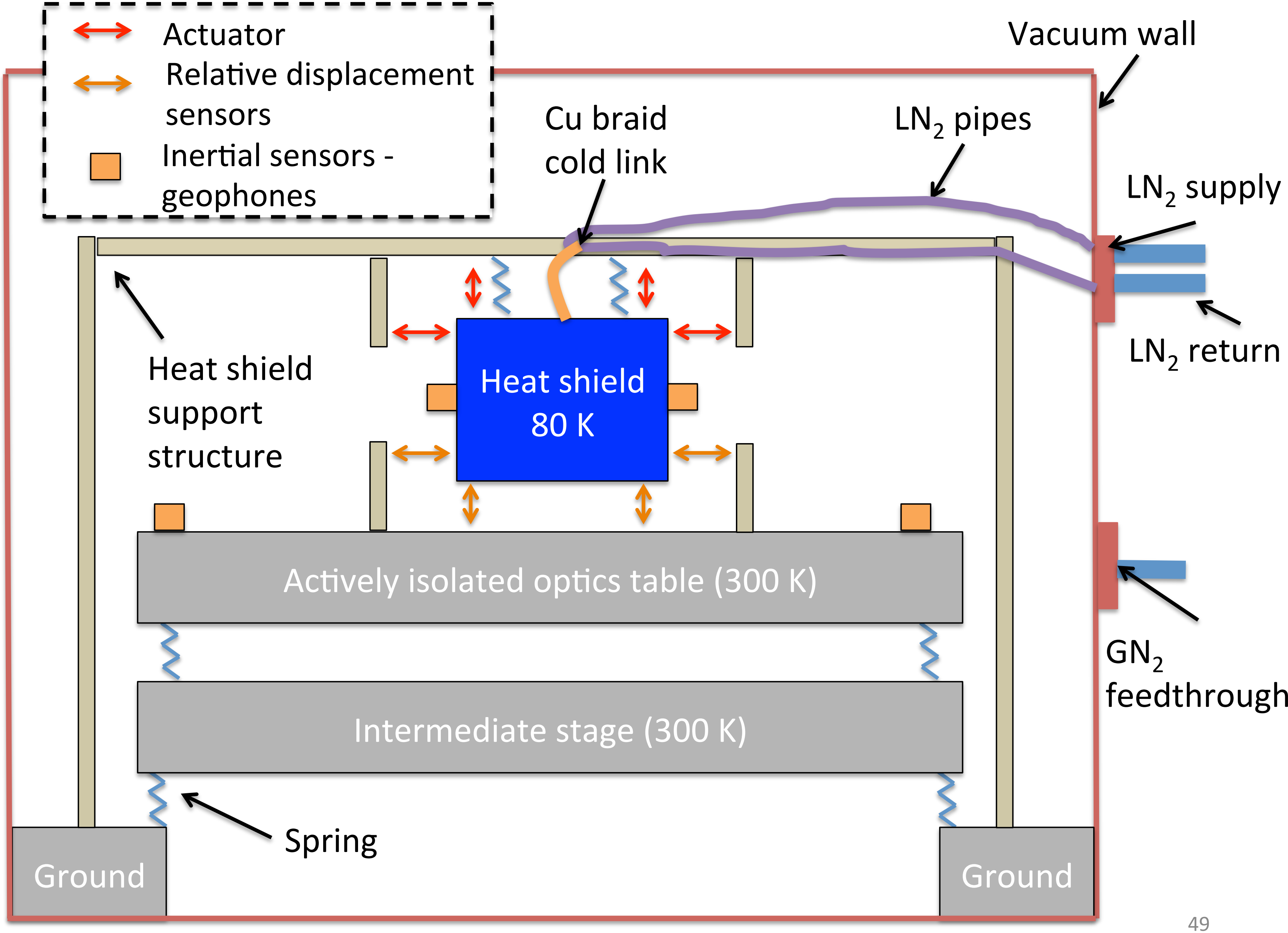
Point mass

R_0 : Distance to CM
θ : Angular Position

Test-mass

b = 0.225 m (Radius).
ℓ = 0.27 m (Semi axial-length).

