

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note	LIGO-T2600151-v1	2026/05/20
Measuring Photon Bunching in Next-Generation Adaptive Optics		
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1 Abstract

The FRONt Surface Type Irradiator (FROSTI) is a new wavefront actuator for LIGO that will enable higher laser power and reduce quantum noise. FROSTI uses an infrared heating pattern projected by a blackbody source onto the highly-reflective surfaces of the LIGO test-masses. FROSTI is named for its ability to return the optic to its cold optical state. Thermal radiation is used as it is the only source with sufficient intensity stability which meets LIGO's strict requirements. An upper limit has been set on the displacement noise caused by intensity fluctuations in FROSTI, but even higher sensitivity measurements are necessary. This project will develop an optical testbed to measure photon bunching described by the Hanbury-Brown-Twiss effect. The result of this measurement would be a demonstration that FROSTI can operate at its theoretical noise minimum.

2 Introduction

2.1 History of LIGO

In 1905, Poincaré made the first explicit mention of gravitational waves; stating that special relativistic gravity could have waves which travel at the speed of light [11]. Ten years later, Einstein formulated his theory of general relativity. In this new theory, he asserted that gravity was not a force, rather a curvature of spacetime itself. Einstein also found that the linearized weak field equations had wave solutions [8]. These wave solutions were transverse strain waves which travel at the speed of light, generated by variations of the mass quadrupole moment of the source. With gravitational waves theorized and a mathematical solution presented, the world was left to confirm this phenomenon with experiments.

Detecting gravitational waves on Earth is exceptionally difficult, as their strain amplitude is extraordinarily small (10^{-21}). Gravitational waves interact weakly with matter in the universe, making them a fascinating complement to electromagnetic astronomy. This unique property allows gravitational waves to reveal insights about astrophysical objects that are not seen with traditional telescopes.

Experiments began in the 1960s to detect gravitational waves with Joseph Weber, who pioneered resonant mass detectors [16]. Four decades later, the first interferometric detectors came to be: TAMA 300 (Japan), GEO 600 (Germany), LIGO Livingston and LIGO Hanford (U.S.), and Virgo (Italy) [1]. These detectors worked for a decade to set upper limits on gravitational wave sources.

Finally, in 2015, a new era of gravitational wave astronomy was ushered in when Advanced LIGO (aLIGO) began operations. In just two days of runtime, aLIGO made history by providing the first direct observation of gravitational waves [1]. Since then, aLIGO has been joined by two other detectors – Advanced Virgo (Italy) and KAGRA (Japan). Together, they form an international network of highly sensitive detectors, enabling localization of gravitational wave sources and opening new windows to physics.

The Laser Interferometer Gravitational-wave Observatory (LIGO) employs a Michelson interferometer design. Its 4km arms are enhanced with Fabry-Pérot cavities to artificially

increase the effective arm length. These cavities are formed between the reflective surfaces of the input test mass (ITM) and the end test mass (ETM). Inside these arms, up to 750 kW of circulating power can theoretically be stored, but during the most recent observing run, LIGO only saw between 250-350 kW [3, 5]. LIGO’s Michelson interferometer also includes two additional mirrors: the power recycling mirror (PRM) and the signal recycling mirror (SRM). The power recycling mirror is placed between the laser and the beam splitter, and reflects light that has already traveled through the arms back into the interferometer [2]. In this way, the PRM increases the power in the interferometer cavities. Placed in the antisymmetric port, the signal recycling mirror works to resonantly build up the GW signal. Through a process known as resonant sideband extraction (RSE) [2], the SRM differentially extracts signals from a passing gravitational wave. In summary, light from the laser source is split into two paths by the beam splitter, reflects off the end mirrors, and is recombined at the beam splitter. When a gravitational wave passes through, it induces a phase shift on the laser light, which is then extracted as a signal at the detection output [2].

