Updates on FroSTI for use in LIGO

G2300506

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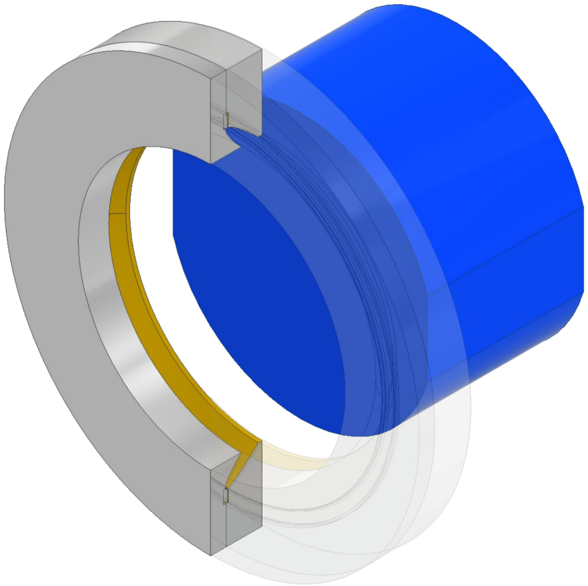
Front Surface Type Irradiator

- Ring heater (RH) mounted in front of test mass reflective (HR) surface
- Irradiates HR surface with infrared heating source

  → Induces surface deformation (and thermal lens in ITM) to better correct for HR coating absorption lensing

  → Bringing IFO back to 'cold state'



Motivation #1: Reduce Point Absorber Risk

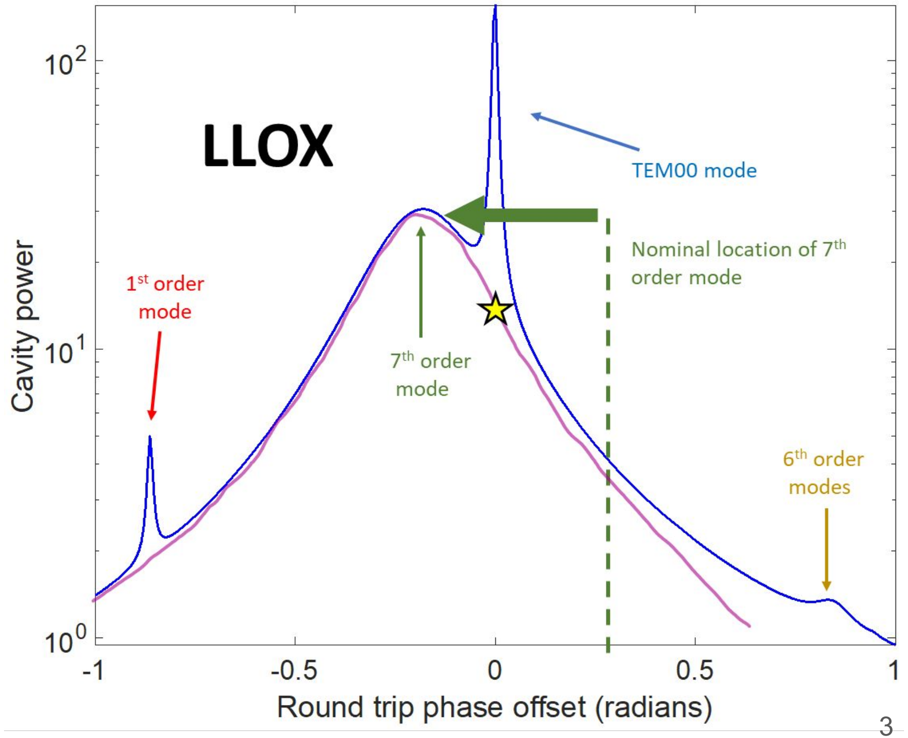
- Address **non-uniform loss** induced by point-absorbers
- Point-absorbers scatter TEM00 mode into higher-order modes
- The 7th order mode scattering loss is resonantly enhanced due to cavity degeneracy.
  - Brooks et al. 2021 (P1900287)
- Loss of power from TEM_{00} to TEM_{mn}

