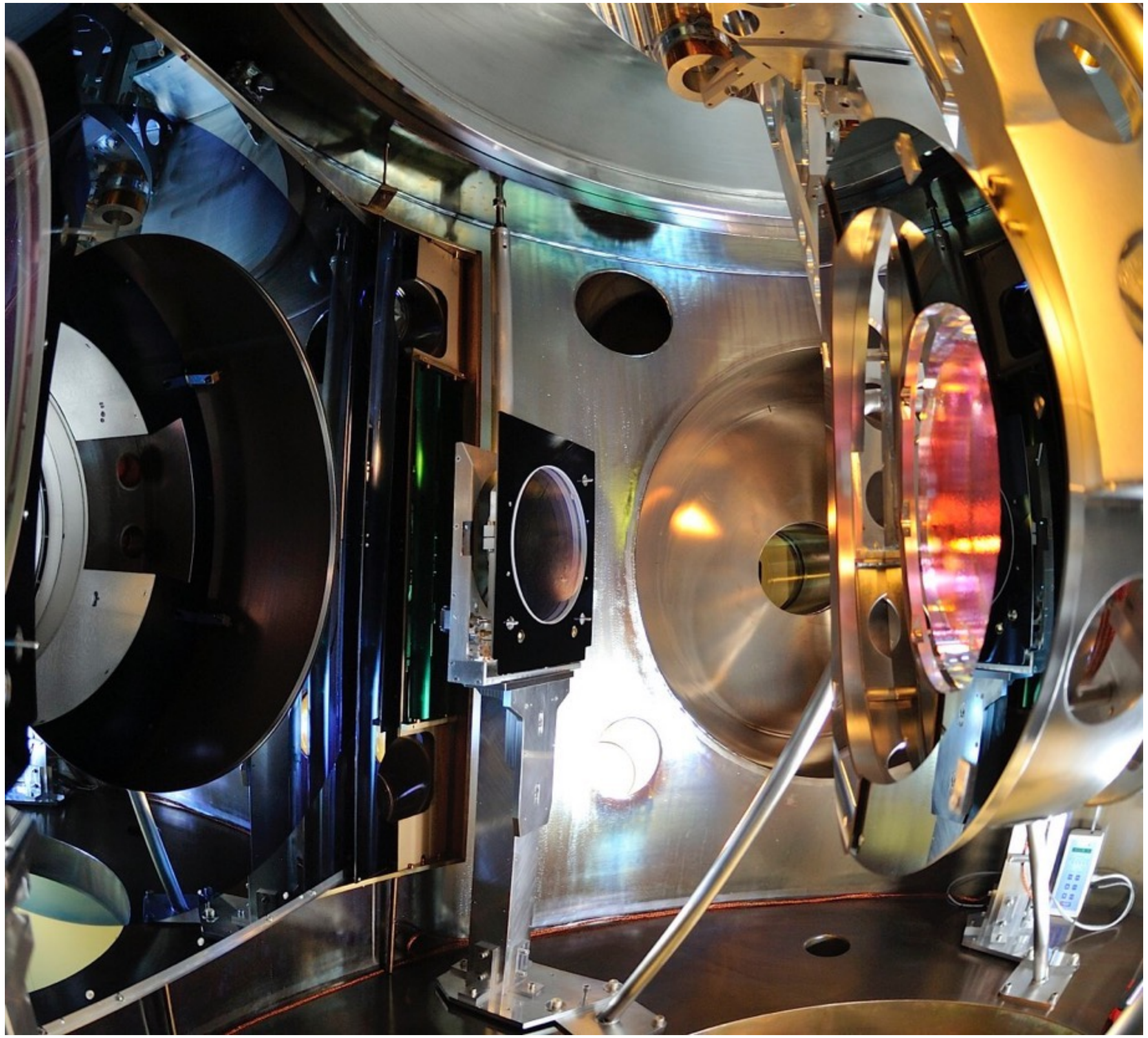

GWADW
Online 2021
GWADW2021 Gravitational Wave Advanced Detector Workshop

Impact on Vacuum Requirements by Cryogenically Cooled Mirrors for Gravitational Wave Detection

