KMOS: an infrared multiple object integral field spectrograph for the ESO VLT

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ABSTRACT

We describe the design of a 2nd generation instrument for the ESO VLT which will deliver a unique multiple deployable integral field capability in the near-infrared (1-2.5µm). The science drivers for the instrument are presented and linked to the functional specification. The baseline instrument concept is described with emphasis on technological innovations. Detailed discussions of specific technologies, and ongoing prototype studies, are described in separate papers.

Keywords: Integral field spectrographs, multiple object spectroscopy, infrared spectrographs

1. INTRODUCTION

KMOS is a near-infrared multi-object integral-field spectrometer which has been selected by the European Southern Observatory (ESO) as one of a suite of second-generation instruments to be constructed for the Very Large Telescope (VLT) at the Paranal Observatory in Chile. The instrument will be built by a consortium of UK and German institutes working in partnership with ESO. The instrument has evolved through a series of design and tradeoff studies[1, 2] aimed at finding the optimal technical approach to maximize scientific productivity whilst controlling risk and delivering reliability in operations. In this paper we describe the baseline concept (known as KMOS-1) developed during the Phase A design studies conducted over the past 18 months.

2. SCIENCE CASE AND DESIGN REQUIREMENTS FOR KMOS-1

Within the next few years it is likely that photometric redshifts, allied with deep wide-angle optical-IR surveys and the current generation of wide-field instruments at large telescopes, will provide distances to unprecedented numbers of young galaxies in the range $1<z<5$.[3] These large redshift surveys will be capable of determining the global properties of the galaxy population such as its luminosity evolution and three-dimensional clustering. The next logical steps will be to investigate the physical processes which drive galaxy formation and evolution over this redshift range and to differentiate between the intrinsic and environmental processes acting on galaxies. To achieve these goals requires a capability to map the variations in star formation histories, spatially resolved star-formation properties, merger rates and dynamical masses of well-defined samples of galaxies across a wide range of environments - stretching from the cores of the richest, highest density clusters out to the low density field - at a series of progressively earlier epochs. A few of the brightest examples[4] are now being observed using single integral field unit (IFU) spectrographs on 8-metre telescopes (Fig. 1) but a statistical survey of these galaxy properties will require a multi-object approach. This is the capability which will be delivered to the VLT with KMOS-1.

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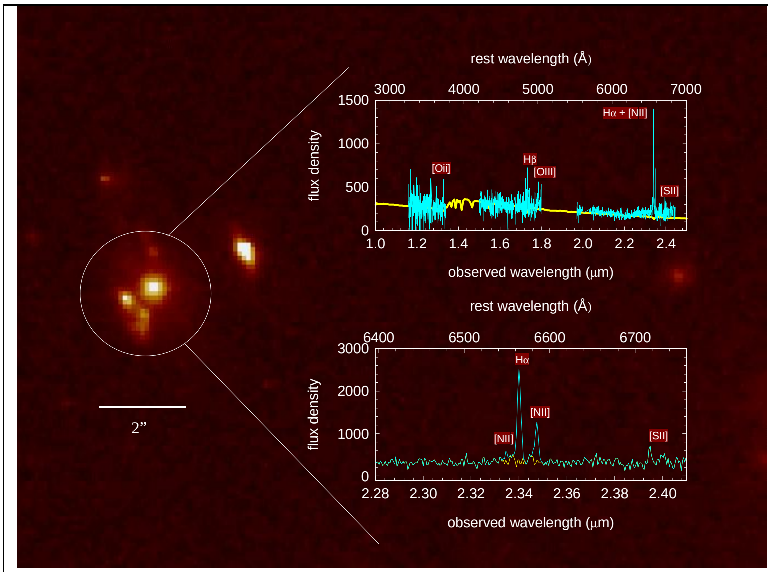

Figure 1: SPIFFI[5] spectra of the central 2.5” of the submillimetre galaxy SMM J14011+0252 centred on source J1c. *Upper spectrum:* JHK spectrum showing a typical starburst emission-line spectrum. *Lower spectrum:* zoom into the region around Hα emission showing the narrow line widths, with a blueshifted residual wing that is probably due to a superwind. The line ratios suggest that SMM J14011+0252 has probably been forming stars for several hundred Myrs.[4]

