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# HARMONI - first light spectroscopy for the ELT: Final design of the Integral Field Unit

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## ABSTRACT

HARMONI is the ELT first light visible and near-infrared (0.45 to 2.45  $\mu\text{m}$ ) integral field spectrograph over a range of resolving power from  $R\sim 3500$  to  $R\sim 18000$ . It will provide 4 different spatial scales from  $4\times 4\text{mas}$  to  $30\times 60\text{mas}$ . It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. The project is preparing for Final Design Reviews. This paper depicts the final design of the Integral Field Unit in charge of splitting, slicing and rearranging the rectangular field of view into 4 long slits ( $\sim 540\text{mm}$ ) to feed the 4 spectrographs. The manufacturing of sensitive optics such as the field splitter or the image slicer are detailed. The mechanical and alignment design strategy is explained as well as the design of some dedicated integration tools, developed for cryogenic environment. The performances of the full unit are deeply discussed in terms of image quality, straylight analysis, tolerancing...

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

## 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. It will provide more than 30000 spectra in one single exposure, spanning the 0.45 to 2.45 $\mu\text{m}$  range. The light going through the ELT is corrected by an adaptive optic system and then enters a cryostat called the Integral Field Spectrograph, described in this conference article [4]. The IFS is made up of 6 sub-systems. The cryostat encloses five sub-systems, and provides them an operating temperature of 130K. The light enters the cryostat into the Pre-Optics sub-system, which provides a pupil cold stop and 4 different spatial scales ( $4\times 4\text{mas}$ ,  $10\times 10\text{mas}$ ,  $20\times 20\text{mas}$  and  $30\times 60\text{mas}$ ). Then it goes through the IFU, 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. 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 2.45 $\mu\text{m}$ , in addition two of them have a visible path covering the wavelength range from 0.45 to 0.8  $\mu\text{m}$ . They are equipped with eight IR detectors and four visible detectors  $4\text{k}\times 4\text{k}$ . 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 and 3. The section 4 describes the error budget allocated to each element and the associated tolerancing of the IFU, and section 5 presents a summary of the Assembly, Integration and Tests (AIT) phases foreseen to validate the sub-system performance.

## 2. INTEGRAL FIELD UNIT OPTICAL 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.

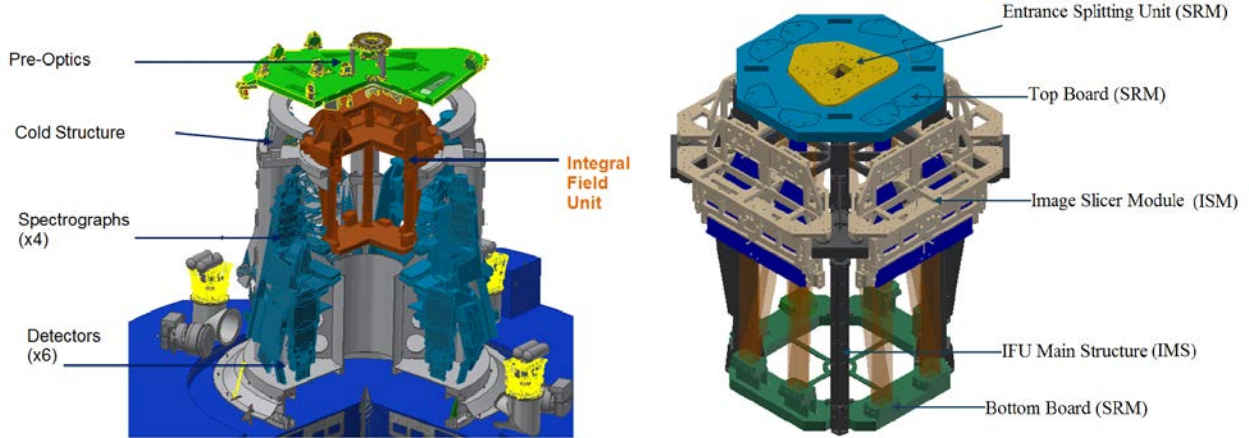


Figure 1: Full Integral Field Spectrograph with its cryostat on the left and Integral Field Unit with its modules on the right

During the Preliminary Design Phase (PDR), several arrangements of the ISM have been analysed to fulfill the main requirements for the IFU sub-system listed in table 1. From three different designs as described in [2], a trade-off has been done to select the most performant design in terms of image quality, and the less risky in terms of manufacturing.

