MUSE Integral Field Unit: Test results on the first out of 24

Florence Laurent[a], Louisa Adjali[a], James Arns[d], Roland Bacon[a], Didier Boudon[a], Patrick Caillier[a], Eric Daguisé[a], Bernard Delabre[c], Jean-Pierre Dubois[a], Philippe Godefroy[b], Aurélien Jarno[a], Paul Jorden[e], Johan Kosmalski[a], Vincent Lapère[b] Jean-Louis Lizon[c], Magali Loupias[a], Arlette Pecontal[a], Roland Reiss[c], Alban Remillieux[a], Edgard Renault[a], Gero Rupprecht[c], Yves Salaun[b]

[a] Université de Lyon, Lyon, F-69003, France; Université Lyon 1, Observatoire de Lyon, 9 avenue Charles André, Saint-Genis Laval, F-69230, France; CNRS, UMR 5574, Centre de Recherche Astrophysique de Lyon; Ecole Normale Supérieure de Lyon, Lyon, F-69007, France
[b] Winlight Optics & Winlight System, 135 Rue Benjamin Franklin, ZA St Martin, 84120 Pertuis, France
[c] ESO, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
[d] Kaiser Optical Systems, Inc., 371 Parkland Plaza, Ann Arbor, MI 48103
[e] E2V Technologies Plc, 106 Waterhouse Lane, Chelmsford, Essex, CM1 2QU, UK

ABSTRACT

MUSE (Multi Unit Spectroscopic Explorer) is a second generation VLT panoramic integral field spectrograph developed for the European Southern Observatory (ESO), operating in the visible wavelength range (0.465-0.93 µm). It is composed of 24 identical Integral Field Units (IFU); each one incorporates an advanced image slicer associated with a classical spectrograph and a detector vessel. The Image Slicer subsystem –ISS– is composed of two mirror arrays of 48 spherical elements each. It is made of Zerodur and uses an innovative polishing approach where all individual components are polished together by classical method. The MUSE Spectrograph –SPS–, with fast output focal ratio of f/1.95, implements a Volume Phase Holographic Grating – VPHG. The last subsystem, the Detector Vessel –DV- includes a chip of 4k by 4k 15µm pixels supported by a Vacuum and Cryogenic System – VCS – provided by ESO.

The first out of 24 IFUs for MUSE instrument has been manufactured, aligned and tested last months. First, this paper describes the optical design, the manufacturing and test results (image quality, pupil and field of view positioning) of each subsystem independently. Second, we will focus on overall system performance (image quality and positioning) of the spectrograph associated with the detector vessel. At the end, the test results (image quality, positioning, throughput, mechanical interfaces) of the first IFU for MUSE instrument will be reported.

Most of them are compliant with requirements that it demonstrates that the manufacturing, integration, alignment and tests processes are mature and gives good confidence for serial production by 24 times applied to MUSE instrument.

Keywords: Integral Field Unit, Image Slicer, Spectrograph, Volume Phase Holographic Grating, 1 out of 24, MUSE instrument.

1. INTRODUCTION

Integral Field Spectroscopy (IFS) is a technique that gives simultaneously the spectrum of each spatial sampling element of a given field. It is a powerful tool which rearranges the data cube represented by two spatial dimensions defining the field and the spectral decomposition (x, y, λ) in a detector plane. In IFS, the "spatial" unit reorganizes the field, the "spectral" unit is being composed of a classical spectrograph. For the spatial unit, three main techniques – microlens array, microlens array associated with fibres and image slicer – are used in astronomical instrumentations.

Built for the European Southern Observatory (ESO) for the second generation VLT instrumentation, MUSE (Multi Unit Spectrograph Explorer) will be installed on the Very Large Telescope (VLT) Nasmyth platform B for a first light in 2012. The MUSE consortium consists of seven European Research Institutes – Centre de Recherche Astronomique de Lyon, Astrophysikalisches Institut Postdam, ESO, Swiss Federal Institute of Technology Zürich, Laboratoire

Modern Technologies in Space- and Ground-based Telescopes and Instrumentation, edited by Eli Atad-Ettedgui,
Dietrich Lemke, Proc. of SPIE Vol. 7739, 77394M · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857004

d'Astrophysique Toulouse Tarbes, Sterrewacht Leiden and University of Goettingen – all managed by CRAL. MUSE is an innovative IFS, named Integral Field Unit (IFU) in MUSE instrument, which combines a 1'×1' Field of View (FoV), with a spectral resolution reaching 3000 and a spatial sampling of 0.2'' matching the spatial resolution provided by a ground layer adaptive optics system named GALACSI. MUSE operates in a large visible and near IR spectral range (0.465 – 0.93 µm) with 2 functional modes a Wide Field Mode (WFM) and a Narrow Field Mode (NFM) where the spatial resolution is divided by 8. It will be especially optimized for the study of the progenitors of normal nearby galaxies out to high redshift. A detailed description of MUSE and its scientific applications are presented by Bacon et al. and Loupias et al. during this conference ([1] and [2]). The MUSE instrument is composed of a Calibration Unit [3], a Fore-Optic which includes an optical derotator and an anamorphoser by 2, a splitting optics cutting the FoV in 24 parts and 24 relay optics [4] which feed 24 identical IFU. Each IFU is composed of an original advanced image slicer associated with a high-throughput spectrograph with a Volume Phase Holographic Grating (VPGH) and a 4k×4k CCD detector. Although different experiments have been carried out on image slicer system ([5], [6], [7] and [8]), MUSE IFU represents a major challenge for MUSE. The Figure 1 gives a mechanical overview of MUSE with all subsystems.

