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**Charge Neutralization in Vacuum for Non-Conducting and Isolated
Objects Using Directed Low-Energy Electron and Ion Beams**

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We propose using ions and electrons of 1 eV to 10 eV energy for neutralizing the charges on the non-conducting or isolated surfaces of high sensitivity experiments. The mirror surfaces of the test masses of the Laser Interferometer Gravitational Observatory are used as an example of the implementation of this method. By alternatively directing beams of positive and negative charges towards the mirror surfaces we ensure the neutralization of the total charge as well as the equalization of the surface charge distribution to within a few eV of the potential of the ground reference of the vacuum system. This method is compatible with operation in high vacuum, does not require measuring the potential of the mirrors, and is expected not to damage sensitive optical surfaces.

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1. Introduction

Charging of the test masses is a potentially significant noise source for ground-based gravitational wave laser interferometers^{1,2} as well as for sensitive instruments with non-conductive or non-grounded surfaces.^{3,4} For the conducting levitated test masses of space-based experiments a technique using UV generated photoelectrons has demonstrated charge control to better than 5 pC with a resolution of 0.1 pC; figure 1 shows the data from the discharge of one of the gyroscopes of the Relativity Mission, Gravity Probe B (GP-B).⁵ This technology, using LED rather than gas discharge UV sources^{6,7}, is proposed for use in the upgraded version of the Laser Interferometer Gravitational Observatory (LIGO)⁸ and the Laser Interferometer Space Antenna (LISA)⁹, and could also be applied to a number of other high precision experiments such as STEP¹⁰, VIRGO¹¹, and GEO600.¹²

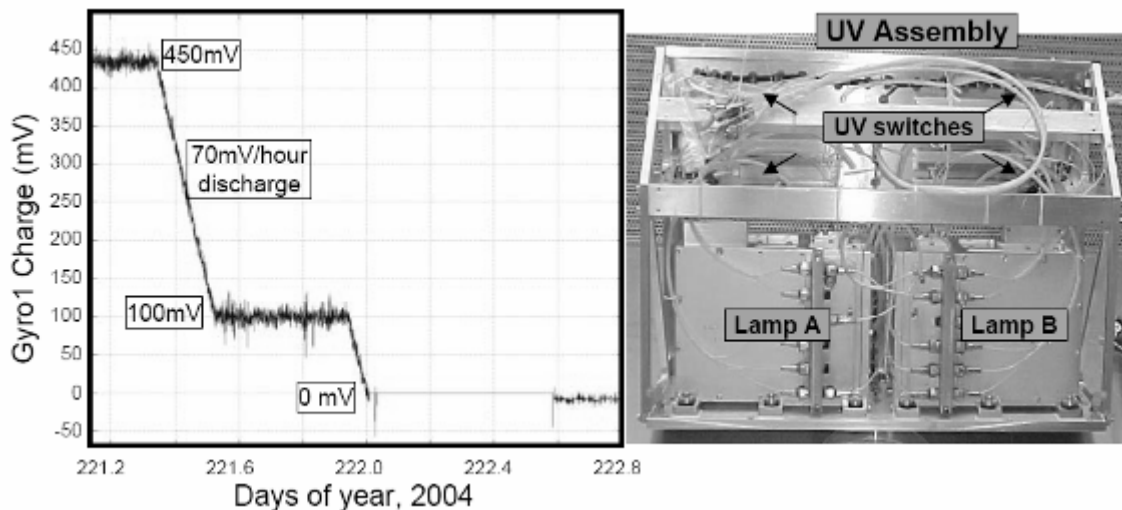


Figure 1. Left: Discharge of GP-B gyroscope #1 using UV photoelectrons (1 pC produces 1 mV for the 1 nF total capacitance). Right: GP-B UV assembly.