**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. After PDR, the optimization of the Splitting and Relay Module has been worked out. First, two flat mirrors have been removed to increase efficiency, to the cost of a higher complexity with the spectrograph interface and a degradation of the optical performance. Three SRM designs - including toroidal, parabolic or spherical powered-mirrors - have been assessed for as-built performance and compared. The spherical design has

finally been selected: although not optimal by design, this combination fares better when manufacturing and alignment errors are taken into consideration.

The IFU will be assembled at room temperature and will be operated at 130K. The cryogenic alignment strategy has been integrated in the design process, see section 3 and 4. 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.

The first optical element of the SRM is the Field Splitter, which divides the incoming field-of-view in  $2 \times 4$  sub-FoVs. 8 paths have been optimised to re-image them at the image slicer input, arranged in a square. The Field Splitter is an assembly consisting of eight rectangular prism mirrors. In order to minimize shadowing, the C and D prism mirrors face each other (as well as the H and G prism mirrors), leading to crossed optical paths, see figure 2. That is why their optical paths are crossing one another, see figure 2.

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  $90^\circ$  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.

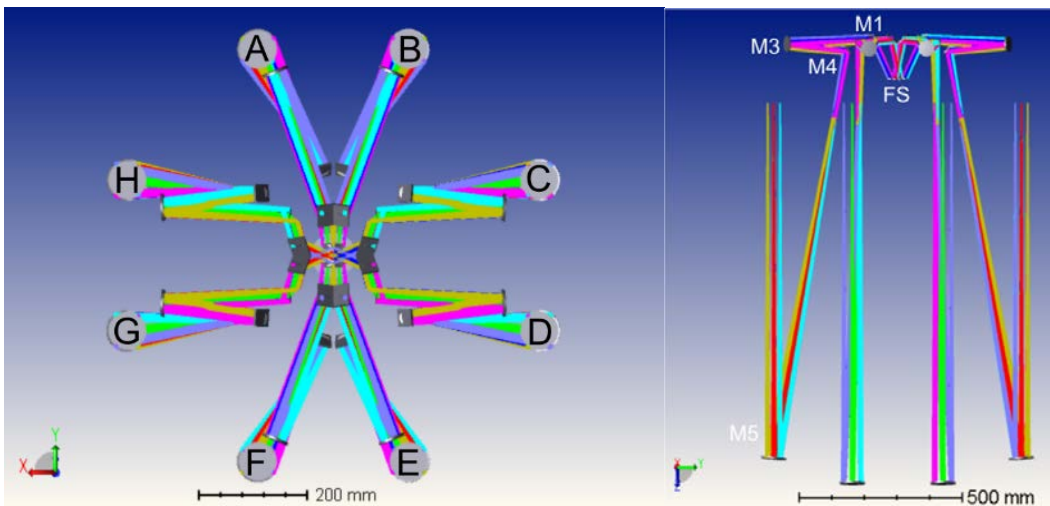


Figure 2: Ray tracing of the Splitting and Relay Module

Four image slicer modules will be produced. Each ISM consists of three optical units called the Image Slicer Unit (ISU), Pupil Mirror Unit (PMU), and the Slit Mirror Unit (SMU). ISU is composed of two stacks of 38 thin mirrors (commonly called slicers) named ISA\_TypeA and ISA\_TypeB. 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. The design of ISU was optimised to fit the process described in [3], which enables manufacturing the eight ISA blocks using four parent parabolas (330 mm diameter). 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  $2 \times 38$  tilted flat mirrors called PMA\_TypeA or PMA\_TypeB. They are located  $\sim 20$  mm 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  $2 \times 38$  off-axis spherical mirrors called SMA\_TypeA or SMA\_TypeB. 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.

