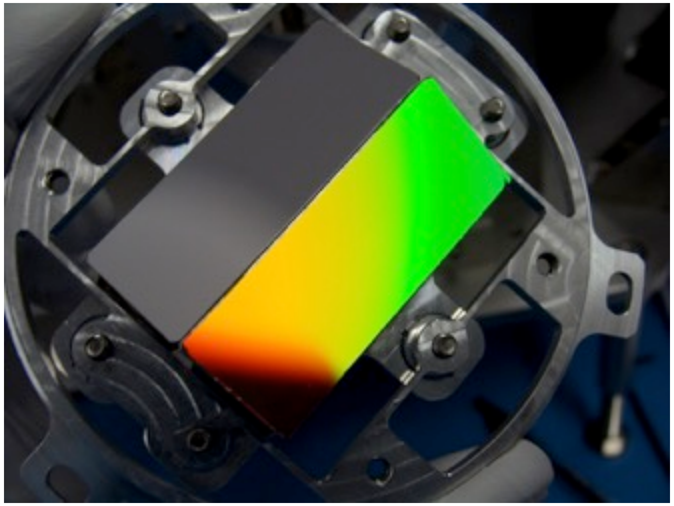
PHEBUS

Probing of Hermean Exosphere by UV Spectroscopy



DESIGN

CALIBRATION

EXPERIENCE FEEDBACK

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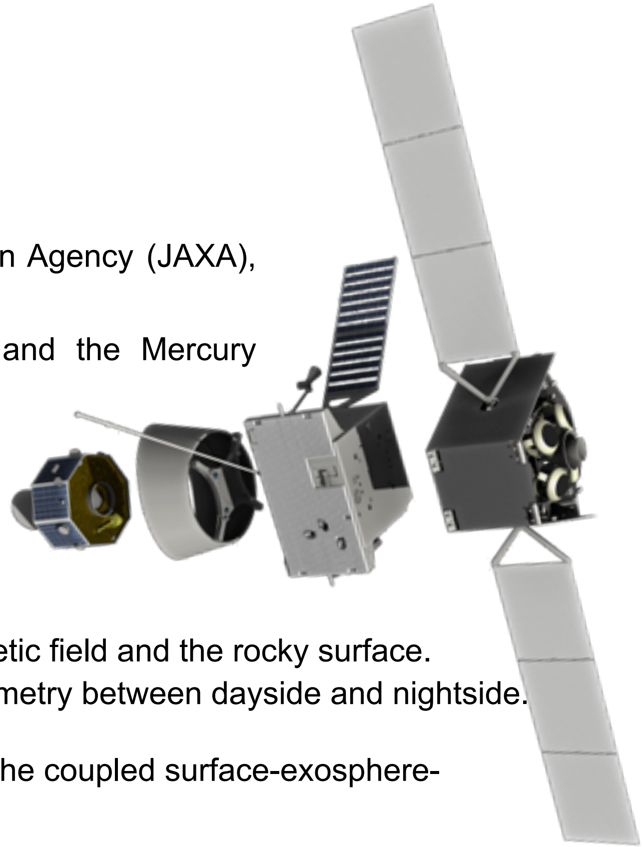
CONTEXT : The BepiColombo mission

Mission

- BepiColombo is the first European mission toward Mercury.
- Cornerstone mission of the ESA Cosmic Vision program.
- BepiColombo is a joint mission between ESA and the Japan Aerospace Exploration Agency (JAXA), executed under ESA leadership.
- The mission comprises two spacecraft: the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO).



PHEBUS: Scientific objectives

- The exosphere of Mercury is very tenuous, with a pressure of a fraction of picobar.
- The exosphere results from a complex interplay of the solar wind, the planetary magnetic field and the rocky surface.
- The exosphere is highly variable with time and space, characterized by a global asymmetry between dayside and nightside.

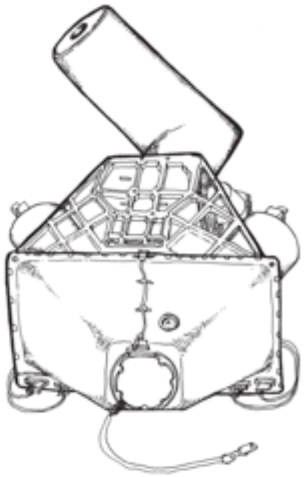
The core scientific objectives of PHEBUS are oriented toward a better understanding of the coupled surface-exosphere-magnetosphere system. The main measurement objectives are the following:

- To detect new species, including metallic species (Si, Mg, Fe, …), atoms (C, N, S, …), molecules and radicals (H_2O, H_2, OH, CO), noble gases (Ar, Ne), ions (He^+, Na^+, Mg^+, …), in addition to already detected species (Na, K, Ca, O, H, He).
- To measure an average exosphere (densities of constituents, vertical structure), with as much as possible species monitored together, at different positions of Mercury around the Sun.
- To measure sharp local and temporal variations of the exosphere content, at specific times and places of interest.
- To search for albedo variations of Mercury's nightside surface, lighted by the interplanetary H Ly-a glow, at 121.6 nm, in order to exhibit possible signatures of surface ice layers (H_2O, SO_2, N_2, CO_2,) in high latitude polar craters.

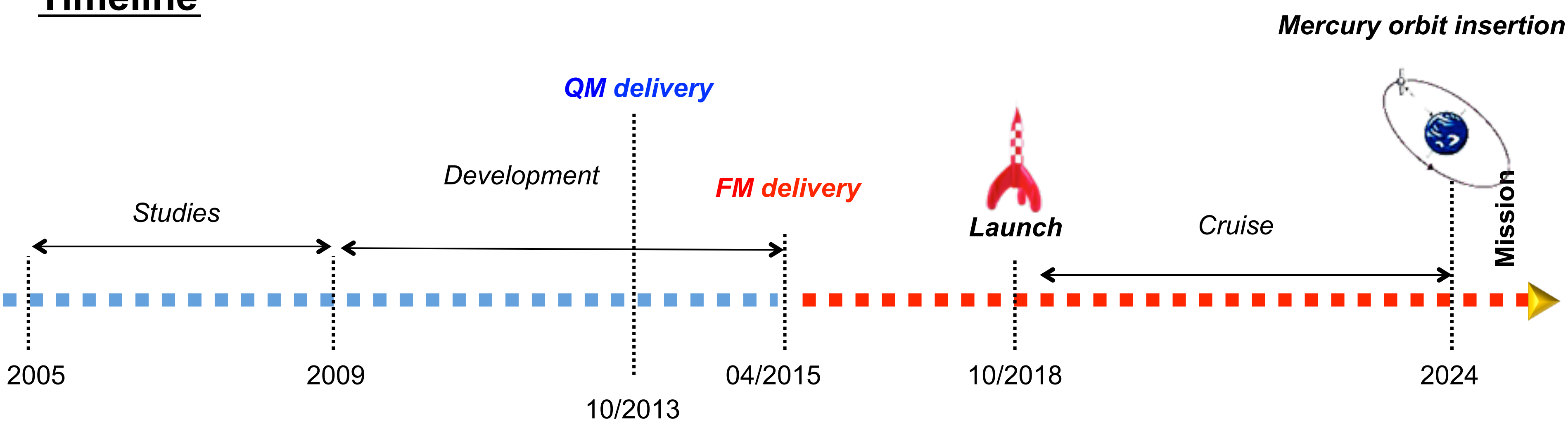
CONTEXT : The PHEBUS Project

French-led instrument with international cooperation

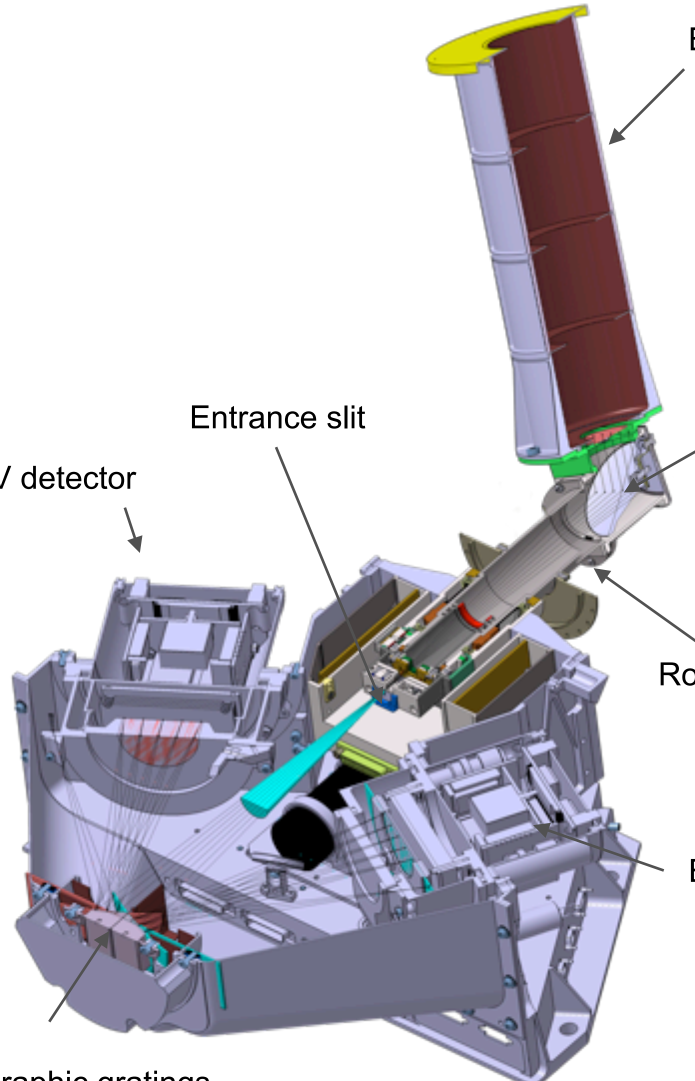
- PHEBUS: The only French PI-Ship instrument on board MPO.
- LATMOS/CNRS : Project leadership.
- CNES : Prime contractor ship of the French contribution.
- International cooperation:
  - Japan – Tokyo University (I. Yoshikawa): FUV/EUV detectors supplier.
  - Russia - IKI (O. Korablev) : Pointing mechanism supplier.
  - Italy - LUXOR Lab, Padova University (M.G. Pelizzo): Optical calibrations.



