Probing Unexplored Territories with MUSE: a Second-Generation Instrument for the VLT

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The Multi Unit Spectroscopic Explorer (MUSE) is a second-generation VLT panoramic integral-field spectrograph presently under preliminary design study. MUSE has a field of 1 × 1 arcmin^2 sampled at 0.2 × 0.2 arcsec^2 and is assisted by the VLT ground layer adaptive optics ESO facility using four laser guide stars. The simultaneous spectral range is 0.465–0.93 µm, at a resolution of R ~ 3000. MUSE couples the discovery potential of a large imaging device to the measuring capabilities of a high-quality spectrograph, while taking advantage of the increased spatial resolution provided by adaptive optics. MUSE has also a high spatial resolution mode with 7.5 × 7.5 arcsec^2 field of view sampled at 25 milli-arcsec. In this mode MUSE should be able to obtain diffraction-limited data cubes in the 0.6–0.93 µm wavelength range.

Imager or spectrograph?

Imagers and spectrographs are the most common tools of optical astronomers. In most cases, astronomical observations start with imaging surveys in order to find the interesting targets and then switch to spectrographic observations in order to study the physical and/or dynamical properties of the selected object. Thanks to the excellent throughput and large format of today's detectors, large fractions of the sky can be surveyed in depth with imagers. As far as spectroscopic follow-up is concerned, this is still a very time-consuming task, given the relatively small multiplex capabilities available. Recent development of large multi-object spectrographs such as VIMOS at VLT (Le Fèvre et al. 2003) or DEIMOS at Keck (Fabers et al. 2003) has somewhat improved the situation. However, the total number of sources in a typical imaging survey is much larger than what is possible to observe with spectroscopy. The selection of sources is then mandatory. Usually the selection criterion is based on a series of multi-colour images and is intended to select the appropriate spectral characteristics of the population of the searched objects. This incurs a direct cost in telescope time since more than one exposure must be made at each sky location. As another disadvantage, the selection process is never 100 % efficient, and thus a fraction of time of the follow-up spectroscopy is lost due to misidentifications.

The major weakness of this approach, however, is probably not the relatively low efficiency of the method, but the *a priori* selection of targets. This pre-selection severely biases the spectrographic observations and limits considerably the discovery space.

Imager and spectrograph

The ideal instrument is one which simultaneously performs both imaging and spectroscopy. The idea is to merge into one instrument the best of the two capabilities: for imaging it is field of view and high spatial resolution; and for spectrography it is high resolving power and large spectral range.

Such an instrument will overcome the difficulty inherent to the classical method. Because there is no longer the need to pre-select the sources, one can even detect objects that would not have been found or pre-selected in the pre-imaging observations. In the most extreme case, such as objects with very faint continuum but relatively bright emission lines, the objects can only be detected with this instrument, not with direct imaging techniques.

A simple computation shows that such an ideal instrument will necessarily need a lot of detector pixels. For example consider a spatial field of view corresponding to a standard 2048 × 4096 pixel detector and a wavelength range of 0.4–0.8 μm with a spectral resolution of 3000, which translate to 4000 spectral pixels. The total number of pixels is then 16×10^9. Given that some optics are needed in front of these pixels, one can immediately see the feasibility problem.

The Multi Unit Spectroscopic Explorer

The Multi Unit Spectroscopic Explorer (MUSE) for the ESO/VLT telescope is a major step towards this ideal instrument. MUSE is being studied and built by a consortium consisting of six major European institutes, at Lyon (PI institute, CRAL, France), Göttingen (IAG, Germany), Potsdam (AIP, Germany), Leiden (NOVA, Netherlands), Toulouse (LATT, France), Zurich (ETH, Switzerland) and ESO. It is an integral-field spectrograph (or IFU) which combines large field of view, high spatial resolution, medium resolving power and large simultaneous spectral range.

