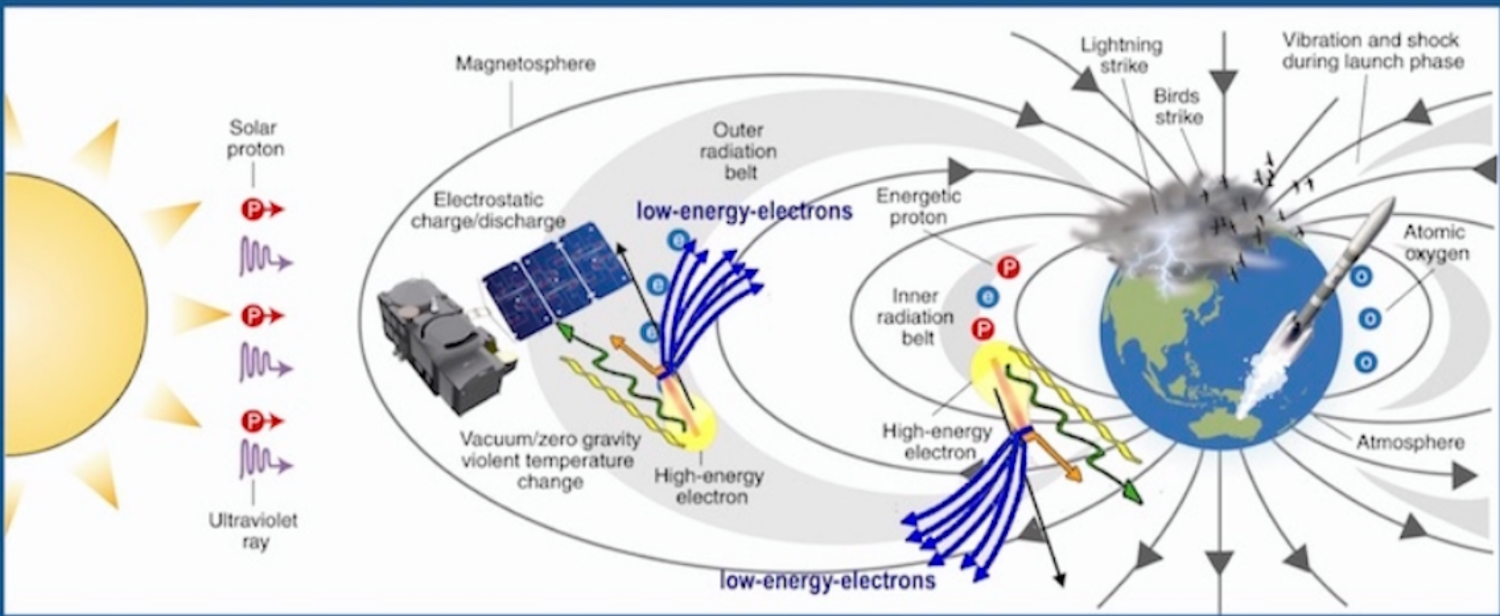
LEE2022

A brainstorming meeting on relevance of Low Energy Electrons in aerospace

(Tuesday, November 15th 2022)

Organized by *Stefano Iacobucci* & *Giovanni Stefani* (ISM-CNR)



List of confirmed Speakers

Marco Angelucci INFN-LNF (Roma)
Paola Bolognesi CNR-ISM (Roma)
Andrea Liscio CNR-IMM (Roma)
Maurizio Dapor ECT*- FBK (Trento)
Piero Diego INAF- IAPS (Roma)
Stefano Nannarone CNR-IOM (Trieste)
Pierfrancesco Riccardi UNI CAL (Cosenza)
Alessandro Ruocco UNI ROMATRE (Roma)
Luisa Spallino INFN-LNF (Roma)
Daniele M. Trucchi CNR-ISM (Roma)

The meeting lasts from 9:00am to 5:00pm

CNR Istituto di Struttura della Materia

Book of Abstracts

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Title

Laser beam power converters based on photo-thermionic emission for future lunar exploration