Equation from G1200625



↔ 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)

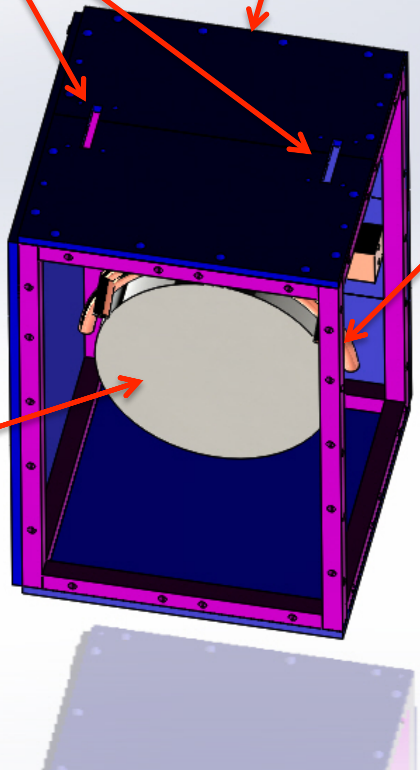
GN_2 feedthrough

Spring

Ground

Ground

Test mass heat shield



Holes for suspension wires

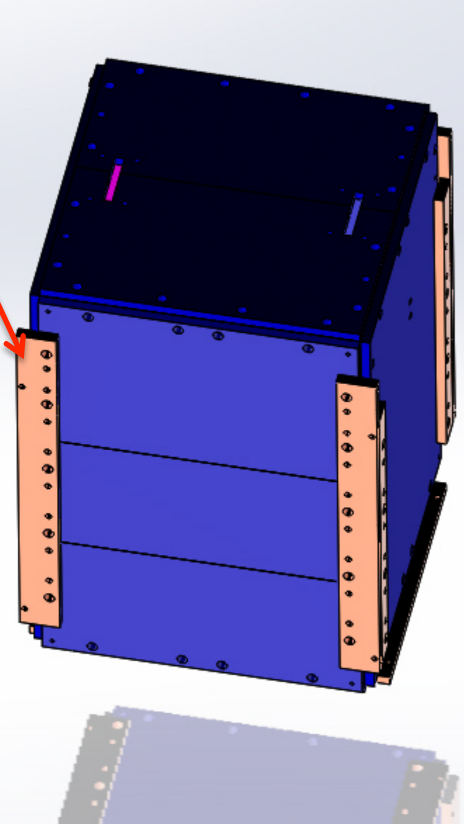
Inner heat shield 80 K

Cold finger for initial cool down