UV charge management of non-conducting surfaces presents three potential difficulties:

a) While the net total charge is reduced to the required value the uniformity of the surface charge distribution is not controlled. Further measurements are required to verify the uniformity of charge distribution on insulators under UV illumination.

b) High flux UV radiation at or below 254 nm can potentially damage or contaminate optical coatings in vacuum. For example, the GP-B UV lamps of figure 1 have an intensity decay time of more than 2000 hours in air, but of only about 230 hours in vacuum.⁵ The cause of the fast deterioration in vacuum is the darkening of optical surfaces by UV induced deposition of residual hydrocarbons.

c) A mechanism for the measurement of the charge of the test mass is required.

The technique proposed in this paper uses positive and negative charge beams alternately propagating in front of a charged surface to both neutralize the total charge and even out the surface charge distribution. For LIGO, partial venting and glow discharges¹³ were also proposed as means of neutralizing the net charge. Partial venting is however a time consuming and difficult process, while glow discharges require significantly increased gas pressures and have the potential of damaging optical surfaces. LIGO continues to investigate the implementation of UV management techniques and is evaluating the effects of UV radiation on coatings in vacuum.

Charge management using UV light from a mercury lamp has already been successfully demonstrated in situ in the GEO600 detector.¹⁴

2. Charge Management of LIGO Test Masses with Charged Beams

2.1 Charging Mechanisms

LIGO is designed to detect gravitational waves in the 40 Hz to a few kilohertz frequency range by measuring the distance between suspended test masses with mirror surfaces to a precision of 10^{-18} m/ $\sqrt{\text{Hz}}$ to 10^{-19} m/ $\sqrt{\text{Hz}}$.⁸ After the completion of the 2007 science run a series of upgrades to the detectors, called Advanced LIGO, will be installed with the aim of enhancing the sensitivity by a factor of 10 and extending the bandwidth down to 10 Hz.¹⁵ Test mass charging is an error source for LIGO as it may introduce excess noise and can change the optimized operating parameters of the system.^{1,2,14,16} For the sensitivity of the advanced LIGO experiments both the net charge and the charge distribution of the test mass will require continuous and accurate control. Making their surfaces conducting and grounding the test masses would be the optimal solution; however work to develop a technology to achieve this goal while maintaining the quality factor and reflection coefficients of the mirrors has so far not been successful.¹⁷

Charging of the test masses in such detectors is caused by three mechanisms:

a) Contact between the test mass and the stops designed to prevent damage in the event of large (mm size) motions. Such events have transferred charges estimated at about 100 pC to the LIGO test mass.^{1,18} To put this value of charge into perspective, if it is evenly distributed over the surface of an Advanced LIGO-sized mass (34 cm diameter by 20 cm thick) the resulting surface field is of order 10 V/m. In practice the charge is very unlikely to be evenly distributed and much higher localized surface fields will be present. The transfer is caused by triboelectric charging¹⁹ and/or by charge transfer due to static charges on the surfaces. Present design improvements include matching the material of the stops to that of the test mass; however, as presently this material is an insulator,

charging due to contact and separation remains uncontrolled. Figure 2 shows a LIGO test mass and an enlarged view of the stops that caused charging on contact.¹

- b) Initial evacuation of the vacuum system. The flow of dust²⁰ (and possibly ionized gas) over the dielectric mirror coatings during pump-out generates triboelectric charges. No quantitative data is presently available for the charging of LIGO test masses due to the pump-down of the vacuum system; however Trinity University is presently conducting measurements of the effect of charging on LIGO-like optics during vacuum pump-down.
- c) Vocca²¹ assumes that the net charging due to cosmic radiation is isotropic and estimates it to be about 10^5 charges/cm²/day; or about 5×10^3 charges/sec for the Advanced LIGO test mass dimensions. This value appears to be a worst case, as detailed measurements and calculations by Mitrofanov et al²² and by Braginsky et al²³ result in a continuous negative charging rate of only 6×10^3 charges/cm²/day. However, Mitrofanov²² also measures fast charging events with rates comparable to those of Vocca.²¹

