Physics Letters A 372 (2008) 5741–5744

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Discharging fused silica test masses with ultraviolet light

D. Ugolini [a,*], M. Girard [a], G.M. Harry [b], V.P. Mitrofanov [c]

[a] Department of Physics and Astronomy, Trinity University, San Antonio, TX 78212, USA
[b] LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[c] Faculty of Physics, Moscow State University, Moscow 119992, Russia

ARTICLE INFO

Article history:
Received 29 February 2008
Received in revised form 11 June 2008
Accepted 15 July 2008
Available online 22 July 2008
Communicated by P.R. Holland

ABSTRACT

A Kelvin probe and tunable light source were used to study fused silica discharging by UV illumination. The discharge rate scales linearly with charge magnitude and illumination intensity. Optimal discharging occurs at 215 nm, likely due to absorption by E' centers. 90% discharge corresponds to $\sim$0.1 J cm^{-2} incident energy.

1. Introduction

Charging is a potentially limiting noise source for both gravitational-wave interferometers [1–3] and other precision measurements of gravitational effects [4,5]. At the Laser Interferometer Gravitational-Wave Observatory (LIGO) [6], charge may build up on the surface of suspended fused silica test masses. Charging can occur due to friction between dust and the test mass surface (particularly when the system is being pumped to vacuum), the deposition of excess electrons from a cosmic ray striking the beam pipe [7], or from contact between the test mass and other materials such as viton-tipped earthquake stops, designed to protect the test mass by limiting its range of motion. Measurements of fused silica optics in vacuum have shown a substantial charging rate of $\sim 10^5$ e^- cm^{-2} month^{-1} [8].

There are several potential noise contributions from charging [9]. Surface charge would generate electric fields that induce a force between a test mass and its metallic suspension frame, displacing the mass beyond the range of its positioning magnets. Sudden changes in charge magnitude or position would discontinuously change this force, moving the test mass in a way that mimics a gravitational-wave burst signal. In the Laser Interferometer Space Antenna (LISA), for example, charge fluctuations from cosmic ray impacts could cause test mass acceleration noise of as much as 1.5×10^{-15} m s^{-2} Hz$^{-1/2}$, exceeding the overall noise budget at the low-frequency end of LISA's sensitivity band [10]. Moving charges would generate fluctuating electric fields that could displace the test mass at frequencies in the interferometer's sensitive band. And static charges could attract dust to the surface of a test mass, reducing optical reflectance and increasing absorption, making thermal compensation more difficult [11].

One possible solution for test mass charging is to discharge through UV illumination. This technique was used for Gravity Probe B, in which the charged surface and an adjacent "charge control electrode" were illuminated with UV light in order to discharge electrons by the photoelectric effect [12]. The net direction of charge flow could then be controlled by adjusting the voltage of the control electrode—a positively-charged surface could be discharged by receiving electrons liberated from the electrode. Researchers at the University of Glasgow found that UV radiation from an ion pump was causing negative charging of an optic by liberating electrons from the walls of a vacuum chamber; illuminating the optic with a UV lamp reversed the effect [2]. Measurements at the GEO 600 gravitational-wave observatory have also shown a substantial reduction in positive charge on a test mass by shining light on a control cathode [13].

A concern with this technique is that exposure to UV light over time may damage the test mass reflective coatings, increasing absorption at the infrared wavelength used in the LIGO interferometers. Experimenters at Stanford University are currently measuring the absorption of a fused silica test mass exposed to a UV LED to quantify this effect [14]. The goal of this project was to measure discharging rate as a function of UV intensity and wavelength. This will allow a determination of the minimum power level required for discharging, which can then be compared to the Stanford absorption measurements to see if UV illumination is a viable discharging technique. In order to maintain maximum fidelity with the conditions of the LIGO experiment, fused silica samples are chosen using the substrate and coating choices for Advanced LIGO [15], charged through contact with the same viton used on LIGO suspension earthquake stops, and measured in an ultra-high vacuum.

* Corresponding author.
E-mail address: dugolini@trinity.edu (D. Ugolini).

