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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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Abstract

We propose using ions and electrons of energy 1 eV–10 eV 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 a 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 STEP [10], VIRGO [11] and GEO600 [12].

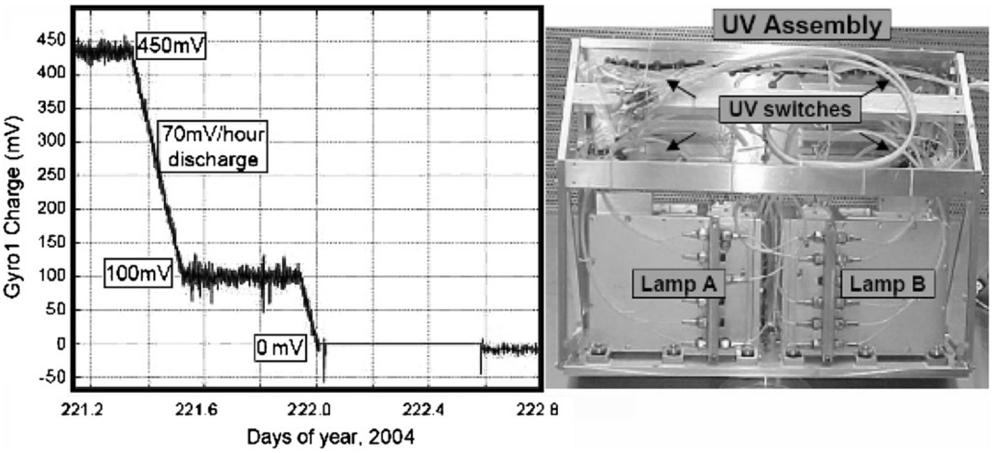


Figure 1. Left: discharge of GP-B gyroscope #1 using UV photoelectrons (1 pC produces 1 mV for the 1 nF total capacitance). Right: GP-B UV assembly.

UV charge management of non-conducting surfaces presents three potential difficulties as follows.

(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 h in air, but of only about 230 h 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 discharges [13] 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 kHz frequency range by measuring the distance between suspended test masses with mirror surfaces to a precision of 10^{-18} m Hz$^{-1/2}$ to 10^{-19} m Hz$^{-1/2}$ [8]. After the completion of the 2007 science run, a series of upgrades to the detectors, called the advanced LIGO, will be installed with the aim

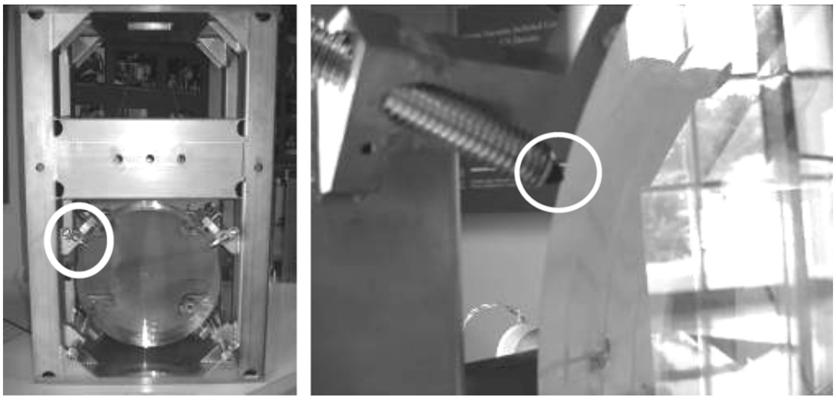


Figure 2. LIGO test mass (left) and enlarged view of test mass stop (right).

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 as follows.

(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^{-1}. 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 charging [19] 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 dust [20] (and possibly ionized gas) over the dielectric mirror coatings during pump-out generates triboelectric charges. No quantitative data are 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) Vocca [21] assumes that the net charging due to cosmic radiation is isotropic and estimates it to be about 10^5 charges cm^{-2} day^{-1}, or about 5×10^3 charges s^{-1} for the advanced LIGO-test mass dimensions. This value appears to be a worst case, as detailed measurements and calculations by Mitrofanov *et al* [22] and by Braginsky *et al* [23] result in a continuous negative charging rate of only 6×10^3 charges cm^{-2} day^{-1}. However, Mitrofanov [22] also measures fast charging events with rates comparable to those of Vocca [21].

