HARMONI-ELT instrument integral field unit test tools development

Magali Loupias, Johan Richard, Alban Remillieux, Jean-Emmanuel Migniau, Florence Laurent, Alexandre Jeanneau, Aurélien Jarno, Eric Daguisé, Adrien Girardot, Matthieu Guibert, Rémi Giroud, Didier Boudon, Nicolas Bouché, Dawn Wasley, Dave Melotte, Niranjan A. Thatte, Fraser Clarke, Matthias Tecza

Published version information:

Citation: Magali Loupias et al., HARMONI-ELT instrument integral field unit test tools development, Proceedings Volume 13100, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation VI; 131004L (2024)

DOI: https://doi.org/10.1117/12.3019704

HARMONI – ELT instrument
Integral Field Unit test tools development

Magali Loupias[a], Johan Richard[a], Alban Remillieux[a], Jean-Emmanuel Migniau[a], Florence Laurent[a], Alexandre Jeanneau[a], Aurélien Jarno[a], Eric Daguisé[a], Adrien Girardot[d], Matthieu Guibert[a], Rémi Giroud[a], Didier Boudon[a], Nicolas Bouché[a], Dawn Wasley[b], Dave Melotte[b], Niranjan A. Thatte[c], Fraser Clarke[c], Matthias Tecza[c]
[a]Univ Lyon, Univ Lyon1, Ens de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint Genis-Laval, France;
[b]UK Astronomy Technology Centre, Royal Observatory, Edinburgh EH9 3HJ, United Kingdom;
[c]Univ. Of Oxford, Keble Road, Oxford, United Kingdom;
[d]LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 92195 Meudon, France;

ABSTRACT

HARMONI is the ELT's first light visible and near-infrared (0.5 to 2.45 µm) integral field spectrograph over a range of resolving powers from R~3500 to R~18000. It will provide 4 different spatial scales from 4*4mas to 30*60mas. It can operate in two Adaptive Optics (AO) modes – Single Conjugate AO (including a High Contrast capability) and Laser Tomography AO - or with No AO. The project is preparing for Final Design Reviews. The Integral Field Spectrograph (IFS) is the science instrument operating at 130K. This paper depicts the test tools developed to validate one sub-system, the Integral Field Unit (IFU), developed in Centre de Recherche Astrophysique de Lyon. The IFU is in charge of splitting, slicing and rearranging the rectangular field of view into 4 long slits (~540mm) to feed the 4 spectrographs. The tools are measuring position, angular deviation, wavefront or geometry of the field at ambient and operating temperature. Their design and validation are described with measurements on prototypes in our test cryostat. Their use for the final validation of the IFU performances is also addressed.

Keywords: ELT, HARMONI, Integral Field Unit, image slicer, 3D spectroscopy, AIT tools

1. INTRODUCTION

The High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph or HARMONI is a first light instrument for the ESO Extremely Large Telescope (ELT). It will provide more than 30000 spectra in one single exposure, spanning a fraction of the 0.5 to 2.45µm range. The light going through the ELT is corrected by an adaptive optic system and then enters a cryostat called the Integral Field Spectrograph (IFS). The IFS is made up of 6 sub-systems, see figure 1. The first is the cryostat which encloses 4 sub-systems, and provides them an operating temperature of 130K necessary to reach the performance in the near infrared wavelength. The light enters the cryostat into the Pre-Optics sub-system, which provides a pupil cold stop and 4 different spatial scales (4x4mas, 10x10mas, 20x20mas and 30x60mas). Then it goes through the Integral Field Unit (IFU) sub-system, which is responsible for dividing the field and reshaping it, to provide four output slits arranged in a square at the input of the four spectrographs sub-systems. The four Infrared Spectrographs include a set of gratings to providing a spectral resolution ranging from 3000 up to 20000. All spectrographs cover the wavelength range from 0.8 to 2.45µm, in addition two of them have a visible path covering the wavelength range from 0.45 to 0.8 µm. They are respectively equipped with detector sub-systems, eight of them being IR detectors and four being visible detectors 4k*4k. The cryostat is held by the sixth sub-system, the rotator wrap, which makes it rotate during the observation. A dedicated paper about the HARMONI instrument capabilities are presented in this conference [1]. The following paper focuses on the IFU. The optical and mechanical designs are developed in section 2. The section 3 describes the Assembly Integration and Test (AIT) strategy of the IFU, and sections 4, 5 & 6 present a summary of the AIT tools developed at CRAL and the test performed on different engineering model mounts.

Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation VI,
edited by Ramón Navarro, Ralf Jedamzik, Proc. of SPIE Vol. 13100, 131004L

2. INTEGRAL FIELD UNIT DESCRIPTION

The Integral Field Unit is composed of two main optical modules, namely the Splitting and Relay Module (SRM) and Image Slicer Module (ISM) together with a structural module called IFU Main Structure (IMS), see figure 1. The input of the IFU is a rectangular field of view delivered by the IFS Pre-Optics (IPO) Sub-System.

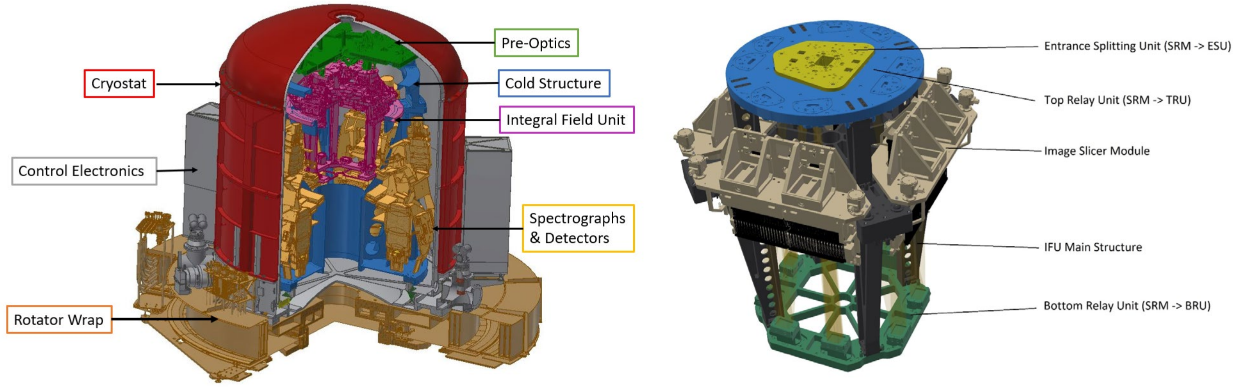


Figure 1: Full Integral Field Spectrograph with its cryostat on the left and Integral Field Unit with its modules on the right

During the Preliminary Design Phase (PDR), several arrangements of the ISM and SRM have been analysed to fulfill the main requirements for the IFU sub-system. A detailed description can be found in [2]. Here are summarized the first order parameter of the IFU sub-system in Table1.

