

Ice impact on thermal noise in cryogenic gravitational-wave detectors

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Future gravitational-wave detectors, such as the Einstein Telescope and Laser Interferometer Gravitational Wave Observatory (LIGO) Voyager, are planned to implement cryogenic technology. For the Kamioka gravitational wave detector, where cryogenics has already been adopted, issues related to the growth of an ice layer on mirror surfaces were reported. Further studies have confirmed the presence of nanometric layers in cryogenic experiments in which ice led to an increase in optical loss and to oscillations of the mirror reflectance. In this study, we investigate the mechanical loss of an ice layer grown on a silicon substrate. The results show that the total mechanical loss increases over time with the thickness of the ice layer, indicating that even a few nanometers of ice can impact the sensitivity of gravitational-wave detectors.

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I. INTRODUCTION

Gravitational waves, first theorized by Albert Einstein in 1916, were measured almost 100 years later for the first time in 2015 by the two detectors of the Laser Interferometer Gravitational Wave Observatory (LIGO) [1]. A few years later, in 2017, the first joint measurement was made between the LIGO detectors and the Virgo detector [2], giving rise to a new type of multimessenger astronomy [3]. Today, the gravitational-wave network consists of four kilometer-scale observatories: LIGO Hanford and LIGO Livingston [4], Virgo [5], and the Kamioka gravitational wave detector (KAGRA) [6].

Gravitational-wave detectors (GWDs) are among the most sensitive measurement devices ever built, capable of measuring length displacements that are a fraction of the diameter of a proton. However, the sensitivity of these kilometer-scale Michelson interferometers is limited by various noise sources, such as quantum noise [7] and mirror coating thermal noise (CTN) [8], which are among the ones that are limiting in the most sensitive frequency range. Future generations of GWDs will implement various technologies to reduce the different noise sources.

Among the technologies envisaged, cryogenics, already used in KAGRA, is planned for LIGO Voyager [9] and for future-generation detectors, such as the Einstein Telescope (ET) [10]. While for ET, a temperature of 10–20 K is envisioned as a baseline, an operation temperature of ≈ 120 K keeps being discussed as an alternative option [10]. For LIGO Voyager, also a temperature of ≈ 120 K is considered [9]. Both ranges, 10–20 K and ≈ 120 K, will be investigated in the ETpathfinder prototype [11].

Operating at cryogenic temperatures significantly reduces thermal noise in both coatings and substrates. However, only parts of the detector are cooled. Because of the resulting temperature gradient, molecules are more likely to be captured by the coldest surfaces, which act as cryopumps. This leads to a net migration of molecules towards the coldest regions, where they are adsorbed by the mirror surface, forming a growing ice layer. In GWDs, molecules can reach the cryogenic mirrors from two main sources: the residual gas in the cryogenic ultra-high-vacuum chamber and the room-temperature vacuum duct along the laser beam path. Simulations performed for the KAGRA detector indicate that the dominant contribution is expected to arise from the room-temperature beam duct, which is in direct line of sight of the mirror and leads to an estimated ice growth rate of about 42 nm/day [12]. The contribution from residual gas molecules in the cryogenic chamber is smaller and estimated to correspond to an ice growth rate of about 9 nm/day [13]. Although the effect of a deposited layer on mirror reflectance is known to be reduced for large deposition angles [14], molecules originating from the chamber walls are expected to reach the mirror with a

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broad angular distribution and may therefore have a weaker optical impact.

This phenomenon was first observed in KAGRA [12] and later confirmed by various tabletop experiments [15,16]. In these studies, it was shown that the ice layer negatively affects the detector sensitivity in several ways. Due to the increasing thickness of the ice layer, the reflectivity of the mirrors was found to oscillate, and additionally to decrease because of the optical absorption of the ice. The oscillations in reflectance translate into oscillations of the power in the detector, affecting quantum noise [12]. The ice growth rate in KAGRA was estimated, from a Monte Carlo simulation, to be 42 nm/day. In a separate study conducted in a small cryostat, the total thickness of the ice was found to be 4.13 nm after ten days [15], which was already sufficient to observe an increase in optical loss.

Considering the ice layer as an additional coating layer on the mirror surface, also a possible increase of CTN has to be considered. Based on this assumption, J. Steinlechner and I.W. Martin simulated the effect of an ice layer on the CTN in the ET low-temperature design [17]. Basing the simulation on literature values for the mechanical loss of ice [18,19], they showed that within a year of operation the total CTN would increase by up to a factor of 6.9 at 10 K or 9.4 at 20 K. It is not simply the presence of an ice layer that causes performance degradation in a cryogenic GWD, but also the fact that this layer continues to grow over time. In the case of ET, for example, this process could persist for months, making it a limiting and concerning phenomenon. While previous studies have addressed reflectivity effects and simulated CTN, the mechanical loss angle of ice grown under conditions relevant to GWDs remained unknown.

