Low energy electrons to cure frost and electrostatic charging in future GW mirrors

ET Italia: 1° Workshop on Coatings

31th May 2024

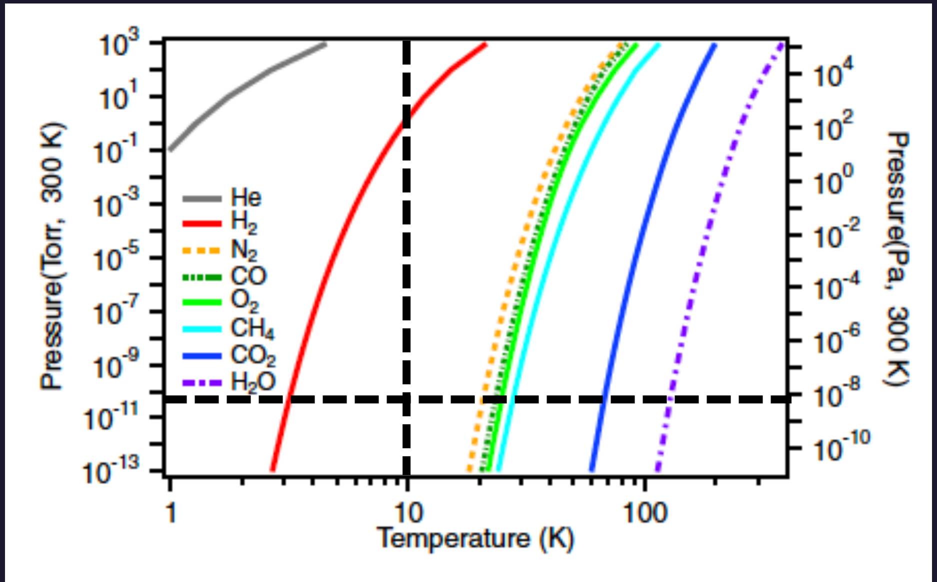
Marco Angelucci, Luisa Spallino and Roberto Cimino

LNF-INFN

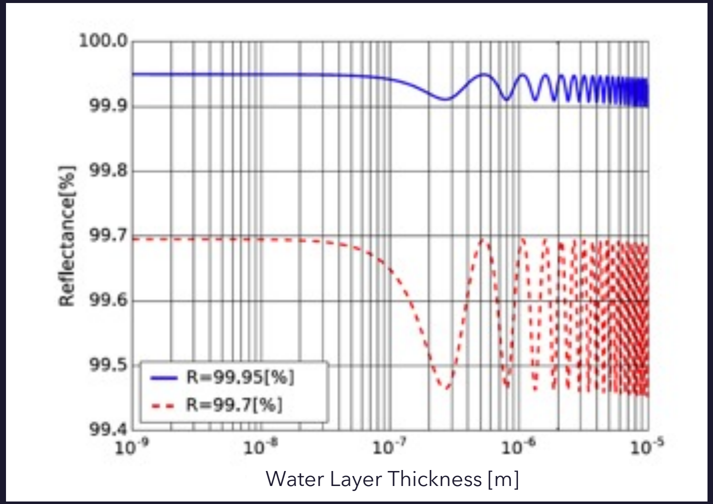
INFN LNF Istituto Nazionale di Fisica Nucleare

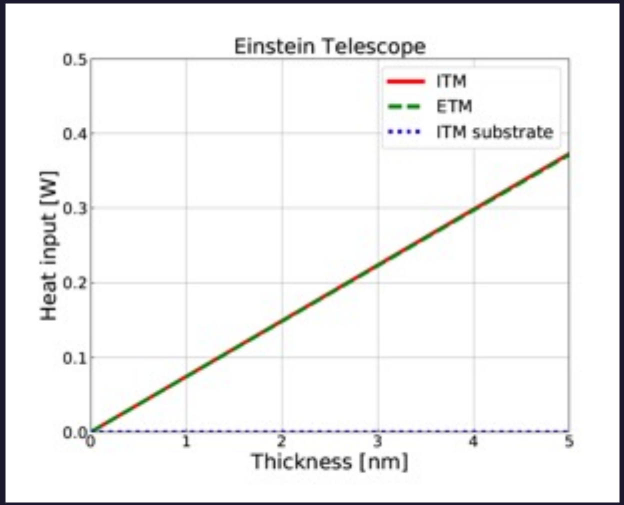
Gas adsorption on cold surfaces

Saturated vapour pressure from Honig and Hook (1960)



Dramatic effects on optical properties and thermal noise





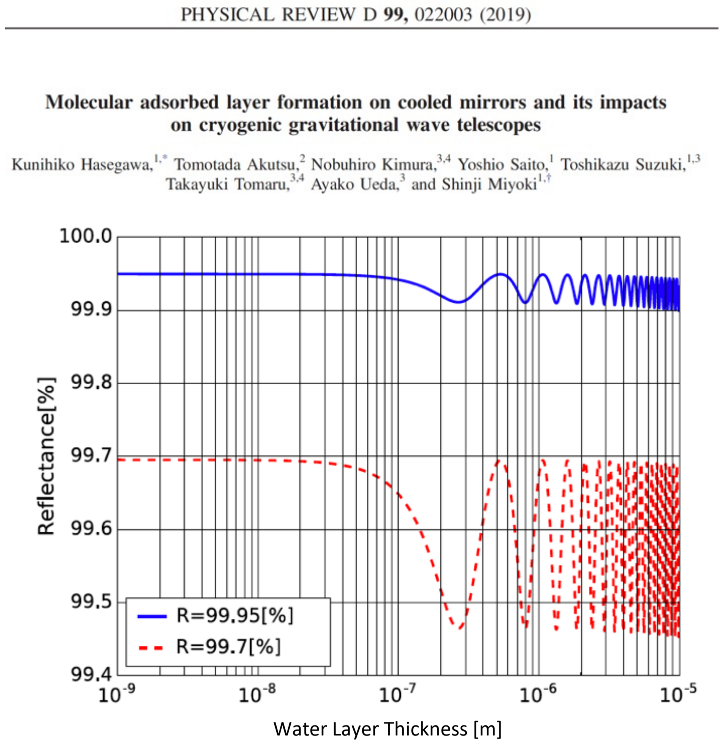
k. Hasegawa et al., Phys. Rev. D. (2019)
S. Tanioka et al., Phys. Rev. D. (2019)

From KAGRA experience, simulations indicate:

- reflectivity gets affected, already after 100 nm of H_2O ice
- ET maximum thermal budget (~100 mW/ 1 W) is expected to be exceeded already after ~1-10 nm of H2O ice!!!

Frost mitigation strategy is mandatory

Cryogenic Vacuum Issues on GWD optics



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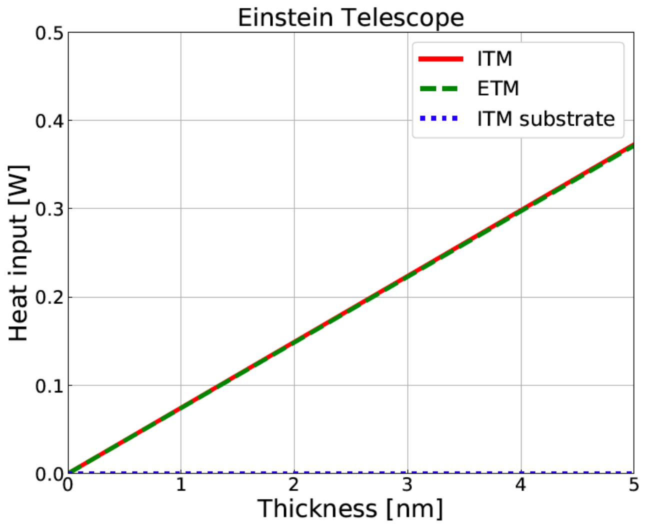
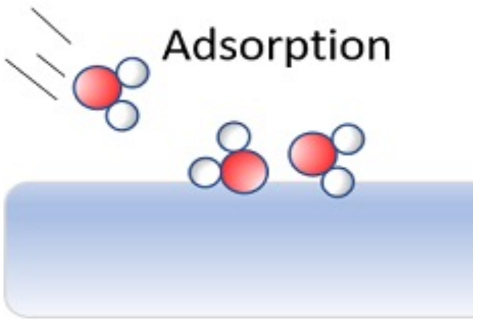




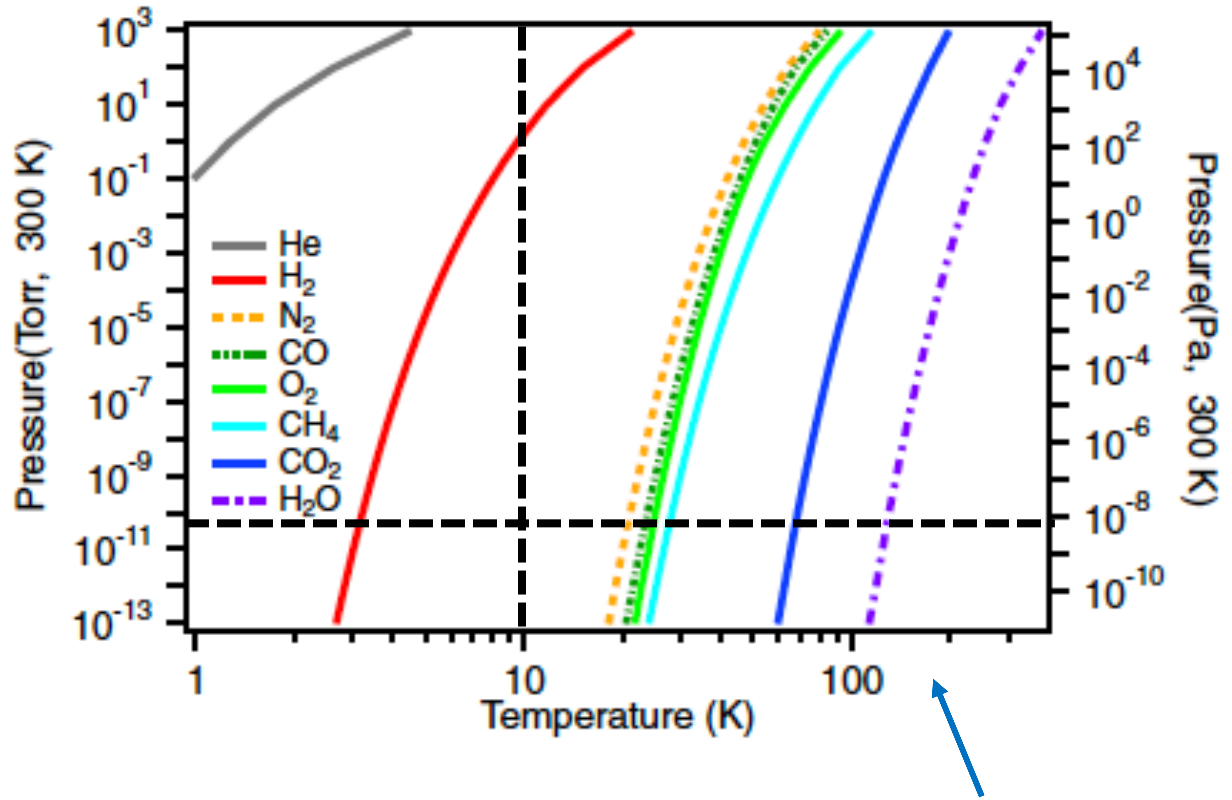
Optical loss study of molecular layer for a cryogenic interferometric gravitational-wave detector

Satoshi Tanioka, Kunihiko Hasegawa, and Yoichi Aso
Phys. Rev. D **102**, 022009 – Published 27 July 2020

→ Can we cure it?

Residual gas adsorption on cold surfaces

Saturated vapour pressure from Honig and Hook (1960)



For T~10 K and p<10^{-10} mbar, the most common residual gas species in a UHV chamber (except H_2 and He) will be adsorbed, forming a molecular ice ("frost") on the surface

Cryosorption depends on:

- surface temperature
- **gas partial pressures**

They have to be correctly evaluated, considering:

- $P_{RT} \neq P_{LT}$ (thermal transpiration correction)
- vacuum history

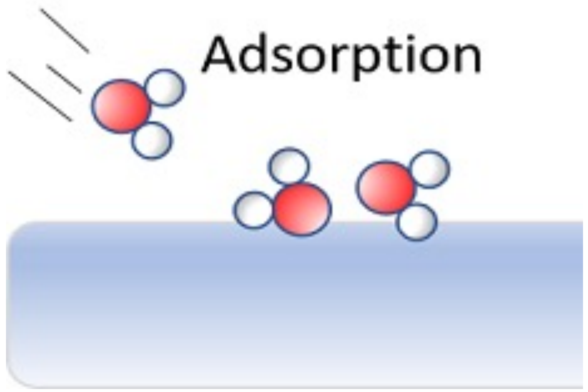
Residual gas adsorption on cold surfaces

The right evaluation of gas pressure allows to give reliable estimates of ice thickness forming on the cold surface.