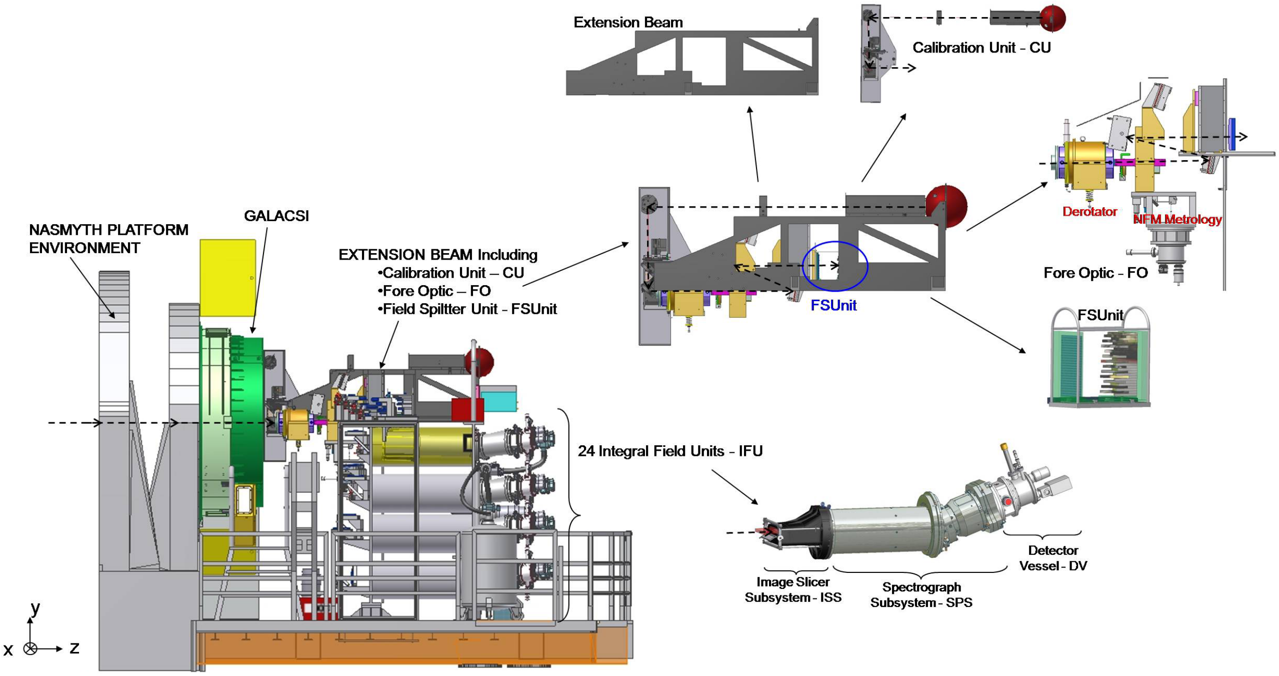


Figure 1: MUSE Mechanical Overview

A Phase A study was performed by the MUSE Consortium and finished with a review in February 2004. The contract was signed in July 2006. In September 2006, an Optic Preliminary Design Review of the instrument (OPDR) was performed during which the optical design was presented and reviewed. The PDR took place on July 2007 and the Board granted it under the condition that critical actions were closed at the Optics FDR. This OFDR took place in December 2007 and gave the Consortium the possibility to start contracting out long lead time items (mostly related to the optics subsystems like Image Slicer Subsystem, Spectrograph and Derotator contracts). The Final Design Review (FDR) was granted in March, 2009 launching all contracts for Manufacturing, Assembly, Integration and Tests (MAIT) Phase. The first main milestone was the IFU MIA (Manufactured Item Acceptance) passed in February 2010 giving the green light for IFU serial manufacturing which is the purpose of this paper. MUSE PAE is currently planned for late 2011 for a first light in 2012. The MUSE project from the first ideas up now is depicted by Caillier et al. during this conference [9].

To pass a successful IFU MIA, an Image Slicer Subsystem, a Spectrograph including a VPHG and a Detector Vessel should be validated independently and integrated together to check global performance. The remainder of this paper is organized as follows: the three main subsystems (design, integration and tests) are presented in section 2, 3 and 4, integration and performance tests performed onto {Spectrograph + Detector Vessel} itself and onto the whole IFU are described in section 5 and main improvements and future developments are discussed in last section.

2. IMAGE SLICER SUBSYSTEM (ISS)

The principle of an image slicer system is based on the concept proposed by R. Content in 1997 [10]. The two main optical functions of the image slicer are to transform a rectangular Field of View (FoV) in a series of mini-slits at the spectrograph entrance plane and to reimage the telescope pupil at infinite distance.

The MUSE slicer reorganizes the subfield of view of 2.5x60 arcsec² into a pseudo-slit of 0.2 arcsec width. The ISS is composed of one Image Dissector Array (IDA) which splits the subfield in 48 slices (4 identical stacks of 12 slices) and creates 48 intermediate pupils of the VLT pupil at different places following a "staircase arrangement". Each slice is an off-axis spherical mirror around x and y-axes with same curvature radius of 300mm and with a useful rectangular aperture of 33.425 mm along x-axis by 0.950 mm along y-axis. Each intermediate pupil is sent on a corresponding mirror (Focusing Mirror Array - FMA) located at 160mm far from IDA. FMA ensures an image of an individual slice in the pseudo-slit plan and re-images all the images of the telescope pupil at the entrance pupil of the MUSE spectrograph. Each focusing mirror is an off-axis spherical mirror tilted around both axes with same curvature radius of 22.8 mm and with a rectangular aperture of 6 mm along x-axis by 2.6 mm along y-axis. Each focusing mirror is shifted along z-axis in order to image all slices in the tilted pseudo-slit plane located at 12.4 far from FMA. The pseudo-slit plane is arranged in three staggered rows of 48 mini-slits within ±30µm accuracy positioning along both axes. A Pupil/Slit mask (PSM) between IDA and FMA prevents possible ghosts and stray light. It is constituted of 48 elliptical holes where the telescope pupil light is coming through and 48 rectangular holes, which is located in the ISS image plane.

IDA were manufactured by Winlight Optics in France with recent innovative methods reaching high performances (accurate roughness, sharp edges, surface form) with standard glass manufactured components where costs and time are saved compared with classical techniques [11]. This technique allows to polish all slices together. Slices made of Zerodur are assembled using molecular adhesion process. IDA is coated stack by stack with temporary coating in aluminium to finalise the qualification coating for serial phase. FMA were also manufactured by Winlight Optics. The manufacturing process is described in previous paper [12]. The PSM was manufactured by Steec in France by laser cutting process onto 200µm thick plate. The mechanical support (SSS) manufactured by the CRAL mechanical workshop, is built in stainless steel and invar to limit thermal deformations. The interfaces are measured by 3D measuring machine with an accuracy better than 5 µm in decentring and 15" in tilt. These interfaces are remachined with CRAL 4-axis numerically controlled machine. Only the PSM is aligned by screws, IDA and FMA are glued onto their support with epoxy glue and maintained by clamps to respect a "plug & play" philosophy.

The integration and assembly procedures are the same as ones presented on our previous paper [13] using the same ISS Illumination and Detection units. That differs from the ISS itself which is mounted onto the final support (Figure 2, Left). The ISS breadboard [13] validated most of critical aspects (high roughness, form accuracy, curvature of radius, system image quality). These requirements were not qualified again for this final one. Only pseudo-slit positioning, pupil vignetting, straylight, ghosts and robustness tests are performed. For pseudo-slit positioning, twelve images of the mini-slit are simultaneously on the detector and presented on the Figure 2 where only 12 mini-slits are represented in order to simplify the understanding. The uncertainty of this measurement is ± 10 µm onto the centroid positioning in the pseudo slit plane. Note that on graph, black square box indicates requirements. At 633nm along both axes, the relative positioning is compliant with the requirement (Figure 2, Right) expect for one mini-slit (maximum shift of 65µm). Nevertheless, we can consider that this error is acceptable because that represents a displacement less than two pixels on MUSE CCD. Moreover, there is no overlapping between each mini-slit. To see any pupil vignetting, the intermediate pupil plane is observed that corresponds to the PSM plane. For that, the full FoV is lighted by the IFU Illumination Unit. A white screen is set behind the PSM and the PSM is lighted with a standard lamp. By using this process and recording intermediate pupil images, we confirm that there is no vignetting onto MUSE ISS. A free gap of 100 µm space is set between each sub-pupil and PSM. The same process is used for field vignetting in the pseudo slit plane giving a free gap of 70 µm space between each mini-slit and PSM. To check straylight and ghosts, an half field of view is lighted. The ratio between unlighted and lighted parts is computed. The straylight was measured at 0.2x10e-4 for a requirement of 1x10e-4. The brighter ghost, ratio between mini-slit illumination and ghost illumination, has a level of 8.10^{-5}.

