Active Wavefront Control for Megawatt Arm Power

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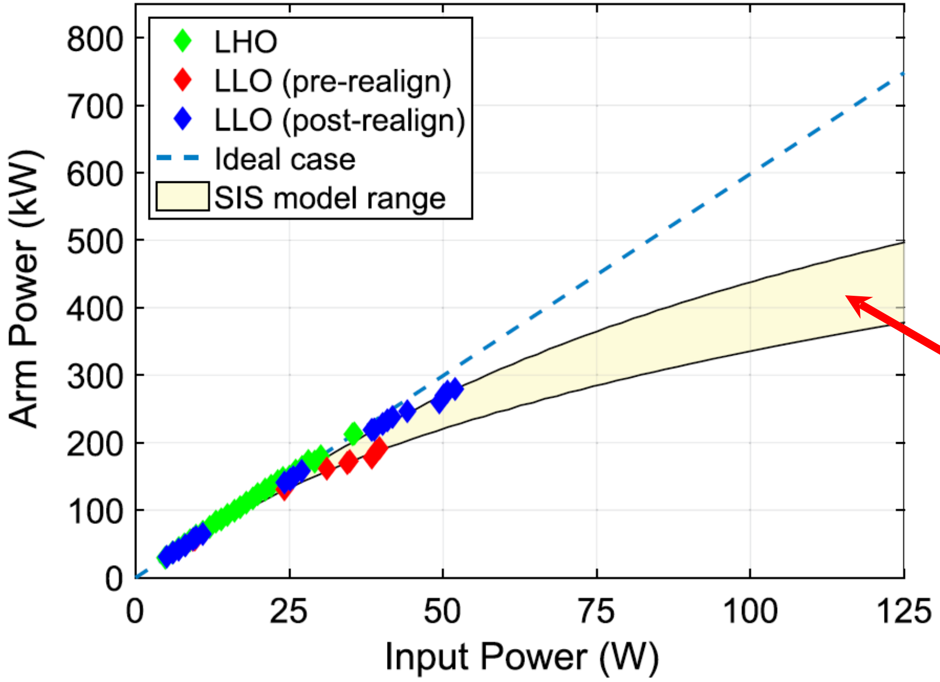
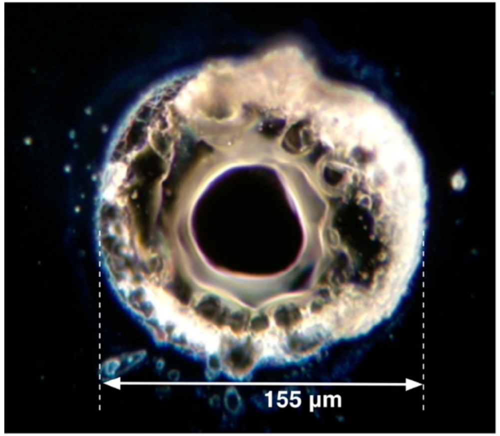
Introduction

- In the push towards higher interferometer power, **coating absorption** is a limiting problem
  - Serious challenges both from nonuniform *and* uniform absorption
- At megawatt power, even uniform absorption will require higher-order (above ROC) wavefront corrections
  - Beyond the capabilities of the current Thermal Compensation System (TCS)
- Here we present a design for a new wavefront actuator targeting these emerging challenges

Challenge #1: Point Absorber Scattering

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

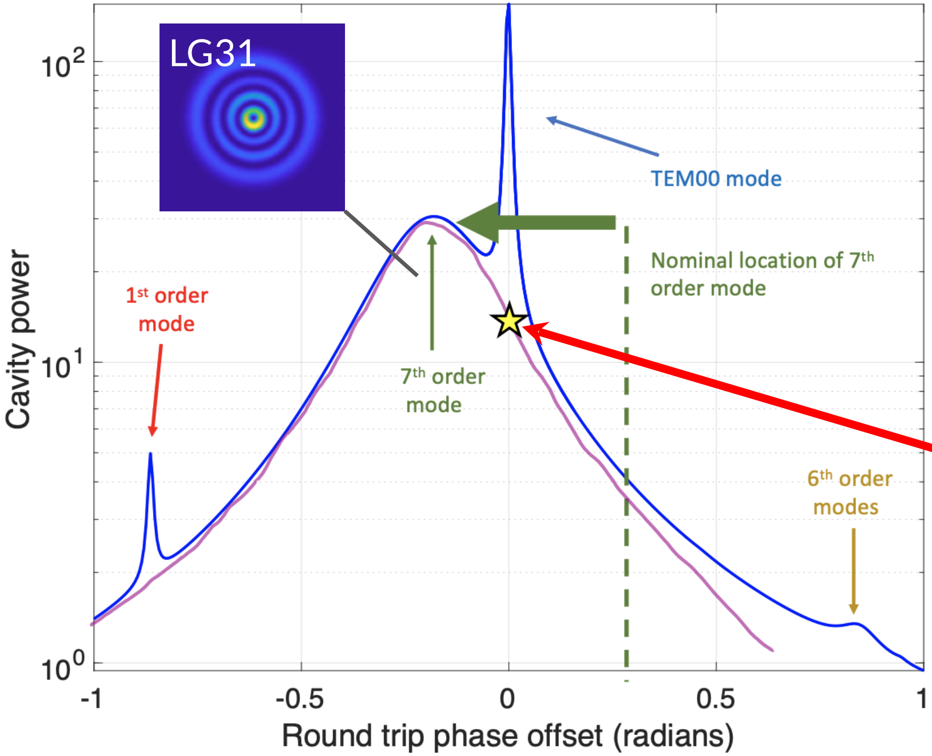




Dependence on point absorber position

Modal Degeneracies Exacerbate Scatter Losses

Simulated arm cavity scan (A. Brooks, G2101232)



- Loss of power from mode HG00 to HG*mn*:

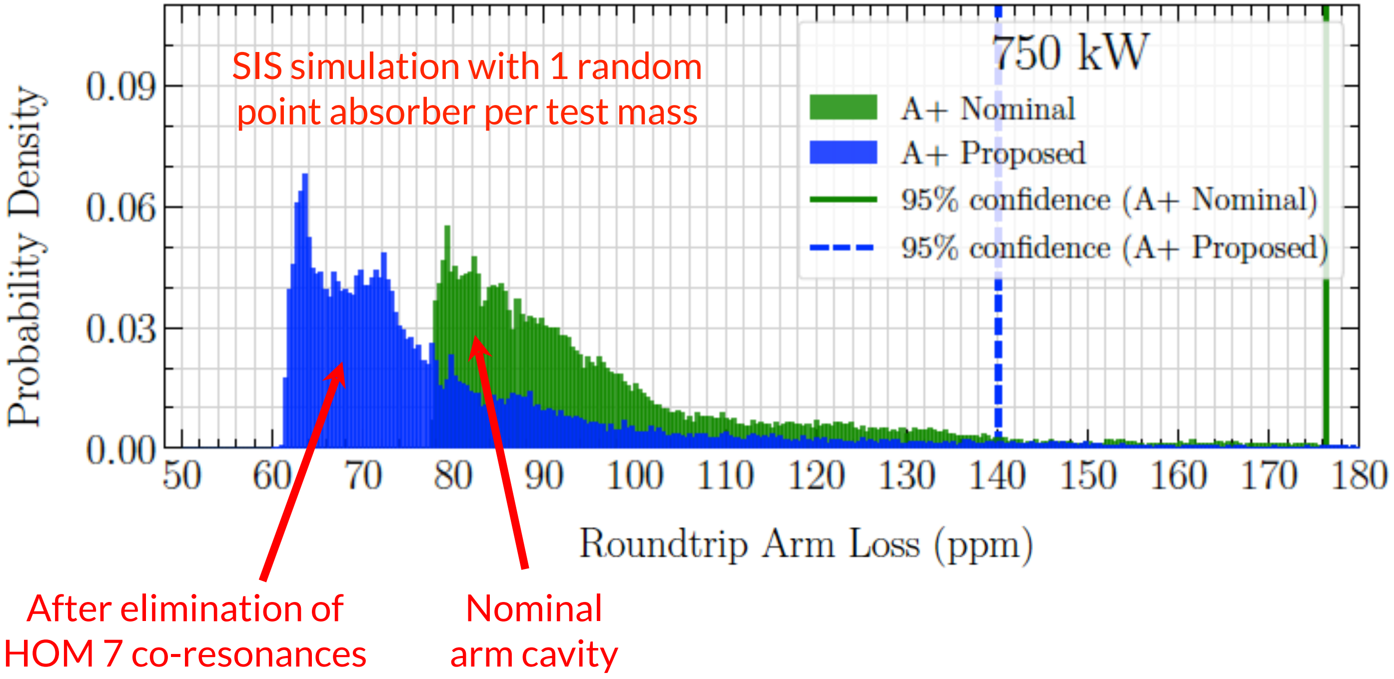
$$\mathcal{L}_{mn} = a^2_{00|mn} g_{mn}$$

Single-bounce scattering coefficient

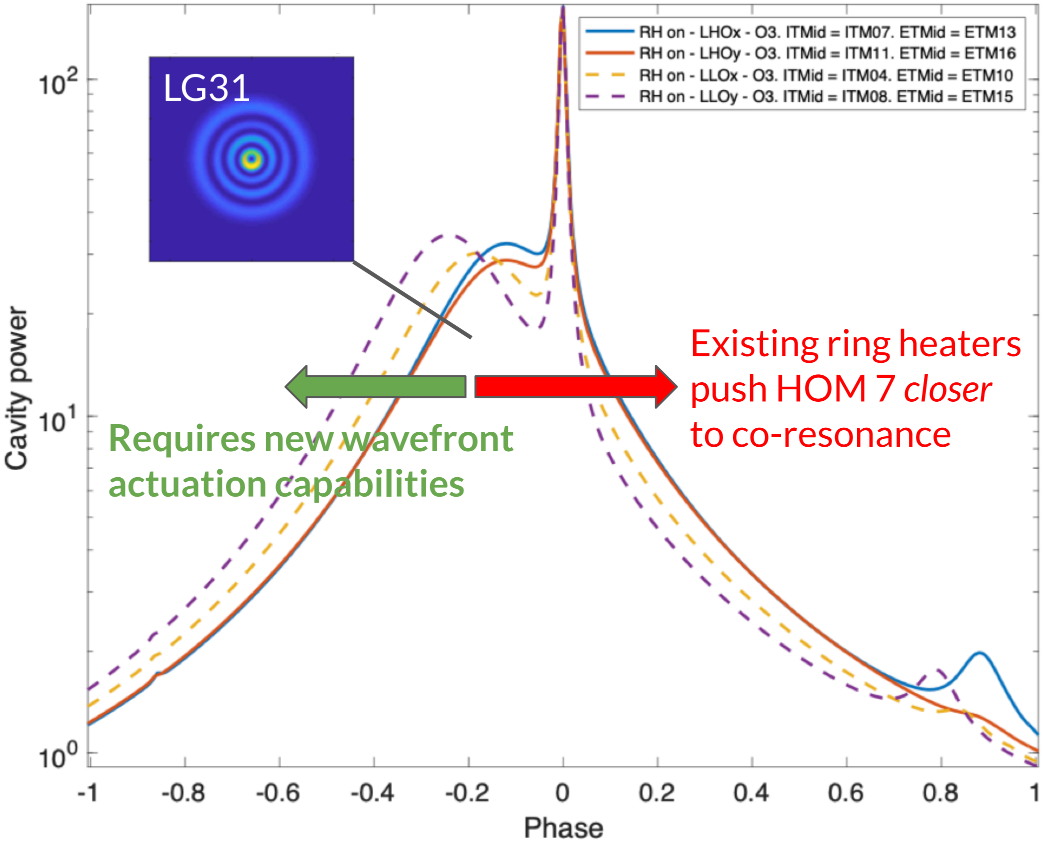
Resonant enhancement/ suppression factor

Modal Degeneracies Exacerbate Scatter Losses

Simulated arm loss distributions (J. Richardson *et al.*, P2100184)