Langmuir (L) unit:

1 L = 1x 10^{-6} mbar x 1s

gas exposure of a surface (or dosage)



→ In 1x 10^{-10} mbar, it takes 10.000 s (~3h) to build up a ML.

For sticking coefficient S_c= 1:
1 L ~ 1 Monolayer (ML) cryosorbed
for H_2O, 1 ML ~ 0.3 nm

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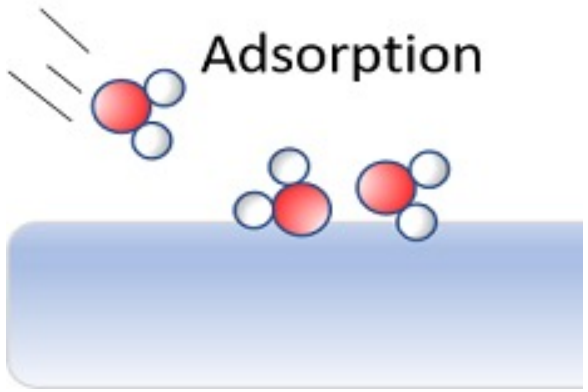
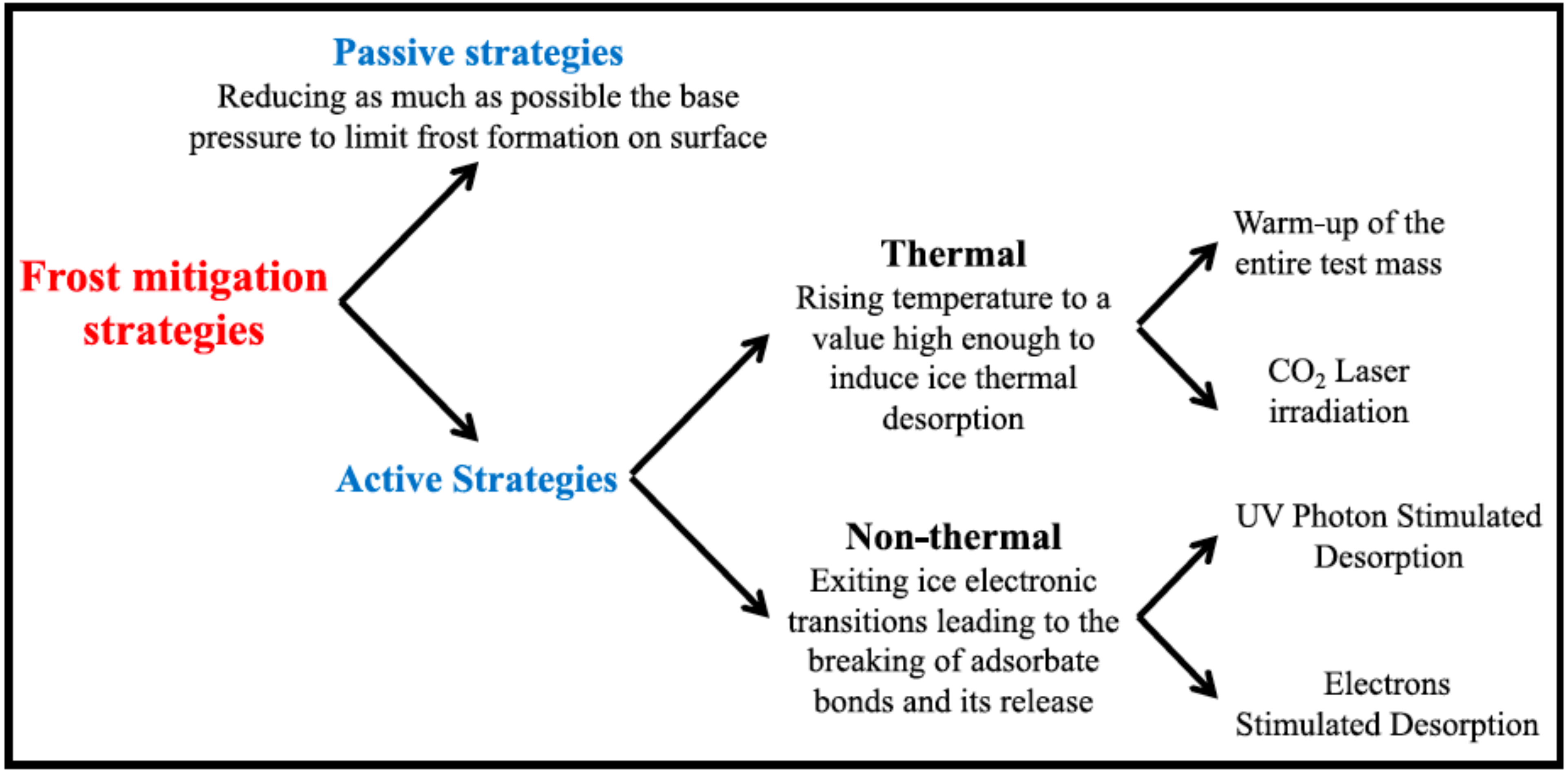


For sticking coefficient S_c= 1:
1 L ~ 1 Monolayer (ML) cryosorbed
for H_2O, 1 ML ~ 0.3 nm

→ In 1x 10^{-12} mbar, it takes 1.000.000 s (~300 h) to build up a ML.

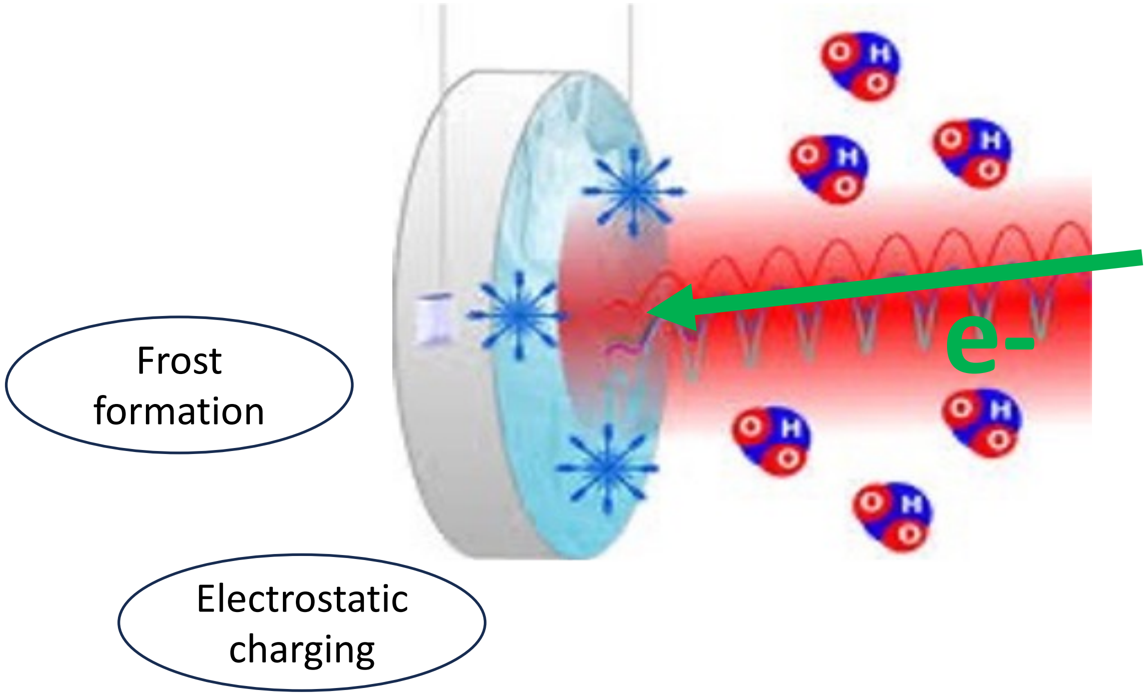
Frost mitigation strategies



L. Spallino et al., Phys. Rev. D, 062001, 104 (2021)

ET ITALIA @ LNF (Gr II)→ Core Optics

WP1: Frost mitigation and Electrostatic Charging



The final goal is to validate the use of low energy electrons as a mitigation method for frost formation and as a neutralization method for mirrors' electrostatic charging.

ET ITALIA @ LNF (Gr II)

WP1: Frost mitigation and Electrostatic Charging *(MaSSLab)*

The final goal of this WP is to validate the use of low energy electrons as a mitigation method for frost formation and as a neutralization method for mirrors' electrostatic charging.

WP2: Material Properties

(Vacuum Group – Latino @ LNF in collaboration with MaSSLab & EGO/Virgo)

The aim of this WP is the characterization of the materials involved in the tower vacuum system containing the mirrors. The investigation of the outgassing properties will define the level and quality of vacuum surrounding the mirror surfaces.

ET-ISB Division IV Vacuum and Cryogenics

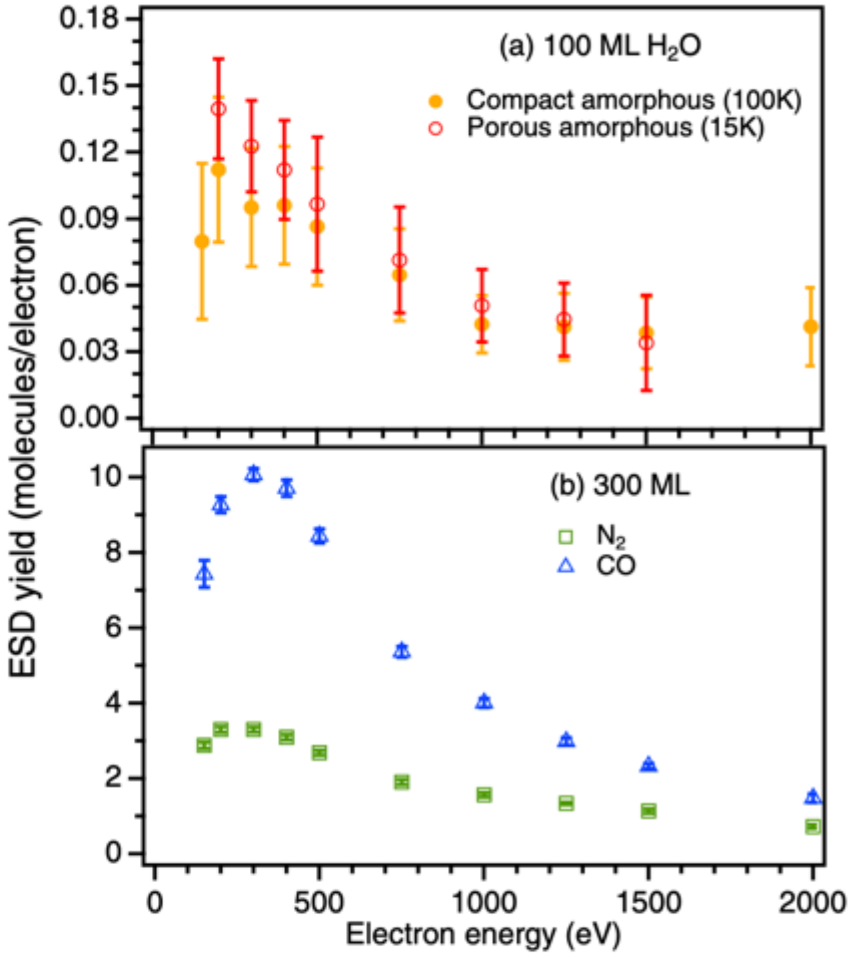
WP3: Passive mitigation method for electrostatic charging

(MaSSLab in collaboration with EGO/Virgo & IFAE and Vacuum Group @ LNF)

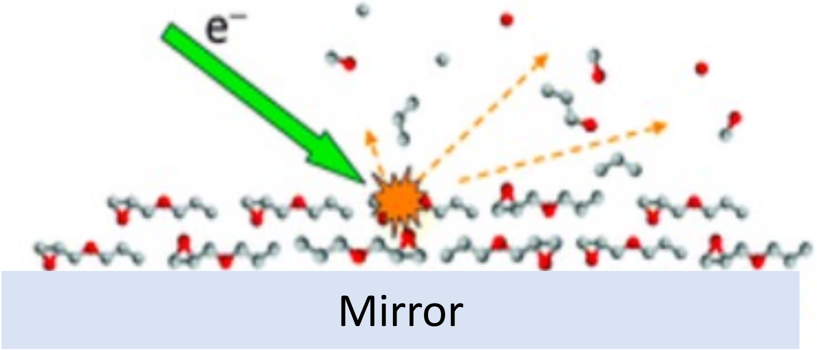
The aim of this WP is to carry out a R&D activity to develop a passive mitigation strategy for the electrostatic charging generated by low energy electrons coming from ion pumps, propagating along the beampipes and finally impinging on the test masses .

