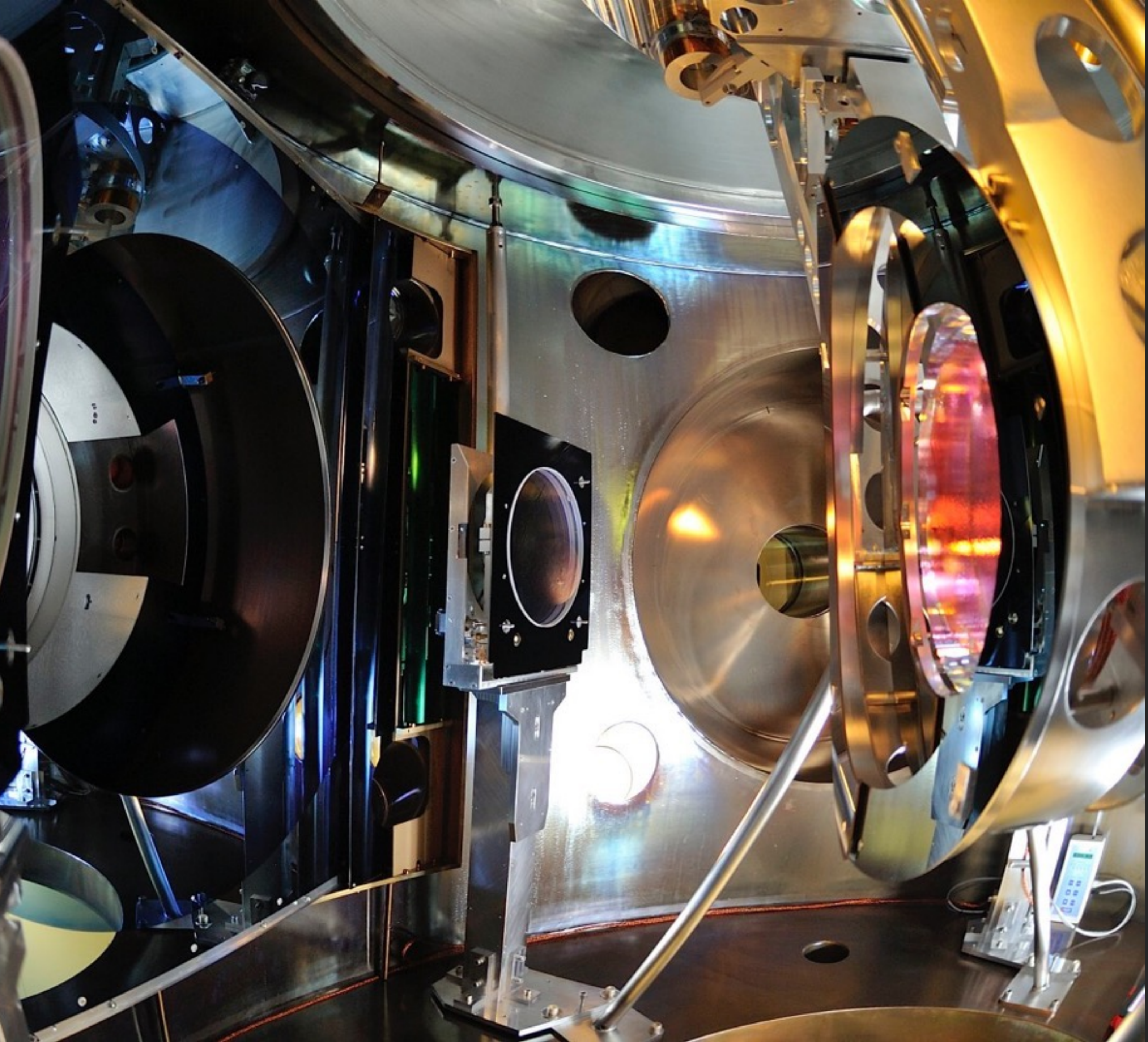


Can electrons neutralize the electrostatic charge on test mass mirrors in gravitational wave detectors?

16th June, 2022

Luisa Spallino, LNF-INFN

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

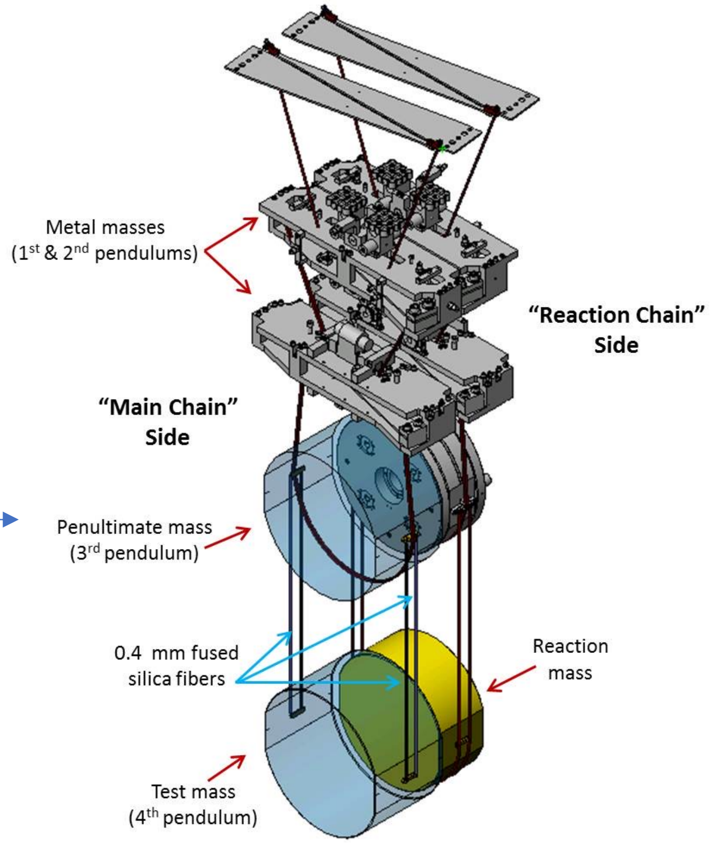
Electrostatic charging on test masses of GW detector

- 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

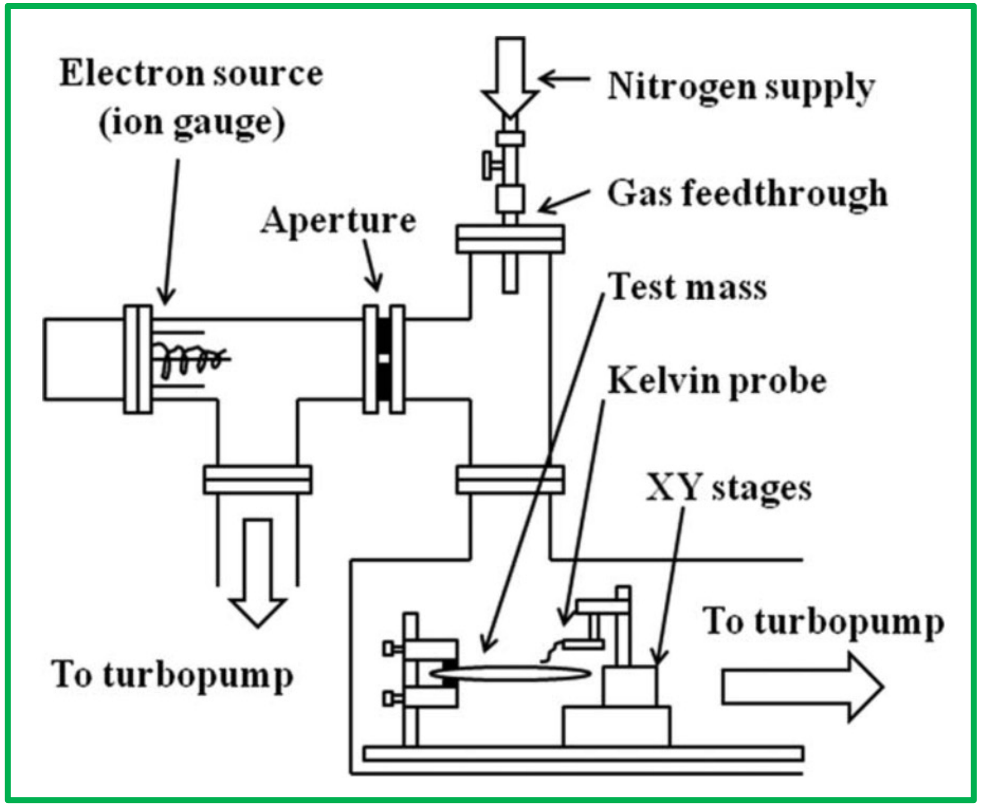
Electric field noise coupling to test mass motion



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)

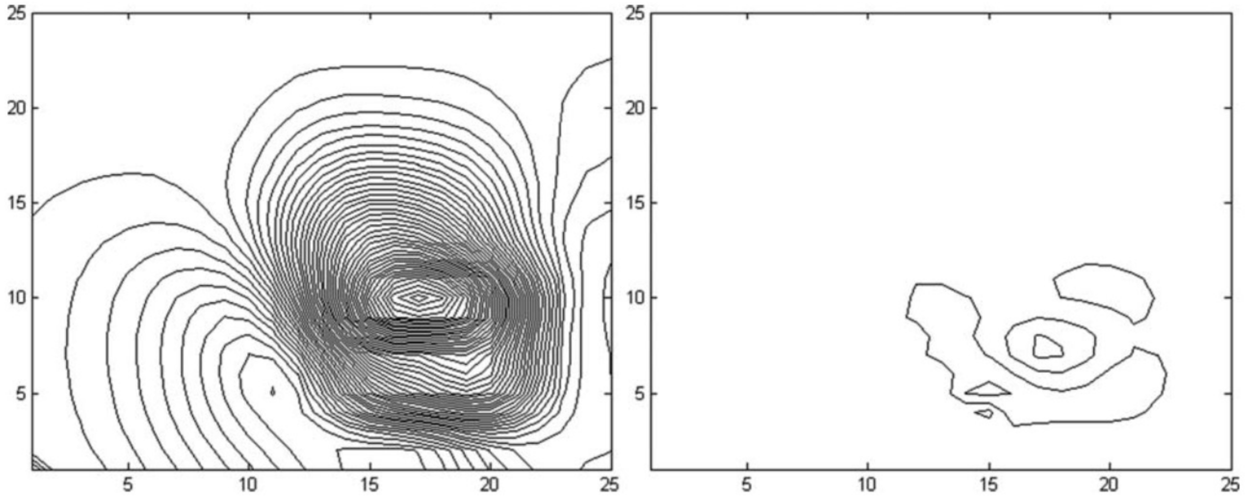
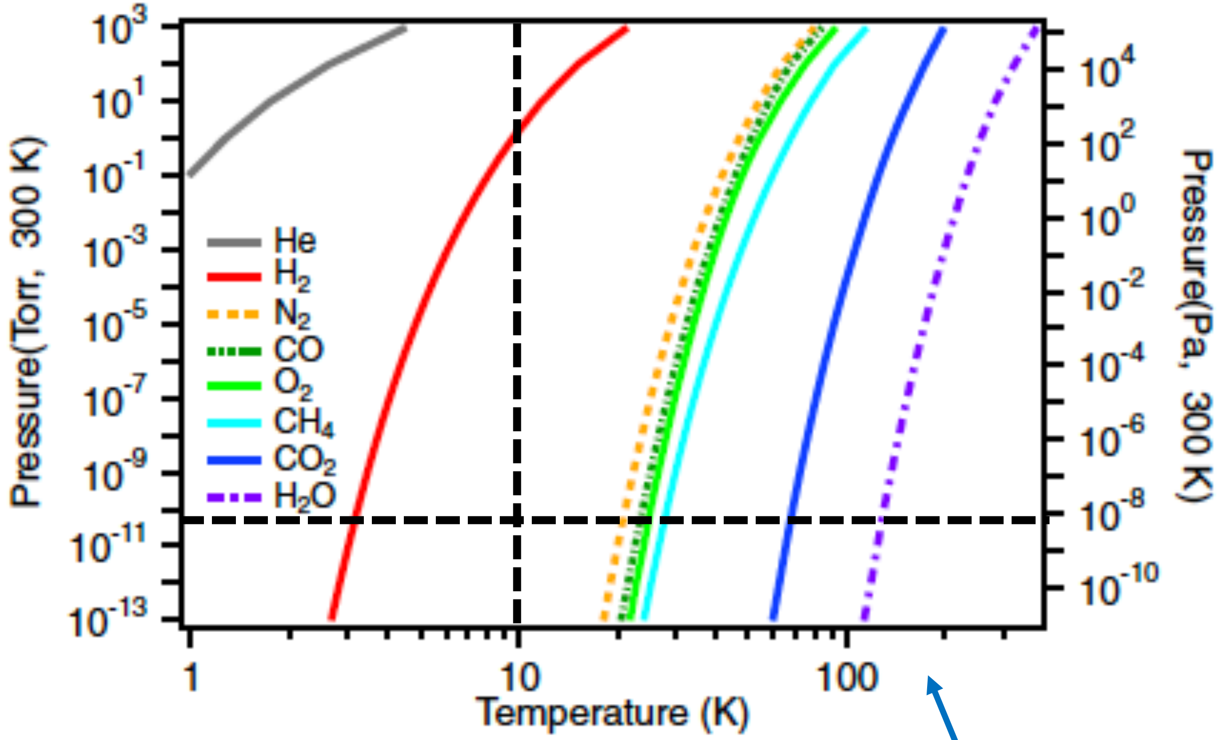


FIG. 4. Contour plots of charge density before (left) and after (right) discharging. Each contour corresponds to 2×10^{-13} C/cm^2.

