# MUSE, a second-generation integral-field spectrograph for the VLT

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## ABSTRACT

We describe MUSE (Multi Unit Spectroscopic Explorer), a second-generation integral-field spectrograph for the VLT, operating in the visible and near IR wavelength range. It combines a 1’ x 1’ Field of View with the improved spatial resolution (0.2”) provided by adaptive optics and covers a large simultaneous spectral range (0.48-1 µm). With this unique combination of capabilities, MUSE has a wide domain of application, and a large discovery potential. It will provide ultra deep fields with a limiting magnitude for spectroscopy of R = 28.

After a brief presentation of the scientific case and the derived instrument requirements, we will focus on the MUSE optical design, including the overall architecture, the major trade-off that were conducted in order to optimize the cost and performance, and a provisional implementation scheme of the instrument on the VLT Nasmyth platform. Then the most important optical subsystems (as the 3 x 8 Field-splitter, the Image Slicers and the Spectrometers) are described. One of MUSE special feature is the impressive number of Image Slicer and Spectrometer modules which must be manufactured, that is 24. The realization of such series has been studied in collaboration with an industrial company. Finally, a preliminary estimation of the expected performance and a technological development program in order to secure the realization of the critical optical subsystems will be presented.

Keywords: Integral Field Spectroscopy, Field-splitter, Image Slicer, Spectrometer, VLT instrumentation

## 1. INTRODUCTION

In the frame of the Call for Preliminary Proposals emitted by the European Southern Observatory (ESO) for second generation VLT instruments, the Centre de Recherche Astronomique de Lyon (CRAL), in association with seven European Research Institutes (University of Cambridge, University of Durham, Sterrewacht Leiden, Laboratoire d’Astrophysique de Marseille, University of Oxford, AIP Potsdam and ETH Zürich), has proposed to ESO the concept of an innovative integral-field spectrograph, named MUSE (Multi Unit Spectroscopic Explorer). The instrument will operate in a large simultaneous visible and near IR spectral range (0.48-1 µm), providing a minimal Field of View (FoV) of 1’ x 1’ corrected with Adaptive Optics (AO), and will be especially optimized for the study of the progenitors of normal nearby galaxies out to very high redshift. This communication intends to summarize the MUSE original proposal, dealing with various topics such as the scientific case and its derived instrumental requirements (§ 2), the instrument overall design, including trade-off and system analyses, baseline optical lay-out and its mechanical accommodation on the VLT Nasmyth platform (§ 3), a rapid description of the major optical subsystems such as the Field-splitter, Image Slicers, and Spectrometers (§ 4), a preliminary estimation of the expected performance (§ 5), and the technological development program of the instrument (§ 6).

# 2. SCIENCE CASE AND DERIVED INSTRUMENTAL REQUIREMENTS

## 2.1. Science case

MUSE is optimized for the study of the progenitors of normal nearby galaxies out to very high redshift. These systems are extremely faint and can only be found by their Lyman $\alpha$ emission. Deep integrations of 80 hours with MUSE will push the VLT to the limit, and provide spectroscopy of systems as faint as R=28. Lyman $\alpha$ emission will be detected to a limiting flux of 3.10-19 $erg.s^{-1}.cm^{-2}$, a factor 100 better than is achieved currently. Such exposures will simultaneously address the following science goals:

(i) Study of intrinsically faint galaxies at high redshift, including determination of the luminosity function, clustering, etc
(ii) Detection of Lyman $\alpha$ emission out to the epoch of reionization and determination of the nature of the reionization
(iii) Detection of population III stellar populations out to z=5
(iv) Map the growth of dark matter halos
(v) Study the link between the evolution of the IGM and star formation
(vi) Study the physics of Lyman break galaxies, including their winds and feedback to the intergalactic medium
(vii) Identification of very faint sources detected in other bands
(viii) Detailed study of luminous distant galaxies
(ix) Serendipitous discovery of new classes of objects

MUSE will also allow very detailed studies of nearby normal, starburst and interacting galaxies, and of galactic star formation regions. Massive spectroscopy of resolved stellar populations will be a key complement to GAIA studies of the Galaxy. The higher resolution modes of MUSE will capitalize on the increased spatial resolution that will be provided by the development of adaptive optics, which may ultimately lead to high Strehl ratios in the visible. In these modes, MUSE will probe, e.g., the relationship between supermassive central black holes and their host galaxy and the physics of winds from accretion disks in young stellar objects, at the best spatial resolution provided by the VLT.

## 2.2. Instrumental requirements

The specifications and design of MUSE are based on a detailed trade-off between the various technical possibilities for multi-object and integral field spectrometers, driven by the science requirements. This has led to the following preliminary technical specification:

- ✓ MUSE should be able to work in both seeing and AO assisted modes
- ✓ It should offer a simultaneous spectral range from 0.48 to 1 µm, with a spectral resolution R equal to 1500 at 0.6 µm.
- ✓ It should offer higher spectral resolution (R > 3000) in a few dedicated spectral ranges
- ✓ It should have a minimal FoV of 1' x 1' sampled at 0.2"
- ✓ It may optionally achieve smaller spatial sampling (e.g. 0.1", 0.05") with a corresponding smaller FoV
- ✓ The instrument should be able to achieve very long integration time (up to 100 hours) without significant degradation of the S/N gain compared to the theoretical value
- ✓ Instrument throughput and image quality shall be optimized for the 0.6-1µm spectral range.