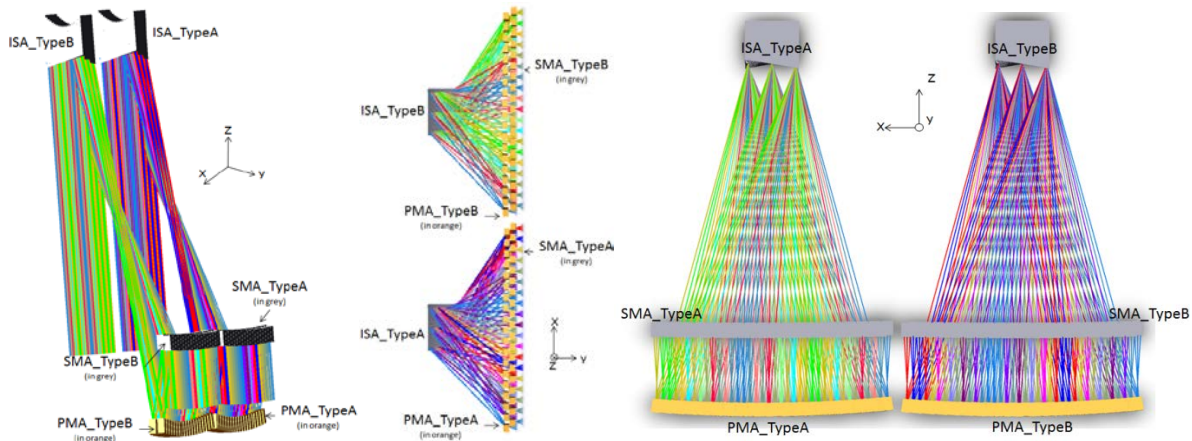


Figure 3: Ray tracing on the Image Slicer Module composed of three units

### 3. MECHANICAL DESIGN AND BUDGET

The IFU sub-system mechanical design is composed of 3 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. The IFU Main Structure and the mount of each optical element have been designed to avoid any tilt of the optical element, whereas their shift due to thermal variation is controlled. 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. 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 of the optics at their nominal position at operational temperature. This method is precise and reliable up to the CTE accuracy and the temperature stability. These errors are taken into account in the budget allocation given to each element (see table 2).

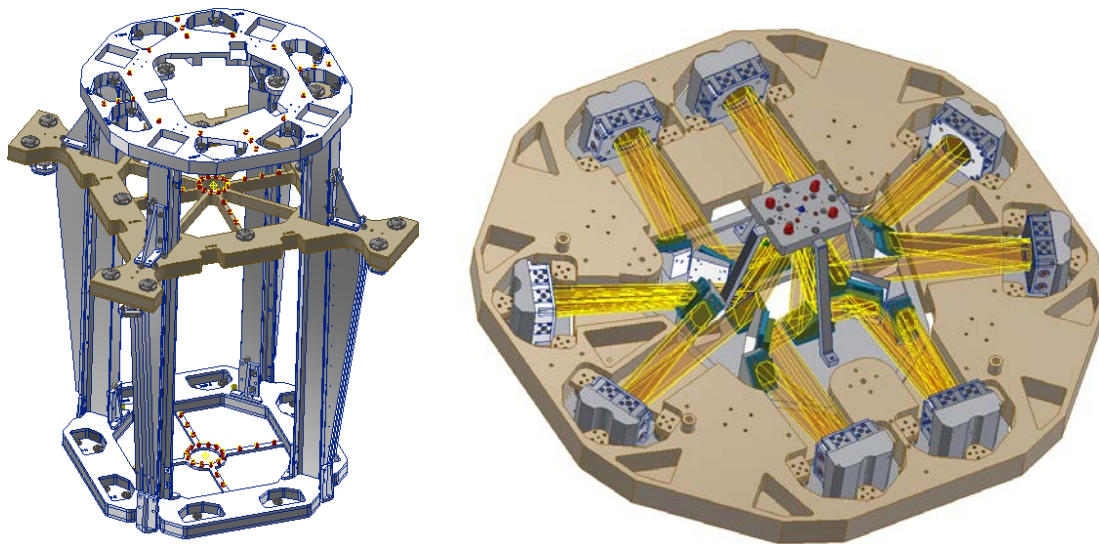


Figure 4: IFU Main Structure with the top and bottom boards on the right, top board with its optics mounted on the left  
Concerning the mechanical design itself, the boards are shimmed on the main structure, and all the SRM mounts are shimmed on the boards. The ISM optical elements are also shimmed on their mechanical support. The metrology used can be through laser tracker or photogrammetry techniques. An accuracy of 20 microns can be achieved for the shim taking into account the metrology and the machining.



Concerning the shimmed mount, the design chosen is to glue the zerodur substrate of the mirrors on an invar plate. 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.

The tolerance analysis shows that M3 and M5 mirrors have to be controlled to a better accuracy (5 microns) to reach the performance. Therefore, these spherical mirrors have a tunable mount, see adjustment screw (in violet) on figure 5. A kinematic system ensures a repeatable interface with the top board. The pins (in pink) are used as shims and could be re-machined to tune the Z degree of freedom (dof). The control after tuning can be done with a Coordinate Measuring Machine (CMM) to accurately measure the mirror in its mount down to 5 microns. Photogrammetry or laser tracker targets can be inserted in the adjustment screws bodies to confirm the position of the mirror once mounted on the top board.

