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Prepared by	N Bouche, S Ramsay Howat, R Sharples

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Abbreviations

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1. Introduction and background

The KMOS essential science requirements call for three baseline gratings to cover the J, H and K infrared atmospheric windows. The optimal requirement, to extend the wavelength coverage of the instrument into the ‘I’ band by including an IZ grating, has been met by the KMOS design, as presented at the Preliminary Design Review. The details of these gratings, as at PDR, are given in Table 1.

In addition, there is a desirable science requirement to include low resolution grating(s), covering more than one atmospheric window. For a desirable requirement to be met there must be minimal impact on the design of the instrument.

Due consideration has been given to the technical, financial and schedule implications of including additional gratings. The development of the spectrograph design up to Final Design Review status has show that the KMOS spectrograph design can incorporate five gratings on the grating wheel and still meet the technical and performance requirements.

Therefore, the selection of a fifth grating has been considered by the KMOS science team. In this paper, the options considered are presented. It was quickly apparent that two options offered the most interesting science capabilities and were studied in further detail. These were an HK grating and a ZJ grating.

Strong science cases were developed for both of these gratings. For the ZJ grating, the strongest science case is for the region ~0.95-1.1μm. During the lifetime of the KMOS project, this has emerged as the key region for planned Lyman alpha searches. Therefore, there is a strong argument for including the region 0.95-1.1μm (Y-band; where many narrow band Lyalpha searches will focus on 1.06 μm), whereas the current KMOS design splits the IZ and J band at 1.05μm. This would have led to poor efficiencies to follow-up high-z sources at 1.05μm.

1.1 Conclusions from the KMOS science team

The performance of an HK grating is known, and this grating is already heavily used in current generation IFUs. The HK grating is appealing for many different science cases (e.g. redshift surveys, 2 line diagnostics).

The 1.0-1.15μm wavelength range opens up *new* science (reinonization sources at z-6-10). Given that the wavelength range of interest is around 1micron, this wavelength range is necessary as KMOS may very well be the only spectrograph for ESO to enter the z>7 science and play a significant role. This region between the Z and J bands ***is not*** available with any current or planned multi-object spectrograph/IFU instrument. In addition, KMOS is a powerful tool as it can rule out spectroscopically outliers over a wide redshift range 0.5-2(& 2.5) simultaneously while performing blind searches. KMOS will cover the same volume as the dedicated instrument DAzLE. Furthermore, DazLE, Hawk-I, and VISTA are all planning to perform deep narrow band searches at 1.06μm, where KMOS would play an important role following-up potential high-z candidates.

1.2 Proposed Change

Given that strong arguments for both HK and ZJ gratings exist, but a single position on the KMOS spectrograph wheel is vacant, the following solution has been arrived at in discussions amongst the KMOS science team. We propose:

- to select the HK grating as the 5th grating;
- to revise the bandpass of the formal J to optimise KMOS for high (z>7) redshift science: the proposed changes would move the J band blue cut-off from1.05μm to ~0.98μm and the red cut-off to 1.33μm; this will know be known as the YJ grating.
- to revise the bandpass of the formal IZ grating to extend the IZ red cut-off from 1.05μm to 1.15μm. Such a strategy would allow for deep Ly-alpha searches (over 0.98-1.15 or z=7-8.5) keeping the broad wavelength coverage (given by 0.8-1.33) to efficiently rule out outliers using both IZ and YJ gratings.

Table 1 lists the approved gratings at PDR, and Table 3 lists our proposed changes.

The next steps will be to confirm the exact details of the design for each of these gratings in consultation with the spectrograph designers. During this period, small changes in the bandpass may be required to optimise the image quality, resolution and throughput. We will also consider the calibration plans for each grating during this period.

This document is presented to the ESO KMOS Instrument Science team to invite their confirmation of the final grating selection for KMOS and for their advice on selection of the grating wavelength ranges based on scientific criteria. We present the PDR baseline grating suite in Section 2 and discuss the science case for the ZJ and HK gratings in Sections 3 to 5. Some notes on the likely performance of these gratings is presented in an Appendix.

2. KMOS spectroscopic modes presented at the PDR

The list of gratings presented and approved around the time of the preliminary design review is given in Table 1.

Table 1

Grating	Resolving power (λc)	Central wavelength (λc)	Wavelength coverage
IZ grating	~4300	0.94 μm	0.83μm – 1.05μm
J grating	3500	1.21 μm	1.05-1.37μm
H grating	3900	1.65 μm	1.45-1.85μm
K grating	3700	2.225 μm	1.95-2.5μm

The IZ grating was initially specified to cut-off at 0.83μm, based on published curves for the quantum efficiency of the Hawaii 2RG detectors. Since the PDR, the detector type has been modified and KMOS will now use the, now standard, Hawaii 2RG substrate-removed detectors which have wavelength coverage into the visible at high QE. Therefore, the cut-off for this grating has been shifted to 0.80 μm. This change has been incorporated in the FDR optical design.

3. New options for KMOS gratings: initial thoughts

The two options considered in detail for the 5th grating were ZJ and the HK gratings, with the outline specifications as listed below.