Table 1: First order parameters of the IFU

IFU	X in mm	Y in mm
Slicing of the field		152
RMS wavefront error for the scale 30*60mas	< 380 nm RMS	
Pupil spread	Within +/- 7.3 arcminutes	
Entrance Field of View	39.8	59.6
Entrance F/# Telecentric	35.5	
Magnification	0.33 (2.56 for SRM and 0.13 for ISM)	
Exit PseudoSlit 4x	< 541mm	< 9mm
Exit F/# Telecentric	11.9	

The selected arrangement divides the input field into eight sub-fields by the Splitting and Relay Module (SRM). After magnification, pairs of sub-fields are delivered to four Image Slicer Module (ISM). Two fields will be delivered to each of the ISM, where the field will be sliced into 2*38 (76) mini slits. The mini slits are arranged along an output slit, ready to be fed to one of the four IFS spectrographs. The IFU divides the input optical beam into 304 output optical beams with 956 mirrors, packaged within a 1.5 m diameter by 1.6 m height cylindrical envelope.

2.1 Optical design

The first optical element of the SRM is the Field Splitter, which divides the incoming field-of-view in 2 x 4 sub-FoVs. The Field Splitter is an assembly consisting of eight rectangular prism mirrors. 8 paths, named from A to H, have been optimised to re-image them at the image slicer input, arranged in a square.

For paths A, B, E and F, four mirrors are used to relay the sub-fields, two of which have a spherical curvature. A fifth flat mirror (named M2) has to be added to paths C, D, G and H, so as to generate a 90° sub-FoV rotation. The M3 mirror makes a pupil plane 212 or 252 mm after the M4 mirror depending on the path, the size of which is around 12 mm in diameter. M5 mirror re-images the field at the ISU plane with a telecentric output.

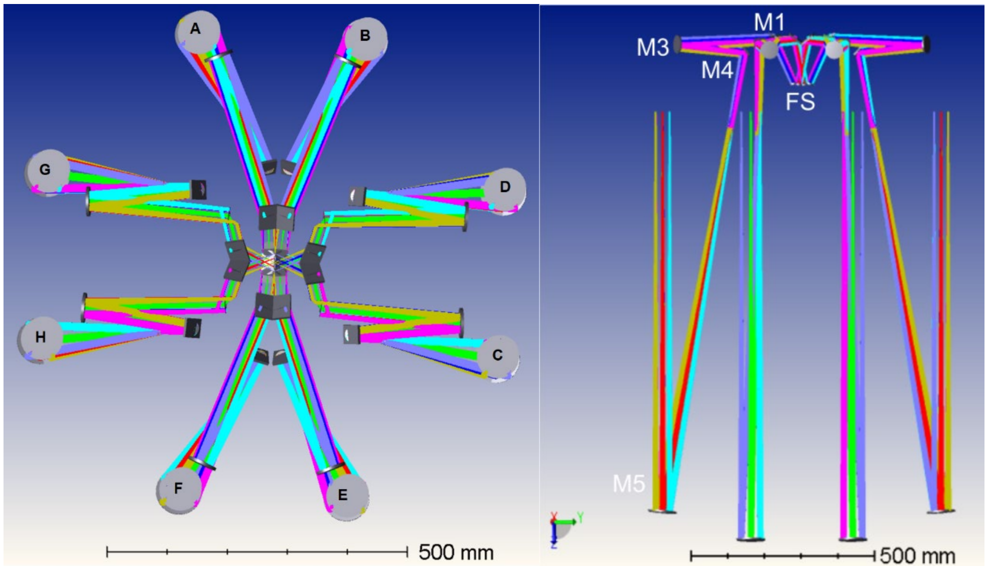


Figure 2: Ray tracing of the Splitting and Relay Module

Four image slicer modules will be produced. A detailed analysis of this module can be found in [3]. Each ISM consists of three optical units called the Image Slicer Unit (ISU), Pupil Mirror Unit (PMU), and the Slit Mirror Unit (SMU), see figure 3. ISU is composed of two stacks of 38 thin mirrors (commonly called slicers) named ISA_A and ISA_B. Note that the two stacks of 38 thin mirrors will be manufactured from the same parabolic mirror with a radius of curvature of R = 800 mm. Each slice has a different off-axis angle and cuts the entrance field into a thin, narrow strip (slice), then redirects the beam towards its own mirror in the Pupil Mirror Assembly (PMA) and images the telescope pupil. PMU is composed of 2*38 tilted flat mirrors called PMA_A or PMA_B. They are located ~20mm before the pupil plane created by the ISU and they are used to compensate the high angle of the beam coming from the ISU towards the SMU. This last unit is composed of 2*38 off-axis spherical mirrors called SMA_A or SMA_B. These 76 mirrors deflect the optical beams so that they are parallel to one another, they create an image of their associated slice, re-image the telescope pupil and superimpose them.