This first ISS allows the validation of the MAIT process (relative positioning, straylight and ghosts) except the coating which has been requalified by the manufacturer. For the serial phase, another coating from European company has been selected by Winlight after successful qualification tests (temperature and humidity cycles) based on coating slicer sample.

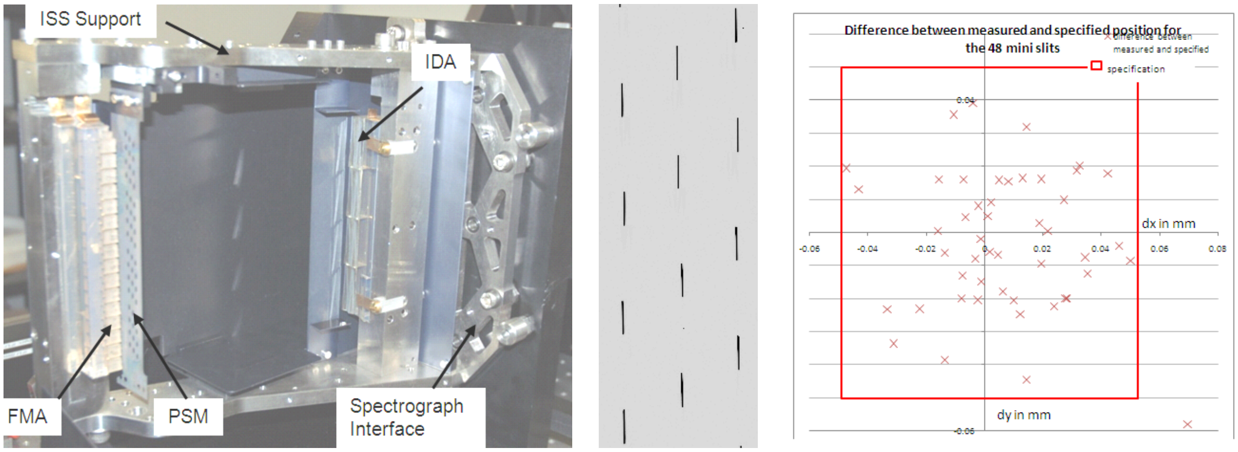


Figure 2 : Left: ISS composed of IDA, FMA, PSM mounted onto its support. Middle: Reconstructed pseudo slit composed of 12 mini slits. Right: Mini-slit Relative Positioning

3. SPECTROGRAPH (SPS)

The full Spectrograph was manufactured and tested by Winlight System in Pertuis, France. It is composed of the four following subsystems (Figure 3, Left):

- A collimator: It images the entrance slit given by the Image Slicer Subsystem to infinite distance and the entrance pupil to the dispersive element. It is composed of 3 lenses.
- A dispersive element: For MUSE, it has been chosen to use VPHG (Volume Phase Holographic Grating) (Figure 3, Right). The grating groove spacing is calculated to disperse all the spectral range on the width of the detector. The VPHG has a lens glued on its back face. The VHPG was manufactured by Kaiser Optical Systems in US. That is described after.
- A camera lens: Composed of 3 lenses, the camera lens images all the spectra on the detector.
- A Field Lens Window (FLW): That ensures the tightness of the Detector Head and has an optical function (conic shape on camera side, Cylinder along y-axis on the CCD chip side).

Note that the FLW and its support is a part of the Detector Vessel (DV) system as well as the CCD chip where the FoV of the spectrograph is imaged. Two adjustments are required: one onto the VPHG tilt around z-axis, one onto the reFocus in order to compensate for the change of atmospheric pressure between Europe and Paranal. This focus will be done once at Paranal and no refocus is foreseen during operation.

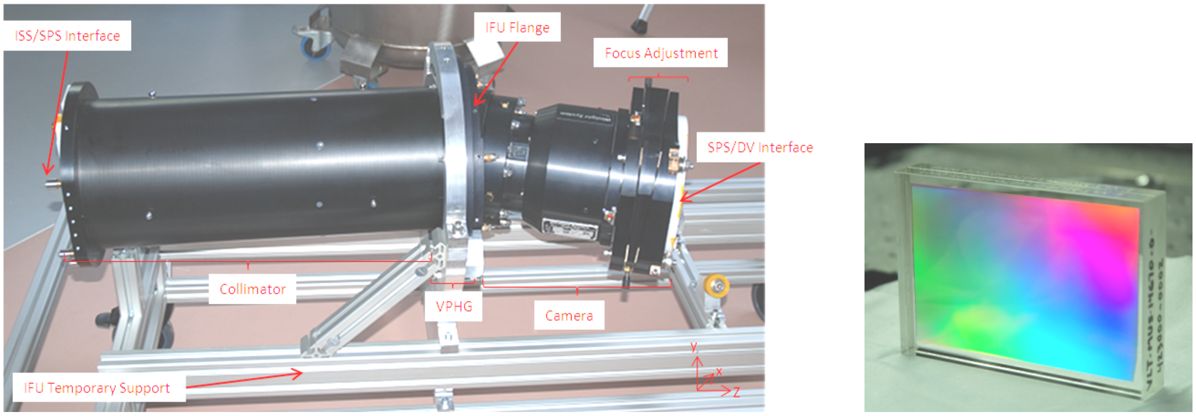


Figure 3: Left: Spectrograph mounted into IFU Temporary Support. Right: MUSE VPHG

The MUSE spectrograph magnification of 0.45 ensures one of the fastest spectrograph ever manufactured giving a CCD image plane dimension of 61.44 mm.

All spectrograph assembly, integration and tests are performed in Winlight premise. The main challenge of this integration is to reproduce an object and image planes with tight interface tolerances (less than 50µm in positioning and 0.5 arcminute in orientation). To reach the best image quality which shall be better than 80% of Diffraction Energy in average in a rectangle of 15x30µm (spatial x spectral) for $\lambda \geq 600$nm associated with a correct spectra positioning and orientation, the internal adjustments only accessible by Winlight staff are the x&y translation stages of its own detection unit. The image quality is optimized in the full FoV at 5 wavelengths thanks to a Detection Unit with a magnification by 10. At the FoV centre, the difference between the PSF centroid coordinate in X of the 2 extreme wavelengths shall be less than 30µm (2 pixels) which corresponds to the requirements. The optical transmission for the SPS shall be higher than 81% excluding the VPHG diffraction efficiency. No global measurements are performed, this requirement has been checked by calculation only, using measurements on test samples and absorption glass. The straylight and ghosts are not performed at Winlight premise due to the high difficulty to cover the full image plane with a small detection. It will be done at CRAL with the final detector. The SPS is athermalized over the full functional temperature range. Tests onto image quality and magnification are done between 25°C and 15°C.