Nowadays, integral-field spectroscopy is part of the panoply of modern telescopes. However, most of the currently operating integral-field spectrographs have only a small field of view and are thus devoted to the detailed physical study of single objects. Some multi-IFUs, like Giraffe at the VLT (Pasquini et al. 2002), have multiplex capabilities of a dozen objects, which increase their efficiency. This however does not break the operational three steps (imaging, selection and spectrography) paradigm.

MUSE has three operating modes: a wide-field mode which can work with and without adaptive optics correction and a narrow-field mode with high spatial resolution. The observational parameters are given in Table 1.

The total number of information elements is given by the product of the number of spaxels[1] (90000) with the number of spectral pixels (4000), resulting in 360 million elements in the final data cubes. Such a large number of pixels is not feasible with a single piece of optics and a single detector. MUSE is thus composed of 24 identical modules, each one consisting of an advanced slicer, a spectrograph and a $(4k)^2$ detector. A series of fore-optics and splitting and relay optics derotates and splits the square field of view into 24 subfields. These are placed on the Nasmyth platform between the VLT Nasmyth focal plane and the 24 IFU modules. AO correction will be performed by the VLT deformable secondary mirror. Four sodium laser guide stars are used, plus a natural star for tip/tilt correction. All guide stars are taken outside the scientific field of view in order to minimise the amount of scattered light, while the only additional optic located within the scientific field of view is a revolutionary Na notch filter, reducing transmission losses with respect to traditional AO systems. This complex AO system is part of the general VLT AO facility (Arsenault et al. 2006). The part specific to MUSE is called GALACSI.

[1] Spatial elements (to be distinguished from detector pixels).

Table 1: MUSE Observational Parameters

Simultaneous spectral range	0.465–0.93 μm
Resolving power	2000 at 0.46 μm 4000 at 0.93 μm
Wide-Field Mode	
Field of view	1 × 1 $arcmin^2$
Spatial sampling	0.2 × 0.2 $arcsec^2$
Spatial resolution at 0.75 μm (median seeing)	0.46 arcsec (AO) 0.65 arcsec (non AO)
AO condition of operation	70th percentile
Sky coverage with AO	70 % at galactic pole 99 % at galactic equator
Limiting magnitude in 80 h	I_{AB} = 25.0 (full Res) I_{AB} = 26.7 (R = 180)
Limiting flux in 80 h	$3.9\ 10^{-19}$ erg s^{-1} cm^{-2}
Narrow-Field Mode	
Field of view	7.5 × 7.5 $arcsec^2$
Spatial sampling	0.025 × 0.025 $arcsec^2$
Spatial resolution at 0.75 μm (median seeing)	0.042 arcsec
Strehl ratio at 0.75 μm	5 % (10 % goal)
Limiting magnitude in 1 h	R_{AB} = 22.3
Limiting flux in 1 h	$2.3\ 10^{-18}$ erg s^{-1} cm^{-2}
Limiting surface brightness (mag)	R_{AB} = 17.3 $arcsec^{-2}$

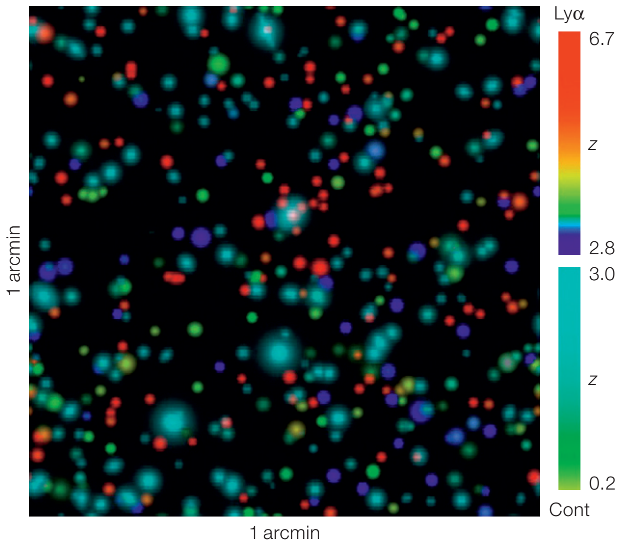
The MUSE narrow-field mode uses an additional optical system inserted into the fore-optics to change the spatial sampling from 0.2 arcsec to 0.025 arcsec. The field of view is proportionally reduced to 7.5 × 7.5 $arcsec^2$. The most significant change is in the AO optimisation and configuration (laser guide stars are moved closer) and the tip/tilt, which is performed at IR wavelengths on either a natural guide star within the field of view or the object itself. With such a configuration, the AO facility is expected to deliver a diffraction-limited image with a Strehl ratio of 5 % (goal 10 %) at 0.75 μm.