Table 2

Grating	Resolving power ($\lambda/\delta\lambda$)	Central wavelength (λc)	Wavelength coverage
ZJ grating	~2000	1.09 μm	0.80μm – 1.37μm
HK grating	~1800	1.65 μm	1.45-2.5μm

The selection of the 5th grating must be heavily weighted towards

1. the science case(s) where the source density is high to make use of the multiplex capabilities of KMOS;
2. the science case(s) where the IFUs are part of the unique scientific return.

3.1 Lessons from SINFONI

The SINFONI HK grating is a well used mode of this instrument. A survey of SINFONI science usage in 2005 reveals the following breakdown:

J	H	K	HK
13n	47n	63n	25n

Although SINFONI does not have a ZJ grating for direct comparison, it is clear that the HK grating is used almost twice as often as the J-band grating, though the poor wavelength coverage of SINFONI below 1.18 may be a factor. Maintaining an HK capability with KMOS is therefore expected to support the ongoing scientific interests of the ESO community.

4. The ZJ grating science cases

4.1 (Blind) Lyman-alpha searches

The universe was reionized at very high-z (>7). The epoch of reionization started early according to the WMAP results (Spergel et al. 2006), and the most distant QSOs indicate that it ended at z~6. What are the sources of the reionization? This question will certainly dominate observational cosmology for the next decade. Ly-alpha searches of the sources responsible for the reionization of the universe are our best chance to constrain their number density, and other physical properties. The number of Ly-alpha emitters (LAE) causing reionization is very uncertain and predictions vary by orders of magnitude. Statiavelli et al. (2006) predict that >1 per 500 Mpc^3/h^3 down to $2e\text{-}17 erg/s/cm^2$. Barton et al. (2004) predicts 140 in that volume, and Thommes and Heisenheimer (2004) predicts a minimum of 0.2 or 0.04 in that volume.

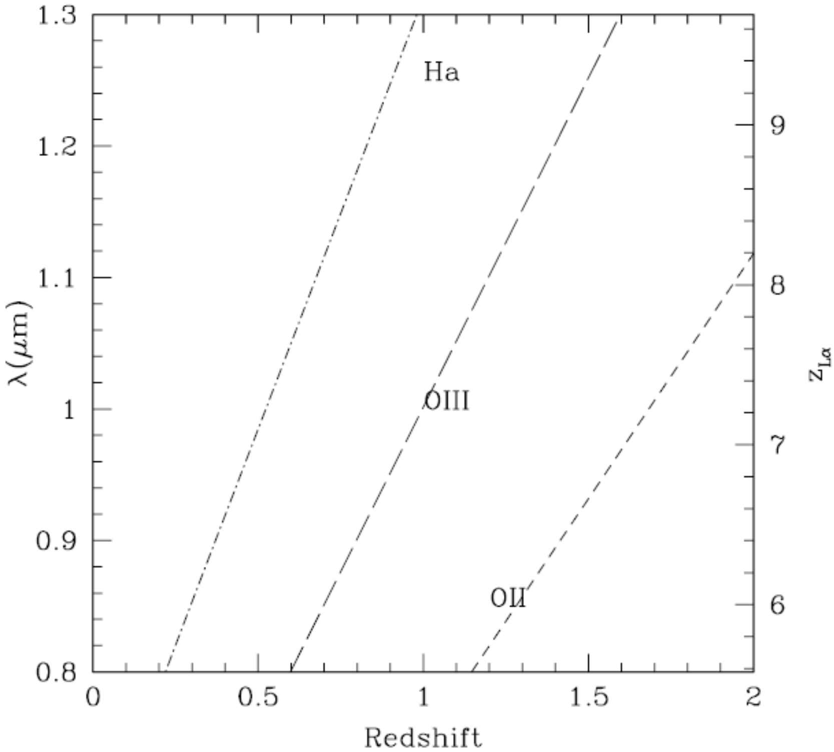

Figure 1. Lines visible in a Z+J grating with the corresponding Ly-alpha redshift (right axis). A single line emitter at ZJ is either Lyalpha, Halpha or OII, since OIII is always with Hbeta. In the absence of continuum, low-z Halpha interlopers can only be ruled out with a second line. This can be achieved in on go with the Z+J grating from z=0.6-1.3. OII emitters can be ruled out either based on the doublet at R~2000 or better with OIII. Only with a 0.8-1.3 wavelength coverage can Halpha interlopers be identified (with OIII) over a wide range of redshifts in one go.

Undoubtedly, these searches will bring many low-z interlopers. Down to a flux 10^{-18}ergs/s/cm2 at z~7.5 (putting Ly alpha in the J-band), one expects 0.1-1 real source per 1' field with anything between 10 and 100 contaminant lower z line emitters, based on extrapolation from Hα surveys at brighter flux limits.

Regardless of the number of true high-z emitters, such surveys are dominated by low-z interlopers. For example, Martin et al. (2006/astro-ph0509157) finds the ratio of interlopers is 8:1 down to 1×10^{-18} erg/s/cmsq at z=5.7. Of these, 2 to 3 are ruled out from the presence of continuum blueward of the identification line and/or with an emission line blueward of the identification line.