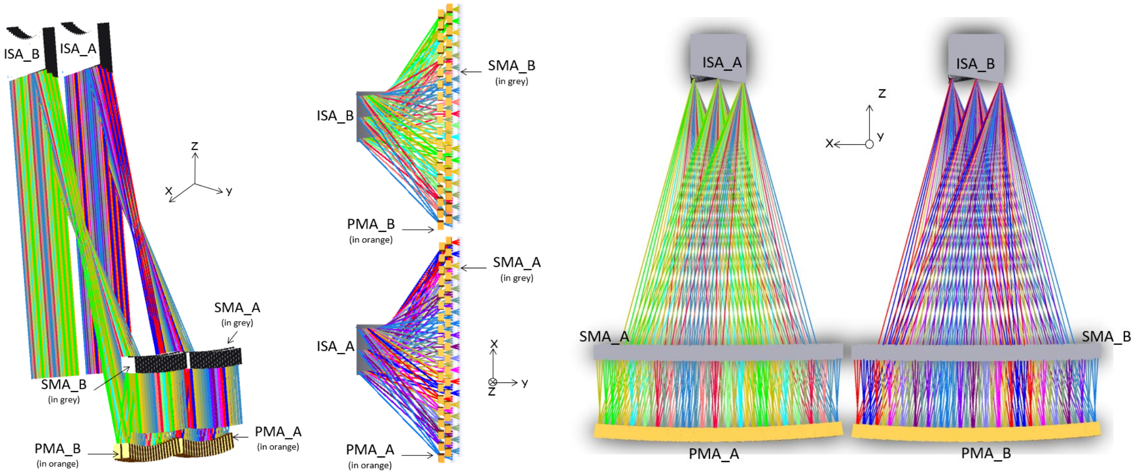


Figure 3: Ray tracing on the Image Slicer Module composed of three units

2.2 Mechanical design

This set of more than 900 mirrors composing the SRM and ISM, have to be aligned, and stay aligned over the full operating life of HARMONI. The IFU sub-system mechanical design provides the capability to align at ambiant temperature, and have the final stable performance at 130K. It is composed of three boards to hold all the optics, see figure 4. The middle level is called the Flange level, as it is the interface with the Cold Structure. This is the only mechanical interface with any other sub-system of the IFS.

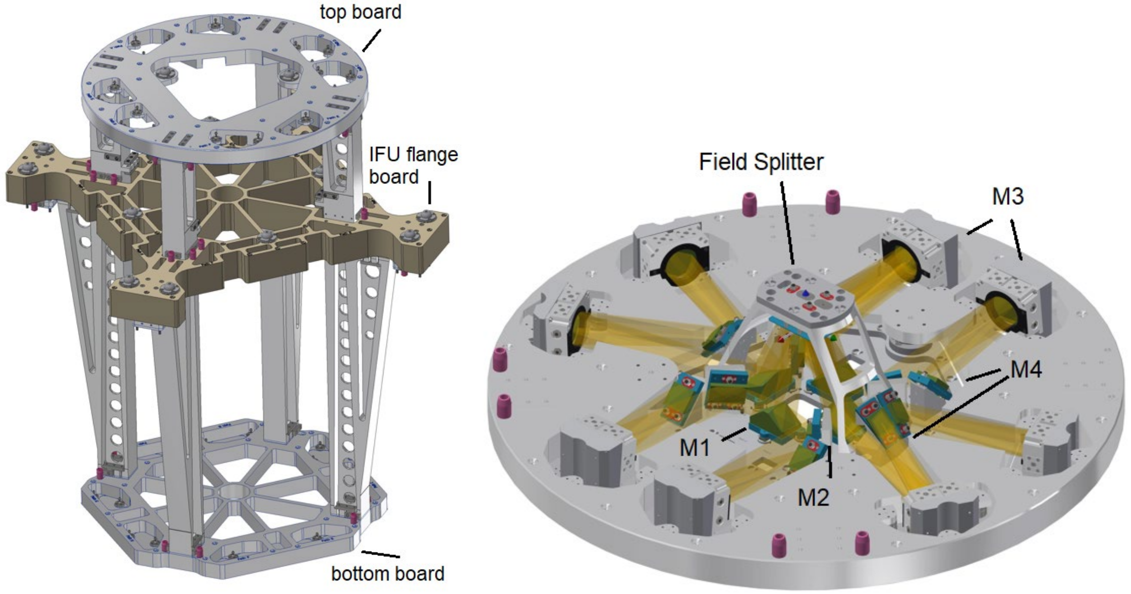


Figure 4: Left: IFU Main Structure with the top and bottom boards, Right: top board with its optics mounted.

Concerning the mechanical design itself, the boards are shimmed on the main structure, and all the SRM mounts are shimmed on the boards. Two kinds of mounts have been designed for this module. The one for M3 and M5, see Figure2, spherical mirrors are laterally adjustable in X and Y, all other degrees of freedom being shimmed. The second mount can only be shimmed in the angular degrees of freedom and longitudinally, as it holds the plane mirrors of the module, so to say the Field Splitter, M1, M2 and M4.

For the ISM mechanical design, see figure 5, and because of the very restricted available space, the kinematic supports of individual optical components are integrated directly onto the same optical bench. For x, z, θy, degree of freedom, shims will be replaceable as a function of supplier measurement or alignment tests. For the degrees of freedom, y, ϴx, and ϴz an irreversible and self-locking micrometric adjustment system was developed in order to reach the most stringent positioning of +/-20arcsec.