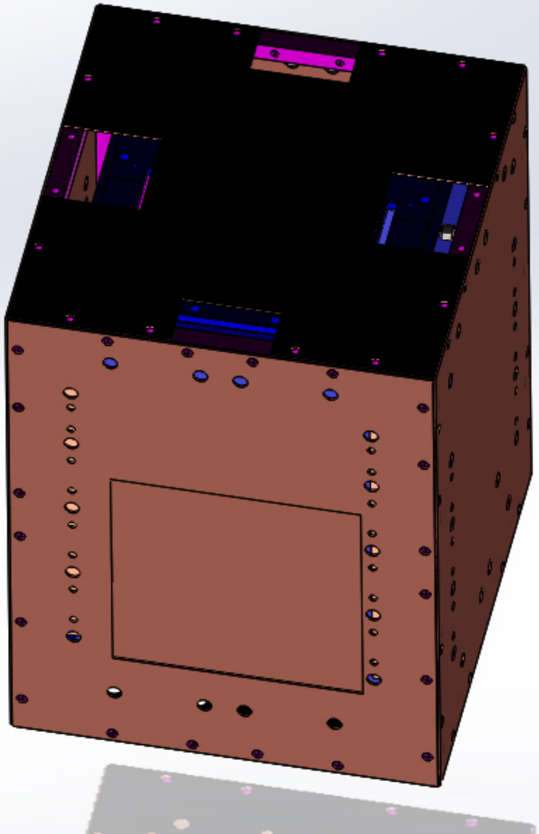
Test mass 124 K

Test mass heat shield

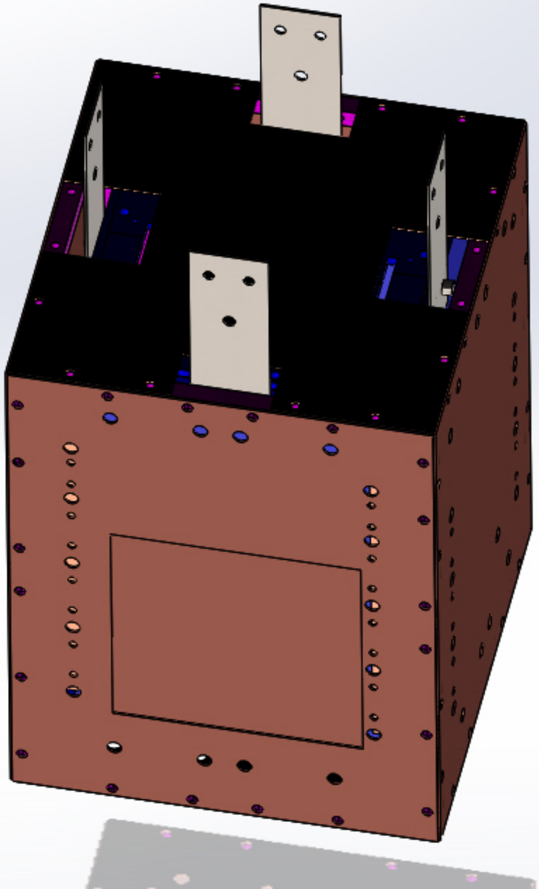
Connections for the Cu cold links that cool the inner shield (cold links not shown)

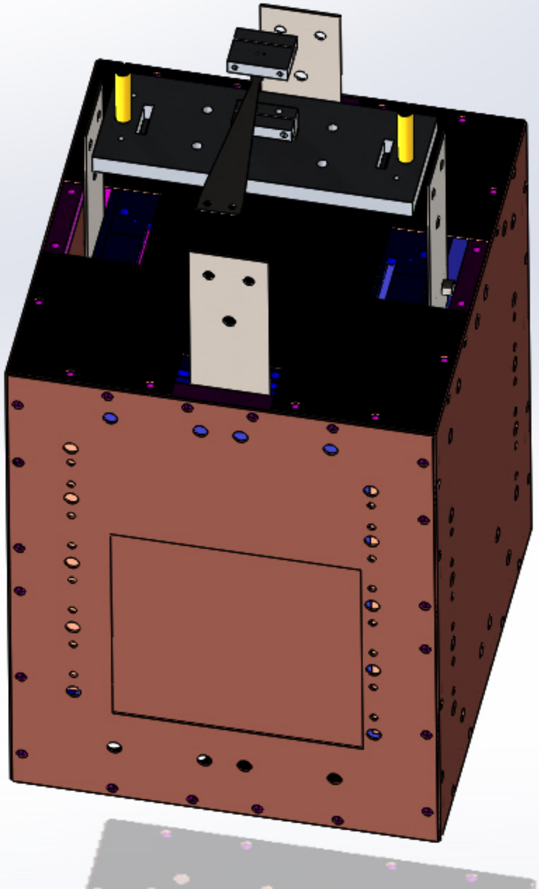


Aluminum low emissivity plates
(ribs boost vibrational frequencies)



