# Manufacturing and verification of ZnS and Ge prisms for the JWST MIRI imager

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## ABSTRACT

The JWST Mid-Infrared Instrument (MIRI) is designed to meet the JWST science requirements for mid-IR capabilities and includes an Imager MIRIM provided by CEA (France). A double-prism assembly (DPA) allows MIRIM to perform low-resolution spectroscopy. The MIRIM DPA shall meet a number of challenging requirements in terms of optical and mechanical constraints, especially severe optical tolerances, limited envelope and very high vibration loads.

The University of Cologne (Germany) and the Centre Spatial de Liege (Belgium) are responsible for design, manufacturing, integration, and testing of the prism assembly. A companion paper (Fischer et al. 2008) is presenting the science drivers and mechanical design of the DPA, while this paper is focusing on optical manufacturing and overall verification processes.

The first part of this paper describes the manufacturing of Zinc-sulphide and Germanium prisms and techniques to ensure an accurate positioning of the prisms in their holder. (1) The delicate manufacturing of Ge and ZnS materials and (2) the severe specifications on the bearing and optical surfaces flatness and the tolerance on the prism optical angles make this process innovating. The specifications verification is carried out using mechanical and optical measurements; the implemented techniques are described in this paper.

The second part concerns the qualification program of the double-prism assembly, including the prisms, the holder and the prisms anti-reflective coatings qualification. Both predictions and actual test results are shown.

**Keywords:** double-prism assembly, Zinc Sulphide, Germanium, qualification

## 1. THE DOUBLE-PRISM ASSEMBLY (DPA) ON THE JWST MIRI IMAGER

The DPA constitutes one of the 18 positions of the JWST Imager Filter Wheel and is used in the Low Resolution Spectroscopy mode of the Imager. The DPA is used as dispersive element. The first prism is made of Germanium (Standard Grade) and is mainly responsible for cancelling the beam-deviation by the second prism. The second prism's material is Zinc Sulfide (MultiSpectral Grade). Both prisms will be coated with antireflective coatings optimized for the range of (5-10) µm. The dispersed light exits the DPA parallel to the incoming light and therefore allows an implementation into MIRIM's filterwheel (Fig. 1).

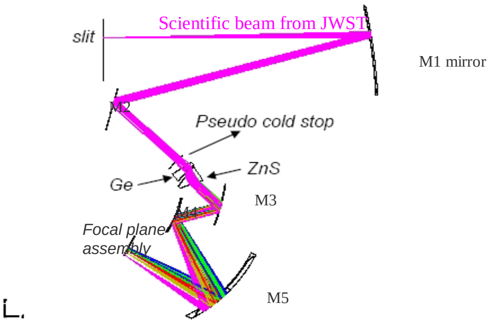

Fig. 1: The optical scheme of the Low Resolution Spectroscopy mode of the JWST MiRi Imager; the filter wheel is not represented on this scheme

The different models of the DPA – the development model (DM), the qualification model (QM) and the flight/flight spare models (FM/FS) – are the fruit of collaboration between University of Cologne, Centre Spatial de Liège and

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Nanoshape. Nanoshape was responsible for the manufacturing of the prisms, for the polishing of the prisms and for the prisms metrology and optical characteristics measurements. University of Cologne was responsible for the design of the DPA (including the prisms and the mechanical parts designs) [1], for the manufacturing of all the mechanical parts of each DPA model and for the metrology of mechanical parts. CSL was responsible for the straylight evaluation, part of the optical requirements verifications, the coating of the prisms, the coating of the mechanical parts and the verification campaigns of the different DPA models. The assembly and integration of DPA models are the fruit of collaboration between CSL and UoC.

## 2. DPA DESIGN OVERVIEW

The DPA is composed of one Germanium prism and one ZnS prism both integrated in an aluminum holder and maintained with aluminum covers. (Fig. 3)

### 2.1 DPA Mechanical Parts

Four washers are used between each prism and its cover (1) to ensure a soft bearing surface for the prism (two 25-µm gold washers), (2) to avoid point-loads onto the prism (Al6061 T6 washer is placed between prism and spring) and (3) to realize a semi-kinematical mounting (one CuBe ondulated spring). (Fig. 2)

Fig. 2: Flight Model Integration of the DPA; view of the first gold washer (left); the stack of four ZnS washers (middle); the stack of four Ge washers (right); covers of the prisms not integrated

Fig. 3: Flight Model of the DPA; views onto the ZnS side (left/middle) and onto the Ge side (right); covers are integrated and maintain the prisms on the holder

To avoid parasitic reflections, the Al6061 T6 aluminium covers are coated with black anodisation preceded by a surface roughness increase; diaphragms are also needed in the covers design; the Ge-diaphragm represents the JWST telescope beam shape.

The bearing surfaces (Fig. 3: view onto the Ge side) are protected with a chromate conversion coating, Alodine 1200, which ensures the thermal conductivity between the DPA and the Imager Filter Wheel.

The holder and covers design presents main challenges including protection of the prisms to external mechanical loads, without inducing stresses due to thermal contractions, positioning of the prisms with respect to Imager interface and respect of the allocated envelope into the Imager Filter Wheel. This design is presented in [1].

All the MiRi Imager aluminum parts, including the DPA’s holder and covers, are manufactured from the same material Al6061T6 to minimize internal thermal stresses. All items were thermally treated between the single machining phases, to avoid major stress impacts after assembly and alignment at room temperature (295 K) and cooling down to 4.2 K.

