LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Final Design of aLIGO TCS Ring Heaters and Associated Electronics

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1 Document Overview

This document provides technical details for the final design of Advanced LIGO (aLIGO) Ring Heaters and associated electronics for the Thermal Compensation System (TCS).

The preliminary design concepts are documented in LIGO-T1000252-v9.

2 Design Requirements

The primary documents to reference for requirements of the ring heaters and associated electronics are:

LIGO-T000092-v2, TCS Design Requirements Document (DRD)

LIGO-T0900597-v3, aLIGO TCS Electronics and Controls Requirements

Additionally, the derivation of requirements for uniformity of the heating profile is presented in:

LIGO-T1000693-v1, Analysis of Required Uniformity of the aLIGO Ring Heater

This document cites higher level requirements from LIGO-E080511-v3 and LIGO-E0900041-v5.

Requirements on current noise that would give rise to magnetic field gradients have been derived with conservative assumptions. This is the topic discussed in LIGO-T1000249-v1. Note that the current limit is more restrictive than the upper limit on power noise. Therefore, meeting this requirement ensures significant margin regarding the power noise.

3 Mechanical Design

Final Ring Heater designs are evolved from the *enhanced baseline design*, having a glass rod former with helical over-wrapped nichrome wire (24AWG). There are two semi-circular segments, referred to as "upper" and "lower" segments.

Primary constraints on these designs are related to electronics packaging and interfaces to the quadruple (quad) suspension assembly. An intermediate 3D assembly (D1002027), which compiles all physical components necessary for implementing Ring Heaters and their electronics, has been created and is indentured to the quad suspension assembly (D0901346). Images of these are included below. Sub-assemblies that, all together, comprise D1002027 are:

D1001838-v4, aLIGO TCS Ring Heater Assembly, Upper Segment
D1001895-v4, aLIGO TCS Ring Heater Assembly, Lower Segment
D1001517-v5, TCS Ring Heater In-Vacuum Cable Assembly
- D1001518-v6, Cable Assembly, Upper Ring Heater Segment
- D1001519-v5, Cable Assembly, Lower Ring Heater Segment
- D1001520-v4, Cable Assembly, Lower Quad Terminal Block to Upper Quad Terminal Block
- D1001521-v5, Cable Assembly from Upper Quad Terminal Block

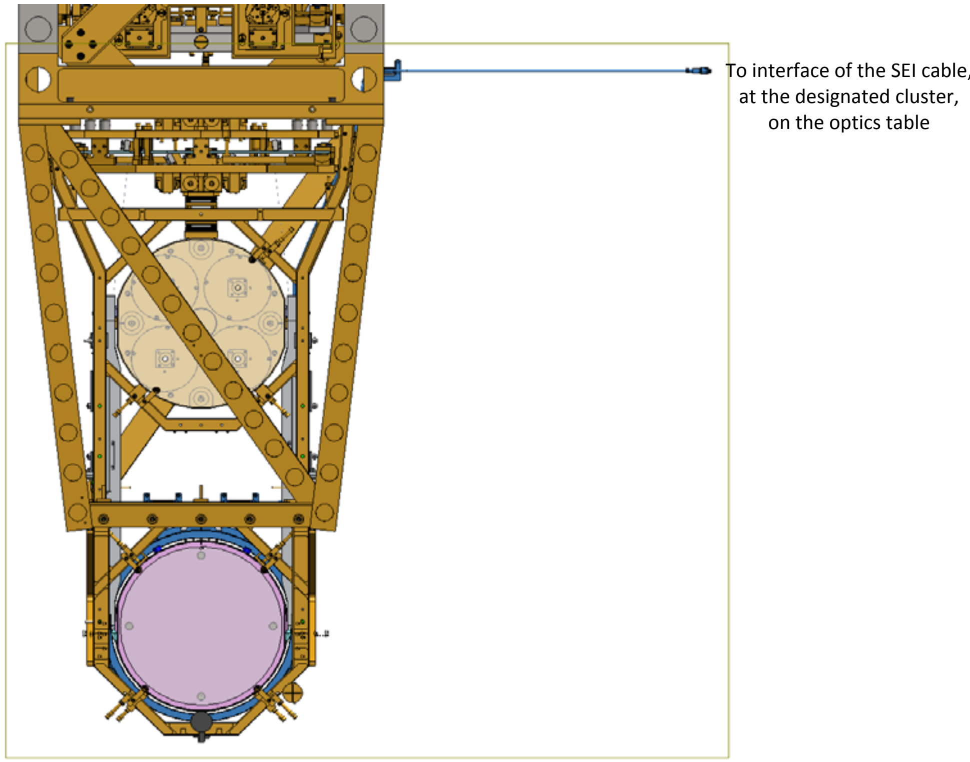


Figure 1: aLIGO 3D Assembly (D1002027) of RH and Electronics Components, highlighted, and integrated within the parent assembly D0901346.

