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Charging Issues in LIGO

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Abstract: The Laser Interferometer Gravitational-Wave Observatory (LIGO) consists of Fabry-Perot Michelson interferometers designed to measure gravitational-waves at frequencies between roughly 40 Hz and 3 kHz. One potential noise source in this frequency range is the buildup and motion of surface charge on the optics, which can be generated through friction with air, contact with other materials, or interaction with the showers of charged particles generated by cosmic rays. Charge contributes noise by generating fluctuating electric fields that produce fluctuating forces on the test masses, and by reducing reflectance by attracting dust to the optical surface. The magnitude of the noise contribution depends on both the amount of charge and the relaxation time associated with its motion; charge densities greater than 105 e-/cm2 and relaxation times smaller than 4 × 107 seconds would result in significant noise in the sensitive frequency band. This paper discusses the role of cosmic rays in charging, measurements of charge buildup and relaxation times, and possible charge mitigation techniques.

Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has been developed to detect and study gravitational waves, the tiny perturbations in the curvature of spacetime produced by the motion of massive astronomical bodies [1]. LIGO is based on the Michelson-Morley interferometer, but uses Fabry-Perot cavity arms 4 km in length. Large (10 kg) fused silica optics are suspended to provide passive attenuation of seismic noise, and magnets are used for position control. LIGO is most sensitive to gravitational waves at frequencies between 40 Hz and 3 kHz.

A potentially limiting noise source in this frequency range is the buildup and motion of surface charge on the optics [2-5]. Surface charge would generate an electric field, inducing a force between the optic and its metallic suspension frame. A sudden change in charge magnitude would discontinuously change this force, displacing the optic in a way that would mimic the effect of a gravitational-wave burst. Moving charges would create fluctuating electric fields that might also displace the optic at frequencies below 1 kHz. Excess charge could also attract dust to the optical surface, reducing reflectance and increasing absorption and scattering.

This note will discuss mechanisms for charge buildup on LIGO optics (with emphasis on cosmic rays), attempts to measure the potential noise contribution, and methods for mitigating the effects of charging.

Sources of Charging

One mechanism for depositing charge is abrasive contact between the optic and another material. Dust, for example, can be stirred into contact with the optic as the interferometer is pumped down to vacuum [2]. The LIGO optic suspension frames also include viton-tipped earthquake stops, designed to protect the optic from damage by limiting its range of motion. Charge can be deposited when the suspended optic collides with the viton.

Another mechanism, suggested by V.B. Braginsky and colleagues [6], is the deposition of negative charge due to interaction with cosmic rays. The idea is that the number of electrons liberated from a material by a cosmic ray is inversely proportional to the critical energy of the material:

$$N_e \sim \varepsilon/\varepsilon_{cr} \qquad (1)$$

where N_e is the number of electrons produced, ε is the cosmic ray energy, and ε_{cr} is the material's critical energy. Since the critical energy of the fused silica optics (47.3 MeV) is larger than the critical energies of the metallic elements in the vacuum enclosure, the emission of electrons from the enclosure to the optic will be greater than the emission of electrons from the optic, resulting in a net increase of negative charge.

Experimenters at Moscow State University have measured a negative charging rate of ~10^5 e^-/cm^2/month on a fused silica optic in vacuum, which could be explained by charging from cosmic rays [3]. More definitive evidence would require measurements over much smaller time scales, to see if the electrons arrive in discontinuous bursts. Note that cosmic rays could also introduce noise in gravitational-wave interferometers through momentum transfer to or thermoelastic heating of the optics. Recent work has allowed several predictions of the noise contributions from these events, and has shown that they can be mitigated by requiring coincidence measurements between multiple interferometers [6, 7].

Measurements of Charging Effects

The noise contribution from charging depends both on the magnitude of the charge and the time scale of its motion. The induced force on the optic from a fluctuating electric field can be described in terms of a relaxation time τ_0, resulting in a power spectrum of [2]:

$$F^2(f) = \frac{2\langle F^2\rangle}{\pi\tau_0\left[\frac{1}{\tau_0^2}+(2\pi f)^2\right]} \qquad (2)$$

where F is the force power spectrum and f is frequency. Note that the noise contribution will be minimal for very long or very short relaxation times, and a maximum when $\tau_0 = 1/2\pi f$, which would be on the order of milliseconds in the sensitive frequency band of LIGO.

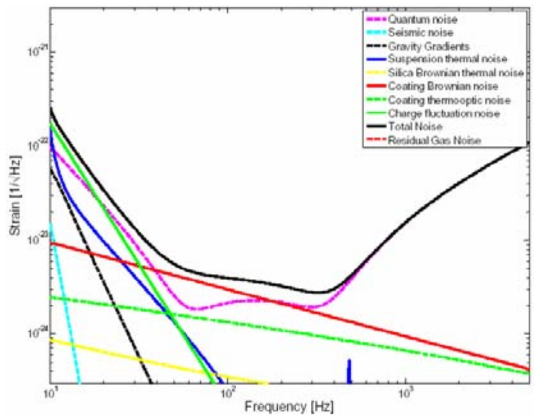

Figure 1: The theoretical charging noise contribution (solid green line) versus the total noise predicted for Advanced LIGO (solid black curve), assuming a total charge of 10^{-11} coulombs and a relaxation time of 4×10^7 s

As LIGO improves in sensitivy, charging effects will take on greater importance. Figure 1 shows the expected charging noise (solid green line) for 10^{-11} C of charge (equivalent to a density of 10^5 e^-/cm^2) and a relaxation time of 4×10^7 seconds, in comparison to other expected noise sources in Advanced LIGO, the planned upgrade to the current LIGO interferometers [8]. One can see that given more charge or a shorter relaxation time (approaching the maximum at $1/2\pi f$), charging would be the dominant noise source at low frequencies. Thus understanding the relaxation time for the motion of charge on fused silica is as important as measuring the magnitude of charging.