In this paper, we report measurements of the refractive index and mechanical loss of ice grown in a custom-designed cryostat, to reproduce similar ice deposition conditions to those expected in GWDs. The ice layer was grown on a float-zone silicon substrate, made of the same material intended for the future test masses of ETpathfinder [11], a cryogenic research and development (R&D) facility dedicated to the experimental demonstration of key technologies foreseen for the Einstein Telescope. Each ice growth process lasted for nearly a month at different cryogenic temperatures. To investigate the chemical composition of the layer, mass spectrometer analysis was performed while heating the system to induce sublimation of the adsorbed species. The measured mechanical losses of the ice were found to be comparable to those reported in the literature under different conditions [19], further validating our results.

II. EXPERIMENTAL SETUP

For this study, we used a closed-cycle cryostat, specifically a COOLPOWER 10 MDi, powered by a Leybold

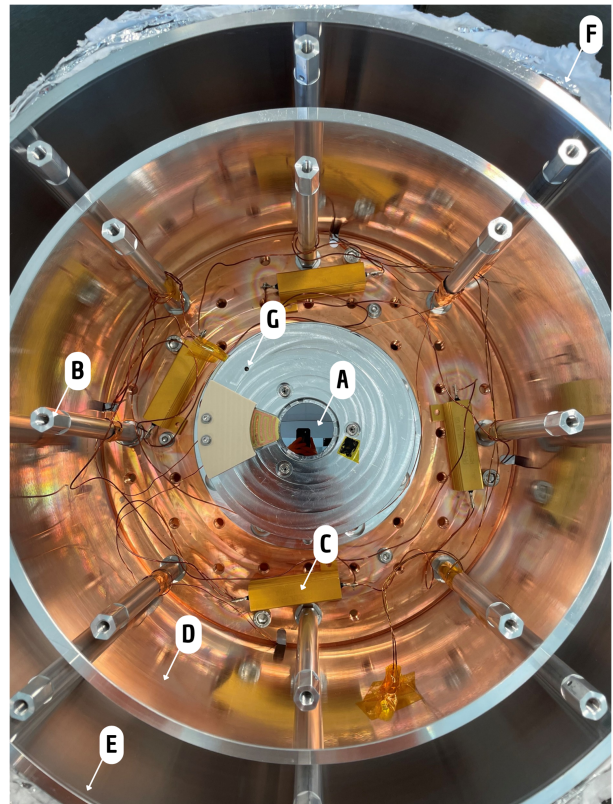


FIG. 1. Photo of the experimental chamber, where the GeNS (A) is placed in the center, surrounded by pillars (B) to improve thermal contact with the top lids and provide thermal anchoring for the electrical wiring. Four heating resistors (C) are placed on the base plate to allow for temperature-dependent measurements. The inner chamber is surrounded by the 20 K shield (D). The 70 K shield (E) is wrapped in multilayer insulation (F). A temperature sensor is placed in the aluminum GeNS support (G).

COOLPACK 5000i compressor unit.¹ The cryocooler had two stages, the first operating at a nominal temperature of 70 K and the second operating at a nominal temperature of 20 K.

The experimental vacuum chamber consisted of two smaller chambers surrounded by thermal shields (Figs. 1D and E) and lids. The base plates of the two chambers were thermally connected to the two cold plates of the cryocooler at the nominal temperatures of 70 K and 20 K, respectively. Columns connecting the base plates to the respective top lids were added to screw the lid and maintain better thermal conduction (Fig. 1B).

The inner vacuum chamber contains a gentle nodal suspension (GeNS) system [20] (Fig. 1A), used to suspend disk-shaped samples on a lens with a curved surface for mechanical loss measurements. To allow ice formation on the sample, two circular openings, one per each top lid, were added. These openings, positioned on top of the

¹<https://www.leybold.com/en>.

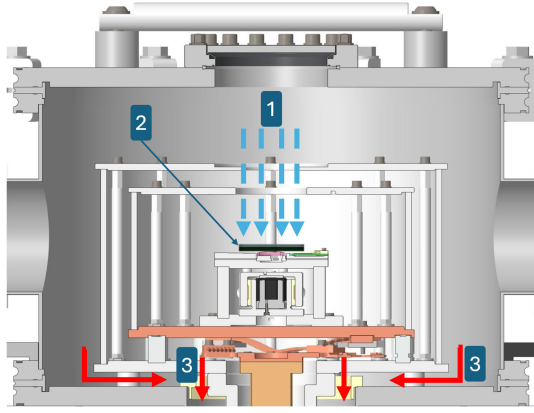


FIG. 2. Cross-sectional schematic of the experimental chamber. Molecules from the room-temperature volume can enter the cryogenic region through the apertures in the 70 K and 20 K shields. The blue-dashed arrows (1) illustrate the flow of molecules being directed and then condensed on the sample mounted on the GeNS (2). The red arrows (3) provide a simplified illustration of the gas flow related to the pumping system located underneath the chamber.

sample surface, create a direct connection between the room-temperature vacuum chamber and the cryogenic chambers, allowing for the cryopumping effect. Upon reaching the sample, these gas molecules condense on its surface, gradually forming the desired ice layer. A cross-sectional schematic of the experimental chamber is shown in Fig. 2. This schematic helps visualizing the position of the openings in the top lids. Arrows show a simplified air-flow direction due to the pumping system which is positioned below the vacuum chamber. The blue-dashed arrows highlight the flow of the molecules that contribute most to ice formation. The air contained in the internal 70 K and 20 K chambers is extracted through holes positioned in their respective base plates.