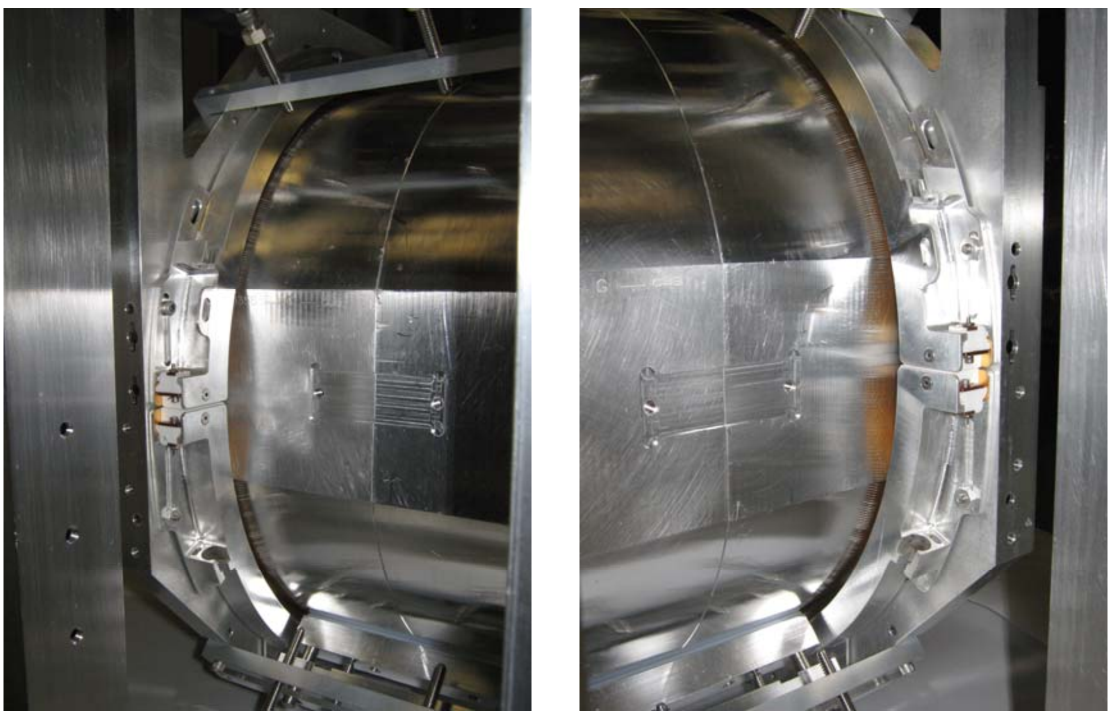


Figure 2: Final Design *Prototype* Assemblies (D1001838-v1 & D1001895-v1) integrated with the aLIGO Production Quad Structure.

To remove the Lower segment, anytime after initial integration, the two mechanical and electrical connections are broken, then the lower pair of earthquake stops are to be temporarily removed.

To remove the Upper segment after initial integration, the two mechanical and electrical connections are broken only after the Lower segment has already been removed. Then, the Upper segment is rotated about the optical axis to the "Lower" position, where it can be removed as though it were the "Lower" segment. The images (above) show the radial gap between the Shield and earthquake stop, allowing for this procedure.

Modifications to the Final Design *Prototype* [-v1] Upper and Lower RH assemblies have been made in order to (a) increase clearances between the Shields and Earthquake stops, (b) increase clearances between the Shields and fiber welding tools, and (c) increase uniformity of heating in the vicinity of the flat regions of the TMs.

Production-ready Final Designs of the Upper and Lower RH assemblies [-v4] are illustrated below:

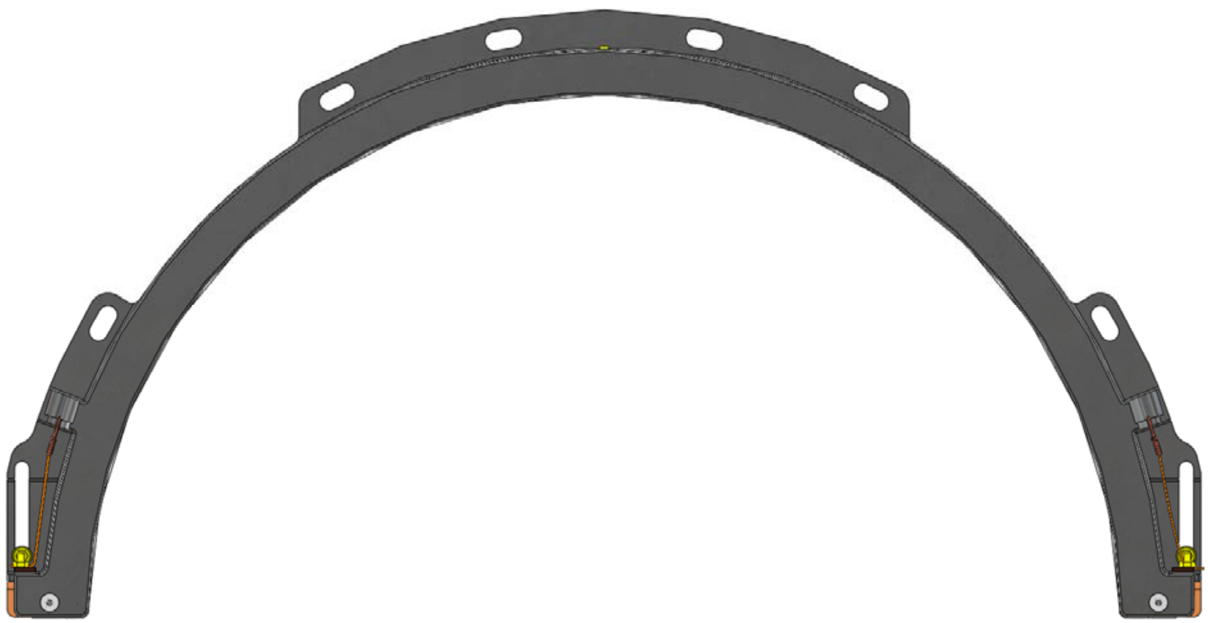


Figure 3: Final Design Upper RH Assembly, D1001838-v4.