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

Single-bounce scattering coefficient

Arm cavity gain factor

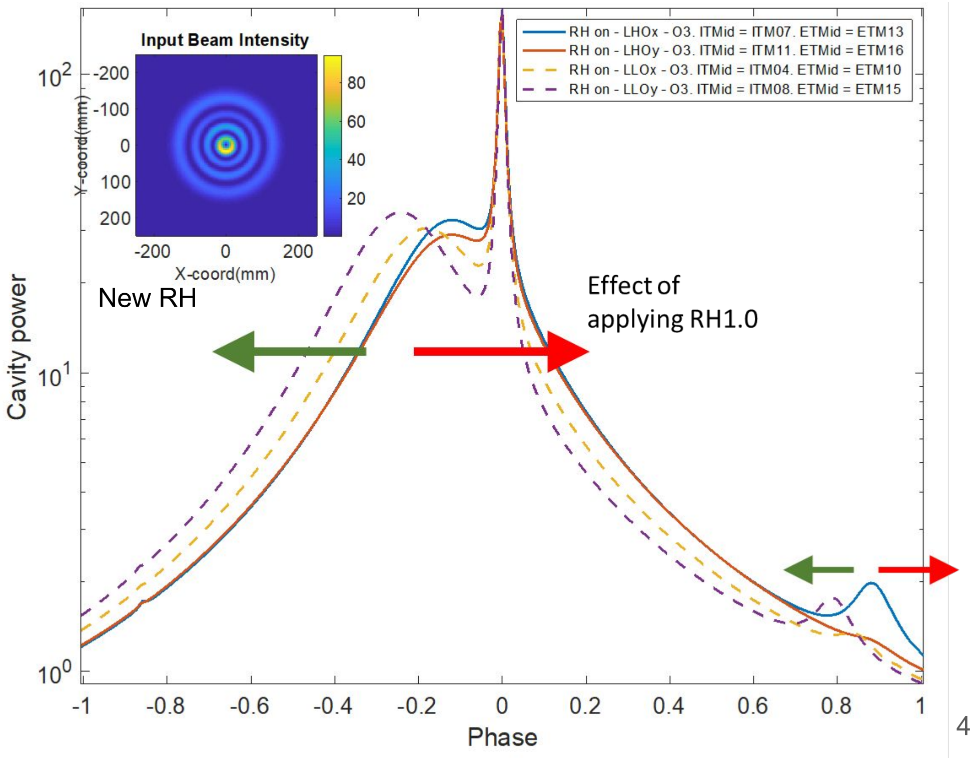
Simulated arm cavity scan (A. Brooks, G2101232)



Mitigating the HOM7 Degeneracy in Arm Cavities

- FroSTI will actively shift the HOM7 resonances away from TEM00, suppressing g_{mn}
- Removing co-resonances will reduce arm loss
  - Richardson et al. 2021 (P2100184)

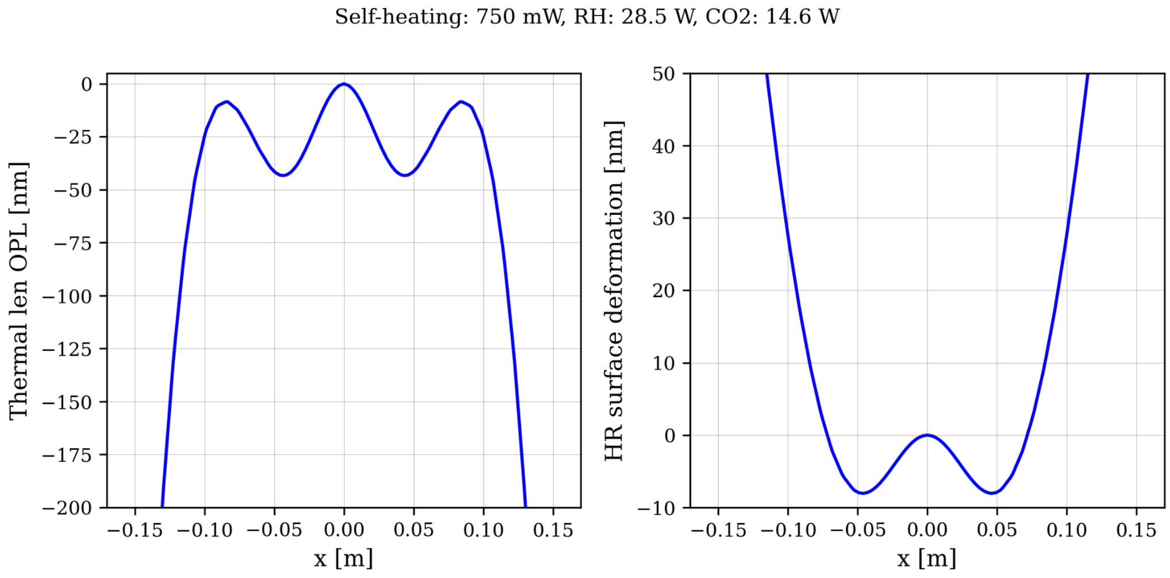
Effects of ring heaters on HOM resonance conditions (G2101232)



Motivation #2: Correcting High Levels of Uniform Absorption

- Post-O5 arm cavity power target: **1.5 MW**
  - Report of LSC Post O5 Study group (T2200287)
- Residual surface deformation *after* optimal correction with barrel RH has a steep edge rise.
- Large ITM residual distortion (20 nm_{RMS}) also

