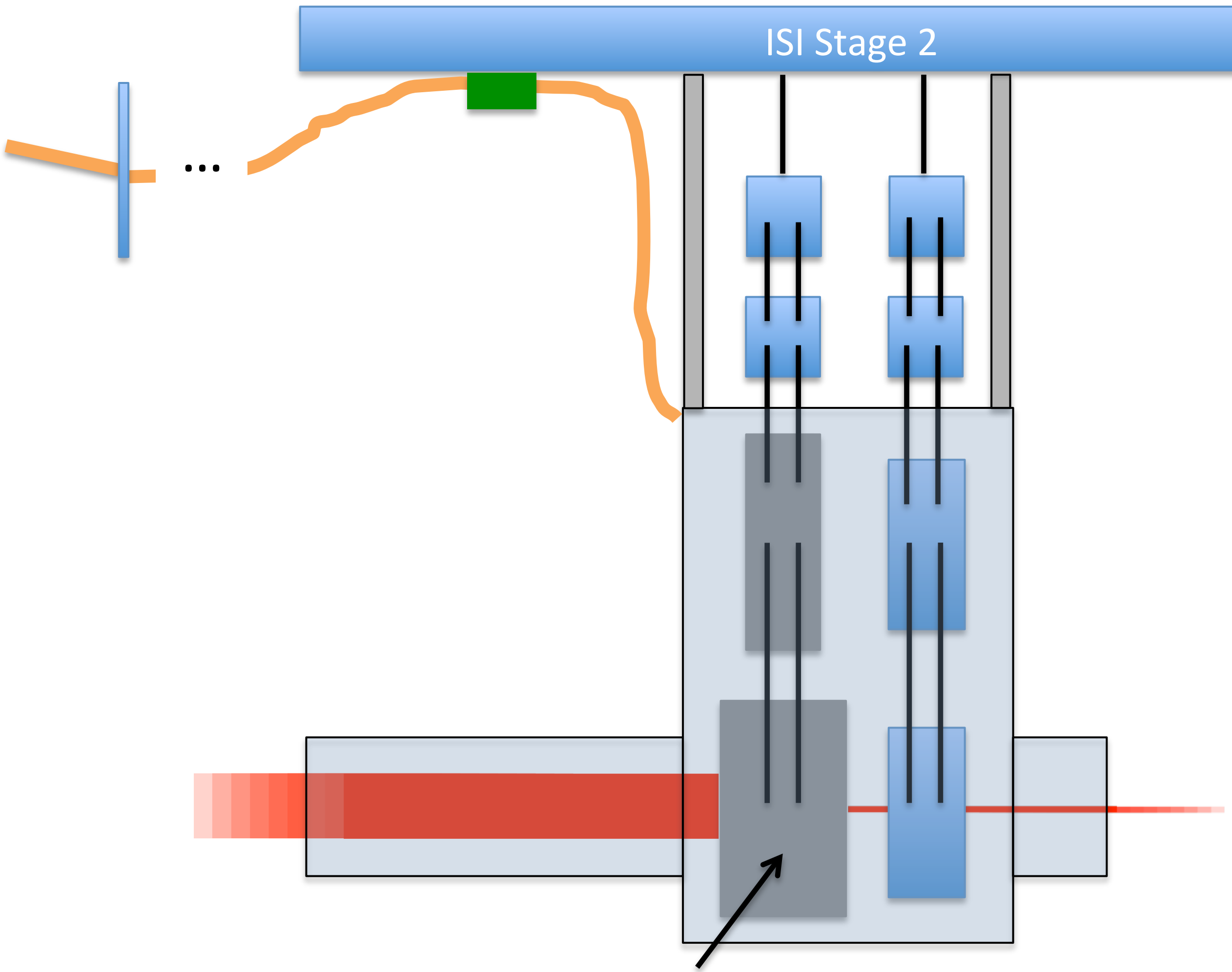
Low Vibration Cryogenics for LIGO Voyager

Brett Shapiro
Stanford University

LIGO III Cryosystem



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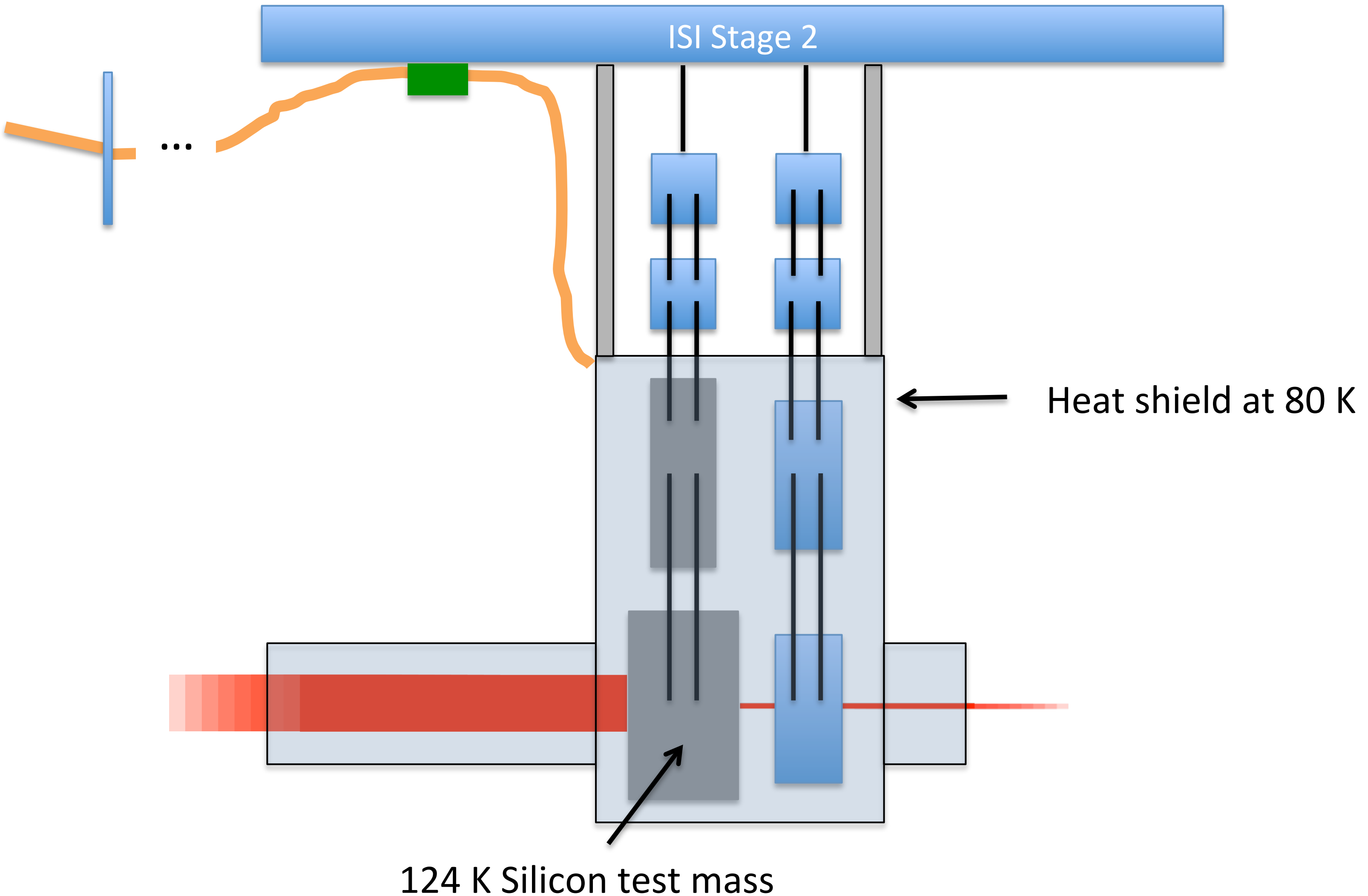

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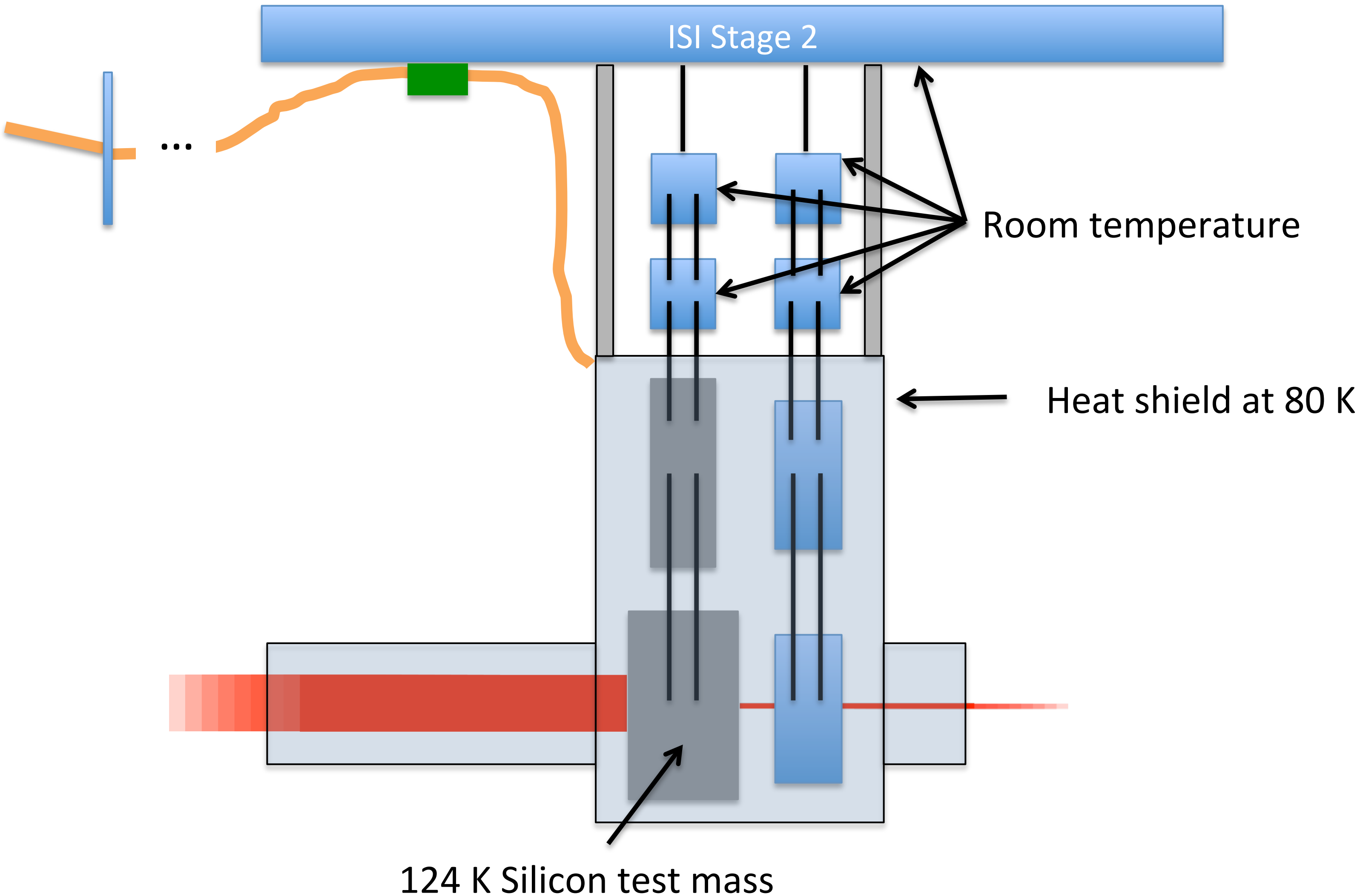

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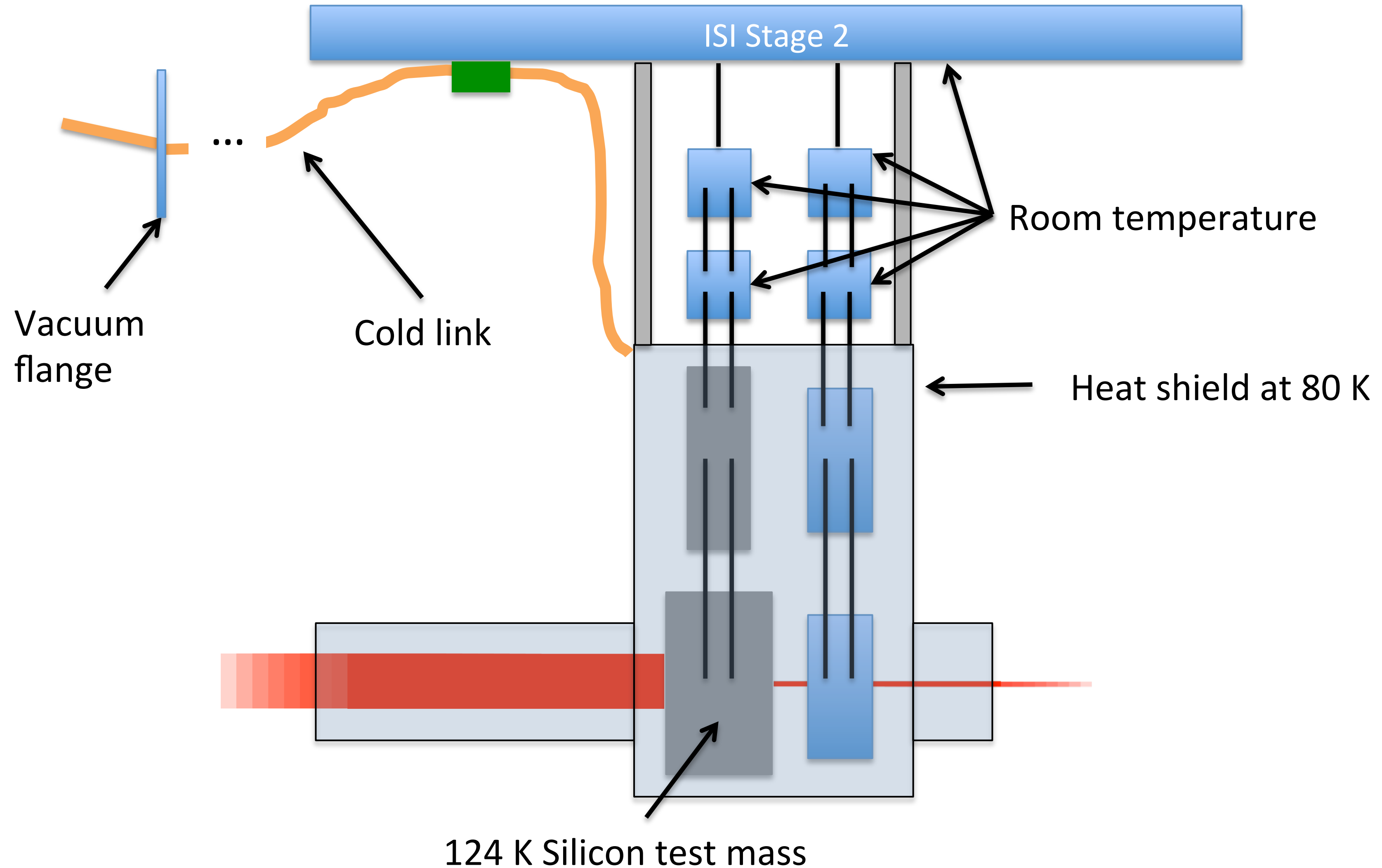

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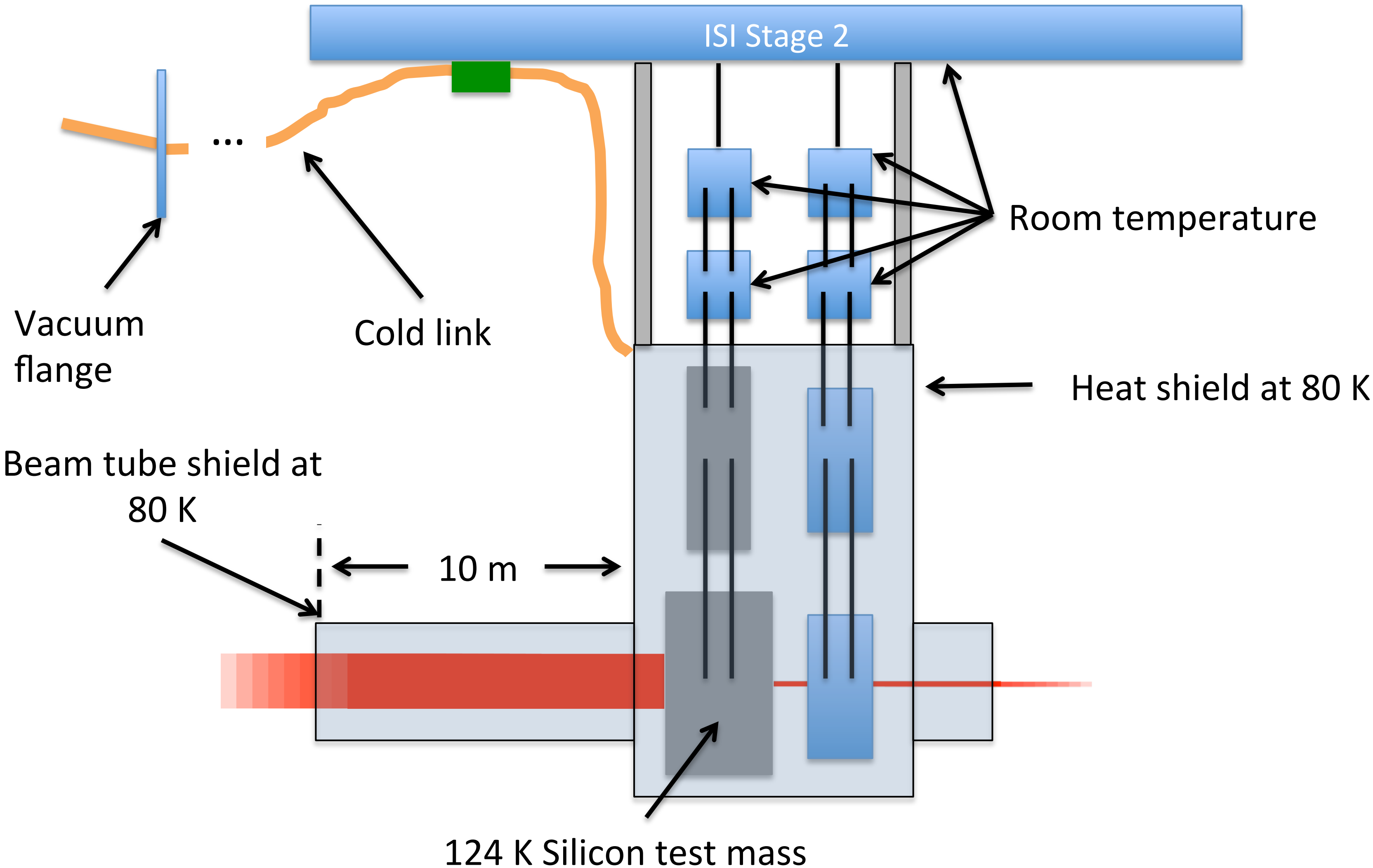

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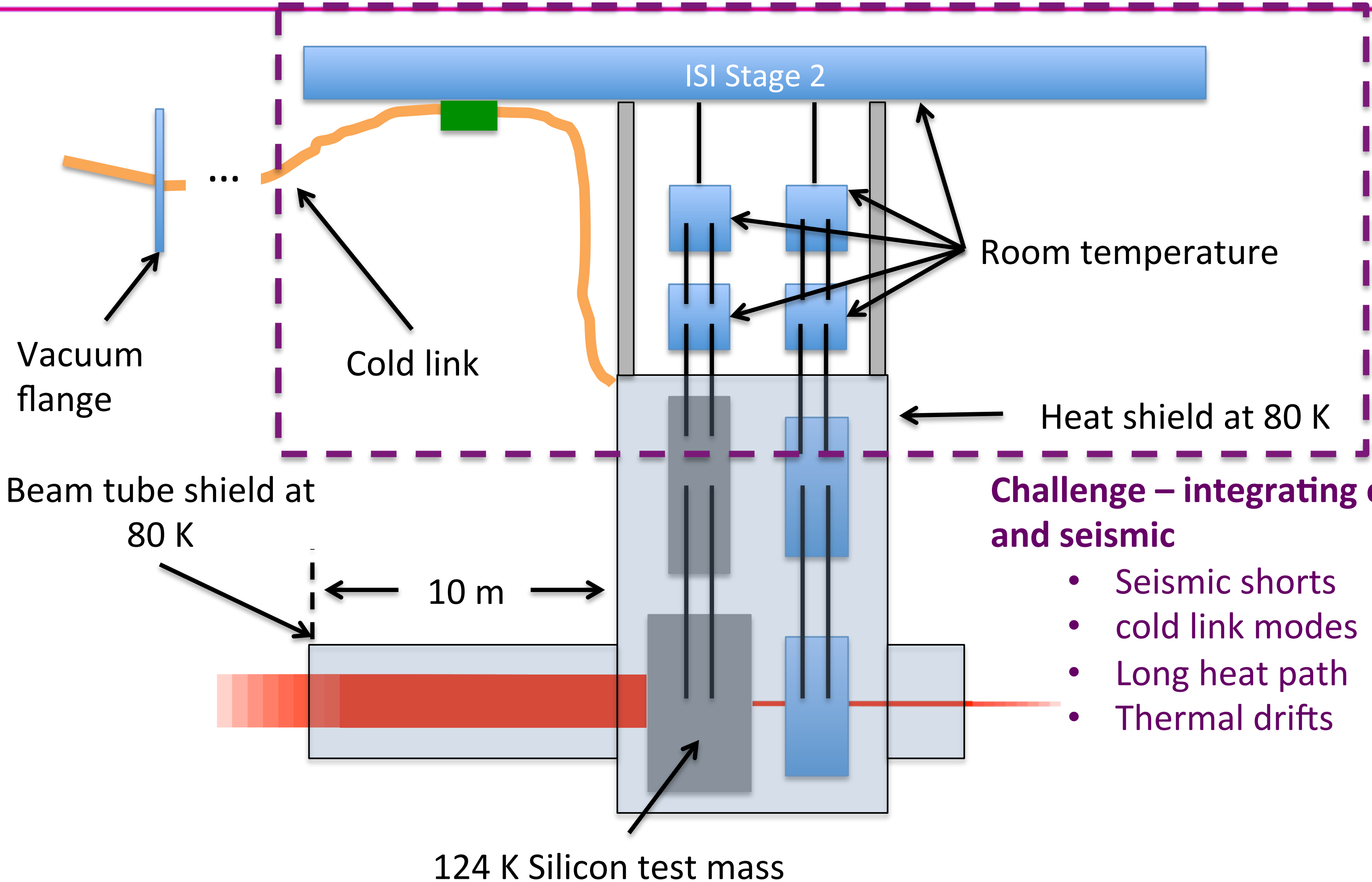
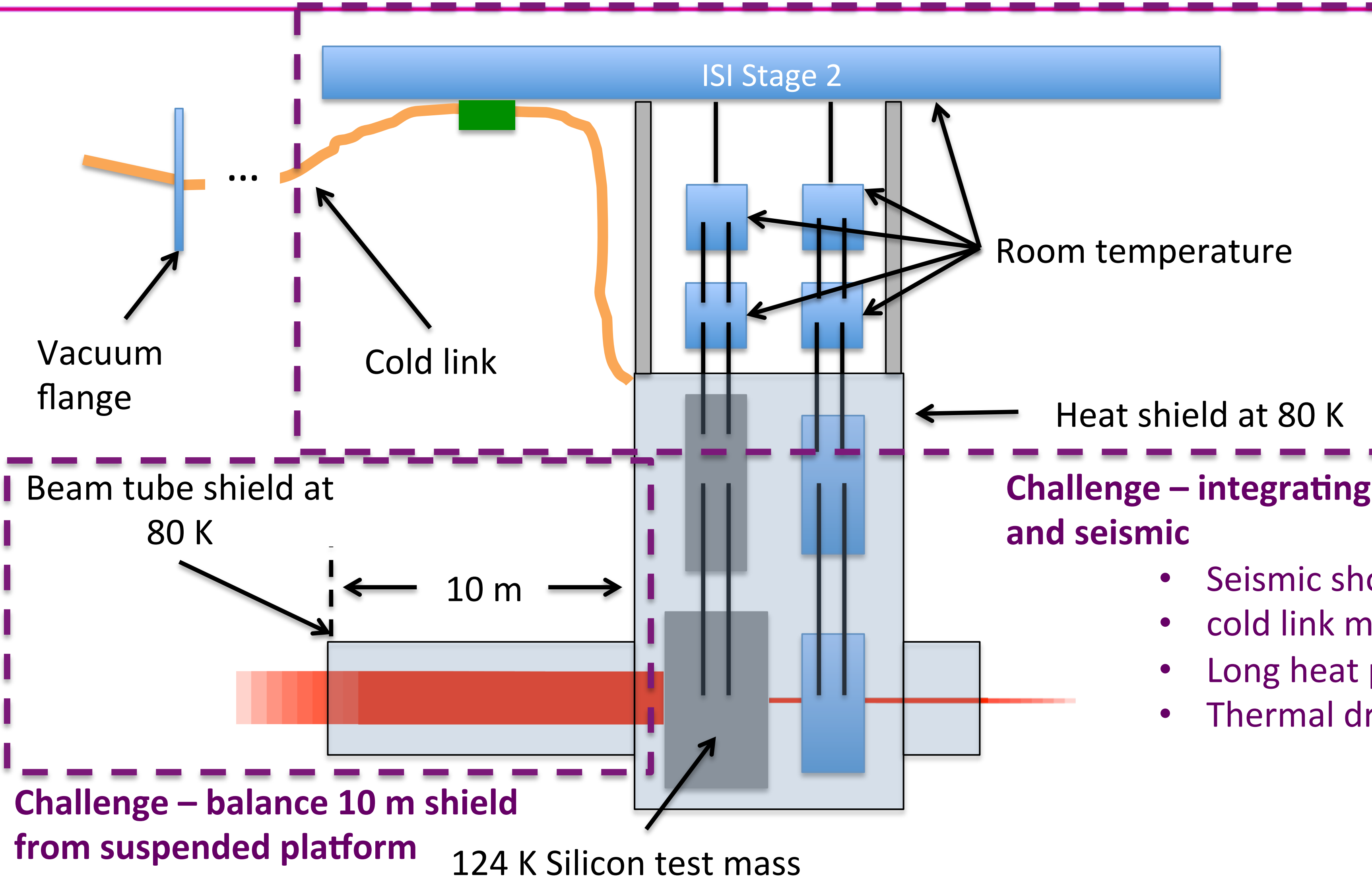