Figure 4: Cross Section of Final Design Upper RH Assembly, D1001838-v4.

Figure 5: Final Design Lower RH Assembly, D1001895-v4.

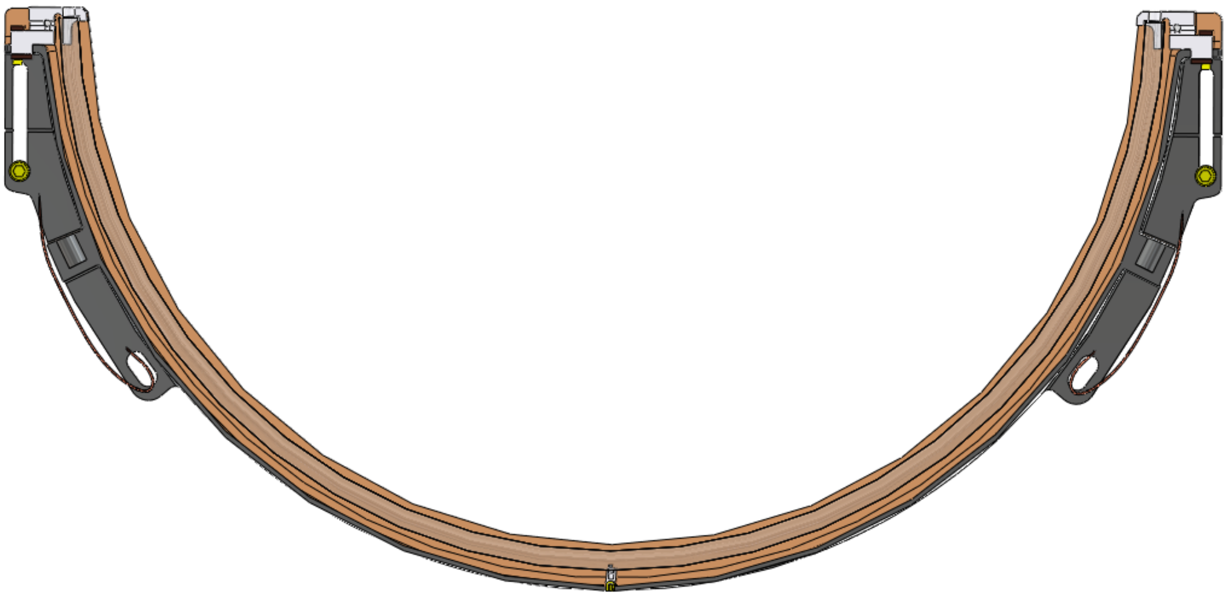


Figure 6: Cross Section of Final Design Lower RH Assembly, D1001895-v4

In-line electrical connections from the heating element (nichrome) wire are performed in the same way for both the Upper and Lower segments. Macor ceramic pieces, which insulate both of the lateral [left / right] electrical connections, have been optimized for minimal thermal conductivity from the heating element to the Shield. The thermal analysis supporting this optimization is collected in LIGO-G1100045-v1. And, key results are shown below.

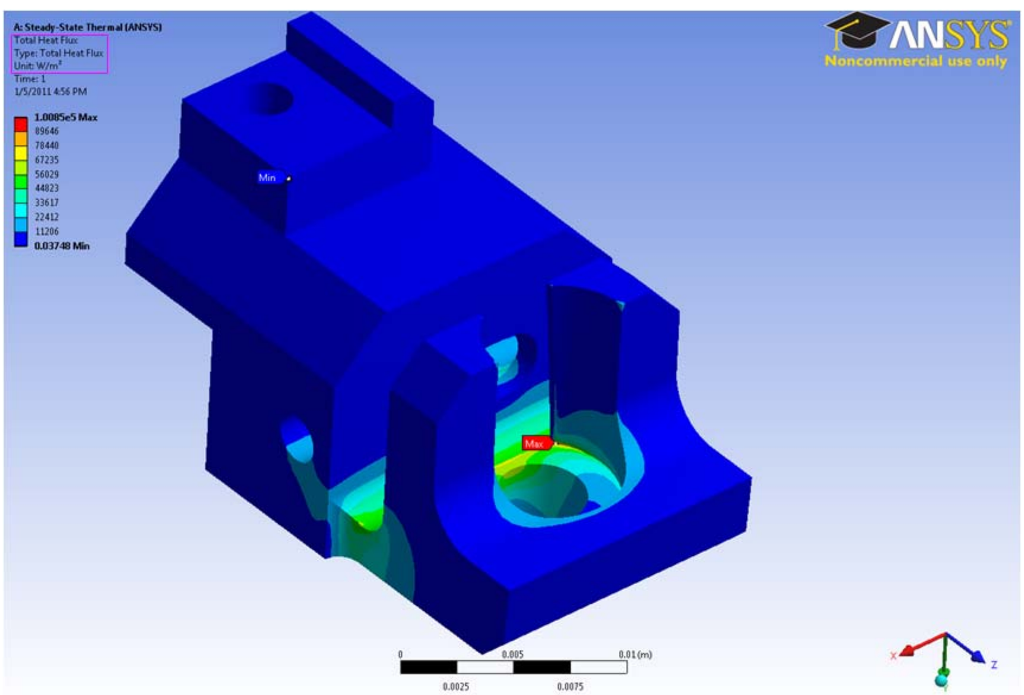


Figure 7: Total Heat Flux Results of Thermal Analysis for Optimized RH Element [Macor] Retainers, D1002543-v4 and D1002544-v4

