# Development Status of HOM Ring Heater

G2201732

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# Motivation #1: Reduce Point Absorber Loss

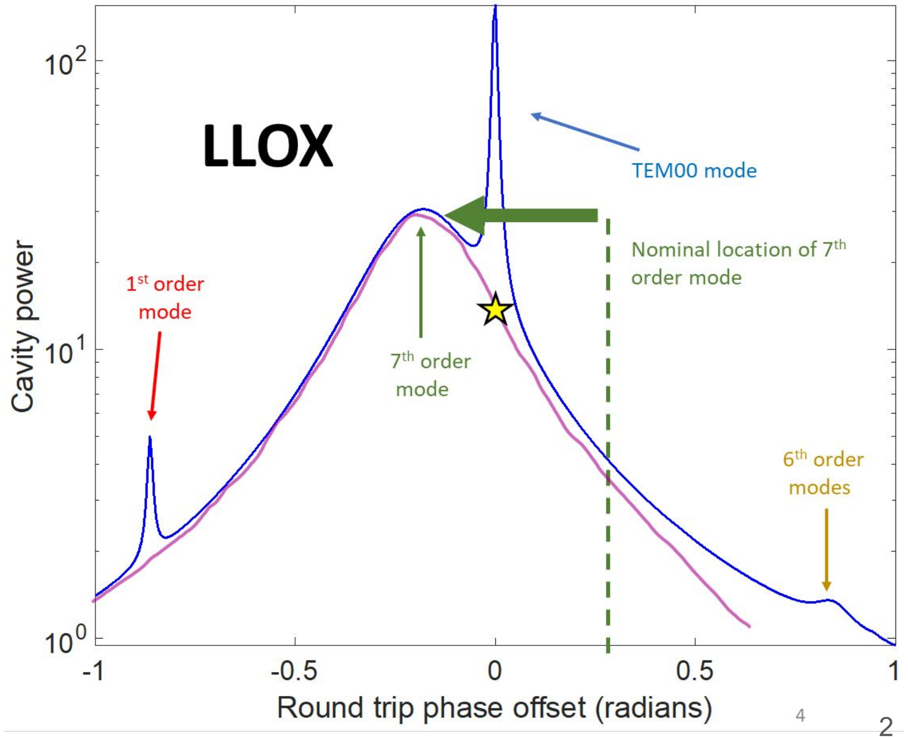
- Address **non-uniform loss** induced by point-absorbers
- Point-absorbers scatter TEM00 mode into higher-order modes
- The 7th order mode scattering loss is resonantly enhanced due to cavity degeneracy.
  - Brooks et al. 2021 (P1900287)
- Loss of power from $TEM_{00}$ to $TEM_{mn}$

$$\mathcal{L}_{mn} = a^2_{00|mn} g_{mn}$$

Single-bounce scattering coefficient

Arm cavity gain factor

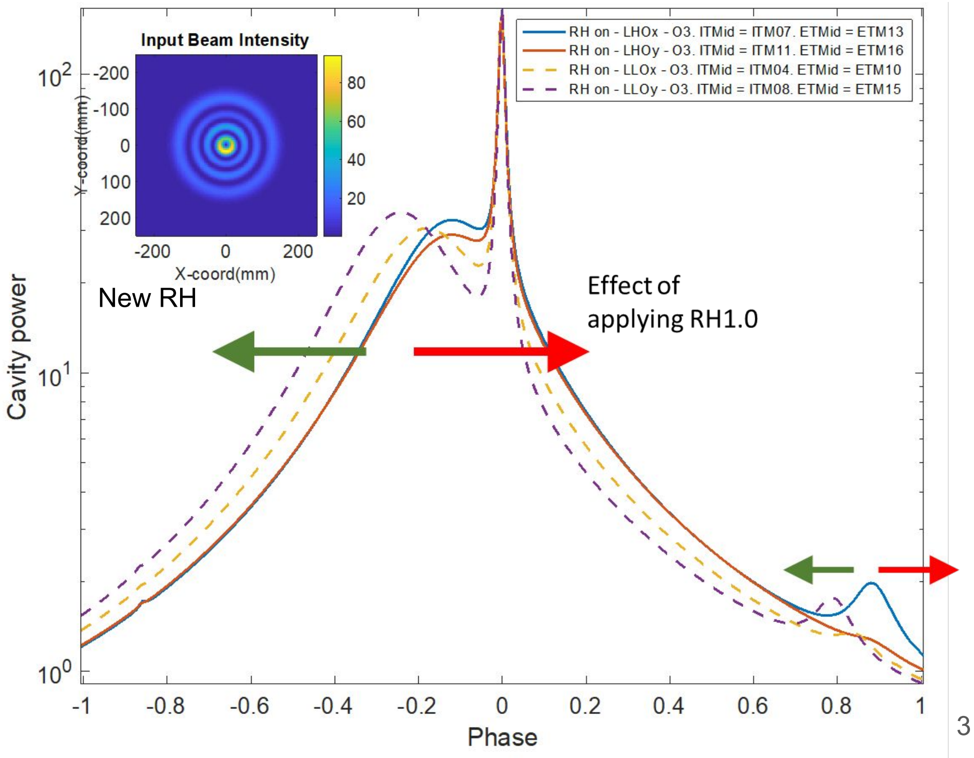
**Simulated arm cavity scan** (A. Brooks, G2101232)



# Shifting 7th Order Mode Resonance

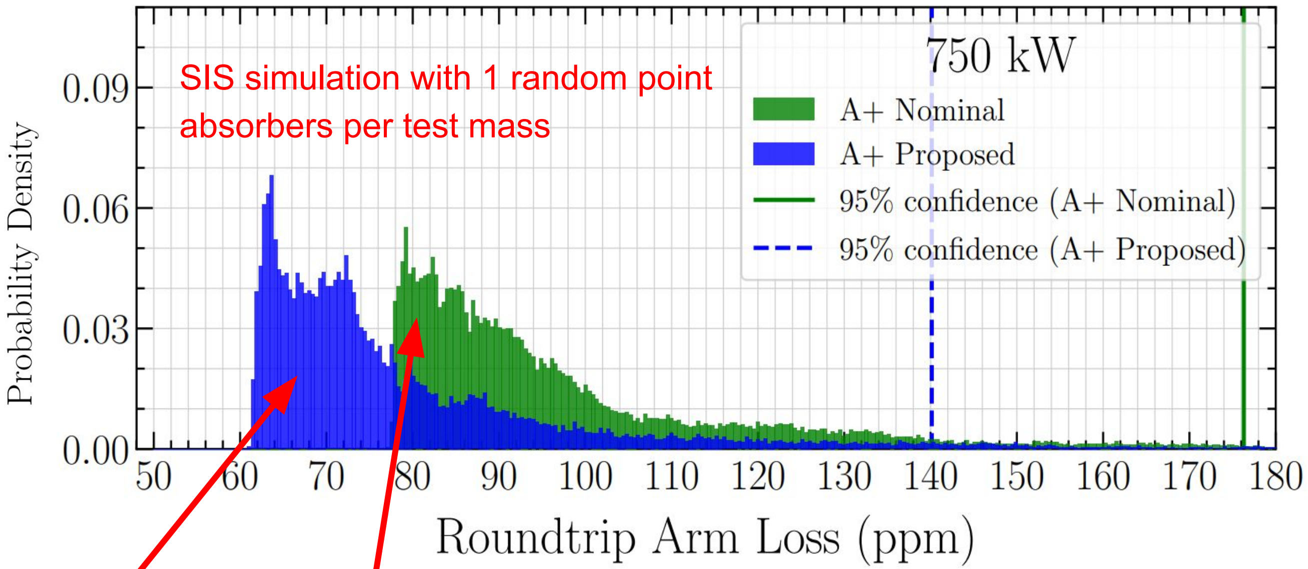
- HOM RH to actively shift the resonance away from TEM00, targeting $g_{mn}$
- Removing co-resonance to reduce arm loss
  - Richardson et al. 2021 (P2100184)

**Effects of RHs on HOM resonance condition (G2101232)**



# Impact of shifting 7th order mode resonance

**Simulated arm loss distribution due to point absorbers (**Richardson, P2100184)



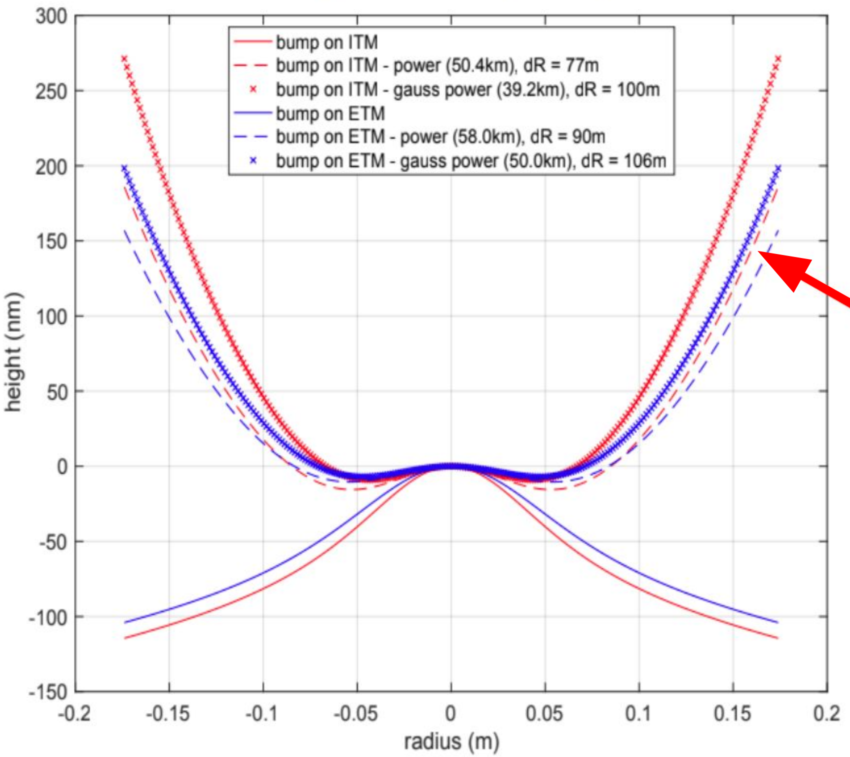

Nominal arm cavity

After elimination of 7th mode co-resonance
→ 30%-40% improvement in loss (*)

(*) Disclaimer: This is not modeling the exact HOM RH profile but one that accomplishes the same effect, and thus is a representative estimate of the amount of arm loss that could be recovered.

