LIGO Laboratory / LIGO Scientific Collaboration

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Charging Noise and Mitigation Research Plan

Gregg Harry, editor

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of the LIGO Project.

California Institute of Technology
LIGO Project - MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

Buildup of electric charge on LIGO test masses is a potential source of both Gaussian and non-Gaussian noise. There have been suggestions that excess noise in the operating initial LIGO interferometers following contact between a mirror and a viton tipped earthquake stop may be due to transferred charge. Understanding and reducing charge noise, then, becomes a crucial problem for Advanced LIGO. This document describes a research plan to better understand the charging problem for Advanced LIGO and explore possible solutions.

BENCH TESTS – June – October, 2007

The short term research will follow on existing bench experiments at various LSC institutions. These tests have primarily been to measure the decay time of charge on silica samples, necessary to predict the level of Gaussian noise, and to determine if there are any deleterious effects of UV on coated LIGO optics. UV has been successfully used to remove charge in LISA, GP-B, and more recently in the GEO 600 interferometer. It is being pursued as a method of mitigating charge problems in Advanced LIGO.

Trinity University

Over the last several years, Trinity has built a capacitive probe and acquired a commercial Kelvin probe to measure charge levels on samples in vacuum. These have been used successfully to measure the decay time of charge on silica substrates charged by contact with viton O-rings and found it to be (1.5 +/- 0.3) X 10^7 seconds over a measurement time of about 10^6 seconds.

One primary goal for bench tests at Trinity in the next six months is to measure this decay time over a longer period of time to get a better estimate. This takes on greater urgency when comparing these results with similar ones measured in Moscow, which finds a much greater decay time. Understanding the cause of this discrepancy is important as it may provide a method of controlling the decay time, and thereby reducing the level of Gaussian noise.

One possible explanation for the differences seen in decay time is that this time may be a strong function of the details of the silica surface. It is known that a surface layer on silica has different mechanical and optical properties than the bulk; it is plausible it could have different electrical properties as well. It is also known that this surface layer can absorb material, like water or components of air, to change properties. This might mean that the details of how the sample was handled and especially cleaned might account for this observed difference. This will be explored systematically by measuring decay times for samples cleaned using various solvent, including ethanol, methanol, acetone, a water and Liquinox solution, and First Contact. The effect of accidental contact with the optic will also be explored by intentionally touching the silica surface with bare fingerprints and with latex gloves.

It is also possible that different types of silica, which differ primarily in the type and concentration of impurities, may account for different decay times. The Moscow measurements used the Russian KV brand. Measuring decay times of different Corning and Heraeus types of silica but handled and cleaned in an identical manner will allow this hypothesis to be tested. Since each of these described experiments can potentially take many weeks to perform, due to the long time constants that are typically seen, not all of this may be able to be accomplished in the next six months. Some work can be done in parallel, and preliminary tests on both different cleaning solvents and different types of silica should provide clues as to the best direction to work in.

Trinity has also just received a 175 W Xenon lamp which will allow UV to be put on the optics with variable wavelengths and intensities. Preliminary tests with a different lamp indicate that UV does fairly rapidly remove charge from the test optics. The new apparatus will allow this phenomenon to be explored as a function of UV wavelength and intensity. This could prove important if other work indicates that UV can cause damage to the LIGO optics or especially the coatings.

Finally, it has been suggested that charge fluctuation noise might be able to be seen directly with a Kelvin probe. This will depend heavily on the other noise sources in the probe. So some work will go into understanding these noise sources, modeling them compared to the expected charging noise. Should modeling and calculations make this appear a promising direction, this research will become higher priority.

Stanford

Stanford's LIGO group will draw on its experience working on charging issues for LISA and GP-B to continue to develop a UV system for charge mitigation in Advanced LIGO. Work with LISA and GP-B, as well as recent experience at the GEO 600 interferometer, indicate that shining UV light at charged test masses can be an effective way to reduce charge. There is continuing work at Stanford to develop UV photodiodes, along with the necessary electronics and sensors, which will be suitable for this. There are concerns, however, that UV light might damage the LIGO optics and especially the coatings. In addition to development of UV photodiodes, exploring any possible damage from UV will be the focus of near term work at Stanford. Development work on the UV photodiodes will concentrate on the electronic driver circuits.

Two of the most critical aspects of the coatings are their mechanical loss and optical absorption. What effect, if any, UV light has on these properties will be explored by exposing coated test samples to UV for varying amounts of time. The optical absorption will then be measured on campus at Stanford, to see if the 0.5 ppm level needed can be maintained. Mechanical loss will be studied in collaboration with Embry-Riddle, by sending sample there for Q measuring. These studies will be carried out a various intensities of UV for various times, as well as on different coating materials. This will include tantala/silica, both titania doped tantala and silica doped titania based coatings, and any new materials found promising for Advanced LIGO. Coated samples cleaned with various solvents (ethanol, acetone, Liquinox, etc.) as well as First Contact will also be studied, to see if the UV interacts with residuals of these materials.