In order to measure relaxation time, experimenters at Trinity University developed a vacuum-compatible Kelvin probe for measuring charge on fused silica optics [9]. The probe uses a tuning-fork optical chopper to modulate the capacitance between the probe tip and a charged sample, and has a sensitivity of (3.5 +/- 0.5) × 10^5 e^-/cm^2. Relaxation time was determined by measuring the decrease in charge over time on a fused silica optic in a vacuum chamber at 10^{-5} torr (higher than the LIGO vacuum, but at which discharging through interaction with air should be negligible).

The optic was charged by abrading a viton O-ring across the surface. Figure 2 shows the result of one such measurement. The relaxation time was found to be 170 +/- 30 days, or (1.5 +/- 0.3) × 10^7 seconds, on the order of the time used to generate the expected noise plot in Figure 1. The low readings were accompanied by significant phase changes between the probe signal and chopper drive, and thus are likely noise.

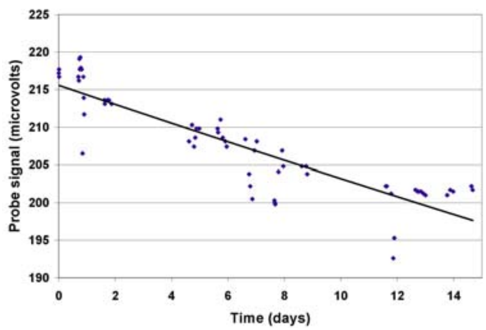

Figure 2: Trinity University measurement of relaxation time for charge on fused silica optic

An independent experiment at Moscow State University used a fixed capacitive probe and a charged optic mounted on a turntable, providing both signal modulation and a spatial profile of the charge distribution [10]. Several measurements with this system showed no measurable decrease in the amount of charge on the optic, as shown in Figure 3, resulting in a lower limit of 8000 hours or 2.9 × 10^7 seconds for the relaxation time.

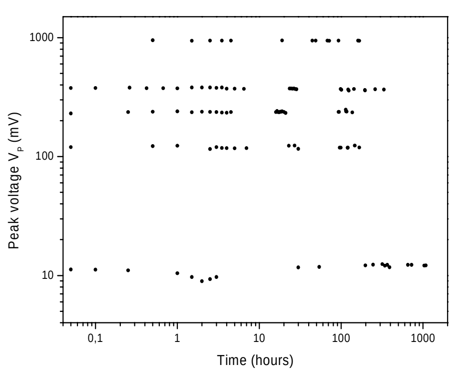

Figure 3: Moscow State measurements of charge relaxation time [10]

A likely explanation for the discrepancy between the two results is the optic handling procedure; the Moscow State optic was given an ultrasound bath with acetone and methanol, followed by an air bake at 300 °C, while the Trinity optic was dry-wiped. This underscores the importance for future study of the relaxation time for different cleaning and handling techniques, different optical materials, and different reflective coatings.

Charge Mitigation

One possible solution for optical charging would be to coat the optic with a very thin layer of conductive material. This would prevent patch effects by causing localized charge distributions to spread across the optic surface. It would also result in a very small relaxation time, which would cause the fluctuating force power spectrum in Equation 2 to trend towards zero. Much study would be required to ensure such a coating would not reduce reflectance or introduce thermal noise through mechanical loss in the reflective coatings. Work on ion implantation and conductive coatings is currently underway at the University of Glasgow.

Another solution that would not require modification to the optics is to discharge through UV illumination. One such system was developed for Gravity Probe B [11], 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. The net direction of charge flow could then be controlled by adjusting the voltage of the control cathode; in other words, a positively-charged surface could be discharged by receiving excess electrons from the control cathode.

The effects of UV illumination on a prototype fused silica pendulum suspensión were previously studied at the University of Glasgow [4]. There it was discovered that UV radiation from an ion pump was liberating electrons from the walls of a vacuum chamber, and that these electrons were then negatively charging an optic and impairing its mechanical Q. Subsequent illumination of the optic with a UV lamp reversed the effect.

Recent measurements at the GEO gravitational-wave observatory have also successfully demonstrated the discharging of a positively-charged optic by shining UV light on a control cathode [12]. The GEO interferometer uses electro-static drives (ESD) mounted on reaction masses as one actuator for controlling the position of suspended optics. The amount of excess positive charge on the optic can be determined by measuring the displacement of the optic as a function of bias on the ESD. UV light liberates electrons from the reaction masses, and has been found to reduce the charge on optics by as much as 85%.

Experimenters at Stanford University are currently developing a deep UV LED, which will allow for a charging system that is very stable in wavelength and intensity [13]. Measurements are underway to test how the LED system discharges a 3” LIGO optic, as well as to measure whether long-term exposure to UV light damages the optic’s reflective coating, causing increased absorption. In addition, studies at Trinity University will test the optimal wavelength and intensity for UV illumination.

Conclusion

Excess charge is deposited on LIGO optics both through interaction with cosmic rays and abrasive contact with other materials. Recent measurements of magnitude and relaxation time have shown that surface charge could be a dominant noise source at low frequencies for future generations of the LIGO interferometers. Research is now underway to study the application of UV illumination to the problem of charge mitigation.

Acknowledgments

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