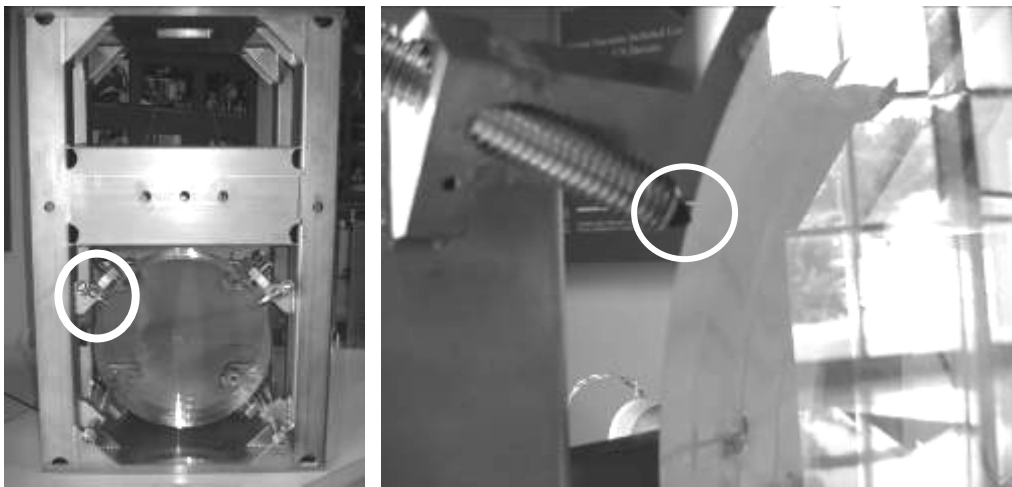


Figure 2. LIGO test mass (left) and enlarged view of test mass stop (right).

2.2 Charge Management Requirements

Continuous compensation of cosmic radiation charging, using a very conservative margin factor of 100, requires the generation and transport of about 5×10^5 charges per second or 80 fA. We therefore propose as system baseline alternating positive and negative beams of 1 second duration and about 100 fA current, with electrons and positive Argon ions as implementation examples.

The LIGO test masses are maintained at room temperature and a pressure of about 10^{-7} Pa in a 3 m diameter vessel, placing the residual gas deep in the molecular flow regime with a mean free path of the order of 10^5 m. Average room temperature thermal velocities ($v_T = \sqrt{(8k_B \cdot T_G)/(\pi \cdot m)}$) for electrons and Ar atoms are 10^5 m/s and 400 m/s respectively. The velocities for beams of particles accelerated in a potential V_V are given by $v_V = \sqrt{(2e \cdot V_V)/m}$; the resulting ratio of accelerated to thermal velocities is consequently $v_V/v_T = \sqrt{(\pi \cdot e \cdot V_V)/4k_B \cdot T_G} = 5.51$ for $e \cdot V_V = 1\text{eV}$ and $T_G = 300\text{K}$. Electrons and Ar^+ accelerated to 1 eV transverse the 3 m vacuum vessel in $7 \mu\text{s}$ and 2 ms respectively; much faster than the proposed 1 s beam switching half period.

The flux of residual gas Φ_G across the test mass surface is given by:

$$\Phi_G = \frac{A_{TM} \cdot \langle v_G \rangle \cdot n_G}{4}; \quad \Phi_G \approx 10^{14} \text{ s}^{-1} \quad \text{Equation 1}$$

where: $A_{TM} \equiv D \cdot h$; $\langle v_G \rangle \equiv \sqrt{\frac{8k_B \cdot T_G}{\pi \cdot m_G}}$; $n_G \equiv \frac{P_G}{k_B \cdot T_G}$;

$P_G = 10^{-7} \text{ Pa}$; $T_G = 300\text{K}$; $D = 34 \text{ cm}$; $h = 10 \text{ cm}$.

