Improving the Robustness of Next-Generation Wavefront Control: Analyzing FROSTI's Performance Against Beam Miscenterings

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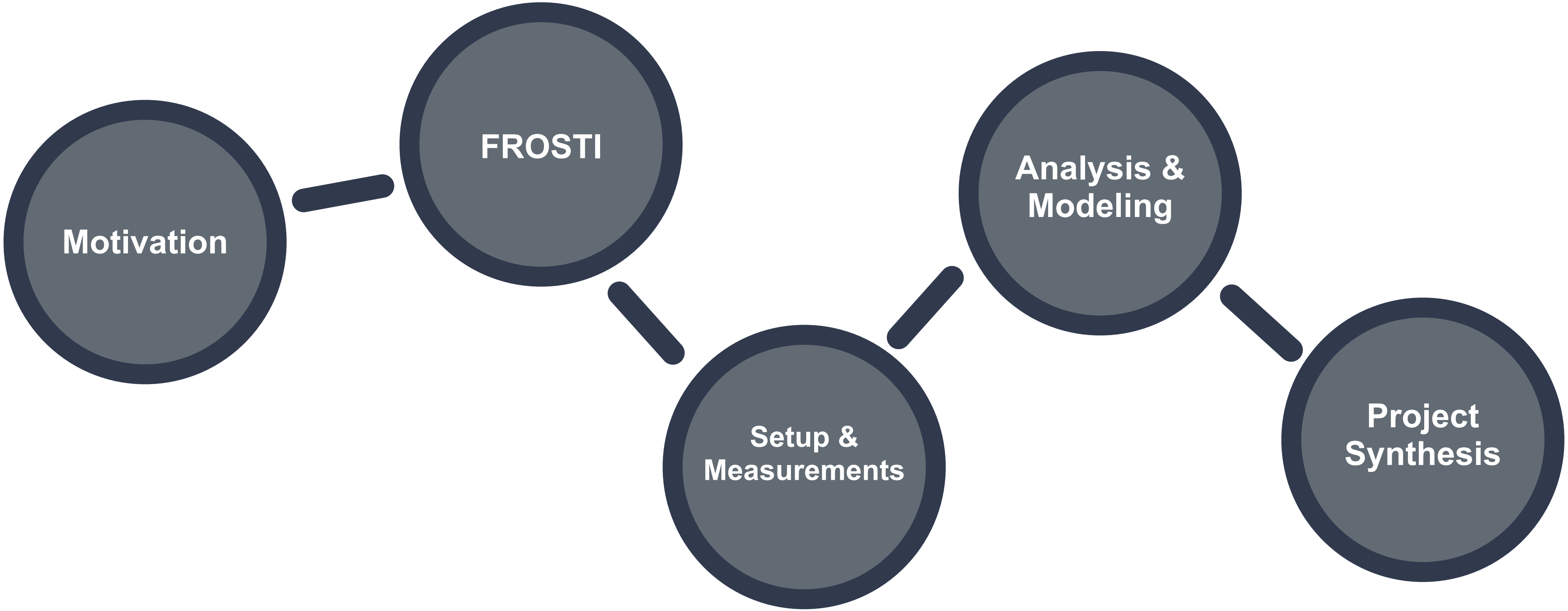
Presentation Outline



Motivation

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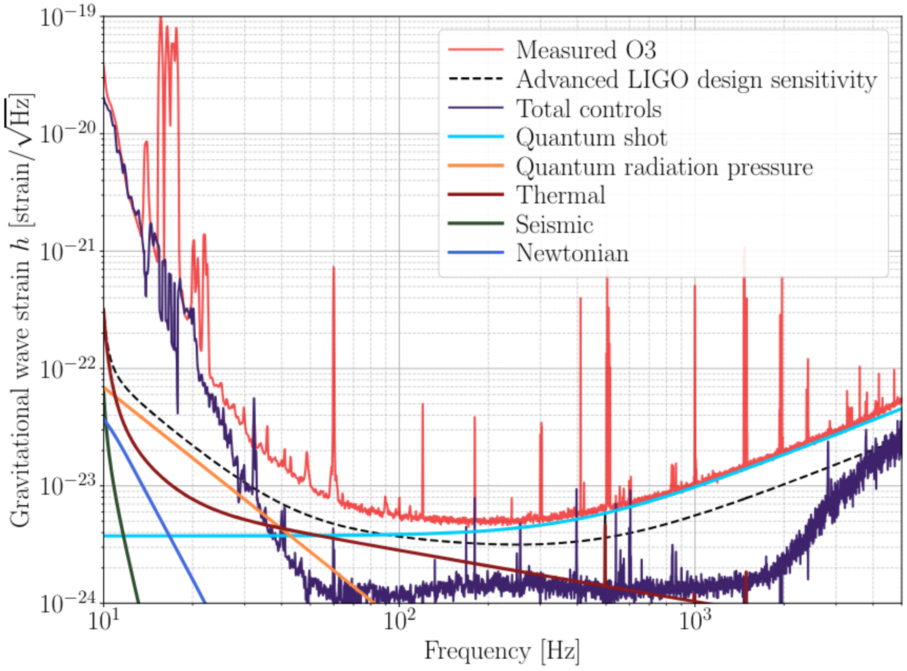
Quantum Shot Noise makes a significant contribution to the noise budget at higher frequencies (over 100 Hz)

Increased arm cavity power reduce this noise

Amplitude spectral density of shot noise scales as 1/sqrt(N) with N being number of photons

Therefore, higher laser power is required



Noise budget of O3 LIGO Hanford
(Cahillane & Mansell, arXiv:2202.00847v1 [gr-qc])