For any instrument to address these fundamental questions about how galaxies evolve it needs to possess several generic characteristics: (1) high-redshift galaxies are faint, so to take advantage of precious 8-m time the instrument should have a substantial multiplex capability, commensurate with the surface density of accessible targets; (2) to understand the physical properties of galaxies and because galaxies are often complex morphologically (with unpredictable emission-line characteristics) it should have the ability to obtain more than just integrated or one-dimensional information; (3) to measure the physical growth of galaxies it should be able to resolve relatively small velocities observed in their rotation curves, velocity dispersions, and relative galaxy velocities in merging pairs; (4) to be able to observe merging galaxies and high redshift cluster galaxies efficiently it should have the ability to observe several targets concentrated in a small area of sky; (5) to take advantage of the large amount of empirical and theoretical information on the optical properties of galaxies, and to gauge more accurately the evolution in the galaxy population, it is essential that the instrument has the capability to observe high-redshift galaxies using the well-studied rest-frame optical diagnostic features used at low redshift. These general characteristics suggest a near-infrared multi-object spectrograph using deployable integral field units (dIFUs).

In addition to the capability of mapping objects with complex continuum and emission line morphologies, the use of IFUs also enables a higher S/N to be achieved on extended sources and opens up the possibility of deep 3D surveys for emission-line objects. With the capability to cover the *J*, *H*, and *K* bands, such a spectrograph would allow for the investigation of the rest-frame optical properties of galaxies over the redshift range of approximately $0.7 < z < 5.3$ and to make the first systematic explorations of the very high redshift universe $z>7$ by blind spectroscopic area surveys for Ly-α emitters[6]. Moreover, in the crucial redshift range $1.2<z<2.5$, where the morphologies of present-day galaxies emerge, important emission lines are only accessible in the near-infrared.

We have investigated in detail a number of observational programmes which exploit these general capabilities in order to determine a specific set of baseline design characteristics which any instrument delivering these capabilities should strive to meet. A summary of these scientific cases is given in Table 1 and the derived design characteristics in Table 2.

Table 1: Reference scientific cases for the KMOS-1 instrument

Science Case	**Scientific Area**
Cluster/group formation and the morphology-density relation	Extragalactic Astronomy/Cosmology
The masses and growth of galaxies	Extragalactic Astronomy/Cosmology
Extremely high-redshift galaxies and re-ionisation	Cosmology
The connection between galaxy formation and active galactic nuclei	Cosmology
Age-dating at z = 2 to 3	Cosmology
Stellar populations in nearby galaxies	Extragalactic Astronomy
High-mass star formation	Galactic Astronomy
A complete survey of star-forming molecular clouds	Galactic Astronomy

Table 2: Baseline capabilities for the KMOS-1 instrument.

Requirement	**Baseline Design**
Instrument Throughput	J=30%, H=40%, K=40%
Sensitivity (5σ, 8hrs)	J=22.0, H=21.0,K=20.5
Wavelength coverage	1.0 to 2.45 μm
Spectral Resolution	R=3380,3800,3750 (J,H,K)
Number of IFUs	24
Extent of each IFU	2.8 x 2.8 sq. arc seconds
Spatial Sampling	0.2 arc seconds
Patrol field	7.2 arcmin diameter circle
Close packing of IFUs	≥3 within 1 sq arcmin
Closest approach of IFUs	≥3 pairs of IFUs separated by 6 arcsec