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 s 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^{-1} and 400 m s^{-1} 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 $e \cdot V_V = 1$ eV and $T_G = 300$ K. Electrons and Ar$^+$ accelerated to 1 eV transverse the 3 m vacuum vessel in 7 μs 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

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

where

$$A_{TM} \equiv D \cdot h; \quad \langle \mathrm{v}_G \rangle \equiv \sqrt{\frac{8k_B \cdot T_G}{\pi \cdot m_G}}; \quad n_G \equiv \frac{P_G}{k_B \cdot T_G};$$

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

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 therefore does not modify the vacuum level across the mirror surface of the test mass. Alternating beams of electrons and Ar$^+$ of about 100 fA–200 fA fulfil the charge-management rate requirements as well as the vacuum-system requirements; a current of about 100 fA will neutralize an initial charge of ~100 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.

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 caused by the '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 ($\delta l/l$), 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: $\delta l/l \approx 10^{-22}$.

2.3. *A model with a 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

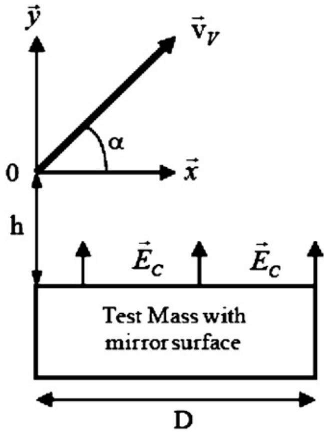


Figure 3. Beam flow model with uniform surface field.

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

$$y = x \cdot \tan(\alpha) \mp x^2 \frac{E_C}{4V_V \cos^2(\alpha)}. \tag{2}$$

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

$$x_i = \frac{2V_V \cdot \cos(\alpha)}{E_C} \left[\sin(\alpha) + \sqrt{\sin^2(\alpha) + \frac{E_C \cdot h}{V_V}} \right]. \tag{3}$$

For $E_C \gg V_V/h$ ($E_C \gg 10$ V m^{-1}) x_i becomes

$$x_i = 2h \cdot \cos(\alpha) \sqrt{\frac{V_V/h}{E_C}}. \tag{4a}$$

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, with $h = 10$ cm and $\alpha = 5°$. The impact parameter x_{iP}, as given by equation (4*b*), has its origin at the field boundary:

$$x_{iP} = \frac{2 \cdot \cos(\alpha)\sqrt{V_V \cdot h}}{\sqrt{E_{CP}}} = \frac{0.63}{\sqrt{E_{CP}}}[m], \tag{4b}$$

where x_{iP} is therefore less than 10 cm for $\vec{E}_{CP} > 40$ V m^{-1}. A full analytical model or a Monte Carlo simulation will be required for the design and implementation of a charge neutralization system using ion beams. For LIGO, such analysis would realistically model the residual charge distribution on the mirrors as well as the resulting noise in the interferometer.

Figure 4 shows the dependence of the impact position x_i for values of E_C between 1 V m^{-1} and 10^6 V m^{-1} and for a beam angle α of 45°, 85° and 5°. 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^{-1}

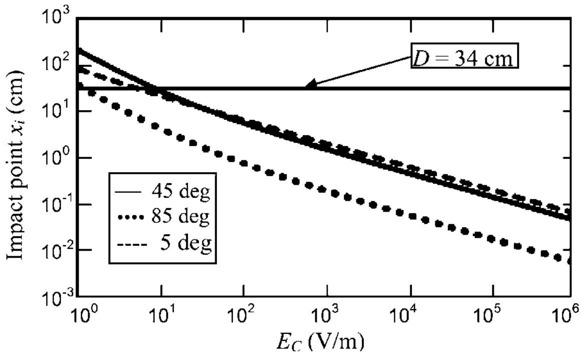


Figure 4. Impact parameter x_i as a function of E_C for $\alpha = 45$, 85 and 5°.