### 2.2 DPA Optical Parts

The DPA prisms design is optimized to satisfy optical, mechanical and thermal requirements.

A flange around the prism body allows positioning inside the DPA holder; the bearing surface of the flange is corrected by diamond turning to achieve - together with the tolerance of the respective bearing surfaces in the holder - the ***positioning tolerance*** ±0.05mm along the optical axis of the prisms.

In the perpendicular plan with respect to prisms axis, the positioning tolerance of ±0.1mm is achieved thanks to cylindrical shape of the prisms.

Rotationally around the prisms axis, the prisms are fixed by the vertical edge of the holder in contact with the edges of the flange. (Fig. 4)

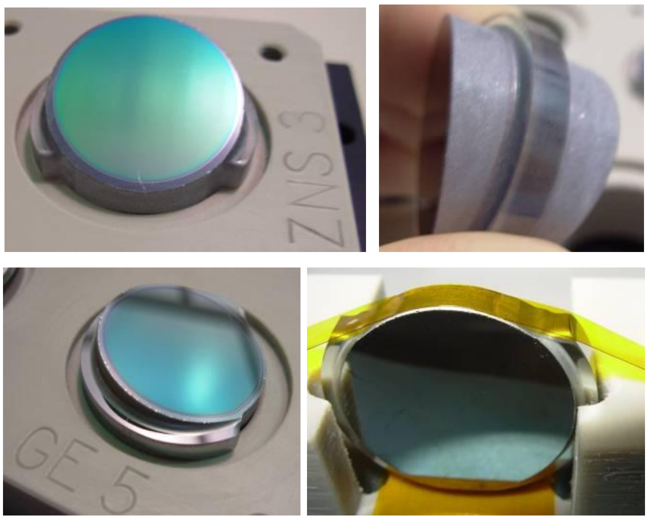

Fig. 4: The prisms of the DPA; Top: ZnS prism; Bottom: Ge prism

The mounting of the prisms via the interface-flanges attached to the prisms induce ***as few stresses as possible*** into the optically active volume of the prisms. The design accomplishes that under all appearing accelerations, the DPA behaves completely rigid, *i.e.* no displacement of a prism (which would inevitably lead to its destruction) occurs. This requirement is fulfilled thanks to the ondulated CuBe springs washers which deliver the desired preload to compensate the external mechanical loads. The design concept avoids any stresses induced on the prisms due to different ***thermal contraction*** of the other components. The holder diameter is larger than the prisms interface-flanges diameter to allow the aluminum contraction without inducing stresses on the prisms.

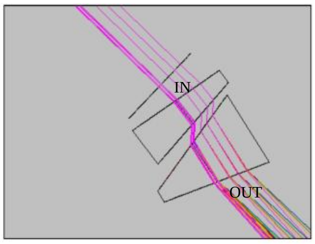

Fig. 5: The DPA optical surfaces definition and the incidence scheme

The prisms are coated with two anti-reflective coatings; a low-angle of incidence coating for the DPA input and output optical surfaces and a high-angle of incidence coating for the DPA intermediate optical surfaces. Fig. 5.

The science drivers and mechanical design of the DPA are detailed in [1].

## 3. PRISMS MANUFACTURING

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## 4. DOUBLE-PRISM ASSEMBLY VERIFICATIONS

The DPA has to withstand without degradation ten cycles of temperature variations between 5K and 313K under vacuum. The verification of the wave front error of the prisms useful optical surfaces is performed after this test at ambient conditions. The main challenging aspects of this thermal test are the cryogenic temperature to be achieved and the temperature variation slope to be respected (1) to avoid important thermal gradients inside the prisms and (2) to achieve the slope the DPA will see at flight conditions.

The DPA has to withstand without degradation the vibrations spectrum which leads to total acceleration of maximum 44 g RMS. The verification of the prisms positioning after this test is performed using the theodolites or/and the 3D measurements.

The qualification model was submitted to the vibrations spectra; this qualification was successful, it validated the design and allowed us to detect two critical points, and to improve them for the DPA Flight Models: the integration process and the ondulated CuBe springs metrology.

The prisms coating qualification was also required during this project; this process was indeed considered as critical as it is the first use of this anti-reflective coating under cryogenic conditions and in an irradiative space environment. Environmental tests were performed under CSL responsibility while transmission measurements were done by Umicore UK before and after the tests.

Environmental tests are detailed in chapter 6.

# 5. OPTICAL VERIFICATIONS

In the frame of the DPA qualification and acceptance, the optical verifications and the positioning measurements were performed at ambient conditions.

