# Can electrons neutralize the electrostatic charge on test mass mirrors in gravitational wave detectors?

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(Received 12 January 2021; accepted 20 January 2022; published 17 February 2022)

The purpose of mitigating all potential effects that can detrimentally influence the sensitivity of present and future gravitational wave detectors has triggered specific research and development worldwide. One of the many issues to be solved is the noise induced by the electrostatic charge forming on test mass mirrors. At LIGO, a mitigation method has been proposed, studied, and successfully applied. This method requires long mirror's exposures to a relatively high pressure of $N_2$ ions flux. It is difficult, if not impossible, to apply this method, the way it is now, when mirrors are at cryogenic temperatures, since a significantly thick condensed gas layer will develop on the mirror surface severely affecting its performance. Hence, we suggest a new method to neutralize test masses electrostatic charge that could be performed in ultra high vacuum (UHV) and could easily be applied to cryogenic mirrors. We suggest the use of selected energy electrons (between 10 to 100 eV) which, at very low doses, can impinge on the surface mirror. The energy of the incident beam can be tuned to neutralize positive and negative charges on the mirror's dielectric surface or part of it. Here, we experimentally prove that this is successful in the case of Si and $SiO_2$, two prototypical materials for mirror surfaces. The method is briefly presented in its basic principles, and a number of further studies are identified in view of developing the appropriate enabling technology.

DOI: 10.1103/PhysRevD.105.042003

## I. INTRODUCTION

The detection of gravitational waves (GW) has recently established a new and very promising research tool for astronomy and astrophisysics [1]. In the ongoing and future research, it is of paramount importance to reduce undesired noise that can limit the sensitivity of gravitational interferometers and therefore, their physical reach. Among many other sources, there have been reports suggesting that electrostatic charge forming on test mass mirrors may have detrimental effects on sensitivity [2,3]. Such charging is unclear with regard to origin, quantity, and even sign. It still represents a puzzle to be solved also in view of the new generation of interferometers to come. This effect is indeed more significant in interferometers where electrostatic damping is used, as in LIGO [3–5]. In Virgo, where inductive damping is in action [6], the detrimental effects of such electrostatic charging on the test mass does not seem to be clearly limiting sensitivity up to present performances [7]. Yet, also in those systems, it is unclear if such phenomena could become an issue when sensitivity will be improved. A crash program was launched within the LIGO Collaboration, and a mitigation method has been proposed and successfully applied [2,8–10]. This method consists in exposing the mirror to some tenth of mbar of a $N_2$ plasma for a long time (∼1 h). The $N_2$ ions are created by electric field effect ionization. Gas is directed past the emitter tips, alternating their polarity at high voltage. Parameters to produce the $N_2$ ionized gas are optimized to have equal negative and positive charges. The ions are then guided into a gas flow created by differential pumping and introduced into the tower containing the mirror test masses, a UHV vacuum chamber of about 10 $m^3$. The positive and negative charges entrained in the gas flowing around the optic are supposed to be drawn by the unbalanced charges on the surface until these become neutral. In LIGO, this controlled operation is periodically and routinely performed. It has been optimized so that preparation, exposure to ions, and tower vacuum recovery cause only 12 to 24 h downtime. Unfortunately, this method is not directly applicable when mirrors are held at temperatures below ∼22 K [11,12]. The use of cryogenically cooled mirrors (down to 10 K) for the new generation of GW observatories is an essential condition to reduce thermal noise, mainly affecting the lower frequencies detection range (below $\sim 10^2$ Hz) [13]. Cryogenic mirrors are already foreseen for the low frequency detector of the