The flux of ions across the same surface is $\Phi_{Ar} \approx 10^6 \text{ s}^{-1}$, eight orders of magnitude smaller than Φ_G , and does therefore not modify the vacuum level across the mirror surface of the test mass. Alternating beams of electrons and Ar^+ of around 100 fA to 200 fA fulfill the charge management rate requirements as well as the vacuum system requirements; a $\sim 100 \text{ fA}$ current will neutralize an initial charge of $\sim 100 \text{ pC}$ in approximately 20 min during the set-up stage of the system. The 100 fA is 100 times higher than the continuous further charging of about 5×10^3 charges per second, and will continuously neutralize the charge of the mirrors.

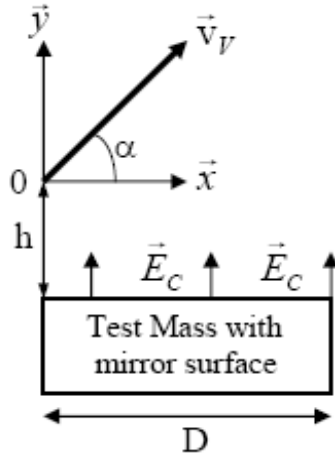


Figure 3. Beam flow model with uniform surface field.

Braginsky et al.^{23,24} discuss the noise created in gravitational wave detectors by cosmic radiation. Of interest for the present work is the effect: “3) fluctuating component of the Coulomb force between electrically charged mirror and grounded metal elements located near the mirror's surface”²⁴, where it is assumed that all surfaces close to the interferometer mirrors are grounded conductors. They calculate that a 2 TeV cascade in iron will produce about 1700 electrons with energies less than 1 MeV that will stop in the mirror and change its charge density by $\Delta\sigma/\sigma \approx 10^{-6} - 2 \times 10^{-5}$. Braginsky et al.²⁴ further show that the resulting strain (δ/l), due to the electrostatic interaction between a 10 cm^2 grounded metal surface and the change in surface charge density, caused by the 2 TeV cosmic ray cascade (one passage per mirror in 3 days – 100 days), is larger than the strain Advanced LIGO must measure: $\delta/l \approx 10^{-22}$.

2.3 Model with Uniform Surface Field

We illustrate the dynamics of the electron and Ar^+ beams by using a simple model of the test mass charging as a uniform surface field \vec{E}_C ; see figure 3. The charged beam of energy $e \cdot V_V$

and velocity \vec{v}_v is directed at angle α and has its origin at height h above the test mass of diameter D . The equation of motion for attractive/repulsive surface fields is:

$$y = x \cdot \tan(\alpha) \mp x^2 \frac{E_C}{4V_v \cos^2(\alpha)} \quad \text{Equation 2}$$

Charged beams in a repulsive field, with the momentum vector pointing away from the surface, will not intersect the test mass and will get neutralized in the walls of the vacuum chamber. For an attractive field the location x_i of the beam impacting the surface is given by:

$$x_i = \frac{2V_v \cdot \cos(\alpha)}{E_C} \left[\sin(\alpha) + \sqrt{\sin^2(\alpha) + \frac{E_C \cdot h}{V_v}} \right] \quad \text{Equation 3}$$

For $E_C \gg V_v / h$ ($E_C \gg 10$ V/m) x_i becomes:

$$x_i = 2h \cdot \cos(\alpha) \sqrt{\frac{V_v/h}{E_C}} \quad \text{Equation 4}$$

For the case of charge patches we show the simple example of a uniform electric field \vec{E}_{CP} of finite size being neutralized by an ion beam of $V_v = 1$ V/m with $h = 10$ cm and $\alpha = 5$ deg. The impact parameter x_{ip} , as given by equation 4a, has its origin at the field boundary:

$$x_{ip} = \frac{2 \cdot \cos(\alpha) \sqrt{V_v \cdot h}}{\sqrt{E_{CP}}} = \frac{6.3}{\sqrt{E_{CP}}} [cm] \quad \text{Equation 4a}$$

x_{ip} is therefore less than 1 cm for $\vec{E}_{CP} > 40$ V/m.

