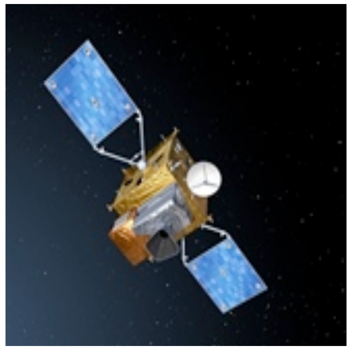
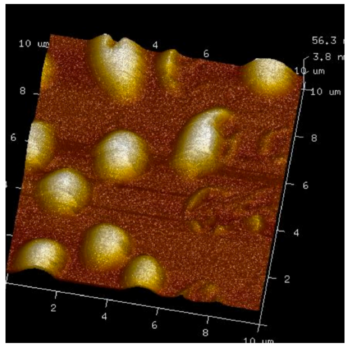
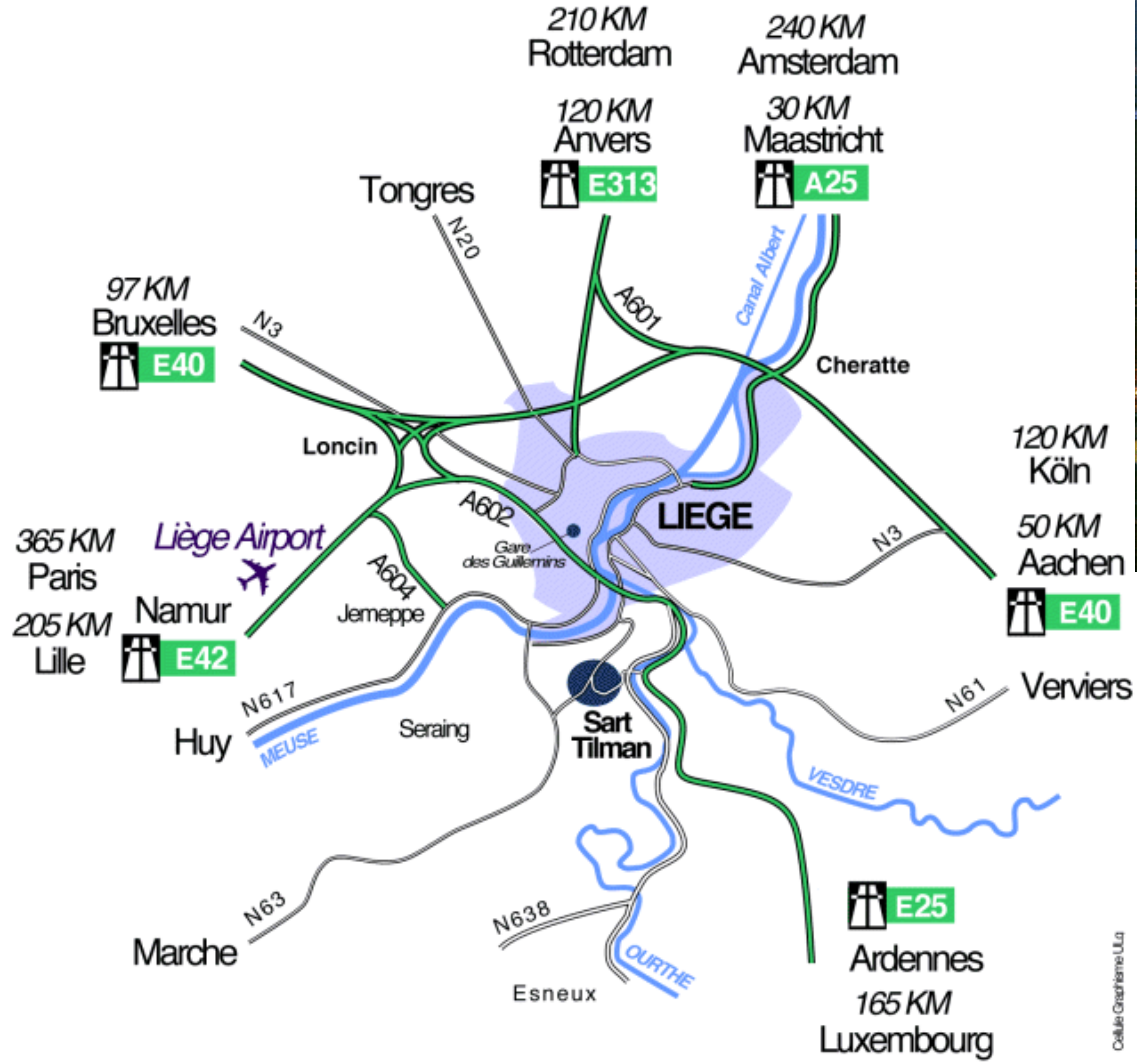
 

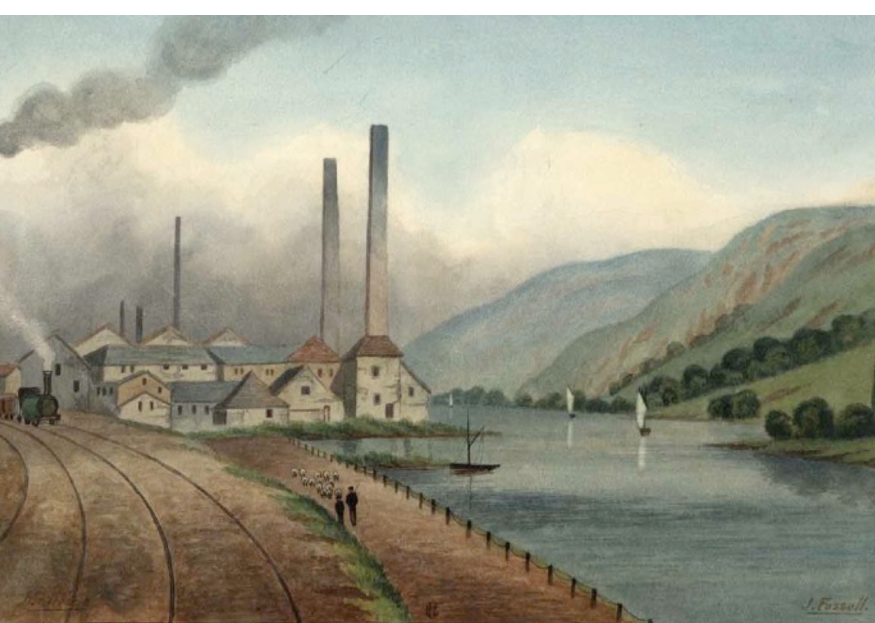
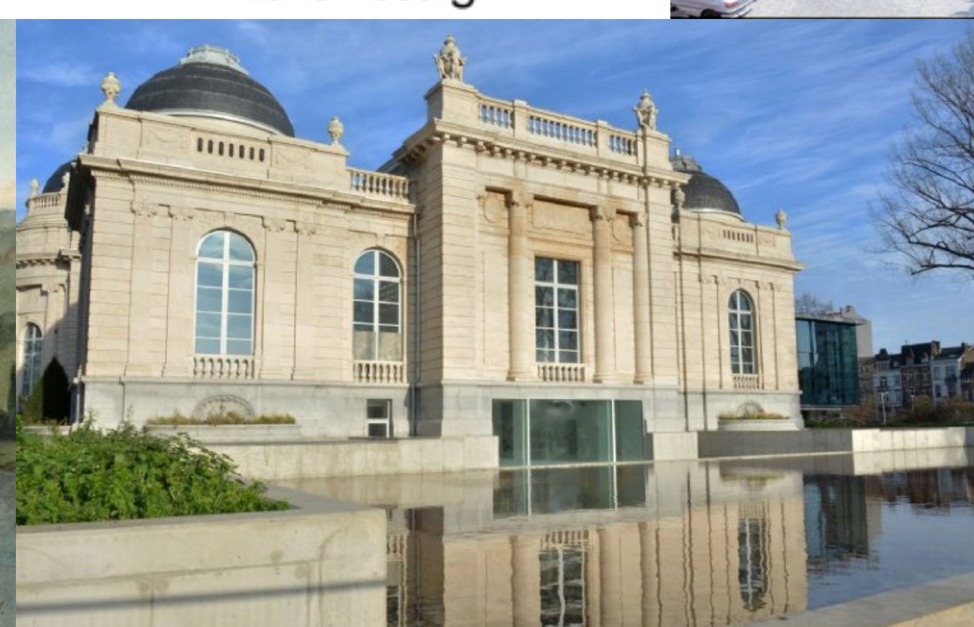
Testing of Materials under Space Radiation Environment Using Particle Accelerators of IPNAS

D. Strivay, L. Rossi, K. Fleury-Frenette, A. Carapelle, G. Chêne

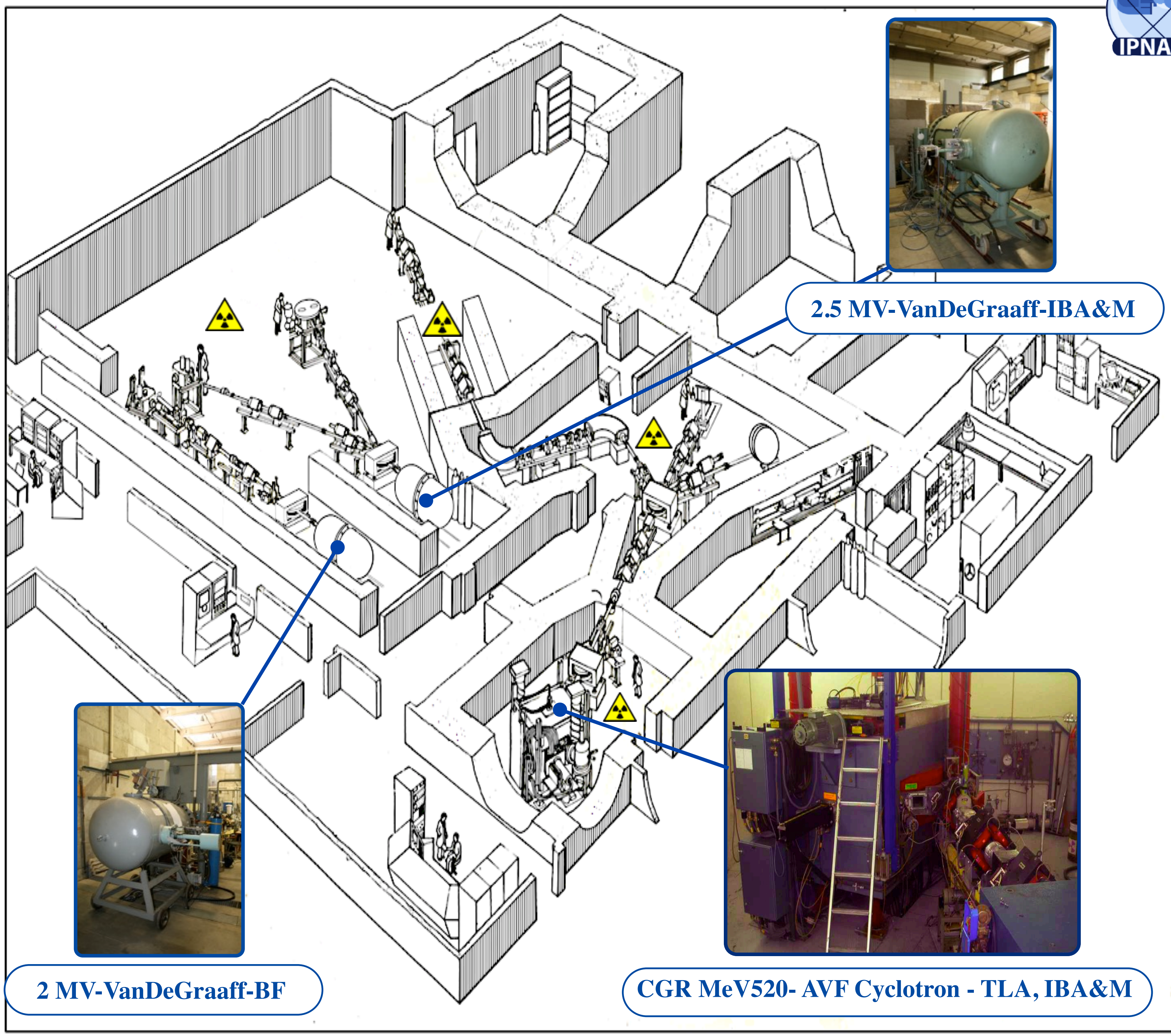
June 16th 2017

CRETE 17
June 11-17 2017
Crete, Greece


210 KM
Rotterdam
240 KM
Amsterdam
120 KM
Anvers
E313
30 KM
Maastricht
A25
Tongres
N20
A601
Canal Albert
97 KM
Bruxelles
E40
N3
Cheratte
Loncin
120 KM
Köln
A602
LIEGE
50 KM
Aachen
365 KM
Paris
Liège Airport
Gare des Guillemins
N3
E40
A604
Namur
Jemeppe
205 KM
Lille
E42
Verviers
N61
N617
Sart Tilman
Huy
MEUSE
Seraing
VESDRE
N63
N638
E25
Marche
OURTHE
Ardennes
Esneux
165 KM
Luxembourg

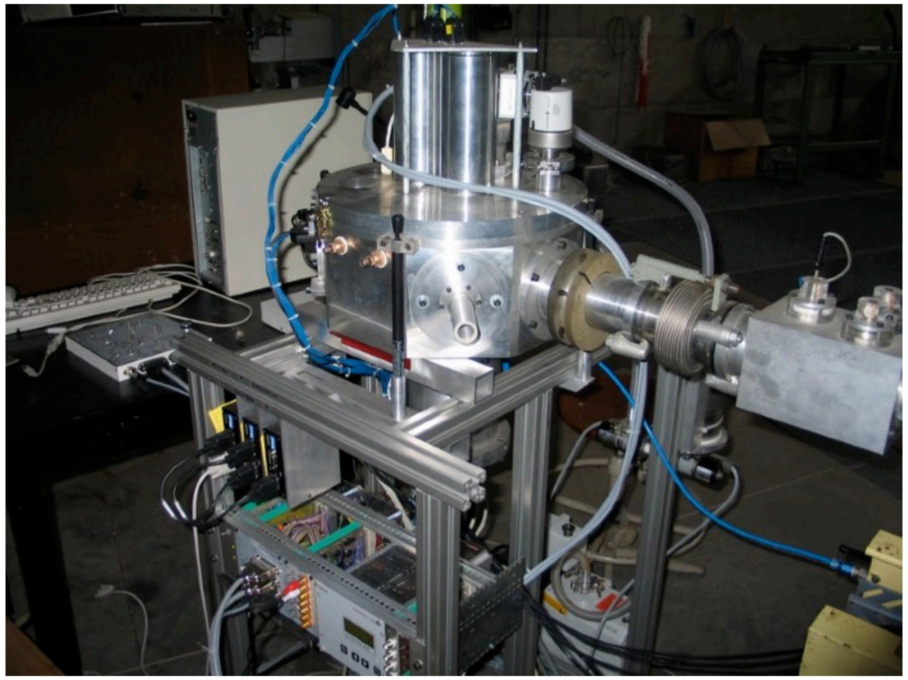

- Fundamental physics:
  - Beam-foil spectroscopy
  - Cold atoms
  - Ionisation by charged particles and non-Rutherford diffusion cross section measurements
- Applied physics:
  - Ion Beam Analysis
  - Thin Layer Activation
  - Irradiation test
  - Cultural Heritage analysis



- **SANA** Atomic and Nuclear Spectroscopy, Archaeometry
- **Accelerators:**
- 2 «oldies» Van De Graaff1 Cyclotron with variable energy
- Access to an extended **range of particle/ energy** to **characterize/irradiate** materials: materials for energy production, Cultural Heritage objects, industrial applications (Thin Layer Activation)

Accelerator	Particles	Energy range
VDG I - 2 MV	H^+,D,He^+, Metallic Ions, Li, Ne,	0.3- 2 MeV
VDG II - 2,5 MV	H^+,D, $^4He^+$, $^4He^{++}$	0.3 - 2.5 MeV 0.3-4.5 MeV
CGR-MeV AVF Cyclotron	H^+, D, $^4He^+$, $^3He^+$	2.5- 22 MeV 4- 20MeV 5.5- 22 MeV

- Long history of IBA
- Applications in biology, thin films, polymers, geology, Cultural Heritage,…

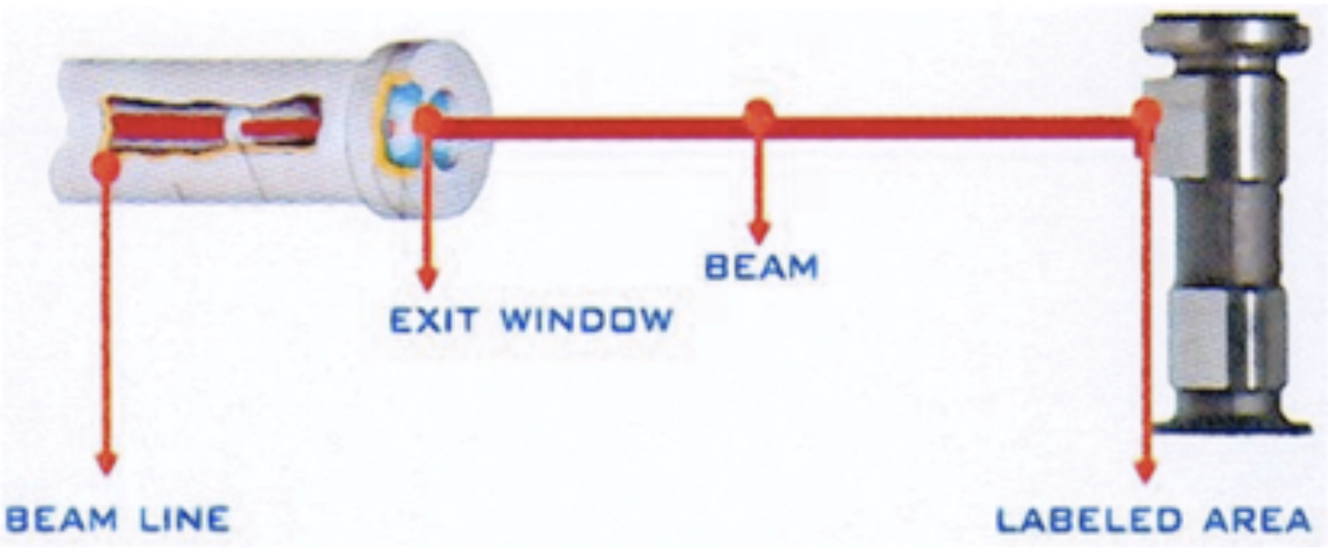


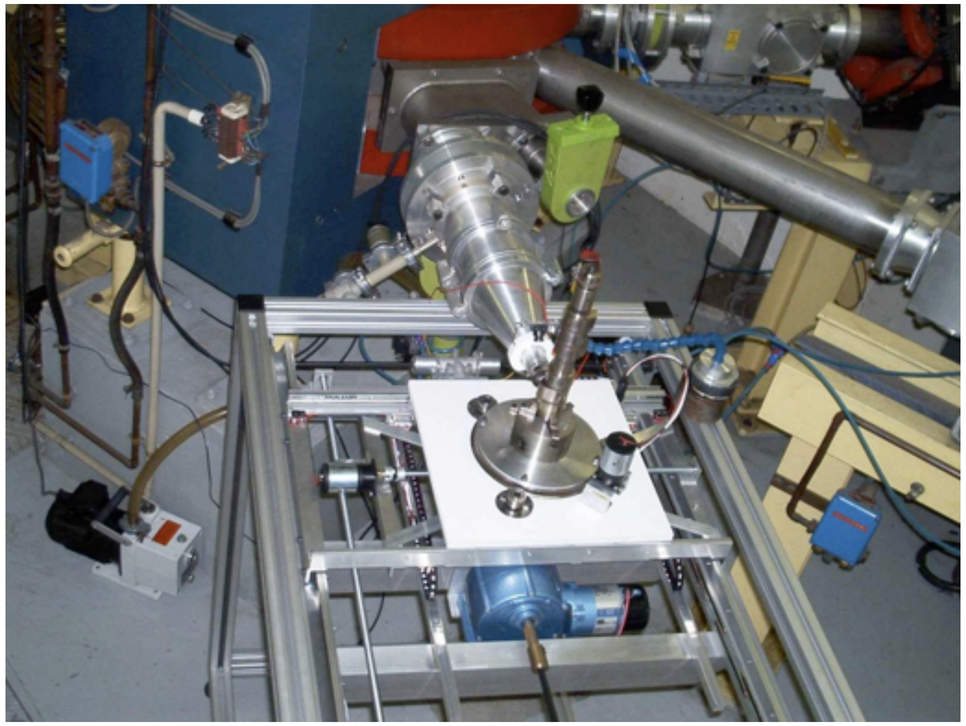
- 2 vacuum chambers on 2.5MV van de Graaff (RBS and multi-analysis)
- 4 beamlines on cyclotron (archaeometry, cross section measurements, irradiation, thin layer activation)