The MUSE VPHG is a rectangular grating with dimension of 120x80x20mm (Figure 3). The 120mm are along the lines orientation. It is composed of two plates is N-BK7 where half of these plates is coated (R>0.992). The number of lines is 639 lines per mm. The grating lines orientation (Theta Z) shall be in a range of +/-2° with regards to the edges of the VPHG and known at +/-1 arcminute. Due to the technology used to realise the MUSE ISS the mini slits have different coordinates along the Y direction. From this pseudo slit plane the collimator is in charge to send the field at infinity and image the pupil on the VPHG. But due the mini slits varying heights the incidence on the VPHG grating is varying from 12.43° up to 13.75. The MUSE VPHG is made to be used at 13.09°.

The first grating from Kaiser Optical Systems has been tested in Lyon. A specific spectrophotometer has been developed to perform the efficiency measurements in the 0, 1st and 2nd orders by reference to an air path, on MUSE wavelength range with a step of 20nm. The incident angle, the wavelength range (visible range) and the wavelength steps are adjustable and controlled by a computer. Obviously, we measure the efficiency of the VPHG assembly and not the gelatine alone. The efficiency in the VPHG center is not very far from specifications. In the blue band, the efficiency is greater than expected. Nevertheless, the measurement shows a non uniformity in efficiency of around 10% over the whole surface of the grating. This has direct impact on the overall throughput of the spectrograph. This non conformity is not acceptable as such for the MUSE spectrograph. The illumination uniformity during gelatin printing process had to be improved for the serial phase. The VPHG serial n°3, was received in July 2009, tested and showed an efficiency uniformity better than 3% over ¾ of the scientific bandwidth, that is acceptable for MUSE.
The test bench description and results onto the first MUSE VPHG and onto VPHG n°3 are fully described in a paper presented into this conference [14].

4. DETECTOR VESSEL (DV)

Each IFU is equipped with its own Detector Vessel, the system architecture following the standard: one CCD served by a vacuum and cryogenic infrastructure and controlled by a controller. What makes the MUSE system special is the fact that many components are new developments, and that we have to deal with a multiplicity of 24. In the realm of astronomical instrumentation this constitutes already a series production with all its practical consequences.

The chips chosen are model CCD231-84 back-illuminated CCDs made by e2v. All have been delivered on time. What distinguishes them from the standard devices in the e2v catalogue is the graduated anti-reflection coating that helps to achieve the quantum efficiency specification (average QE above 85% from 465-800nm and above 60% from 800-930nm). All six devices tested so far show a remarkably uniform QE (within about 3%) approaching 100% at about 700nm. Average cosmetic quality is excellent. Given the limited resources and the large number of detector vessels to be prepared we decided to subject all CCDs to a standardized handling, mounting and test procedure. It starts with an incoming inspection that includes a full photographic documentation, continues with the mounting in the detector head and the subsequent characterization on the ESO CCD test bench and ends with the precise CCD position and attitude measurement (see below). All handling operations of the CCDs are performed in the ESO Garching cleanroom to keep the contamination of the chips at a minimum.

The chip characterization on the test bench is standardized and nearly identical for all CCDs. Automated scripts take all necessary exposures and determine parameters like quantum efficiency, photo response non-uniformity, read-out noise, conversion factor, linearity, dark current, charge transfer efficiency and cosmetic defects. On sporadic samples we also measure the point spread function. All results are automatically written to a spreadsheet that constitutes the test report.

The detector head is an improved version of the standard ESO head used already in many instruments. A dedicated measuring machine was built to determine the precise position and attitude (better than 15µm in positioning and 30 arcseconds in orientation) of the CCD inside the head; this is necessary for the correct positioning of the CCD with regard to spectrograph/detector interface, which shall be interchangeable. This positioning is done by an intermediate flange that is custom made for each head/lens combination. The standard ESO continuous flow cryostat is used for keeping the CCD at its operation temperature of 163K thanks to 120 litre dewars delivering the liquid nitrogen [15]. A turbo molecular pump delivers the necessary vacuum. The exhaust gas escaping from the cryostat is collected and thermalized with the ambient temperature. It is then channeled into the spectrograph to ensure a clean, dry atmosphere that will prevent the anti reflection coatings of the lenses from degrading. A JUMO process controller controls the operating temperature of the detector as well as the state of the vacuum. The JUMO in turn is addressed through a programmable logic controller that allows access to every individual function of every detector head and cryostat. For the actual control of the detectors we use the New General detector Controler (NGC), recently developed at ESO for both optical and infrared detectors. They are fully programmable and combine high performance and speed with a compact, lightweight design.

The Detector Vessel currently installed on the Detector Vessel n°01 which is a part of IFU01 is the Ceres detector. Two main discrepancies are encountered in DV01. This CCD exhibits a hot pixel that blurs over a few column and even lines of a quadrant of the detector. This forbids the use of this chip for science, and implies to use this detector at a lower temperature to reduce the effect. This effect has not been seen in the next chips of the series. Moreover, the chip alignment setup has introduced a 100 microns discrepancy in position along optical axis. The setup and the criterion to align the chip have been updated to insure better positioning to 15 microns.