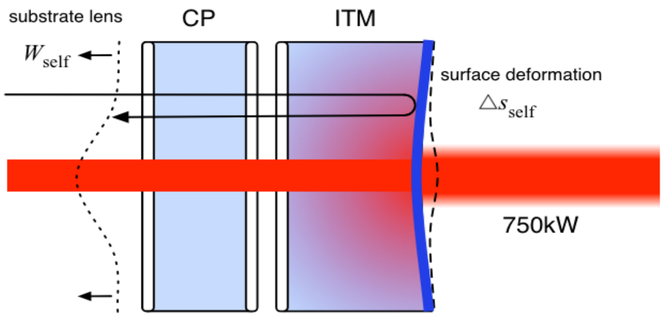
Motivation

Uniform coating absorption and point absorbers create loss of power

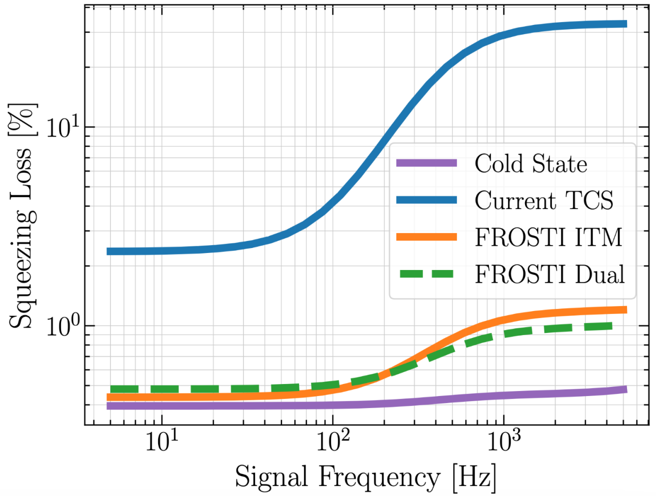
Thermal Compensation System (TCS) unable to fully compensate for uniform coating absorption in the future with greater arm power

Thermal aberrations cause mode mismatch between arm cavities and signal recycling cavity increasing squeezing loss

FROSTI helps return test mass to “cold state” lowering such losses



Thermal deformation of lens
(Brooks, arXiv:1608.02934 [physics.ins-det])

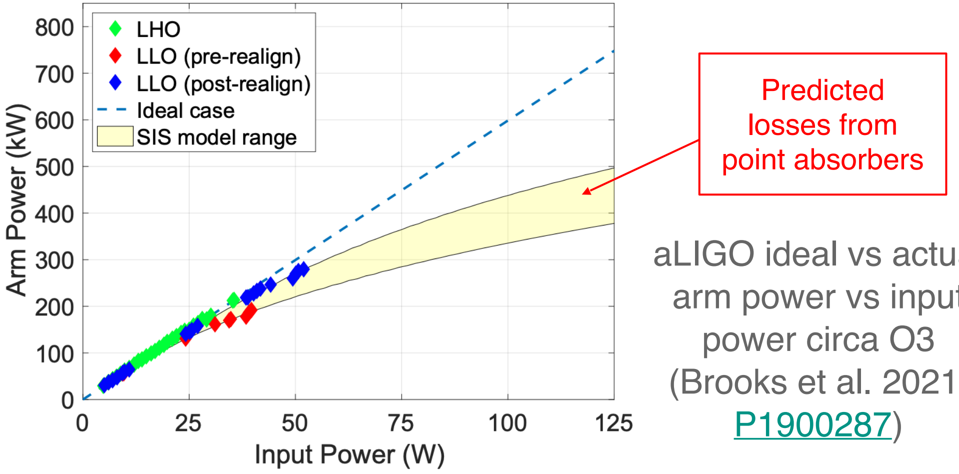


Squeezing loss comparison between just TCS and with FROSTI

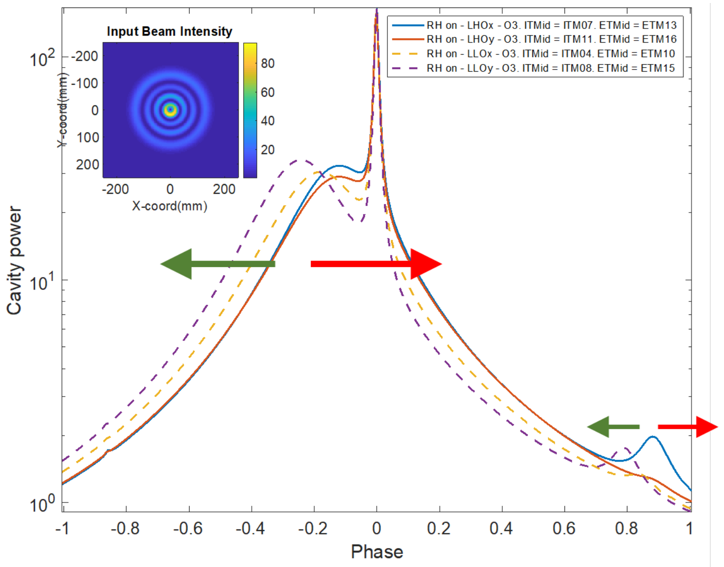
Effects of RHs on HOM Resonance Condition (G2101232)

Issue of point absorber has mostly been dealt with

FROSTI shifts seventh order modes away from resonance



aLIGO ideal vs actual arm power vs input power circa O3 (Brooks et al. 2021, P1900287)



Scattering into higher order modes shifts seventh order mode toward resonance (red arrow), FROSTI shifts it away (green arrow)

FROSTI (FROnt Surface Type Irradiator)

FROSTI

Next generation ring heater

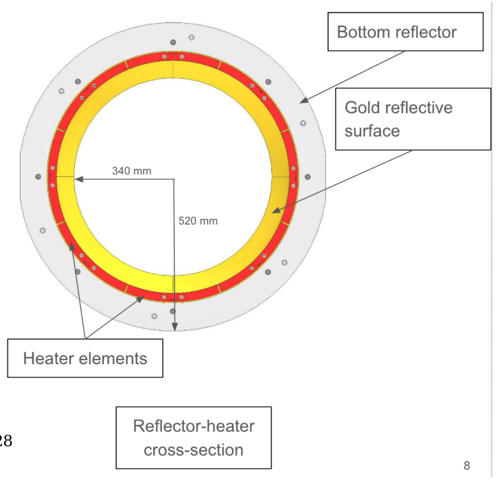
Annular ring heater placed 5cm in front of test mass