From this preliminary set of scientific requirements, the instrument technical specifications are summarized in the Table 2-1, including the most important interface constraints (VLT and CCD focal plane characteristics). The table also shows that a square angular sample of 0.2" side shall be imaged at the CCD plane on a rectangle of 15 x 30 µm along the cross-dispersion and dispersion directions respectively, in order to comply with the Nyquist criterion for spectral sampling. This implies that the instrument shall include one or several anamorphosing optical subsystems, as noticed on the next paragraph.

| | | |
|---|---|---|
| **SCIENTIFIC REQUIREMENTS** | | |
| Angular FoV dimensions | 1 x 1 arcmin | |
| Angular sampling | 0.2 arcsec* | |
| Spectral range | 0.48-1 μm | |
| Spectral resolution | 1500 at 0.6 μm | Nominal |
| | 3000 at 0.6 μm | High resolution |
| Image quality | 80 % of encircled energy within 0.2 arcsec (1 sample) | From 0.6 to 1 μm |
| | 80 % of encircled energy within 0.4 arcsec (2 samples) | Below 0.6 μm |
| Optical transmission | ≥ 30 % | |
| **VLT INTERFACE REQUIREMENTS** | | |
| Telescope pupil diameter | 8 m | |
| Telescope F/D number | 15 | |
| **FOCAL PLANE CHARACTERISTICS** | | |
| Pixel number | 4096 | Cross-dispersion direction |
| | 2048 | Dispersion direction |
| Pixel/sample | 1 | Cross-dispersion direction |
| | 2 | Dispersion direction |
| Pixel size | 15 μm | |
| Output F/D number | 1.93 | |

Table 2-1: Main scientific and interface requirements

# 3. MUSE OVERALL DESIGN

In the next paragraph is discussed the global arrangement of the main optical subsystems constituting the instrument, and the number of each of these units is defined. The major trade-off and system analyses that led to this choice are discussed in § 3.2, while the proposed optical and mechanical architectures are described in paragraphs 3.3 and 3.4 respectively.

## 3.1. Instrument subsystems architecture

From the VLT Nasmyth flange to the CCD detectors, the MUSE instrument shall be composed of (at least) the following optical subsystems:

- One FoV de-rotator installed at the VLT Nasmyth flange
- One Beam Selector allowing to alternatively use the calibration and adaptive optics modules (see below)
- One calibration module placed at the entrance of the instrument, regularly operated for flat-field and wavelength calibrations
- One adaptive optics module, that could eventually be exchanged with a Multi-Conjugated Adaptive Optics (MCAO) system at a later stage of the project
- One Enlarger/Anamorphoser enlarging the AO focal plane up to the desired magnification ratio. The anamorphosing function of the MUSE instrument can also be fulfilled by this entrance optical subsystem
- One Field-splitter, splitting the enlarged and anamorphosed FoV into "N" sub-FoVs, where N is an integer equal to 24 (see below)

* The angular sampling, together with the FoV dimensions, could be reduced by a factor 2 or 4, thus allowing MUSE to work in an additional, high angular resolution mode. This option is not considered as a design driver for the instrument due to the lower required numerical apertures

- N Image Slicers, splitting each sub-FoV and re-arranging it into an optical "pseudo-slit" that will be placed at the Spectrometer entrance. This concept was preferred to other types of integral-field spectrograph (equipped with micro-lens arrays[1] or optical fibers) with regard to its noticeably higher FoV packing efficiency.
- N Spectrometers, each composed of one collimator, all the needed dispersing elements, and one camera having an output F/D number of 1.93

Excepting the FoV de-rotator, all the opto-mechanical modules will be installed on the VLT Nasmyth platform. In this paper we have chosen to focus our attention on the "rear" part of the instrument, going from the Enlarger/Anamorphoser to the Spectrometer optical subsystems, and schematically represented in Figure 3-1.