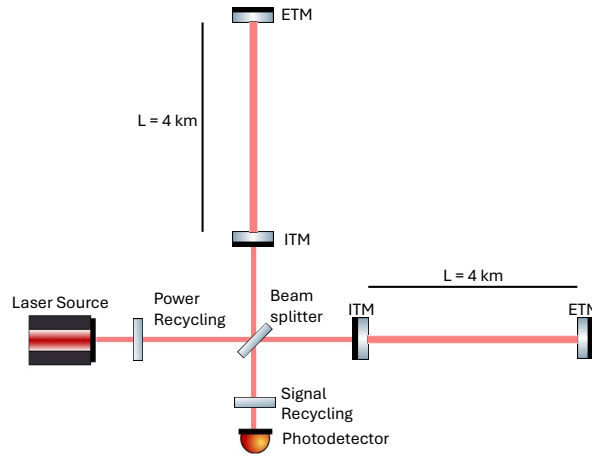


Figure 1: LIGO’s Michelson Interferometer design with Fabry-Pérot cavities, power recycling mirrors, and signal recycling mirrors.

2.2 Planned upgrades

As of writing, LIGO has completed four observation runs, and both detectors are now in a period of upgrades and commissioning. The fifth observing run (O5), set for 2028, will occur after a brief, six-month intermediate run (IR1) in 2027 [12].

Prior to the fifth observing runs, an incremental upgrade to aLIGO will leverage existing technology to improve the detectors. This upgrade is known as LIGO A+, and is intended to be a stepping stone to third generation detectors. A+ will bring the following enhancements: improved coatings, frequency dependent squeezing, boosted optical efficiency, balanced homodyne readout, an enlarged beam splitter, and improved suspension fibers [13]. After A+, are more key upgrades known as A#. In this batch of upgrades, LIGO will receive new optical coatings, larger 100 kg test masses, and significantly larger 1.5 MW of laser power [7].

These changes intend to push gravitational wave sensitivity by an order of magnitude each, see Fig. 2. More sensitive detectors can detect compact binary merger events at further

redshifts, and observe more events per year. A# detectors will see past a redshift of 5, and detect several thousand binary black holes and several hundred binary neutron stars annually [15]. Acquiring the sensitivities necessary to enable this science depends on reducing quantum noise.

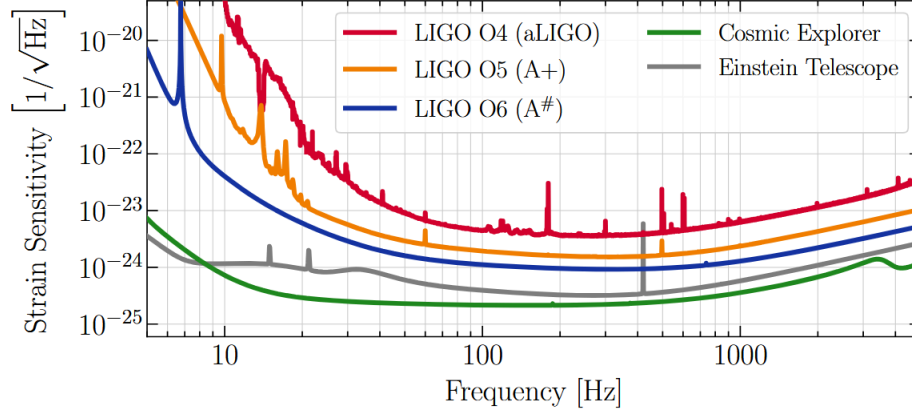


Figure 2: Planned sensitivities of upcoming LIGO upgrades. Projected sensitivities for Cosmic Explorer and Einstein Telescope are included as well [15]

The most significant noises in LIGO come in two types: thermal noise and quantum noise. Although the thermal noise contributes more in the mid-band, quantum noise dominates both low and high frequency regimes [5]. The origin of quantum noise lies in the quantization of the electromagnetic field used in the interferometer’s arms. Quantum noise is largely dominated by radiation pressure noise at low frequencies, and shot noise at high frequencies. In lower frequencies, amplitude-quadrature fluctuations physically displace the test masses by radiation pressure [2]. Higher frequency quantum noise is dominated by phase-quadrature fluctuations that result in shot noise [2]. In Fig. 3, it is easily seen that the quantum noise (shown in dashed purple) dominates the noise budget across most of LIGO’s detection frequencies.

