LIGO Hanford Observatory
LIGO SURF 2023
LIGO-T2300318-v1

Analyzing LIGO Ring Heaters: Investigating Electrical Shorting, Troubleshooting Mechanical Failures, and Modeling Future Designs

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1 | Abstract

LIGO interferometers use frequency and amplitude-stabilized lasers that are reflected using test masses (large, cylindrical mirrors) to detect gravitational waves. Because the laser light is stored in optical cavities within the interferometer, the test masses heat up. This physically deforms the surface of the mirror and modifies the index of refraction of the optic. Physical deformation causes the test masses to not reflect the laser optimally and the interferometer will not function at its highest sensitivity. Ring heaters are coils that heat the outside of a test mass through resistance to counteract this effect and allow us to control the deformation of the test mass surface. Our objective is to modify the current ring heater design and develop improvements to be implemented in future ring heaters. We accomplish this by troubleshooting issues in the current design, comparing designs between versions, and modeling different designs in COMSOL. We have built spare ring heaters, identified causes of grounding issues and weaknesses in the current design, successfully modeled how differently sized heating elements heat the test mass, and compared their effectiveness to the current design. With these results, we are now able to avoid grounding problems observed at other LIGO locations, as well as improve the ring heater design for future use.

2 | Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) consists of a pair of 4 km long arms set at a 90° angle from one another. LIGO's first gravitational wave discovery was in 2015 when it first detected gravitational waves from the collision of two black holes [1]. This was the first time that a binary black-hole merger was observed. As of observing run 3 (O3), LIGO has successfully detected 98 significant events. LIGO is currently in observing run 4 (O4) and has detected 29 gravitational wave candidates as of August 14, 2023.

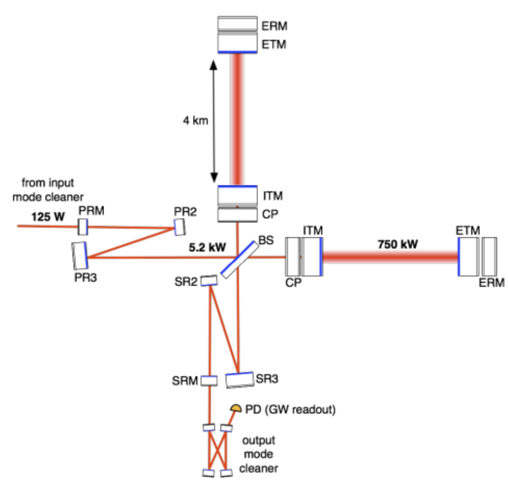

Figure 1: A simplified diagram of the interferometer. The Y arm goes in the y direction (vertically), while the X arm goes in the x direction (horizontally) [2].

LIGO detects gravitational waves by measuring the differential change in the arms through measuring how the distance between the test masses changes. The test masses are large, fused silica mirrors that are .2 m thick with a radius of .17 m at both ends of each 4 km-long arm which forms the optical cavities. These mirrors reflect a highly powerful infrared laser (roughly 400kW inside the arms). There are four test masses in total, two end test masses (ETMs) and two input test masses (ITMs) *(Fig 1).*

When a gravitational wave passes through the interferometer, spacetime distorts and the distance between the test masses changes. This distortion changes the relative lengths of the two interferometer arms, delaying the arrival of a wavefront in one arm from that of a wavefront in the other arm. The resulting destructive interference is what indicates a gravitational wave has passed through. Laser light is stored in the arms of the interferometer. Because these lasers are so powerful, some power is absorbed in the test masses and the surface of the test mass deforms. Once they deform, their index of refraction changes, and they don’t reflect the laser wavefront optimally. When the wavefronts don’t match up it causes noise. Noise causes the interferometer to be less sensitive to incoming gravitational waves, so unnecessary noise is strictly avoided. The purpose of the ring heater is to counteract this deformation and allow us to control the test masses’ indices of refraction. The ring heaters are integral to the interferometer’s functions and would not work optimally without them.