Another aspect of the LIGO optics that may respond negatively to UV light is the silicate bond that connects the core optic with the suspension. Optics with a silica ear bonded to it will be exposed to UV in a similar manner to the coated samples. The silicate bond will then be tested for strength and mechanical loss, to check for any degradation.

A new Kelvin probe has just been installed at Stanford, and it can be used similarly to the one at Trinity. In addition to collaborating on some of the projects at Trinity, Stanford will explore the effect of UV on both positive and negative charge on test optics. This will be used to determine if any differences will be needed in the UV mitigation scheme for different signs of charge. These changes to the UV system can be verified using the Kelvin probe, as well.

Moscow State University

Research on charging issues will continue at Moscow State. Work on measuring charge decay times will continue, with an emphasis on understanding what causes changes in the decay time. The effect of different types of silica will be researched, with Corning 8980 and various Heraeus Suprasils planned. The change an optical coating has on decay time will also be studied. Preliminary work on tantala/silica coatings indicate decay times of at least several weeks. Plans are in place to study titania-doped tantala/silica, the Advanced LIGO baseline coating, and other coating materials (silica-doped titania/silica, etc) may be studied as well. These studies will likely continue into the prototyping phase as the long decay times make each experiment take many weeks to months.

Current work on the level of charge buildup from different charging mechanisms will continue, in particular from contact between fused silica and other materials. Viton and silica as contact materials have been studied so far, and work with other materials is planned. Theoretical calculations of the expected charging rate from cosmic rays has been done and further refinements will be pursued as will the effects of background radiation and absorption-desorption processes on the surface of silica. Any effect from the gold electrostatic drives planned for use in Advanced LIGO on charging will also be studied. Work on how charge distributes itself across the optic once in place will also continue.

Research into UV mitigation of charging is also planned. In particular, determination of ways to minimize the residual charge after UV irradiation and studying any aftereffects of charging that may be associated with formation of nonequilibrium states in fused silica will be studied.

Caltech

The Thermal Noise Interferometer at Caltech is the best prototype in the LIGO community to make direct measurements of potentially limiting noise sources. Its primary mission is to study thermal noise, but it may also be able to directly measure Gaussian noise from charge. For the next three months, the feasibility of doing this will be studied using modeling and analytical tools. It has been pointed out that charging noise is primarily a low frequency noise, below about 80 Hz, while the TNI remains limited by seismic noise up to about 200 Hz. However, as charging noise increases with the amount of charge on the test mass, in theory any noise level can be obtained at any frequency with sufficient charge. Determining whether the amount of charge required to directly measure charging noise is realistic will form the basis of the feasibility study. This will allow a more informed decision about whether it is an effective use of TNI to study charging noise late in the summer of 2007.

In anticipation of deciding that it is realistic to proceed with direct measurement of charging noise at the TNI, some effort will go into developing necessary hardware. The primary hardware needed will be an *in situ* charging mechanism to allow charge to be deposited on the TNI mirrors. This will likely need to be done in vacuum to avoid changes in charge levels during pump down. One possibility for a charging mechanism would be a viton tipped rod that can be dragged across the mass. Viton contacting glass is known to be a good way to transfer charge. Thought will need to be given to a deposition method that allows for both positive and negative charge to be left on the test masses. It will also likely be necessary to have hardware in place to measure the level of charge. It is possible this could be done using offsets in the angles that the mirrors hang at and therefore measured with the TNI alignment system. A capacitive sensor developed specifically for charge measuring may also be necessary. It will also be desirable to test charge mitigation schemes with a UV system the most valuable. The UV diode with necessary electronics being developed at Stanford can be used, possibly with some modifications for the TNI. The infrastructure of the TNI will also have to be examined to make sure a UV system can be installed. Such a UV system in the TNI will allow direct testing of the reduction of noise from charge.

One important concern about UV charge mitigation is its possible deleterious effect on LIGO optics and especially coatings. Much of this is being studied at Stanford, but Caltech has an optical ringdown cavity specifically designed for long term studies of optical deterioration. During the summer of 2007, an optical cavity formed with titania-doped tantala/silica coated optics will be maintained with UV light shining on one of the mirrors. The intensity and wavelength of the UV will be informed by the studies at Stanford and Trinity. The finesse of this cavity will be monitored to see if there is any decrease over time. If there are indications of degradation, further studies with lesser power and/or different wavelengths can be made. This will be done in close collaboration with the group at Stanford developing and studying UV charge mitigation.