Frost mitigation by low energy electrons

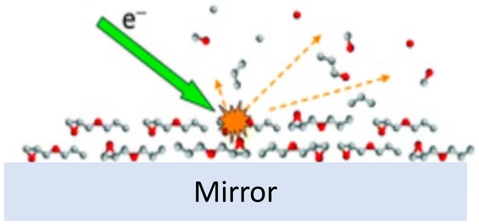
R. Dupuy et al. J. Appl. Phys. 128, 175304 (2020)
L. Spallino et al., Phys. Rev. D, 062001, 104 (2021)



Electrons efficiently induce molecular ice nonthermal desorption!



Low energy electrons irradiation



If $P_{eff} \sim 1x10^{-10}$ (H_2O,CO,CO_2, etc) mbar; sticking coefficient = 1

➔ 1 monolayer (~ 10^{15} mol/cm^2 ~ 0.3 nm) will be cryosorbed in 10.000 s.
(~ 2.5nm/day ~ 10 times less than in KAGRA)

If we assume a mean **ESD η= 0.1 mol./electron (as for H_2O) @ 100eV**.
(R. Dupuy et al. J. Appl. Phys. 128, 175304, 2020)

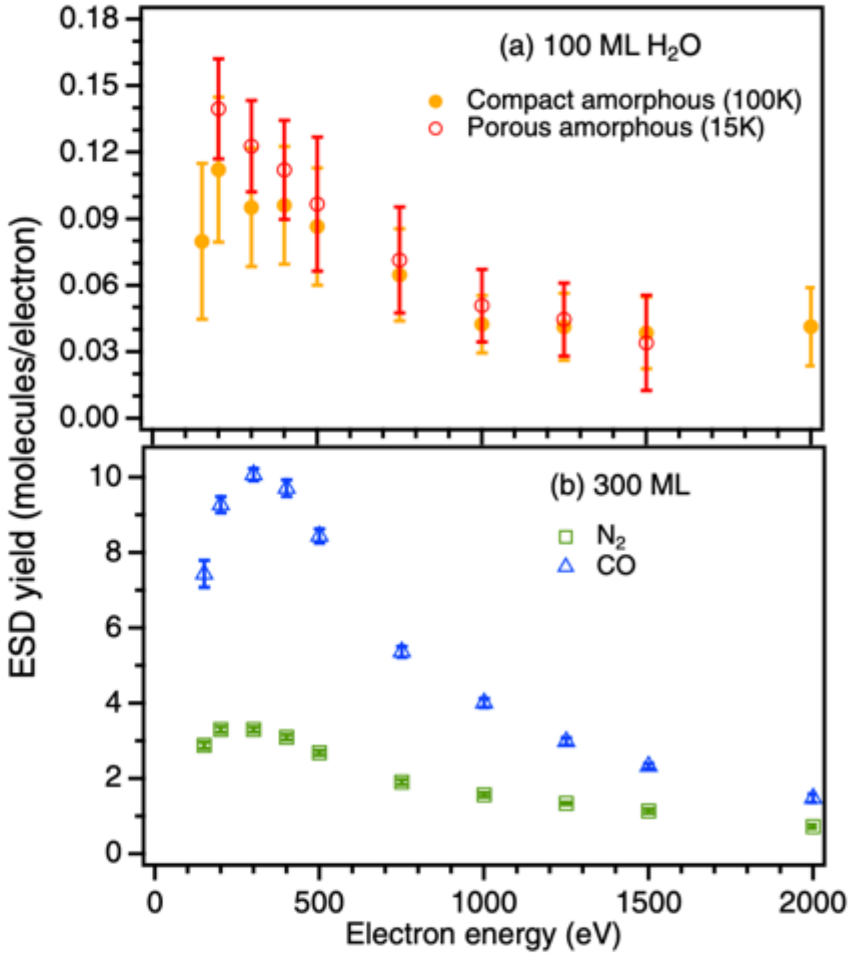
To remove **1 ML** we need an el. current of: **~ 1 mAmps/cm^2 in one second**

… depositing less than 100 mW/ML/cm^2 (not all el. energy goes in thermal heat!)

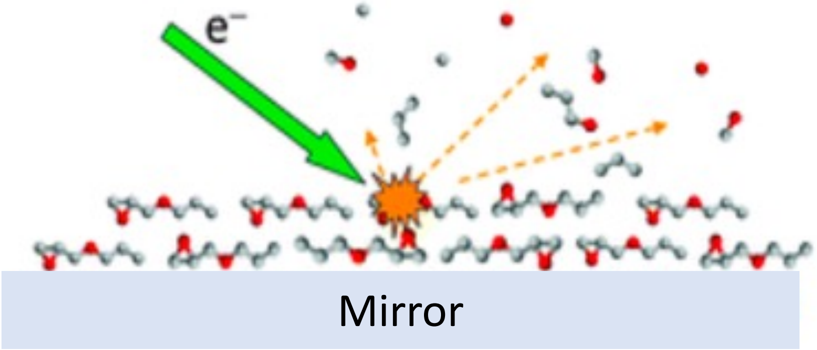
All in UHV, with marginal heating up of the mirrors and (possibly) reduced downtime.
Deserves further investigation!

Frost mitigation by low energy electrons

R. Dupuy et al. J. Appl. Phys. 128, 175304 (2020)
L. Spallino et al., Phys. Rev. D, 062001, 104 (2021)



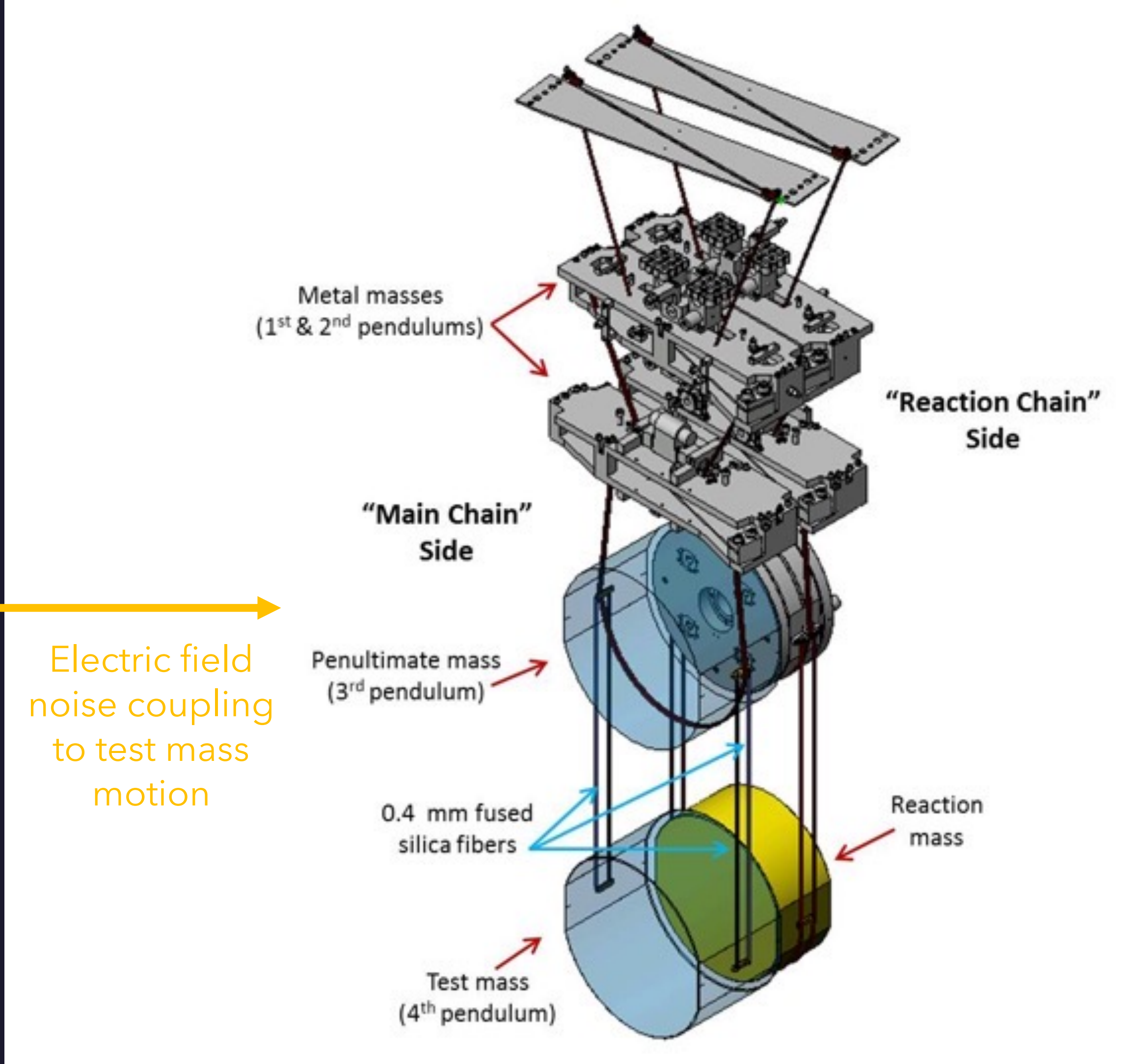
Possible if a charging mitigation method compliant with cryogenics is proved!



Electrostatic charging on test masses of GW detector

- Unclear in origin, quantity and even sign
- Effects of charging:
  - Interferers with optical position control
  - Accumulation and motion of charges can generate fluctuating electric fields that could move the test mass at frequencies in the interferometer's sensitive band
  - Attracts dust, reducing reflectance, increasing scattering and absorption

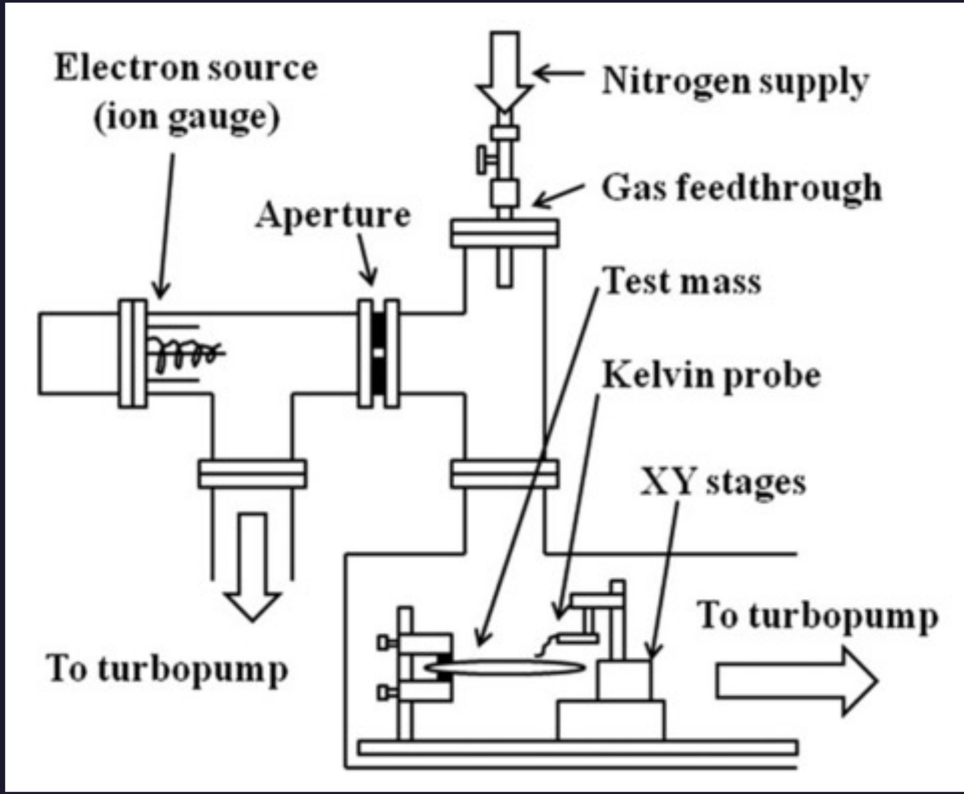
Electric field noise coupling to test mass motion