Challenge – integrating cryo and seismic

- Seismic shorts
- cold link modes
- Long heat path
- Thermal drifts

LIGO III Cryosystem



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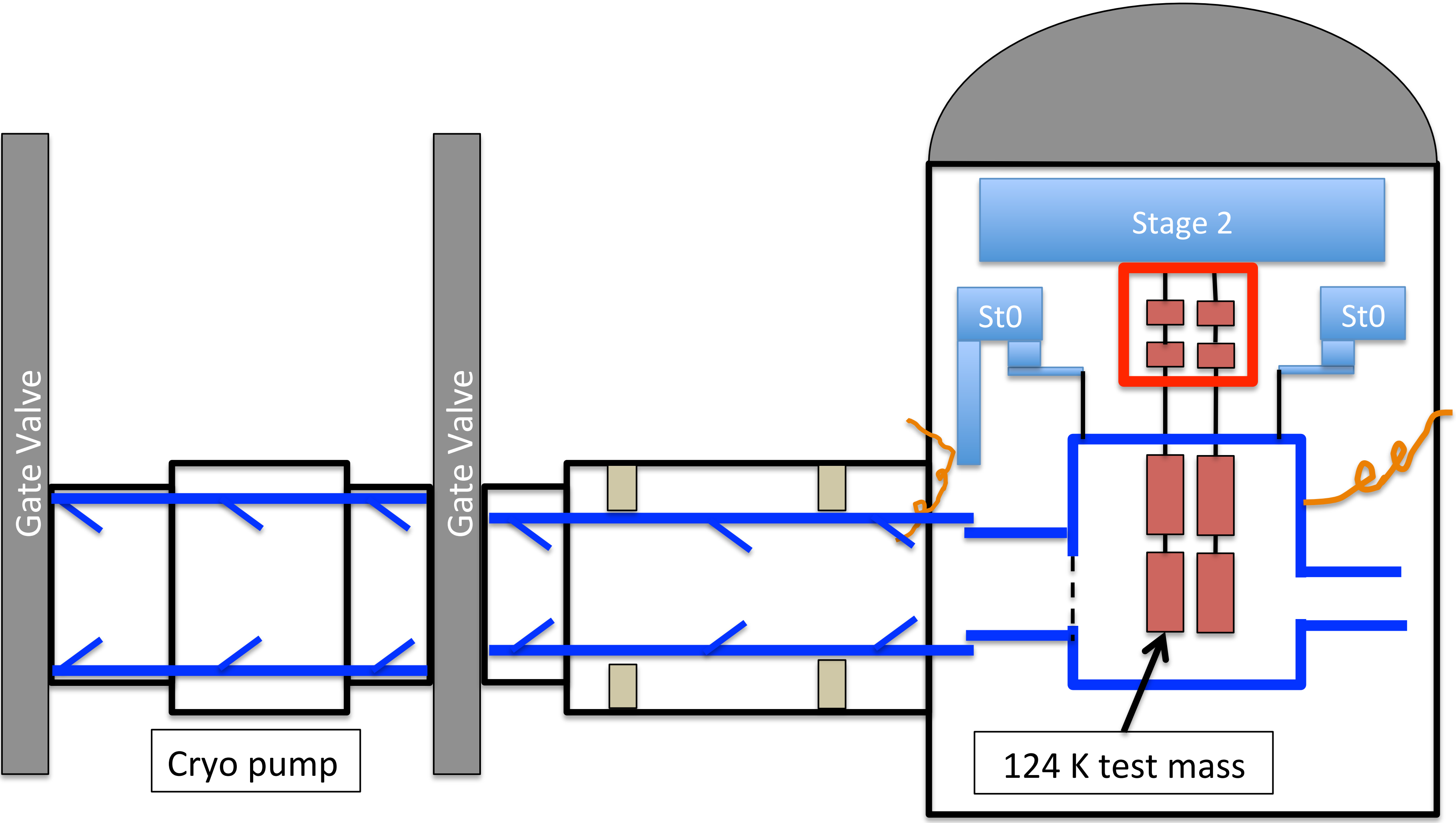
- Seismic shorts
- cold link modes
- Long heat path
- Thermal drifts

Challenge – balance 10 m shield from suspended platform

Actively controlled shield (ETM)



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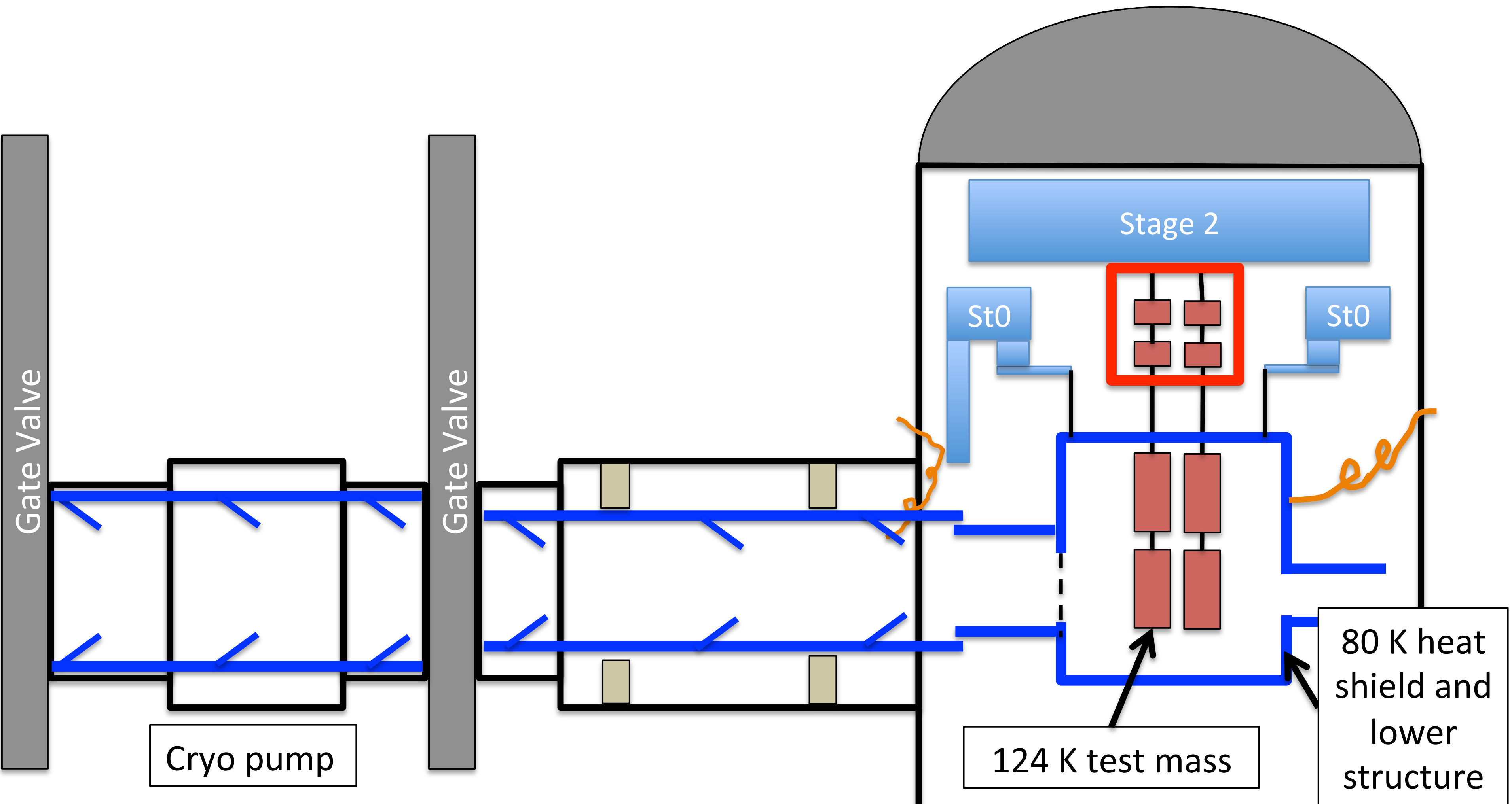

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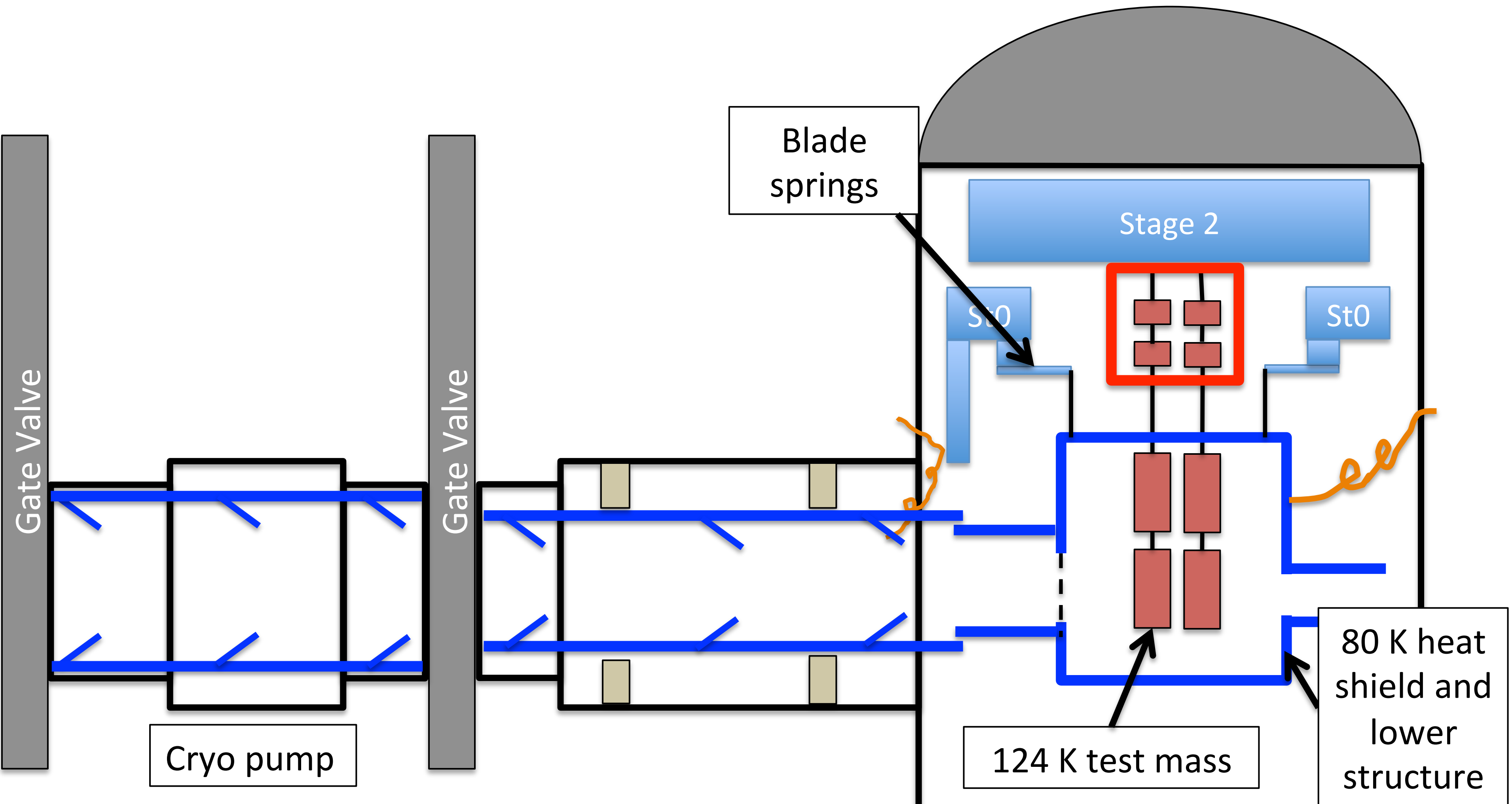

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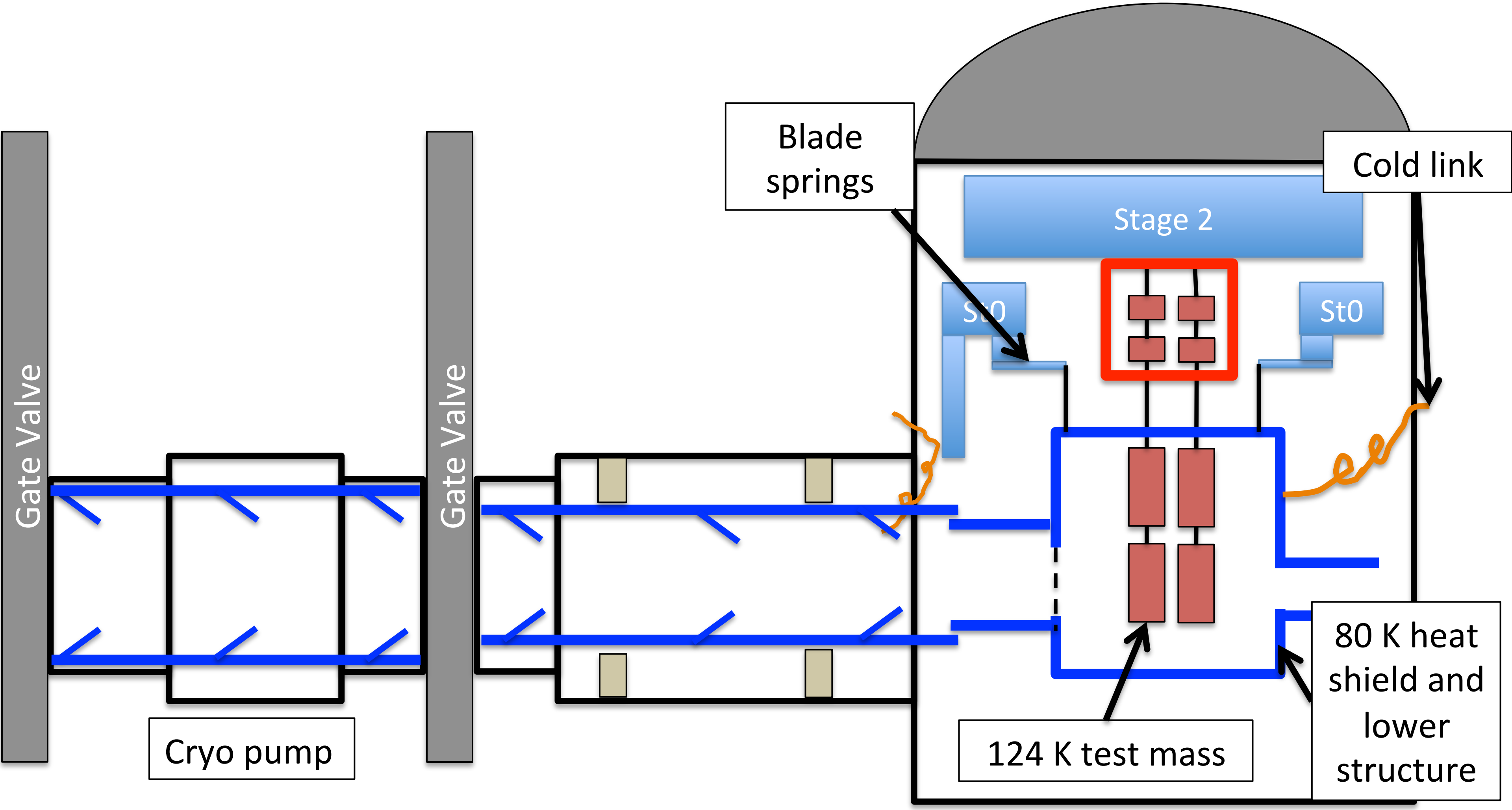

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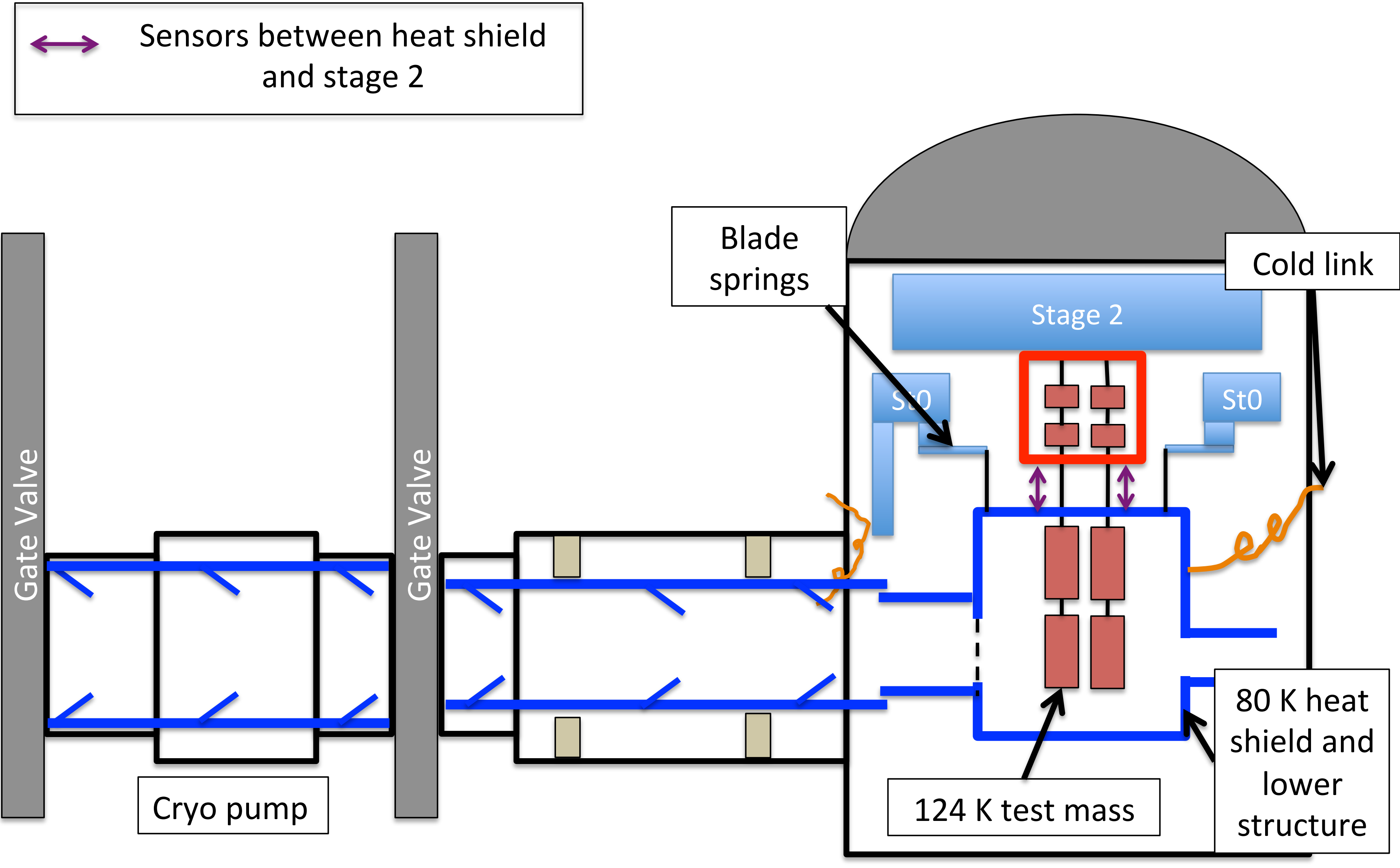
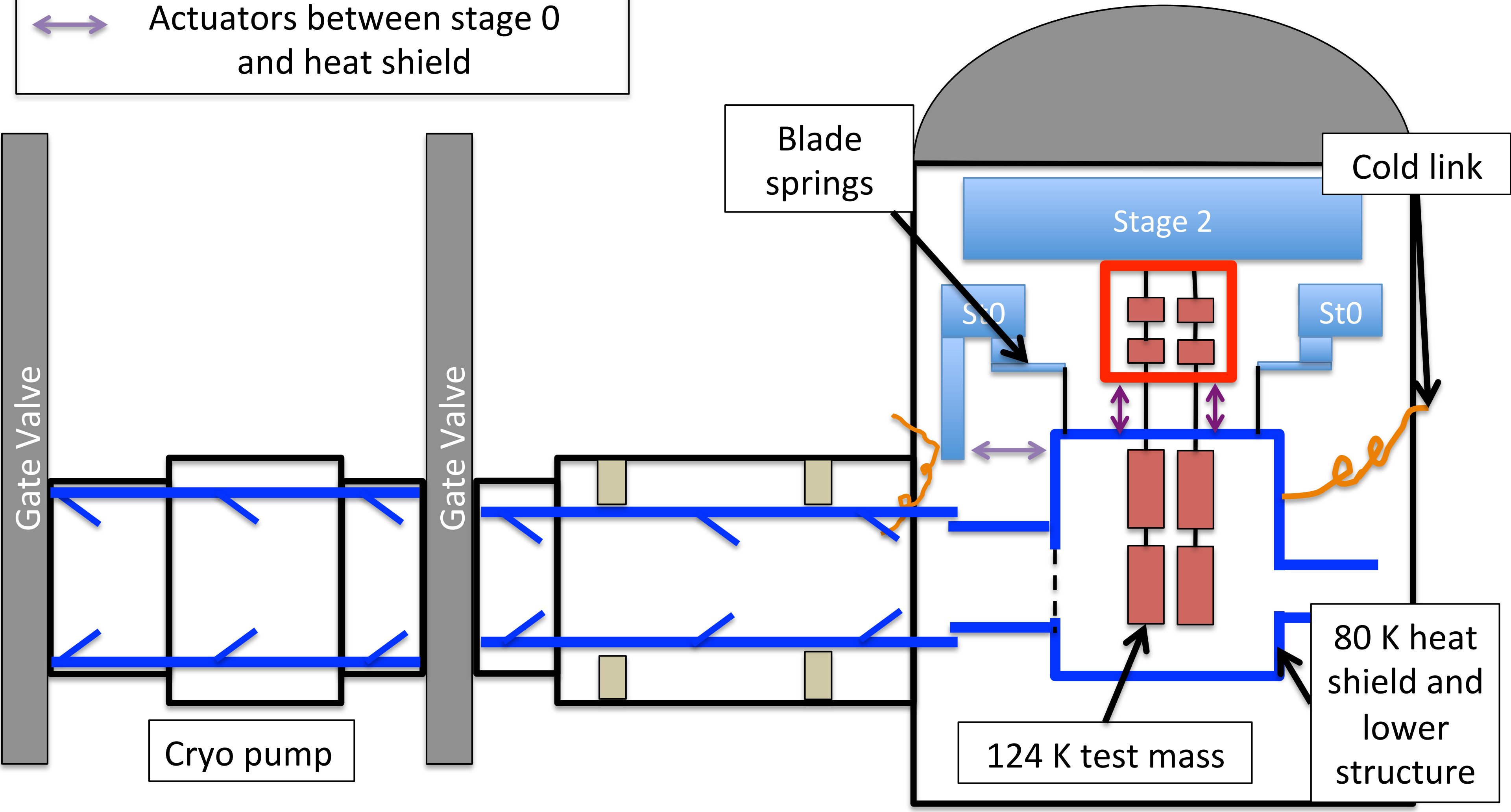


Actively controlled shield (ETM)

Sensors between heat shield and stage 2

Actuators between stage 0 and heat shield



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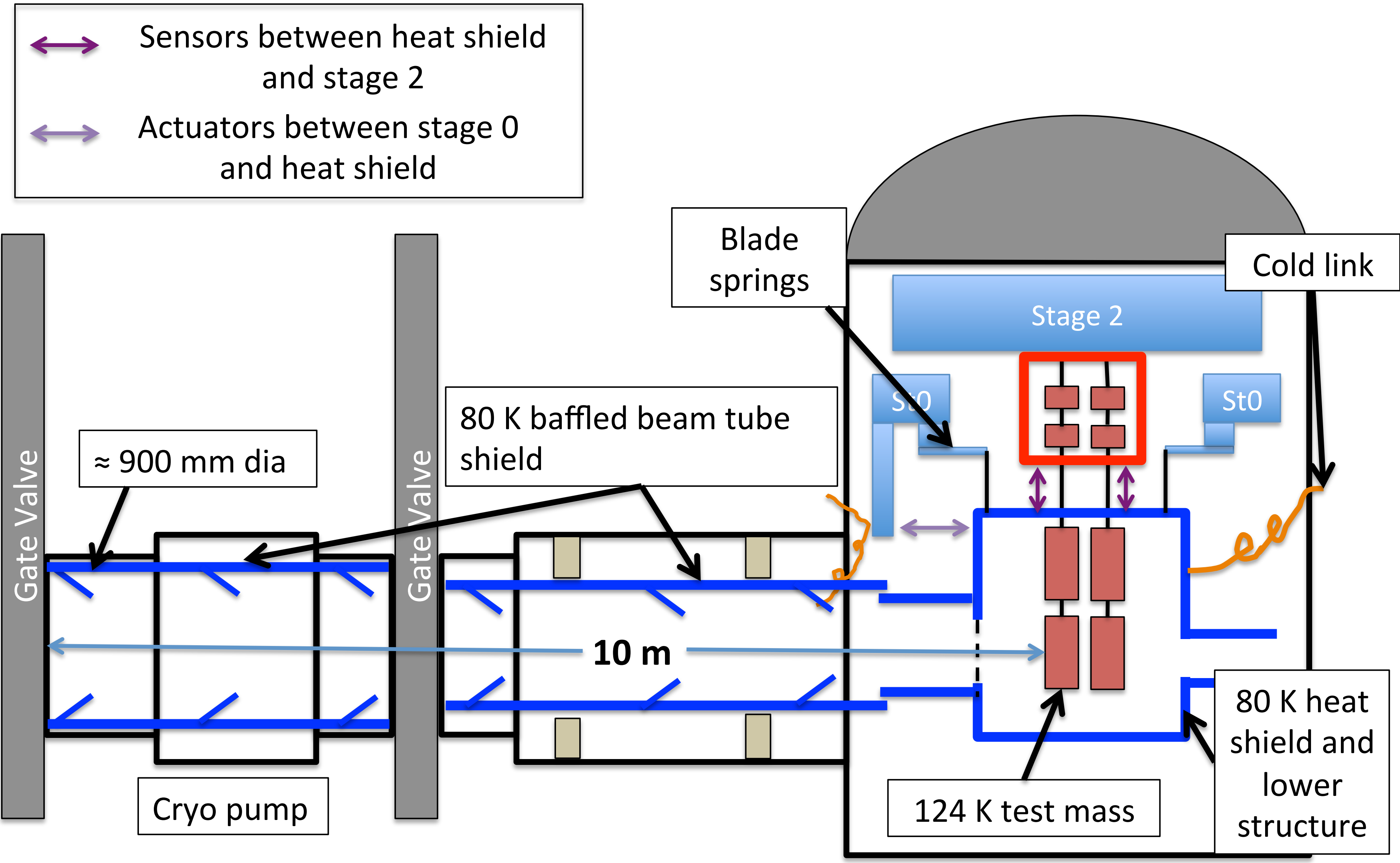