If the interlopers can be identified as an integral part of the survey, then there is a significant advantage due to the reduced requirement for follow-up spectroscopy. KMOS+ZJ grating would be very efficient in ruling out the interlopers. For instance, Figure 1 shows that with Z+J, one can distinguish between LAE and Halpha interlopers at z=0.6-1.0 using OIII, and OIII outliers at z=1.2-1.6 using OII ; against Lya at z=6-9. Thus, for any contaminant in [OII], Hbeta, [OIII], Halpha, there is always be at least one other line in the ZJ bandpass, so many contaminants can be straightforwardly removed using ZJ spectroscopy. Interlopers can also be ruled out by the presence of continuum blueward of Ly-alpha from deep photometry or from the KMOS spectrum directly.

In addition, KMOS+ZJ is ideally suited to following up Lyman-alpha searches carried out with the Hawk-I narrow band filters at 1.06 and 1.18 microns, thanks to the excellent match of the 7arcmin diameter patrol field of KMOS to the HAWK-I field of view.

4.1.1 Competitiveness

We have considered the question of the competitiveness of KMOS with a ZJ grating for blind Lyman alpha searches when compared with other surveys planned on similar timescales.

The table below lists the volume searched by KMOS and the expected sensitivity in 10hr. The numbers are based on the assumption that KMOS is as sensitive at 1.0µm as SINFONI at 1.2µm, [SINFONI is 15% efficient at that wavelength; KMOS is expected to be >20%]. The sensitivity to detection of faint lines is excellent with an (IFU) spectrograph compared with narrow band filters, as the filter bandwidth is not well matched to the width of the emission line. KMOS+ZJ is equivalent to having ~400 narrow band filters sampling regions free of OH lines.

Although the area on the sky searched by KMOS is small (188"=24x2.8x2.8), the broad spectral range means that KMOS covers a 3D volume 150~Mpc^3/h^3 per pointing, covering the redshift range 6-10.

MUSE, DazLE, and wide field NB searches with Hawk-I will survey a large area contiguously, however if the sources are clustered, KMOS will have an advantage over narrow band searches as the volume is broader.

KMOS has the advantage that it covers a much deeper volume in redshift (albeit over a smaller area). We note that, a blind search with KMOS would cover the same volume as narrow band search such as DazLE.

The simultaneous rejection of interlopers offers KMOS an advantage in speed over NB searches that is not quantifiable, and not reflected in the simple comparison of survey speeds. Therefore we believe KMOS will be competitive with DAzLE and Flamingos-2 surveys and will offer efficient spectroscopic follow-up to HAWK-I.

KMOS may be a factor of three slower than MUSE (below 0.95microns), but will have the advantage of earlier delivery to the telescope.

Instrument	Volume	Volume (Mpc3) (h=1)	10hr Flux limit	Note	Redshift (<1.3µm)	Lambda
KMOS	188sq" x Dz=4	150	5e-18[1]		5.6-9.6	0.8-2.5µm
MUSE	1sq' x Dz=0.7	500 (1.7*1)^2*200	?		<6.5 5.6-6.4	<0.9 0.8-0.9
Hawk-I (NB 0.010µm)	49sq' x Dz=0.1	3000 (1.7*7)^2*20	5e-18[2]	Need spectro.		0.8-2.5µm
Flamingos 2	36sq' x Dz=0.01	200 (1.7*6)^2*2		MOS cap.	6.5-9.6	0.9-2.5µm
DazLE	45sq' x	250[3]	3e-18[4]	Need	7.5-	>1.05

[1] The SINFONI ETC gives a SNR of 2.5 in 10hr.
[2] From the latest ETC simulations (for a SNR of 5) in 10hr.

(NB 0.001μm)	Dz=0.01	(1.7*6.5)^2*2		spectro.		

4.2 Emission Line Surveys at z~8

VISTA plans to have a NB filter at 1.18 microns for Ly-alpha searches at z>8. The science is the same as with the Hawk-I NB filters (1.06).

The windows at 1.05 and 1.18 (relatively) free of atmospheric OH-lines will play an important role for z>7 searches. KMOS with the current plan would put the 1.05 window on the edge between the z-band and the J-band, thereby fuelling the need for a ZJ grating.

4.3 Z~1 clusters

KMOS+ZJ will be a powerful tool for studying the star formation rate as a function of environment in z~0.4-1.1 clusters where the source density is high and the multiplex advantage full exploited.

One can study the metallicity as a function of environment using OIII/Hbeta in one setting at z~0.6-1.1. Clusters and dense environment at z=1 are rare, but all-sky X-ray surveys like e-Rosita will bring many thousands of clusters in that redshift range. The goal for the e-Rosita mission is 10^5 clusters in total.

This project is not currently accessible to SINFONI at z~0.5-0.8 given the sharp sensitivity cut off at 1.15microns. H-alpha can only be detected at redshifts >0.8. Multi-IFU spectroscopy is invaluable when the source morphology is not well known and so KMOS is better suited to this project than MOS follow up.

5. The HK grating science cases

The HK grating will provide broad coverage of the H+K windows at a resolution of R~1800. The principal science cases are based on simultaneous observations of multiple emission lines ratios (in many cases optical rest frame lines redshifted into the infrared) and also continuum shape measurements where the broad baseline improves the constraints and helps discriminate the effects of reddening.