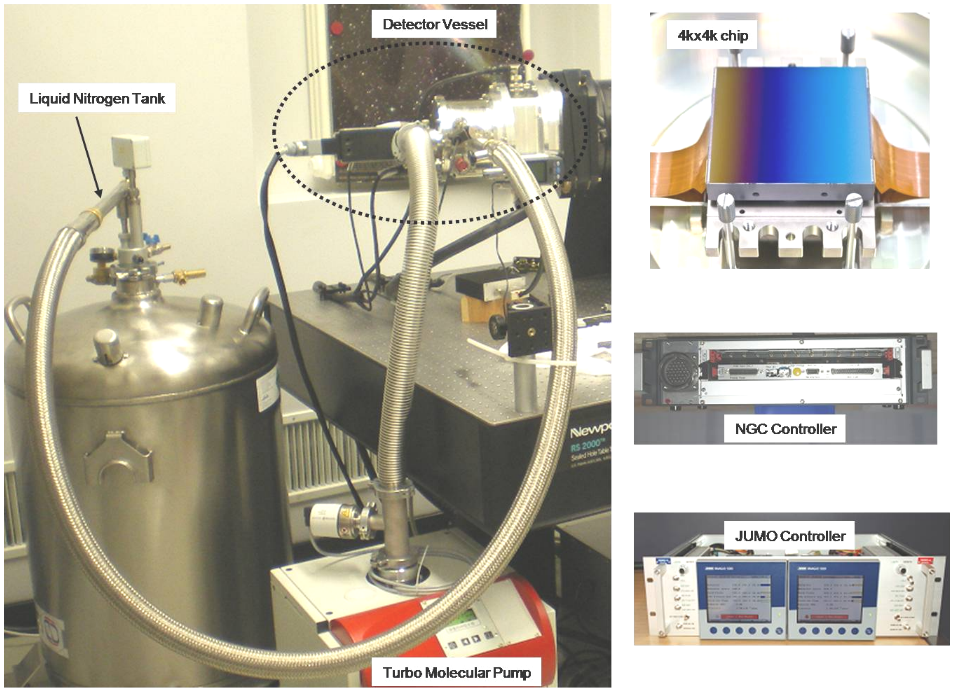


Figure 4: Detector vessel n°01 mounted into the spectrograph

5. INTEGRAL FIELD UNIT (IFU)

As there are 24 channels in MUSE Instrument, the goal is to minimize the number of tests but to guarantee the system requirements, a correct stability during the time and reduce the time for MAIT. The IFU AIT is the longest sequence. All IFUs will be validated before being inserted into the MUSE Structure in CRAL Optical Clean Room. First, the Detector Vessel (DV) is mounted onto the Spectrograph (SPS) which are qualified together. Second, the Image Slicer Subsystem (ISS) is mounted and aligned with {SPS+DV}. Once the IFU is fully characterized in performances, it is then moved to the integration hall either to insert it in MUSE Structure or to store it. To perform all sequences, thirteen AIT Tools are developed going from illumination units including calibrated lamps, handling and storage tools, reference targets, positioning tool up to analysis software. All these AIT tools and the global alignment procedure are described in a paper presented in this conference [16].

5.1. Spectrograph and Detector Vessel

A simple visualization during Detector Vessel mounting showed that the antireflection coating of the DV Field Lens Window was degraded due to condensation (combination of an high humidity level into the Integration Hall and temperature of the Field Lens Window). The AR coating was demonstrated to be hydroscopic. Due to this non conformity, the manufacturer has started the process of changing coating supplier based on a complete performance and environmental qualification. This first SPS will be retrofited in July, 2010 with another coating.

To test the {SPS+DV}, a Spectrograph Illumination Unit (SPS IU) is used. This main function is to create an object plane with the correct F/# and location. It is attached in front of the collimator and composed of 6 principal elements:

1. A Calibration Tool which is a propotype of MUSE Calibration Unit [3]. It is composed of 2 spectral lamps (Mercury-Cadmium and Neon) and a continuum source. Note that the Neon lamp can be replaced by a Xenon one.
2. A mechanical interface between the optical fibers provided by the calibration tool and the shutter
3. A shutter (because the MUSE CCD has no shutter)
4. An integrating box (box with a Barium sulphate like internal cover)
5. 2 masks of holes: one for the PSF in the SPS object plane composed of 11 pinholes of 10µm diameter each and another one 15 mm behind with elliptical holes (allowing the correct pupil and f/number)
6. An ISS/SPS interface same as ISS one,

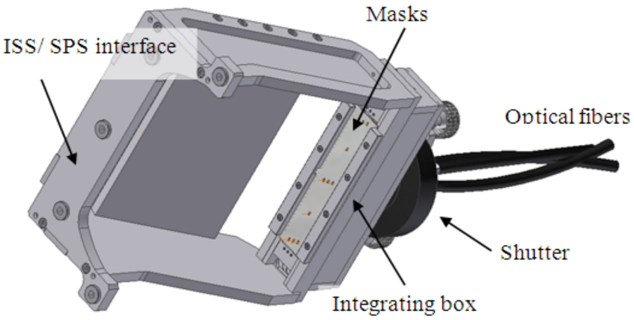


Figure 5: Mechanical drawing of SPS Illumination Unit without Calibration Tool.

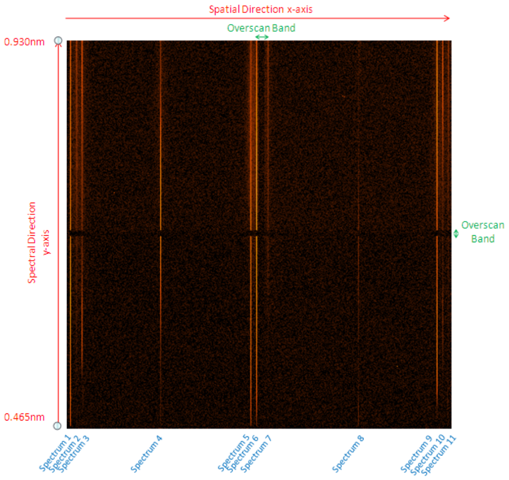


Figure 6: {SPS+DV} CCD Image with continuum lamp (logarithm scale)

The Figure 6 presents a raw CCD image of {SPS+DV} subsystem at the best focus. It is lighted with a continuum lamp through 11 pinholes provided by the SPS IU. The SPS Illumination Unit works with its grid of pinholes lighted with spectral sources (HgCd+Ne lamps) done by Calibration Tool. To reach the best focus, the SPS camera is shifted with regular steps of 20µm on a range of ±0.100mm. For each step, one CCD exposure is done. Focusing is computed using the central wavelength range. At each step the mean and standard deviation of the A80 (see below) is computed and a parabola is fitted using a weighted polynomial fit on the data set. A typical focusing curve is shown in Figure 7 at different spectral range.

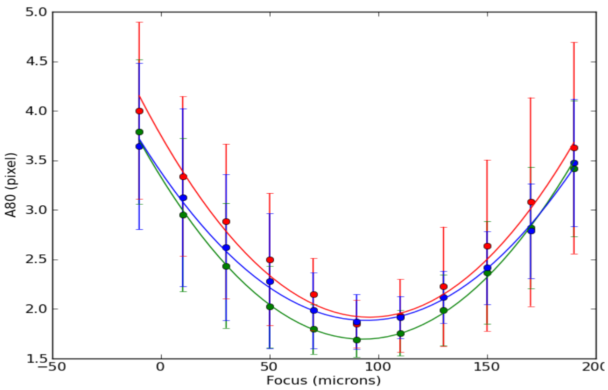


Figure 7: Focus curves in the blue, green and red spectral range.

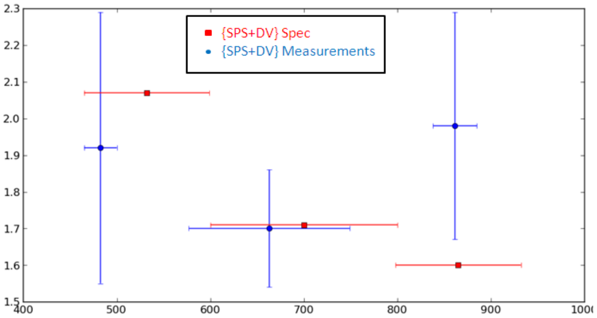


Figure 8: Mean measured A80 values compared to A80 specifications.