Idealized residual distortion of ITM after TCS at 750 mW absorption



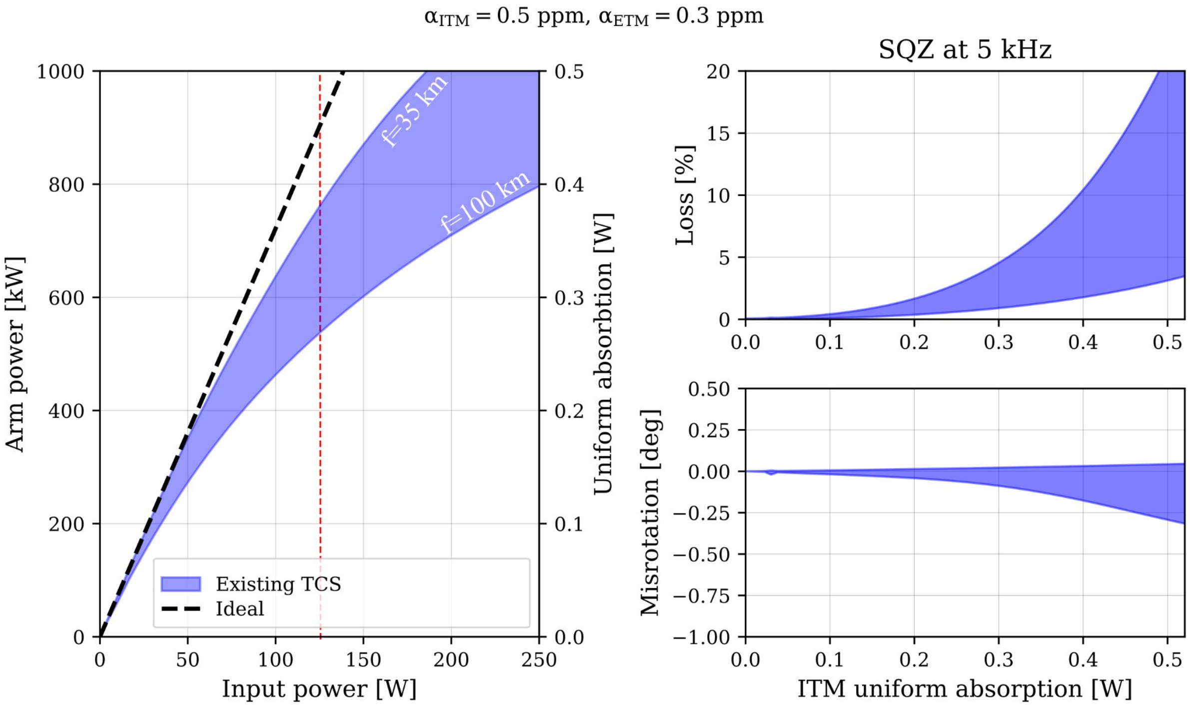
Motivation #2: Correcting High Levels of Uniform Absorption

- Distortion causes drop in PRG, and hence arm power

  → Can only achieve 750 kW with an ideal TCS

- Residual thermal lens causes **significant SQZ loss** at high frequencies (> 400 Hz)
  - **~5% at 1 kHz**
  - **~10% at 5 kHz**

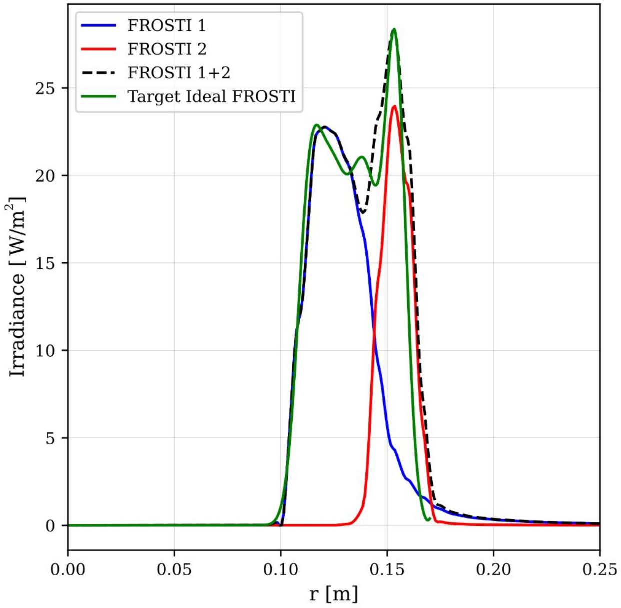
Performance of IFO with existing TCS (Ideal)



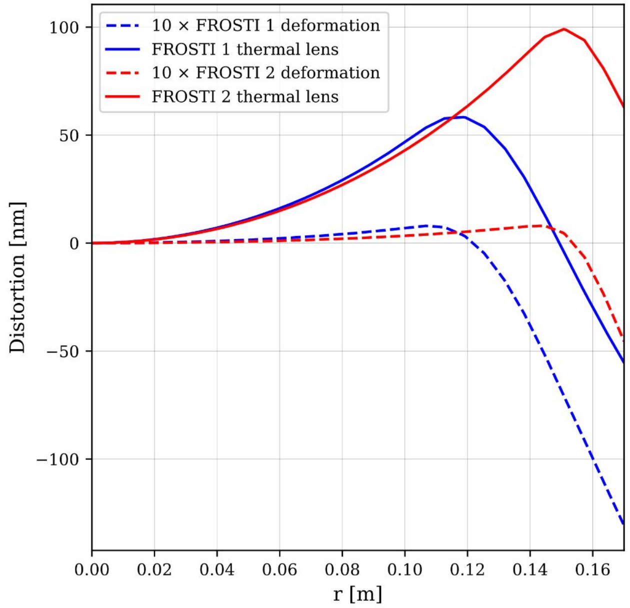
Optimization of FroSTI Profile

- Assume nominal aLIGO annular CO2 correction profile (P1600169)
- Use FEA to optimise test mass optical response to flatten out thermal lens + deformation across full aperture
  → green trace
- Construct optimal profile with two irradiance patterns from two FroSTI
- Inner FroSTI profile (blue trace) is sufficient to improve IFO performance