5.1 Phenomenology of Starburst/Lyman break galaxies at z~2

Experience of single IFU work on z~2 galaxies is that the combination of HK coverage at R=2000 is well suited to probing the emission line ratios and morphologies of starburst galaxies at an epoch where the global star formation rate density reaches its peak. Simultaneous coverage of OIII/Hβ/Hα allows the derivation of power sources, reddening, star formation rates and metallicity. Environmental studies of SFR properties through Hα/Hβ ratios in HK at z>2 is an area where the K-band optimised KMOS can make a unique contribution.

The space density of these sources (based on VISTA, SCUBA2 450um, LOFAR radio, etc) will easily approach 1 per sq. arcmin and overdensities selected from these new next-generation surveys will yield potential z>2 clusters with higher projected surface densities of targets. The surface density of "normal" R<22.5 LBGs with dynamical mass ~few10^10 and line widths

[3] Single filter, whereas the strategy calls for difference imaging, doubling the volume.
[4] From the DAzLE recent VLT run , numbers are for SNR of 2.5.

~200km/s from Giavalisco et al (1998) & Steidel et al (1996) is ~1 per sq arcminute. Because the lines are resolved at R=2000 at this redshift (the observed line widths are (1+z)*Δv), the effects of contaminating OH lines can be mitigated. Populating the KMOS IFUs should therefore not be a problem for deep observations of "normal" SF galaxies at these epochs. Some of the QSO sight line projects (i.e. LBGs overdensities in the field of QSOs) will increase the surface density of targets and make it even easier to populatie most of the IFUs.

5.2 SCUBA2 galaxies at z~2

The SCUBA2 legacy survey will provide many dusty submm sources with relatively good positional accuracy, 1". The need will arise to obtain redshifts of these sources without the usual radio selection which biases the redshift to z<2.5.

IFUs are needed because the sources are known only with a rms of 1". The survey will provide 20 sources over 50sq arcmin, i.e. the source density will be 0.5/sq. arcmin, and the multiplex capability of KMOS can be used.

5.3 Growth of Galaxy Bulges and Supermassive Black Holes

HK at z~2 also gives access to OIII/Hα which together provide a clean route to derive galaxy dynamics and black hole masses for AGN to trace the build up of SMBHs at the peak era of activity in the QSO population. Deep X-ray samples provide source surface densities approaching ~1 sq. arcmin in the appropriate redshift ranges. In order to trace the predicted joint build up of super-massive black holes and their galaxy spheroids, it is necessary to identify AGN populations at z>1, where the bulk of the black-hole--spheroid growth in today's massive galaxies occurred.

The source density of AGN is high. The most complete census of AGN activity to date is provided by deep X-ray surveys, which identify **typical** AGN populations in massive galaxies and have found a z>1 AGN source density >3000 sq/deg (e.g., Alexander et al. 2001; Mainieri et al. 2005). Deep Spitzer surveys are also now starting to uncover an X-ray undetected AGN population at z>1. KMOS promises significant advances in constraining the importance of these z>1 AGNs by (1) identifying the redshifts for the z>1 AGNs without optical spectroscopic redshifts, and (2) tracing the AGN-related and star-formation-related outflows that are predicted to be important in "forging" the black-hole—spheroid relationship at high redshift (e.g., Bower et al. 2006) using the strongest diagnostic emission lines for these (predominantly X-ray obscured) AGN are [OIII], H-beta, and H-alpha, which fall at 1.45-2.6um for z~2-3 sources (~1-1.3um for z~1 sources). Naturally, line ratios from these can indicate the presence of energetic outflows, quantify the amount of optical extinction, and provide a measurement of the intrinsic luminosity of the AGN.

5.4 Gravitationally Lensed Systems

KMOS will be able to target the gravitationally lensed arcs/arclets in cluster cores (cf Swinbank et al 2007). Massive lensing clusters at z~0.5 (e.g. from the Massive Cluster Survey [MACS], etc) are efficient at amplifying z=1.5--3 galaxies. This technique allows for the study of the dynamics/SF/metallicities of highly magnified (and therefore sub-L* galaxies). A few of the brightest examples have already been observed with SINFONI (Nesvadba et al. 2006, Swinbank et al. 2007) using either K or H+K. The source density of arc/arclets is high enough to fill 24 IFUs.

5.5 Very High Redshift (z>5) Galaxies

Searches for very high (Z~5) galaxies will be a growth industry at the end of the next decade with the *deep* versions of the optical (VST, PanStarrs) and infrared (UKIDSS, VISTA) panoramic surveys for photo-z's. For instance, the deep part of PanStarr will reach I~29 over 28 square degrees. Much of the contamination on photometrically selected z>>5 galaxies is from dusty z~2-3 galaxies - so the easiest way to remove this contamination is actually to use HK to go after the strongest lines (Halpha/OIII) at these redshifts, along with the R=4000 J to target Ly-alpha.