Timeline



DESIGN – Instrument configuration



PHEBUS Spectrometer – Schematic view

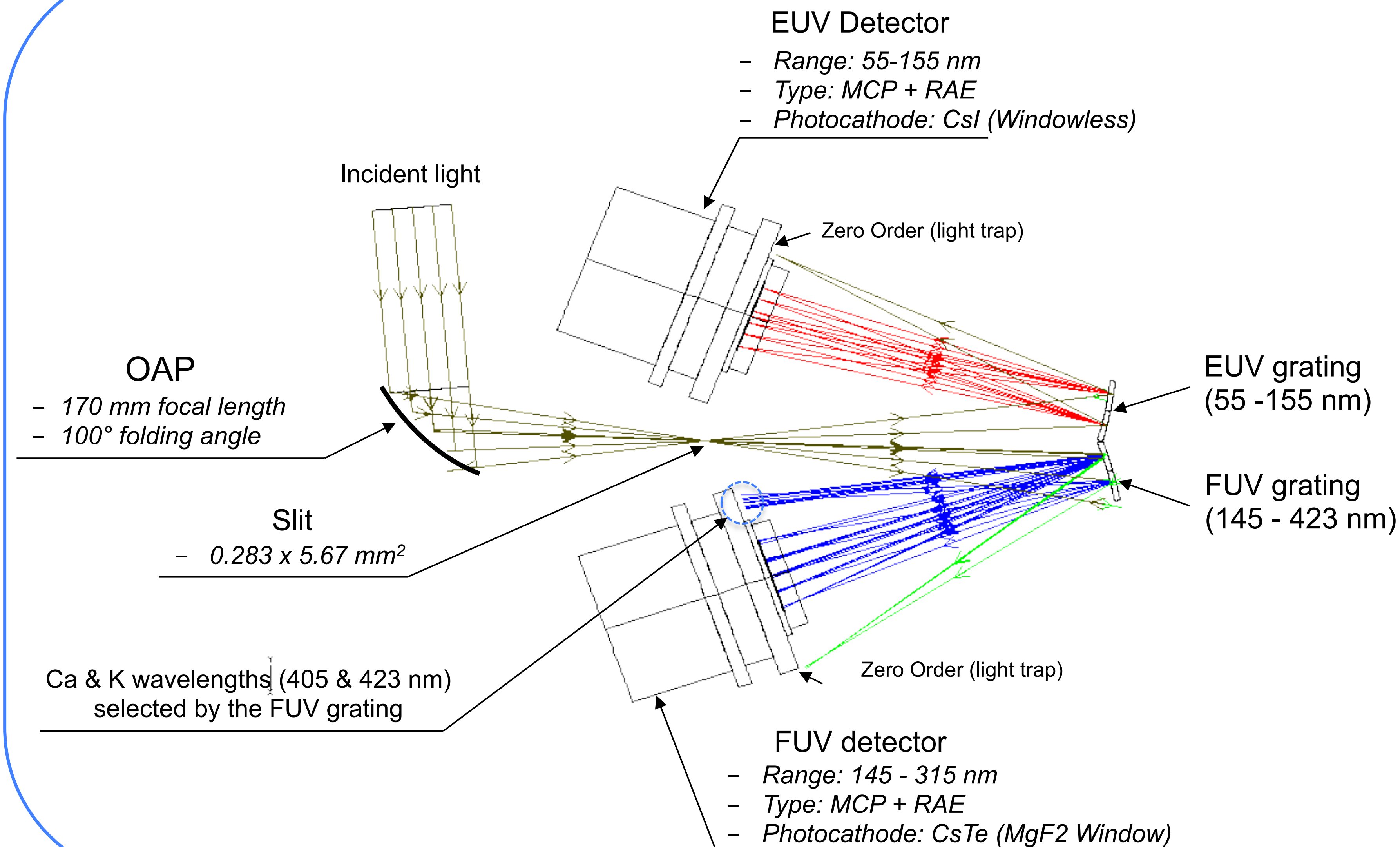
Spectral range	EUV : 55 nm - 155 nm FUV: 145 nm – 315 nm NUV lines: 404.7 nm & 422.8 nm
Spectral resolution	EUV : 0.5 nm FWHM FUV : 0.8 nm FWHM
f number	f/# = 6.7
Paraxial FOV	2° x 0.1°
Detection mode	Counting mode
Sensitivity	0.1 $ct.s^{-1}.R^{-1}$
Guard angle	± 8.3° (attenuation > 10^7)

Performances de l'instrument

Dimensions	500 x 400 x 400 mm^3
Weight	7.5 kg
Electric comsumption	25 W (max)

Caractéristiques dimensionnelles

OPTICAL DESIGN



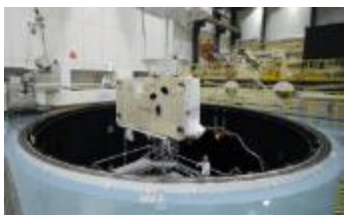
PHEBUS spectrometer – Optical design

DESIGN – Instrumental Philosophy

5 models

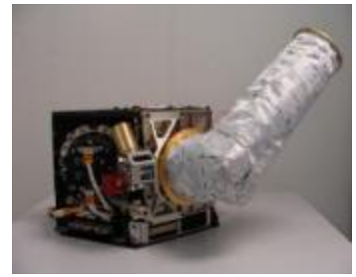
2009
Optical Prototype

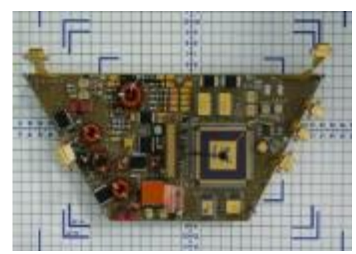
2010
Structural & thermal Model



2011
Electrical Model

2012 >> 2013
Qualification Model





2013 >> 2015
Flight Model

May 2015 >> 2017
Flight Spare

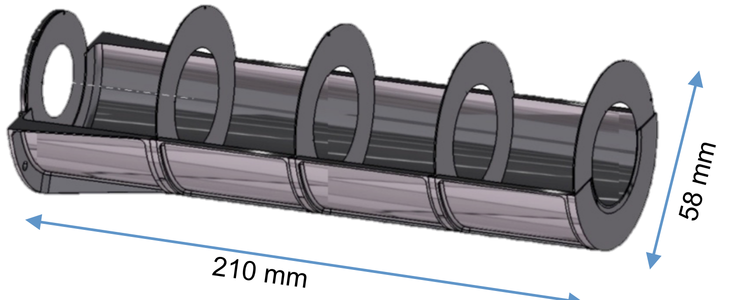
FS

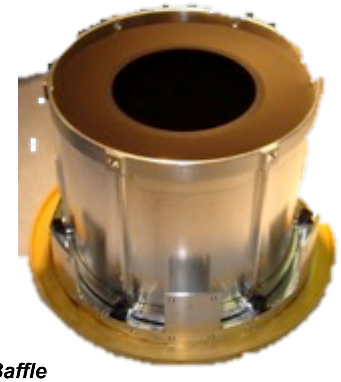
DESIGN – Optical subsystems

TELESCOPE

- Entrance baffle

Poids : 170g





PHEBUS Entrance Baffle

Objectives :

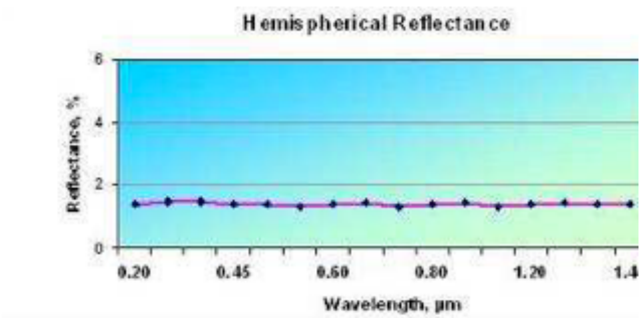
- Prevent direct illumination of the entrance mirror by a bright source located outside the guard angle (~8°)
- Attenuate the diffused light inside the baffle with multi-reflections before reaching the mirror
- Specification : Attenuation of 10^8 outside guard angle

Design guidelines (to apply to any surface inside the baffle):

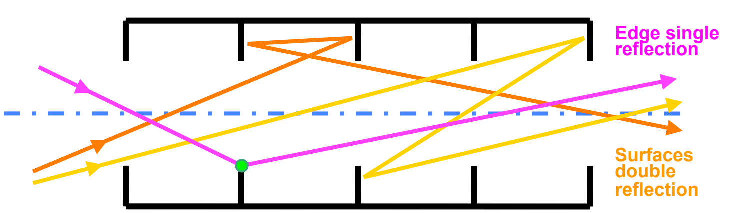
- Surface is not seen from the slit.
- OR: surface is not illuminated by direct light

Design:

- Cylindrical body with 4 stages / 5 diaphragms, including entrance pupil.
- Screwed aluminium assembly.
- Minimum of 2 diffuse reflections on the surfaces (geometry).
- Only 1 diffuse reflection on the edges (geometry).
- Black diffuse coating on surfaces : TIS ~ 1% (« Magic black » Acktar).
- Edges as thin as possible, also covered with black coating (Rc < 5 µm).