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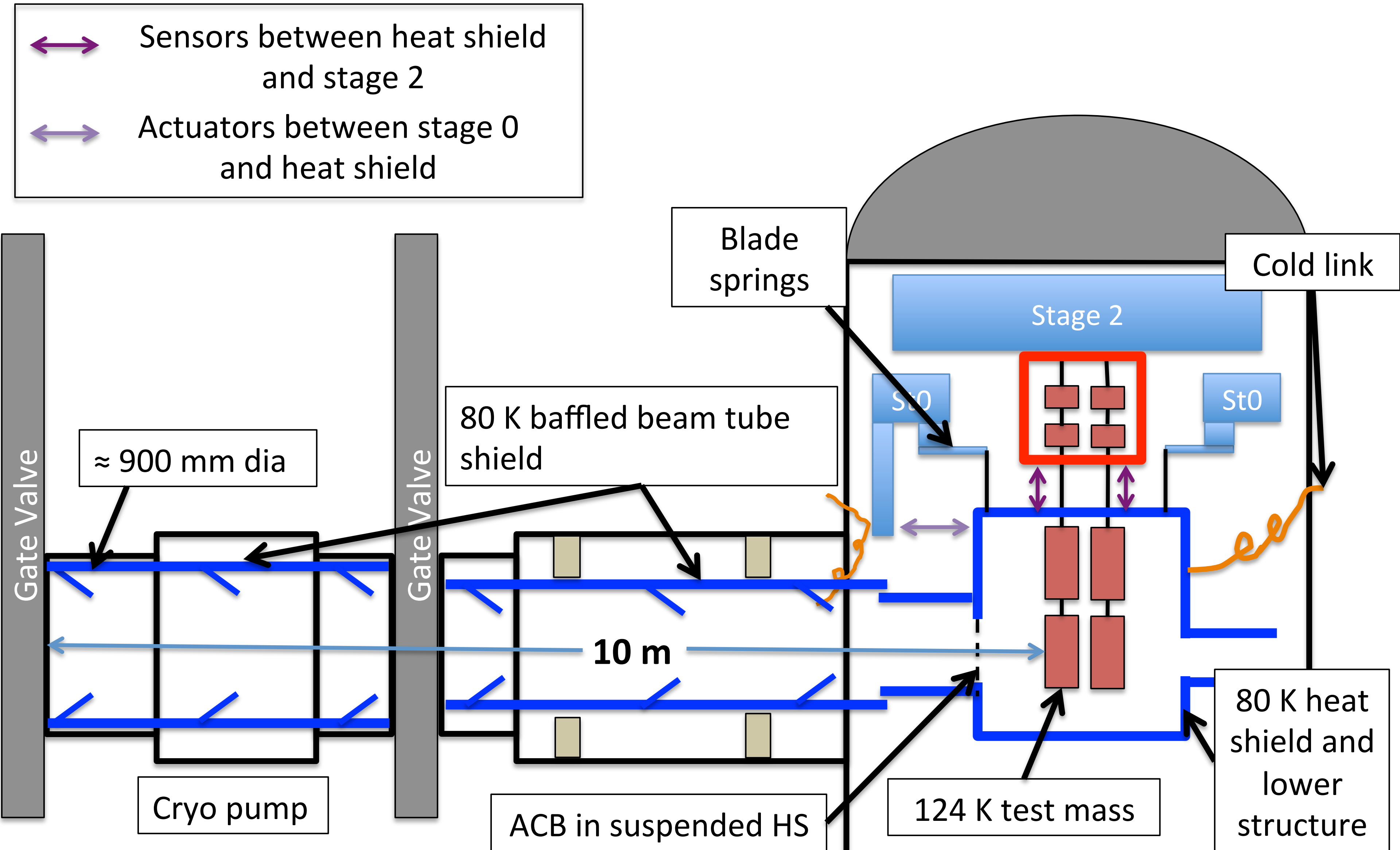
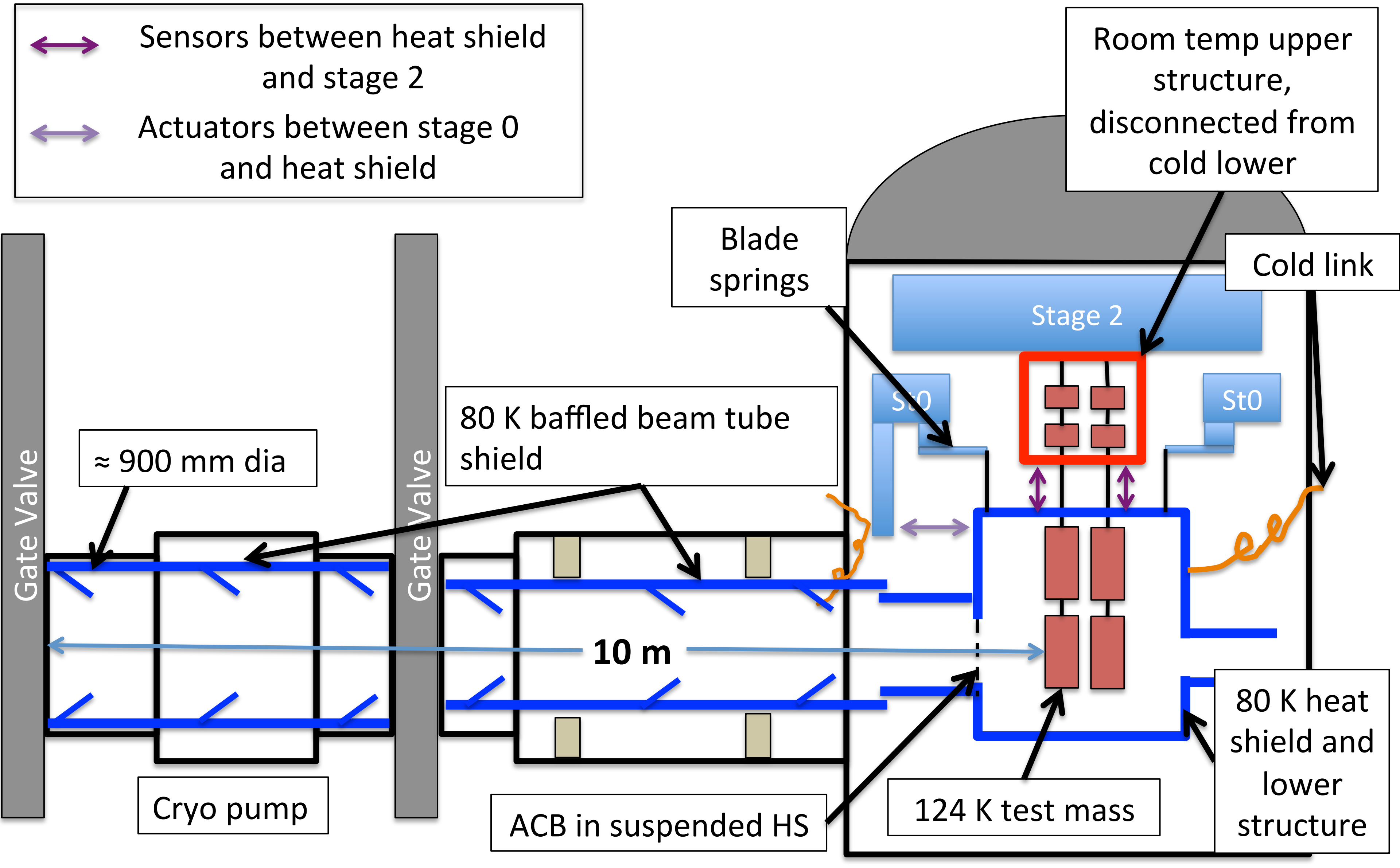


Actively controlled shield (ETM)



Pros/cons of separate cryo and seismic

- Pros
  - No seismic isolation impact
  - Shorter heat transfer path
  - Much greater choice of heat transfer methods
  - Allows more science payload (bigger test masses)

- Cons
  - Requires another active control system with many additional sensors and actuators per BSC

To make 1 structure or 2?

- in the case of a suspended heat shield

	Temperature of cold part	Thermal stress + alignment of warm part	Vibrational mode frequencies	Damping of vibrational modes	Relative complexity of construction
1 structure					
2 structures: warm & cold					

Note:

- For 1 structure, the heat shield is not integrated. It cools the lower structure radiatively, along with the suspension.
- For 2 structures, the heat shield is fully integrated into the lower structure as 1 unit.

Good | Fair | Risky | Show stopper

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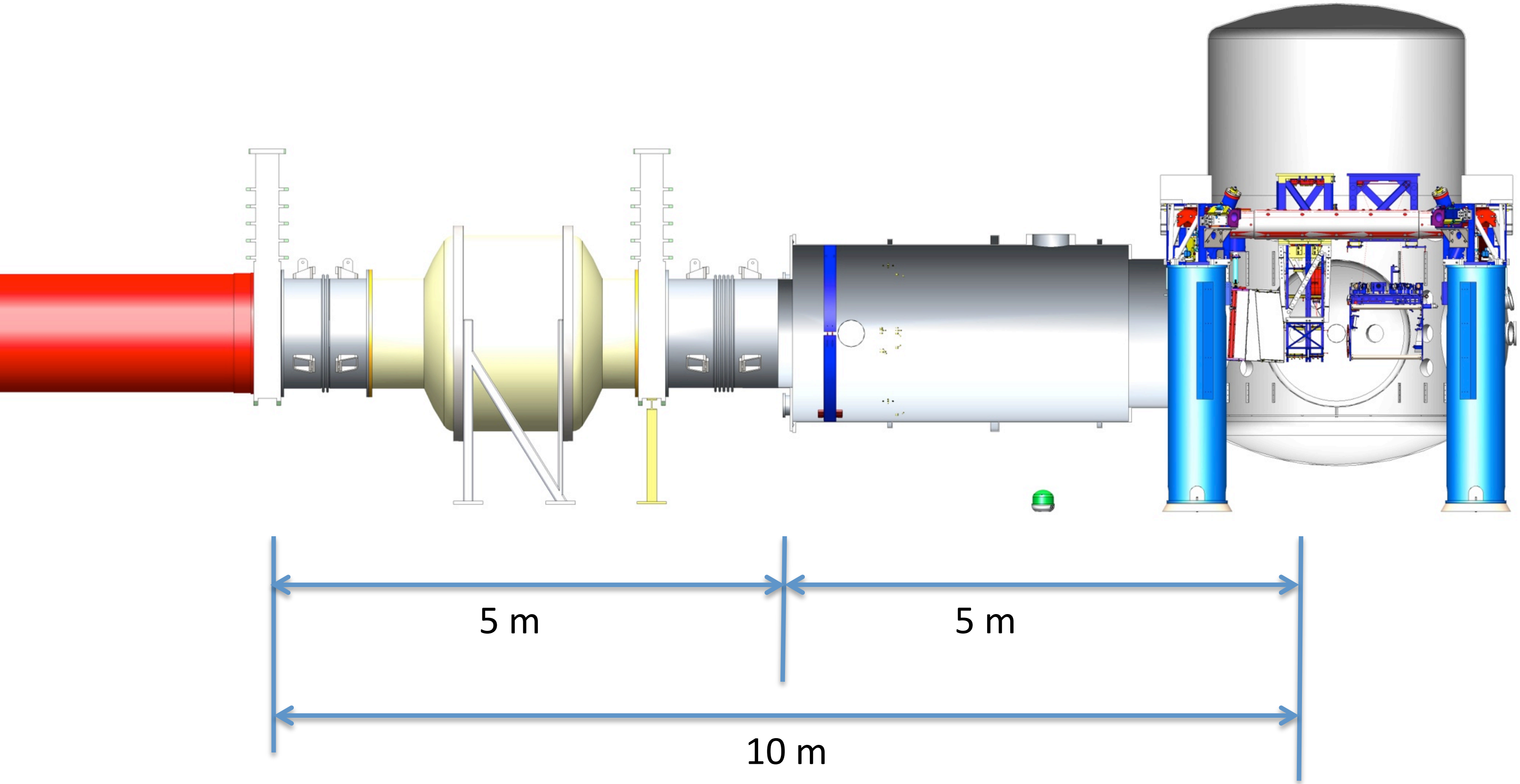
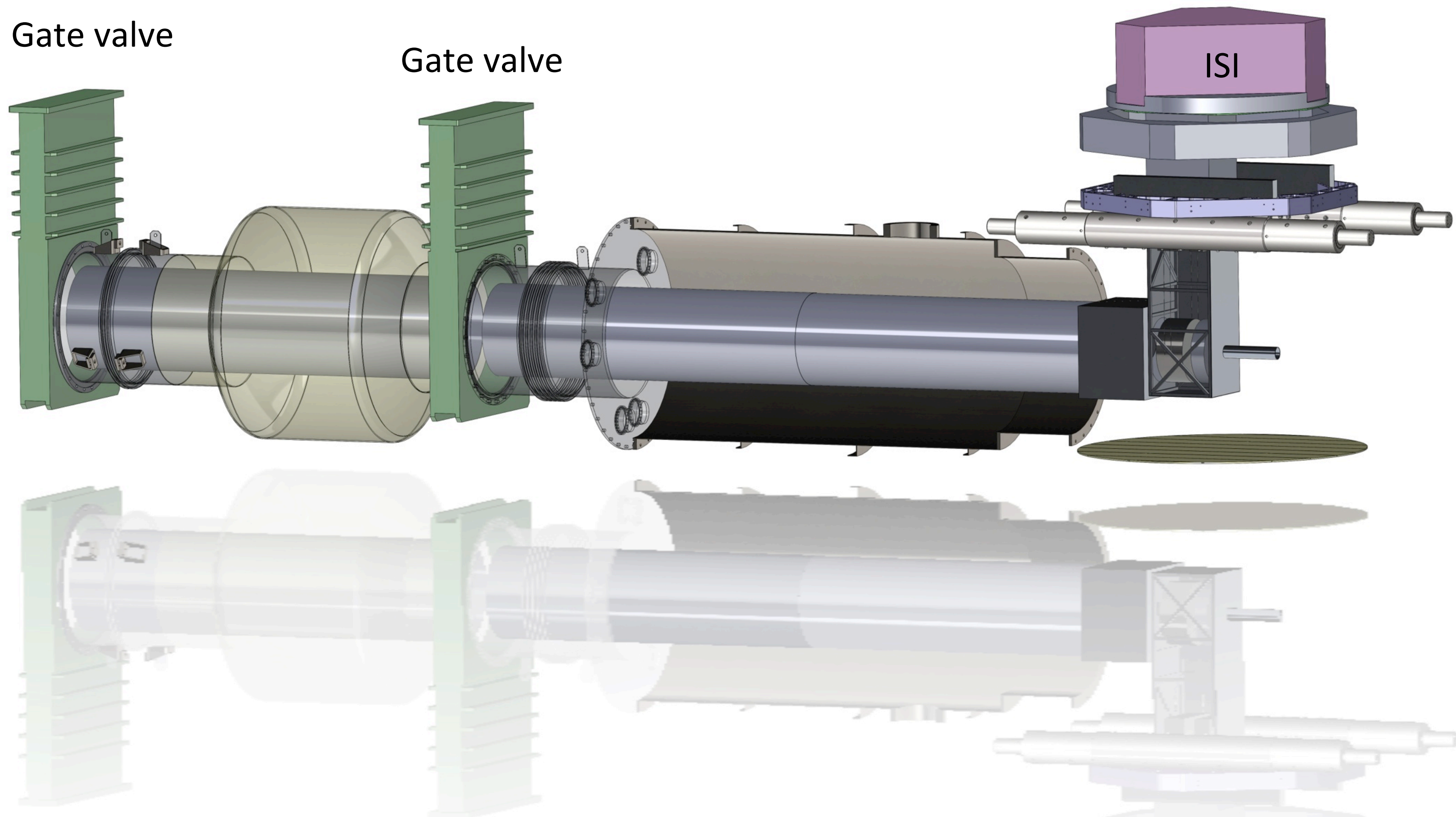
Conceptual LIGO III SolidWorks Sketches

aLIGO LLO Y End SolidWorks Model



LIGO III End Station Conceptual Model



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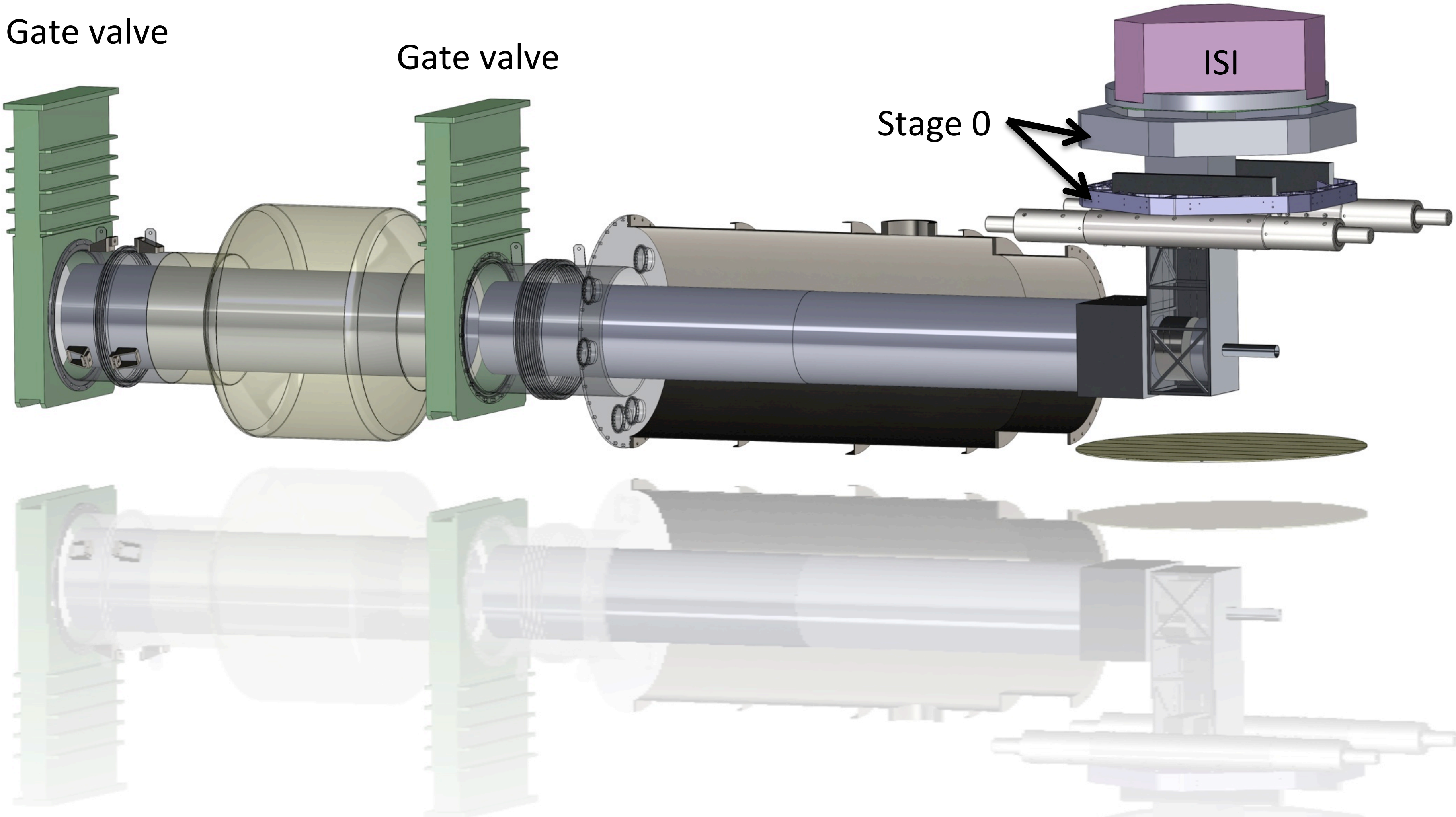
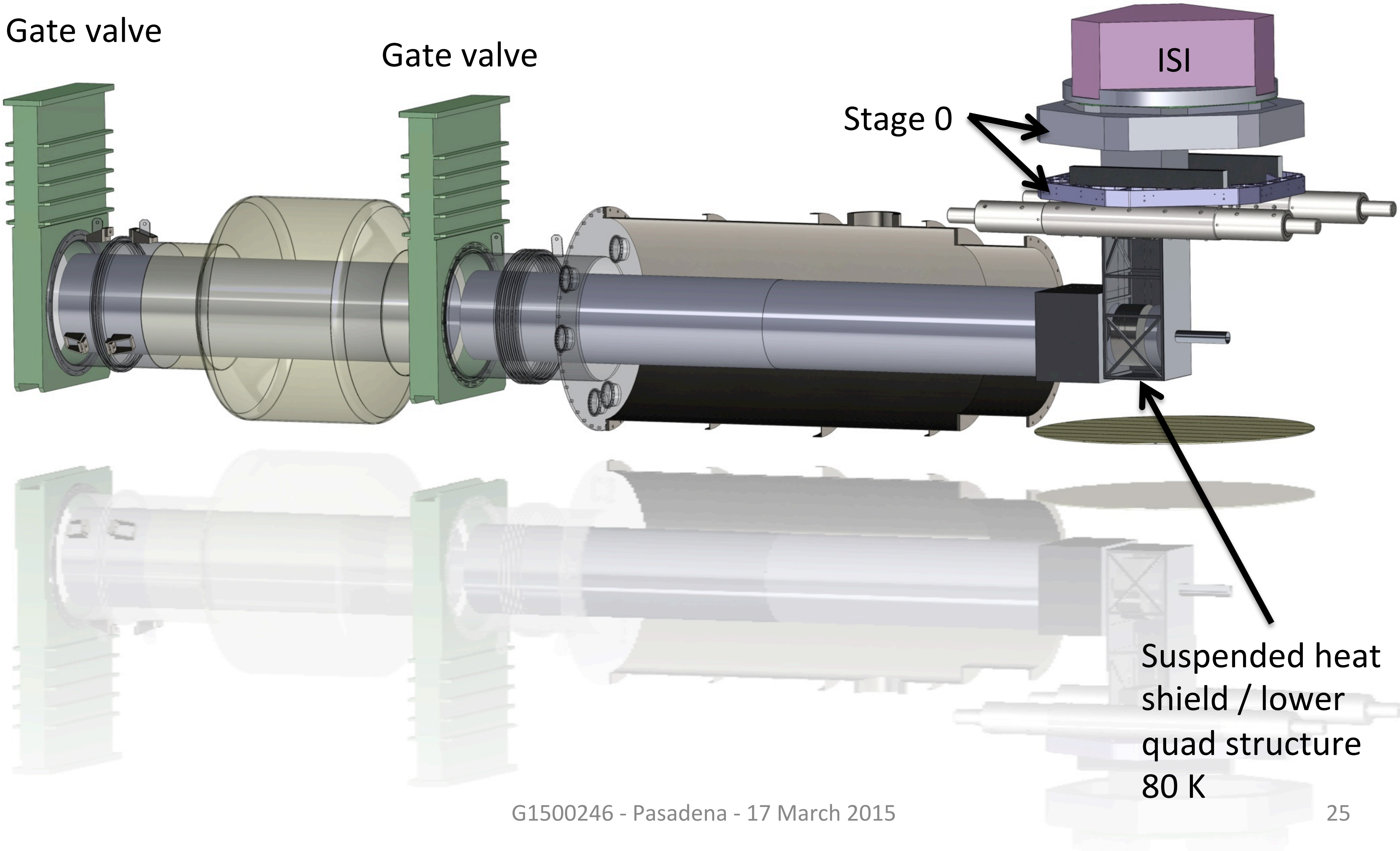


LIGO III End Station Conceptual Model



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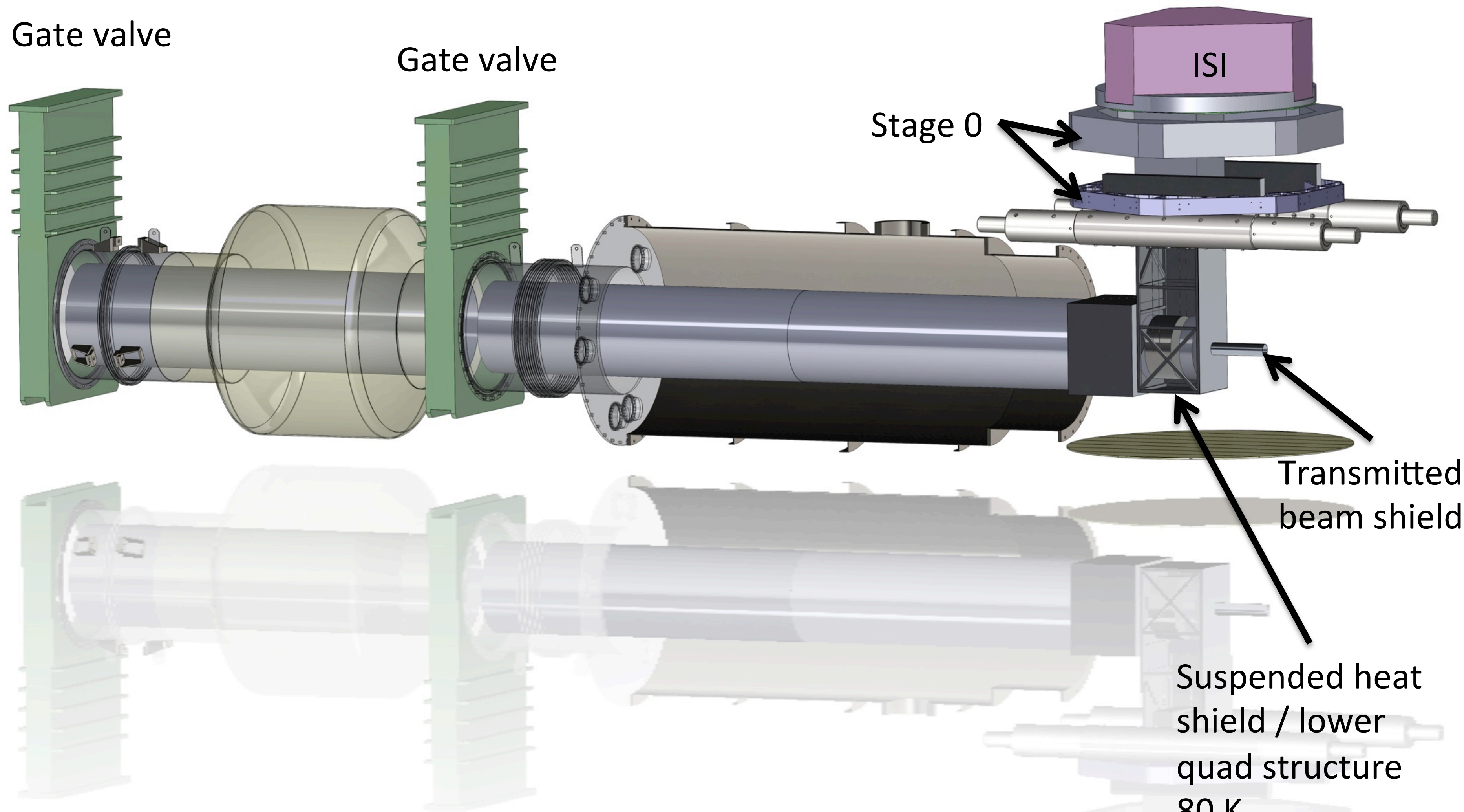