5.6 Emission line Surveys at z~2

Narrow-band near-infrared surveys for star-forming galaxies form part of both the WFCAM and VISTA survey plans. These will identify 1000's of H-alpha emitters at z~2.2, including overdensities (proto- clusters), where the identifications, energetics, dynamics, etc can be simultaneously determined using the HK grating.

5.7 Summary of the H+K Extragalactic Science Case

The HK science for high-redshift (z>2) sources falls into 3 categories.

1. Emission line diagnostics, and the need for >2 lines in one spectrum for proper spatial registration. Observing the lines simultaneously removes issues of spatial registration (though note that the spatial registration accuracy of KMOS is expected to be extremely high due to the tight requirements on arm positioning accuracy).
2. `Redshift surveys' for sources with uncertain redshifts or photometric redshifts.

In the case, where the exact position of the source is not known (such as from SCUBA2 and Spitzer/Hershell), IFUs have the major advantage that the requirement of accurate astrometry (<0.5") for MOS spectroscopy is lifted.

3. Continuum fitting: After rebinning, the HK grating can be used to measure the HK continuum/SED.

6. Proposed solution for the KMOS grating suite

As a result of the science cases proposed above, the KMOS science team had strong support for both the ZJ and HK gratings. Therefore a solution was sought that would permit all the science cases to be met given that only one additional grating can be accommodated in the KMOS design.

The ZJ science case, and specifically the high-z LAE searches, can in fact be met with wavelength coverage from ~0.95μm. The 0.8μm to ~0.95μm will be covered by the IZ grating at high resolution. The idea of extending the blue coverage of the J band grating, from the original complement, has therefore been developed (Section 6.1) leaving way for the inclusion of the HK grating (Section 6.2).

6.1 Extension of the J grating to YJ

The original J band specification is from 1.05μm to 1.37μm. At the blue end, the spectrum will be limited to ~0.98μm, set by the atmospheric transmission (Figure 2) and balanced against the desire to maintain the highest spectral resolution. The red end of this grating (currently

1.37) was outside the atmospheric window as modelled for Paranal and as observed for SINFONI (Figure 2). Therefore, a reduction of the red limit of the J grating to 1.33µm is suggested.

The initial specification of the J band grating has spectral resolving power at the centre of the band of R = λ/Δλ = 3500. The extension to 0.97µm in the blue end and reduction of the red cut-off to 1.33µm results in R~3300 at the centre of the band.