Can this method be applied at Cryogenic Temperature?

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 pressure

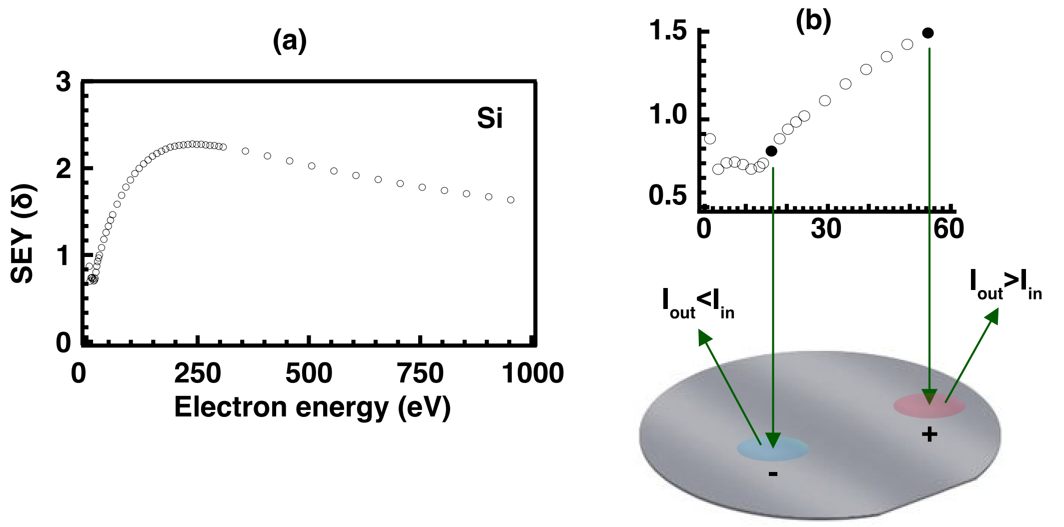
If the LIGO neutralization method will be applied at cryogenic temperature, a significant layer (~μm) of the injected **N_2 will be cryosorbed on the mirror surface**

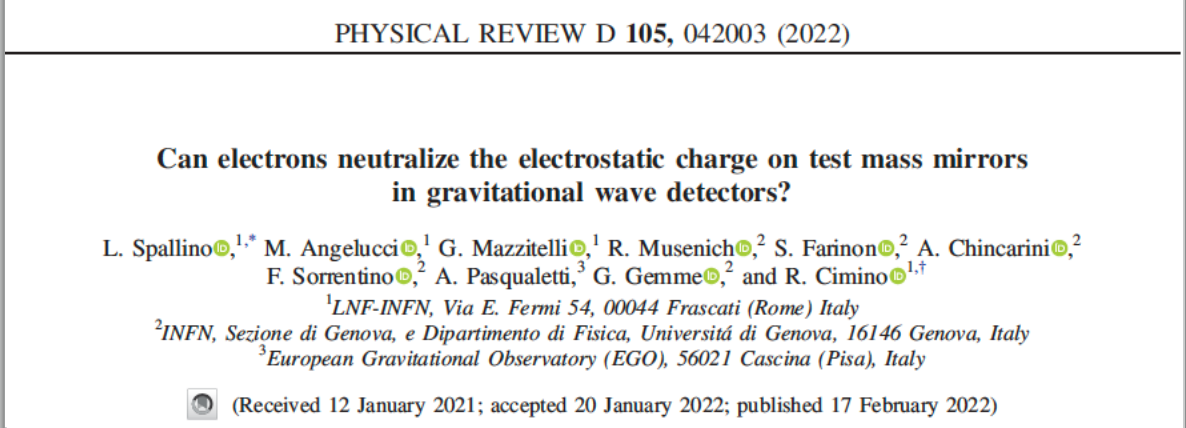
Dramatic effects on optical properties and thermal noise

Low energy electrons irradiation

OUR PROPOSAL

We propose to use electrons of variable but low energy (between 10 to 100 eV) to neutralize unwanted electrostatic charge on test mass mirrors. Low energy selected electrons can indeed compensate charges of both polarity on mirror optics.





PHYSICAL REVIEW D **105**, 042003 (2022)

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

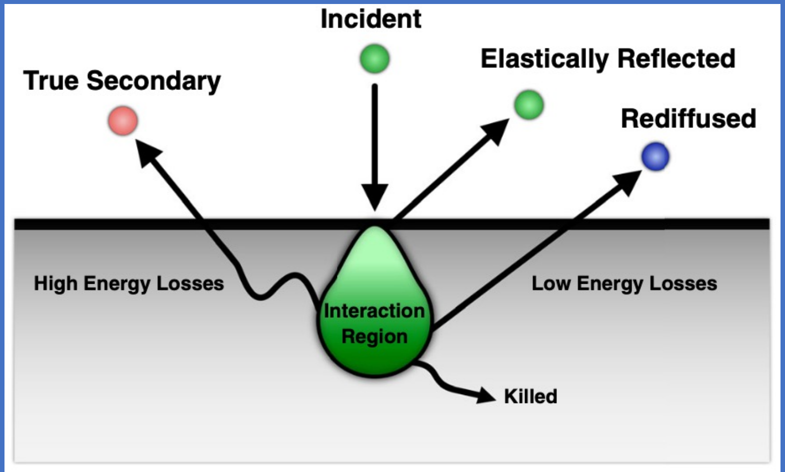
L. Spallino,[1,*] M. Angelucci,[1] G. Mazzitelli,[1] R. Musenich,[2] S. Farinon,[2] A. Chincarini,[2] F. Sorrentino,[2] A. Pasqualetti,[3] G. Gemme,[2] and R. Cimino[1,†]

[1]*LNF-INFN, Via E. Fermi 54, 00044 Frascati (Rome) Italy*
[2]*INFN, Sezione di Genova, e Dipartimento di Fisica, Universitá di Genova, 16146 Genova, Italy*
[3]*European Gravitational Observatory (EGO), 56021 Cascina (Pisa), Italy*

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

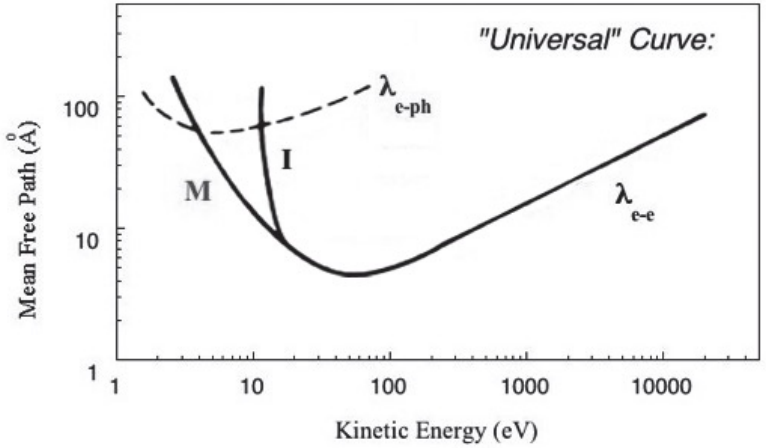
Secondary Electron Yield

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

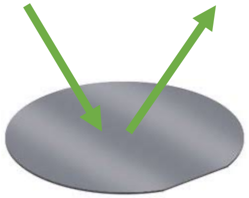


Electron mean free path up to ~10 nm

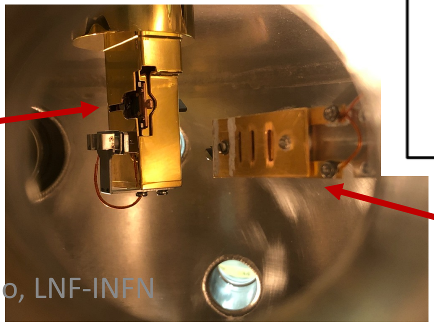
SEY is an intrinsic surface property of materials

Incident electrons current (I_p)

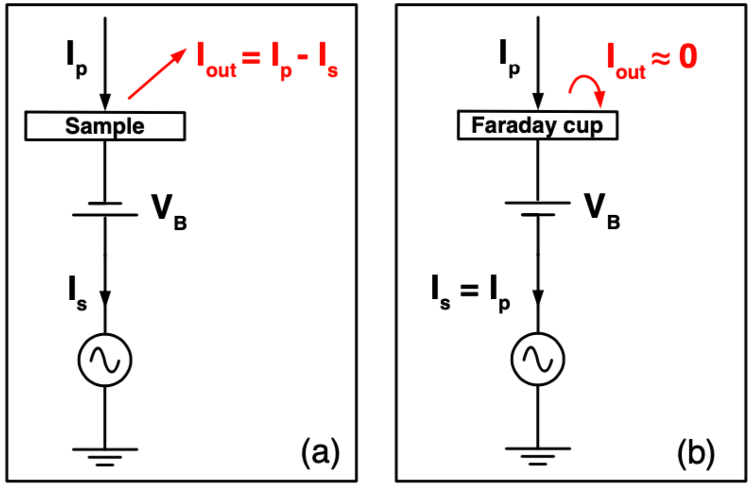
Emitted electrons current (I_{out})



Sample

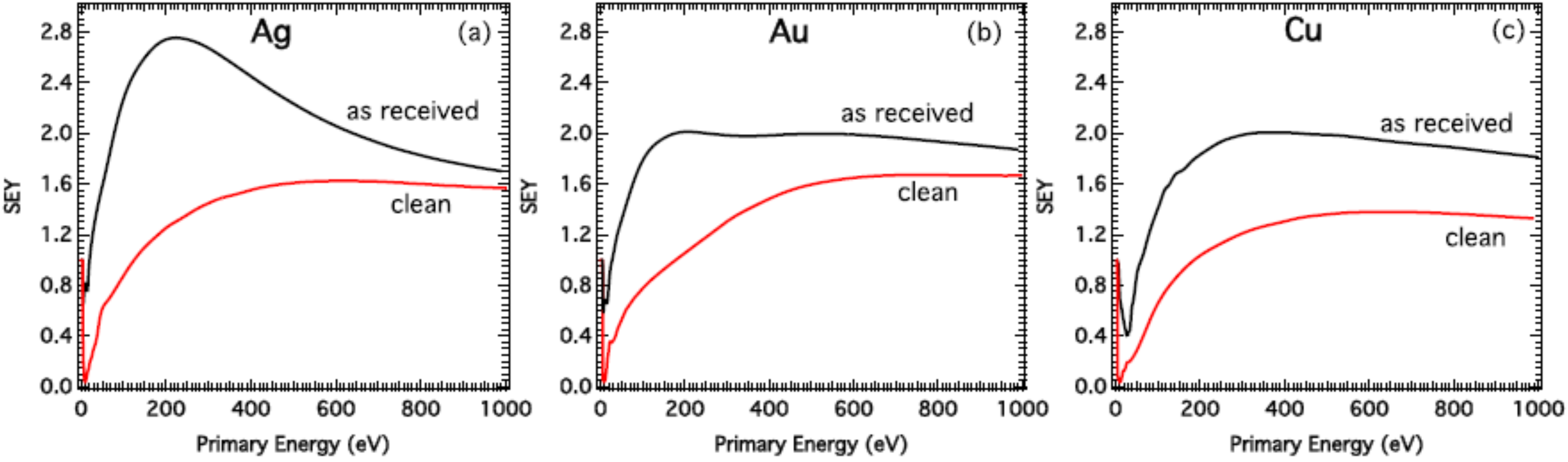


Farady cup



Secondary Electron Yield

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



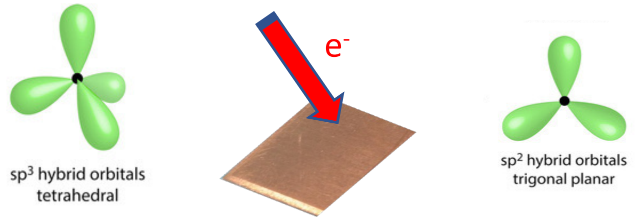
<u>Chemisorbed</u> compounds modify the chemical bonds at the metal surface