3. INSTRUMENT DESCRIPTION

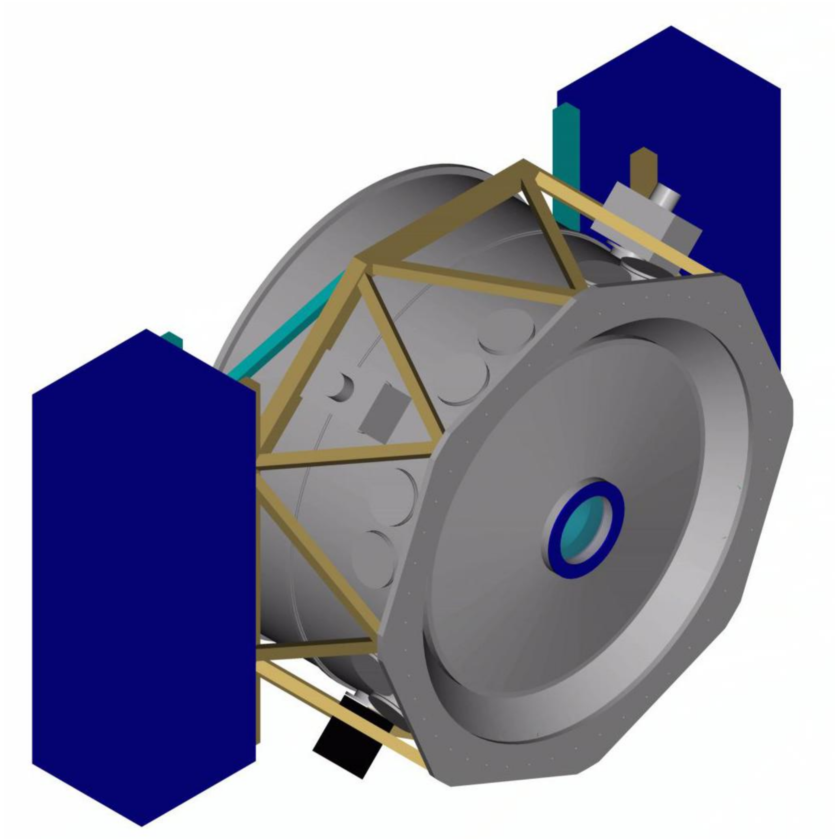

Figure 2: Exterior view of the KMOS-1 cryostat and electronics cabinets mounted at the VLT Nasmyth focus.

KMOS-1 will mount on the VLT Nasmyth rotator (Fig. 2) and will use the Nasmyth A&G facilities. The top-level requirements are: (i) to support spatially-resolved (3-D) spectroscopy; (ii) to allow multiplexed spectroscopic observations; (iii) to allow observations across the *J*, *H*, and *K* infrared atmospheric windows (extension to shorter wavelengths will be incorporated at lower priority). The baseline design employs 24 configurable arms that position fold prisms at user-specified locations in the Nasmyth focal plane (Fig. 3). The sub-fields thus selected are then fed to 24 advanced image slicer[7] IFUs that partition each sub-field into 14 identical slices, with 14 spatial pixels along each slice. Light from the IFUs is dispersed by three cryogenic grating spectrometers which generate 14x14 spectra with ~1000 Nyquist-sampled spectral resolution elements for each of the 24 independent sub-fields. The spectrometers each employ a single 2kx2k HgCdTe detector. Our goal is to employ careful design choices and advances in technology to ensure that KMOS-1 achieves a comparable sensitivity to the current generation of single-IFU infrared spectrometers.

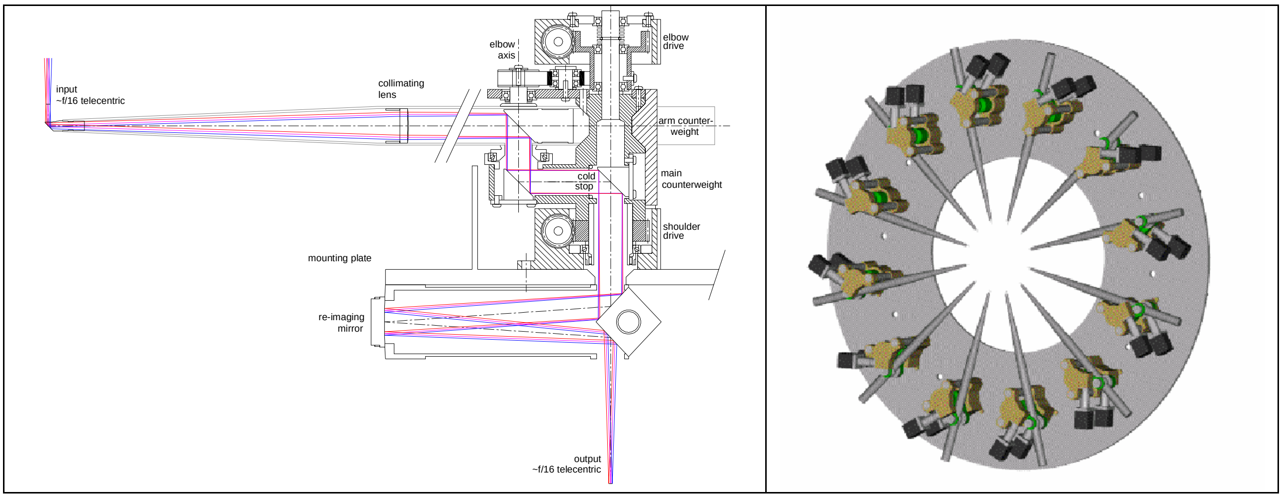

Figure3: *Left:* Mechanical design and optical path through a KMOS-1 pickoff arm; *Right:* Layout of one of the two layers of 12 pickoff arms.

