Surveying the High-Redshift Universe with KMOS

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KMOS is a near-infrared multi-object integral-field spectrometer which has been selected by ESO as one of a suite of second-generation instruments to be constructed for the VLT. The instrument will be built by a consortium of UK and German institutes working in partnership with ESO and is currently in the preliminary design phase. KMOS will be capable of obtaining simultaneous spatially resolved spectroscopy at a sampling of 0.2 arcseconds for up to 24 targets distributed over a field of view of 7.2 arcminutes diameter.

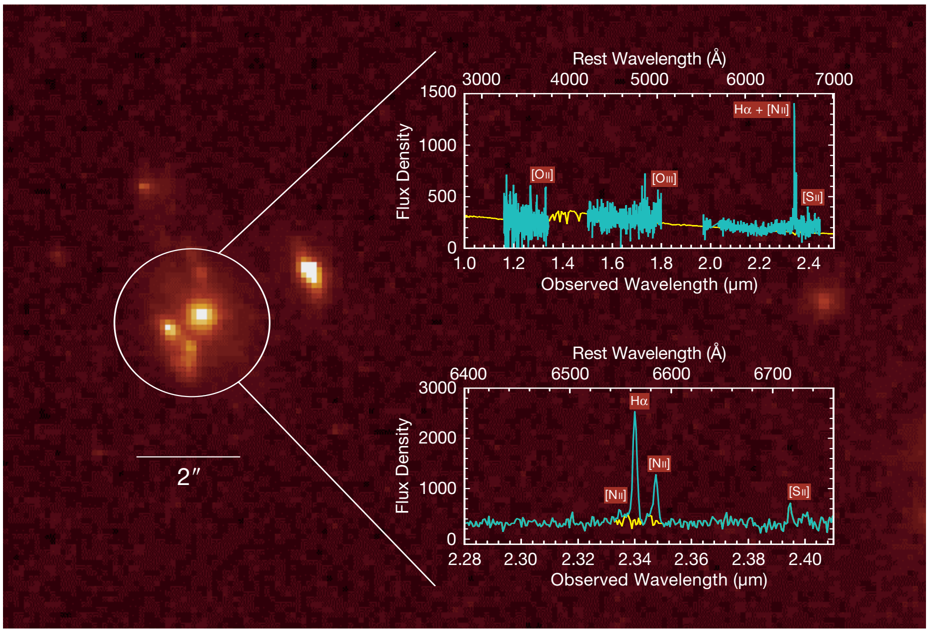
The past decade has seen remarkable progress in cosmology, with the combination of measurements from microwave background experiments and large-scale redshift surveys placing precise constraints on many of the fundamental parameters of the cosmological world model. Photometric selection techniques and gravitational lensing have opened up the universe beyond $z = 1$ and allowed the detection of massive star-forming galaxies which must have formed within a few billion years of the Big Bang. The precise details of the physical processes which drive galaxy formation and evolution in these models remain elusive however. To study these processes in detail requires a capability to map the variations in star-formation histories, merger rates and dynamical masses for well-defined samples of galaxies across a wide range of redshifts and environments. Single-integral-field-unit (IFU) spectrographs like SINFONI/SPIFFI are beginning to provide exquisite views of some of the most spectacular examples (e.g. Figure 1) but statistical surveys of these galaxy properties, and follow-up of future surveys of high-redshift galaxies obtained, for example, with HAWK-I and SCUBA-2, will require a spectrograph that can observe many objects simultaneously. This is the capability which will be delivered by a new instrument now under development known as KMOS (*K*-band Multi-Object Spectrograph) which, when commissioned on the VLT in 2010, will be unique on any 8-metre-class telescope.

For any instrument to address these fundamental questions about how galaxies evolve it should: (1) have a substantial multiplex capability and field of view, commensurate with the surface density of accessible targets; (2) have the ability to obtain more than just integrated or one-dimensional information since forming galaxies are often observed to have complex morphologies; (3) be able to resolve the relatively small velocity differences observed in rotation curves, velocity dispersions, and merging galaxy pairs; (4) have the ability to observe several targets in proto groups and clusters concentrated in small areas of the field; (5) enable observations of high-redshift galaxies using the well-studied rest-frame optical diagnostic features used at low redshift. These general characteristics imply a near-infrared multi-object spectrograph using deployable integral field-units (d-IFUs). Deployable IFUs also have a significant advantage over multi-slit spectrographs because of the reduced slit contention in crowded fields and their insensitivity to galaxy morphology and orientation. The specific choices made to deliver these capabilities involve a complex trade of cost and scope which is reflected in the baseline capabilities of KMOS listed in Table 1.

