Slicing the Universe at affordable cost: The Quest for the MUSE Image Slicer

François Hénault, Roland Bacon, Robert Content, Blandine Lantz, Florence Laurent, Jean-Pierre Lemonnier, Simon Morris

CRAL - Observatoire de Lyon, 9, Avenue Charles André, 69230 Saint-Genis-Laval, France
Astronomical Instrumentation Group, University of Durham, Durham DH13LE, UK

ABSTRACT

The introduction of Image Slicers in Astronomy has been growing rapidly in the recent years. These optical devices allow the simultaneous observation on the same detector matrix of two-dimensional sky maps and the spectral decomposition of light on all of their angular samples, therefore dramatically reducing the observation times and getting rid of the spectro-photometric variations of the atmosphere. Today the implementation of Image Slicers is planned on various ground and space telescopes, covering a spectral domain ranging from blue to mid-IR wavelengths. Among such different projects, we describe the Image Slicer of MUSE (Multi Unit Spectroscopic Explorer), a second-generation Integral-Field Spectrograph for the VLT combining a 1’ x 1’ Field of View with a spatial resolution of 0.2” and a spectral resolution of 3000.

The most efficient principle of an Image Slicer consists in a combination of several different optical channels, each made of three mini-mirrors having different tilts and curvatures. After a brief presentation of the MUSE Image Slicer requirements, we will explain the followed logic in order to optimise the opto-mechanical design and cost of the Slicer: indeed one of MUSE peculiarity is the total number of its individual modules, that is 24. The realization of such series at an affordable cost actually is a design driver of the study. The communication also deals with the used optical design models, the expected performance, the candidate technologies for the manufacturing of all the components, and the future development of a prototype of this critical optical subsystem.

Keywords: Integral Field Spectroscopy, Image Slicer, Micro-lenses, MUSE, VLT instrumentation.

1. INTRODUCTION

Since the mid 90’ of last century, the introduction of Image Slicers (also named Integral Field Units, or IFU) in Astronomy has been growing extremely rapidly. These optical devices allow the simultaneous observation on the same detector matrix of two-dimensional sky maps and the spectral decomposition of light on all of their angular samples, therefore dramatically reducing the required observation times and getting rid of the spectro-photometric variations of the atmosphere. Today the implementation of Image Slicers has already been completed or is planned on various ground and space telescopes, such as SPIFFI for the VLT, NIFS and GNIRS for the Gemini, UIST for the UKIRT, or NIRSpec for the James Webb Space Telescope (JWST).

Among all these projects raised the Multi Unit Spectroscopic Explorer (MUSE) instrument: this is an innovative Integral-Field Spectrograph, that has been proposed to the European Southern Observatory (ESO) for its second-generation VLT instrumentation, by a consortium of eight European Research Institutes (Centre de Recherche Astronomique de Lyon, University of Cambridge, University of Durham, Sterrewacht Leiden, Laboratoire d’Astrophysique de Marseille, University of Oxford, AIP Potsdam and ETH Zurich). The instrument will operate in a large simultaneous visible and near IR spectral range (0.465-1 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. In this way MUSE can be seen as a spectro-photometric sounder that will literally cut the Universe into very deep and narrow stripes.

One of MUSE peculiarity is the total number of its individual modules, that is 24 (see Figure 1-1). In order to cover all the required FoV, each module will be equipped with one Image Slicer, followed by a Spectrograph. Hence MUSE prefigures
the “clustered” instrumentation that will be installed at the focal planes of the future Extremely Large Telescopes*, and should provide appreciable experience for their future conception, realization, and integration. In particular, the realization of such a series of Image Slicers at an affordable cost soon appeared as a design driver of the whole instrument. In this paper is summarized the “Quest for the MUSE Image Slicer”, narrating all the work and ideas that were emitted by several teams of engineers in order to reduce the costs of the MUSE Slicers, while staying compliant with the required performance.

Figure 1-1: An artist view of the MUSE instrument installed at the VLT Nasmyth platform. The Image Slicers components are shown in red and green

2. PRINCIPLES OF AN ADVANCED IMAGE SLICER

The two main functions of an Image Slicer are to transform a rectangular Field of View (FoV) into a series of mini “slits” that are re-arranged along a Pseudo-slit, that will be located at the entrance of a classical “long-slit” Spectrograph, on one hand, and to re-image the input pupil of the telescope at the entrance pupil of the Spectrograph, on the other hand (see Figure 2-1). Then we can see that the assembly constituted by both the Slicer and Spectrograph actually allows acquiring the two-dimensional FoV and the spectral decomposition of all its angular samples on the same CCD detector matrix.