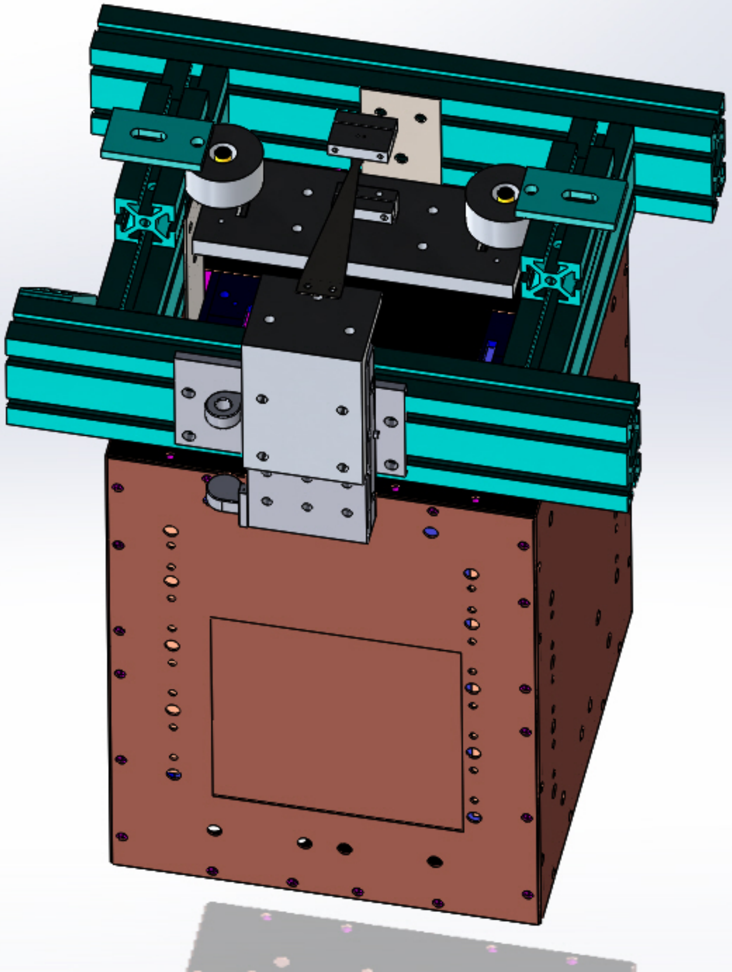
Flexible stainless strips attach the heat shield to its (warm) suspended stage