Typical reactions

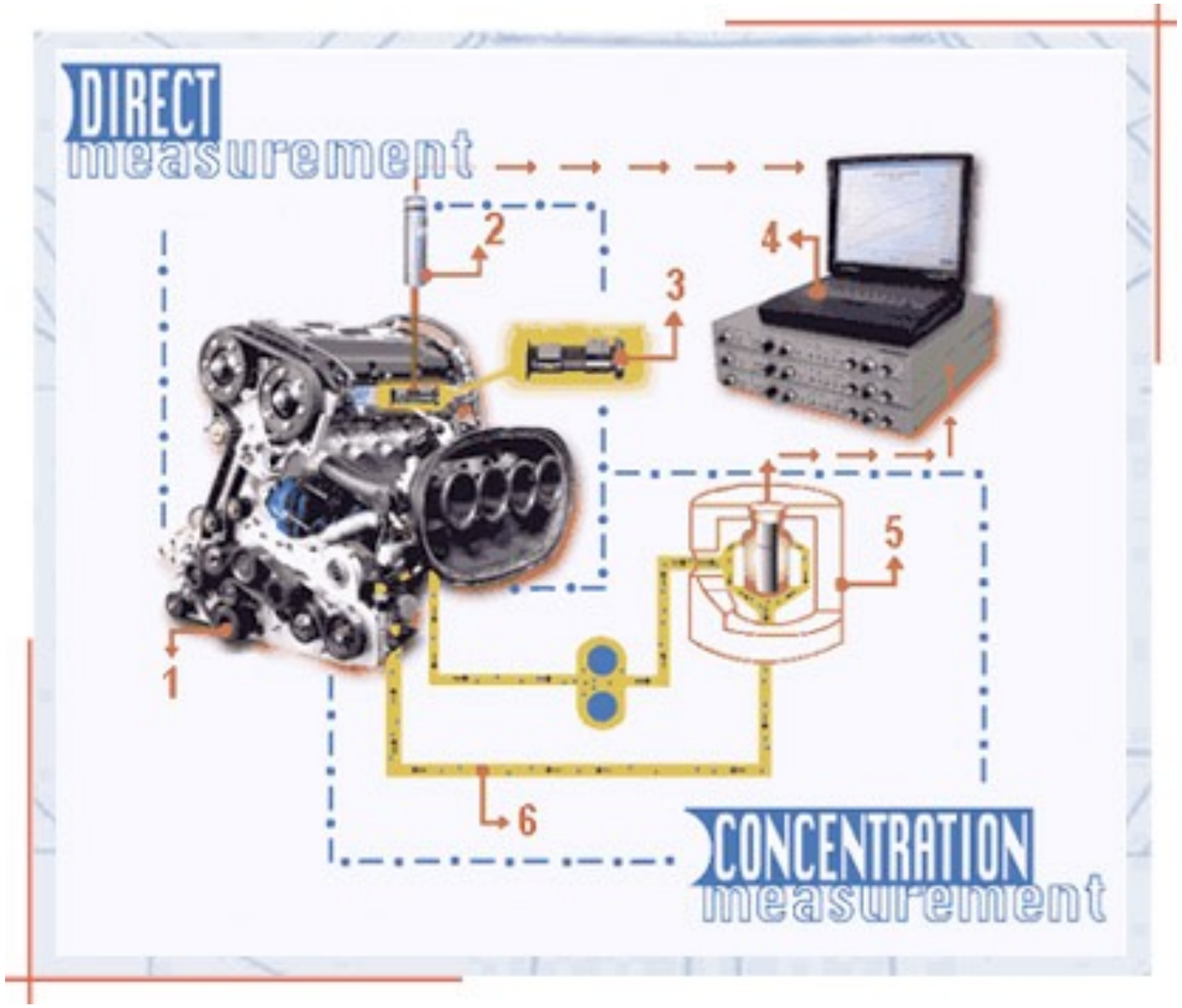
$^{56}Fe(p,n)^{56}Co$ ($T_{1/2} = 77$ days)

$^{48}Ti(d,2n)^{48}V$ ($T_{1/2} = 16$ days)





- Direct measurement
  (precision ~ 0.1 μm)
- Indirect measurement in the oil
  (precision ~ 0.01 μm)



M. Scherge, K. Pölmann, A. Gervé, Wear **254** (2003) 801-817

IPNAS IBA atmospheric setup

Archaeometry center

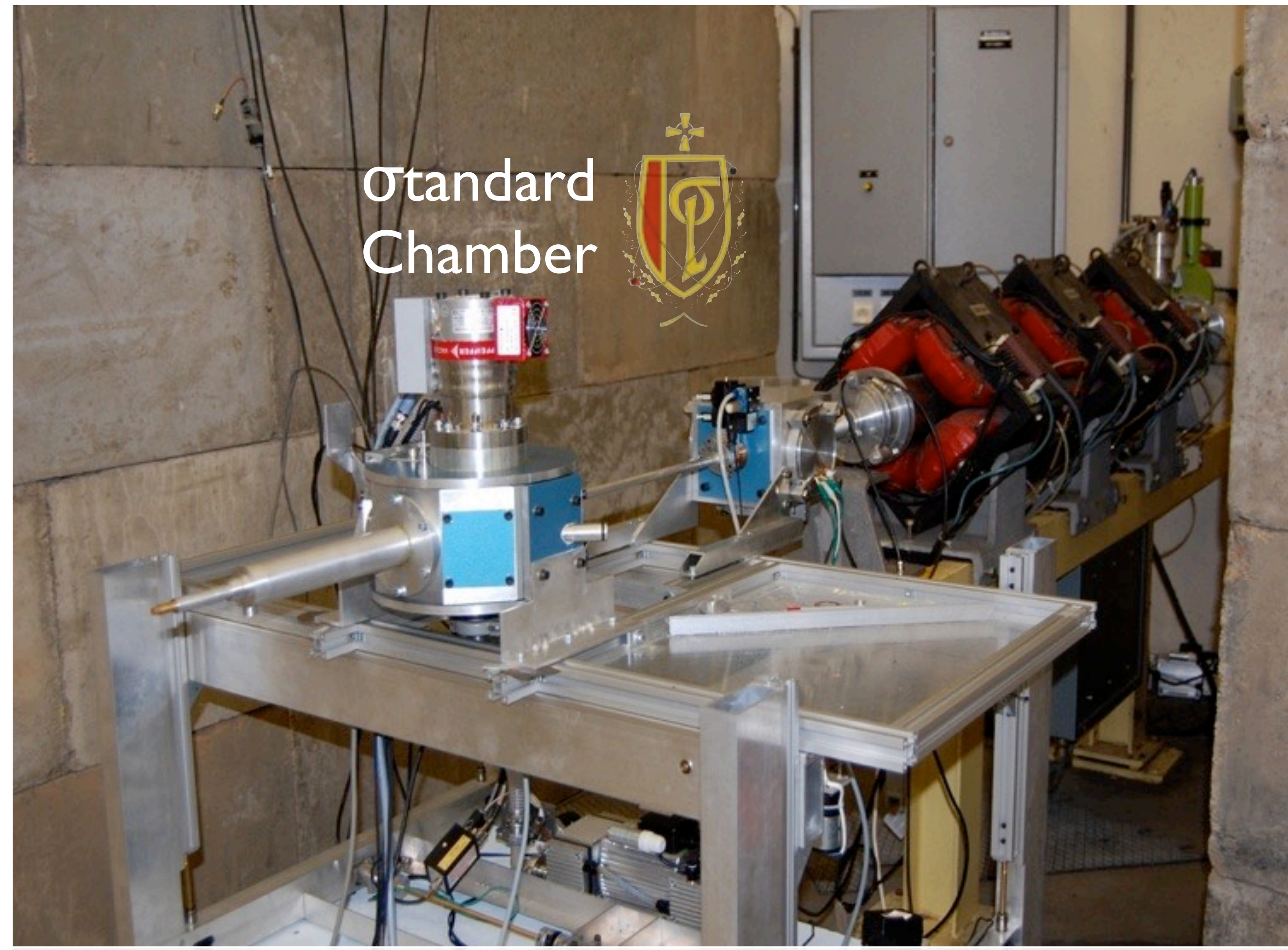
- Funded in 2002, now part of the Research Unit Art, Archéologie et Patrimoine
- Analytical methods available: Ion Beam Analysis, SEM, Raman, FT-IR, XRF, IR reflectography, X-ray imaging, dendrochronology, 3D imaging…
- Expertise

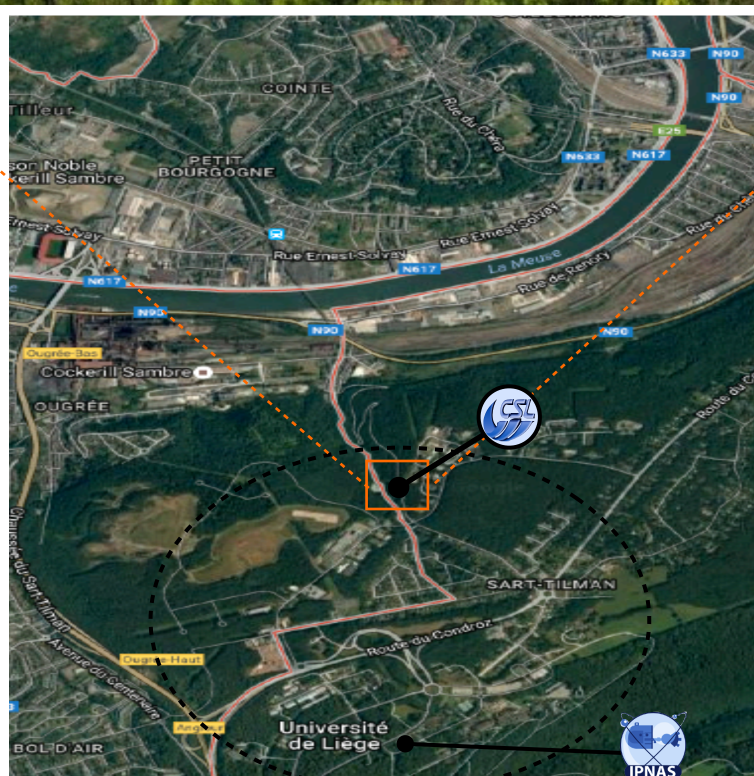
Recent projects

- Analysis of Modern and Contemporary art paintings by Magritte, Picasso, Ensor, Chagall, Sam Francis, Otto Dix, Gauguin,…
- Roman wall-paintings
- Cave painting project (Font de Gaume)
- Medieval glass and tesserae production
- Modern pigment degradation
- Medieval manuscript degradation
- Polyurethane for outdoor sculptures

Cross section measurements

- Beamline for cross section measurements by 3-20 MeV proton and alpha
- Beam energy resolution of 1 keV
- Energy measured by TOF system
- X-ray production cross sections for high energy PIXE
- Non-Rutherford diffusion cross sections





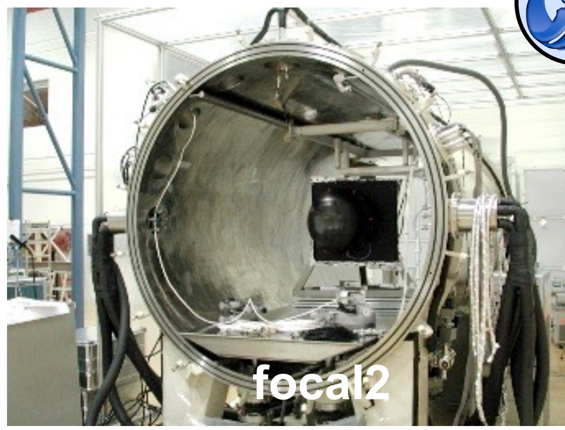
- **C**entre **S**patial de **L**iège (**CSL**) : Applied research center (spin-off) from Liège University specialized in conception and testing of space instruments
- **Environment Testing** **for European Space Agency (ESA)**, space companies (**Thales, Airbus,OHB, RUAG....**) and regional firms (**AMOS,TechSpaceAero, TNO**)
- 100 scientists
- **Expertise** Electronics, Signal treatment, Metrology, Laser, Optics, Cryogeny, Vacuum

  Laboratory of Micro&Nano Surface Engineering

  Optical, thermal and mechanical tests under space environment
- **Equipements**

  Coating techniques and surface Engineering system

  Optical techniques surface characterization



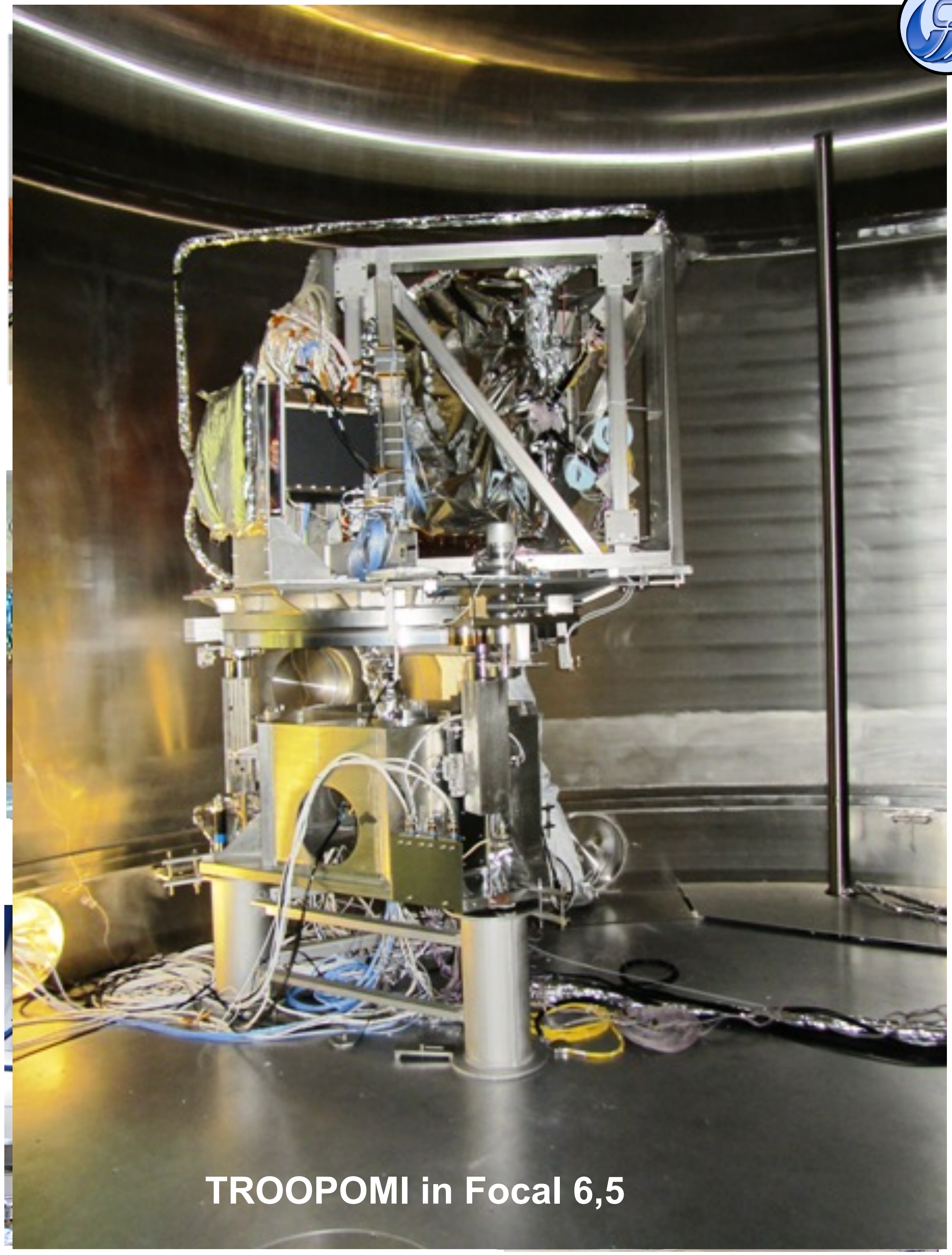
- **C**entre **S**patial de **L**iège (**CSL**) : Applied research center (spin-off) from Liège University specialized in conception and testing of space instruments
- **Environment Testing for European Space Agency (ESA),** space companies **(Thales, Airbus,OHB, RUAG....)** and regional firms **(AMOS,TechSpaceAero, TNO)**
- 100 scientists
- **Expertise** Electronics, Signal treatment, Metrology, Laser, Optics, Cryogeny, Vacuum

  Laboratory of Micro&Nano Surface Engineering

  Optical, thermal and mechanical tests under space environment
- **Equipements**

  Coating techniques and surface Engineering system

  Optical techniques surface characterization



- **C**entre **S**patial de **L**iège (**CSL**) : Applied research center (spin-off) from Liège University specialized in conception and testing of space instruments
- **Environment Testing for European Space Agency (ESA),** space companies **(Thales, Airbus,OHB, RUAG....)** and regional firms **(AMOS,TechSpaceAero, TNO)**
- 100 scientists
- **Expertise** Electronics, Signal treatment, Metrology, Laser, Optics, Cryogeny, Vacuum

  Laboratory of Micro&Nano Surface Engineering

  Optical, thermal and mechanical tests under space environment

- **Equipements**

  Coating techniques and surface Engineering system

  Optical techniques surface characterization

IBA…

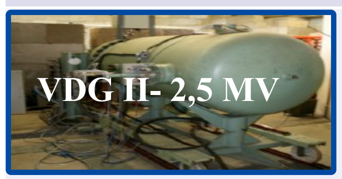
Quantitative analysis of materials: thickness control, reproductibility, reverse engineering … of optical coatings

IBMM…

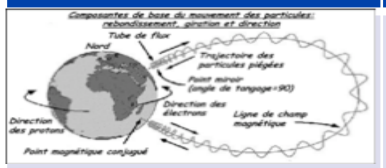
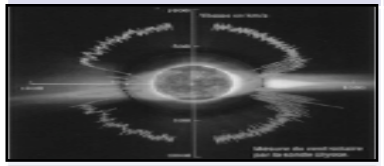
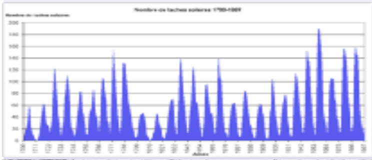
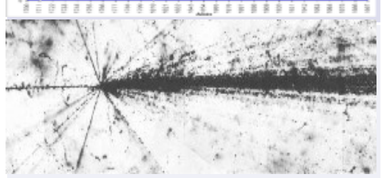
Irradiation test platform :
H+ from 100 keV to 22 MeV
e- ?? … conversion of VDG-I to produce e- beams

Aim : Produce charge particle beams characteristics of space radiation environment

Charge particles of interest

Accelerator	Particles	Energy range	Current range	Beam size
 *	H^+,D,He^+,* Metallic Ions, Li, Ne,	0,5- 2 MeV	X	X
	**H^+**,D, $^4He^+$, $^4He^{++}$	**0,1 - 2,5 MeV** 0,5-4,5 MeV	0,1 nA - 1 µA	0,4 mm - 6 cm
	**H^+,** D, $^4He^{++}$, $^3He^{++}$	**2,5- 22 MeV** 4- 20MeV 5,5- 22 MeV	0,3 nA - 100 µA	0,8 mm - 12 cm

Primary radiation environment : *Boudenot et al. RADECS 1999*

Provenance	Particles	Energy range	Flux
	H^+ e-	<qq. 100 MeV **(dont 99% <10MeV)** <7 MeV (dont 99% <2 MeV)	10 - 10^6 cm^{-2} s^{-1} 10^{-2} - 10^7 cm^{-2} s^{-1}
	H^+, e- $^4He^{++}$	<100 keV <qq keV	10^8 - 10^{10} cm^{-2} s^{-1}
	H^+, $^4He^{++}$ ions lourds	10 MeV- 1 GeV 10 MeV à qq 100 MeV	10^{10} cm^{-2} s^{-1} ~10^2 - 10^3 cm^{-2} s^{-1}
	H^+,87% $^4He^{++}$ 12% IONS LOURDS 1%	10^2 - 10^6MeV Fortes énergies 1-10^{14} MeV	1 cm^{-2} s^{-1} 100 MeV 10^{-4} cm^{-2} s^{-1} 10^6MeV

Challenge: how to attain these objectives with QA, ISO criteria used by Space agencies

IBA…

Quantitative analysis of materials: thickness control, reproductibility, reverse engineering … of optical coatings

IBMM…

Irradiation test platform :
H+ from 100 keV to 22 MeV
e- ?? … conversion of VDG-I to produce e- beams

Aim : Produce charge particle beams characteristics of space radiation environment

Charge particles of interest

Accelerator	Particles	Energy range	Current range	Beam size
VDG I - 2 MV	H^+,D,He^+, Metallic Ions, Li, Ne,	0,5- 2 MeV	X	X
VDG II - 2,5 MV	**H^+**,D, $^4He^+$, $^4He^{++}$	**0,1 - 2,5 MeV** 0,5-4,5 MeV	0,1 nA - 1 µA	0,4 mm - 6 cm
CGR-MeV AVF Cyclotron	**H^+,** D, $^4He^{++}$, $^3He^{++}$	**2,5- 22 MeV** 4- 20MeV 5,5- 22 MeV	0,3 nA - 100 µA	0,8 mm - 12 cm

Primary radiation environment : *Boudenot et al. RADECS 1999*

Provenance	Particles	Energy range	Flux
Radiation ring **250km< H< 80 000 km**	H^+ e-	<qq. 100 MeV **(dont 99% <10MeV)** <7 MeV (dont 99% <2 MeV)	10 - 10^6 cm^{-2} s^{-1} 10^{-2} - 10^7 cm^{-2} s^{-1}
Solar wind	H^+, e- $^4He^{++}$	<100 keV <qq keV	10^8 - 10^{10} cm^{-2} s^{-1}
Cyclic solar eruption (10 years)	H^+, $^4He^{++}$ ions lourds	10 MeV- 1 GeV 10 MeV à qq 100 MeV	10^{10} cm^{-2} s^{-1} ~10^2 - 10^3 cm^{-2} s^{-1}
Cosmic ray	H^+,87% $^4He^{++}$ 12% IONS LOURDS 1%	10^2 - 10^6MeV Fortes énergies 1-10^{14} MeV	1 cm^{-2} s^{-1} 100 MeV 10^{-4} cm^{-2} s^{-1} 10^6MeV