0375-9601/$ – see front matter
doi:10.1016/j.physleta.2008.07.035

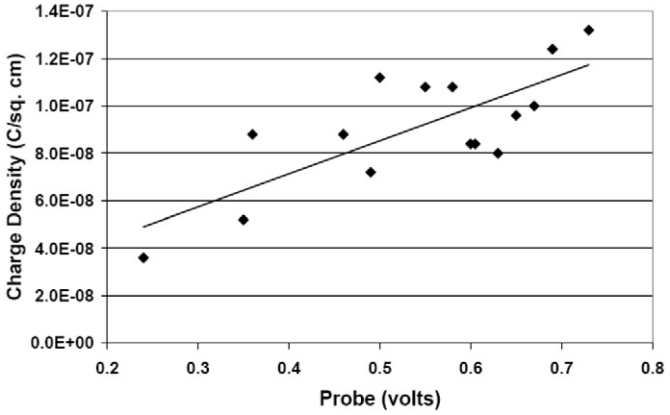

Fig. 1. Calibration of Besocke Kelvin probe with Alphalab surface DC voltmeter.

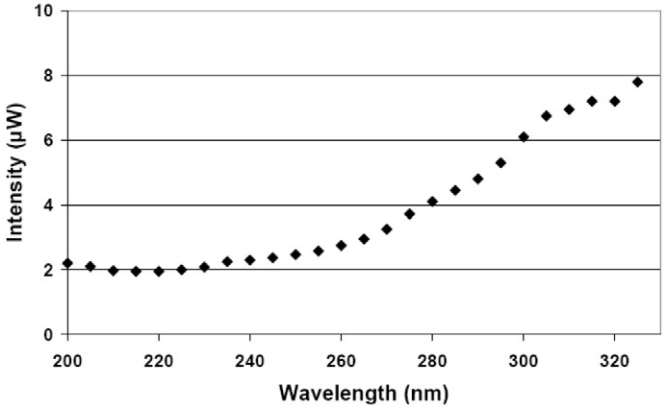

Fig. 2. Measured intensity of the Xenon based light source at UV wavelengths.

2. Experimental setup

The charge measurements were made with a capacitive device called a Kelvin probe. A charge layer on a sample induces a voltage that causes opposite charge to flow to the surface of the probe element. Modulating the capacitance creates an alternating current signal proportional to the potential difference between the probe and sample, which depends on the magnitude of charge on the sample [16]. The modulation can be achieved by vibrating the probe tip with a piezoelectric transducer (PZT) or voice coil, or by periodically occluding the sample with an optical chopper [17]. The AC signal is read with a lock-in amplifier set to the modulation frequency; the sign of the charge can be determined from the phase difference between the modulation and the probe signal.

We used a Kelvin Probe S from Besocke delta phi GmbH. The probe has a 2.5 mm diameter electrode which is vibrated vertically at an amplitude of 0.5 mm by a PZT. One lead of the AC signal to our lock-in amplifier was connected to the probe element, and the other was grounded to the vacuum chamber. The probe was found to be sensitive to 0.1 mV, and a charged fused silica sample at 10^{-6} Torr gave a signal constant to this precision over several hours of measurement.

We calibrated the probe using a 15 cm by 10 cm clear acrylic sample, which was charged by rubbing with felt. The charge was measured in air simultaneously by the probe at 1 mm from the sample (the same spacing later used with our fused silica samples) and an Alphalab surface DC voltmeter at 25 mm. The voltmeter reading was then converted to a surface charge density. Fig. 1 shows the results of many such measurements; the scatter is a result of the voltmeter averaging the charge over a larger area than the probe. A linear fit gives a calibration of $(1.4 \pm 0.3) \times 10^{-7}\ \mathrm{C\,m^{-2}\,V^{-1}} = (8 \pm 2) \times 10^{7}\ e^{-}\,\mathrm{cm^{-2}\,V^{-1}}$. Thus the probe sensitivity of 0.1 mV corresponds to a minimum charge resolution of $(8 \pm 2) \times 10^{3}\ e^{-}\,\mathrm{cm^{-2}}$. Over several trials, the signal from a charged fused silica sample varied by less than 5% during pumpdown from air to vacuum, so the calibration also applies in vacuum to within the uncertainty of the measurement.

