Proposal for ADTR funds to provide LIGO Lab support for UCR development of a Front Surface Ring Heater

M2200050-v3

This document details a proposal for ADTR funds a front surface ring heater.

Note on collaboration with University of California Riverside

The NSF have funded development of a front surface ring heater at UCR. They have urged that the UCR effort be supported by the LIGO Lab (see reviewer comments below). Approximately 2/3 of this work will be done at UCR (focused on development, design and procurement). CIT will provide support for testing as necessary, help with modeling of IFO effects and noise couplings and mechanical design of integration of the RH into aLIGO.

1. **Panel Reviewer 1:**
   "The proposal is very well organized, the case to develop such a device is made and the R&D plan is well organized and realistic. ... However, there is also a chance for the PI to try to leverage the NSF funding to accelerate the R&D by collaborating even more closely with the LIGO lab to get this installation ready earlier."

2. **Panel Reviewer 2:**
   "It would be advisable to initially rely on collaboration with the LIGO Laboratory for testing, and then gradually transfer capability to UCR."

Background

We have observed significant losses in the aLIGO interferometers due to the presence of point absorbers on the test masses. These points absorb incident power resulting in localized thermal hot spots. The localized thermal expansion (on the scale of 20-40mm in diameter) around these points scatters laser power from the cavity TEM00 mode into multiple higher order modes. The amount of loss scales with this scattering coefficient but is also amplified or suppressed as a function of how close or far a given HOM is from resonance in the Fabry-Perot cavity [P1900287]. The front surface ring heater [G2101232] is proposed to mitigate these losses by heating and distorting the surface profile of the optic, near the edges, to move HOM further away from resonance and thus lower their resonant gain. The design is intended to have minimal effect on the TEM00 mode resonance.

The design aims to shift resonances of HOM, not to reduce the amplitude scattering coefficient of thermal distortion.

Additionally, Peter Fritschel and others have requested that such a device could aid in minimizing the losses from surface deformation from uniform absorption – which will be the dominant loss in the arms as we move to high operating power.

Furthermore, Jon Richardson's research group at UC Riverside [UCR] has been granted funds by the NSF to pursue such a device[1]. They are willing to contribute time and money to assist with this.

Scientific Motivation

1. Models by Hiro Yamamoto, Jon Richardson and others have shown that front surface deformation can reduce round-trip arm losses by as much as from 90-100ppm to 60-80ppm (when point absorbers are present), see Figure 5 in T2100282, or around 150ppm down to 90ppm, Figure 7 in T2100282. See also, G2100878, G2101093.
2. In contrast to statically polishing a front surface deformation (see T2100282), a HOM actuator, in the form of a front surface heater, allows for dynamic tuning on each individual optic.
3. Hiro Yamamoto has identified losses from deformation due uniform absorption as one of the principle losses as we get to full power in aLIGO (see Slide 19, G1900361). This is due to deviations from spherical in the surface deformation on the test masses. A front surface ring heater could be shaped to partially mitigate those effects.
4. This R&D will lay the infrastructure groundwork for future multi-element front surface heaters that are able to provide many different spatial distributions of heating on the surfaces of the test masses. This more future-looking R&D goal is already endorsed/funded by the NSF (through UCR's same grant NSF-2110348).

Scope

The end goal is to install a front surface ring heater on, at least, each ETM in aLIGO. Modeling will explore if ITM surface heaters will be required as well. Work will be divided between CIT and UCR. This R&D project is intended to:

1. Determine the Optimum Heater Configuration [UCR]
   o that can be practically built (through modeling in ZEMAX and COMSOL with input from Solidworks to guide what can be physically constructed),
2. Fabricate Prototypes [UCR]
   o of one or more heater configurations
   o Test Different Fabrication Techniques [UCR]
      ▪ traditional manufacturing, ~~electro-forming~~ and 3D printing
3. Evaluate the Heating Profiles [UCR/CIT]
   o from all heater prototypes,
   o compare this to the simulated ZEMAX/COMSOL models and