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planned Einstein Telescope (ET-LF) [14] and for Cosmic Explorer [15]. The first cryocooled mirrors are actually in commissioning at the Japanese KAGRA GW detector [16,17]. Indeed, KAGRA mirrors showed a decrease in reflectivity due to ice growth, induced by residual water molecules moving from the warm to the cold sections of the detectors vacuum system [18]. If, in the presence of a mirror at low temperature, the presently adopted neutralization method will be applied, a significant layer of the injected $N_2$ will be cryosorbed on the mirror surface, dramatically influencing its reflectivity and thermal noise [19]. While the precise thickness of such a coating is not easily predictable, since it depends on the detailed dosing conditions and the assumed sticking coefficient, the result of a rough estimate can be given by introducing the Langmuir (L) as a useful unit for the gas exposure of surface (or dosage) [20,21]. 1 L is defined as

$$1\ \mathrm{L} = 10^{-6}\mathrm{Torr} \cdot 1\ \mathrm{s}. \tag{1}$$

If every gas molecule hitting the surface sticks to it (that is, the sticking coefficient is 1), an exposure to 1 L leads to a coverage of about one monolayer of the adsorbed gas molecules on the surface [20]. The thickness of one monolayer of a condensed gas depends on the molecular species and typically, is few tenths of nm (for H2O, for example, 0.3 nm [12]). In general, the sticking coefficient varies depending on the temperature and on the reactivity between surface and gas particles [20]. Assuming a sticking coefficient between 0.1 and 1 and an exposure time of 3600 s (1 h) at $10^{-1}$ mbar (1 mbar $\approx$ 0.75 Torr), without considering pressure transients, one can see that tens of microns will be attached to the surface. In addition, the huge quantity of $N_2$ injected in the tower to neutralize charging will be condensed not only on the mirror surface but also in the cryostats. If unwanted temperature variations will occur, leading the cryostats above ~22 K, this huge amount of $N_2$ will be abruptly desorbed, thus increasing the pressure in the tower [21]. This can cause a serious issue for the vacuum stability of the towers, preventing to reach stable working conditions. One could think to operate the $N_2$ neutralization method at a temperature just above ~22 K. Indeed, in the pressure range of interest for the mirror towers (below $\sim 10^{-10}$ mbar), above such a temperature $N_2$ is in its gas phase [11]. In this case, $N_2$ would not condense on the surface, and, in principle, discharging could be possible. However, unless one thinks to heat the test masses or the mirrors surface up to more than ~120 K (a solution hard to be implemented in the complex GW detection system), other residual gases (such as $CO, CH_4, CO_2, H_2O, \ldots$) will be condensed on the surface [11]. The frost forming on the mirrors due to condensation of residual gas in the cryogenic vacuum of GW detectors is already a known problem, calling for a mitigation procedure [21,22]. Considerations on cryogenic vacuum issues and on possible mitigation methods for future GW detectors have been reported in our recent paper [21]. In that work, we have proposed the use of low energy electrons (below ~200 eV) to actively mitigate the frost formation. It is known, indeed, that electrons efficiently stimulate desorption of molecular ices [12]. However, electrons do induce charging (as extensively explained below), so their use to remove frost from the optics will be possible only if a new charging neutralization method, compliant with the cryogenic constraints, will be developed. A serious effort needs to be devoted to adapt the $N_2$ neutralization method to the new requirements deriving from the use of cryogenic optics. In the absence of such a successful effort, the noise induced by the presence of an electrostatic charging, if already detrimental for the present a-LIGO sensitivity limit, would represent a very serious limitation to the required detection sensitivity.

Here, we propose an alternative mitigation method to electrostatic charge on mirrors promising to be fully compatible with UHV and cryogenically cooled mirrors. Rather than using ions, which seems to need fraction of millibars and significant exposure time, we propose to use electrons of variable but low energy to neutralize unwanted electrostatic charge on test mass mirrors. Low energy-selected electrons can indeed compensate charges of both polarity on mirror optics. The method has a number of significant advantages with respect to the existing one since:

(i) electron (or flood) guns are commercially available and, once placed in the same UHV vacuum system hosting the cold mirrors, can be operated without further actions, being fully compatible with the cryogenic environment;
(ii) electrons can be easily focused or defocused and directed to regions where charge may be more significant;
(iii) at low density, low energy (10–100 eV) electrons are expected to be extremely mild to the optical surfaces. Electrons do not significantly penetrate the mirror surface due to their low mean free path, so that minimal effects on mirror quality are expected;
(iv) a mock-up set up could be designed and run to properly induce a charge (well defined in sign, quantity, and geometrical dimension) to refine and qualify tests apt to measure the presence of charging on mirrors. The same set up could then be used to see how efficient is this mitigation process.