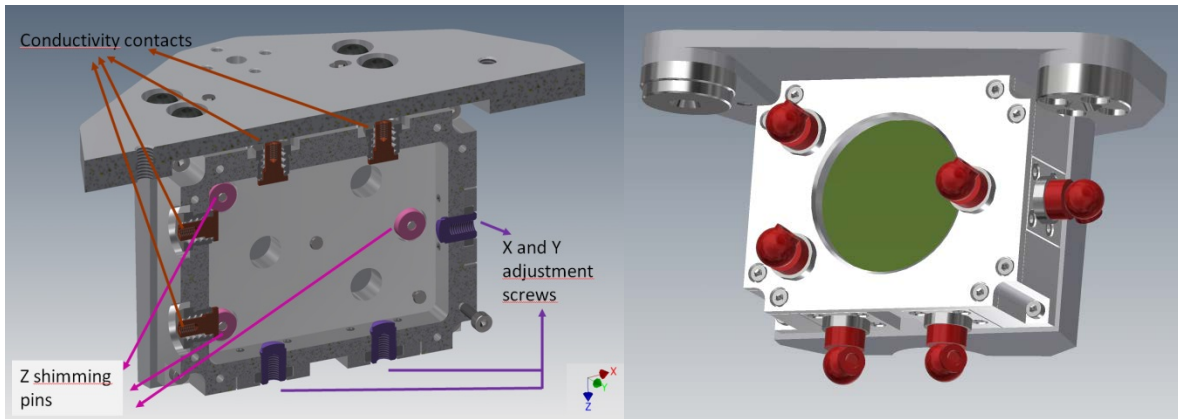


Figure 5: M3 relay assembly showing degree of freedom controls and laser tracker targets

For the ISM optical elements, see figure 6, shape details (such as oblong through holes) are directly machined on the zerodur substrate, to leave space for shims and clamps, and therefore optimise the ISM bulk. The shims could be re-machined as a function of supplier measurement or alignment tests. The 6 degrees of freedom are controlled. The relative location of ISA with respect to PMA and SMA being so critical, and because of the very restricted available space, the kinematic supports of individual optical components are integrated directly onto the same optical bench.

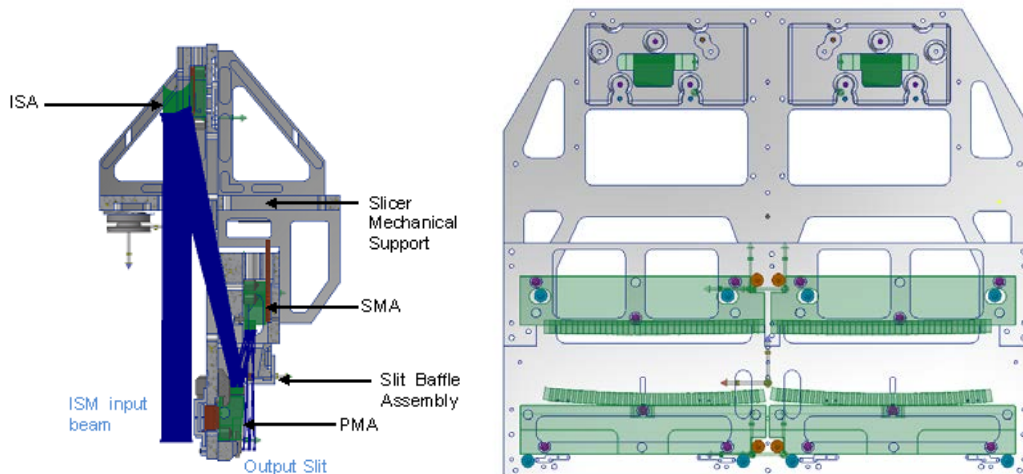


Figure 6: Image Slicer Module, optical zerodur assembly with the 6 degrees of freedom potentially remachined.

The error positioning budget for each kind of optics are summarized in the following table. The columns content is defined as follows. The Manufacturing error is the one given to the supplier. The measuring error is the accuracy of the tool available to measure the position of the mirror with respect to its mechanical reference. The CTE error is the 1%

estimation error coming from the cold to ambient model. The warm alignment shim is our capacity to correct this degree of freedom. The FEA is the budget given to the bending of the structure, impacting the location of optics. The Root Squared Sum is composed of all the fore mentioned errors except the manufacturing ones which are compensated. And the budget is the allocation given to the mirror for the tolerancing detailed in the next section.