Challenge: how to attain these objectives with QA, ISO criteria used by Space agencies

IBA…

Quantitative analysis of materials: thickness control, reproductibility, reverse engineering … of optical coatings

IBMM…

Irradiation test platform :
H+ from 100 keV to 22 MeV
e- ?? … conversion of VDG-I to produce e-beams

Aim : Produce charge particle beams characteristics of space radiation environment

Charge particles of interest

Accelerator	Particles	Energy range	Current range	Beam size
VDG I - 2 MV	H^+, D, He^+, Metallic Ions, Li, Ne,	0,5- 2 MeV	X	X
VDG II - 2,5 MV	**H^+**, D, $^4He^+$,	**0,1 - 2,5 MeV**	0,1 nA - 1 µA	0,4 mm - 6 cm
	$^4He^{++}$	0,5-4,5 MeV		
CGR-MeV AVF Cyclotron	**H^+,**	**2,5- 22 MeV**	0,3 nA - 100 µA	0,8 mm - 12 cm
	D,	4- 20MeV		
	$^4He^{++}$, $^3He^{++}$	5,5- 22 MeV		

Altitude & mission duration
Primary radiation environment : *Boudenot et al. RADECS 1999*

Provenance	Particles	Energy range	Flux
Radiation ring **250km< H< 80 000 km**	H^+	<qq. 100 MeV **(dont 99% <10MeV)**	$10 - 10^6$ cm^{-2} s^{-1}
	e-	<7 MeV (dont 99% <2 MeV)	$10^{-2} - 10^7$ cm^{-2} s^{-1}
Solar wind	H^+, e-, $^4He^{++}$	<100 keV <qq keV	$10^8 - 10^{10}$ cm^{-2} s^{-1}
Cyclic solar eruption (10 years)	H^+,	10 MeV- 1 GeV	10^{10} cm^{-2} s^{-1}
	$^4He^{++}$, ions lourds	10 MeV à qq 100 MeV	˜$10^2 - 10^3$ cm^{-2} s^{-1}

Orbite	Duration	Altitude	Inclinaison	Longitude λ
LEO (Low Earth Orbit)	7 ans	**800 km**	60°	λ (t)
GEO (GEOstationnaire)	18 ans	**35786 km**	0°	36°

Challenge: how to attain these objectives with QA, ISO criteria used by Space agencies

Constrain 1: reduction & monitoring of molecular contamination

Contamination sources defined in **«Space product assurance - ECSS-Q-ST-70-05C»**

- Back−streaming from pumping ✌
- Outgassing products during vacuum integration ✌
- Cleaning products residues ✌
- Handling residues (e.g. human grease). ✌
- Unfiltered external pollution ☹

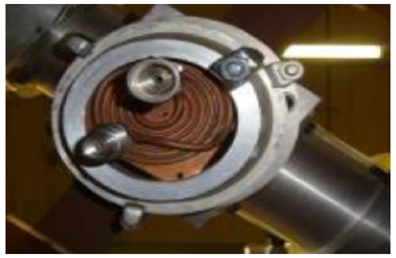
Table D-1: Assignment of infrared absorption bands for the four main groups of contaminants

Type of contaminant	Characteristic wave number (cm^{-1})	Functional group	Signal strength [a]	Remarks
Hydrocarbons	3000 - 2850	Alkanes (CH, CH_2, CH_3)	s	2 or 3 bands, stretching
	3100 - 3020	Alkenes	m	Stretching
	1470 - 1440	$-CH_3$	ms	Asymmetric deformation
	1390 - 1370	$-CH_3$	m	Symmetric deformation
Esters	1750 - 1735	C=O	s	Stretching (saturated ester)
	1300 - 1050	C-O	s	Stretching
Methyl silicones	1280 - 1255	$Si-CH_3$	vs	CH_3 deformation
	1130 - 1000	Si-O-Si	s	Asymmetric stretching
	860 - 760	$Si-CH_3$	vs	Si-C stretching or CH_3 rocking [b]
Methyl phenyl silicones	1280 - 1255	$Si-CH_3$	vs	CH_3 deformation
	1130 - 1000	Si-O-Si	s	Asymmetric stretching
	1125 - 1100	Si-Aryl	vs	
	860 - 760	$Si-CH_3$	vs	Si-C stretching or CH_3 rocking [b]

[a] Strength of signal: vs = very strong, s = strong, ms = medium to strong, m = medium.

[b] One methyl: 765 cm^{-1}; two methyls: 855 cm^{-1} and 800 cm^{-1}; three methyls: 840 cm^{-1} and 765 cm^{-1}.

- **New pumping groups**
- **Integration of cold traps in the vacuum chambers**
- **New connections and vacuum feedthroughs**
- **Systematic cleaning procedure at each opening**
- **Use of contamination witnesses before and during irradiation and analysis by FTIR (labo QA - CSL) following protocol described in «Space product assurance - ECSS-Q-ST-70-05C»**



Constrain 1: reduction & monitoring of molecular contamination

Contamination sources defined in **«Space product assurance - ECSS-Q-ST-70-05C»**

- Back−streaming from pumping ✌
- Outgassing products during vacuum integration ✌
- Cleaning products residues ✌
- Handling residues (e.g. human grease). ✌
- Unfiltered external pollution ☹

Table D-1: Assignment of infrared absorption bands for the four main groups of contaminants

Type of contaminant	Characteristic wave number (cm^{-1})	Functional group	Signal strength [a]	Remarks
Hydrocarbons	3000 - 2850	Alkanes (CH, CH_2, CH_3)	s	2 or 3 bands, stretching
	3100 - 3020	Alkenes	m	Stretching
	1470 - 1440	$-CH_3$	ms	Asymmetric deformation
	1390 - 1370	$-CH_3$	m	Symmetric deformation
Esters	1750 - 1735	C=O	s	Stretching (saturated ester)
	1300 - 1050	C-O	s	Stretching
Methyl silicones	1280 - 1255	$Si-CH_3$	vs	CH_3 deformation
	1130 - 1000	Si-O-Si	s	Asymmetric stretching
	860 - 760	$Si-CH_3$	vs	Si-C stretching or CH_3 rocking [b]
Methyl phenyl silicones	1280 - 1255	$Si-CH_3$	vs	CH_3 deformation
	1130 - 1000	Si-O-Si	s	Asymmetric stretching
	1125 - 1100	Si-Aryl	vs	
	860 - 760	$Si-CH_3$	vs	Si-C stretching or CH_3 rocking [b]

[a] Strength of signal: vs = very strong, s = strong, ms = medium to strong, m = medium.

[b] One methyl: 765 cm^{-1}; two methyls: 855 cm^{-1} and 800 cm^{-1}; three methyls: 840 cm^{-1} and 765 cm^{-1}.

- **New pumping groups**
- **Integration of cold traps in the vacuum chambers**
- **New connections and vacuum feedthroughs**
- **Systematic cleaning procedure at each opening**
- **Use of contamination witnesses before and during irradiation and analysis by FTIR (labo QA - CSL) following protocol described in «Space product assurance - ECSS-Q-ST-70-05C»**

Contamination sources defined in **«Space product assurance - ECSS-Q-ST-70-05C»**

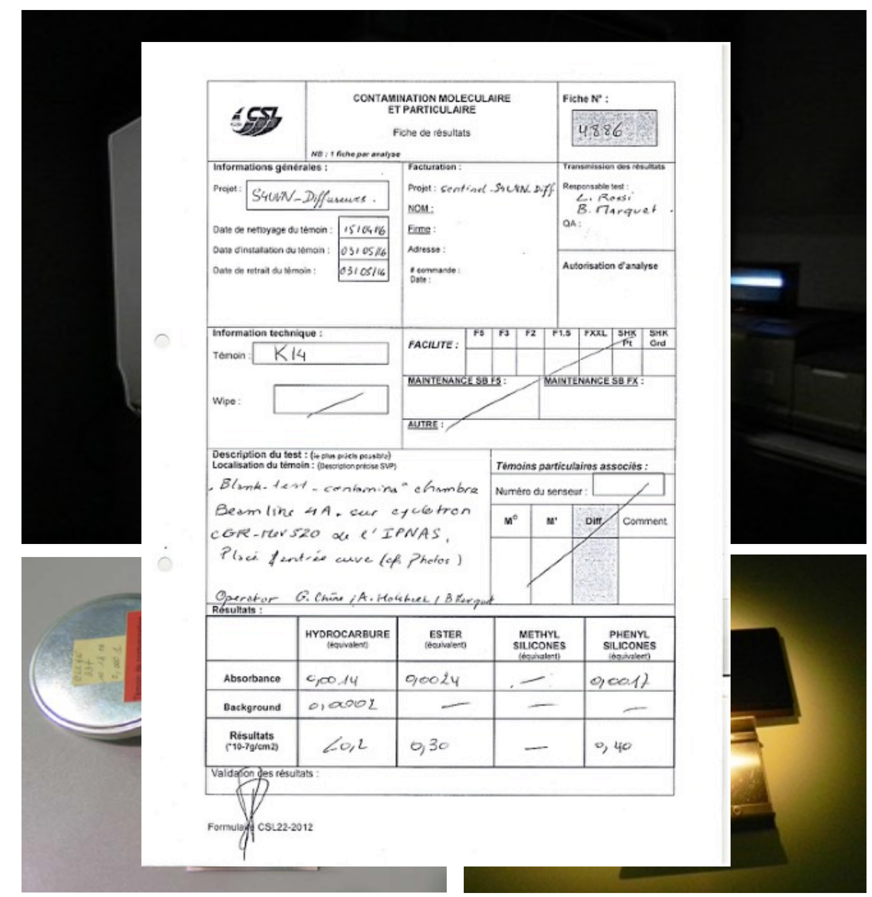
- Back−streaming from pumping ✌
- Outgassing products during vacuum integration ✌
- Cleaning products residues ✌
- Handling residues (e.g. human grease). ✌
- Unfiltered external pollution ☹

Table D-1: Assignment of infrared absorption bands for the four main groups of contaminants

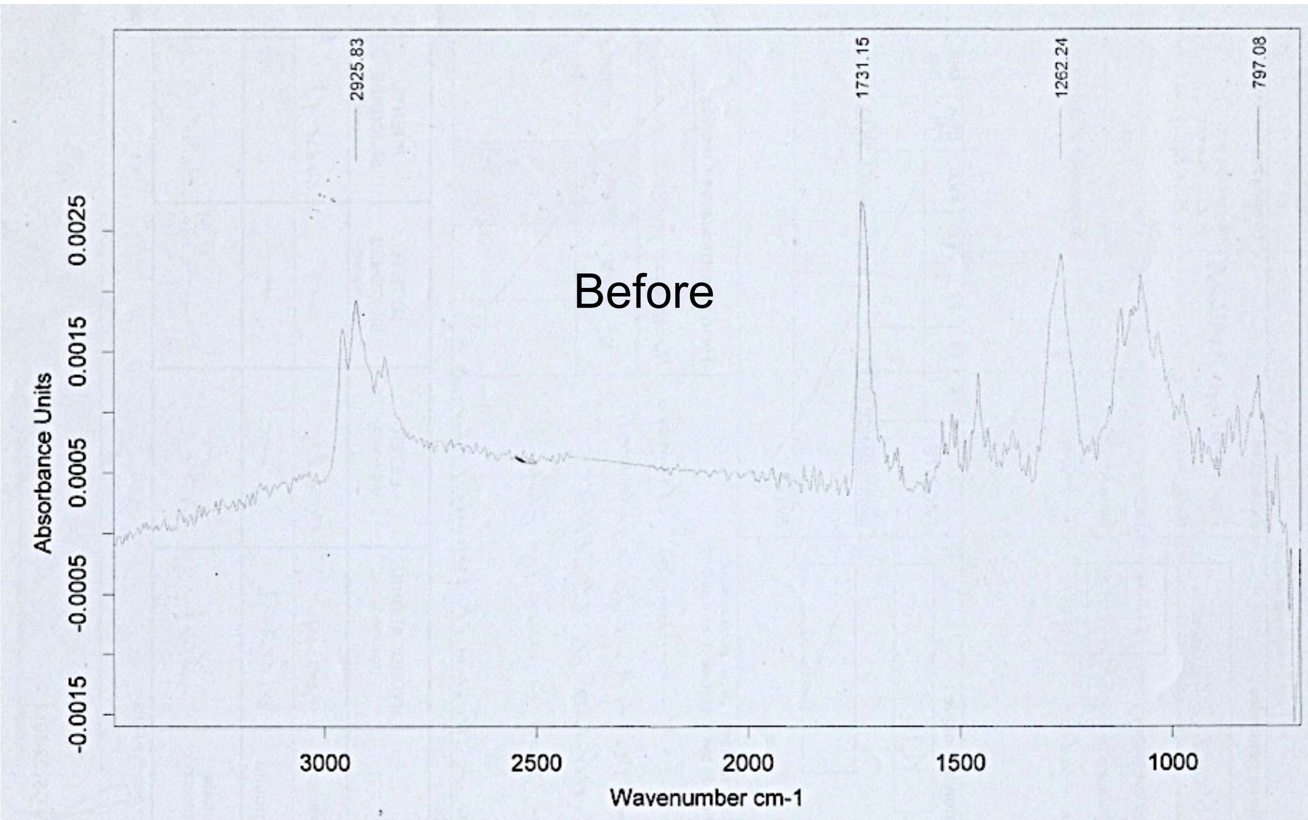
Type of contaminant	Characteristic wave number (cm⁻¹)	Functional group	Signal strength [a]	Remarks
Hydrocarbons	3000 - 2850	Alkanes (CH, CH_2, CH_3)	s	2 or 3 bands, stretching
	3100 - 3020	Alkenes	m	Stretching
	1470 - 1440	$-CH_3$	ms	Asymmetric deformation
	1390 - 1370	$-CH_3$	m	Symmetric deformation
Esters	1750 - 1735	C=O	s	Stretching (saturated ester)
	1300 - 1050	C-O	s	Stretching
Methyl silicones	1280 - 1255	$Si-CH_3$	vs	CH_3 deformation
	1130 - 1000	Si-O-Si	s	Asymmetric stretching
	860 - 760	$Si-CH_3$	vs	Si-C stretching or CH_3 rocking [b]
Methyl phenyl silicones	1280 - 1255	$Si-CH_3$	vs	CH_3 deformation
	1130 - 1000	Si-O-Si	s	Asymmetric stretching
	1125 - 1100	Si-Aryl	vs	
	860 - 760	$Si-CH_3$	vs	Si-C stretching or CH_3 rocking [b]

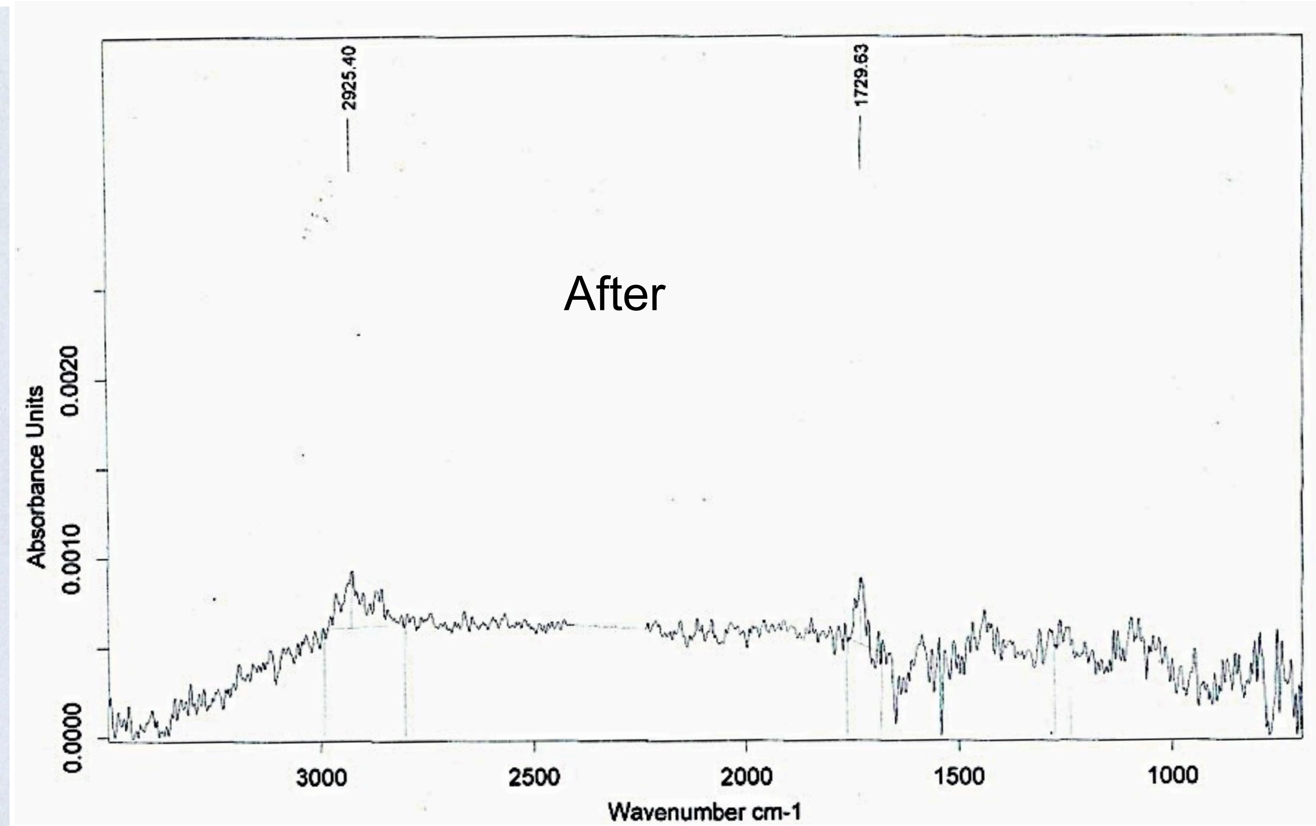
[a] Strength of signal: vs = very strong, s = strong, ms = medium to strong, m = medium.
[b] One methyl: 765 cm^{-1}; two methyls: 855 cm^{-1} and 800 cm^{-1}; three methyls: 840 cm^{-1} and 765 cm^{-1}.

- **New pumping groups**
- **Integration of cold traps in the vacuum chambers**
- **New connections and vacuum feedthroughs**
- **Systematic cleaning procedure at each opening**
- **Use of contamination witnesses before and during irradiation and analysis by FTIR (labo QA - CSL) following protocol described in «Space product assurance - ECSS-Q-ST-70-05C»**



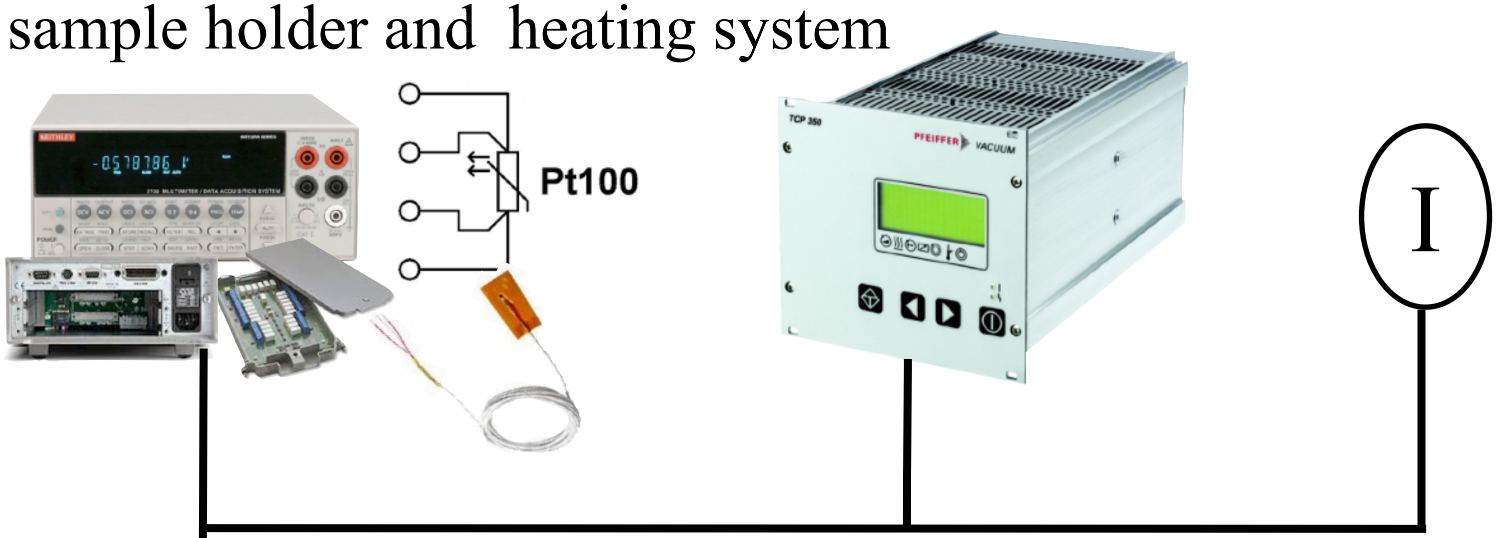
Constrain 1: reduction & monitoring of molecular contamination





	HYDROCARBURE (2925 cm^{-1})	ESTER (1735 cm^{-1})	METHL SILICONES	PHENYL SILICONES
Absorbance	0,0014	0,0024	/	0,0017
Background	0,0001	/	/	/
Results (x 10^{-7} g.cm^2)	< 0,2	0,3	/	0,4
Absorbance	0,0003	0,0004	/	/
Background	0,0001	/	/	/
Results (x 10^{-7} g.cm^2)	< 0,2	/	/	/