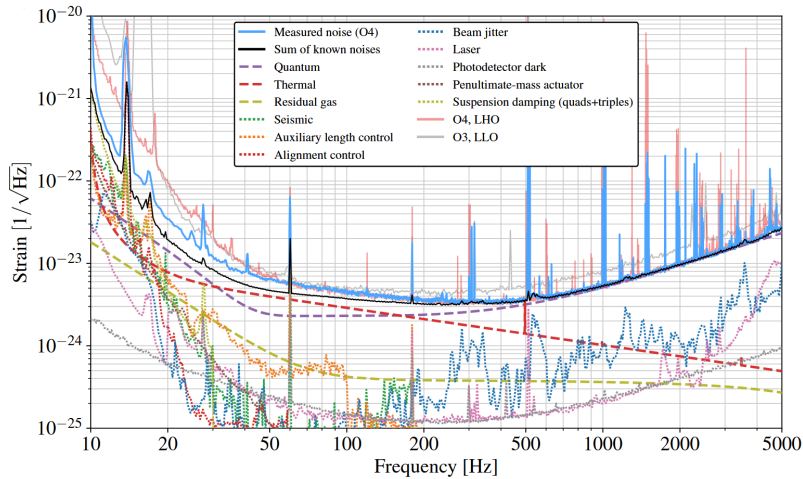


Figure 3: Noise budget for the LIGO Livingston observatory in the fourth observing run [5]

Quantum noise can be mitigated with increased laser power and squeezing. Higher laser power can reduce the shot noise as $1/\sqrt{P_{arm}}$. With the increased power, there is also increased radiation pressure noise as $\sqrt{P_{arm}}$ [2]. To mitigate the increased radiation pressure noise, frequency-dependent squeezed light is injected to the arms. This injection reduces amplitude fluctuations in the low frequencies, reducing the radiation pressure. It simultaneously reduces the phase fluctuations at high frequency, which reduces the shot noise [2].

Upgrading LIGO to meet the A+ and A# sensitivity targets depends on reducing quantum noise, which is achieved by maximizing laser power and implementing squeezing techniques to lower the noise floor as much as possible.

2.3 Thermal effects and FROSTI

Thermal effects in the optics limit both achievable laser power and squeezing levels. Absorption of higher laser power within the coatings of the test masses results in a radial temperature gradient in the optics and thermo-elastic surface deformation in the test mass [3]. Both of these effects result in thermo-elastic deformations of the optical surfaces and thermo-refractive lensing within the substrate. Higher levels of squeezing become ineffective if thermo-refractive lensing inside the ITM introduces too much wavefront distortion [14]. To mitigate the wavefront errors, LIGO currently uses the Thermal Compensation System (TCS).

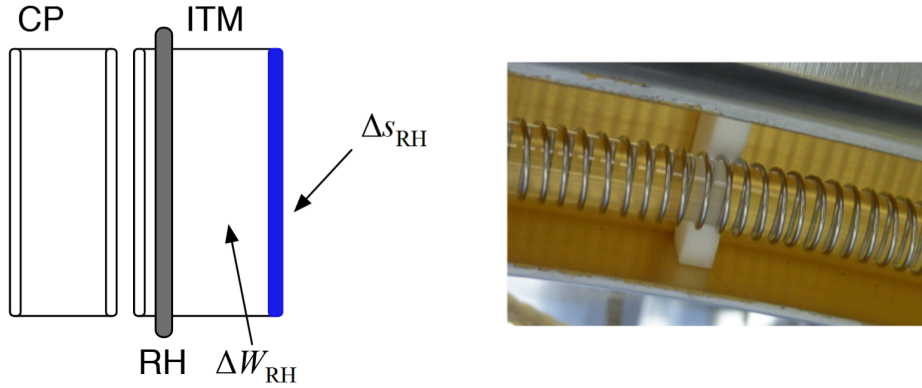


Figure 4: Overview of aLIGO ring heaters mounted as part of the Thermal Compensation System (TCS) [3]