FroSTI optimised profile

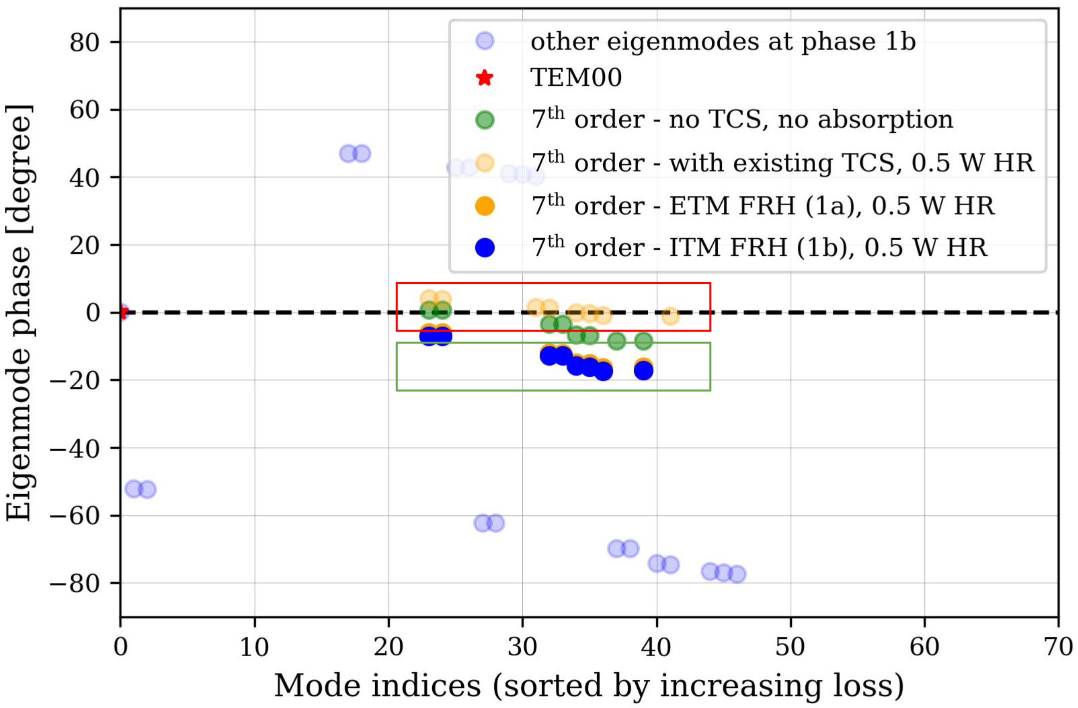


Opto-thermal response of test mass to FroSTI



Performance with FroSTI: Shifting of HOM7

- Simulation with existing test mass coating plume and optimised at 500 mW absorption shows FroSTI can **shift HOM7 by 8% of FSR (sufficient)**

