Radiation testing of optical coatings for space

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Main goals

- Investigate with a methodological approach the effects of low energy ions (i.e. protons, He ions) on optical coatings.
  - Produce an experimental dataset as background for the future.
- Investigate with a methodological approach the effects of keV-electrons (i.e. 100 keV) on optical coatings.
- Give some experiments for testing that MeV ions and electrons for verifying that they have no effects on coatings.
- Gain knowledge on how representative (for space) ground accelerated tests can be performed.
  - Drawing conclusions and recommendations for the design and test of optical coatings.

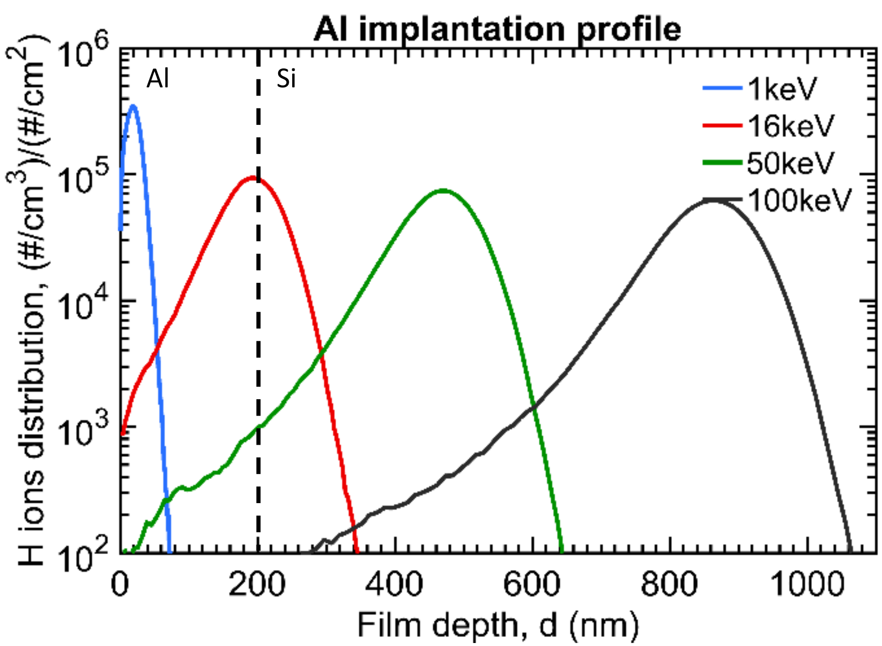
Low energy ions (what means?)

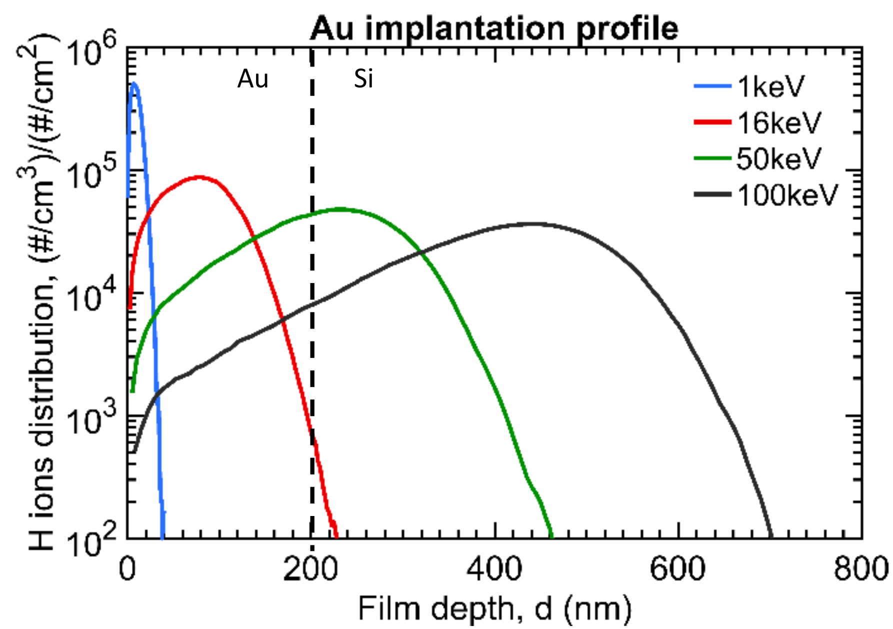
- **Low energy ions (LEI)**: protons and ions having a mean free path lower than the coating thickness;
  - The most or total part of the energy is deposited into the coating;
  - Ions stop mainly into the coating;
  - Potential damage effects in the coating;
  - No or negligible damage effects in the substrate;

- **High energy ions (HEI)**: protons and ions a mean free path much longer than the coating thickness.
  - The most or total part of the energy is deposited into the substrate;
  - Ions stop mainly into the substrate;
  - Potential damage of the substrate (darkening due color centers activation);
  - No or negligible damage effects in the coating;

Examples of LEI and HEI: bare and protected Al mirrors

- LEI and HEI definitions depend on
  - the kind of particle;
  - the materials in the coating;
  - the thickness of the coating;

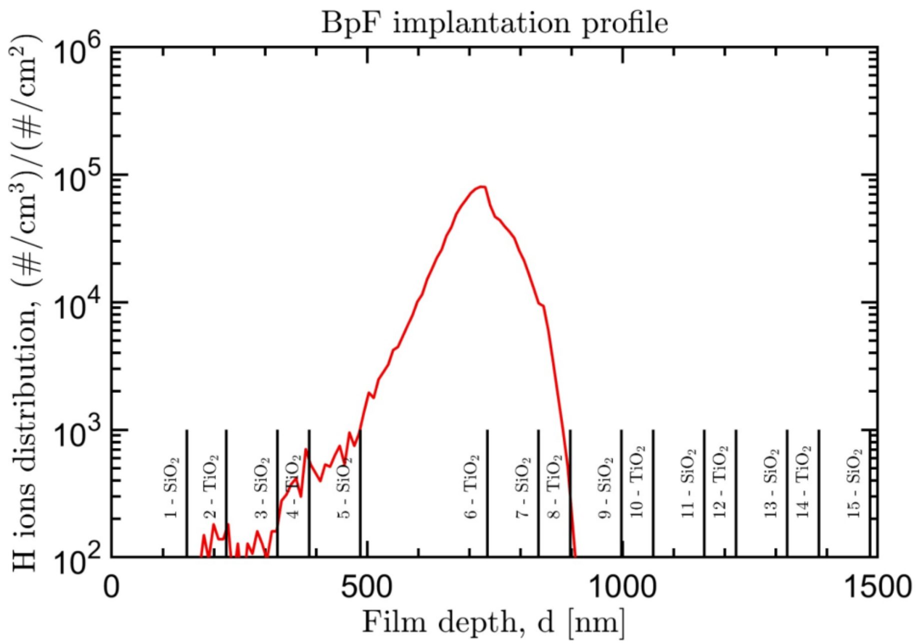




TRIM/SRIM simulations of the implanted protons distribution into bare and protected Al coatigns for different energies.

Examples of LEI and HEI: bare and protected Al mirrors

- LEI and HEI definitions depend on
  - the kind of particle;
  - the materials in the coating;
  - the thickness of the coating;



TRIM/SRIM simulations of the implanted protons distribution into a SiO_2/TiO_2 band pass filter tuned at 590 nm (BpF) for a energy of 100 keV.

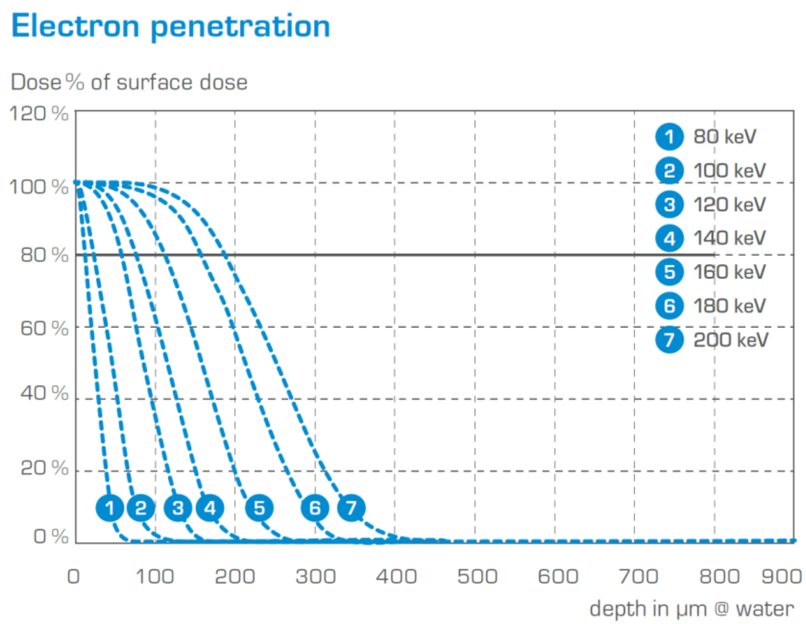
100-200 keV electrons dose deposition

- The typical depth-dose profile as a function of the penetration depth at different energies and normalized for the surface dose is usually given in H_2O. For other materials, the curve can be scaled for the densities:

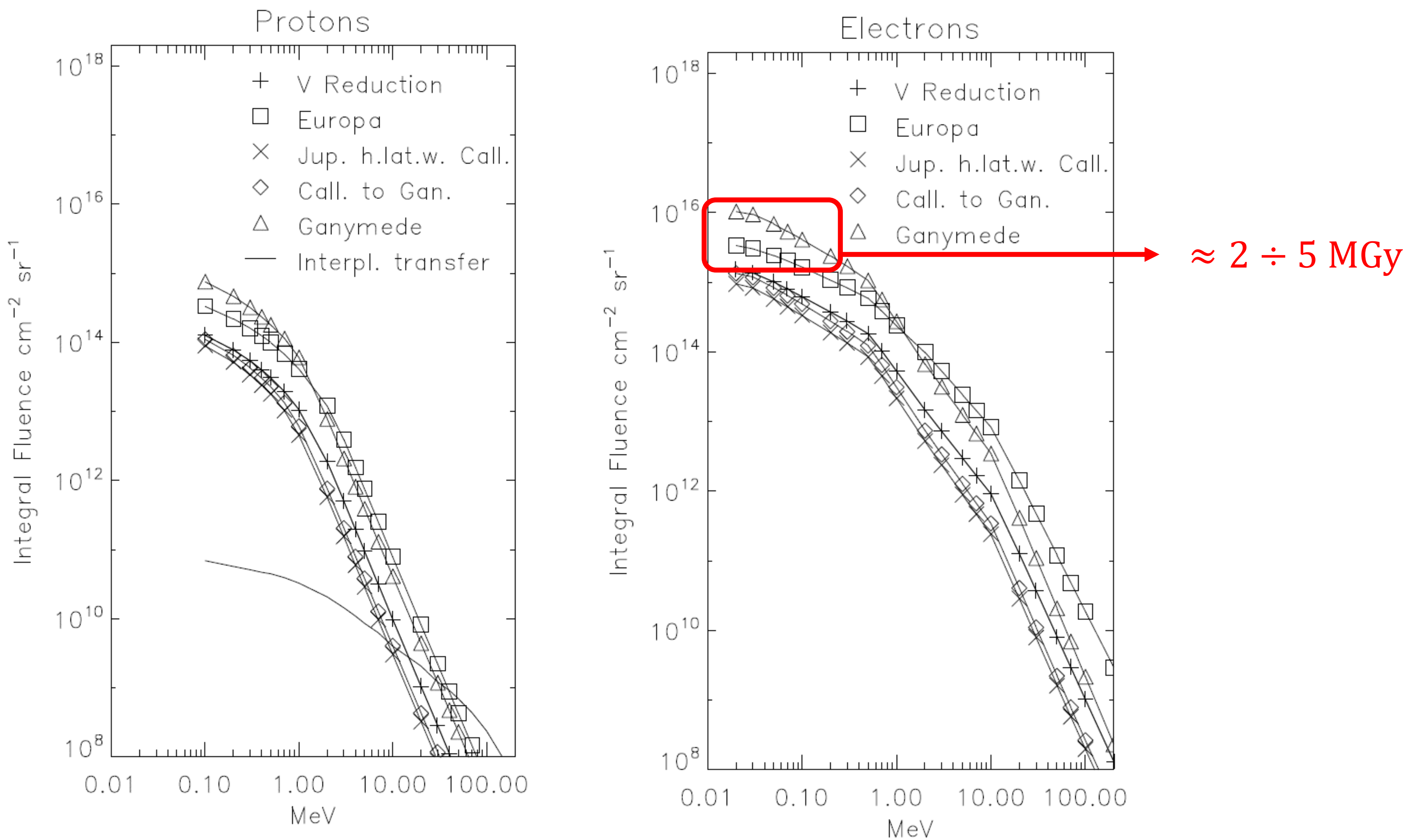
$$D_{\text{mat}} = D_{\text{H}_2\text{O}} \frac{\rho_{\text{H}_2\text{O}}}{\rho_{\text{mat}}}$$

  where ρ_{mat} is the density of the considered material.

- We can hence predict that electrons can pass through each of coating considered within the project and reach the substrate. However, for bulk materials, the damage should be limited the surface.



Protons and electrons fluences



Integrated protons and electrons fluences estimated during the ESA JUICE mission (from ESA JUICE Yellow Book, pag.94)

Samples of the project: simple coatings

#	Sample type	Structure	Parameters	Substrates	Ref	p	He+	e	Tot
Simple coating samples									
Samples dimensions: 2.5 cm² diameter									
1	S1W Au	single layer	240 nm adhesion: Cr	Si wafer	5	29	22	9	65
2	S1G Au	single layer	240 nm adhesion: Cr	Suprasil	5	5	2	9	21
3	S2W Al	single layer	200 nm adhesion: Cr	Si wafer	5	29	22	9	65
4	S2G Al	single layer	200 nm adhesion: Cr	Suprasil	5	7	4	9	25
5	S3GUV SiO_2	single layer	520 nm	Sapphire	5	29	22	9	65
6	S3W SiO_2	single layer	520 nm	Si wafer	5	13	10	9	37
7	S4G TiO_2	single layer	360 nm	Suprasil	5	29	22	9	65
8	S4W TiO_2	single layer	360 nm	Si wafer	5	13	10	9	37
9	S5G ZrO_2	single layer	340 nm	Suprasil	5	27	20	9	61
10	S5W ZrO_2	single layer	340 nm	Si wafer	5	10	7	9	21
13	S8G SiO_2/TiO_2	bi-layer	230/83.4 nm	Suprasil	5	15	13	9	42
14	S8W SiO_2/TiO_2	bi-layer	230/83.4 nm	Si wafer	5	17	14	9	45
15	S9G SiO_2/ZrO_2	bi-layer	230/104.2	Suprasil	5	15	13	9	42
16	S9W SiO_2/ZrO_2	bi-layer	230/104.2	Si wafer	5	12	10	9	36
11	S6W Al/SiO_2	bi-layer	200/80 nm adhesion: Cr	Si wafer	5	15	13	9	42
12	S7W Ag/SiO_2	bi-layer	210/80 nm adhesion: Cr	Si wafer	5	15	13	9	42
17	S10G Au/MgF_2	bi-layer	200/80 nm adhesion: Cr	Suprasil	5	16	13	9	43
18	S10W Au/MgF_2	bi-layer	200/80 nm adhesion: Cr	Si wafer	5	17	14	9	45
21	G			Suprasil	5	18	11	9	38
23	G1			S-FPL51	5	8	5	9	27
24	G2			N-KZFS11	5	8	5	9	27
25	G3			S-FTM16	5	8	5	9	27

Bare metallic coatings (rows 1–4)

Single dielectric layers (rows 5–10)

Dielectric bi-layers (rows 13–15)

Protected mirrors (rows 11, 12, 17, 18)

Substrates (rows 21–24)

Samples of the project: simple coatings

- The coating designs were deliberately kept simple (single or bi-layer metals and oxides) to ensure distinct material effects could be identified and distinguished from that of the substrate.

- The coating were deposited by Leonardo Company, following the standard adopted for space application.

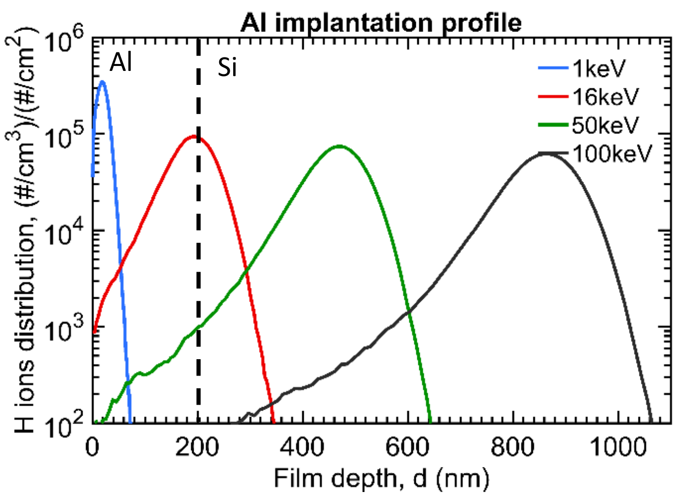
- The simple coatings were designed taking into account the penetration depth profile of protons at 1 keV, 16 keV, 50 keV and 100 keV (simulated with TRIM/SRIM).

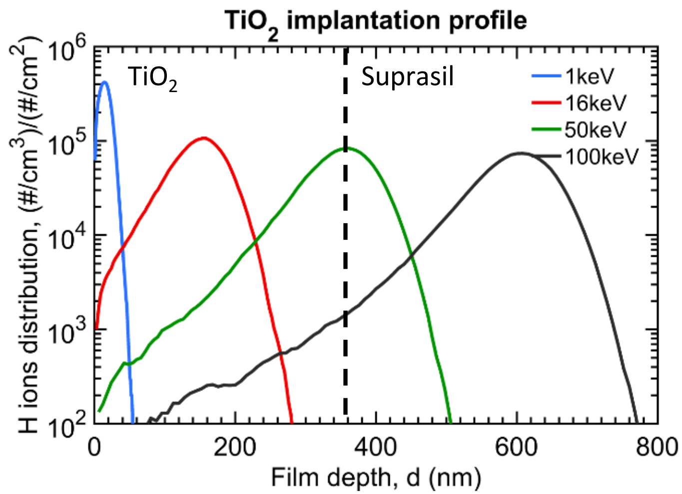
  a. 1 keV protons must implant close to the coating surface and far from interfaces. In case of multilayer, 1 keV protons implantation profile must fall inside the first layer.

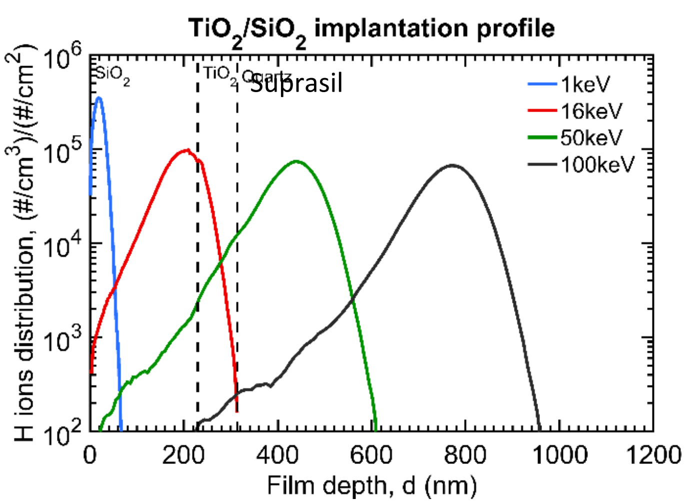
  b. 16 keV or 50 keV protons must have the implantation peak close to the interfaces between the layers or coating-substrate (characteristic energy for that coating). In general, in mirrors the protons at 16 keV mainly implant on the metal spreading the whole layer. In dielectric coatings, 16 keV protons mainly implant and spread into the whole coating.