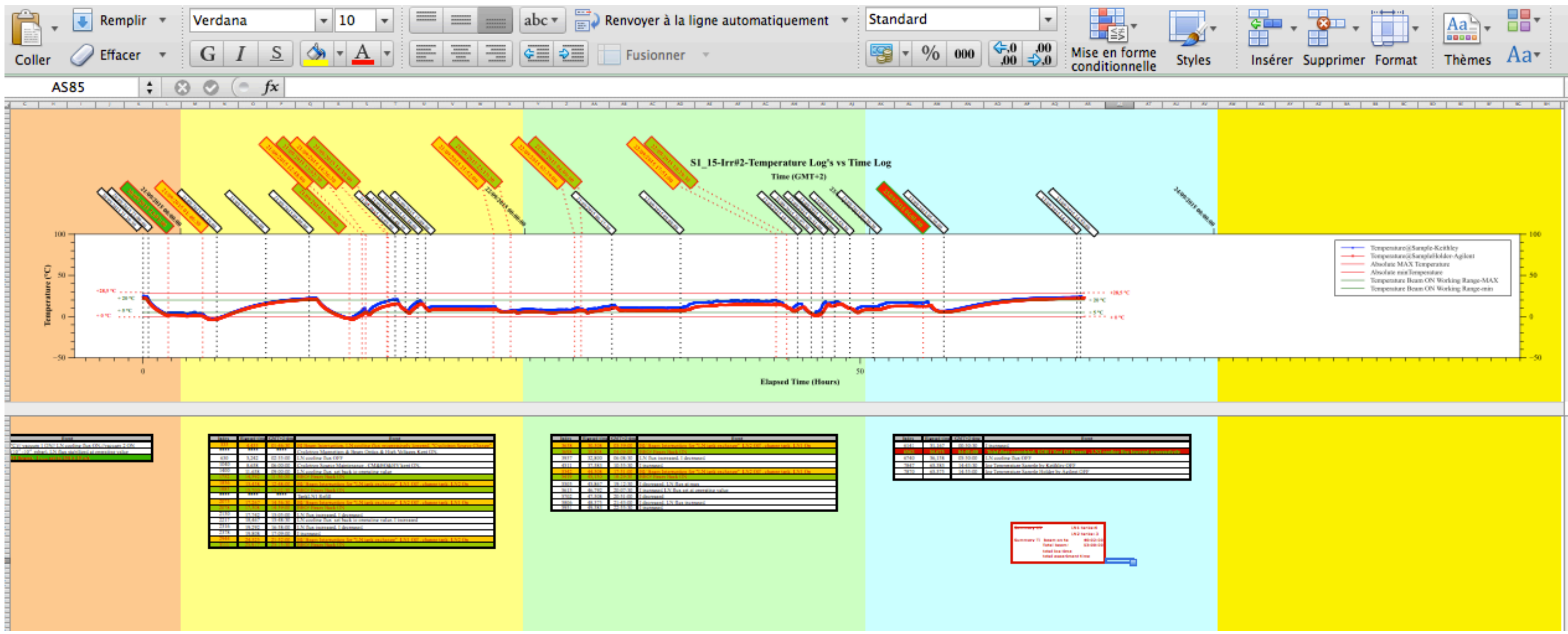
Thermal bridge between cold trap/ sample holder and heating system



Standards CSL

- T,P measurement and T control
- Low beam current (nA) and total dose measurements (<5%)
- Logs files .txt
- Deliverable .xls

```
date;hour;P;T1;T2;I
date;hour;P;T1;T2;I
date;hour;P;T1;T2;I
date;hour;P;T1;T2;I
date;hour;P;T1;T2;I
```



Cyclo Beam Line 4a - CSL I chamber // VDG II - Beam Line 30° - CSL chamber

cyclotron «CSL Beam Line»
H+ @ 10 MeV (S4UVN) , 20 MeV (Sider)
use of Al foil as beam homogeneizer
«CSL Cyclo Chamber»
LN Cold Trap & I, T, P control and log (S4UVN)

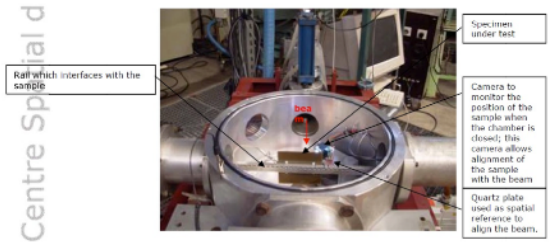
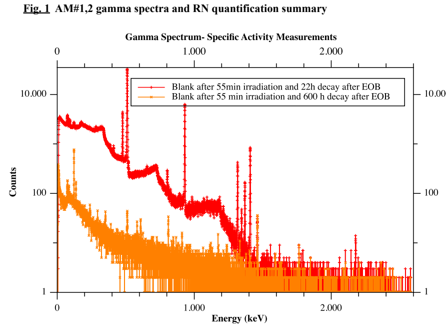


Figure 2: ULg-IPNAS Van de Graaff vacuum chamber

Table 8-2: Measurement tools

	Description	Type	Type no	Accuracy
Current measurement	The current is measured directly on the chamber (~nA). This current is integrated by a Digital Current Integrator Model 439 (Ortec). This device produces a digital pulse for each collected charge (1 pulse = 1E-10 C).	Ortec digital current integrator	439	5%
Temperature measurement	Two thermal sensors (PT100) (one nominal and one redundant) will be accommodated on the sample; One Keithley will read the PT100 and send the data to PC.	PT100 2701 Ethernet multimeter		+/-1°C
Pressure Measurement		Pfeiffer Vacuum compact full range gauge		

Fig. 1 AM#1,2 gamma spectra and RN quantification summary



Data Processing Results Summary

Blank: S1_08-55min irradiation 14/07/2015

Activité résiduelle le **15/07** (après **22h** de décroissance):

385 kBq de Co55,
900 Bq de Co57,
500 Bq de Co58,
560 kBq de Cu64

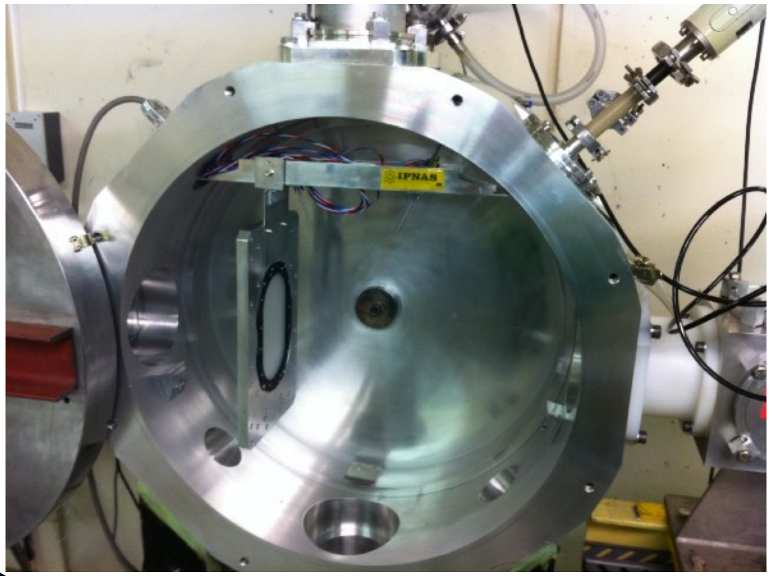
Activité résiduelle le **10/08** (après 25 jours (**env.600h**) de décroissance)):

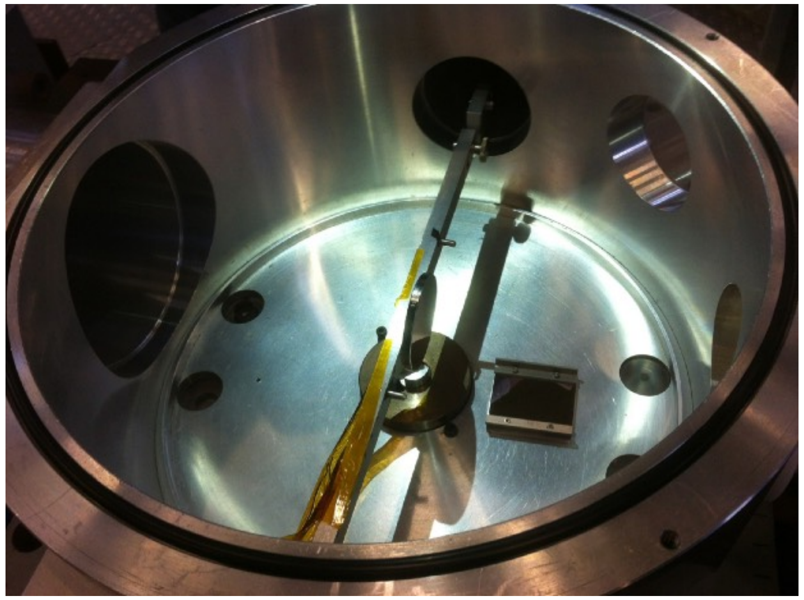
inf LOD de Co55,
900 Bq de Co57,
500 Bq de Co58,
inf LOD de Cu64

Conclusions

- Identification du Co55 confirmée par AM#2

- «Confinement/Cooling» time evaluation to allow release for Safe Transport and Visual Inspection @ CSL facility: evaluated : 4 - 5 x ($T_{1/2}$ (Co55)) = 70-90hrs





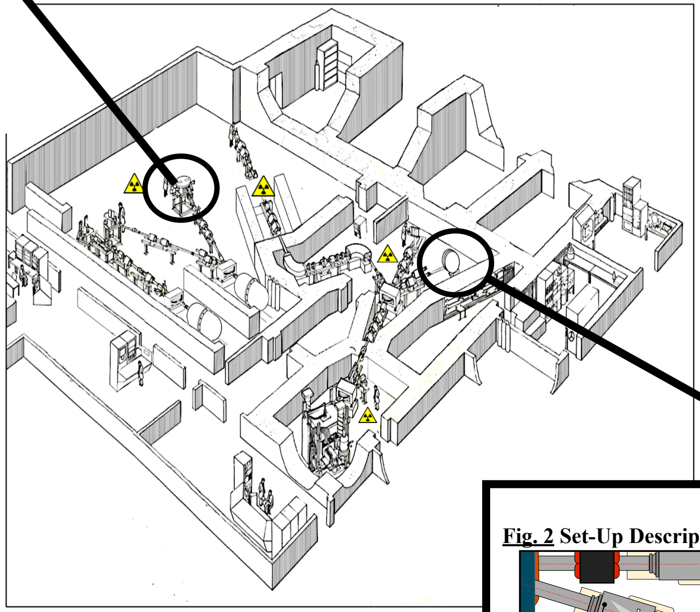
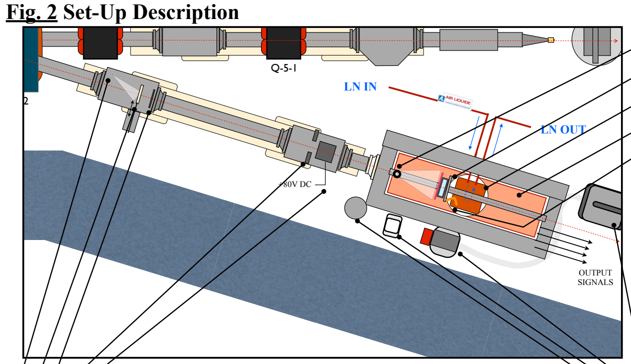


Fig. 2 Set-Up Description



Camera CCD 2	no beam
Thermocontrolled Sample Holder	Aluminium Bulk + 2 PT1OO
Liquid Nitrogen Cold Trap	Copper Bulk / no beam
Internal Faraday Cup Copper Coated	Thick Copper Coating
Thermal Bridge LNCT-SH	Copper , no beam

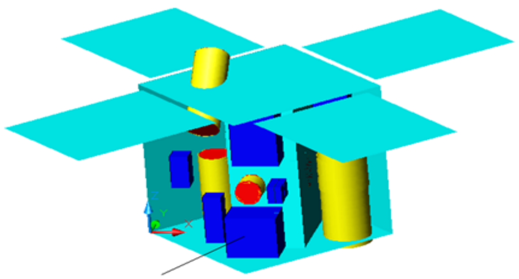
Secondary Electron Supressor	Stainless Steel Tube at +80V
Beam Defining Collimator	Aluminium
Beam Homogeneizer	Aluminium Foil 20 microns
Retractable Luminescent Alumina	Al_2O_3 : Cr, no beam
Camera CCD 1	no beam

Primary Pump	Agilent Tech. SH110 DryScrollPump
Turbo Molecular Secondary Pump	Pfeiffer HiPace 80
Full Range Vacuum Gauge	Pfeiffer Compact Full Range
Remise à l'air	Zeolite Molecular Sieve & Dry Nitrogen

Description : CSL Beam Line, CSL Vacuum Irradiation Chamber, Vacuum Temperature & Fluence control

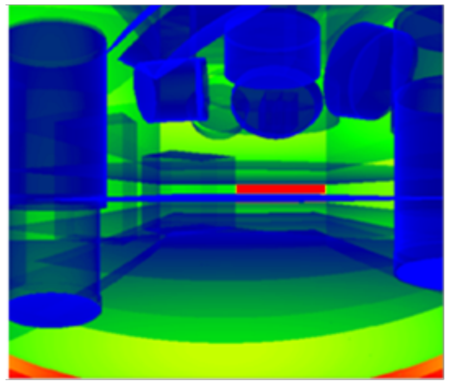
VDG «CSL Beam Line»
H+ @ 595 keV / 100 keV on target(S4UVN)
use of Al foil as beam homogenizer
«CSL VDG Chamber»
LN Cold Trap & I, T, P control and log (S4UVN)

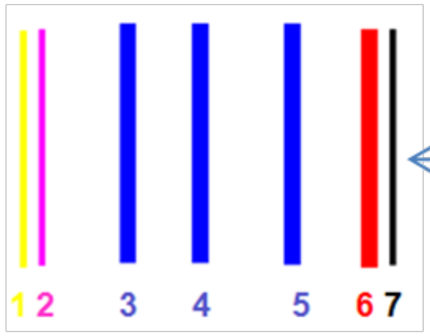
- **Spatial hardware:** use of **Al** as **radiation shielding** as well as container
- Replace Al by **composite materials** with better weight/mechanical properties
- Graphite/epoxy composites:
  - at equal mass, composites attenuate 30 à 40% less than Al
  - at equal attenuation, composites are 30 to 40% thicker than Al
- Optimization
  - **Z to add** to attain similar shielding with minimal mass
  - **Quantity** to add;
  - **Position** in composite/enveloppe

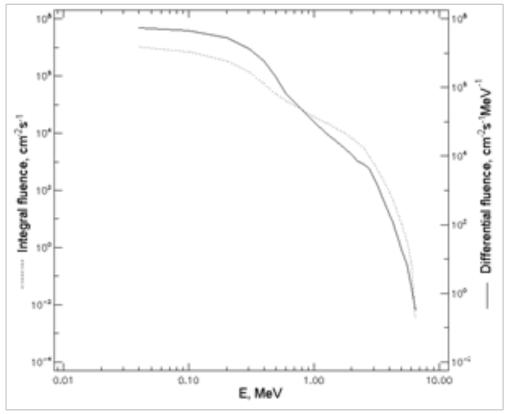


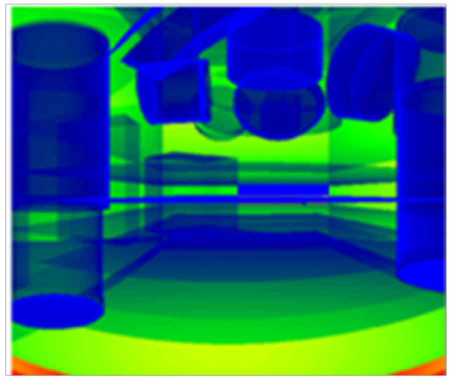
Block of onboard radioelectronic equipment been used for example of calculations

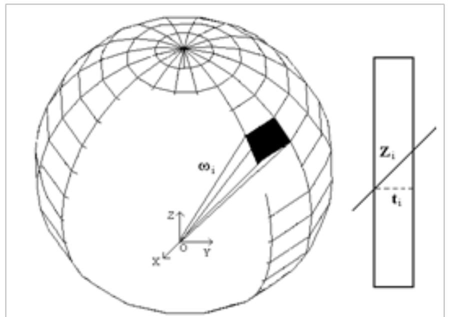
Sector analysis to find place for additional shielding → MULASSIS macro generation → Calculation of ionizing and nonionizing doses with MULASSIS tool → Replacement of dose values in arrays → Calculation of total ionizing and nonionizing doses at the defined point











$$D^{ion} = \frac{1}{4\pi}\sum_{i=1}^{N} D_i^{ion} \cdot \omega_i$$

$$D^{non-ion} = \frac{1}{4\pi}\sum_{i=1}^{N} D_i^{non-ion} \cdot \omega_i$$

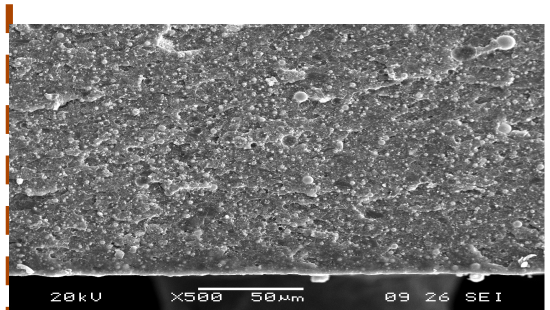
SIDER

Materials for composite shieldings
MTM44 epoxy from ACG
fibres M40J

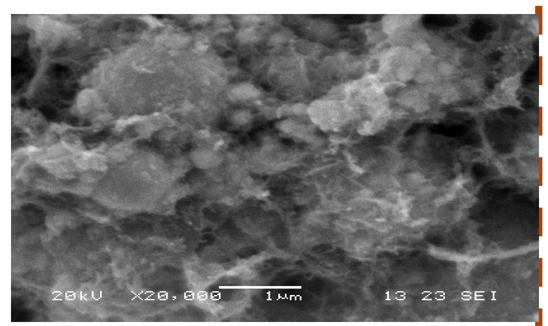
Nanomaterials

Doped resin

Buckypaper



Tec4 (30% wt nW/0.5% wt CNT)



CNT/W 6/94

Integration of Foils

Different foils (steel, W)

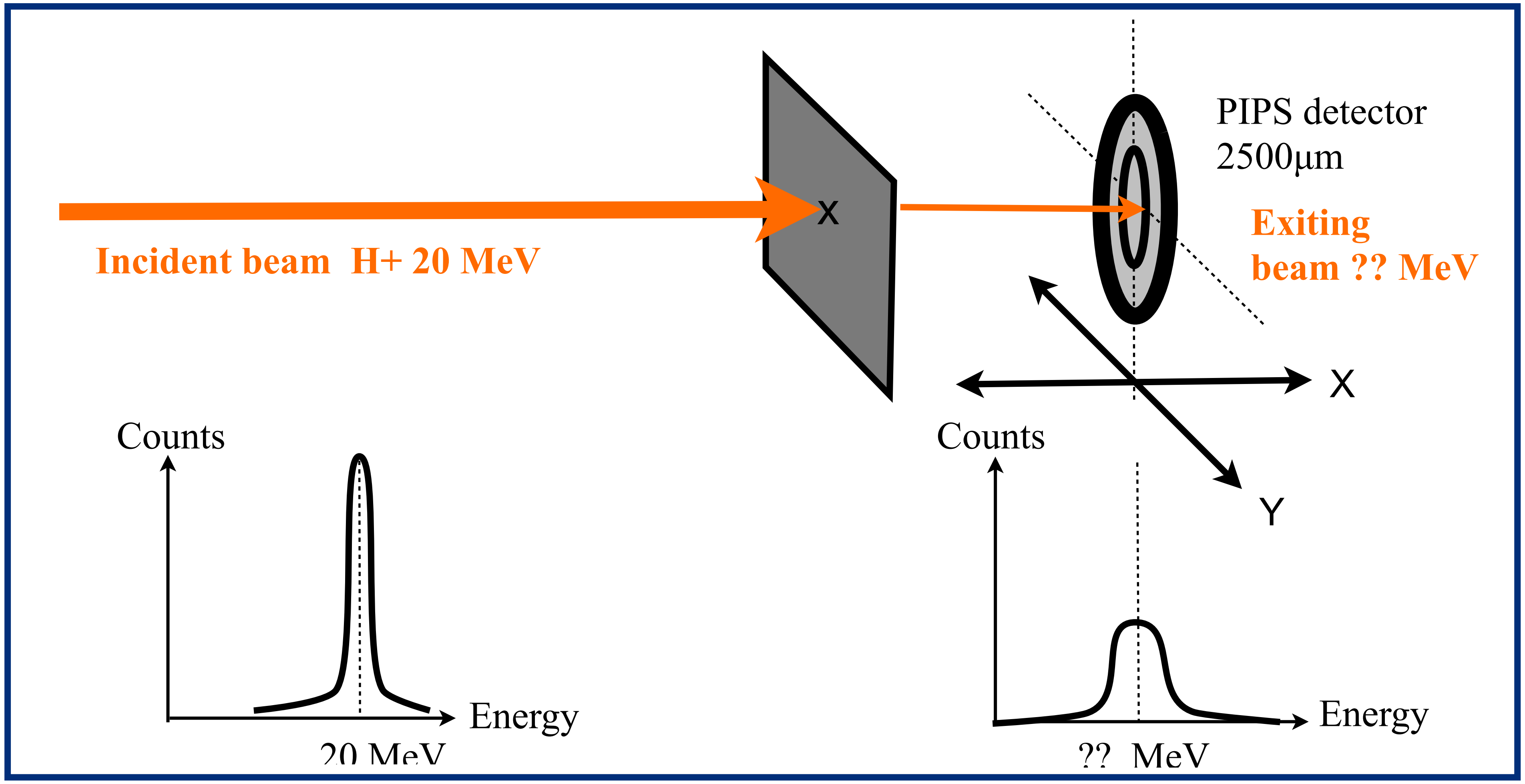
Various surface treatments (grit blasting, etching…)