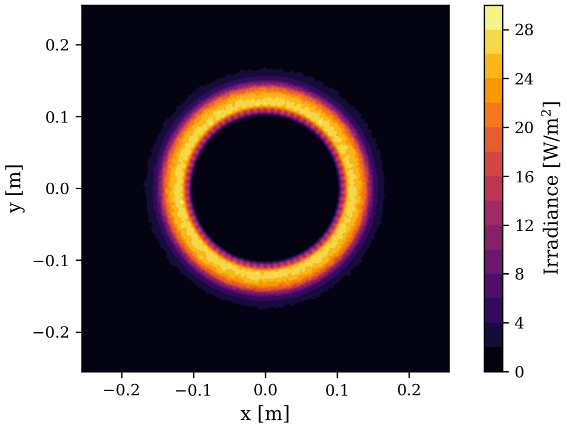
Shape based on nonimaging elliptical concentrators to maximize radiative transfer

Reflector component coated in gold film for maximum reflectivity

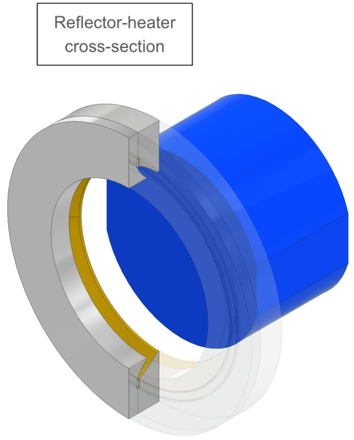
Eight individual heater elements oriented octagonally

FROSTI's components and structure (G2400546)



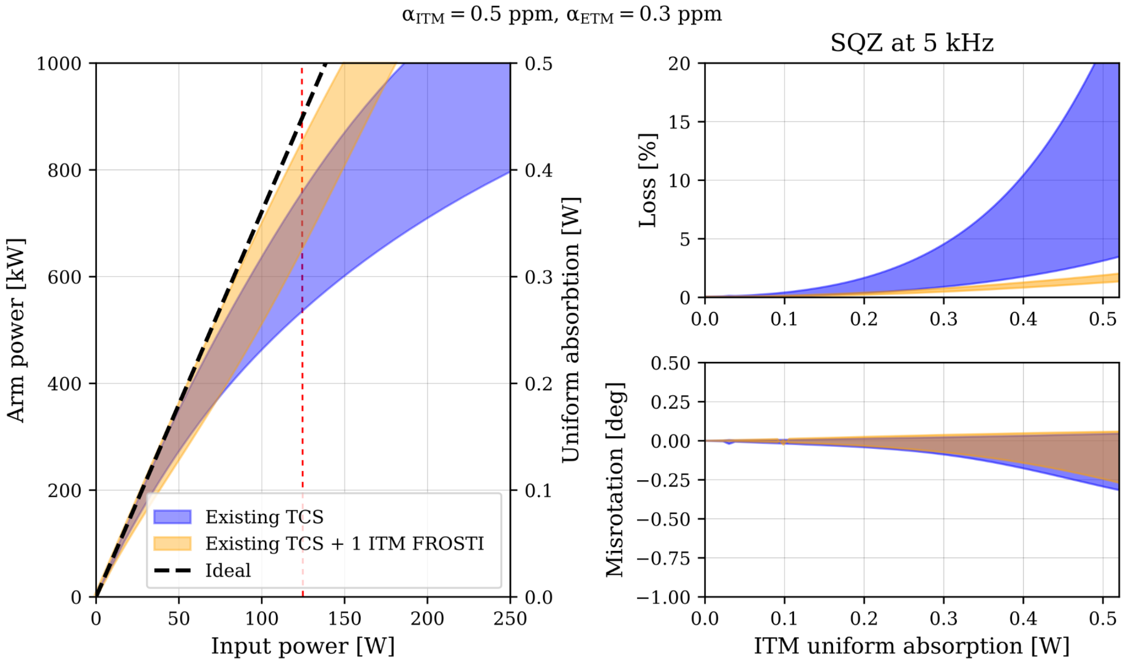


Profile FROSTI generates



FROSTI's placement relative to the test mass (blue)

FROSTI



Comparison of achievable arm power using just TCS vs TCS + FROSTI

FROSTI helps deal with squeezing loss in O5

Small power loss causes great squeezing loss due to nature of squeezed light

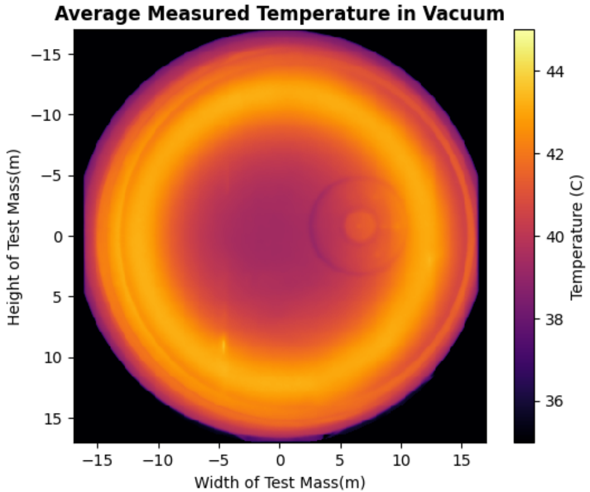
Also corrects thermal deformations and minimize higher-order scattering that limits power build up