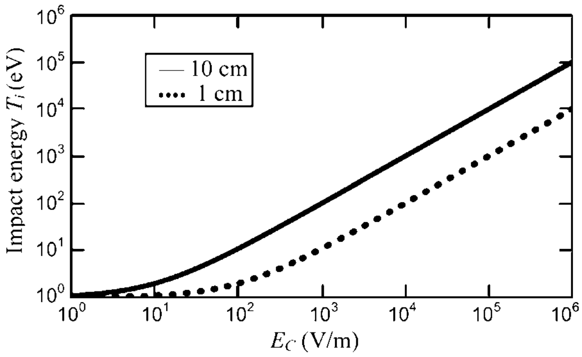


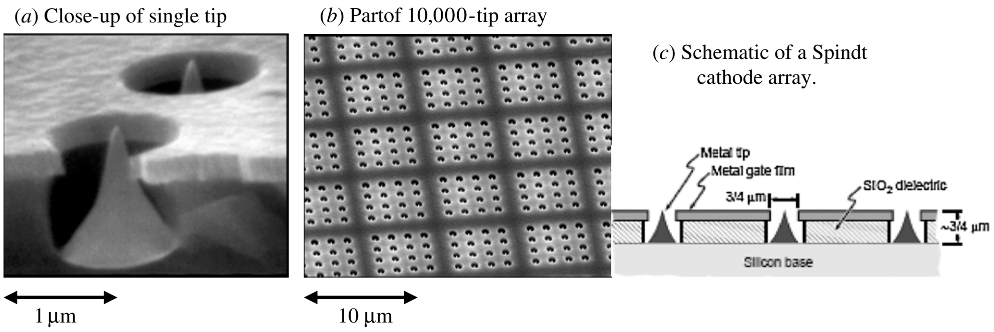
Figure 5. Impact energy T_i as a function of E_C for $h = 10$ cm and 1 cm.

and 10 V m^{-1}. Thus we expect that the maximum residual electric field after neutralization with alternating polarity beams will be below 10 V m^{-1}. The impact point x_i increases linearly with V_V for $E_C \leqslant V_V/h$ and varies as $\sqrt{V_V}$ for $E_C \gg V_V/h$.

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:

$$T_i = e \cdot (V_V + E_C \cdot h). \tag{5}$$

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^{-1} 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 $e \cdot V_V \leqslant 10$ eV and $h \leqslant 10$ 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.


(*a*) Close-up of single tip

(*b*) Partof 10,000-tip array

(*c*) Schematic of a Spindt cathode array.

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.

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 the 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 voltages [26]; 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 need 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^{-1}, 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.

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References

[1] Amin R S 2007 Brief of the May 2006 LIGO charging event *Workshop on Charging Issues in Experimental Gravity, July 26–27* (Cambridge, MA: MIT) http://www.ligo.caltech.edu/docs/G/G070572–00/

[2] Rowan S, Twyford S, Hutchins R and Hough J 1997 Investigations into the effects of electrostatic charge on the Q factor of a prototype fused silica suspension for use in gravitational wave detectors *Class. Quantum Grav.* **14** 1537–41

[3] Buchman S, Quinn T, Keiser G M, Gill D and Sumner T J 1995 Charge measurement and control for the gravity probe B gyroscopes *Rev. Sci. Instrum.* **66** 120

[4] Sun K-X, Allard B, Buchman S, Williams S and Byer R L 2006 LED deep UV source for charge management of gravitational reference sensors *Class. Quatum Grav.* **23** S141–S150

[5] Buchman S 2007 Overview of GP-B charging issues *Workshop on Charging Issues in Experimental Gravity*(*26–27 July*) (Cambridge, MA: MIT) http://www.ligo.caltech.edu/docs/G/G070568–00