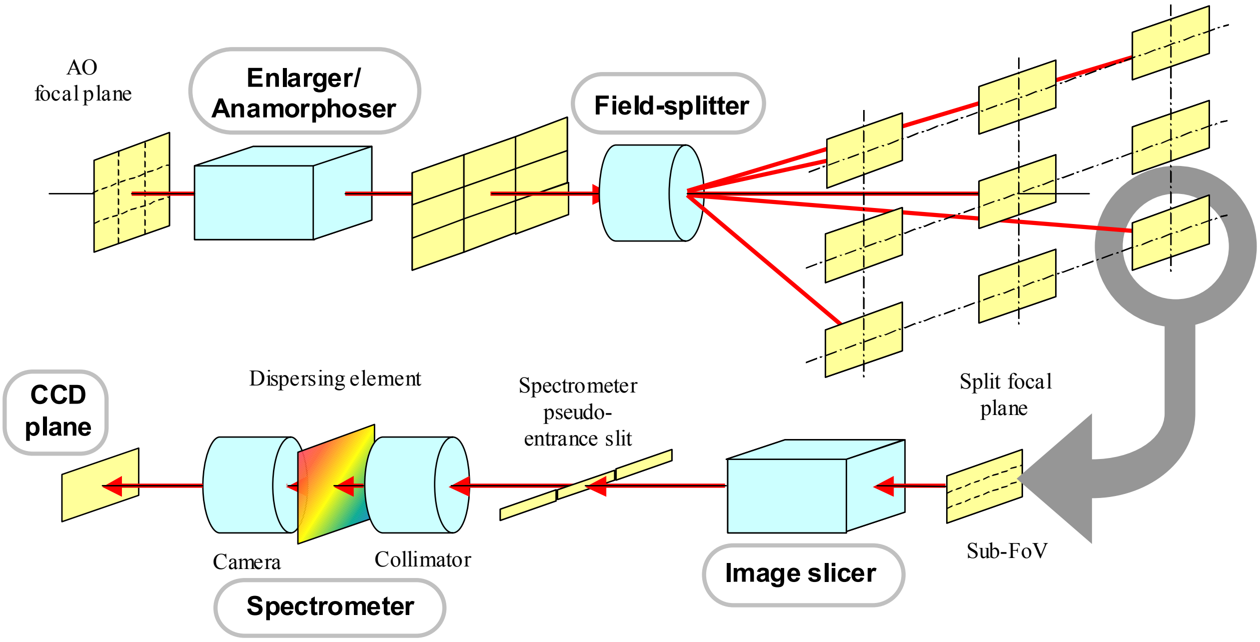


Figure 3-1: Schematic view of the "rear" instrument subsystems

Of paramount importance is the numerical value of the number N of sub-FoVs, because once the instrument FoV has been split, each following optical unit has to be manufactured N times (this also is the reason why the Enlarger/Anamorphoser is located before the Field-splitter in the baseline optical design). The N number is first estimated from a very simple calculation: if we divide the total number of spatial and spectral samples (300 x 300 x 2000) by the CCD pixel number (4096 x 2048), we obtain 21.46 that is the minimal number of sub-FoVs. Adding an 8 % margin in order to separate the individual images of the sliced sub-FoV at the entrance pseudo-slit of the Spectrometer leads to a more realistic value of 23.17. Finally, we select the most convenient integer superior to this value, that is 24[*]. Then the instrument shall be equipped with 24 Image Slicer and 24 Spectrometer units.

### 3.2. Trade-off and system analysis

The FoV-splitting optical device rapidly appeared as a core subsystem of the MUSE instrument. Because it has to be placed at the entrance of the instrument (just after the AO focal plane), and launches all sub-FoV beams in different directions, it has major consequence on the optical and mechanical arrangement of all the succeeding modules (Image Slicers, Spectrometers and CCDs). We investigated several Field-splitter concepts redirecting the beams into a circular or rectangular symmetry. The circular symmetry was discarded because of a too high number of optical elements needed for image transfer to the entrance of the Image Slicers. Rectangular symmetry looks much simpler, and the next choice was to select the appropriated ratio for splitting the focal plane along the cross-dispersion and dispersion directions (denoted X and

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[*] Corresponding to a global FoV packing efficiency of 89.4 %

Y respectively): as represented in Figure 3-2, a square FoV may be split into 24 sub-FoVs in many different ways, for example into 2 x 12, 3 x 8, or 4 x 6 sub-FoVs along the X and Y axes. This choice has a direct impact on the number $N_S$ of slices constituting the Image Slicer, according to the following relationship:

$$\theta/d\theta = N_S N_Y$$

where θ is the angular FoV, dθ is the angular sampling, and $N_Y$ is the number of sub-FoVs along the dispersion direction. But for a given slice number $N_S$ we can also optimize the magnification ratios of the Enlarger/Anamorphoser, Image Slicer, and Spectrometer subsystems in order to find the best compromise between the global instrument cost and performance. Once the slice number and all three magnification ratios are defined, the major characteristics of the entrance and exit optical beams are easily determined for each optical subsystem of the instrument. We have then tried different values of $N_Y$, respectively corresponding to the 2 x 12, 3 x 8, and 4 x 6 Field-splitters schemes in Figure 3-2, and to slice numbers $N_S$ equal to 25, 38, and 50. Among the various possible cost and performance criteria, the following were selected before optimizing the magnification ratios of the optical subsystems:

- The slices height H and length L, and their aspect ratio L/H. For technological reasons the latter should be as low as possible, and the slice height should be kept above 0.9 mm, which is the value adopted for the NIRSpec Image Slicer currently under development[2]
- The Image Slicer performance, here expressed in terms of WFE, as a rough estimate of the third-order geometrical aberrations of the spherical mirrors constituting the Slicer unit
- The length of the entrance pseudo-slit and the estimated diameter of the Spectrometer optics, which should be as small as possible, in order to reduce the cost, mass, and maximal volume of each of the 24 Spectrometer modules.

The here above criteria showed clear contradictory tendencies with respect to $N_Y$, leading to the selection of the 3 x 8 Field-splitter as a strong basis for the MUSE optical and mechanical design.

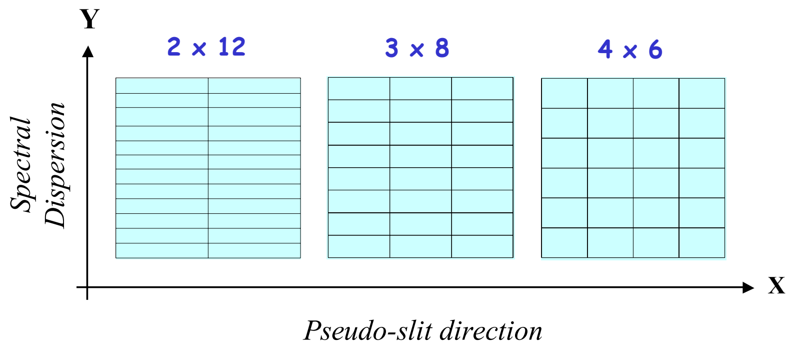


Figure 3-2: Rectangular Field-splitter trade-off

### 3.3. Baseline optical design

The baseline optical architecture is illustrated in the Figure 3-3. It presents the main following features.