Science with the Wide-Field Mode

MUSE has a broad range of astrophysical applications, ranging from the spectroscopic monitoring of the Solar System's outer planets to very high-redshift galaxies. We give in the following sections a few examples of scientific applications that are considered to be important instrument drivers.

The most challenging scientific and technical application, and the most important driver for the instrument design, is the study of the progenitors of normal nearby galaxies out to redshifts $z > 6$. These systems are extremely faint and can only be found by their Lyα emission. MUSE will be able to detect these in large numbers (~ 15000) through a set of nested surveys of different area and depth (Figure 1). The deepest survey will require very long integration (80 hrs per field) to reach a limiting flux of 3.9×10^{-19} erg s^{-1} cm^{-2}, a factor of 100 times better than what is currently achieved with narrow-band imaging. These surveys will simultaneously address the following science goals:
- Study of intrinsically faint galaxies at high redshift, including determination of their luminosity function and clustering properties,
- Detection of Lyα emission out to the epoch of reionisation, study of the cosmic web, and determination of the nature of reionisation,
- Study of the physics of Lyman break galaxies, including their winds and feedback to the intergalactic medium,
- Spatially resolved spectroscopy of luminous distant galaxies, including lensed objects (Figure 2)
- Search of late-forming population III objects,

Figure 1: Simulated MUSE deep field. Galaxies are coloured according to their apparent redshift. Galaxies detected by their continuum (I_{AB} < 26.7 mag) and/or by their Lyα emission (Flux > 3.9 × 10^{-19} erg s^{-1} cm^{-2}) are shown.



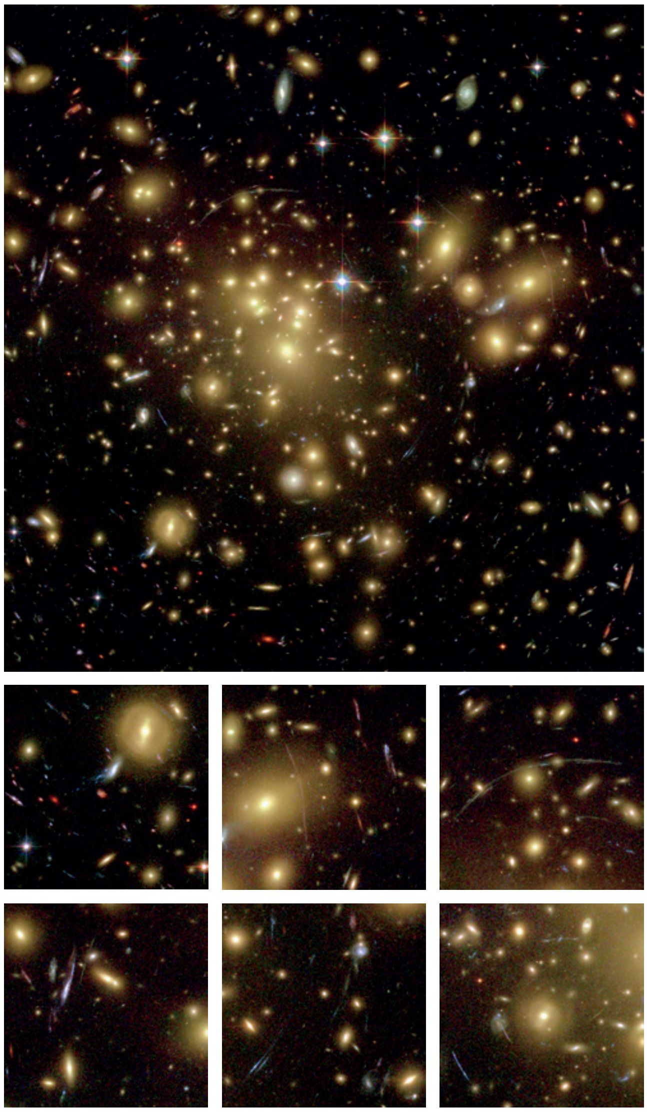
- Study of active nuclei at intermediate and high redshifts,
- Mapping of the growth of dark matter haloes,
- Identification of very faint sources detected in other bands, and
- Serendipitous discovery of new classes of objects.