The cryocooler and the 70 K chamber were wrapped in multiple layers of multilayer insulation (Fig. 1F) to minimize radiative heat transfer from the surrounding 300 K surfaces. This insulation allowed the outer shield to be maintained at a temperature of 71 K.

A DT670B-LR silicon diode by Lake Shore Cryotronics² was placed into the GeNS aluminum support (Fig. 1G) to monitor the temperature of the inner vacuum chamber. Due to the relatively large opening in the lids, the inner vacuum chamber temperature only reached a minimum of 53 K, instead of the target temperature of 20 K. The temperature of a disk placed directly on the aluminum plate, i.e., with the GeNS lens removed, is therefore assumed to be 53 K. Under the same conditions, we monitored the temperature of a disk placed on the GeNS by attaching a second silicon diode to the surface of the disk and recorded a minimum temperature of 120 K. Consequently, we were able to

measure ice growth at temperatures as low as 53 K, but mechanical loss only at 120 K. The difference between the temperature of the aluminum part of the GeNS and that of the sample is attributed to the limited thermal contact between the lens of the GeNS and the lower surface of the sample. The system is also equipped to measure mechanical loss at temperatures higher than the lowest achievable one. To this end, heating resistor elements (Fig. 1C) are mounted on the cold copper plate.

III. REFRACTIVE INDEX AND GROWTH RATE ESTIMATION

The growth of an ice layer was tracked by analyzing the intensity of a laser beam reflected by the sample surface, which exhibits periodic variations due to the increasing thickness of the ice layer. This behavior is governed by thin-film interference, where the reflected light undergoes constructive and destructive interference depending on the film thickness. The incident laser beam was nearly normal to the surface, and a range of laser sources with output powers below 1 mW were used. The substrate was crystalline silicon with $\langle 100 \rangle$ orientation, which has a higher refractive index than ice.

When a thin film is deposited onto a substrate in a vacuum, the total reflectivity is given by [21]:

$$R = |r_{123}|^2. \quad (1)$$

The reflection coefficient r_{123} is defined in terms of the interface reflection coefficients r_{12} (vacuum-film) and r_{23} (film-substrate) as well as the phase shift (δ) induced by the film:

$$r_{123} = \frac{r_{12}r_{23}e^{2i\delta}}{1 + r_{12}r_{23}e^{2i\delta}}. \quad (2)$$

For a negligible incidence angle, the reflection coefficients can be expressed as:

$$r_{ij} = \frac{n_i - n_j}{n_i + n_j}, \quad (3)$$

where n_i and n_j are the refractive indices of the two media, with light propagating from medium i to medium j . The phase shift induced by the film becomes

$$\delta = \frac{2\pi dn_2}{\lambda}, \quad (4)$$

where n_2 is the refractive index of the film, d is the film thickness, and λ is the laser wavelength.

In our case, the film thickness changes over time, affecting the phase shift in Eq. (4) and causing Eq. (2) to oscillate. During the oscillations, the first reflectivity maximum occurs when the film reaches a thickness

²<https://www.lakeshore.com/>.

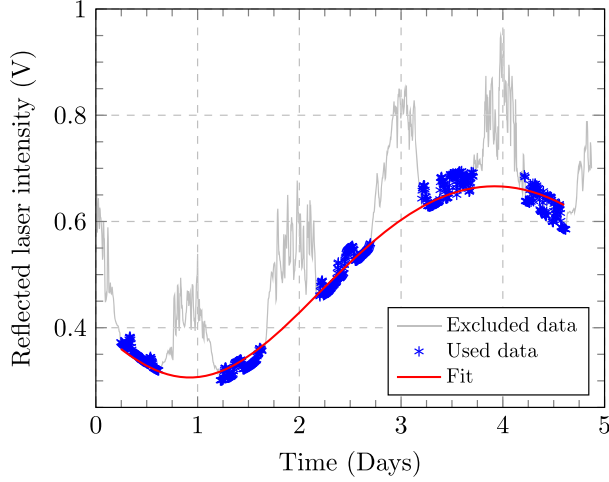


FIG. 3. Intensity data over five days where noise due to daylight (gray data points) has not been taken into account for the fit (red curve), which considers the remaining data (blue data points). The temperature was 120 K and the laser wavelength was 632 nm.

corresponding to a half-wave layer, $n_2 d = \frac{\lambda}{2}$, while the first minimum occurs when the film reaches a thickness corresponding to a quarter-wave layer, $n_2 d = \frac{\lambda}{4}$. Additional maxima and minima occur at optical thicknesses of even and odd multiples of $\lambda/4$.