Daniele Trucchi

CNR-ISM, Via Salaria km 29.300, 00015 Monterotondo, Rome, Italy

daniele.trucchi@ism.cnr.it

Abstract

The development of a compact, lightweight, scalable, and efficient power generation technology for mobile platforms and satellites is mandatory for planetary science and exploration missions. In order to meet such requirements, CNR proposes a scientific concept based on the novel solid-state photon-enhanced thermionic emission converter (PETEC) supplying energy to robotic systems from conversion of intense laser light. The PETEC is made of a semiconducting cathode absorbing solar radiation and emitting low energy photo-generated and thermal electrons. CNR development proposes active materials based on a diamond emitter with a low or even negative electron affinity coupled with a solar absorber (black diamond, diamond-on-silicon/SiC). The diamond emitter surface has to be accurately terminated to finely control the electron affinity and, consequently, maximize the electron emission. Under analysis are also the issues limiting the device performance such as the transport of emitted electrons needing the optimization of the inter-electrode spacing technology to avoid space charge effects and their collection by a work-function matched anode.

Under development for concentrated solar power, the advantage of PETEC is the capability to manage laser fluxes even higher than 100 W/cm2 with a potential conversion efficiency outperforming photovoltaic and benefiting from the higher operating temperatures. PETEC is able to surpass the historical limitations of thermionic energy converters (TECs) thanks to lower temperature operations (<700 °C) and to the application of refined concepts and methods in materials science and engineering. Moreover, the operations in vacuum conditions typical of some extraterrestrial conditions, such as the lunar environment, facilitates significantly the device structure.

The proposed technology can pave the way to sustainable planetary missions: it can operate under harsh environments and greatly reduce issues in thermal stresses of extra-terrestrial day/night cycles, that pose the biggest technical challenge for power supply of rovers, drones, and satellites. The technology specifically focuses on exploration of permanently shadowed regions on the moon with valuable resources for sustainable lunar missions and where the proposed compact power unit enables cheaper and less complex operations.

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Title

Role of low-energy electrons in developing novel materials for highly demanding space missions and applications

Andrea Liscio

CNR-IMM, via del fosso del cavaliere 100, 00133 Roma

andrea.liscio@artov.imm.cnr.it

Abstract

The development of suitable materials for space application must take into account several constraints due to harsh operating conditions that are not found on Earth such as temperature, gravity, radiation, pressure, etc. Several classes of materials that have been successfully used in the space environment are Kevlar, aluminum alloys, reinforced carbon-carbon composite coated with silicon carbide, silica, etc because their strength, light weight, resistance on impact, withstands high and low temperatures and thermal shocks, as well, sealing of cracks, etc. In particular, the use of matrix nanocomposites allows to develop a portfolio of on-demand materials,[1] in which 2D nanofillers introduce new physical properties that the pristine matrix do not possess, resulting in high performance and multi-functional materials.

The interactions of the composite materials with the space radiation environment are a considerably complex process due to the individual components: matrix and filler, and the interface regions as well, where secondary charge generation mechanisms can be generated causing chemical modification of materials. Typically, these are secondary electrons ionized from core or valence levels by incident radiation and slowed by multiple inelastic scattering events.[2]

Several studies have been carried out on the damage to polymers due to impact of plasma electron flux or due to the production of secondary electrons (i.e. charge trapping generated by UV absorption in material defects).[3] Similarly, attention has been devoted to the stability and radiation tolerance of the emerging class of 2D materials.[4] Despite great efforts, a general analysis of the mechanisms occurring at the interfaces is still lacking. Such aspect is crucial in the case of nanostructured composites the role of interfaces plays a fundamental role in the description of the macroscopic properties of the composite.

Here we present two cases in which low-energy electrons can play a fundamental role in the stability of composite materials and their functioning in devices (active and passive), such as

- ✓ Van der Waals 2D thin films as ultra-thin coatings to tune the wettability of meso-porous metal foams as heat exchangers;
- ✓ Gamma-ray assisted reduction of graphene oxide mediated to the radiolysis of water.

1. Vargas-Bernal, R. and M. Tecpoyotl-Torres, *Nanocomposites for Space Applications: A Review*, in *Diverse Applications of Organic-Inorganic Nanocomposites: Emerging Research and Opportunities*, G. Clarizia and P. Bernardo, Editors. 2020, IGI Global: Hershey, PA, USA. p. 191-222.
2. Mucke, M., et al., *A hitherto unrecognized source of low-energy electrons in water.* Nature Physics, 2010. **6**(2): p. 143-146.
3. Canning, G., et al., *Morphological Contributions to Interfacial Charge Trapping and Nongeminate Recombination in Polymer Solar Cells Revealed by UV Light Soaking.* ACS Applied Materials & Interfaces, 2018. **10**(23): p. 19853-19862.
4. Vogl, T., et al., *Radiation tolerance of two-dimensional material-based devices for space applications.* Nature Communications, 2019. **10**(1): p. 1202.

