Design of the KMOS multi-object integral field spectrograph

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ABSTRACT

KMOS is a near-infrared multi-object integral field spectrometer which has been selected as one of a suite of second-generation instruments to be constructed for the ESO VLT in Chile. The instrument will be built by a consortium of UK and German institutes working in partnership with ESO and is currently at the end of its preliminary design phase. We present the design status of KMOS and discuss the most novel technical aspects and the compliance with the technical specification.

Keywords: Infrared spectrographs, integral field spectroscopy, multi-object spectroscopy

1. INTRODUCTION

Understanding the physical processes by which galaxies form and evolve is one of the holy grails of modern cosmology. 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 distant 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 specific examples (e.g. [1]) but statistical surveys of these galaxy properties 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 MultiObject 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 form and 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) 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.

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Table 1. Baseline design specification for the KMOS spectrograph.

Technical Specification	Baseline (Essential) Requirement	PDR Design Status
Instrument Throughput	J>20%, H>30%, K>30%	J>30%, H>35%, K>35%
Wavelength coverage	1.05 to 2.5 μm	0.8 to 2.5 μm
Spectral Resolution	R>3200,3800,3800 (J,H,K)	R=3500,3900,3700 (J,H,K)
Number of IFUs	24	24
Extent of each IFU	2.8 x 2.8 arcseconds	2.8 x 2.8 arcseconds
Spatial Sampling	0.2 x 0.2 arcseconds	0.2 x 0.2 arcseconds
Patrol field	5'x5' square field	7.2 arcmin diameter circle
Close packing of IFUs	≥ 3 within 1 sq. arcmin	≥ 3 within 1 sq. arcmin
Closest approach of IFUs	edge-to-edge separation of 6 arcsec	edge-to-edge separation of 6 arcsec plus ability to put 24 IFUs into mapping configuration

2. TECHNICAL DESCRIPTION

KMOS will mount on the VLT Nasmyth rotator (Fig. 1) and will use the Nasmyth A&G facilities. 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 2.8x2.8 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. The spatial sampling is 0.2x0.2 arcseconds. Light from the IFUs is dispersed by three identical cryogenic grating spectrometers which generate 14x14 spectra, each with ~1000 Nyquist-sampled spectral resolution elements, for all of the 24 independent sub-fields. The spectrometers will each employ a single 2kx2k 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. An end-to-end raytrace through four of the pickoff arms in one of the three spectrometers is shown in Fig. 2. Our goal has been 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.

2.1 Pickoff Module

One of the more novel 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 pickoff 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 <0.1 arcseconds. 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 (Fig. 2), one of which forms the entrance window to the cryostat. The arms are mounted on one of three front segments, each containing eight arms, the field alignment k-mirrors, two filter wheels and an integral field unit module. A calibration unit for wavelength and flatfield calibration is located at the centre of the field (Fig. 3).

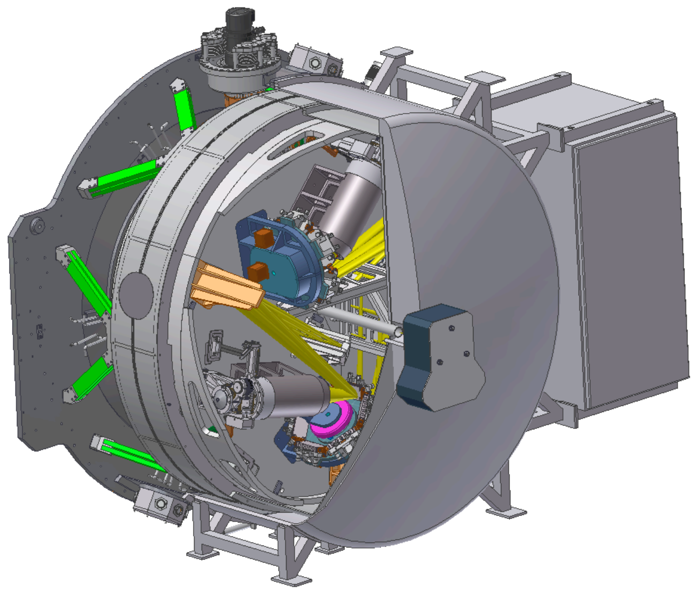

Fig. 1. Cutaway view of the main KMOS cryostat showing the spectrograph modules at the rear. The cryostat will be an aluminium/stainless steel hybrid to reduce weight whilst retaining stiffness. Only one of the three electronic racks is shown here which will all mount on a supporting frame around the cryostat. The cryostat is approximately 2 metres in diameter and the full instrument weighs 2700 kgs.