The patrol field of the pickoffs is 7.2 arcmin in diameter, which is the diameter of the unvignetted field at the VLT Nasmyth focus, thus minimising the thermal background in the K-band. Each IFU has a square field of view of 2.8x2.8 arcsec; anamorphic magnification in the IFU foreoptics ensures uniform spatial sampling of 0.2x0.2 arcsec whilst maintaining Nyquist sampling of the spectral resolution element at the detector. Experience with single element IFUs indicates that this pixel size is a good compromise for faint objects even in excellent seeing conditions (i.e. < 0.4 arcsec) since significantly smaller pixels would likely make it difficult to detect low surface brightness extended features.

The field of view for each IFU is large enough to allow local sky-subtraction for compact high-redshift targets, doubling the effective multiplex gain over systems which would have required beam-switching. A crossed beam-switching mode is also possible for multiple extended sources or for critical applications which require minimal systematic effects. The use of focal-plane pickoffs allows considerable flexibility in selecting targets and the important capacity to deal with strongly clustered or close-paired sources. In addition to observing multiple individual sources, KMOS-1 will also have the capability for integral field mapping of contiguous areas (~1.0 sq. arcmin) in a 16-point dither pattern. This mode is useful for very extended sources or blank-field surveys. The three spectrographs may be configured independently to allow simultaneous observations (of different targets) in the J, H or K bands. The spectral resolution of R~3500 provides velocity resolution for studies of low-mass objects and is optimal for OH-avoidance in the J & H bands. Lower resolution modes will allow simultaneous J+H or H+K observations. Since we cannot predict all science applications in the future, our goal is to make KMOS-1 as versatile as possible without compromising reliability or increasing complexity significantly.

From a hardware perspective the instrument partitions into the following key subsystems (Fig. 4):

- Pickoff subsystem
- IFU subsystem
- Spectrograph subsystem
- Detector subsystem

Each of these is mechanically supported, and cooled, by an annular optics bench that is enclosed in a vacuum chamber which mounts onto the Nasmyth flange (Fig. 2). The estimated total weight of the instrument is 2200kg with a mass moment of 1750 kg m.

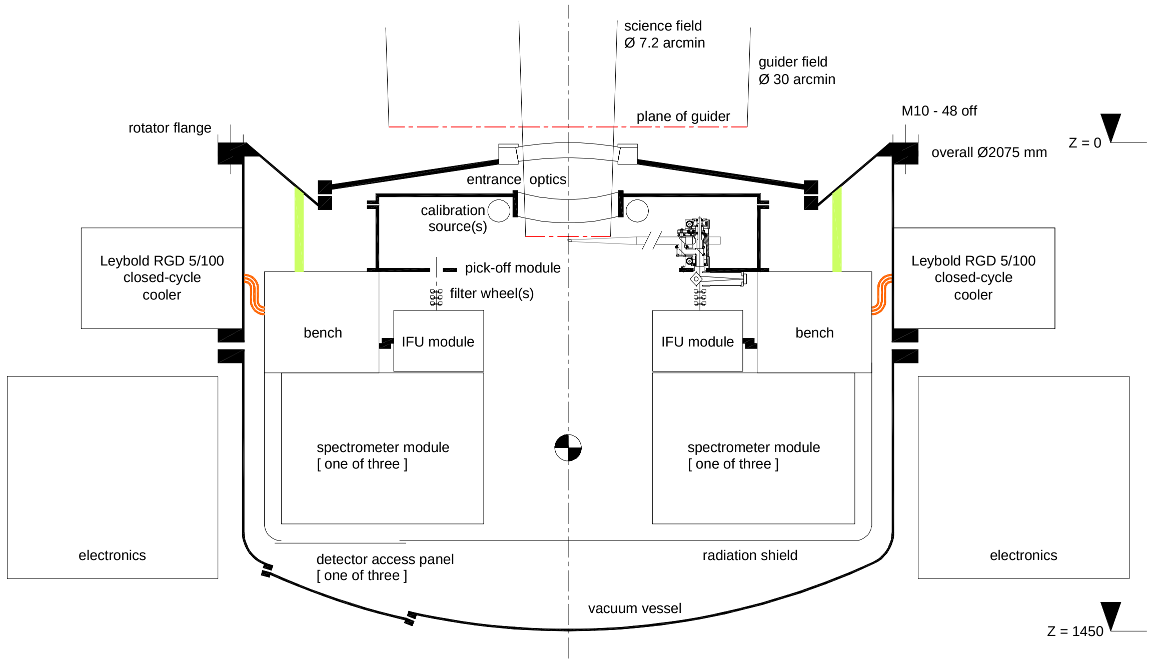

Figure 4: Cross-sectional schematic view of KMOS-1 looking down towards the Nasmyth platform. The vacuum vessel is cylindrical with its axis of symmetry aligned with the Nasmyth axis. The electronics racks are supported from the Nasmyth rotator flange by a framework (not shown) which is independent of the vacuum vessel. The annular bench carries all the cooled subsystems and is supported from the rotator flange by a thermally insulated truss structure.