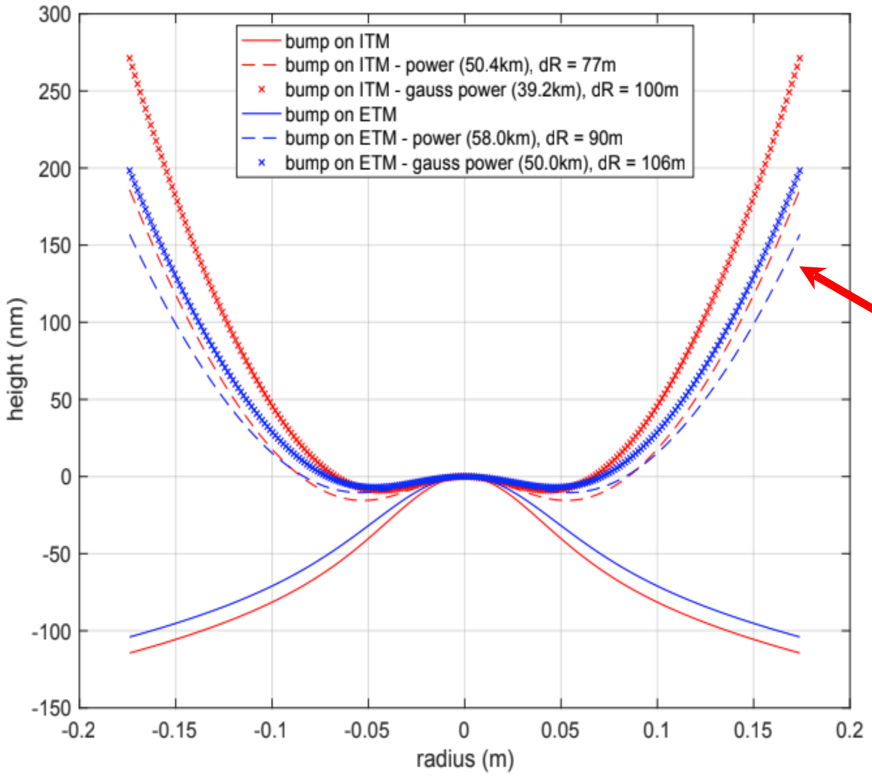
Active Mitigation of HOM 7 Co-Resonances



(A. Brooks, G2101232)

Challenge #2: Uniform Coating Absorption

Deformation by 1W absorption (H. Yamamoto)

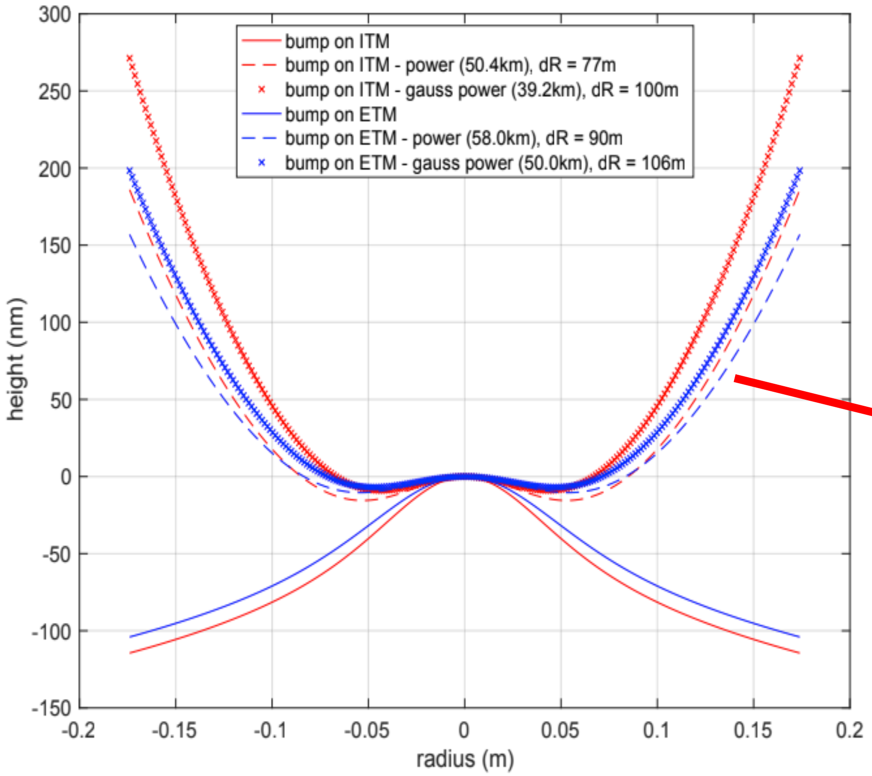


1W coating absorption = (2 MW arm power) x (0.5 ppm)

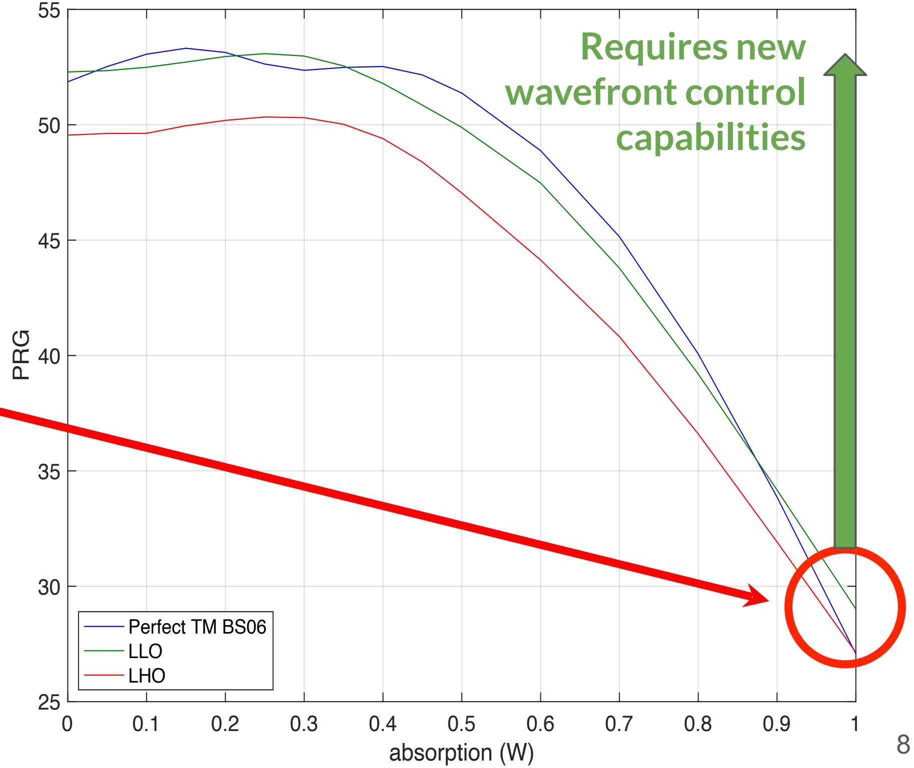
Residual ETM/ITM surface deformation
after optimal ring heater correction