A precise wavefront control technology that reduces power loss

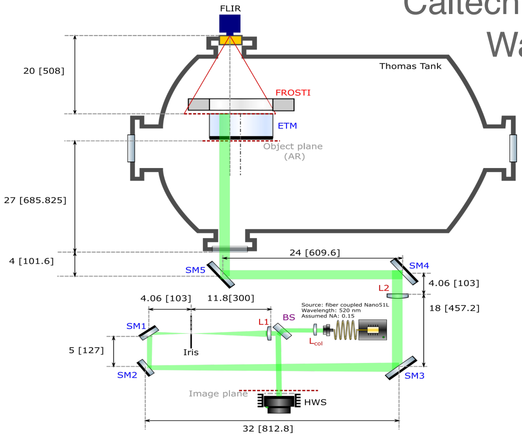
Initial in-vacuum tests have been conducted

Confirmed FROSTI's compatibility with LIGO environment and thermal profile measurement

Heater Elements in UCR Vacuum Chamber (G2400546)



Measured FROSTI thermal profile in-vacuum



Caltech Vacuum Chamber with Hartmann Wavefront Sensor (G2400546)

Objective

FROSTI performs well in idealized simulations with perfect beam centerings so how does it perform with realistic beam miscenterings?

Measure the sensitivity of FROSTI's corrections against static beam miscenterings

See if introducing more degrees of freedom (tuning individual heater elements) can compensate for the degradation in performance

One of the first times being able to use actual measured data from a completed FROSTI prototype

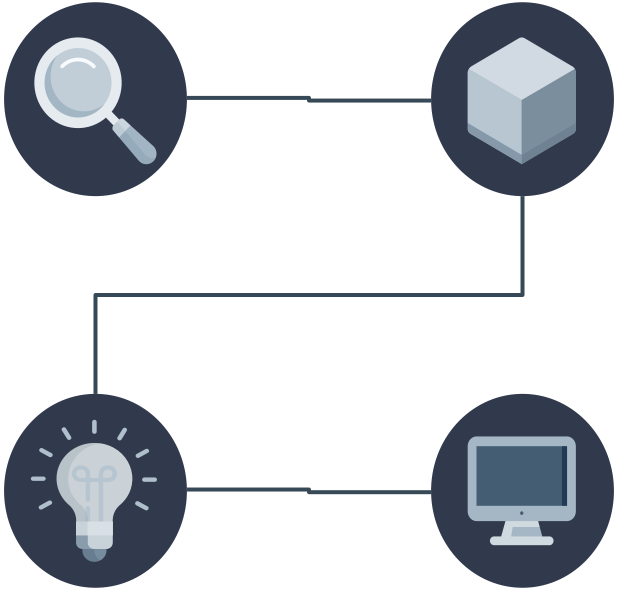
Implementation

Idealized Average Heating Profile

- FROSTI setup
- Take heater element measurements

COMSOL Model

- Construct blackbody screen model



Irradiance Profile

- Generate inferred irradiance profiles
- Use as input in COMSOL model

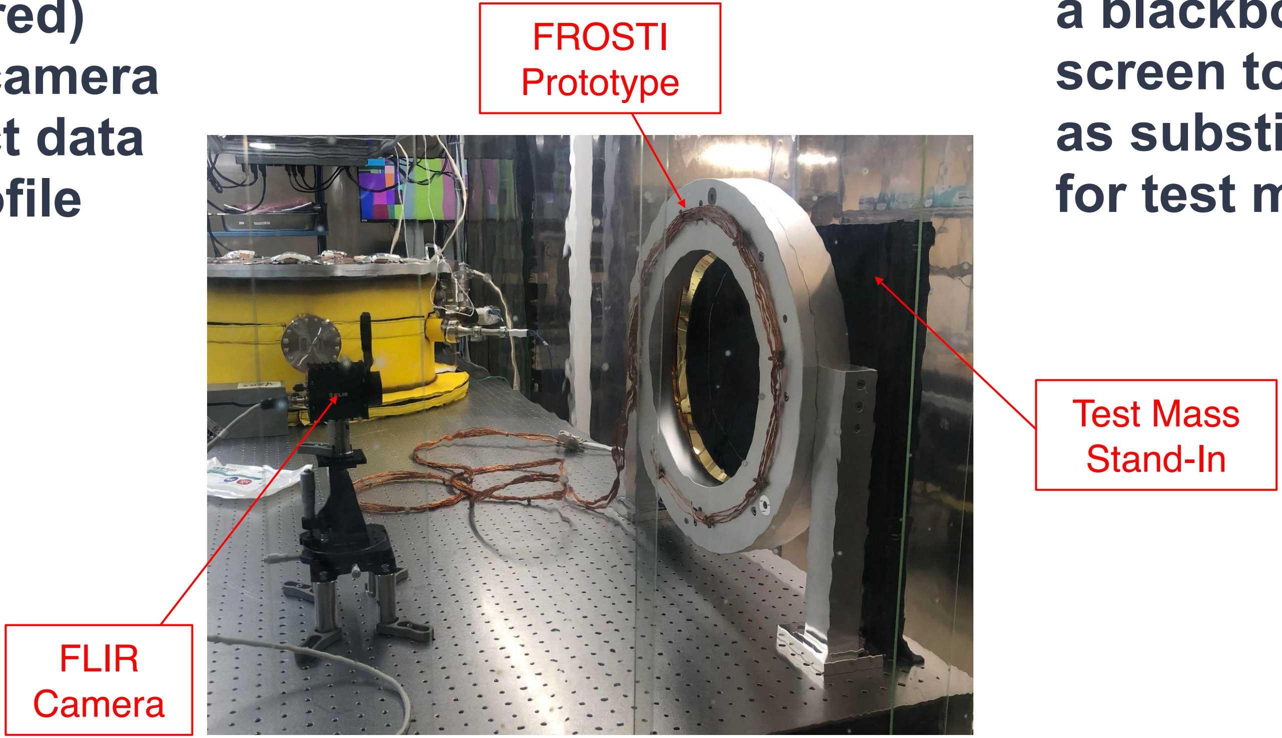
Finesse Model

- Create script to automate stabilizing thermal test mass and checking various beam miscenterings