As a part of the LIGO TCS, ring heaters (seen in gray and labeled RH in Fig. 4) are mounted along the barrel of the Initial Test-Mass ITM and End Test-Masses (ETMs). These ring heaters heat the optic to alter the surface curvature and substrate lenses. This results in a radially quadratic correction on the substrate and surface lenses, which is designed to mitigate the wavefront error in the center of the optic. Looking forward, the correction provided by the TCS is not sufficient for A# requirements. The residual wavefront errors on the LIGO's ITM can be seen in Fig. 5. Even with optimal TCS corrections, hundreds of nm of wavefront error persist. This residual wavefront error prevents A# targets of 1.5 MW of power and 10 db of squeezing [7].

The need to correct the remaining wavefront errors demands a new method of active wave-

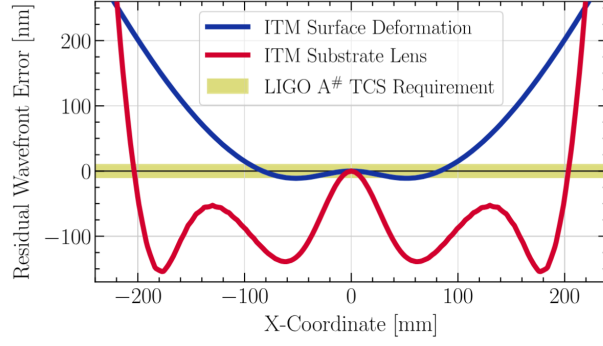


Figure 5: Residual wavefront error in LIGO A# 100 kg Initial Test-Masses (ITMs). [15].

front control. The group at University of California, Riverside has developed a system known as the FROnt Surface Type Irradiator (FROSTI). This active wavefront control is named for its ability to return the optic to its optically *cold* state [15]. It works by projecting 3-14 μm thermal radiation in an annular spatial pattern onto each test-mass. The heat is produced by an internal graybody source, and is reshaped by non-imaging reflectors which create the annular pattern. A graybody source is chosen for its ability to radiate with intensity stability near the shot-noise limit. FROSTI represents a new method of adaptive optics designed to operate under higher laser power [14].