Note that MUSE system image quality budget has been built using a Gaussian approximation of the PSF. Performance requirements have been translated in FWHM or ensquared energy in 1 pixel for sub-systems. The subsystems have FWHM that are always less than 2 pixels and thus undersampled. The spectrograph PSF shapes are not at all Gaussian and not even symmetric. Therefore the FWHM is not a good indicator of the image quality. Measurement of the ensquared energy on one pixel is also very difficult and subject to large errors because of the undersampling. We have then decided to change the image quality criteria to the size of the square that contains 80% of the total energy (hereafter A80). Moreover, in order to take undersampling problem into account we have derived the final A80 values which result from the convolution of a Gaussian with a 1 pixel step function. The new requirements for {SPS+IDS} expressed in A80 are 2.07 for the blue (465-600nm), 1.71 for the middle range (600-800nm) and 1.6 for the red wavelength (800-930nm).

With the present set of data, the SPS+DV is in specifications in the blue and central wavelength range and marginally out of specifications in the red (Figure 8). However because of the uncertainties due to the limited number of points with good S/N in the red, no definite conclusions can be achieved with these data. A new mask with a larger number of pinholes, correct pinhole size and a better distribution over the CCD will be implemented to improve this. Moreover, the implementation of a Xenon lamp onto the Calibration Tool will allow to better cover the red wavelengths.

At the best focus, the average magnification, computed with the distance between each spectrum, on the whole FoV is 0.45±0.002 which is in concordance with requirements (0.45+0/-0.01). Moreover, the spectral resolution is calculated onto 31 wavelengths onto MUSE wavelength range at the central FoV and that is compliant with requirements. The spectra orientation along the spectral direction is within requirements which shall be lower than 2 CCD pixels. The spectra positioning is conform to requirements which shall be better than ± 40pixels. It has been measured onto the central pinhole corresponding to Spectrum_6 at 546.0742nm. The errors onto SPS Illumination Unit positioning have been translated onto CCD plane and subtracted to the measured values. Along optical axis, the best focus has been determined at 200µm far away from the nominal one. The zero point of focusing is not well centrered as expected on the focusing range but this will be corrected for the next SPS. We are able to make the focus in Lyon, but not in Paranal due to atmospheric pressure difference. This misalignment has been explained by a bad absolute positioning of CCD chip with respect to this interface. The tool allowing to align the CCD with regard to this interface has been modified. That has been tested on the next Detector Vessel – DV04 where the z-positioning has been set 100µm far away from DV01 one. The repositioning of the SPS IU, the DV or focus spacer motion is better than 2 CCD pixels in both directions and does not introduce measurable residual tip tilt (<1 arcminute).

The major non compliance onto light tightness stems is located near the focus spacer and IFU Flange giving an average noise of 50 ADU above the background level. This is critical to validate this performance since covers cannot be put at the back side of the instrument. Winlight will develop a better shielding particularly at the focusing tuning level to insure tightness, and will perform the tests onto SPS series.

5.2. Image Slicer Integration

To set ISS in correct position, an ISS Positioning Tool is used. It allows to push ISS against its interface and remains in position thanks to eccentric drives.

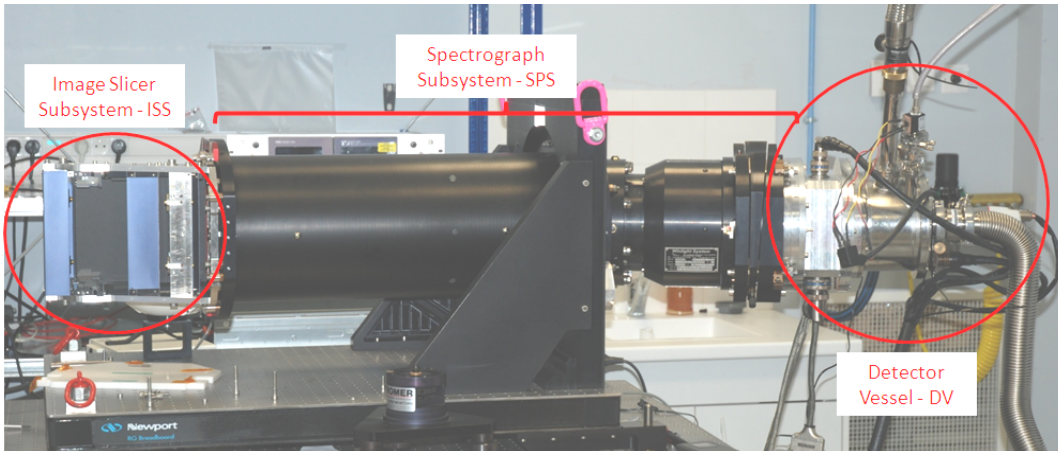


Figure 9: The first MUSE IFU composed of ISS, SPS and DV

5.3. Global Tests

To align the FoV and pupil coming from IFU Illumination Unit (mimicking MUSE Splitting and Relay Optics) with respect to IFU Flange which is the reference, we used an IFU Simulator. Thanks to a Romer Arm (for positioning purpose) and an autocollimator (for orientation), a mirror target is located in the IFU Input Plane and adjusted with respect to IFU Flange.

To perform system tests on full IFU, an IFU Illumination Unit mimics the IFU input focal ratio and images the FoV onto IFU/ISS. The IFU Illumination Unit is aligned with regard to the IFU Simulator. Thanks to the CCD camera associated with camera objective into the IFU Simulator, image & pupil positioning, image size and quality image are checked. The Calibration Tool with light guides provides the same source as for {SPS+DV} tests. The IFU IU works with different FoV masks (Grid of pinholes, full FoV, half FoV). All these AIT tools and the global alignment procedure are described in a paper presented in this conference [16]. Note that the IFU Illumination Unit is the same as one presented in [13].

The Figure 10 presents a raw CCD image of IFU subsystem at the best focus. It is lighted with a continuum lamp through the whole FoV. Forty eight spectra corresponding to 48 mini slits provided by ISS are represented onto the Figure 10.