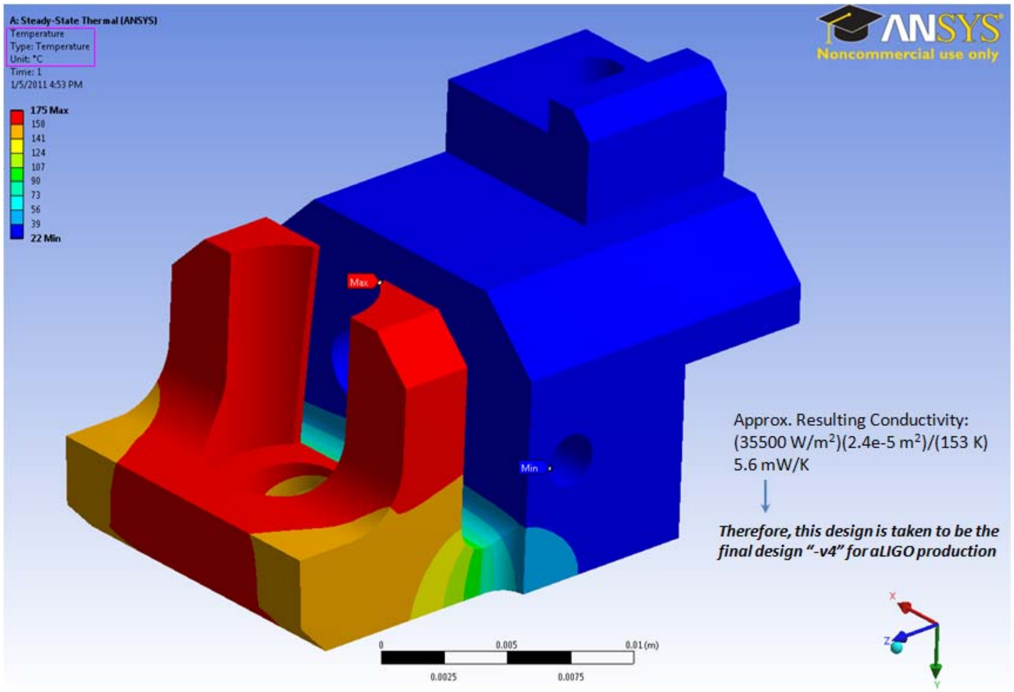


Figure 8: Temperature Distribution Results of Thermal Analysis for Optimized RH Element [Macor] Retainers, D1002543-v4 and D1002544-v4, Yielding a 10x Reduction in Conductance from the Prototypes

Static structural analysis of the optimized RH Element Retainers has also been performed, to confirm that they are not expected to break during assembly, assuming limit loads equivalent to the maximum allowable for handling of the glass formers.

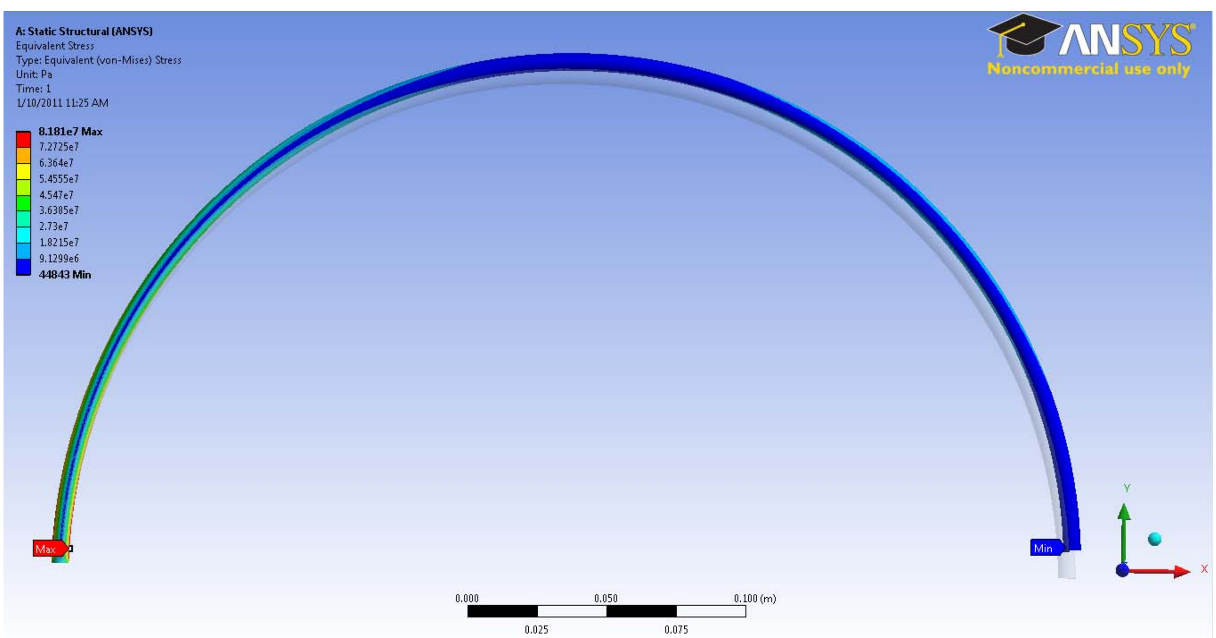


Figure 9: Maximum Allowable Handling Stresses for the Glass Former, for 34.5 in-lbf (3.9 N-m) Torque Acting on Either One of the Fixed Ends