Requirement	Baseline Design
Instrument throughput	$J = 20\%$, $H = 30\%$, $K = 30\%$
Sensitivity (5 σ, 8 hrs)	$J = 21.2$, $H = 21.0$, $K = 19.2$
Wavelength coverage	1.0 to 2.5 µm
Spectral resolution	R = 3400, 3800, 3800 (*J*, *H*, *K*)
Number of IFUs	24
Extent of each IFU	2.8 × 2.8 arcseconds
Spatial sampling	0.2 × 0.2 arcseconds
Patrol field	7.2 arcmin diameter circle
Close packing of IFUs	> 3 within 1 arcmin^2
Closest approach of IFUs	edge-to-edge separation of 6 arcsec

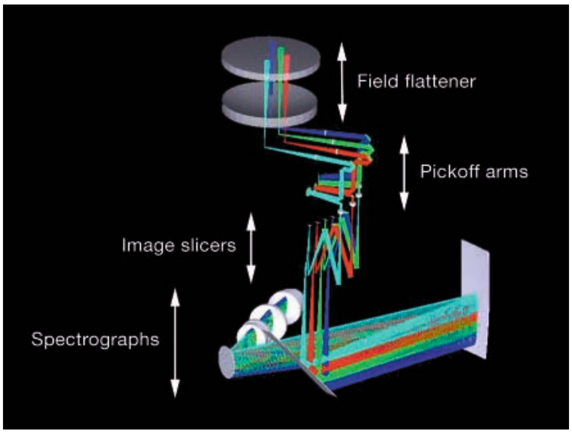
Table 1: Baseline design specification for the KMOS spectrograph.

Figure 1: SPIFFI spectra of the central 2.5″ of the submillimetre galaxy SMM J14011+0252 showing the often complex morphology of these targets (from Eisenhauer et al. 2003).



KMOS will be mounted on the VLT Nasmyth rotator 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 may be incorporated). The baseline design employs 24 configurable arms that position fold mirrors at user-specified locations in the Nasmyth focal plane, each of which selects a sub-field of 2.8 × 2.8 arcseconds. The size of the sub-fields is tailored specifically to the compact sizes of high redshift galaxies. The sub-fields are then anamorphically magnified onto 24 advanced image slicer 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 identical cryogenic grating spectrometers which generate 14 × 14 spectra, each with ~ 1000 Nyquist-sampled spectral resolution elements, for all of the 24 independent sub-fields. The spectrometers will each employ a single 2k × 2k Hawaii-2RG HgCdTe detector. The optical layout for the whole system has a threefold symmetry about the Nasmyth optical axis allowing a staged modular approach to assembly, integration and test. End-to-end raytraces through four of the pickoff arms in one of the three spectrometers are shown in Figure 2. Our goal is to employ careful design choices and advances in technology to ensure that KMOS achieves a comparable sensitivity to the current generation of single-IFU infrared spectrometers and gains at least an order of magnitude in survey speed for typical target fields.

Figure 2: Optical raytrace through four pickoff arms, their associated IFUs and one of the spectrometers. Light exiting the pickoff arms is brought to an intermediate focus using a 3-element *K*-mirror, which aligns the edges of all 24 IFU fields on the sky so that they can be put into a compact sparse array configuration for blind surveys of contiguous areas on the sky.



Pickoff module

One of the more unusual KMOS elements is the pickoff module which relays the light from 24 selected regions distributed within the patrol field to an intermediate focus position at the entrance to the integral-field-unit module. The method adopted for selecting these subfields uses robotic pick-off arms whose pivot points are distributed in a circle around the periphery of the patrol field and which can be driven in radial and angular motions by two stepper motors which position the pickoff mirrors with a repeatable accuracy of < 0.2 arcsec. The arms patrol in one of two layers positioned either side of the Nasmyth focal plane to improve the access to target objects in crowded fields. This focal plane is flattened and made telecentric by a pair of all-silica field lenses, one of which forms the entrance window to the cryostat. The arm design has been refined to allow maximum versatility in allocation of targets whilst achieving stringent goals on accuracy and reliability. Independent monitoring of arm positions to avoid collisions will be available using both step counting and position encoders; a collision-detection sensor will also be implemented as a third level of protection. The efficiency of allocation has been benchmarked against several real target fields selected from deep imaging surveys; Figure 3 shows one such configuration with the arms overlaid on a sample of high-redshift targets selected from the FORS Deep Field (Noll et al. 2004).