## 5.1 Wave Front Error

The wave front error of the useful optical surfaces of the prisms was measured during the integration of the DPA to understand the impact of the mounting design on the surfaces deformation. WFE was also measured before and after the environmental tests to check no permanent deformations occurs. (Fig. 6)

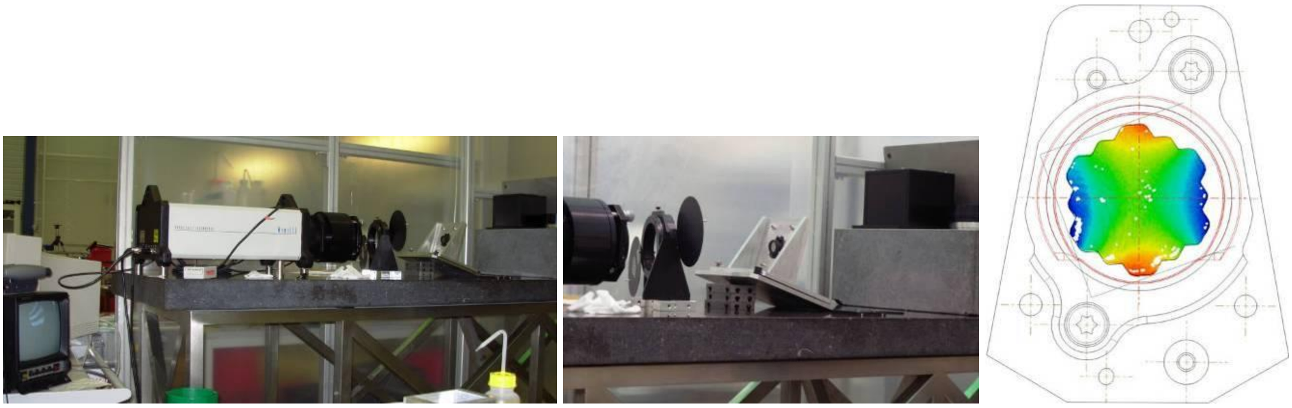

Fig. 6: WFE measurement set-up with the surface mapping Fizeau Interferometer (left); ZnS side set-up is shown (middle); the surface front error map was integrated in the DPA holder drawing (right) to understand the mounting design impact (QM Germanium prism map is shown)

The WFE measurements during the DPA integration showed the mounting design is responsible for a deformation of 40nm RMS of the useful optical surfaces of the prisms. The prisms are maintained on the holder thanks to ondulated springs compressed to the preload required to compensate the external accelerations; the springs being compressed by the covers thanks to two screws per cover. This compression leads to a deformation of the prisms which is transferred to the optical surfaces.

## 5.2 Prisms Positioning

***Theodolites measurements*** were made to check the alignment of the DPA input and output optical surfaces with respect to the interface of the DPA holder with the filter wheel (Fig. 7). These measurements are made after integration and before and after the environmental tests, at ambient conditions.

The DPA input and output optical surface angles in ambient conditions are specified in Table 1:

| | |
|---|---|
| Ge input optical surface angle with respect to holder I/F: | 2° 44’ 2’’ ± 1’ 1’’ |
| ZnS output optical surface angle with respect to holder I/F: | 16° 37’ 26’’ ± 1’ 1’’ |
| Ge input optical surface angle with respect to ZnS output optical surface: | 13°53’24” ± 2’ 2’’ |

Table 1: The specifications for DPA input and output faces angles wrt holder interface

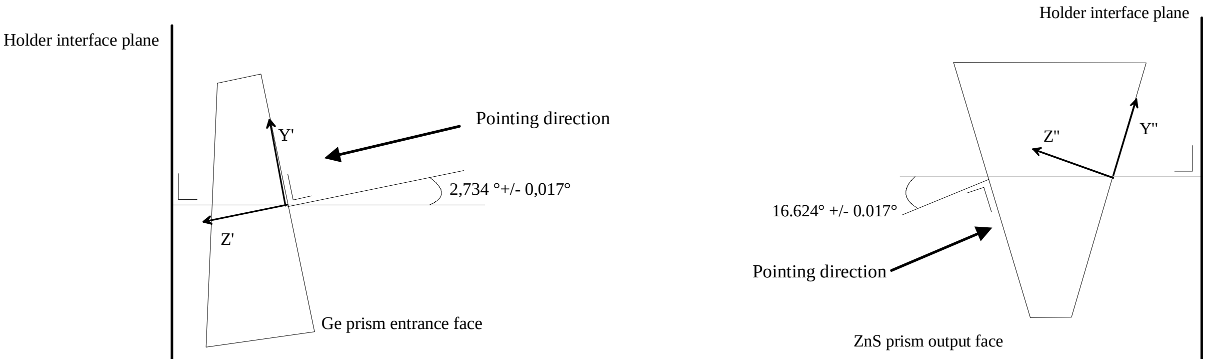

Fig. 7: Input (left) and output (right) optical surfaces angles with respect to DPA holder interface

The dedicated test support equipment has the following characteristics:

- A diameter 10 mm reference mirror is glued on the front side (Ge input side) of the test support equipment (Fig. 8)
- An interface on the rear side to mount either the DPA or a diameter 50 mm mirror whose optical surface is visible from the front side. Both DPA and mirror are pushed against 3 interface pads representing the Image filter wheel interface.
- The 50 mm diameter mirror materializes the interface axis.

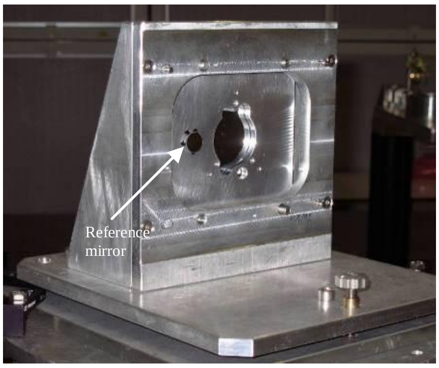

Fig. 8: Front view of the test support equipment

The optical surfaces angles measurement is performed in three steps:

- Deviation measurement of the reference mirror with respect to the interface plane (materialized by the 50mm-mirror).
- Deviation measurement of the input optical surface with respect to the reference mirror.
- Deviation measurement of the output optical surface with respect to the reference mirror.