# Motivation #2: High Power Operation

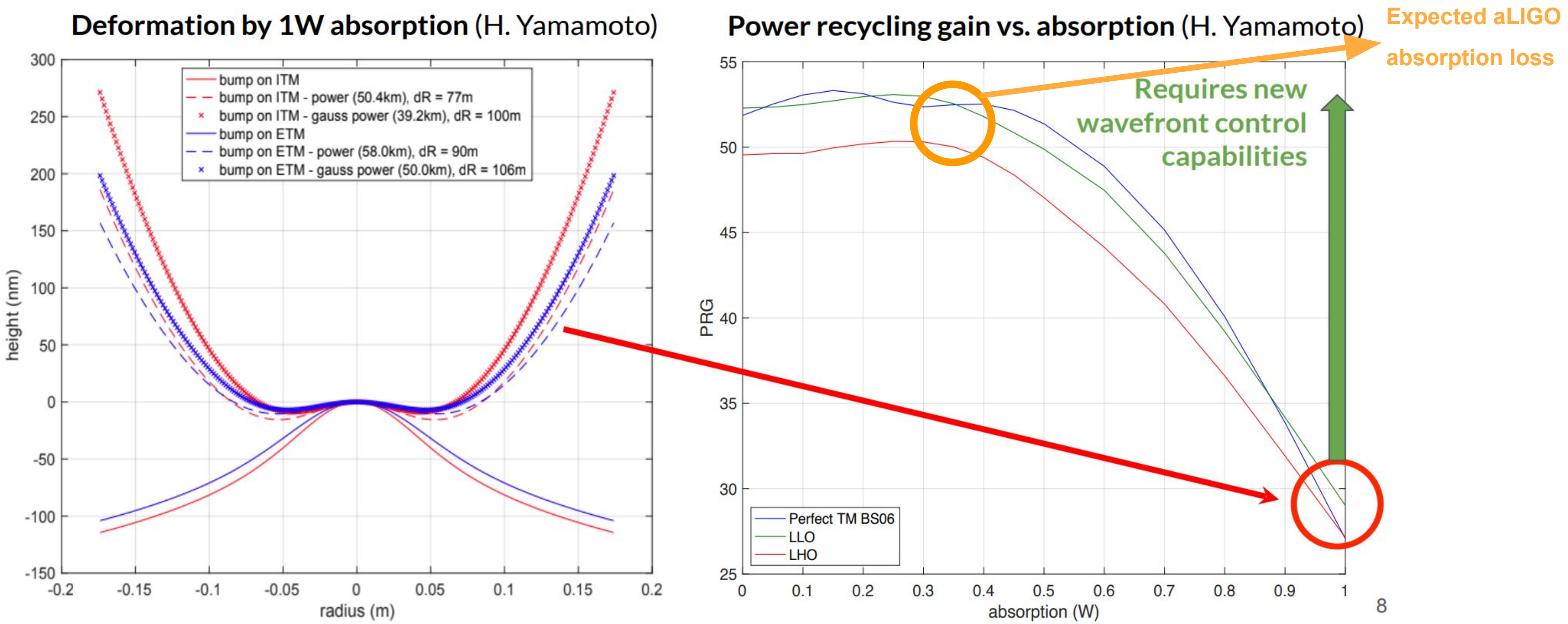
Deformation by 1W absorption (H. Yamamoto)




- Post-O5 arm cavity power target: **1.5 MW**
  - Report of LSC Post O5 Study group (T2200287)
- Residual surface deformation after correction with barrel RH has a steep edge rise.

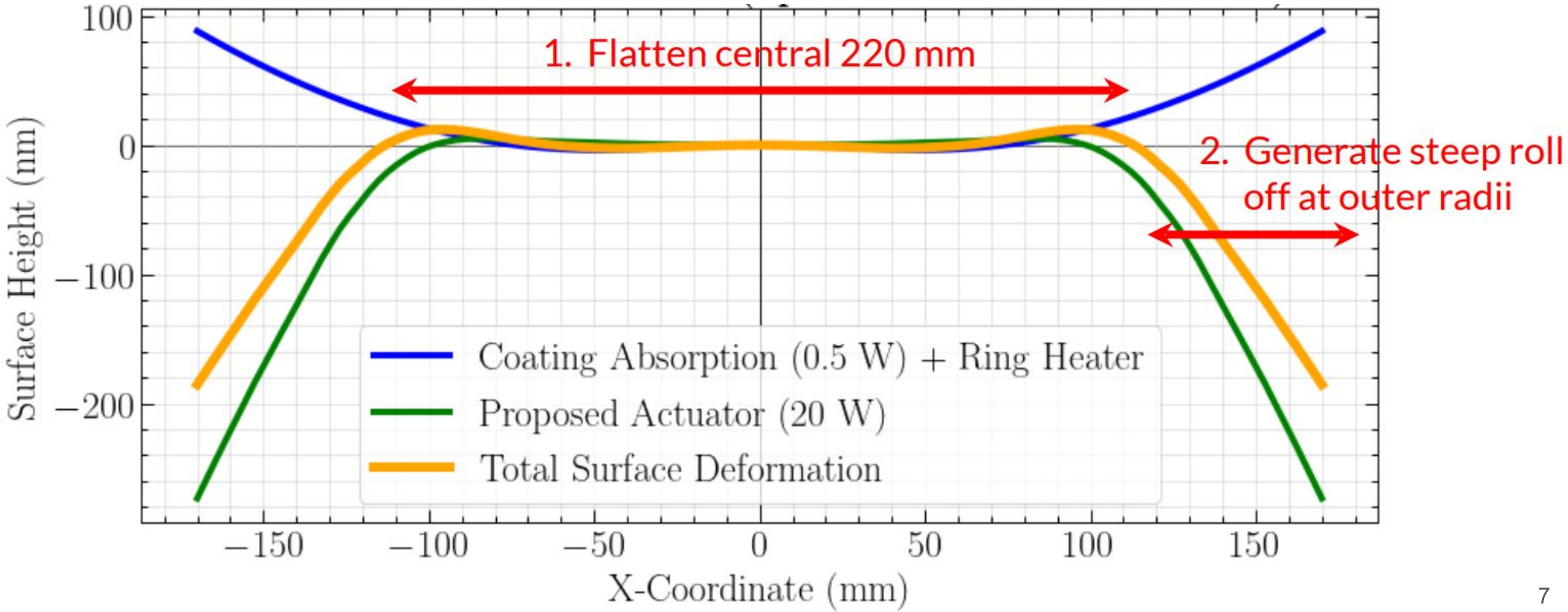
# Motivation #2: High Power Operation

- Uniform coating absorption cannot be fully compensated with current TCS above aLIGO full power → Severe PRG loss (G2200743)