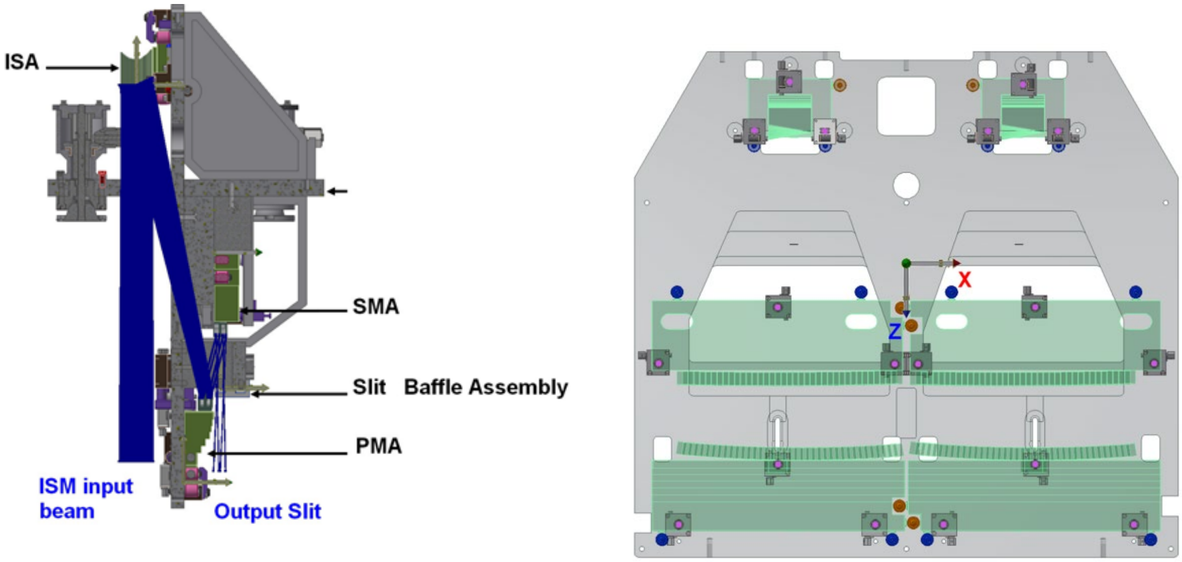


Figure 5: Image Slicer Module, optical zerodur assembly with the 3 degrees of freedom shimmed (blue and orange shims) and the 3 others adjustable (pink tuning systems).

The complete tolerance analysis of the IFU sub-system is provided in [2]. In a nutshell, as summarized in table2, the positioning of the SRM mirrors will be done within 50µm accuracy and within 1 arcmin. For the ISM, the metrology in position has to be within 20 µm accuracy and the angular positioning which is the most stringent has to be within 40arcsec.

Table 2: tolerancing orders of magnitude

IFU	Positioning in µm	Angular dof in arcsec
Splitting and Relay module	50	60
Image Slicer module	20	40

3. IFU AIT STRATEGY

3.1 Position degrees of freedom

In order to reach these tight tolerances in a cryogenic environment, a method has been developed to assess as precisely as possible and reduce the error risk in the thermal shrinkage estimation. The method is to build two CAD models linked by the thermal variation from ambient to operational temperature, see figure 6. The first main hypothesis is the use of the same shade of aluminium for the main structure and the mounts of our sub-system. The ambient CAD model is composed of mechanical parts with integer dimensions, fitted to the machining temperature. A few thermal compensators are identified in the model to set the position degrees of freedom (dof) of the optics at their nominal ensquared position at operational 130K temperature. With a 1% error in the thermal expansion coefficient of the material, the estimation of the X, Y, Z positions are well within the 50µm. The CAD model is considered reliable enough to predict the position of our optics at 130K. This error has been allocated in our positioning budget.

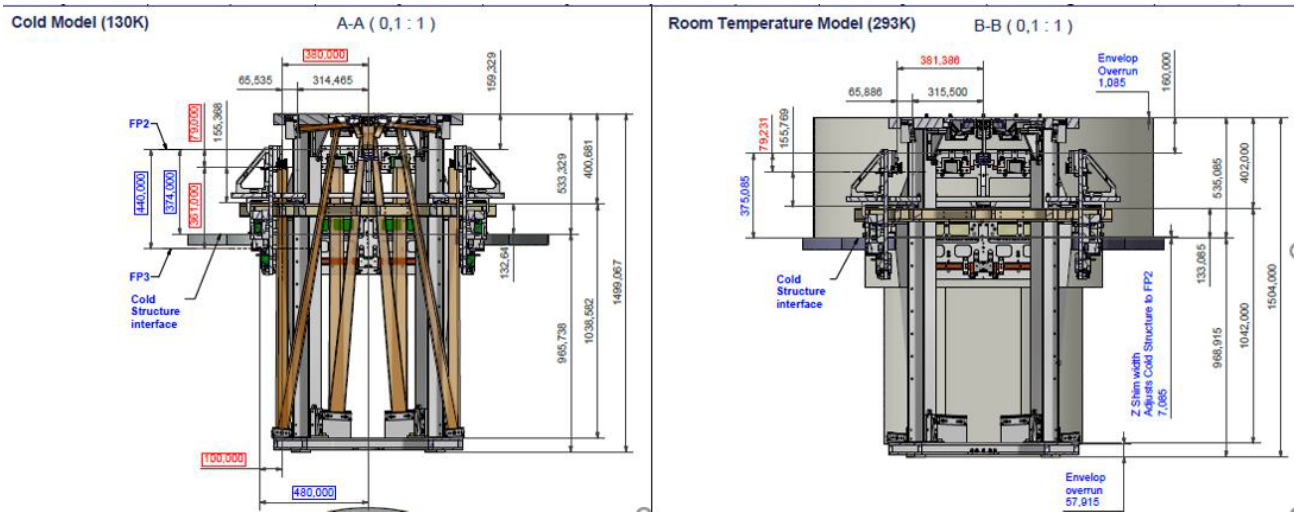


Figure 6: Warm to cold CAD models drawings of the IFU

3.2 Angular degree of freedom

Concerning the angular deviation of the mirrors, not any model will be accurate enough to estimate properly the deviation of the mirror. This is why engineering models are necessary to assess the mount of each optical element have been designed to repeatably control the tilt of the optical element. Three engineering models have been developed to validate this assumption. An engineering model has been developed for each of the different IFU mounts, see figure 7. Some results on these prototypes have already been reported in [4]. The current developments of the test tools are presented in sections 4, 5, 6 and 7.

- The first prototype is a glued one that is used to test the performance of one glued zerodur mirror substrate on an invar plate, to be representative of the Field Splitter, M1, M2 and M4 mount. The invar plate is shimmed onto the aluminium mount. The gluing process and the measurement of the position of the mirror onto the referenced invar plate are sub-contracted to the supplier. This strategy has been chosen to save space on the central part of the top board, see figure 4. A reference mirror is on the invar pad and reference mirror is on the baseplate which receives the invar pad.
- The second is a laterally adjustable prototype that is used for M3 and M5 spherical mirrors which are our compensators in the alignment strategy. The aim of the tuning is to reach the 5µm lateral positioning accuracy. A reference mirror is on the mount.
- A third prototype is a slicer size adjustable prototype that has been developed to validate the constraints linked to the shape of the mirrors and assess the stringent angular positioning repeatability needed. The zerodur optical elements can be as long as 270mm. A dedicated prototype has been developed to assess better the behavior of such a long component.