- The Field-splitter divides the entrance FoV into a 3 x 8 rectangular arrangement. This is realized by means of an entrance Mini-Lens Array (MLA) imaging the telescope pupil at the entrance of a second MLA, whose functions are to spatially separate and to anamorphose the 24 sub-FoVs at the entrance of the enlarger. A third MLA (not shown on the Figure) is placed there, where it acts as the field lens in classical optical systems
- The second stage of the Field-splitter consists in a "Wide-Angle Enlarger" (WAE), re-imaging at long distance each individual sub-FoV, to the entrance of its associated Image Slicer. Fold mirrors can eventually be placed between the enlarger and the Image Slicer for mechanical accommodation

- The advanced Image Slicer is derived from the concept proposed for the NIRSpec instrument of the NGST[2,3,4]: it slices the input sub-FoV beam into 38 different optical arms that are re-arranged along a pseudo-slit. Each arm is composed of three spherical mirrors (the “slice”, the “pupil” mirror, and the “slit” mirror)
- Finally, the Spectrometer, although it may look quite classical, is the result of an arduous compromise between image quality, optics diameter, and cost. Its study was performed in collaboration with an industrial company

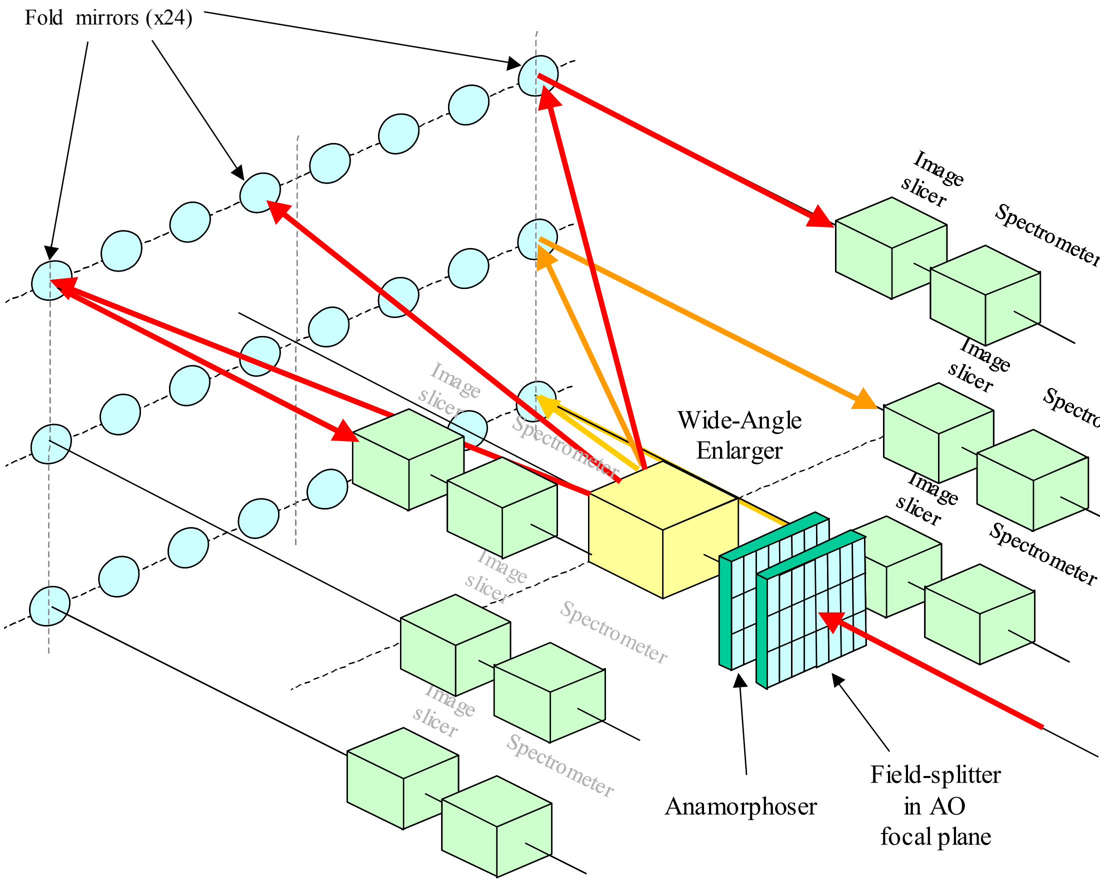


Figure 3-3: Baseline optical architecture of MUSE

## 3.4. Mechanical accommodation on the VLT

Figure 3-4 shows the different opto-mechanical subsystems of MUSE installed on the Nasmyth platform of the VLT. The main constraints of the platform environment were taken into account:

- Space limitation: 6m x 4m x 5m (width x length x height)
- Mass limitation: 8000 kg
- Maintenance needs: leaving enough space on the platform for the installation, maintenance, and easy replacement of the whole subsystems.

The preliminary estimated volume of MUSE is around 4.5m x 4m x 2m, including a dedicated space for AO implementation. The long working distance of the Field-splitter (3 m) allowed to fold the optical beams downward to the base of the platform, ensuring a low centre of gravity and avoiding the implementation of high and heavy structural elements. Hence the total instrument mass should be between 6 and 7 tons, that complies with the VLT requirements.