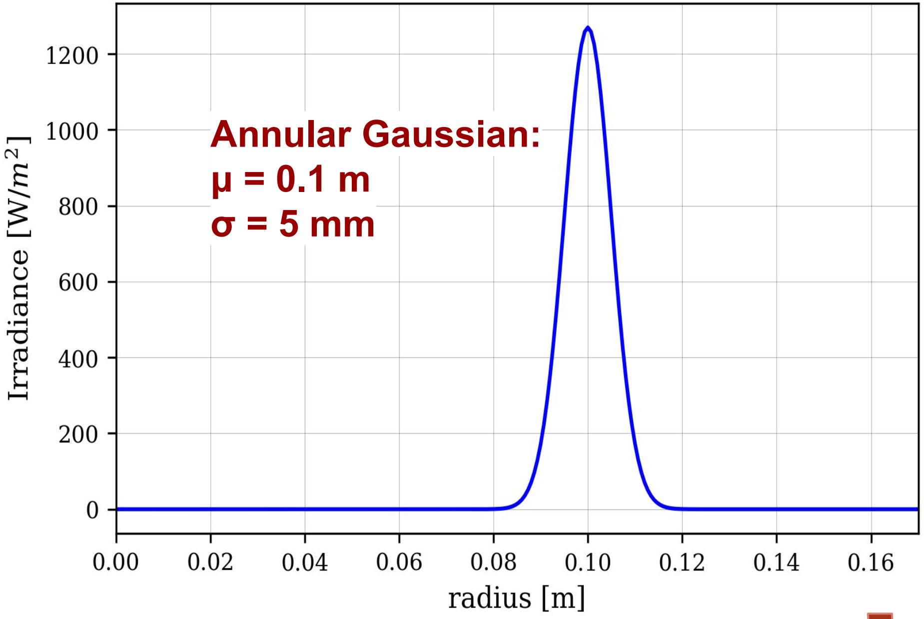
# HOM Ring Heater Goals

**ETM Surface Deformation (Spherical Power Removed) (**Richardson, G2200399)

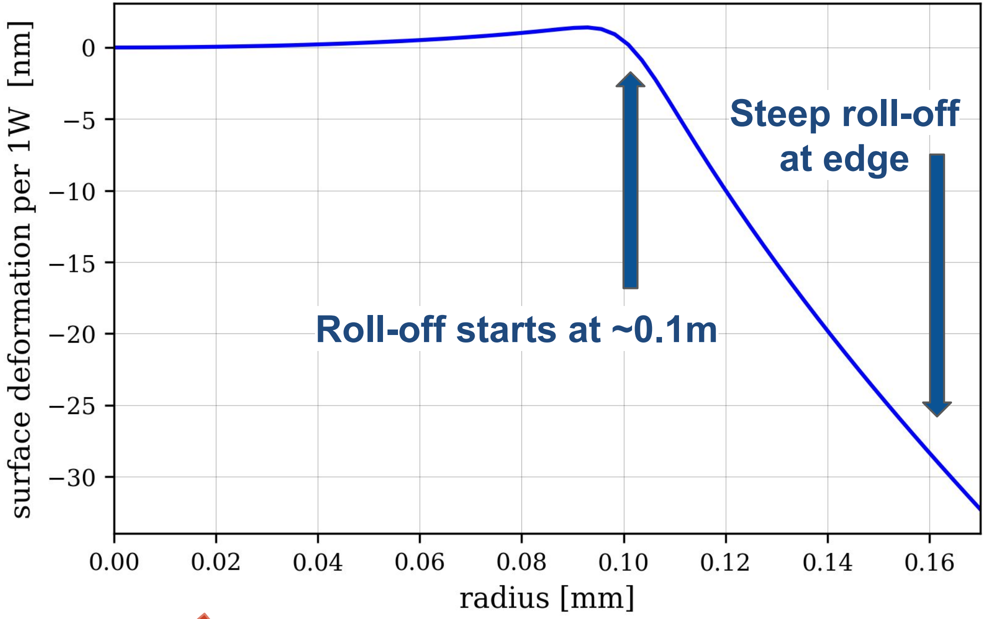


# Achieving the Right Deformation

**Target (nearly) ideal heating irradiance (G2101232)**

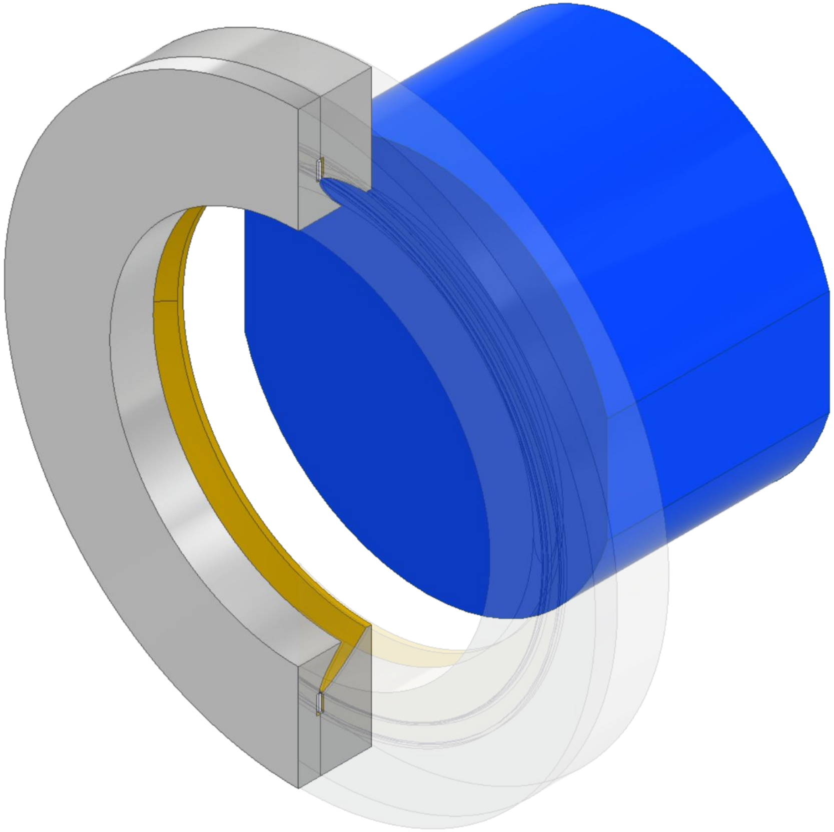



**Target surface deformation**



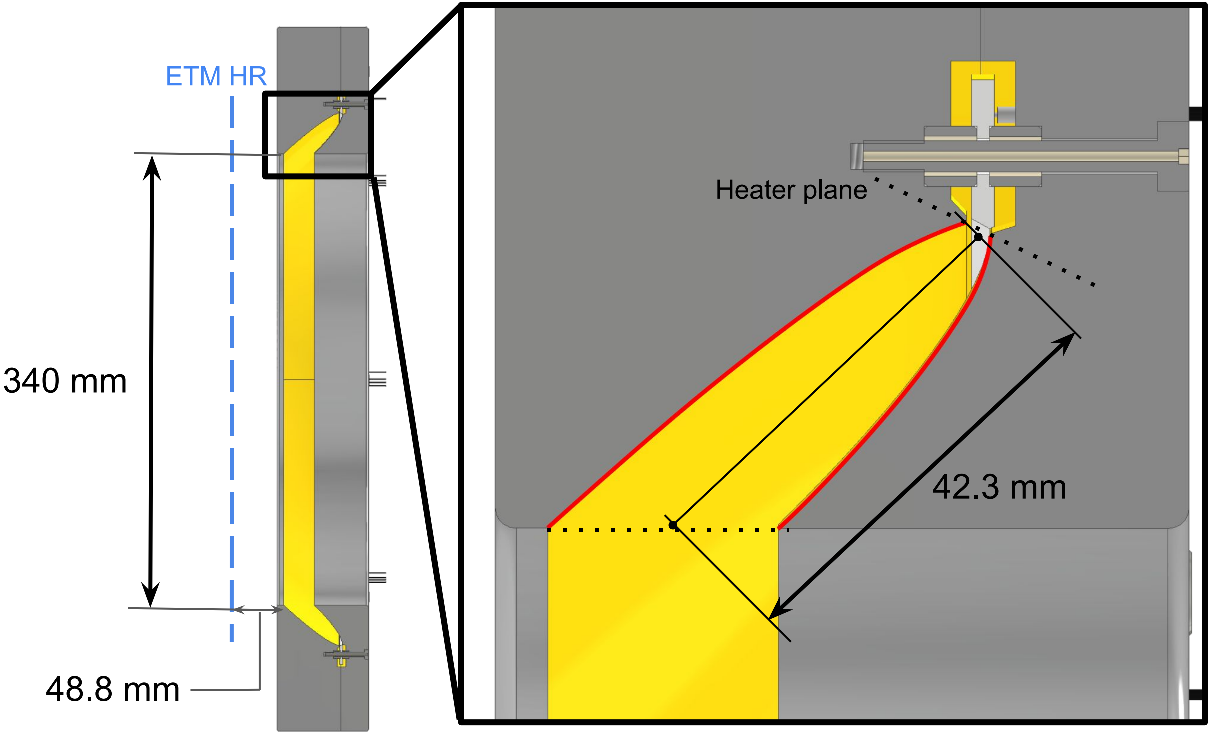

**Thermo-elastic deformation simulated with FEA**

# The HOM Ring Heater



- Annular heating pattern projected onto front surface of test mass
- Consists of an annular heater and a reflector.
- Reflector interior:
  - Diamond-turned surface
  - Polished to < 10 nm RMS
  - Thin-film gold coating deposited
- Reflector exterior:
  - Bead-blasted to increase effective emissivity and reduce specular reflection at 1064 nm

# Ring Heater Cross-section

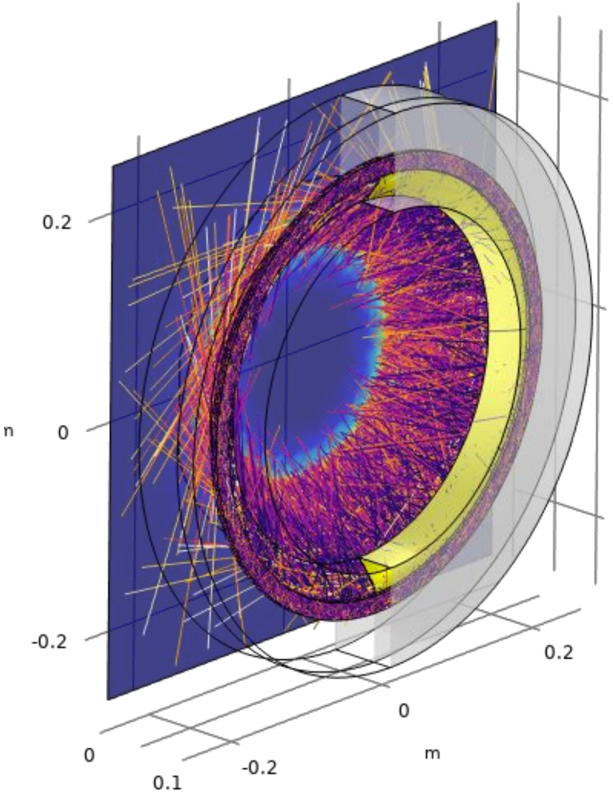


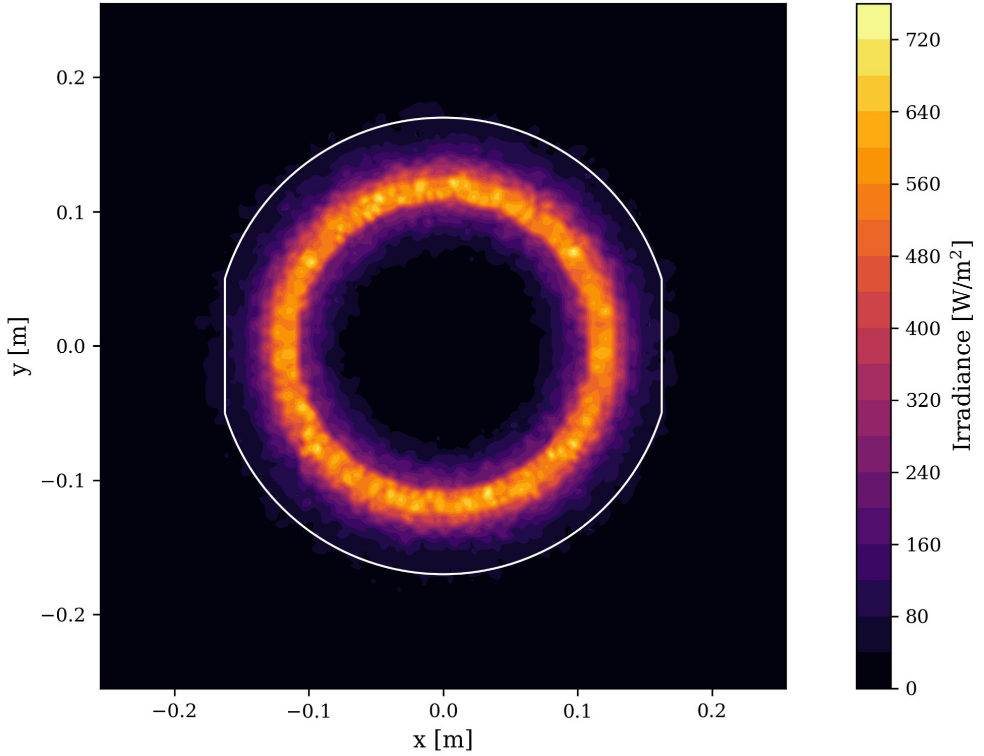

- Truncated asymmetric compound elliptical reflector
- Constructed using non-imaging edge-ray technique for maximum delivery efficiency to a target from a source of finite dimension