Multi-wavelength coverage of the same fields by MUSE, ALMA, and JWST will provide nearly all the measurements needed to answer the key questions of galaxy formation.

At lower redshifts, MUSE will provide exquisite two-dimensional maps of the kinematics and stellar populations of normal, starburst, interacting and active galaxies in all environments, probing sub-kiloparsec scales out to well beyond the Coma cluster. These will reveal the internal substructure, uncovering the fossil record of their formation, and probe the relationship between super massive black holes and their host galaxies (Figure 3).

MUSE will enable massive spectroscopy of the resolved stellar populations in the nearest galaxies, outperforming current capabilities by factors of over 100. This will revolutionise our understanding of stellar populations, provide a key complement to GAIA studies of the Galaxy, and a preview of what will be possible with an ELT (Figure 4).

Figure 2: An HST-ACS image of the lensing cluster Abell 1689 (Broadhurst et al. 2005). This cluster is a prime candidate for strong lensing studies with MUSE, given its very large Einstein radius, and the large number of arcs identified. Broadhurst et al. identified at least seven systems which were multiply imaged. The upper panel shows the full image, the lower panels show some of the strongly lensed galaxies.



Science with the Narrow-Field Mode

In contrast to the Wide-Field Mode, the Narrow-Field mode science is dedicated to detailed studies of single objects at very high spatial resolution. We give in the following a few examples.

The study of supermassive black holes: During galaxy mergers, supermassive black holes sink to the bottom of the potential well, forming binary systems which 'scour out' lower-density cores in the central regions of the remnant. Such processes should leave detectable signatures in the environment of the SMBH. Likewise, accretion of mass onto supermassive black holes should trigger activity and feedback to the local regions and beyond. However, observationally very little is known about this environment, either in terms of stellar orbital structure or chemical enrichment history.

Young stellar objects: The key contribution from MUSE will be both in spectral grasp (covering key diagnostics of density, temperature and ionisation) and the ability to provide very high spatial resolution over a relatively large field of view. This will allow the physical processes involved in the formation and structure of the jets to be investigated in detail.

Solar System: MUSE NFM would allow observations of various bodies within our Solar System at a spatial resolution approaching that of more costly space