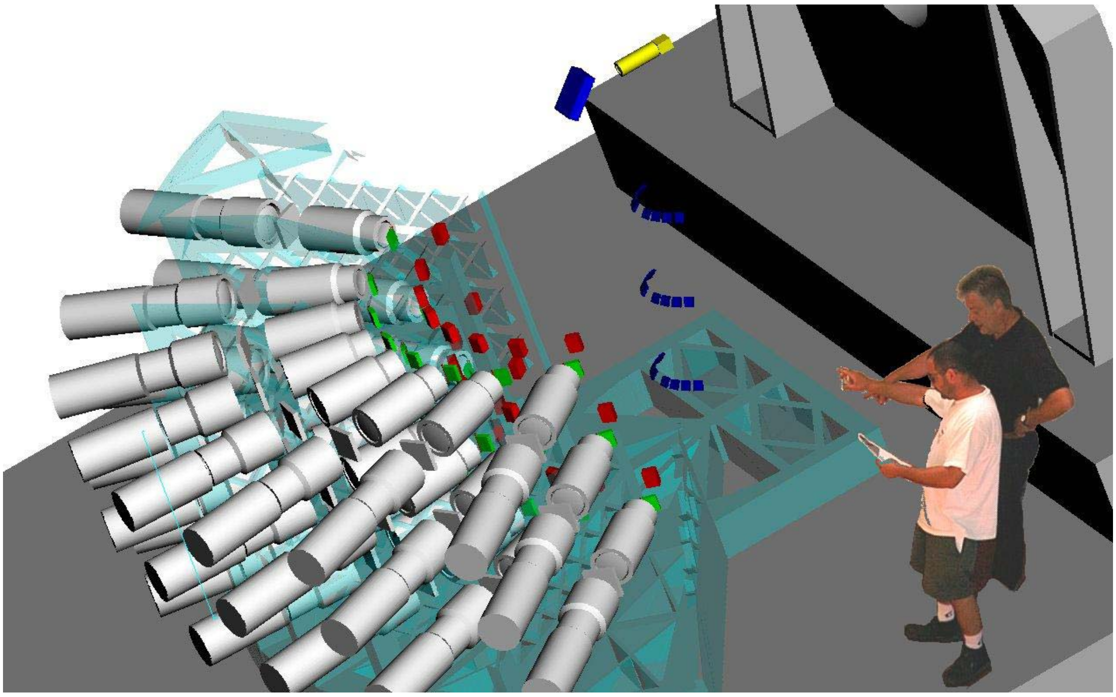

Figure 3-4: MUSE instrument installed at the VLT Nasmyth platform

## 4. DESCRIPTION OF MAIN OPTICAL SUBSYSTEMS

This section provides a brief overview of the major optical subsystems constituting the MUSE instrument, namely the Field-splitter (§ 4.1), advanced Image Slicer (§ 4.2), and Spectrometer (§ 4.3).

### 4.1. The Field-splitter

As already mentioned in § 3.3, the 3 x 8 Field-splitter is composed of a series of entrance Mini-Lens Arrays (MLA) realizing the FoV splitting and anamorphosing functions, and of a "Wide-Angle Enlarger" (WAE), enlarging each sub-FoV and focusing it at the Image Slicer entrance plane.

#### 4.1.1. Entrance Mini-Lens Arrays (MLA)

Three mini-lens arrays are placed at the entrance of the instrument (i.e. at the AO focal plane), in order to split the Field of View into 3 x 8 sub-FoVs and to anamorphose each of them (see Figure 4-1):

- The first MLA ("FoV-splitting MLA") is located just at the AO focal plane, where the FoV is split by the edges of each mini-lens. In addition, each lens forms an image of the telescope pupil at the entrance of the second MLA
- The second MLA, or anamorphic MLA, images the entrance faces of each FoV-splitting lens at the WAE object plane, and performs an anamorphic demagnification of each sub-FoV, in order to spatially separate them. This MLA may consist in two crossed cylindrical arrays (such as those manufactured by the LIMO Company) with their cylindrical faces disposed at the entrance and exit faces of the MLA
- Finally a third MLA will be placed at the WAE object plane, where it shall act as a set of field lenses (one for each individual sub-FoV), subsequently reducing the required numerical aperture for the WAE.

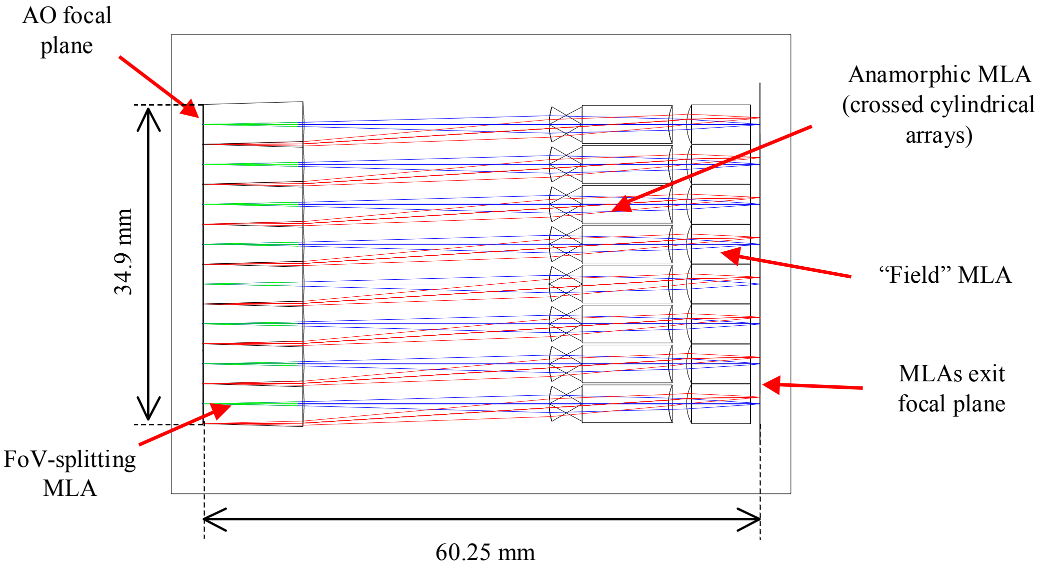


Figure 4-1: Optical design of the entrance MLAs

### 4.1.2. Wide-Angle Enlarger (WAE)

The Wide-Angle Enlarger has been designed to answer to both following important constraints:

- A working distance not longer than 3 m, in order to stay compliant within the allowed volume on the VLT Nasmyth platform
- A minimal distance between each adjacent sub-FoV equal to at least 200 mm, providing the necessary clearance for the implementation of the 24 Image Slicer and Spectrometer modules on the platform.