The UV light source was a 175 W Xenon based lamp from Spectral Products. At the output is a monochromator with a 2400 line $\mathrm{mm^{-1}}$ grating, allowing wavelength selection from 190–680 nm. Fig. 2 shows measurements of the lamp intensity at UV wavelengths with 0.6 mm wide apertures at the input and output of the monochromator. The spot size at the charged sample is roughly 4 $\mathrm{cm^2}$ in area, so we are working with intensities of approximately 0.5 $\mu\mathrm{W\,cm^{-2}}$ over this range of wavelengths.

The vacuum chamber is a 60 cm long, 20 cm diameter cylinder, with a Pfeiffer Vacuum TSH-071E turbomolecular drag pumping station to generate pressures down to 4×10^{-7} Torr. At one end of the chamber, facing our UV light source, is an MDC Vacuum quartz viewport with a transmission of nearly 95% at wavelengths down to 200 nm. The Kelvin probe power and signal wires run through separate feedthroughs at opposite sides of the chamber to minimize noise pickup.

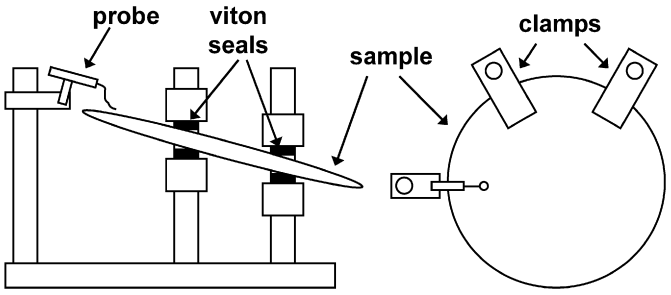

Fig. 3. Side view (left) and top view (right) of Kelvin probe experimental setup.

3. Discharging measurements

The samples were superpolished Corning 7980 fused silica substrates, 7.6 cm in diameter and 0.25 cm thick. One of the samples had a thirty layer, quarter wave stack of titania-doped tantala/silica with silica as the top layer as a high reflection coating on one side. Both samples were chosen as representative of Advanced LIGO coatings and substrates.

A diagram of the experimental setup is shown in Fig. 3. The samples were mounted at a 15 degree angle to the horizontal, facing the UV light source, and were held in place with two viton-tipped clamps. The Kelvin probe is mounted on a post on the opposite side of the sample from the light source, with the probe element 1 mm above the sample. The samples were charged through contact with a viton O-ring, then brought down to vacuum and illuminated with UV light while the charge level was measured with the Kelvin probe. Note that the Kelvin probe measurements indicated that the sample was positively charged after contact with the viton; this will be further discussed at the end of this section.

Fig. 4 shows the rate of discharge (given by the change in the Kelvin probe reading per second) versus total charge, measured over 15 hours with a single sample and a UV wavelength of 215 nm. There is a clear linear relationship between the discharge rate and total charge. This allows us to compare future discharge measurements made at different starting charge levels, by correcting all measurements to a standard initial charge. It also implies that UV illumination may be adequate for dealing with uneven distributions of charge across the test mass surface. Since the discharge rate scales with charge density, areas of high charge density

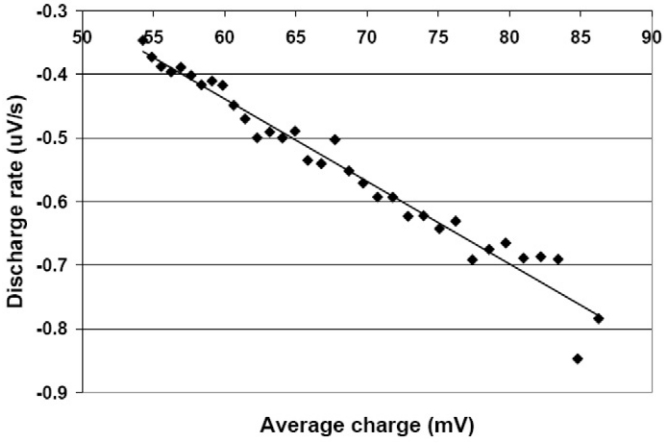

Fig. 4. Relationship between discharge rate and charge on sample at 215 nm.