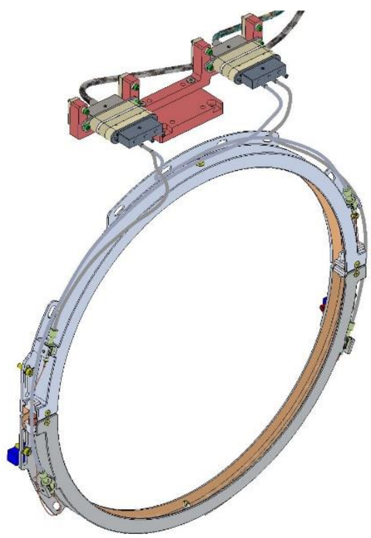

Figure 2: Image of both halves of the ring heater together with the wires attached [3].

The ring heaters are arch-shaped coils that heat the outside of the test mass through resistance *(Fig 2).* The outer metal shield is made from an aluminum alloy with the inside painted gold to reflect the heat back onto the test mass. The heating element is a nichrome wire wrapped around a glass former. This glass also acts as an insulator *(Fig 3).* At the ends of the heating element are the end pieces. The main component of this structure is a ceramic macor retainer. This structure also acts as an insulator *(Fig 4).* The nichrome wire from the heating element is fed into the retainer and connected to the external wires by a copper clamp. Lastly, in order to keep the heating element from touching the metal shield and grounding the circuit, there is a structure called the midspring in the center of the shield to keep the heating element from touching the metal shield and grounding the circuit *(Fig 5).*

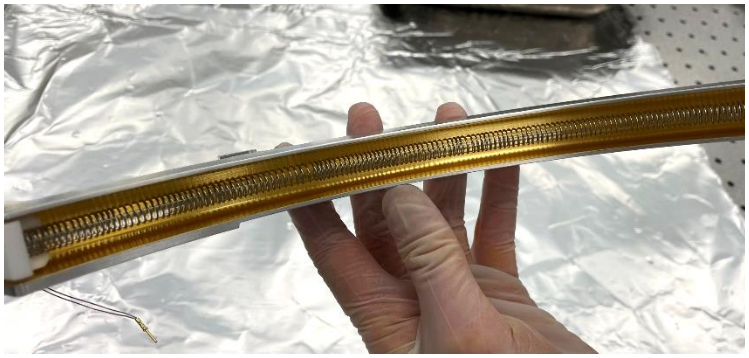

Figure 3: Image of the inside of one half of the ring heater. The heating element and gold painted interior of the shield are visible.

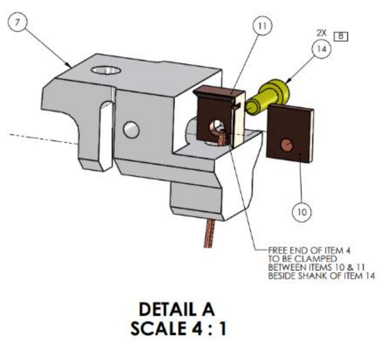

Figure 4: Image of one of the end pieces. The white structure is the ceramic macor retainer and the brown structures are the copper clamps [4].

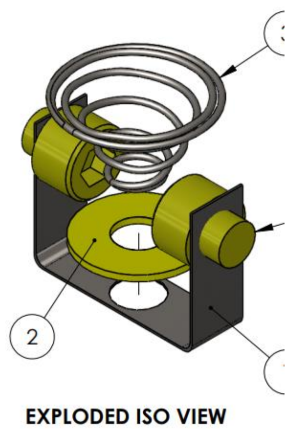

Figure 5: Image of the midspring. The yellow structures are made of ceramic, while the grey is made of metal [5].

Before the summer began, LIGO Hanford (LHO) had no spare ring heaters. The first goal was to remedy this problem and build more spares. The second goal was to assess some mechanical failures that arose while constructing these spares. Lastly, the third goal was to model a potential future ring heater design in COMSOL Multiphysics to potentially be implemented after observing run 5 (O5). By working towards these goals, we determined that there are multiple ways in which the ring heaters can be assembled incorrectly and that an 8-sided ring heater design could theoretically be just as effective as the current design. This paper will discuss these three goals, the results of these projects, and the implications they may have for the future of the ring heaters and LIGO in general.