**Table 2: Error budget for each kind of mirror**

mirror	dof	Budget	RSS	FEA	Manufacture	Measure	CTE error	Warm alignment shim
M2	X (mm)	0.300	0.102	0.005	0.100	0.020	0.003	0.000
	Y (mm)	0.300	0.102	0.005	0.100	0.020	0.005	0.000
	Z (mm)	0.050	0.025	0.005	0.200	0.020	0.010	0.010
	$\theta_x$ (arcmin)	1.500	1.255	0.160	0.500	0.330	0.000	1.200
	$\theta_y$ (arcmin)	1.500	1.255	0.160	0.500	0.330	0.000	1.200
	PTV SFE	$\lambda/8$						
M3	X (mm)	0.040	0.030	0.005	0.100	0.020	0.022	0.005
	Y (mm)	0.040	0.030	0.005	0.100	0.020	0.022	0.005
	Z (mm)	0.050	0.031	0.005	0.200	0.020	0.011	0.020
	$\theta_x$ (arcmin)	0.500	0.525	0.160	0.500	0.330	0.000	0.000
	$\theta_y$ (arcmin)	0.500	0.525	0.160	0.500	0.330	0.000	0.000
	PTV SFE	$\lambda/8$						
ISA	X (mm)	0.015	0.013	0.005	0.050		0.006	0.010
	Y (mm)	0.015	0.011	0.005	0.050		0.001	0.010
	Z (mm)	0.025	0.023	0.005	0.100		0.010	0.020
	$\theta_x$ (arcmin)	0.540	0.536	0.080				0.530
	$\theta_y$ (arcmin)	0.390	0.388	0.080				0.380
	$\theta_z$ (arcmin)	0.740	0.734	0.080				0.730
	PTV SFE (nm)				300			

#### 4. ANALYSIS AND TOLERANCING

The largest spatial scale namely 60x30mas and hence the fastest F-number is the most constraining scale to optically design in terms of image quality and pupil spread. In order to show the performances along the output slit, three representative fields along x-axis and three wavelengths (0.43, 0.8, 2.45 microns) are selected per configuration i.e. per mini-slit. That means 228 fields. The geometry of the output slit is within its specification, and compliant to the optical interface with the spectrograph, see table 3. These performances are robust against manufacturing and alignment errors, unlike image quality and pupil spread which require careful examination.

**Table 3: Geometry of the output slit**

Requirement Name	Requirement	Value
Slit Size	The IFU shall produce four output slits	Number of slit = 4 Slit Size = 541.8 mm CCD Gap = 14.89 mm
y-positioning of the slit	Within each slit, all slitlets shall be within +/-4mm (in the spectral dispersion direction) of a nominal line	± 4.0 mm

The ghost and straylight analysis performed since PDR led to both improve the fan shape of the slicer, and introduce an output slit baffle. This baffle is composed of 2 lines of 38 slits of 700microns height separated by 2 mm. Here after can be seen the impact of such mask of a factor 7 in the straylight in the output plane.

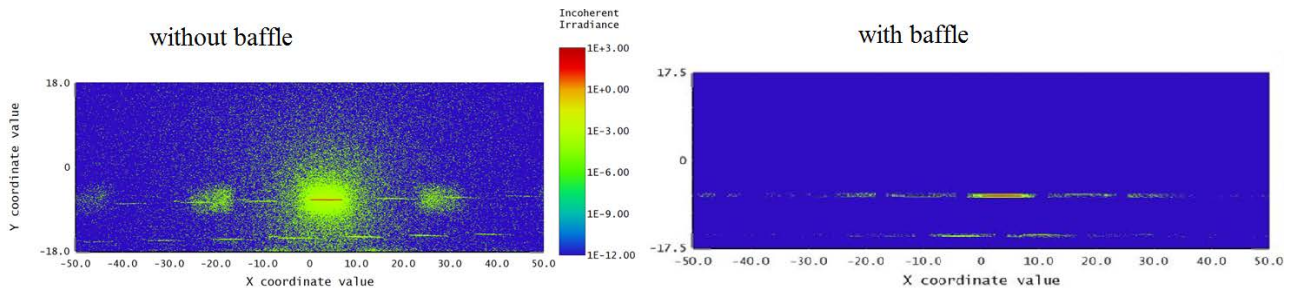


Figure 7: Straylight analysis at the output slit plane without and with the baffle