Potentially limiting noise source

Charging mitigation at a-LIGO (Room Temperature)

Mirror exposure to some tenth of mbar of a N_2 plasma for a long time (~1 h)



D. Ugolini et al., Rev. Sci. Instrum., 82, 046108 (2011)

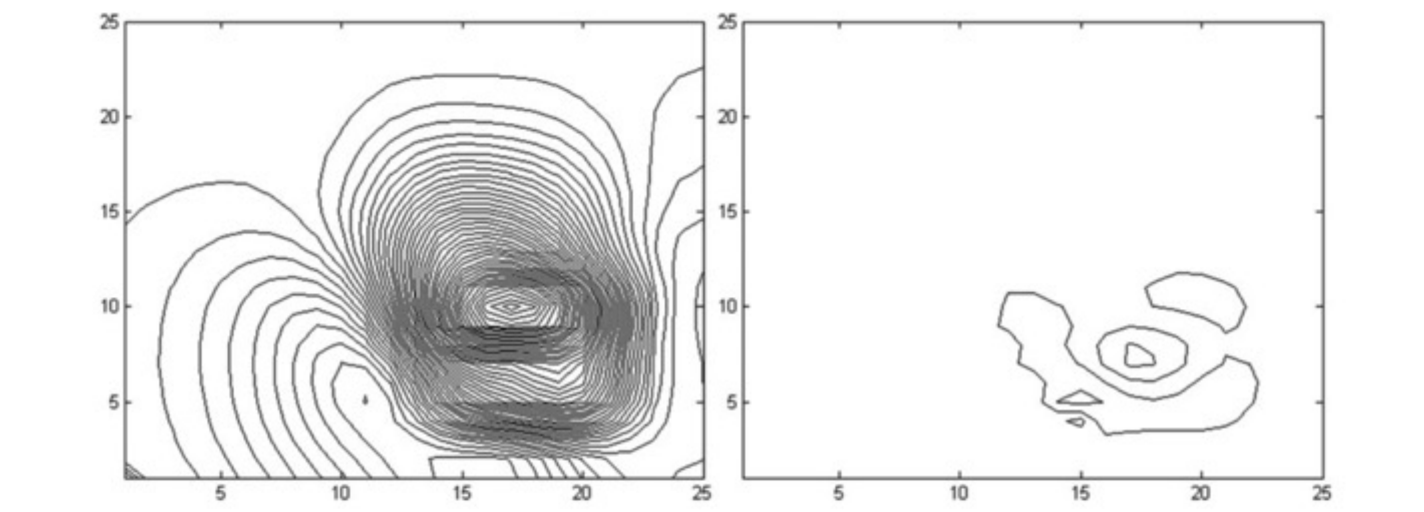
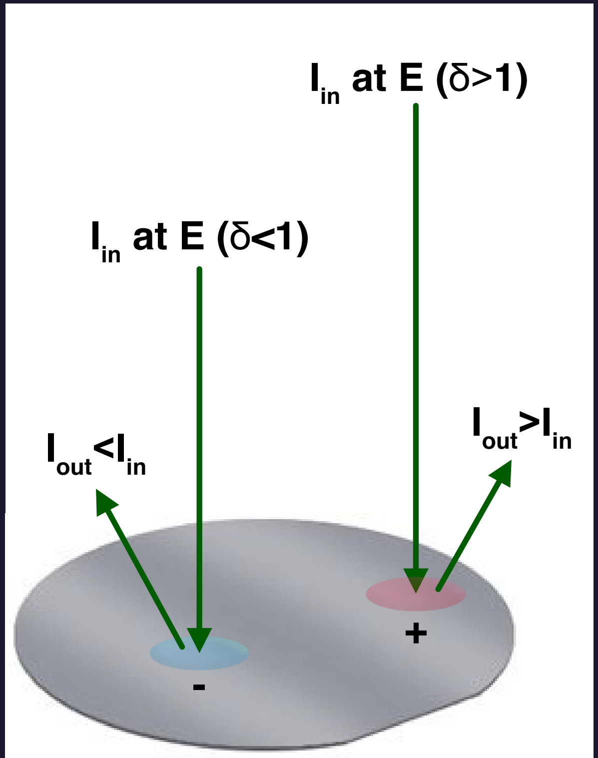


FIG. 4. Contour plots of charge density before (left) and after (right) discharging. Each contour corresponds to 2×10^{-13} C/cm^2.

If the LIGO neutralization method will be applied at cryogenic temperature, a significant layer (~μm) of the injected N_2 will be cryosorbed on the mirror surface → N_2 frost formation

Charging mitigation by low energy electrons

Proof of concept

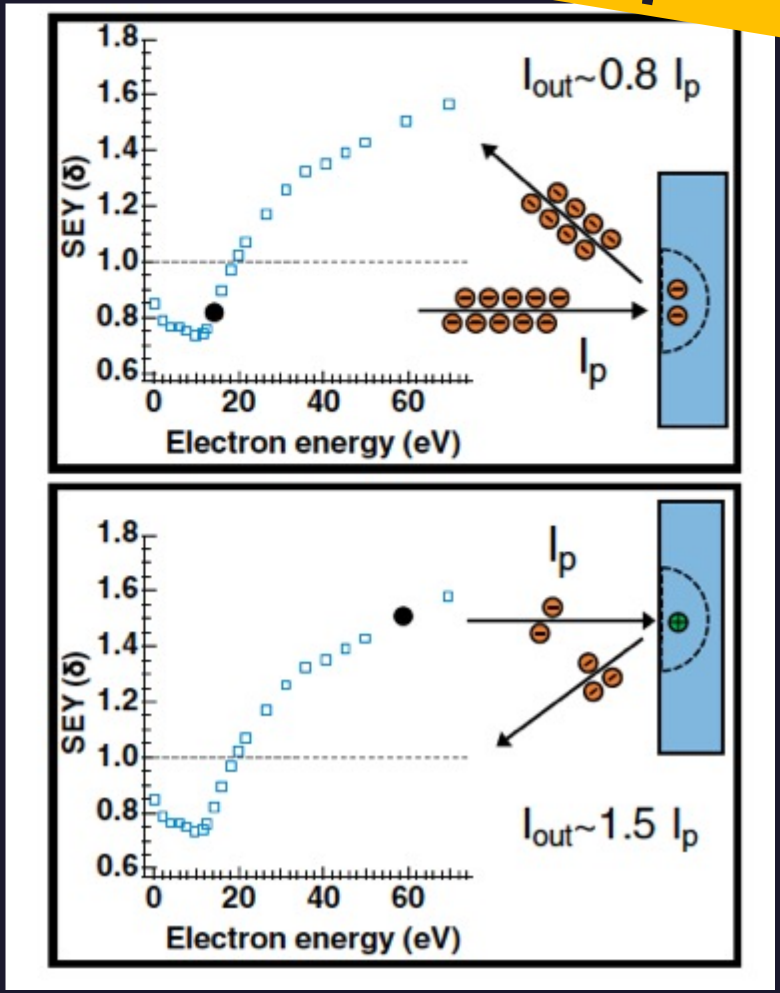


L. Spallino, IL NUOVO CIMENTO C (2022)

Electrons of variable but low energy (below few hundreds eV) can compensate charges of both polarity

Secondary Electron Yield (SEY or δ)

SEY=I_{out}/I_{In}

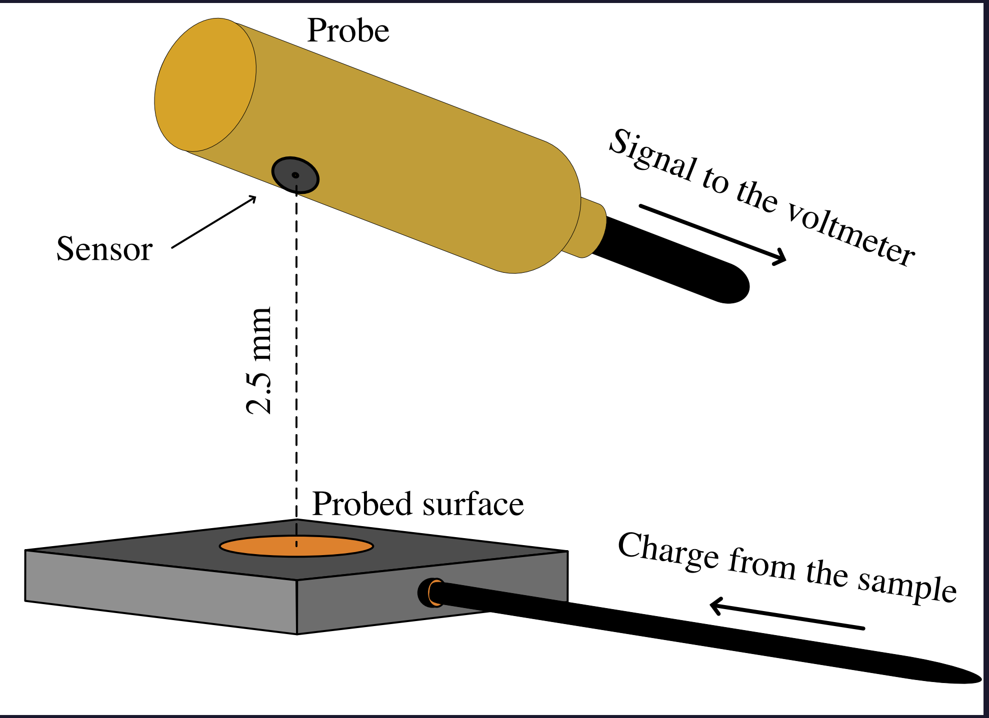


L. Spallino et al., Phys. Rev. D. (2022)

Alternative solution for electrostatic charging, compatible with cryogenic vacuum

Electrostatic measurements

Set-up scheme



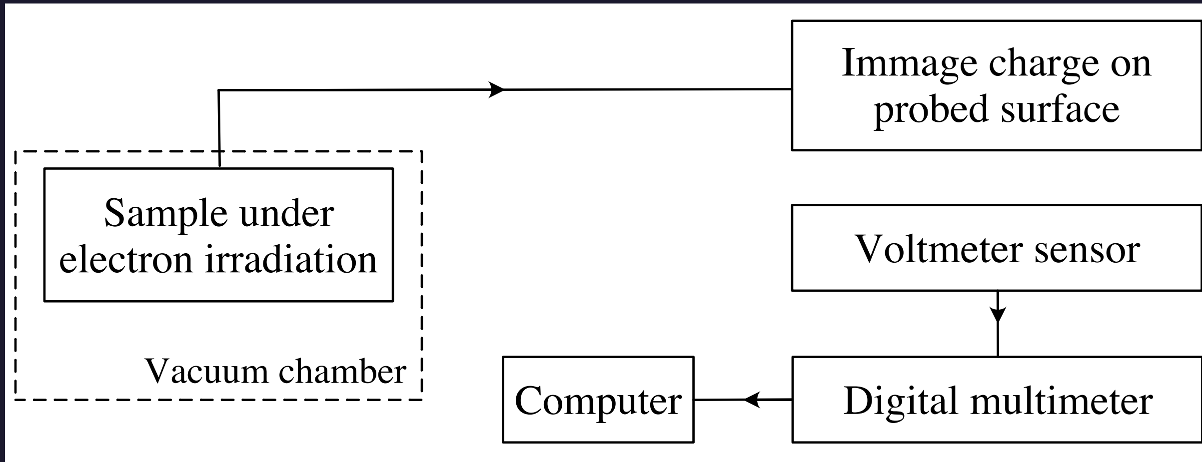
The voltage generated by the surface charge is revealed by the voltmeter sensor and acquired by a digital multimeter with a resolution of the order of tens of mV

Electron irradiation is performed in UHV as a function of energy, maintaining an incident current of the order of tenth of nA on a sample area ~10 mm^2.