Figure 4 shows the dependence of the impact position x_i for values of E_C between 1 V/m and 10^6 V/m and for a beam angle α of 45 deg, 85 deg, and 5 deg. For all angles the maximum value of the non-compensated field (impact point $x_i > D$) is at the very low value of between 1 V/m and 10 V/m. Thus we expect that the maximum residual electric field after neutralization with alternating polarity beams will be below 10 V/m. The impact point x_i increases linearly with V_v for $E_C \leq V_v / h$ and varies as $\sqrt{V_v}$ for $E_C \gg V_v / h$.

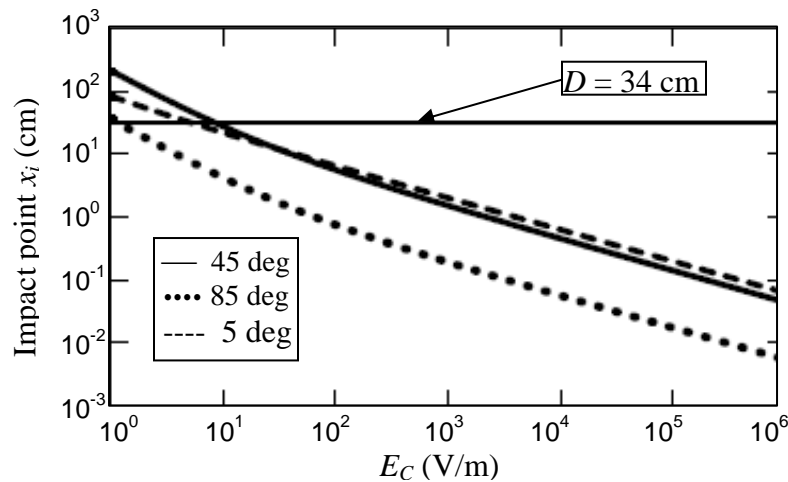


Figure 4. Impact parameter x_i as a function of E_C for $\alpha=45, 85,$ and 5 deg.

The value of the impact energy T_i as a function of E_C is given by the sum of the initial beam energy and the energy acquired in the field E_C over the distance h :

$$T_i = e \cdot (V_V + E_C \cdot h) \quad \text{Equation 5}$$

Note that T_i is independent of the angle α . For $E_C \gg V_V/h$ the impact energy T_i is independent of V_V and linearly dependent on h . Figure 5 shows T_i in eV as a function of E_C in V/m for $h=10$ cm and $h=1$ cm. Suitable operational procedures can ensure that the initial electric field to be neutralized on the LIGO mirrors is low enough that the positive ions do not damage the surface: a) handling with conductive tools and gloves, b) initial discharge before pump-down using atmospheric pressure ion sprayers, and c) slow pump-down possibly with the low energy charge beams functioning. Charged beams with $e \cdot V_V \leq 10$ eV and $h \leq 10$ cm are therefore suitable for LIGO charge neutralization. No coating damage is expected from eV energy ions and electrons, as higher energy particles are used in the coating process. However, a test of the dielectric coatings under and after exposure to 10 eV ions would provide the final qualification of this discharge approach.

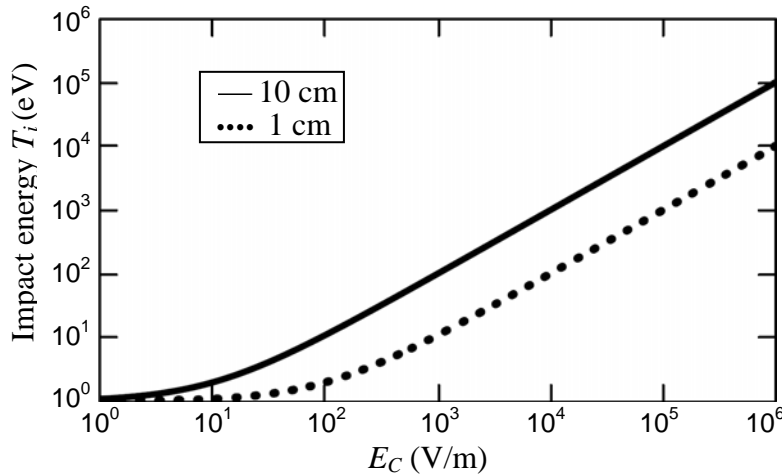


Figure 5. Impact energy T_i as a function of E_C for $h=10$ cm and 1 cm.