3 | Methods

3.1 | Assembling Spare Ring Heaters

The main goal for the project was to create four spare ring heaters since there previously were none at LHO. We accomplished this by following the assembly drawings and instructions. There were two components that needed to be updated in this process: the midspring and the copper clamps. The copper clamps had an entirely new design for the most up-to-date version of the ring heaters, and the midspring itself is a new addition to this latest version. The old version of the midspring, called the midspan, was a simple arch-shaped piece of ceramic held in by a set screw *(Fig 7)*, whereas the midspring is held in by a ceramic screw and two or three ceramic washers *(Fig 6)*. All the new spare assemblies and changes were documented in various travelers and were submitted to the Document Control Center for wider use within the LIGO Scientific Collaboration.

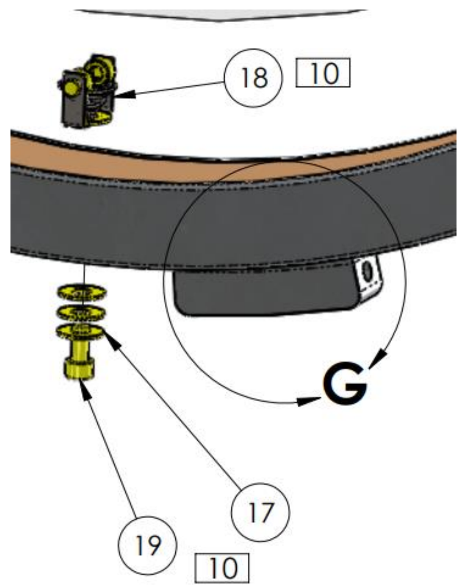

Figure 6: Image of the midspring (left) and the temperature sensor (right, labeled "G"). Item 18 is the midspring structure, while items 19 and 17 are the ceramic screw and washers respectively [4].

3.2 | Troubleshooting and Ameliorating Mechanical Failures

The features of the ring heater that we dealt with are the temperature sensor, ceramic retainers, and the copper clamps. The latter two components were the subject of investigations into potential grounding hazards.

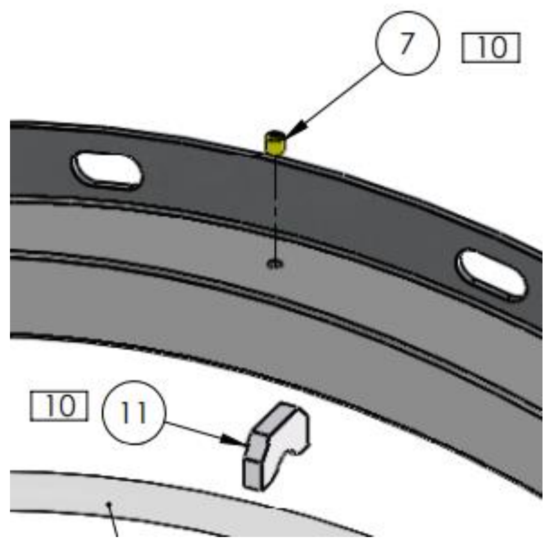

Figure 7: Image of the midspring's predecessor, the midspan. Item 11 is the midspan itself and item 7 is the metal set screw [6].

3.2.1 | The Temperature Sensors

These temperature sensors measure the temperature of the ring heater through contact with the metal shield. The sensor works via a probe that is inserted into a metal block on the lower frame of the ring heater *(Fig 6)*. This metal block is part of the frame, so its temperature changes with the ring heater. Having this metric would be extremely useful to determine how well the ring heater is working, however only one out of the four temperature sensors on the installed ring heaters works. And unfortunately, that temperature sensor has fallen out and only measures the ambient temperature of the vacuum.

The main problem with the temperature sensors is that the probe is flimsy, and the cable can break very easily. It is not secured into the metal block well, only held there by ceramic glue because standard glue cannot go into the vacuum. However, this glue is insufficient for maintaining the probe's position. Any potential movement of the quad could cause it to fall out.