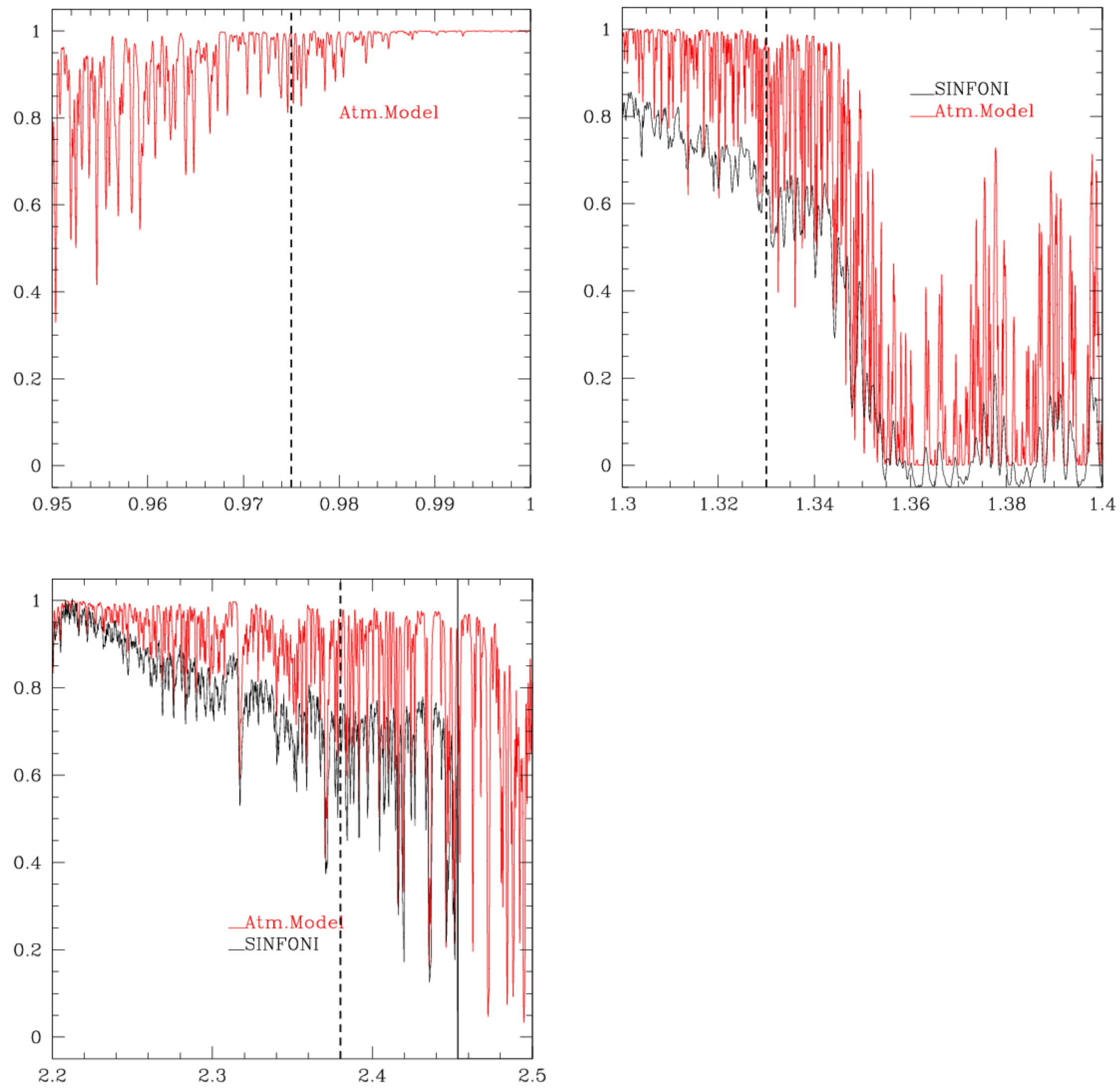

Figure 2: Zoom at the edge of the ZJ (top) and (K) bands to choose the end cut-off point of the band. The proposed cut-off is shown by the vertical dashed.

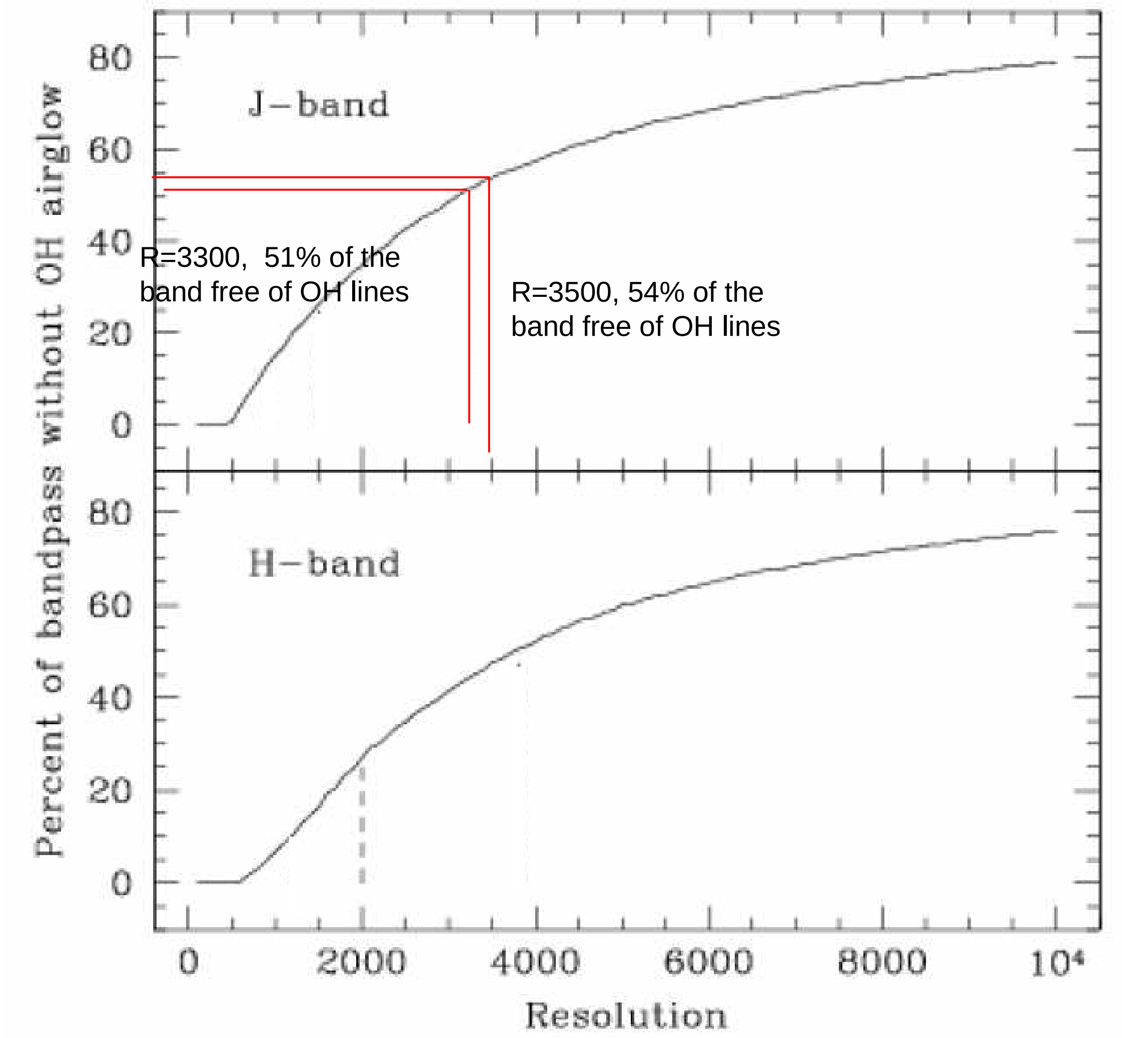

Figure 3: From Depoy & Martini, the effect of resolution on OH line coverage.