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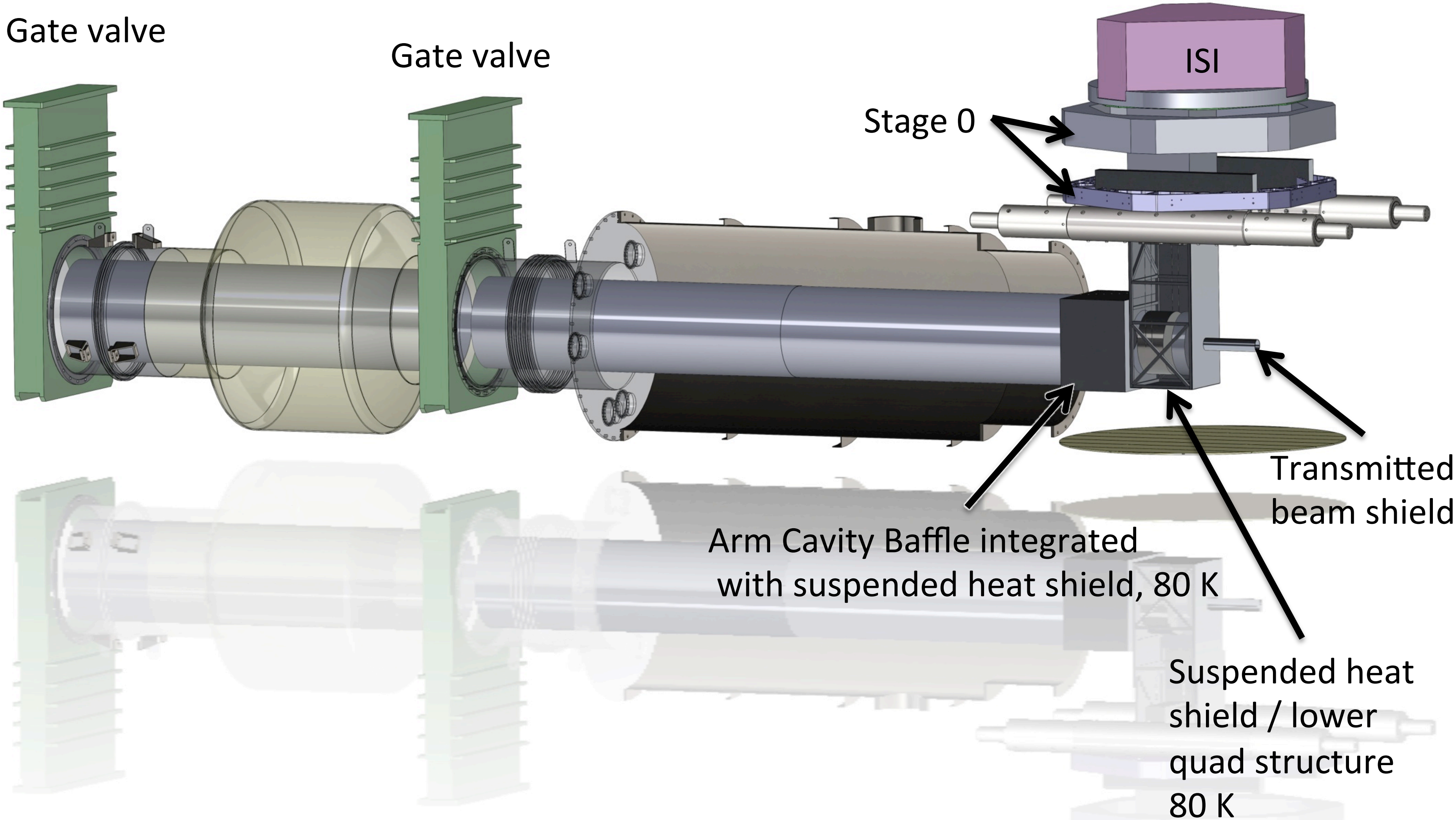

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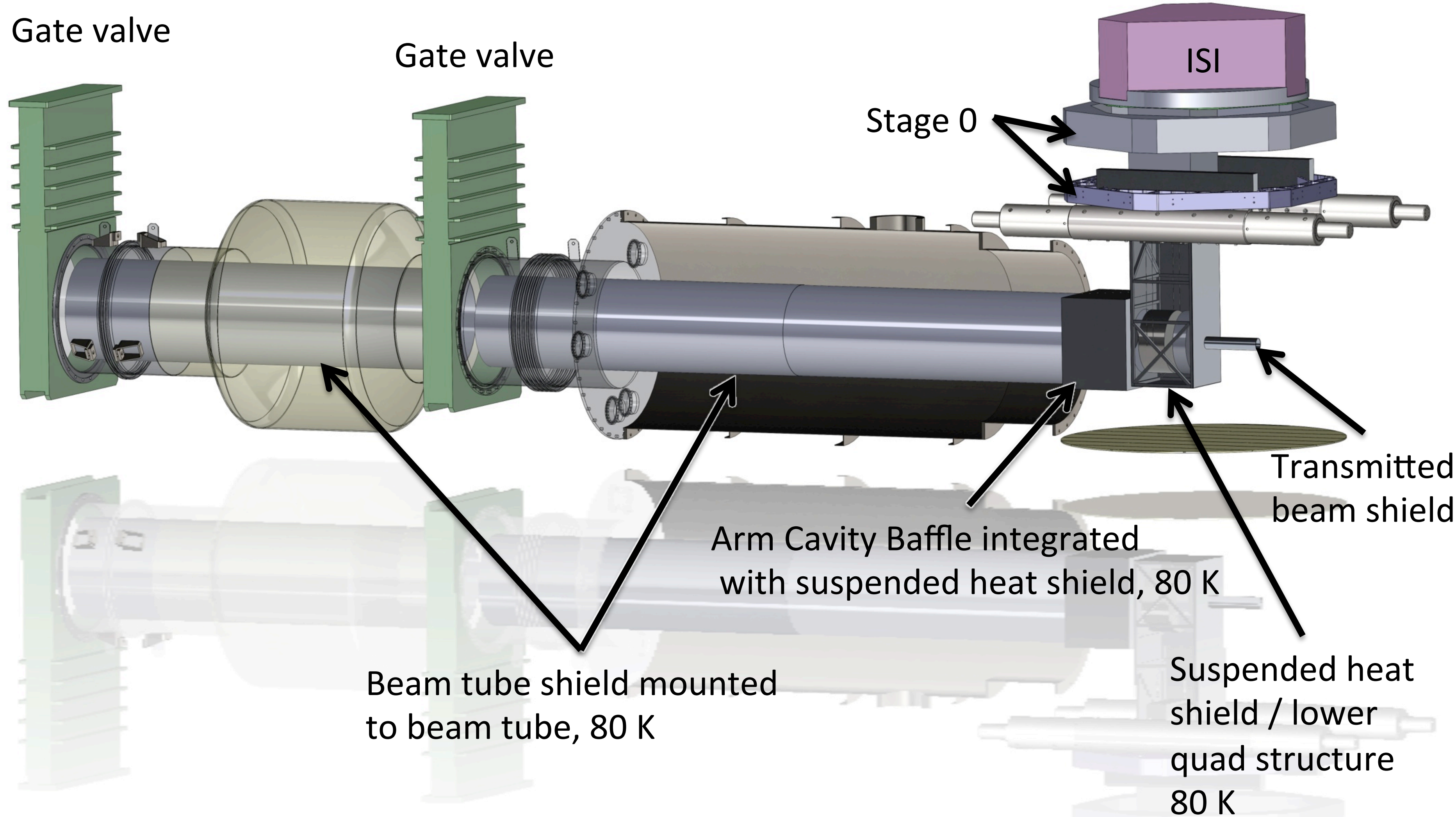

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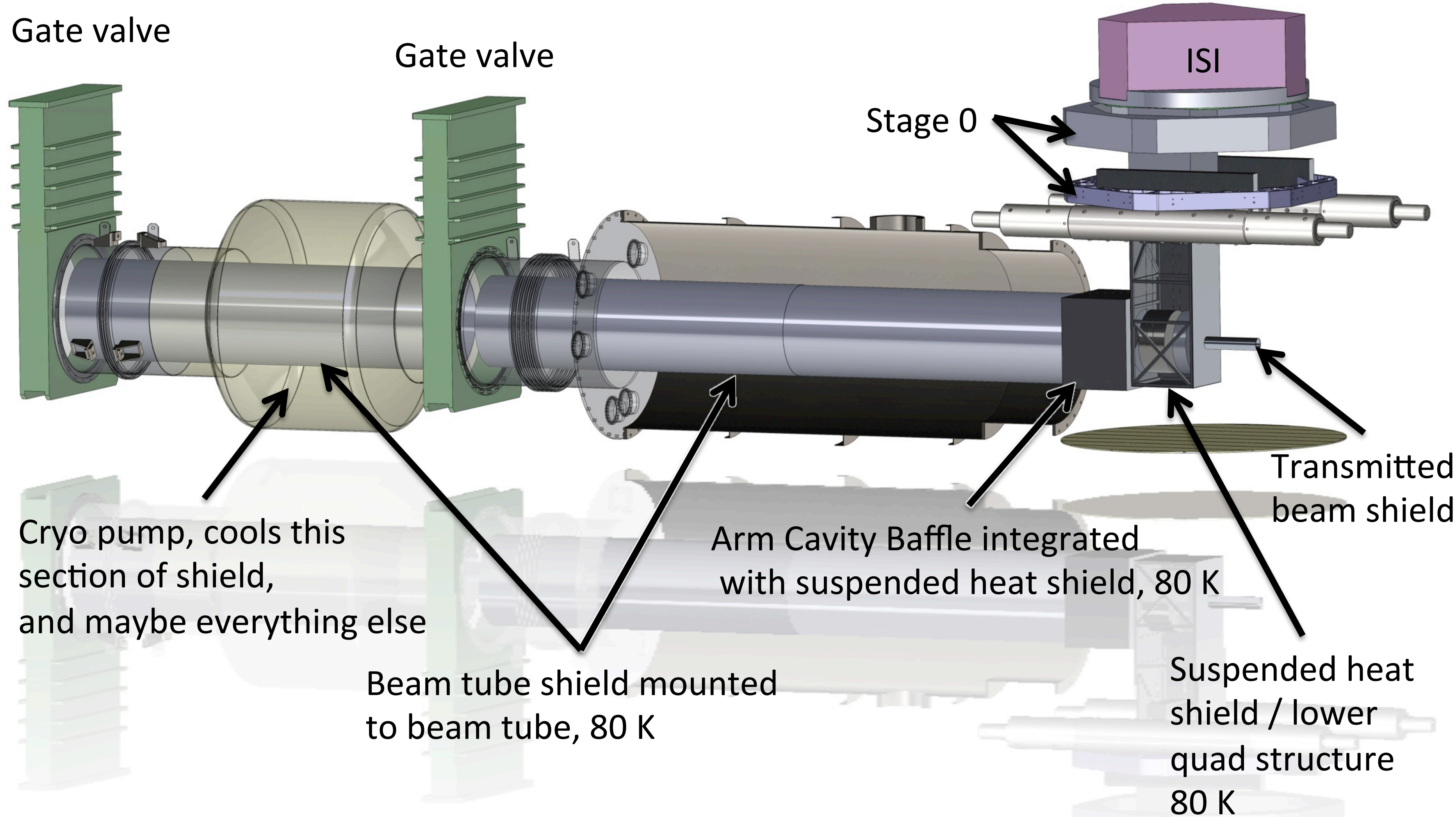
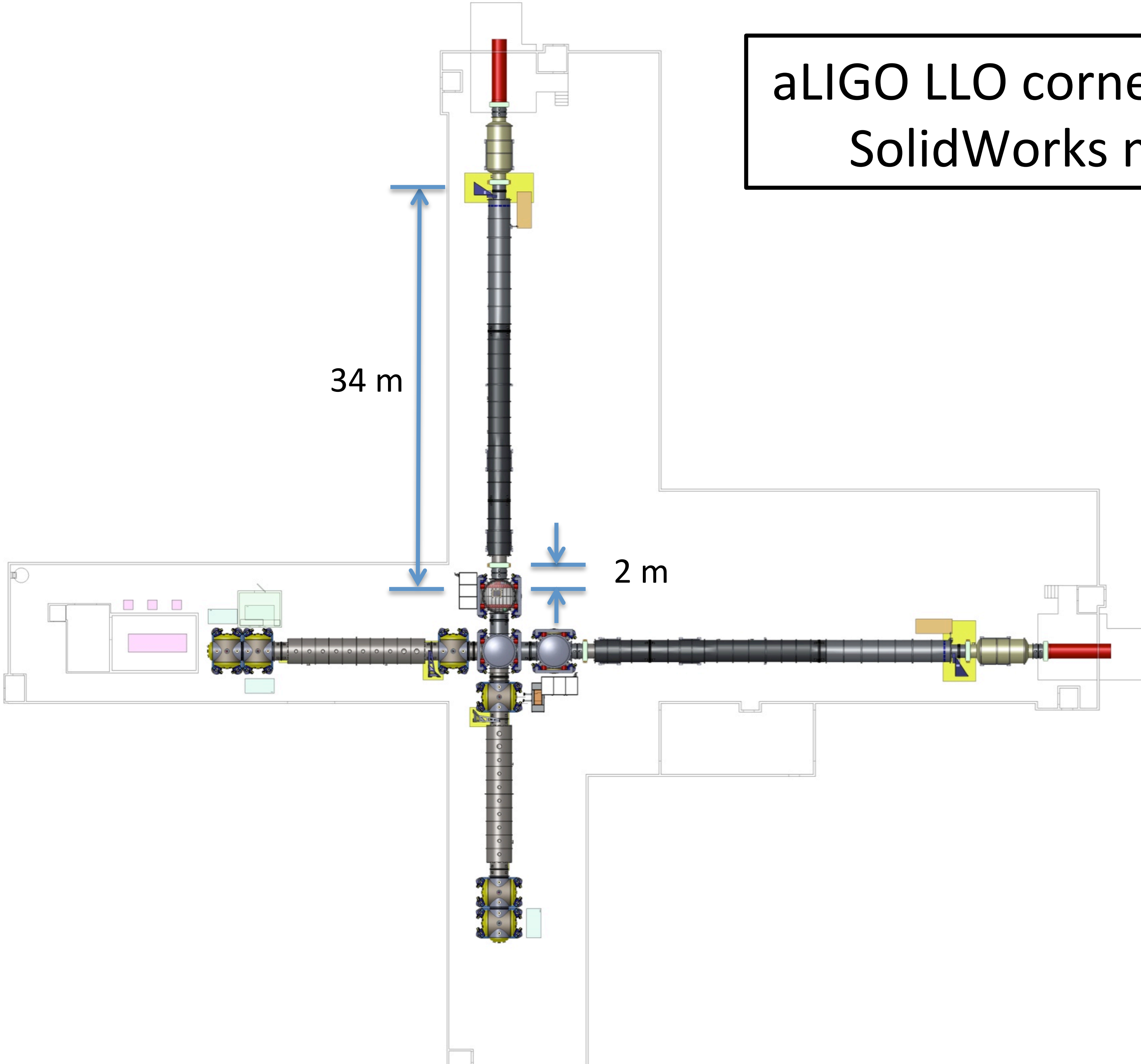
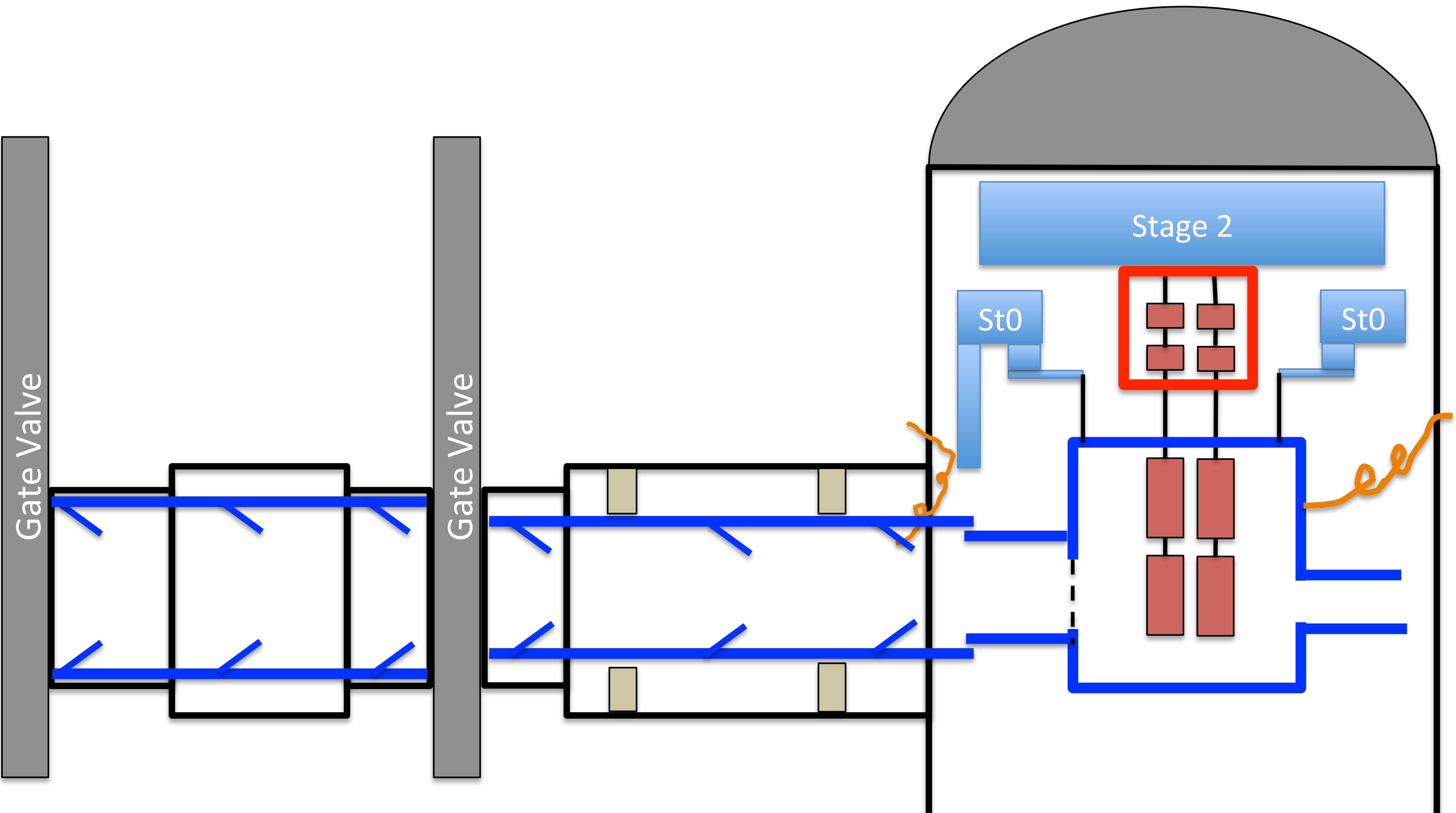


aLIGO LLO corner station SolidWorks model



Conclusions: Work/info needed for a low vibration cryo system



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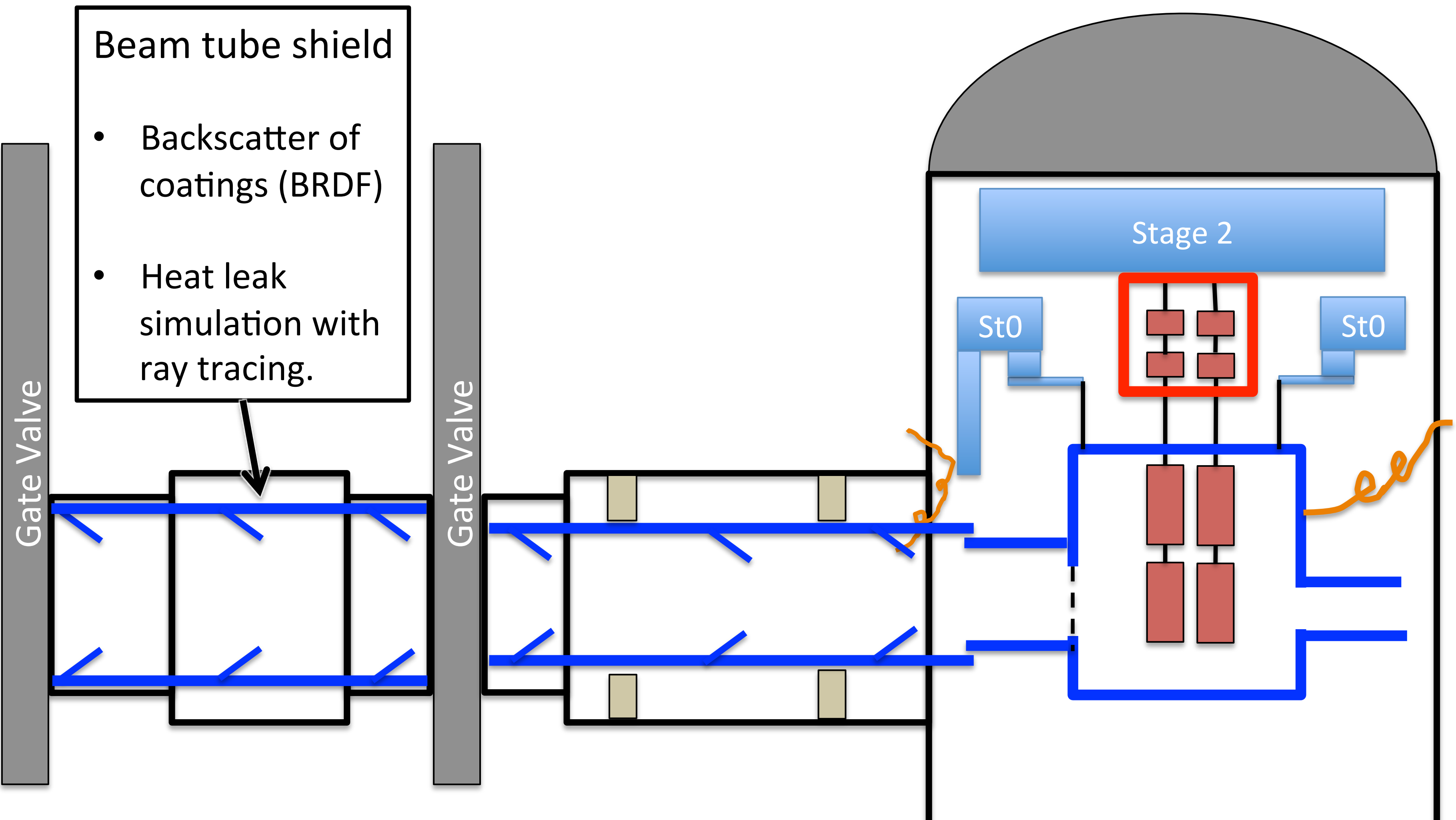

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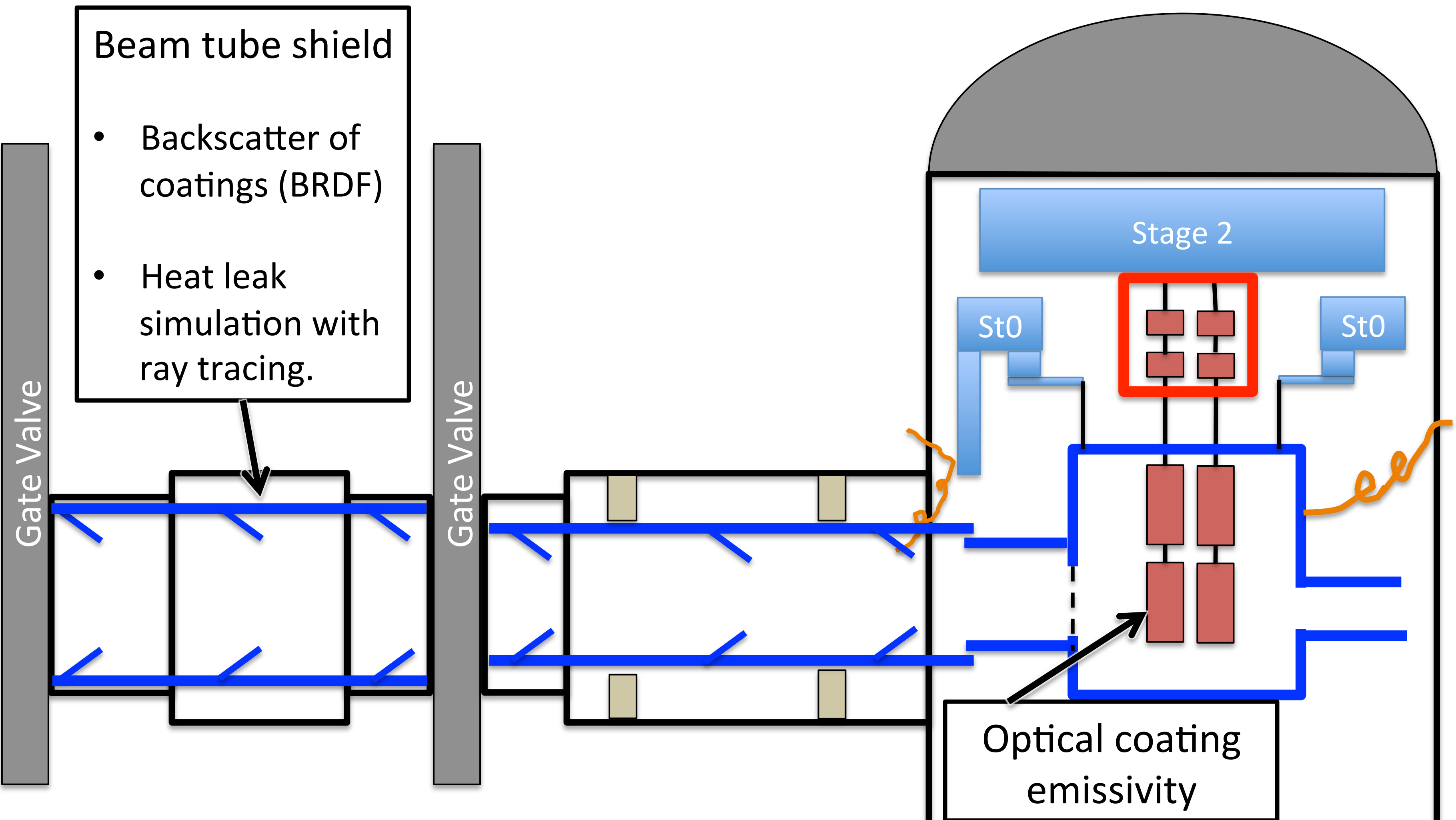

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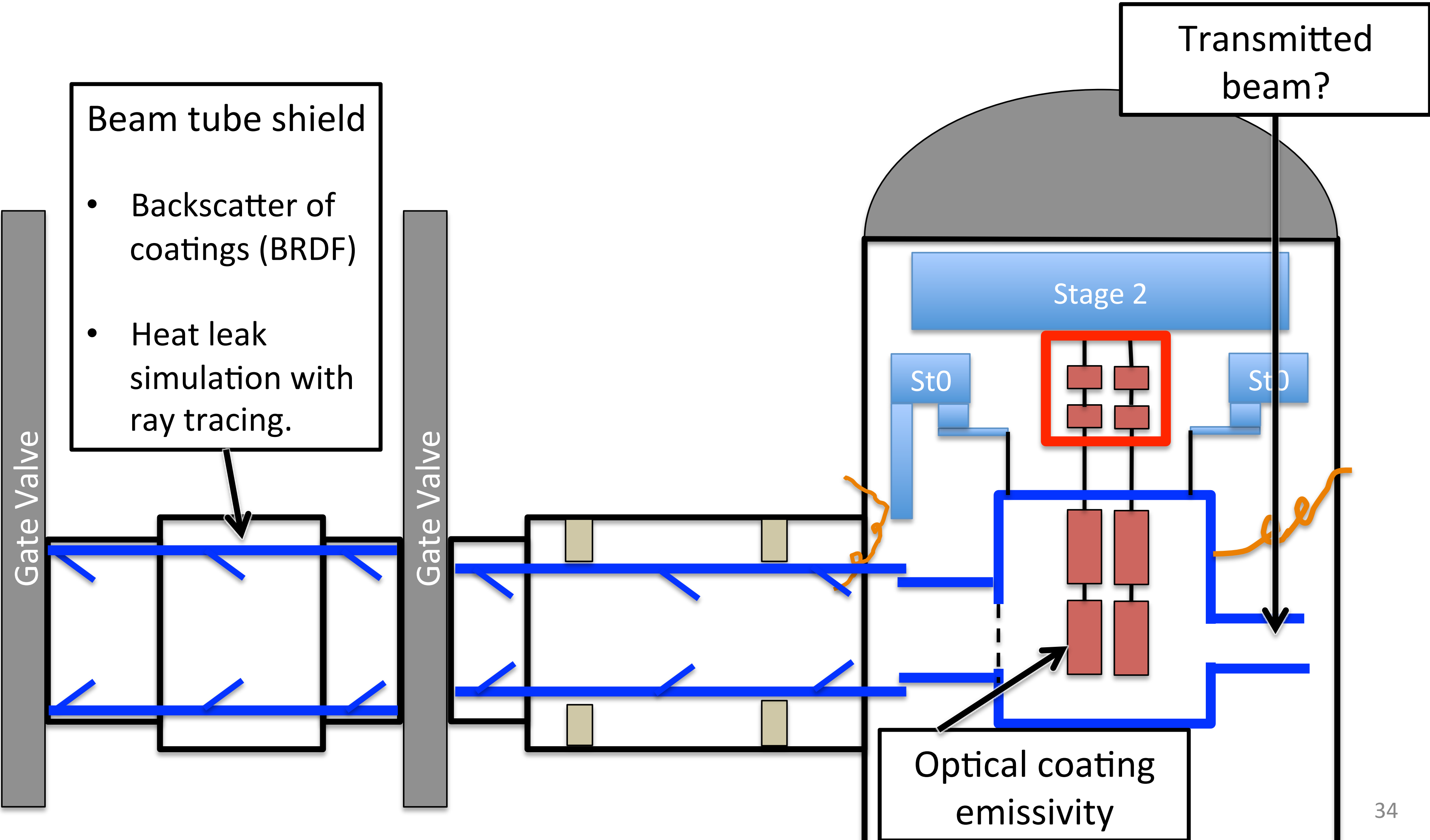