There are specific materials that can and cannot go into the vacuum, so this had to be considered when looking for a new temperature sensor. We found multiple different products that either could work themselves or could be used to brainstorm a custom design. Infrared sensors were discussed due to the ease of not having to have the sensor touch the ring heater, however, these could introduce extraneous noise into the interferometer, so further investigation into this would be required for it to be considered. We also found sensors that function through physical contact. These could be mounted on the quad frame to touch the ring heater, but many of these products were not all vacuum compatible. Lastly, we found a different version of the sensor that the ring heaters currently use. This one has a larger radius, so this could theoretically fix the issue of falling out of the hole. Less glue can be used, and it could fit more snugly in the metal block.

All these options and ideas were recorded and then sent to the Lead Detector Engineer at LHO for further evaluation.

3.2.2 | Grounding Investigations

There have been many issues in recent years with the ring heaters grounding for various reasons. In addition, nearly every instance of these shorts appears to have different causes.

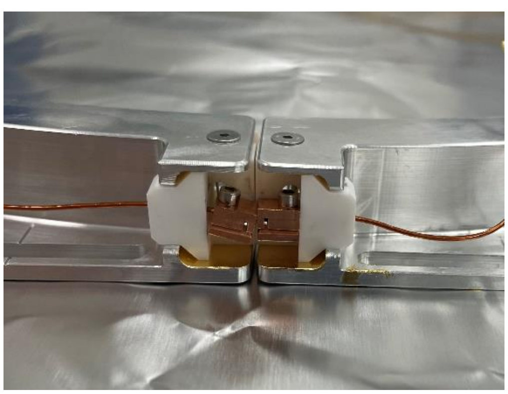

Figure 8: Example of how the copper clamps can touch.

Figure 9: Image from LHO alog 12229 [8] that shows how the close the copper pieces are when the RH is installed, and they've been built correctly

One cause was the copper clamps. The clamps are made in a way that they have two jobs: holding the nichrome wire from the heating element and the copper wire together simultaneously. This makes it easy for the wires to be loose or misaligned, and if the wires are internally misaligned, the clamp itself can be lopsided *(Fig 8)*. Because, when they are installed onto the quad, the clamps are very close to one another *(Fig 9)*, so the clamps being lopsided could potentially cause them to touch which, because the electrical wires run through them, could cause a short [7].

To avoid this, when building ring heaters, one must take care to make sure that the clamps are flush with the ceramic retainer. The nichrome wire must also be as straight as possible before assembling the copper clamps. If they are not, then the same problem can occur because the clamps are only attached to the ceramic retainer by those wires.

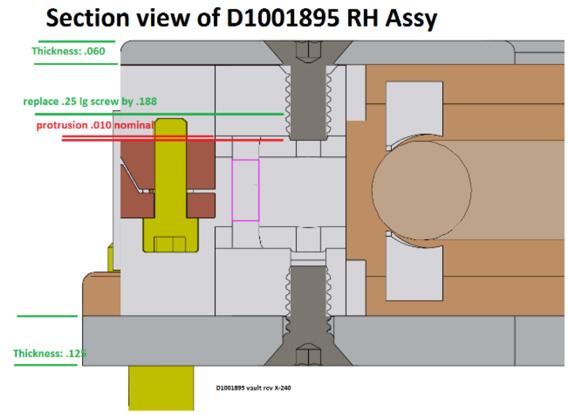

Figure 10: Image from FRS Ticket 4552 [9] that shows the inside of the ceramic macor retainer. The dark grey structures on the top and the bottom of the image are the screws in question.

The other cause that we investigated centered around the ceramic macor retainers. The hypothesized issue was that the screws that fasten the ceramic retainer to the metal frame were too long and could be touching the nichrome wire on the inside of the retainer. The suggested solution was to use shorter screws. Figure 10 shows how this could potentially be possible by showing the internal structure of the ceramic retainer with the screws in it. We concluded that the screws were not the cause of the shorts so this solution should not be implemented. In addition to this, we found that the shorter screws had a higher chance of breaking the retainer when swapping them, so this decision was also made with diminishing the chance of damaging parts in mind.

There were other, less involved causes that we investigated. All of which, along with the forenamed causes, we documented in a comprehensive report for other scientists working with the ring heaters to reference in hopes that this problem can be avoided in the future [7].