## II. ELECTRON—SURFACE INTERACTION

The physical process describing the emission of secondary electrons is schematically shown in Fig. 1. Once a beam of primary incident electrons impinges on the surface, they can penetrate below the surface or can be elastically reflected, depending on their energy. The absorbed electrons interact with the material, following a

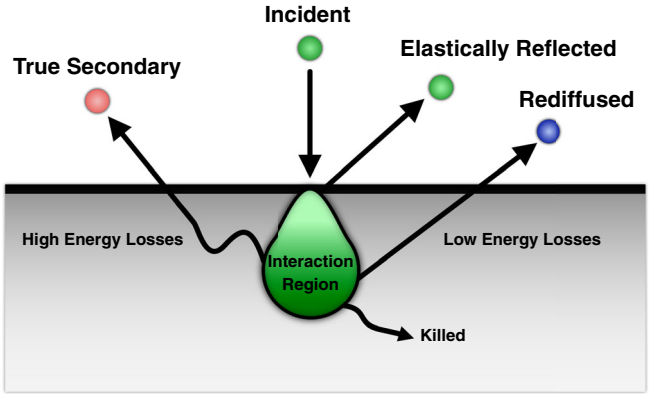


FIG. 1. Schematic representation of the secondary electron emission originating by the interaction of an incident electron beam with a surface. Incident electrons can be elastically reflected or absorbed by the surface. If absorbed, secondaries are produced in the interaction region below the surface (green zone). Such secondaries can be absorbed by the bulk (killed) or emitted from the surface, as true secondary or rediffused electrons depending on the energy losses.

scheme that, in simple terms, is described as a three-step process: (a) production of secondary electrons (secondaries) below the very top surface (interaction region in Fig. 1); (b) transport of the secondaries with energy losses during travel toward the surface; (c) emission of secondaries across the surface barrier. This process is very surface sensitive and involves, at most, the first few nm closer to the surface [23,24]. Secondaries lose their energy due to electron-electron, electron-phonon, and electron-defect interactions. Secondaries reaching the surface can be emitted if they have enough energy and emission angle to escape into vacuum. Based on the energy lost, they are distinguished between true secondaries (high energy losses) and rediffused (low energy losses). Secondaries with energy and angle not enough to overcome the surface barrier are absorbed by the bulk (killed).

### A. Secondary electron yield

The driving parameter quantitatively defining electron interaction with a material surface is called secondary electron yield (SEY). SEY is defined as the ratio between the number of all emitted electrons (secondary electrons) and the number of incident electrons (also called primary electrons) and is often indicated as $\delta$. By definition, therefore, SEY ($\delta$) is equal to

$$\mathrm{SEY} = \frac{I_{\mathrm{out}}}{I_p}, \tag{2}$$

where $I_p$ is the current of the primary electron beam impinging on the sample, $I_{\mathrm{out}}$ is the electron current emerging from the sample (accounting for true secondaries, elastically reflected and rediffused electrons sketched in Fig. 1). From Eq. (2) is evident that SEY $> 1$ if the surface emits more electrons than the incident ones; SEY $< 1$ if the electrons leaving the sample are less than those deposited.