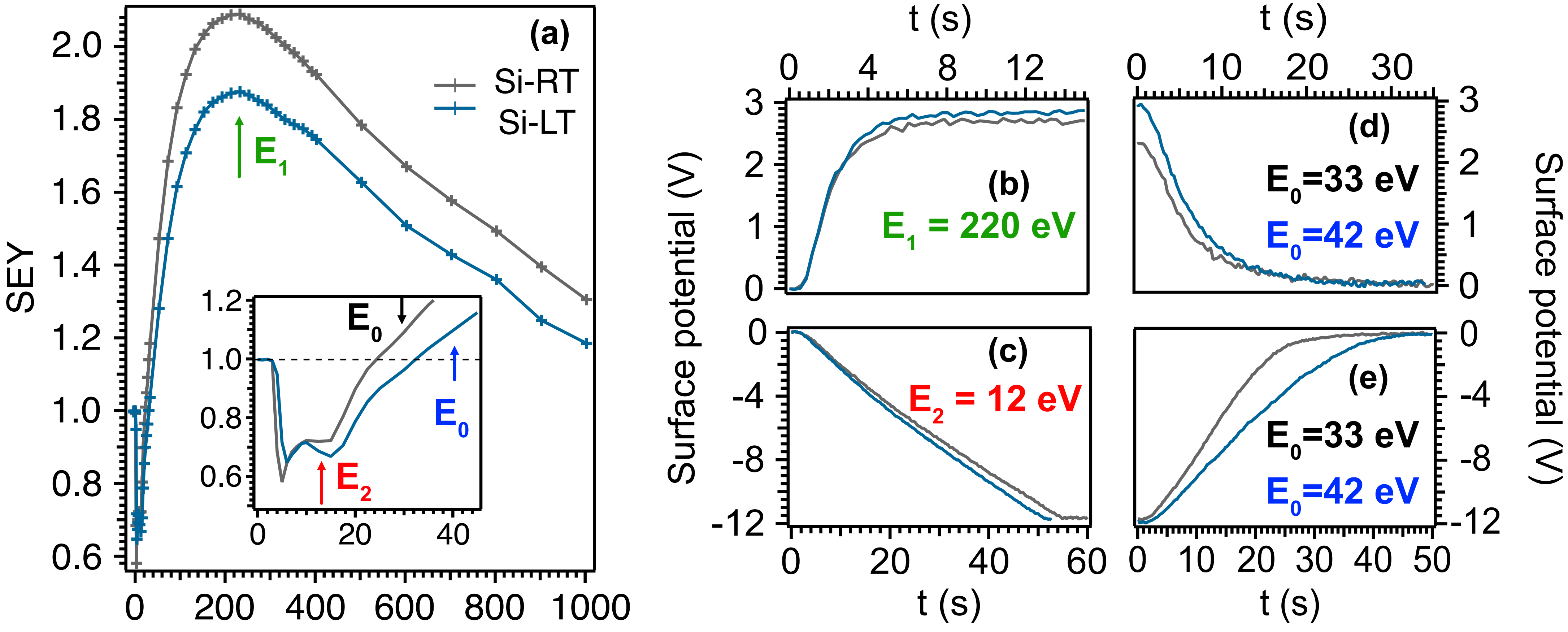
Voltage measurements are performed in ambient atmosphere with a non-contact electrostatic voltmeter

The electrostatic voltmeter measures the voltage of the image charge induced on a a metallic plate connected to the irradiated sample

Data acquisition scheme



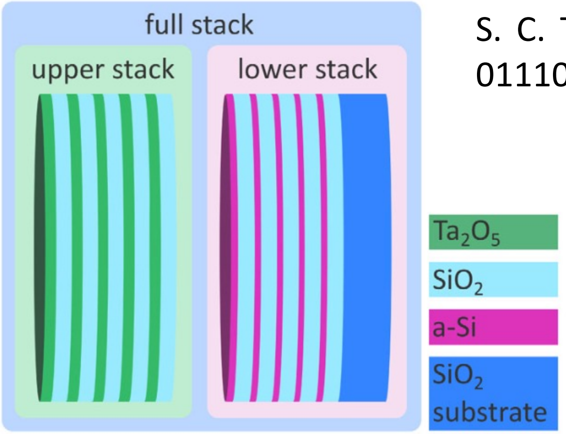
From a proof of concept to the experimental validation on small (10 x 10 mm) commercial samples mimicking optics materials



L. Spallino et al., Poster presentation @ XIV ET Symposium, Maastricht, May 6-10, 2024

Low energy electrons to neutralize electrostatic charging

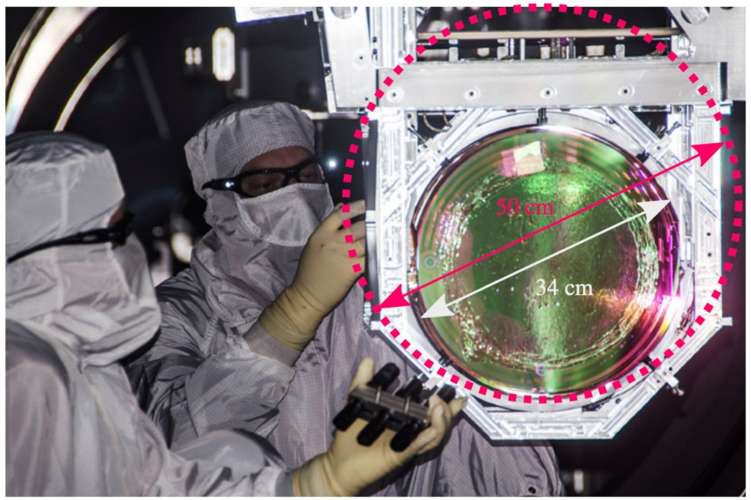
Fundamental detailed SEY investigation of specific materials
(as the ones composing optics in GW detectors) →



S. C. Tait et al. Phys. Rev. Lett. 125, 011102 (2020)

Each layer has a thickness of the order of hundreds of nm

- SEY measurements on insulators (critical from the measuring point of view) → useful comparison with simulations
- Understanding of charging mechanisms and charge distribution in such kind of materials
- Taking into account environmental conditions and external interactions



Considerations

- ✓ **At RT and LT as well, by properly tuning impinging electrons energy, it is possible to induce at will both positive and negative charges or to neutralize them.**

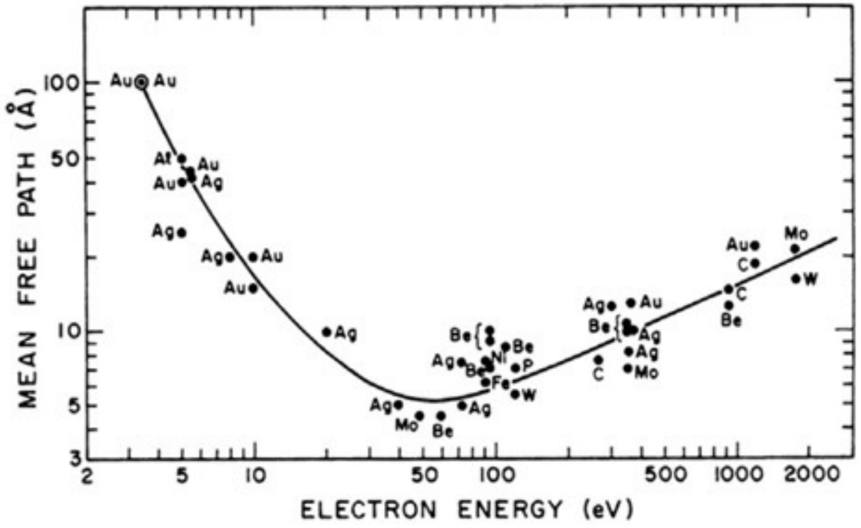
- ✓ **There is a strict correlation between neutralization parameters and SEY: in principle, by studying SEY features of any coating, it is possible to extract operational parameters to discharge it.**

Mandatory next step– Investigations on materials

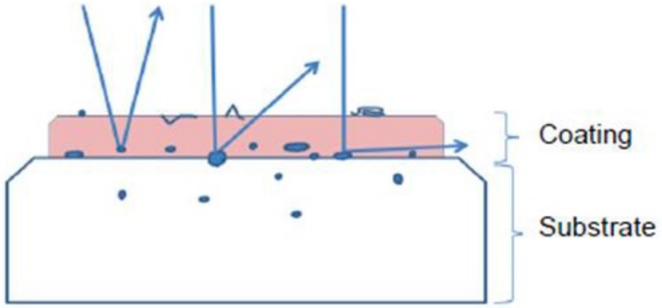
- ➢ **GW-quality research samples → Necessary interaction with ET coating community**

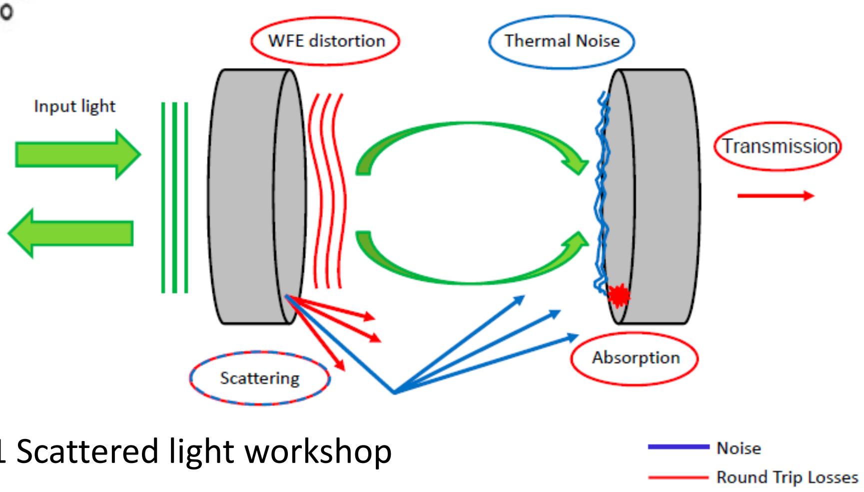
- ➢ **Charge distribution and neutralization on “big” samples (1 inch) → implementation of LNF set-up with a Kelvin Probe in a dedicated chamber**

Low energy electrons and defects formation



Low energy electrons do not significantly penetrate into the mirror surface due to their low mean free path, so that **minimal effects on mirror quality are expected**.





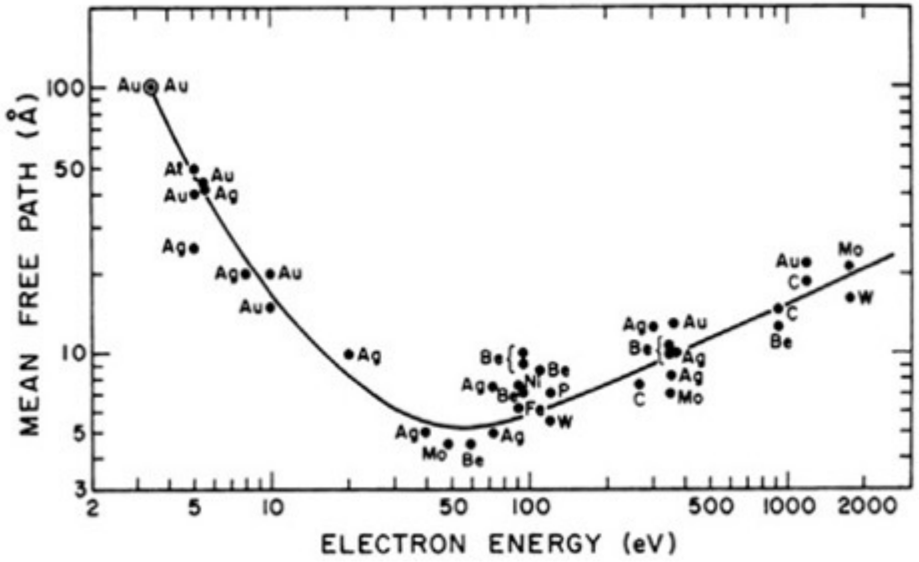
S.Sayah et al., GWADW2021 Scattered light workshop

Any defects formation could spoil the mirrors' sensitivity.

→ The accurate investigation of the effects induced by electrons irradiation is mandatory

Considerations

- Electrons do not significantly penetrate into the mirror surface due to their low mean free path, so that, **in principle, minimal effects on mirror quality** are expected. →



- Preliminary XPS and Raman investigations on our samples have shown that, within the detectability limit, electron irradiation below few hundreds' eV does not induce observable structural defects on the substrate.

Mandatory next step– Investigations on materials

- More investigation are needed, especially on realistic materials.