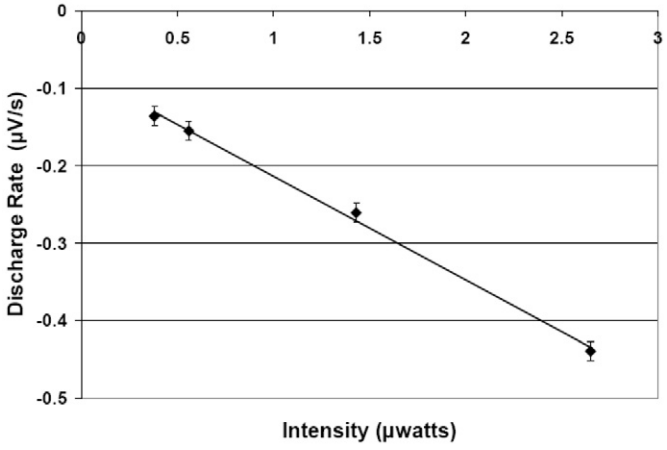

Fig. 5. Relationship between discharge rate and UV illumination intensity.

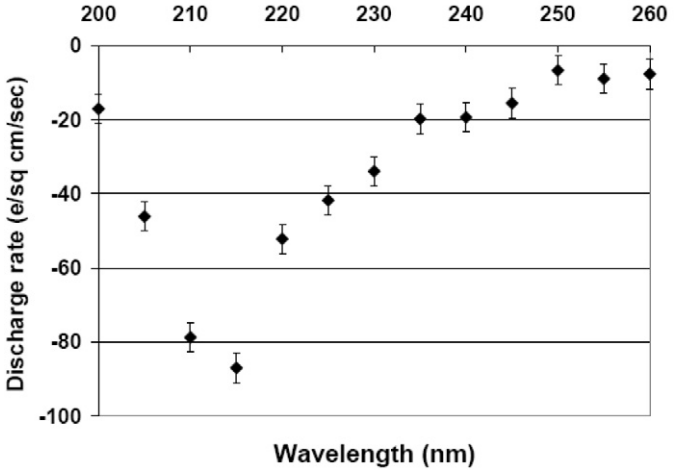

Fig. 6. Discharge rate versus UV illumination wavelength for uncoated fused silica sample.

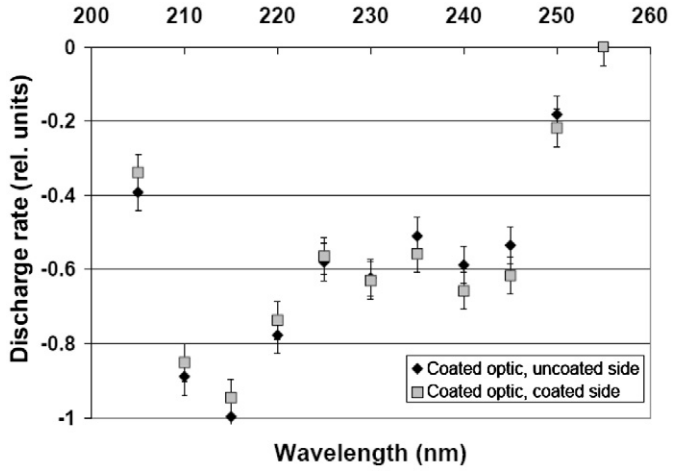

Fig. 7. Discharge rate versus UV illumination wavelength for the coated and uncoated sides of a single fused silica sample.

will discharge more rapidly than areas of low charge density, resulting in a more even distribution over time.

Similarly, Fig. 5 shows the discharge rates for different UV light intensities at the same wavelength, accomplished by inserting different aperture widths at the monochromator output. This allows us to compensate for the varying intensities of the light source at different wavelengths, by correcting all measurements to a standard intensity.