3.3 | 3D Modeling Future Ring Heater Designs

After O5, LIGO will be increasing the size of the test mass. With it, everything else must be increased in size to accommodate that change. Because of this, a potential new ring heater design was suggested by Aidan Brooks. This new design is an 8-sided design, where each side is an individually controlled heating element *(Fig 11).*

To evaluate the effectiveness of this design, a COMSOL model was made to deduce whether this design is feasible. This model must show how much the new design affects the temperature gradient and the amount that the test mass deforms due to the heat produced in relation to the laser. The design needs to counteract the deformation either in the same way or better than the current design does.

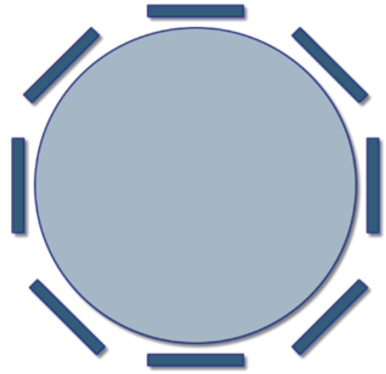

Figure 11: A basic drawing of the suggested 8-sided design. The large circle in the middle is the test mass, and the darker rectangles around it are the ring heater sections.

The design was evaluated through two types of models: a stress model, showing the amount of stress that is put on the test mass due to the heat, which in turn translates to where the deformation is and how it propogates, and a temperature model which shows the temperature gradients caused by the laser and the ring heater on the test mass.

In the stress models *(Fig 12 & Fig 13)*, the current design has a maximum amount of stress (the red coloring) is

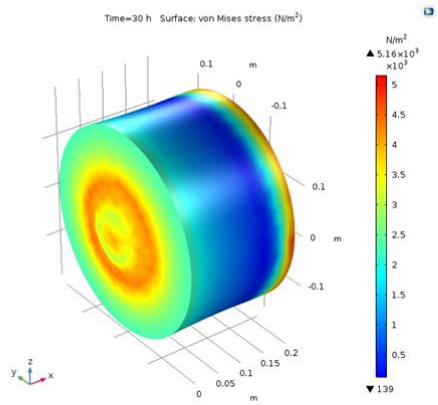

Figure 12: Stress model of the test mass with the current ring heater design. On the front is the laser and on the back is the ring heater.

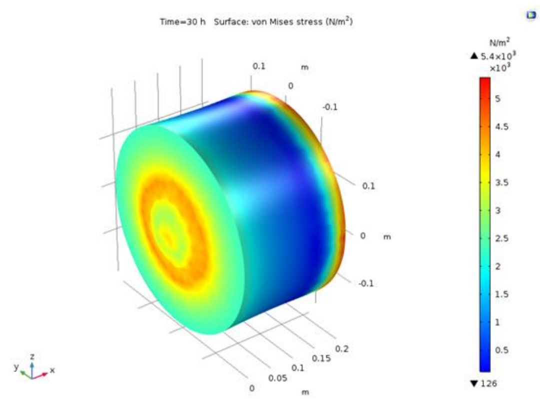

Figure 13: Stress model of the test mass with the new ring heater design. On the front is the laser and on the back is the ring heater.

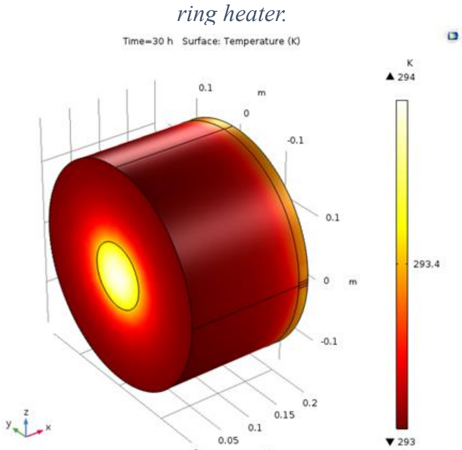

Figure 14: Temperature model of the test mass with the current ring heater design. On the front is the laser and on the back is the ring heater.