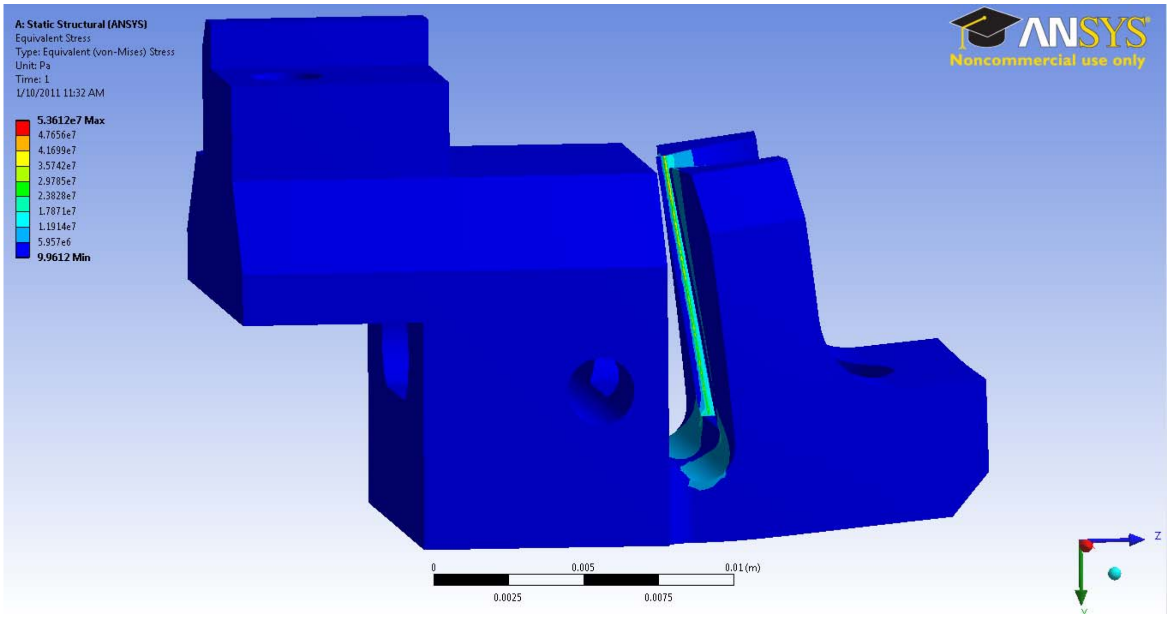


Figure 10: Resulting Stresses for RH Element Retainers, Assuming Maximum Allowable Limit Loads for the Glass Former, Yielding a Margin of Safety on Rupture > 2

Securing the windings of each RH element is ensured by the assembly process, which follows steps that have been optimized for production; see LIGO-T1100123-v1. The winding template can printed to full-scale on (11"x17" paper) from LIGO-F1100002-v2.