In our measurements, the variables were intensity $I(t)$ and time t . The unknown parameters were instead the refractive index of the ice n_2 and the time-dependent thickness $d(t)$. Considering the refractive index of the vacuum as $n_1 = 1$, the refractive index of the silicon as $n_3 = n_{\text{Si}}$, and with I_0 being the intensity of the incident beam, Eq. (1) can then be rewritten as:

$$I(t) = I_0 \left| \frac{\left(\frac{1-n_2}{1+n_2} \right) + \left(\frac{n_2-n_{\text{Si}}}{n_2+n_{\text{Si}}} \right) e^{i \frac{4\pi d(t)}{\lambda} n_2}}{1 + \left(\frac{1-n_2}{1+n_2} \right) \left(\frac{n_2-n_{\text{Si}}}{n_2+n_{\text{Si}}} \right) e^{i \frac{4\pi d(t)}{\lambda} n_2}} \right|^2. \quad (5)$$

The reflectivity is monitored since the start of the cooling down. When the inner chamber is sufficiently cold, air molecules start to be pumped onto the sample surface to form the ice layer. We considered a linear growth rate (α) and the thickness can be written as:

$$d(t) = \alpha t. \quad (6)$$

IV. EXPERIMENTAL ICE GROWTH MONITORING

To validate the theoretical model and extract meaningful parameters for the ice layer, a set of three independent measurements was conducted under different experimental conditions. Each experiment aimed to track the optical interference pattern generated by the growth of the ice layer

on the surface of the silicon sample, allowing the simultaneous estimation of the refractive index of the ice and the growth rate using Eq. (5). The uncertainties associated with each fitted parameter—refractive index and growth rate—are calculated by plotting the χ^2 surface in the space of the fit parameters and by consequently determining the 1σ confidence interval.

These measurements also served as preparatory steps for mechanical loss characterization and to assess the reproducibility of the interference-based analysis in different optical and thermal configurations.

A. First measurement at 120 K and 632 nm laser: Ice growth related to mechanical loss

The first measurement was made at a temperature of 120 K, which is the lowest achievable by the sample without an improved thermalization as explained at the end of Sec. II. This experiment served as the reference for mechanical loss studies, as it was directly followed by ring-down measurements to quantify the effect of ice on the total mechanical loss, which is presented in Sec. VI. The sample was placed on the GeNS and a laser with a wavelength of 632 nm and output power of 0.8 mW was used to monitor the formation of the ice layer on the surface. Silicon refractive index used in Eq. (5) was $n_{\text{Si}} = 3.83$ [22].

The measurement began 21 days after the cryostat was turned on. The monitoring lasted for five days, during which the reflected laser intensity was recorded as shown in Fig. 3. Unfortunately, daylight affected the measurements, which can be seen from the noisy gray data. Therefore, all data segments affected by daylight oscillations, typically lasting eight to ten hours, were excluded from the fit.

The remaining data was analyzed with a two-parameter fit through Eq. (6), as shown in Fig. 3, revealing a refractive index of $n = 1.29 \pm 0.02$ and a growth rate of $\alpha = (42.2 \pm 0.2)$ nm/day.

B. Second measurement at 50 K with daylight shielding and 520 nm laser

The second measurement was carried out at a stable temperature of 50 K. Due to practical constraints, the laser source was replaced by a 520 nm laser with an output power of 0.9 mW. Silicon refractive index used in Eq. (5) was $n_{\text{Si}} = 4.12$ [22]. This experiment aimed to validate the presence of an ice layer in the system under more controlled optical and thermal conditions. With respect to the measurement in Sec. IVA, the photodiode was shielded from ambient light and the sample was placed in direct contact with the GeNS support, ensuring a more stable temperature and better thermal contact.

The measurement started at room temperature and lasted for 32 days as shown in Fig. 4. During this time, condensation occurred on the exterior surface of the viewport due to the high humidity in the laboratory, which introduced artifacts into the recorded signal. Although the

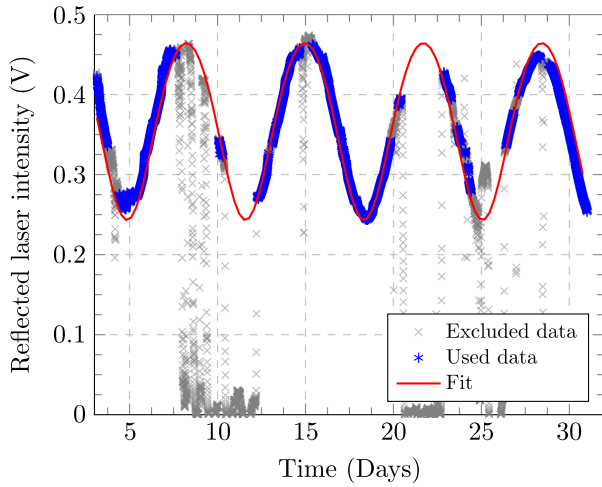


FIG. 4. Intensity data over 32 days where spikes due to water condensing on the system's viewport (gray data points) have not been taken into account for the fit (red curve) which utilizes the remaining data (blue data points). The temperature was 50 K and the laser wavelength was 520 nm.

affected data were excluded from the analysis, this contamination may still have influenced the accuracy of the fit. In particular, the first minimum (day 5), is clearly higher in comparison to the third one (day 18), which is the same for the first two maxima (days 7 and 15).

The remaining data were then fitted (see Fig. 4) using Eq. (6). From the fit we obtained a refractive index of $n = 1.26 \pm 0.01$, while $\alpha = (35.3 \pm 0.1)$ nm/day.