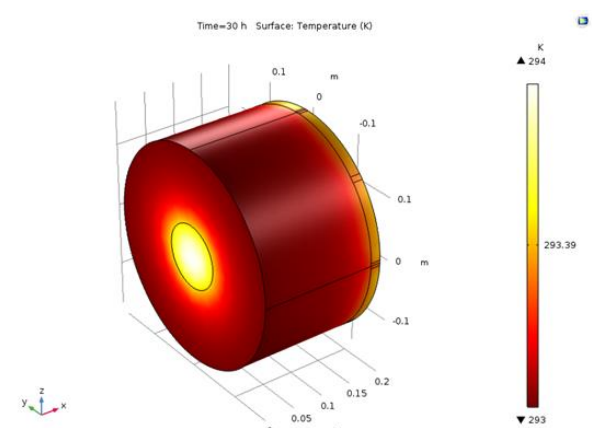

Figure 15: Temperature model of the test mass with the new ring heater design. On the front is the laser and on the back is the ring heater.

5.16×10³ N/m2 and the minimum amount of stress (the blue coloring) is 139 N/m2 *(Fig 12)*. The new design causes the entire range to increase. The maximum is 5.4×10³ N/m2 and the minimum is 126 N/m2 *(Fig 13)*. The temperature models are nearly identical *(Fig 14 & Fig 15)*, with very slight differences that are not perceivable by simply looking at the wide, general range of models. The graphs for all four models reflect these visual observations *(Fig 16 & Fig 17)*. When examined closer, the graph for the new design in Figure 17 shows that the temperature slightly increases by a few hundredths or so. This corresponds to the differences with the stress models.

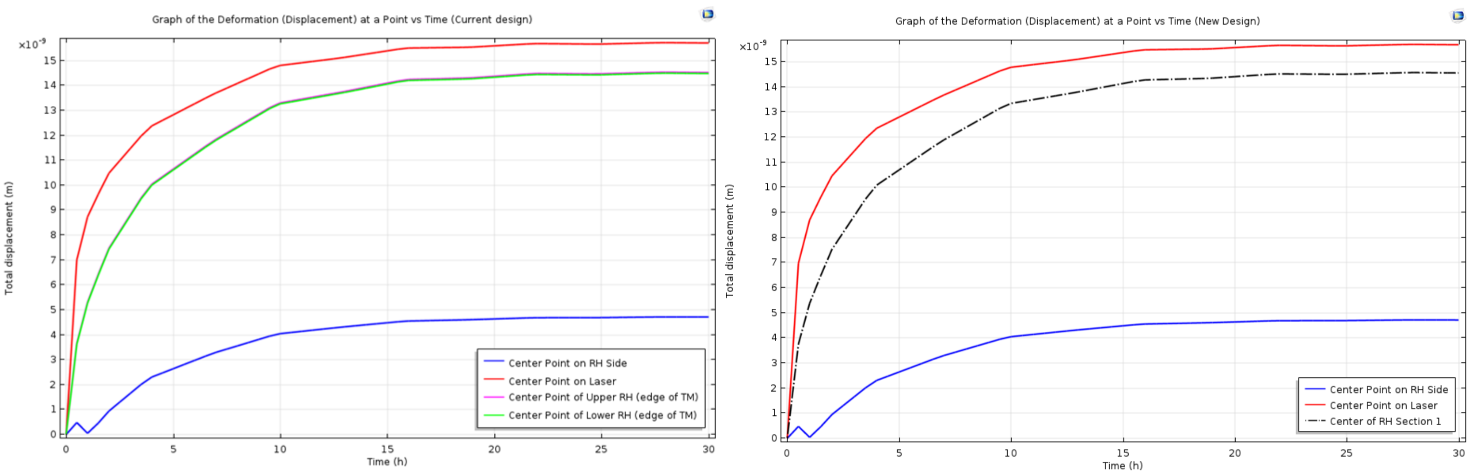

Figure 16: Graph of the displacement (meters) from the original model of the current (left) and new (right) ring heater design. The values on these graphs correspond to the values in Figure 19 and Figure 20 respectively.