Setup & Measurements

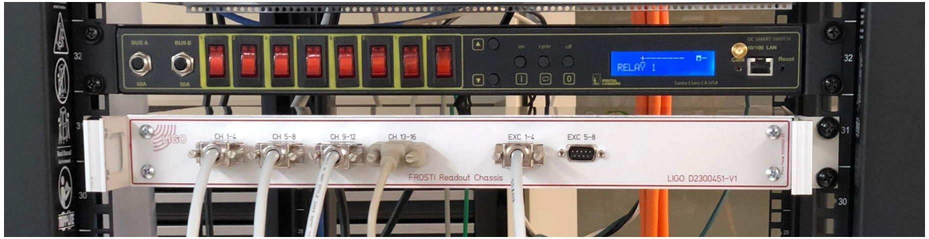
Optical System Setup

FLIR (Forward Looking Infrared) A70 infrared camera used to collect data of thermal profile



Setup utilized a blackbody screen to act as substitute for test mass

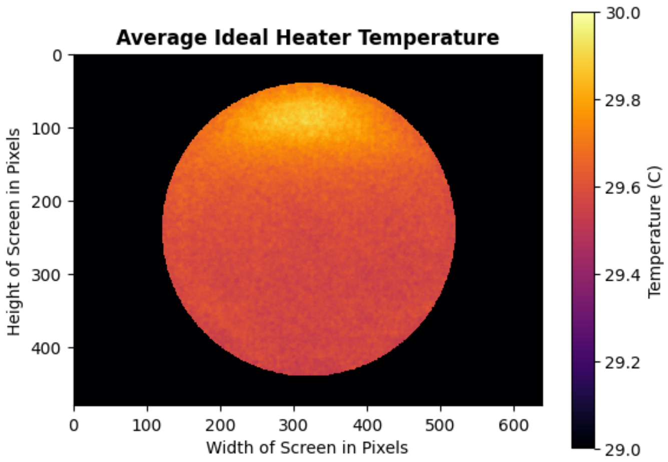
Measurements



Chassis connected to all eight elements and controls which ones are on and off

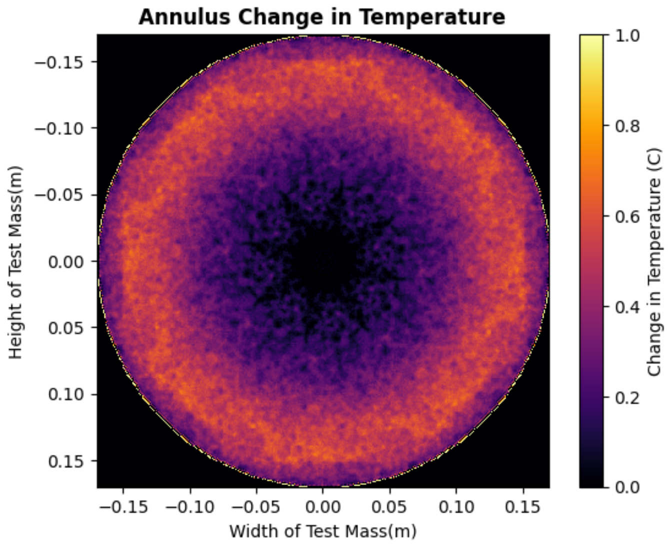
Steps

1. Turn element on, wait for it to reach steady state
2. Once at steady state, record temperature values
3. Turn element off, wait for it to cool considerably
4. Repeat 1-3 for the remaining 7 elements



Snapshots of each element selected, rotated and stacked on top of each other

Averaged out to single idealized heater element



Ideal heater element copied and rotated 8 times to produce annulus pattern

Averaged by taking mean sweep of central 10 pixels and subtracting from profile

Analysis & Modeling

Analysis

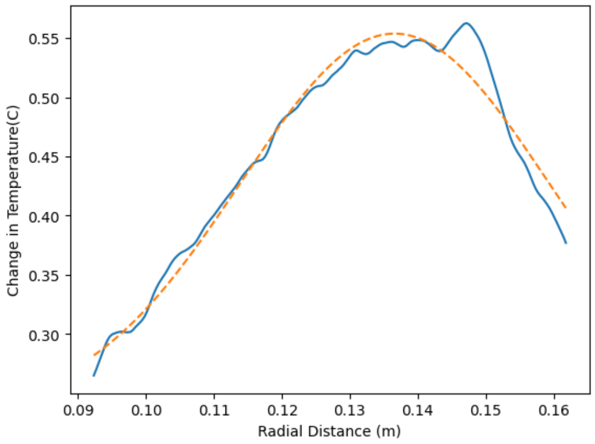
Irradiance profile needs to be inferred from measured ΔT profile

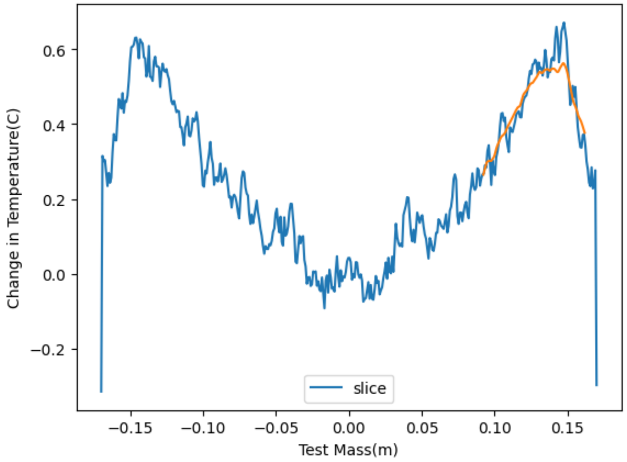
Need width and location

Gaussian fit on a 1D slice through x = 0 after integrating radially around the profile