Challenge #2: Uniform Coating Absorption

Deformation by 1W absorption (H. Yamamoto)

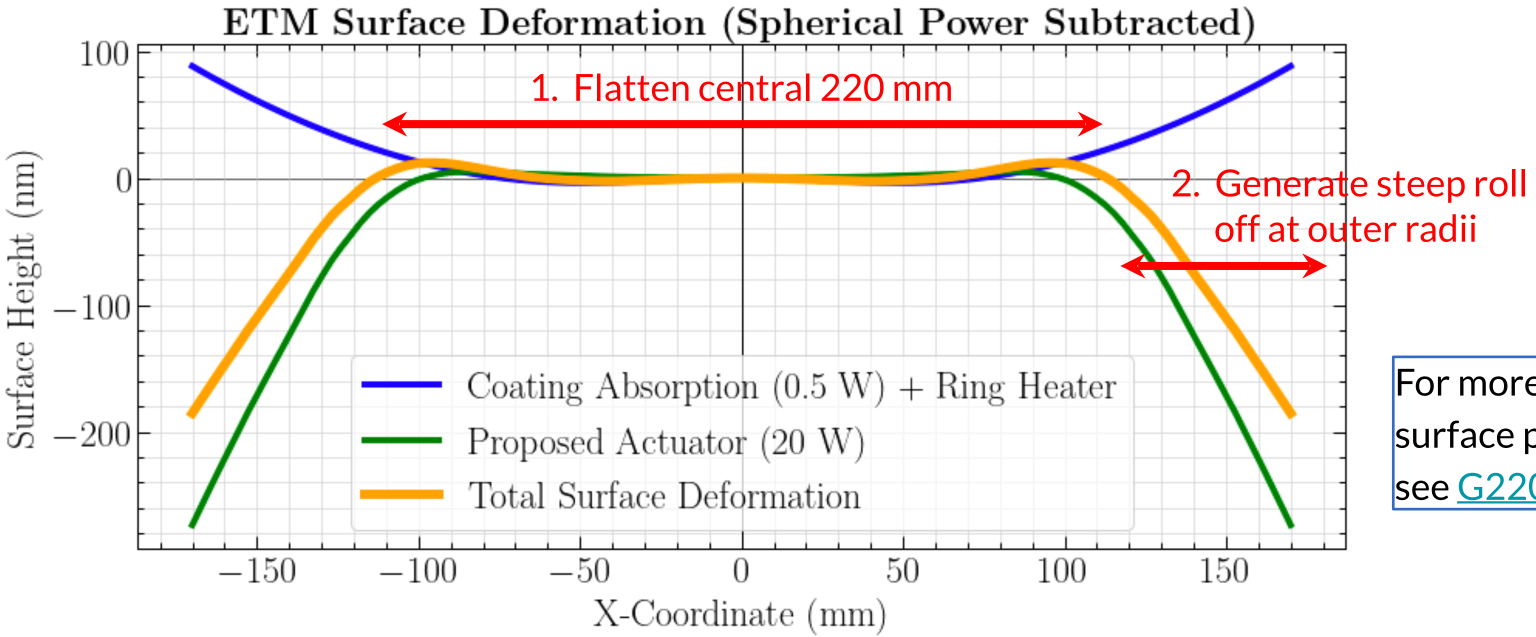


Power recycling gain vs. absorption (H. Yamamoto)



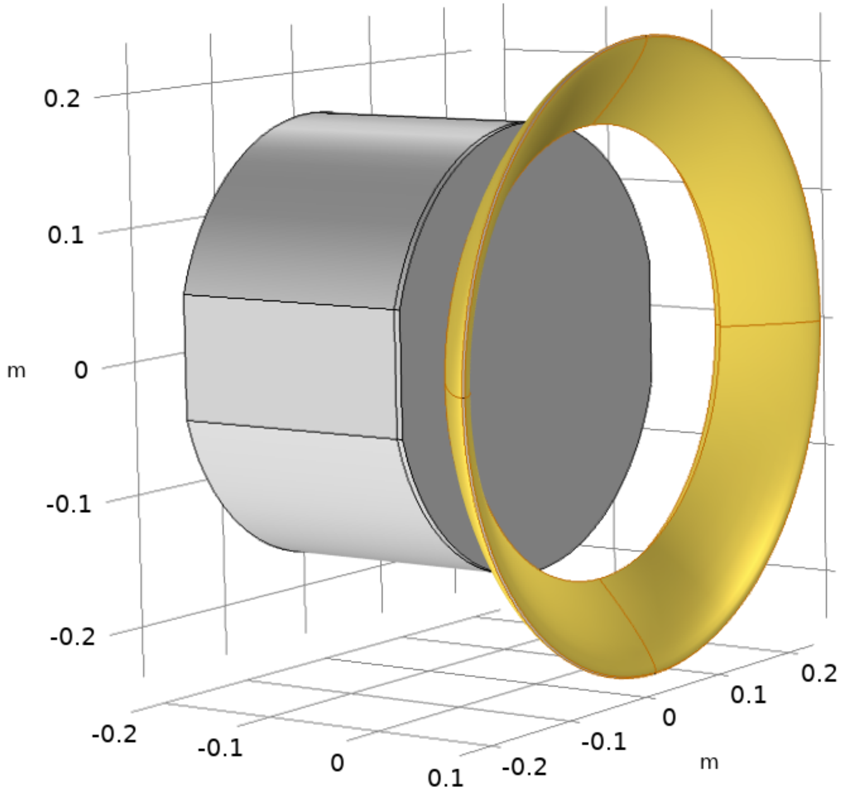
The Higher-Order Mode (HOM) Ring Heater

- We have designed a new wavefront actuator aimed at both of these problems:



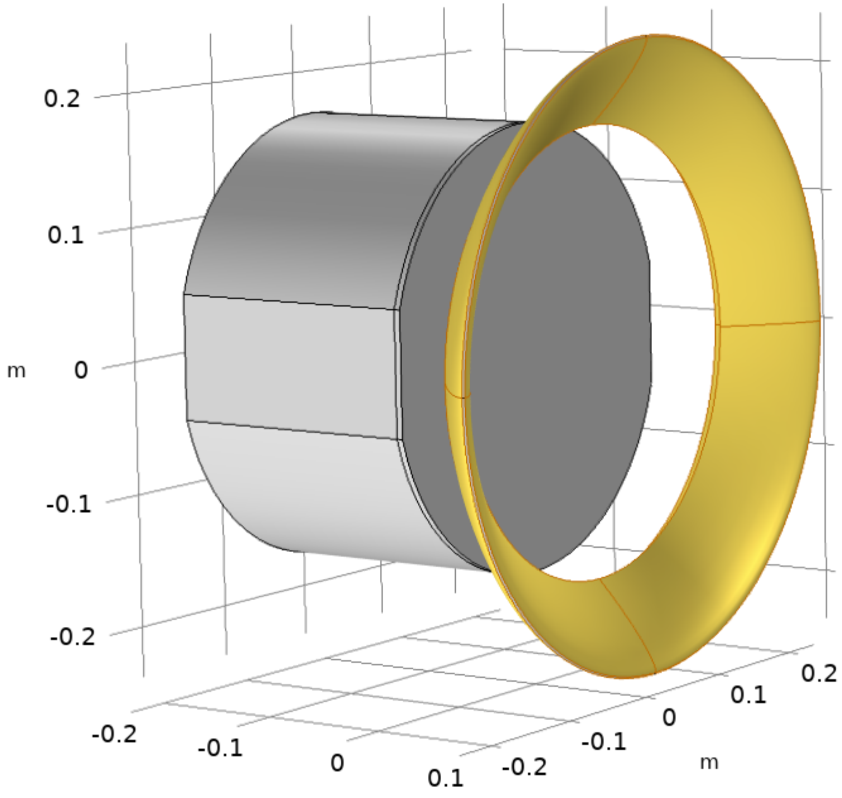
For more details on the surface profile design, see G2200284

HOM Ring Heater Design

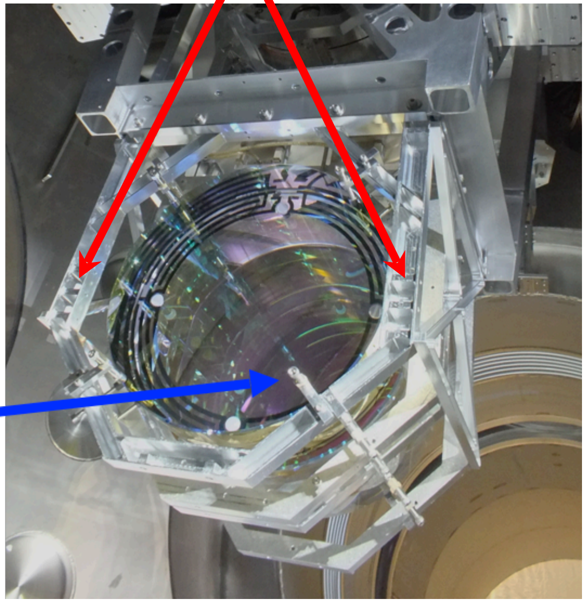


- Annular heating pattern projected onto front surface of test mass
- **Simple design:** Consists of ring heater element and 8.25 cm-long reflector
- Reflector interior:
  - Superpolished to < 10 nm RMS
  - Metallic thin film broadband reflective coating (e.g., gold)
- Reflector exterior:
  - Sandblasted for minimal specular reflection of 1064 nm light
  - 1064 nm absorptive coating (possibly)

HOM Ring Heater Design



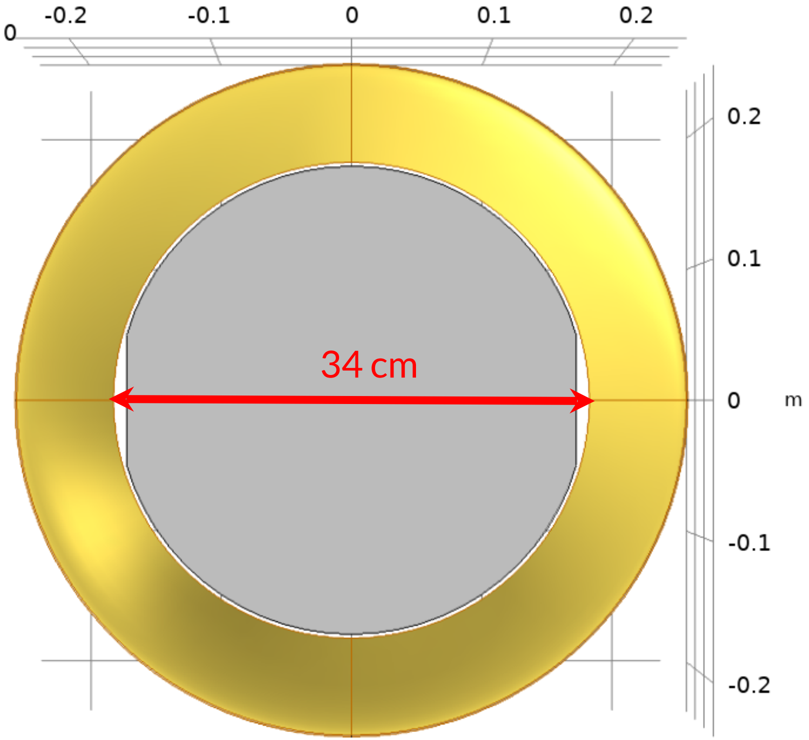
Mounted to lowest section of suspension cage