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]

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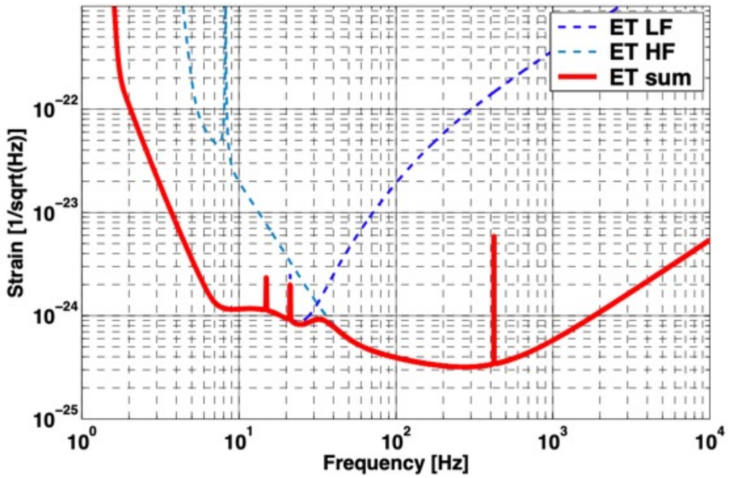
Outline

- Cryogenic Vacuum Issues
- Cryogenic Vacuum Considerations
- Potential mitigation methods

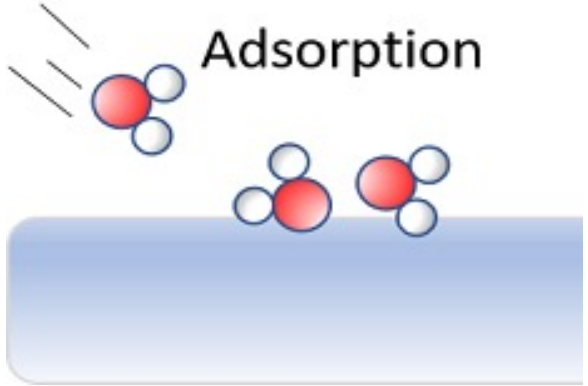
Cryogenic Vacuum Issues



Cryogenic optics to reduce the thermal noise in Low Frequency (LF) detectors

Cryosorption on cold optics (frost):

- **LT optics (as shown in KAGRA GWO) suffers from gas cryosorbed on the mirror surface inducing detrimental effects on the optics.**



→ How to cure it?

Cryogenic Vacuum Issues

Gas Cryosorption depends

Surface temperature ($p<10^{-10}$ mbar)