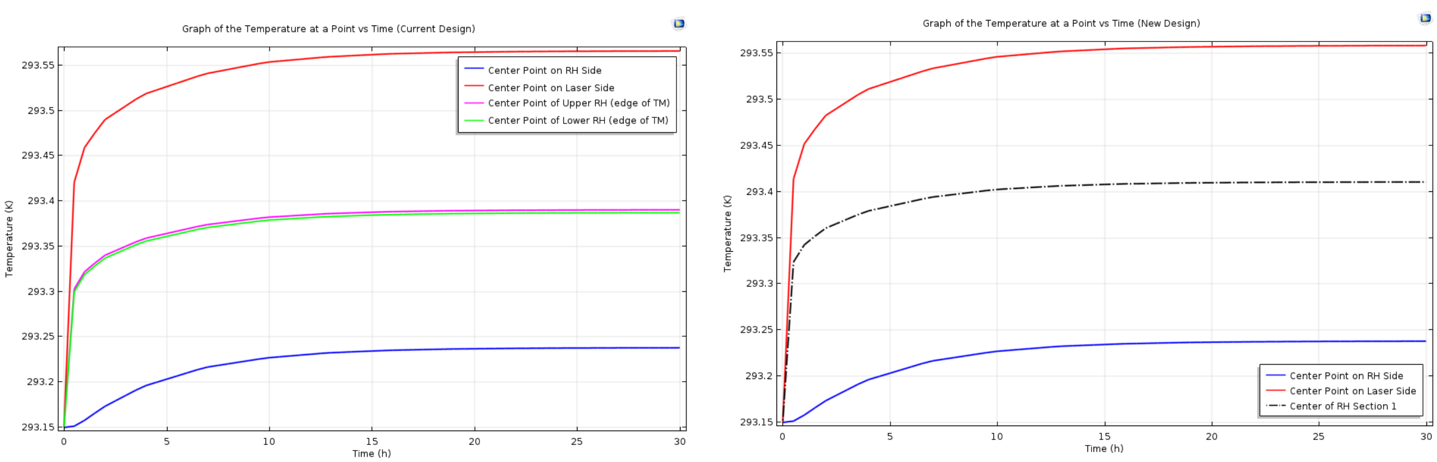

Figure 17: Graph of the temperature of the current (left) and new (right) ring heater designs. There is very little variation between the two.

4 | Discussion

The purpose of documenting the various grounding investigations is to help ensure that these problems do not arise again in the future, especially when new designs for the ring heaters are being created. The document highlights potentially problematic components that could be improved upon when redesigning the ring heaters. It's meant to be used as a resource for anyone working with the ring heaters at all, and as such a link to this document has been added to the assembly instructions for the ring heaters.

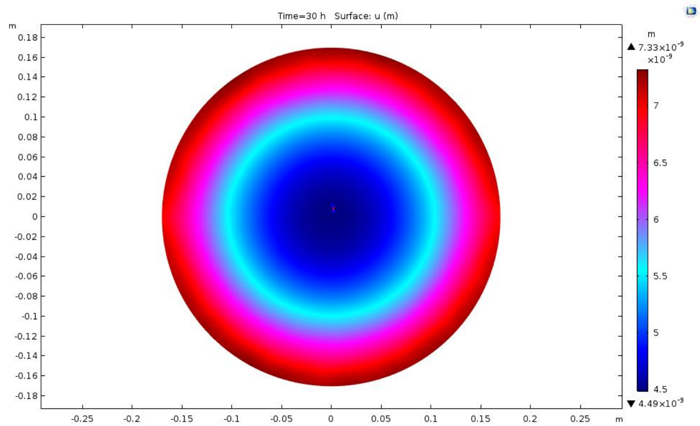

Figure 18: Image of the displacement of the test mass from the original model of the current design caused by heat deformation. Red indicates more displacement and blue indicates less displacement.

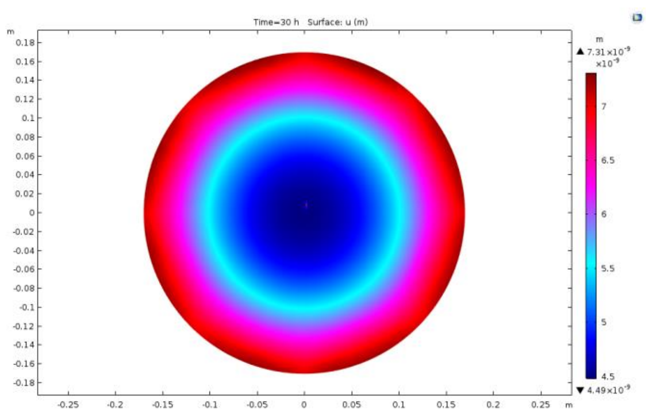

Figure 19: Image of the displacement of the test mass from the original model of the new design caused by heat deformation. Red indicates more displacement and blue indicates less displacement.