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[1] NSF-2110348, https://www.nsf.gov/awardsearch/showAward?AWD_ID=2110348

- o determine the efficacy of a measured heating profile in mitigating losses using interferometer simulations (SIS/Finesse).
4. [Possibly] Test for Vacuum Compatibility [CIT]
    - o of different configurations, manufacturing techniques and reflective coatings.
    - o This might not be needed. First pass is trying to use materials used for SR3 heater.
5. Evaluate Possible Noise Couplings [UCR/CIT]
    - o (seismic, electro-static, magnetic, optical scattering) from this ring heater design
6. Solve Mechanical and Electrical interface issues [CIT] – This is possibly DI work
    - o for the heater, starting from the assumption that it will be mounted on the arm cavity baffle immediately in front of the ETM.
    - o Design electrical interfaces for each heater to accommodate capacity for many channels such that future designs with multi-element heaters can be retro-fitted into the system.

Activities & Effort Details

This section provides an overview of the different research and development activities foreseen for this work. Rough estimates of expected cumulative efforts are provided for each task. The estimate for effort refers to total time spent actively working on a project – it does not include durations such as wait time for procurements to arrive, or wait time for longer term vacuum testing). Additionally, specific individuals are identified to pursue these tasks

1. Modeling activity: Design optimum heating profile based upon interferometer performance. Done with IFO modeling to determine effect of on higher order modes and IFO sensitivity improvement, if any (with and without point absorbers). At Peter Fritschel's recommendation, we will also look at profiles which allow use to compensate for surface deformation from uniform absorption. Design of optimum ring heater reflector and element profile to produce the desired heating profile. This will be done in conjunction with graduate students at UCR working on COMSOL. Modeling of heating profiles will be done using ZEMAX. Design activity:
    1. COMSOL modeling: 2-3 weeks FTE (cumulative): UCR grad student, Ryan Anderson
2. Fabrication:
    1. create Solidworks design for prototype reflector profile based on optimum profiles determined in ZEMAX and COMSOL. [UCR/CIT (Don)]
        - Estimated time: Solidworks design: 1 weeks FTE (cumulative), Eddie or Don?
    2. create design for heating element to fit into reflector. Consider upgraded heating element proposal from University of Florida, see G2101232. [UCR]
        - Electrical design: 1 week FTE (cumulative), UCR
        - Thermo-mechanical design: 2 weeks FTE (cumulative), [UCR]
    3. Manufacturing activity: get prototypes of these profiles manufactured via electro-forming, 3D printing and traditional manufacturing processes. This is

another area where UCR would like to contribute. They've already been in touch with two vendors (both happen to be in Southern California) that specialize in electroforming for optical applications. Coating exploration: explore coatings for these reflectors to maximize performance

- Procurement: 1 week FTE (cumulative time for ordering, not including wait time), UCR
- Research: 1 week FTE (cumulative), UCR

3. Heating profile tests: construct and run the heater/reflector assemblies. Using a thermal imaging camera, record the heating profile from all prototypes and judge efficacy by comparing to original optimum profile and simulating IFO performance directly with measurements from these assemblies.
   1. Assembly: 1 weeks FTE (cumulative), UCR
   2. Heating profile testing: 3 weeks FTE (cumulative).
      From Jon Richardson: "I would expect at least a portion of this work to be done at UCR by students/postdocs (as was promised in the NSF proposal). However, if we can't get all the optical equipment in place quickly enough, one option would be to send the UCR personnel to work at CIT in the short term." UCR
   3. Hiro/SIS modeling: 2 weeks FTE (cumulative), Hiro

4. Vacuum testing of coating: Vacuum performance tests: in parallel, run RGA scans on the different designs to ensure they can operate as design in the IFO without outgassing too much material into the vacuum system.