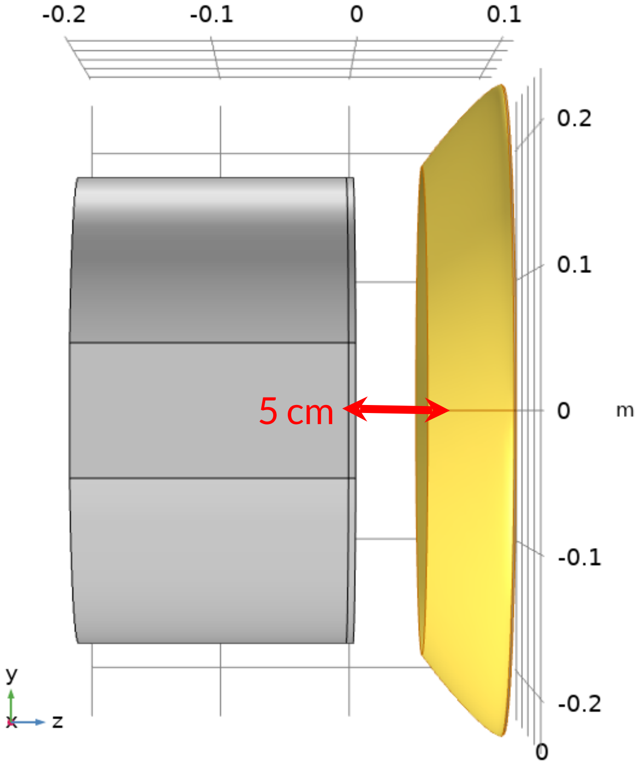
EQ stop

HOM Ring Heater Design

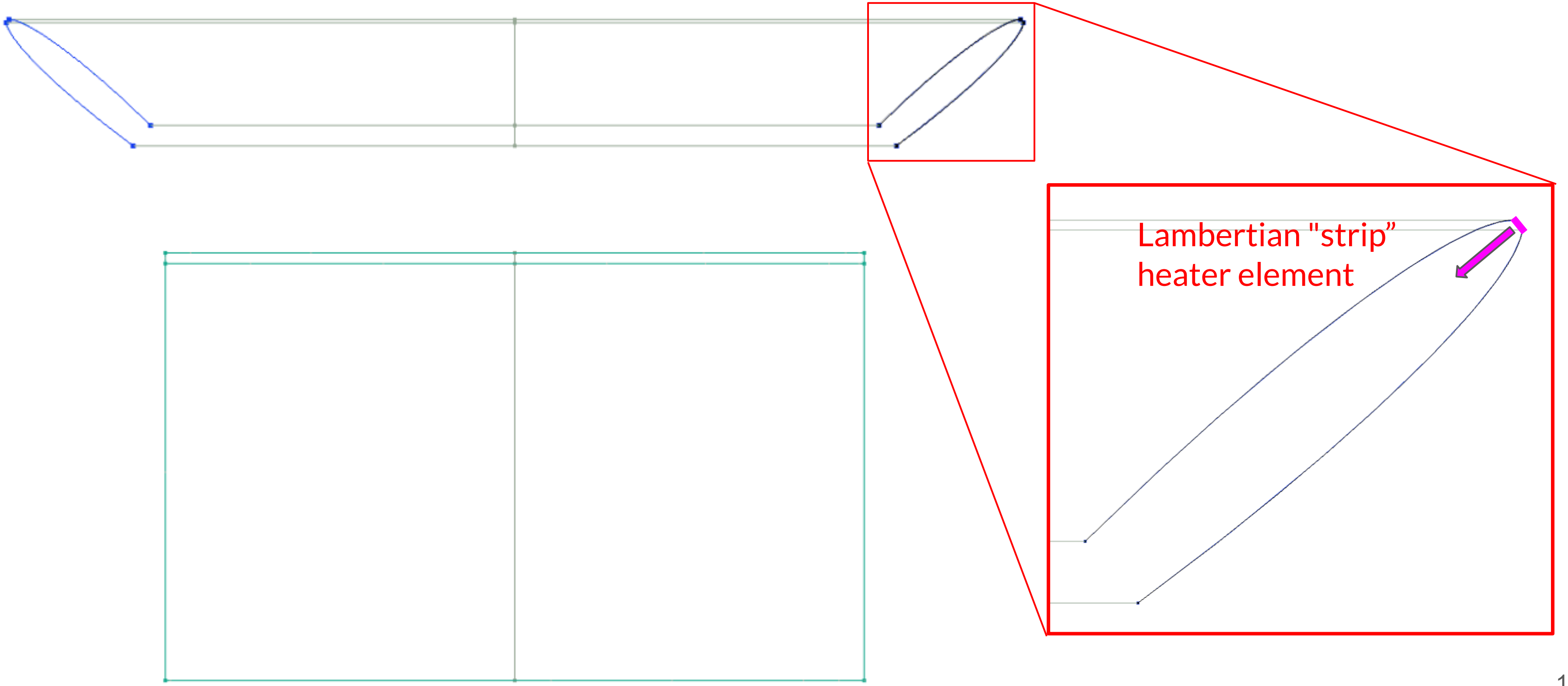
Face-On View



Side View

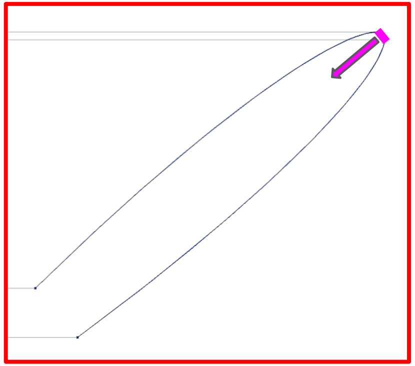