H_2O cryosorbs at T < 125 K

CO_2 cryosorbs at T < 60 K

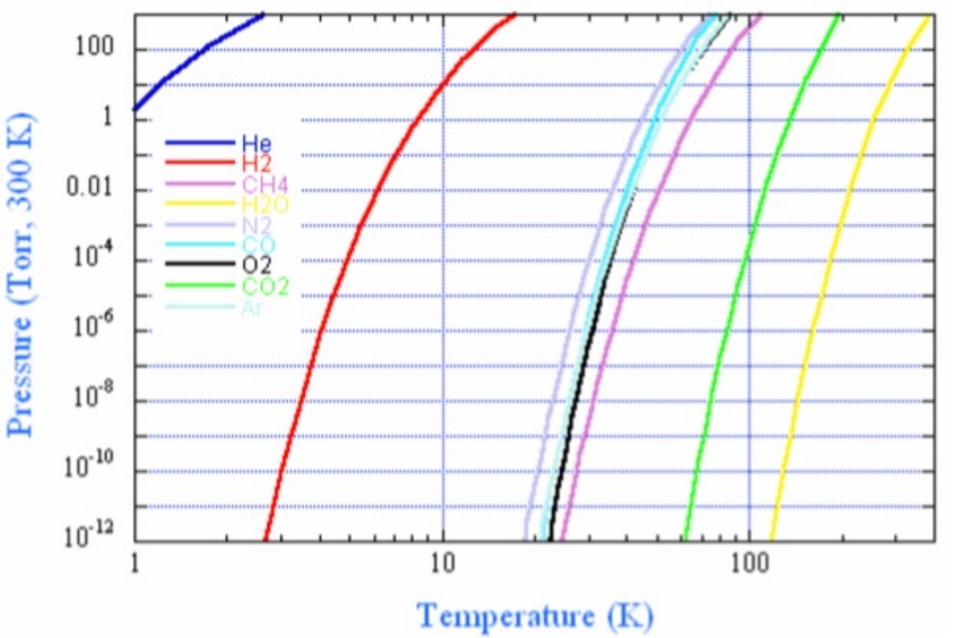
O_2 cryosorbs at T < 30 K

Partial pressure

Defining:
1 L (Langumir) = 1x 10^{-6} mbar x 1s

For S_c= 1 ; 1 L ~ 1 Monolayer cryosorbed

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



Saturated vapour pressure from Honig and Hook (1960)

For H_2O:

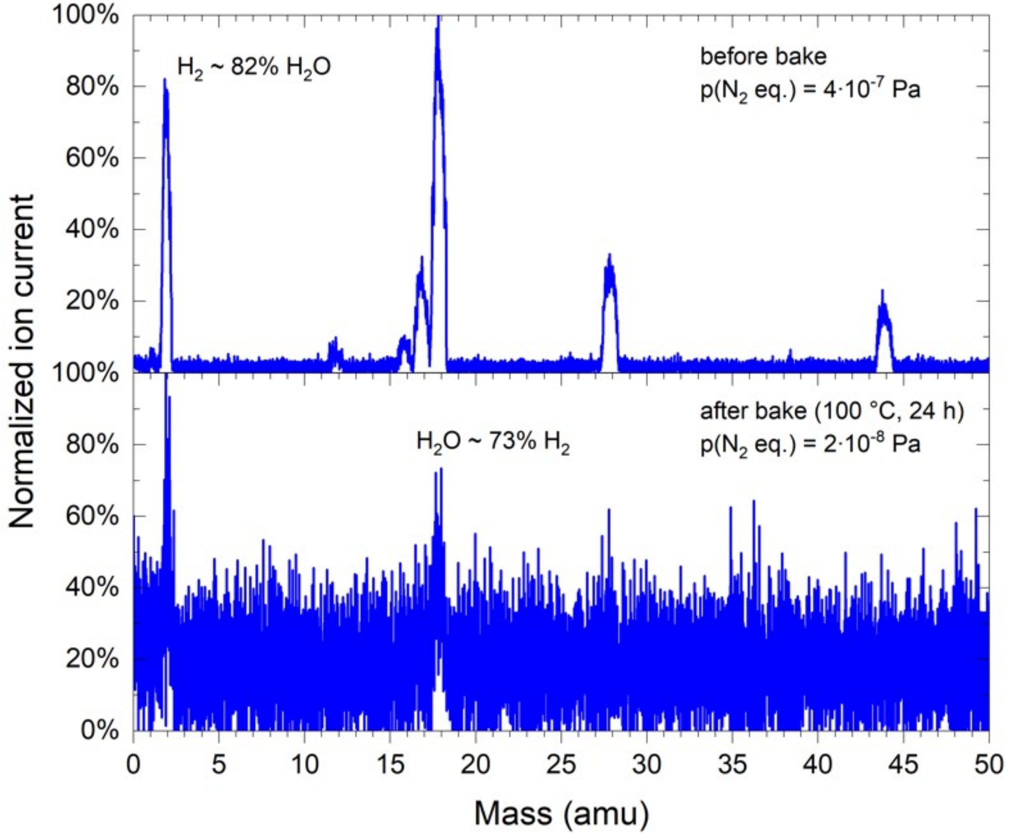
1 ML ~ 0.3 nm

Cryogenic Vacuum Issues

- $P_{RT} \neq P_{LT}$

- What is of interest are the gas <u>partial pressures</u>

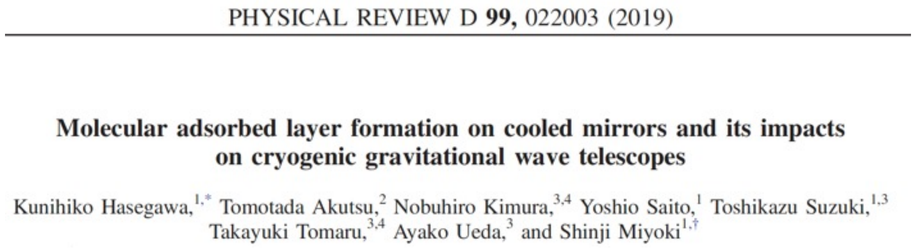
- For a given P they depend on the vacuum history.