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Title

Space Plasma simulator for experimental evaluations of particle-matter interactions

Piero Diego

Istituto Nazionale di Astrofisica, via del fosso del cavaliere, 100 - Roma

piero.diego@iaps.inaf.it

Abstract

The space plasma at LEO altitude is characterized by very low energy electrons (< 1 eV) surrounding satellites parts and instruments. Electrons isotropic flux produces spurious polarizations and parasitic currents on any kind of sensors.

The Solar Wind and Ionospheric Plasma Simulator (SWIPS) of INAF-IAPS, is a large facility
capable to reproduce both the ionospheric and the solar wind plasma.

Its peculiarity is mainly due to sources that produce the plasma with parameters (i.e. electron density, temperature, and ion energies) very close to the values encountered in the ionosphere and in the interplanetary space.

The plasma generated by the sources is accelerated into the chamber at a velocity that can be adjusted to simulate both the relative motion between an object orbiting in space and the ionosphere (≅ 8 km/s) and the velocity of solar wind (> 300 km/s) respectively.

In addition, the facility is equipped with a two-axis magnetic coil system capable to control the ambient magnetic field. Thus, the plasma beam and the magnetic field pattern can be set to reproduce the conditions encountered by satellites in both equatorial and polar orbits.

The magnitude of the field can be varied between 10^{-6} and 10^{-4} T. The residual field is low enough to consider the plasma non magnetized.

Various kind of diagnostic sensors have been developed to check the plasma parameters in order to control the actual particles fluxes on the instrument or material under test in the facility.

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Title

Electron emission from surfaces and nanostructured materials under ion and electron irradiation

P. Riccardi

Dipartimento di Fisica – Università della Calabria – Italy
Pierfrancesco.riccardi@unical.it

Abstract
Secondary electrons (SE) are those electrons of a target material that are emitted in vacuum by the impact of energetic (primary) particles. The phenomenon is the basis for several techniques of spectroscopy and microscopy of materials. It also plays a crucial role in a wide variety of areas, including electron multipliers, electrical discharge and plasma processing of materials, particle accelerators and plasma–wall interactions in fusion reactors, astrophysics. Electron emission may be a problem that needs to be avoided or reduced, such as the electron cloud effects in high-energy accelerators and storage rings. Progress in all these areas call for advances in the basic understanding of electron emission in particle–solid interactions. This motivates the study of the energy distribution of emitted electrons *N(E)* and of its integral, the electron emission yield δ, as a function of several variables, such as impact energy, incidence and emission angles, as well as surface conditions. This contribution will give an overview of the current understanding of electron emission phenomena from surfaces under ion and electron irradiation. We will consider the basic mechanism of electron emission from metals and insulators, addressing the issue of the enhanced emission from these last. Focus will be given to the capability of angle resolved secondary electron emission (ARSEE) to probing the excited states of 3D materials derived from 2D crystals. Comparison with state of the art Density Functional Theory (DFT) calculations shows how the band dispersions obtained in ARSEE experiments can be related to hybridized energy states found in DFT calculations. The technique shows show how peculiar properties of the electronic structure of 2D materials are reflected in 3D derived systems, which is therefore interesting in materials science as 2D crystal can be the building blocks of more complex three dimensional (3D) hetero-structures with properties tailored to suit specific demands.
The contribution will report also on measurements of the energy distributions of electrons emitted by Aluminum and Magnesium surfaces under the impact of low energy singly charged noble gas and sodium ions, focusing on Auger decay of electronic excitations produced in both projectile and target atoms during binary atomic collisions. These excitations are well described by the Fano-Lichten molecular orbital promotion model adopted for gas-phase experiments. For their electronic structure and the larger atomic density, the use of solid targets in experimental studies of inner-shell vacancy production often results in photon and Auger electron emission which differs from the emission observed in experiments with gas target. Many of these solid target effects have been sparsely studied and they are often neglected in studies of ion-solids interaction. In This contribution we present our recent experimental research on electron promotion and examine some of these solid target effects, showing their importance within the current context of research in energy loss and energy deposition by ions in solids.