At the Material Science Laboratory of the LNF, SEY is routinely measured as described in detail in Refs. [24–31]. Briefly, the sample is irradiated by an electron beam emitted by a Kimball physics electron gun equipped with a standard Ta disc cathode. SEY is performed at normal incidence and the irradiated area is of the order of 0.8 $\mathrm{mm}^2$. Figure 2 schematically shows the circuit diagram to perform SEY measurements. SEY is determined by measuring, with a precision amperometer, $I_p$ and the sample drain current to ground ($I_s$). $I_p$ and $I_s$ are measured independently, putting alternatively the sample [Fig. 2(a)] or a Faraday collector [Fig. 2(b)] in front of the electron gun. In fact, being $I_{\mathrm{out}} = I_p\text{-}I_s$, from Eq. (2), SEY can be obtained as: $\mathrm{SEY} = 1\text{-}(I_s/I_p)$. To measure $I_p$, the Faraday cup collector is positively biased ($V_B = +75$ V) to prevent backscattered reemission to vacuum and, then, collect all electrons incident on it. A negative bias voltage $V_B = -75$ V is applied to the sample to measure $I_s$, so as to confidently measure SEY down to low impinging electron energy (few hundreds of meV).

Conductive and semiconductive materials can be easily measured since they do not incur in charging issues that may invalidate the measurements. To measure SEY of an insulating surface, two different methods can be applied:

(i) pulsing the impinging electron flux in order to minimize the flux reaching the sample and, eventually, measure with a heterodyne technique the very low $I_s$;

(ii) measure a very thin film of the insulating layer deposited on a conductive surface [30,31]. With those thin coatings and an $I_p$ as reduced as possible,

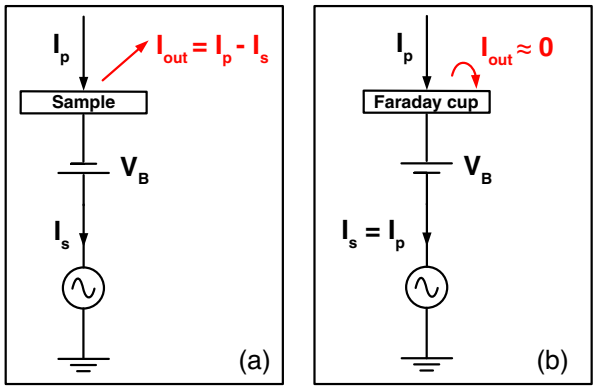


FIG. 2. Circuit diagram to measure SEY. (a) $I_{\mathrm{out}}$ from the sample is derived measuring, independently, the sample drain current to ground, $I_s$, and the current of the primary electron, $I_p$. The negative bias voltage applied to the sample surface allows to confidently measure SEY up to low impinging electron energy. (b) $I_p$ is measured by a Faraday cup positively biased to collect all incident electrons.

one can measure an insulating layer without charging it.

For the present investigation, we adopted this second approach. Primary electron currents of few nA have been used to measure SEY, corresponding to a total electron dose $\sim 10^{-7}$ C/mm$^2$ delivered on the surface during a single curve acquisition. These conditions have turned out to be optimal to avoid charging during measurements.

## III. CHARGING NEUTRALIZATION BY ELECTRONS

The challenge here is to experimentally prove charging neutralization by electrons on representative surfaces compositionally close to the mirrors materials for the future GW test masses [32–35]. Presently, an intense research and development activity is ongoing to individuate the mirror coating materials that, at cryogenic temperature, match the thermal noise and absorption needs. Their uniform deposition on a large scale is a mandatory requirement for their application in GW detectors. Different options are under evaluation, comprising crystalline and amorphous materials [36]. Among crystalline materials, AlGaAs coatings show very low thermal noise and low optical absorption [37,38]. However, currently they cannot be homogeneously deposited on large surfaces [38]. A general advantage of amorphous coatings is that they can be grown directly onto suitable mirror substrates. Among them, the combination of low-absorbing $SiO_2$ and $Ta_2O_5$ with low-loss a-Si and $SiO_2$:$HfO_2$ in a multimaterial design [34,36] is, up to now, the more feasible option meeting both the optical and thermal noise requirements at 10 K. In this work, as representative surfaces, we studied a Si substrate (Siltronix), p-boron doped to grant the necessary conductivity to perform SEY measurements, and 20 nm of stoichiometric $SiO_2$ (IHP Microelectronics), thermally grown on the same type of aforementioned Si substrate. Even if the $SiO_2$ is intrinsically insulating, its thickness and the substrate conductivity, as well as the use of a very low $I_p$, allow us to confidently acquire SEY without incurring in charging issues during measurements.