   From Jon Richardson: "I also have grad and undergrad students that can contribute person-hours toward cleaning/baking parts and performing basic RGA scans. We're planning to install a small test chamber in the UCR lab. One option might be to use UCR students to do an initial screening of potential materials, then forward only the most promising candidates on to CIT for more rigorous testing."

   1. Assembly and testing: 2 weeks FTE (cumulative), Jordan [Aug/Sep]
   2. Coating 2 weeks FTE (cumulative), Stephen [Aug/Sep]

5. Noise couplings Run noise simulations to determine if we will inject an unacceptable amount of displacement noise into the IFO.
   1. Modeling: 1 week FTE (cumulative), Gabriele/Aidan/Hiro and UCR postdoc Cao
   2. Scattered Light: 2 week FTE (Alena)

6. Integration around IFO. Expand design of mechanical and electrical interfaces.
   1. Should include some consideration of mechanical and electrical integration into the IFO. Base design calls for mounting to the arm cavity baffle.
   2. Design: 1 week FTE (cumulative), Don/Luis

Breakdown of costs

For the breakdown of costs, we have not included cabling and drivers as these are not necessary for this R&D phase (we can do testing using existing cables and power supplies). This will need to be procured if/when this project moves to Detector Improvement phase.

From Jon Richardson: "UCR's NSF grant can cover the fabrication costs (~$25k)."

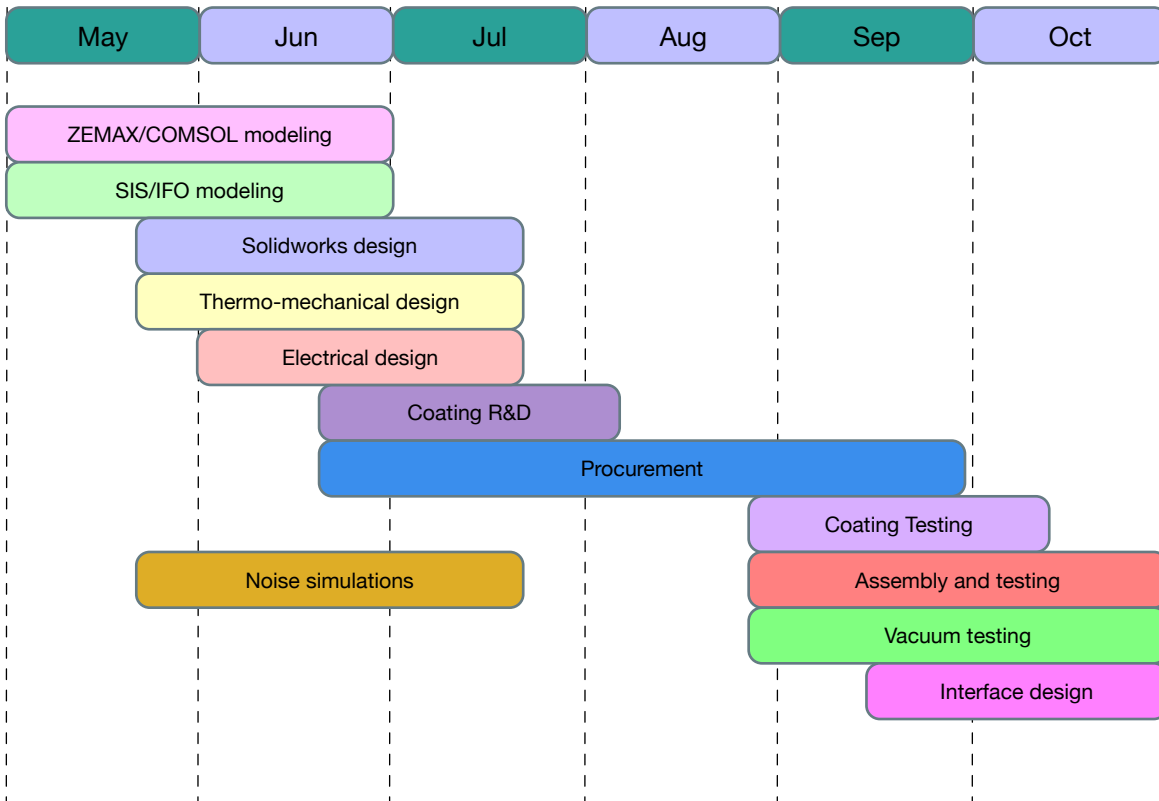Equipment (estimate): $42K funded by lab
- despite UCR providing some resources, we (Calum and Aidan) determined that this project should request funds from the Lab for all required resources as we may want the option to build some or all of the parts in addition to those supplied by UCR. **Particularly if we want to fast track a second-generation prototype at Caltech.**