Title

Low energy electrons and biomolecules

P. Bolognesi, J. Chiarinelli, L. Carlini, M.C. Castrovilli, A.R. Casavola and L. Avaldi,
CNR-ISM, Area della Ricerca di Roma 1, Via Salaria n. 29.300, Monterotondo (Roma)
Paola.Bolognesi@ism.cnr.it

Living beings are constantly exposed to high energy radiations from natural and anthropic sources, which can produce serious diseases from mutagenesis to cellular death. On the other hand, a wise and well controlled use of radiation provides unvaluable diagnostic and therapeutic tools. Among many examples that could be cited, radiotherapy for cancer treatment is probably one of the most widely recognized. In this application, high energy radiation from beams of photons (variable between 60 KeV to 25 MeV depending on the application), electrons (4–20 MeV), protons (230 to 250 MeV) or multiply charged ions (100-450 MeV/u) are used to irradiate and kill tumor cells in specific areas of the body of the patients.

These high energy radiations deliver a large amount of energy when directly targeting the DNA of tumor cells, inducing a dramatic genotoxic effect. However, most of the energy of the radiation beam crossing the body of the patient is deposited in cells and their surrounding media and only rarely directly in the DNA that, even though being the most sensitive part of the cell represents by far a minor component. Therefore, all along its penetration path in the human body, the energy of the ionizing radiation is channeled into the production of a huge amount of secondary species [1], like radicals and free secondary electrons. The latter quickly thermalize down to energies between 1 and 20 eV [2] and it has long been debated whether such low-energy electrons are able to induce genotoxic damage in DNA.

At the beginning of this century, the revolutionary work of the group of Leon Sanche [3] has clearly demonstrated that electrons of energy as low as few eV, i.e. well below molecular ionization thresholds, play a crucial role in the nascent stages of DNA radiolysis inducing substantial yields of single- and double-strand breaks in DNA. Since then, the scientific community has looked at processes related to the release and effects of such low energy electrons with increasing efforts, as it is only through a complete understanding of such early events in the generation of genotoxic damage that we may hope to eventually manipulate the effects of ionizing radiation at a molecular level.

The radiation damage mechanisms of low energy electrons (Figure 1) as well as their potential use as radiosensitisers (Figure 2) will be presented.

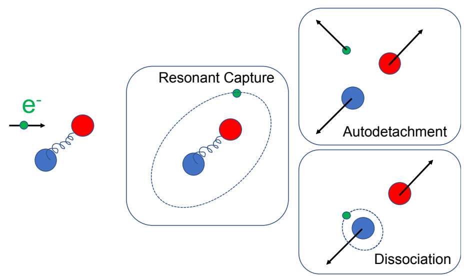

Figure 1. *A simplified view of the Dissociative Electron Attachment (DEA) mechanism in the case of a diatomic molecule. Boudaiffa et al [3] concluded in their work that the observed DNA strand breaks are initiated by resonant electron attachment to the various DNA building blocks (base, deoxyribose, phosphate), followed by bond dissociations.*

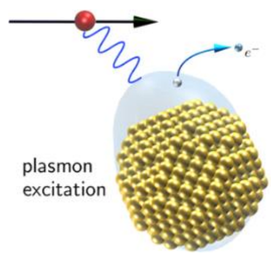

Figure 2. *The mechanisms of plasmon excitation/decay of metallic nanoparticles can be an excellent source of low energy electrons, thatnks the the huge cross section for plasmon excitation. Therefore metallic nanoparticles have been proposed as radiosensitisers in radiotherapy treatments.*

1 C. von Sonntag, The Chemical Basis for Radiation Biology (Taylor and Francis, London, 1987).
2 V. Cobut et al., *Radiat. Phys. Chem*. 51, 229 (1998)
3 B. Boudaıffa et al. SCIENCE 287, 1658, (2000)

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Title

Secondary electrons production with EUV synchrotron radiation: experiment and modeling

Stefano Nannarone

IOM-CNR

nannarone@iom.cnr.it

The electron scattering processes mainly among the electrons belonging to low energy portion of the electron cascade triggered by the creation of photo-electrons with the material's constituents are widely accepted as the main responsible of the non-resonant photosensitivity and radiation damage processes.

Our group involving IOM-CNR, IMEC, and UniCam is currently concentrated on two classes of phenomena including the solubility switching of photoresists and the damage of optical elements typically those of synchrotron radiation optics.