→ **WHAT is the effects induced by electron irradiation on optics?**

different investigation techniques and competences coming from the ET coating group

Charge and Frost mitigation on cryogenic optics

Marco Angelucci, Roberto Cimino (LNF)

Objectives:

- Validate the use of low energy electrons as a mitigation method for frost formation and as a neutralization method for mirrors' electrostatic charging
    - Studies of electron desorption and charge neutralization on specific samples
    - Studies of the effect of electron irradiation on optical properties (in vacuum?)

Groups involved: Frascati, Sannio, Roma TV, Roma

Production:

- measure on small samples (10 mm x 10 mm) at low T,
- measure on 1 inch room T,
- asking for different coatings materials (Sannio, ...)

Characterizations: SE, XPS, assorbimento PCI (Roma TV), XPS (Roma)

ET ITALIA @ LNF (Gr II)

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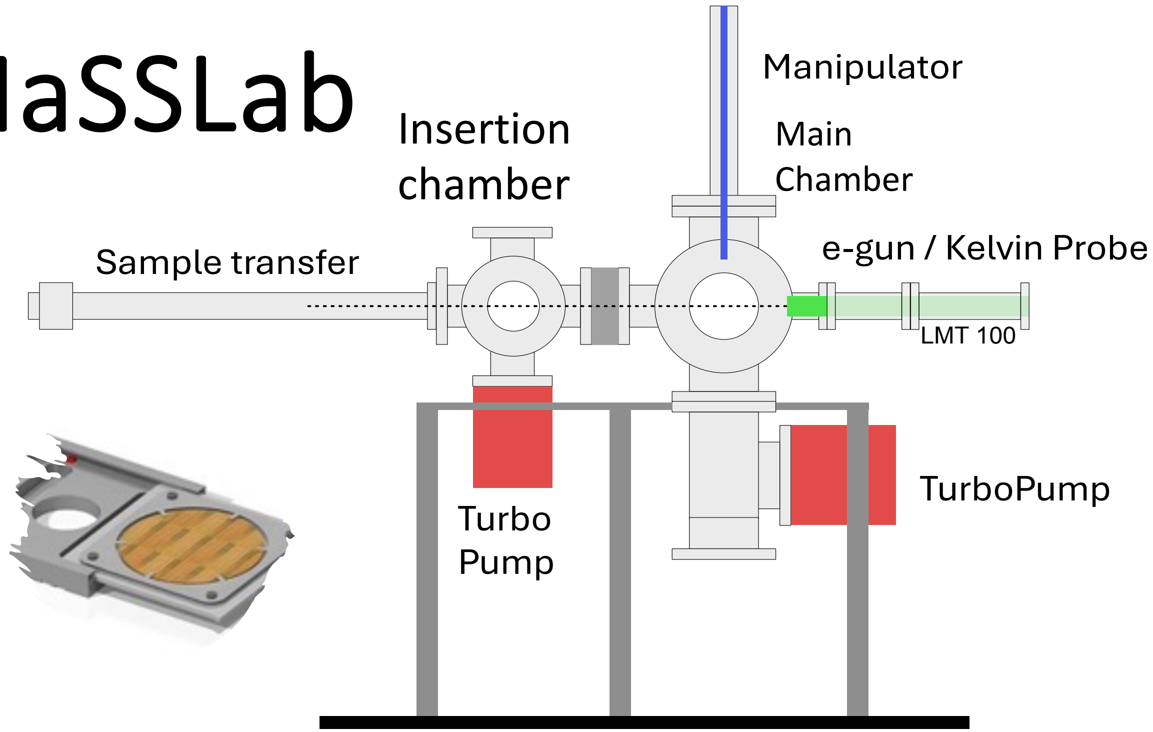
The aim of this WP is to carry out a R&D activity to develop a passive mitigation strategy for the electrostatic charging generated by low energy electrons coming from ion pumps, propagating along the beampipes and finally impinging on the test masses .

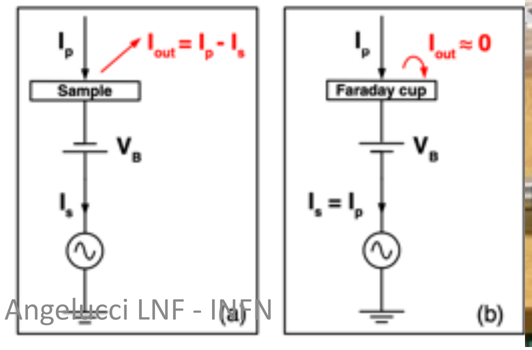
Experimental stations at MaSSLab

Implementation during 2024



The system will be composed by:

- a UHV chamber equipped with:
  - Electron gun (from Kimball)
  - Kevin Probe from (KP technologies)
  - 4-axis manipulator remotely controlled, with a **specific sample holder for 1” sample**
- An UHV insertion chamber with:
  - **A magnetic transfer equipped with a specific sample grabber**
- **Picoammeters for primary and sample current measurements**
- **Sample holder.**



WP2: Material Properties

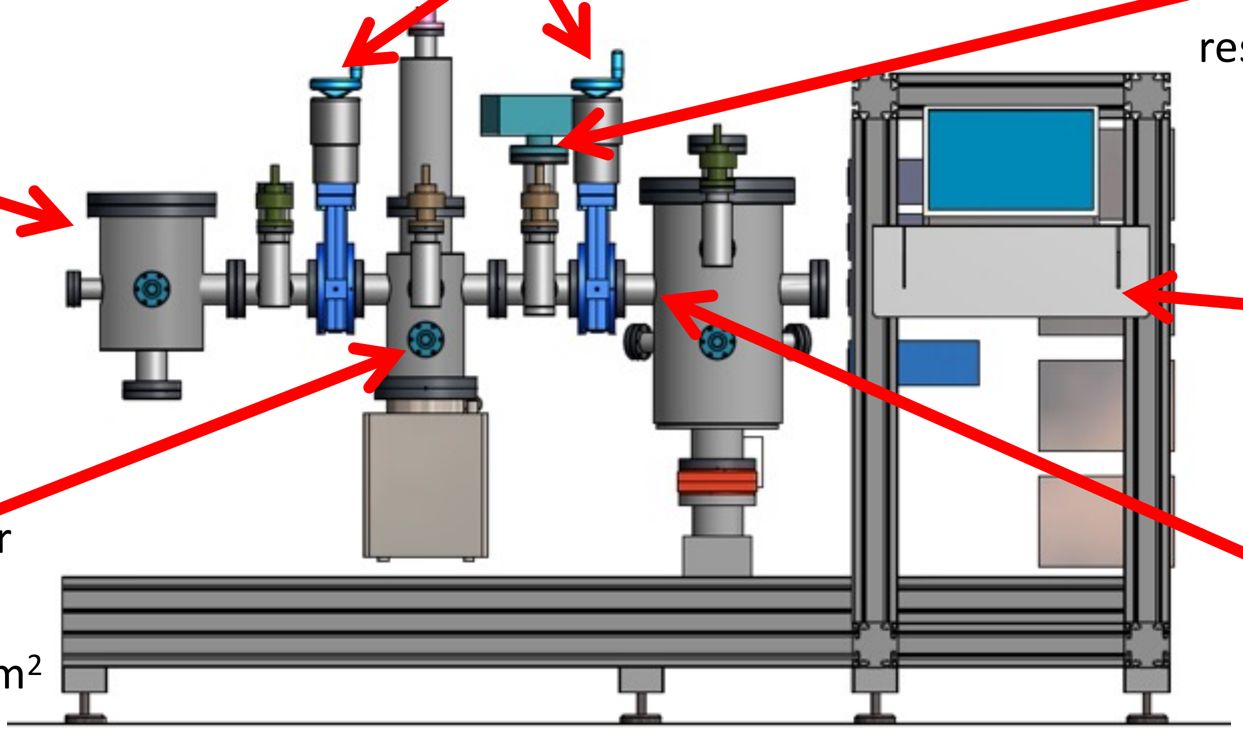
(Vacuum Group – Latino @ LNF in collaboration with MaSSLab & EGO/Virgo)

LATINO «OUTGASSING RATE SYSTEM» AT LNF-INFN

Separation Valves

<u>Residual Gas Analyzer</u>
Mass Range: 200 amu
resolution: $2x10^{-14}$ mbar
Max $P_{oper.}=10^{-4}$ mbar

«High Outgassing Chamber»
L= 300 mm
ϕ= 200 mm



Control System

Measure Chamber

Size: ~$2x1.5\ m^2$

«Low Outgassing Chamber»
h= 500 mm
ϕ= 250 mm

G. Delle Monache Gr. II

LATINO (Laboratory in Advanced Technologies for INnOvation) is a cofunded project (INFN-Regione Lazio) - Call "Open Research Infrastructure"

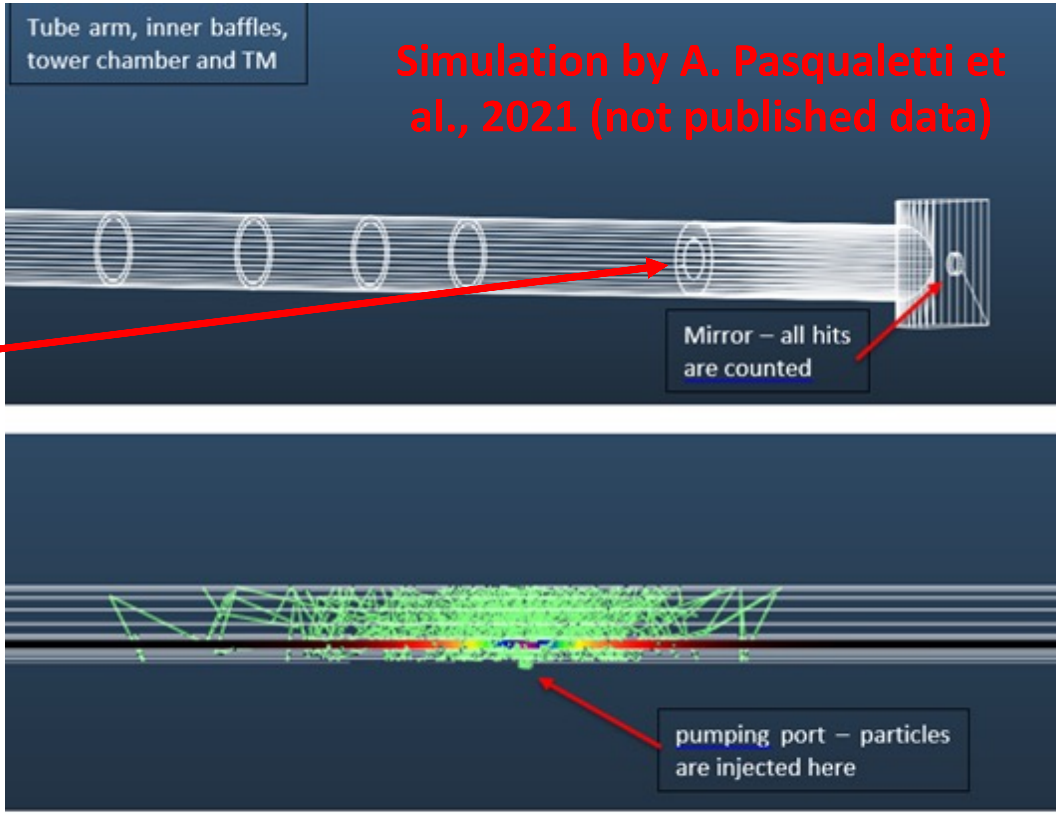
WP3: Passive mitigation method for electrostatic charging

(MaSSLab in collaboration with EGO/Virgo & IFAE and Vacuum Group @ LNF)

Electrostatic charges are generated by low energy electrons impinging on the test masses

Careful evaluation of the distance of the ion pumps from the test mass

Electrostatic ring on baffle



R&D activity LNF-EGO/Virgo-IFAE to test the possibility of integrating an electrostatic ring on selected baffles to mitigate the charges' flow from the beampipes to the mirrors' chamber.