It appeared after integration that the deviation with respect to the requirement is:

| | |
|---|---|
| Ge input optical surface angle with respect to holder interface: | 1’ 29” of deviation with respect to requirement |
| ZnS output optical surface angle with respect to holder interface: | 1’ 27” of deviation with respect to requirement |
| Ge input optical surface angle with respect to ZnS output optical surface: | 2” |

And it appeared after vibrations that the deviation with respect to the requirement is:

| | |
|---|---|
| Ge input optical surface angle with respect to holder interface: | 1’ 36” of deviation with respect to requirement |
| ZnS output optical surface angle with respect to holder interface: | 1’ 35” of deviation with respect to requirement |
| Ge input optical surface angle with respect to ZnS output optical surface: | 1” |

We cannot conclude on a significant movement of the prisms after the vibrations; the measurements errors are 3” for the Ge positioning and 5” for the ZnS positioning. And the measurement of the angle between both input and output optical surfaces did not show any movement of the prisms after vibrations with respect to each other.

During the DM and QM vibrations campaigns, we used the ***3D-measurements*** to check no movement of the prisms occurred. These measurements were made using a mounting interface providing three reference polished surfaces (Fig. 9).

The prisms optical surfaces and the three reference surfaces were positioned in space thanks to the Wenzel 3D LH 65. Three calibrated sensors were used for the measurements. Five planes were measured: the input Ge surface, the output ZnS surface and the three reference surfaces.

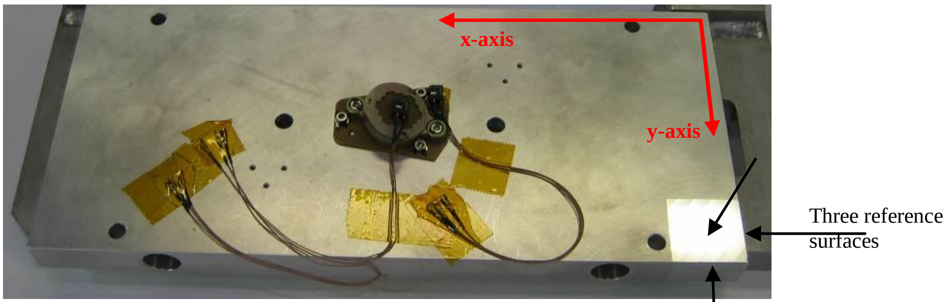

Fig. 9: The set-up for 3D-measurements performed on the DPA Development Model (DM shown on this picture)

**Results:** During the QM vibration tests, the 3D-measurements did not show any movement of the prisms:

The success criterion was that the prisms do not move by more than the tolerances given below:

*Germanium positioning tolerance with respect to the holder:*

| | |
|---|---|
| Δx, Δy | ± 100 µm |
| Δz | ± 70 µm |

*ZnS positioning tolerance with respect to the holder:*

| | |
|---|---|
| Δx, Δy | ± 100 µm |
| Δz | ± 70 µm |

*Positioning variation before and after the vibration qualification:*

*We did not observe any significant displacement of the prisms with respect to the three reference surfaces accommodated on the interface plate, as shown by measurements Table 2:*

| | before vibration qualification | | | after vibration qualification | | | DELTA | | |
|---|---|---|---|---|---|---|---|---|---|
| | X | Y | Z | X | Y | Z | X | Y | Z |
| face 1 | | | | | | | | | |
| point 1 | -162.596 | 76.311 | -10.894 | -162.596 | 76.310 | -10.896 | 0.000 | 0.000 | -0.002 |
| point 2 | -163.688 | 63.467 | -10.846 | -163.688 | 63.467 | -10.847 | 0.000 | 0.000 | 0.000 |
| point 3 | -151.776 | 69.375 | -11.412 | -151.776 | 69.375 | -11.414 | 0.000 | 0.000 | -0.002 |
| | | | | | | | | | |
| face 2 | | | | | | | | | |
| point 1 | -160.987 | 63.423 | 12.216 | -160.988 | 63.423 | 12.215 | 0.000 | 0.000 | 0.000 |
| point 2 | -159.815 | 76.324 | 11.869 | -159.815 | 76.324 | 11.868 | 0.000 | 0.000 | -0.001 |
| point 3 | -147.064 | 69.085 | 8.052 | -147.064 | 69.086 | 8.051 | 0.000 | 0.000 | -0.001 |

Table 2: 3D measurements before and after the qualification vibrations of the DPA QM; faces 1 and 2 are respectively the Ge input optical surface and the ZnS output optical surface; they are positioned with respect to the three reference surfaces using three calibrated sensors

# 6. DPA ENVIRONMENTAL TESTS

The full assembly, integration, all the environmental tests and the DPA optical characteristics measurements were performed in the facilities of the Centre Spatial de Liège (CSL Belgium).

The qualification of the anti-reflective prisms coating was performed on Ge and ZnS samples. The tests were conducted at CSL facilities and - for the radiation (8.5 krad-Si) - at University of Liège, at IPNAS department (Institut de Physique Nucléaire, atomique et de spectroscopie), using the cyclotron.