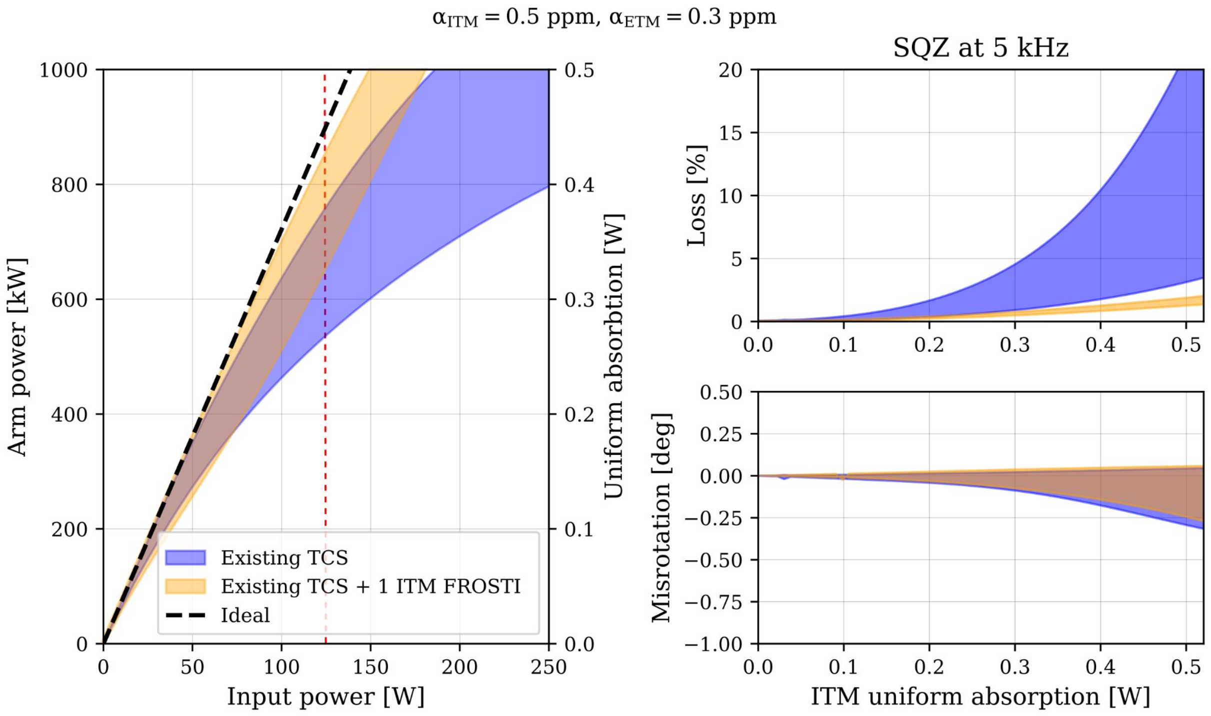


IFO Performance with Ideal FroSTI

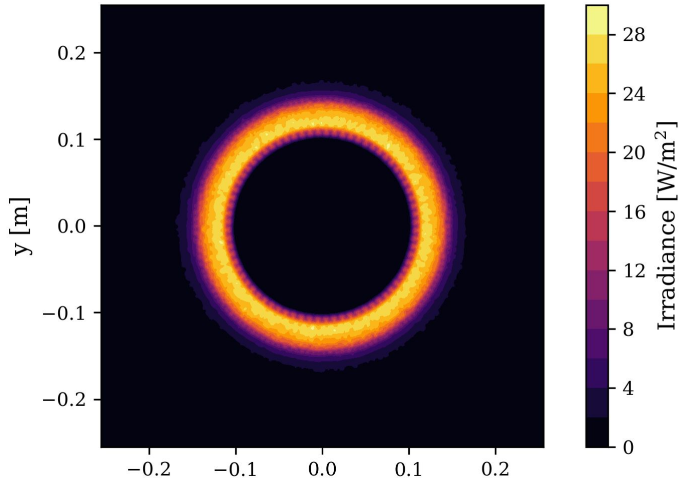
- Higher likelihood to achieve 750 kW at 125 W laser injection
- **Limits SQZ loss to better than 1% at 1 kHz**

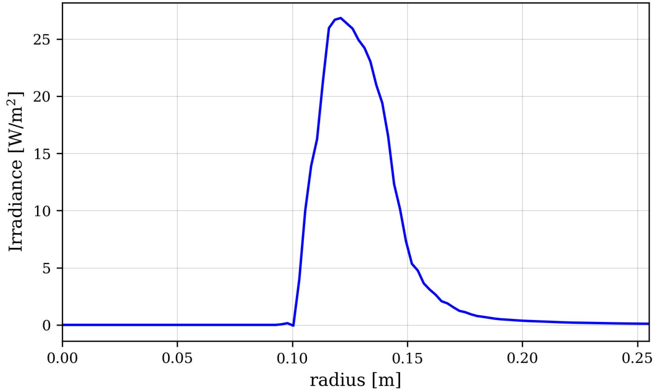
*Assuming ideal correction (uncertainty in sensing + actuation are yet to be taken into account)

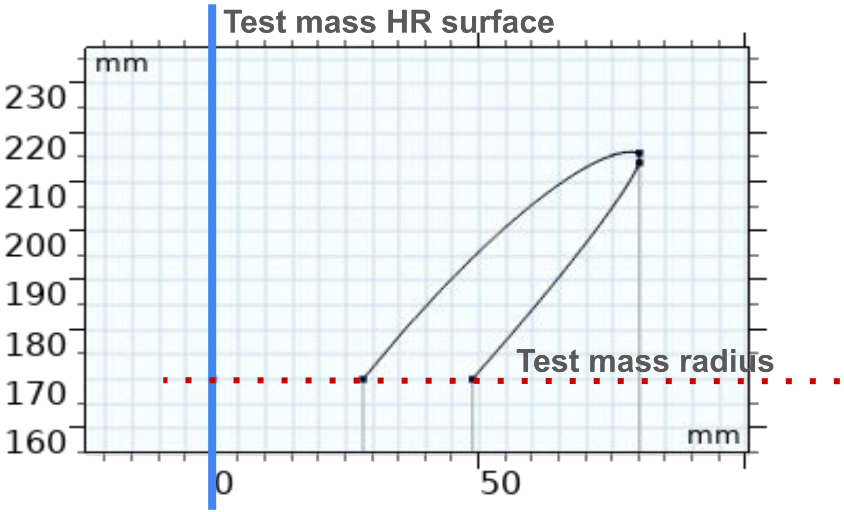
Performance of IFO with TCS + FroSTI (inner profile)