R. Cimino et al., Phys. Rev. Lett. (2012)

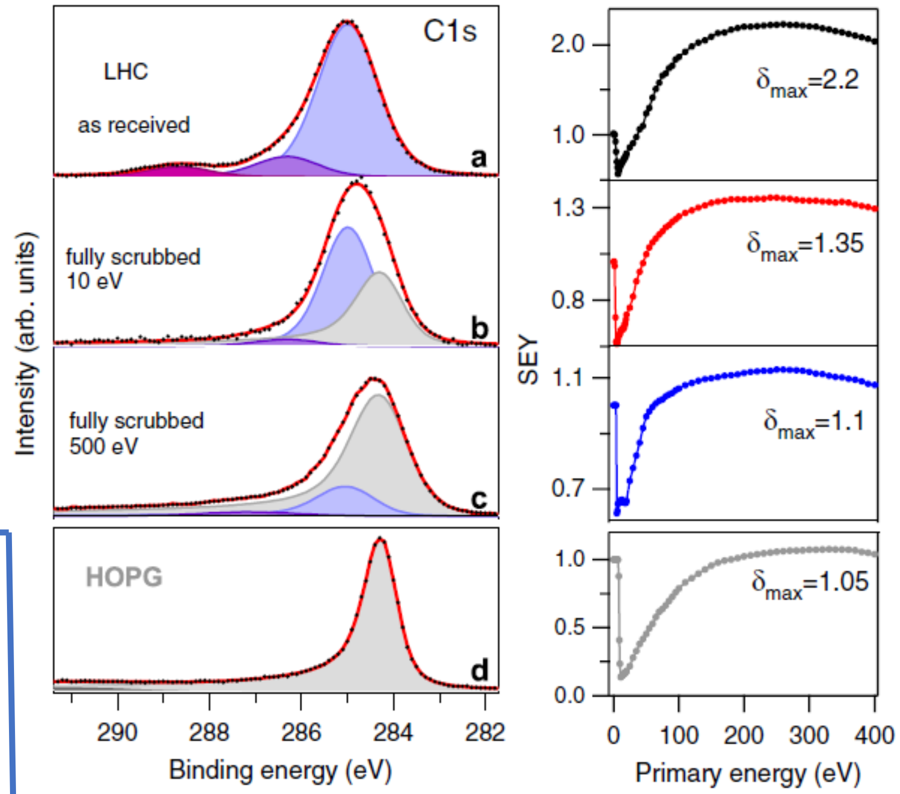
Secondary Electron Yield

sp^3 → sp^2 carbon surface contamination conversion

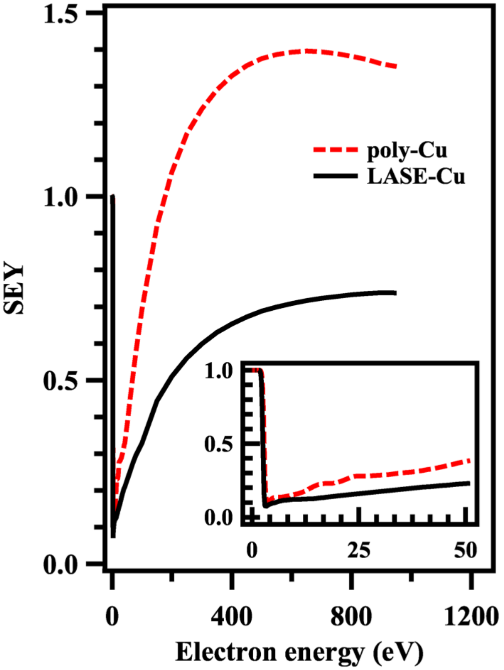
- **SEY depends on the surface chemical state**

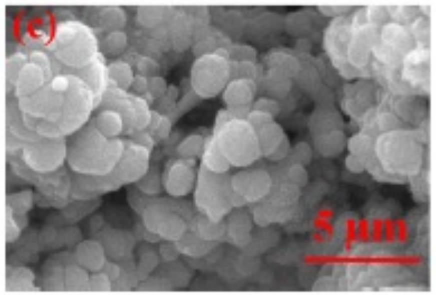


As received LHC-Cu sample

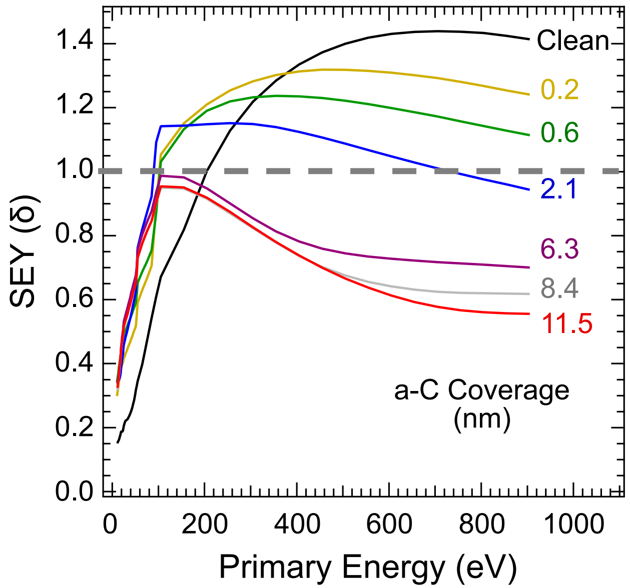


L. Spallino, J. Vac. Sci. Technol. B (2020)





- **SEY depends on the surface morphology**

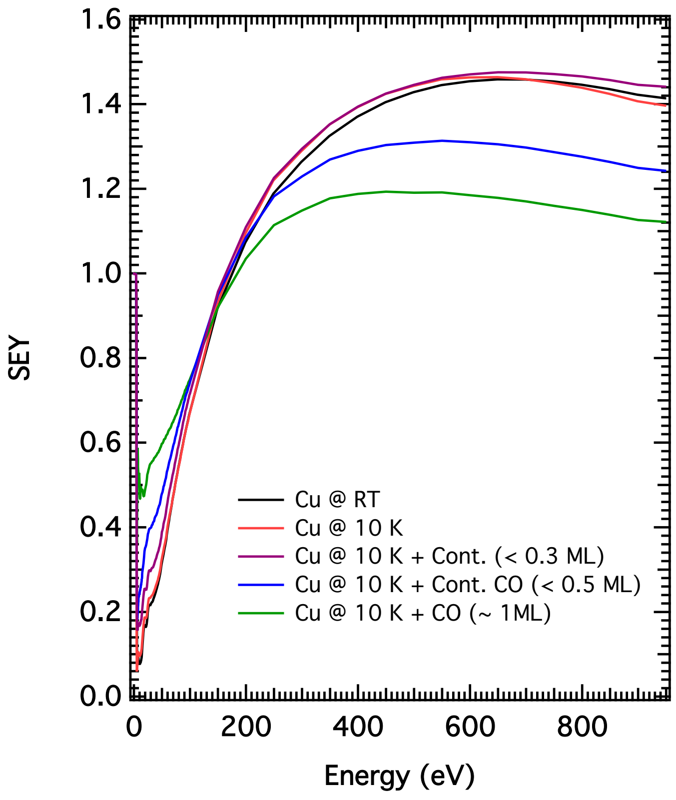


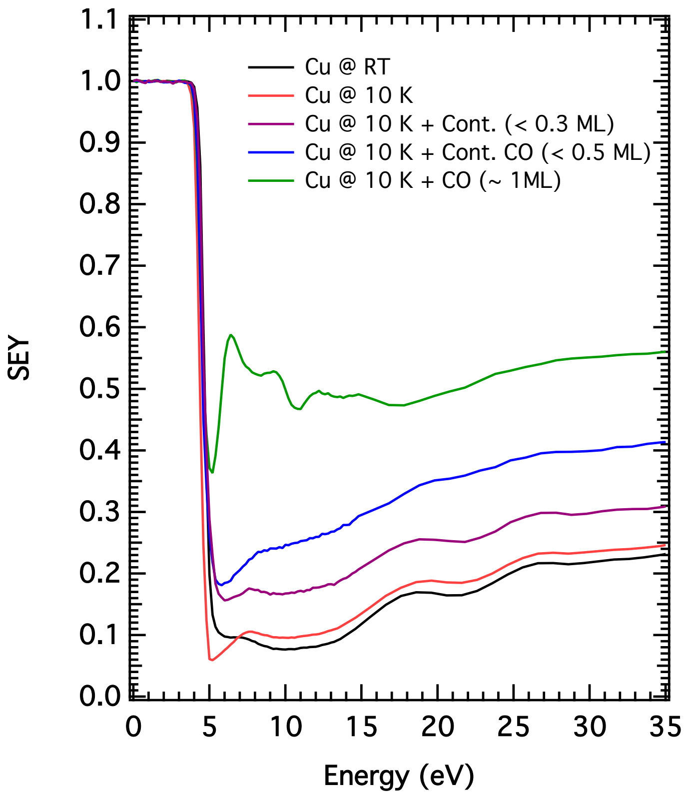
- **SEY depends on the coverage thickness, even at sub-monolayer coverage**

M. Angelucci et al., Phys. Rev. Res. (Rapid Comm.) (2021)

Secondary Electron Yield

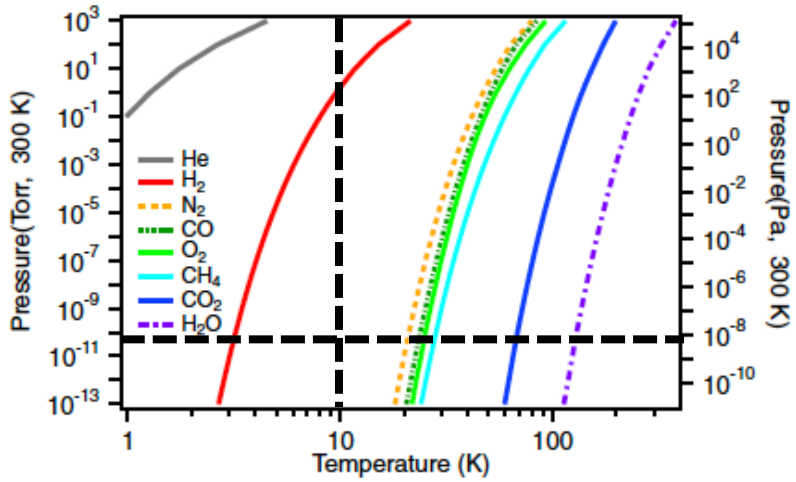
L. A. Gonzalez et al., AIP Adv. (2017)