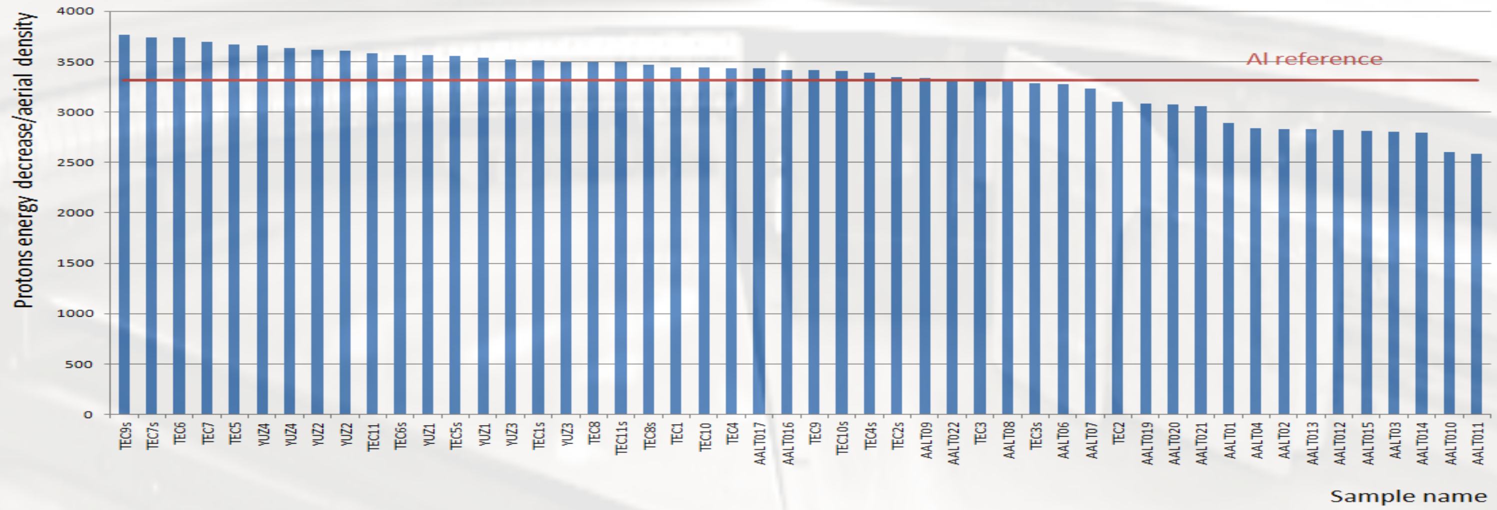
SIDER project: test of shielding materials

SIDER

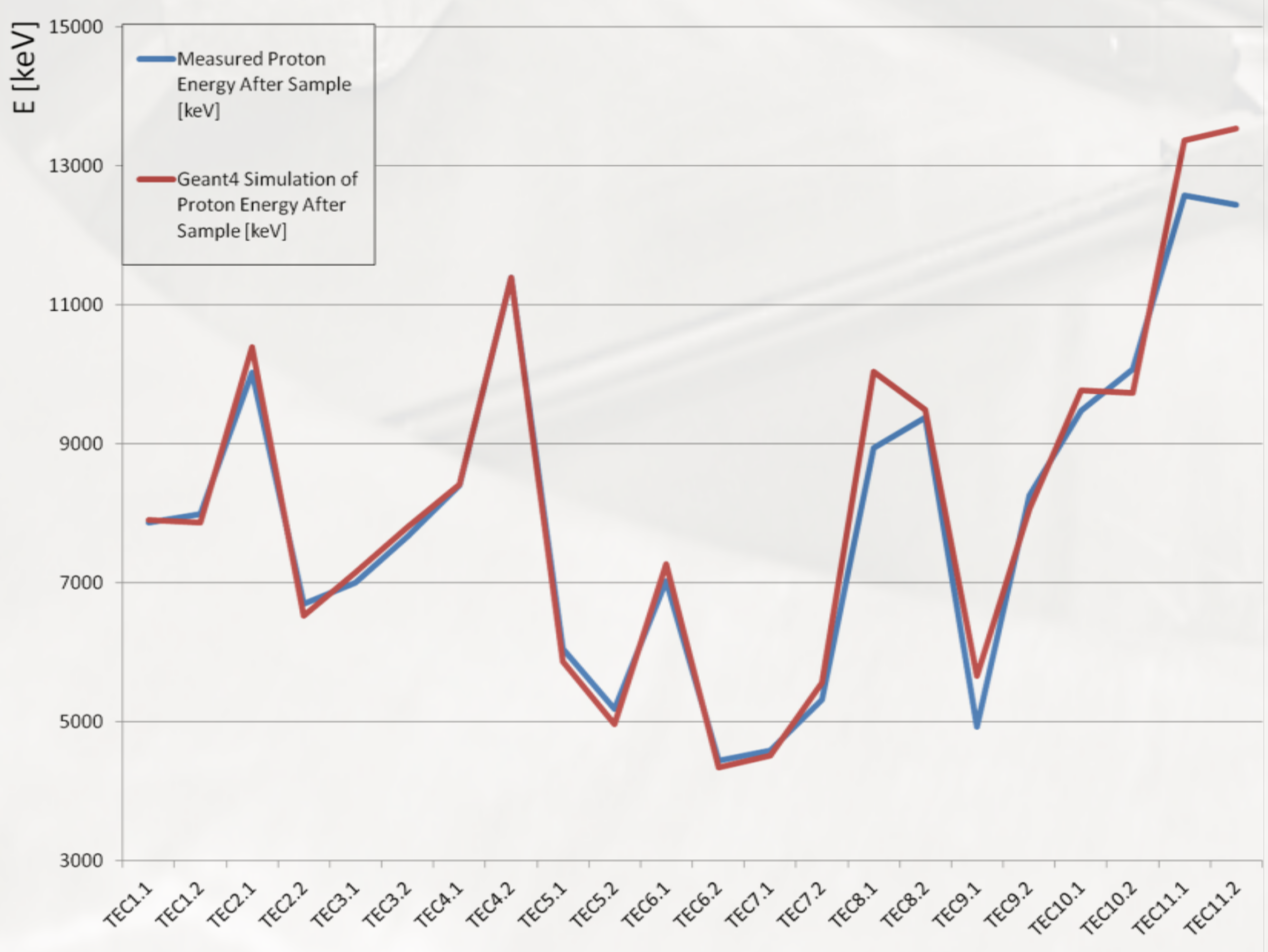
Reference	Details
TEC1	Doped resin with 2,21%CNT
TEC2	Doped resin with 88%W
TEC3	Doped resin with 63%W
TEC4	Doped resin with 30%W/0,5%CNT
TEC9	Buckypaper 100%CNT
TEC8	Buckypaper 76,60%CNT/23,4%W
TEC7	Buckypaper 50%CNT/50%W
TEC6	Buckypaper 24%CNT/76%W
TEC5	Buckypaper 6%CNT/94%W
TEC11	0,Buckypaper 76,60%CNT/23,4%W,90,Buckypaper 76,60%CNT/23,4%W,0
TEC10	Impregnated Buckypaper 30%W
Aalto-1 & Aalto-6	2 prepreg layers + 0.05 mm Tungsten + 4 prepreg layers
Aalto-2 & Aalto-7	3 prepreg layers + 0.05 mm Tungsten + 3 prepreg layers
Aalto-3 & Aalto-8	4 prepreg layers + 0.05 mm Tungsten + 2 prepreg layers
Aalto-4 & Aalto-9	5 prepreg layers + 0.05 mm Tungsten + 1 prepreg layer
Aalto-10:	3 prepreg layers + 0.05 mm Tungsten + 1 prepreg layer + 0.05 mm Tungsten + 2 prepreg layers
Aalto-11:	4 prepreg layers + 0.05 mm Tungsten + 1 prepreg layer + 0.05 mm Tungsten + 1 prepreg layer
Aalto-12:	3 prepreg layers + 0.05 mm steel + 1 prepreg layer + 0.05 mm Tungsten + 2 prepreg layers
Aalto-13:	4 prepreg layers + 0.05 mm steel + 1 prepreg layer + 0.05 mm Tungsten + 1 prepreg layer
Aalto-14:	2 prepreg layers + 0.05 mm steel + 2 prepreg layers + 0.05 mm Tungsten + 2 prepreg layers
Aalto-15:	3 prepreg layers + 0.05 mm steel + 2 prepreg layers + 0.05 mm Tungsten + 1 prepreg layers
Aalto-18:	8 prepreg layers + Gadolinium paint
Aalto-19:	4 prepreg layers + 0.05 mm Tungsten + 4 prepreg layers
Aalto-20:	6 prepreg layers + 0.05 mm Tungsten + 2 prepreg layers
Aalto-21:	7 prepreg layers + 0.05 mm Tungsten + 1 prepreg layer
Aalto-16:	6 prepreg layers (reference)
Aalto-17:	8 prepreg layers (reference)
Aalto-22:	2 mm Al-2024-T3 (reference)

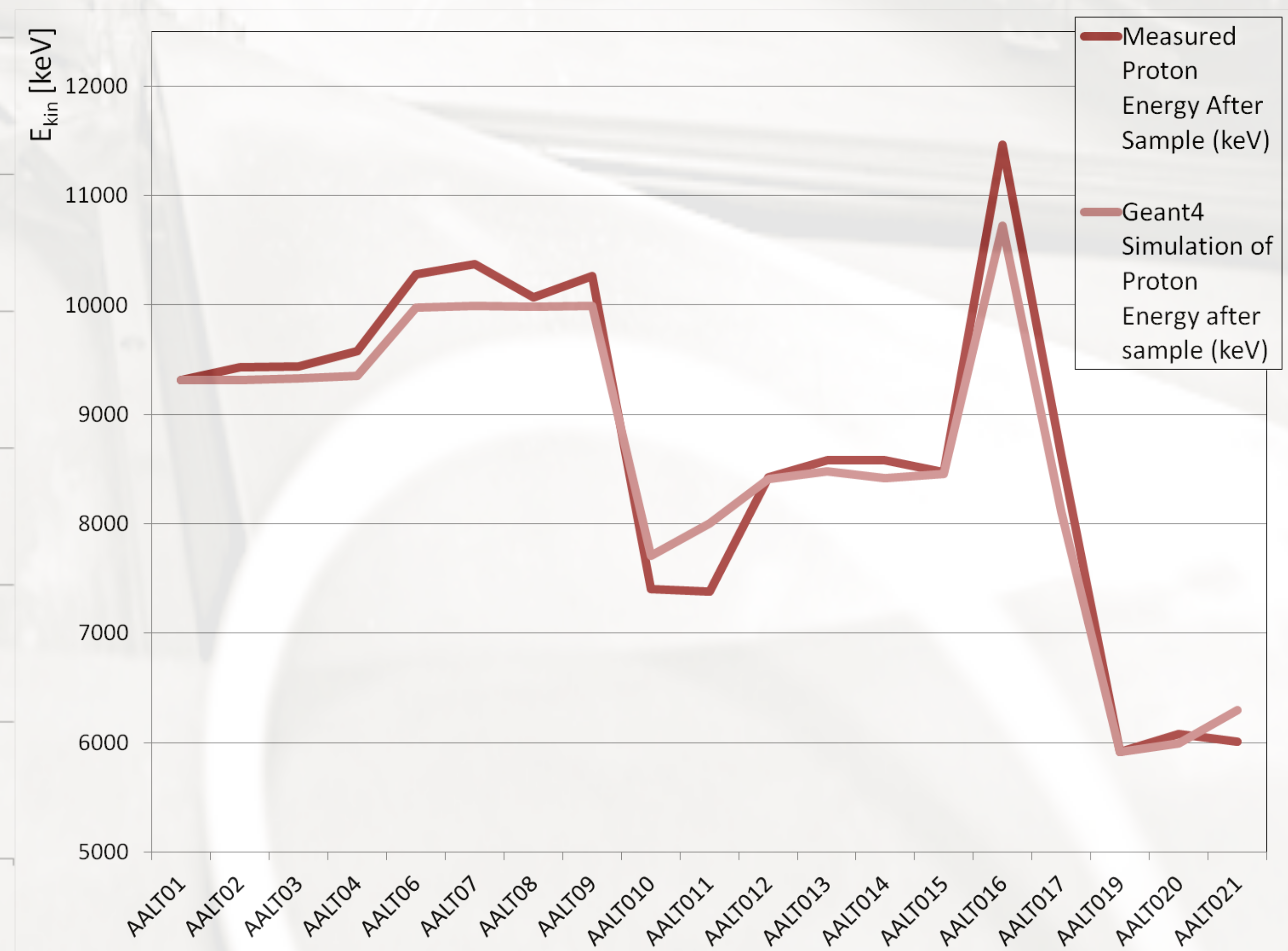
Particles	Energy	Facility	Deliverable
H+	20 MeV	IPNAS ULg Cycclotron AVF	• Fast acquisition H^+ energy spectrum with detector placed behind each sample (collimated PIPS, 2500 Microns, Schlumberger) • Scan Y & X vs different beam sizes
e-	6 MeV	Medical accelerator	Acquisition of e- energy spectrum with detector placed behind each sample
γ	^{60}Co	^{60}Co ULN	Acquisition of intensity with detector placed behind each sample



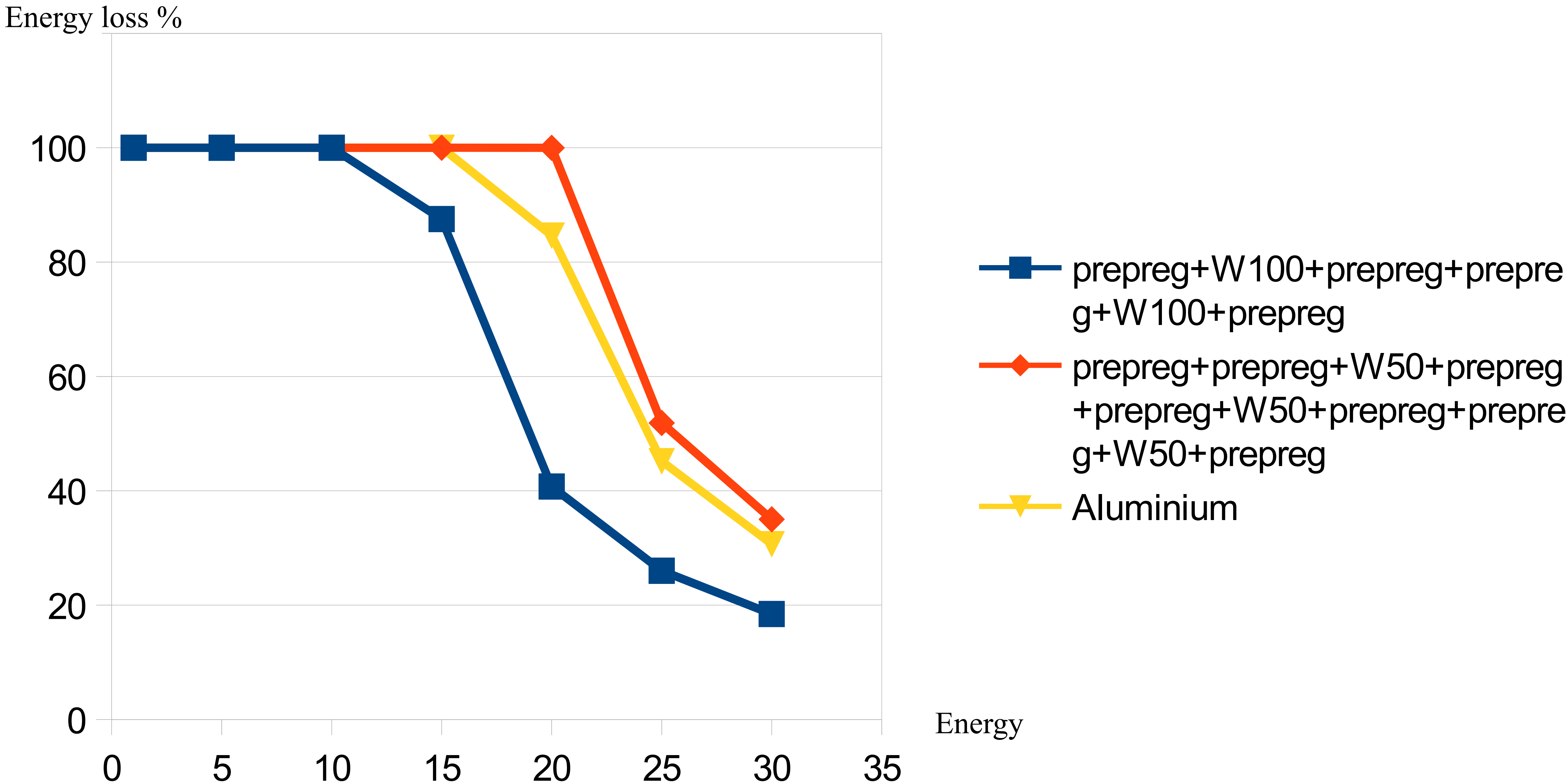


Correlation between Geant4 Model & Experimental



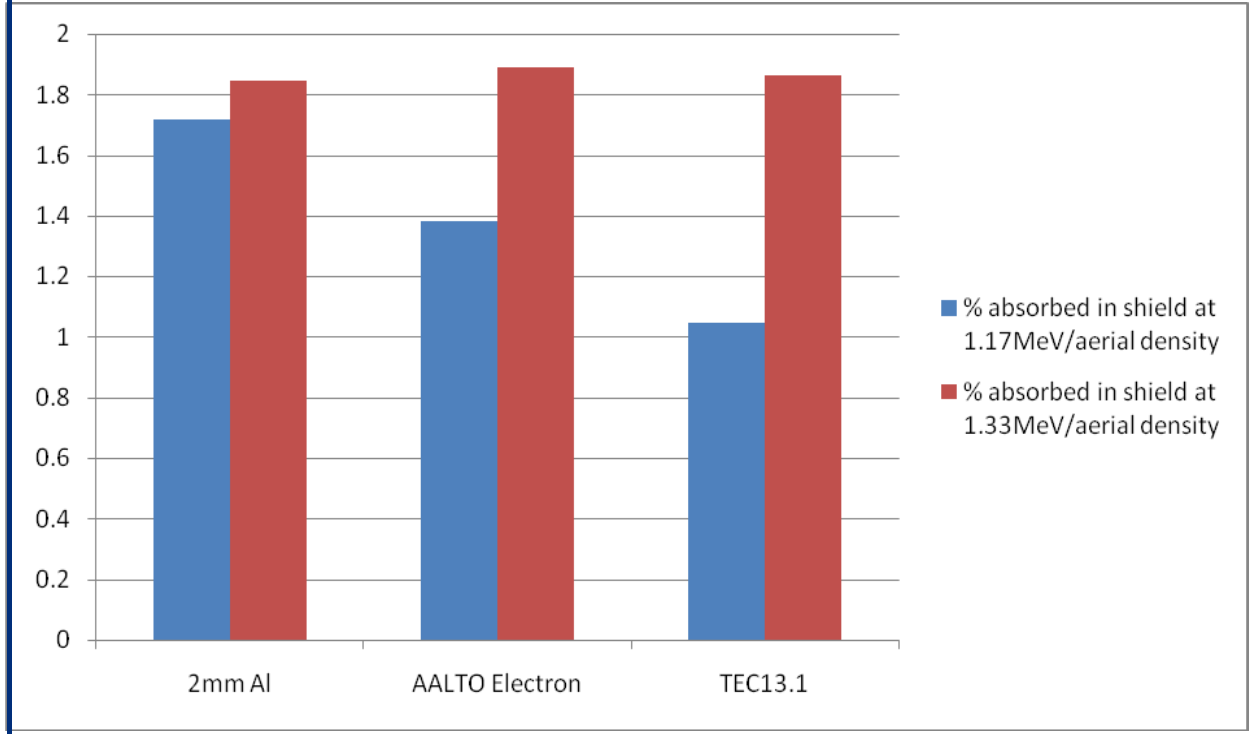


Performance predicted by Geant4 for the next test with respect to 2mm Al



γ

Source : ^{60}Co, measurement of photons spectrum after shielding



Gamma peak at 1.33 MeV the composite sample is more efficient shielding than Al. However, it is less efficient for the 1.17 MeV peak