« Magic Black » Reflectance



Multi reflection example

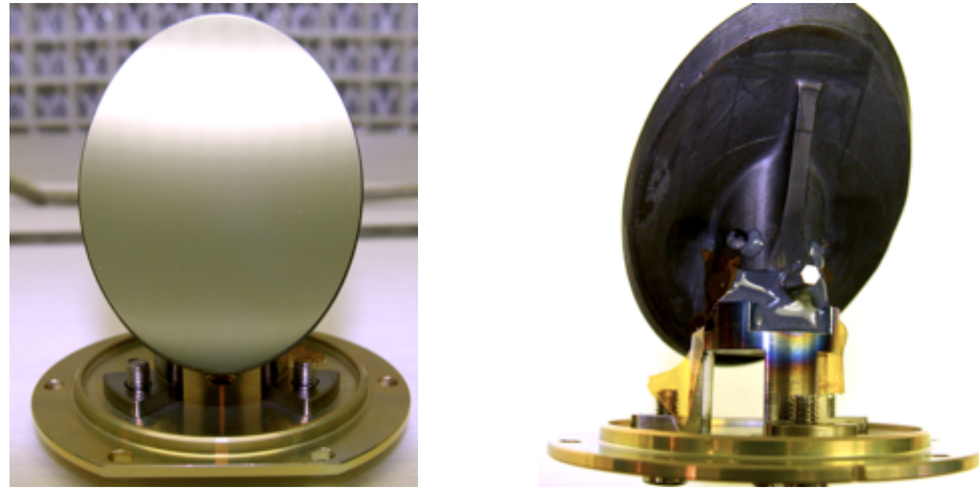
DESIGN – Optical subsystems

TELESCOPE

- Off axis parabola

Characteristics :

- f' = 170 mm.
- 100° folding angle – ϕ = 50 mm.
- Sintered SiC + SiC CVD (thickness~ 400 µm).
- Super polishing : roughness < 0.7 nm RMS.
- Shape error: SFE = 190 nm.



Off axis parabola

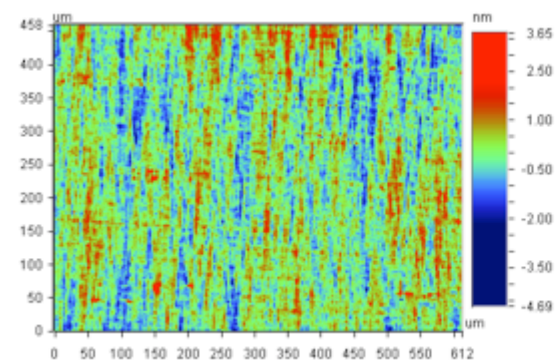
Justification of the Silicon Carbide choice :

- UV reflectivity.
- Thermal and mechanical properties (Low CTE, high thermal conductivity).

Manufacturing steps and industrial scheme:

1. Sintered SiC substrate manufacturing: *Boostec (France)*.
2. Rough machining & grinding (shape tolerance 3µm PV): *Nanoshape (Belgium)*.
3. CVD preparation (surface roughness ~ 0.2µm) : *AMOS (Belgium)*
4. CVD: *Schunk*.
5. Dye penetrant inspection: *AMOS*
6. Fine grinding and polishing down to 1nm of RMS roughness: *AMOS*
7. Correction of shape error by ion etching: *AMOS*

} AMOS (steps 2–7)



Roughness measurement

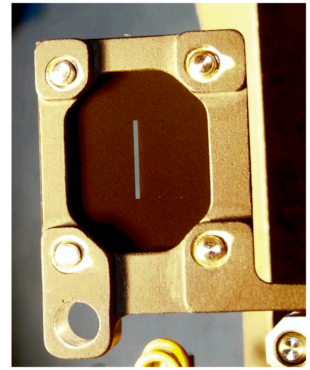
DESIGN – Optical subsystems

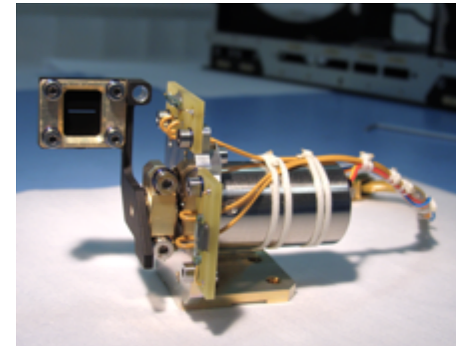
SPECTROMETER

- Entrance slit

Characteristics:

- Nickel electroforming (0.283 x 5.67 mm^2).
- CuO black coating.
- Movable mechanism (star calibration).



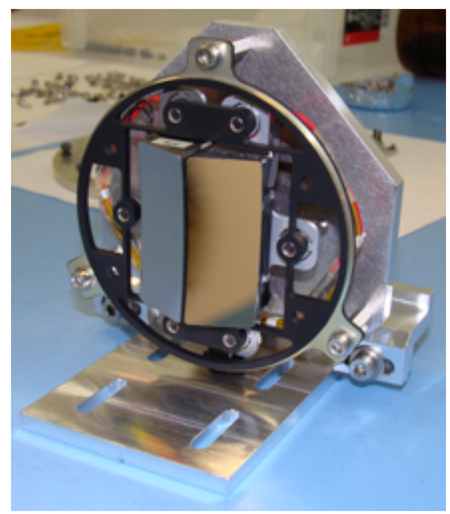


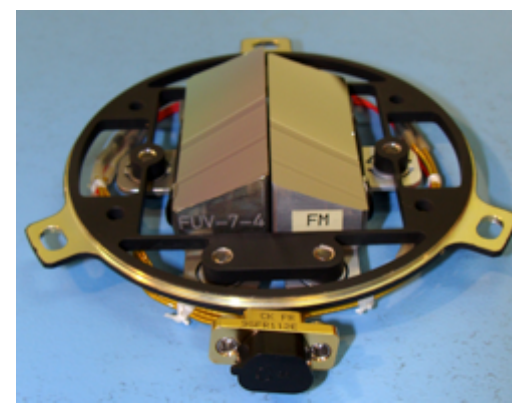
Entrance slit

- Diffraction gratings (*Horiba JobinYvon*)

Type	Holographic (aberrations corrected)
Shape	Spherical (R = 173.55 mm)
Materials	Substrate : Aluminium 7075 Reflective coating : + Pt coating
Groove profile	Laminar ion-etched
Groove density	EUV grating : 2726 gr/mm FUV grating : 1603 gr/mm
Size	14 x 44 mm^2

Characteristics





Holographic gratings

DESIGN – Optical subsystems

- Detectors

- Mode: photon counting.
- Technology : Micro Channel Plate (MCP) + Resistive Anode Encoder (RAE).
- Gain : ~2×10^7.

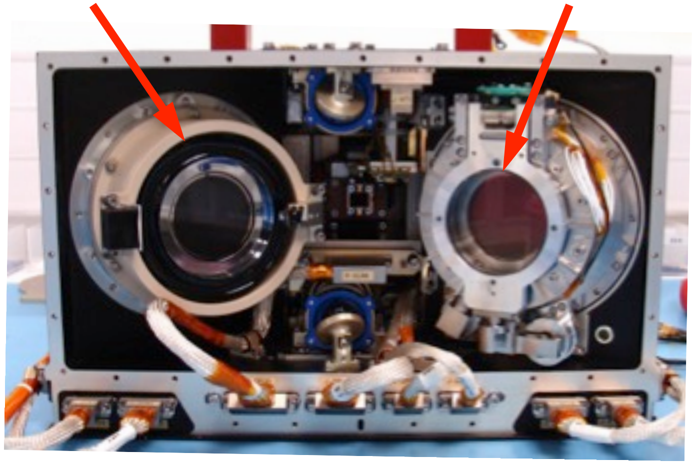
Dimensions: active area is 40x25 mm^2 , equivalent to a matrix of 1024x512 virtual pixels (spectral x spatial).