In addition the WAE has to present an acceptable image quality (encircled energy performance) and a moderate number of lenses in order to preserve a reasonable instrument throughput. The computation of a WAE optical design answering to these preliminary specification was not an easy task: starting from classical solutions, tenths of optimization runs were carried out and resulted in the preliminary optical prescription presented in Figure 4-2. It is composed of 7 lens elements* and is only constituted of spherical surfaces, thus realizing a reasonable compromise between performance and manufacturing costs.

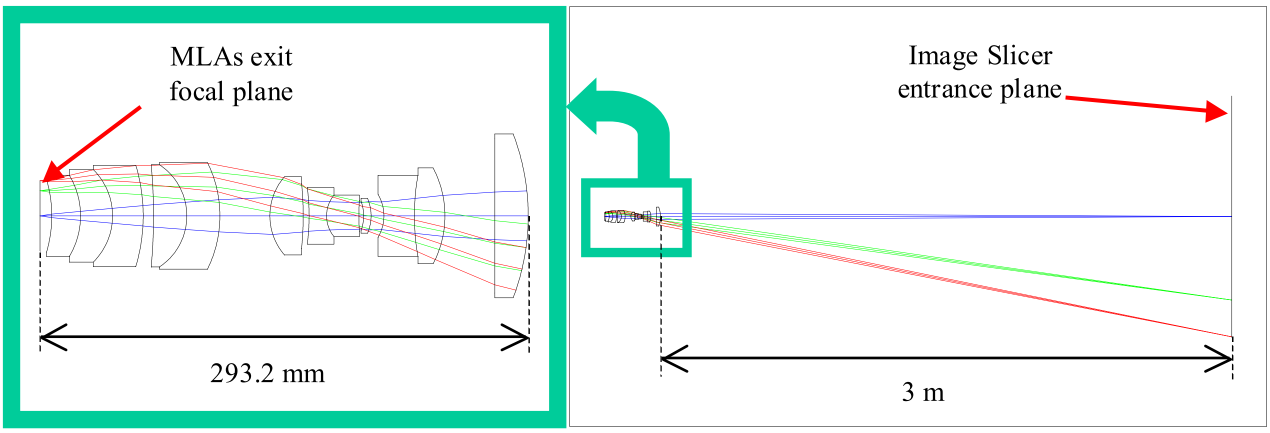


Figure 4-2: Optical design for the Wide-Angle Enlarger

* Here doublets and triplets are considered as one single optical element

### 4.2. The advanced Image Slicers

The main optical functions of the MUSE Image Slicer are to transform the entrance sub-FoV into a pseudo-slit perpendicular to the dispersion direction (to be located at the Spectrometer entrance plane), and to re-image the telescope pupil at infinite distance. Its main optical requirements are summarized in Table 4-1.

| IMAGE SLICER REQUIREMENTS | |
|---|---|
| Slicer mirror dimensions | 79.4 x 59.5 mm |
| Slices number | 38 |
| Entrance F/D # | 102.3 |
| Entrance pupil position | ≈ -3 m |
| Magnification factor | 0.03 |
| Pseudo-slit length | ≥ 96.13 mm |

Table 4-1: Image Slicer requirements

The theoretical principle of the advanced Image Slicer is not detailed here, since it is based on the concept proposed by R. Content[5] in 1997, that has been shown to present the highest FoV packing efficiency. It consists of three reflective elements, each made of 38 different mini-mirrors having different geometrical characteristics (mirror tilts and curvature radius). This principle has already been partly validated on such instruments as NIRSpec for the NGST[2,3,4], or GNIRS[6] for the Gemini telescope. For MUSE, where the FoV to be sliced is unusually large (and the Slicer magnification ratio particularly small), a preliminary optical design of the advanced Image Slicer was computed, defining the overall dimensions and geometrical characteristics of all the slices and the pupil and slit mirrors. Two views of this provisional concept are shown in Figure 4-3.