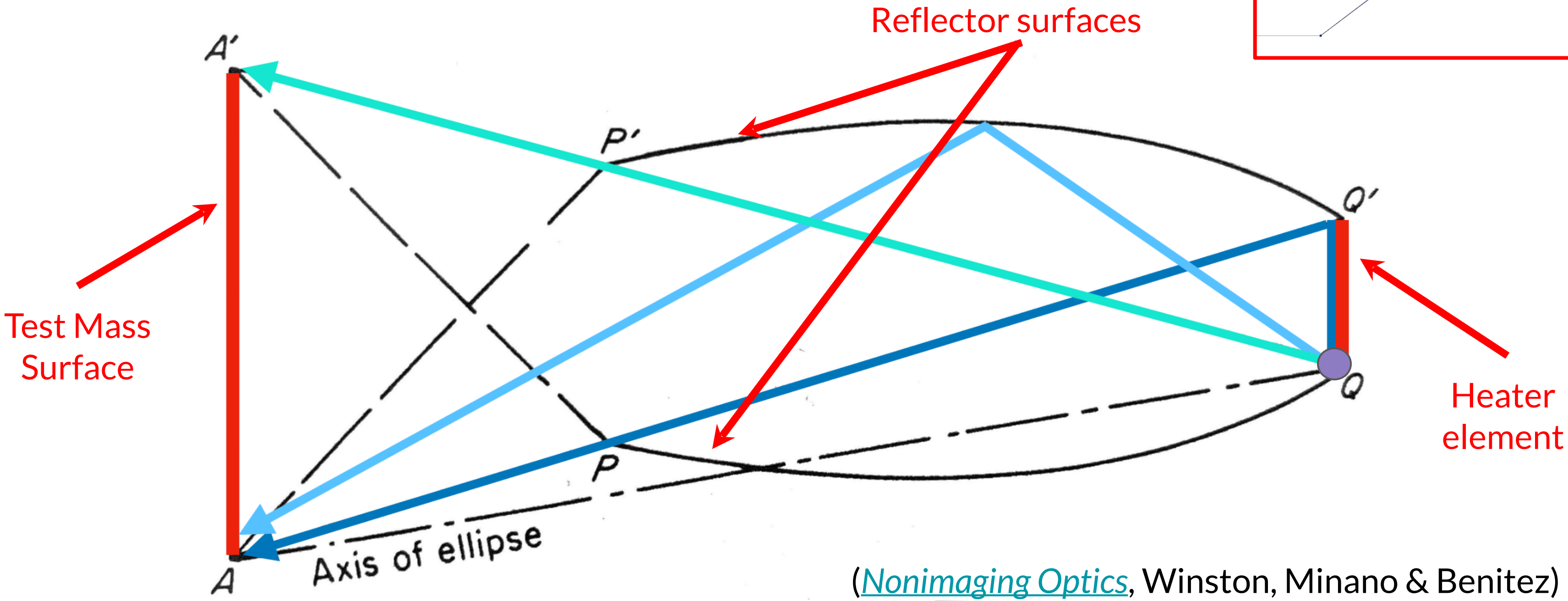
Two-Dimensional Cross-Section



Optical Design Principle

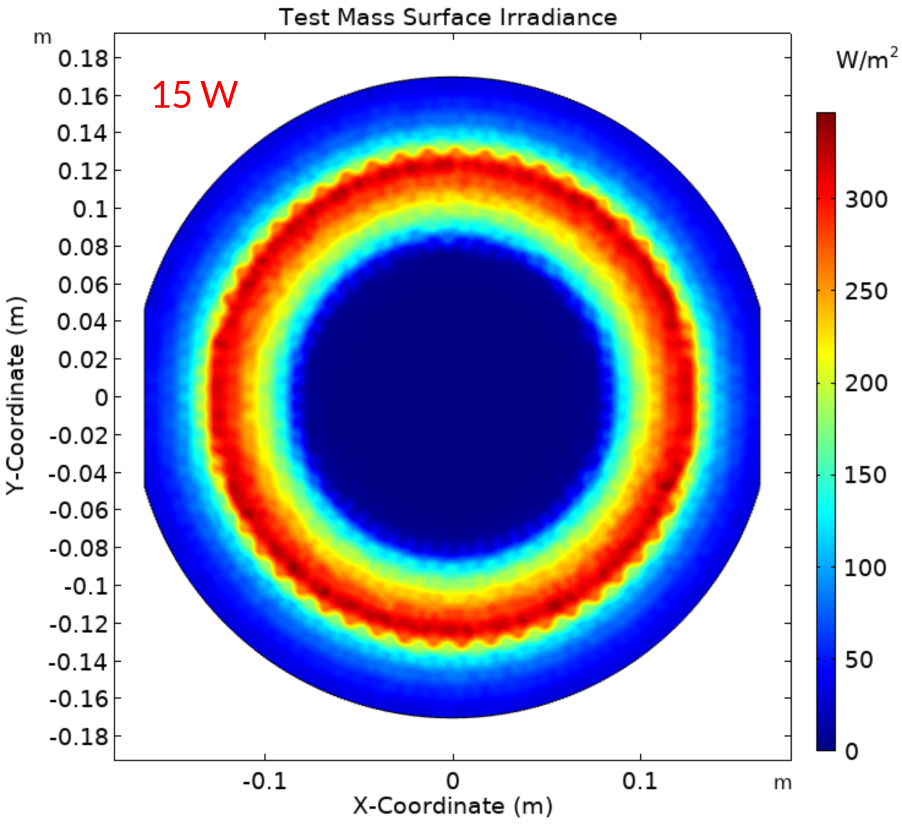
Based on the ***nonimaging elliptical concentrator*** from solar energy