→ numerical simulation
→ electrostatic measurements
→ mock-up system design/realization for validation

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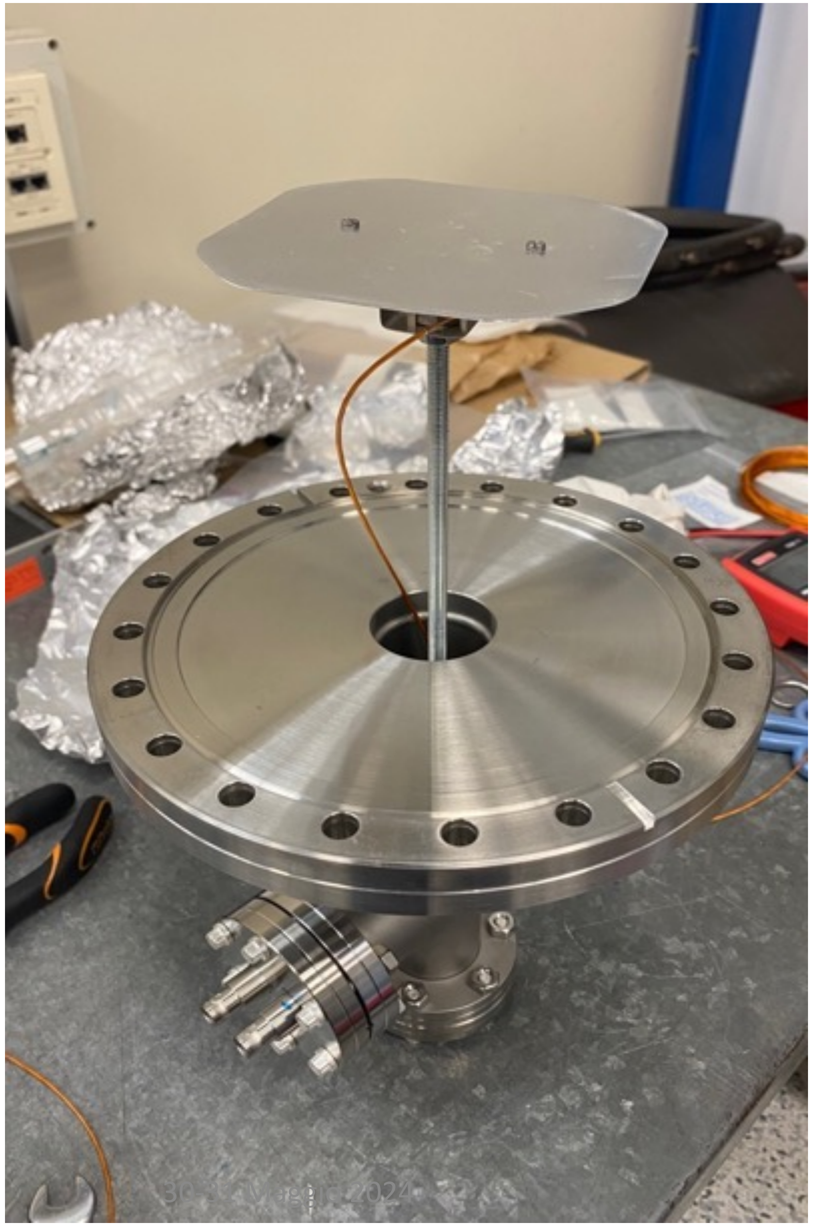
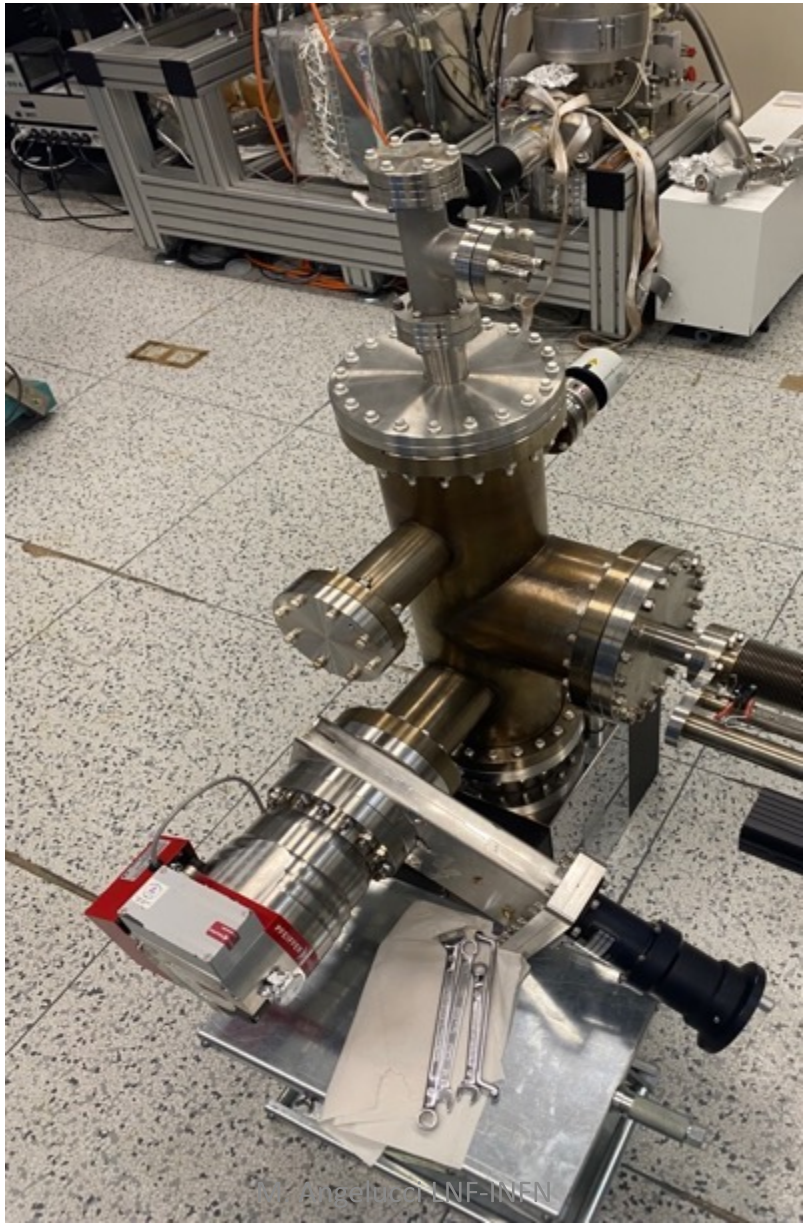
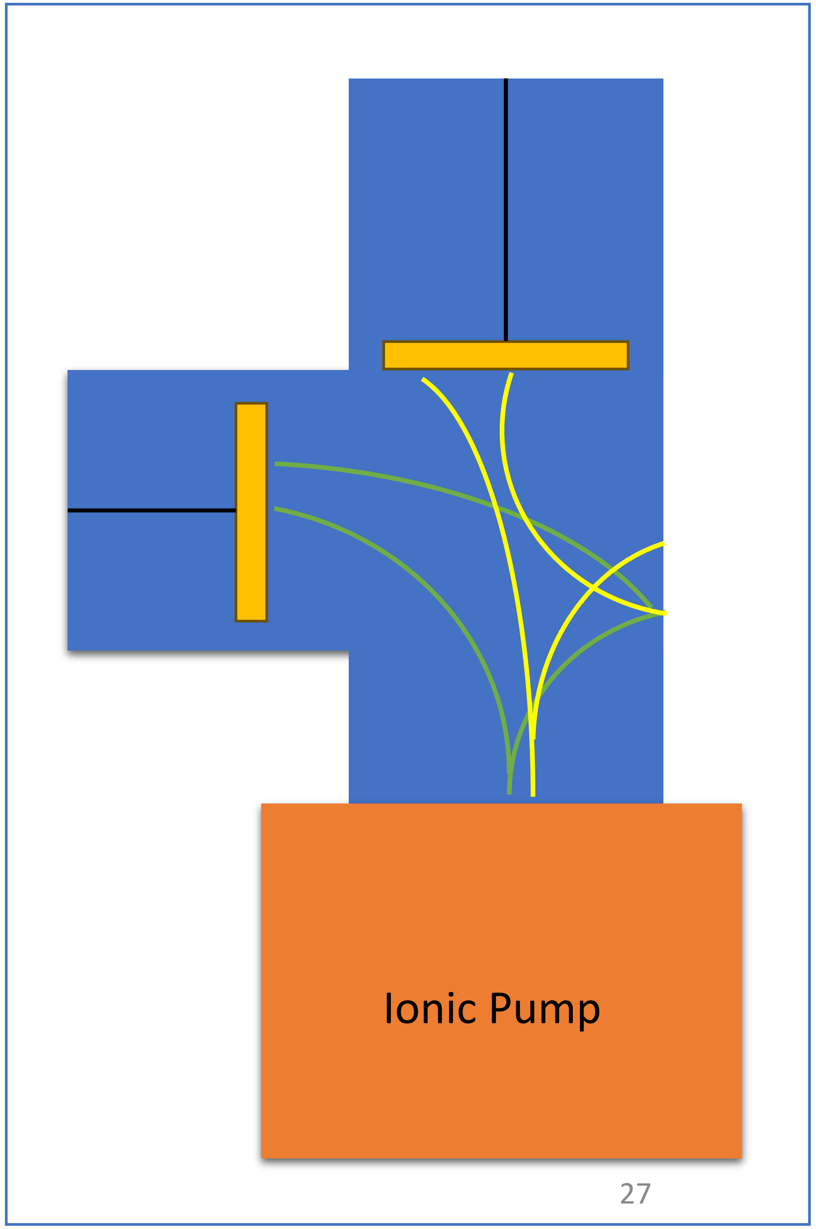
(MaSSLab in collaboration with EGO/Virgo & IFAE and Vacuum Group @ LNF)



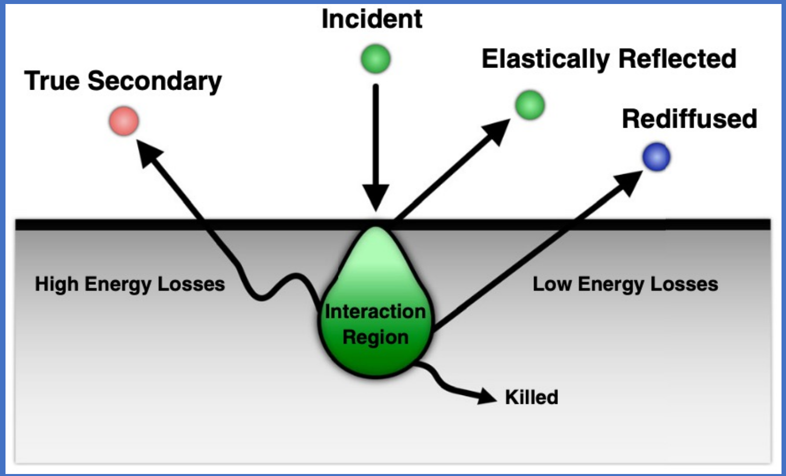




Back Up Slides

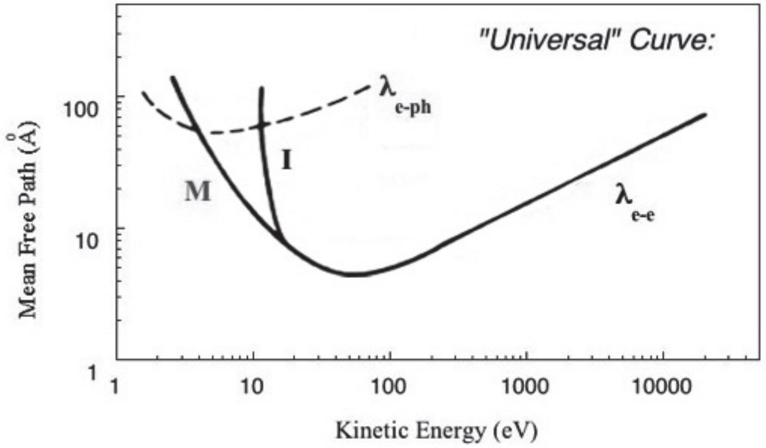
Secondary Electron Yield

Secondary Electron emission



Three-step process:

- Production of SE at a depth *z*
- Transport of the SE toward the surface
- Emission of SE across the surface barrier

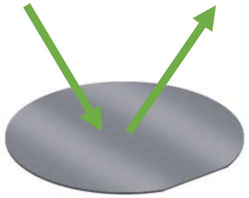


Electron mean free path up to ~10 nm

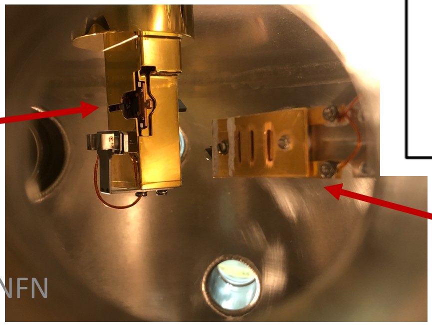
SEY is an intrinsic surface property of materials