Residual gas analysis, as measured with a QMS in case of a clean UHV system prior (top panel) and after a bake out (bottom panel) at 100°C for 24 h .

Cryogenic Vacuum Issues

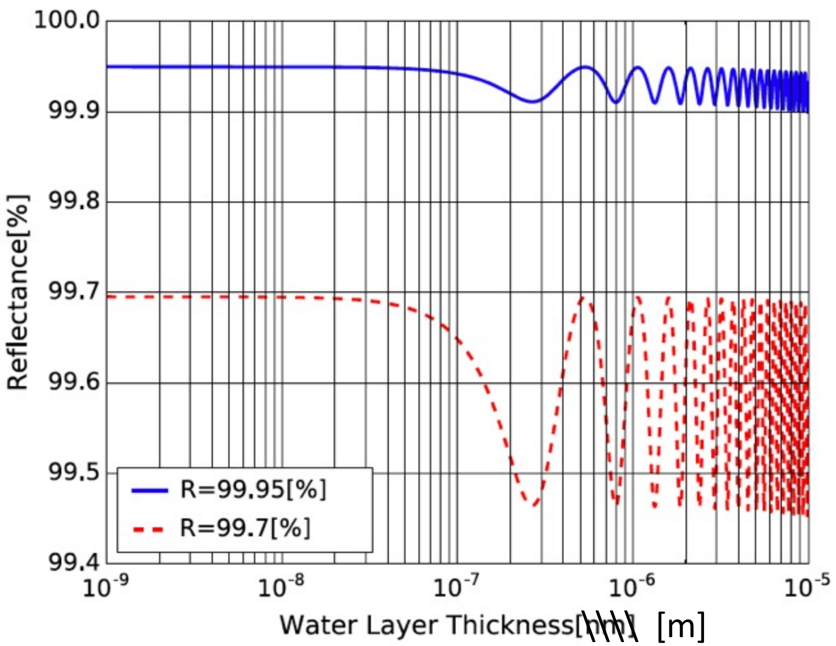
Reflectance changes induced by molecular adlayer growth



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 the literature: studies at KAGRA show that already after 100 nm of H_2O ice Reflectivity gets affected.

100 nm H_2O → ~ 300 L

If P_{H2O} ~ 1x 10^{-10} mbar → it takes (10.000x 300) s (~900 h) to start observing detrimental effects!!!

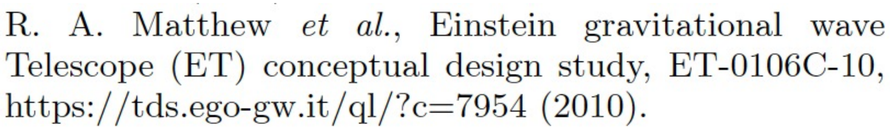
If P_{H2O} ~ 3x 10^{-12} mbar → ~ 3 years

Great design challenge!