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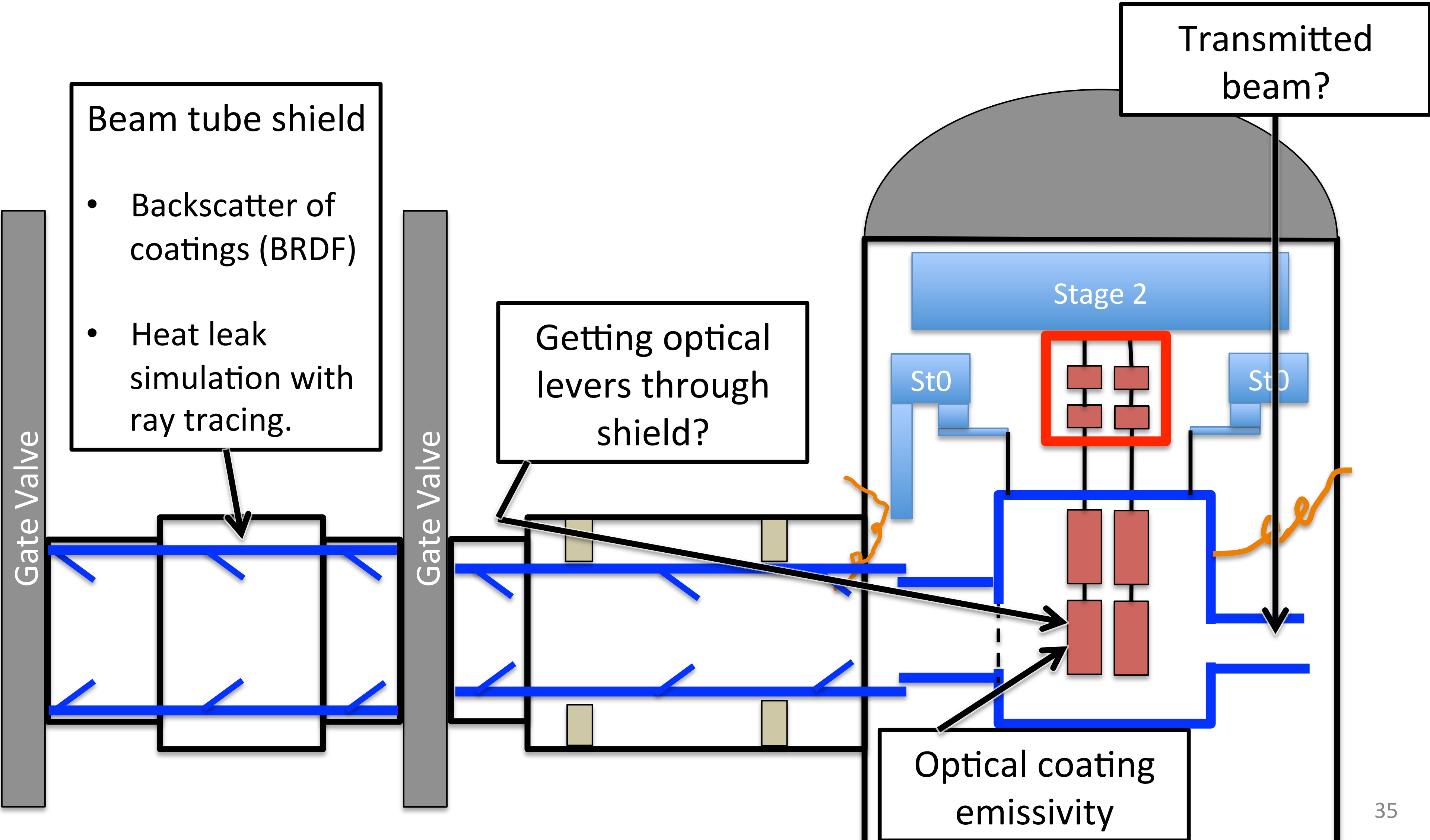

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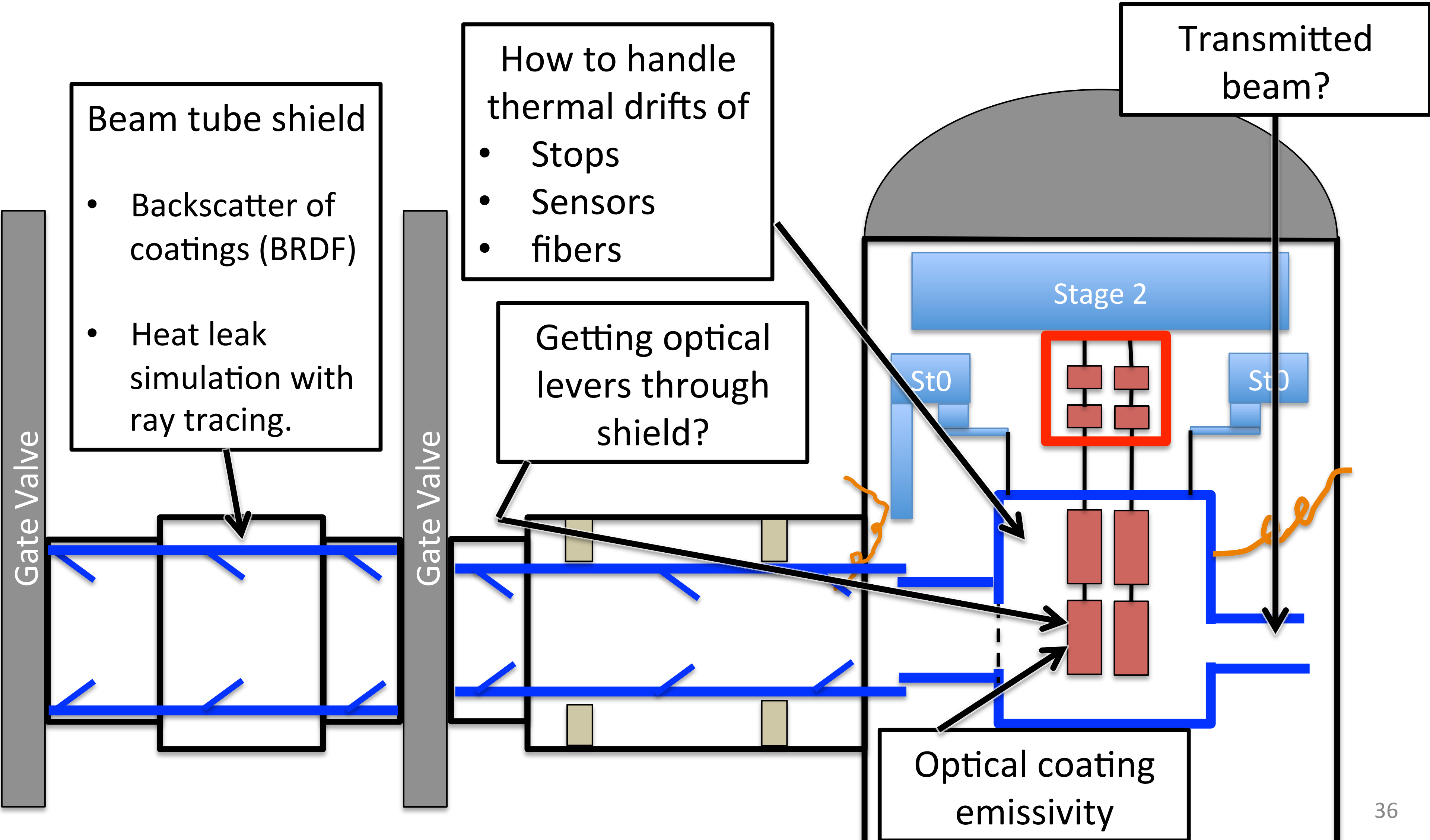

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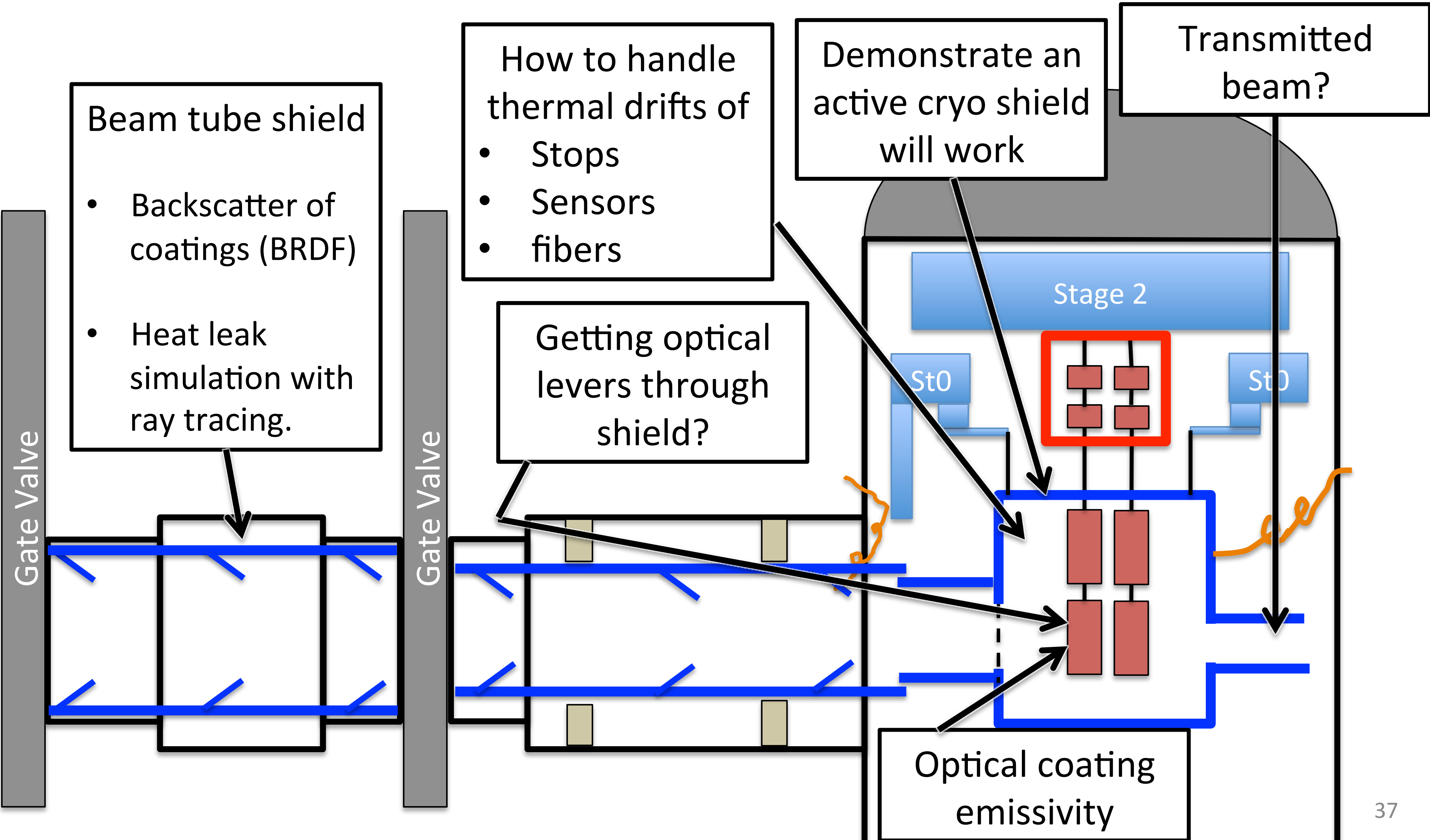
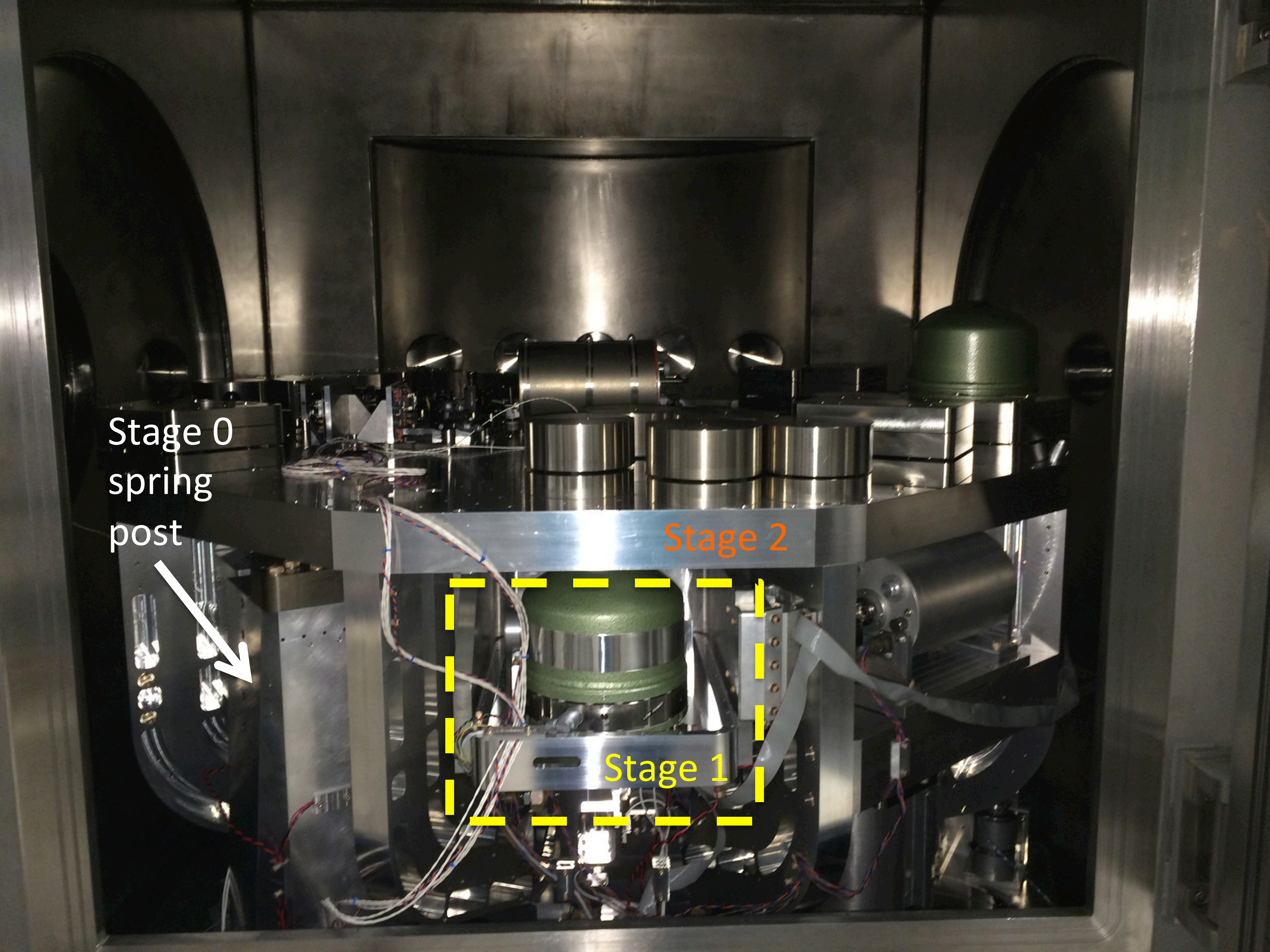
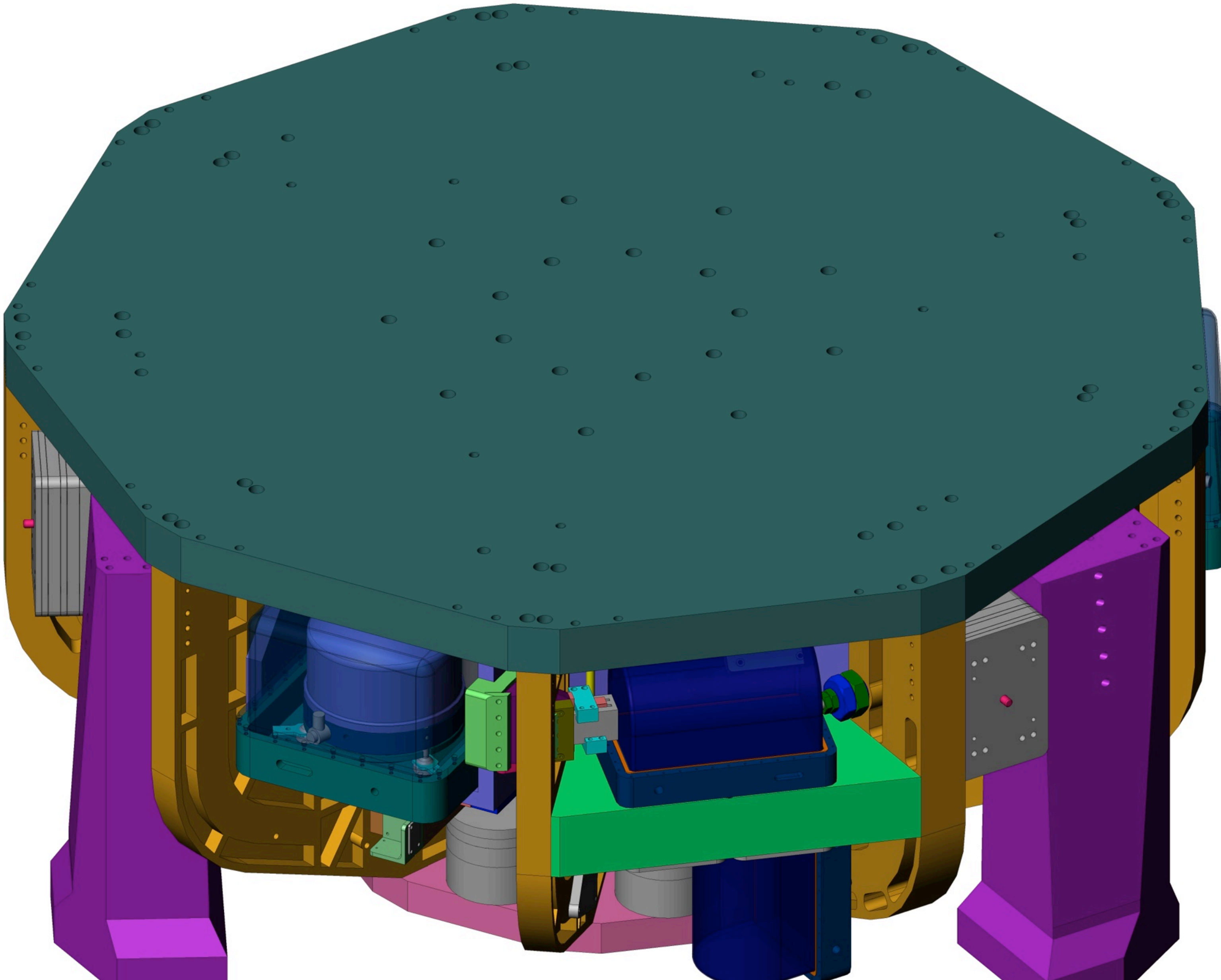
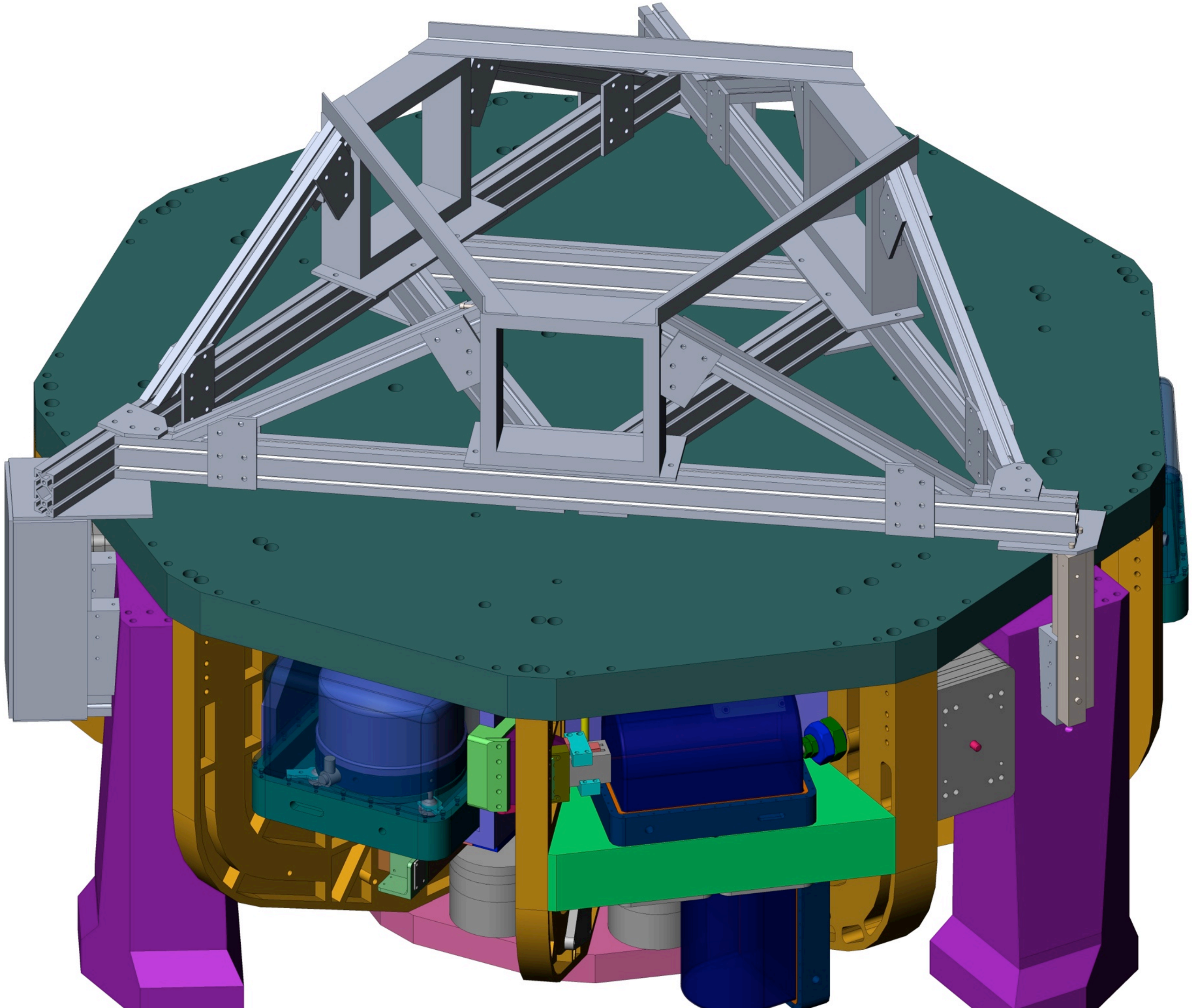
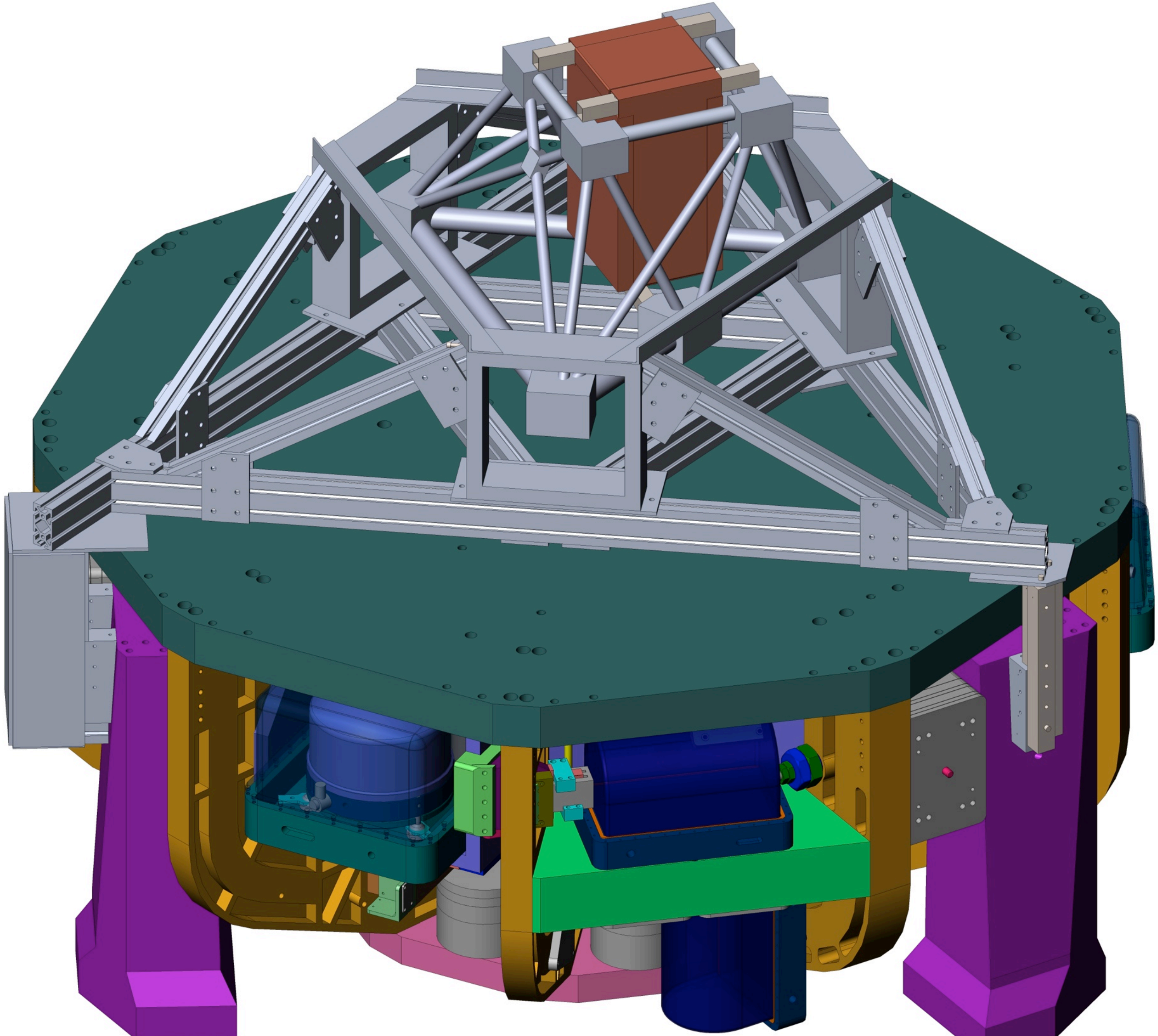