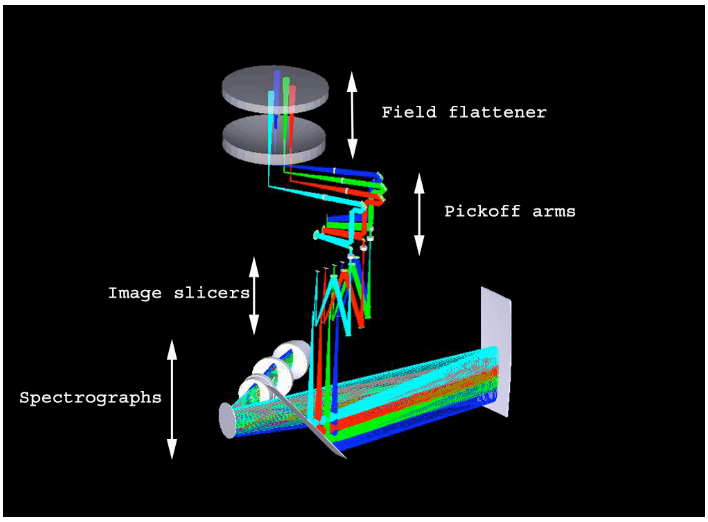

Fig. 2. Optical raytrace through four pickoff arms, their associated IFUs and one of the spectrometers. Light exiting the pickoff arms is brought to an intermediate focus using a 3-element K-mirror, which aligns the edges of all 24 IFU fields on the sky so that they can be put into a compact sparse array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

The arm design has been refined to allow maximum versatility in allocation of targets whist achieving stringent goals on accuracy and reliability. Arm positioning on both axes is via step-counting from a micro-switch datum with position encoding via an LVDT for health monitoring and power failure recovery; a hardware collision detection sensor will also be implemented as a third level of protection against software errors. The efficiency of allocation has been benchmarked against several real target fields selected from deep imaging surveys and a prototype GUI has been developed which the astronomer will use to optimally assign targets to pickoff arms. The changing path length within the arm is compensated via an optical trombone which uses the same lead screw, but with half the pitch, as for the main radial motion of the pickoff mirror. 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 within the arm, after which an intermediate image is formed by a K-mirror assembly which also acts to orientate the IFU fields so that their edges are parallel on the sky. This enables a mapping mode for the instrument in which the 24 IFUs are arranged in a sparse 6x4 matrix which can then cover a ~1 $arcmin^2$ contiguous area using a 4x4 dither pattern. A prototype pickoff arm has been manufactured, and is currently undergoing an extensive series of tests in a cryogenic environment before manufacturing the full batch of 24 arms. The optical layout and a solid model of one of the upper layer pickoff arms is shown in Fig. 4.

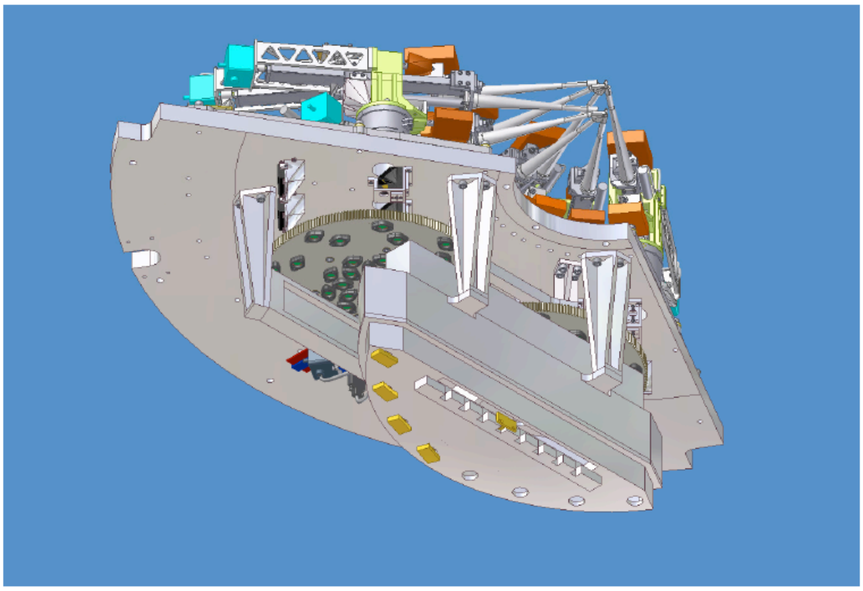

Fig. 3. One of the three identical front segments. Light from the pickoff arms travels through the K-mirrors, shown here attached to the underside of the baseplate, then through the 8-position filter wheel (2 wheels per segment) and into the box which contains the IFU optics. Each segment is attached to the main cryogenic optical bench within the cryostat. The integrating sphere of the calibration unit sits at the centre of the segments and is fed by a light pipe which directs light from the external calibration sources into the calibration sphere.