# Irradiance Profile

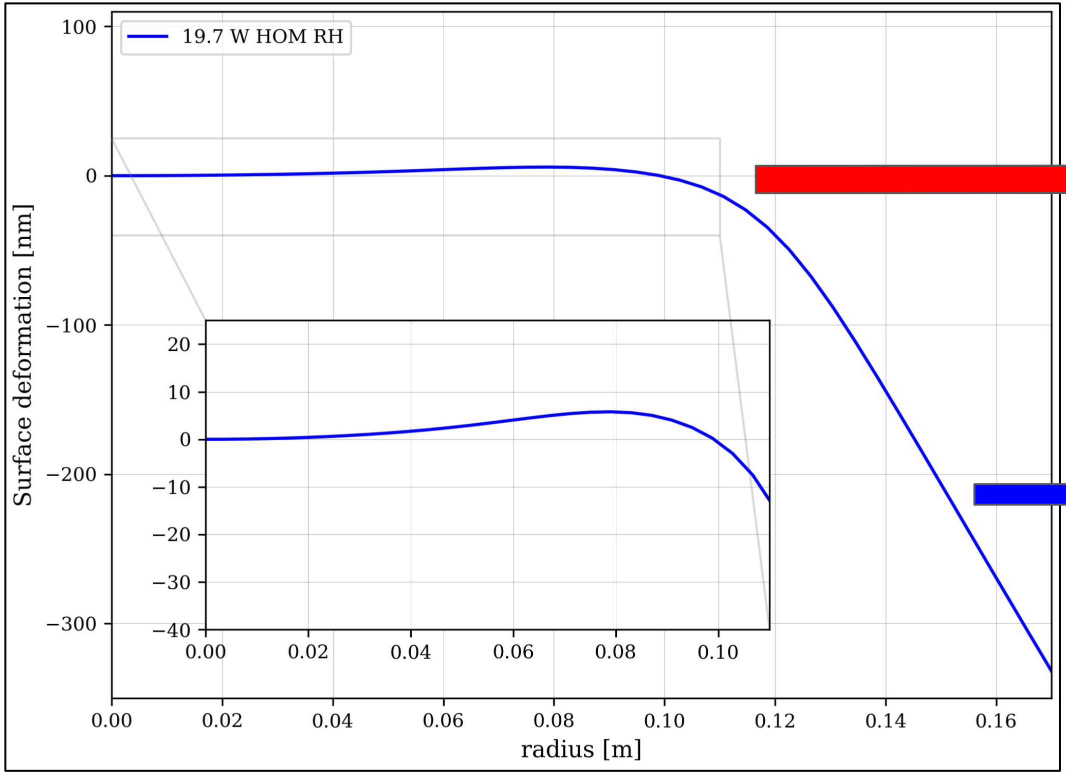
Results simulated with COMSOL ray tracing:

- Total source power : 19.7 W
- Total delivered power : 16.8 W, Efficiency: 85.4%



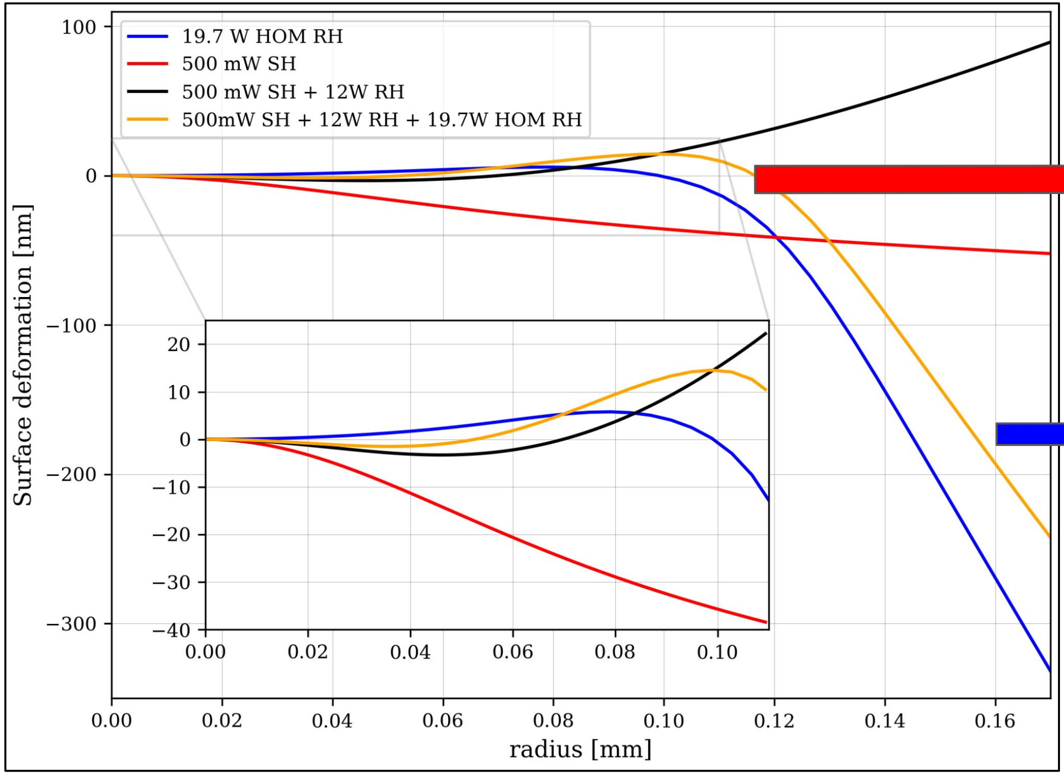
# Surface Deformation




Roll off starts at ~100 mm to correct for surface deformation caused by uniform absorption (designed for up to 500 mW)