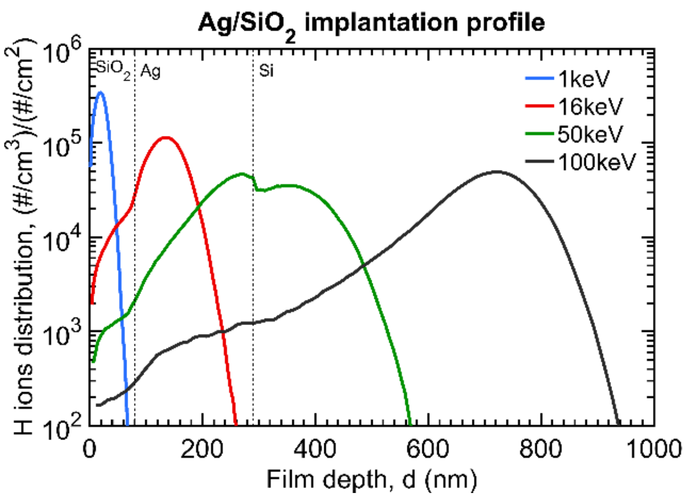
  c. 100 keV protons mainly implants in the substrate.

Simple coatings design example









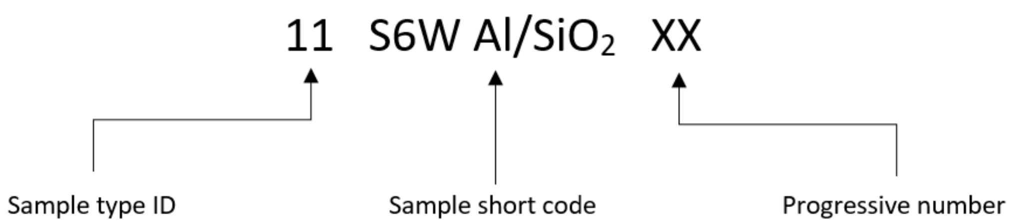
Flight-like coatings

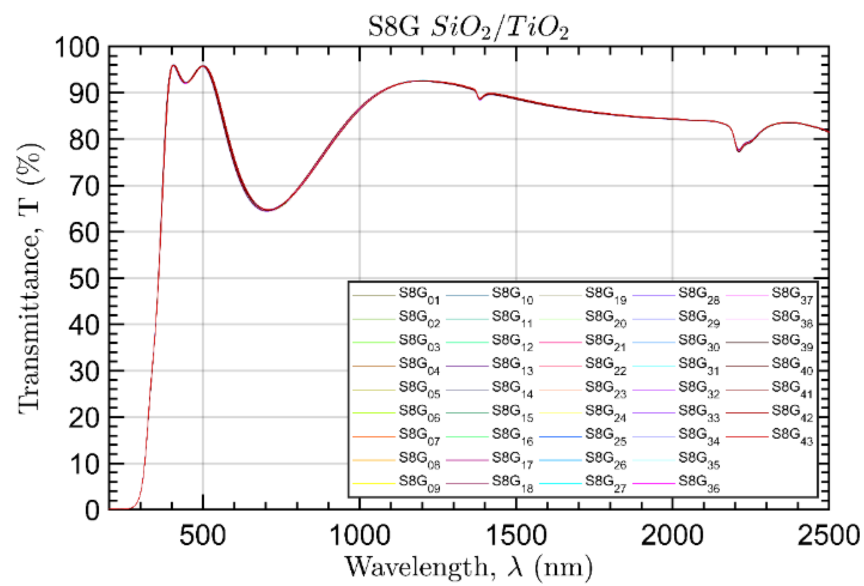
- Two different flight-like coating were considered for the tests.
- The TiO_2/SiO_2 multilayer is an interferential filter tuned at 590 nm composed by three Fabry-Perot cells.
- The second coating is an Al mirror protected with SiO_2.
- Both coatings are fully representative to those that will be employed on JANUS camera that will be onboard of JUICE mission.

	Sample type	Structure	Substrates	p	He+	e^-	ref
F1	C1Filter TiO_2/SiO_2	multilayer	Suprasil	6	6	3	3
F2	C6G Al/SiO_2 Top layer: SiO_2	bi-layer	Suprasil	6	6	3	3

Pre-irradiation characterizations

- All specimens of each sample have been characterized before any irradiation by using a double grating spectrophotometer (Agilent Cary 5000) in normal transmittance or (absolute) reflectance at 7° of incidence in the wavelength range 300-2500 nm.
- In order to be able to repeat the measurements with the same conditions after the irradiation process, samples have been positioned taking note on the orientation.
- The error attributed to the measurements is lower than 1.5%.
- Profilometer measurements and optical performance fitting to verify the real layers thickness (when possible)





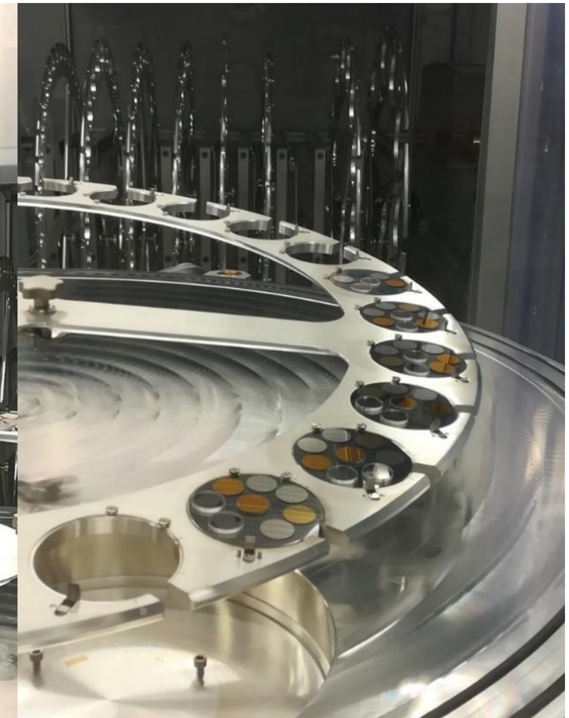
Irradiation plan: example of protons

Energy	Flux	Fluence	Irradiation label	S1W	S1G	S2W	S2G	S3GUV	S3W	S4G	S4W	S5G	S5W	S6W	S7W	S8G	S8W	S9G	S9W	S10G	S10W	S11W	G	GUV	G1	G2	G3	F1	F2
1 keV protons	$2\cdot10^{11}$ #/cm^2/s	10^{15} #/cm^2	P1LDLF	•		•		•		•		•										•	•						
		10^{16} #/cm^2	P1MDLF	•		•	•	•		•		•										•							
	10^{12} #/cm^2/s	10^{15} #/cm^2	P1LDMF	•		•		•		•		•		•	•	•	•	•	•	•	•	•							
		10^{16} #/cm^2	P1MDMF	•		•		•	•	•	•	•	•	•	•		•			•	•	•							
		$5\cdot10^{16}$ #/cm^2	P1HDMF	•		•		•	•	•				•	•	•	•	•	•	•	•	•							
	$2\cdot10^{12}$ #/cm^2/s	10^{15} #/cm^2	P1LDHF	•		•		•		•		•										•	•						
		10^{16} #/cm^2	P1MDHF	•	•	•	•	•		•		•				•	•	•		•	•	•	•						
		$5\cdot10^{16}$ #/cm^2	P1HDHF	•		•		•		•	•	•										•							
16 keV protons	$2\cdot10^{11}$ #/cm^2/s	10^{15} #/cm^2	P16LDLF	•		•		•		•		•										•	•						
		10^{16} #/cm^2	P16MDLF	•		•	•	•		•		•										•							
	10^{12} #/cm^2/s	10^{15} #/cm^2	P16LDMF	•		•		•		•		•		•	•	•	•	•	•	•	•	•							
		10^{16} #/cm^2	P16MDMF	•		•		•	•	•	•	•	•	•	•		•			•	•	•							
		$5\cdot10^{16}$ #/cm^2	P16HDMF	•		•		•	•	•				•	•	•	•	•	•	•	•	•						•	•
	$2\cdot10^{12}$ #/cm^2/s	10^{15} #/cm^2	P16LDHF	•		•		•		•		•										•	•						
		10^{16} #/cm^2	P16MDHF	•	•	•	•	•		•		•				•	•	•		•	•	•	•						
		$5\cdot10^{16}$ #/cm^2	P16HDHF	•		•		•		•	•	•										•							
		10^{17} #/cm^2	P16HHDHF	•		•		•		•	•	•		•	•	•	•	•		•	•	•							
50 keV protons	$2\cdot10^{11}$ #/cm^2/s	10^{14} #/cm^2	P50LDLF	•		•		•		•		•											•	•					
		10^{15} #/cm^2	P50MDLF	•		•		•		•		•											•	•					
	$5\cdot10^{11}$ #/cm^2/s	10^{14} #/cm^2	P50LDMF	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•		
		10^{15} #/cm^2	P50MDMF	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•		
		10^{16} #/cm^2	P50HDMF	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•		
	$2\cdot10^{12}$ #/cm^2/s	10^{15} #/cm^2	P50MDHF	•		•		•		•		•											•	•					
		10^{16} #/cm^2	P50HDHF	•		•		•		•		•											•	•					
100 keV protons	10^{11} #/cm^2/s	10^{13} #/cm^2	P100LDLF	•		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
		10^{14} #/cm^2	P100MDLF	•		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
		10^{15} #/cm^2	P100HDLF	•		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
1 MeV protons	10^{11} #/cm^2/s	10^{14} #/cm^2	P1000HDLF	•		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
10 MeV protons	10^{10} #/cm^2/s	10^{12} #/cm^2	P10000HDLF	•		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		

- Fluences determined considering the JUICE environment or a mission close-solar mission environment (e.g. Solar Orbiter).
- Integration on a semi-sphere along the total mission lifetime (15 years).
- For keV experiments, at least 3 different fluences: the nominal one, one lower and one higher.
- For some keV experiments, different fluxes selected to be reasonable with the facility occupations (some irradiation sessions took 15 h).
- For MeV experiments were tested only the nominal fluence at one flux.