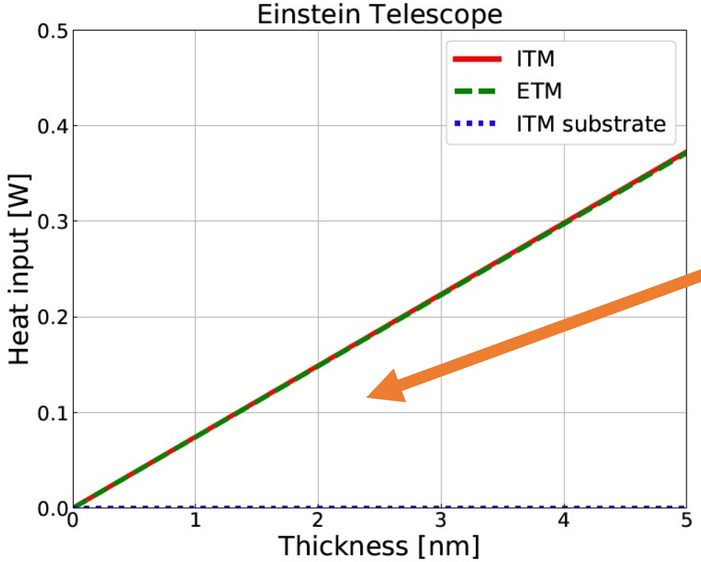
Cryogenic Vacuum Issues

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



R. A. Matthew *et al.*, Einstein gravitational wave Telescope (ET) conceptual design study, ET-0106C-10, https://tds.ego-gw.it/ql/?c=7954 (2010).



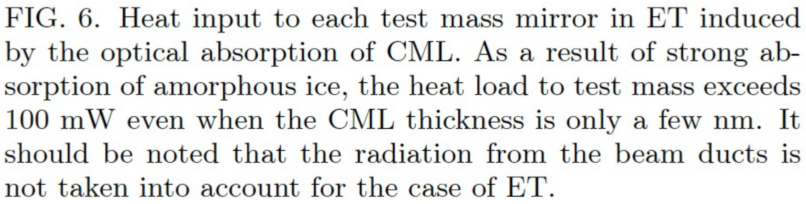


FIG. 6. Heat input to each test mass mirror in ET induced by the optical absorption of CML. As a result of strong absorption of amorphous ice, the heat load to test mass exceeds 100 mW even when the CML thickness is only a few nm. It should be noted that the radiation from the beam ducts is not taken into account for the case of ET.

ET Available thermal budget ~ 100 mW

1 nm H_2O → ~ 3 L

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

If P_{H2O} ~ 1x 10^{-12} mbar → ~ 1 month

Cryogenic Vacuum Issues

All that must be cross checked but:

FROST is an issue!

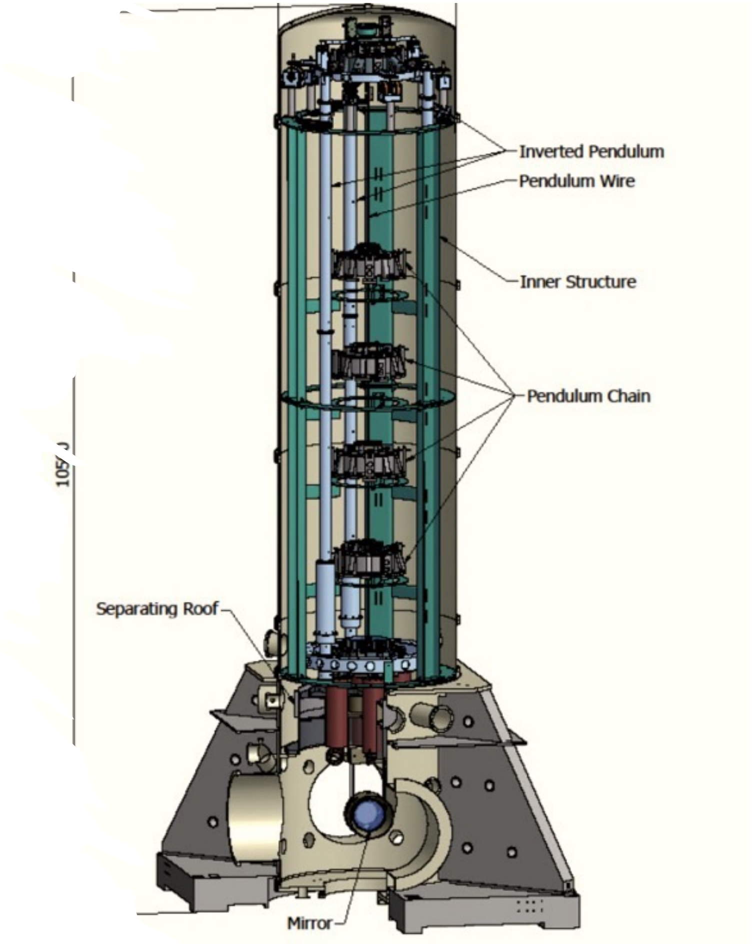
Need of mitigation strategies:

- Passive methods
- Active methods

Mitigation Strategies

Passive mitigation methods

- Very low base pressure in:
  - Very big volumes
  - Very complex structures
- Optimization of transients (cooling down etc)



VERY HIGH COSTS AND R&D REQUIRED to reach:

P_{H2O} ; P_{CO} ; $P_{CH4} < 1x\ 10^{-12}$ mbar
Severe limitations in design and material choice in the tower!!!

$P_{H2} < 1x\ 10^{-10}$ mbar
Importance of P transient (integral gas load!)

Mitigation Strategies

Active mitigation methods

➢ Thermal

- Bring the mirror or its surface above 125 K.

➢ Non-Thermal

- Exiting the overlayer molecules to induce their (non-thermal) desorption

Mitigation Strategies

Active mitigation methods

- Thermal

☐ Warm up the entire mirror above 125 K

☐ Warm up the surface with CO_2 laser

Mitigation Strategies

Active mitigation methods

- Thermal

☐ Warm up the entire mirror above 125 K

☐ Warm up the surface with CO_2 laser

It is presently difficult to tell how long it takes and how often it should be foreseen.

Mirror cooling down and warming up effects on other cryogenics and on vacuum

Possibly implying unacceptable GWD downtime!

Mitigation Strategies

Active mitigation methods

- ➢ Thermal

☐ Warm up the entire mirror above 125 K

☐ Warm up the surface with CO_2 laser

CO_2 Laser beam penetrated some microns within the mirror surface:

Can Induce damage to Optics?

Can give H_2O ice sufficient thermal energy to be removed (>125 K) without heating too much the mirror?

Mitigation Strategies

Active mitigation methods

- Non-Thermal
  - ☐ UV photons irradiation
  - ☐ Low energy electrons irradiation

Mitigation Strategies

Active mitigation methods

- Non-Thermal

☐ UV photons irradiation

☐ Low energy electrons irradiation

UV light induce electronic transition in H_2O and its desorption

H_2O yield ~1×10^{-3} molecules/photon

UV photons penetrate well below the mirror surface and are prone to induce defect formation deteriorating optical properties

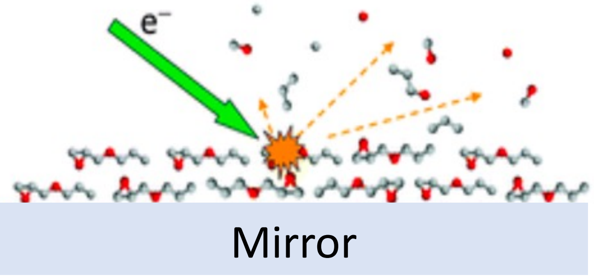
Mitigation Strategies

Active mitigation methods

- ➢ Non-Thermal

☐ UV photons irradiation

☐ Low energy electrons irradiation



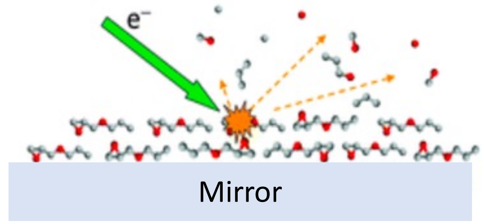
Low Energy Electrons (20-200 eV) induce transitions in H_2O and its desorption