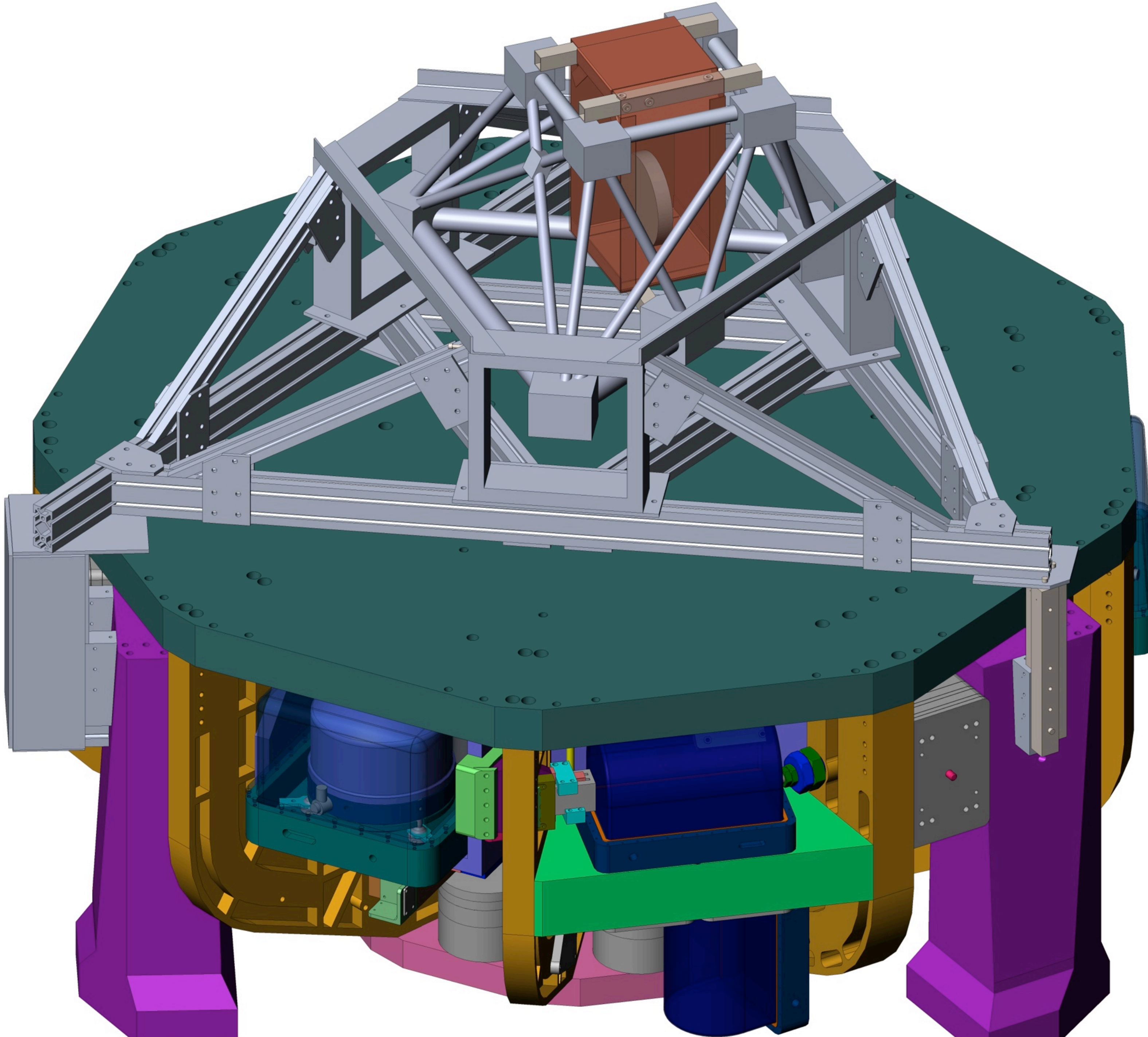
Stanford Active Heat Shield Experiment

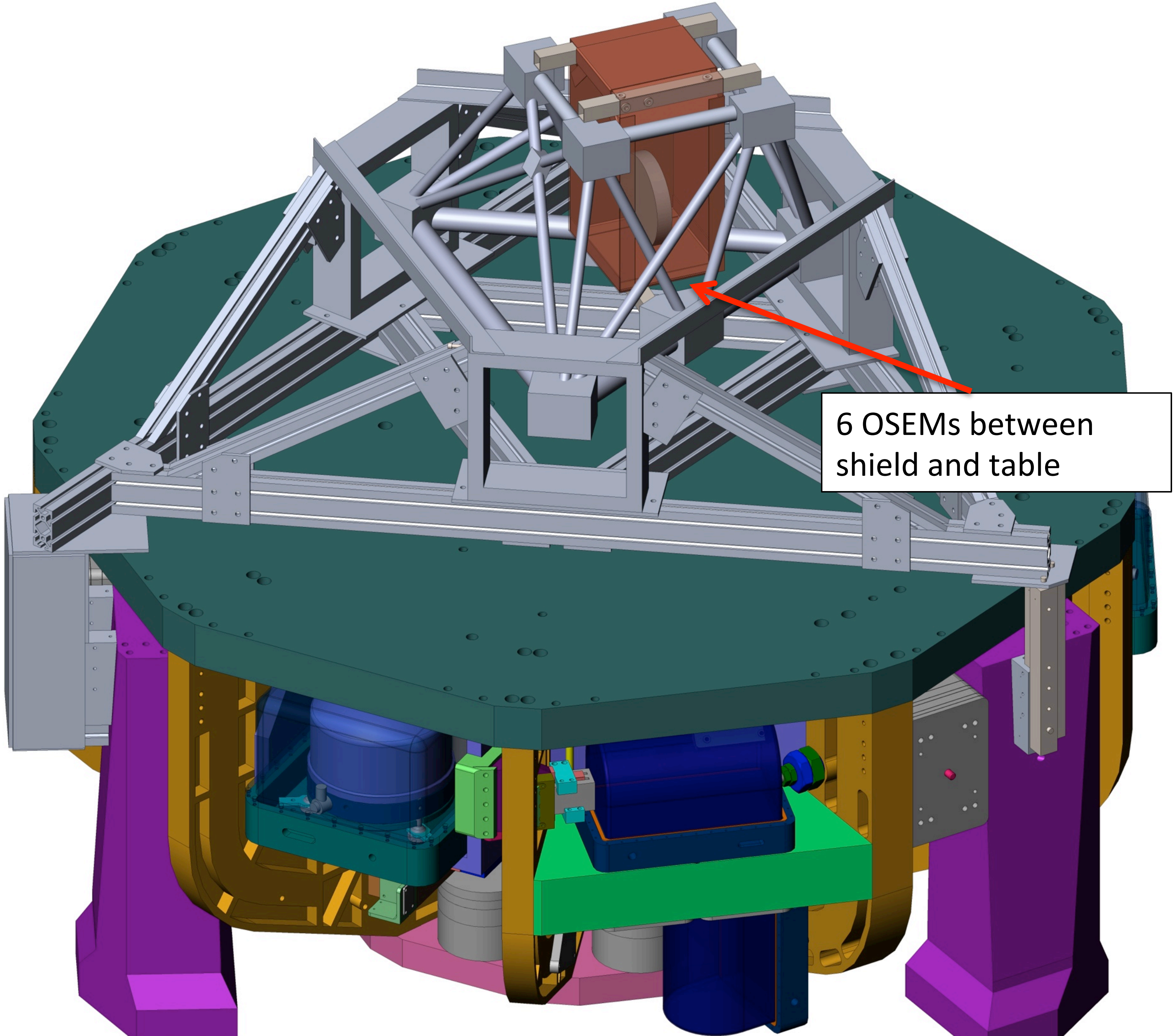

Stage 0
spring
post
Stage 2
Stage 1

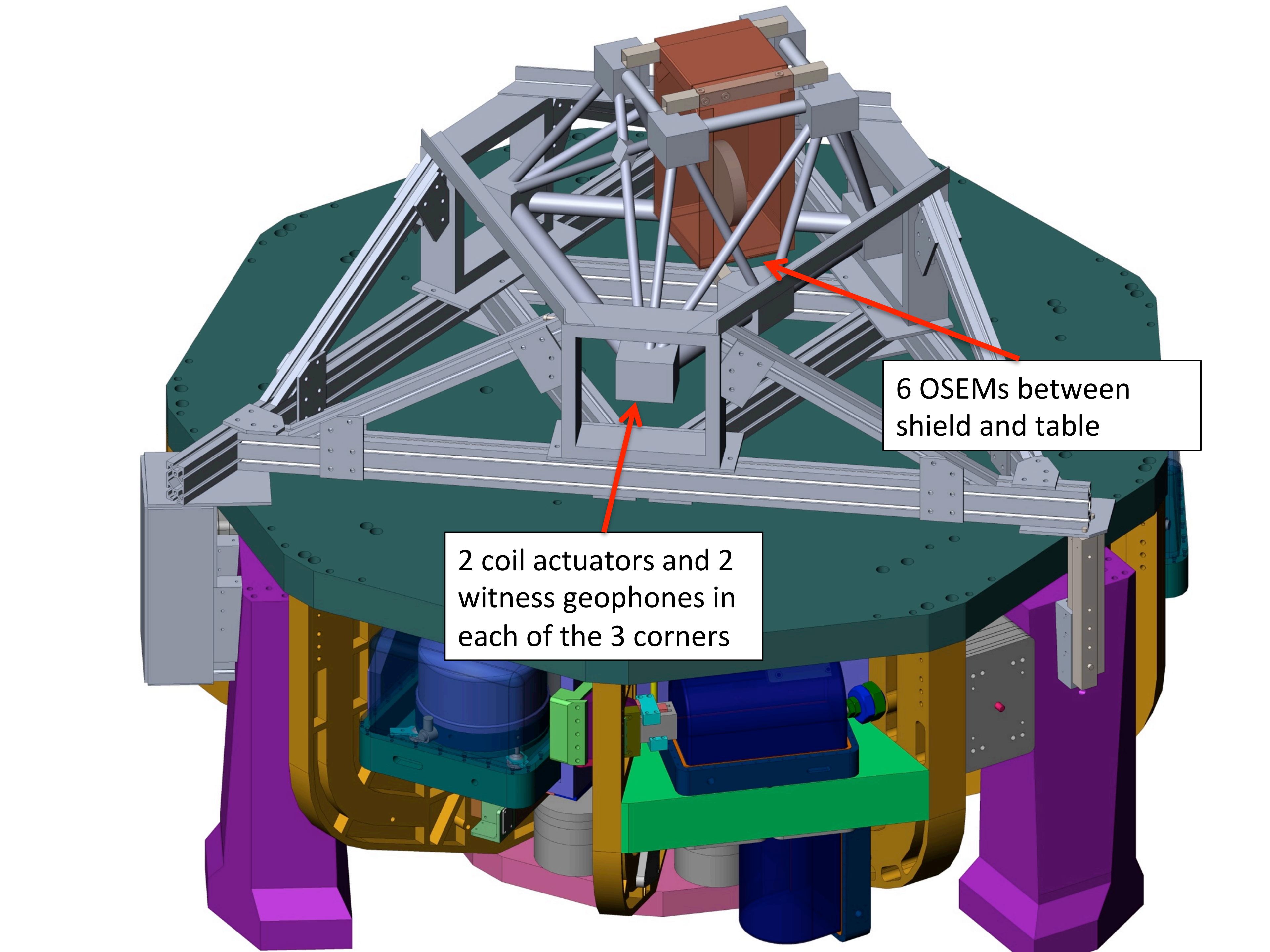


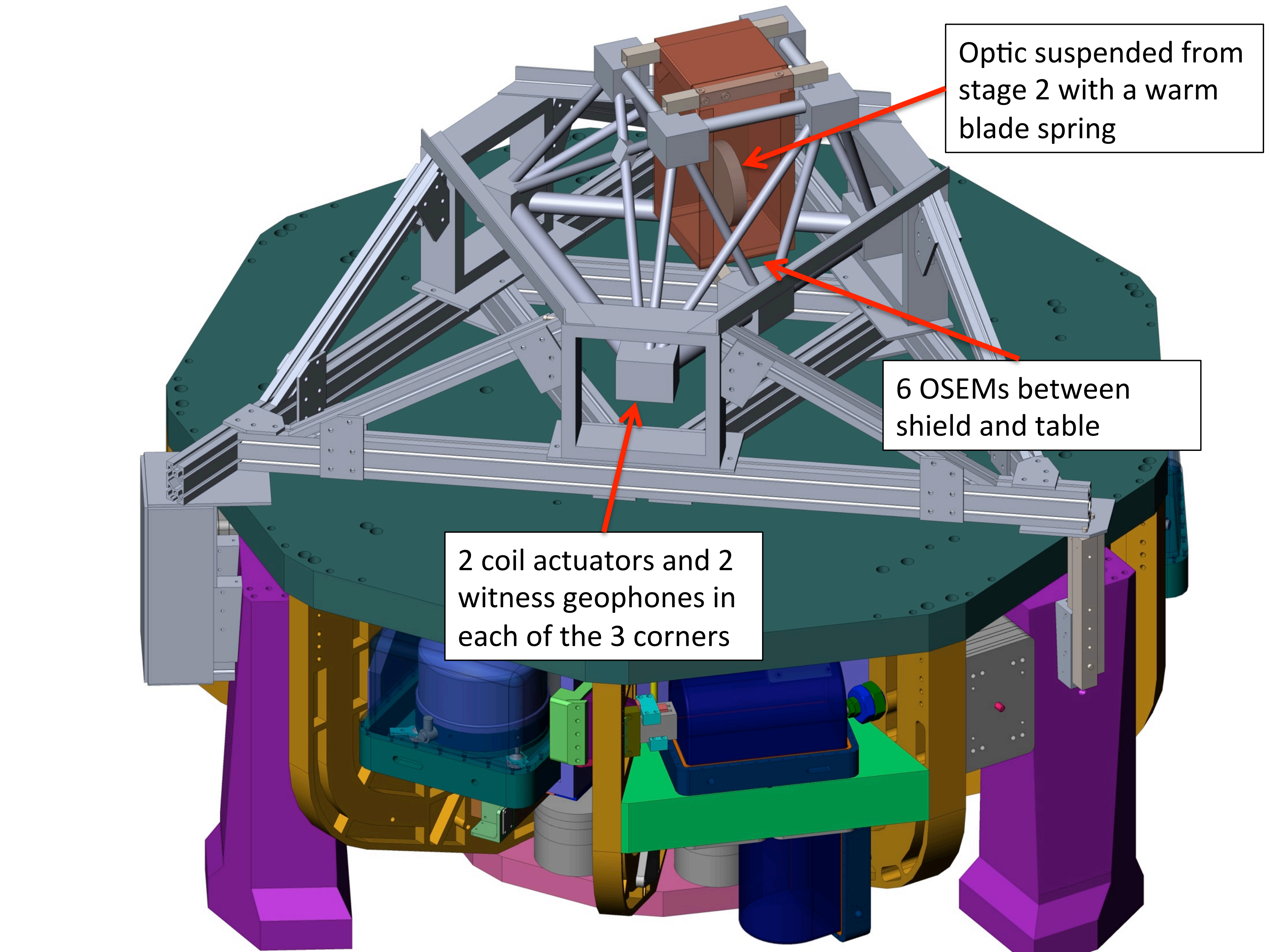







6 OSEMs between
shield and table

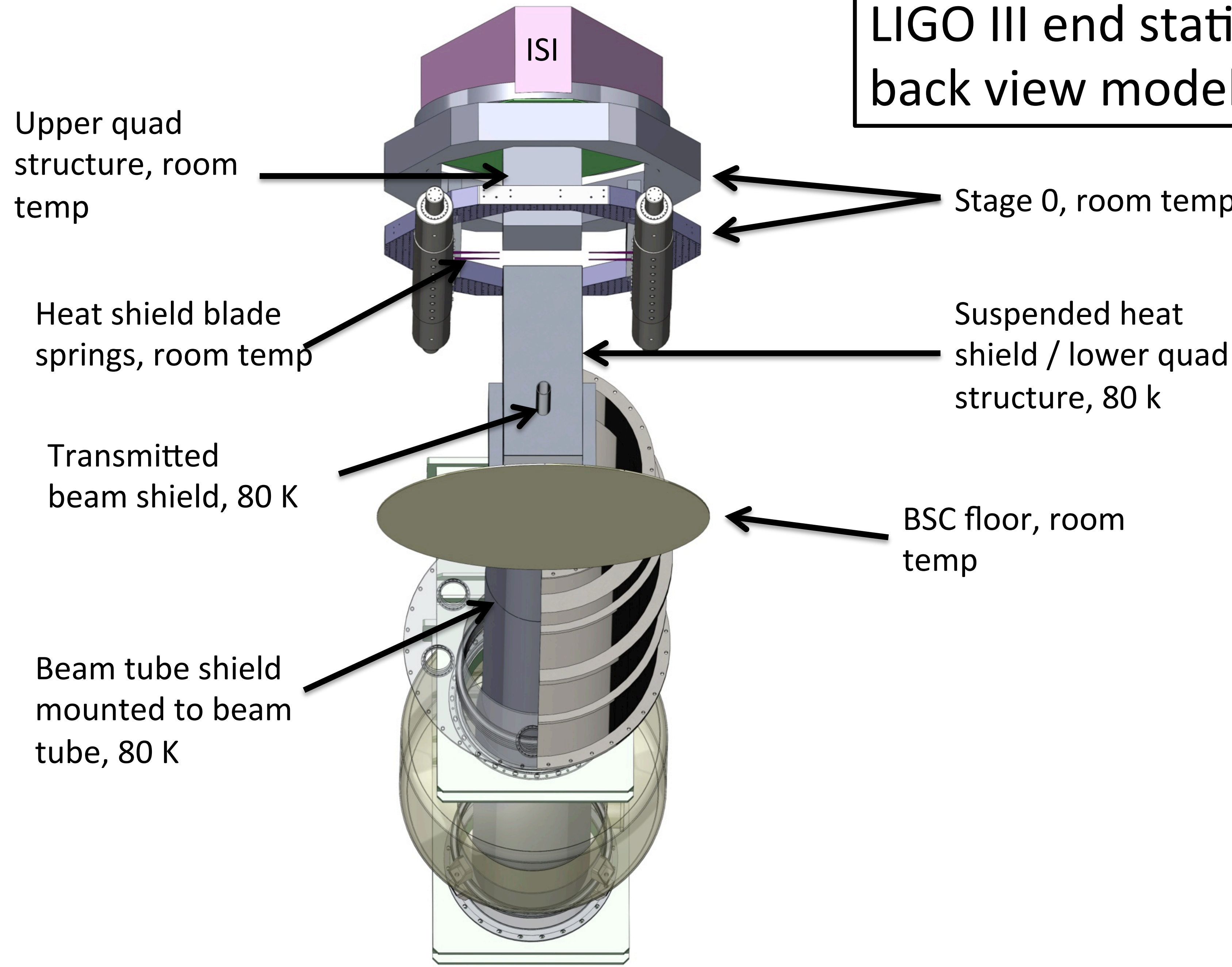

6 OSEMs between shield and table
2 coil actuators and 2 witness geophones in each of the 3 corners


Optic suspended from stage 2 with a warm blade spring
6 OSEMs between shield and table
2 coil actuators and 2 witness geophones in each of the 3 corners

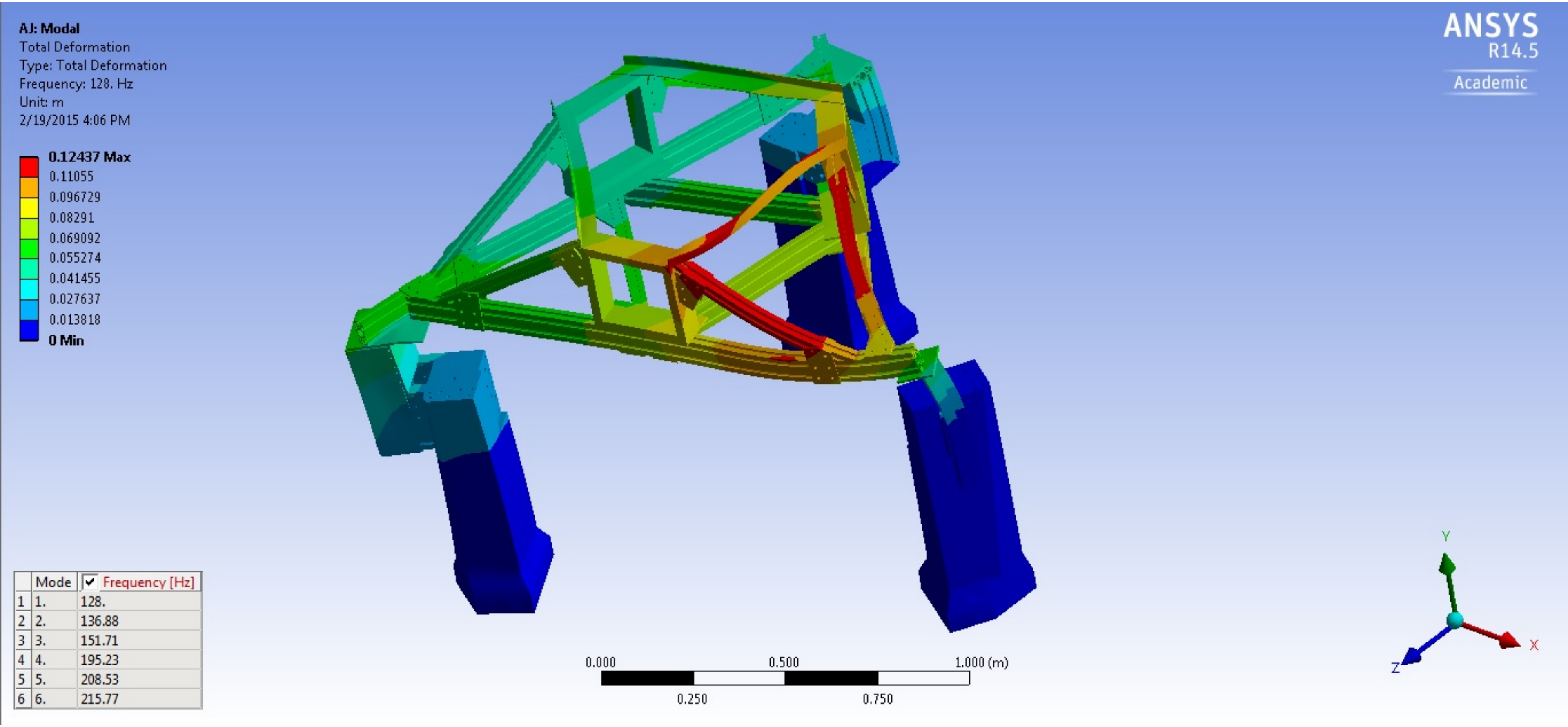
Construction well underway!
Photo taken 12 March 2015

BackUps

LIGO III end station back view model



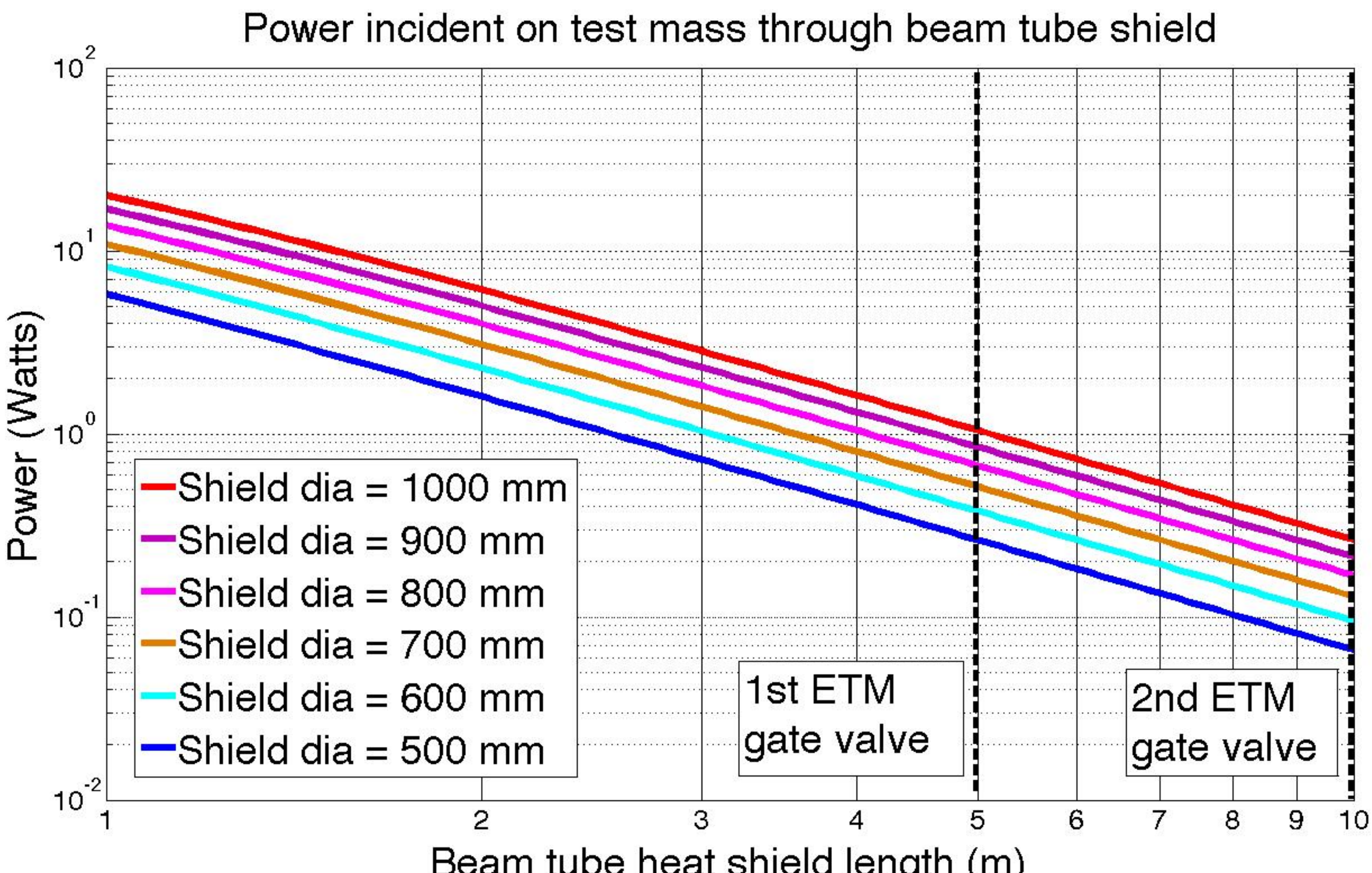
Vibrational modes of support structure



Heat Shield Requirements

1) Beam tube length
2) Scattered light (much uncertainty to overcome)

Radiation leak from Beam Tube



Light scattering noise estimates

Scattered light modeling for shield

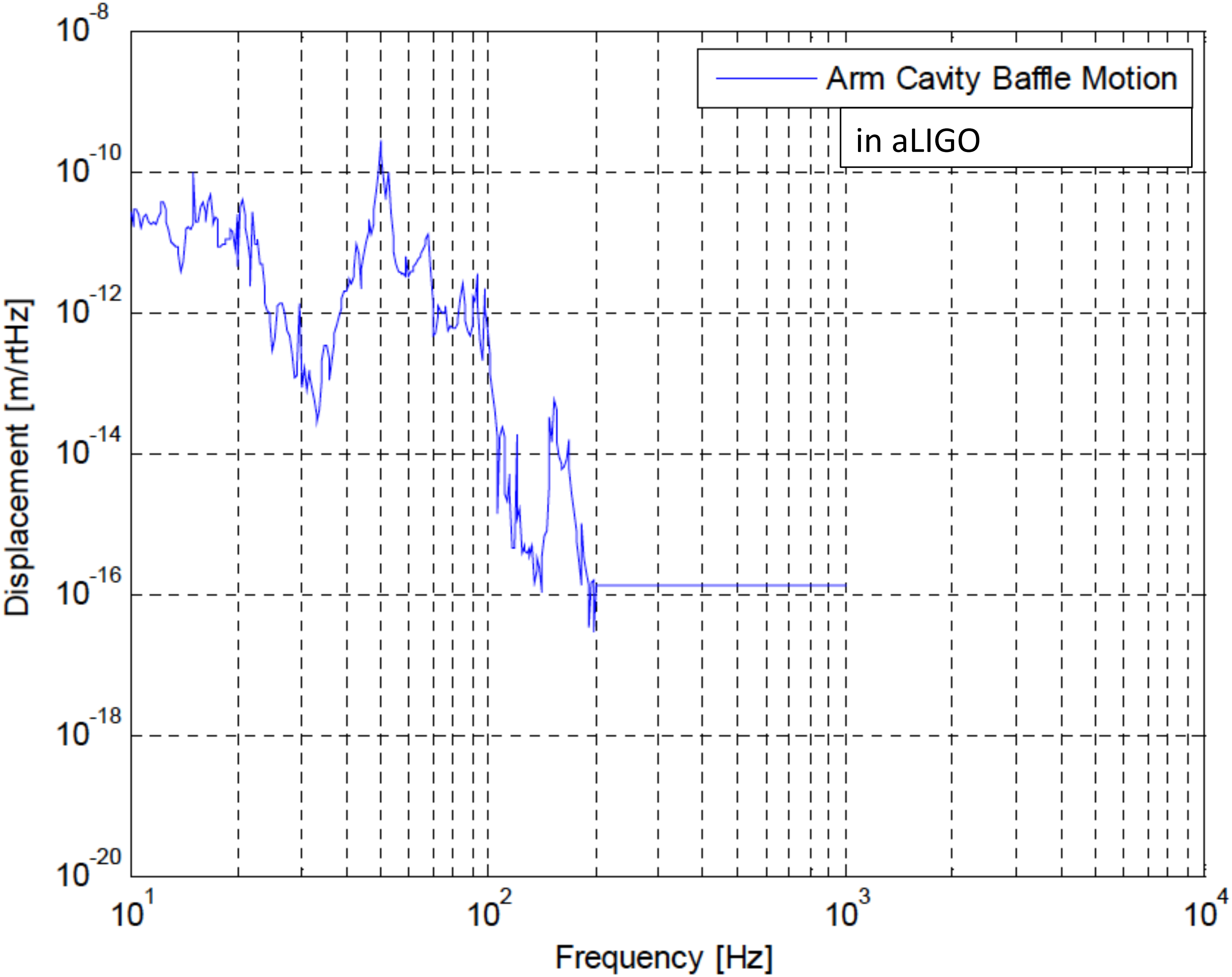
- Linear regime – differential displacement between cavity and scattering surface much less than light wavelength. Only worry about > 10 Hz
- Nonlinear regime – differential displacement comparable to or greater than a wavelength. Upconversion is an issue, must worry about large amplitude low frequency motion.