Sharp drop at edge to break 7th-order-mode co-resonance

# Compensation at 500 mW Absorption

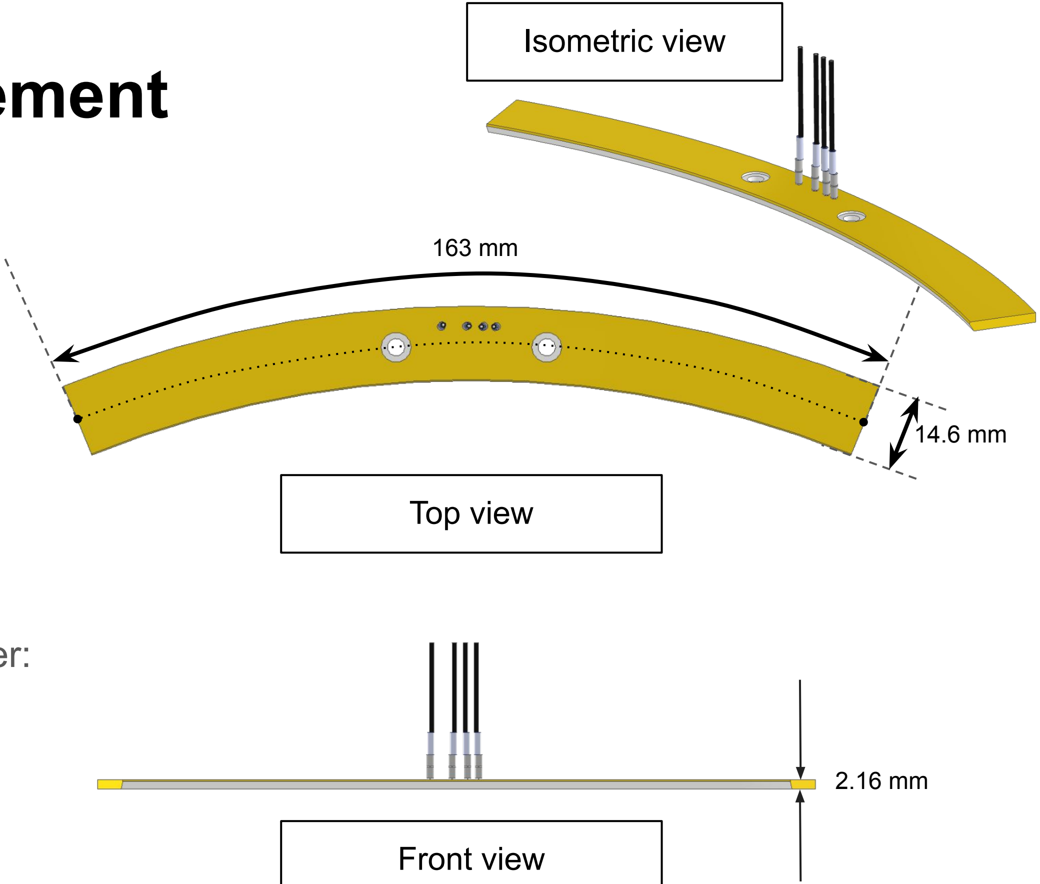



Flatten central region

Edge roll-off

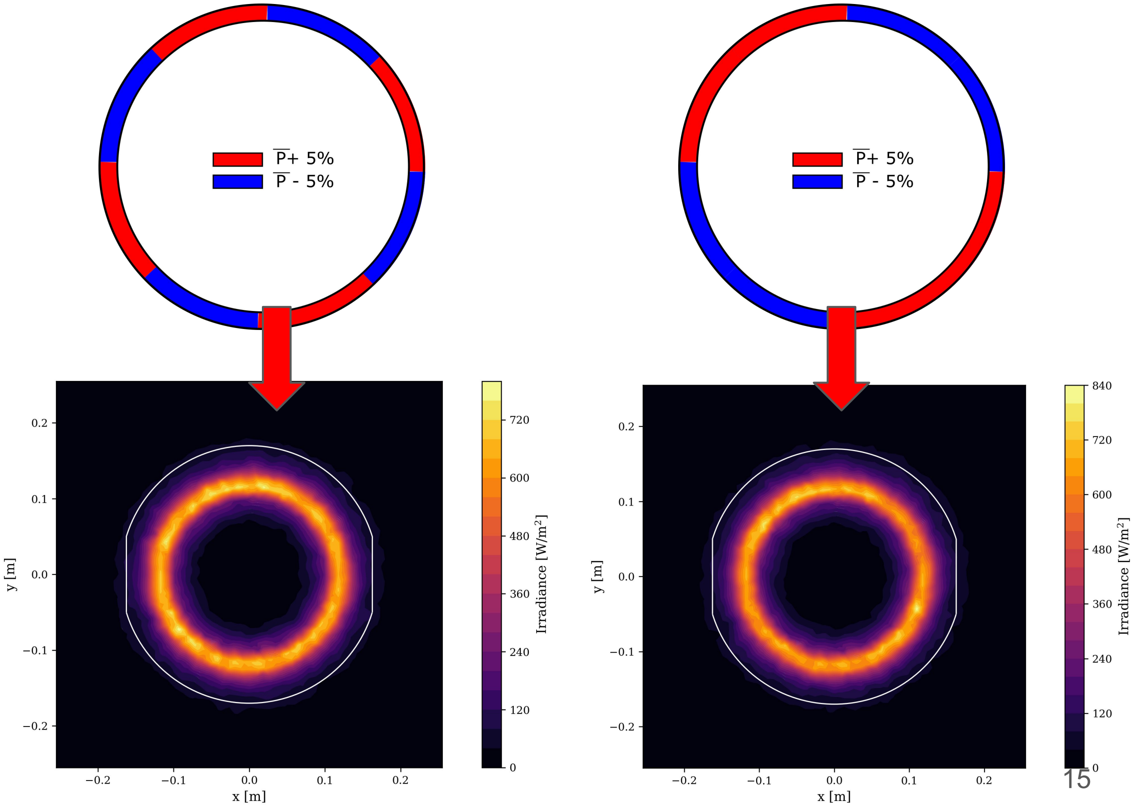
# Fabrication: Heater Element

- 8 elements to form a ring
- Material: Aluminum Nitride (same material used for SR3 heater)
- Gold coated on all sides apart from front surface
- Integrated RTD for temperature monitoring
- Anticipated maximum operating power: 30 W, T = 653 K (380 $^{o}$C)
- Maximum rated temperature: 400$^{o}$C
- **Currently in fabrication. Expected delivery: mid November 2022**

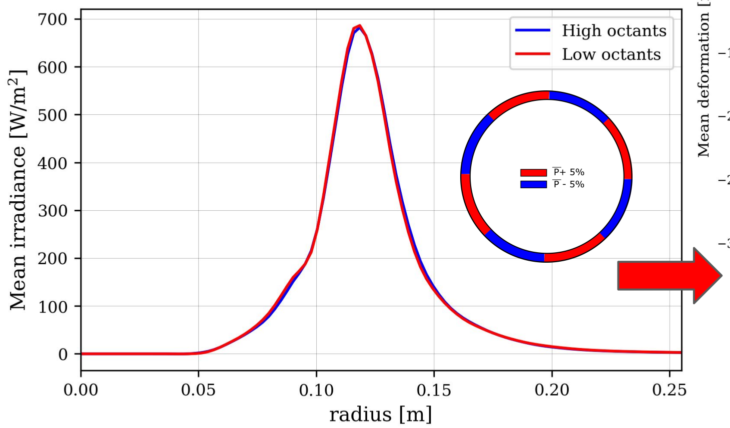


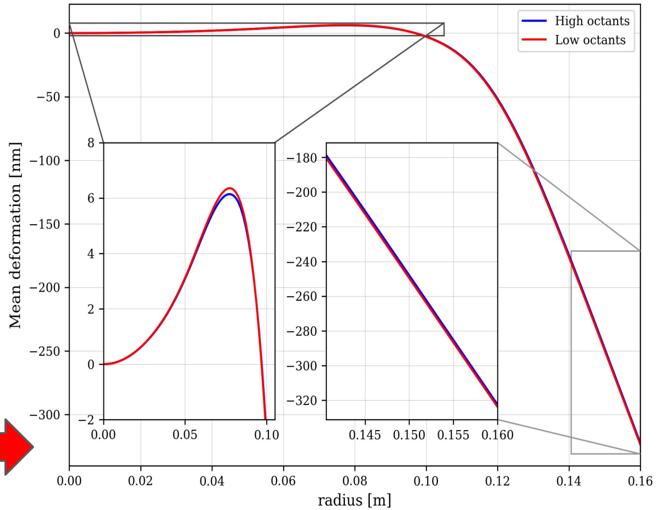
# Heater Element Resistance Consistency

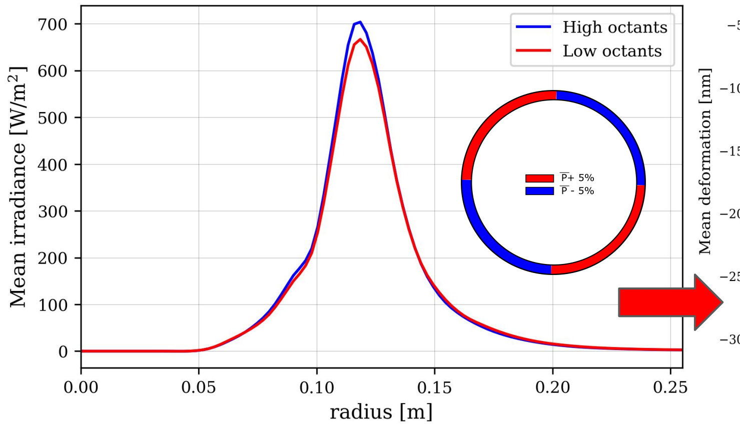
- Variation in resistance between different batches: ±20% (63.2-94.8 Ω)
- Variation in resistance of elements from the same batch: ±5%
- Causes variation in total power radiated from each element