Figure 2-1: Typical implementation of an Image Slicer (between a telescope and its spectrograph)

* such as the ESO’s OWL project
The most efficient principle of an Image Slicer was invented by R. Content in 1996. It consists of a series of reflective elements, each made of three different mini-mirrors having different geometrical characteristics (mirror tilts and curvature radii). Its principle is summarized below (see Figure 2-2 and Figure 2-3).

- The first optical element of the Advanced Image Slicer is the “slicing mirror” placed at the image plane of the telescope (or at any other conjugated plane within the optical system). It is constituted of very thin spherical mirrors (or “slices”) whose lengths are parallel to the X axis and thin dimensions are parallel to the Y axis. The slices are stacked together along the Y axis, then constituting a monolithic block whose rectangular contours correspond to the dimensions of the FoV. Ideally there should be no “dead areas” between each slice, so that no significant region of the observed FoV is lost. Each slice reflects the incident rays in a different direction of the XZ plane, toward its associated pupil mirror, where an intermediate image of the telescope pupil is formed.

- The second optical elements are the “pupil mirrors”, that are disposed along a row parallel to the X axis. Each pupil mirror images its associated slice at the pseudo-slit plane (i.e. at the Spectrograph entrance), and ensures a correct positioning and magnification of the slice image within the pseudo-slit, so that no overlap can occur between two adjacent mirrors.

- The third and last optical elements are the “slit mirrors”, also disposed along a row parallel to the X axis, and located at the pseudo-slit plane. Their main optical function is to re-image all the pupil mirrors at the entrance pupil of the Spectrograph, thus allowing a significant reduction in the diameters of its optics. In fact these slit mirrors act as field lenses in classical optical systems.
3. REQUIREMENTS OF THE MUSE IMAGE SLICER

The technical requirements of the MUSE Image Slicers were derived from the instrument top level requirements and are summarized in Table 3-1. A preliminary optical design, inspired from the GNIRS and the NIRSpec Integral Field Units and entirely constituted of spherical mirrors, has even been shown in this reference paper, but it soon appeared to be affected by strong geometrical aberrations (third-order coma and astigmatism) generated by the high incidence angles on the spherical pupil mirrors, thus destroying the image quality/encircled energy performance. In addition the system was also suffering from too large pupil aberrations.

<table>
<thead>
<tr>
<th>REQUIREMENT</th>
<th>VALUES</th>
</tr>
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<tbody>
<tr>
<td>Spectral range</td>
<td>From 0.465 to 1 µm</td>
</tr>
<tr>
<td>Slice number N₃</td>
<td>38</td>
</tr>
<tr>
<td>Magnification ratio</td>
<td>0.043 ± 0.01</td>
</tr>
<tr>
<td>Pseudo-slit curvature</td>
<td>Between ~2 and +2 m⁻¹</td>
</tr>
<tr>
<td>Slice length</td>
<td>80.5 -0/+0.5 mm</td>
</tr>
<tr>
<td>Slice height</td>
<td>1.59 mm (average value)</td>
</tr>
<tr>
<td>Mini-slit arrangement and positioning accuracy</td>
<td>Mini-slits arranged in alternate rows, within a 30 µm accuracy</td>
</tr>
<tr>
<td>Input F/D #</td>
<td>103.7</td>
</tr>
<tr>
<td>Output F/D #</td>
<td>Nominal value = 4.5†</td>
</tr>
<tr>
<td></td>
<td>Minimal value ≥ 4.05 (corresponding to a 10% margin)</td>
</tr>
<tr>
<td>Output pupil location</td>
<td>Between +1 m and infinite distance</td>
</tr>
<tr>
<td>Image quality</td>
<td>Higher than 80 % of encircled energy within one spatial sampling element† at Pseudo-slit plane</td>
</tr>
<tr>
<td>Lateral chromatism</td>
<td>Lower than one spatial sampling element</td>
</tr>
<tr>
<td>Micro-roughness of optical surfaces</td>
<td>≤ 2 nm RMS</td>
</tr>
<tr>
<td>Optical transmission</td>
<td>Higher than 95 % (TBC)</td>
</tr>
</tbody>
</table>

Table 3-1: MUSE Image Slicers requirements

Here some comments must be made about these functional and performance requirements.