Figure 3(a) reports the SEY spectra of the two samples. Both are in agreement with the curves reported in literature for the same kind of systems [39–41]. The samples have been characterized by x-ray photoelectron spectroscopy (XPS), using nonmonochromatic Mg K$\alpha$ radiation to induce photoemission. The XPS spectrum in the Si2$p$ region reported in Fig. 3(b) highlights the presence of a $SiO_x$ component also in the Si sample, compatible with the unavoidable presence of native oxide on the sample surface (usually of the order of about 2 nm [42]) and contaminations. Therefore, electrons emitted by the surface originate both within the Si substrate and the thin overlayer, and the resulting SEY is governed by both material properties. No core level contribution of the Si substrate is noticeable from the XPS spectrum of the $SiO_2$ sample, thus suggesting

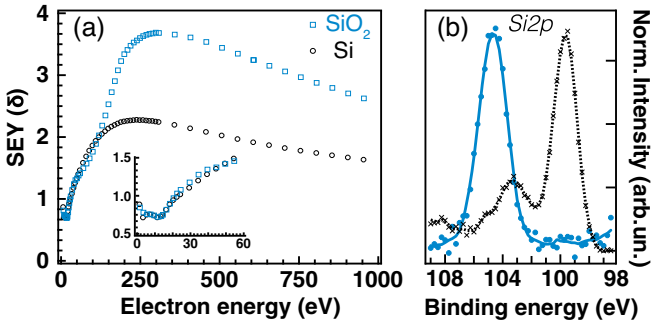


FIG. 3. (a) SEY curves from $SiO_2$ (blue squares) and Si (black circles) sample. The inset shows the low energy part of the spectrum for both samples. (b) Si2$p$ XPS spectra from $SiO_2$ (blue circle) and Si (black markers). The curves are arbitrarily normalized to the main peak intensity. The blue and dashed black lines serve as a guide for eyes.

that the SEY measurements reported in Fig. 3(a) is mainly governed by the oxide layer. This allows us to consider such SEY as characteristic for the surface of Si and $SiO_2$ bulk sample. From the SEY curves, it can be deduced that, depending on the impinging electron energy, we can deposit electrons to the surface (at low energies, when SEY $\leq 1$) or force the surface to emit more electrons than the ones deposited by the gun (at higher energies, when SEY $\geq 1$). This simple notion can not only justify why electrons from an ion pump can charge the optical element (positively or negatively, depending on their energy) but also suggests to tailor electron energies to induce positive or negative charge on a surface. For electron with energy less than ~25 eV, the SEY of Si and $SiO_2$ is $\leq 1$ and such electrons will neutralize positive charges. Higher energy (more than ~25 eV) electrons will cause neutralization of negatively charged samples and sample's patches.

SEY in dielectrics is generally quite high in comparison with the one of conductive materials but, as confirmed by this study and the literature [23,43,44], there is always a region, at very low impinging energy, where SEY is less than 1 [see inset in Fig. 3(a)]. Reports on the low energy part of SEY on insulators are not very numerous due to the aforementioned intrinsic experimental difficulties to perform electron spectroscopy on insulators. A detailed SEY measure campaign should be launched to study the characteristic properties of the surface coating finally chosen to be used on the various mirrors. This will be done not only once the method validity will be finally proven but also when its integration will be shown to be compatible with the high complexity of the design of the mirror towers. Our aim here is to strongly suggest the possibility to cure electrostatic charging on test mass mirrors in gravitational waves interferometers by relatively low energy ($\leq$100 eV) electrons irradiation. The use of this method would give us the unique opportunity to design and construct a mock-up test bench where deliver on purpose a specific charge (with a given sign and in a reasonably well-defined region).