FUV detector

- *145 - 315 nm*
- *Photocathode CsTe*
- *Window MgF_2*

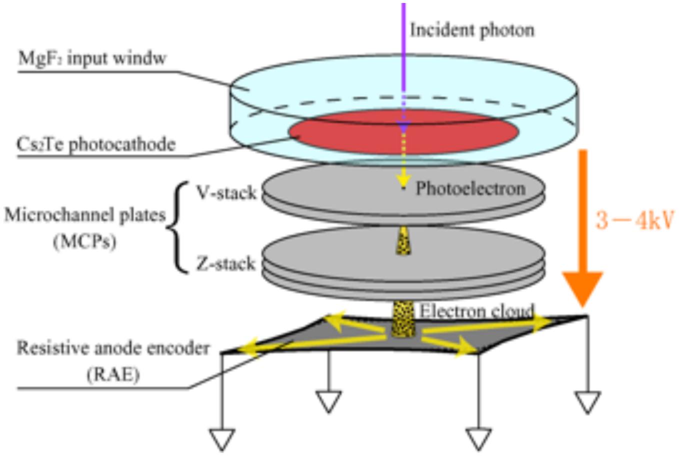
EUC detector

- *55 - 155 nm*
- *Photocathode CsI*
- *Windowless*

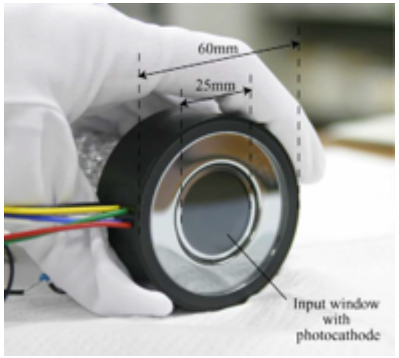


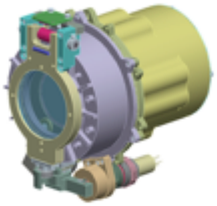
Advantages :

- Very high sensitivity mainly due to a very low dark current : < 1 ct/s/cm^2 (from -20°C to 40°C)
- No cooling system => avoid mass and power expensive devices

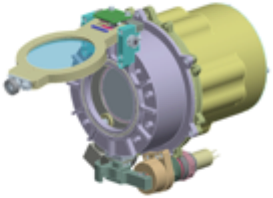


MCP+RAE schematic diagram





EUV detector : closed window



EUV detector: open window

CALIBRATION PHILOSOPHY

Specific effort was done for the calibration activities
⇒ To know the instrument response and behaviour as precisely as possible

- A precise calibration is essential to process relevant scientific data.
- We put forward a theoretical calibration plan as complete as possible.
- The link between what we measure (the count rate *R*) and what we want to know (the radiance *L*) is the main purpose of the calibration.

$$R = G_{eff} . L \quad *$$

Unpolarized incident light:
1 scalar: G_{eff}

L : Radiance ($ph.s^{-1}.m^{-2}.sr^{-1}$)
G_{eff} : Effective Etendue ($m^2.sr$)
R : Count rate (ct.s-1)

$$\begin{vmatrix} Q_0 \\ Q_1 \\ Q_2 \\ Q_3 \end{vmatrix} = \begin{bmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{bmatrix} \times \begin{vmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{vmatrix}$$

Output Stokes vector — *PEHBUS Mueller Matrix (M_{0i} : Mueller parameters)* — *Stokes vector of Incident beam*

$$R = M_{00} L_0 + M_{01} L_1 + M_{02} L_2 + M_{03} L_3$$

Polarized incident light:
4 scalars M_{0i}

Normalization by M_{00} and L_0

$$m_i = \frac{M_{0i}}{M_{00}} \quad , \quad L_i' = \frac{L_i}{L_0}$$

$$R = L_0 \underbrace{M_{00}}_{G_{eff}} \underbrace{\left(1 + m_1 L_1' + m_2 L_2' + m_3 L_3'\right)}_{\text{Corrective factor or Factor of error}}$$

- We must know, a priori, the polarization state of the source !!
- If we only know the fraction of incident light which is polarized, we can estimate an upper bound of the error factor.

* *in the linear working range*

CALIBRATION PHILOSOPHY

- Calibration plan conclusion

System

Geometric
- Etendue G
- FOV
- Solid angle Ω

Radiometric
- Effective Etendue G_{eff}
- Effective area S_{eff}
- Mueller parameters M

Spectral
- ISRF
- PSF

Sub-Systems

Radiometric
- Mirror reflectivity
- Grating efficiency
- Baffle attenuation

- From theory to practice

The calibration plan has been translated into technical specifications

Division of calibration activities into work packages (~20):

- Description of experimental methods: How to measure ?.
- Description of the experiment: Optical Ground System Equipment (OGSE).

CALIBRATION: OGSE

Experimental constrains

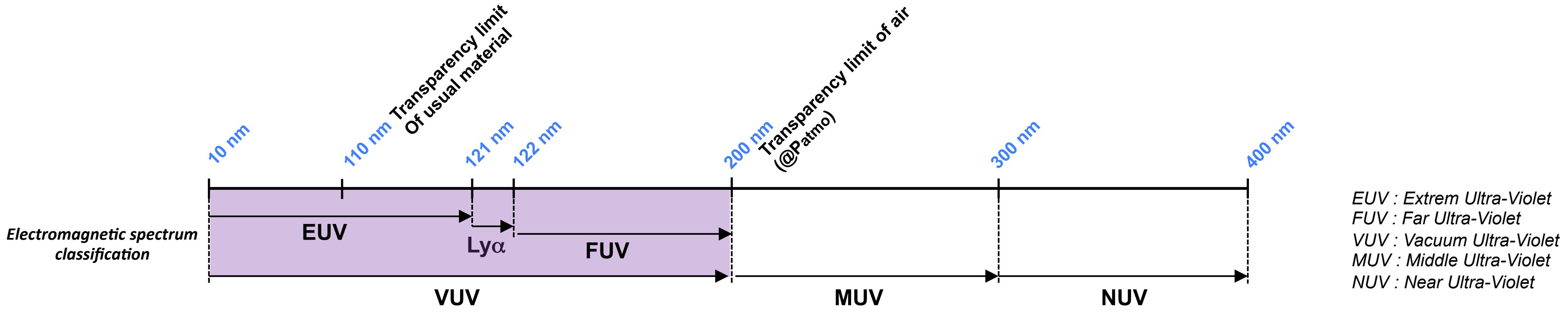
- Wide spectral range : from 55 nm to 423 nm

Requirements:
- Wide variety of sources, sensors and optical components.
- Well known OGSE (absolute calibration)

- Vacuum optics

- To reach wavelengths < 200 nm => Need to be under vacuum (ambient air transparency limit).
  - Instrument accessibility is made difficult (alignments ☹).
  - Electrical feedthroughs.

- To reach wavelengths < 110 nm => material transparency limits ☹.
  - The use of mirror at grazing incidence.
  - The use of diffuser is made not possible (how to make an extended source?).
  - Windowless sources and detectors.



Example : Vacuum optical bench

Goals

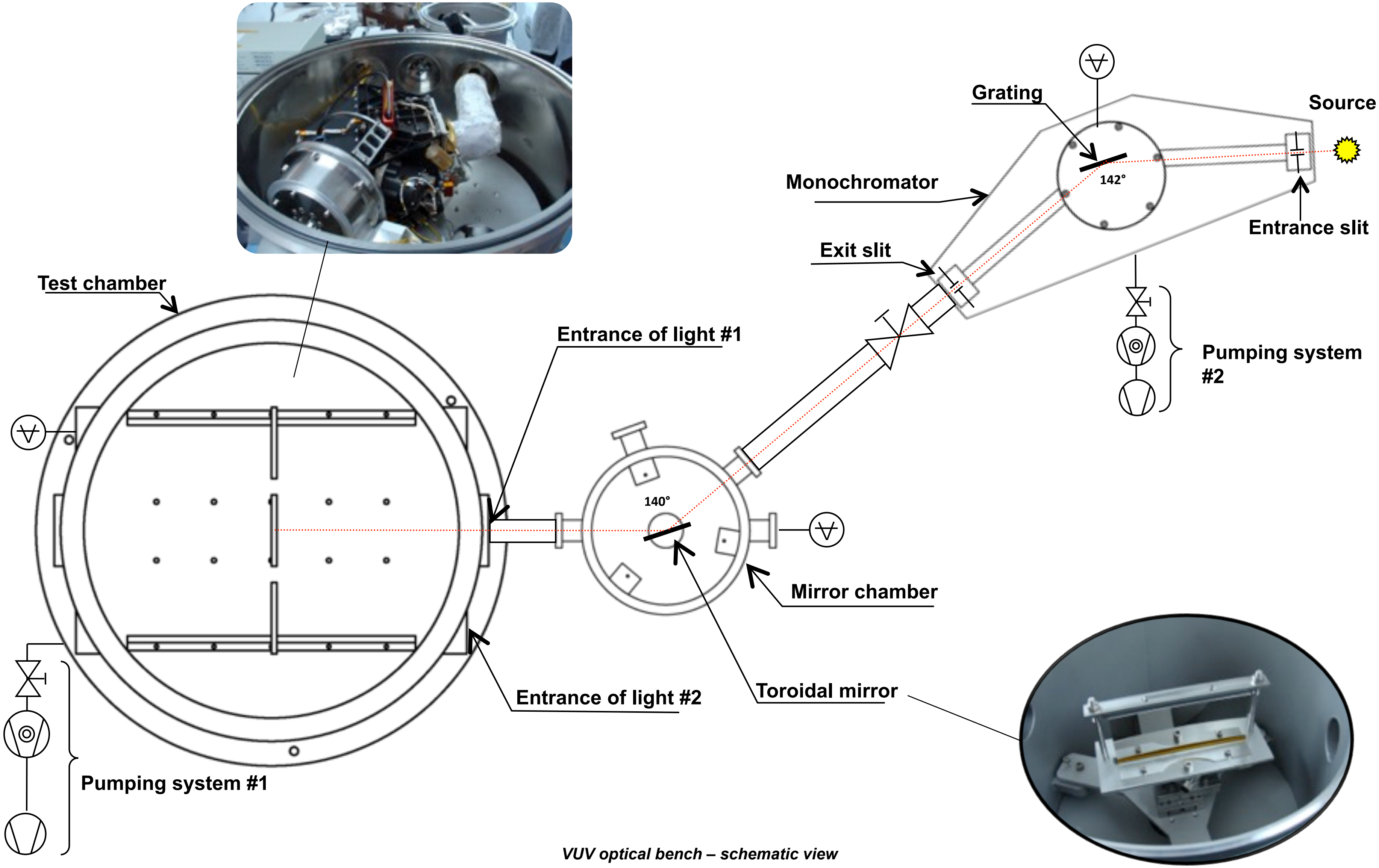
- To carry out spectral and radiometric calibrations.
- To enable calibrations of optical subsystems by measuring either the reflectivity (optical mirrors), the transmission (filters, windows) or the efficiency (gratings) in VUV.