2.4. Electron and ion beam sources

Required beam currents for this application are well below 1 pA, making it possible to choose among a large variety of sources, subject to convenience of use. Electron sources include thermal emitters, photoelectrons and field emission cathodes.²⁵ Ion sources are widely available in the thin film coating industry in a variety of geometries and using a number of emission technologies including hot filaments, thermionic emitters, and high magnetic fields combined with acceleration voltages²⁶; most of these can be adapted to the present application. Electron and ion guns using differential pumping of the gas source, and therefore compatible with high vacuum operations, are producing focused nA beam currents at an energy of 10 eV.²⁷ Ion and electron generation using a laser of appropriate wavelength for gas dissociation is also an option.

In the very low current and energy regime the most suitable sources for both electrons and ions are the field emission cathodes.²⁵ Due to their compactness, reliability, low voltage mass and power, and no magnetic field, the field emission cathodes are particularly suited for the space implementation of charge management. Ground observatories would of course also profit from these advantages. Figure 6 shows photographs and details of Spindt field emission cathode

arrays.²⁵ Depending on the technology used for ion generation, high vacuum applications could include differential pumping of the beam sources.

The final choice of source may be dictated by the specific materials included in the source, given the very stringent requirements on allowed materials in the LIGO vacuum chambers to avoid contamination of the very low loss optics. In addition possible effects of the ion and electron flux on the optics surfaces needs to be investigated.

3. Conclusions

Charge management for non-conducting and/or non-grounded surfaces using low energy electron and ion beams has a number of significant advantages for use in high sensitivity experiments. This technique reduces both the total charge and the surface charge distribution variations to below 10 V/m, is compatible with ultra-high vacuum operations and is expected not to cause damage to surface coatings. The implementation of this technique will make use of alternating positive and negative low-energy beams directed above the surface to be discharged.

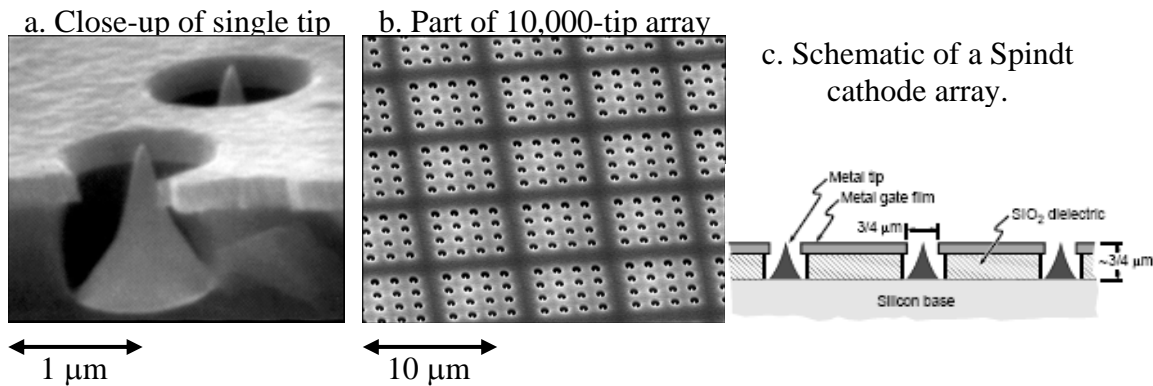


Figure 6. (a) Electron micrograph close-up of Spindt cathode tips, (b) Close-up of a section of a 10,000 tip cathode array, and (c) Schematic of a Spindt cathode array.

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