The FM and FS mechanical parts were vacuum baked out before assembly in order to prevent contamination from outgassing. Then the full DPA was assembled and prepared for the acceptance tests.
The assembly was vibrated according to specific levels specified by the MIRIM instrument. These tests were conducted with the hardware in the real flight configuration. Post-vibration key checks were performed to verify the integrity of the prisms and to check that no misalignment occurred between the prisms and the holder mechanical interface.
The assembly was thermally cycled between survival temperatures specified by the mission environment.

## 6.1 Prisms anti-reflective coating qualification

The MiRi experiment is the first application of the UMICORE anti-reflective coatings under cryogenic conditions and irradiative environment. Hence the qualification process is critical to check the behaviour in terms of optical characteristics, integrity and adherence.

The ageing test, the cryogenic thermal cycles and the radiation test were performed on germanium and zinc sulphide coated samples.

1. The samples were exposed to 95% relative humidity[2] at 50°C for 24 hours within a dedicated climatic chamber according to the MIL-F-48616 procedure.

   A dedicated procedure was developed for this application to avoid any risk of condensation on the samples optical surfaces; first the temperature was increased with a relative humidity rate set to 30%; second the relative humidity variations were controlled with a 0.1%/min slope to achieve 95% RH (Fig. 10).

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[2] RH = Pv/Ps; Pv = partial water vapor pressure; Ps = water vapor pressure at saturation

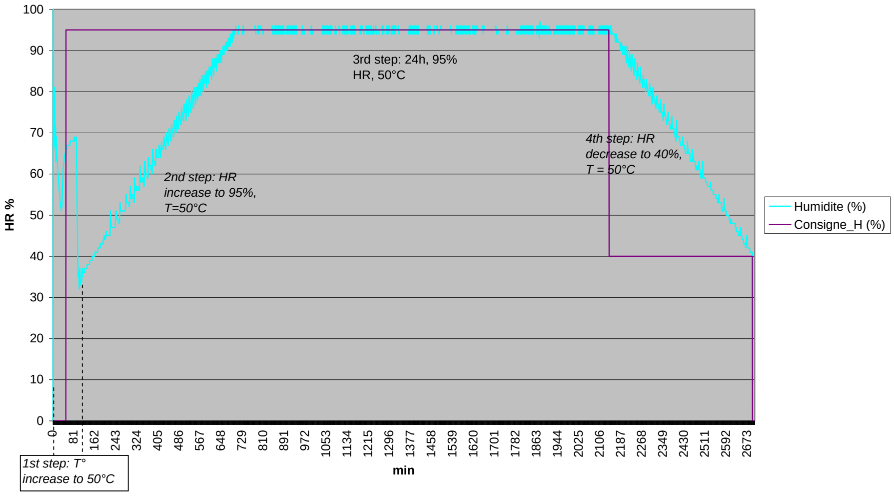


Fig. 10: Ageing test humidity conditions for the qualification of the anti-reflective coatings

2. The CSL cryostat was used to qualify the prisms coatings and the DPA at liquid helium temperature. The coated samples are tested under vacuum, cooled by conduction through GHe inside the cell (Fig. 11) and heated by conduction with copper interfaces around which heaters are wound. A nitrogen shroud surrounds the helium core of the cryostat to minimise the helium consumption. The cryostat is equipped with an electrical harness for interface with the thermal sensors and the heaters. The ten cycles were run successfully (Fig. 12).