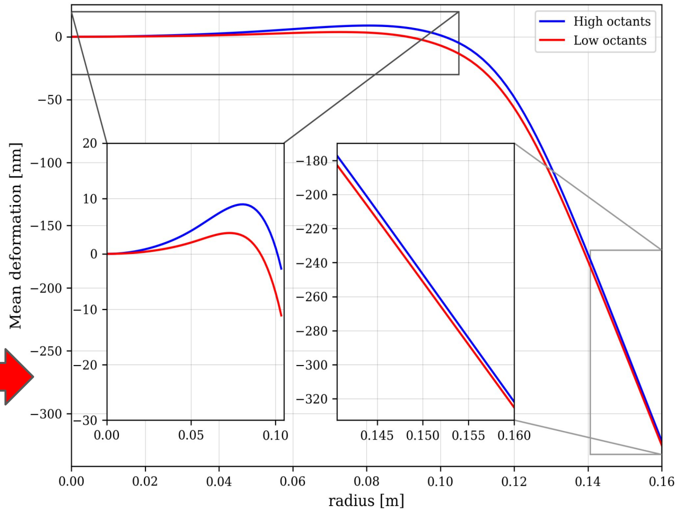


# Deformation Uniformity



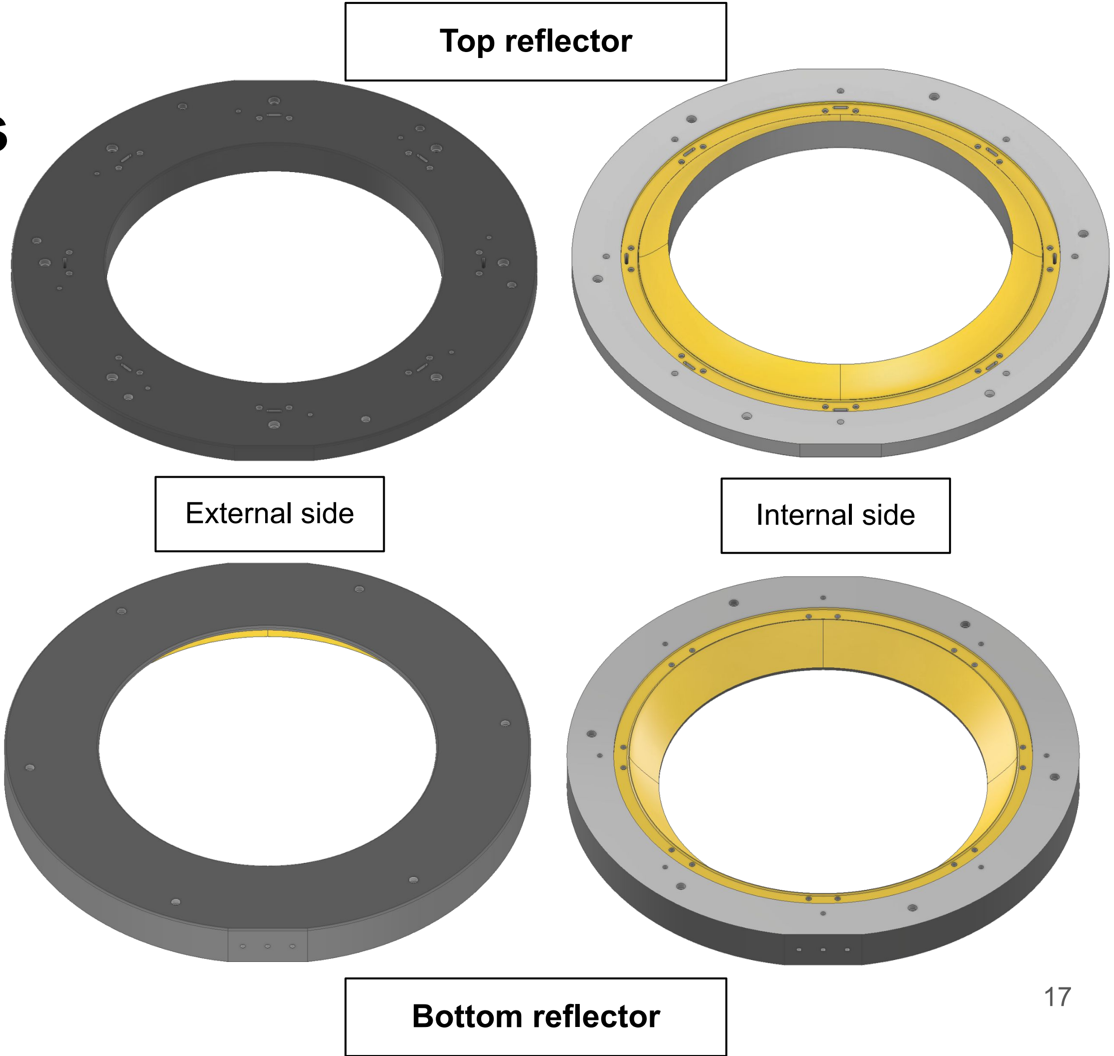



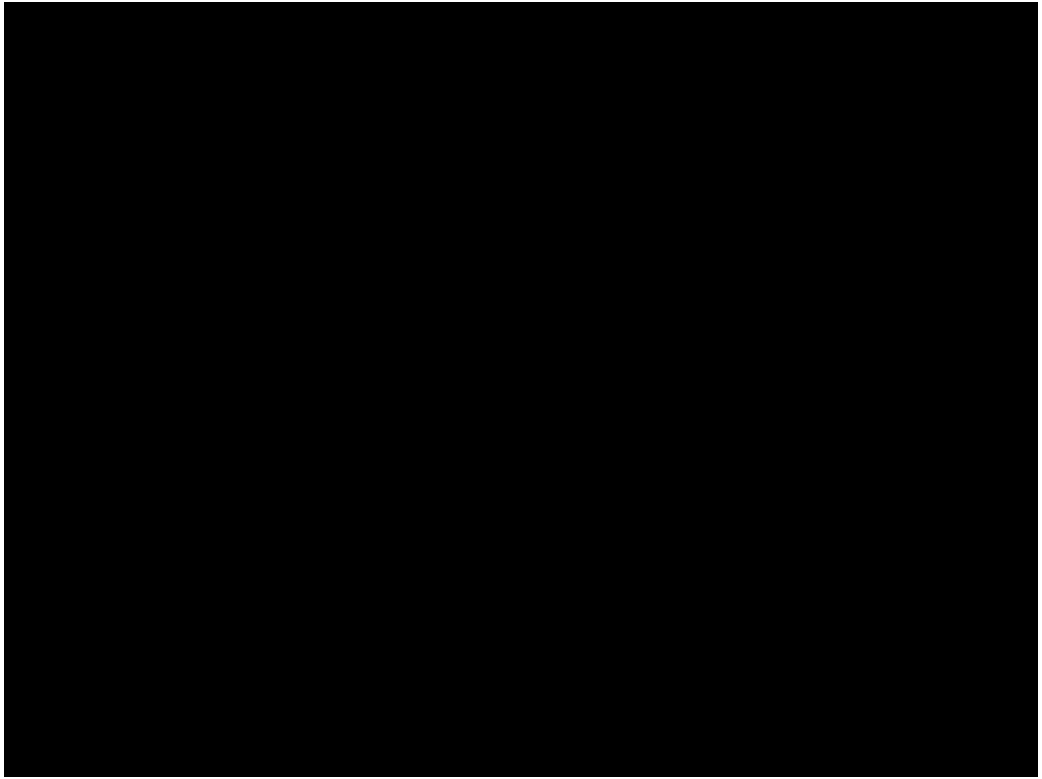

- Rays are not constrained in azimuthal direction → less variation in projected irradiance.
- Avoid having any pair of adjacent elements with mean resistance 8% higher than other element
- **Conclusion: Heater elements can be powered by 2 x 24V DC supplies, same as existing RH.**

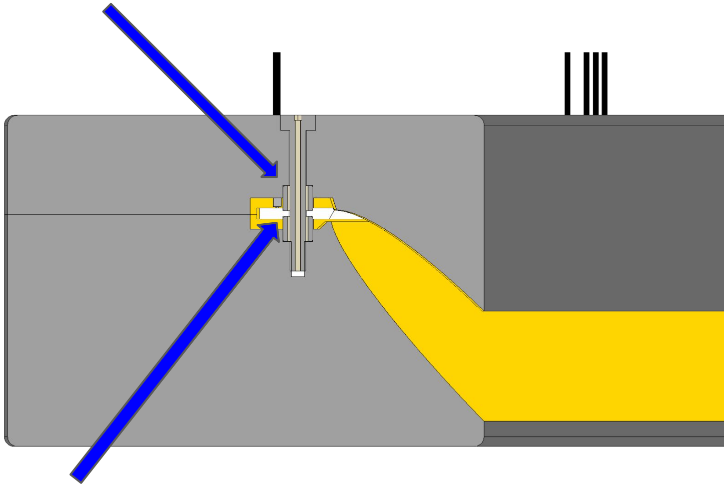
# Fabrication: Reflectors

- Consist of 2 halves
- Material: Aluminum 6061
- Reflector surface produced with diamond turned machining and thin-film gold coated
- External facets are bead-blasted to increase emissivity and reduce 1064 backscattering
- Coatings are being considered for future designs to further reduce backscattering risk (e.g. black nickel)
- **Beginning fabrication. Expected delivery: mid December 2022**

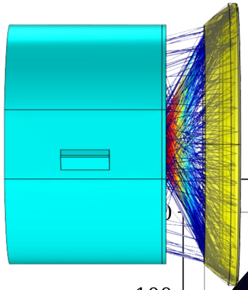


# Fabrication: Assembly

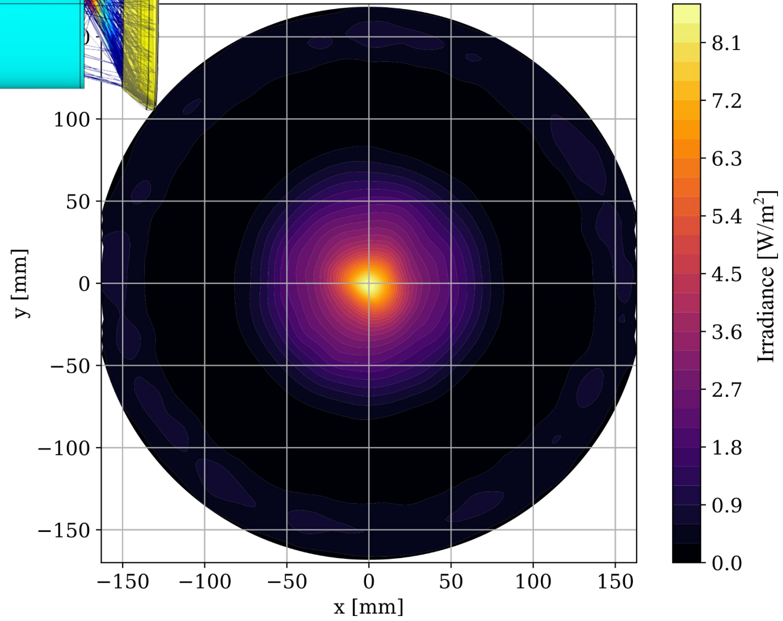




# Backscatter Analysis (T2200238): Scattering from Reflectors



**Backscattered intensity simulated**
**Lambertian ray released from ETM HR**




- Large angle scattering of 1064nm from ETM to reflector then scatter back onto ETM
- Assume large angle BRDF: (G070240):