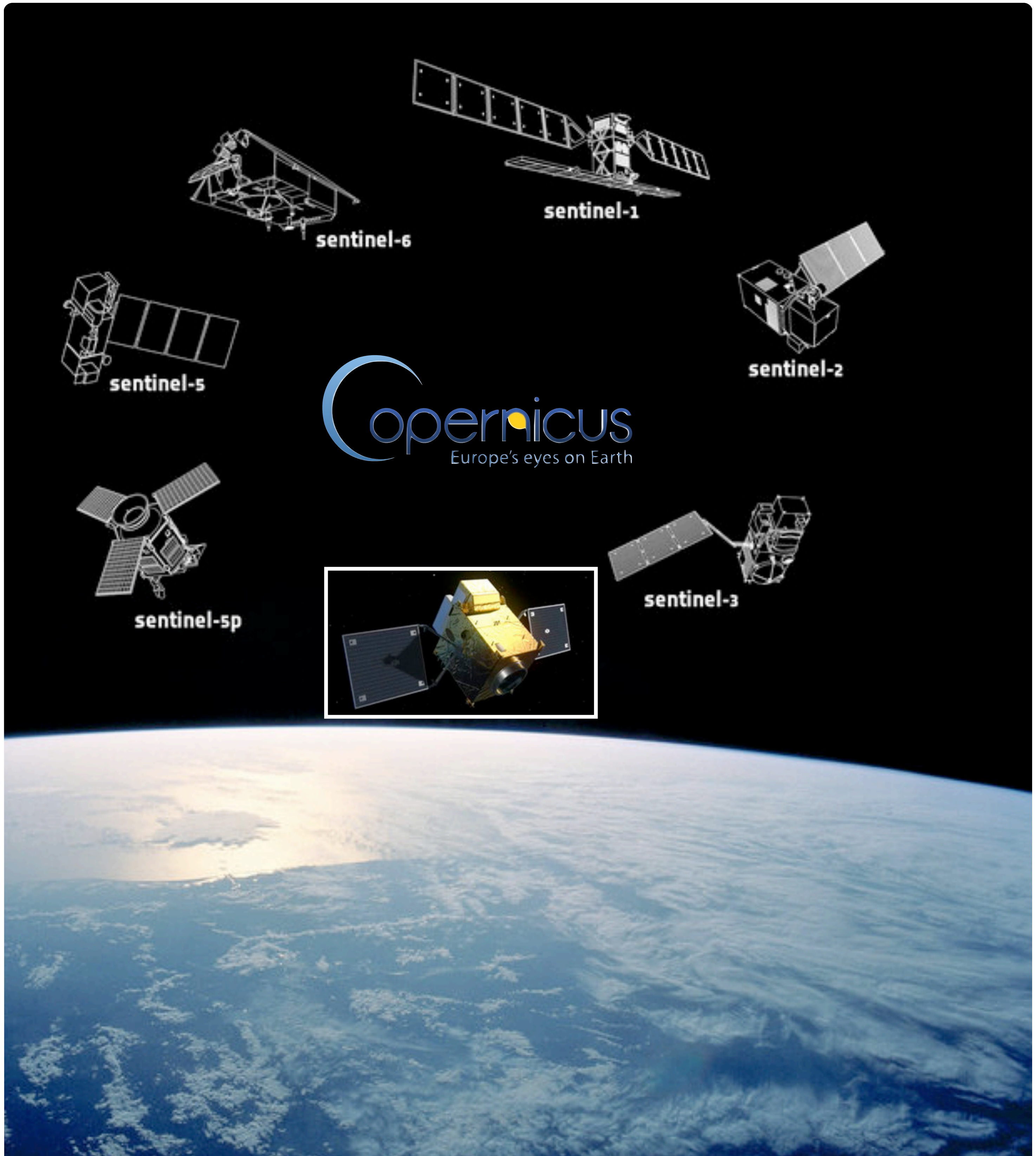
e-

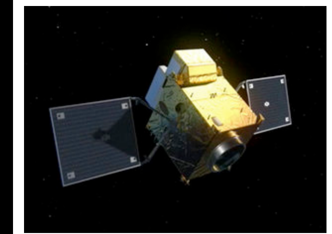
Medical electron accelerator was used to irradiate samples with 6 MeV electrons beam.

	No shield	Al 2mm shield	AALTO shield	TEC13_1 shield
Calculated dose Radfet 1 (cGy)	78.92	18.34	75.74	78.13
Calculated dose Radfet 2 (cGy)	80.52	23.92	74.94	82.91

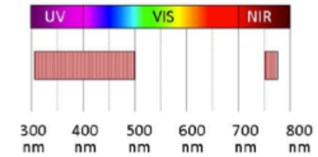
No more efficient than aluminium. New combinations will be tested in the next phases of the project

Sentinel 4 : optical coating testing





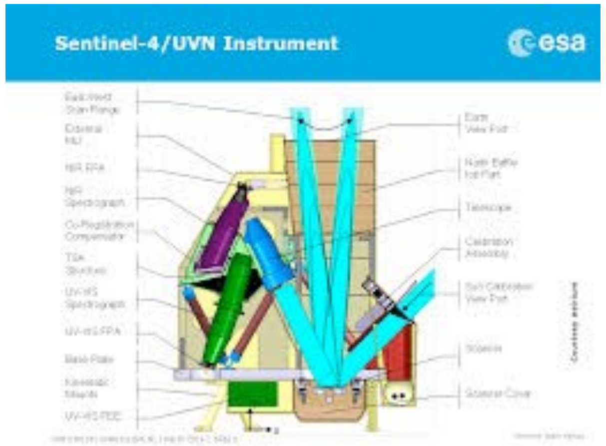
programme Copernicus



mission : monitoring de qualité air, O3, NO2, SO2, HCHO et aerosol optical depth

Orbit : GEO

hyperspectral spectrometer operating with designated spectral bands in the solar reflectance spectrum



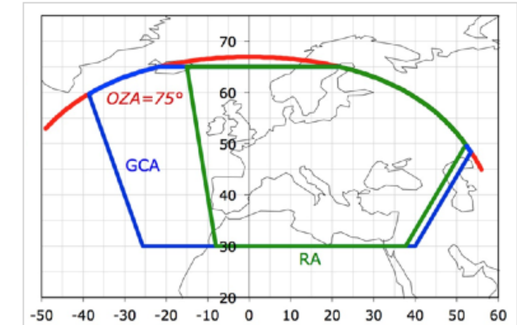
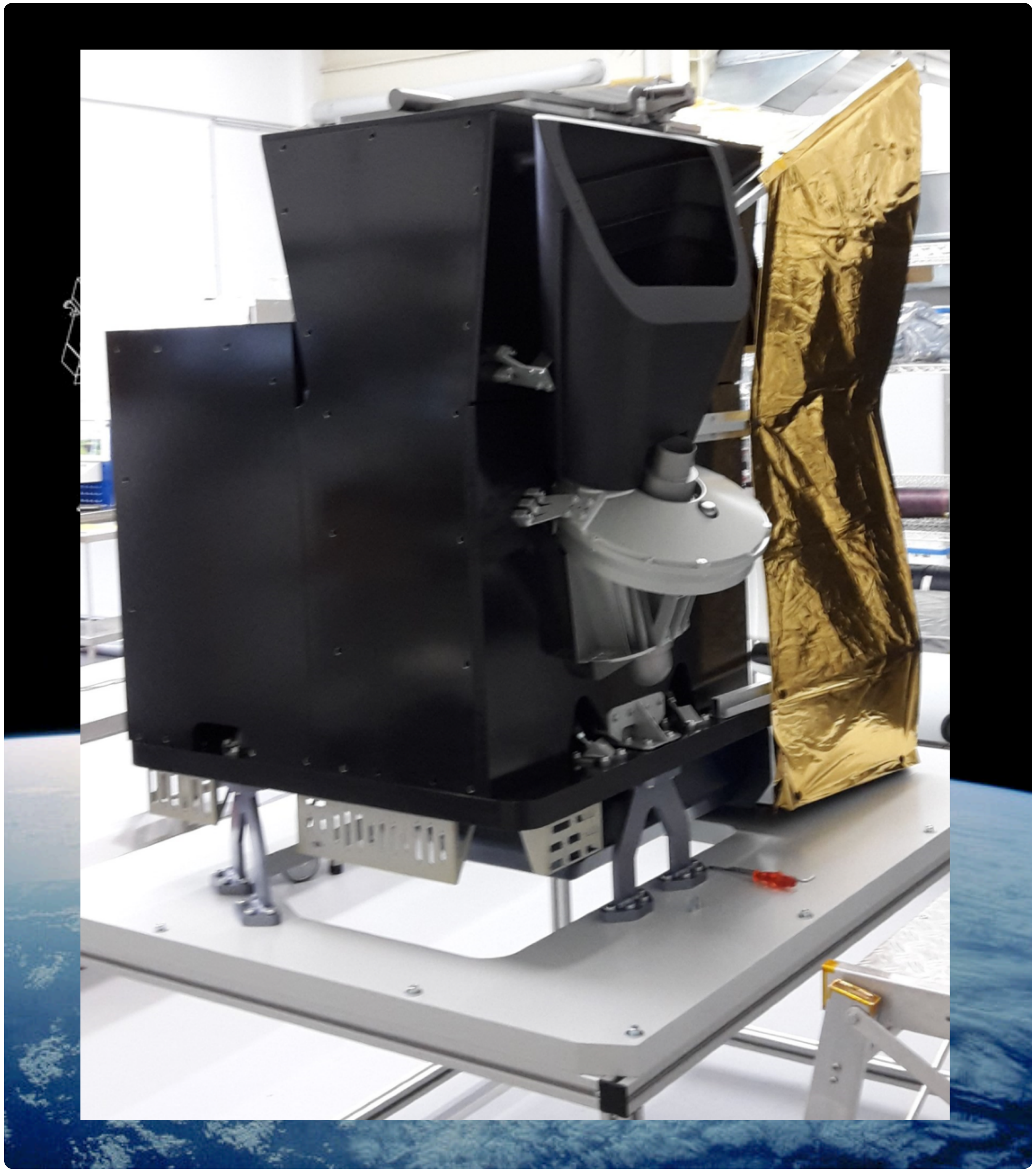
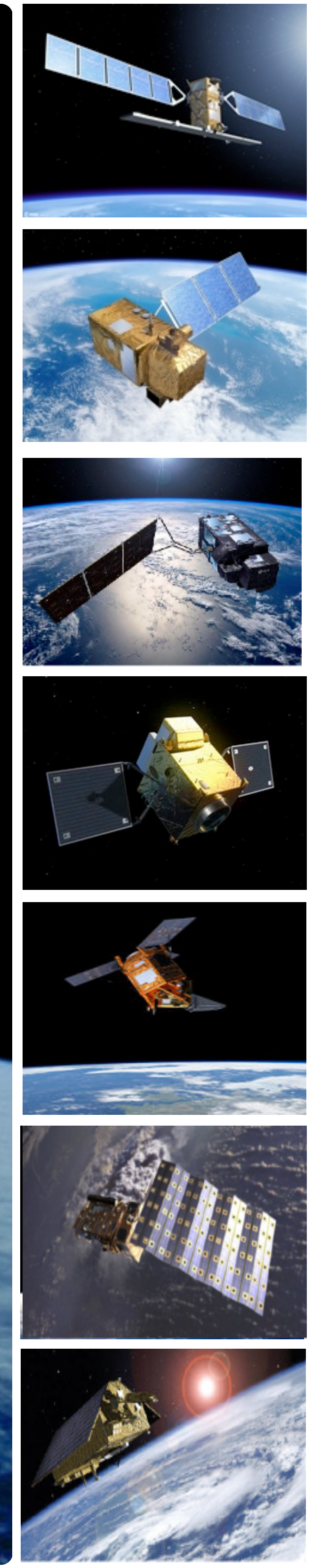


Figure 1: SENTINEL-4 Geographical Coverage Area (GCA) Reference Area (RA) and Observation Zenith Angle (OZA). (Credit: ESA)

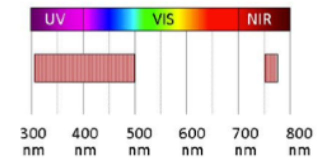
key features spectral range from 305 nm to 500 nm with a spectral resolution of 0.5 nm, and from 750 nm to 775 nm with a spectral resolution of 0.12 nm, in combination with low polarization sensitivity and a high radiometric accuracy.

Sentinel 4 : optical coating testing





programme Copernicus

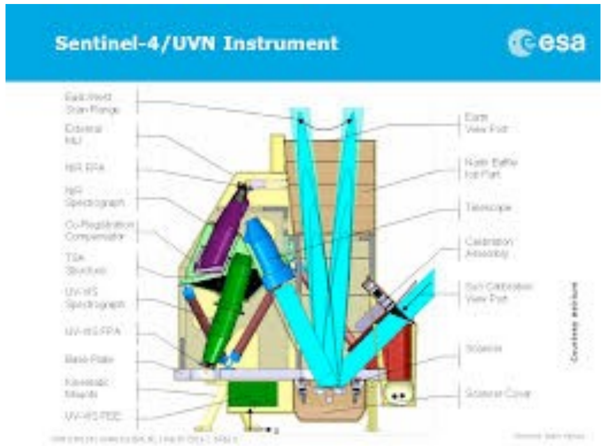


mission : monitoring de qualité air,

O3, NO2, SO2, HCHO et aerosol optical depth

Orbit : GEO

hyperspectral spectrometer operating with designated spectral bands in the solar reflectance spectrum



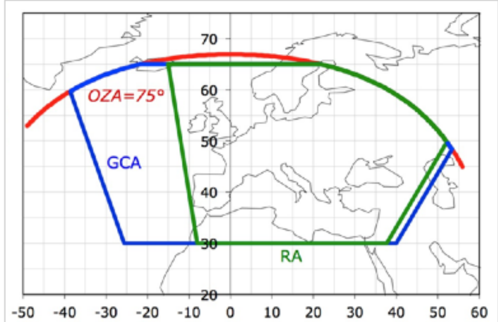


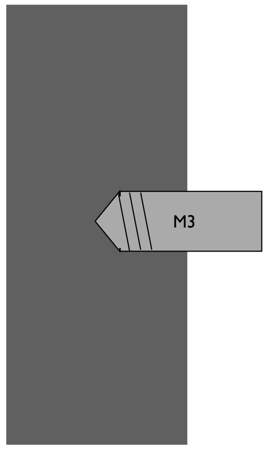
Figure 1: SENTINEL-4 Geographical Coverage Area (GCA) Reference Area (RA) and Observation Zenith Angle (OZA). (Credit: ESA)

key features spectral range from 305 nm to 500 nm with a spectral resolution of 0.5 nm, and from 750 nm to 775 nm with a spectral resolution of 0.12 nm, in combination with low polarization sensitivity and a high radiometric accuracy.

Fig. 1 Samples Description

Description: Test Sample

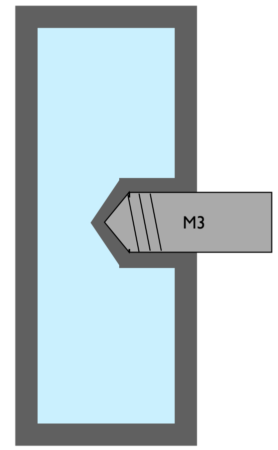
Material	Thicknes s (µm)
Al	5550



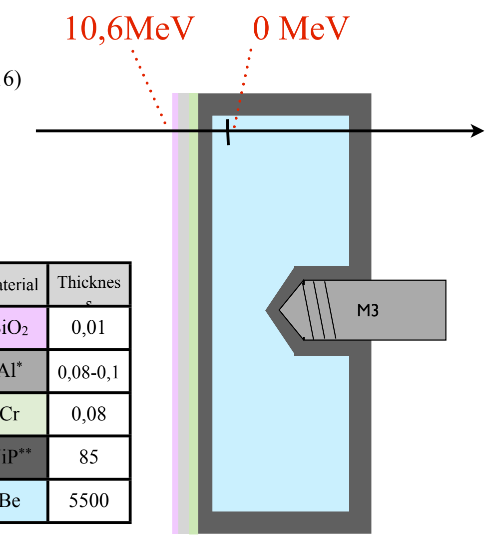
Description: Blank Sample S1_08

Layer name-Role	Material	Thicknes s
Optical Coating L#1 protective layer	x	x
Optical Coating L#1 protective layer	x	x
Interface - Adhesion layer	x	x
Encapsulating Coating	NiP**	85
Bulk	Be	5500

**(stoechiometry needs to be checked)



Description: Samples S1_xx (04,11,15,16)



Layer name-Role	Material	Thicknes s
Optical Coating L#1 protective layer	SiO_2	0,01
Optical Coating L#1 protective layer	Al*	0,08-0,1
Interface - Adhesion layer	Cr	0,08
Encapsulating Coating	NiP**	85
Bulk	Be	5500

*(Alflex® from OBJ)

**(stoechiometry needs to be checked)

given in the order of a cross-section from the optical surface to the rear surface of the mirror

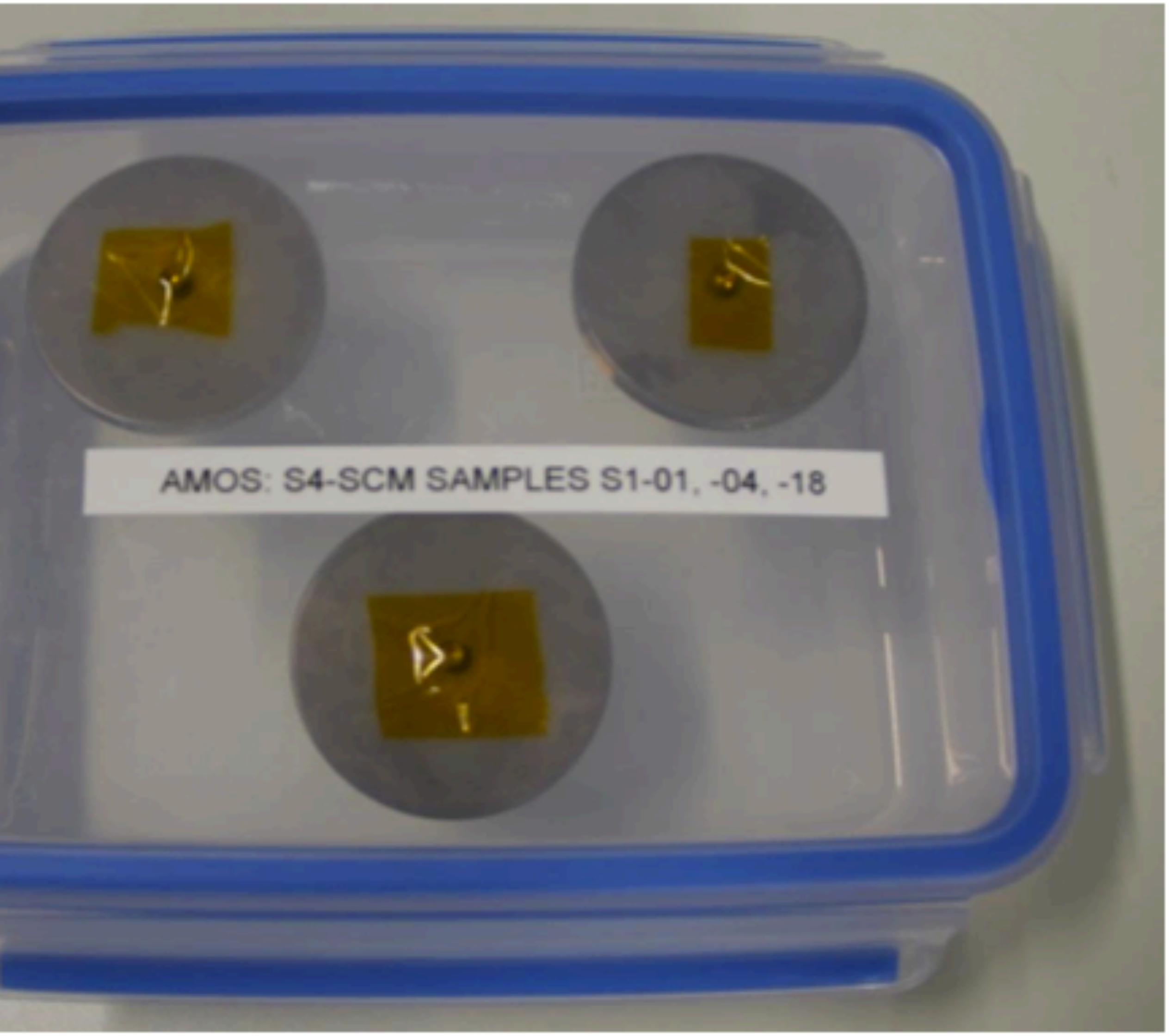
10,6MeV → 0

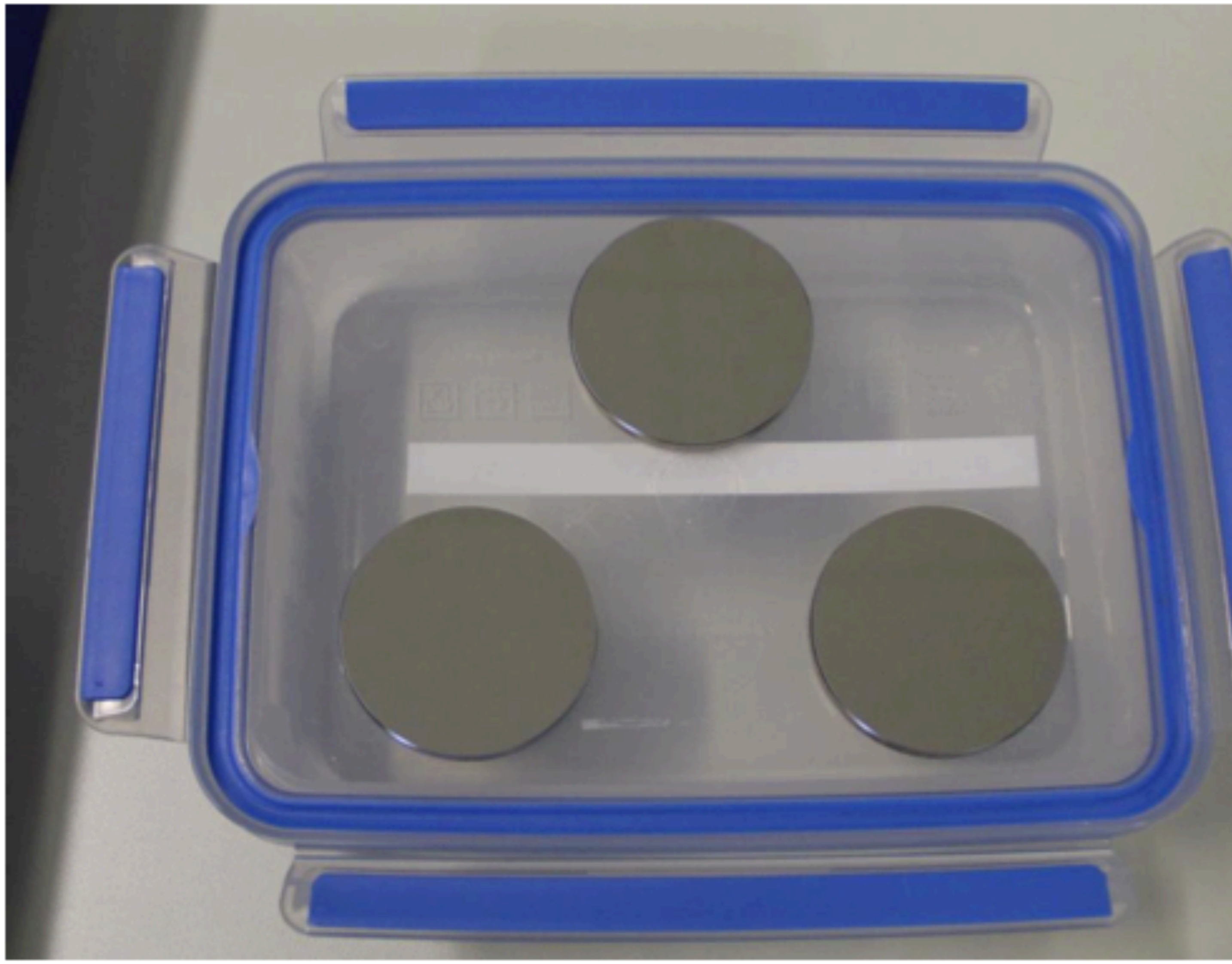
Material/LayerThickness	Impinging/Outgoing Energy (keV)	Energy Loss (keV)
SiO_2/0,010µm	10600/10599	1
Al/0,08-0,1µm	10599/10598	1
Cr/0,08µm	10598/10596	2
NiP/85µm	10596/8613	1983
Be/5500µm	8613/0	8613 (All) (Range:623,4µm)
NiP/85µm (rear)	0/0	0