Main features

- Spectral range: 30 – 200 nm (2 gratings).
- Spectral resolution < 1 nm.
- 2 operating modes : focused or collimated beam.
- Available sources:
  - Pen Ray (Hg, Zn/Cd).
  - Deuterium lamp (Hamamatsu *L10366 series*).
  - RF flow lamp windowless (He, Ne, N_2, Ar, O, H).
- Available detectors:
  - Channel Electron Multiplier (Amptektron MD-502).
  - Photomultiplier (Hamamatsu R6835P).
- Vacuum tank: 250 L – Min pressure = 10^{-6} mbar.
- Automated system:
  - Pumping operations.
  - Remote control & monitoring.
  - Safety device to protect sample/instrument under vacuum.
  - Alarm operating anomalies (notifications sent by e-mails & sms)

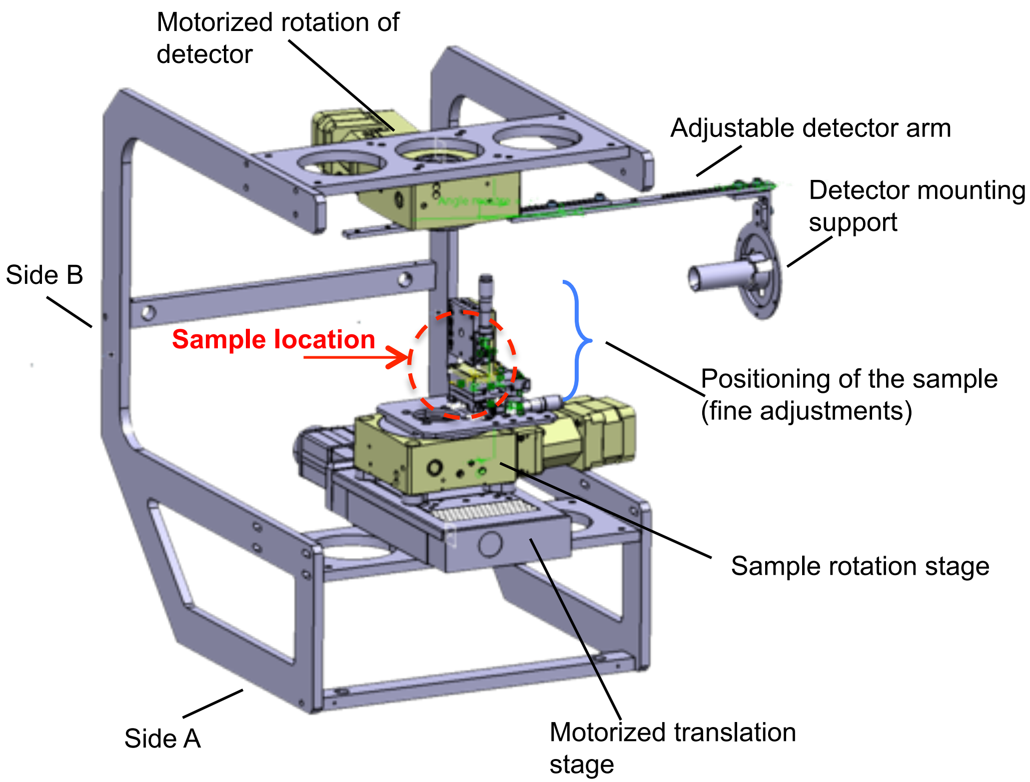
Banc optique VUV

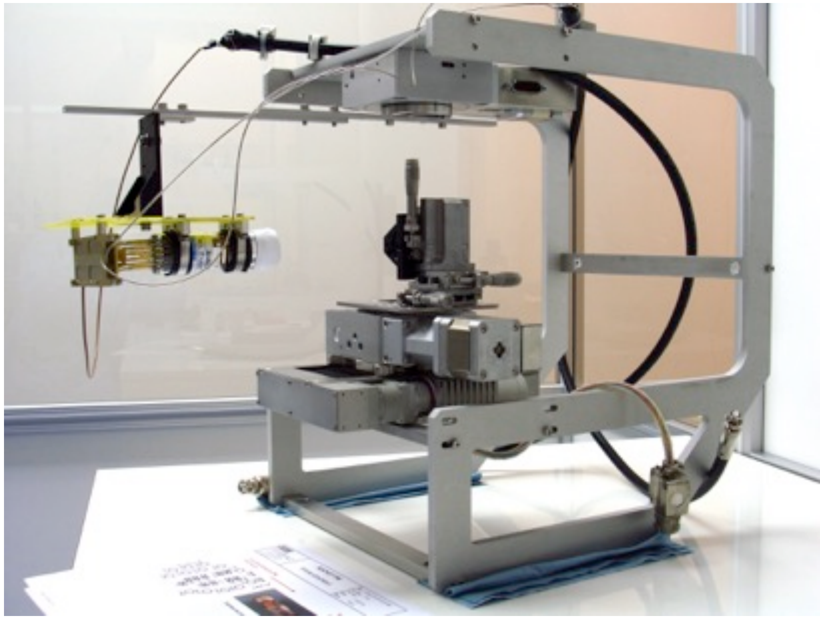
CALIBRATION: OGSE



VUV optical bench – schematic view

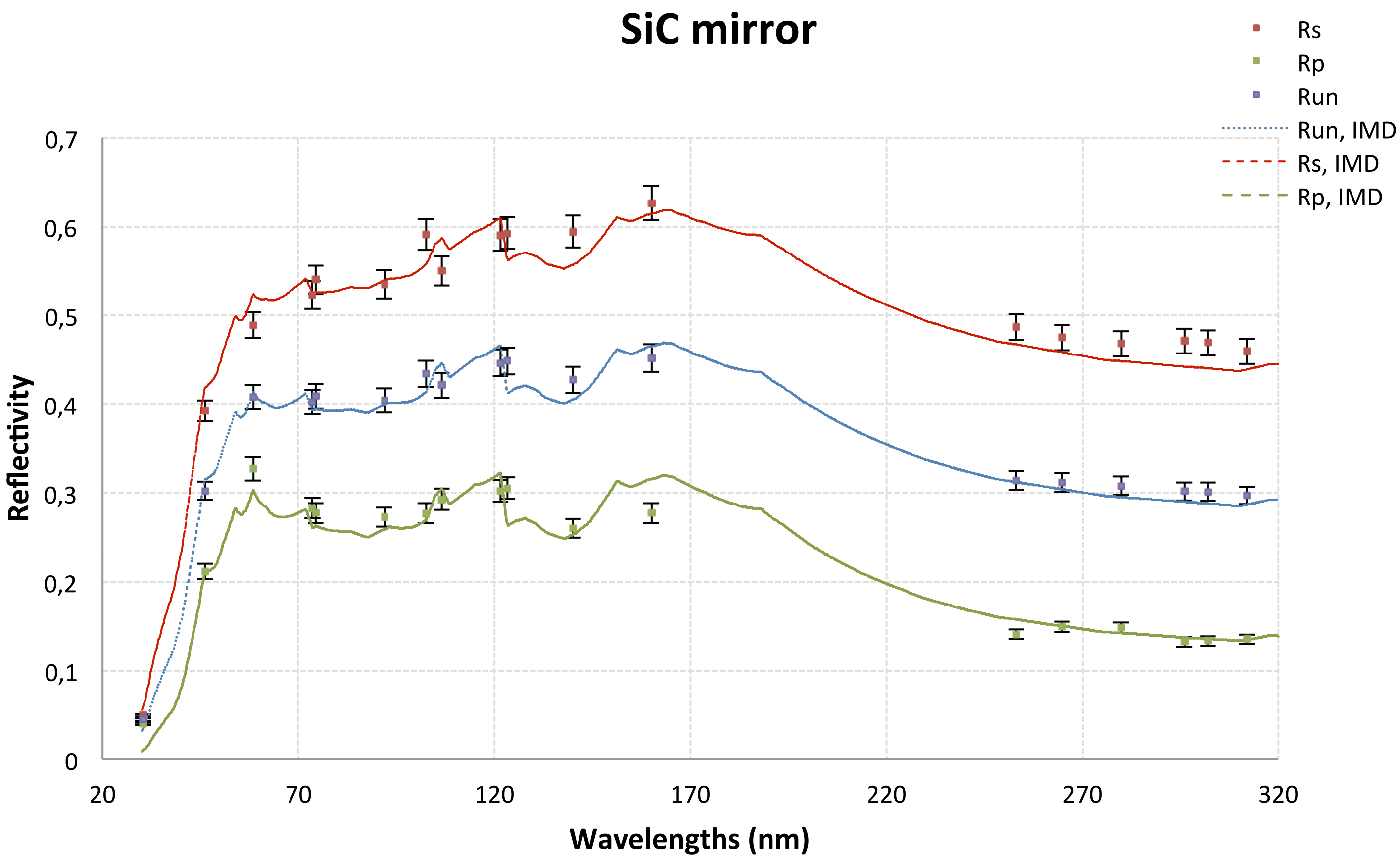
CALIBRATION: OGSE



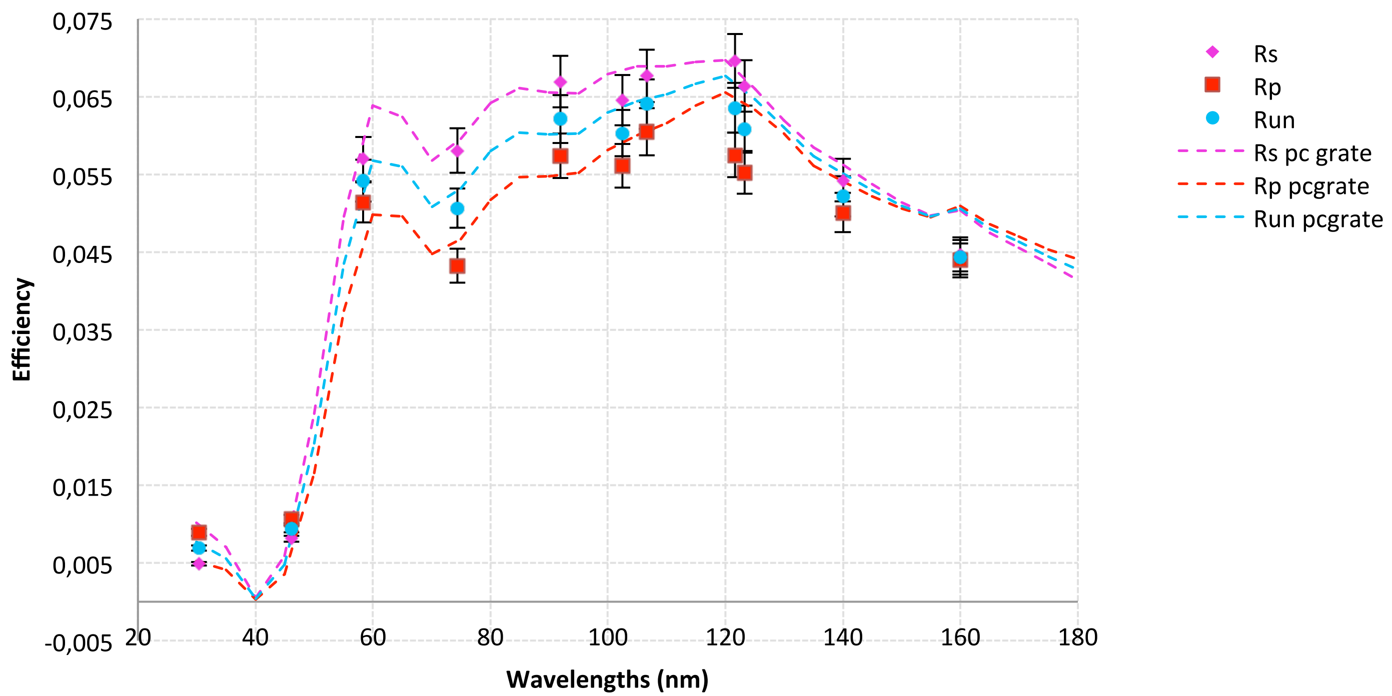


VUV Reflectometer

Mirror reflectivity

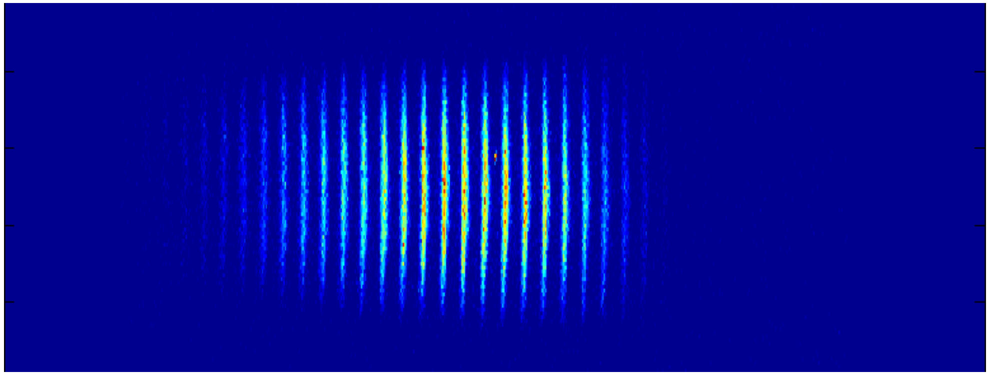


EUV Grating efficiency

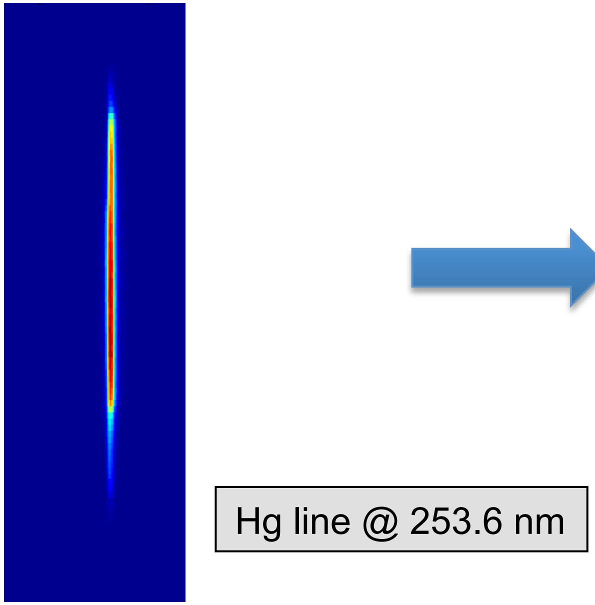


CALIBRATION: some results

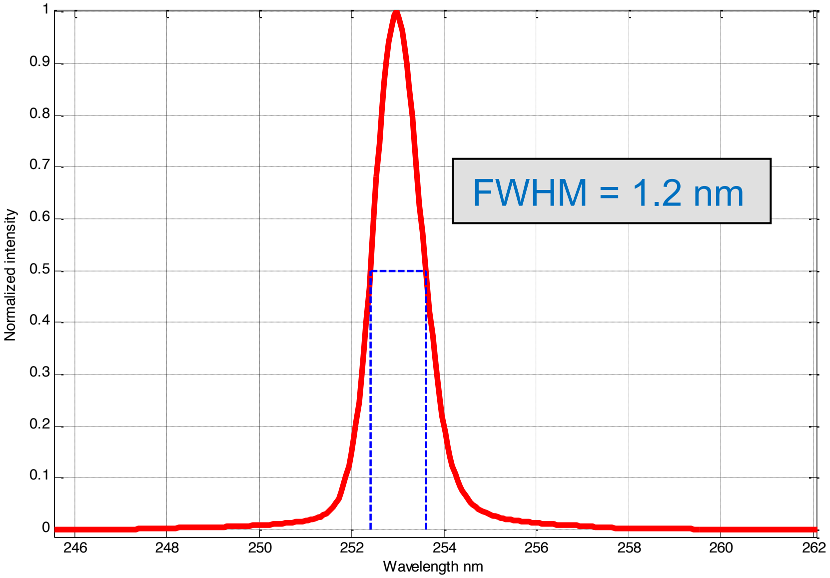
Spectral calibration – FUV channel (145 – 315 nm)



Spectral scanning from 180 nm to 320 nm

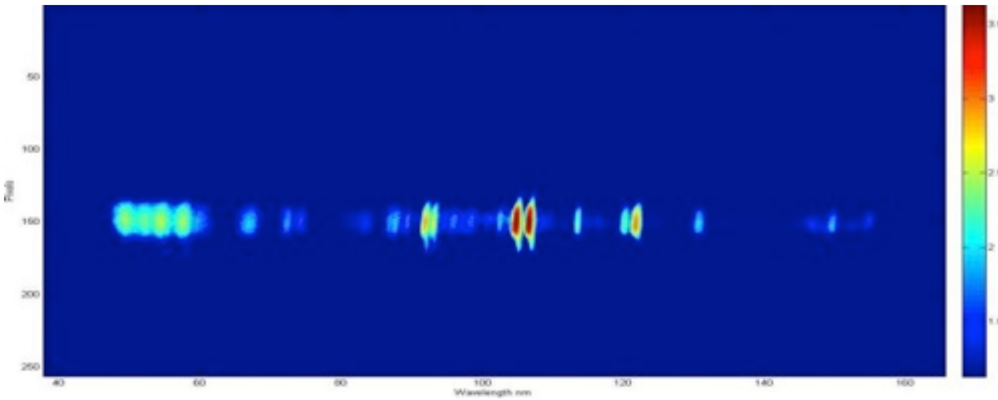


Hg line at 253.6 nm (Integration time = 10 min).