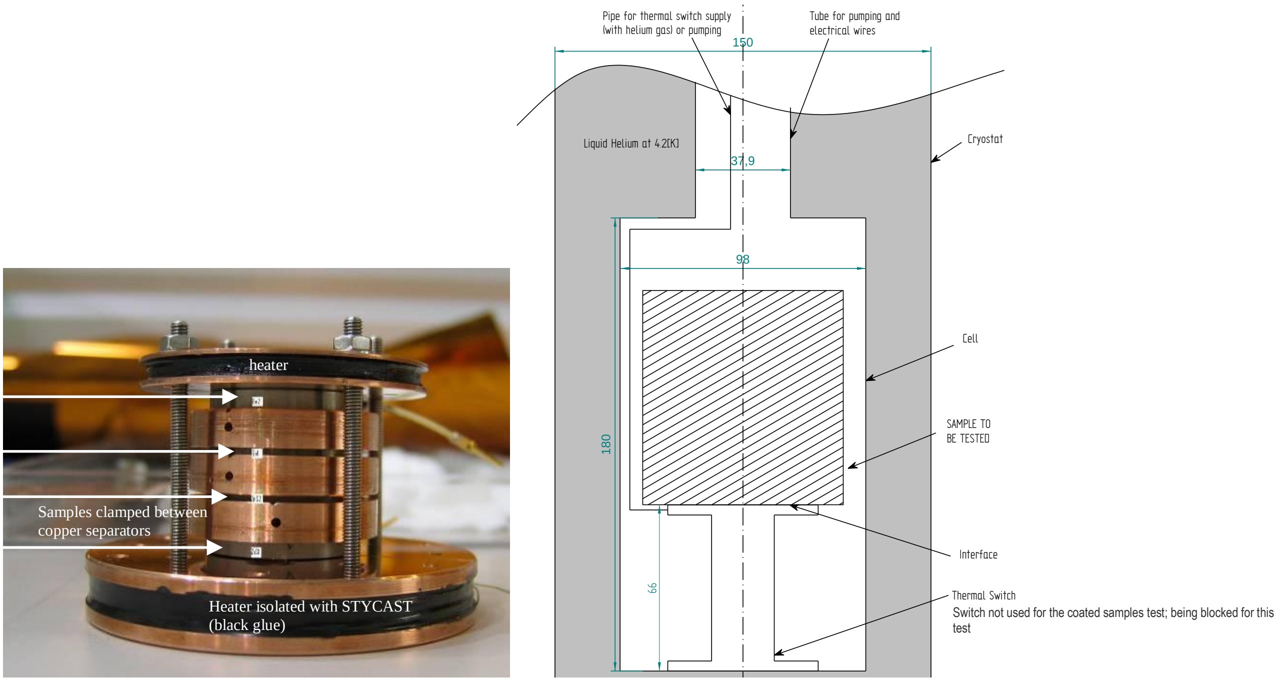


Fig. 11: The samples are heated by conduction through copper interfaces and copper separators, using heaters isolated with Stycast glue (left); samples are cooled by conduction through GHe injected inside the cell, which is in contact with the liquid helium core (right)

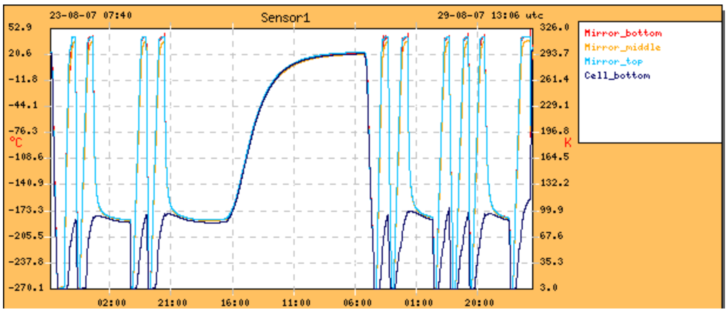


Fig. 12: The samples were cycled between 4.2K and 316K; the ten cycles were successful

3. The radiation test was made at University of Liège, at IPNAS department (Institut de Physique Nucléaire, atomique et de spectroscopie), using the cyclotron; type CRC520, 104 cm-diameter, 28 tons.
   The *cyclotron number of pulses* was calculated as follows:

$$Number\ of\ \ pulses = \frac{TID}{Dose/\,proton}.1.6.10^{-19}.\ \ \overset{\text{Cyclotron range is set by operator}}{\overleftrightarrow{10^{-10}C/\,pulse}}$$

*With TID (Total Ionizing Dose) = 8.5 krad-Si*

*Dose/proton = Energy loss in Si [MeV] x Irradiated Mass [kg]*

*Notes:*

- *The coating chemical characteristics are not known and the specification is given for Si specimen, hence calculation is made taking into account Si specimen.*
- *The specification was calculated by the JWST MiRi Optical Bench Assembly Assembly, Integration and Test Lead Team*
    - *Taken the ray-trace analysis results for the MiRi Imager;*
    - *Assumed a shielding around the DPA*
    - *The result is an expected radiation exposure level of 8.5 krads*

The energy loss is calculated using the Energy Loss curve in Si; the cyclotron energy was set to 10MeV. The Si density and the thickness of coating layer are used to obtain the irradiated mass:

E1 = 10 MeV

E2 – E1 = Energy loss per proton of 10MeV in Si

Fig. 13 schematizes the process of energy loss.

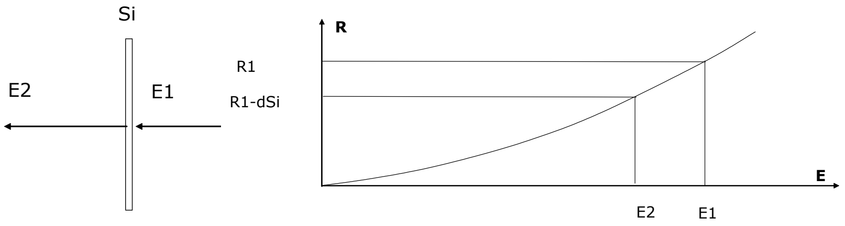


Fig. 13: Energy loss in Si sample

The prisms coatings qualification was a success; the adherence test and the optical verifications did not show any degradation or damage of the coatings after the environmental tests. Umicore made transmission measurements before and after the tests. There was no difference higher than 2.4% for the ZnS sample and than 3.2% for the Ge sample between 5µm and 10µm as requested by the MiRi Imager Low Resolution Spectroscopy Mode (Fig. 14).