A representative measurement of the uncoated sample discharge rate is shown in Fig. 6, normalized to an illumination intensity of 0.5 $\mu W\,cm^{-2}$ and a charge magnitude of 8×10^6 $e^-\,cm^{-2}$ (equal to a probe reading of 100 mV). The 200 nm discharge rate is rechecked every fourth measurement, to ensure that there is no consistent trend in our results that would indicate systematic error. The statistical fluctuation in the measurements at 200 nm are also used to determine error bars. When the sample is brought back to atmospheric pressure, recharged, and remeasured, the shape of the curve versus wavelength remains the same, but the absolute discharge rate can vary by as much as a factor of two.

Fig. 6 allows an order-of-magnitude estimate of the UV light energy necessary to discharge the sample at the optimal wavelength of 215 nm. In one second the charge magnitude is reduced by a fraction of approximately $80/(8 \times 10^6) = 10^{-5}$ of its original value. The linear relationship between charge magnitude and discharge rate implies an exponential discharge over time, which implies a time constant $\tau = 10^5$ s. This corresponds to a time of 2.3×10^5 s for 90% discharging, and multiplying by the illumination intensity gives a total incident energy of 0.11 $J\,cm^{-2}$ for 90% discharging.

The optimal wavelength of 215 nm is strongly suggestive of the optical absorption band of 5.83 eV (equivalent to a wavelength of 213 nm) associated with paramagnetic E' centers in fused silica [18]. These centers are not impurities, but point defects in the bonding of an sp3 electron in silicon, and have been studied in many types of fused silica. The centers are unstable, and can be induced through UV illumination and removed through exposure to molecular hydrogen [19]. The shape and central wavelength of the optical absorption spectrum should remain the same from one sample to the next, but the magnitude of absorption will depend on the concentration of E' centers. This agrees well with our observations of discharging rate versus wavelength.

Fig. 7 shows the discharge rate versus wavelength for both the coated and uncoated side of the tantala/silica coated sample. Both curves have been normalized to the same discharge rate at 230 nm to allow comparison of the shapes. The curves match to within the measurement uncertainty. Both show a greater response between 230 nm and 250 nm than the uncoated sample; the reason for this is not yet understood. But the optimal discharging wavelength is again found to be 215 nm, and the equivalent results from both sides of the sample suggest that the properties of silica, not the coating, determine the discharge rate. This also supports a correlation with E' centers.

A reduction in positive charge implies that either positive ions, possibly deposited from contact with viton, are being removed

from the sample surface, or electrons are being liberated from nearby material and are neutralizing the sample. Electrons could originate from the probe or from the surrounding vacuum chamber. We have found that discharging only occurs when the UV light is aimed directly at the optic, which eliminates the second possibility. We see similar discharging rates when the light is aimed slightly to the side of the probe element, but it is unclear how much stray light still reaches the probe; a better test would require motor control over the probe position, allowing us to move it aside, illuminate the optic, and bring it back into position without making vacuum. But our favored interpretation is that the light is liberating positive ions from the sample surface. The transfer of positive ions during contact electrification has been seen in other experiments [20], and a possible mechanism by which positive ions can be removed from the surface is discussed in [21].

4. Conclusions

We have demonstrated that fused silica test masses of the type intended for use in Advanced LIGO acquire positive charge through contact electrification with viton. Illumination with UV light can remove this positive charge, with peak response at a wavelength of 215 nm, likely due to optical absorption by paramagnetic E' centers. At this wavelength, on the order of 0.1 $\mathrm{J\,cm^{-2}}$ will result in a 90% discharge. We also found that the discharge rate varies linearly with charge density, suggesting that over time UV illumination may be able to damp out uneven distributions of charge.

Given that different mechanisms can result in either positive or negative charging of a test mass, it appears that the Gravity Probe B "control electrode" strategy described in the introduction may also be an appropriate plan for LIGO. Future use of the Kelvin probe setup will include testing such a strategy, as well as adding motion control for the probe in order to map the spatial charge distribution on samples and how it is affected by UV illumination.