Theses prototypes have been tested with the different test tools described in the following sections.

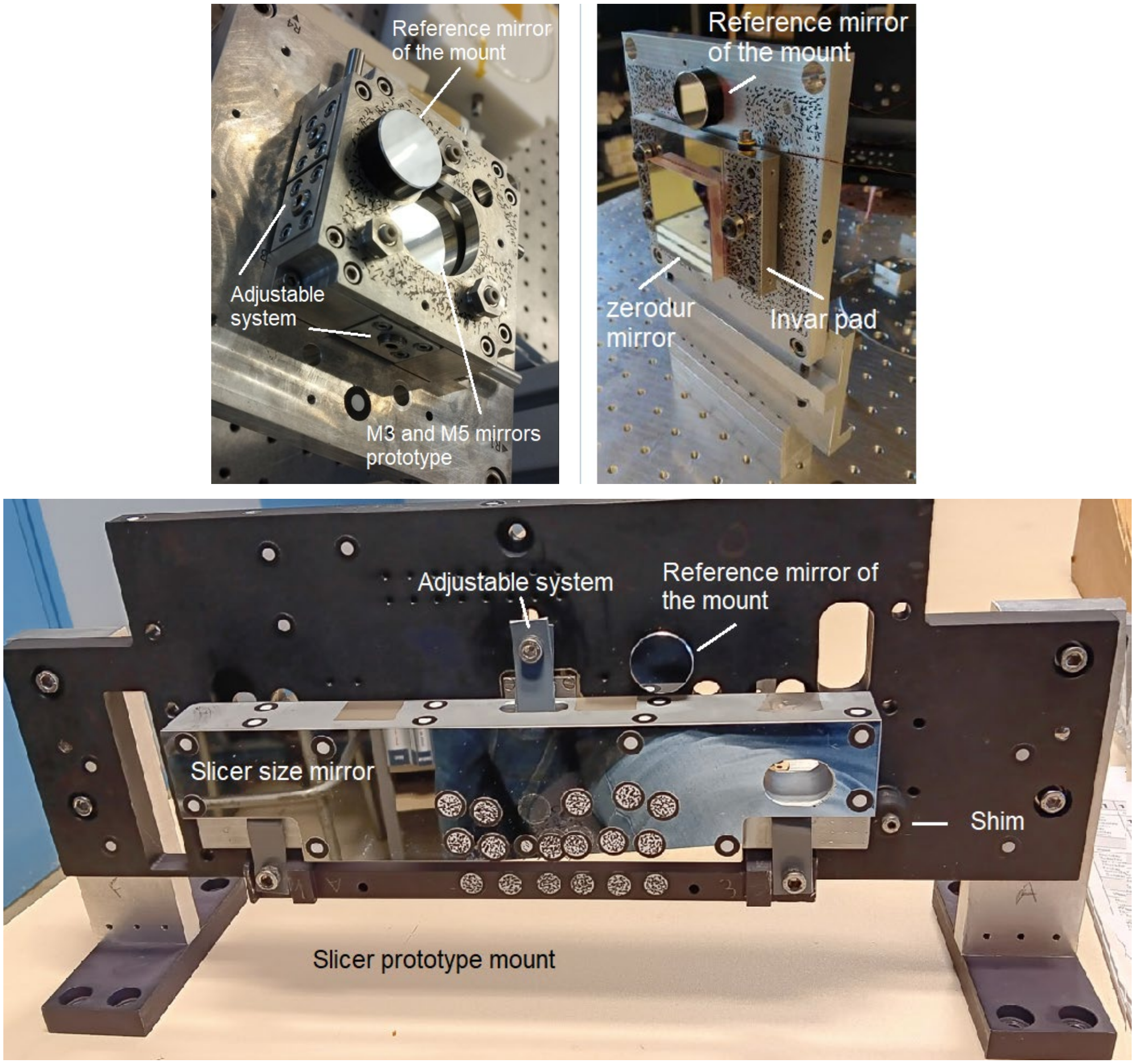
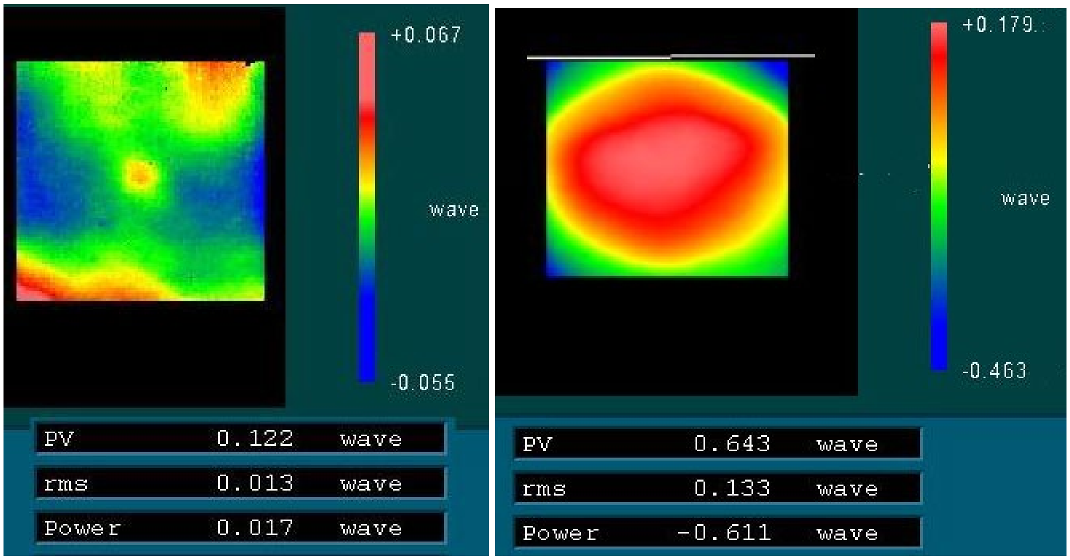


Figure 7: three prototypes: (top left) laterally adjustable prototype, (top right) glued prototype, (bottom) slicer adjustable prototype

4. WAVEFRONT INSIDE CRYOSTAT

All prototypes have to validate that the mount is not constraining the wavefront of the mirror when undergoing the 293K to 130K temperature variation above the specified value of 80nm PTV. A 100mm diameter wavefront interferometer is set in front the viewport of our test cryostat. A wavefront measurement is done each 10 minutes during the cool down process to check the behavior of the mirror within its mount.