C. Third measurement at 50 K with 405 nm laser and optical filtering

The third measurement was performed at 50 K using a laser with a wavelength of 405 nm and output power of 0.9 mW. Silicon refractive index used in Eq. (5) was $n_{\text{Si}} = 5.28$ [22]. In this case, a blue filter was introduced in front of the photodiode to attenuate background light and isolate the laser signal more effectively.

The choice of the 405 nm wavelength, combined with a narrower filter, was aimed at achieving higher resolution in tracking the ice growth. However, the laser at 405 nm had relatively low output power, and the photodiode exhibited reduced sensitivity at this wavelength. As a result, the detected signal was weak and noisy, limiting the precision of the interference pattern acquisition. Abrupt intensity spikes were observed after six and 20 days. This is likely to be attributable to a mechanical disturbance on the optical table, possibly a slight displacement of a component that was not properly secured, which may have altered the beam alignment or optical path. As a result, the experimental curve slightly deviates from the fitted model, though the overall trend remains consistent.

The measurement started at room temperature and was carried out continuously for 27 days. As shown

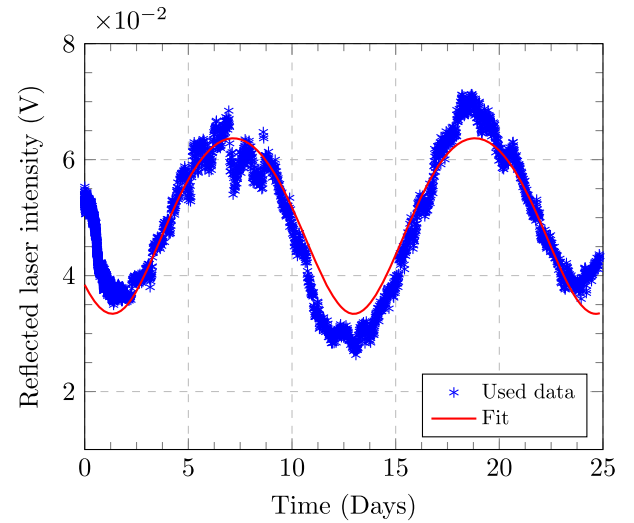


FIG. 5. Intensity data over 25 days. The fit (red curve) in this case utilizes all the data (blue data points). The temperature was 50 K and the laser wavelength was 405 nm.

in Fig. 5 no significant condensation effects were observed on the viewport. The fit of the data yielded a refractive index of $n = 1.34 \pm 0.01$, a growth rate of $\alpha = (13.0 \pm 0.1)$ nm/day.

V. MOLECULAR LAYER COMPOSITION

During the third experimental run dedicated to monitoring the ice growth, an RGA, model PrismaPro,³ was integrated into the system to allow mass spectrometry *in situ* while heating the system through resistive elements (see Fig. 1) after the ice measurement was completed. The aim was to capture the sublimation of the ice layer deposited on the surface of the sample. The analysis of the desorbed molecular species was intended to provide insight into the composition of the ice layer. The goal was to establish that the deposited material consisted predominantly of amorphous ice formed under low-temperature and low-pressure conditions within the cryostat.

Due to operational constraints, the RGA was switched off at 130 K and the measurements were later resumed at 140 K. As a result, measurements were acquired in two separate temperature intervals, together covering the range from 90 to 180 K. Furthermore, no calibration of the RGA was performed prior to the measurements, which prevents quantification of the absolute amount of each detected species. Consequently, the data presented in Fig. 6 are expressed in terms of relative intensity, normalized to the maximum value observed within each temperature interval. For clarity, only the molecular species that show the most significant variations during the warm-up are reported in the plots. In both panels of Fig. 6, the x-axis corresponds to

³<https://www.pfeiffer-vacuum.com/global/en>.