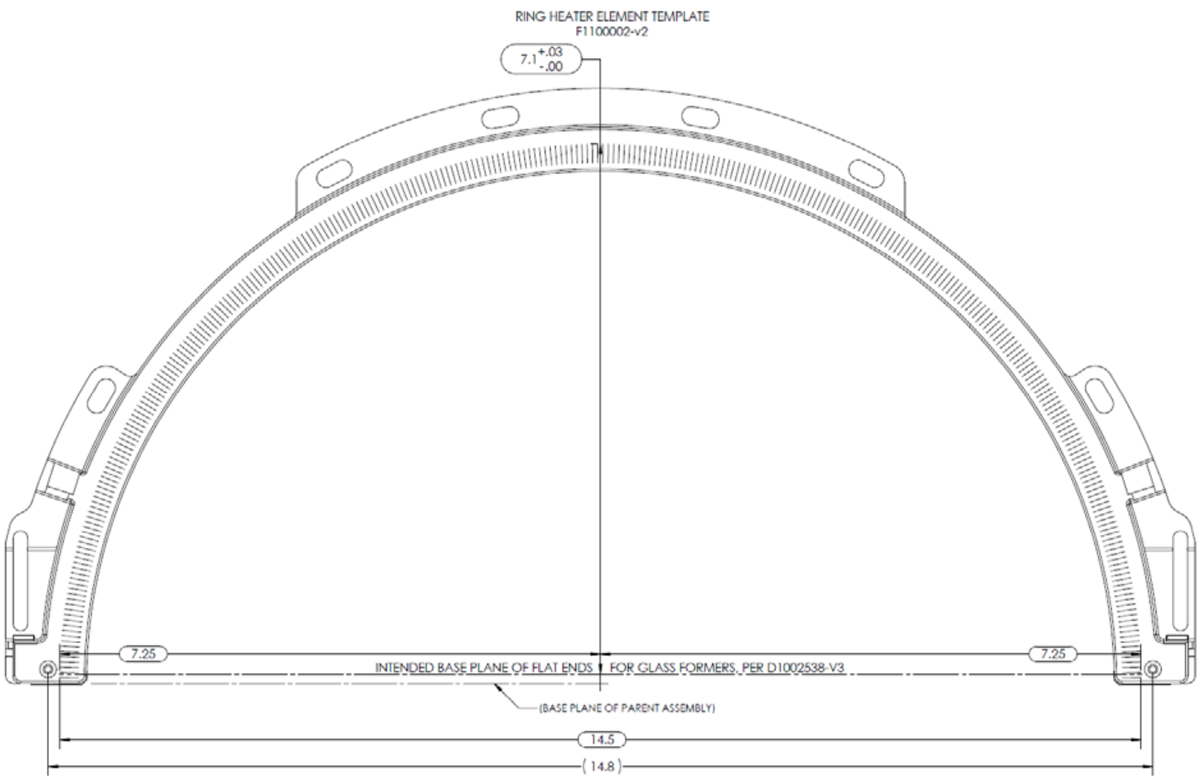


Figure 11: Ring Heater Element Template, shown sub-scale

After the nichrome wire is sleeved into place on the glass former, extended leads of nichrome are wound around screws used to ensure the in-line electrical connection from the heating element and to each of the Upper and Lower segment cable assemblies, D1001518 and D1001519, respectively.

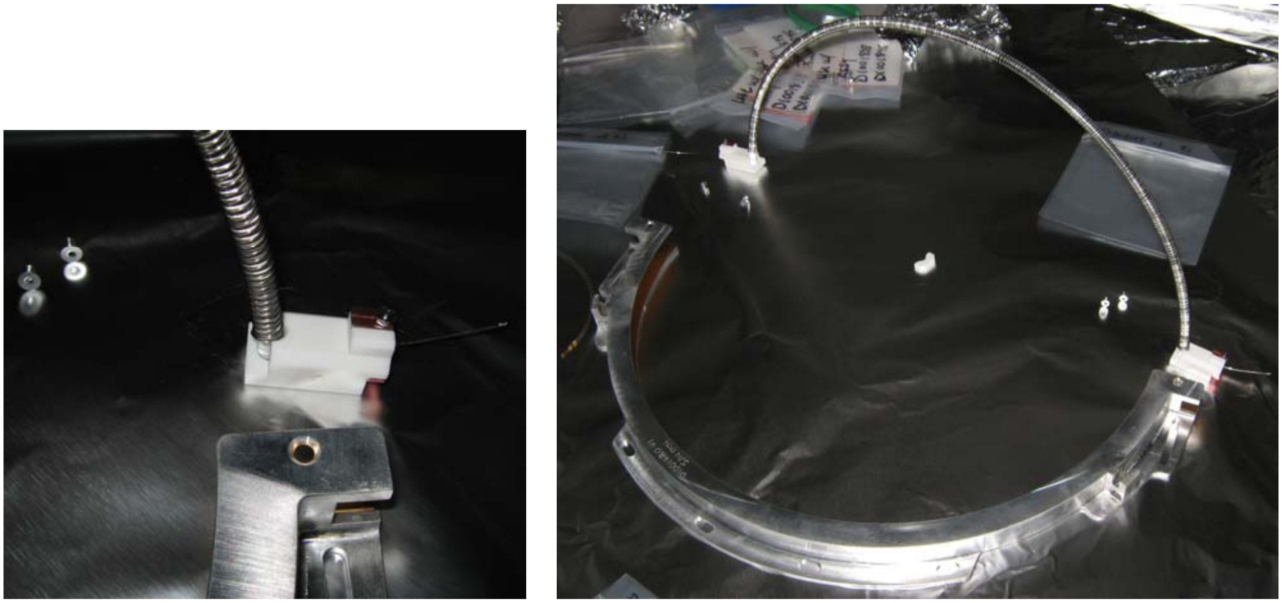


Figure 12: Heating Element Electrical Connection During Final Design *Prototype* Assembly

Completing the in-line electrical connections to Upper and Lower segment cable assemblies (carrying < 1.5A to each heating element) is performed during the integration process. The figure below illustrates this, omitting the quad structure for clarity.

The Appendix to this document includes actual heat distributions of three pair of (lower and upper) ring heater segment assemblies, tested in a vacuum environment (per LIGO-T1000733).

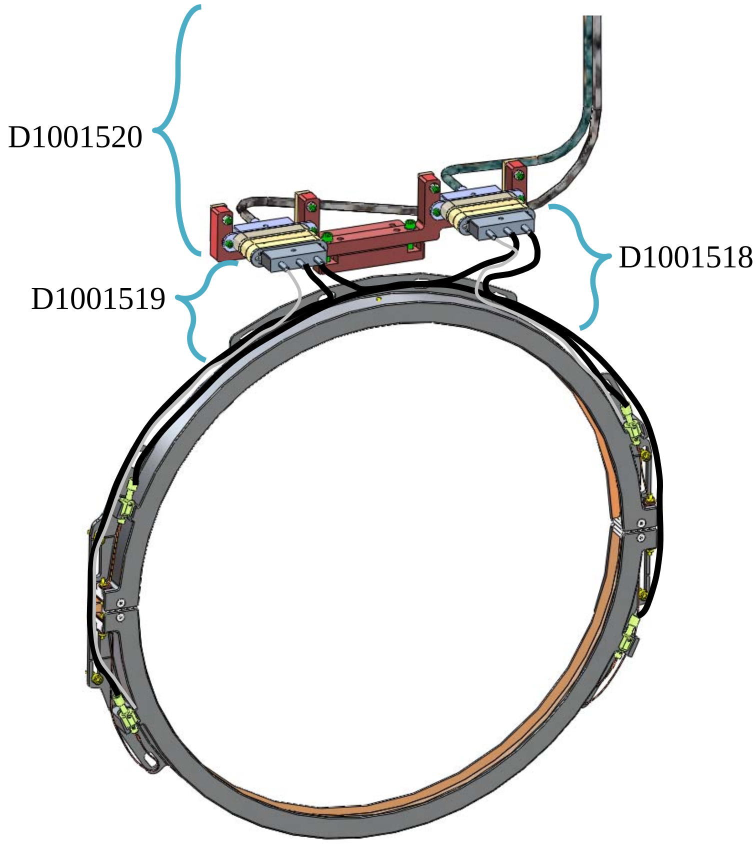


Figure 13: Illustration of Heating Element Electrical Connection During Integration