Location found to be at 13.7cm with 4.53cm width

Gaussian fit on portion of ring slice

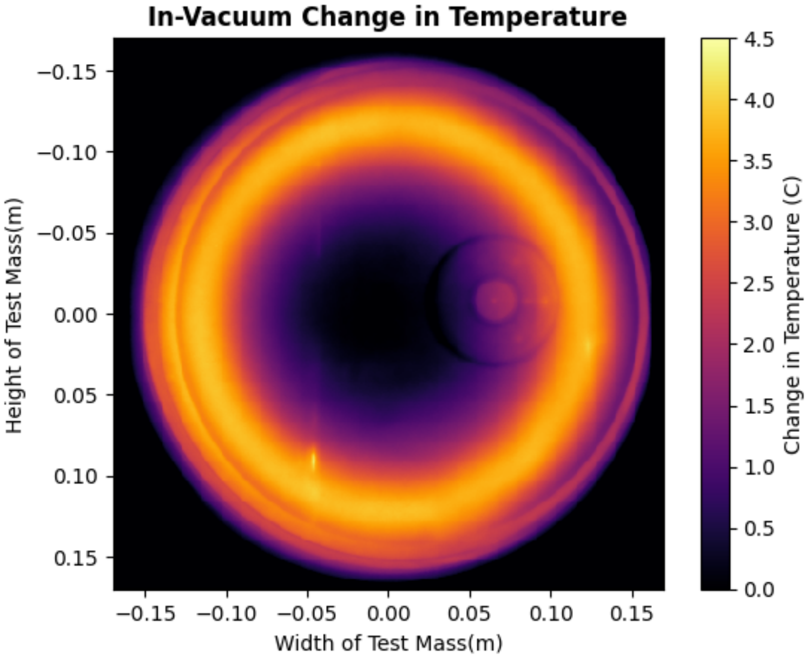




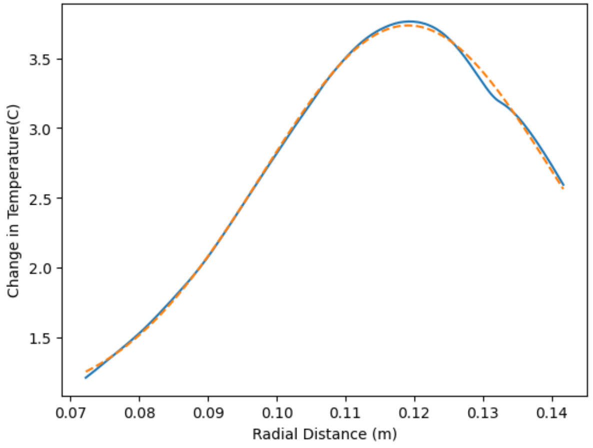
Central vertical slice of annulus w/ gaussian curve fit overlayed

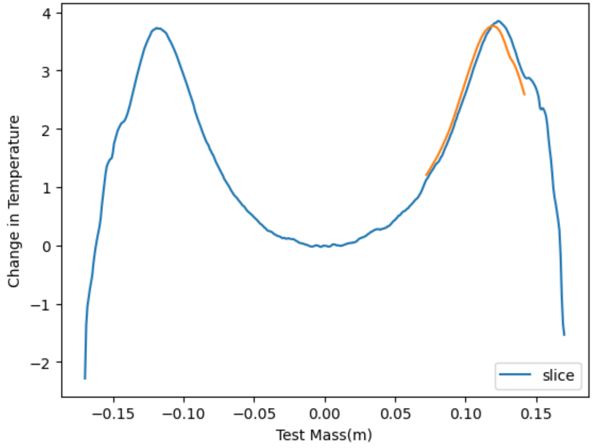
Comparison to in-vacuum profile and analysis

Location at 11.9cm from center with 4.1cm width



Gaussian fit on portion of ring slice





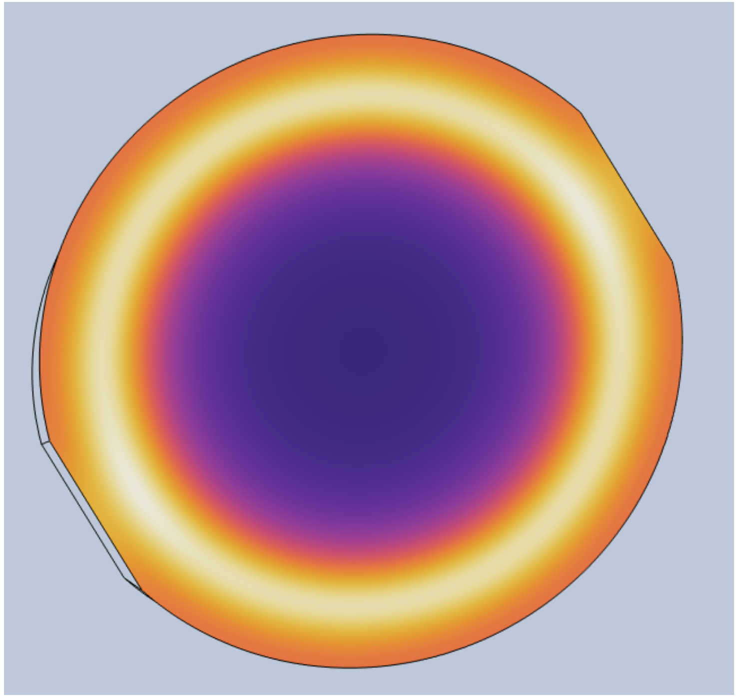
Central vertical slice of annulus w/ gaussian curve fit overlayed