The pupil spread is the most constraining parameter for the IFU sub-system. The magnification of the sub-system being 0.33, any misalignment at the IFU input produces a three times worse effect at the output. The ISM magnification is 0.13, and any tilt in the ISM assembly leads to the degradation of the pupil spread. The IFU overall pupil spread is mostly due the ISM and its manufacturing, assembly accuracies. The tolerancing analysis is based on a series of 100 Monte-Carlo runs for the 60 x 30 mas spatial scale, the worst case in terms of image quality and required alignment accuracy. The tolerance set includes translations, tilts, radii of curvature, and surface irregularities, all of which are representative of the current budget, see table 2. The tolerancing analysis conservatively assumes a uniform distribution for tolerances, and is meant to be representative of the planned MAIT strategy:

- The Image Slicer Module (ISM = ISA + PMA + SMA) and the SRM are perturbed so as to reveal the limits of their internal alignment.
- The average chief ray ( $\theta_X$ ,  $\theta_Y$ ) at the exit slit is computed and minimized/compensated using both SRM-M3 and SRM-M5 mirrors X and Y translations. The translations are also tuned so that the SRM FoV is aligned on the slicer.
- A perturbation of SRM-M3 and SRM-M5 X and Y translations, accounting for compensator inaccuracy (SRM-M3/5 X/Y deviation measurement error + shimming precision and resolution), is added afterwards.

The key takeaway of this tolerancing analysis is that the image quality performance degrades by ~50 nm RMS but stays within the specification, whereas the pupil spread degrades by a factor ~3, and is non-compliant with the specification, see figure 8. Nevertheless, the overall impact of this non-compliance is mild: ~ 0.2% vignetting inside the spectrograph, for two out of four slits. The local light loss reaches 2% on a fraction of the worst mini-slit.



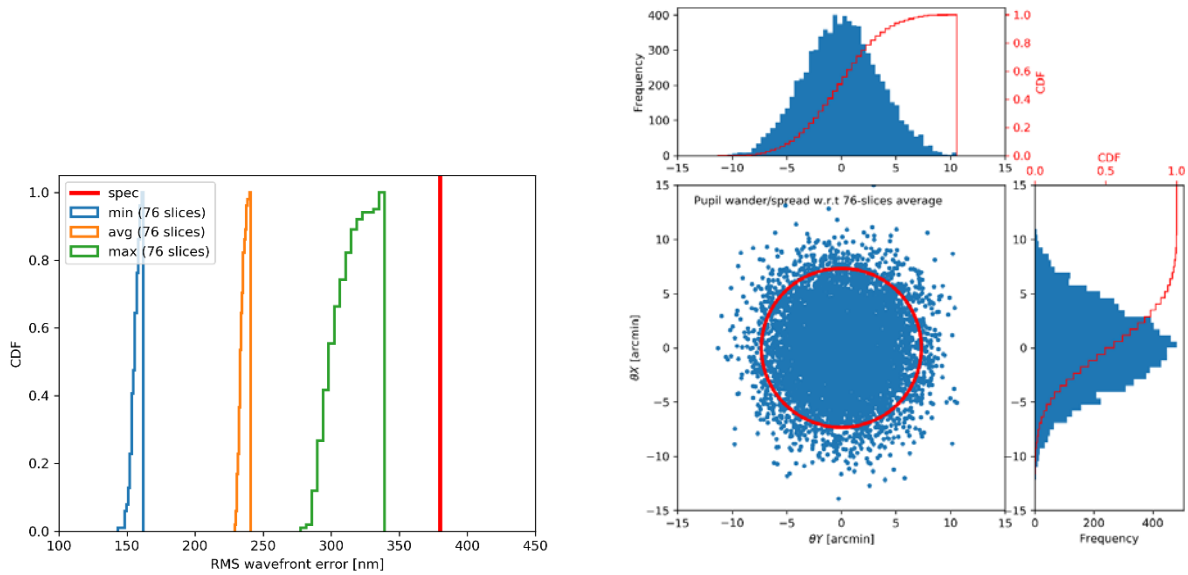


Figure 8: RMS wavefront error and pupil spread, each dot represents one sub-field of a Monte Carlo run (3 sub fields per 76 slices per 100 Monte Carlo runs)

The Finite Element Analysis model of the IFU is mandatory to check the structural performance of the sub-system. The stability static and dynamic submitted to earthquake load cases have been checked. Some reinforcement of the IFU Main Structure has been added, to increase the first eigenfrequency above the specification of 30Hz. The thermal static and transient analyses are being currently addressed to check the proper behavior of the IFU through the cool down curve of the cryostat from 293 to 130K. The thermal links already foreseen are under-dimensioned to reach the operational performance within 48 hours. Some mechanical prototypes are currently being tested to confirm the models of conduction, or resistivity used.