Secondary electrons are the image, though deformed by the solid-vacuum barrier crossing, of the low energy distribution inside the materials exposed to an excitation beam - a photon beam in present case – and possibly a measure of the out-of-equilibrium electron distribution function f*(E).

To have a quantitative reference tool a simple model of the electron yield, somehow a revisiting of the three-step-model of photoemission, in presence of monochromatic photon excitation (92 eV in present case) has been constructed. It involves the material's parameters including the optical constants, the electron mean free path, and the electron affinity together with the impinging radiation parameters (angle of incidence, light polarization and beam foot print).

Related simulations of secondary electron spectra are compared with experimental secondary spectra obtained at the IOM-CNR BEAR synchrotron beamline at Elettra (Trieste, Italy).

The writing of equations describing the energy and angle dependent electron yield will be presented together with the preliminary results obtained for the derivation of f*(E) for an Argon ion sputtered sample of crystalline Au [100].

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Title

Modelling of electron spectra and of total yield of backscattered and secondary electrons by electron impact

Maurizio Dapor

European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT-FBK) 38123 Trento, Italy*

dapor@ectstar.eu

One of the most interesting applications of the Monte Carlo method consists in the simulation of the spectrum of the emitted electrons when a solid target is bombarded with an electron beam of given initial kinetic energy. Knowing the elastic and inelastic scattering cross-sections of the electrons in their interaction with the atoms of the target, it is possible to calculate the probabilities of angular diffusion and loss of kinetic energy for each collision between the electrons of the incident beam and the atoms of the target. In this way, it is possible to model the history of each electron, following its trajectory, calculating its energy losses, and simulating the entire cascade of secondary electrons.

By averaging over a large number of trajectories, it is possible to obtain a spectrum representing the energy distribution of the electrons from any given solid target. Many electrons of the primary electron beam can be backscattered and a fraction of them conserves the original kinetic energy. They constitute the zero-loss peak, also known as the elastic peak. The plasmon peak collects the electrons of the primary electron beam that emerge from the surface after having suffered a single inelastic collision with a plasmon. Surface and bulk plasmon peaks can be observed in the spectrum. Multiple collisions with plasmons are also present in the spectrum as a series of plasmon peaks with decreasing intensities. Finally, the secondary electrons produced by a cascade process are those electrons that have been extracted from the atoms and are able to emerge from the target surface.

We will describe the SEED (Secondary Electron Energy Distribution) Monte Carlo code and compare simulated results with experimental data concerning electron spectra and the total yield of backscattered and secondary electrons.

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Title

Contribution of plasmon decay to secondary electron emission

Alessandro Ruocco

Dipartimento di Scienze Università Roma Tre, Via della Vasca Navale 84, 00146 Roma - Italy

alessandro.ruocco@uniroma3.it

Abstract

We measured the contribution of the bulk and surface plasmons decay in the secondary electron spectrum of Aluminum by means of time-coincidence techniques; we highlighted the evidence of such contribution independently from the kind of probe (both intermediate energy electrons and soft x-ray) used for exciting the collective valence electron modes, rather relating the mechanism of secondary electron production to the sample electronic structure.

Title

Low Energy Electrons Relevance in Accelerator Technology

M. Angelucci, L. Spallino, and R. Cimino

LNF-INFN, via E. Fermi 54 (ex 40), 00044 Frascati (Rome), Italy

marco.angelucci@lnf.infn.it

In 1989 an instability driven by photoelectrons was observed at the National Laboratory for High Energy Physics (KEK) Photon Factory. It was not until 1994 that its origin was correctly identified as due to the formation of an electron cloud (EC). The low energy electrons, produced either by synchrotron radiation hitting the accelerator walls or by direct ionization of residual gases, might undergo a rapid multiplication driven by the actual SEY properties of the wall surface. These electrons are accelerated by the bunch electric field in the direction perpendicular to the beam motion. If the bunch charge and the bunch spacing satisfy certain conditions, the traversal time of the electron across the vacuum chamber equals the time interval between successive bunches, and a resonance condition is established. If, in addition, the effective secondary electron yield (SEY) at the chamber is larger than unity, the electron population grows rapidly in time with successive bunch passages, leading to a high electron cloud density.

In general, the EC is significant in machines with intense, closely spaced, short, positively charged bunches, and vacuum chambers of relatively small transverse dimensions.