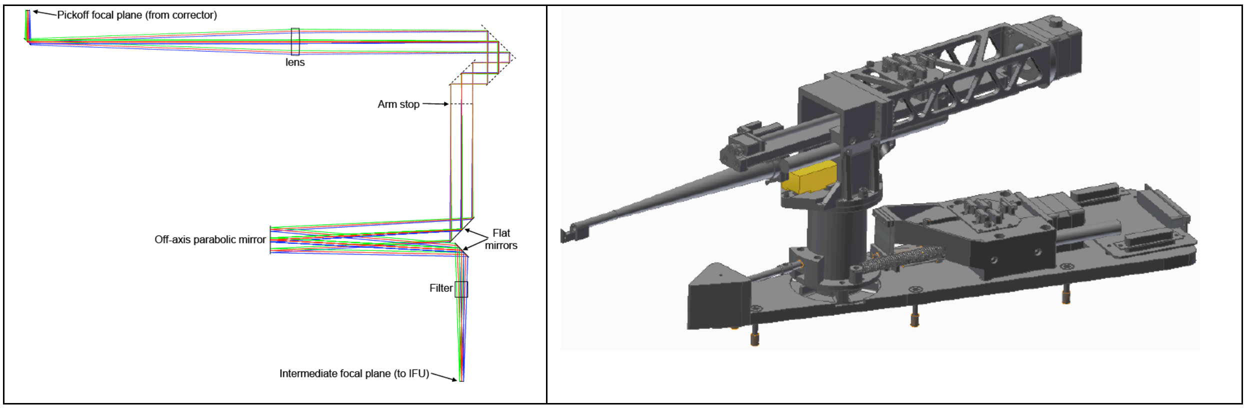

Fig. 4. Left: Optical design of a KMOS prototype arm. The singlet field lens in the arm forms an image of the telescope pupil on the cold stop which is oversized by 5% to allow for aberrations and alignment errors. Chromatic errors in the intermediate image are compensated by adjusting the thickness of the order-sorting bandpass filters. Right: Solid model of the prototype arm. The pickoff mirror at the tip of the arm can move ~125mm radially and ±11 degrees in angle, and covers approximately 20% of the pickoff field with an accuracy of ~40 microns. Careful finite element modelling of the structure was required to ensure that the flexure of both output image and pupil was within stringent specifications.

2.2 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 and includes the effect of anamorphic magnification due to the grating in the spectrograph. The slices from groups of 8 sub-fields are aligned and reformatted into a single 254mm long slit for each of the three spectrometers. The optical design of the IFU sub-systems (Fig. 5) is based on the Advanced Image Slicer concept [2] and draws heavily on experience developed in building the GNIRS integral-field unit for Gemini South [3]. 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 (Fig. 5). 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 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 254mm long slit containing 112 separate slices from 8 subfields. More details of the optical design of the KMOS integral field units are given in [4].