1. Heater element: coated alumina piece: $3K (WAG)
2. Heater element: glass torus: $2K (WAG)
3. Radiation shield: machined: $5K (WAG)
4. Radiation shield: electro-formed: $5K (WAG)
5. Radiation shield: 3D printed: $5K (WAG)
6. Coating on shields: $5K (WAG)
7. Vacuum testing: "UCR's NSF grant can cover any costs associated with cleaning and testing parts (services and/or supplies; ~$10k)."
8. Miscellaneous parts: $7K (WAG)

	FTE						
		CIT		**UCR**			
	Activity	**Duration (weeks)**	**Cumulative (weeks)**	**Duration (weeks)**	**Cumulative (weeks)**	**Equipment Cost (K)**	**Cumulative cost (K)**
1	Modeling: ZEMAX	0	0	2	2	$0	$0
2	Modeling: SIS	0	0	2	4	$0	$0
3	Design: Solidworks	2	2	0	4	$0	$0
4	Design: Electrical	1	3	0	4	$0	$0
5	Thermo-mechanical design	0	3	2	6	$0	$0
6	Modeling: noise simulations	3	6	1	7	$0	$0
7	Procurement	0	6	1	8	$32	$32
8	Coatings: Research	0	6	1	9	$0	$32
9	Coatings: Testing	2	8	1	10	$0	$32
10	Heater: assembly and profile testing	0	8	4	14	$0	$32
11	Testing: Vacuum performance	2	10	1	15	$10	$42
12	Design: Interfaces	1	11	0	15	$0	$42

Schedule:

2022

May	Jun	Jul	Aug	Sep	Oct

- ZEMAX/COMSOL modeling
- SIS/IFO modeling
- Solidworks design
- Thermo-mechanical design
- Electrical design
- Coating R&D
- Procurement
- Coating Testing
- Noise simulations
- Assembly and testing
- Vacuum testing
- Interface design

Concerns for further review

Jon Richardson has identified the following potential worries that should be explored as part of the ADTR. See below.

Intensity to displacement noise couplings

- Radiation pressure
- Photo-elastic noise of the optical surfaces
- Photo-refractive noise in ITM substrate

Possible fix: Long thermal time constant of heater element (minutes); use a stabilized current source

Vibrational noise of reflectors

- Found to be insignificant for Virgo[2]

Possible fix: Passive suspension could be explored if necessary

Worsened scattered light noise (probably the biggest concern)

- Retro-reflection of scattered 1064 nm light from the reflectors back into the IFO beam

Possible fixes:

- Shield with optical filter absorbing at 1064 nm
- Design reflector opening to minimize acceptance angle; polish outside surface for diffuse scattering and/or coat outside for 1064 nm absorption

Vacuum compatibility of coatings

UCR is looking into this as well, as part of the discussions with vendors. They seem to have little to no data on outgassing – will probably have to do own in-house vacuum testing.

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[2] Specifically, for the CHRoCC in Virgo+. Accadia et al. 2013 Class. Quantum Grav. 30 055017