Modeling

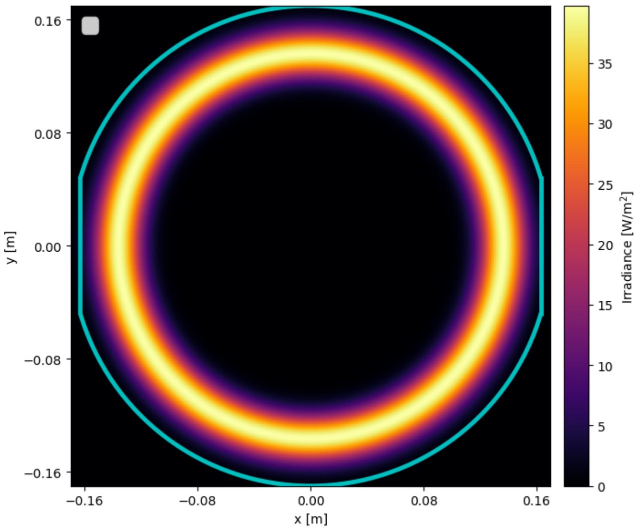
Built model of blackbody screen in COMSOL with shape of test mass

Consideration of convection through air included

Aside from the coating emissivity ($\varepsilon = 0.99$), the thermal properties of the screen are that of the aluminum substrate



COMSOL model with thermal profile



Generated irradiance profile with temperature change output most resembling measured profile

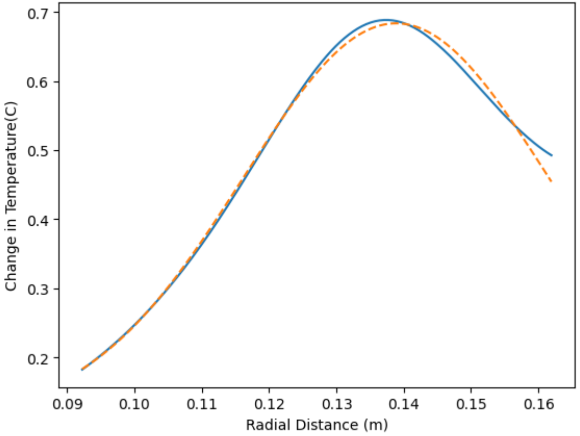
Thermal properties and air convection resulted in different irradiance and temperature widths (unlike in-vacuum on fused silica), location was the same

Inferred irradiance profiles generated in Python

Tested irradiance profiles with various widths as input for COMSOL model and applied gaussian fit

Irradiance profile with temperature change profile output most resembling measured temperature change was 2.33cm in width

Gaussian fit on change in temperature profile produced by most fitting irradiance profile



Finesse

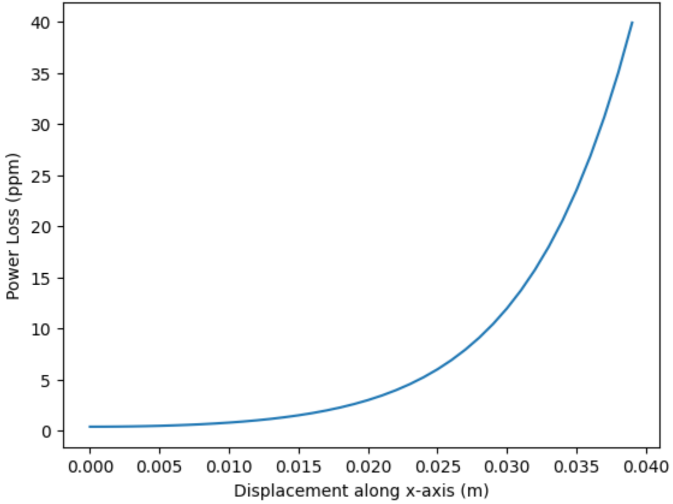
Displace beam along only one axis to simulate beam miscenterings

Limit range of beam displacement

Only focused on ETM (End Test Mass)

Loss in ETM is 30 ppm making 3.6cm maximum displacement

Similar process has been done for ITM (Input Test Mass) with a similar graph result



Graph of Power Loss vs Displacement of ETM

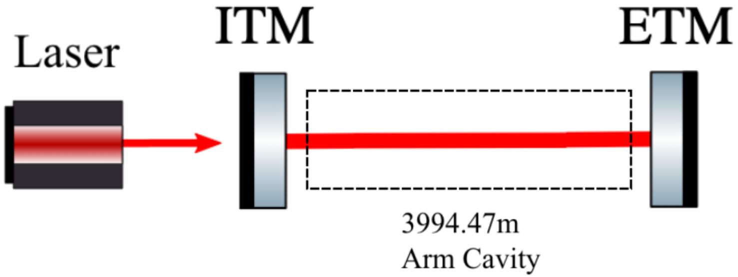


Diagram of Simple Arm Cavity Finesse Model

Finesse

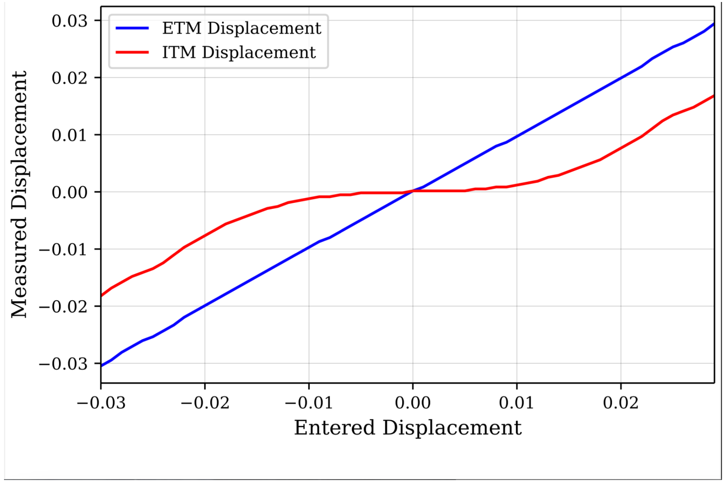
Inverse matrix done to get mirror tilts in terms of beam displacement for Finesse model