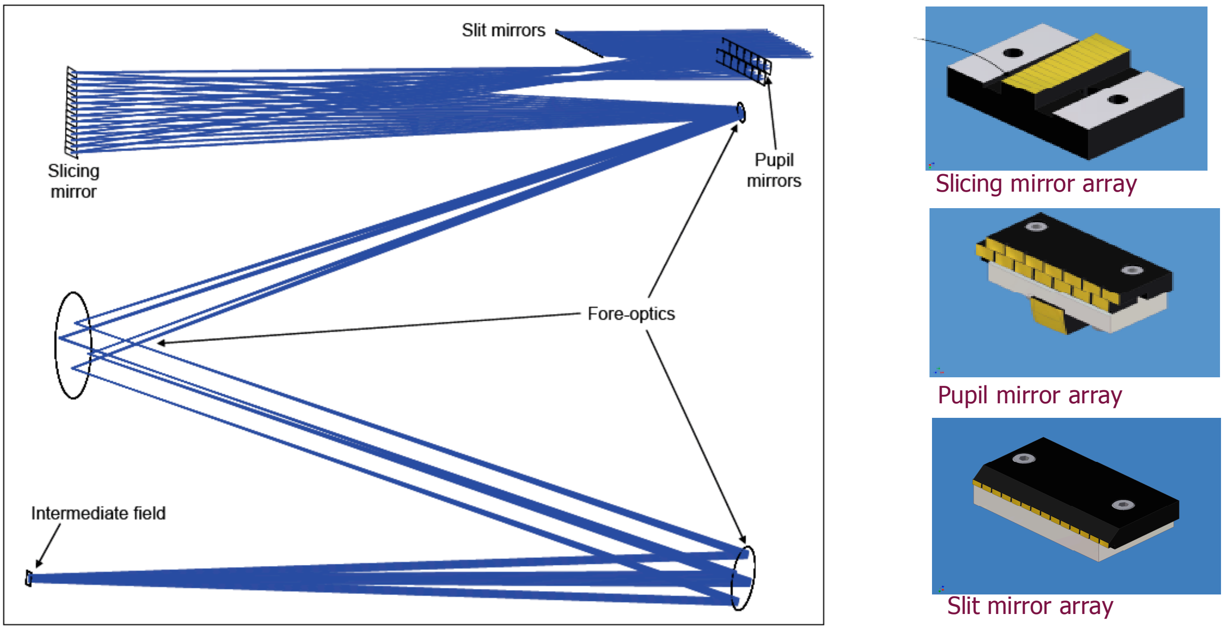

Fig. 5. Optical layout of the KMOS integral field units. The 3 fore optics mirrors relay the intermediate focal plane onto the image slicers with appropriate anamorphic magnification. Four different prescriptions are required depending on the position of the pickoff arm output relative to the centre of the slit. The optics are produced with monolithic diamond machining techniques which use machined datum surfaces to simplify optical alignment and fine-tunig by the use of alignment cylinders (see [5]).

2.3 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 optimized gratings to be used for the individual J,H,K bands together with two lower resolution gratings and the option of an IZ-band (0.82-1.05 μm) grating to enhance versatility (Fig. 6). Each spectrograph contains a 2048x2048 Hawaii-2RG HgCdTe array which is mounted on a remotely operated focus stage. Further details on the opto-mechanical design of the spectrograph are given in [6].

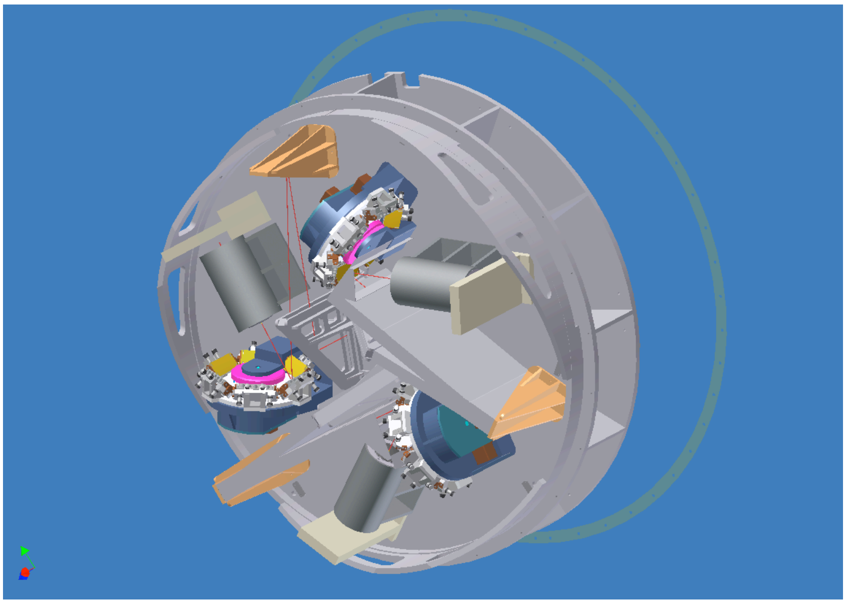

Fig. 6. Layout of the three KMOS spectrographs. The light from the IFU slit is folded through 90 degrees so that the spectrographs can be orientated in a stable configuration perpendicular to the Nasmyth optical axis. The light is collimated with a single toroidal mirror and reflected off a 6-position grating wheel into the 6-lens achromatic camera. The Hawaii-2RG detector is mounted on a focus stage for easy adjustment during instrument AIT.

2.4 Software and Electronics

KMOS will be a complex astronomical instrument for which 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.

3. 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 at the end of its preliminary design phase and is expected to be shipped to Paranal Observatory in mid-2010. The performance of the current opto-mechanical design at PDR, with preliminary tolerancing, meets or exceeds all of the essential requirements in the instrument specification shown in Table 1. The list of key milestones is given in Table 2.

Table 2. Key milestones for the KMOS project.

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

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