Handling and ions irradiations procedure

- The protons and He ion irradiations have been performed at Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Institute of Ion Beam Physics and Materials Research Ion Beam Center.
- Glasses irradiated at 10 MeV have been activated by irradiation and therefore had been safely stored in Dresden for two months before re-measuring.



Handling and electron irradiations procedure

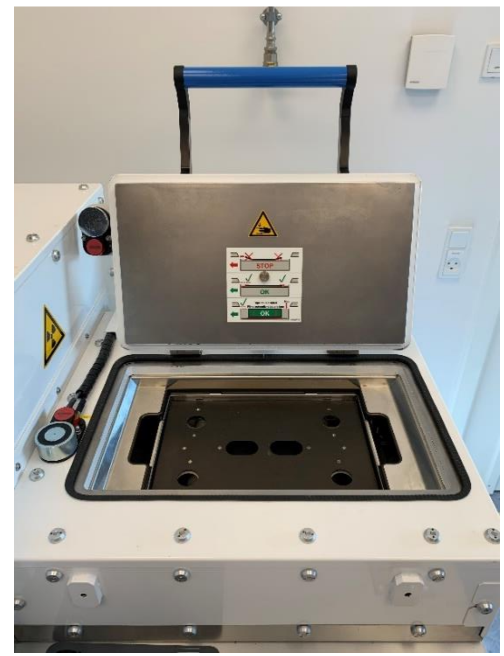
- 100 keV electron irradiations were performed by using the EBLab 200 facility at the Risø High Dose Reference Laboratory (HDLR) at DTU, Denmark.

- In order to deliver the total dose required, individual sessions of 100 kGy each are performed. This value is based on the initial calibration of the EbLab accelerator, according to which the correct value for the input current is:

$$I[\mathrm{mA}] = v\left[\frac{\mathrm{m}}{\mathrm{min}}\right] \cdot (D\ [\mathrm{kGy}] - q)/m$$

  where v is the speed of the transport carrier, and q and m are the calibrated parameters.

- The experiment is performed in air.



Handling and electron irradiations procedure

- For the 10 MeV irradiations, samples were mounted with tape on a sheet of high-density polystyrene together with 2 dosimeters (ID 1022 and 1023) placed in the center.

- The final delivered dose was estimated to be 45.2 Gy (the target was 35 Gy).

Post-irradiation characterizations

- A huge amount of data have been produced.

- A first estimation of the optical performance degradation is obtained by the computation of the *root mean square error* (RMSE)

$$RMSE = \sqrt{\frac{1}{\lambda_f - \lambda_i} \sum_{j=\lambda_i}^{\lambda_f} [\mathrm{T}_0(j) - \mathrm{T}_{irr}(j)]^2}$$

where reference (T_0) and irradiated (T_{irr}) curves (transmittance or reflectance) are compared in the wavelength region between $\lambda_i = 300$ nm and $\lambda_f = 1500$ nm. The samples which have not been affected by the different irradiation sessions are reported in green (RMSE<1.35). Case in which high degradation have been observed is in red (RMSE>1.35).

Irradiation with protons and He ions

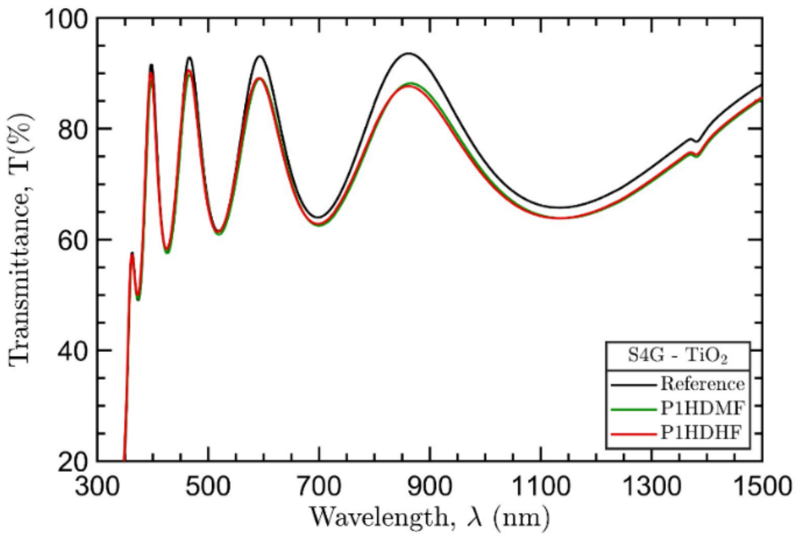
Partiale and Energy	Irradiation session code	S4G	S4W	S5G	S5W
Protons 1 keV	P1LDLF	0,14	-	0,05	-
	P1MDLF	1,23	-	0,38	-
	P1LDMF	0,16	-	0,07	-
	P1MDMF	0,98	0,56	0,31	0,42
	P1HDMF	2,75	-	-	-
	P1LDHF	0,16	-	0,05	-
	P1MDHF	0,84	-	0,27	-
	P1HDHF	2,88	2,75	0,13	-
Protons 16 keV	P16LDLF	0,4	-	0,17	-
	P16MDLF	3,81	-	1,65	-
	P16LDMF	0,36	-	0,22	-
	P16MDMF	3,68	3,18	1,68	1,52
	P16HDMF	16,9	-	-	-
	P16LDHF	0,34	-	0,06	-
	P16MDHF	3,43	-	1,41	-
	P16HDHF	16,5	5,31	6,02	-
	P16HHDHF	27,8	8,44	5,83	-
Protons 50 keV	P50LDLF	0,14	-	0,2	-
	P50MDLF	0,14	-	0,08	-
	P50LDMF	0,19	0,17	0,05	0,14
	P50MDMF	0,14	0,12	0,1	0,2
	P50HDMF	0,66	0,32	0,32	0,97
	P50MDHF	0,1	-	0,21	-
	P50HDHF	0,69	-	0,23	-
Protons 100 keV	P100LDLF	0,09	0,17	0,09	0,13
	P100MDLF	0,12	0,3	0,08	0,21
	P100HDLF	0,24	0,37	0,12	0,31
Protons 1 MeV	P1000HDLF	0,11	0,31	0,13	0,16
Protons 10 MeV	P10000HDLF	0,11	0,23	0,15	0,1

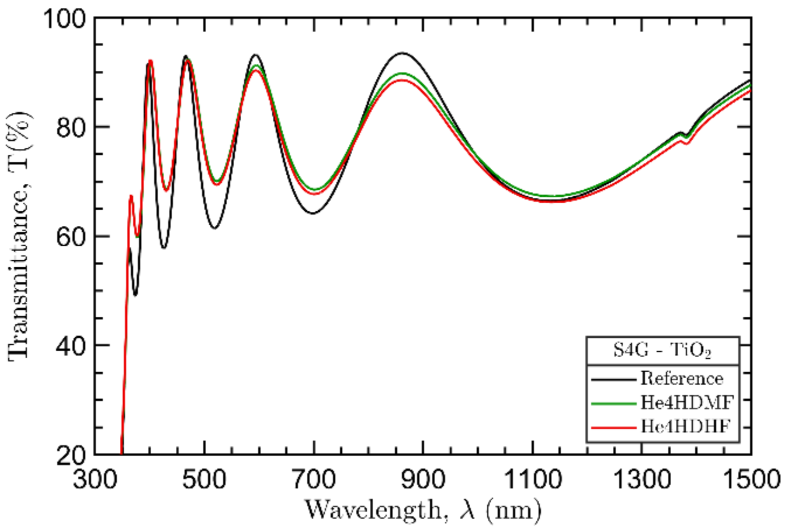
Some samples shows a degradation of the optical performance after the irradiation session.
In this case additional investigation techniques are carried on:

- Integrating Sphere
- Atomic Force Microscope
- Optical Microscope

Samples reported in green do not show any damage associated with the irradiation session.
In this case there is **no need for further investigation.**

Example 1: TiO_2 layer (360 nm) on Suprasil

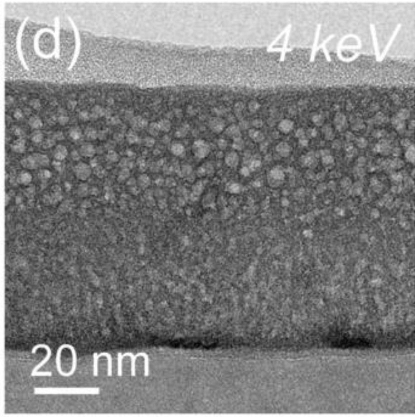




1 keV protons (top) and 4 keV He ions (bottom) irradiation with fluence $5 \cdot 10^{16}$ #/cm^2 on TiO_2:

- Particles implant only in the topmost part of the coating;
- Attenuation without shift of interferential fringes;
- No flux dependence;
- Protons damage the whole observed spectral range; He ions mainly UV-VIS range.