H_2O yield ~1 × 10^{-1} molecules/electron

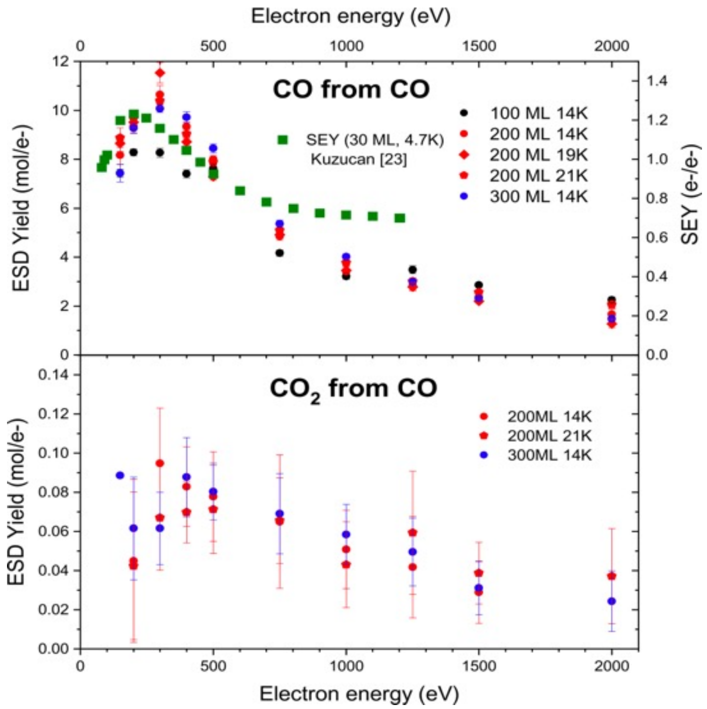
Low en. electrons penetrate some nm below the mirror surface and are not expected to induce significant defect formation

Mitigation Strategies

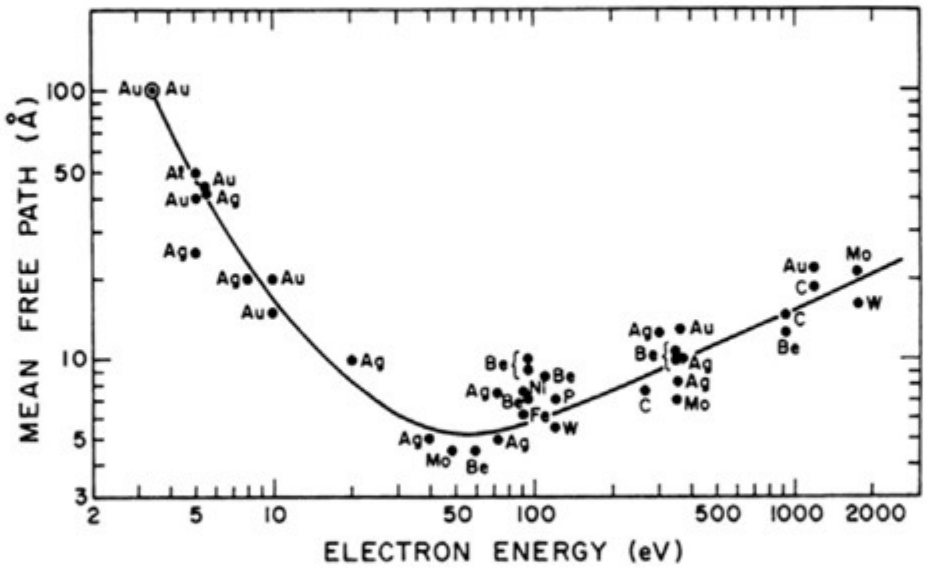
Low energy electrons irradiation



- Much more efficient than Photons (factor 100 – 1000)

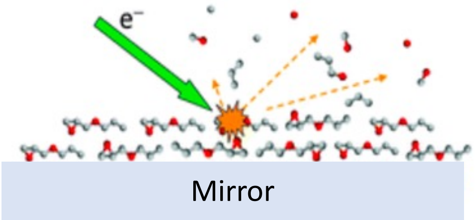


- Much less penetrating.



Mitigation Strategies

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)

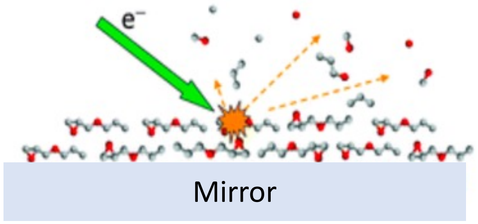
To remove 1 ML we need an el. current of: ~ 1 mAmps/cm^2 in one second

… 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!