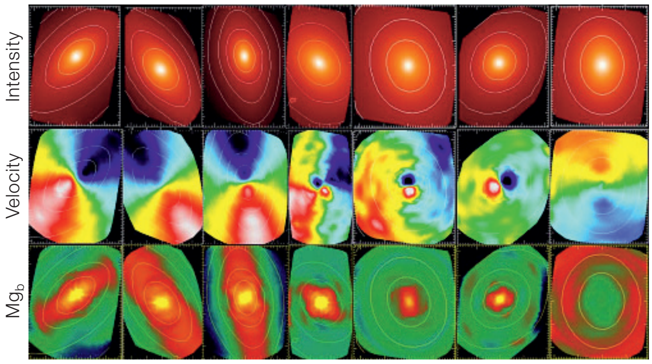


Figure 3: Selection of nearby early-type galaxies observed with SAURON (de Zeeuw et al. 2002). Top row shows the reconstructed images, which are regular and smooth. The middle row shows the velocity field, and the bottom row shows the distribution of Mg_b absorption strength. MUSE will be able to expand this pilot study at larger distance and in different cluster environments.

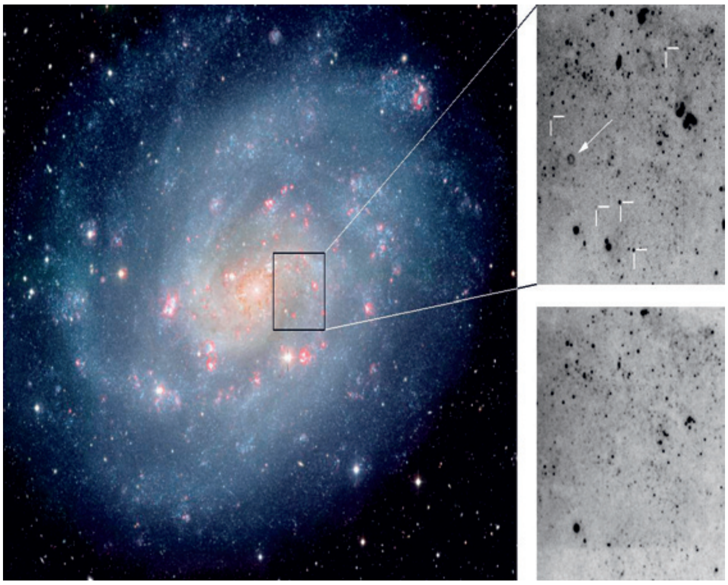


Figure 4: Left: Composite image of the southern spiral galaxy NGC 300, illustrating the power of massive spectroscopy with MUSE. The frames to the right are a narrowband [O III] 5007 exposure (top), and a corresponding nearby continuum exposure (bottom), obtained with the NTT over a FOV of 2.2 × 2.2 $arcmin^2$ (Soffner et al. 1996). MUSE will cover the same field in a total of four exposures. Unlike the narrowband imaging example, the MUSE data cube will provide full spectral information for each spatial element, with a huge discovery potential for massive stars, super bubbles, H II regions, PNe, SNRs, novae – virtually the full inventory of the stellar and gaseous constituents of the galaxy.

missions. Applications are: monitoring volcanic activity on the Galilean satellites, spectral monitoring of Titan's atmosphere, global monitoring of the atmospheres of Uranus and Neptune, internal structure and composition of comets and mineralogical surface heterogeneities of asteroids.

Opto-mechanical concept

The opto-mechanical concept has to fulfil the following challenging requirements:
– Replication of modules at low cost in order to achieve the required number of spatial and spectral elements.
– High throughput despite the required number of optical surfaces
– High image quality in order to optimally use the image quality delivered by the AO facility
– High stability and reliability over long exposures
– Maintain cost, mass and volume

The 24 IFUs are central to MUSE. They have been designed to achieve an excellent image quality (85 % enclosed energy within 15 × 30 μm^2 in the detector plane), and make use of innovative slicer and spectrograph concepts. The slicer is based on a two-mirror compact design, suitable for diamond machining (Figure 5 and 6). Recent progress of the manufacturing process has enabled high-precision metal surfacing with good surface roughness (3 nm rms). Such mirrors are now compatible with optical wavelength requirements and are much more cost effective than other approaches for the large-scale production foreseen for MUSE. The compact spectrograph design achieves an excellent image quality over the large spectral bandwidth of MUSE. In this design, the tilt of the detector compensates for the axial chromatism, which then does not need to be corrected optically. This is a cost-effective solution, avoiding the use of expensive optical materials, e.g. CaF2.