The changing path length within the arm is compensated via an optical trombone which uses the same lead screw, but with a different pitch, as for the main radial motion. The pickoff module also contains the instrument calibration unit and a filter wheel which acts as a focus compensation device between the different bands. The cold stop for the instrument is at the base of the arm, after which an intermediate image is formed by a *K*-mirror assembly which also acts to orientate the pick-off fields so that their edges are parallel on the sky. A prototype pickoff arm is currently being manufactured, which will be subject to an extensive series of tests in a cryogenic environment before manufacturing the full batch of 24 arms. A solid model of one of the pickoff arms, together with its patrol space envelope, is shown in Figure 4.

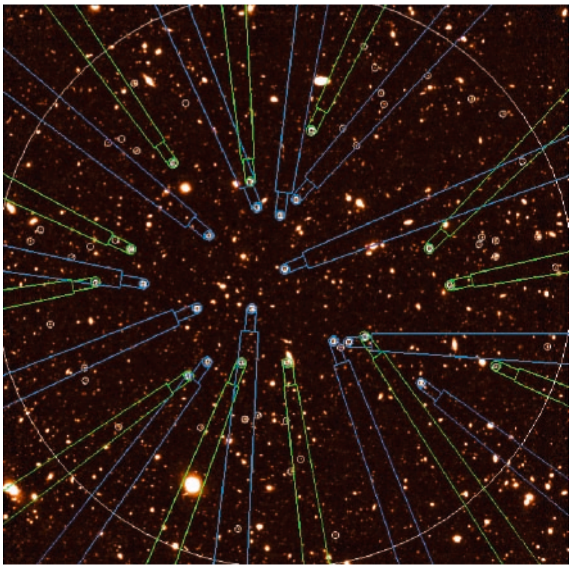


Figure 3: *I*-band image of the FORS Deep Field (Noll et al. 2004) with KMOS pickoff arms assigned to 24 Extremely Red Objects (EROs). The blue arms belong to the lower plane (and can therefore be vignetted by arms in the upper plane) whilst the green arms patrol the upper plane. The positioning efficiency of the arms has been checked against a number of important science cases which demonstrate a high multiplexing factor on interesting targets.

Integral Field Unit module

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 anamorphic magnification is required in order that the spatial sampling pixels (“spaxels”) on the sky are square whilst maintaining Nyquist sampling on the detector in the spectral dimension. The slices from groups of 8 sub-fields are aligned and reformatted into a single slit for each of the three spectrometers. The optical design of the IFU sub-systems is based on the Advanced Image Slicer concept (Content 1997) and draws heavily on experience developed in building the GNIRS integral-field unit for Gemini South (Dubbeldam et al. 2000). Three off-axis aspheres are used in the fore-optics to facilitate a production method based on diamond-turning, rather than raster fly-cutting, in order to improve the surface roughness. Important considerations in developing the design for 24 optical trains, have been the need to incorporate manufacturability into the optimisation process, and a desire to use monolithic optical components wherever possible. In the current design the slicer mirrors are all spherical with the same radius of curvature, and so are the pupil mirrors. The slit mirrors are toroidal with the same radius of curvature in the spectral direction, but different radii of

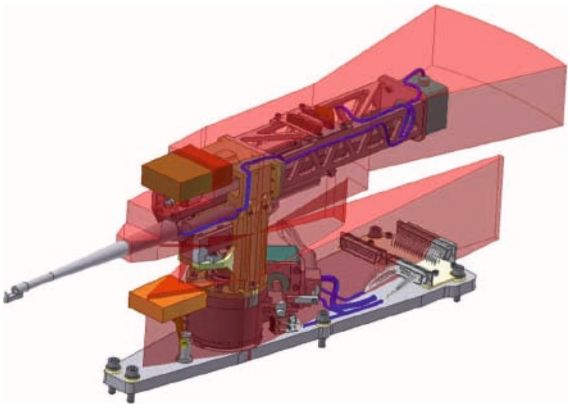


Figure 4: Solid model of a KMOS arm in the upper plane. The lower arms contain identical components but are compressed vertically. The transparent red region shows the space envelope occupied by the arm over its full range of motion. Each arm patrols approximately 30 % of the pickoff field.