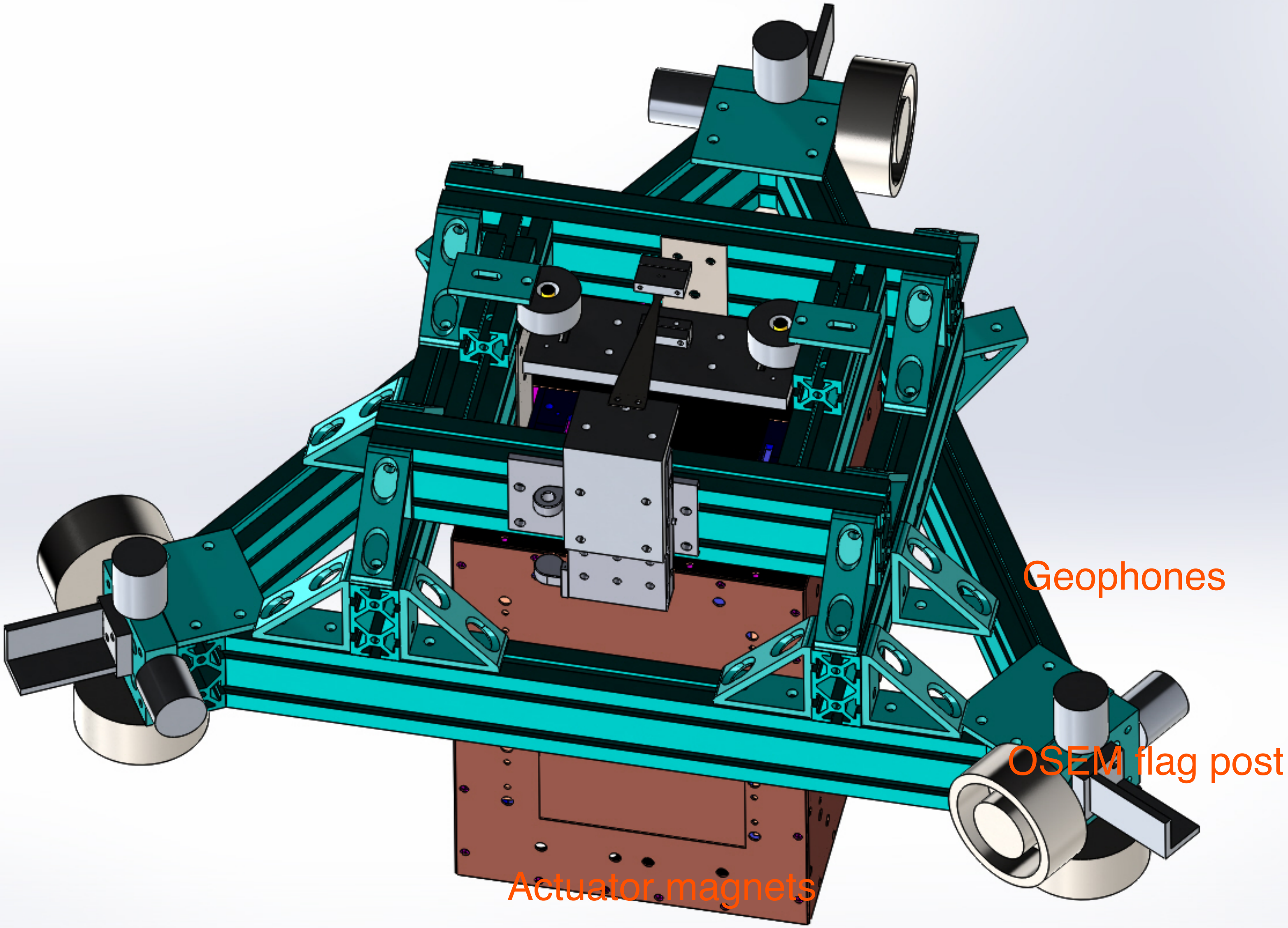


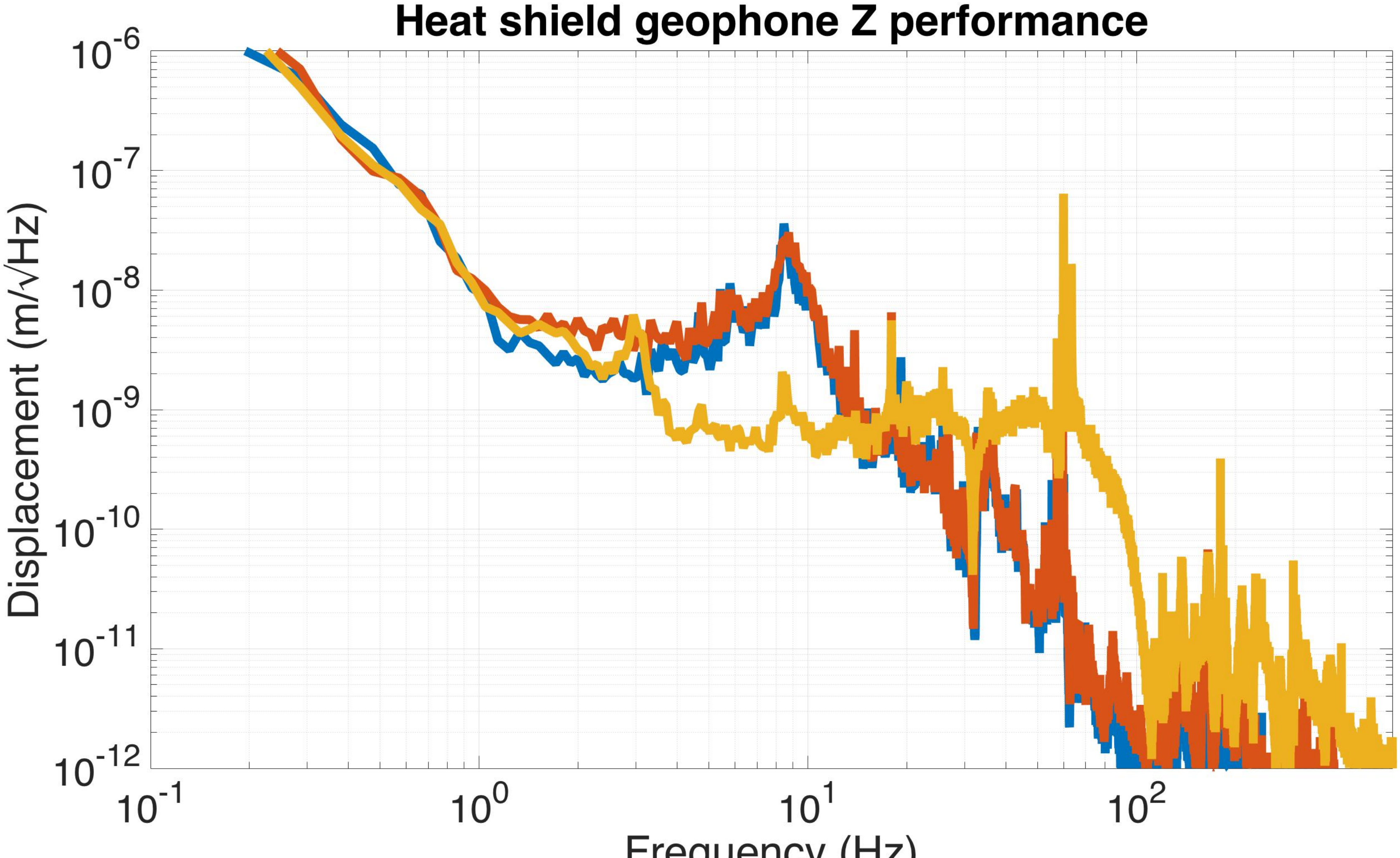
Vertical suspension OSEMs

Suspension spring mounted to vertical translation stage

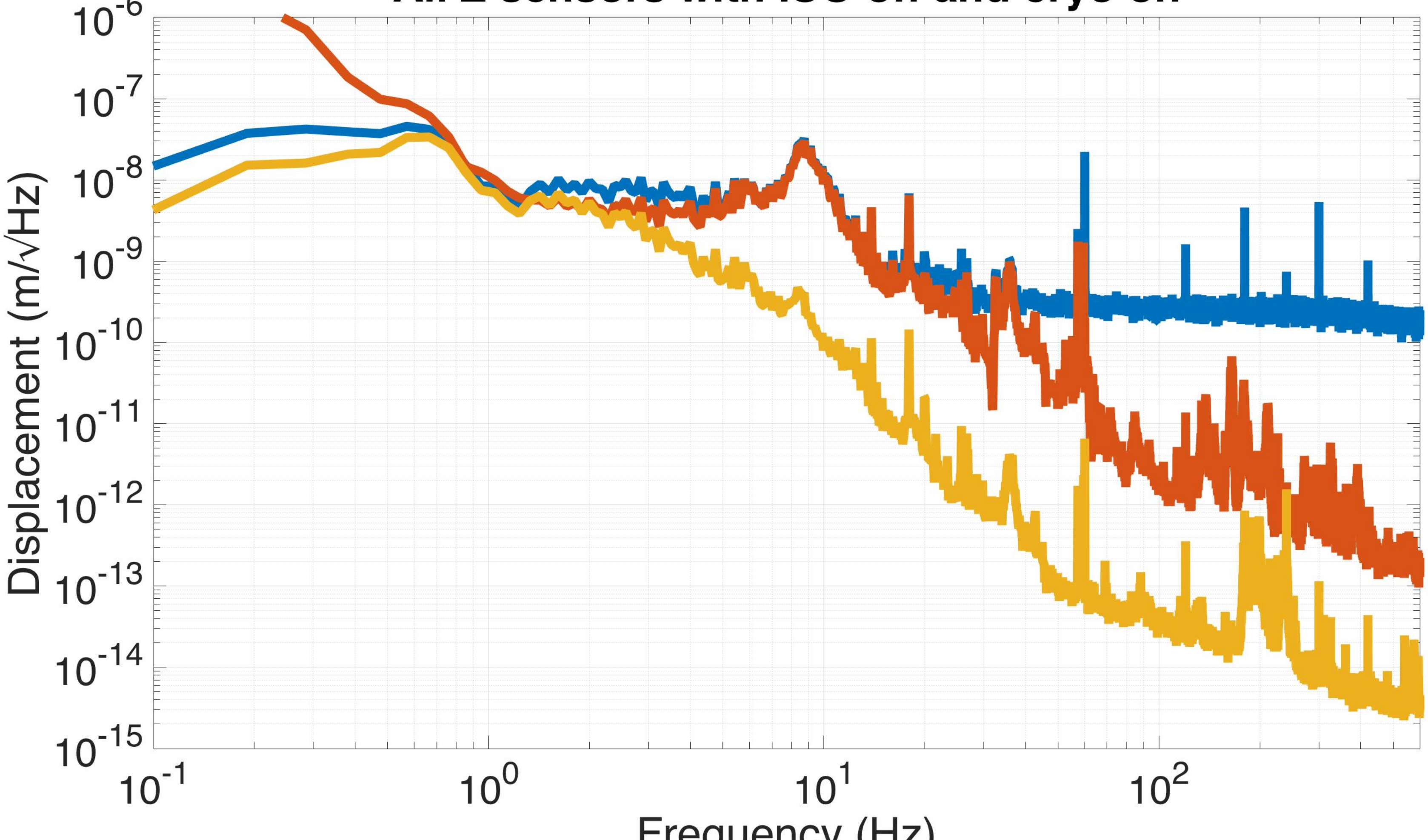


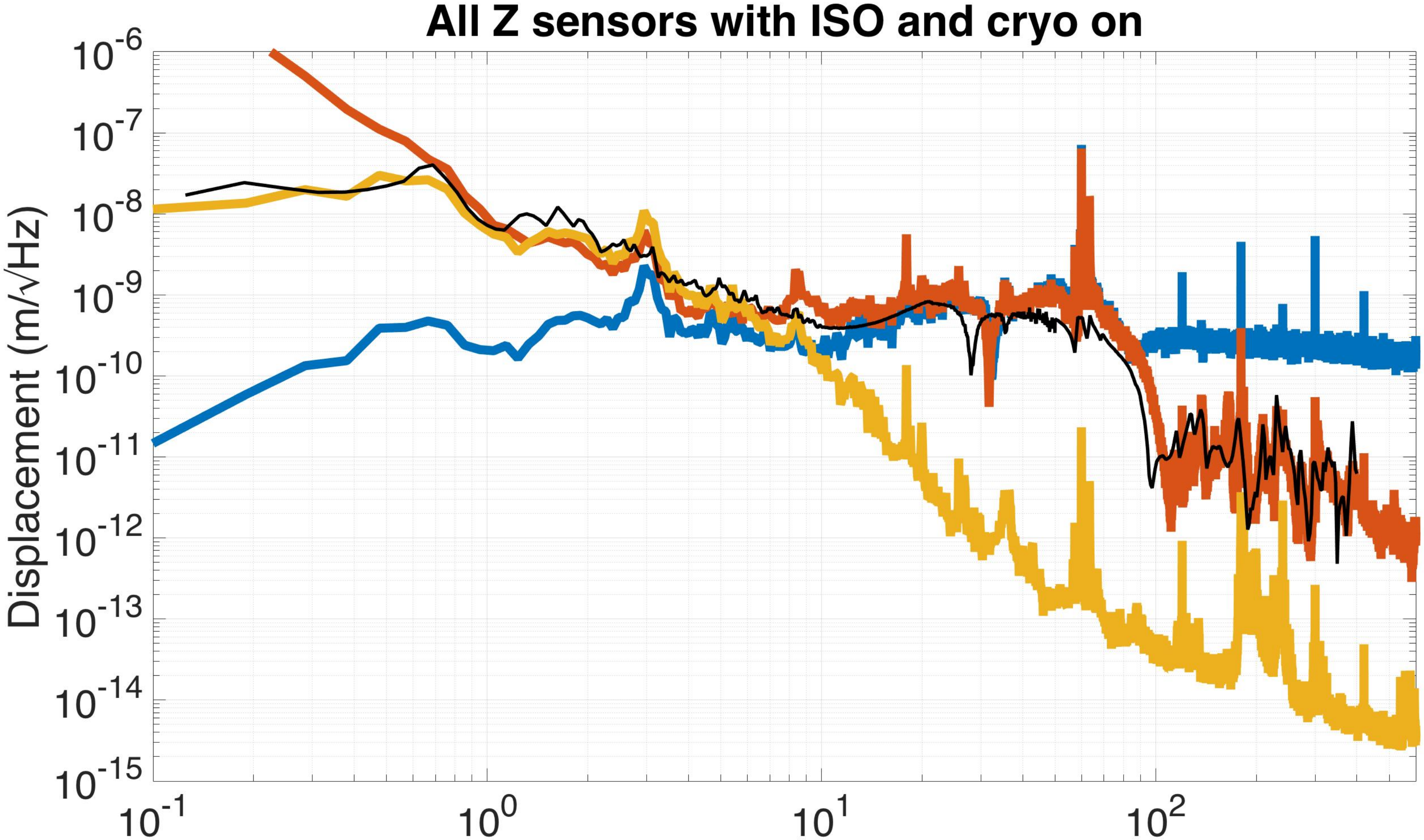