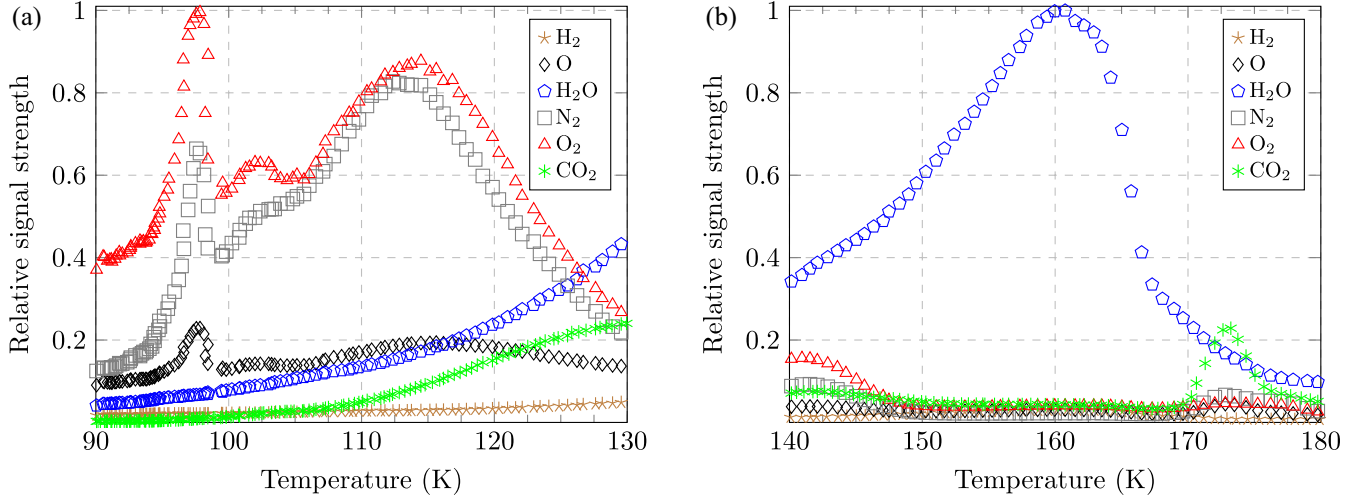


FIG. 6. Relative signal strength of selected molecular species measured via residual gas analyzer (RGA) during the cryostat warm-up phase. Between 90 K and 130 K (a) N₂ and O₂ have been released, while (b) H₂O has been released at about 160 K. All curves are normalized to the maximum detected value within each temperature range. As a result, qualitative comparisons can be made within a given panel, but comparisons across different panels are not meaningful.

the temperature of the cryostat during the warm-up phase, while the y-axis shows the relative intensity of each species detected by the RGA. The RGA signals were interpolated to the temperature measurements, so small fluctuations in the temperature readout appear as corresponding oscillations along the x-axis. Two distinct desorption events were observed. In Fig. 6(a), around 97 K and 115 K, the release of molecular nitrogen (N₂) and oxygen (O₂) is evident. Although mass 28 could also correspond to carbon monoxide (CO), the absence of a simultaneous carbon peak together with the simultaneous presence of the oxygen peak supports the assignment to molecular nitrogen. The release of frozen nitrogen could indicate the presence of a leak in the system or a virtual leak due to the use of multilayer insulation. The temperature was measured at the GeNS, in the center of the internal chamber, and the occurrence of two nearby peaks is expected because different parts of the system may have reached the temperature for releasing oxygen and nitrogen at different times. In Fig. 6(b), a more pronounced desorption of water (H₂O) is observed near 160 K, accompanied by a smaller increase in CO₂.

VI. ICE MECHANICAL LOSS

In this section, we present the results of the mechanical loss measurements performed on a 2" diameter, 5 mm thick crystalline silicon disk. The measurement procedure involves a GeNS [20], where a sample is balanced on a lens. The process of placing the disk in equilibrium on the lens is referred to as a suspension, and performing multiple suspensions of the same sample usually is necessary to reduce the variability induced by the operator. While in equilibrium, the sample's vibrational modes are excited using a comb-shaped capacitor driven by an AC voltage.

Mechanical losses are then measured using the ring-down method.

The sample was part of a batch of 15 geometrically identical disks, for which the error in mechanical loss of each mode, evaluated in multiple suspensions, has previously been identified to be at most 10% of the measured value [23]. Specifically, the reported study considered about three suspensions per sample and about five ring-down measurements per mode. For this reason, the same 10% relative error is assumed here for each frequency. However, because of the impossibility of reproducing identical ice layers in repeated suspensions, mechanical losses have been measured only for one suspension and with two ring-down measurements per mode.

The ice layer has been considered as a coating, and its contribution has been obtained using [24]:

$$\phi_{\text{ice}} = \frac{Y_s t_s (1 - \nu_c)}{3 Y_c t_c (1 - \nu_s)} (\phi_{\text{total}} - \phi_{\text{substrate}}), \quad (7)$$

where the thickness for the ice layer has been obtained considering $t_c = \alpha \times \text{days}$, with $\alpha = 42.2 \text{ nm/day}$. The mechanical parameters used in Eq. (7), listed in Table I, were taken from literature. Specifically, the Young's modulus of amorphous ice was taken from Hessinger *et al.* [19], who measured the elastic properties of thin ice films at

TABLE I. Mechanical parameters for substrate and coating.

Material	Y (GPa)	ν	Thickness (m)
Silicon	169 [25]	0.28 [25]	0.00515
Ice (21 days)	3.46 [19]	0.30 [26]	8.862×10^{-7}
Ice (26 days)	3.46 [19]	0.30 [26]	1.097×10^{-6}