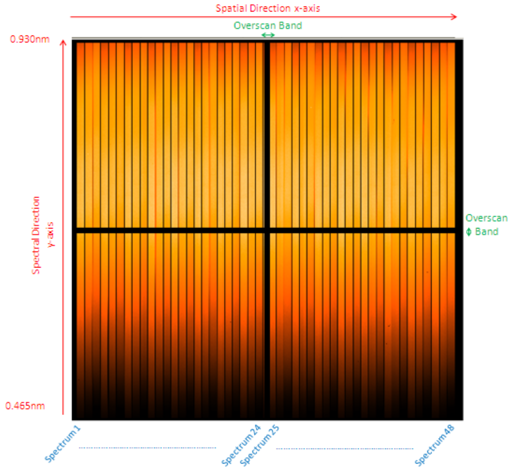


Figure 10: IFU Continuum flat field exposure

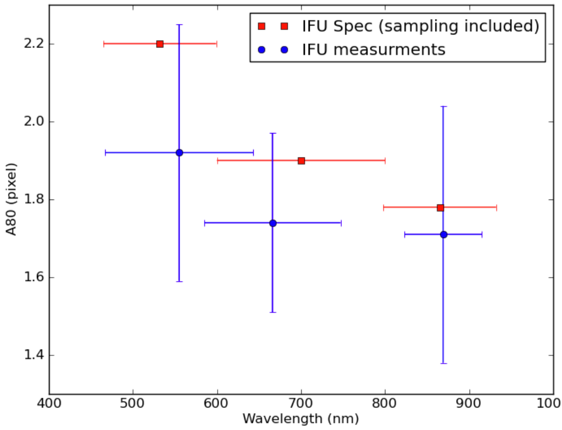


Figure 11: IFU Image Quality

To compute the IFU image quality, the IFU Illumination Unit works with a grid of pinholes lighted with independent spectral sources (HgCd, Ne and Xe) done by Calibration Tool. The focus position is the same as the one of {SPS+DV} and 3 CCD acquisitions for each lamp and bias have been recorded. After removing cosmetics and spectral lines where signal is lower than 250 ADU above background level, the A80 is averaged on each MUSE wavelength range and is within the requirements (Figure 11). This confirms that the non compliance of PSF measurements on {SPS+DV} (Figure 8) in the red is not real. That also demonstrates that ISS has very little impact on image quality and set up associated with tools used for {SPS+DV} testing shall be improved for serial phase. To compute the IFU straylight, the IFU Illumination Unit works with an half FoV lighted with continuum lamp. The diffused light level will be measured in summing all pixels of the CCD dark area and compared ones on illuminated area. Straylight level is 4.7e-3 of the incident power which is compliant with requirement of 5e-2 of incident power.

To perform IFU ghost tests, the IFU Illumination Unit works with a full FoV mask lights with spectral lamp. Exposure time is calculated in order to reach a dynamic range higher than 10e-4 on CCD. The ghost introduced by the cylindrical surface of the Field Lens Window, and already foreseen at FDR time, has been seen. Another ghost coming from the first lens of the collimator has been discovered during the test (Figure 12) and confirmed by Zemax. These ghosts are inferior to the 1e-4 relative power specification if we consider a point source. They can be 6 times the specification if we consider extended illumination. This underlines the fact to maximize the performance of the AR coating on these surfaces. This does not degrade the performance of the flat field uniformity. The science impact is: The brightest OH sky emission line produces a ghost. Its intensity by pixel is 0.08 of the faintest object in Lya to be detected in a 80hours exposure. When translated in counts/pixel on the detector the impact of the ghost is negligible. Nevertheless, an optical design optimisation to remove this ghost was not possible without a huge impact in the design. On the other hand, a mechanical upgrade of the Pupil Slit Mask in the Image Slicer System has been proposed to completely remove both ghosts. The Figure 13 shows the design proposed for the PSM. The alignment is not constrained by this new design. This baffle consists in 3 thin plates of 200µm positioned closed to the PSM and oriented with different angles. It is mounted on a repositionable support linked to the PSM support. This new mask has been implemented and tested onto ISS01. It is really efficient to stop ghosts because nothing was measurable.

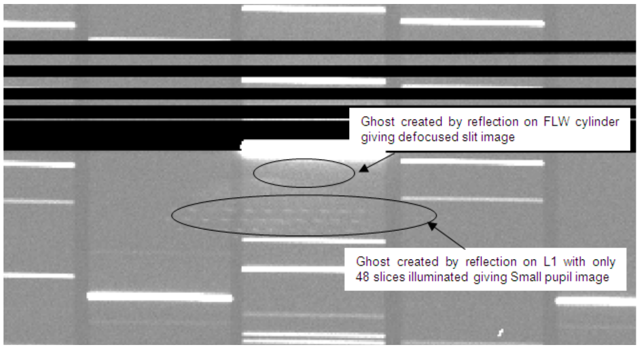


Figure 12: Ghost images in the red part of the spectra (saturated spectral line).

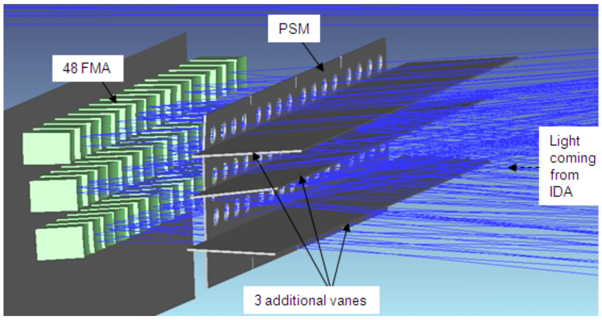
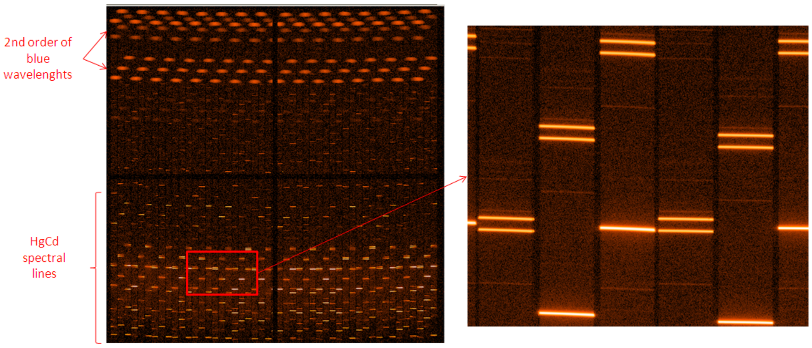


Figure 13: To remove both ghosts, a new PSM mask is proposed. Three vanes are added.

To measure the spectrum positioning, the IFU Illumination Unit is used with a full FoV lighted with HgCd lamp. The spectrum positioning is compliant with requirements which shall be better than ± 40pixels. It has been measured onto the full FoV located between Spectrum 24 and 25 at 546.07nm (Mercury line). Along optical axis, the best focus has been determined at the same position as the {SPS+DV}. That validates the absolute positioning of ISS along z-axis. There is no overlap between each mini slit (Figure 15). In FWHM, the mini-slit average gap is 7.4 ± 1 CCD pixels. The minimum gap is 6 CCD pixels and the maximum one is 9 pixels. That is due the misalignment of mini-slits provided by FMA onto ISS. Slit width is 2.1 pixels (Figure 15). The 2nd order of blue wavelengths appears onto CCD acquisitions with HgCd lamp because no filter is used onto IFU Illumination Unit (Figure 14). It will not be the case for MUSE because filters are set in MUSE Fore Optics.