- The total spectral range of the Image Slicer is quite extended (from 0.465 to 1 mm), but does not prevent for inserting lenses or dioptic elements within the overall optical layout.
- The Slicer magnification ratio, input F/D number, and output F/D number are related one to each other. These characteristics lead to a nominal output F/D # of 4.5, that is to our knowledge the “Fastest Image Slicer in the World”. This actually is a natural consequence of the large on-sky geometrical etendue that must be transmitted by the MUSE instrument (i.e. 0.2” angular resolution on a 8 m-diameter telescope), and has been found critical with respect to the image quality performance.
- The output F/D # is also constrained by a minimal value of 4.05, in order to limit potential light losses induced by pupil aberration and manufacturing and/or alignment errors in the whole instrument.
- The entrance FoV of the Image Slicer (i.e. the dimensions of the image to be sliced) is 80.5 x 60.4 mm, making it one of the largest “image slicing area” ever built. This also has additional consequences on the global image quality of the subsystem and on pupil aberration, since the angles of the incident rays on the slicing elements will attain significant values (i.e. 5 degrees or more).
- An additional difficulty with respect to previously realized image Slicers such as UIST or GNIRS is the fact that the micro-roughness of optical surfaces must be matched to the useful spectral range of the instrument, leading to a preliminary requirement of 2 nm RMS in the visible. This specification induced a strong preference on optical elements entirely made of glass.

* deduced from the Slicer magnification ratio and entrance F/D #
† i.e. a square of 34.5 µm width
Finally, it must be pointed out that since the total number of Slicer modules to be manufactured is rather important (i.e. 24), these studies had not only to take the performance aspect (as discussed above) into account, but also additional considerations about the manufacturing of large amounts of mini-optical components at a reasonable cost.

4. MANUFACTURING THE SLICERS AT AN AFFORDABLE COST

Based on the experience acquired on previous instruments (such as GNIRS\(^3\)) or on a recent glass prototype (i.e. the NIRSpec IFU prototype recently developed in CRAL\(^5\)), we soon realized that one of MUSE greatest challenges was the realization of a considerable amount of mini individual optical elements having numerous different geometrical parameters (curvature radii and mirror tilts) at an affordable cost. Indeed, each major component (the slicing mirror, the pupil elements row, and the slit elements row) must be composed of 38 different mini-mirrors, and it has to be manufactured 24 times. This led us to a total of 2736 optical components divided in 114 different types. Furthermore, some of these mini-mirrors (e.g. the slices or the pupil mirrors) showed evidence of tight manufacturing and assembly tolerances.

To face this technical and financial challenge, several solutions were envisaged by the CRAL and the University of Durham, who are among the MUSE Consortium the most involved in the design and realization of the Image Slicers. Two very promising approaches finally came out from this joint study effort, each relying upon rather different principles. Both designs are described with more details in § 4.1 and § 4.2:

- The most classical approach was studied by the CRAL and consists in using only traditional technologies and replacing the pupil and slit mirror rows by a set of identical mini-lenses, always disposed along rows. In the next pages of this paper we call this solution the “Catadiotric Image Slicer”.
- The most innovative method was proposed by the University of Durham. The principle is to replace the entire individual mirrors constituting one single mirror row by a monolithic assembly thanks to a new manufacturing process. This solution is named the “All-reflective Image Slicer” in the following paragraphs.

4.1. The Catadiotric Image Slicer (CIS)

The idea of replacing pupil and slit mirror with dioptic elements (i.e. mini or micro-lenses) in order to improve the image quality of the whole Image Slicer is not a real innovation in the young History of these systems, since it has already been proposed by a few authors\(^9,10,11\). Here the originality more exactly relies upon the fact that all the used mini-lenses must be of the same type, in view of reducing their costs. Some additional variants to this principle are also presented in the last paragraphs.

4.1.1. General principle

The CIS basically relies upon the same optical principle than the “All-reflective Image Slicer” with respect to FoV and pupil imaging: then we simply have transformed the pupil mirrors into “pupil lenses” and the slit mirrors into “field lenses”, as shown in Figure 4-1. However, one of the most important goals of the CIS was the improvement of the performance while reducing the manufacturing costs. For this purpose we had to solve two particular drawbacks of this family of optical systems, being:

- Just like the pupil mirrors, each single mini-lens within the pupil lens row should present three different geometrical characteristics: the decentering of the optical axis along the X and Y directions (i.e. the lenses are prismatic, or wedged), and the effective focal length of the mini-lens.
- In the general case when the entrance pupil of the Spectrograph is not located at infinite distance (i.e. the optical system is not telecentric) the geometrical characteristics of each mini-lens should also present the same types of differences all along the field lens row.