FWHM @ 253.6 nm

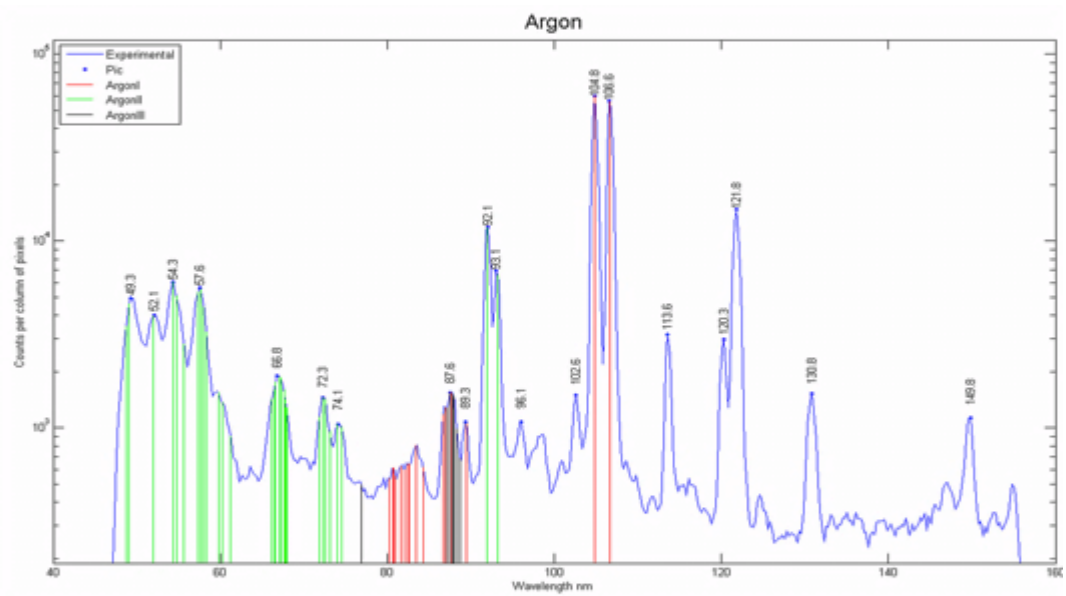
Spectral calibration - EUV channel (55 – 155 nm)



EUV detector Image for Argon gas: HV = -3436 V, this image corresponds to a cumulated integration time of 10 min.
Count rate is about 1500 counts per second. (Levels are in log_{10}-scale)

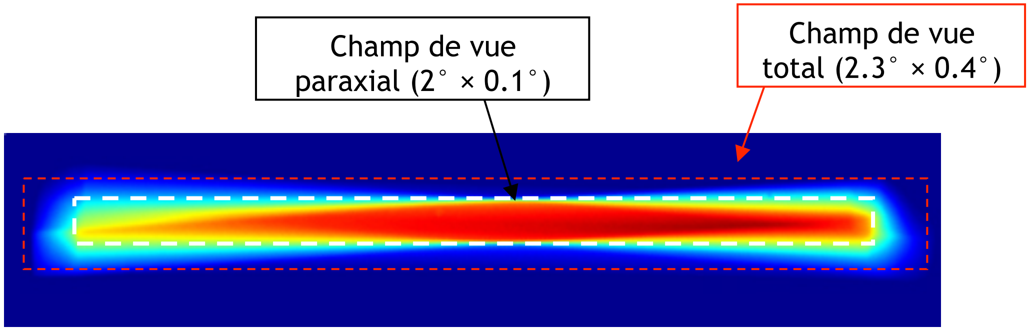
EUV spectrum of Argon gas
And NIST lines assignment (Levels are in log_{10}-scale)

FWHM ~ 0.8 nm

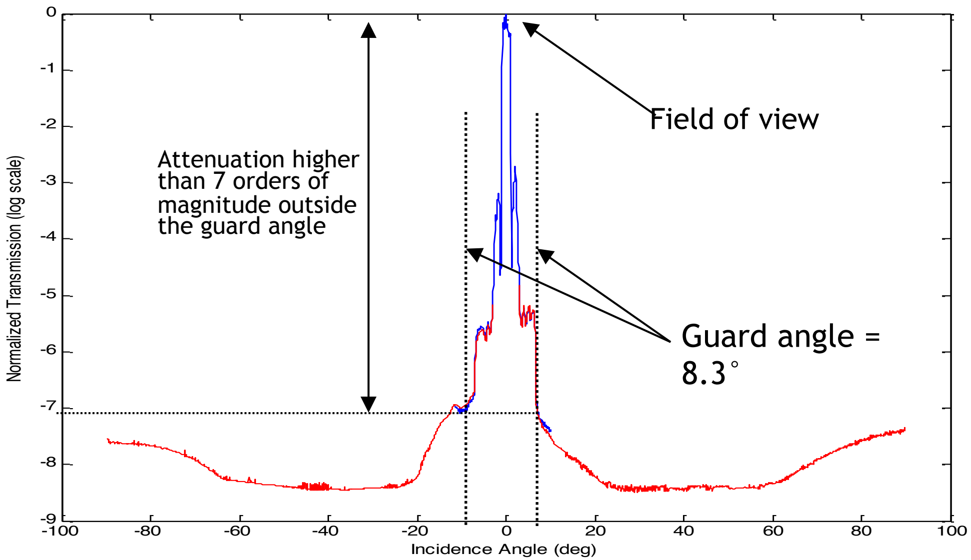


CALIBRATION: some results

Field of view



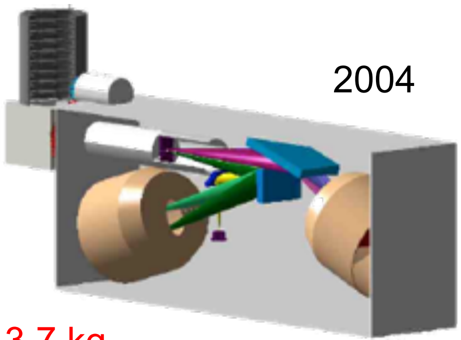
Baffle attenuation



Maturity of the concept

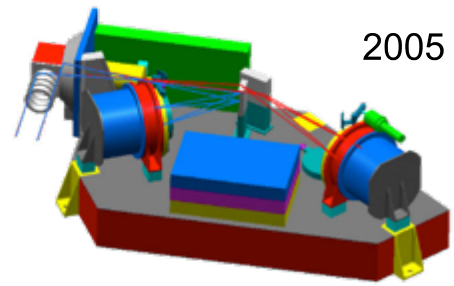
- Maturity level at selection: unproven feasibility and unrealistic budget.
- More than 3 years spent doing prototyping to ensure feasibility in parallel to the overall design
- 100% increase in mass between proposal and Flight Model.

2004

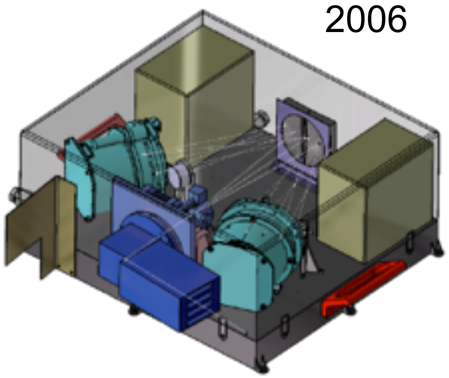


Selection at 3.7 kg

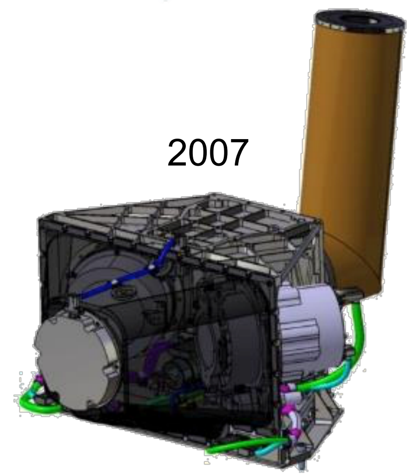
2005



2006



2007



Final design at 7.5 kg

EXPERIENCE FEEDBACK

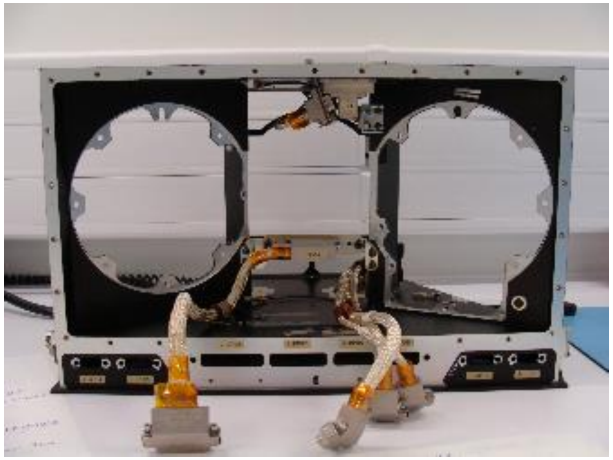
Technical challenges

Many subsystems have proved to be early industrial achievements: Entrance baffle, SiC mirror, diffraction gratings, Al Structure, carbon cover…).