Effect of scattering due to bubbles formation



From:
Maria G Pelizzo, Alain J Corso, Giovanni Santi, et al, Scientific Reports 11(1), 1-12 (2021)

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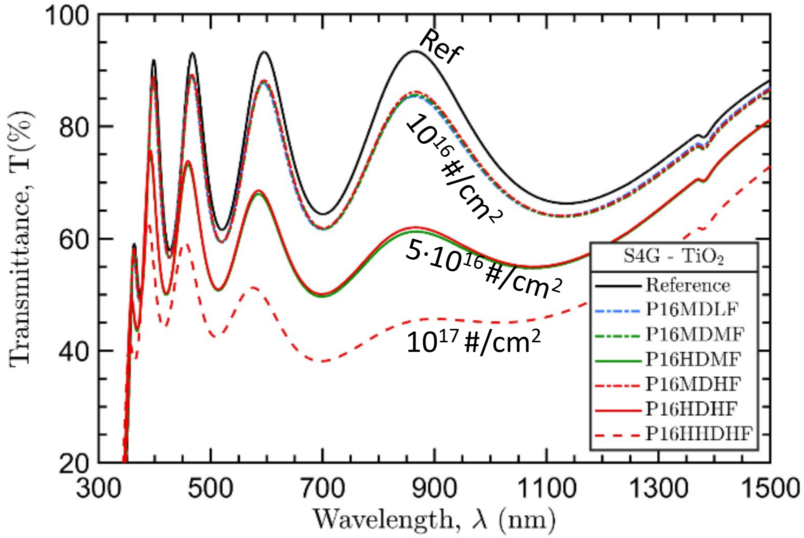
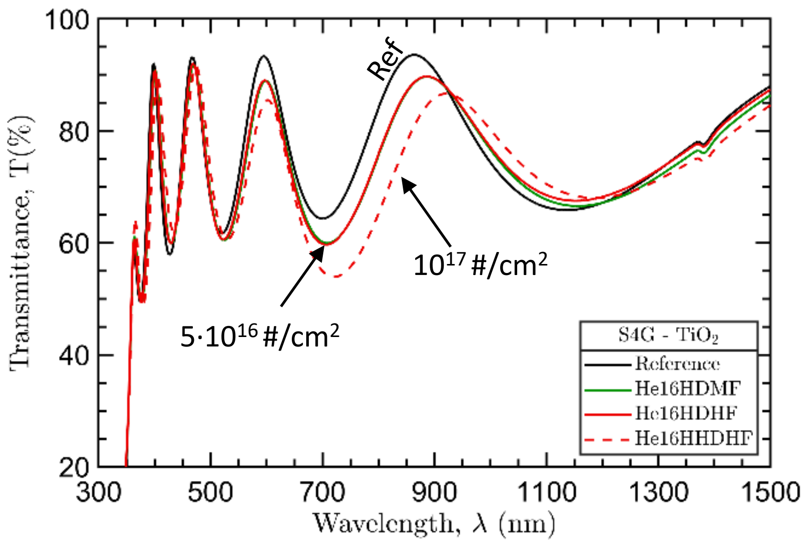




16 keV protons (top) and He ions (bottom) irradiations on TiO_2:

- Attenuation and shift of interferential fringes;
- Particles implant in the whole coating;
- No or negligible flux dependence;
- Damage increase with the fluence;
- Protons damage the whole observed spectral range; He ions mainly UV-VIS range.

Possible modification due to

- n and k modification or thickness expansion.
- Bubbles formation inside the coating.

Example 2: SiO_2/TiO_2 bi-layer (230/83 nm) on Suprasil

Partiale and Energy	Irradiation session code	S4G
Protons 1 keV	P1LDLF	0,14
	P1MDLF	1,23
	P1LDMF	0,16
	P1MDMF	0,98
	P1HDMF	2,75
	P1LDHF	0,16
	P1MDHF	0,84
	P1HDHF	2,88
Protons 16 keV	P16LDLF	0,4
	P16MDLF	3,81
	P16LDMF	0,36
	P16MDMF	3,68
	P16HDMF	16,9
	P16LDHF	0,34
	P16MDHF	3,43
	P16HDHF	16,5
	P16HHDHF	27,8
Protons 50 keV	P50LDLF	0,14
	P50MDLF	0,14
	P50LDMF	0,19
	P50MDMF	0,14
	P50HDMF	0,66
	P50MDHF	0,1
	P50HDHF	0,69
Protons 100 keV	P100LDLF	0,09
	P100MDLF	0,12
	P100HDLF	0,24
Protons 1 MeV	P1000HDLF	0,11
Protons 10 MeV	P10000HDLF	0,11

- Damage for 1 keV protons is removed;
- Protons fully implant on the SiO_2 layer;
- Effect of SiO_2 layer that is highly rad-hard;

- Damage for 16 keV protons is reduced;
- Protons implantation peak is on the SiO_2/TiO_2 interface;
- Effect of SiO_2 layer mitigates the TiO_2 damage;

- HEI no damage

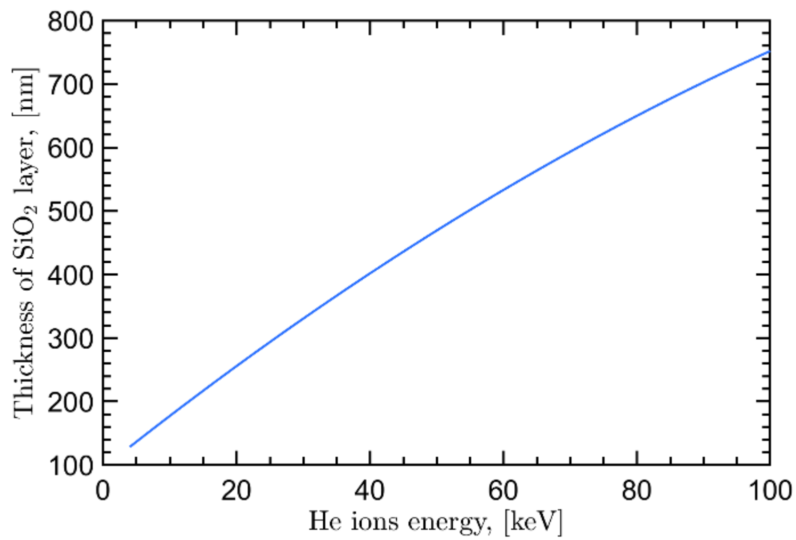
Partiale and Energy	Irradiation session code	S8G
Protons 1 keV	P1LDLF	-
	P1MDLF	-
	P1LDMF	0,18
	P1MDMF	-
	P1HDMF	1,18
	P1LDHF	-
	P1MDHF	0,5
	P1HDHF	-
Protons 16 keV	P16LDLF	-
	P16MDLF	-
	P16LDMF	0,53
	P16MDMF	-
	P16HDMF	10,8
	P16LDHF	-
	P16MDHF	3,04
	P16HDHF	-
	P16HHDHF	15,4
Protons 50 keV	P50LDLF	-
	P50MDLF	-
	P50LDMF	0,16
	P50MDMF	0,21
	P50HDMF	0,58
	P50MDHF	-
	P50HDHF	-
Protons 100 keV	P100LDLF	0,05
	P100MDLF	0,13
	P100HDLF	0,25
Protons 1 MeV	P1000HDLF	0,18
Protons 10 MeV	P10000HDLF	0,16

Example 2: SiO_2/TiO_2 bi-layer (230/83 nm) on Suprasil

Partiale and energy	Irradiation session code	S4G
He ions 4 keV	He4LDLF	0,14
	He4MDLF	0,86
	He4LDMF	0,22
	He4MDMF	0,85
	He4HDMF	3,65
	He4LDHF	0,16
	He4MDHF	0,83
	He4HDHF	3,46
He ions 16 keV	He16LDLF	0,14
	He16MDLF	0,81
	He16LDMF	0,13
	He16MDMF	0,82
	He16HDMF	3,37
	He16LDHF	0,16
	He16MDHF	0,88
	He16HDHF	3,51
	He16HHDHF	8,1
He ions 100 keV	He100LDLF	0,06
	He100MDLF	0,28
	He100HDLF	0,39
	He100HDMF	0,1
	He100HHDMF	0,71
	He100HHHDMF	-

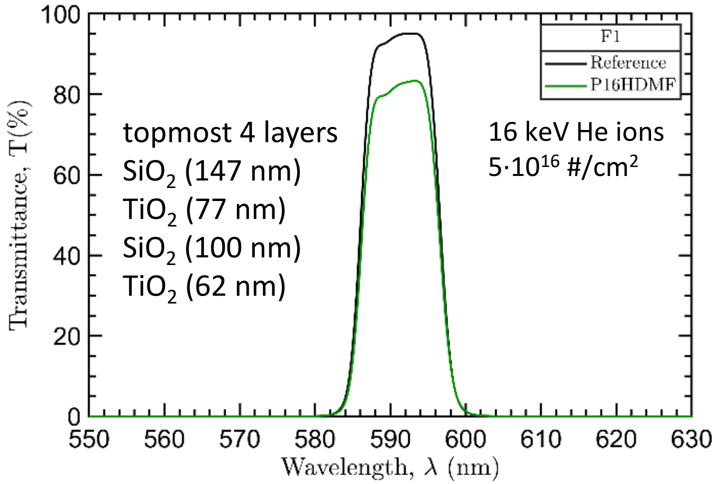
SiO_2 layer prevents the damage

Partiale and energy	Irradiation session code	S8G
He ions 4 keV	He4LDLF	-
	He4MDLF	-
	He4LDMF	0,56
	He4MDMF	-
	He4HDMF	0,65
	He4LDHF	-
	He4MDHF	0,4
	He4HDHF	-
He ions 16 keV	He16LDLF	-
	He16MDLF	-
	He16LDMF	0,48
	He16MDMF	-
	He16HDMF	0,58
	He16LDHF	-
	He16MDHF	0,79
	He16HDHF	-
	He16HHDHF	0,56
He ions 100 keV	He100LDLF	0,15
	He100MDLF	0,2
	He100HDLF	0,41
	He100HDMF	0,39
	He100HHDMF	0,9
	He100HHHDMF	1,18



SiO_2 thickness required for stopping He ions at different energies. Data obtained from TRIM simulations.