Incident electrons current (I_p)

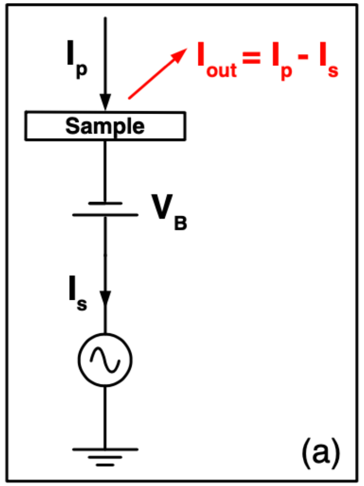
Emitted electrons current (I_{out})

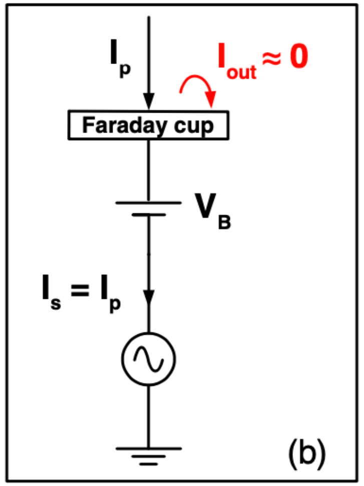


Sample



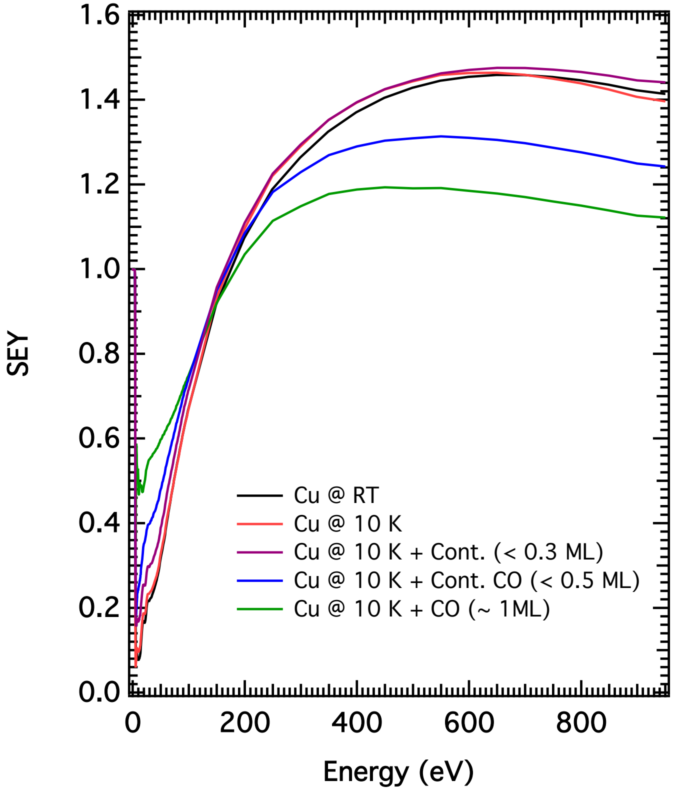
Farady cup

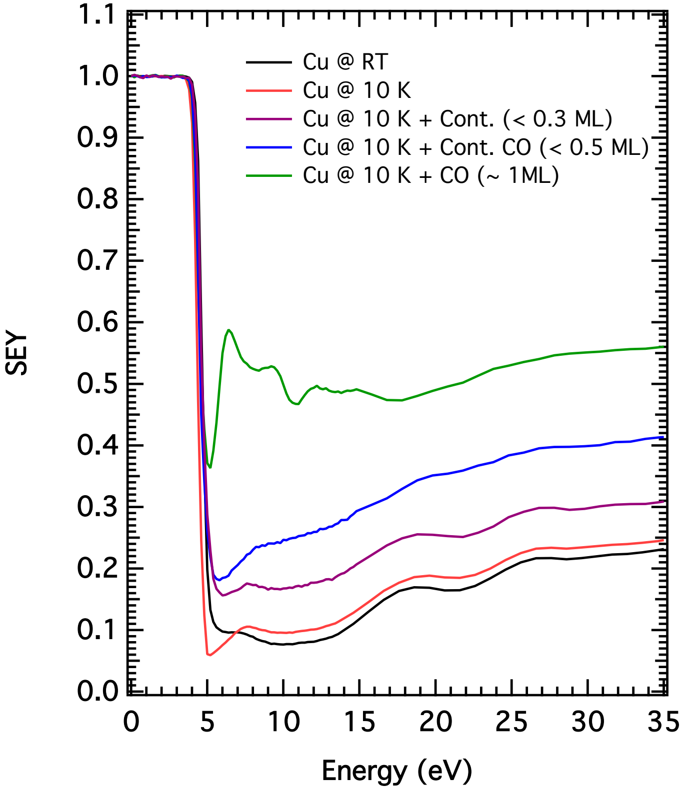




SEY at cryogenic temperatures

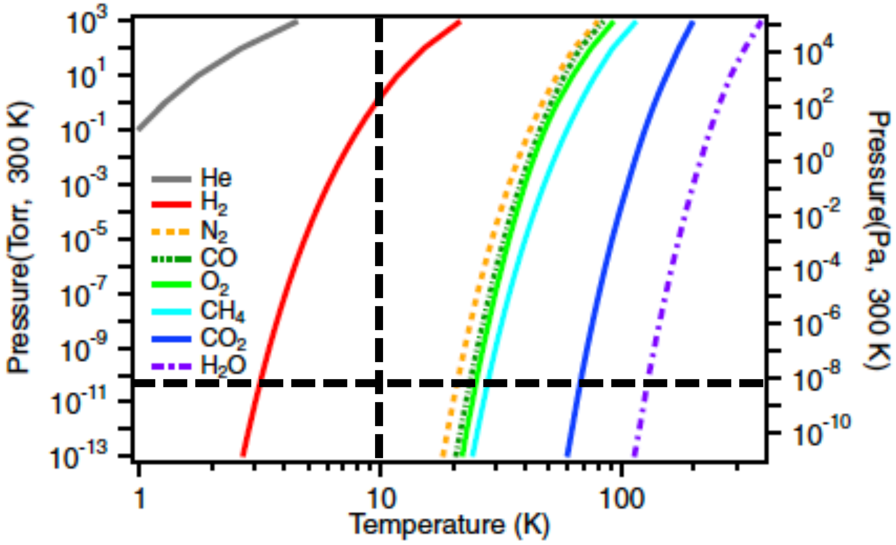
L. A. Gonzalez et al., AIP Adv. (2017)





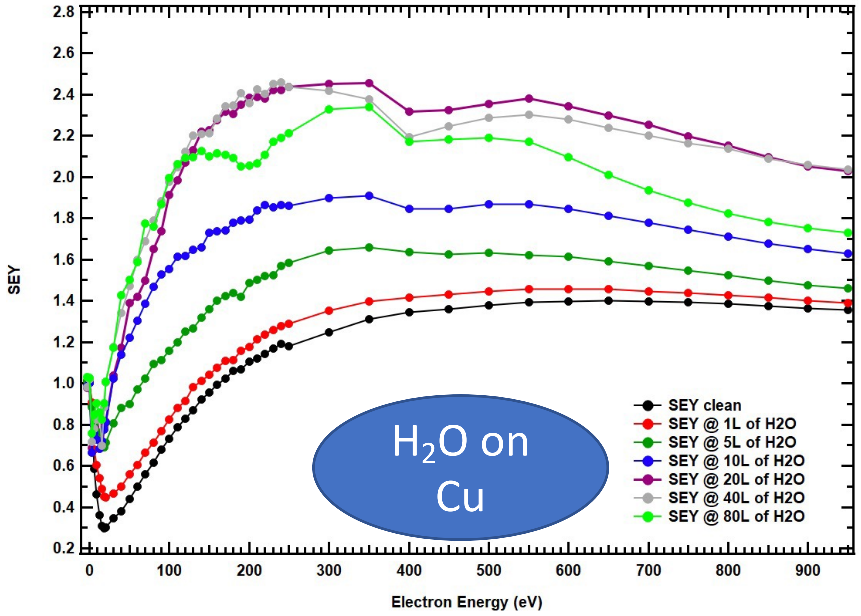
Residual gas in a vacuum at cryogenic temperature

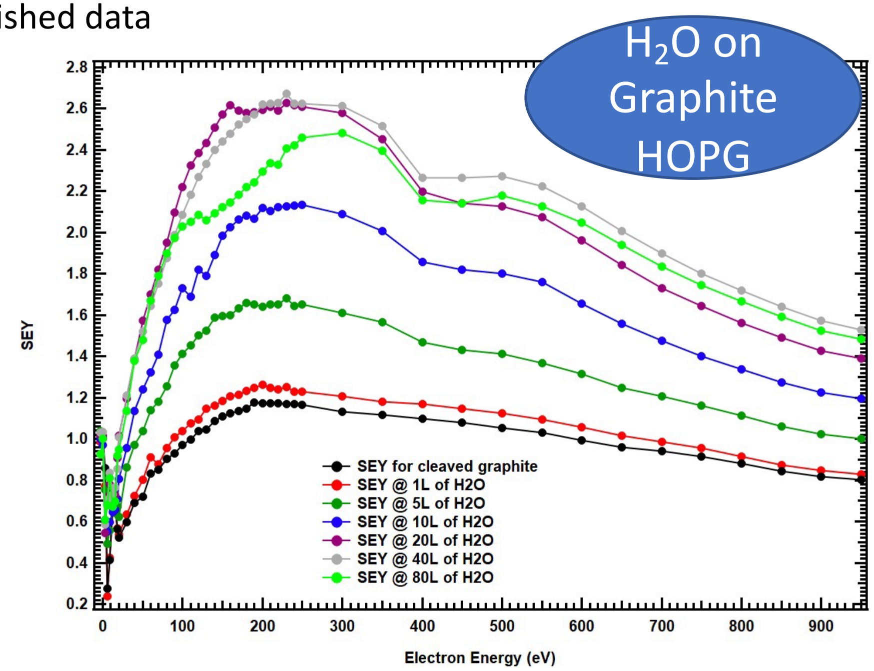
SEY of cold surfaces influenced by gas physisorption



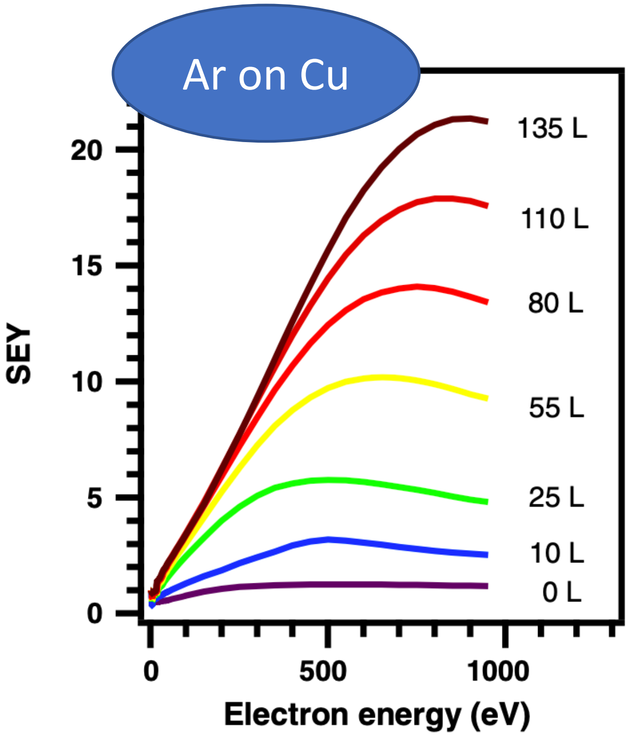
SEY at cryogenic temperatures

Not published data





L. Spallino et al., Phys. Rev. Accel. Beams (2020)



Fundamental SEY investigation of gas condensed on a cryogenic surface

Experimental stations at MaSSLab

- Electron guns (Secondary Electron Yield, conditioning, charging)
- Kelvin Probe
- XPS/UPS
- TDS (10-300 K or 300-1000 K)
- QMS
- CVD
- Raman
- LEED/Auger
- SEM
- EDS