To maintain a high throughput (40 % for the whole instrument) despite the relatively large number of required surfaces, attention is paid to use state-of-the-art transmission and reflection coatings. Detectors are 4k × 4k 15 µm deep depletion devices with improved quantum efficiency in the red. Furthermore we will use new volume phase holographic gratings with a high efficiency over the large (one octave) spectral range.

To simplify the interfaces between GALACSI and MUSE, all AO components, including the tip/tilt sensor, are mounted in the Nasmyth derotator. There is therefore a risk of misalignment of the AO

Figure 5: Each MUSE slicer consists of four stacks of 12 slit-mirror arrays (right side of the figure) and four stacks of 12 pupil-mirror arrays (left side). This gives a total of 2304 spherical mirrors for the full instrument.

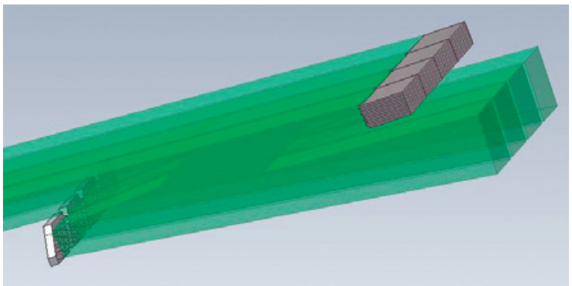
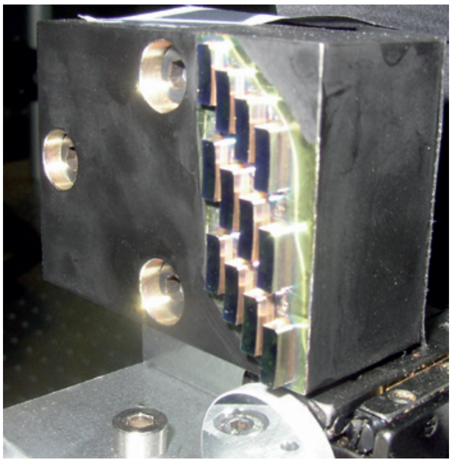
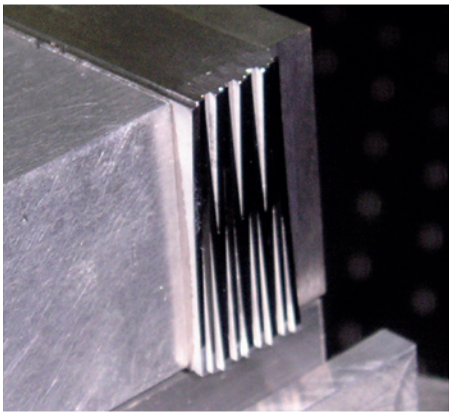


Figure 6: Breadboard slit (bottom) and pupil mirror array (top) in test at CRAL.