Two glued prototypes have been ordered to different suppliers. They are flat mirrors with an irregularity below λ/8 PTV @633nm. On Figure 8 one can easily compare two different behaviors at 130K. The wavefront measurement @ λ=633nm shows that the technique used by supplier1 does not constraint the mirror, whereas supplier 2 technique induces a few hundreds of nm PTV curvature to the mirror.



PV 0.122 wave
rms 0.013 wave
Power 0.017 wave

PV 0.643 wave
rms 0.133 wave
Power -0.611 wave

Figure 8: 2 different glued mirrors wavefront measurement at 130K: left supplier 1, right supplier 2

We are currently iterating with the supplier 2, to improve its glueing technique. To be noted that the measurement for the supplier 1 prototype is limited by the viewport wavefront deformation. The correction is not implemented in this measurement. But a calibration of the viewport deformation has been done measuring a flat calibration mirror insisde the cryostat. This mirror was not clamped to remove any stress that could be induced by any mount during cool down. From ambient to 130K temperature this viewport induces a Surface Figure Error (SFE) PTV amplitude of 0.2 wave, taking into account the 36 first Zernike modes. A routine has been developed to remove the viewport deformation from the measurement at operational temperature. Work is still in progress to assess the accuracy of the measurement, the current estimation being below λ/10 PTV.

5. ANGULAR MEASUREMENT TOOL

The most critical parameter to control is the angular position of the IFU mirrors. In order to validate the angular performance of the mirror inside its mount during several thermal cycles, a 100mm diameter aperture autocollimator is set up in front of the test cryostat, see figure 9.

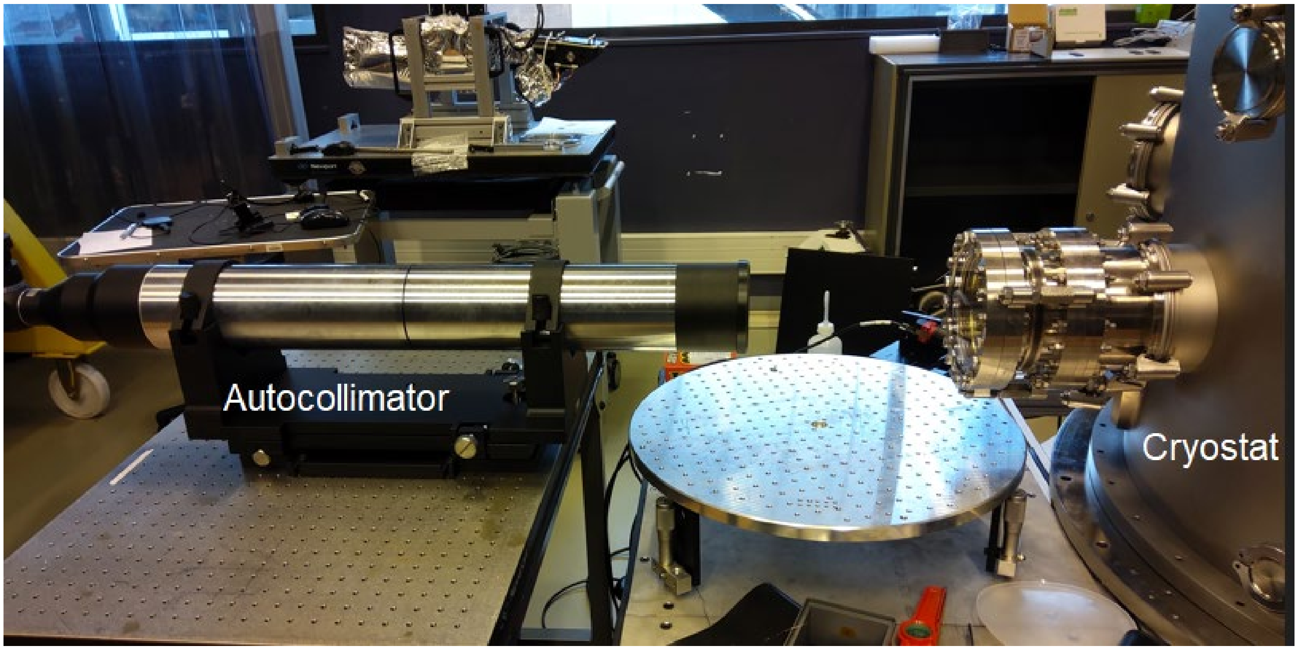


Figure 9: Autocollimator measuring differential motion between the mirror and its mount inside the cryostat

The autocollimated targets reflected back from the 2 mirrors surfaces, the mirror itself and the reference mirror on the mount, are recorded during the full thermal cycle, see Figure 10. The in plane X and Y positions of the targets are directly proportional to the angular deviation. The differential motion in both directions is plotted in figure 10, and exhibits a repeatability of measurement within 10 arcsec. All prototypes have passed this test.