LASTI - MIT

At MIT, it will primarily be the LASTI facility that is used for charging studies. LASTI's mission is to test Advanced LIGO hardware at full-scale in as close to the actual environment as possible. This will mean testing the UV mitigation scheme for connections with other Advanced LIGO subsystems, installation and commissioning along with other subsystems, and control during operation. This will primarily happened during the later prototype phase, but some preliminary development must be done at this earlier stage.

Much of this hardware development will be analogous to that needed for the TNI, and will closely follow work done there. The difference is that the optics and other hardware at LASTI will be very similar to that planned for use in Advanced LIGO. So much of what is developed at LASTI can be used later at the sites. Two primary articles to be developed are a charge sensing system and a charge deposition system. This will follow from work done at Stanford and Caltech, and will be in close collaboration with researchers there. The different geometry of the optics in LASTI, specifically the reaction mass with the electro-static drive, will cause some differences. Viewports in the chambers will also be examined and possibly changed, as fused silica windows are necessary to pass UV light into the vacuum.

In addition, further tests on the improved earthquake stop design will be conducted. This redesign makes the contact between the stops and the test mass be a silica on silica contact, to minimize charge transfer. Viton is still used as a cushioning material, but a silica rod which is surrounded by viton makes the actual contact. A preliminary design has already shown it can withstand motion like that from an earthquake without damaging the optic. Further refinements are being considered to improve the mechanical design to improve stability.

INITIAL LIGO EXPLORATIONS

It has been suggested that charge on the test masses has caused excess noise in the initial LIGO interferometers at certain times; specifically at LLO on time, May 2006, at the 2k at LHO on time and date, and on the 4k at LHO on time and date. These are all correlated with events where at least one test mass hit the viton tipped earthquake stops, which are known from studies at Moscow to transfer significant charge to silica mirrors. Studying these potential charging events, to learn as much as possible, is an important aspect of preparing for charge mitigation in Advanced LIGO.

Work is ongoing primarily at LSU and the sites on studying these events. Efforts have started with looking for evidence of excess charge on mirrors through DC forces. The amount of charge needed to create any DC shifts can then be compared to the amount needed to create the observed noise to see if it is plausible that charge is responsible for both. Examination of optical lever data from Livingston does indicate that there was a shift in the optics position after contacting the earthquake stops.

Should it prove plausible that the observed noise is due to charge as described by a Markov process, the noise can be fit to get estimates of relevant parameters. If the level of charge is known, the only free parameter will be the decay time of charge on the optic. This can be compared to results found from bench tests at Trinity and Moscow State to determine how well these experiments do in predicting behavior at the sites. It will also be additional information to help determine what role the type of silica, cleaning, handling, and vacuum state plays in the decay time. This could be especially valuable if data from all three interferometer and/or multiple mirrors can be obtained. Similarities or differences in decay time might help resolve the discrepancy in the measurements of decay time.

It may also be possible from studying noise data from the sites to study the effects of different mitigation schemes. At LLO, a partial vent was used to presumably discharge the optic and remove the excess noise. By studying optical lever and noise data before and after this vent, it may be possible to determine how much charge was removed. This information could be used to inform possible bench tests into venting as a charge mitigation scheme. At LHO, shaking the optic was used to remove the excess noise attributed to charge. Similar studies with LHO data could determine if charge was responsible and if the shaking did remove charge from the optic. If these both prove true, it could serve as the basis for investigating new mitigation methods.

PROTOTYPE TESTING – October 2007 – July 2008

TNI

Assuming the modeling and studies in the previous phase do indicate the value of direct charging noise measurements, the TNI will proceed to do so in this phase. Any remaining hardware development of a charge deposition, a charge sensing, or a UV charge mitigation subsystem will be completed. Some of this development, notably the UV mitigation subsystem, can be primarily done elsewhere, as at Stanford. This necessary hardware will then be installed prior to noise measuring.

The exact mirrors used are not crucial, but the ones coated with closest to the Advanced LIGO baseline coating should be used. This is both to do the charging tests on as close to the real mirrors as possible, but also because the baseline coating should give the lowest thermal noise and thereby allow for greater visibility of charging noise. As of June 2007, this would be LMA coated quarter wave titania doped tantala/silica coatings. If an LMA coated titania doped tantala/silica coating with optimized layers or some other improved coating becomes available, it would be preferred.