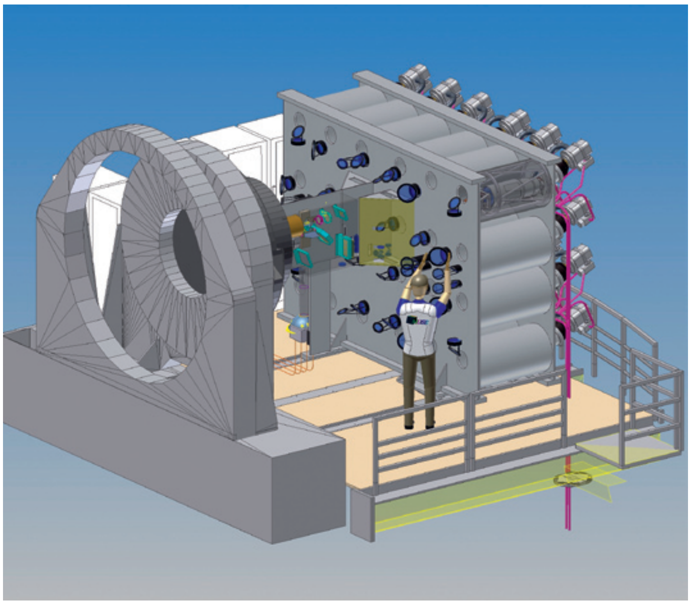


Figure 7: General view of MUSE at the VLT Nasmyth platform.

reference system with respect to MUSE, which is located on the platform. To mitigate this risk and to maintain the optical axis within the tight tolerances required by the spatial performances and stability, a metrology system has been designed. It is a closed-loop system based on four reference light sources located in the fore-optics and imaged into the AO system.

The cryogenic system is based on pulse tubes, which are compact and which avoid refilling 24 dewars with liquid nitrogen. The accompanying compressors are located outside the Nasmyth platform on the telescope floor to avoid any possible transmittance of vibrations onto the instrument.

The instrument weight is approaching eight metric tons in total and its size will fill basically the entire volume of the Nasmyth platform of roughly 50 m^3. This is bigger than every instrument that has been built so far for the VLT and will make MUSE an impressive instrument (Figure 7 and 8). With these dimensions, assembling and providing the necessary access to all the components is a challenge. The main instrument structure is designed as a single unit to fulfil the highly demanded stability of all optical components with respect to each other in order to maintain the superb image quality given by GALACSI on long exposures.

The latter is done with a complex optical system that has to derotate and to split the observing field and to distribute and feed the spectrographic units with these sub-fields. Despite its 24 spectrographs mounted into a monolithic structure, MUSE will act as a single instrument with respect to the telescope and the AO system. Nevertheless, the instrument is set up with a highly modular character for the assembly, maintenance and any operational exchange.

Operations and data reduction

Despite its impressive number of opto-mechanical elements, MUSE will be easy to operate. There are no moving parts in the 24 modules and the switch between wide to narrow-field mode implies only the addition of some optics within the fore-optics train. MUSE has only three operating modes: non-AO and AO wide field mode, and AO narrow-field mode. The three modes differ only by the presence of AO and the spatial sampling. In the wide-field non-AO mode, operations will be limited to the simple point-and-shoot scheme. In the other modes, the complexity is related to the operations of AO including the lasers. All modes share the same spectroscopic configurations (wavelength range and resolution).

On the other hand, with 1.6 Gb per single exposure, the data reduction is a challenge, not only because of this data volume, but also because of its 3D characteristics. The handling of such large data cubes is not straightforward. As an example, one can mention the optimal summation of a series of data cubes obtained with AO and different atmospheric conditions. This is intrinsically a 4-dimensional problem because the AO-delivered PSF changes with time, location within the field of view, and wavelength.

Project status

The project is currently in its preliminary design phase. In July 2006, the optical preliminary design review will be the starting point for the manufacturing of a complete breadboard consisting of a slicer, a spectrograph and a detector, while the full preliminary design review is scheduled for early 2007. Results of the breadboard will be analysed for the final design review in July 2008. Manufacturing, assembly and integration will then take place up to mid 2011. First light is scheduled on Paranal in early 2012.

Conclusions

Astronomy is to a significant degree still driven by unexpected discovery (e.g. dark matter and dark energy). These discoveries are often made by pushing the limit of observations with the most powerful telescopes and/or opening a new area of instrumental parameter space. MUSE is designed to push the VLT to its limit and to open a new parameter space area in sensitivity, spatial resolution, field of view and simultaneous spectral coverage. We are convinced that it fulfils all the required conditions to have a large potential of discoveries:
- It will be the first spectrograph that can blindly observe a large volume of space, without any imaging pre-selection.
- It will be the first optical AO-assisted IFU working at improved spatial resolution in most atmospheric conditions with large sky coverage.