This phenomenon has been recognized as a problem in positron/proton rings like DAΦNE, B (Beauty) factories, PEP-II, KEKB, LHC and plays a crucial role in the realization of the new generation of accelerators like HighEnergy-LHC, Electron Ion Collider (EIC) and the Future Circular Collider (FCC). Detrimental effects of the EC include interference with diagnostic devices, coupled-bunch coherent beam instabilities, heat load, and single-bunch incoherent effects such as emittance increase.

Different solutions have been proposed to mitigate di EC effects. Modifications in terms of geometry and coating can be used to reduce the secondaries emission from the surface. But, since the SEY is influenced by the presence of contaminants and overlayer, it is essential to take into account the environmental conditions (cryogenic temperature, residual gas..) inside the accelerator during the operation. Moreover, important SEY variation can be induced by the interactions with electrons and photons inside the vacuum chamber, modifying the chemical state of atoms and molecules on the surface.

For these reasons, different experimental and theoretical campaigns were lunched to study and predict SEY of materials of interest for accelerators. The accurate measurements and predictions of the SEY of proposed materials are crucial for simulation codes used to study and validate the design and performance of present and planned accelerators machines.

Results related to metal surfaces exposed to the atmosphere and cleaned in UHV will be presented to show the effect on SEY of surface contaminants, and the role of adsorbed gas multilayers and structural disorder in influencing the properties of SEY of materials of interest.

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Title

Low Energy Electrons Significance in Gravitational Wave Detector Technology

L. Spallino, M. Angelucci and R. Cimino
LNF-INFN, via E. Fermi 54 (ex 40), 00044 Frascati (Rome), Italy
luisa.spallino@lnf.infn.it

Abstract

The mitigation of all potential noise sources that detrimentally affect gravitational wave (GW) detection is mandatory for present and future GW interferometers. One of the many issues is the noise induced by the electrostatic charge forming on test mass mirrors. A mitigation method has been successfully applied for detectors working at room temperature. It consists in mirror's long exposures to tenth of mbar of N_2 ions flux. This method is not conceivable if mirrors are at cryogenic temperatures. Indeed, a significantly thick condensed N_2 layer will build up on the mirrors' surface, affecting their optical properties. In absence of a different solution compatible with a cryogenic vacuum environment, surface charge on GW mirrors will be a severe limit for their physical reach. The use of cryogenic mirrors in future gravitational wave detectors is a key factor to reduce thermal noise and improve their sensitivity. However, due to residual gas in the Ultra High Vacuum (UHV) chambers containing the optics, when operating at cryogenic temperatures, an ice layer ("frost") will inevitably form on the mirrors' surface. Such ice adlayer can perturb or even prevent GW detection and nowadays a series of solutions are under investigation both to reduce and remove frost forming on the optics.

In this context, great significance can assume the use of low energy electrons to both mitigate charging issues and to remove frost from mirrors' surface of future GW detectors.

The asset for using electrons as charging mitigation method is the ability of electrons to induce charges of both polarity on an insulating surface. Then, if the Secondary Electron Yield (SEY) characteristics of the GW optics are known, by properly choosing the impinging electron energy, it could be possible to irradiate the GW detectors up to neutralize charges on them. Moreover, when electrons impinge on an ice layer, they can interact wit the molecules through inelastic collisions. While losing energy, electrons can induce Electron Stimulated Desorption (ESD), the transport of secondary electrons in the molecular ice being the principal mechanism governing ESD. This suggests the possibility to remove the frost forming on cryogenic GW mirrors' surfaces by electron irradiation.

SEY (and consequently ESD, in the case of a condensed gas layer) is a peculiar property of each material, being this latter metal, insulator o semi-conductor. It is strictly related to the surface state and can be strongly influenced by any physico-chemical modification induced by environmental conditions and external interactions. All these aspects are crucial to be understood if electrons are considered as mitigation method both for charging and frost formation on GW detectors. A deep SEY investigation of specific insulators (as the ones composing optics in GW detectors) and molecular ices is a priority. Moreover, with the aim of validating the use of electrons in the context of GW detectors, the mirrors' optical quality upon electron irradiation has to be guaranteed. Indeed, any defects formation and surface modifications could spoil the mirrors' sensitivity. The accurate investigation of the effects induced in the optics by electrons irradiation is therefore absolutely mandatory.