Acknowledgements

The authors would like to thank George Whitesides for his useful insight and discussion. LIGO was constructed by the California Institute of Technology and Massachusetts Institute of Technology with funding from the National Science Foundation and operates under cooperative agreement PHY-0107417. This work was supported by the National Science Foundation under Grant No. 0646718. This article has been assigned LIGO Document No. LIGO-P080001-00-Z.

References

[1] R. Weiss, LIGO technical note (1996), http://www.ligo.caltech.edu/docs/T/T960137-00.pdf.
[2] S. Rowan, S.M. Twyford, R. Hutchins, J. Hough, Class. Quantum Grav. 14 (1997) 1537.
[3] P.L. Bender, et al., MPQ Report No. 233 (1998).
[4] S. Buchman, C.W.F. Everitt, B. Parkinson, J.P. Turneaure, R. Brumley, D. Gill, G.M. Keiser, Y. Xiao, Adv. Space Res. 25 (2000) 1177.
[5] E.G. Adelberger, B.R. Heckel, A.E. Nelson, Annu. Rev. Nucl. Part. Sci. 53 (2003) 77.
[6] S.J. Waldman, Class. Quantum Grav. 23 (2006) S653.
[7] V.B. Braginsky, O.G. Ryazhskaya, S.P. Vyatchanin, Phys. Lett. A 350 (2006) 1.
[8] V.P. Mitrofanov, L.G. Prokhorov, K.V. Tokmakov, Phys. Lett. A 300 (2002) 370.
[9] Ugolini, R. Amin, G. Harry, J. Hough, I. Martin, V. Mitrofanov, S. Reid, S. Rowan, K.-X. Sun, in: Proceedings of the 30th International Cosmic Ray Conference, 2007.
[10] R. Stebbins, P.L. Bender, J. Hanson, C.D. Hoyle, B.L. Schumaker, S. Vitale, Class. Quantum Grav. 21 (2004) S653.
[11] R. Lawrence, D. Ottaway, P. Fritschel, M. Zucker, Opt. Lett. 29 (2004) 2635.
[12] S. Buchman, T. Quinn, G.M. Keiser, D. Gill, T.J. Sumner, Rev. Sci. Instrum. 66 (1995) 120.
[13] M. Hewitson, K. Danzmann, H. Grote, S. Hild, J. Hough, H. Luck, S. Rowan, J.R. Smith, K.A. Strain, B. Willke, Class. Quantum Grav. 24 (2007) 6379.
[14] K.-X. Sun, N. Leindecker, S. Higuchi, A. Markosyan, R. Route, M. Hennessey, J. Perales, S. Buchman, M. Fejer, R. Byer, G. Harry, LIGO Science Collaboration meeting presentation (2007), http://www.ligo.caltech.edu/docs/G/G070208-00.
[15] G.M. Harry, M.R. Abernathy, A.E. Becerra Toledo, H. Armandula, E. Black, K. Dooley, C. Nwabugwu, A. Villar, D.R.M. Crooks, G. Cagnoli, J. Hough, I. MacLaren, P. Murray, S. Reid, S. Rowan, P.H. Sneddon, M.M. Fejer, R. Route, S.D. Penn, P. Ganau, J.-M. Mackowski, C. Michel, L. Pinard, A. Remillieux, Class. Quantum Grav. 24 (2006) 405.
[16] L. Kronik, Y. Shapira, Surf. Sci. Rep. 37 (1999) 1.
[17] D. Ugolini, R. McKinney, G.M. Harry, Rev. Sci. Instrum. 78 (2007) 046102.
[18] R.A. Weeks, R.H. Magruder III, A. Stesmans, J. Non-Cryst. Solids 354 (2008) 208.
[19] F. Messina, M. Cannas, J. Phys.: Condens. Matter 17 (2005) 3837.
[20] J.A. Wiles, B.A. Grzybowski, A. Winkleman, G.M. Whitesides, Anal. Chem. 75 (2003) 4859.
[21] C. Bandis, S.C. Langford, J.T. Dickinson, Appl. Phys. Lett. 76 (2000) 421.