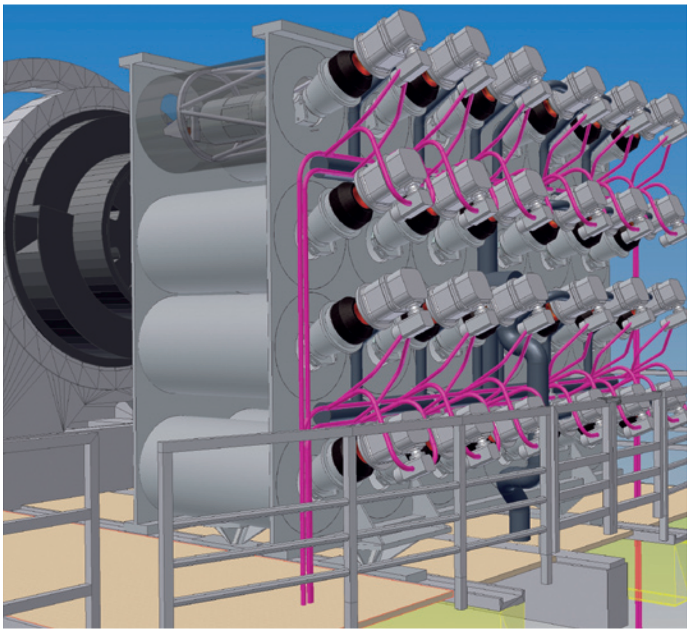


Figure 8: MUSE view from the back of the Nasmyth platform. One can see the 24 spectrograph cameras and the cryogenic systems.

- It will be the first spectrograph optimised to work with very long integration times and to reach extremely faint emission-line detection.

MUSE will thus be able to discover objects that have measurable emission lines, but with a continuum that is too faint to be detected in broad-band imaging. For example, the deepest broad-band imaging available today is the HST Ultra Deep Field (UDF) with $I_{AB} < 29$. According to CDM simulations, however, only 15 % of MUSE high-z Lyα emitters ($z > 5.5$) will have a continuum bright enough to be detected in the UDF. MUSE is also the only instrument capable of detecting faint diffuse ionised gas, like extended halos or filaments. Finally, objects with unusual spectral features should also be detected by MUSE, whatever their broad-band magnitude and colours are. The unprecedented capabilities of MUSE should also lead to discoveries far away from our present expectations.

In many aspects, MUSE is a precursor of future ELT instrumentation. For example, manufacturing, integration and maintenance of a large number of identical, high-performance optical systems at low cost and on reasonable time scale will be a critical aspect for most of the ELT instruments.

Acknowledgements

MUSE is funded by ESO and the following funding agencies and Universities:
- The *Institut National des Sciences de l'Univers* (INSU) of CNRS, the University Claude Bernard Lyon I, the University Paul Sabatier Toulouse III and the *Ministère de la Recherche et de la Technologie* for the French participation
- The *Verbundforschung* of the Federal Ministery for Education and Research (BMBF), managed by PT-DESY, by the Astrophysical Institut Potsdam and by the University of Göttingen for the German participation
- The Netherlands Research School for Astronomy (NOVA) and the Netherlands Organisation for Scientific Research (NOW) for the Dutch participation
- The Swiss Federal Institute of Technology Zürich (ETH) and the Swiss National Science Foundation through the FINES fund for the Swiss participation

A dedicated integration hall for MUSE will be build at CRAL. This building is funded by the *Région Rhône-Alpes*, the CNRS, the city of Lyon, the *Ministère de la Recherche et de la Technologie*, the University Claude-Bernard Lyon I, the Grand Lyon, the town of Saint-Genis-Laval and the Rhône department.

MUSE public web site: *http://muse.univ-lyon1.fr*

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