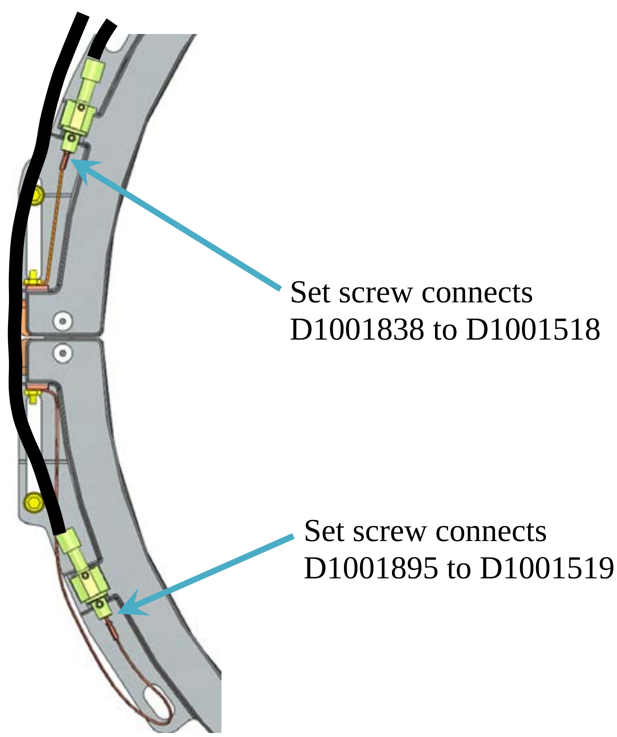


Figure 14: Detailed Illustration of Heating Element Electrical Connection During Integration

4 Electronics Design

As an overview, the block diagram from LIGO-T0900597-v3 is repeated, below. The associated end-to-end wiring diagram is given by LIGO-D1003312-v1.

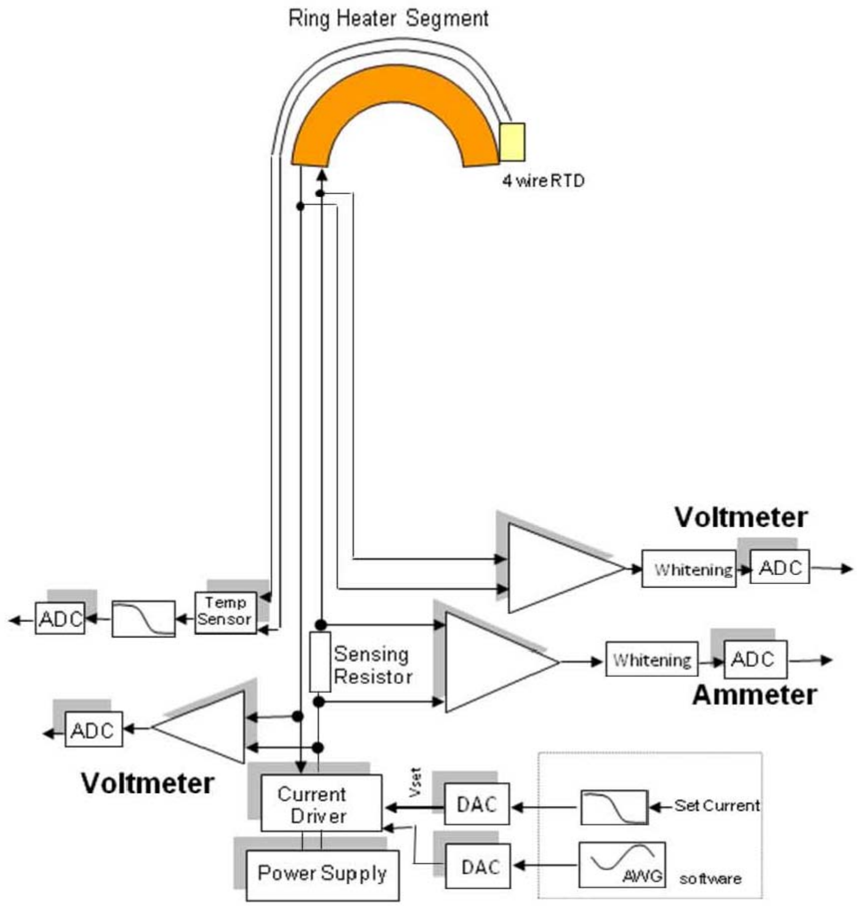


Figure 15: Ring Heater Electronics Block Diagram

The RH Driver design, serving each segment individually, is documented in D1002529. The wiring diagram for a chassis designed to enclose a pair of Drivers is given by D1003254-v1.