Example 3: Flight-like SiO_2/TiO_2 multilayer interferential filter



Protons

Partiale and energy	Irradiation session code	F1
Protons 16 keV	P16LDLF	-
	P16MDLF	-
	P16LDMF	-
	P16MDMF	-
	P16HDMF	8,64
	P16LDHF	-
	P16MDHF	-
	P16HDHF	-
	P16HHDHF	-
Protons 100 keV	P100LDLF	-
	P100MDLF	-
	P100HDLF	1,27

He ions

Partiale and energy	Irradiation session code	F1
He ions 16 keV	He16LDLF	-
	He16MDLF	-
	He16LDMF	-
	He16MDMF	-
	He16HDMF	-
	He16LDHF	-
	He16MDHF	-
	He16HDHF	0,79
	He16HHDHF	-
He ions 100 keV	He100LDLF	-
	He100MDLF	-
	He100HDLF	-
	He100HDMF	1,62
	He100HHDMF	-
	He100HHHDMF	-

Conclusions on dielectric coatings:

- TiO_2 and ZrO_2 materials are sensitive to LEI irradiations;
- SiO_2 is rad hard for LEI irradiations with fluences up to 10^{17} #/cm^2
- SiO_2 topmost layer can be used to prevent or mitigate the LEI effects;

Final rules of thumb for dielectric coatings:

- SiO_2 topmost layer thickness > 150 nm: protection for He ions up to 16 keV;
- SiO_2 topmost layer thickness > 300 nm: protection for protons up to 16 keV;

Example 4: bare metals

Protons

Partiale and Energy	Irradiation session code	S1W	S1G	S2W	S2G
Protons 1 keV	P1LDLF	0,16	-	0,35	-
	P1MDLF	0,27	-	4,91	0,33
	P1LDMF	0,15	-	0,37	-
	P1MDMF	0,17	-	3,64	-
	P1HDMF	0,17	-	26,1	-
	P1LDHF	0,27	-	0,25	-
	P1MDHF	0,14	0,09	1,91	0,12
	P1HDHF	0,21	-	14,4	-
Protons 16 keV	P16LDLF	0,13	-	0,24	-
	P16MDLF	0,21	-	3,16	0,25
	P16LDMF	0,19	-	0,2	-
	P16MDMF	0,08	-	2,41	-
	P16HDMF	0,93	-	35,8	-
	P16LDHF	0,16	-	0,21	-
	P16MDHF	0,06	0,11	2,72	0,21
	P16HDHF	1,08	-	32,7	-
	P16HHDHF	1,82	-	27,8	-
Protons 50 keV	P50LDLF	0,07	-	0,11	-
	P50MDLF	0,11	-	0,32	-
	P50LDMF	0,09	0,03	0,3	0,1
	P50MDMF	0,12	0,06	0,3	0,12
	P50HDMF	0,31	0,14	0,31	0,19
	P50MDHF	0,08	-	0,25	-
	P50HDHF	0,19	-	0,19	-
Protons 100 keV	P100LDLF	0,1	-	0,28	-
	P100MDLF	0,09	-	0,25	-
	P100HDLF	0,12	-	0,27	-
Protons 1 MeV	P1000HDLF	0,1	-	0,27	-
Protons 10 MeV	P10000HDLF	0,15	-	0,18	-

Bare Gold (S1W, S1G) — Bare Aluminum (S2W, S2G)

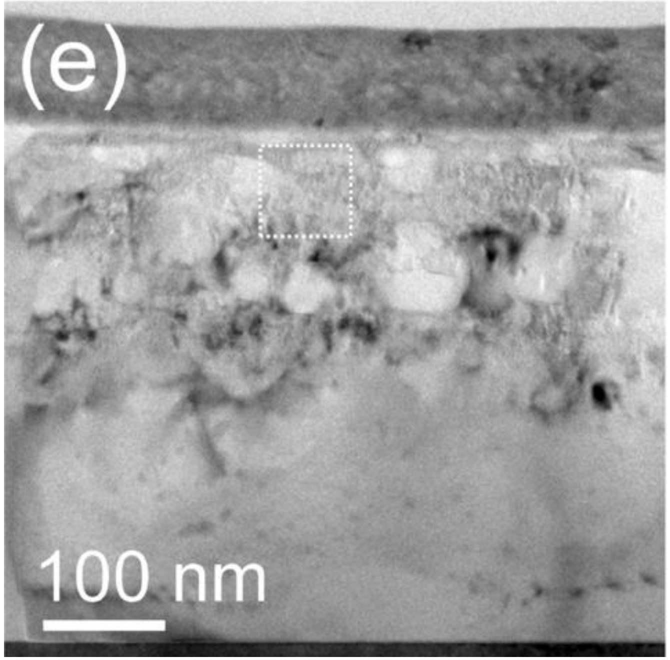
He ions

Partiale and energy	Irradiation session code	S1W	S1G	S2W	S2G
He ions 4 keV	He4LDLF	0,21	-	0,25	-
	He4MDLF	0,72	-	0,49	0,36
	He4LDMF	-	-	-	-
	He4MDMF	0,71	-	0,48	-
	He4HDMF	2,26	-	1,84	-
	He4LDHF	0,19	-	0,25	-
	He4MDHF	0,79	0,84	0,58	0,47
	He4HDHF	2,42	-	1,95	-
He ions 16 keV	He16LDLF	0,25	-	0,24	-
	He16MDLF	0,56	-	0,5	0,43
	He16LDMF	0,21	-	0,19	-
	He16MDMF	0,46	-	0,34	-
	He16HDMF	1,03	-	2,02	-
	He16LDHF	0,24	-	0,23	-
	He16MDHF	0,56	0,68	0,26	0,18
	He16HDHF	1,1	-	1,84	-
	He16HHDHF	1,52	-	5,68	-
He ions 100 keV	He100LDLF	0,07	-	0,2	-
	He100MDLF	0,07	-	0,25	-
	He100HDLF	0,07	-	0,23	-
	He100HDMF	0,1	-	0,3	-
	He100HHDMF	0,18	-	0,2	-
	He100HHHDMF	-	-	-	-

Bare Gold (S1W, S1G) — Bare Aluminum (S2W, S2G)

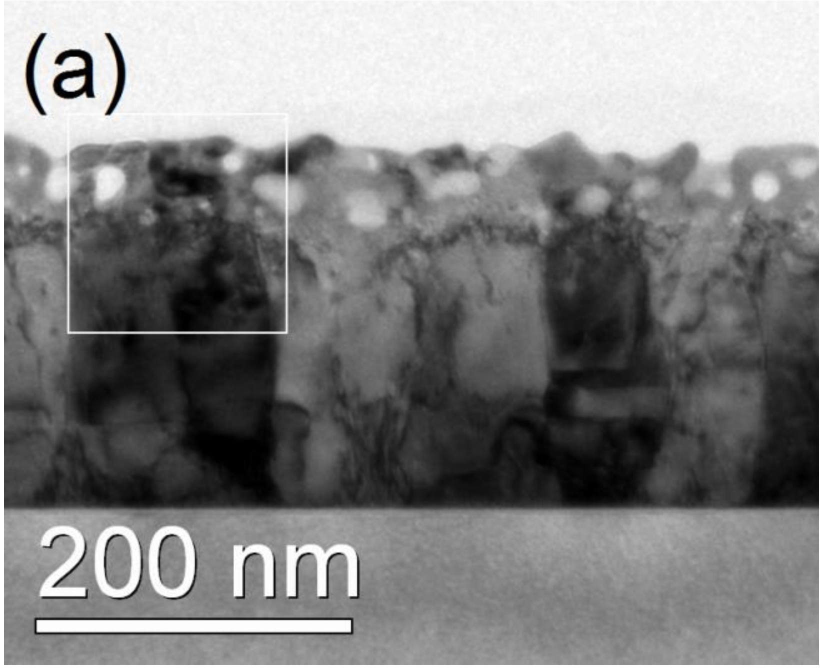
Example 4: bare metals

Aluminum



From:
Maria G Pelizzo, Alain J Corso, Giovanni Santi, et al, Scientific Reports 11(1), 1-12 (2021)

Gold



From:
Maria G Pelizzo, Alain J Corso et al, ACS applied materials & interfaces 10(40), 34781-34791 (2018)

Example 4: bare metals

- Bare gold shows:
  - High stability to low energy protons (at least up to $5 \cdot 10^{16}$ #/cm^2).
  - Good to low energy He ions (at least up to 10^{16} #/cm^2).
- Bare Aluminum shows:
  - Highly sensible to low energy protons (even at 10^{16} #/cm^2).
  - Stability comparable to gold for low energy He ions (at least up to 10^{16} #/cm^2).
- Flux effects.
- Substrate effects.

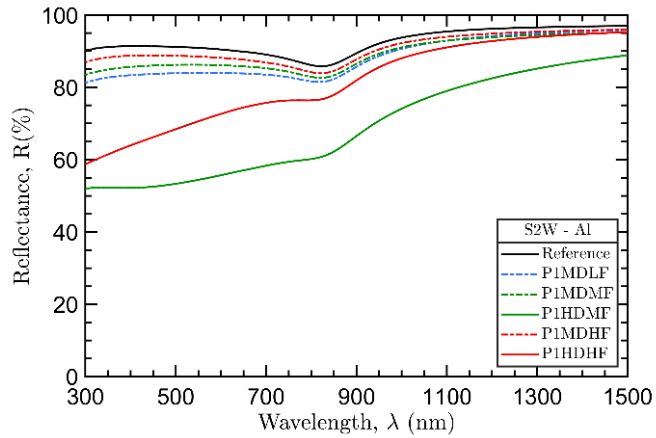
Protons

Bare Al on Si wafer (S2W) — Bare Al on Suprasil (S2G)

Partiale and Energy	Irradiation session code	S1W	S1G	S2W	S2G
Protons 1 keV	P1LDLF	0,16	-	0,35	[illegible]
	P1MDLF	0,27	-	4,91	0,33
	P1LDMF	0,15	-	0,37	[illegible]
	P1MDMF	0,17	-	3,64	-
	P1HDMF	0,17	-	26,1	-
	P1LDHF	0,27	-	0,25	-
	P1MDHF	0,14	0,09	1,91	0,12
	P1HDHF	0,21	-	14,4	-
Protons 16 keV	P16LDLF	0,13	-	0,24	-
	P16MDLF	0,21	-	3,16	0,25
	P16LDMF	0,19	-	0,2	-
	P16MDMF	0,08	-	2,41	-
	P16HDMF	0,93	-	35,8	-
	P16LDHF	0,16	-	0,21	-
	P16MDHF	0,06	0,11	2,72	0,21
	P16HDHF	1,08	-	32,7	-
	P16HHDHF	1,82	-	27,8	-