## 5. ASSEMBLY, INTEGRATION AND TEST

The AIT strategy for the HARMONI IFU relies on the ability to manufacture parts at 293 K and then to verify the dimensional and mechanical properties at 130 K at CRAL. We will refer to 293 K as “warm” or ambient temperature and 130 K will be referred to as “cold” or operational temperature.

The optical performance of the IFU is driven by the ISM. The ISM shall be fully tested at the IFU operational temperature at CRAL. Each Image Slicer Module (ISM) will be aligned and measured to confirm each critical dimension and compare these with the as designed values. A first warm test will be done, using AIT shims compensating for thermal expansion. The optical element will be then positioned at a warm value where the optical performances of the slicer will be the nominal operational ones. This will confirm the nominal performance of each optical component. A second warm test will be done with the final shims, so at ambient temperature the performances are degraded. The position of the slit is shifted by 1 mm along the longitudinal axis, the geometry of the slit and the image quality are marginally equivalent but the first and foremost degradation is the pupil spread, see figure 9. This warm test will check the pupil.

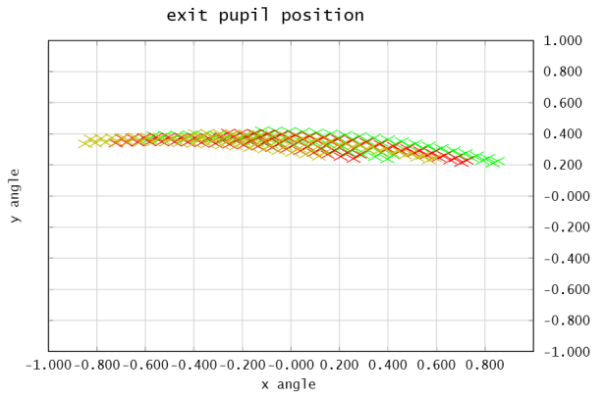


Figure 9: Exit pupil degradation at 293K

The optical final performances of each Image Slicer Module will be measured at operational temperature. Dedicated tools to image the field outside the cryostat, to measure the image quality and to measure the orientation of the chief ray for different field points spanning the full field, are being developed.

For the SRM, all optical elements: Field Splitter Assembly, Mirrors assemblies, will be tested at 130K individually to measure their wavefront, and check that no any constraint is induced on the mirror. Their angular accuracy with respect to their mechanical references will be checked with prototypes but might be also tested on each mirror if necessary. Once the mirror is well positioned in its mount, the assembly on the boards can start. The Splitting and Relay Module (SRM) will be aligned at ambient temperature using a tool to image the field at the slicer position. The behavior of the shift of the field position over a 10 to 20K temperature variation will be checked. The image quality is marginally degraded over the thermal variation.

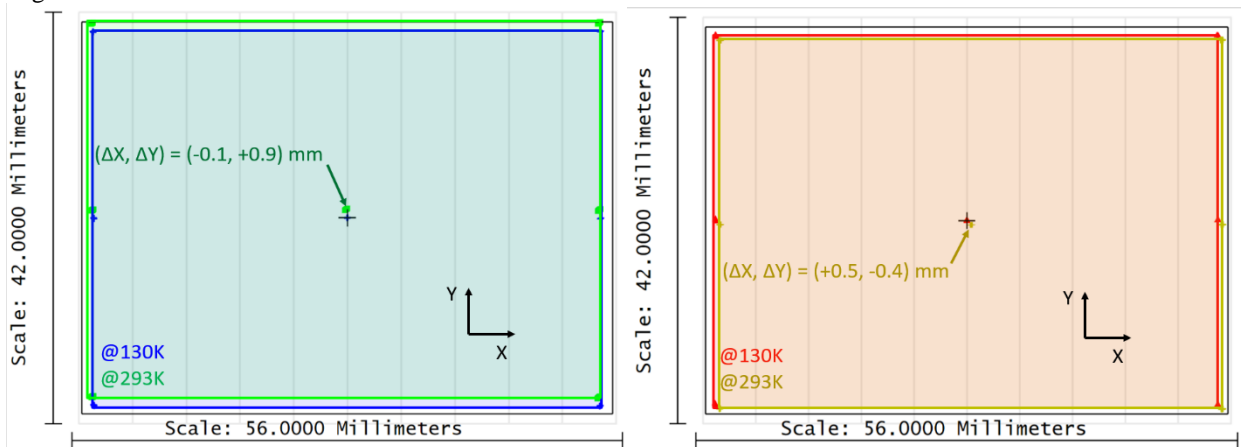


Figure 10: Shift of the field at the slicer plane between cold and warm temperature for 2 kinds of path of the SRM

The top and bottom boards are then checked in the cryostat separately.