With the COMSOL models, the difference between the stress models is likely due to the decrease in the surface area that each individual section is heating, therefore the heat is more concentrated because it does not diffuse across the surface as much. Though it is unclear from these models whether this will be detrimental to the new design's application or not. The resulting models and graphs show that both designs perform similarly enough to conclude that the new design is theoretically possible.

Another difference that was noticed was that the shape that the displacement gradient takes on the side of the test mass that the ring heater is on *(Fig 18 & Fig 19).* The shape on each respective design matches the number of sections there are.

Like the deformation model, the maximums are slightly different in these plots as well: 7.33×10^{-9} m for the current design and 7.31×10^{-9} m for the new design. A potential cause for this can be attributed to the difference in stress, but it is difficult to say this definitively. It is unclear whether these differences will affect how effective this design will be, so this will likely be something for future researchers to evaluate as well.

A portion of the project that we did not have the time to address was the subject of mode matching. For the ring heaters to work effectively, they need to counteract the high order modes effectively as well. This would require a more in-depth analysis and a more complicated set of models. Considering the circumstances, this would be another task for future researchers to take over.

At the moment, it does appear that the differences in these designs are minimal at the center, however, they are increasing at the edges of the optic. It is unclear how important these differences will be, so further investigation, both in modeling and experimental studies, should be pursued.

6 | Conclusion

Our objective for the summer was to modify the current ring heater design and develop improvements to be implemented in future ring heaters. We accomplished this by troubleshooting issues in the current design, comparing designs between versions, and modeling different designs in COMSOL. We have built spare ring heaters, identified causes of grounding issues and weaknesses in the current design, successfully modeled how differently sized heating elements heat the test mass, and compared their effectiveness to the current design. With these results, we are now able to avoid grounding problems observed at other LIGO locations, as well as improve the ring heater design for future use.

7 | Acknowledgments

The author would like to thank and acknowledge the financial support of the National Science Foundation, the California Institute of Technology, and the Carl Albert Rouse Fellowship as well as the general support by Camilla Compton, Michael Landry, Betsy Weaver, Aidan Brooks, the LIGO Scientific collaboration, and Haverford College.

8 | References

[1] B.P. Abbott, R. Abbott, T.D. Abbott, and M.R. Abernathy, “Observation of Gravitational Waves from a Binary Black Hole Merger,” Physical Review Letters **116**(6), 16 (2016).

[2] Aidan F. Brooks, Benjamin Abbott, and Muzammil A. Arain, “Overview of Advanced LIGO Adaptive Optics,” (2016).

[3] Mindy Jacobson and Calum Torrie, “LIGO Document D1002027-v1: aLIGO SYS-TCS Integration of RH w TM,” (2018).

[4] Giacomo Ciani, Christopher Guido, Mindy Jacobson, Cheryl Vorvick, and Phil Willems, “LIGO Document D1001895-v8: aLIGO TCS Ring Heater Assembly, Lower Segment,” (2013).

[5] Mindy Jacobson, "LIGO Document D1300954-v1: aLIGO TCS Ring Heater Element MidSpan Spring Assembly," (2013).

[6] Mindy Jacobson, Ayodele Cole, and Phil Willems, "LIGO Document D1001838-v6: aLIGO TCS Ring Heater Assembly, Upper Segment," (2013).

[7] Rachel McQueen, "LIGO Document T2300296-v2: Ring Heater Grounding Investigations," (2023).

[8] Greg Grabeel, "LHO Alog 12229: Ring Heater Check in BSC 1 and 3," (2014).

[9] Aidan Brooks, "FRS Ticket 4552: ETMX upper ring heater is grounded somewhere on the coil - new screws for all RHs," (2015).