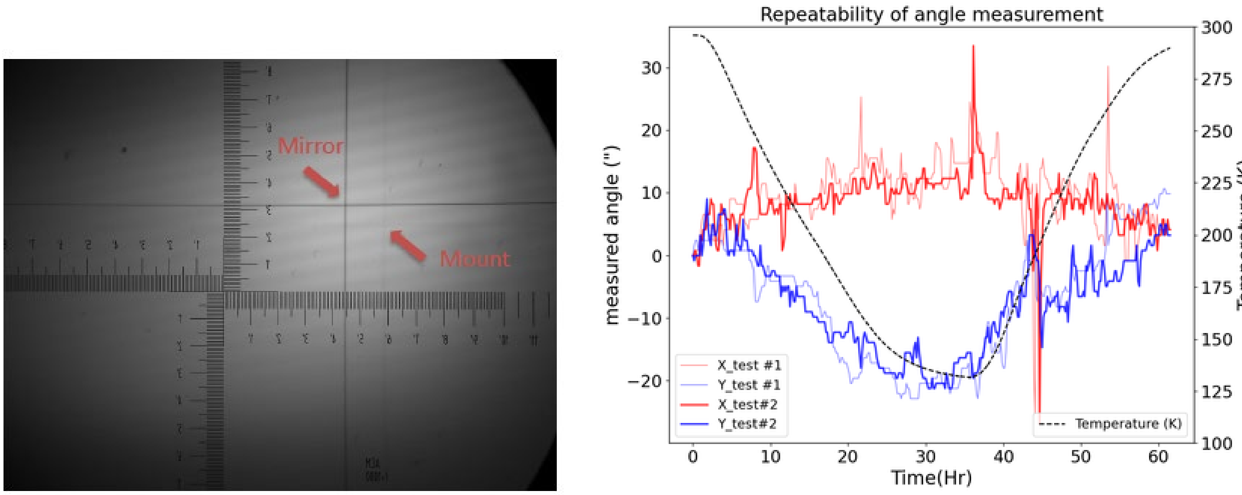


Figure 10: Left: Autocollimation on the mirror and its mount, Right: Repeatability of the angular measurement during 2 cycles of cooling.

Today all our prototypes are within 30 arcsec deviation from ambient to operational temperature. This gives us confidence in our alignment strategy process.

6. CHIEF RAY TOOL

One major tool developed for the IFU integration and used for the final test is The Chief Ray Tool (CRT). This tool is designed to measure the ISM pupil quality (chief ray coordinates with respect to the ISM flange and pupil spread). This is the most challenging optical interface. The spectrograph needs to be aligned with the output slit chief ray with a ±40 arcsec accuracy. A test bench has been developed using the former instrument MUSE slicer module. This module is made up of 2 blocks: one with 4 stacks of 12 slices called Slicer stack, and the other with 48 pupil mirrors called Slit Mirrors Array (SMA). The double pass measurement scheme using a Fizeau interferometer is set in front of the MUSE slicer module, see figure 11. An autocollimation mirror is positioned at the output of the Slicer module, and a reference mirror is attached to the Slit Mirror Array mount. The output chief ray angle of each slice is proportional to the differential tilt between the autocollimation mirror and the reference mirror.

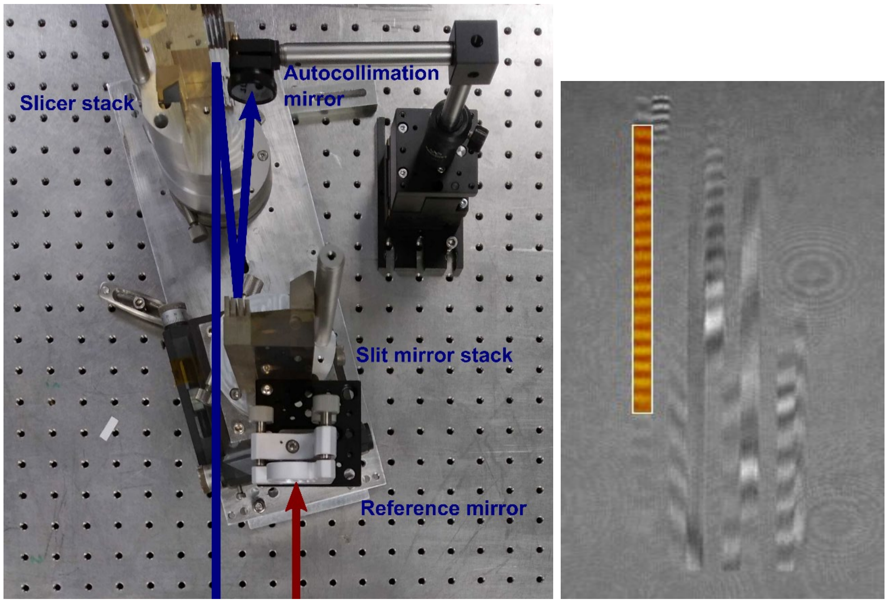


Figure 11: Left: MUSE slicer module illuminated by a 100mm interferometer beam, Right Interferogram measured on one slice

The return beam from the Slicer module is measured and compared with the reference mirror tilt slice by slice. After fitting and substracting the reference tilt offset, correcting for the magnification of the full slicer module (0.076 factor, fixed by design), the Figure 12 plot is obtained. 13 angular offsets of the Slit mirror stack have been measured, using the interferogram on one slice shown in Figure 11. Their output chief ray angle is computed with an average of 15 measurements, and lies within the goal of 10 arcsec angular accuracy.

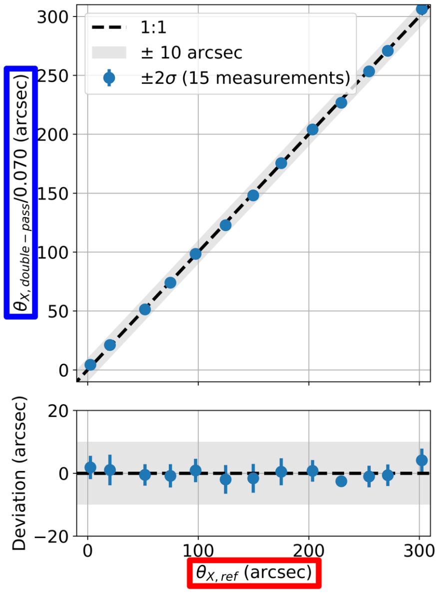


Figure 12: Chief ray measurement accuracy of the double pass interferometer test bench

This method will be used for HARMONI slicer module, as the goal is to know the mean ISM chief ray to ~20 arcsec with respect to the ISM flange, which will be used as a mechanical reference by the spectrograph.

Hence the Chief Ray Tool (CRT) designed for HARMONI, comprises the following optical elements:

-A laser tracker

-Three laser tracker targets mounted on the ISM flange, in order to define the mechanical reference and provide it to the global IFS integration procedure.

-A referencing mirror, bonded to the ISM flange (or a mirror-finished area of the flange).