The *pickoff subsystem* contains fore-optics to produce a flat, telecentric Nasmyth focal plane, the set of configurable carbon-fibre arms driven by cryogenic stepper-motors which pick off the required sub-fields of the 7.2 arcmin diameter Nasmyth field, and optics/mechanisms to filter the resultant output beams. In addition, the sub-system houses a calibration unit that provides the ability to verify and calibrate the end-to-end performance of the instrument. The availability of a flat, telecentric focal plane allows the arms to patrol in one of two planes perpendicular to the optical axis and minimizes contention of the arms during object acquisition. The use of robotically controlled pickoff arms to select the sample of multiple objects for IFU spectroscopy is one of the more novel aspects of the KMOS-1 design. Positioning systems of this type offer the versatility required to address the science programmes listed in Table 1 and the capacity to engage entirely new areas of study which will undoubtedly be developed in the next 5-10 years. Prototyping of the carbon-fibre arm technology has been undertaken via the POPS project (Precision Optical Pickoff System) funded through the UK PPARC Industrial Support Scheme. The goals of the POPS project were (i) to demonstrate the use of carbon fibre in a cryogenic environment; (ii) to confirm that tight tolerances on positioning and alignment can be met and maintained; (iii) to develop an industrial link to investigate manufacturing issues for a significant numbers of arms. The first phase of this project is now complete and has demonstrated that the basic positioning accuracies required can be achieved in both warm and cryogenic operation. The cryogenic mechanisms employed have demonstrated high reliability and have been the subject of extensive technology tests described in an accompanying paper[8].

The *IFU subsystem* contains optics that collect the output beams from each of the 24 pickoffs and reimages them with appropriate anamorphic magnification onto the image slicers. The slices from groups of 8 sub-fields are aligned and reformatted into a single slit for each of the three spectrographs. The IFU sub-system has no moving parts and has gold-coated surfaces diamond-machined from aluminium for optimal performance in the near-infrared and at cryogenic temperatures. The design and manufacture of the IFUs draws heavily on experience we have developed in building other cryogenic integral-field spectrometers, in particular for the GNIRS IFU for Gemini South, and is described more fully elsewhere.[9, 10]

The *spectrograph subsystem* is comprised of three identical units, which supply three detector sub-systems. Each spectrograph uses a single off-axis toroidal mirror to collimate the incoming light, which is then dispersed via a reflection grating and refocussed using a 6-element transmissive achromatic camera. The gratings are mounted on a 6-position turret which allows optimized gratings to be used for the individual J,H,K bands together with two lower resolution gratings and the option of a z-band grating to enhance versatility. A full description of the KMOS-1 spectrograph design is given in an accompanying paper[11].

The *detector subsystem* is comprised of three units, which house identical 2048x2048 HgCdTe arrays with 18 micron pixels. Each detector is mounted on a three-axis translation stage in order that focus can be adjusted and, if required, some components of flexure can be compensated.

In use at the telescope, KMOS-1 will be a complex instrument requiring high-level software control and pipelined data analysis. We have studied extensively the operations requirements including field setup, acquisition, calibration and data reduction, building on our extensive experience with commissioning the SPIFFI(VLT)[5], GNIRS(Gemini)[9] and UIST(UKIRT)[12] integral field spectrometers within the past 18 months.

4. CURRENT STATUS

The KMOS project is currently at end of the final downselect stage for the instrument concept and will begin Phase B (Preliminary Design Phase) in July 2004. The key milestones for the project are listed in Table 3. Commissioning at Paranal Observatory will begin in 2009.

Table 3: Key milestones for KMOS-1

Key Milestone	Provisional Date
Phase B Start	July 2004
Preliminary Design Review	July 2005
Final Design Review	June 2006
Start Assembly Integration Verification Phase	April 2008
European Acceptance	March 2009

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