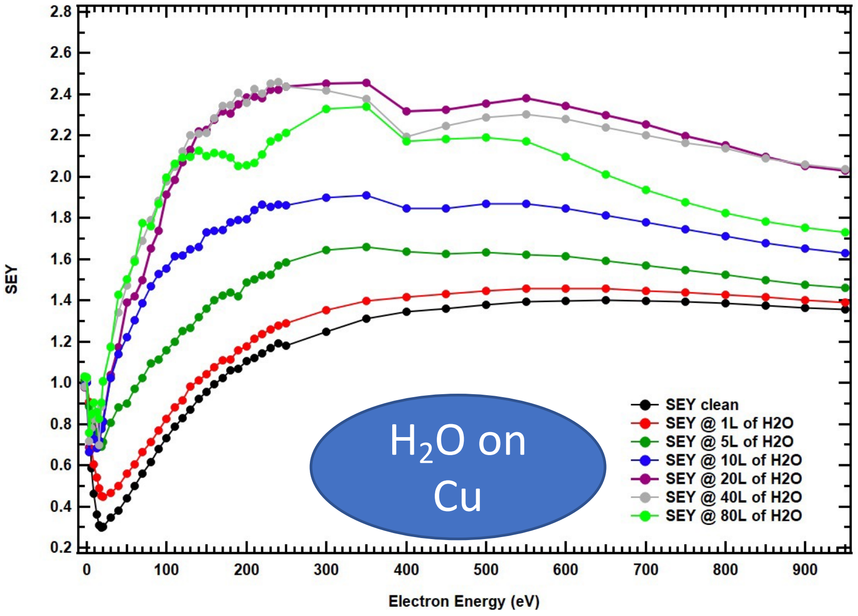
Residual gas in a vacuum at cryogenic temperature

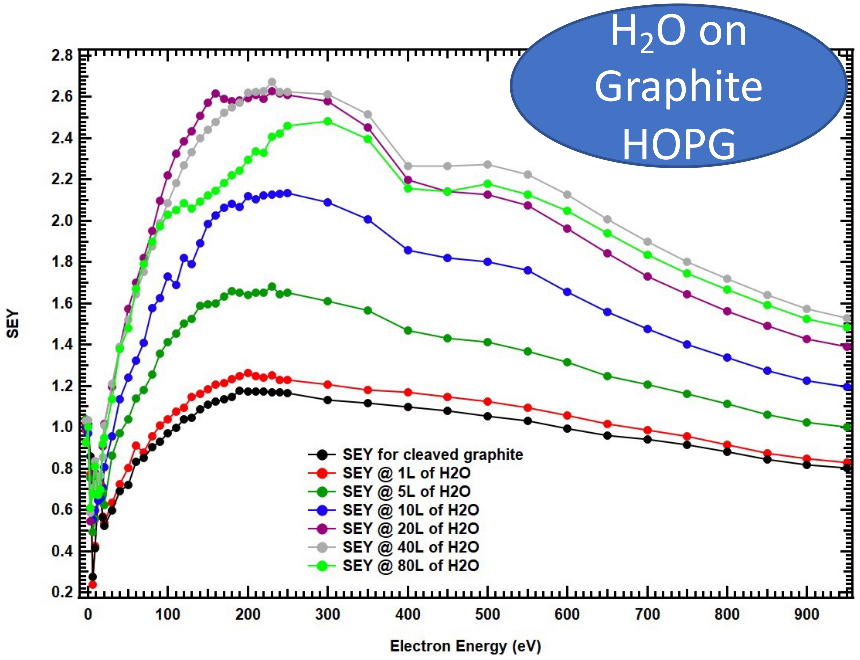
SEY of cold surfaces influenced by gas physisorption



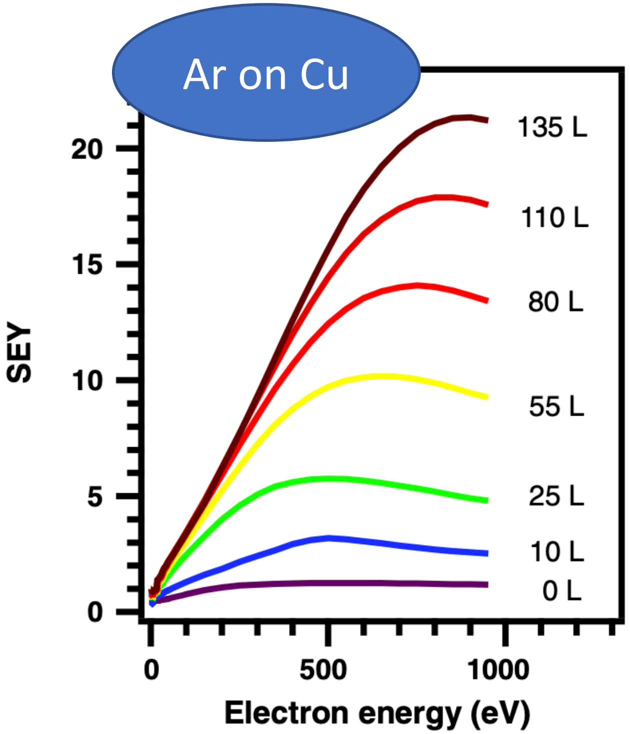
Secondary Electron Yield

Not published data



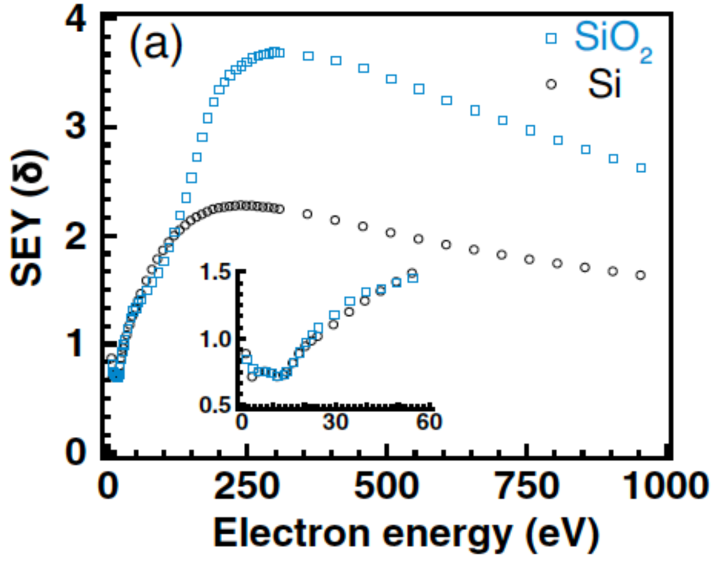


L. Spallino et al., Phys. Rev. Accel. Beams (2020)

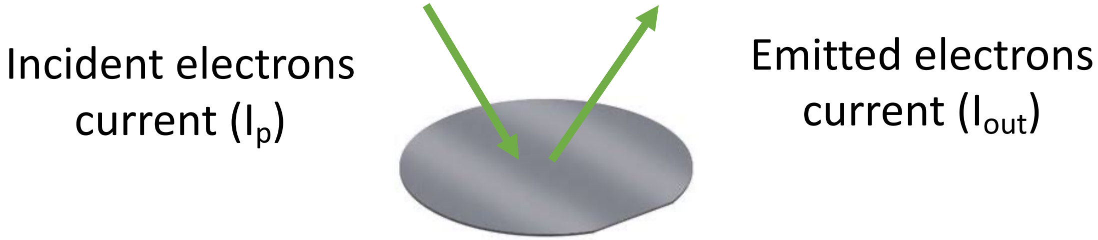


SEY of gas condensed on a cryogenic surface

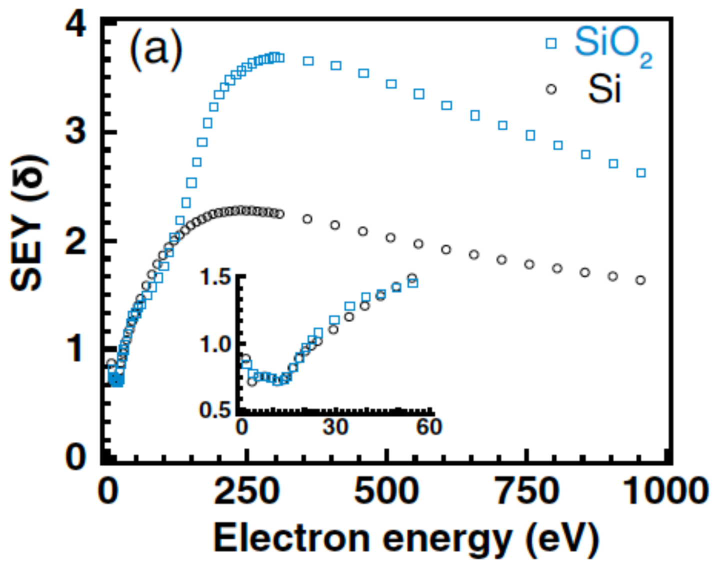
Using low energy electrons to neutralize electrostatic charging: a proof of principle



Secondary Electron Yield
$SEY=I_{out}/I_p$



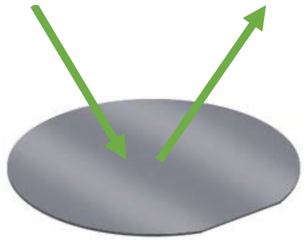
Using low energy electrons to neutralize electrostatic charging: a proof of principle



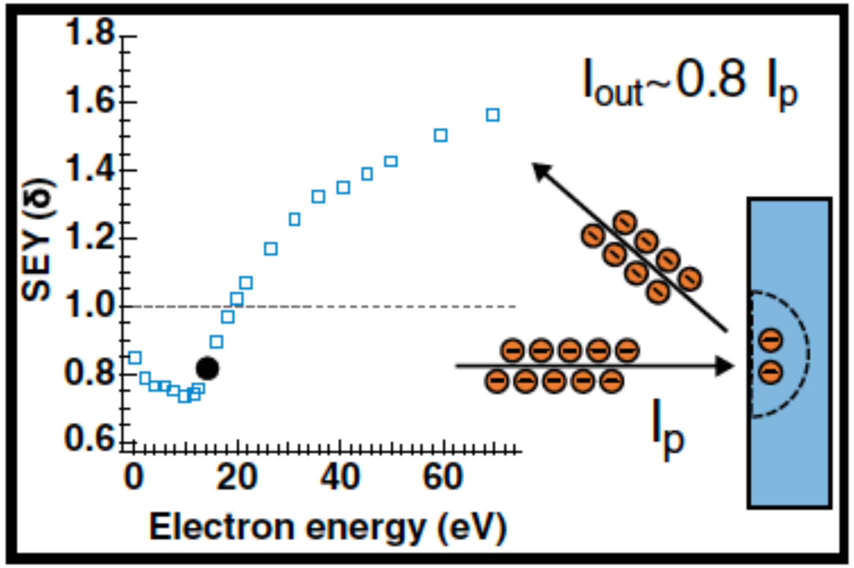
Secondary Electron Yield

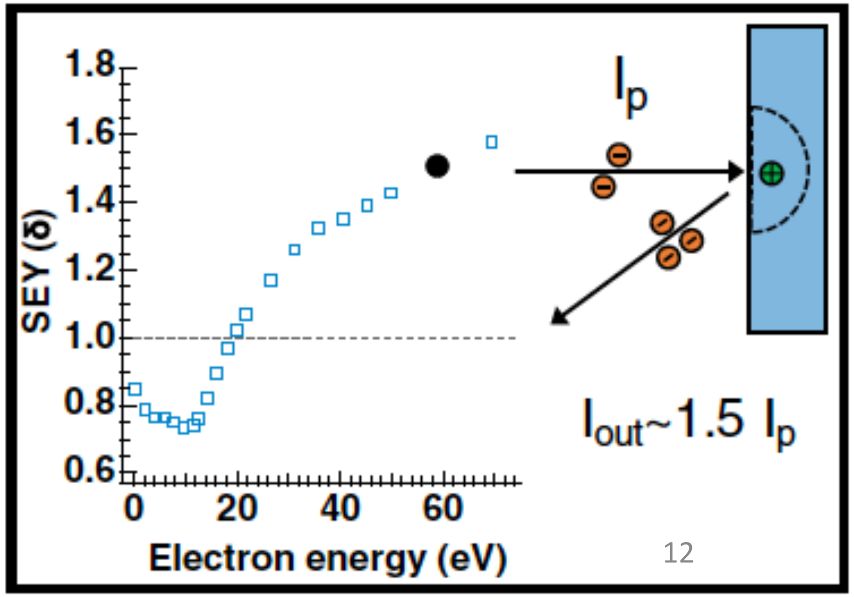
$SEY = I_{out}/I_p$

Incident electrons current (I_p)



Emitted electrons current (I_{out})





The energy of the incident electrons can be opportunely tuned to neutralize positive and negative charges on the mirror's dielectric surface

To do (first steps!)