This can be used to refine/optimize the way to measure this charge, its effect in relation to other observables and to develop a feedback loop to quantify (at a given time) the charge on the surface to manage electron irradiation parameters up to the total charge neutralization.

In the following, for a more detailed discussion of the proposed mitigation method, we consider the SEY of the $SiO_2$ sample, shown in Fig. 3(a), as representative for a realistic test mass mirror surface.

### A. Charging a neutral sample

*Negative charging* Let us assume that the sample is neutral. On this surface, we can deposit electrons by irradiating it with a beam of energy lower than 20 eV. As shown in Fig. 4 (top panel), let us first assume we use $E_p \approx 15$ eV (where the substrate SEY is ≈0.8), and we deliver a current of $1.6 \times 10^{-9}$ A for one second (i.e., $10^{10}$ el). 20% of them will be deposited on the irradiated spot. Of course, by doing so, a fully insulator will start charging negatively in the irradiated spot. This charge will decelerate the impinging electrons and eventually repel them. This will happen when the impinging electrons will feel a potential equivalent to a bias voltage of 15 eV. Then, electrons have no actions anymore. Knowing the SEY and the delivered flux, we are indeed able to estimate the charge left on the surface.

*Positive charging* Let us assume that the sample is neutral. If we deliver a current of $1.6 \times 10^{-9}$ A for one second (i.e., $10^{10}$ el) at $E_p \approx 60$ eV (where the substrate SEY is ≈1.5), as shown in Fig. 4 (bottom panel), the sample will be depleted by $0.5 \times 10^{10}$ electrons (two go in and three go out). Then, of course, the sample will charge up positively, accelerating the impinging primary electrons to higher energies. They will bombard the surface and induce a higher number of secondaries to leave. Secondaries have all low energies (between 0–20 eV), as reported in the literature [26,27] and as soon as they escape, they will interact with the surface positive charge and be mostly readsorbed. Also, this process seems self-limiting: if we want to charge more positively the surface, we need to increase $E_p$ and the detailed knowledge of the SEY will allow us to finally estimate the positive charge on the surface.

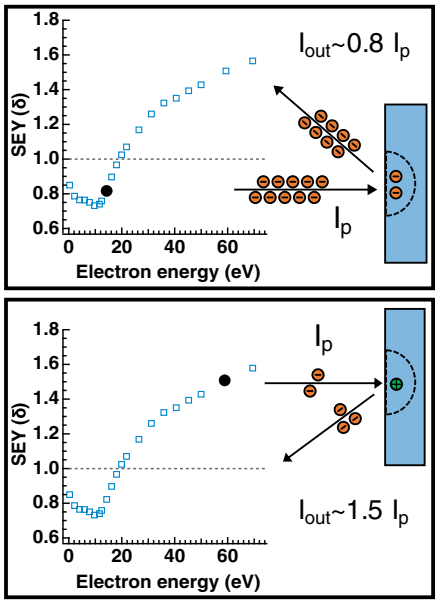


FIG. 4. Schematic view of the negative charging (top) and positive charging (bottom) process of a neutral 20 nm $SiO_2$ layer [SEY curve from Fig. 3(a)].

### B. Discharging a positive sample

In this case, all electrons will be accelerated to the surface at their initial energy plus the one induced by the charge. They will produce quite a high number of low energy secondaries that, once out, will interact with the surface positive charge and mainly go back to the surface. The net process should then reduce the positive charge to a final value that depends on the set energy and on the SEY of the neutral sample: if the energy is low (SEY < 1), the sample will charge negatively, if the energy is high (SEY > 1), the sample will stay positive, if we set the energy of the impinging electrons where SEY = 1, the sample will be neutralized.