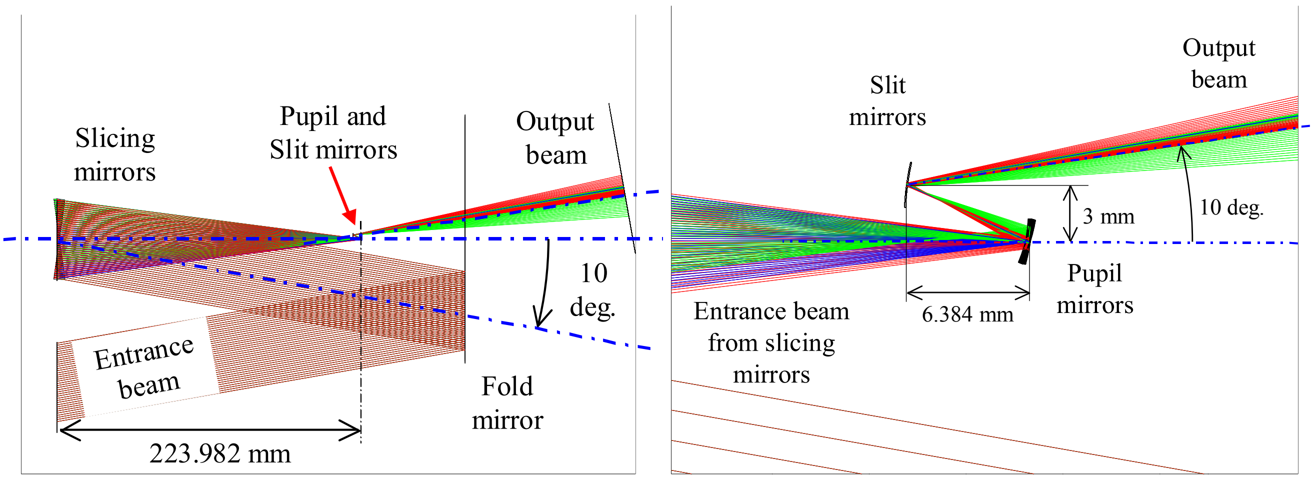


Figure 4-3: Image Slicer optical design (general and detailed views)

This optical design is the best that has been obtained so far. However, it suffers from two identified drawbacks that shall be corrected during the next phase of the study:

- The main problem is the achieved encircled energies that do not exceed 35 %. This is due to the high incidence angles on the spherical pupil mirrors (that can attain 20 deg.), generating strong geometrical aberrations (third-order coma and astigmatism). In the next phase, we will try to reduce these angles by refining the global specification of the Image Slicer (and particularly its magnification ratio). If this is not successful, other solutions will be to aspherize the pupil mirrors, or to replace them with a row of mini-lenses
- Another remaining task will be to "standardize" the curvature radius of the slices or of the pupil mirrors (that present 19 different values in the current design) in order to reduce their manufacturing costs.

### 4.3. The Spectrometers

In view of its preliminary requirements (large spectral range and fast F/D number of the camera) and of the large quantity of manufactured units, the MUSE Spectrometer soon appeared as one of the most critical optical subsystems of the MUSE instrument. Its optical design was studied in collaboration with a French industrial company. Here are summarized the main conclusions of this study:

- The cost of the Spectrometer increases with the diameter of the optics: for example, when the pupil size exceeds 155 mm, the mean diameters of the lenses become higher than 220 mm, thus generating encumbrance problems. For similar reason, the overall length, weight and size of the instrument tend to increase with the focal length of the camera, inducing some difficulties for mechanical integration.
- On the contrary, a small pupil size implies an increased field angle, which is a strong constraint for optical design: the correction of field aberrations becomes very difficult for half-field angle higher than 10 degrees.
- The properties of the diffraction gratings have also been considered: a too large diameter will result in a global cost increase, while a small diameter implies a short focal lengths and a highly-dispersing element with a consequent efficiency loss when the grooves frequency exceeds 500 $mm^{-1}$.

The result of this analysis showed that the best working range for the pupil diameter is 100-150 mm, corresponding to camera focal lengths of 200–300 mm. Given encumbrance constraints on the VLT platform, we finally gave preference to the “reduced pupil/short focal length” option, leading to the preliminary optical solution shown in Figure 4-4: excepted $CaF_2$ material (temporarily selected with respect to its excellent chromatic properties), it is only constituted of common SCHOTT and OHARA glasses, and does not include any aspherical surface. Each Spectrometer module is composed of the three opto-mechanical sub-assemblies:

- One telecentric collimator matched to the Image Slicer output FoV and numerical aperture
- Dispersing elements and their positioning mechanism*. Grisms (or possibly VPH) were preferred to reflection gratings because they do not require a folded mechanical configuration
- One camera lens having a 1.93 F/D number.

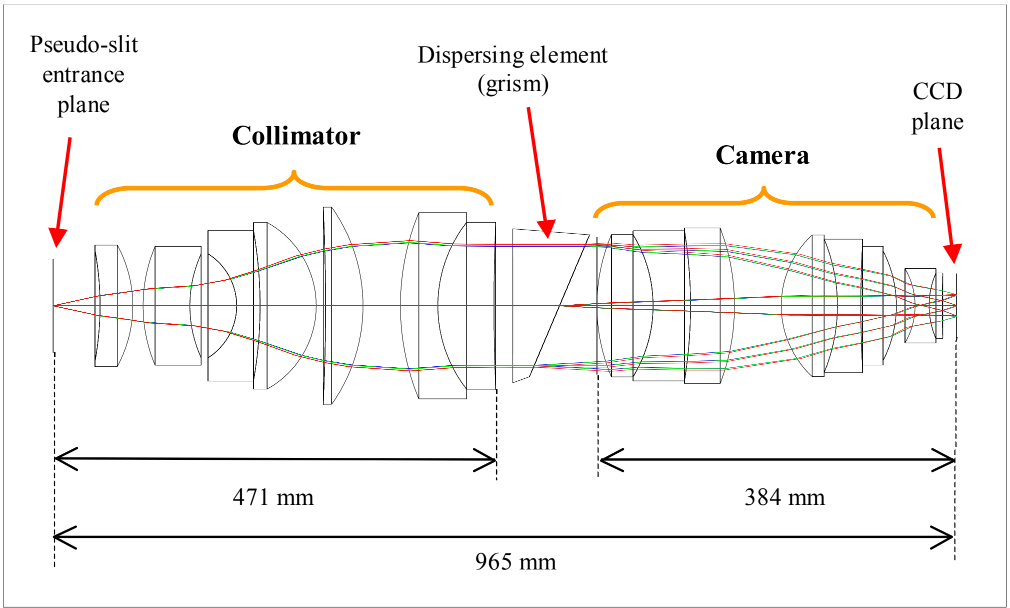


Figure 4-4: Preliminary optical design of the MUSE Spectrometer

* Since two different spectral resolutions are required

## 5. INSTRUMENT PERFORMANCE

A preliminary estimation of the instrument throughput in different operating modes (with and without AO) is provided in Table 5-1. These values were obtained within the MUSE primary spectral range (from 0.6 to 1 µm), assuming state-of-the-art anti-reflective coatings.