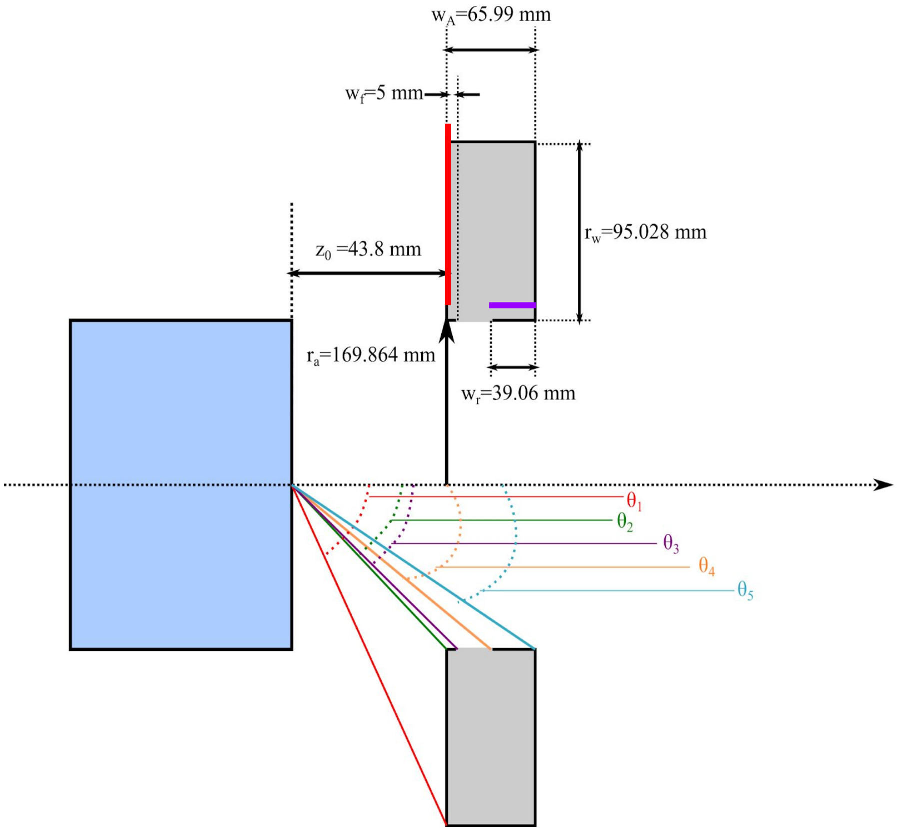
$$BRDF = \frac{\alpha \cos\theta}{\pi}, \ \alpha = 10\ ppm, \ \theta \in [62°, 72°]$$

→ Power fraction scattered into reflector: 0.072 ppm

- Use ray tracing to estimate power fraction returned to ETM: 57%
- Most of these rays scattered back at large angle. Only a small portion can scatter back in to $TEM_{00}$
  - Use reciprocity relation (T940063) to compute fraction of power scattered back in IFO beam:

$$\frac{dP_{scatter}}{P_{ifo}} = 1.36 \times 10^{-24}$$

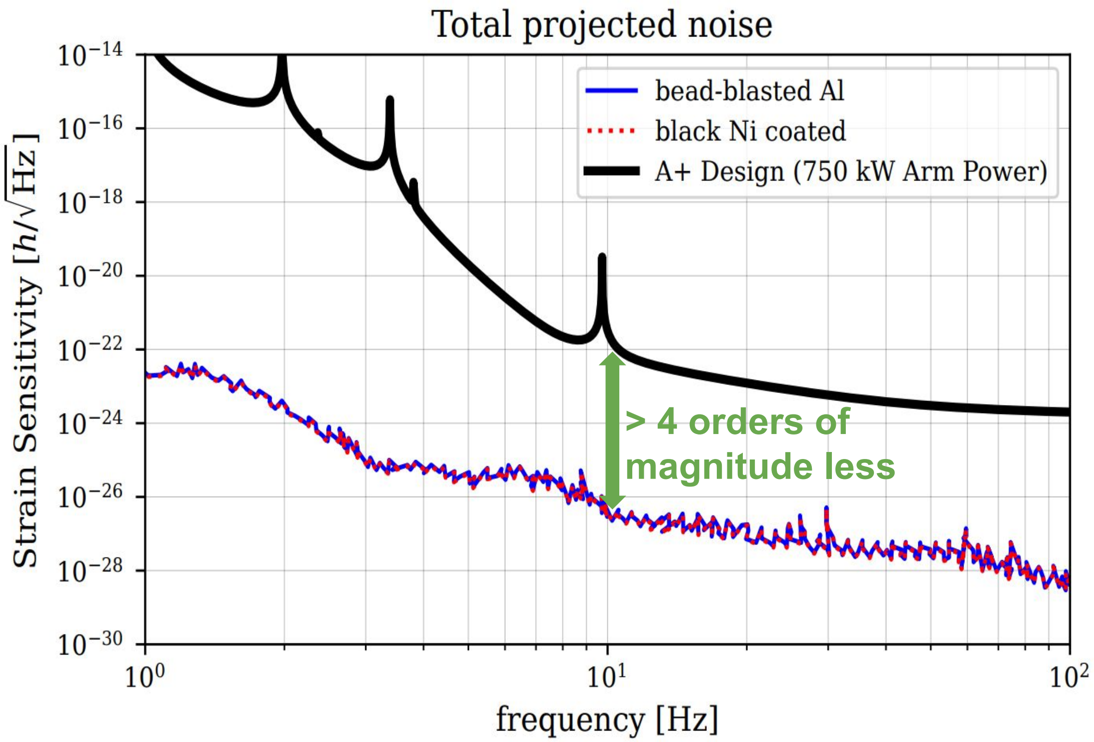
# Scattering from Exterior Surfaces




| Front surface | | | |
|---|---|---|---|
| $\theta_i$ | $\theta_f$ | $\delta I_{sc}/I_{mb}$ | |
| | | bead-blasted aluminium | black nickel coated |
| $\theta_2 = 75.5°$ | $\theta_1 = 80.6°$ | $1.93 \times 10^{-25}$ | $2.57 \times 10^{-26}$ |
| **Inner diameter, front reflector** | | | |
| $\theta_3 = 74.0°$ | $\theta_2 = 75.5°$ | $1.28 \times 10^{-25}$ | $1.70 \times 10^{-26}$ |
| **Inner diameter, rear reflector** | | | |
| $\theta_5 = 57.1°$ | $\theta_4 = 67.4°$ | $2.00 \times 10^{-24}$ | $2.66 \times 10^{-25}$ |

- Large angle BRDF of bead-blasted Al: 0.03 $sr^{-1}$(source, measured BRDF at 3.39 micron, BRDF, most likely higher at 1.064 - needs measurement)
- Large ange BRDF of black Ni coated: 4e-3 $sr^{-1}$(E0900028)

# Total Projected Backscattering Noise in DARM



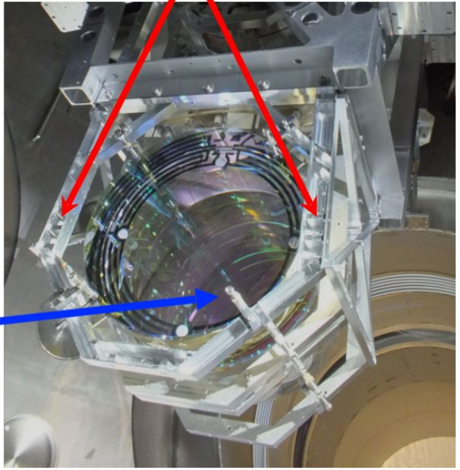

- Backscatter from reflector introduces phase noise & radiation pressure noise
- Noise projection assumes ST2 BSC-ISI ASD (G2000186)
- Backscattered from reflective component is the dominant source.
- At 10 Hz:
  - **Total - bead blasted Al:** 2.90e-27 [1/sqrt(Hz) ]
  - **Total - black Ni coated:** 2.73e-27 [1/sqrt(Hz) ]

# HOM RH Mounting

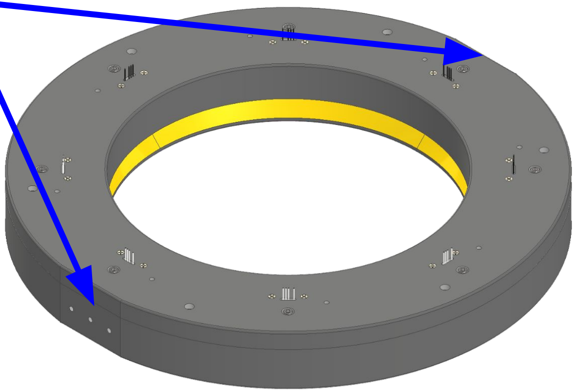
- Proposed mounting location: bottom of the Quad suspension cage.
- Estimated weight of HOM RH prototype:  42 - 45 lbs due to structure’s large outer diameter (OD) to facilitate machining.
- Total weight can be reduced by approximately 50% in final design by reducing OD.
- **Question**: How would mounting of the HOM RH on the Quad cage affect BSC-ISI?