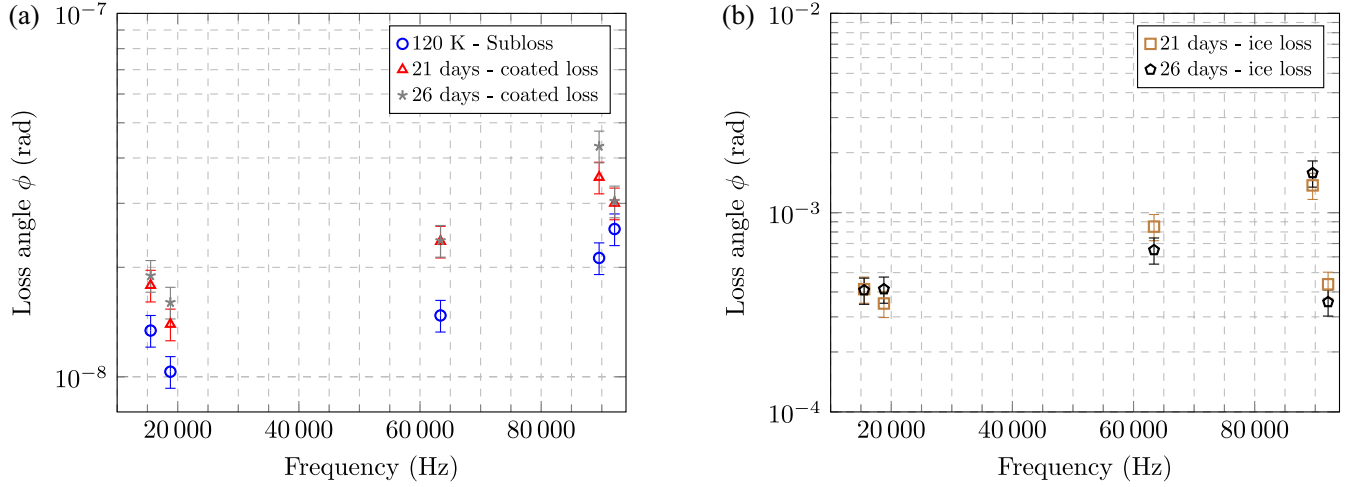


FIG. 7. Mechanical loss at a constant temperature of 120 K. (a) The first measurement (blue circle) constitutes the substrate loss for the related ice loss calculation. Ice plus silicon losses have been measured after 21 days (red triangle) and 26 days (gray star). The ice mechanical losses (b) were calculated as coating loss after 21 days (brown square) and after 26 days (black pentagon).

cryogenic temperatures. The Poisson's ratio was taken from Gromnitskaya *et al.* [26], who experimentally measured the elastic properties of amorphous ice at cryogenic temperatures, including at 120 K. In our setup, the ice layer formed under low-temperature and low-pressure conditions similar to those found in space, where high-density amorphous ice is known to form [27]. Given this similarity, we consider their measured value a suitable reference for estimating the mechanical behavior of the ice formed in our experiment. Furthermore, for calculating the ice mechanical loss, the assumption of a homogeneous ice layer thickness across the sample was made.

We have monitored the loss of the disk at the beginning when there was no ice, after 21 days, and again after 26 days. The coating losses, shown in Fig. 7, were calculated from Eq. (7). The coating loss values, per resonant frequency, of the ice layer, shown in Fig. 7, are expressed in Table II.

VII. IMPACT ON COATING THERMAL NOISE

Using the average mechanical loss result of 6.6×10^{-4} obtained, the impact of CTN in the Einstein Telescope was

TABLE II. Ice loss-angle values after 21 and 26 days. All values must be multiplied by 10^{-4} , a factor omitted in the table for readability. Each value corresponds to a different resonant mode. The quoted uncertainties include the error on the growth rate and a 10% contribution from the substrate.

Modes	21 days	26 days
$(0, 2)_1$	4.03 ± 0.43	3.92 ± 0.43
$(0, 2)_2$	3.50 ± 0.37	4.35 ± 0.48
$(0, 4)_2$	8.51 ± 0.89	7.00 ± 0.77
$(1, 2)_1$	13.7 ± 1.43	17.0 ± 1.86
$(0, 5)$	4.37 ± 0.46	2.67 ± 0.24

estimated. Since CTN scales linearly with the layer thickness, the total impact is obtained by multiplying this intrinsic loss by the thickness of the deposited ice. The CTN baseline was chosen identical to that used in [17]. For simplicity, the ice growth was assumed to be identical on all test masses.

Figure 8 shows the envisioned CTN in the Einstein Telescope at 120 K without ice growth (red, constant line identical to [17]). The red, oscillating line shows the total CTN for a growing ice layer as a function of ice thickness. The oscillation results from the changing light field buildup as the ice layer grows—see [17] for more detail. After growth of approximately 100 nm, the contribution of the ice layer to the total CTN exceeds 20%.

The blue constant and oscillating lines show an extrapolation of the 120 K measured data to 10 K. The anticipated reduced CTN level originates from the change in temperature and the reduced CTN of the mirror underneath the ice. The dashed, gray line shows CTN assuming a mechanical loss of ice reduced by a factor of two at 10 K compared to 120 K, as expected based on literature [17–19]. The parameters used for calculating CTN are listed in Table 1 in [17], except for the mechanical loss of ice, for which our measurement results were used.

VIII. SUMMARY AND DISCUSSION

The primary goal of this study was to investigate the mechanical loss of ice grown under conditions—i.e., angle of incidence, growth rate, and substrate material—similar to that in future gravitational-wave detectors. Two growth measurements were used for confirming the reproducibility of the reflectivity investigation and the overall stability of the ice growth process, while from the third measurement series, the mechanical loss was extracted.