Generation of Target Heating Profile



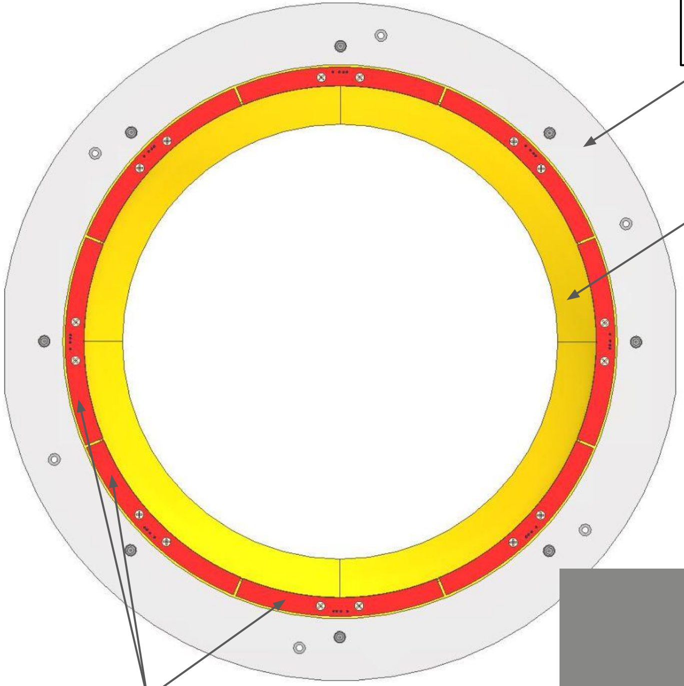


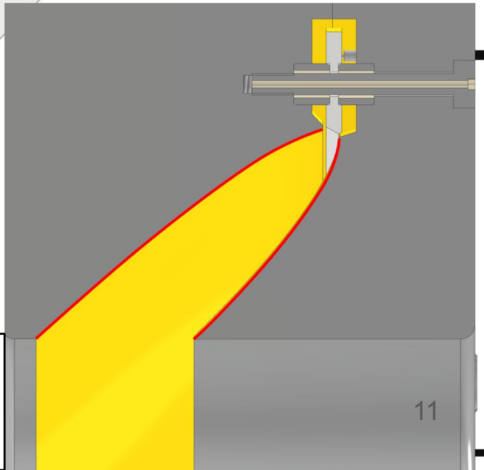


- Non-imaging optics using elliptical-surface reflectors to achieve target irradiation pattern
- Results verified with COMSOL ray tracing

Conceptual Design

- **Reflectors:**
    - Two halves machined from aluminium
    - Reflective surface produced with diamond-turning, gold coated
    - 340 mm ID, 520 mm OD
    - 30 kg mass, but will be reduced to 15 kg in future production
- **Heaters**:
    - 8 aluminium nitride elements
        - 2 mm x 15 mm x 162 mm
    - 2 mm separation gap between each heater
    - Integrated RTD to monitor temperature of each element

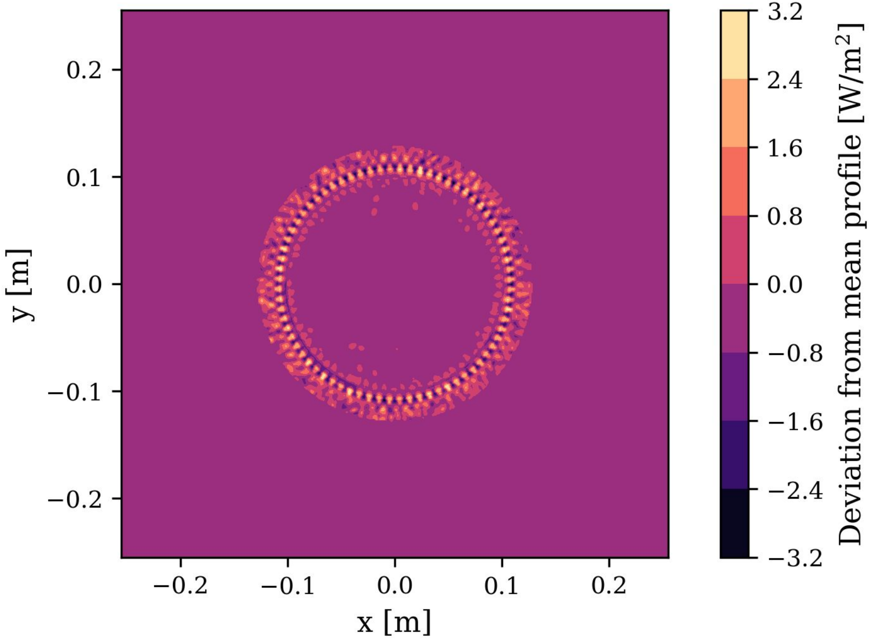




FroSTI Design Irradiance Uniformity

- Subtraction of mean profile shows approx. 1% of intensity fluctuation with spatial wavelengths between 8-9 mm (finite element ray tracing artifacts)
- Requires resistance of heater elements to be consistent within 8% across operating temperature range (G2201732)