- SEY studies on thin dielectric samples in neutral and unperturbed conditions.

- Quantification of the surface charge.

- Definition of electron beam parameters to induce surface charging/discharging. Study of the surface charge induced (or removed) as a function of electron irradiation parameters.

To do (first steps!)

- SEY studies on thin dielectric samples in neutral and unperturbed conditions.

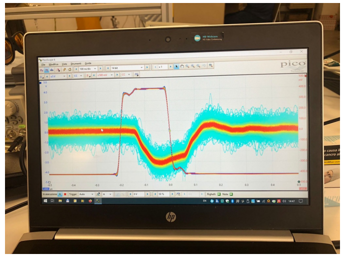
- Quantification of the surface charge by electrostatic voltmeter.

- Definition of electron beam parameters to induce surface charging/discharging. Study of the surface charge induced (or removed) as a function of electron irradiation parameters.

Extreme low continuous imping current ($<10^{-7}$ C/mm^2) finding best electron gun parameters

Pulsed mode (100 ns):

- ➢ Implementation of measuring system (Labview)
    - Oscilloscope
    - Waveform generator
    - Remote control



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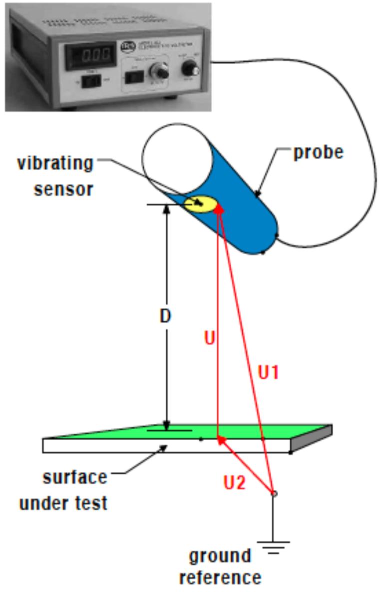
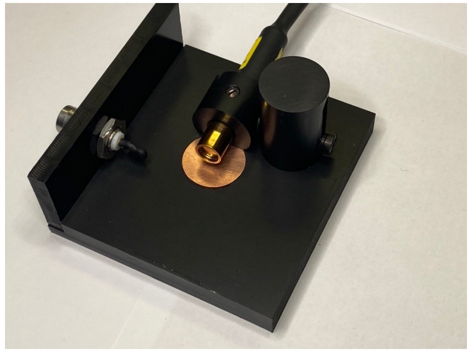




- Labview interface for data acquisition

POWERED BY LabVIEW

To do (first steps!)

- SEY studies on thin dielectric samples in neutral and unperturbed conditions.

- Quantification of the surface charge by electrostatic voltmeter.

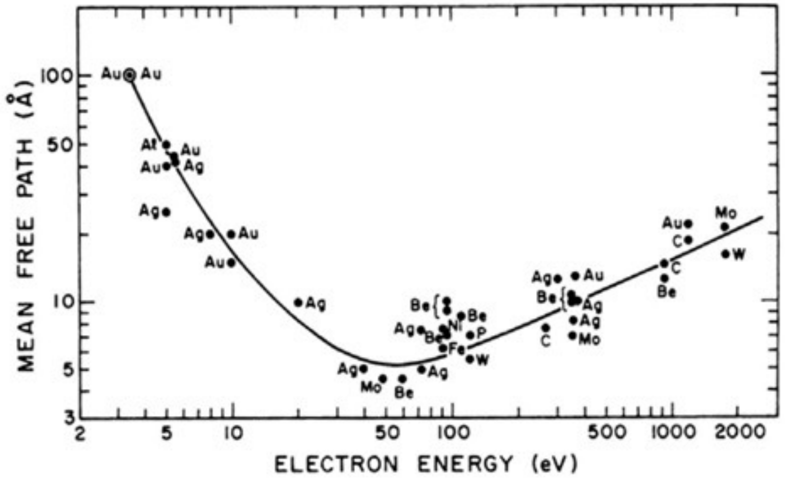
- Definition of electron beam parameters to induce surface charging/discharging. Study of the surface charge induced (or removed) as a function of electron irradiation parameters.

Labview implementation for the feedback control (charge measured – irradiation parameter)

POWERED BY LabVIEW

Advantages

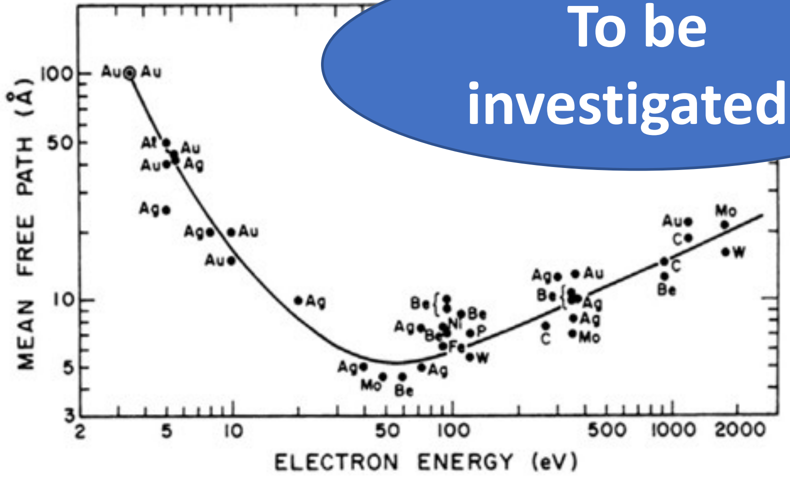
- Electron guns are commercially available, can be stably placed and immediately operated in UHV, and are compatible with cryogenic environments.



- 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.

Advantages

- Electron guns are commercially available, can be stably placed and immediately operated in UHV, and are compatible with cryogenic environments.



To be investigated!

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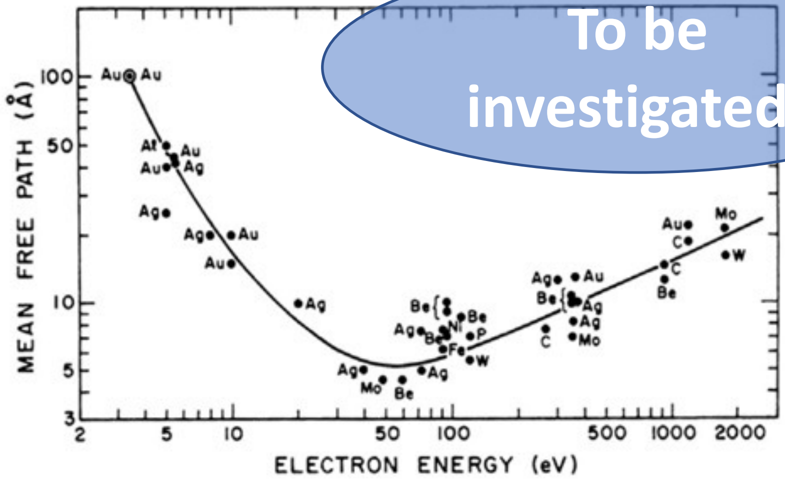

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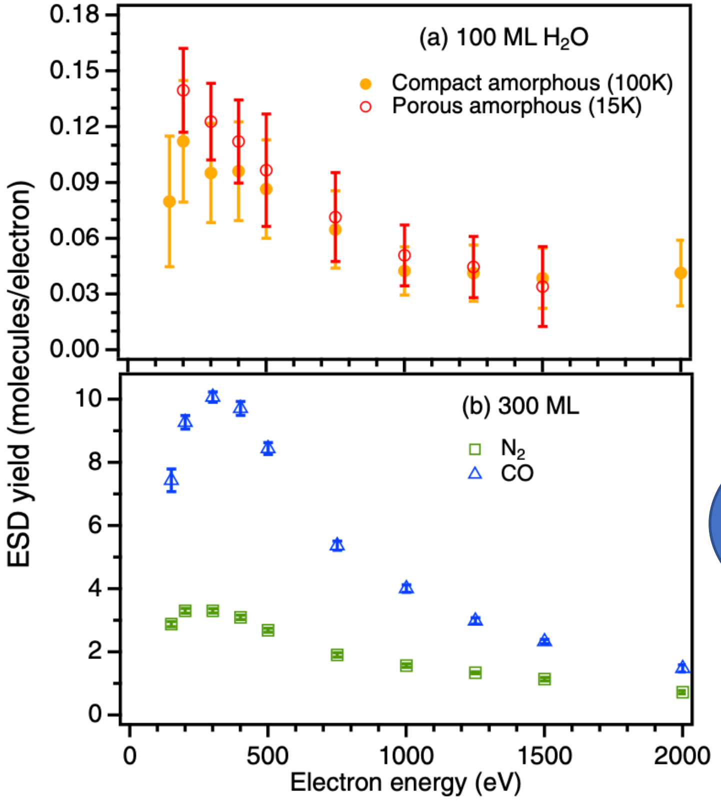
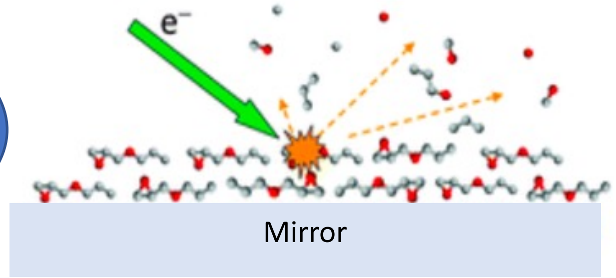


Electrons efficiently induce molecular ice nonthermal desorption

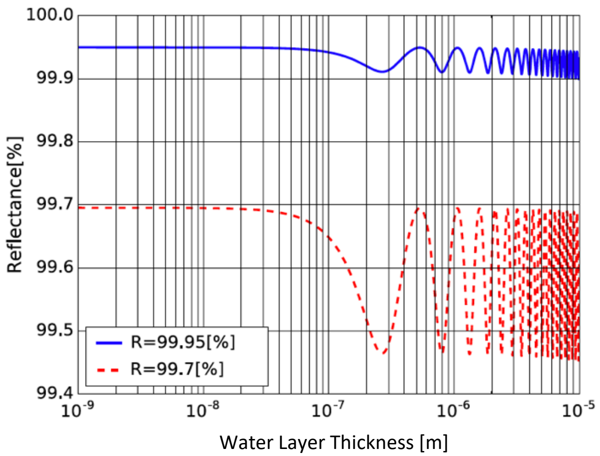


Cryogenic Vacuum Issues on GWD optics

PHYSICAL REVIEW D **99**, 022003 (2019)

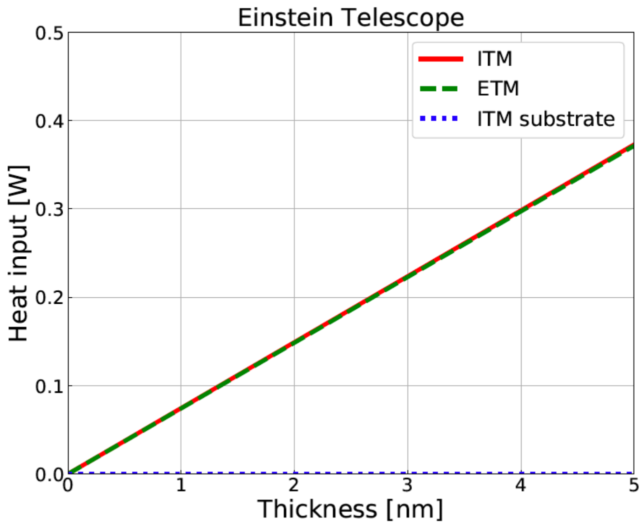
Molecular adsorbed layer formation on cooled mirrors and its impacts on cryogenic gravitational wave telescopes

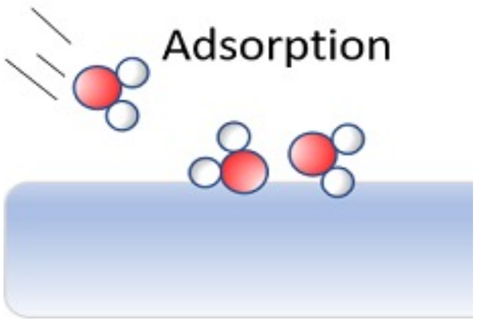
Kunihiko Hasegawa,[1,*] Tomotada Akutsu,[2] Nobuhiro Kimura,[3,4] Yoshio Saito,[1] Toshikazu Suzuki,[1,3] Takayuki Tomaru,[3,4] Ayako Ueda,[3] and Shinji Miyoki[1,†]



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 H_2O ice!!!