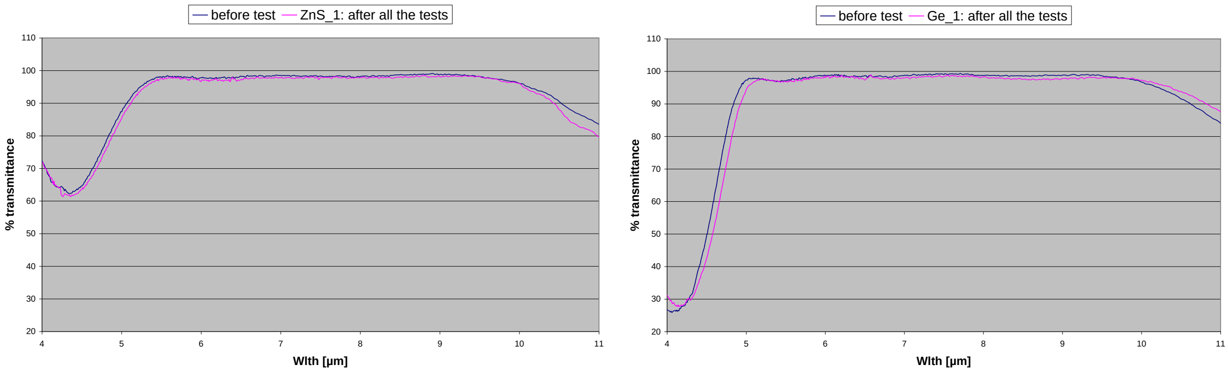


Fig. 14: The transmission measurements before and after all the environmental tests the Ge and ZnS coated samples underwent; the transmission of the system Low AI coating + substrate + High AI coating is measured.

## 6.2 DPA Environmental Tests

1. The DPA Qualification Model, fully representative of the Flight Model (excepting that QM prisms are not coated), was vibrated using CSL shaker facility 2016U 88 kN (Fig. 15), and according to qualification levels specified by the MiRi Imager (Fig. 15).

Fig. 15: DPA QM on the shaker in vertical configuration (left); the CSL 2016U shaker in vertical configuration (middle); the DPA FM mounted on the shaker interface and instrumented with mini-accelerometers (ENDEVCO model 23): 0.8 gm accelerometers which effectively eliminate the mass loading.

The DPA Flight Model was vibrated at acceptance levels, which correspond to the qualification levels reduced by 3dB.

The specified levels were a real issue for the prisms design elaboration; the Geometric Elements Method Analysis is described in [1]. The pilot accelerometers levels are shown on Fig. 16; these answers (blue on the graphs) correspond to the specified random levels and lead to 30.6g RMS along x axis, 28.2g RMS along Y axis and 44.3g RMS along Z axis (axes Fig. 17). (Red and yellow curves set the shaker alarm and abort levels)

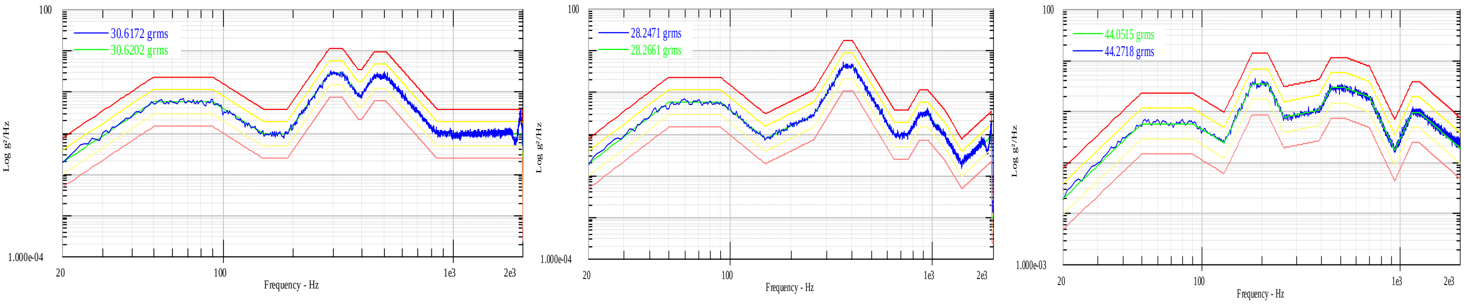
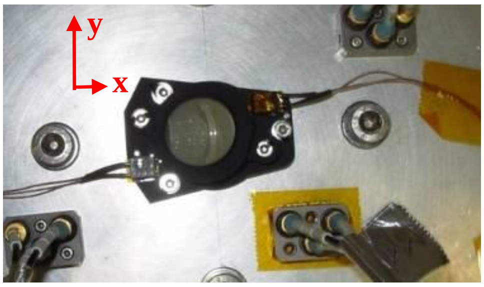


Fig. 16: Qualification Vibrations: Pilot Accelerometers Levels



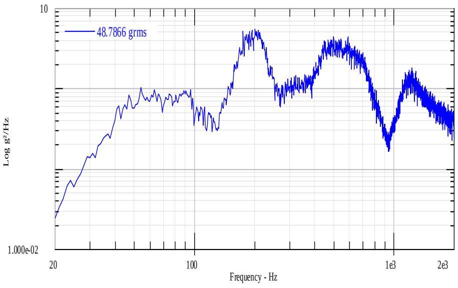


Fig. 17: Qualification Vibrations: Axes for the test (DPA QM and three accelerometers shown on the picture)

Fig. 18: Qualification Vibrations along Z (44.3g RMS): response of the ENDEVCO mini-accelerometer placed on the DPA holder.

The qualification and the acceptance tests were a success; the results validated the design and confirmed the predictions; the QM vibrations campaign highlighted the necessity to ***improve the ondulated springs metrology*** in order to obtain the correct compression of the springs' six waves.

Indeed, the Ge prism-spring shall be contracted from a free height of 1.6mm to a compressed height of 1.5mm, and deliver a force of 145N (within 10%) to compensate the external acceleration and protect the prism. It appeared during the vibration run that the individual waves of the spring were differing strongly in their free height.