### C. Discharging a negative sample

In this case, all impinging electrons will be decelerated from their initial energy by the surface charge. If the surface charge is not so high to repel all the incoming electrons, we need to tune the impinging electron energy so that, after deceleration, electrons are in the region where the SEY of neutral sample is ≥1. In this case, the surface will emit more electrons than the ones deposited inside the solid, and, therefore, the negative charge will reduce. Further electrons will then reach the surface by a reduced deceleration and produce even more secondaries (depending on the SEY form). If the impinging electron energy is not controlled during the neutralization process, we will end up by depleting the surface and changing the sign to the deposited charge. Then, irradiation by low energy electrons will, as shown in the previous section, neutralize this positive charge. If the surface charge is high enough to repel all incident electrons, no neutralization is possible. This situation, however, seems quite unlikely. First, it needs a source of high energy electrons impinging on the surface and producing more electrons out than electrons in. Secondly, all SEY curves have a maximum (typically at 200–800 eV) but then SEY gets reduced below 1 at high energies. This is simply due to the fact that very high energy electrons penetrate to a great extent inside the solid and the generated secondaries are too far beneath the surface to reach it. Even if it is an unrealistic case, the

discharging of a highly negatively charged surface can deserve further studies.

It is important to notice here that the expected currents to be delivered to test mass samples in view to cure such effect may be extremely low. Moreover, electrons can be easily directed on small or larger mirror areas and driven in different parts by simple electrostatic lensing. It could be even conceivable to see whether the process here proposed needs a periodically downtime period (during which no data taking is possible) or it can be performed when the GW detector is operational. The foreseen improvement on the detector sensitivity may imply a more frequent need to statically discharge the mirrors as presently done. Limiting all side effects and down time periods connected to such operation is indeed essential for the new interferometers. The electron beam is not expected to affect the mirror reflectivity or introduce excess thermal noise since the electron beam only interacts with the topmost 10–20 layers (of the order of few nm), much smaller than the thickness of coating layers which are of the order of $\lambda$, the wavelength at which the coating is designed to be reflective ($\sim\mu$m). This topic is of paramount importance and should deserve further studies.

## IV. CONCLUSIONS

We have presented a conceptually simple method that could be applied to neutralize electrostatic charges formed on test mass mirrors in gravitational waves interferometers. We have suggested the use of selected energy electrons (between 10 to 100 eV) which, at very low doses, can impinge on the surface mirror. As we have shown, according to the incident electron energy, SEY could be $\leq 1$ or $\geq 1$, i.e., removing or adding electrons at will on a mirrors dielectric surface up to charging neutralization. Its actual refinement and implementation are indeed a challenge and will involve specific research and development on many issues. A first mandatory step is a detailed surface characterization of all mirror surfaces that will be finally proposed and adopted. This also involves the study of the effect, if any, of such very low energy electrons on the optical properties of the mirrors. Once these aspects have been tackled, the realization of a realistic mock-up system, where to test the process, is indeed required. This setup will allow to study the way to measure any charged density on the mirrors, their effect on observables and, finally, to determine a feedback system to validate the neutralization prior to the interferometer operation. The design and optimization of newly developed, or existing, electron guns (or flood guns) will then lead to the installation design. The final aim of this research line seems worth the effort since the goal of having an efficient measure of the electrostatic charge on mirrors, a way to neutralize it in UHV, also in presence of cryogenic surfaces, is one of the technological challenges we need to tackle for the successful operation of future gravitational wave interferometers.

## ACKNOWLEDGMENTS

The authors thank J. Bilotto and the DAΦNE-L team for technical assistance, F. Ricci, E. Majorana, and B. Barish for enlightening discussions. We acknowledge L. Di Gaspare and A. Notargiacomo for providing the investigated materials.

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