| CASE | Instrument throughput* | | Global throughput† | |
|---|---|---|---|---|
| | *Without AO* | *In AO mode* | *Without AO* | *In AO mode* |
| Typical values | 38.8 % | 35.8 % | 28.4 % | 26.2 % |
| Worst case | 33.0 % | 30.5 % | 24.1 % | 22.3 % |

Table 5-1: MUSE estimated throughput

We have estimated the MUSE performances in the case of point sources and high z extended objects with 0.1" light half radius and an exponential surface brightness distribution. Two modes were considered: a natural seeing mode (without AO) and an AO improved spatial resolution with a 1% Strehl ratio. Both modes assume median turbulence and sky brightness conditions at the VLT site. Objects were convolved with appropriate PSFs. We assume a value of 3 $e^-$ as the detector readout noise and $2e^-.hour^{-1}$ as the dark current. Flat-field accuracy was assumed to be 1%. With such parameters and the here above instrument throughput we then computed the limiting magnitude and flux corresponding to a S/N=5 per resolved spectral element, corresponding to a total integration time of 80 hours, split in 80 exposures of 1 hour. Results are given in the Table 5-2 for the nominal spectral resolution (R=1500). The corresponding limiting magnitudes after summing 10 spectral pixels (i.e. R=150) are also given.

| CASE | R band | | | I band | | |
|---|---|---|---|---|---|---|
| | Magnitude (Cousin) | | Flux $erg.s^{-1}.cm^{-2}$ | Magnitude (Cousin) | | Flux $erg.s^{-1}.cm^{-2}$ |
| | R=1500 | R=150 | | R=1500 | R=150 | |
| Point Source without AO | 25.9 | 27.2 | $6. 10^{-19}$ | 24.6 | 25.9 | $8. 10^{-19}$ |
| Point Source in AO mode | 26.9 | 28.3 | $2.5\ 10^{-19}$ | 25.6 | 27.0 | $3. 10^{-19}$ |
| Extended Object without AO | 25.9 | 27.2 | $6. 10^{-19}$ | 24.6 | 25.9 | $8. 10^{-19}$ |
| Extended Object in AO mode | 26.7 | 28.2 | $3. 10^{-19}$ | 25.1 | 26.4 | $5. 10^{-19}$ |

Table 5-2: MUSE foreseen limiting magnitudes

## 6. DEVELOPMENT PROGRAM

Here are summarized the main open points identified in the MUSE original Preliminary Proposal, and the development program that will be pursued during the next study phase, in order to assess the feasibility of the proposed optical concept. It shall include at least:

* From FoV de-rotator to CCD focal plane (including CCD efficiency)

† Also including atmospheric transmission and VLT mirrors

- The reopening of all the major trade-offs and system analyses described in section 3, in order to confirm the present instrument architecture, and the re-optimization of the major optical subsystems, including the Wide-Angle Enlarger and the Spectrometers (definition of the final pupil size, materials selection, nature of the dispersing elements...)
- The adaptation of the Image Slicer concept (for example, with the introduction of one or several dioptric elements) in order to improve the encircled energy performance and to become compliant with instrument requirements. This study shall cover both theoretical and practical aspects (optimization of the optical design, tolerance analysis, and realization of a preliminary breadboard of the advanced Image Slicer)
- The key-point of producing 24 Image Slicer and Spectrometer modules at an affordable cost, to be pursued in collaboration with industry
- The management of 24 CCD detectors running in parallel, including such different aspects as control electronics, harness, or cryogenics.

In parallel, the CRAL will continue its Research and Development effort on the advanced Image Slicers, in order to define more precise manufacturing requirements and to finalize its own Image Slicer test bench[4], conceived to validate the performance of the various types of components (slicing mirrors, pupil mirrors, and slit mirrors) and candidate technologies (optical contact, gluing, monolithic machining, or other).

## 7. CONCLUSION

We described MUSE, the second-generation integral-field spectrograph for the VLT optimized for ultra deep fields with a limiting magnitude of R = 28. MUSE should not only provide the critical spectral information that is currently missing in our understanding of high-z galaxies, but will also allow major progress in many other areas of astronomy, pushing our knowledge of galaxy formation back towards the epoch of reionisation, and measuring the distribution and physical properties of objects well below the current narrow band survey limits.

Beside its scientific objectives, MUSE rises a lot of new exciting technical issues, such as the realization of an advanced Image Slicer having an unusually large Field of View and small magnification ratio, or the industrial production of medium-scale series (24) of Image Slicer or Spectrometer modules at an affordable cost. In this context, MUSE can also be envisaged as a major step towards Extremely Large Telescopes[*] "clustered" instrumentation, and provide appreciable experience for their future conception and implementation.

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[*] Such as the ESO's OWL project