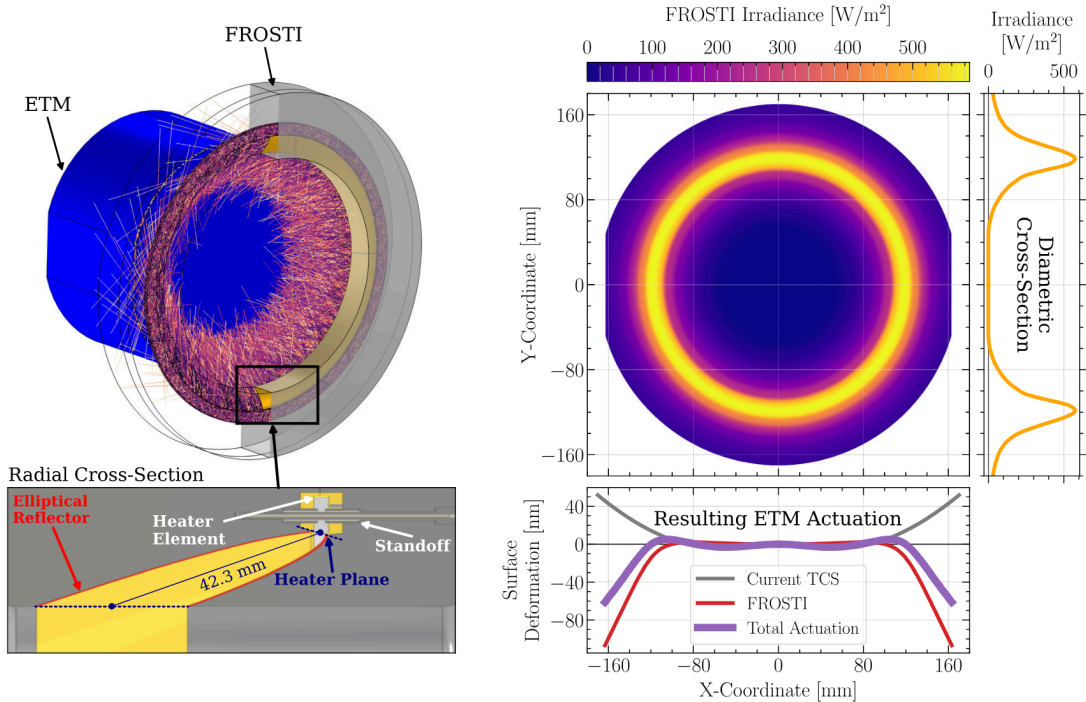


Figure 6: Ray tracing (left) and FEA (right) simulations of the FROSTI concept. Resulting surface deformation shown in the bottom right. The annular irradiance pattern designed to reduce thermal aberrations at the edges can be clearly seen [15].

A major experimental challenge is posed by the fact that the corrective heating is applied directly onto the highly-reflective surface of the test-masses. As these are the most displace-

ment sensitive optics, intensity noise from FROSTI will couple into optomechanical and photothermal displacement noise [2, 14]. The dominant source of noise coupling stems from photothermal "bending" caused by thermoelastic motion of the HR surface relative to its center of gravity. Quantifying FROSTI's relative intensity noise (RIN) is essential to ensure it meets LIGO stringent requirements.

For this purpose, we seek to develop an optical test bed designed to set improved upper limits on FROSTI's RIN (see Fig. 7 for current upper limit, seen in red). We can measure photon bunching, described the Hanbury-Brown-Twiss effect, which lies just above the shot noise produced by FROSTI's radiation. Detecting this relatively small effect would provide critical information about the system's noise performance. Successfully measuring this would demonstrate that FROSTI can operate near its theoretical noise floor.

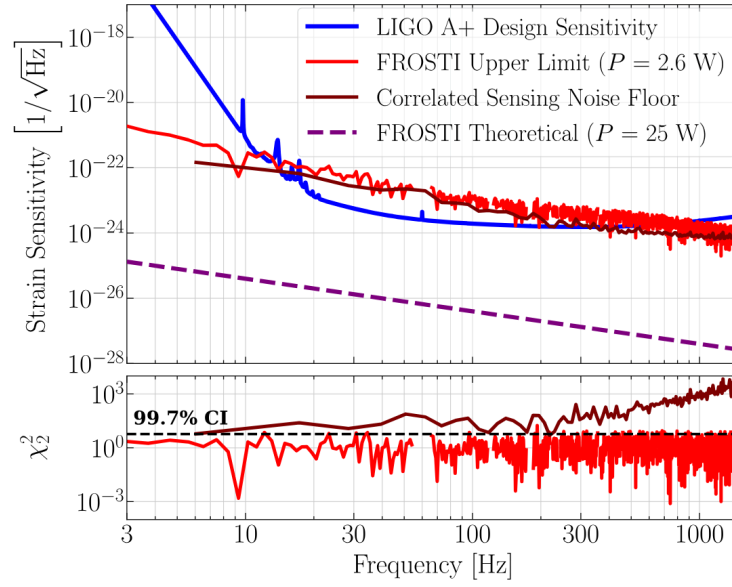


Figure 7: Measurement of relative intensity noise (RIN) of FROSTI prototype project into strain sensitivity. In blue, the LIGO A+ sensitivity target. In red, the experimental upper limit measured. In dashed purple, the theoretical noise limit of FROSTI. Finally, in maroon is the correlated sensing noise floor. Bottom figure is the reduced chi-squared statistic for the cross-spectra based measurements.[14]

3 Objectives

1. Design and construct the optical setup with the FROSTI instrument to measure the Hanbury Brown-Twiss effect
2. Construct a data analysis pipeline using the group's integrated Cymac system to analyze data

3. Investigate the characterization of dual RedPitaya STEMLAB 125-14 ADC performance

4 Approach/Method

4.1 Measurement of photon bunching

The cardinal objective of this project is to probe the measurement of Hanbury Brown and Twiss (HBT) correlations from photons in FROSTI's radiation [4]. The cross correlations described in this experiment come from temporal correlation of photons (which obey Bose-Einstein statistics) using an HBT apparatus.