Linear regime scattered light References

- T940063 - Noise due to backscatter off baffles, the nearby wall, and objects at the far end of the beam tube; and recommended actions – Flanagan and Thorne.
  - This is a useful reference for the basic theory and derivations.
- T1300354 - Scattered light noise due to the ETM coating ripple – Fritschel and Yamamoto
  - Good example of applying the equations in T940063
- T1300332 - Noise from baffle motion with the current ETM coating – Rai
  - Complements the example of T1300354

Nonlinear regime scattered light References

- P1100117 - The impact of upconverted scattered light on aLIGO – Ottaway, Fritschel, and Waldman



Ref T1000747-v4, pg 41

Linear scattered light noise estimates

- **Small angle scatter** across beam tube length – beam tube parameters in E940002 and P990007

Parameters of calculation following notation in T1300354

$\frac{dP}{d\Omega_{bs}} = 0.02$ heat shield backscatter probability from aLIGO baffle

$\frac{dP}{d\Omega_{ms}} \delta\Omega_{ms} = 10^{-5}$ 10 ppm light on heat shield, predicted 6 ppm in aLIGO

$\delta\Omega_{ms} = 7e-9$ str solid angle of heat shield seen by far end of beam tube, 1.83 large BT dia, 1.25 shield dia (same as small BT dia)

$\frac{dP}{d\Omega_{ms}} = \frac{10^{-5}}{7e-9} = 1429$ / str

λ=1.55e-6 m = laser wavelength

$r = 4$ km = distance to far optic

$N = 10^{-20}$ m/Hz$^{0.5}$ estimated noise requirement at 10 Hz

Calculated heat shield displacement requirement from small angle scatter

$$x_{bs} = \frac{Nr\sqrt{2}}{\lambda\sqrt{\left(\frac{dP}{d\Omega_{ms}}\delta\Omega_{ms}\right)\frac{dP}{d\Omega_{ms}}\frac{dP}{d\Omega_{bs}}}} = \frac{10^{-20} * 4000 * \sqrt{2}}{1.55 * 10^{-6}\sqrt{10^{-5} * 1429 * 0.02}} = 2.16 * 10^{-9} \text{ m/Hz}^{0.5} \text{ at 10 Hz}$$

Linear scattered light noise estimates

- **Large angle scatter** in local heat shield – assuming 150 W of local scatter out of 3 MW cavity

  Parameters of calculation following notation in T1300354

$$\frac{dP}{d\Omega_{bs}} = 0.02 \text{ heat shield backscatter probability from aLIGO baffle}$$

$$\frac{dP}{d\Omega_{ms}}\delta\Omega_{ms} = 50*10^{-5} \text{ 50 ppm light on heat shield, predicted 20 ppm in aLIGO}$$

$$\delta\Omega_{ms} = 2\pi \text{ str solid angle of heat shield seen by HR surface}$$

$$\frac{dP}{d\Omega_{ms}} = \frac{50*10^{-5}}{2\pi} = 8*10^{-6} \text{ / str}$$

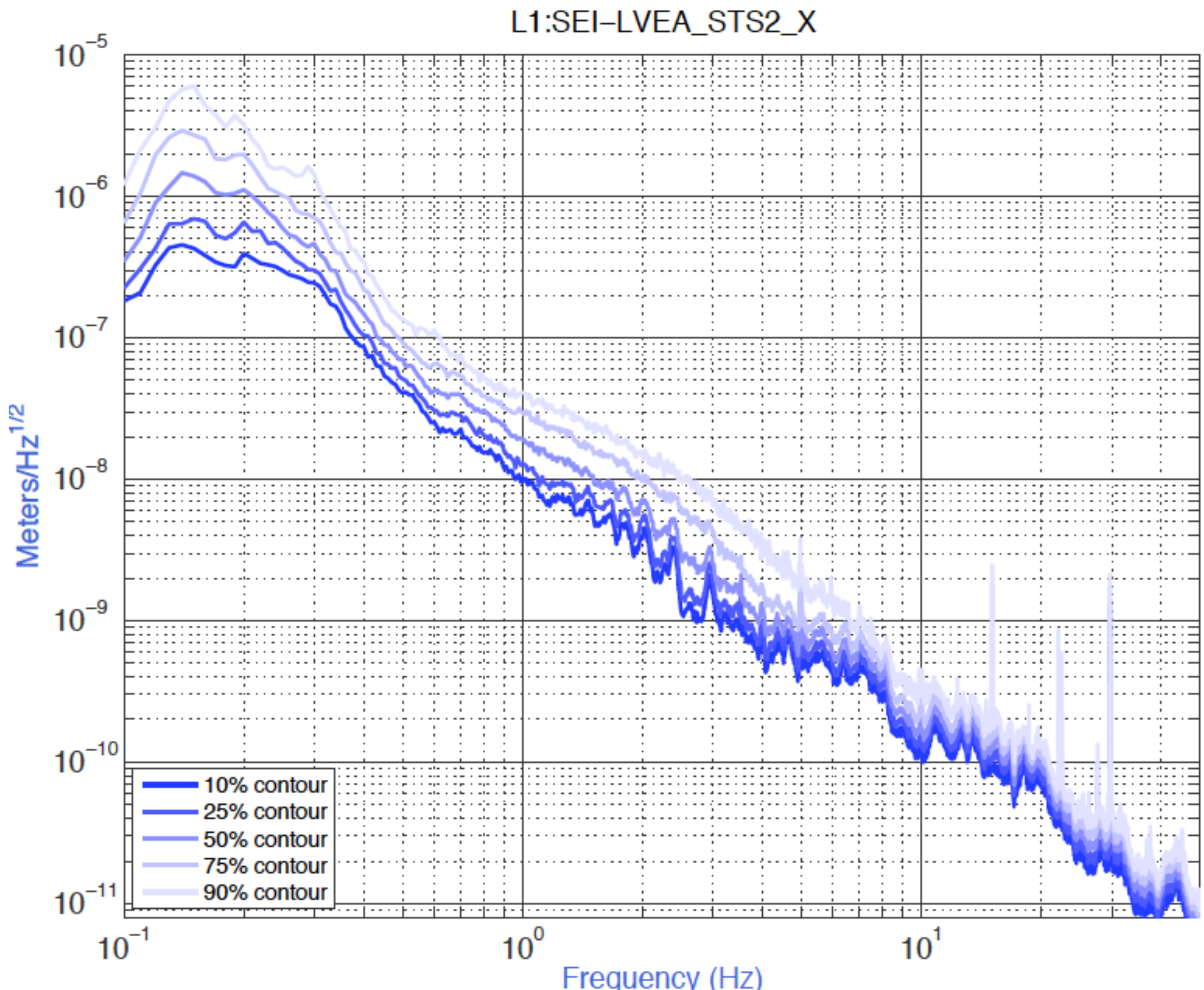
$$\lambda\text{=1.55e-6 m } = \text{laser wavelength}$$

$$r = 0.2 \text{ m } = \text{ distance of shield to optic}$$

$$N = 10^{-20} \text{ m/Hz}^{0.5} \text{ estimated noise requirement at 10 Hz}$$

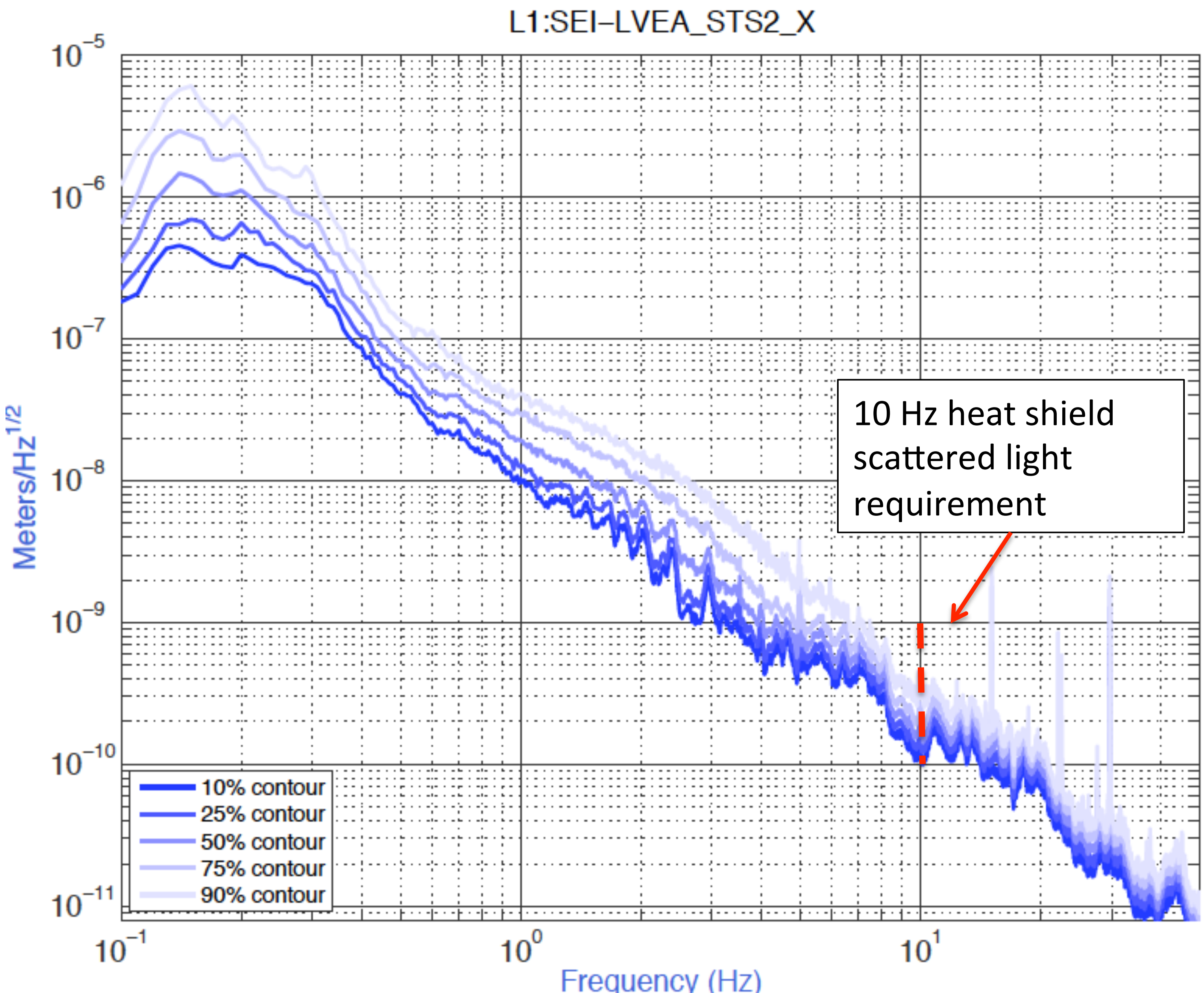
Calculated heat shield displacement requirement from large angle scatter

$$x_{bs} = \frac{Nr\sqrt{2}}{\lambda\sqrt{\left(\frac{dP}{d\Omega_{ms}}\delta\Omega_{ms}\right)\frac{dP}{d\Omega_{ms}}\frac{dP}{d\Omega_{bs}}}} = \frac{10^{-20}*0.2*\sqrt{2}}{1.55*10^{-6}\sqrt{50*10^{-5}*8*10^{-6}*0.02}} = 2*10^{-10} \text{ m/Hz}^{0.5} \text{ at 10 Hz}$$



T0900312

Figure 5. LLO seismometer data for LVEA horizontal motion (X-direction); all percentiles.



T0900312

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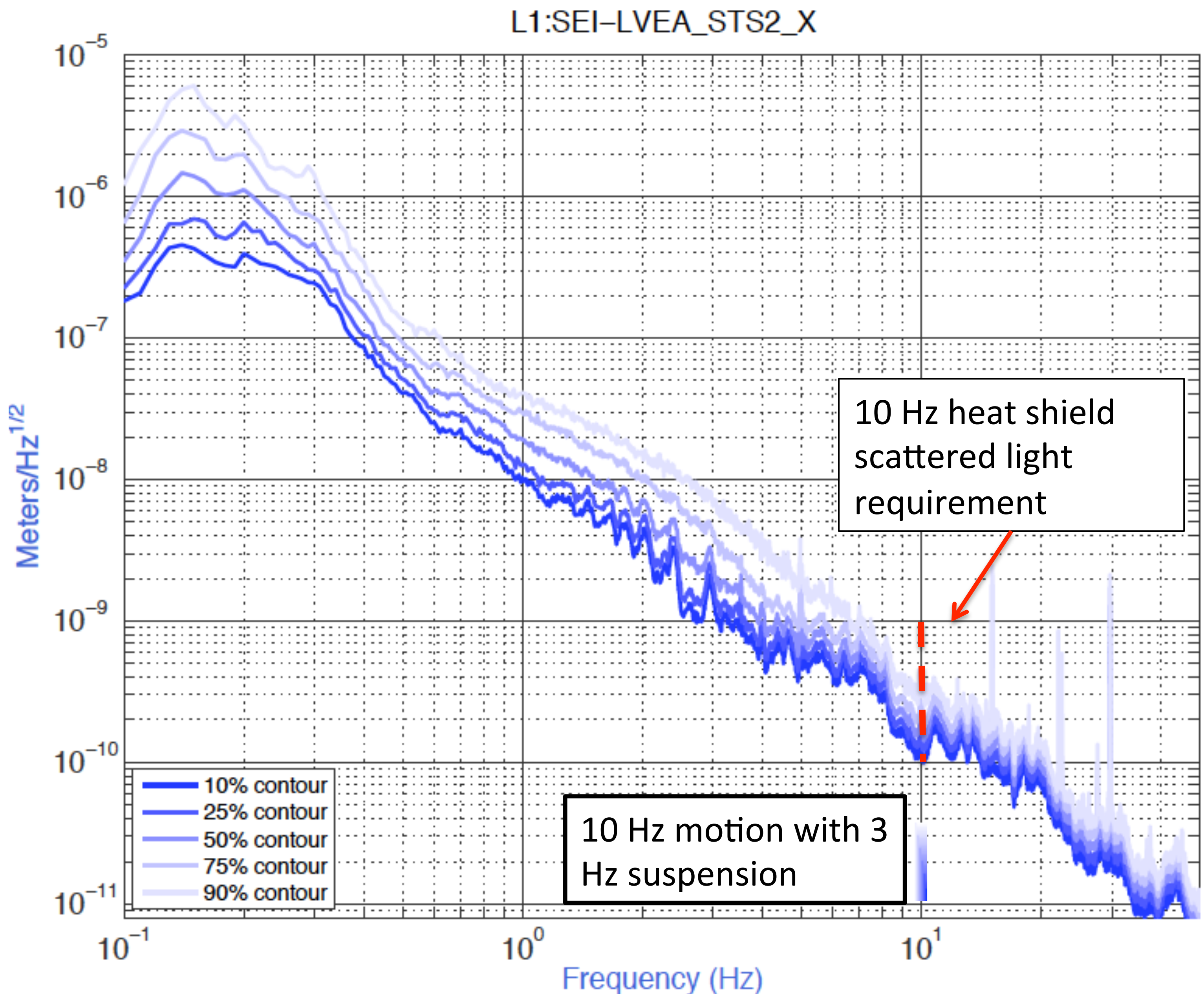

T0900312

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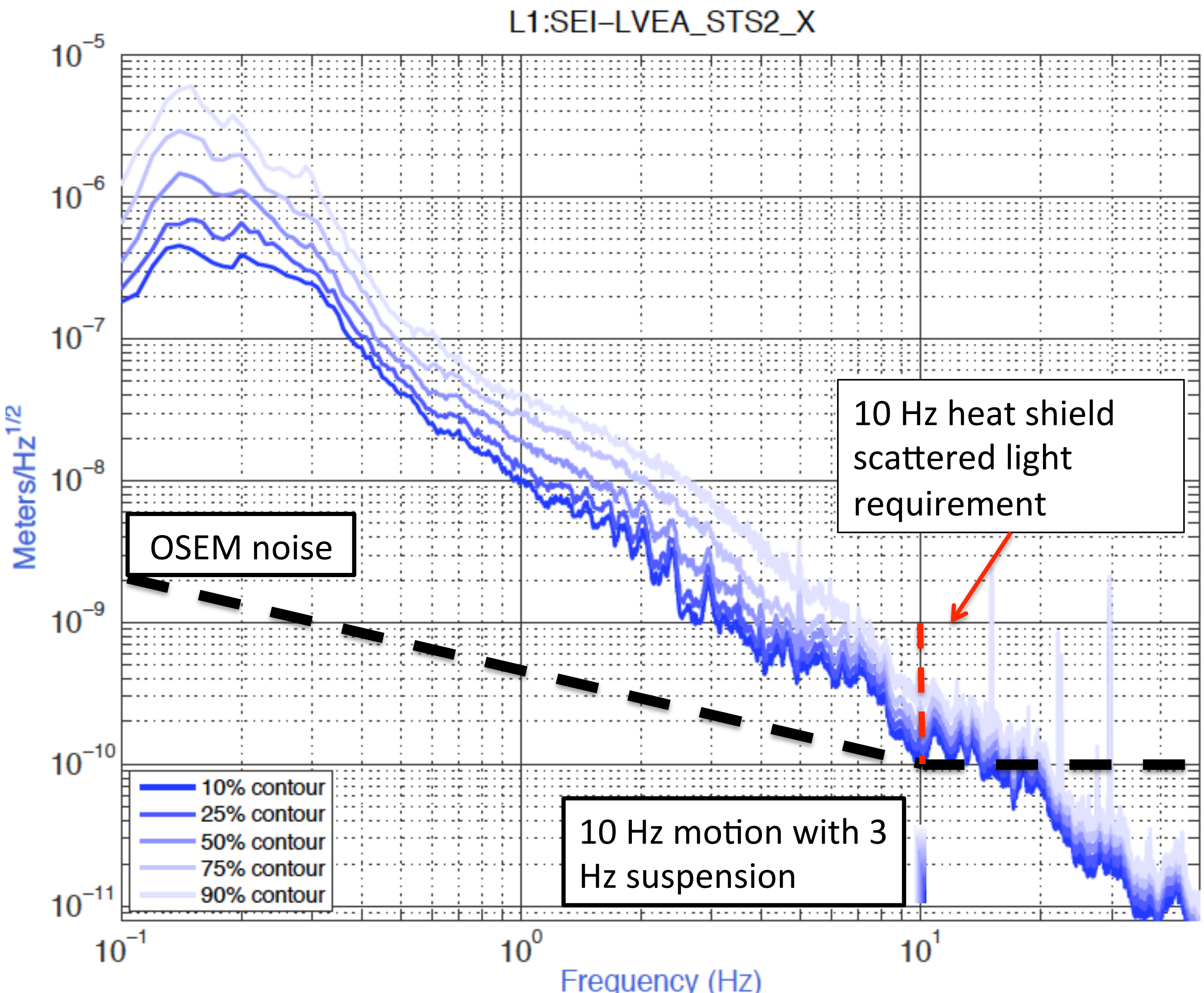
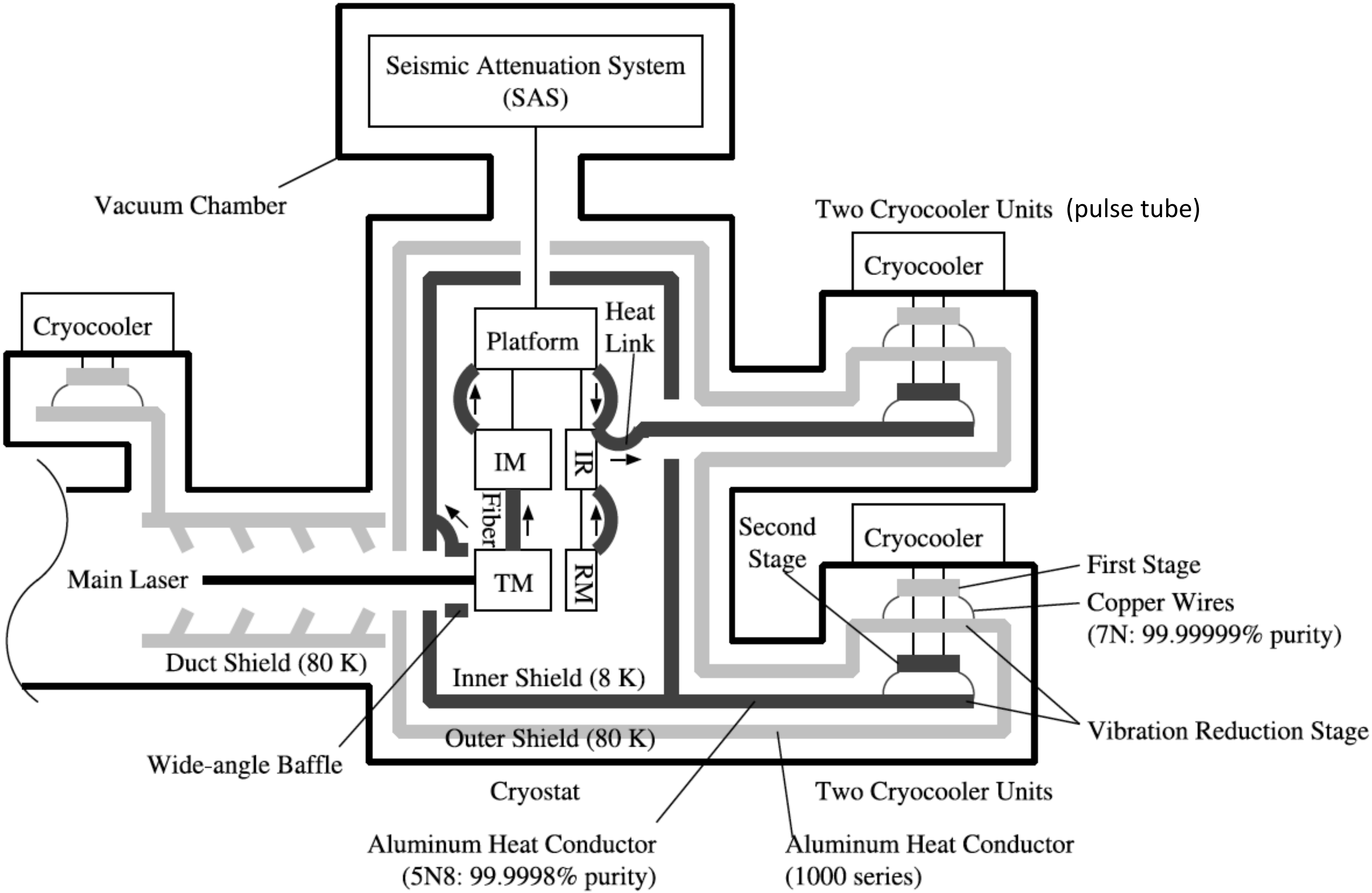


T0900312

Figure 5. LLO seismometer data for LVEA horizontal motion (X-direction); all percentiles.