Noise measurements will then be collected to see if charging noise is visible. Noise can be collected as a function of a number of interesting parameters and effects. First, noise as a function of charge level will be studied. This will allow a verification of the expected noise formula, but also will allow an appropriate level of charge for future measurements to be determined. Secondly, the rate and efficiency of UV mitigation can be studied, by applying various intensities of UV to the mirrors for various times before measuring noise. This will allow appropriate intensities and times of UV to be developed. The effect of UV on both positive and negative charge can be studied, to see if both are mitigated equally. Finally, informed by the bench tests, the effect of cleaning and handling techniques on the noise can be studied. If bench tests indicate that the charging decay time depends strongly on which cleaning solvent is used or if a fingerprint is left on the mirror, this can be directly measured as noise with the TNI. It will require the vacuum chambers to be opened and the mirrors cleaned for each measurement, so it will take longer than other charging noise experiments. The importance of doing this will be determined after examining the results of bench tests.

LASTI

The full scale UV mitigation subsystem will be installed at LASTI when cavity tests are beginning. This will be after installation of Advanced LIGO seismic platforms and quad suspensions. The installation of charging hardware will be done in close collaboration with those scientists at Stanford and elsewhere who developed it. During installation it will be checked for compatibility with Advanced LIGO subsystems including mechanical and electrical aspects.

Once installed, the UV charge mitigation technique can be tested while optical and mechanical tests are performed. This will include developing the necessary software to control the UV and any charge sensors that prove necessary. Operation will also serve as a final check on any effects the UV has on optical properties or other aspects of the Advanced LIGO optics, suspensions, or seismic isolation.

Stanford

During the prototype testing of the charge mitigation subsystem, Stanford researchers will participate in the experiments at the TNI and LASTI. This can include participation in installation, commissioning, and interpretation of data. It is also likely that continuing bench tests on the UV subsystem will be beneficial, either to develop improvements or to debug any problems encountered. Bench tests will also be conducted on optics with the proposed gold barrel coating, to see how that effect UV charge mitigation. The gold barrel coating is not currently baseline for Advanced LIGO optics, but may become so or may be part of an enhancement to Advanced LIGO after initial operation. Understanding the gold coatings effect on charge behavior and UV mitigation could become important so it will be investigated at a priority below the prototype tests.

Other LSC Institutions (Trinity, Moscow, ERAU, etc)

Other LSC groups, including Trinity and Moscow State, will continue to work on charging issues during the prototype testing phase. They may participate in some aspects of the prototyping, likely data analysis and interpretation but possibly also installation and commissioning. Following up on results from the bench tests in the first phase will be the focus of their charging research.

Any research from the first phase that was not completed, or suggested important follow on work, will be pursued. This may include the effects of solvents, silica types, or other explanations for different charge decay times. They will also begin to investigate the effect of the proposed gold barrel coating on decay time. There may be interactions between the gold and other effects on decay time (solvents, etc.) that must be explored in some detail. The importance of vacuum level and cleanliness may also prove important to explore at this time. Much of this bench testing will be informed by the results of the first phase.

If concerns occur with the UV mitigation scheme, or if otherwise it seems warranted, other mitigation schemes can be researched. One possibility would be developing a conductive surface on the test mass using ion implantation. Preliminary work on this idea was done at Glasgow, but much follow up is needed. The largest concern with ion implantation is the effect it may have on thermal noise, optical absorption, scatter or other properties of the optics. So research into ion implantation must be done in close collaboration with groups measuring Q's (ERAU, HWS), optical absorption (Stanford), scatter (Stanford, Syracuse), and any other effected property. The goal would be to find an ion and implantation technique that reduces the charge decay time of the optic to the point where charging noise is unlikely in Advanced LIGO without compromising any other test mass property.

Another mitigation technique that may be pursued at this time is controlled venting, possibly including the introduction of ionized gas into the vent. This has been the preferred method for discharging initial LIGO optics, without the ionized gas. If this could be perfected to minimize down time due to re-pumping out of the chamber, it could be a viable solution to occasional charging events. Venting with ionized gas has been demonstrated at Moscow State using a glow discharge. Concerns have been raised about possible contamination of the optic, this would have to be studied and minimized.

Work on non-Gaussian noise from charge will also progress during this phase. Rapid charging events can mimic burst gravitational waves and may be an important limitation to burst sensitivity. Some work has been done on rapid charging, notably at Moscow, but further work is planned. Some of this will inevitably be seen at the TNI, so analyzing TNI data for bursts is very valuable. This can be done as a function of charge level, solvent, UV, or other important parameters. Plans are being developed at Embry-Riddle to adapt LIGO burst pipeline code to look for non-Gaussian noise in bench and prototype experiments. There is also some planning going into developing an experiment at Embry-Riddle to look for non-Gaussian charging events.