An HBT apparatus is built such that photon bunching noise can be transformed to a signal [17]. A schematic of the optical setup can be seen in Fig. 8. Radiation from the FROSTI radiation is focused using a lens, and sent to the beam splitter. A 50/50 beam splitter directs half of the light to each respective identical photodetector.

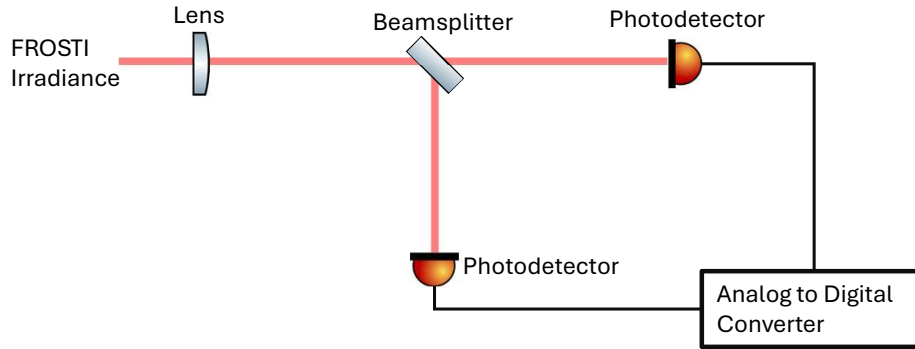


Figure 8: Apparatus designed used to measure photon bunching described by the Hanbury-Brown-Twiss effect.

The principal measurement of a photon "bunch" is as follows. As FROSTI uses a graybody source, photon emission is governed by the Bose-Einstein distribution [9]. This allows n photons to be excited for a given mode at a given frequency with a certain probability. A photon "bunch" contains $n > 1$ or significantly more incident photons on the beamsplitter [17]. When this bunching occurs, it is likely that some photons within the bunch are split to two different paths by the beam splitter. As this happens, the photodetectors along the two paths will read a *coincident* spike. Finally, an analog-to-digital converter (ADC) digitizes the data for further analysis.

The amplitude of the Cross Spectral Density (CSD) of the two time-domain data streams will spike at frequencies where they are correlated with some delay [10]. If found, this measurement would demonstrate FROSTI's ability to operate below LIGO's displacement noise requirements.

4.2 Investigation of dual ADCs

If time permits, this project will also seek to determine the performance of two, daisy-chained, RedPitaya STEMLab 125-14 ADCs. The current configuration relies on one ADC, the CyMAC system, which may limit more sensitive measurements of the intensity noise. When the photodetectors share the same ADC, any noise originating from the ADC will appear as coincident in the cross spectral density, complicating analysis. It is proposed to utilize two separate ADC cards for power spectral density (PSD) and cross spectral density (CSD) measurements. This approach could reduce correlated noise by eliminating a few shared noise sources. Some progress has already been made in comparing the dual RP configuration against the existing CyMAC [6] ADC. Further efforts are necessary to achieve a better measurement, particularly longer acquisition times.

5 Timeline

<i>Week Number</i>	<i>Objectives</i>
Week 1 (Remote) June 10th - June 17th	Procurement period - compile parts list, design optical system in Solidworks, place orders for necessary materials
LISA Symposium June 21st - June 26th	Parts arriving; Work will be paused to await shipping and attend LISA Symposium
Weeks 2 and 3 June 29th - July 10th	Construct optical system (assembly, alignment, data acquisition); Assemble dual RP data acquisition measurement
Weeks 4 and 5 July 13th - July 24th	Assemble FROSTI instrument and connect to measurement bench. Write interim project report. Begin taking measurements of ADC performance
Weeks 6 and 7 July 27th - Aug. 7th	Measurement campaign and complete cross correlation data analysis; Continued measurements on ADC performance
Week 8 Aug. 10th - Aug. 14th	Finalize data analysis; Complete other measurements necessary
Week 9 Aug. 17th - Aug. 21st	Write final paper and presentation.

Table 1: 9-week schedule for the project.

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