KAGRA Cryo System

KAGRA's cryogenic system



Yusuke Sakakibara *et al* 2014 *Class. Quantum Grav.* **31** 224003
http://iopscience.iop.org/0264-9381/31/22/224003/

KAGRA beam tube heat shield

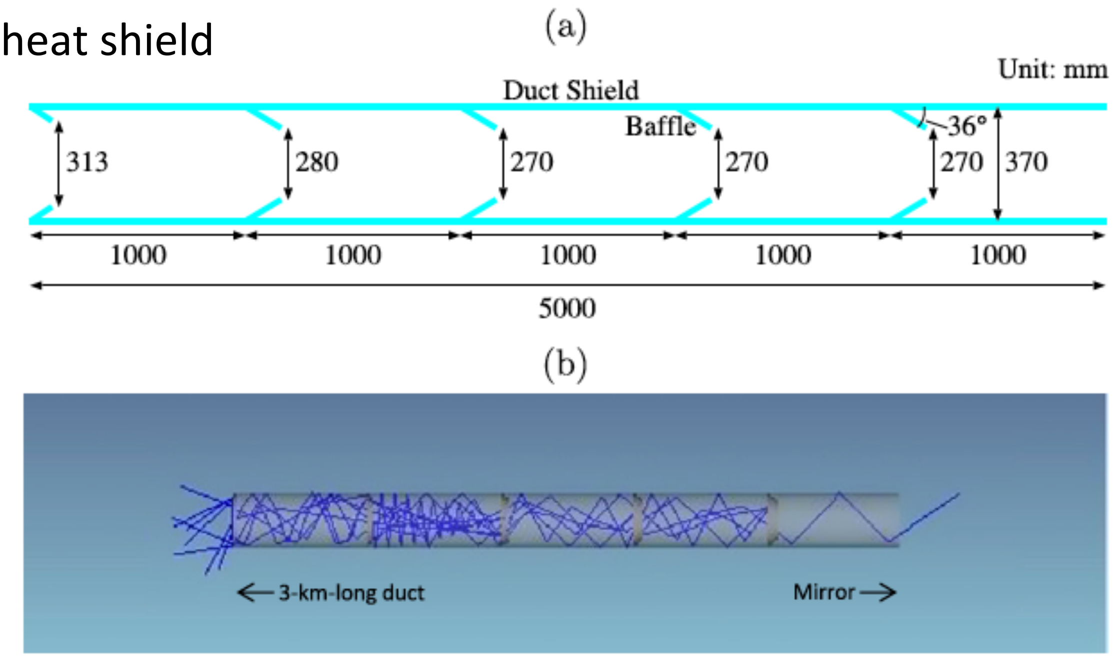


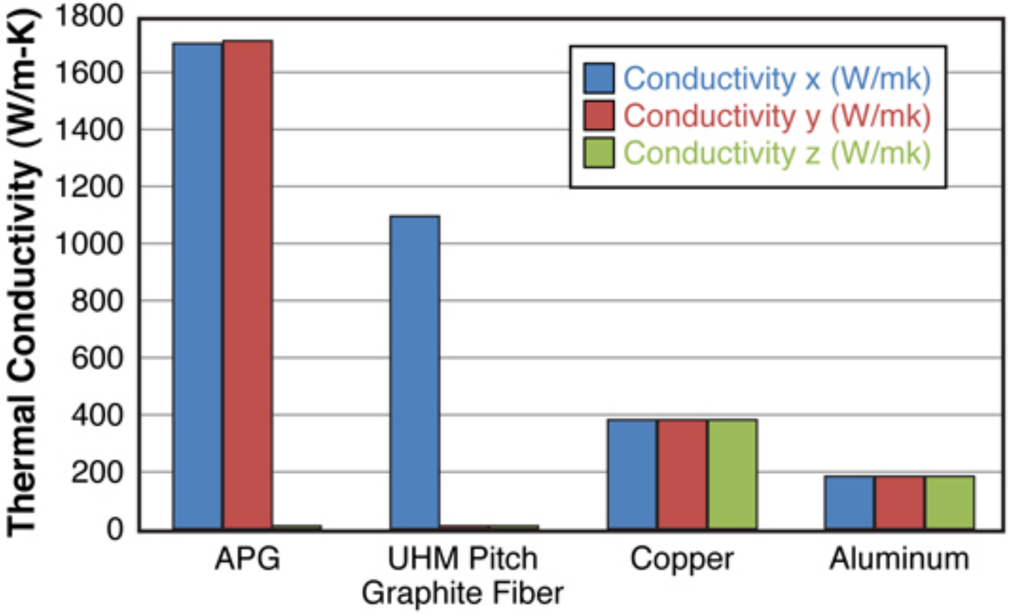
Figure 9. (a) Schematic diagram of a duct shield. To reduce thermal radiation, baffles are installed. The baffles are cone-shaped to catch the scattered light. To absorb thermal radiation and scattered light, the duct made of aluminum 1000 series and baffles made of aluminum 5000 series are treated with ECB (electro-chemical buffing), and coated with a black coating, Solblack, made by Asahi Precision Co Ltd. Five 1 m ducts and five baffles for each duct shield are manufactured, and these baffles are inserted between the ducts. (b) Representation of the duct shield constructed in the commercial ray-tracing software ZEMAX. Rays of thermal radiation were introduced from the left-hand side with a uniform probability distribution in all directions. Based on the Monte Carlo method, the number of rays was increased to make the calculation error less than 1%. Although 10^7 rays were traced in the calculation, only ten example rays are shown here. One of the ten rays passes through the duct, which corresponds to the heat input through the duct shield.

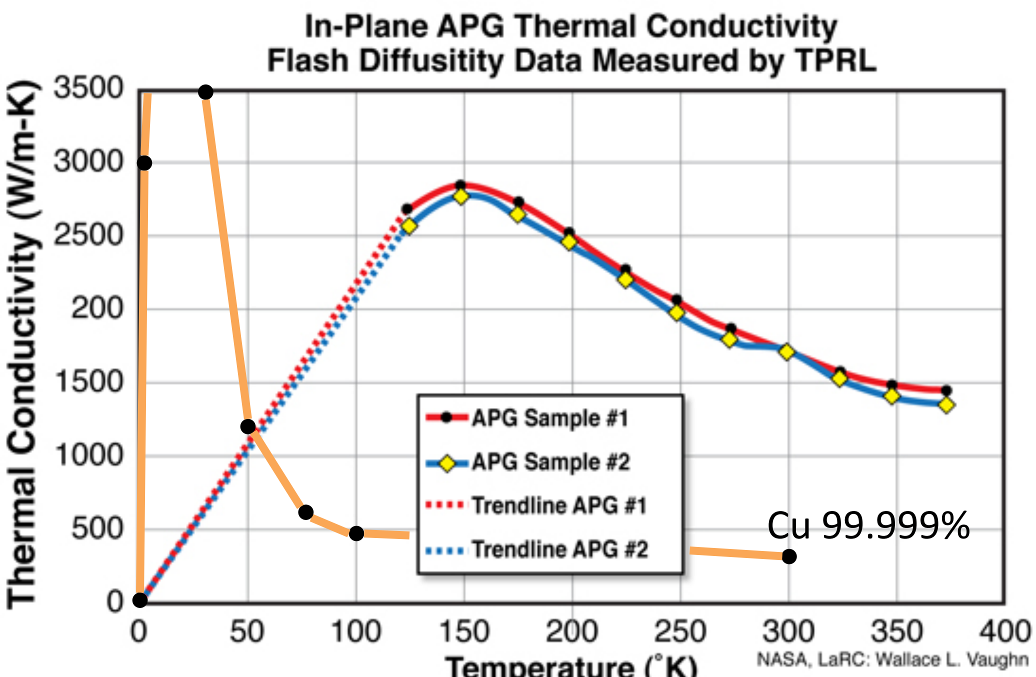
Quote from text pages 2-3: “In CLIO, thermal radiation through the duct shield (described in section 4) was 1000 times larger than our expectation because we had neglected reflections from the duct shield. To reduce this heat load, donut-shaped structures (called baffles) were introduced.”

Annealed Pyrolitic Graphite (APG)

K core technology from thermacore

~ 3 times the conductivity of copper, in plane, but magnetic



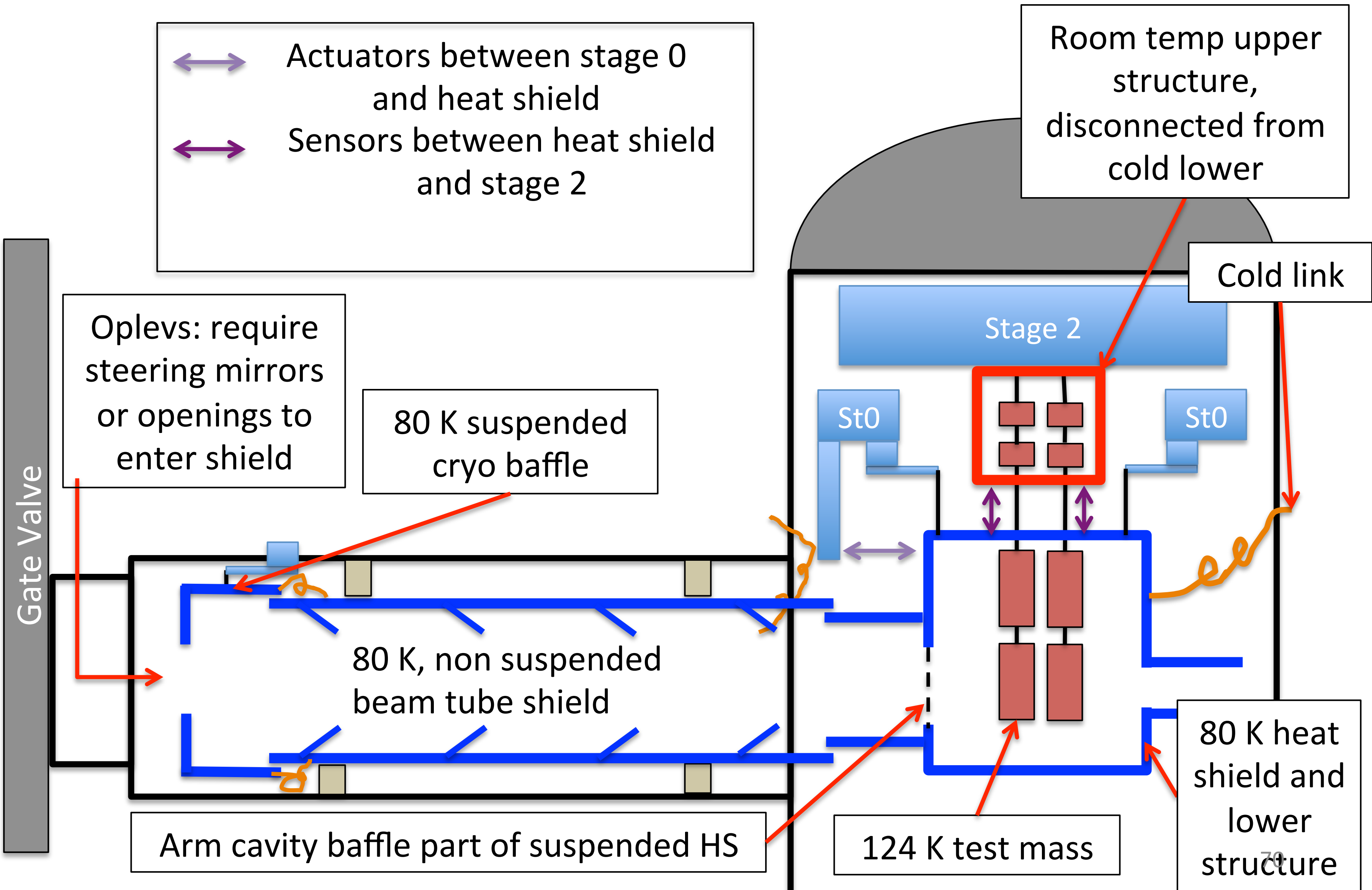


Annealed Pyrolitic Graphite (APG)

- See a brief video intro https://www.youtube.com/watch?v=kMD0GUZmoy0
- The graphite can be made flexible by making it into thin strips
- Vacuum compatible, at least to NASA specs for outgassing
- Conductive peak around 120-150 K
- The graphite is highly **diamagnetic**

http://www.thermacore.com/thermal-basics/advanced-solid-conduction.aspx

Shorter shield with cryo baffle



Cold SUS structure configurations

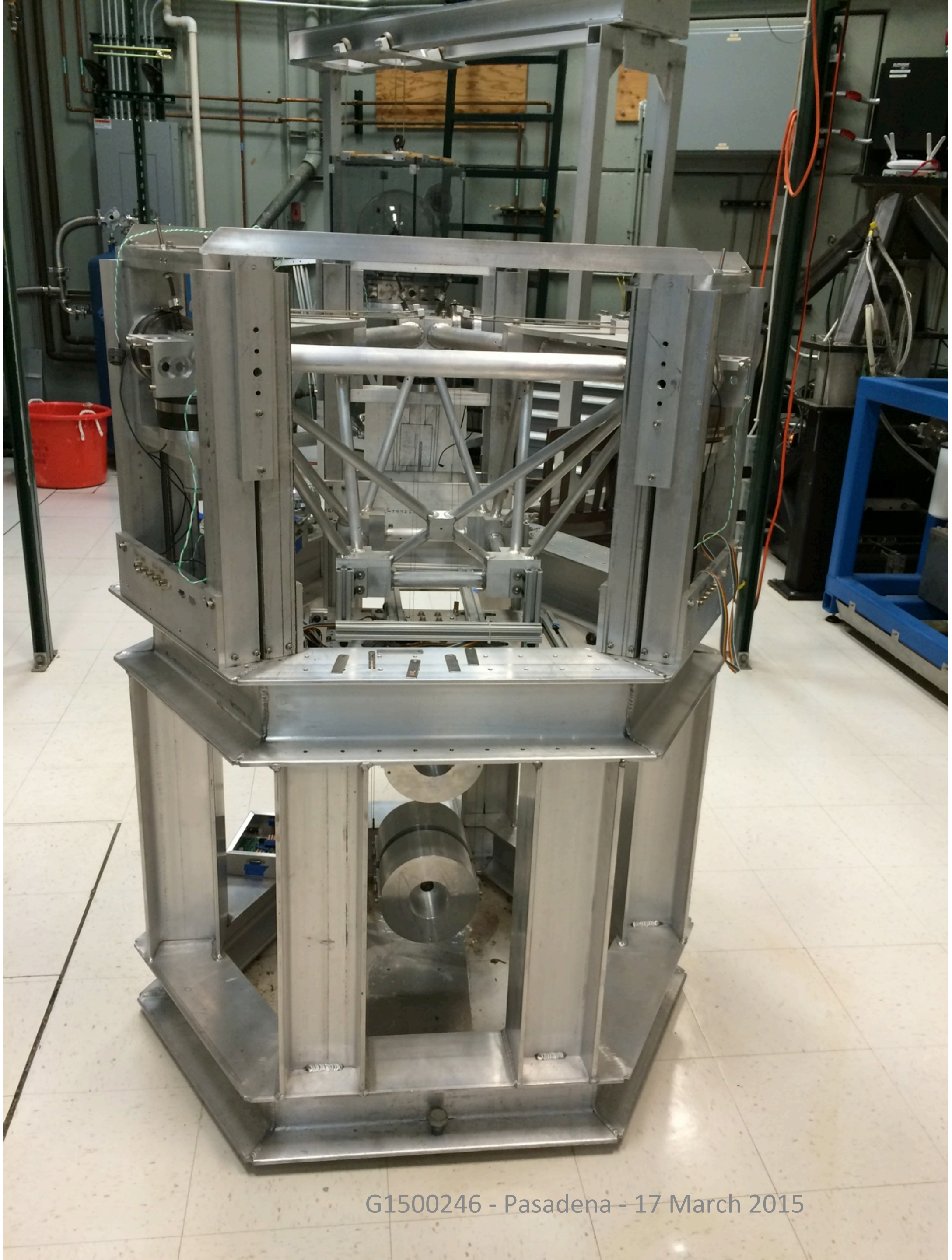
	Temperature of cold part	Thermal stress + alignment of warm part	Vibrational mode frequencies	Damping of vibrational modes	Relative complexity of construction
1 structure					
2 structures: warm & cold					
Cold suspended from warm				Low freq sus modes	

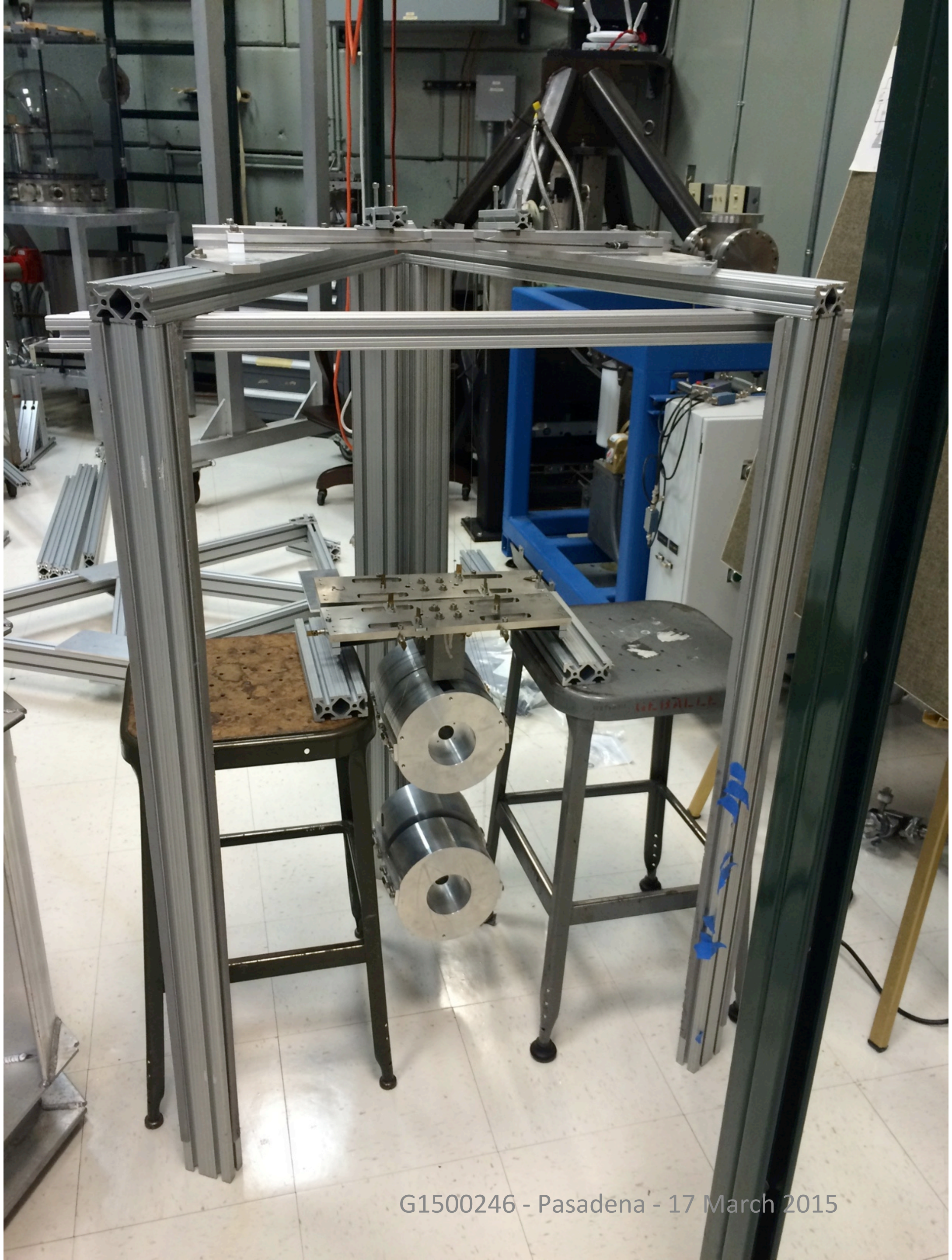
Good

Fair

Risky

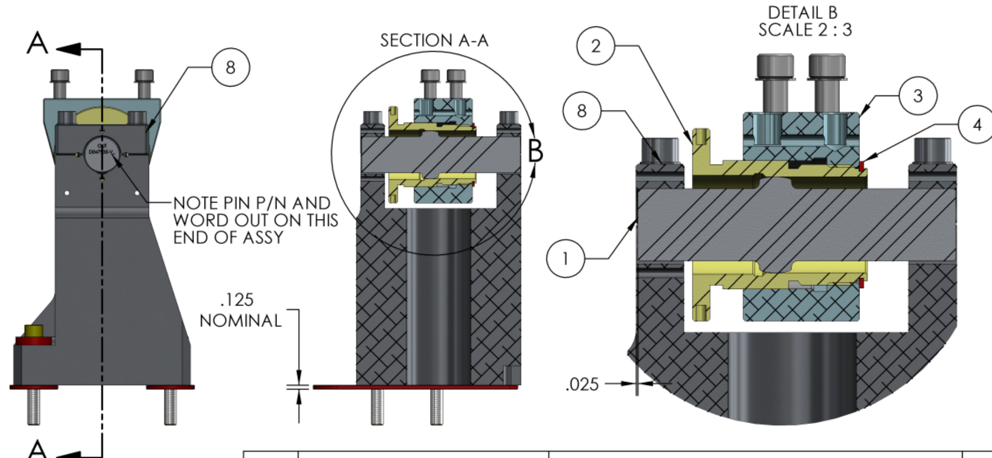
Show stopper

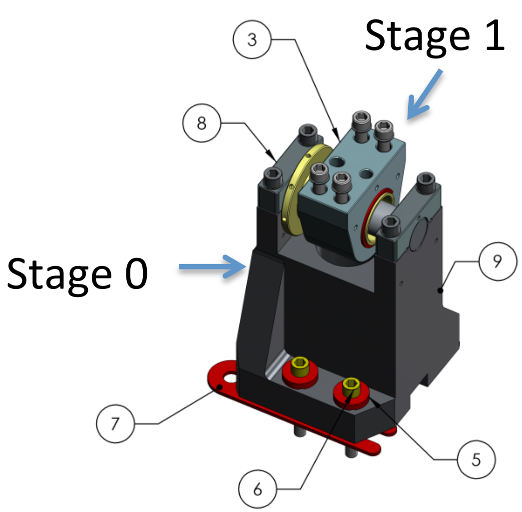



GEBALLE

BSC ISI Stage 0-1 lockers - D1000854

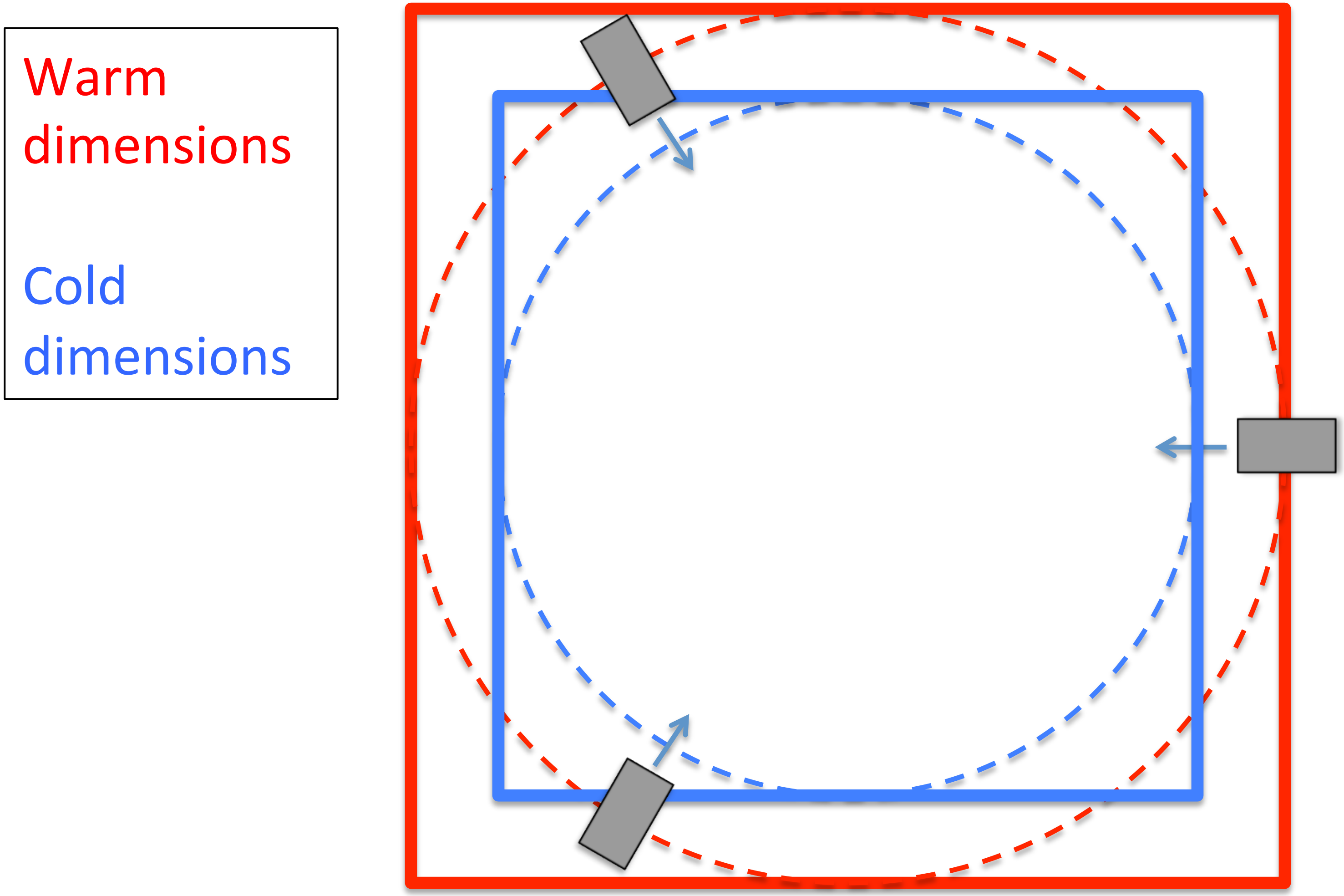
Something like this could be used to limit the suspended heat shield / lower quad structure range of motion. The design makes it impossible for the suspension to fall in the event of a wire or spring failure.





ITEM NO.	PART NUMBER	DESCRIPTION	Stage 0-1 Locked/QTY.
12	HOLOKROME_78102	SHCS, 3/8"-16x1.5"	4
11	McMASTER_92196A627	SCREW SHCS, 3/8-16 X 1.38 LG.	4
10	UC_COMPONENTS_WFV-38	Washer Vented, .39 ID X .63 OD X .032 THK #3/8"	8
9	D1000861	POST, STAGE 0-1 LOCKER, aLIGO BSC ISI	1
8	D1000862	PIN CAP, LOCKER, aLIGO BSC-ISI	2
7	D0901805	STAGE 0-1, LOCKER, BASE SHIM SPACER	2
6	MSC_05682273	SHCS 3/8-16 x 2.75 lg. 1 1/4 to full thd	4
5	D047942	WASHER ADJUSTABLE FOOT, aLIGO BSC ISI	4
4	SMALLEY_FSE-0175	SNAP RING 1.75 OD X 1.64 ID X .067 THK	1
3	D1000908	HOUSING LOCKER SLEEVE, aLIGO BSC ISI	1
2	D1000860	SLEEVE, STAGE 0-1 LOCKER, aLIGO BSC-ISI	1
1	D047935	LOCKER SPHERICAL PIN	1

Possible arrangement of lower-structure-to-upper-structure lockers considering thermal contraction



Top view of lower structure (square cross-section). Thermal contraction occurs along an unconstrained DOF of the lockers, for a spatially uniform lower structure temperature. The clearance in the lockers will set a requirement on the maximum thermal gradient in the structure.

How much cooling is lost if the shield is warmer than 80 K?