Power to each ring heater is controlled by individually setting the current to each segment of the ring heater. A DAC sets a reference voltage which controls the current to the ring heater. In order to keep magnetic effects low, the frequency response of the control voltage will be $\leq$ 0.1Hz. During a commissioning phase, a second large bandwidth input to the driver with a will allow the addition of a sine wave onto the control line to test noise couplings. It will be capable of producing 1 W p-p variation in power in a bandwidth of 10 – 1000 Hz. Low noise power ICs will provide up to 10W of power to each segment. Each driver will have two ICs with +/- 24V supplies in a differential arrangement. The 16 bit DAC will enable the driver to step the power with an accuracy of at least 0.005W. The PCB will have two fuses for over current protection.

The current to each ring heater segment is measured by sensing the voltage across a small series resistor with a high impedance differential amplifier. The resulting voltage will undergo whitening and anti-aliasing before ADC conversion.

The voltage across the ring heater will be measured with a high impedance differential amplifier using sensing wires from the ring heater. This voltage will undergo whitening and anti-aliasing before undergoing ADC conversion.

The voltage across the PCB driver will be measured using a high impedance differential amplifier. This signal provides a measure of the voltage drop along the driver cable, which can be very long. This voltage will undergo anti-aliasing before undergoing ADC conversion.

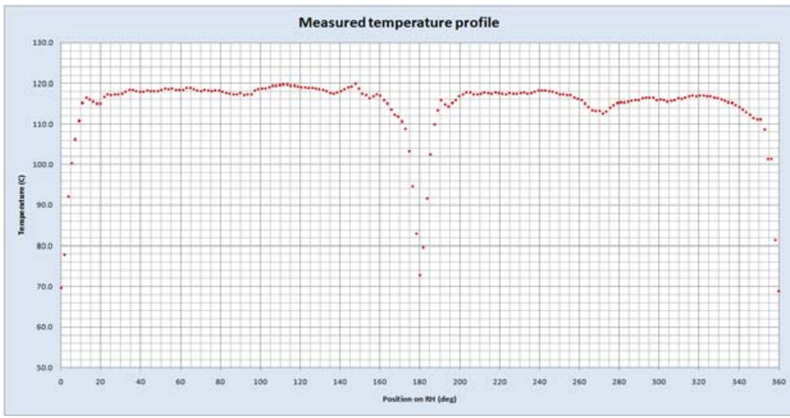
The temperature of each segment of the ring heater will be measured with a 4 wire RTD. Using a standard circuit, a voltage proportional to the temperature is produced. This voltage is low pass filtered and undergoes anti-aliasing before ADC conversion.

4.1 Driver Noise

Performance of final design prototype Drivers have been studied in great detail. Methods and conditions of this verification testing have been described in E1000785-v2. In summary, noise is three orders of magnitude below the stated requirement of 0.1mA/rt-Hz, per Section 2.1.2 of T0900597.

APPENDIX

Measured ring heater patterns in vacuum and a corresponding prediction of the thermal lens produced solely by a pair of ring heater segments acting at full power.

<table>
<tr><td>
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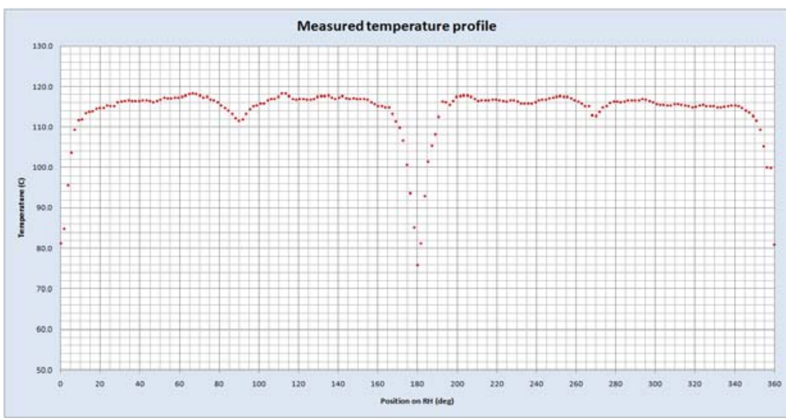
SN-001</td></tr>
<tr><td>
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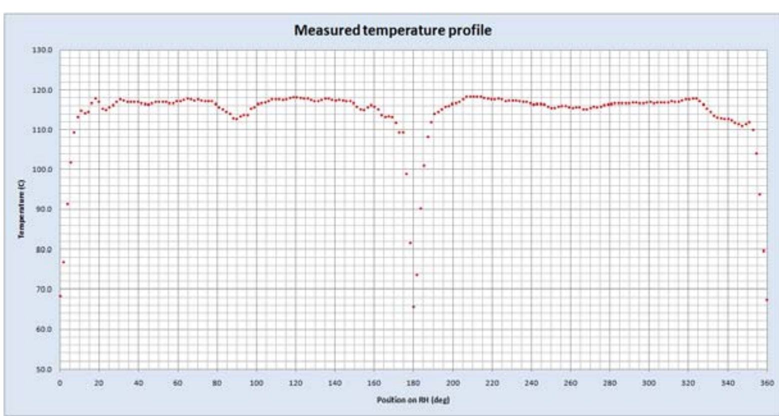
SN-003</td></tr>
<tr><td>
</td><td>Upper and Lower Ring Heater Segment Assemblies

SN-004</td></tr>
</table>

Per LIGO-T1000727-v4

Predicted thermal lens produced by the ring heater acting alone at full power.

The color scale represents meters of optical path distortion.