Properties	Phosphorus content (%)		
	Low	Medium	High
Nickel, % (mass)	96 - 99	92 - 95	88 - 91
Phosphorus, % (mass)	1 - 4	5 - 8	9 - 12
Vickers microhardness without heat treatment, HV	650 - 750	500 - 550	450 - 500
Vickers microhardness with heat treatment, HV	1000 - 1050	900 - 950	850 - 900
Melting point, °C	1200	890	870
Density, g/cm^3	8.5 - 8.7	8.1 - 8.3	7.7 - 7.8
Resistivity, µΩ/cm	50	70	90
Resistance to abrasion	Superior	Very good	Very good
Weldability	Good	Regular	Bad

Compound	density (g/cm3)
SiO_2	amorphous 2,196
NiP	(m%Ni88P12) 7,7

AMOS
ADVANCED MECHANICAL AND OPTICAL SYSTEMS





Vickers microhardness without heat treatment, HV	650 - 750	500 - 550	450 - 500
Vickers microhardness with heat treatment, HV	1000 - 1050	900 - 950	850 - 900
Melting point, °C	1200	890	870
Density, g/cm^3	8.5 - 8.7	8.1 - 8.3	7.7 - 7.8
Resistivity, µΩ/cm	50	70	90
Resistance to abrasion	Superior	Very good	Very good
Weldability	Good	Regular	Bad

AMOS
ADVANCED MECHANICAL AND OPTICAL SYSTEMS

Sentinel 4 : optical coating testing

Particles	Energy	Facility	Dose	Deliverables
H+	10 MeV	Cyclotron	TID	T control, grounding, P control, contamination , induced activity (gamma spectro)
H+	100keV	VDG	TNID	Grounding, P control, contamination

Table 7-1: TID and TNID figures for Sentinel-4 environment in the coating and in the substrate

Radiation Environment	Irradiation	Fluence [#/cm²]	TID coating rad(SiO2)	TID interface rad(Be)	TNID coating MeV/g(Si)	TNID interface MeV/g(Si)
Space	-	-	1.8E+09	2.0E+05	4.8E+14	8.3E+07
On-ground	20 keV electrons	1.3E+16	3.6E+09	0.0E+00	-	-
	10 keV protons	2.9E+14	1.2E+09	-	9.9E+14	-
	14.1 MeV neutron	4.6E+10	-	-	1.7E+08	1.7E+08
	Co-60	2.8E+15	3.27E+04	4.0E+05	-	-
		RDM	2.0	2.0	2.1	2.0

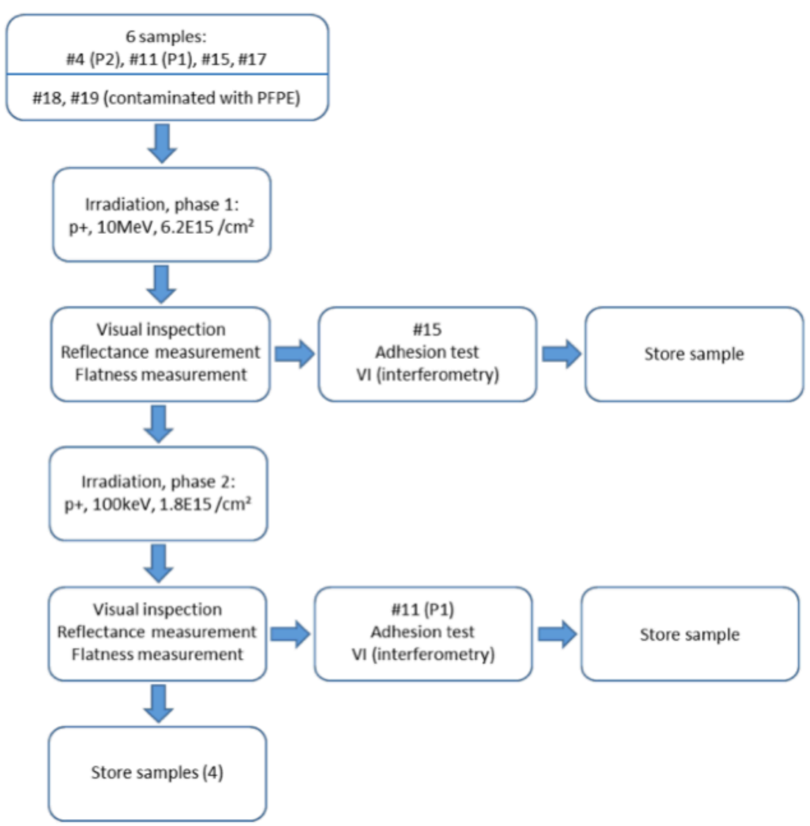
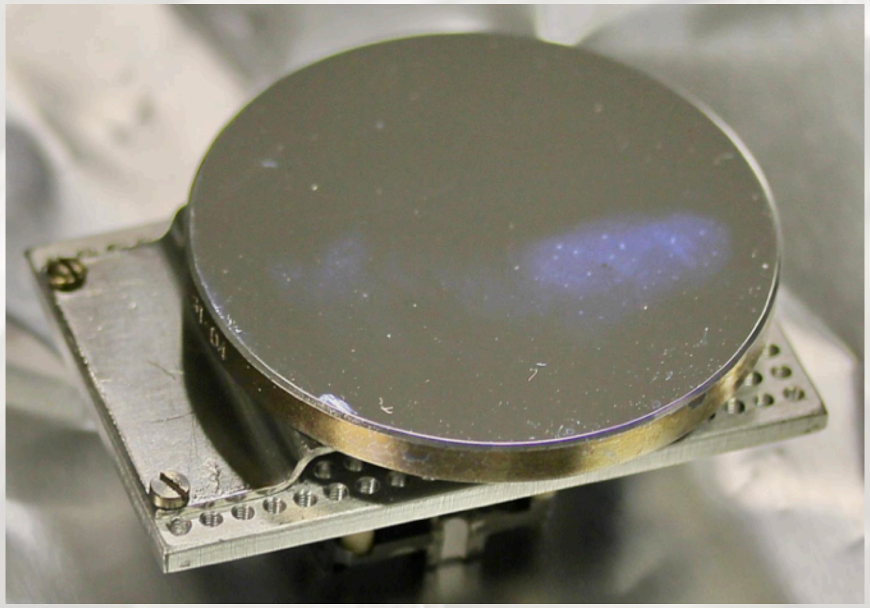


Figure 1: Radiation test flow

Table 7-2: tests parameters

Irradiation step	Irradiation type	Fluence [#/cm²]
Phase 1	10 MeV protons	6.2E+15
Phase 2	100 keV protons	1.8E+15

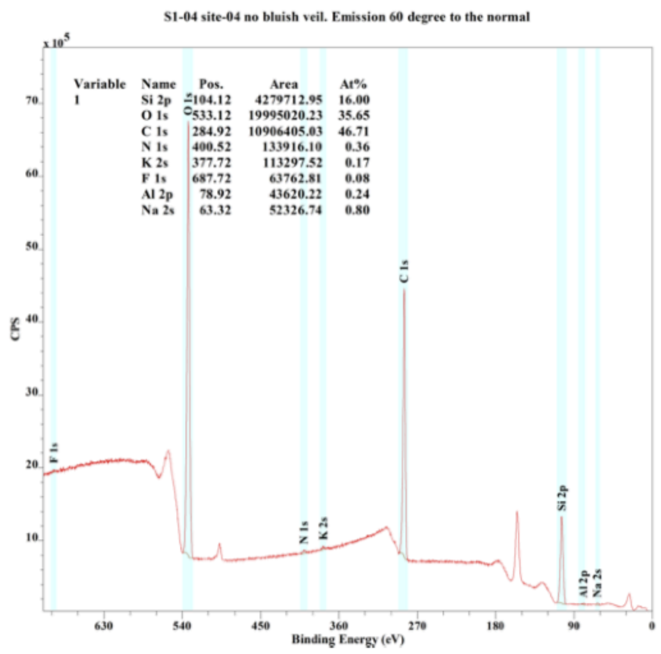
10MeV 6,2 10^{15} p/cm^2

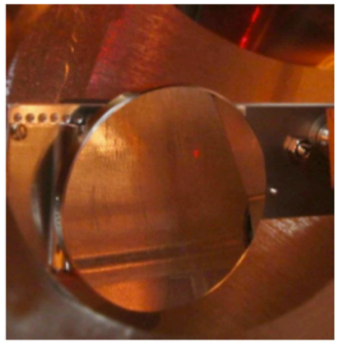


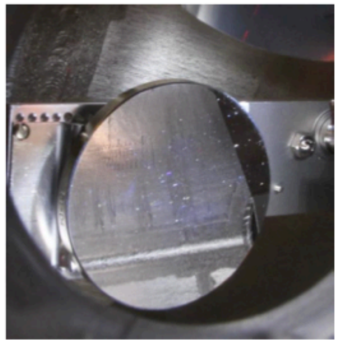
Disqualified mirror set:

- Apparition of a blue voile
- Degradation of optical performances
- Investigation of causes of **«surface contamination ?»**
  - LogFile,
  - FTIR of contamination witness
  - XPS measurements
  - Optical Microscopy and 3D AFM

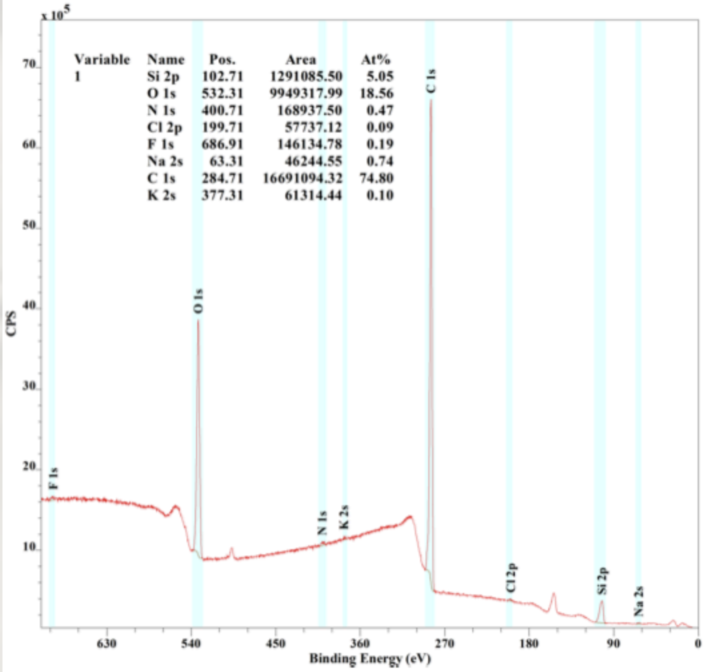
cf. theory

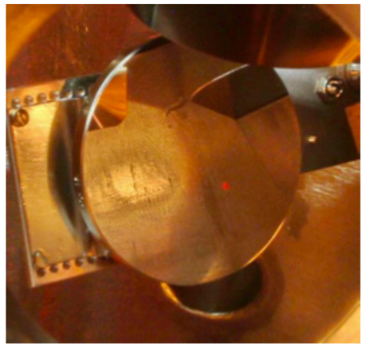


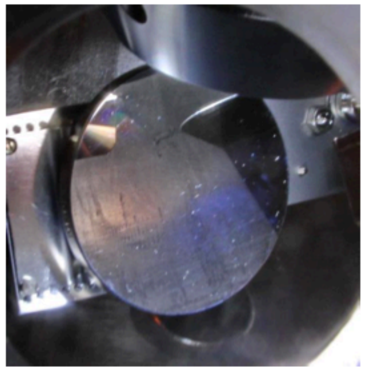




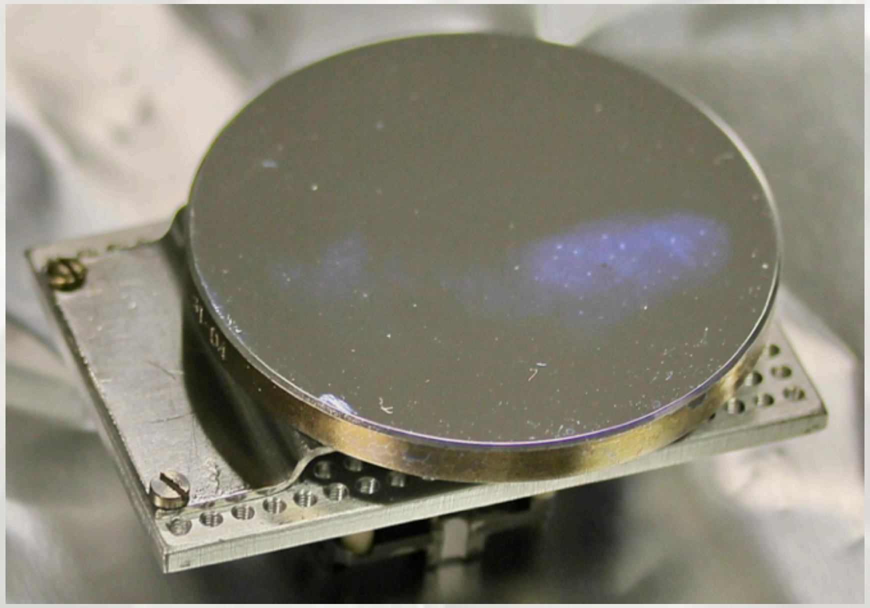
Texte







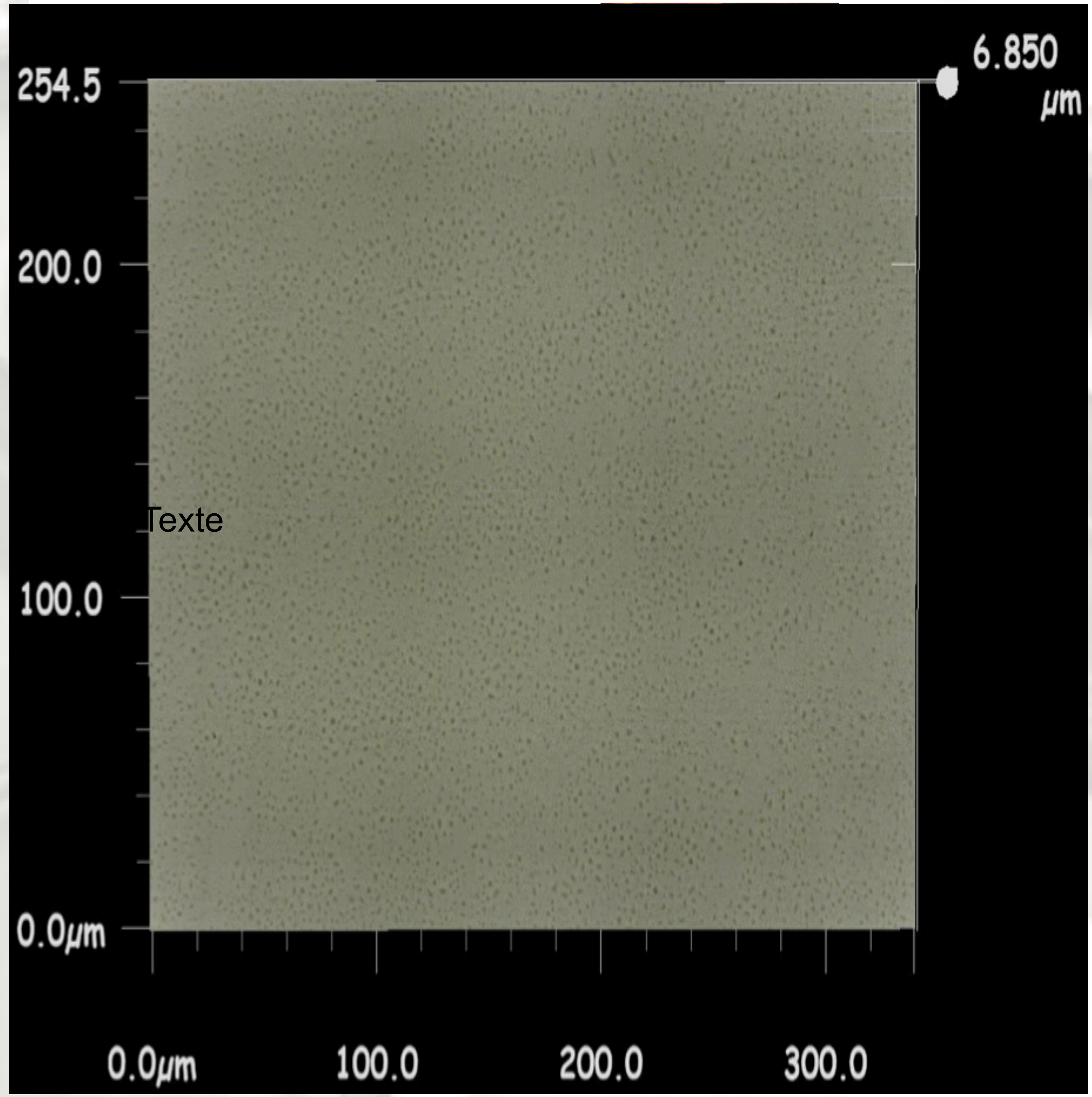
10MeV 6,2 10^{15} p/cm^2



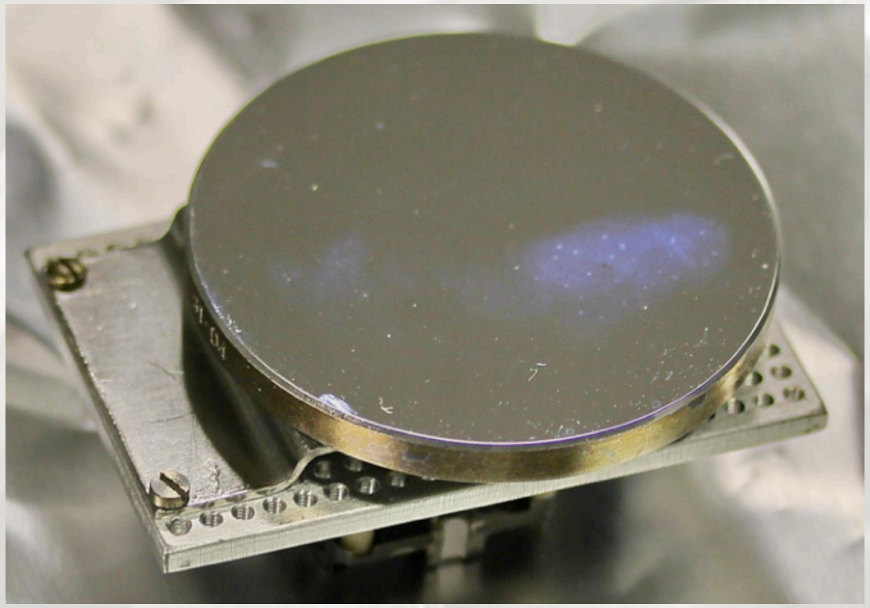
Disqualified mirror set:

- Apparition of a blue voile
- Degradation of optical performances
- Investigation of causes of **«surface contamination ?»**
  - LogFile,
  - FTIR of contamination witness
  - XPS measurements
  - Optical Microscopy and 3D AFM

cf. theory



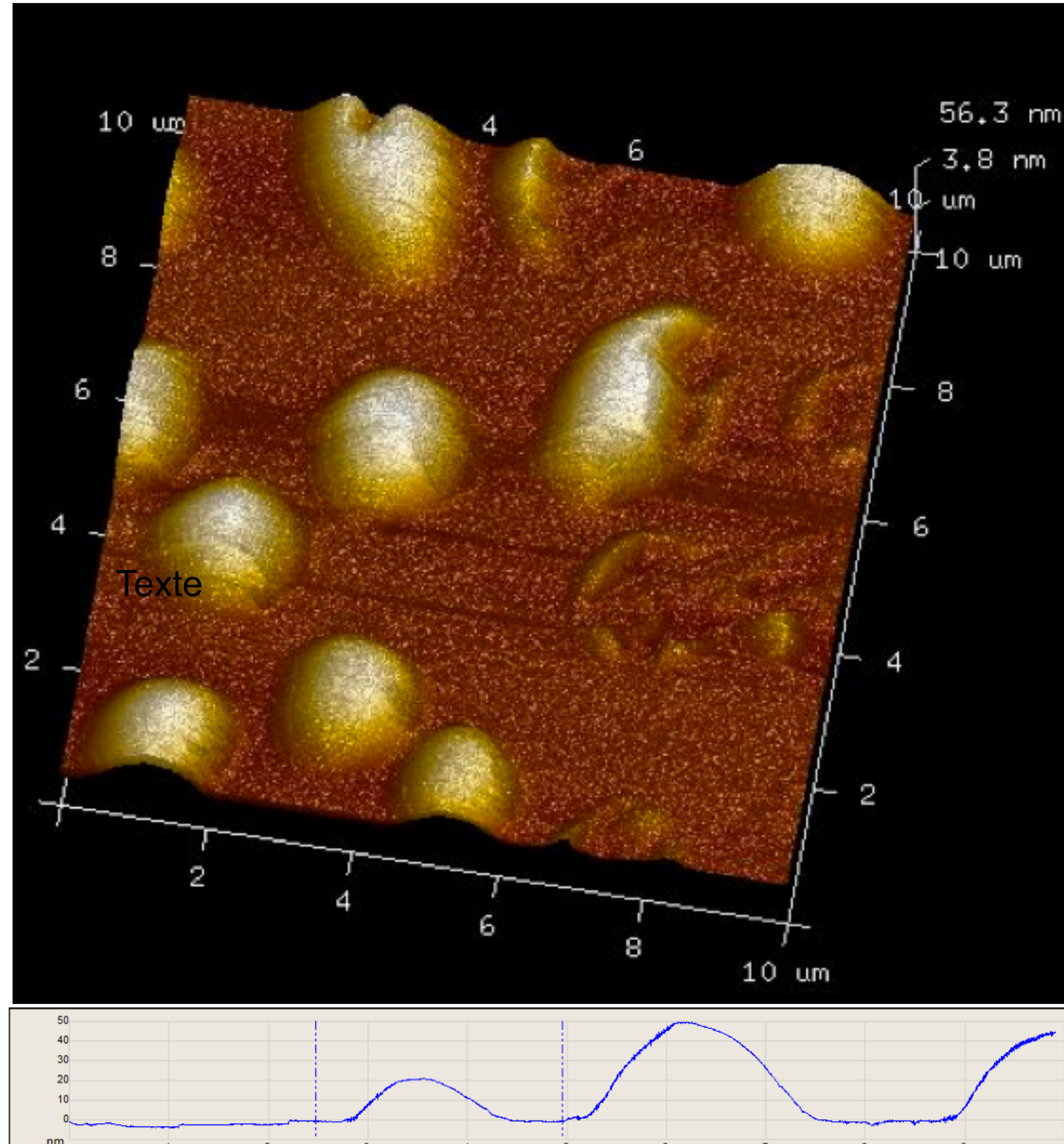
10MeV 6,2 10^{15} p/cm^2



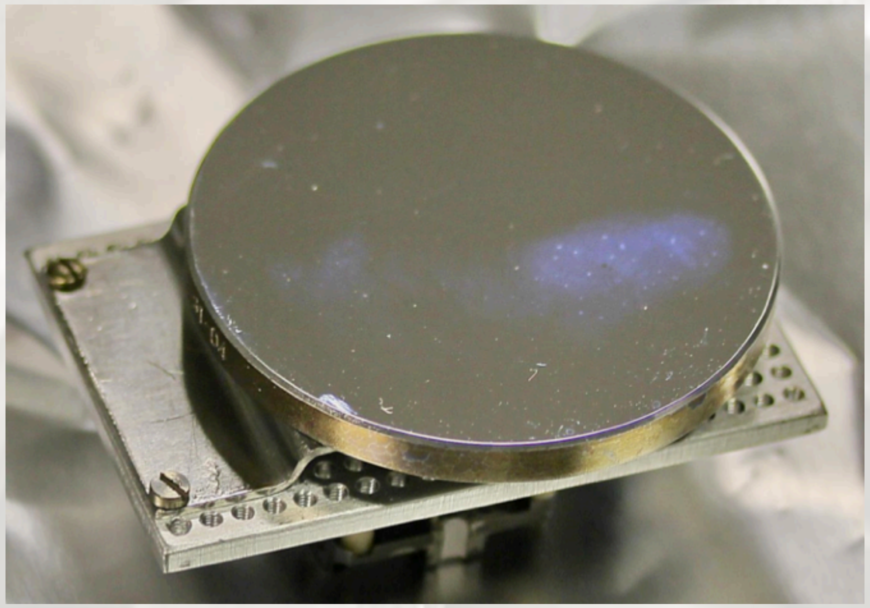
Disqualified mirror set:

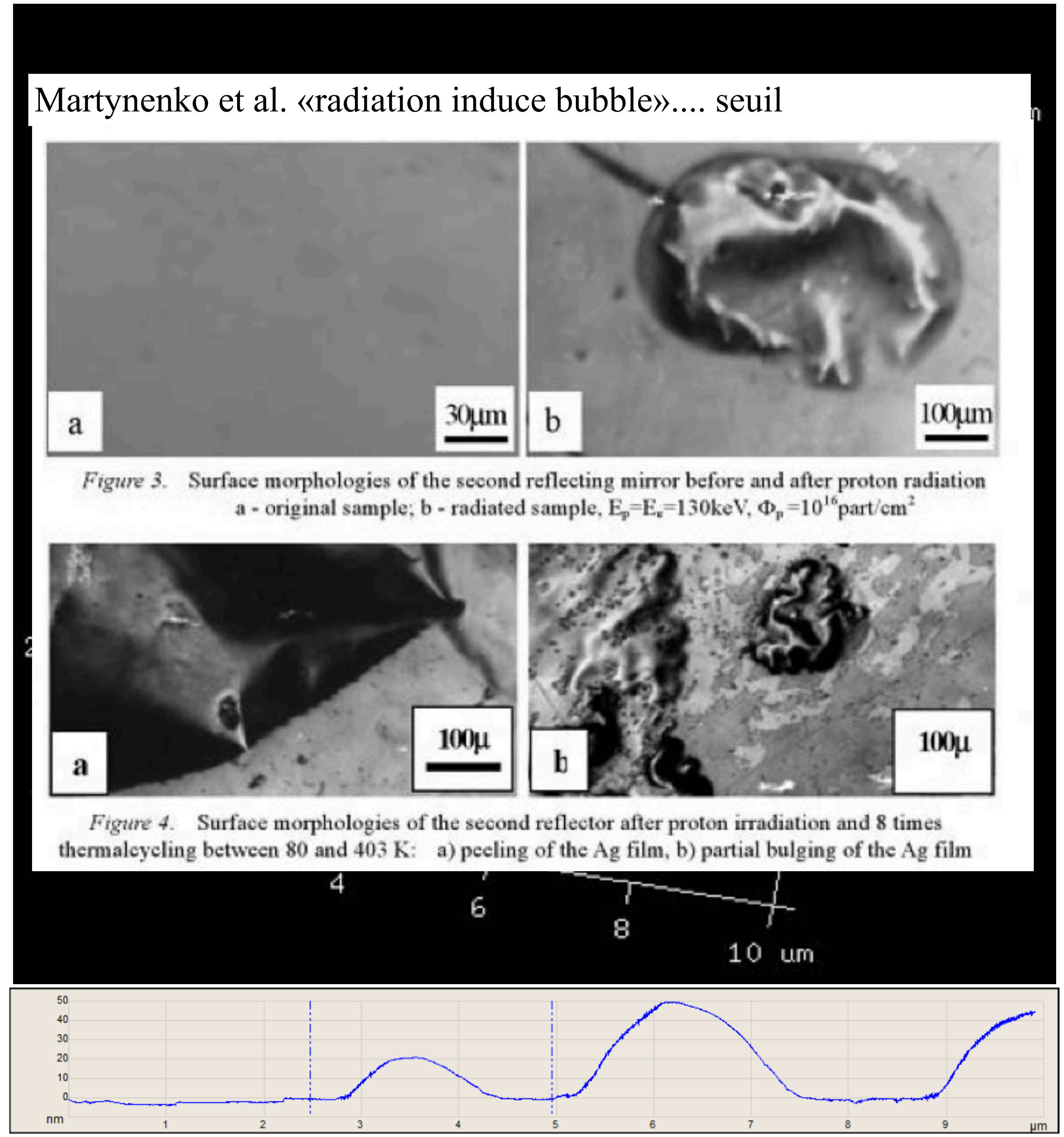
- Apparition of a blue voile
- Degradation of optical performances
- Investigation of causes of **«surface contamination ?»**
  - LogFile,
  - FTIR of contamination witness
  - XPS measurements
  - Optical Microscopy and 3D AFM

cf. theory



10MeV 6,2 10^{15} p/cm^2





Disqualified mirror set:

- Apparition of a blue voile
- Degradation of optical performances
- Investigation of causes of **«surface contamination ?»**
  - LogFile,
  - FTIR of contamination witness
  - XPS measurements
  - Optical Microscopy and 3D AFM

cf. theory

Sentinel 4 : optical coating testing - Test 2

Particules :	Energie:	Facilité:	Dose :	Délivrables
H+	100keV	VDG	TID	T control, grounding, P control, contamination
H+	100keV	VDG	TNID	T control, grounding, P control, contamination

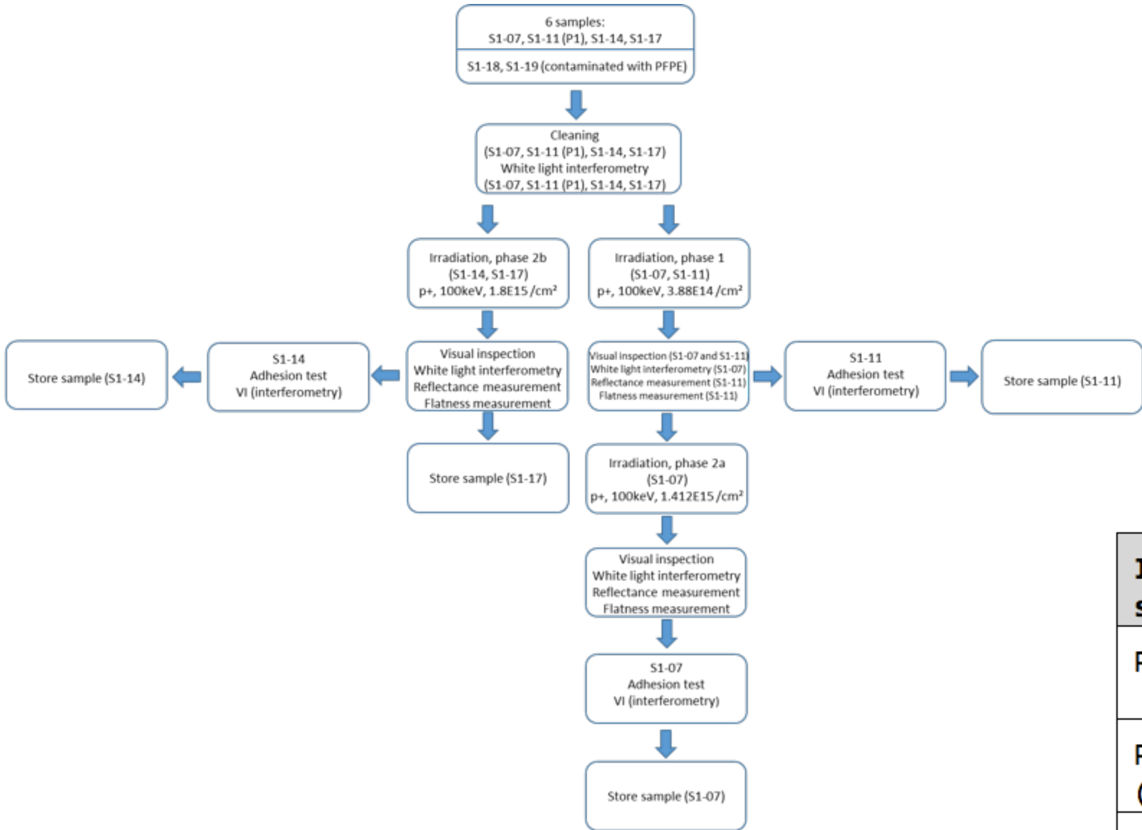


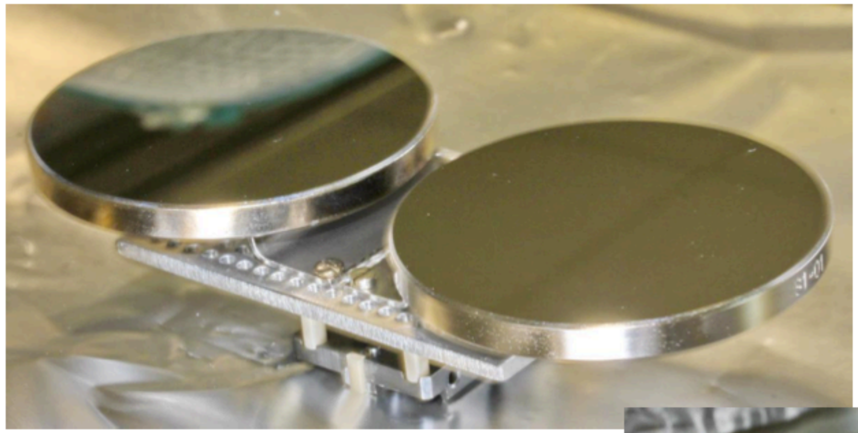
Table 7-1: TID and TNID figures for Sentinel-4 environment in the coating and in the substrate

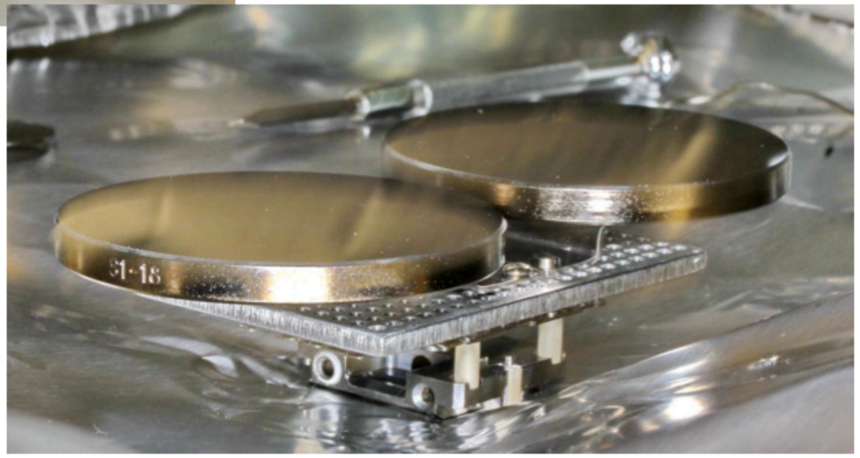
Radiation Environment	Irradiation	Fluence [#/cm²]	TID coating rad(SiO2)	TID interface rad(Be)	TNID coating MeV/g(Si)	TNID interface MeV/g(Si)
ace	-	-	1.8E+09	2.0E+05	4.8E+14	8.3E+07
n-ground	20 keV electrons	1.3E+16	3.6E+09	0.0E+00	-	-
	10 keV protons	2.9E+14	1.2E+09	-	9.9E+14	-
	14.1 MeV neutron	4.6E+10	-	-	1.7E+08	1.7E+08
	Co-60	2.8E+15	3.27E+04	4.0E+05	-	-
		RDM	2.0	2.0	2.1	2.0

Table 7-2: tests parameters

Irradiation step	Irradiation type	Fluence [#/cm²]	Flux [#/cm²/s]	Duration	Samples #
Phase 1 (TID)	100 keV protons	3.88E+14	4.49E+9	24h	#7, #11
Phase 2a (TNID)	100 keV protons	1.412E+15	4.49E+9	86h	#7
Phase 2b (TNID)	100 keV protons	1.8E+15	4.49E+9	111h	#14, #17

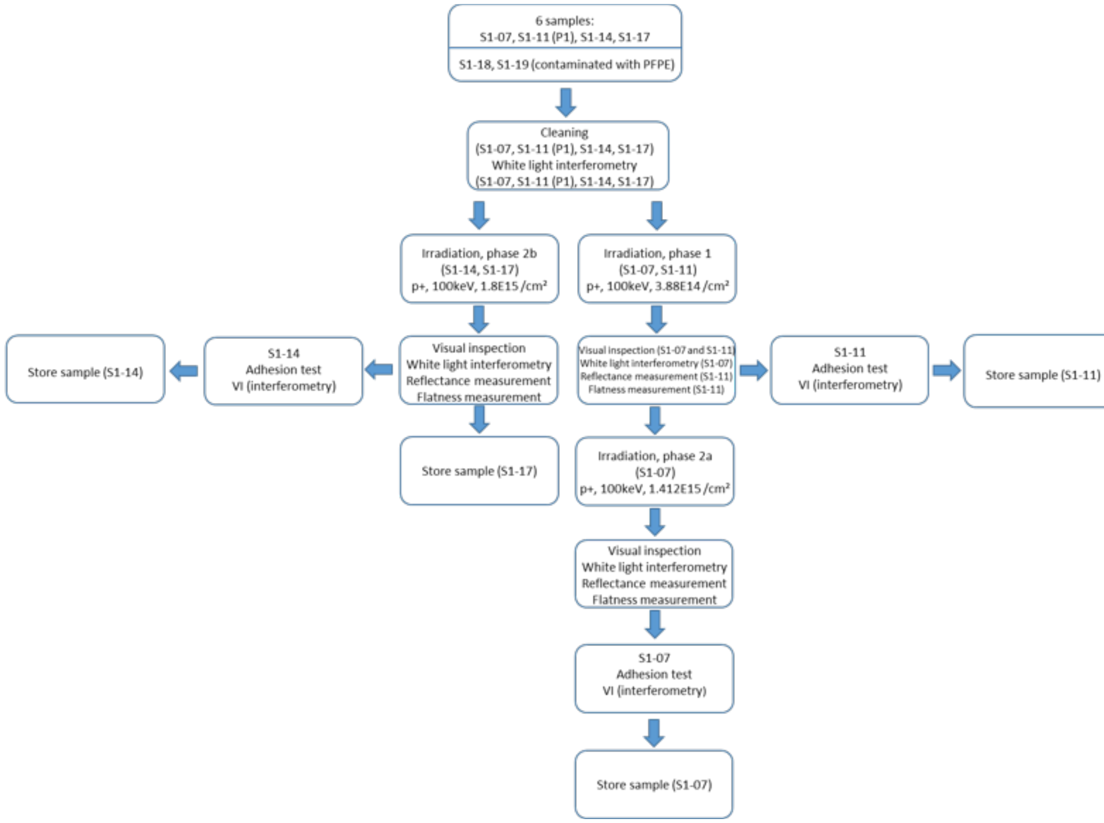
100 keV All doses





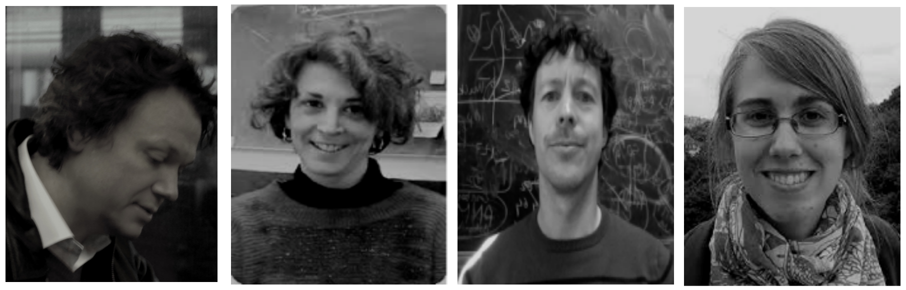
visual inspection **OK**
optical performance test **OK**
I,P,T LogFile analysis, **OK**
FTIR measurements **OK**

Test successfull



Perspectives

- New accelerator: use of proton therapy center to get 20-230 MeV protons (2019)



Thank you for your attention

Fundings :

Université de Liège

ULg

ILSN

esa

Acknowledgements:

Centre Spatial de Liège

K. Fleury-Frenette
B. Marquet
J. Y. Plesseria
J. H. Lecat
L. Rossi
A. Carapelle
O. Dubreuil
T. Jacquemart
A. Marchal
T. Schoonjans ....

Aalto University School of Science and Technology

AMOS Advanced Mechanical and Optical Systems