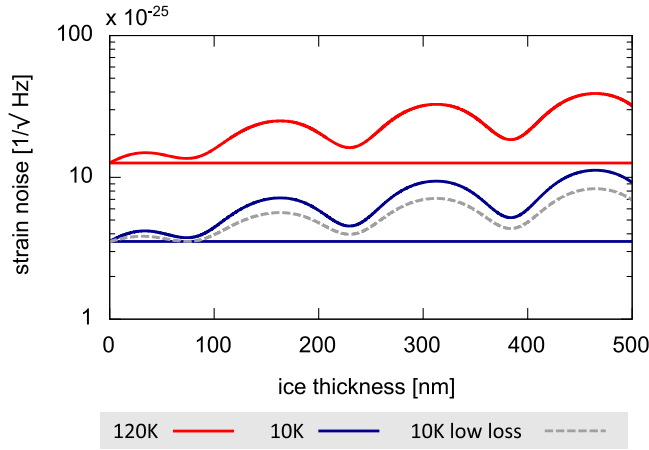


FIG. 8. CTN at a frequency of 10 Hz without ice growth (straight lines) and with ice growth (oscillating lines) at 120 K and at 10 K as a function of ice thickness. The ice mechanical loss measured at 120 K was used for simulations shown by the solid lines. The dashed line shows a CTN estimate at 10 K for an assumed two times reduced mechanical loss of ice. The straight, blue line also marks the design CTN level of the Einstein Telescope [10,28].

The growth rates obtained were 42.2 nm/day for the 120 K case, 35.3 nm/day for the second measurement at 50 K, and 13.0 nm/day in the third. The corresponding refractive indices were $n = 1.29$ at 632 nm, $n = 1.26$ at 520 nm, and $n = 1.34$ at 405 nm, respectively. The variation observed in the measured growth rates and refractive indices can be attributed to specific experimental conditions. These include the optical wavelength used in each test, which affects the resolution and contrast of the interference pattern, the temperature of the sample, the condensation of water on the viewport in the second experiment, and the intensity of the laser beam. Furthermore, differences in ambient humidity, the level of shading from daylight, and the degassing state of the cryostat at the time of each run probably contributed to the observed discrepancies. However, despite being performed under different optical and thermal configurations, all tests revealed growth rates of the same order of magnitude, supporting the consistency of the deposition conditions across different runs.

It should be noted that the laboratory is not a clean-room environment and the ambient humidity is uncontrolled, a factor that clearly affected the second test, which was conducted under particularly humid conditions. Although the second test occurred closer in time to the third than to the first, the growth rate observed in the third was significantly lower, although it was of the same order of magnitude. A similar consideration can be made for the refractive index obtained in the third experiment. The presence of CO_2 released together with water allows us to assume that the layer was partly composed of CO_2 . At the same time there was no release of N_2 together with the one of H_2O , which indicates the absence of trapped nitrogen molecules in the

layer [29]. The mixed composition $\text{H}_2\text{O}:\text{CO}_2$, possibly including an apolar component, could therefore explain the higher refractive index obtained in the third measurement [30]. In contrast, the refractive indices from the first two measurements are consistent with those of amorphous ice at the same wavelength and temperatures [15].

For the first time in the context of gravitational-wave detectors, we have experimentally observed an increase in mechanical loss due to the formation of an ice layer, using a setup that closely reproduces realistic cryogenic conditions. The average mechanical loss of ice was found to be 6.6×10^{-4} and therefore resembles literature values, even though these were obtained under different growth conditions [18,19].

From the RGA measurements performed during warm-up, it is clear that, in our experiment, most of the desorbed material was released below 180 K. This suggests that, at least under conditions similar to those of our experiment, complete warming to room temperature may not be required, but that warming of the relevant cryogenic components to temperatures of about 180 K could already be sufficient. This observation may be relevant for future cryogenic GWDs, as limiting the temperature required for ice removal could significantly reduce the time needed for both warm-up and subsequent cooldown. This result may help guide the development of strategies to mitigate ice accumulation while minimizing detector downtime.

It should be emphasized, however, that the present study does not address several important aspects related to ice removal and subsequent re-adsorption, such as molecular re-adsorption during the recooling phase deserves further consideration. Such a process is possible and is expected to depend strongly on the warm-up strategy adopted, since the released molecules may preferentially recondense on the coldest surfaces available within the system. If these surfaces include suspension elements, the resulting ice accumulation could potentially affect suspension thermal noise. Furthermore, adsorption is already expected to occur during the cooling phase of the detector, as seen in Fig. 5. This does not only imply new ice to have grown already again once the detector reached operating temperature, but also that, if the system is cooled down too rapidly after warm-up, the pumping system may not have sufficient time to remove all the desorbed molecules from the vacuum chamber. As a result, part of the released material could be re-adsorbed onto cryogenic surfaces before the detector reaches its nominal operating temperature adding to the ice growth.

While the analysis presented in Sec. VII assumes identical ice growth on all mirrors, in reality the ice thickness could vary between the different test masses. Assessing the consequences of asymmetric ice growth therefore represents an important topic for future detector-level studies.

We believe that this work can serve as a baseline for the development of a setup that allows measurements in the 10–20 K regime, where all the lessons learned from the present experiment could be implemented to further verify the behavior of the growing ice layer and its impact on the CTN.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [31].

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