We then imposed that all the mini-lenses within the pupil lens and field lens rows shall rigorously have the same geometry. Hence we could envision the use of “standard” micro or mini-lens arrays or rows, similar to those that already are
manufactured and available in the fields of Integral Field Spectroscopy, Shack-Hartmann wavefront sensing, or Laser Beam Shaping techniques.

Nevertheless, as each mini-lens of e.g. the pupil row has to deviate the incident beam so that it becomes parallel to the main optical axis of the Image Slicer (marked Z in all the Figures), an additional optical component deviating the input beam around the X and Y axes had to be inserted in the system. The Figure 4-2 illustrates the trick that was employed with respect to the $\theta_y$ angles:

A. In Figure 4-2, five slicing mirrors are represented as viewed from the top (Y axis), with their reflective surfaces oriented around different $\theta_y$ angles. In order to deviate the incident beams on the pupil lenses so that they become parallel to the main optical axis, one can imagine inserting mini-prisms (having different wedges) at the exit of the pupil lens row.

B. The set of needed mini-prisms can be approximated by a single lens (that will be named “Input lens” and noted L1) located behind and very close to the pupil lens row.

C. Finally, the best arrangement between L1 and the pupil lens row is determined with computer ray-tracing. It showed that the best configuration is to set the L1 before the row. Then the focal length of L1 should approximately be equal to the distance $O_sO_p$ from the slicer stack to the pupil lens row. The lens can also be transformed into a doublet in the purpose of better chromatic compensation.

\textbf{NOTA} Each mini-lens of the pupil row should also present different decentring along the Y direction, otherwise the images of the slicing mirrors should no more be aligned along a Pseudo-Slit line, but be disposed along a “staircase arrangement”. Fortunately, this effect can be corrected quite easily by tilting the pupil lens row of a small quantity around the Z axis. An approximated, first-order calculation shows that the value of the compensating angle $\psi$ is given by the simple relationship:

$$\psi \approx -\gamma_s \frac{d_s}{d_p}$$
where $d_S$ is the slice height (along Y), $d_P$ is the pupil lens width (along X), and $\gamma_S$ is the Image Slicer magnification ratio.

The final optical principle of the CIS is summarized in Figure 4-3 (only two slicing mirrors are represented). In the same way than for the pupil lens row, we have associated an “Exit lens” (noted L2) to the field lens row, so that all the images of the telescope pupils will be located in one single given location, that is the Spectrograph entrance pupil. Then the CIS fulfills all the classical FoV and pupil imagery functions of Content’s Advanced Image Slicer. In addition, it provides mechanical clearance for the installation of a series of pupil stops at the intermediate pupil locations and eventually “slit masks” in the plane of the Pseudo-Slit, in order to block potential ghost images of the slices (see Figure 4-3).
4.1.2. Other cost-saving tricks

*Standardizing the slice curvatures*

Another critical point of the CIS is the total number of the different required curvature radius within one stack of slices: ideally for a 38 slices stack this number should be 19, since all distances from each individual slice to its associated pupil lenses differ from each other, and we assume that the geometry of the system is anti-symmetric. It is possible, however, to use only one single and identical curvature value, common to all the slices, provided that they can be slightly shifted along the Z optical axis, as represented in Figure 4-4. It has been checked that this arrangement introduce negligible shadowing or blocking areas between each slice that could reduce the CIS efficiency.

![Figure 4-4: Slicing mirrors having the same curvature radius (schematic and 3D views)](image)

*The flat facet slicer*

Another option to reduce the Slicer cost would be to replace the curved slicing mirrors with flat facets, thus saving the necessary time and money required for the polishing of 24 x 38 spheres on the slicing mirrors. This can be realized by means of an additional spherical or cylindrical field lens, located very close the slicer stack, as represented in Figure 4-5. The lens is actually ensuring the optical re-imaging between the input pupil and the pupil lens row. However, this configuration has the drawback of slightly decreasing the instrument throughput (around -2 %) and is so far considered as a back up solution.

![Figure 4-5: Flat facet slicer associated with a field lens](image)
4.1.3. Preliminary CIS design

The Figure 4-6 below displays the preliminary optical design of the CIS, including a general view (top), the footprints of the beams on the pupil lens rows (note that they are staggered in two rows), and a detailed view of the mini-lens rows area.