6.2 Impact of reduced spectral resolving power

The increased wavelength coverage for the IZ and J grating means that the spectral resolution of the gratings is reduced. The percentage of the bandpass free of OH lines is therefore lower than for the single window gratings, and the affect on sensitivity must be considered.

The Depoy & Martini (2000, SPIE Vol 4008, p695) model for the fraction of the J and H bands free of OH lines as a function of spectral resolution is shown below in Figure 3. The increase in coverage of the J band reduces the percentage of the band free from OH lines by just 3%.

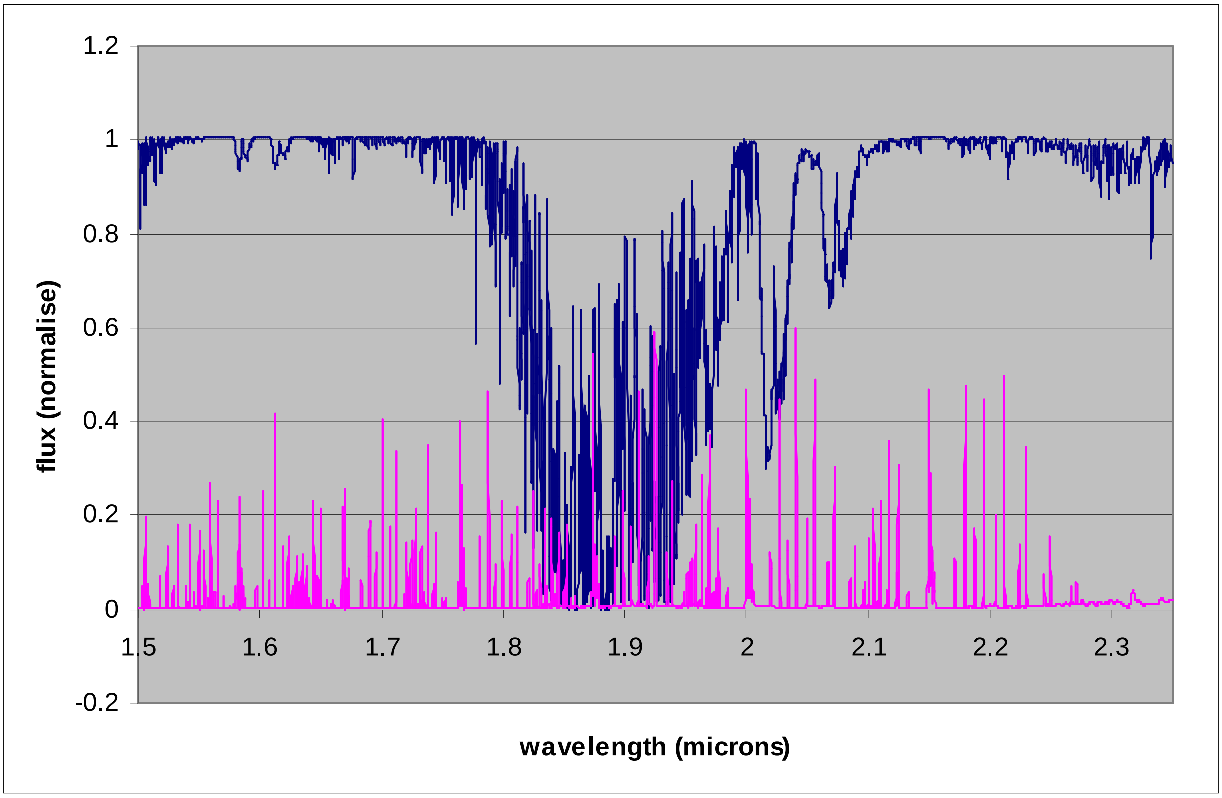

Figure 4: Simulated transmission and OH emission spectrum for the HK grating. The OH units are arbitrary, scaled to be plotted alongside the transmission.

6.3 HK and simultaneous line detections

The H+K science cases described in section 5 call for observations of sources with unknown redshift, or simultaneous observations of >2 lines (typically Halpha in K-band, and OIII and H-band). The goal is to remove any issues of spatial registrations of the different lines (though, note that the spatial registration and arm positioning accuracy of KMOS is expected to be very high).

We estimate the probability of being able to observe such multiple lines in a H+K spectrum given the OH lines and the resolution. Scanning through the redshift range from 2.1-2.6 at one pixel resolution, the following estimates of the statistics of observing the lines in the HK window are obtained.

- a 60% chance of one line falling on a dark pixel (no OH line)
- 40% of the H-beta/OIII pair both being on dark pixels
- 30% for the other pairings (H-beta/H-alpha and H-alpha/OIII)
- 30% for all three lines being free of OH lines.

The figures are pessimistic, as they assume an unresolved target lines two pixels wide Broader lines (~200km/s or ~3pixels) would be observed from these targets and could be analysed by clipping the OH affected pixels, therefore increasing the signal/noise.