University of Cologne was able to manufacture new springs for the DPA Flight Model and spare, with dimensions and performance according to the specifications foreseen in the design of the DPA.

The results were very good, the dimensions of the springs are correct within 0.01mm. Their performance is as specified. The new springs were qualified by UoC: (1) the springs have been exposed to more than 20 contractions to 1.5mm, a load of 39kg, and (2) shock cooling with liquid nitrogen bath. To check the performance of the springs produced by UoC, the contraction of the springs under increasing load has been measured with micrometer precision [1].

The qualification vibrations highlighted also the necessity to ***improve the integration procedure*** in order to check the springs can correctly achieve their compressed height while the covers are screwed to the final 1.2Nm torque.

2. The DPA Development Model, Qualification Model and Flight Model and Spare, were cycled in the CSL cryostat.

The DPA was tested under vacuum, cooled by conduction through a copper support interfacing with a thermal-switch (Fig. 11 right and Fig. 19); GHe is injected inside the thermal switch to allow a conductive path between the DPA support and the Helium bath. The DPA is heated by conduction with the copper interface around which a heater is wound; pumping is performed inside the thermal-switch during the hot phase to avoid any contact with the helium bath. A nitrogen shroud surrounds the helium core of the cryostat to minimize the helium consumption. The cryostat is equipped with an electrical harness for interface with the thermal sensors and the heater.

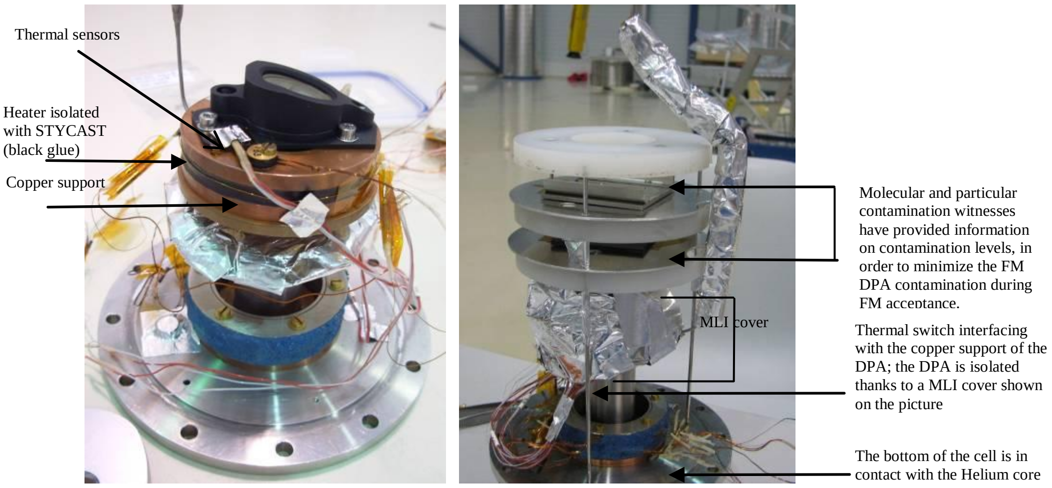


Fig. 19: The DPA models are heated by conduction through copper interface using a heater isolated with Stycast glue (left); DPA models are cooled by conduction through GHe injected inside the thermal-switch, which is in contact with the cell (right)

During the first qualification cycle, several careful trials were performed in order to finalize the heating and cooling procedures. For the cooling phase, the pressure increase in the thermal switch was carefully set in order to avoid gradient inside the prisms larger than 20K, the DM cycles experience helped us to find the optimal setting. For the heating phase, the sequence of pumping in the thermal switch and heater powering was also critical and carefully set to avoid too high temperature increase slope, but still fulfill the increase slope requirement of minimum 20K/hour. At the time of writing of this paper, the DPA QM is still being cycled. The first cycles are shown on Fig. 20.

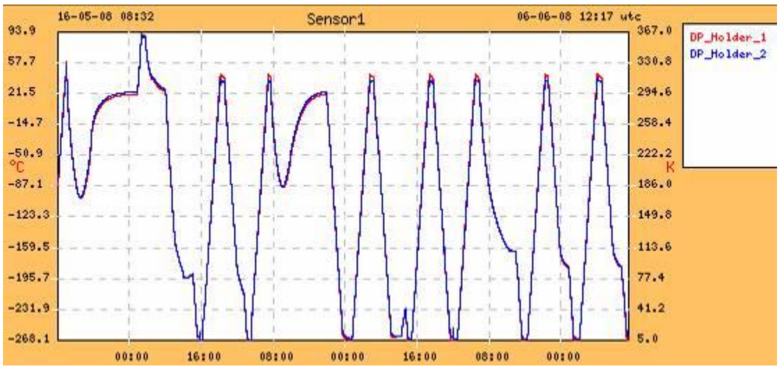


Fig. 20: The survival cycle (5K – 363K) and the seven first qualification cycles (5K – 313K) of the DPA QM

# 7. CONCLUSION

The DPA is a science optical assembly with several technological challenges. The severe thermal and mechanical MiRi specifications required iterations and refurbishment of the DPA design. The germanium and zinc sulphide materials are used for their infrared optical characteristics but their machining created a significant difficulty. Their fragile and brittle behaviour were the most significant parameters during the DPA design elaboration, taking into account the high external loads. Several models were used during the DPA development and several tests campaigns were held to validate the design and to finally bring us to a successful end.

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