![Figure 4-6: Preliminary optical design of the Catadiotic Image Slicer](image)
4.2. The All-reflective Image Slicer (AIS)

As explained at the beginning of section 3, a preliminary design of reflective slicer was abandoned because of its low image quality in the field and pupil planes. For this new design, the basic principles of the Advanced Image Slicer used for other instruments as the GNIRS slicer were directly applied to the MUSE slicer. However, the field of view is now much larger (7.5” x 20” per slicer compared to a few arcsec in both directions for GNIRS) and the spectrographs needed to have fast collimators due to the space and weight constrains of a large number of spectrographs. The larger aberrations of the large field and fast collimator forced us to look for new solutions. While the CRAL design team, pursued the idea of the Catadiotric IS described above, the Astronomical Instrumentation Group of Durham successfully pursued a solution for an improved reflective design.

4.2.1. The improved reflective design

Three main modifications were needed to the GNIRS concept. First, the focal ratio of the collimator was slowed from F/3 to F/4.5. This does not significantly reduce the available space on the VLT platform but does significantly reduce the aberrations. Second, the line of pupil mirrors was split in 2 and positioned on each side of the slit (Figure 4-7). This allows us to place the pupil mirrors twice as far away while maintaining the slit location so that the largest off-axis angles are reduced by a factor of 2. As is generally known, the larger a beam is off-axis the larger the aberrations. Finally, in the classic design there is a large angle between the incident and reflected beams on the pupil mirrors, but not on the slit mirrors. The latter normally almost sends the light back on itself. In the MUSE reflective slicer, this is reversed (Figure 4-8); the pupil mirrors almost send back the light on itself, while a significant angle between incident and reflected rays is now on the slit mirrors. The image on the slit is greatly improved by this change, because the slice images on the slit are now almost on-axis with respect to the pupil mirrors. One might think this improvement would result in a degradation of the pupil image, since it is now off-axis with respect to the slit mirrors, but this does not happen. The reason seems to be that the incident angle on a slit mirror is the reverse of the angle on the preceding slice mirror. This probably cancels many of the aberrations. The disadvantage of this solution is that the edges of the slit mirrors are no longer in the focal plane. This makes the PSF footprint larger on its slit mirror. Since the slit mirror edges are used as baffle, especially in the spatial direction, there is a danger of losing light at the edge. Fortunately, this defocus remains small in the MUSE slicer design. Another consequence is that the edges of adjacent slices are not at the same height, which makes the machining more difficult but, again, the effect is small.

![Figure 4-7: The 2 lines of pupil mirrors on each side of the slit. The beam to the spectrograph passes between them](image-url)
The resulting encircled energy for a single pixel is 95% for the worst PSF. We are investigating reflective coatings, but preliminary indications are that losses of ~1% per reflection for the MUSE wavelength range may be possible. We also have some initial results for scattering losses from diamond machined surfaces. For the GNIRS slicer, 7nm RMS roughness was achieved, which when translated into the MUSE wavelength range would result in 1.5% scattering losses per diamond machined surface. We are confident this surface roughness can be reduced. As an example, if it were reduced to 2nm RMS, then the scattering losses per machined surface would be reduced to 0.1%.

![Diagram of the reflective slicer system](image)

**Figure 4-8:** Top view of the reflective slicer system. The incident angles on the pupil and slit mirror are different than in previous designs as the GNIRS slicer

### 5. CONCLUSION

In this paper, we attempted to narrate “The Quest for the MUSE Image Slicer”, that is a long story starting one year ago and involving the participation of different optical and mechanical engineer teams on both sides of the Channel. We have briefly recalled the principles of the Advanced Image Slicers, presented the MUSE instrument which strongly depends on the development of this technique, and underlined the main related difficulties (a very fast Slicer system working in the visible range, to be manufactured in 24 units at a reasonable cost). These studies were finally concluded by the successful design of two different types of Image Slicer, each relying upon very different principles, and both meeting all the MUSE challenging requirements. The optical design study phase is now completed, and the CRAL has undertaken in its laboratories the realization of a test bench of a Slicer prototype in order to evaluate the potential performance of both solutions (it is foreseen that the micro-lens arrays and the monolithic mirror rows could easily be exchanged during the course of the tests). The prototyping activities should begin at mid-October and the first consistent results of the MUSE Image Slicer prototype are expected in February 2004. In the mean time, both the CRAL and the University of Durham will pursue their effort in collaboration with industry in order to identify the cheapest ways of “Slicing the Universe”. 
REFERENCES