Substrate effect

Flux effect



Example 5: protected mirrors

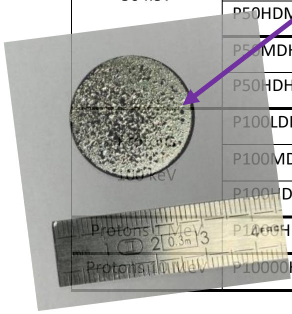
Partiale and Energy	Irradiation session code	S6W	S7W	S10G	S10W
Protons 1 keV	P1LDLF	-	-	-	-
	P1MDLF	-	-	-	-
	P1LDMF	0,06	0,22	0,46	0,46
	P1MDMF	0,3	1,13	0,53	[illegible]
	P1HDMF	0,78	5,35	0,84	[illegible]
	P1LDHF	-	-	-	-
	P1MDHF	-	-	0,47	0,35
	P1HDHF	-	-	-	
Protons 16 keV	P16LDLF	-	-	-	-
	P16MDLF	-	-		-
	P16LDMF	0,15	0,18	0,54	0,42
	P16MDMF	2,13	0,7	2,07	0,36
	P16HDMF	12,2	2,82	8,21	3,35
	P16LDHF	-	-	-	-
	P16MDHF	-	-	2,04	0,71
	P16HDHF	-	-	-	-
	P16HHDHF	58,8	Destroyed	13	12,3
Protons 50 keV	P50LDLF	-	-	-	-
	P50MDLF				
	P50LDMF	0,11	0,16	0,54	0,36
	P50MDMF	0,18	0,2	0,75	0,47
	P50HDMF	0,6	0,32	0,72	0,62
	P50MDHF	-	-	-	-
	P50HDHF	-	-	-	-
Protons 100 keV	P100LDLF	0,2	[illegible]	0,46	0,26
	P100MDLF	0,07	0,28	0,7	0,32
	P100HDLF	0,18	0,13	0,64	0,56
Protons 1 MeV	P1[illegible]HDLF	0,36	0,14	0,48	0,4
Protons 10 MeV	P10000HDLF	0,32	0,13	0,21	0,3

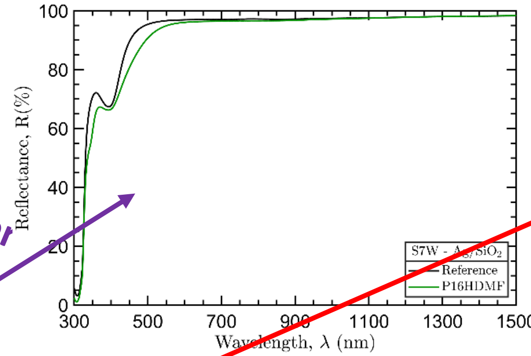
SiO$_2$ layer protects Al from 1 keV protons

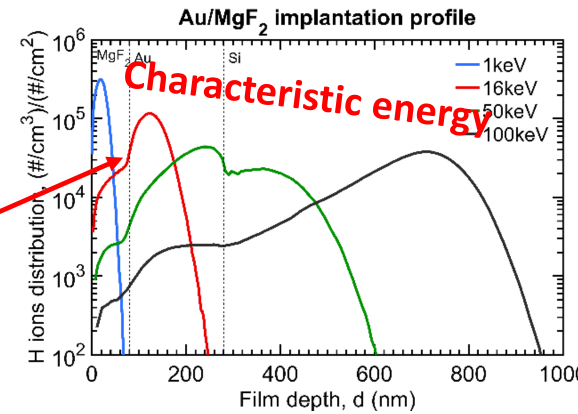
SiO$_2$ protected silver mirrors are critical

SiO$_2$ layer too thin for mitigating 16 keV protons effects

HEI: no damage







Conclusions on protected mirrors coatings:

- Reactive metals are very sensitive to low energy particles (Al, Ag).
- Coatings with metals are prone to have flux or substrate effects in accelerated ground tests.
- SiO$_2$ or MgF$_2$ top-layers help to reduce low energy particles effects.
- Pay attention to characteristic energies of the protected mirrors.

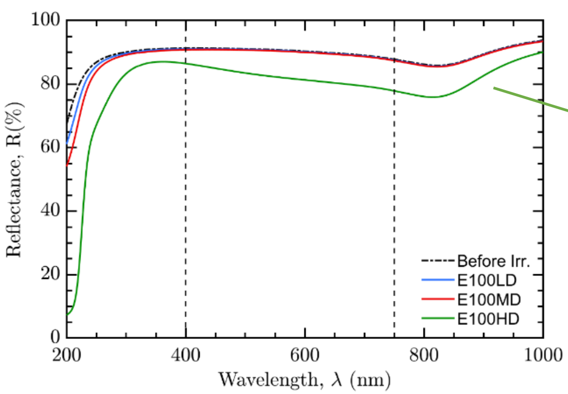
Final rules of thumb for coatings with metals:

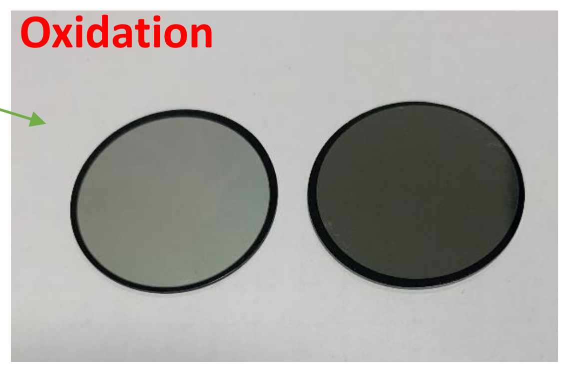
- Tests the characteristic energy of the coatings;
- With insulating substrate, the coating should be grounded;
- Use low flux in ground experiment (suggested: $2\cdot10^{11}$ #/cm^2/s) or a local thermal control.

Electron irradiations - Summary

		S4G	S4W	S5G	S5W	S8G	S8W	S9G	S9W
Electrons 100 keV	E100LD	0,13	0,23	0,13	0,25	0,12	0,27	0,20	0,40
	E100MD	0,17	0,23	0,17	0,19	0,27	0,36	0,17	0,32
	E100HD	0,18	0,30	0,12	0,28	0,33	0,37	0,31	0,44
Electrons 10 MeV	E10000L D	0,33	0,21	0,13	0,48	0,17	0,48	0,28	0,82

		S1W	S1G	S2W	S2G	S6W	S7W	S10G	S10W
Electrons 100 keV	E100LD	0,15	0,23	0,24	0,14	0,19	0,18	0,60	0,88
	E100MD	0,15	0,18	0,39	0,21	0,18	0,23	1,60	1,67
	E100HD	1,43	0,14	7,76	6,80	0,22	0,21	7,42	11,35
Electrons 10 MeV	E10000L D	0,21	0,09	0,19	0,13	0,11	0,12	0,90	0,62





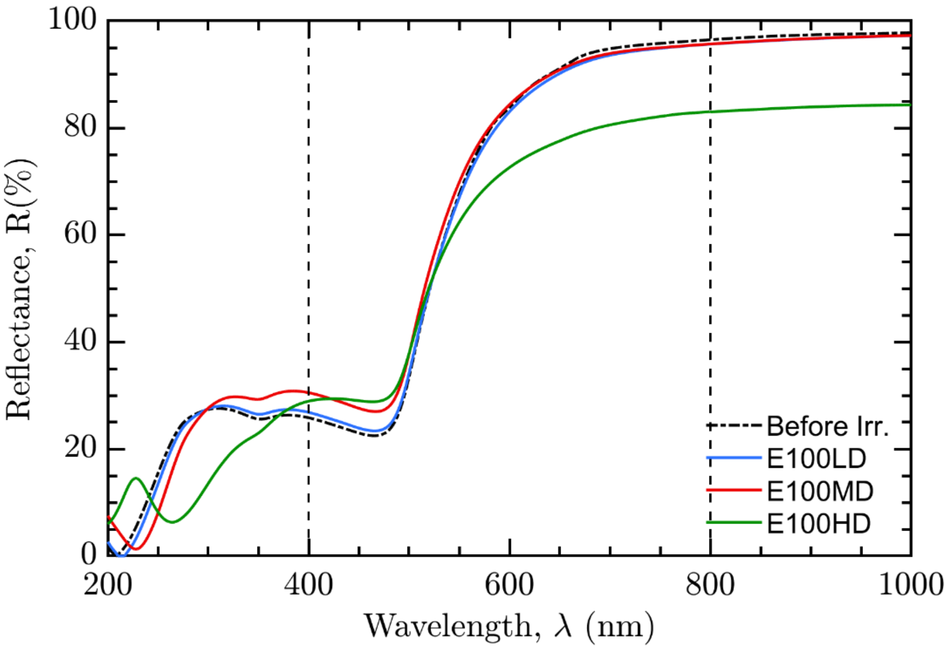
- Tested doses @100 keV:
  - LD: 500 kGy
  - MD: 5 MGy
  - HD: 25 MGy
- Tested dose @10 MeV:
  - LD: 45.2 Gy

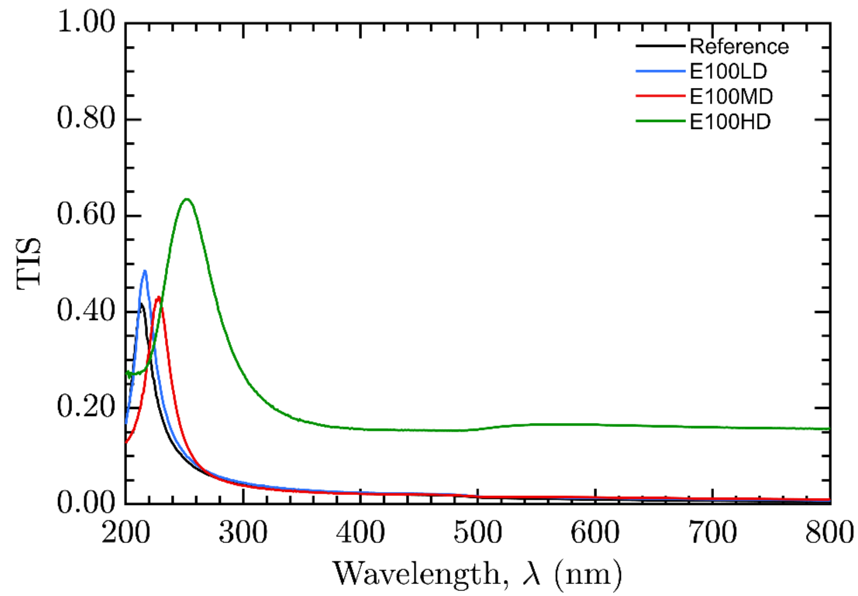
- **Dielectric coatings** are stable to 100 keV electron irradiation up to 25 MGy;

- Some **metallic coatings** show degradation which increases when the Dose is increased from 5 MGy up to 25 MGy.