Residual intensity after subtract mean irradiance

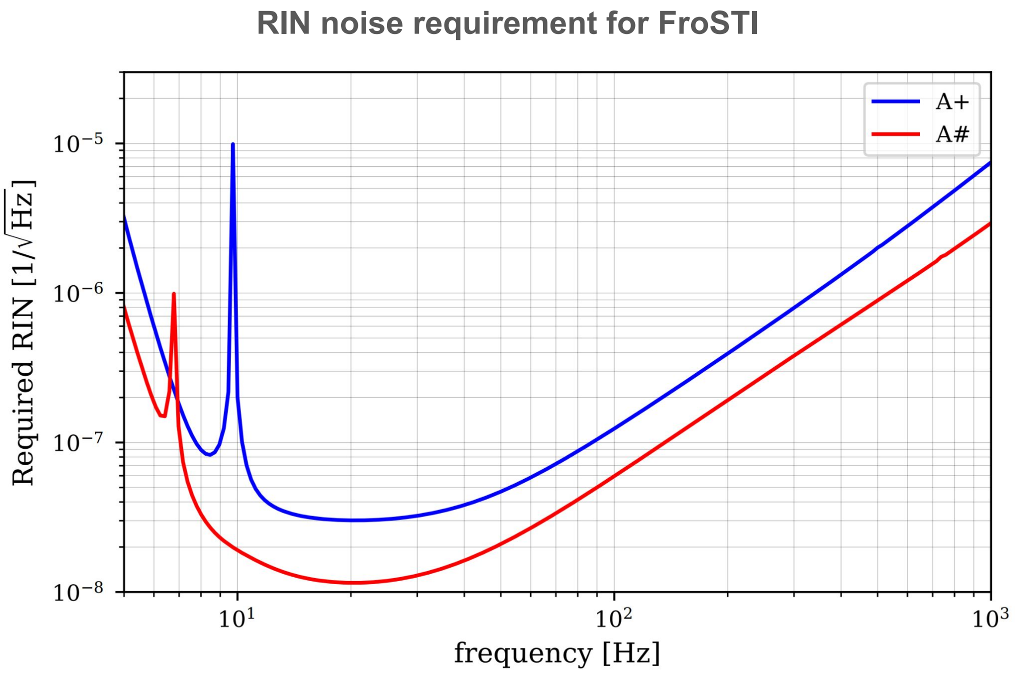


Displacement Noise Requirement

- FroSTI actuates on test mass HR surface → Flexure (bending) noise is the dominant displacement noise source (P060043, T060224):

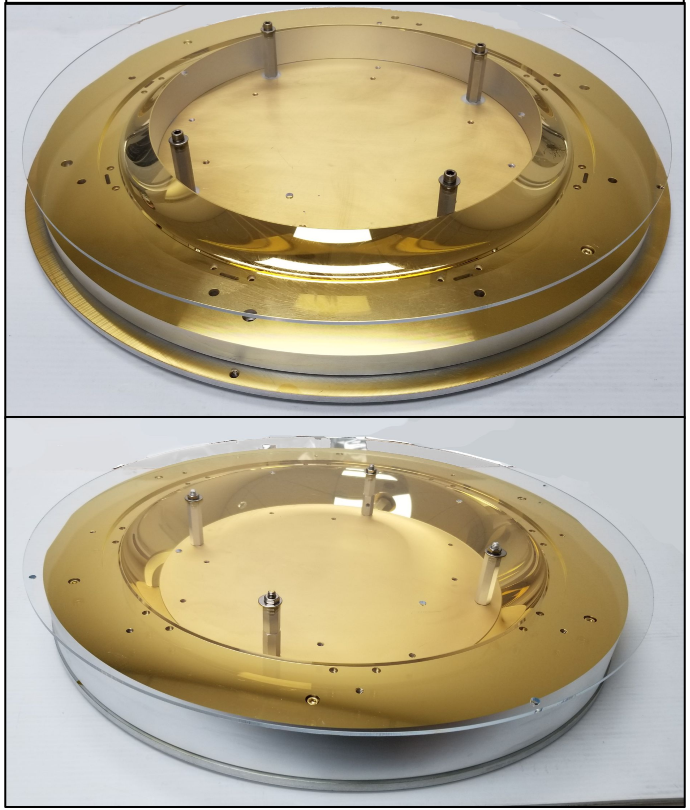
$$\Delta z_{\mathrm{F}} = \left(5.21 \times 10^{-14}[\mathrm{m}]\right) \frac{10[\mathrm{Hz}]}{f} \frac{P}{1[\mathrm{W}]} \mathrm{RIN}$$