6.4 The final grating suite

In summary, we propose

- to select the HK grating as the 5th grating;
- to revise the bandpass of the formal J to optimise KMOS for high (z>7) redshift science: the proposed changes would move the J band blue cut-off from1.05µm to ~0.98µm and the red cut-off to 1.33µm; this will know be known as the YJ grating.
- to revise the bandpass of the formal IZ grating to extend the IZ red cut-off from 1.05µm to 1.15µm. Such a strategy would allow for deep Ly-alpha searches (over 0.98-1.15 or z=7-8.5) keeping the broad wavelength coverage (given by 0.8-1.33) to efficiently rule out outliers using both IZ and YJ gratings.

Table 1 lists the approved gratings at PDR, and Table 3 lists our proposed changes.

Table 3

Grating	Old Wavelength Coverage (µm)	New Wavelength coverage (µm)	Central wavelength (µm)	Resolving power at central wavelength (µm)
IZ grating	0.83-1.05	0.80 – 1.15	0.975 µm	2800
HK grating	--	1.5-2.38	1.94 µm	2200
YJ grating	1.05-1.37	0.975-1.33	1.15 µm	3300
H grating	1.45-1.85	1.45-1.85	1.65 µm	3900
K grating	1.95-2.5	1.95-*2.5*	2.225 µm	3700

In Figure we show that overlap of the proposed grating set with the Hawk-I filters. The grating curves are illustrative only, as the details of the grating and blocking filter designs including throughput will be developed before FDR in July 2007. This plot clearly illustrates the strength of this final design for KMOS in following up NIR surveys.

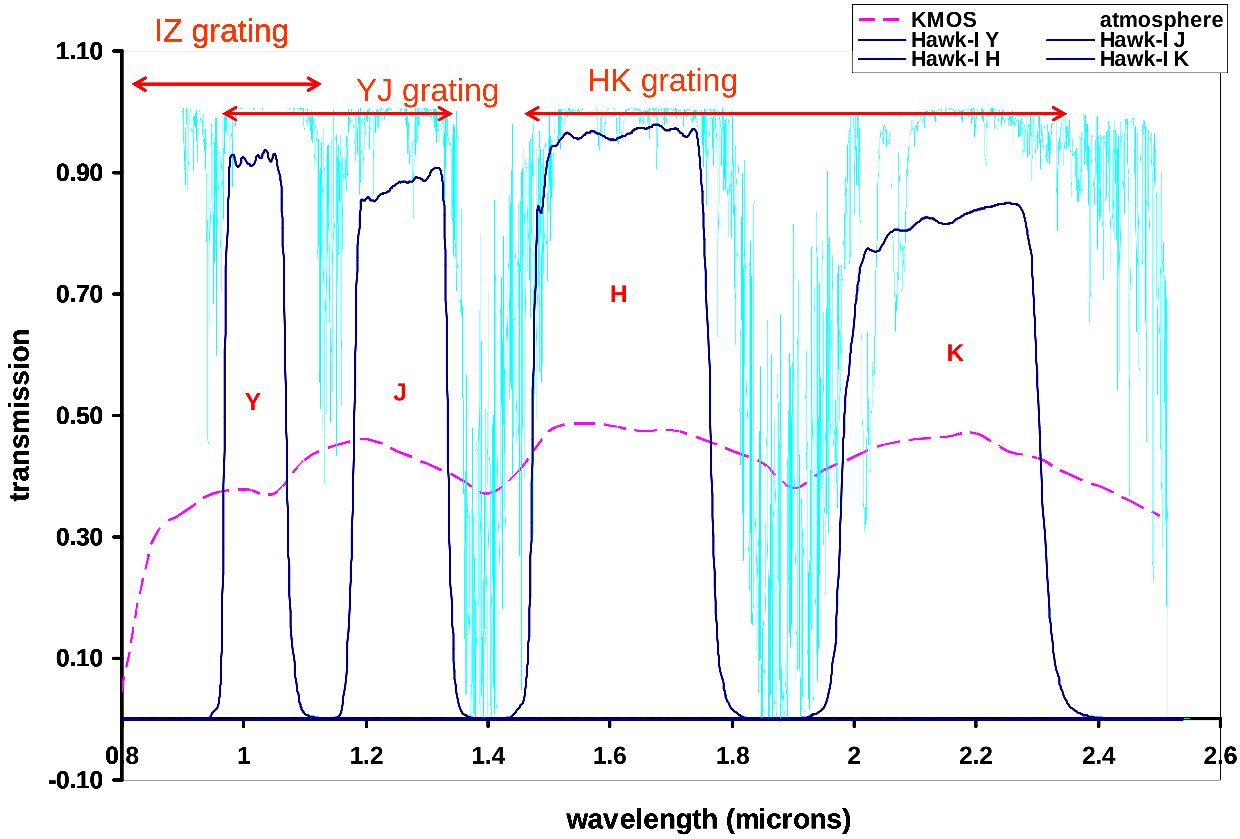

Figure 5 Hawk-I filters and KMOS wide (IZ, ZY, HK) gratings shown in red for comparison. The KMOS transmission curve includes filters and the grating efficiency curves for the original grating suite. The 0.8µm transmission will be improved with optimisation of the blocking before FDR. The detector QE is not included.