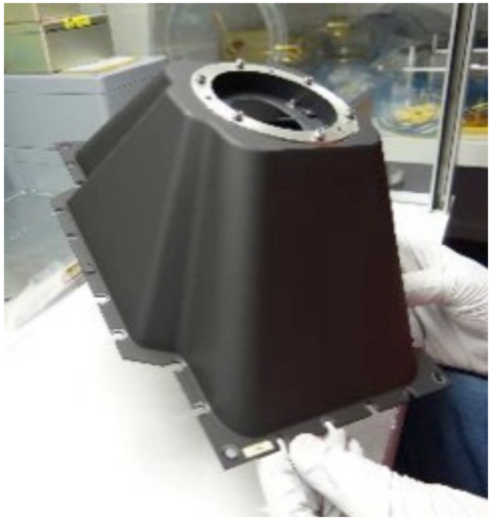
- Aluminium structure and carbon cover

- One-piece structure machined from solid (40kg → 830g), Certal SPC7022 - 200h of machining→ Corrosion problems of the treatment, 20k€/piece.

- Choice of a mechanical architecture minimizing the final mass, but dependent on all interface subsystems, including co-PI supplies => AIT constraints.
- Carbon cover with strong geometric constraints (Gratings support, therefore subject to the constraints of the optical dimensioning)



Main structure



Carbon cover

- Diffraction gratings

– Aluminium substrate Vs. Glass: SPICAM –SPICAV heritage to make mechanical interfaces easier, BUT :
    - It required 2 different companies: one for the Al substrate and the other one for the grating recording (Horiba Jobin-Yvon): Too many intermediaries, difficulty to go back to the source of a possible problem.
    - At reception of the substrate Horiba JY had difficulties in cleaning and surface preparation: change of cleaning products to meet RoHS standards. Surface of substrate too well polished (<5µm)=> grip problem !
    - Alodine treatment (residual on the edges of surfaces) was also questioned for the grip of the different grating layers
    - Manufacturing replicas on aluminium is more difficult than on glass.

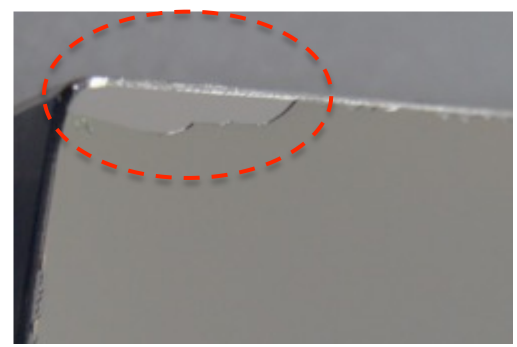
– Recording area Vs. Total area.
    - In order to maximize the useful area: Grating etching up to 1mm from the edge

=> Too difficult to satisfy (usually 3 to 4 mm for the edges).

– Mounting interfaces
    - The fixing tabs (connected to the substrate) interfered with the with the tools for manufacturing the substrates.

Separation of the coating on the FUV grating – Qualification model

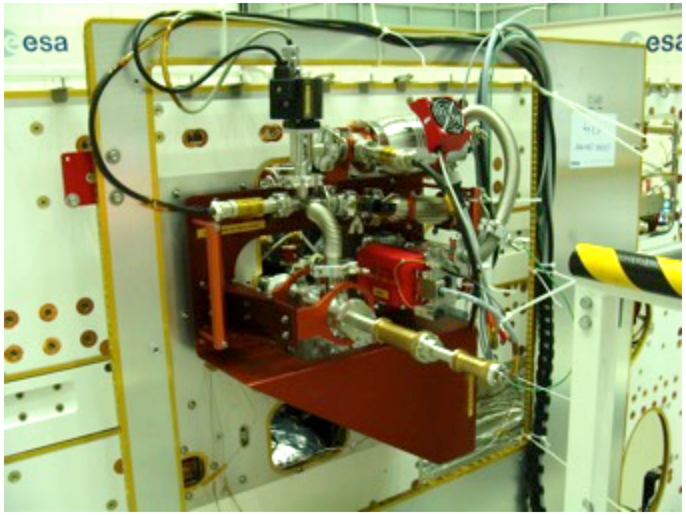
⇒ **Separation of the coating**



EXPERIENCE FEEDBACK

- Mirror
  - Originally built-in foot to make mechanical interfaces easier BUT:
    - Too difficult to machine (ceramic => very brittle, small peace => interface with machine tools difficult)
    - Finally bonding on titanium base (3M 2216 glue).
  - Roughness < 0.7 nm RMS (to minimise straylight) :
    - Feasible but with an extremely high cost + long machining time.
  - Convergence Shape Error Vs. Roughness
    - Difficult to reach => required a long iterative process between diamond polishing and ion etching

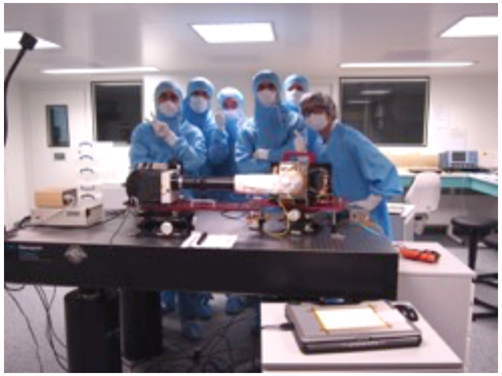
- EUV detector
  - Requires dedicated pumping system until launch
    - ATEX certification (Explosive Atmosphere).
    - Training of spacecraft AIT staff
    - Constrains during AIT phase on spacecraft.
  - Window opening system non reversible:
    - Requires an additional, complex closing system during the vacuum calibration phases of the instrument.



Pumping system integrated on the MPO spacecraft

EXPERIENCE FEEDBACK

- The human and technical extraordinary adventure
  - Flight Model delivered on time.
  - An instrument reaching the expected performances.
  - A fantastic human adventure with a lot of international collaborations.
  - A capitalized experience feedback for the future UV projects…



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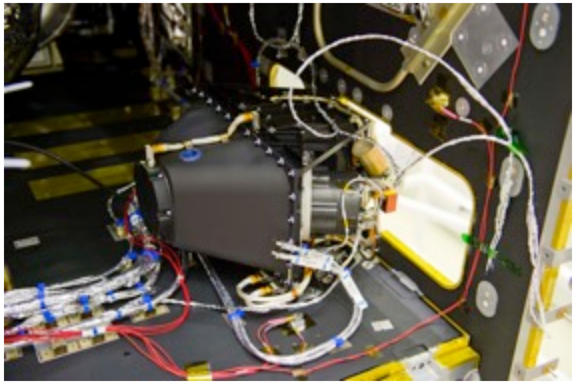
PHEBUS Qualification and Flight Models



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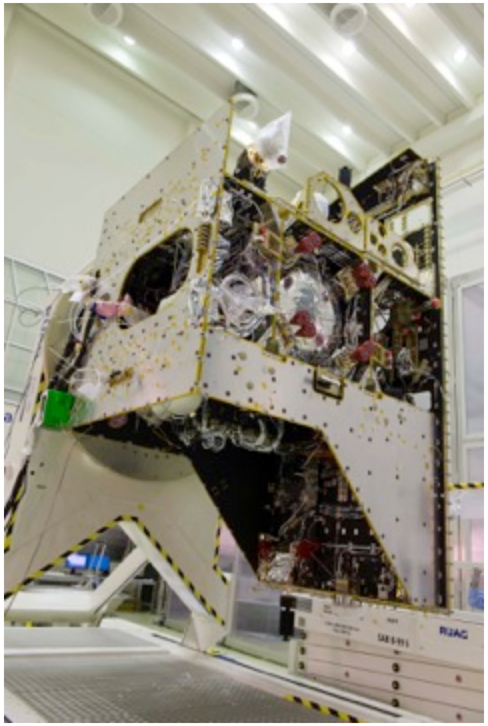
PHEBUS onboard MPO



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MPO Spacecraft

Thank you

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