Mounted to lowest section of suspension cage

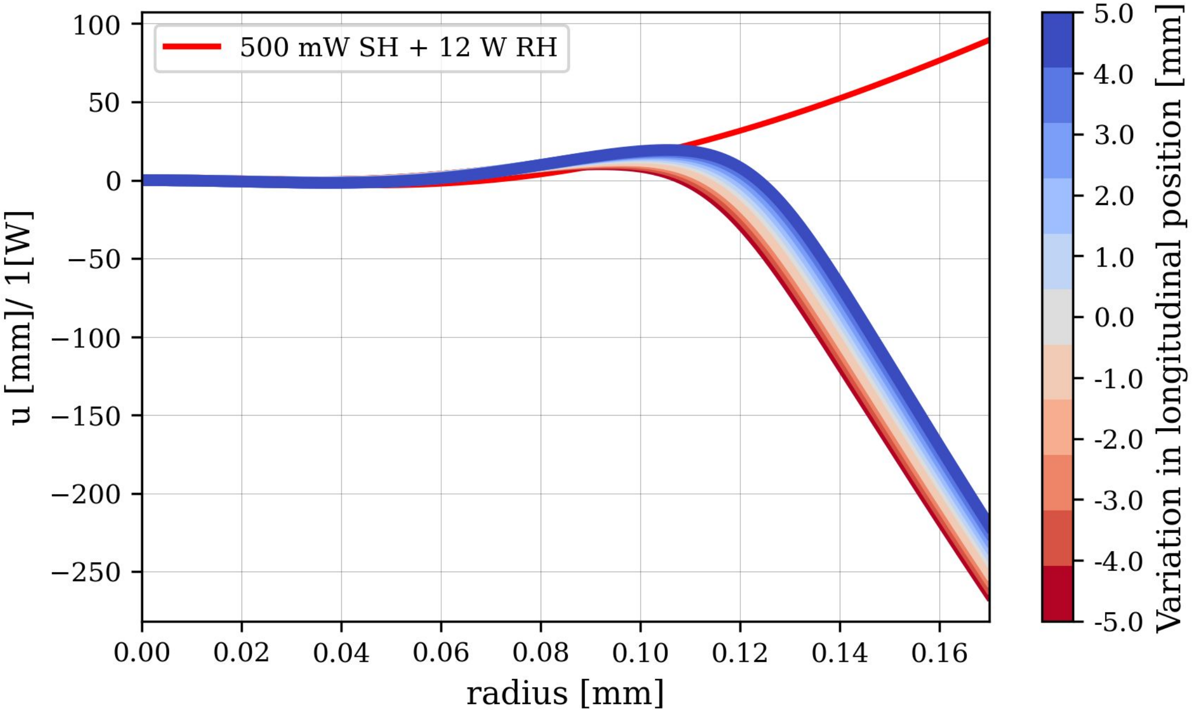
EQ stop



Flat sides for attaching interfacing arms

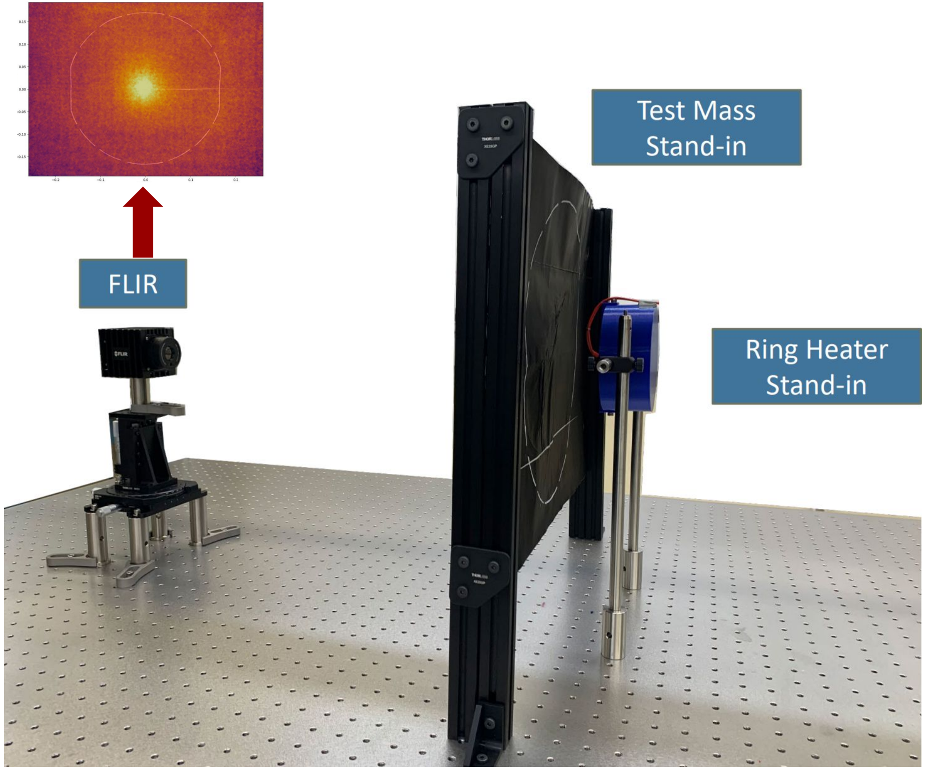


# Sensitivity to Position Error




→ **Surface deformation is not strongly sensitive to uncertainty in position**

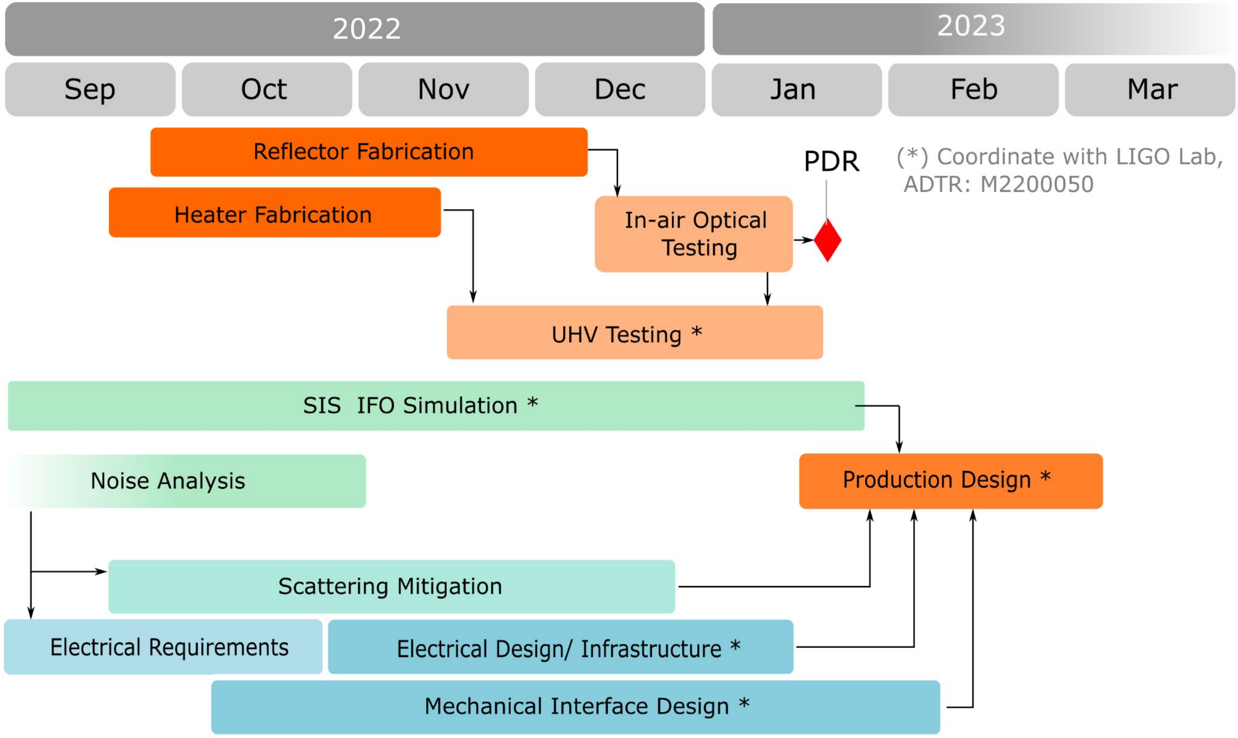
# Testing Plan




In-air test setup for HOM RH (SURF report: T2200205, T2200206)

- In-air optical measurement of irradiance profile:
  - Using thermal camera to verify irradiance profile from HOM RH
  - **Status**: Constructed, currently improving sensor calibration
- UHV compatibility testing:
  - RGA outgassing measurement using calibrated Ar/He leak
  - **Status**: Vacuum system under construction

# Testing Schedule

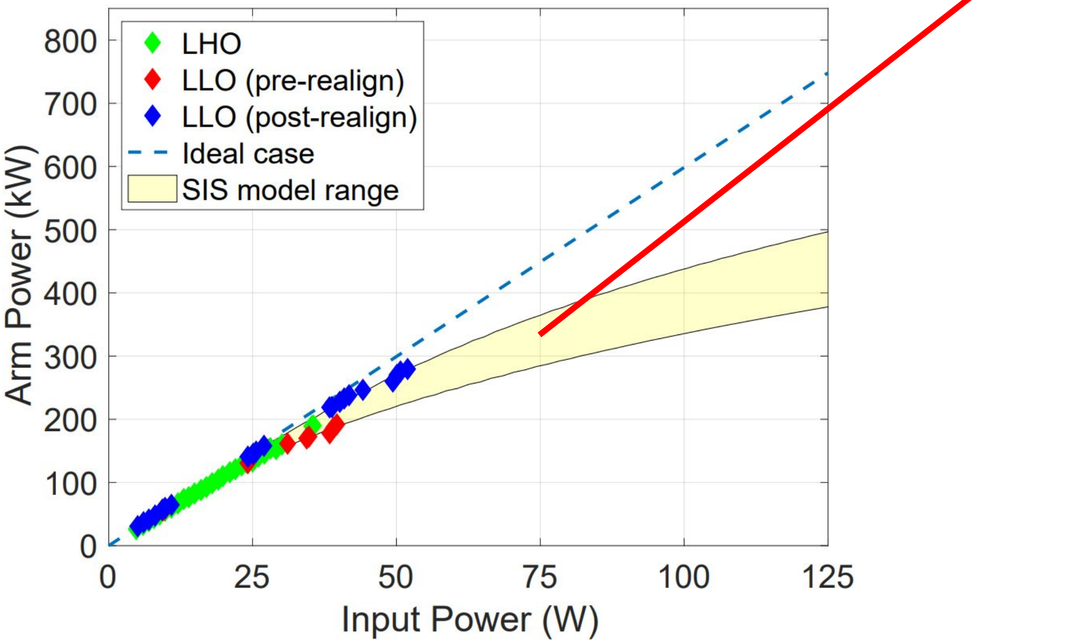



## Next steps:

- Complete noise analysis of HOM RH and specify electrical requirements.
- SIS simulation of O4 cavities with HOM RH to quantify effects on point absorbers and uniform absorption
- UHV testing of heater elements in November
- Prototype assembly and optical testing before December holidays.
- PDR and final production design are contingent on testing results

# Motivation for O4b Delivery

**The aLIGO picture circa O3** (Brooks et al., P1900287)




- Point absorbers cause significant loss in arm power gain. Modeling of HOM RHs predicts a substantial loss reduction → **allow pushing IFO to higher power in O4**

- Using the HOM RHs in situ will be invaluable experience ahead of O5.

  → **O4b experience will directly inform design of a more sophisticated HOM RH for O5 (UCR has already secured funding from the NSF)**

# Conclusion

- Prototype design and modelling finalized, currently in production; ready to start on mechanical / electrical interfacing work with support from LIGO Lab (under ADTR M2200050)
- Transition from ADTR to Detector Improvement (DI) is contingent on prototype testing results.
- Estimated cost as DI: $75k-$150k