Mitigation Strategies

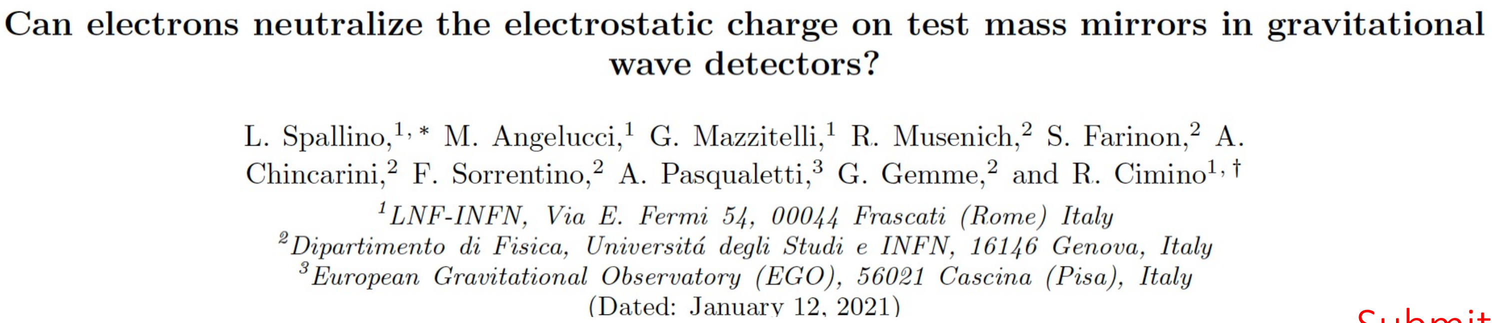
Low energy electrons irradiation



Electrons will induce detrimental electrostatic charge

- Both VIRGO and LIGO optics undergo to inhomogeneous electrostatic charging of variable (or unknown) sign that may induce unwanted noise.

→ procedures are undertaken for neutralization with positive/neg ions. (Not applicable at LT)



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] *Dipartimento di Fisica, Universitá degli Studi e INFN, 16146 Genova, Italy*
[3] *European Gravitational Observatory (EGO), 56021 Cascina (Pisa), Italy*
(Dated: January 12, 2021)

Submitted to Phys. Rev. Lett.

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
Divisione Ricerca: DAFNEL

LNF-INFN MaSSlab "Material and Surface Science laboratory"

Two "state of the art" UHV set-ups equipped with cryogenic manipulators for hosting small samples (10x10mm^2) at <20 K, electron guns, XPS, SEY, QMS and other spectroscopies to perform (with minor upgrades):

Proof of principle SEY and surface characterization of mirrors materials at RT and LT before and after cryosorption of gases.

Wrap-up

- **Thermal**
  - Warm up above 125K.
    - How long and how often???.
    - **Possibly implying unacceptable GWD downtime!**
    - Great impact on design: Temperature cycles AND improve $P_{H2O} < 1 \times 1 \times 10^{-13}$ mbar
  - CO_2 Laser
    - CO_2 Laser beam penetrated some microns within the mirror surface:
    - **Can induce damage to optics?**
    - Can give H_2O ice sufficient thermal energy to be removed (>125 K) without heating the mirror?
  - Inductive?
- **Non thermal**
  - **UV Photons**
    - UV light induce electronic transitions in H_20 and its desorption
    - H_2O yield ~1×10^{-3} molecules/photon
    - **UV photons induce defect formation deteriorating optical properties**
  - Electrons
    - Low (20-200 eV) Electrons induce transitions in H_20 and its desorption
    - H_2O yield ~1×10^{-1} molecules/electron
    - Low en. electrons penetrate only nm below the mirror surface
    - Charge issues can be cured by electron irradiation too
  - .....

Conclusions

- **Frost formation on mirrors defines new vacuum limits for operating cryogenic GW detectors**

- **Frost mitigation strategies are mandatory to implement the use of cryogenics in the design of future GW detectors**
  - **Passive methods will certainly be implemented.**
  The improvement of the vacuum conditions will not avoid frost formation, but only impact on the frequency of intervention.
  - **Active methods will be fundamental to regularly remove the frost forming on mirrors.**

Thank you for your attention