-Two auto-collimator mirrors covering a full slit, parallel to the ISM flange, mounted on a tip-tilt stage. The accuracy of theses motors ensures a positioning well below 1 arcsec. The space at the slit level is very constrained and imposes a delicate positioning of this tool.

-A referenced illumination based on a Fizeau interferometer.

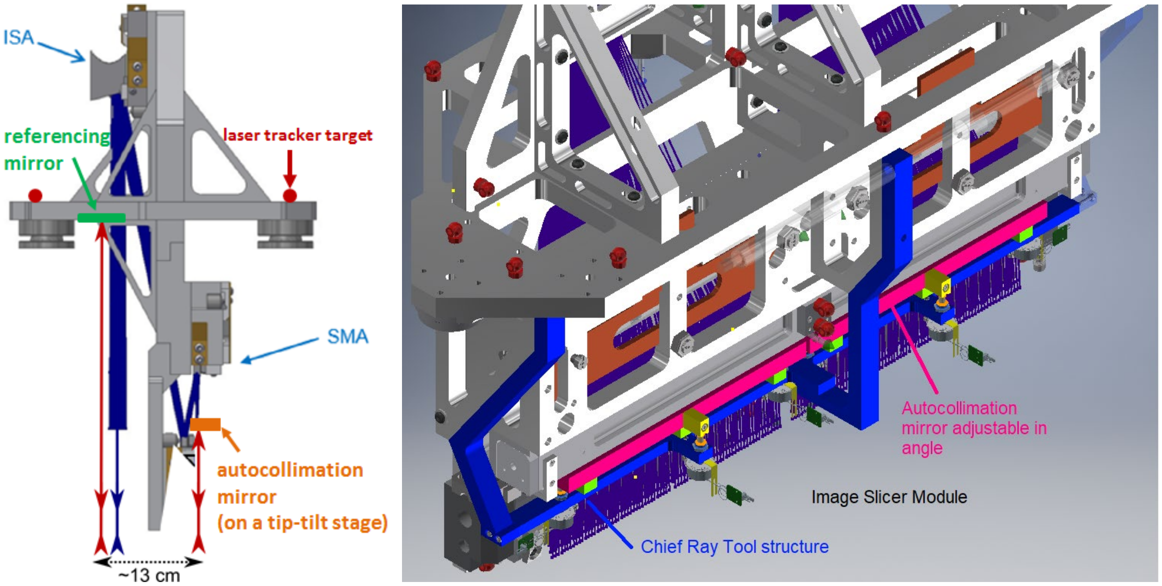


Figure 13: Chief Ray Tool principle scheme and CAD model, (in pink is the orientable mirror used for autocollimation).

This complex tool is still under development. It will be used also during IFS integration to check this sensitive parameter: the output chief ray of the IFU sub -system.

7. OTHER AIT TOOLS

One test tool, which is measuring the position inside the cryostat, is based on a photogrammetry technique. Targets are positioned on our optics. Pictures are taken with different view angles and recombined by a dedicated software to reconstruct the 3D shape of the mount. This photogrammetry system has been adapted within our cryostat, using a motorized periscope that reimage the scene inside the cryostat, on the camera attached outside of the cryostat. This tool is the subject of a dedicated SPIE paper [5] and is not reported here.

The global positioning of all the mirrors of the IFU will be done at room temperature using a laser tracker. Retroreflector corner cubes targets are positioned over the IFU and will be measured within 20 microns. The angular position of all plane mirrors will also be measured within 10 arcsec at room temperature. Once the measurement at room temperature is fully completed, the cold position is given by the warm to cold model. All mounts with their mirrors will pass the tests inside the cryostat depicted in chapters 4 and 5. This validates the proper behavior in cold of the IFU.

One tool has been developed using Digital Image Correlation (DIC) technique. A camera is set in front the viewport our cryostat to record images during the cool down. The mount and mirror of our prototypes are marked with a speckle pattern, see Figure 7. The software to analyse the images allows the selection of different zones on the image where the speckle has been marked. It computes the motion of each speckle pattern and its analyses gives the differential motion between the different zones and their shrinking during cool down. This tool will be useful to validate within 10 μm accuracy on X and Y the behavior of our prototypes.

8. CONCLUSION

The IFU sub-system is progressing well towards the Final Design Review. The optical design is frozen. The mechanical design has been improved based on the cold to warm model process. This process is reliable for the positioning estimation of the optics at operational temperature, given the hypothesis that the same shade of aluminium is used over our sub-system. Concerning the angular degrees of freedom, the prototyping of the different mounts in play inside our sub-system, has proven their performances with respect to the specifications. The prototype tests validate the foreseen AIT strategy. The feasibility of the test tools has been demonstrated in our laboratory. The tools testing on our prototypes will still go on to secure the accuracy, the repeatability and the automation of our measurements. The secured AIT plan will be provided for HARMONI Final Design Review currently scheduled for end 2026.

9. ACKNOWLEDGEMENTS

The CRAL IFU team thanks the CNRS/INSU and specially the Commission spécialisée Astronomie Astropyhsique (CSAA), University Claude-Bernard Lyon I, and LIO the EQUIPEX F_CELT for their strong support to the HARMONI project. All members of the HARMONI project office and lead engineers are thanked for their valuable contribution and acknowledge the support from UKRI-STFC grants ST/S001409/1 and ST/X002322/1 for UK ELT Instrument Development at Oxford.

REFERENCES

[1] HARMONI - first light spectroscopy for ELT: project status and instrument overview, N. Thatte & al., Proc. of SPIE 2022 Paper 13096-40.

[2] HARMONI - first light spectroscopy for ELT: Final design of the Integral Field Unit, M. Loupias and al., Proc. of SPIE 2020 Paper 11461-162.

[3] ELT HARMONI: Image Slicer Preliminary Design, F. Laurent & al., Proc. SPIE 2018 paper 10702-335.

[4] HARMONI ELT instrument: Integral Field Unit cryogenic engineering models results, M. Guibert and al., SPIE 2022, paper 121881H.

[5] Metrology inside a cryostat using a cutting-edge periscope, A. Girardot and Al., Proc. SPIE 2023, paper 126180