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

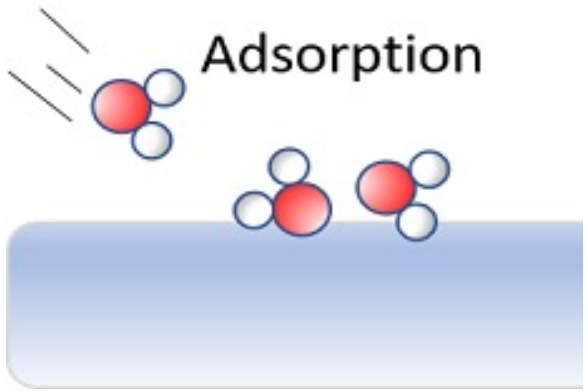
Residual gas adsorption on cold surfaces

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

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.

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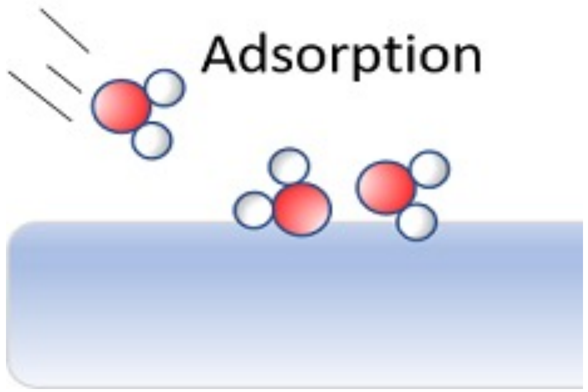
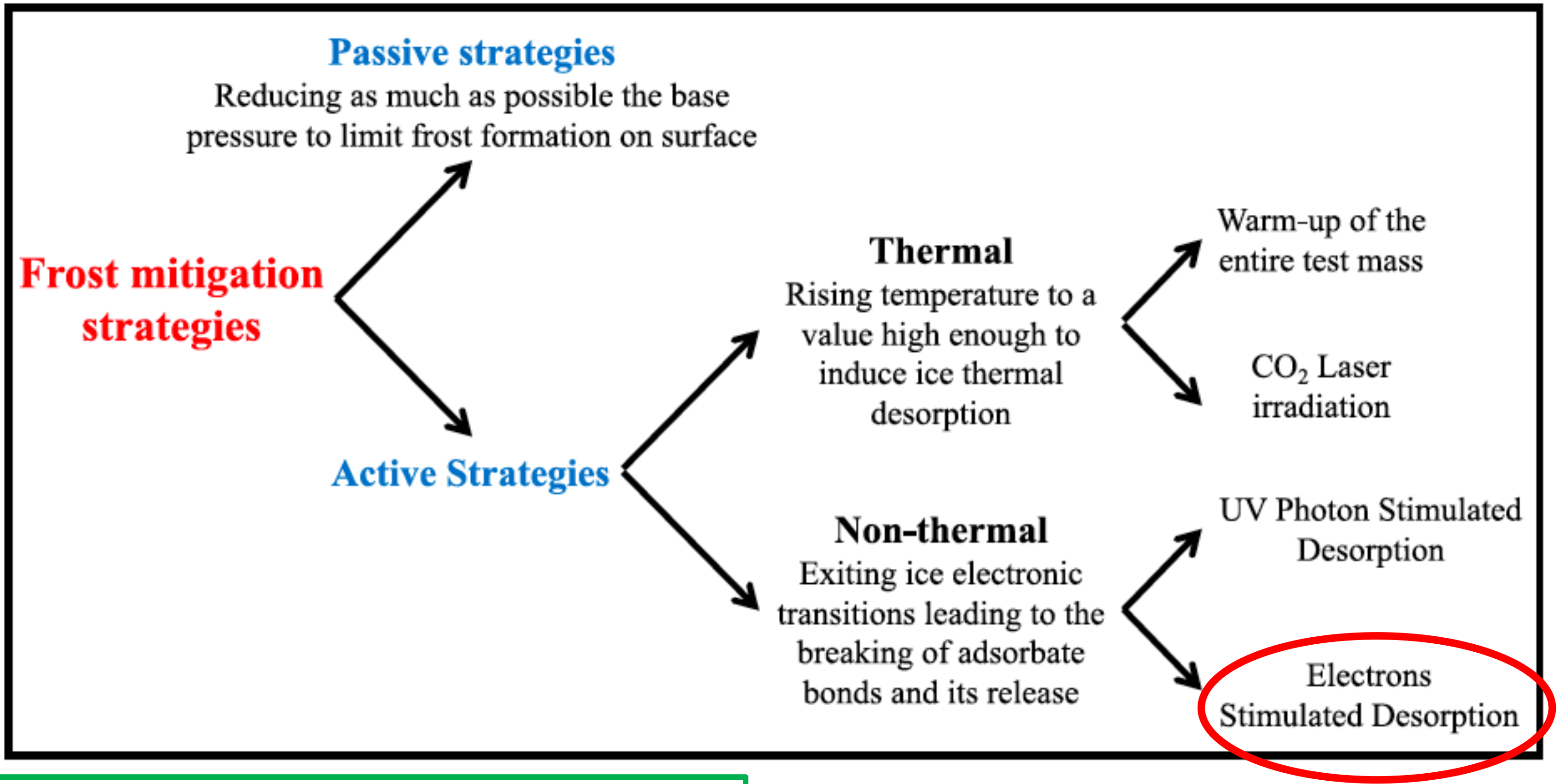


For sticking coefficient S_c= 1:
1 L ~ 1 Monolayer (ML) cryosorbed
for H_2O, 1 ML ~ 0.3 nm

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

Active mitigation strategies: Wrap-up



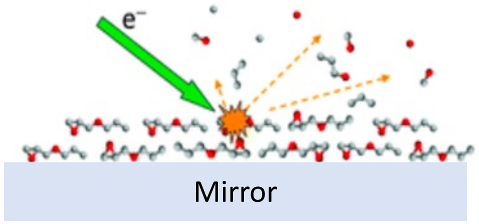
PHYSICAL REVIEW D **104**, 062001 (2021)

Cryogenic vacuum considerations for future gravitational wave detectors

L. Spallino,[1,*] M. Angelucci,[1] A. Pasqualetti,[2] K. Battes,[3] C. Day,[3]
S. Grohmann,[3] E. Majorana,[4] F. Ricci,[4] and R. Cimino[1,†]

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

Low energy electrons irradiation



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

➔ 1 monolayer ($\sim 10^{15}$ mol/cm^2 $\sim$ 0.3 nm) will be cryosorbed in 10.000 s.
($\sim$ 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!

Take-home messages

- The electrostatic charge mitigation method so far adopted is inapplicable at cryogenic temperature, since a significant layer of N_2 will be cryosorbed on the mirror surface.

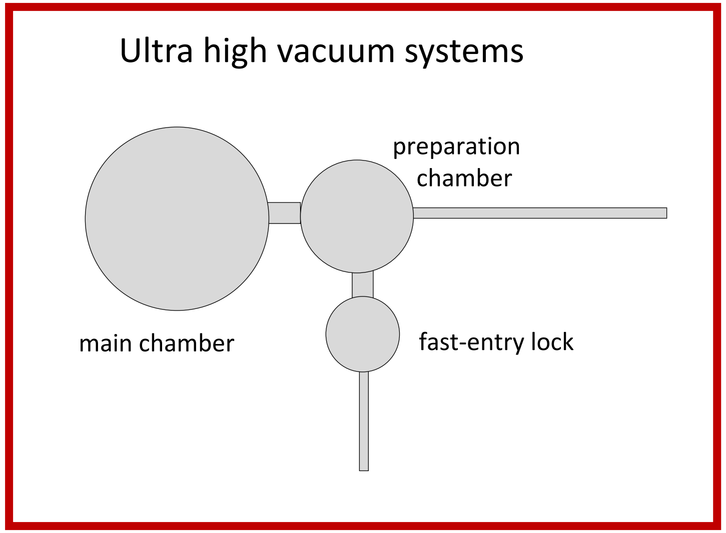
- An intense effort needs to be devoted to find new charging neutralization methods compliant with the constraints derived by the use of cryogenic optics.

- Inevitably, when operating at cryogenic temperature, an ice layer will form on the mirrors' surface. As the ice layer grows, the mirror optical properties will deteriorate.

- An intense research and development effort is mandatory to properly control and opportunely mitigate such frost formation.

If definitely proved, low-energy electrons allow both electrostatic charge mitigation and non-thermal ice desorption

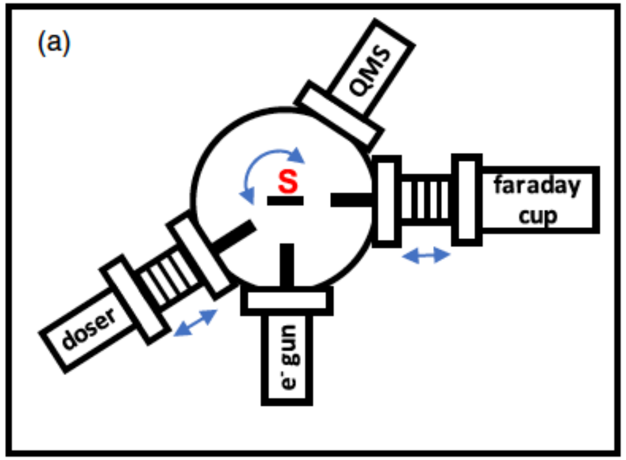
Experimental stations at XUV MaSSLab -INFN



2 UHV systems (P~1 x 10^{-10} mbar) equipped with a cryogenic manipulator (T_{sample}~10 – 300 K)

a UHV system (P~1 x 10^{-10} mbar) for measurements at RT

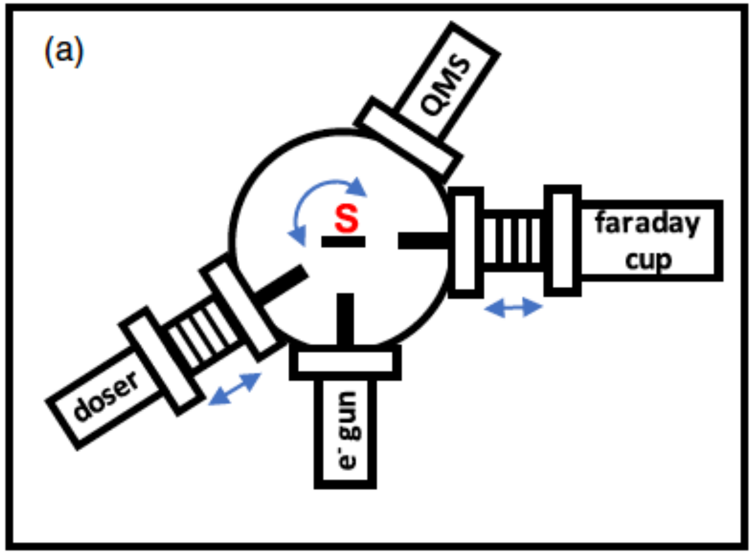
Main chamber



Common elements of the main chambers:

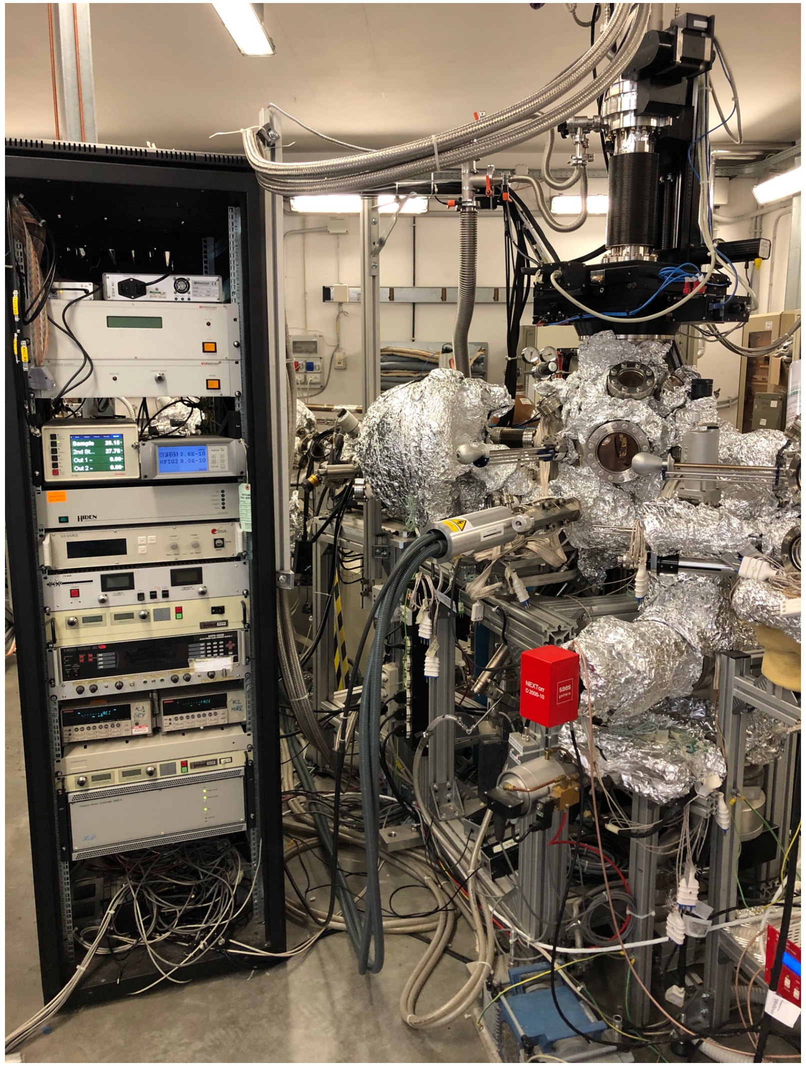
- Set-up for SEY measurements TPD and electron irradiation
- Gas line and Quadrupole Mass Spectrometer (QMS)

Experimental stations at XUV MaSSLab -INFN



HE Chamber:

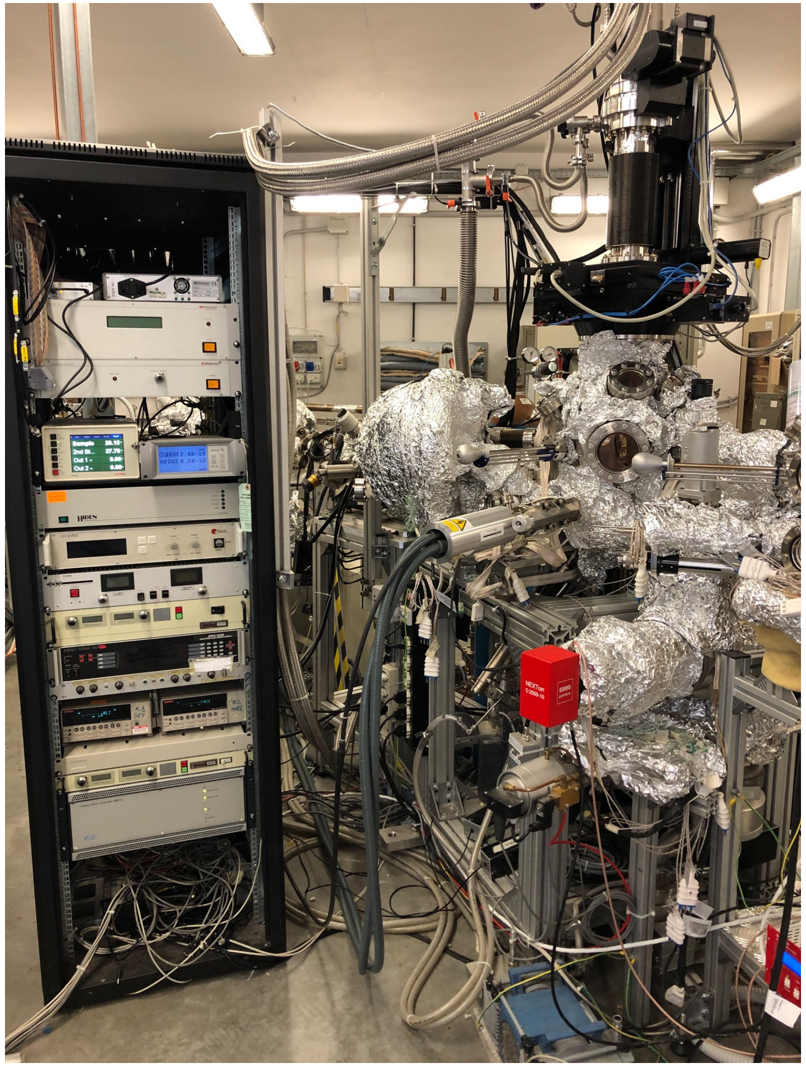
- + XPS set-up (Al and Ag monocromatic and Al and Mg nonmonocromatic sources)
- + Electron flood gun
- + Quadrupole Mass Spectrometer



Experimental stations at XUV MaSSLab -INFN

HE Chamber:

- + XPS set-up (Al and Ag monocromatic and Al and Mg nonmonocromatic sources)
- + Electron flood gun
- + Quadrupole Mass Spectrometer



We can host students, PhD students, post-docs, researchers…

…and for all curious minds feel free to contact us!

luisa.spallino@lnf.infn.it
marco.angelucci@lnf.infn.it

See also information on XUV beamlines at

http://dafne-light.lnf.infn.it/

28 – 30 September 2022
Hotel Hermitage at La Biodola (Isola d'Elba) Italy

GWD Vac'22

Registrations are open!

INFN Istituto Nazionale di Fisica Nucleare
ET EINSTEIN TELESCOPE
KIT Karlsruher Institut für Technologie
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Thank you!

M. Angelucci

A. Liedl

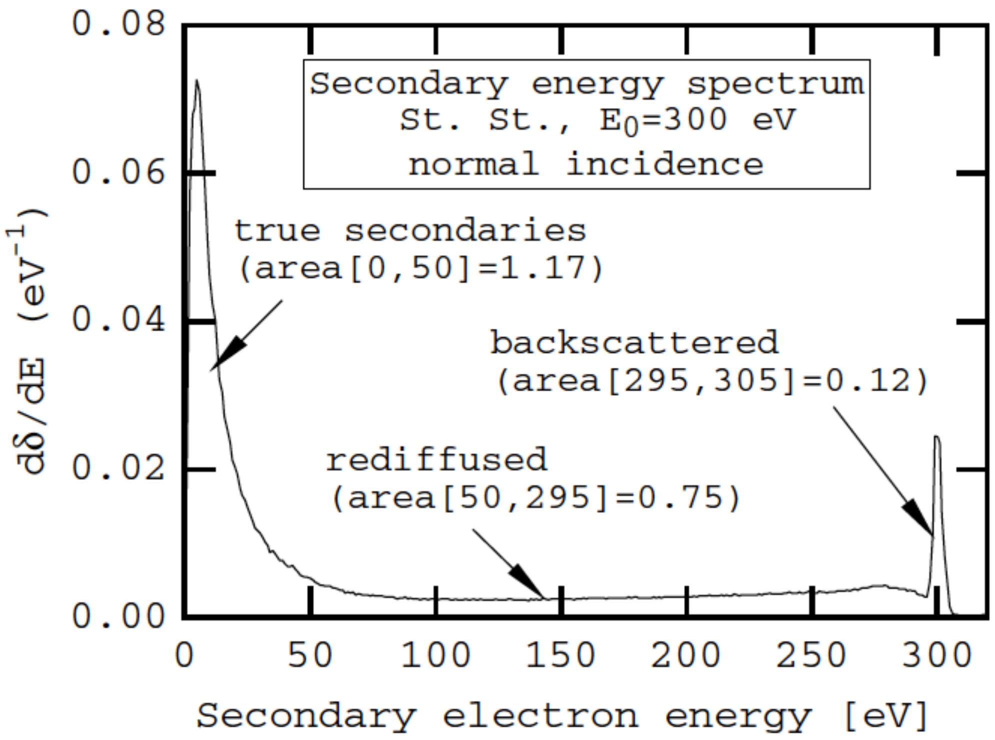
R. Cimino

R. Larciprete

and thanks to….

The team at LNF

Low Energy SEY



"Probabilistic model for the simulation of secondary electron emission" M. A. Furman and M. T. F. Pivi Phys. Rev. ST Accel. Beams 5, 124404 (2002)

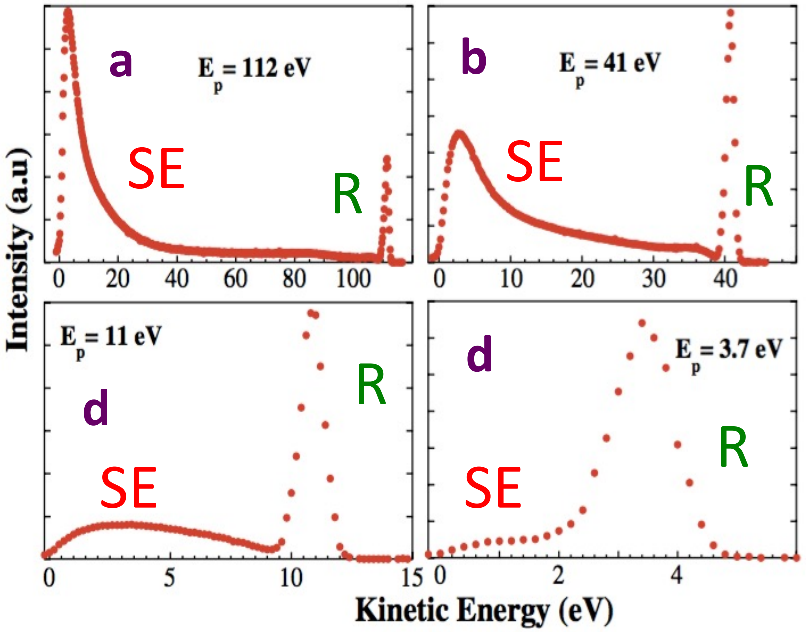
SEY: Total number of electrons emitted (TEE , TEY,...)

True secondaries: number of electrons emitted between 0-50 eV. (if $E_P > 50$ eV.)

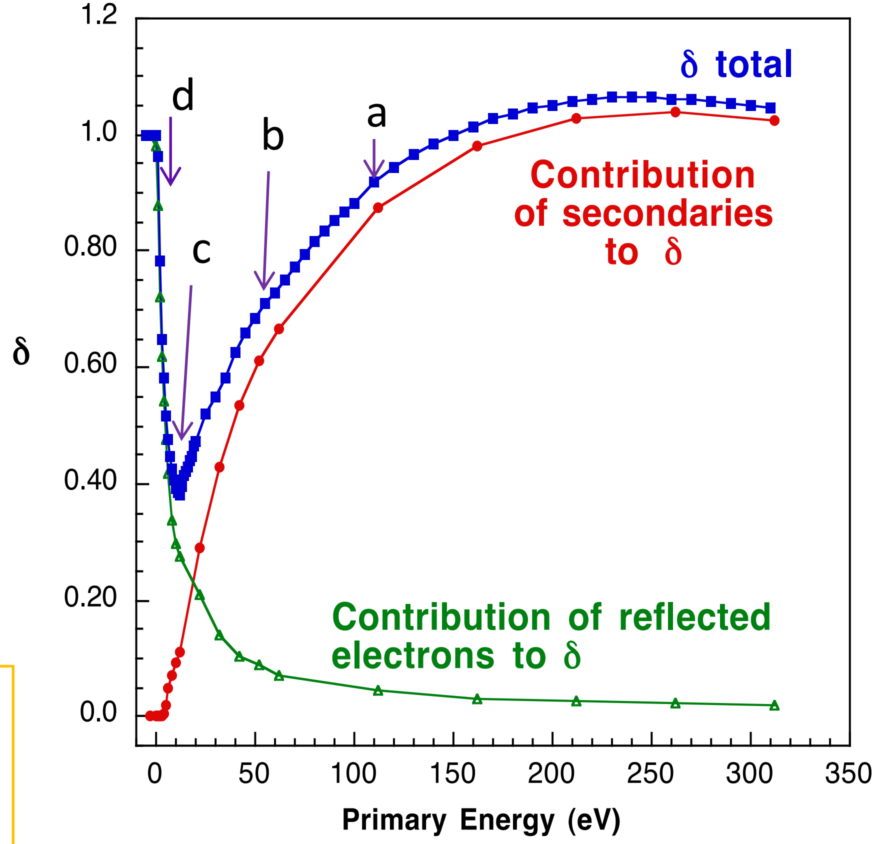
Backscattered electrons (Reflected): number of electrons emitted at E_P ($\pm\ \Delta$)

Rediffused electrons: number of electrons emitted between 50 eV and $E_P - \Delta$ (if $E_P > 50$ eV.)