The complete heat shield stage



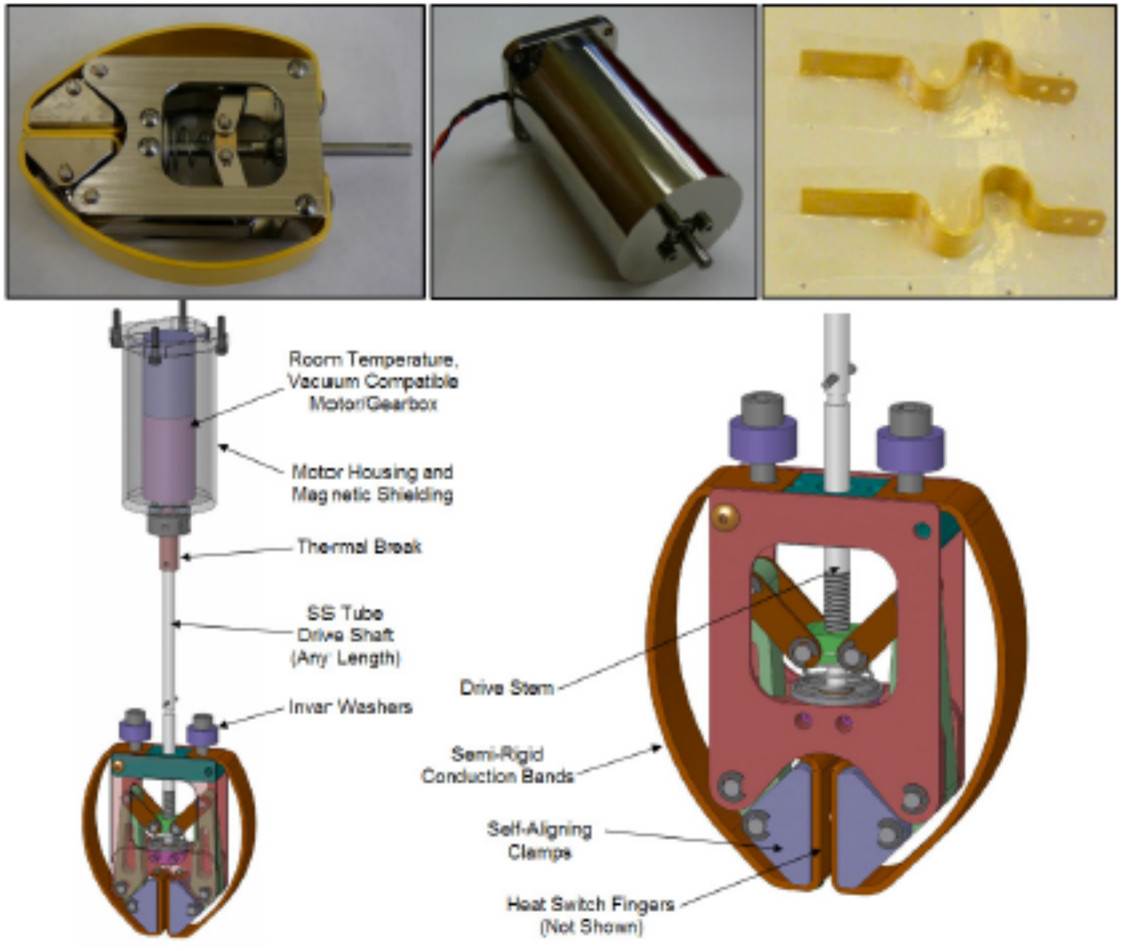

Heat shield geophone Z performance
Displacement (m/√Hz)
Frequency (Hz)
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-1
10^0
10^1
10^2

All Z sensors with ISO off and cryo on




All Z sensors with ISO and cryo on
Displacement (m/√Hz)
Frequency (Hz)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-1}
10^{0}
10^{1}
10^{2}

HPD cold fingers



HPD's Motor Operated Mechanical Heat Switch.

Figure 2. The HPD Heat Switch Vise (Left, Above) and Motor Assembly (Center, Above) and Fingers (Right, Above) are used in a broad variety of applications. The vise and motor are used to provide active control of thermal links.

HPD Braids