- **All coatings** are stable to 10 MeV electrons irradiation with 45.2 Gy

Electrons Irradiation on Au/MgF2



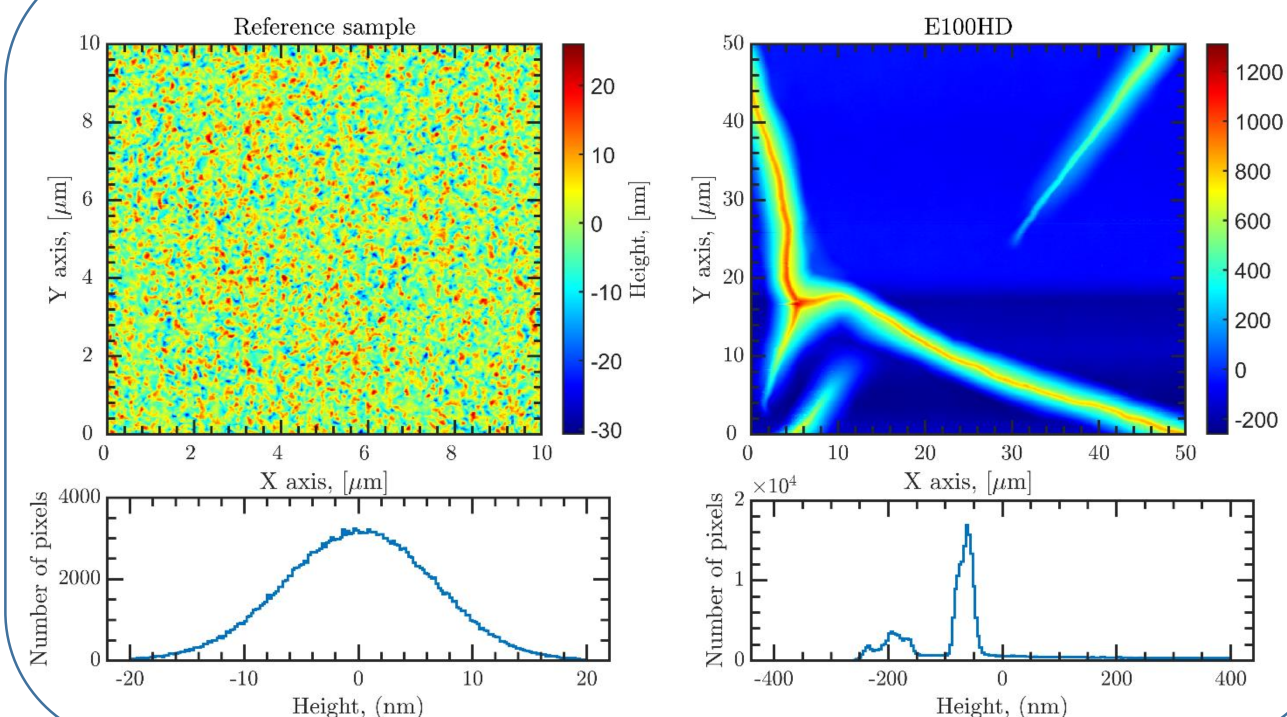


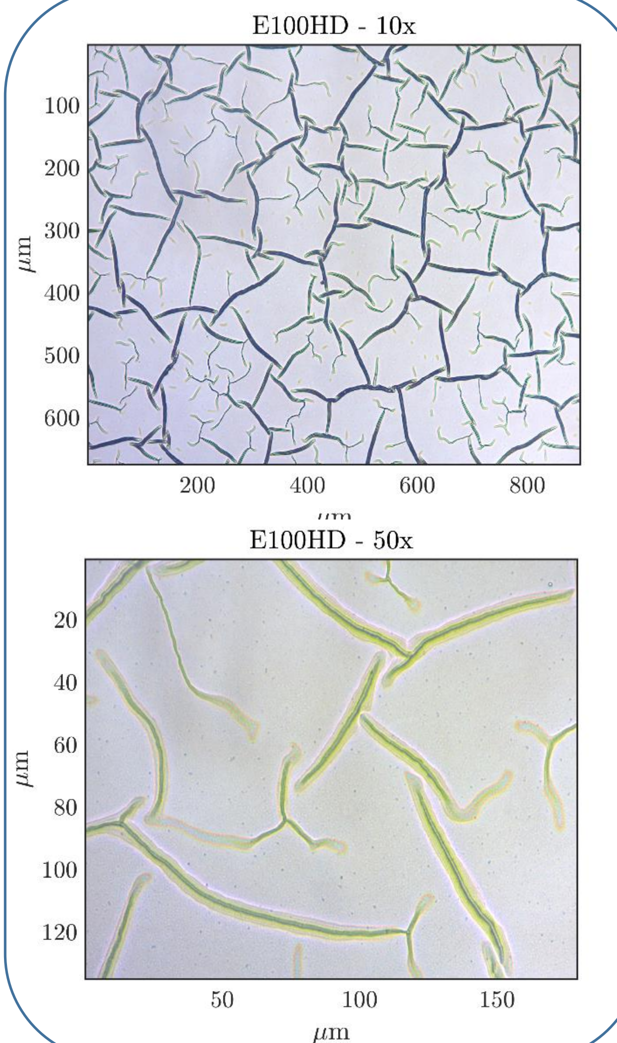
$$RMSE = \sqrt{\frac{1}{\lambda_f - \lambda_i}\sum_{j=\lambda_i}^{\lambda_f}[ref(j) - irr(j)]^2}$$

		UV	VIS	NIR
Electrons 100 KeV	E100LD	1.21	0.95	0.38
	E100MD	3.27	1.89	0.43
	E100HD	10.22	10.91	13.41

Electrons Irradiation on Au/MgF2

		S1W	S1G	S2W	S2G	S6W	S7W	S10G	S10W
Electrons 100 keV	E100LD	0,15	0,23	0,24	0,14	0,19	0,18	0,60	0,88
	E100MD	0,15	0,18	0,39	0,21	0,18	0,23	1,60	1,67
	E100HD	1,43	0,14	7,76	6,80	0,22	0,21	7,42	11,35
Electrons 10 MeV	E10000LD	0,21	0,09	0,19	0,13	0,11	0,12	0,90	0,62





Outcomes and conclusions: guard threshold fluences

Sample typology	Spectral range	1 keV protons	16 keV protons	50 keV protons	100 keV protons	1 MeV protons	10 MeV protons
Au single layer	UV	$5 \cdot 10^{16}$ #/cm^2	$5 \cdot 10^{16}$ #/cm^2				
	VIS						
	NIR		10^{17} #/cm^2				
Al single layer	UV	10^{15} #/cm^2	10^{15} #/cm^2				
	VIS						
	NIR						
TiO_2 single layer	UV	10^{16} #/cm^2	10^{15} #/cm^2				
	VIS						
	NIR						
ZrO_2 single layer	UV	$5 \cdot 10^{16}$ #/cm^2	10^{15} #/cm^2				
	VIS						
	NIR		10^{17} #/cm^2				
SiO_2/TiO_2 multilayer (*)	UV	$5 \cdot 10^{16}$ #/cm^2	10^{15} #/cm^2				
	VIS			10^{16} #/cm^2	10^{16} #/cm^2	10^{15} #/cm^2	10^{12} #/cm^2
	NIR						
SiO_2/ZrO_2 multilayer (*)	UV	$5 \cdot 10^{16}$ #/cm^2	10^{15} #/cm^2				
	VIS						
	NIR		10^{17} #/cm^2				
SiO_2-protected Al mirror	UV	$5 \cdot 10^{16}$ #/cm^2	10^{15} #/cm^2				
	VIS						
	NIR						
SiO_2-protected Ag mirror	UV	10^{16} #/cm^2	10^{16} #/cm^2				
	VIS						
	NIR	$5 \cdot 10^{16}$ #/cm^2	$5 \cdot 10^{16}$ #/cm^2				
MgF_2-protected Au mirror	UV	$5 \cdot 10^{16}$ #/cm^2	10^{16} #/cm^2				
	VIS						
	NIR		10^{17} #/cm^2				

- For each coating family, three different guard thresholds were obtained, one for the UV range, one for the VIS range and the last one for the NIR range.
- These values of guard thresholds represent the maximum fluence that demonstrated in our tests no optical performance degradation in that specific wavelength range.
- Fluences higher than the guard thresholds have a high probability of inducing effects in the coating performance and therefore specific tests devoted to evaluating their effect for a specific application are required.
- With interpolation of the experimental data, the damage threshold can be also estimated.

Outcomes and conclusions:
set of advice for the testing/validation/qualification

- Tests the LEI, privileging the energies that involve the whole coating structure.
- Test the coating with its characteristic energies (peak implantation at the interfaces).
- Tests the VIS/NIR coatings for protons/He ions fluences > 10^{15} #/cm^2.
- In accelerated ground test use the lowest possible flux (compatible with the time occupation). The flux should not exceed $2 \cdot 10^{11}$ #/cm^2/s in case of metal layers and 10^{12} #/cm^2/s in case of pure dielectric coatings.
- Ground the surface coating if you have metal on it.
- Use SiO_2 or MgF_2 ad topmost layer for avoiding damage due to few-keV ions. Typical thickness > 150 nm.

Outcomes and conclusions: Browsing and interpolation APP