Low Energy SEY

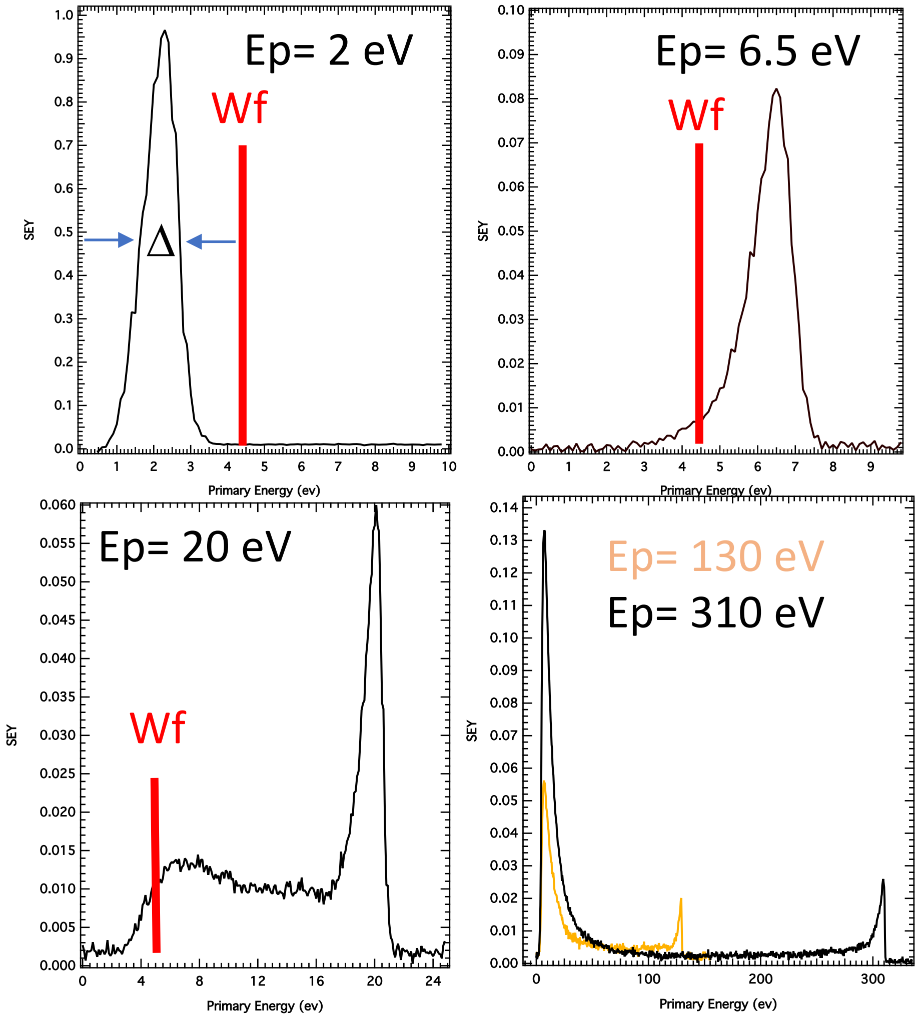


Evaluation of Reflected (R) and True Secondary (SE) electrons parts



Cimino et al., PRL 93 (2004)

Low Energy SEY



Plotting all the data normalizing to UNITY the intensity of the EDC @ Ep< Wf

Or

Integrating the curves:

(when Ep <50 eV)

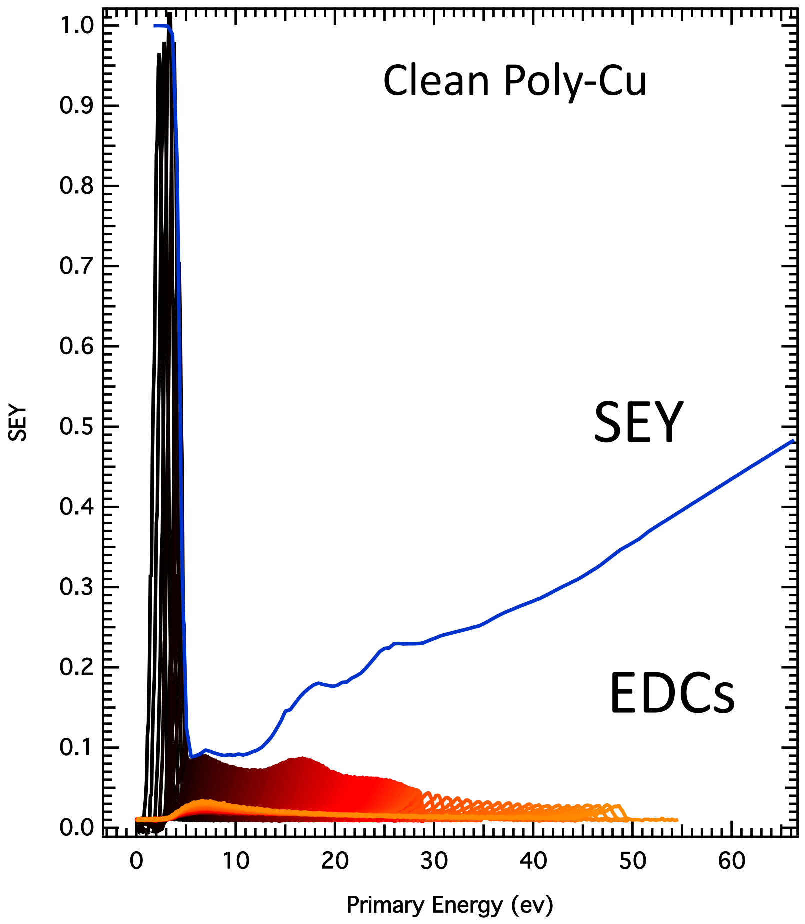
- 0 to $E_P - \Delta$ (True Secondary)
- $E_P - \Delta$ to $E_P + \Delta$ (Elastically Back.)

(when Ep > 50 eV)

- 0 to 50 eV (True Secondary)
- 50 eV to $E_P - \Delta$ (Rediffused)
- $E_P - \Delta$ to $E_P + \Delta$ (Elastically Back.)

Low Energy SEY

Reflected electrons in Copper

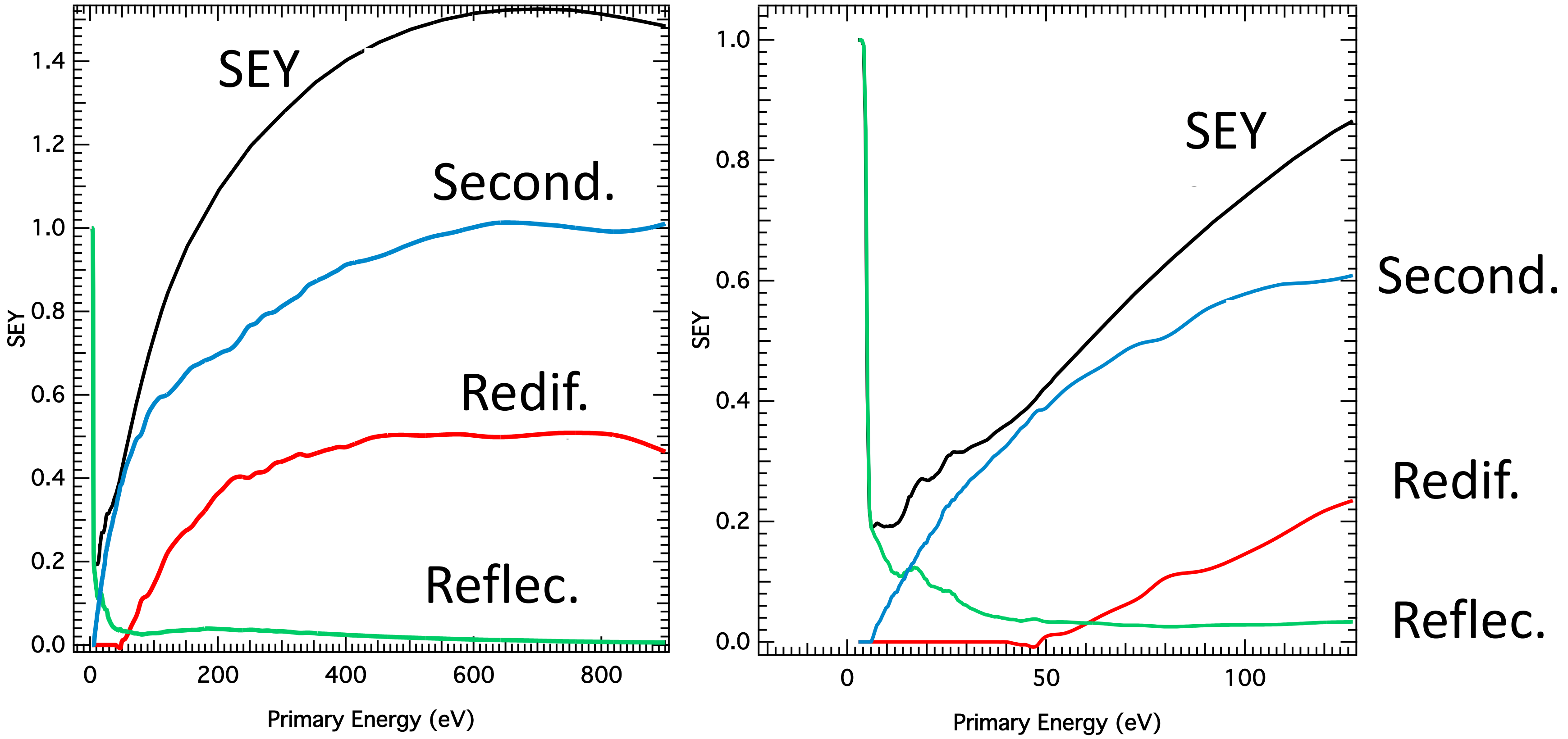


Plotting all the data normalizing to UNITY the intensity of the EDC @ Ep< Wf

Structures in SEY are oscillations in the elastically backscattered components

Low Energy SEY

Reflected electrons in Copper
Different Contributions



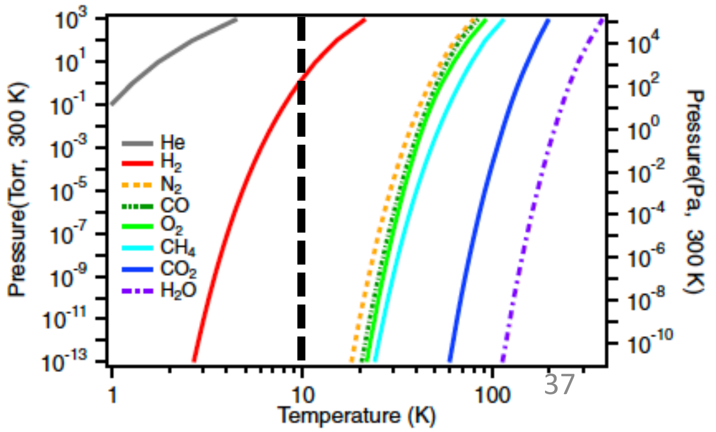
Limit for the base operating vacuum in the ET LF tower

If P_{H2O} ~ 1x 10^{-10} mbar → it takes (10.000 x 3-30) s (~9-90 h) to start observing detrimental effects!!!

Considering 1 W maximum thermal budget (new limit)

If P_{H2O} ~ 1x 10^{-12} mbar → it takes ~11000 hours to form 12 nm

A full year of operation!



This reasoning applies to all gases (CO, CO_2, N_2, etc.) that have desorption temperatures higher than 10 K