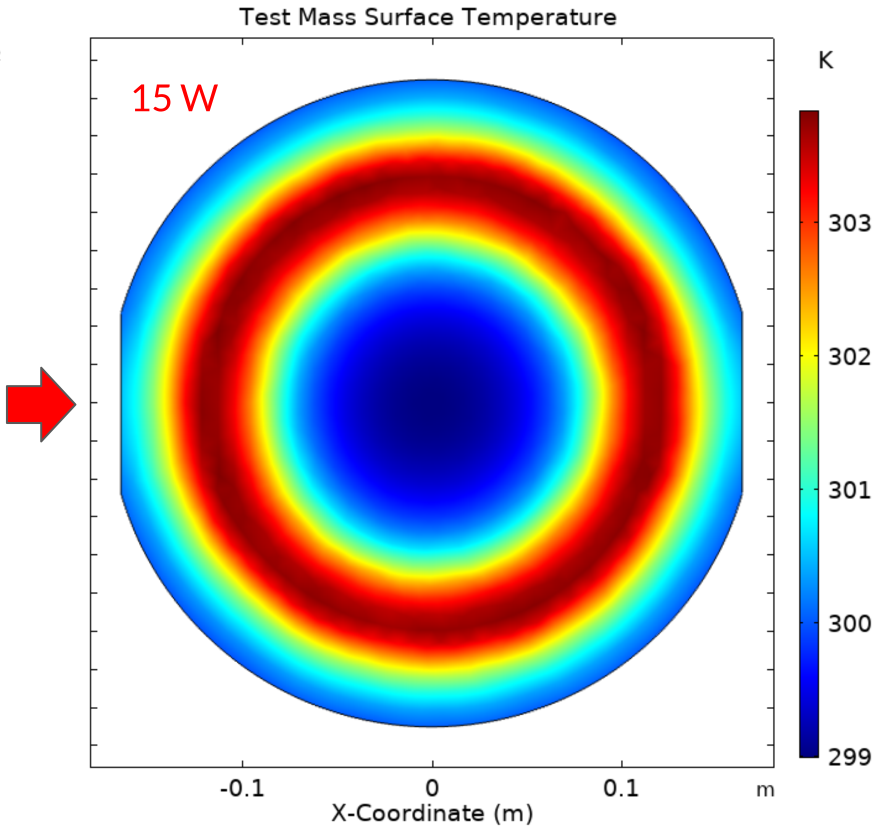




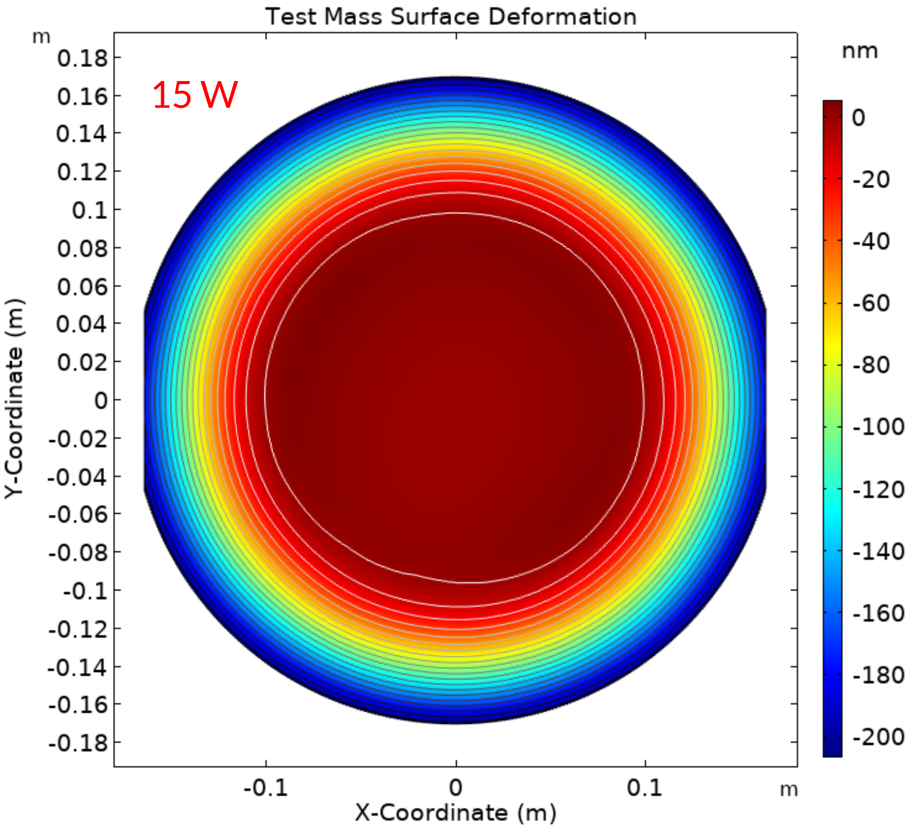
(Nonimaging Optics, Winston, Minano & Benitez)

COMSOL Ray-Tracing Analysis



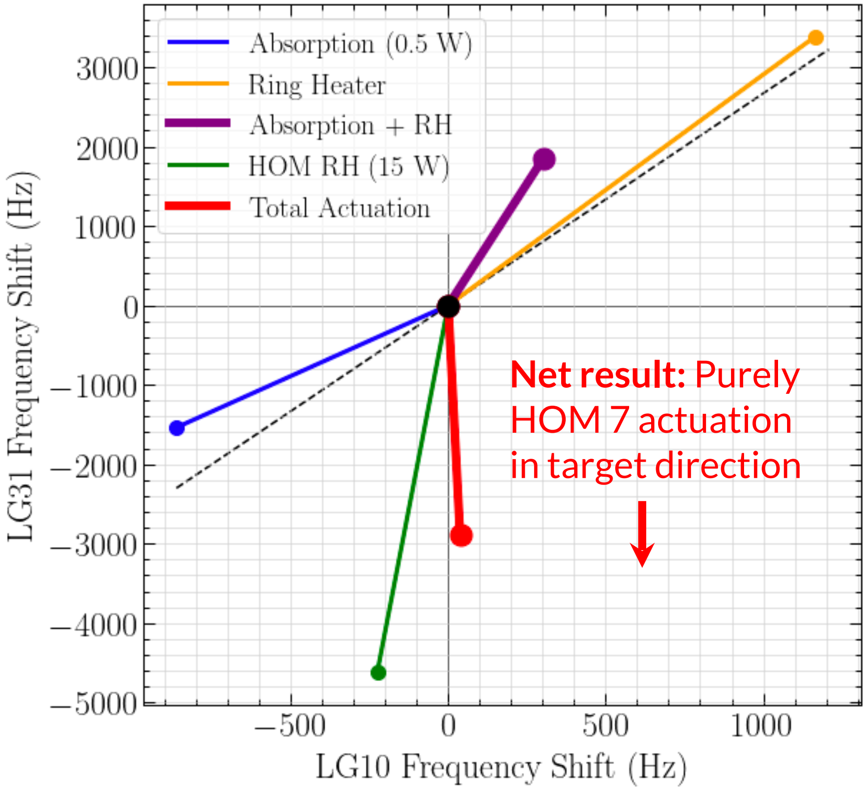


COMSOL Thermal Stress Analysis



- **70.0%** power transfer efficiency
- Nominal operation:
  - $P = 15$ W
  - $T = 560$ K (287 C)
- Max-power operation:
  - $P = 40$ W
  - $T = 716$ K (443 C)

Performance Metric



- Compare the shift in resonance frequencies of LG31 vs. LG10 modes
- Design objective:
  - **Maximize overall LG31 shift** (dynamic range)
  - **Minimize overall LG10 shift** (impact on low-order modes)

Project Status & Next Steps

- NSF-supported joint development effort between UC Riverside (Richardson group) and LIGO Lab (ADTR led by A. Brooks, M2200050)
- Targeted as an O4 Detector Improvement
- Next steps:
    - Mechanical design (mounting structure)
    - Electrical design (in-vacuum cabling, feedthroughs)
    - Materials selection (coatings, etc. may require UHV qualification)
    - Prototype fabrication