At higher displacements, ITM deviates from the expected value of 0

Range of beam displacement to simulate lowered to -1 cm to 1 cm due to this matching closer to expected realistic beam displacements

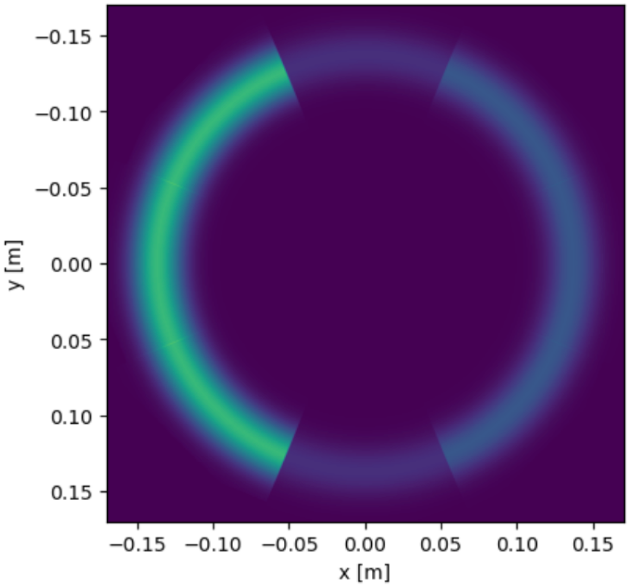
$$\Delta x_1 = \frac{g_2}{1 - g_1 g_2} L \cdot \theta_1 - \frac{1}{1 - g_1 g_2} L \cdot \theta_2$$
$$\Delta x_2 = \frac{1}{1 - g_1 g_2} L \cdot \theta_1 - \frac{g_1}{1 - g_1 g_2} L \cdot \theta_2$$

Relation between beam displacements and mirror tilts



Relationship of entered vs measured beam displacement on ETM and ITM in Finesse model

Project Synthesis

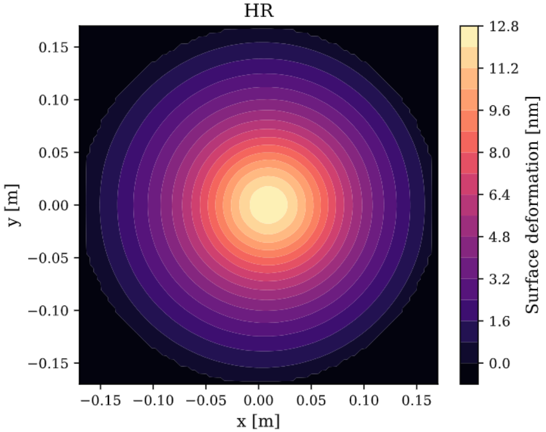


3 regions with left three elements increased by a factor of 5, right three elements increased by a factor of 2, and top and bottom at original power

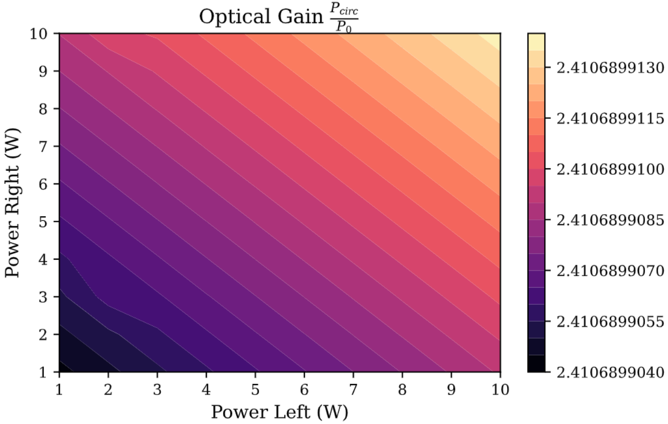
Utilizing Finesse and Fenics, script to test various configurations of elements with different power coefficients against different displacement values has been created

Code can be optimized further and automated but this is a start

Relationship between optimal configuration and beam displacement can be likely discerned with further analysis and measurements



A phase map with 1cm displacement generated with Fenics



Summary

Big step into characterizing how much degradation occurs

Focus on realistic performance and not just simulated perfect beam is necessary

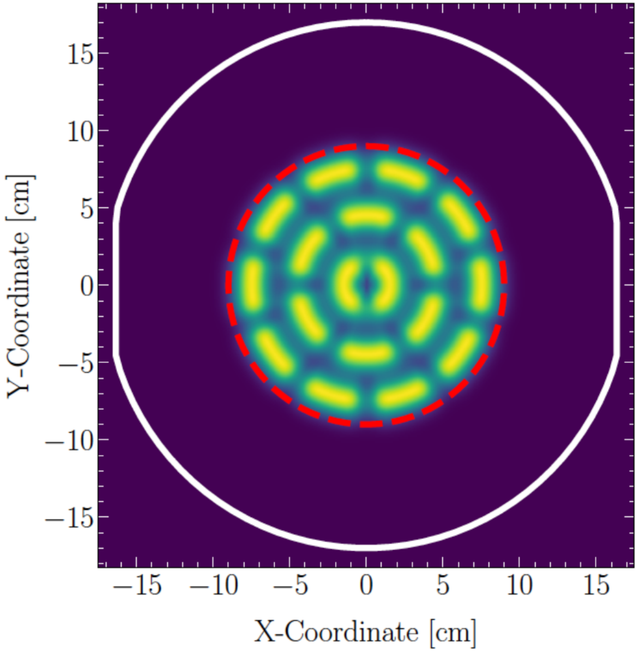
Constructed COMSOL model can be used for future in-air measurements

Gathered data on individual heater elements useful for future projects requiring them

Process created will provide a way to test various displacements and individual element tunings

Can provide insight on how future FROSTI prototypes should be constructed including a potential multi-element FROSTI for non-uniform absorption effects

Multi-Element FroSTI Concept



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