The final step in CRAL is to integrate the ISM into the IFU Main Structure and a warm check is performed to validate the degraded performance of the IFU. All the main performances will be partially tested at 130K and our effort will be put on warm tests and the reliability of the analysis to prove the whole IFU performance. The final test for IFU will be done in the HARMONI cryostat, where the chief ray angle, the most challenging performance, will be measured at 130K with a dedicated tool the Chief Ray Tool, see figure 11. This measurement will be used to prepare the IFS spectrographs alignment shims to ensure that the IFU output slit and the spectrograph input field are aligned within the tolerances. The first IFU delivery will consists of the complete IFU with two ISM among four. This approach will allow the team to integrate the first full optical end-to-end path of the IFS earlier. This installation and integration exercise will provide the opportunity to improve the alignment procedures.

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  $\pm 40$  arcsec accuracy. Therefore, the mean ISM chief ray must be known to  $\sim 20$  arcsec with respect to the ISM flange, which will be used as a mechanical reference by the spectrograph.

The Chief Ray Tool (CRT) 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 these 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 laser.

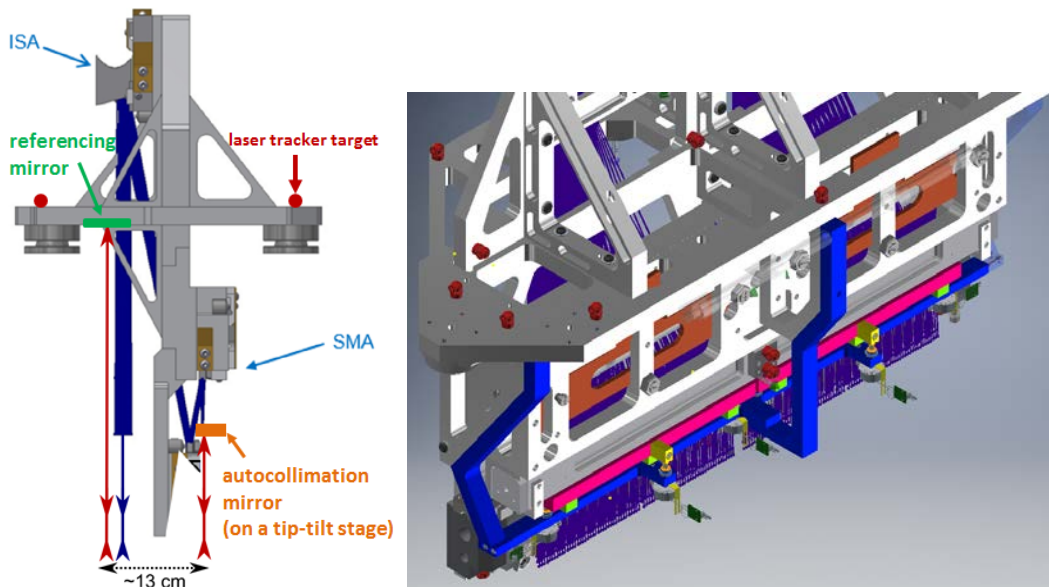


Figure 11: Chief Ray Tool principle scheme and CAD model, (in pink is the orientable mirror used for autocollimation).

## 6. CONCLUSION

The IFU sub-system is progressing well towards the Final Design Review. The optical design has been optimized as far as possible. The remaining discrepancy concerning the pupil spread, cannot be improved due to the manufacturing accuracy of the critical optical element in the Image Slicer Module. Except this pupil spread non-compliance, which is the most critical and sensitive to tolerancing performance, the IFU is within its specification. The mechanics is progressing well too: the structural design is done, the mechanical design reliability has been improved based on the cold to warm model process, and the prototyping of the mount is giving valuable inputs, especially for the thermal link dimensioning.

HARMONI IFS Final Design Review is scheduled for February 2022, and a first light at Cerro Armazones can be expected in 2027.

## 7. ACKNOWLEDGEMENTS

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