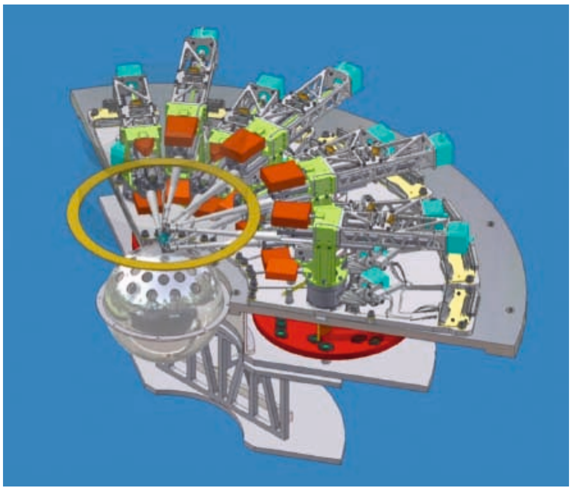


Figure 5: One of the three integrated pickoff and IFU sub-modules showing the three mounting plates for the pickoff arms, the filter wheels and the IFU optics. Each sub-module is attached to the main cryogenic optical bench within the cryostat. At the centre of the unit is shown the integrating sphere of the calibration unit and the ring mirror which reflects light from the calibration sources in to the pickoff arms.

curvature in the spatial direction. This configuration was chosen because it is well adapted to the available methods of machining. Each IFU sub-module produces a 254 mm long slit containing 112 separate slices from 8 subfields. The mechanical design of a single pickoff and IFU sub-module containing eight pickoff arms and eight integral field channels is shown in Figure 5 and emphasises the three-fold symmetry of the KMOS system and the advantages from a mechanical perspective of positioning common components in a single plane.

Spectrograph module

The three identical spectrographs use a single off-axis toroidal mirror to collimate the incoming light, which is then dispersed via a reflection grating and refocused using a 6-element transmissive achromatic camera. The gratings are mounted on a 6-position wheel which allows optimised 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 (Tecza et al. 2004). Each spectrograph contains a 2048 × 2048 Hawaii-2RG HgCdTe array which 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. All three spectrographs are mounted in a plane perpendicular to the Nasmyth rotation axis for maximum stability (Figure 6).

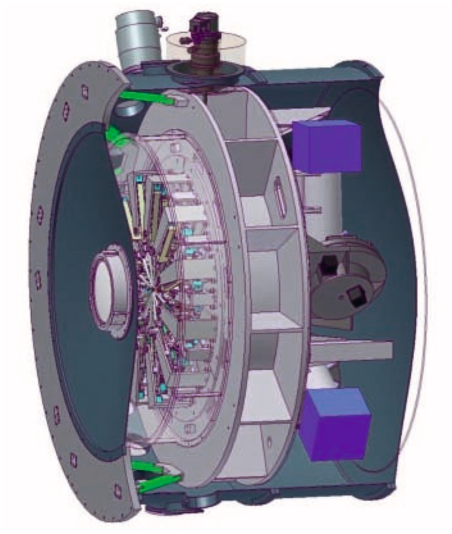


Figure 6: Cutaway view of the main KMOS cryostat showing the entrance window and the pickoff arm module at the front, and the spectrograph module at the rear. The cryostat will be an aluminium/stainless steel hybrid to reduce weight. Not shown here are the electronic racks which will mount on a supporting frame around the cryostat.

Software and electronics

KMOS will be one of the most complex astronomical instruments ever built for a ground-based telescope with over 60 degrees of freedom in the cryogenic mechanisms alone. Robust efficient software and reliable control electronics will be key to successful long-term operations. In addition to instrument control software and housekeeping diagnostics, KMOS will have an optimised target allocation tool, currently known as KARMA, in the ESO observation preparation software (P2PP). KARMA will assign arms to targets in a prioritised way, whilst ensuring that no invalid arm positions are selected and allowing the user to manually reconfigure the list of allocated targets. A customised data reduction pipeline will be provided which will allow the observer to precisely reacquire the targets during multiple visits to the same field and to evaluate the data quality after each readout. With over 4000 spectra per integration, automatic data processing and reduction methods will be essential to fully exploit the scientific potential of KMOS.

Project status

KMOS is being built by a balanced consortium of UK (University of Durham, University of Oxford and the UK Astronomy Technology Centre) and German (Universitätssternwarte München and the Max-Planck-Institut für Extraterrestrische Physik) institutes working in collaboration with ESO, who will provide the science detectors and associated readout electronics and software. The project is currently in the preliminary design phase and is expected to be shipped to Paranal in mid-2010. The list of key milestones is given in Table 2.

Table 2: Key KMOS milestones.

Milestone	Date
Preliminary Design Review (PDR)	March 2006
Final Design Review (FDR)	March 2007
Preliminary Acceptance Europe (PAE)	March 2010
Preliminary Acceptance Chile (PAC)	September 2010

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