- RIN is required to be 1e-8 [1/sqrt(Hz)] at ~ 20 Hz



Status of Prototype

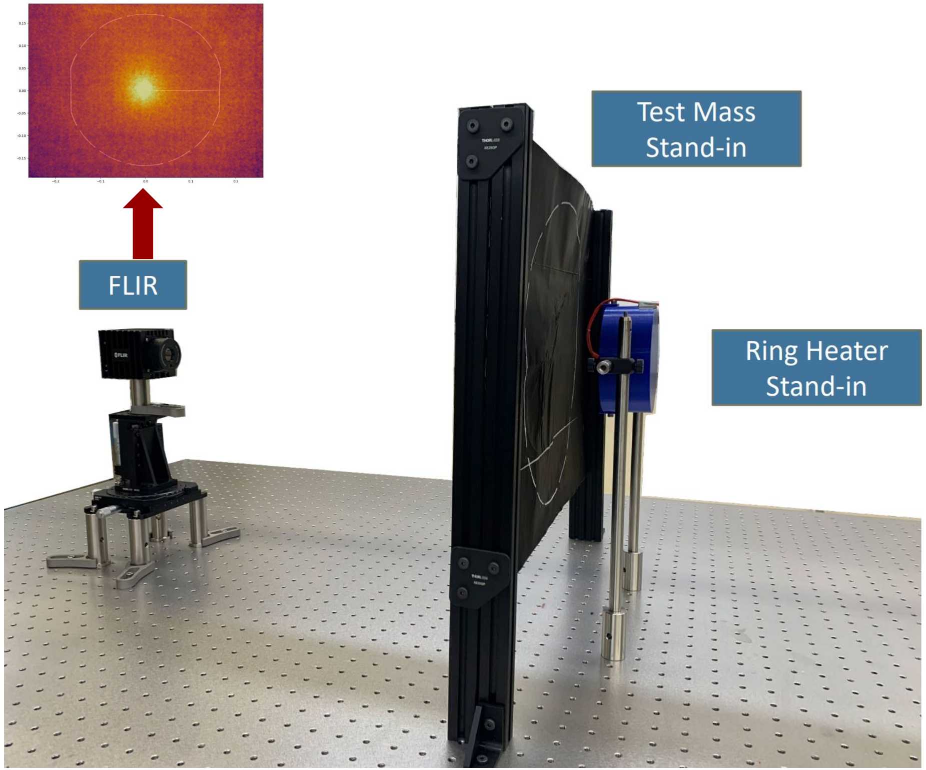
Reflectors



- **Reflectors**: Received
- **Heaters**: In production; expected to be received in April

Heaters

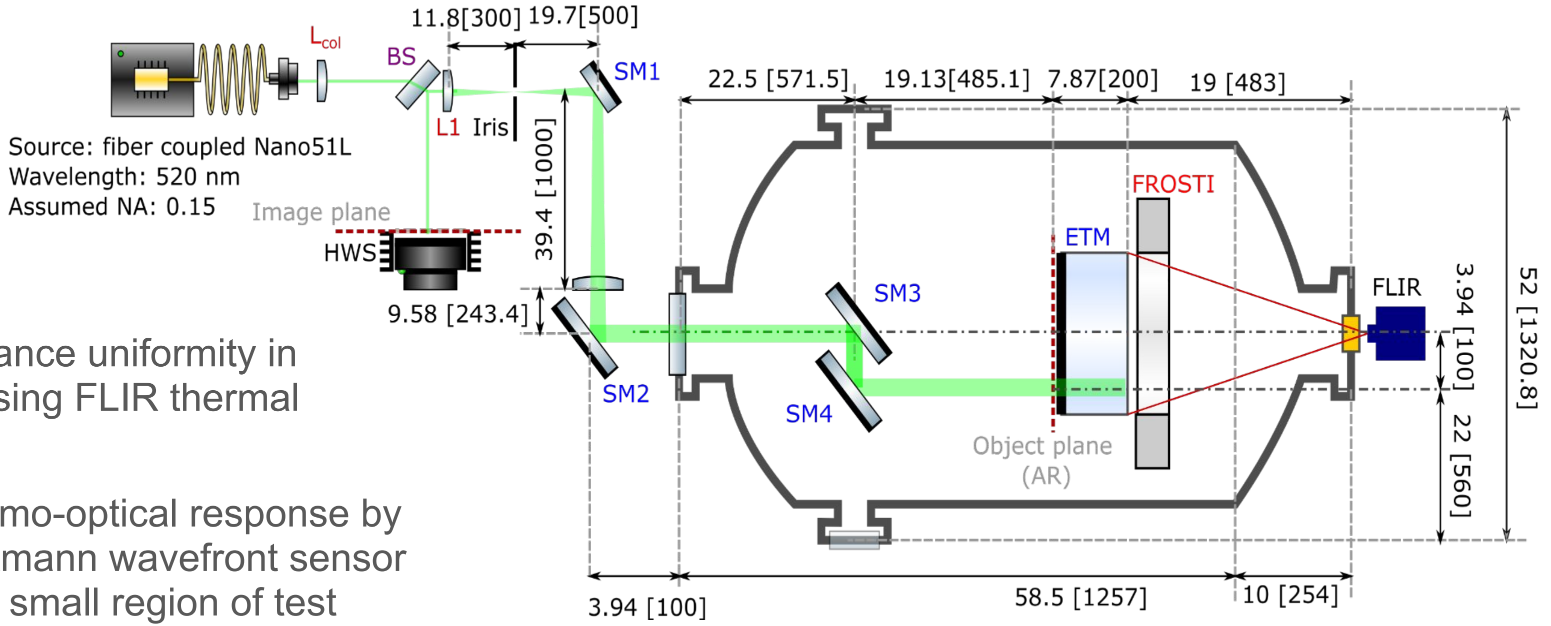
Testing Plan: (1) In-Air Test; (2) Vacuum Compatibility



In-air test setup for FroSTI prototypes (SURF report: T2200205, T2200206)

- In-air optical measurement of irradiance profile:
  - Using thermal camera to verify irradiance profile from FroSTI
  - Late April - May 2023
- UHV compatibility testing:
  - RGA outgassing measurements using calibrated Ar/He leak
  - May - June 2023

Testing Plan: (3) In-Vaccum Optical Test



Optical layout of FroSTI in-vacuum optical testing

- Test irradiance uniformity in vacuum using FLIR thermal camera
- Verify thermo-optical response by using Hartmann wavefront sensor to probe a small region of test mass
- Planned to be conducted in summer 2023 at CIT

Future Direction

- **A+ delivery:**
  - Target to deliver FroSTI for O5
  - Measure and quantify errors in FroSTI performance to provide a more accurate estimation of IFO performance improvement
- **O5 and beyond:**
  - Develop multi-element FroSTI actuator to compensate for non-uniform absorption effects at low spatial frequencies