[6] Sun K-X, Allard B A, Byer R L and Buchman S 2007 Charge management of electrically isolated objects via modulated photoelectric charge transfer *Patent S05-145/ US–ID:3507*

[7] Sun K-X, Higuchi S, Allard B, Gill D, Buchman S and Byer R 2006 LIGO test mass charging mitigation using modulated LED deep UV light *LIGO Science Collaboration (LSC) Meeting, LIGO Hanford Observatory, March 22* LIGO-G060172–00-Z

[8] Abbott B et al (LIGO Scientific Collaboration) 2004 Detector description and performance for the first coincidence observations between LIGO and GEO *Nucl. Instrum. Methods* A **517** 154–79

[9] For a comprehensive collection, see special issue of Sun K-X et al 2005 *Class. Quantum Grav.* 10 **22**

[10] Worden P 1976 A cryogenic test of the equivalence principle *PhD Thesis* Department of Physics, Stanford University

[11] Virgo Collaboration 2006 The status of VIRGO *Class. Quantum Grav.* **23** S63–S69

[12] Lueck H *et al* 2006 Status of the GEO600 detector *Class. Quantum Grav.* **23** S71–S78

[13] DeSalvo R 2006 private communication (to Ke-Xun Sun, October 16)

[14] Hewitson M, Danzmann K, Grote H, Hild S, Hough J, Lück H, Rowan S, Smith J R, Strain K A and Willke B 2007 Charge measurement and mitigation for the main test masses of the GEO 600 gravitational wave observatory *Class. Quantum Grav.* **24** 6379–91

[15] Fritschel P 2003 Second generation instruments for the laser interferometer gravitational wave observatory (LIGO) *Gravitational-Wave Detection* vol 4856 ed M Cruise and P Saulson (Bellingham, WA: SPIE) pp 282–91

[16] Ugolini D, McKinney R and Harry G M 2007 Developing an optical chopper-modulated capacitive probe for measuring surface charge *Rev. Sci. Instrum.* **78** 046102

[17] Rowan S 2007 Charging experiences in the GEO project and investigations of mitigation techniques *Workshop on Charging Issues in Experimental Gravity (26–27 July)* (Cambridge, MA: MIT) http://www.ligo.caltech.edu/docs/G/G070575–00.pdf

[18] Amin R S and Weiss R 2007 private communications

[19] Moore A D (ed) 1973 *Electrostatics and its Applications* (New York: Wiley)

[20] Weiss R 1996 Note on electrostatics in the LIGO suspensions *LIGO T960137–00-E*

[21] Vocca H 2007 Charging research for LISA and plans for Virgo *Workshop on Charging Issues in Experimental Gravity, July 26–27* (Cambridge, MA: MIT) http://www.ligo.caltech.edu/docs/G/G070577–00

[22] Mitrofanov V P, Prokhorov L G and Tokmakov K V 2002 Variation of electric charge on prototype of fused silica test mass of gravitational wave antenna *Phys. Lett.* A **300** 370–4

[23] Braginsky V B, Ryazhskaya O G and Vyatchanin S P 2006 Limitations in quantum measurements resolution created by cosmic rays *Phys. Lett.* A **359** 86–9

[24] Braginsky V B, Ryazhskaya O G and Vyatchanin S P 2006 Notes about noise in gravitational wave antennas created by cosmic rays *Phys. Lett.* A **350** 1–4

[25] Aguero V 2001 Experimental results and considerations on use of field emission devices in space *AIAA-2001-3338, 37th Joint Propulsion Committee Conference and Exhibit (Salt Lake City, Utah)*

[26] See for example: Advanced Energy Industries Inc., 1625 Sharp Point Drive, Fort Collins, CO 80525

[27] See for example: the *E/IMG-16 electron/ion gun* by: Kimball Physics Inc. 311 Kimball Hill Road, Wilton, New Hampshire 03086–9742 USA, www.kimballphysics.com