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KMOS: A multi-object deployable-IFU spectrometer for the ESO VLT

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Abstract

We describe the design of a 2nd generation instrument for the ESO VLT which uses 24 cryogenic pickoff arms linked to diamond-machined image slicing integral field units to deliver a unique multiple deployable integral field capability in the near-infrared (1–2.5 μm). The science requirements for the instrument are presented and linked to the functional specification. The baseline instrument concept is described with emphasis on technological innovations.

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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 and is currently in the preliminary design phase. In this paper we

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describe the functional requirements derived from the KMOS science case and describe the baseline instrument concept.

2. Science case and functional specification

The focus of cosmological studies at the start of the 21st century is rapidly shifting from accurate determinations of the parameters of the world model into investigations of the physical processes which drive galaxy formation and evolution. To achieve this goal 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 redshifts and environments. A few of the brightest examples (Genzel et al., 2002; Lehnert, 2005) are now being observed using single integral field unit (IFU) spectrographs on 8-m telescopes but statistical surveys of these galaxy properties will require a multi-object approach. This is the capability which will be delivered to the VLT with KMOS.

For any instrument to address these fundamental questions about how galaxies evolve it should: (1) have a substantial multiplex capability, commensurate with the surface density of accessible targets; (2) have the ability to obtain more than just integrated or one-dimensional information; (3) be able to resolve the relatively small velocity differences observed in rotation curves, velocity dispersions, and in merging galaxy pairs; (4) have the ability to observe several targets concentrated in a small area of sky; (5) have the capability to observe 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 (dIFUs). The specific choices in delivering these capabilities involves a complex trade of cost and scope which is reflected in the baseline capabilities listed in Table 1.

3. Instrument description

KMOS will mount 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 will be incorporated at lower priority). The baseline design employs 24 configurable arms that position fold mirrors at user-specified locations in the Nasmyth focal plane. The sub-fields thus selected 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 each employ a single $2k \times 2k$ HgCdTe detector. 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.

Table 1
Baseline capabilities for the KMOS instrument

Requirement	Baseline design
Instrument throughput	J = 20%, H = 30%, K = 30%
Sensitivity (5σ, 8 h)	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	$2.8 \times 2.8''$
Spatial sampling	$0.2 \times 0.2''$
Patrol field	7.2′ diameter circle
Close packing of IFUs	>3 within 1 sq. arcmin
Closest approach of IFUs	Edge-to-edge separation of 6″

4. Pickoff module

One of the key 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 $<0.2''$. The arms patrol in one of two layers positioned either side of the Nasmyth focal plane. 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 the intermediate image is formed by a K-mirror assembly which also acts to orientate the pickoff fields so that their edges are parallel on the sky.

5. 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 slices from groups of 8 sub- fields are aligned and reformatted into a single slit for each of the three spectrographs.

The optical design (Fig. 1) 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

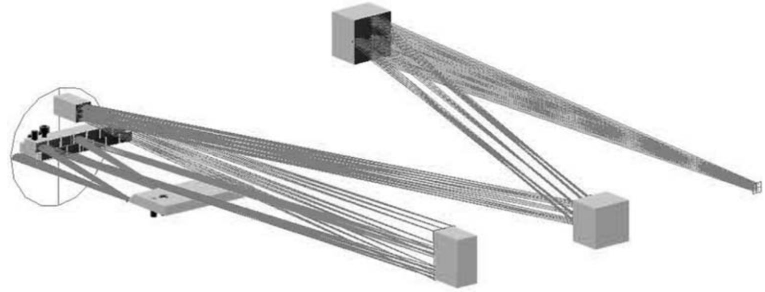

Fig. 1. Optical layout for a single pickoff field showing the three mirrors in the anamorphic fore-optics, the image slicer and the monolithic pupil mirror and slit mirror arrays.

Fig. 2. Optical layout of the IFU optics in a single IFU sub-module. There are 4 different fore-optics designs in each sub-module of 8 IFUs but common slicer, pupil mirror array and slit mirror array designs. The optical design has also been optimised to put these common components in the same planes for easier mechanical mounting and production.

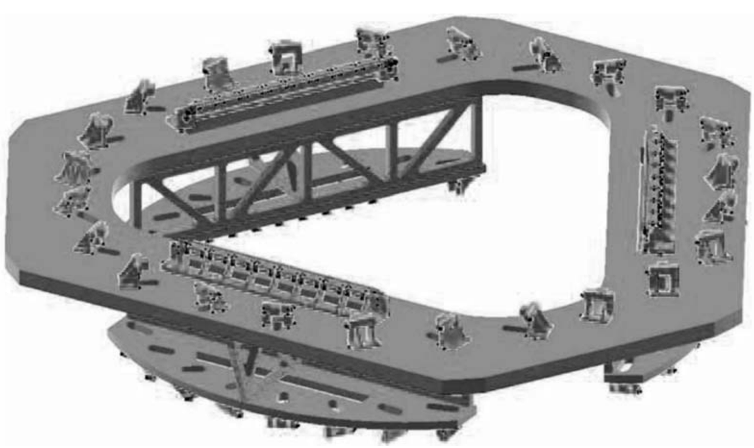

Fig. 3. Mechanical layout of the IFU module. Light passes through the optical bench from below and reflects off one of the individually mounted fore-optics mirrors. The light path returns to the second set of fore-optics which are located on a secondary optical bench mounted on standoffs from the main bench. The third fore-optics mirrors, the slicers, pupil mirrors arrays and slit mirror arrays are all mounted directly off the main optical bench.

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 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 256 mm long slit containing 112 separate slices from 8 subfields (Fig. 2).

The mechanical design of the whole IFU module is shown in Fig. 3 which emphasises the three-fold symmetry of the KMOS system and the advantages from a mechanical perspective of positioning common components in a single plane.

6. 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 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 (Lewis et al., 2004). Each spectrograph contains a 2048×2048 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.

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