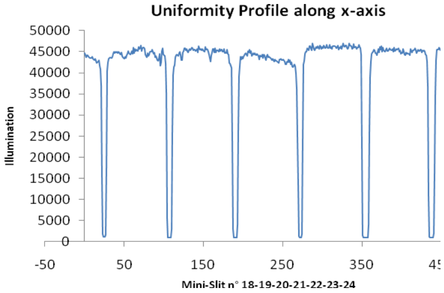


Figure 15: Slice along x-axis

Figure 14: CCD acquisition with full FoV with HgCd lamp (logarithm scale).

The throughput performance of the IFU is well within its specification. All sub-systems are above its specification. The throughput calculation of the first IFU has been done using:

- The hypothesis for reflective coatings of the slicer, since the current coating is not the final one,
- The measured efficiency of VPHG n°03 (it will replace the current one after the SPS retrofit),
- The measured transmission of the spectrograph substrates and their AR coating. (The AR coating will be retrofitted too since it is hydroscopic)
- The measured efficiency of the Psychee DV02 detector.

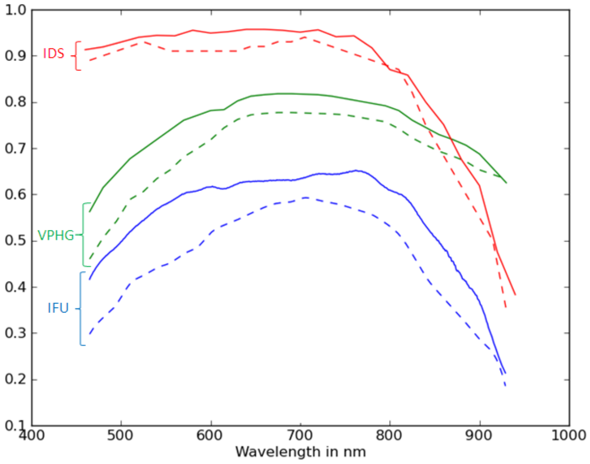


Figure 16: MUSE efficiency Current versus FDR (dashed line)

The IFU01 mass was designed at 86.6kg. The IFU01 total mass (80.8kg without ISS protection cage estimated to 0.6kg) is lower than requirement (<95kg with DV cables). The centre of gravity is measured with respect to the IFU flange interface at (x = no measure; y=+40 ± 5mm; z=+34 ± 1mm) in adding 1.82 ± 0.1 kg at the ISS01 centre of gravity. The centre of gravity was designed along z-axis at -10mm and +35mm along y-axis.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

The Manufactured Item Acceptance (MIA) is the formal milestone giving authorization for one sub-system to be sent for integration into MUSE instrument. It validates first of all the sub-system Design, MAIT process and top level performances. In the present case, this first IFU and associated sub-systems revealed a certain number of non compliances mostly linked to coating aspects and CCD defects. The first IFU as it is, is therefore not acceptable for MIA.

Nevertheless, the step achieved by this first IFU realization and testing is tremendous as it is the first of MUSE Sub-System to be MANUFACTURED, ASSEMBLED and FULLY FUNCTIONNAL.

Moreover, the major non compliances identified are all linked to manufacturing defect and most of them have been solved since IFU MIA. The VPHG serial number 3, has been received in July 2009, tested and shows an efficiency uniformity better than 3% over ¾ of the scientific bandwidth. The first CCD exhibits a hot pixel that blurs over a few column and even lines of a quadrant of the detector. This effect has not been seen in the next chips of the series. Concerning the coating problems some solutions are identified. The coating of the slicer is a critical parameter and a new coating from European company is being selected. Performance and environmental qualification (humidity and temperature cycles) based on coating slicer sample has been performed and is compliant with requirements. The AR coating of the spectrograph was demonstrated to be hydroscopic and Winlight has changed the coating supplier. The IFU ghost performances are not clearly in specification but it has been removed by a new PSM mask into the Image Slicer Subsystem. Moreover, critical performance like the image quality and tight tolerances onto SPS/DV interface are into specifications and even better than expected.

At the end, no major design showstoppers have been identified and it can be concluded that the IFU design is validated. Concerning the MAIT process, it has been demonstrated to be feasible. A huge experience has been collected from this first IFU realization and tests. Some modifications on parts and on the process have been identified in order to optimize the serial phase. The IDA+FMA and Spectrograph SERIAL phase has been launched.

ACKNOWLEDGMENT

We thank CNRS/INSU and University Claude-Bernard Lyon I for their strong support to the MUSE project.

REFERENCES

[1] Bacon et al., “The second-generation VLT instrument MUSE**”,** Proc. SPIE, 7735-7, in prep (2010)
[2] Loupias, M et al., “MUSE instrument global performance analysis**”,** Proc. SPIE, 7733-3, in prep. (2010)
[3] Kelz et al., “The calibration unit and detector system tests for MUSE”, Proc. SPIE, 7735-186, in prep (2010)
[4] Nicklas et al., Analyzing the MUSE opto-mechanics serving as an optical bench in 3D space”, Proc. PIE, 7735-169, in prep (2010)
[5] Laurent et al., “Optical Design, Fabrication and Testing a prototype of the NIRSpec IFU”, Proc. SPIE, 5252, 443 (2005)
[6] Laurent et al., “Designing, manufacturing and testing of an advanced image slicer prototype for the James Webb Space Telescope”, Proc. SPIE, 5494, 196 (2004)
[7] Laurent et al., “Design of an Integral Field Unit for MUSE, and Results from Prototyping”, PASP, 118, 1564 (2006)
[8] Laurent et al., “Innovative slicer design and manufacturing”, Proc. SPIE, 6273, 71 (2006)
[9] Caillier P., et al., “The MUSE project from the dream toward reality”, Proc. SPIE, 7738-29, in prep. (2010)
[10] Content et al., “A new design for Integral Field Spectroscopy with 8-m Telescopes”, Proc. SPIE, 2871, 1295 (1997)
[11] Vives et al., “New technological developments in Integral Field Spectroscopy”, Proc. SPIE, 7018, 86 (2008)
[12] Laurent, F et al., “Optical Design, manufacturing and tests of the MUSE Image Slicer”, Proc. SPIE, 5965, 184 (2005)
[13] Laurent, F et al., “MUSE image slicer: test results on largest slicer ever manufactured”, Proc. SPIE, 7018, 71 (2008)
[14] Renault, E et al., “Efficiency measurements performed on the MUSE VPHG”, Proc. SPIE, 7739-100, in prep. (2010)
[15] Lizon, JL et al., “LN2 continuous Flow Cryostats, a compact vibration free cooling system for single to multiple detector systems**”,** Proc. SPIE, 7739-154, in prep. (2010)
[16] Renault, E et al., “Optomechanical system of AIT tools to perform tests and integrations of 24 IFU**”,** Proc. SPIE, 7739-174, in prep. (2010)