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A high resolution multi-object spectrograph for the VLT: a pre-concept design

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ABSTRACT

Following the idea originally proposed during the ESO-Workshop The Very Large Telescope in 2030, the concept of a high resolution spectrograph for the VLT has been further explored, both for the science and technological aspects. Such an instrument will fill a gap in capabilities amongst the landscape of future instrumentation planned for the next decade. Its key characteristic will be high spectral resolution (R = 60000-80000) with multi-object (50-100) capabilities and, possibly, a stability that would provide high radial velocity precision ($\sim$10m/s). In this work, we describe the science cases and driving science requirements for the instrument. Furthermore we will present some design solutions and technical options considered to meet these requirements.

Keywords: ESO-VLT, multi-object spectrographs, high-resolution spectroscopy

1. INTRODUCTION

In the next decade the new generation multi-object spectroscopic facilities and surveys, such as 4MOST[1] and WEAVE,[2] will obtain spectroscopy for millions of stars in the Milky Way at moderate spectral resolution, in support of the *Gaia*[3] mission follow-up, to study the chemo-dynamical substructures in the Milky Way discs, halo, and bulge region with samples of unprecedented size over the entire sky. The discovery space of those surveys is significant, but one can anticipate that new discoveries (e.g., streams, and substructures), but also, simply the characterization of these broad populations, will require more detailed follow-up of sizeable samples at much higher resolution, to obtain more precise radial velocities and abundances and/or abundances "difficult to measure" but key elements (e.g. n-capture elements) and/or crucial isotope ratios.
High-resolution multi-object spectroscopy (MOS) will definitely allow the follow-up of discoveries obtained with

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the aforementioned surveys. Such detailed information for relatively large samples of stars is also needed to make significant progress in stellar physics, nucleosynthesis, open and globular cluster science, including the search for exoplanets in clusters.
The development of an instrument which can guarantee high resolution and multiplex extending down to relatively blue wavelengths (from 380 nm), will push the boundaries of our knowledge in the context of Galactic and Local Group science, and is envisioned as a workhorse instrument in the future.

Table 1. Requirements for the main science cases. Signal to Noise (S/N) ratio values are reported per resolution element.

	Resolution ($\lambda/\Delta\lambda$)	Spectral Range/ lines to be covered	Multiplexing	RV accuracy	Efficiency
Galactic Science	80000	Various windows in 380-800 nm in 380-800 nm	20-100	100m/s	S/N>100 for G=15.0 in 1hr exp
Satellite Galaxies	60000	402nm[Th],406nm[Pb] 481nm[Zn], other key elements	100	100m/s	S/N >90 for V=16.5 in 2hrs exp; for B=17.5 in 5hrs exp
Exoplanets	80000	As large as possible. Simultaneous CaII lines + window at 500nm	100	10m/s	Limit. magn. of V=16.5 in 1hr exp
Young Stars	80000	Hα to CaII H&K; higher Balmer lines; 100nm simult. coverage	50	<1km/s	S/N=30 for V=15 in 300s exp
Star Clusters	>60000	800nm (C isotopic ratio, Rb abundance); 400nm (Pb and n-capture elem.);	>20	1km/s	S/N>100 for G=15.0 in 1hr exp

1.1 Science Drivers

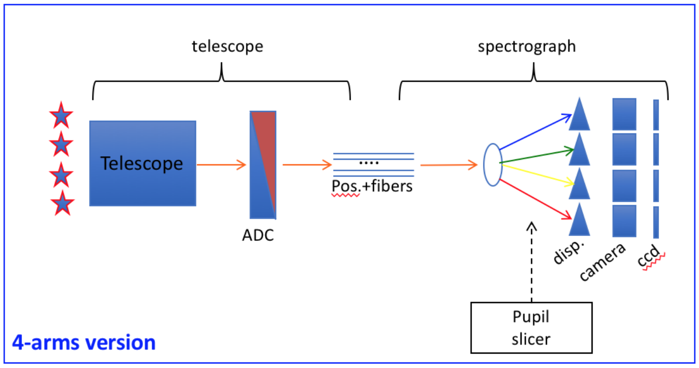
Since 2019 different science groups have been organized with the goal to specify the main science case requirements for each area. In the following, Table 1 summarizes the requirements for the different science drivers.
Two slightly different resolving powers are proposed: a solution with lower resolution (R$\sim$60000) in favour of higher S/N ratio and the possibility to observe fainter targets, as opposed to a very high resolution instrument (R$\sim$80000). Multiplexing and the minimum object separation that can be reached are other relevant parameters. A critical aspect is the simultaneous total wavelength range covered, which particularly important for the case of exoplanetary science where the maximum range is required. The same science cases also implies a stringent requirement in terms of radial velocity (RV) precision, of the order of $\sim$10 m/s. To guarantee that, the possibility to consider simultaneous wavelength calibration is under evaluation. In particular, the possibility to dedicate a certain number of fibers optics that deliver the light from the focal plane of the VLT telescope to the spectrograph is relative easy to be implemented. In addition, the introduction of a new concept for the front-end/fiber positioner has been also discussed.

2. INSTRUMENT BASELINE DESIGNS

On the base of the scientific requirements, two main concept designs and a hybrid solution have been development for the new HR-MOS.

2.1 4-Arms concept design

Figure 1 shows a possible solution for the HR-MOS, as proposed by the technical team, based on a 4-arms design, an HERMES[4] like configuration. The main optical specification are summarized in Table 2.



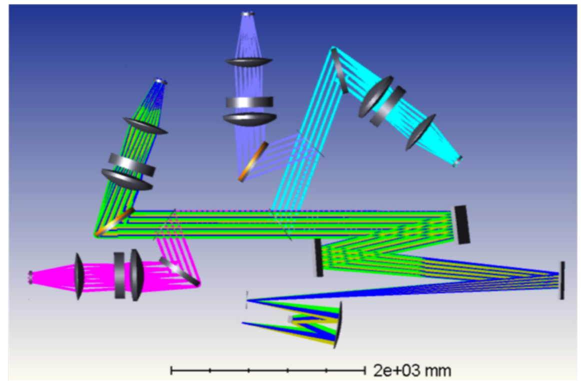


Figure 1. Instrument topology (left) and optical layout (right) of the 4-Arms concept design for HR-MOS

Table 2. 4-Arms concept design specifications.

Fiber size on Sky	1 arcsec
Minimal Spectral Resolution	80000
Detector size	9216
Pixel size (micron)	10
Number of fibers	137
Fiber F/#	5
Anamorphism	4
Pupil Slicing	4
Spectral sampling	2.5
Fiber size spatial	10
Number of fiber images on detector	548
Collimator focal length spatial	1500
Collimator focal length spectral	6000
Camera focal	789.47
Camera F/#	2.64 x 2.64
Grating Size	300/516
Grating AoI in degree	54.6
Number of lines blue grating	4415
Spectral bandwidth in the blue	15.5nm
Fiber maximal space on the detector	6.83 mm

From a scientific point of view, this solution could allow a very large simultaneous wavelength coverage and a short observing time. On the other hand, the very big dimensions, the presence of 4 dichroics, 4 dispersing elements, 4 cameras and 4 detectors makes the realization of this design demanding in terms of costs. Moreover, the drawback is that such a configuration would need to use of a huge Atmospheric Dispersion Corrector (ADC), placed very close to the VLT focal plane: if this, by a technical point of view, is an extremely interesting and challenging opportunity, it has some effects on the other instruments attached to that focal plane.

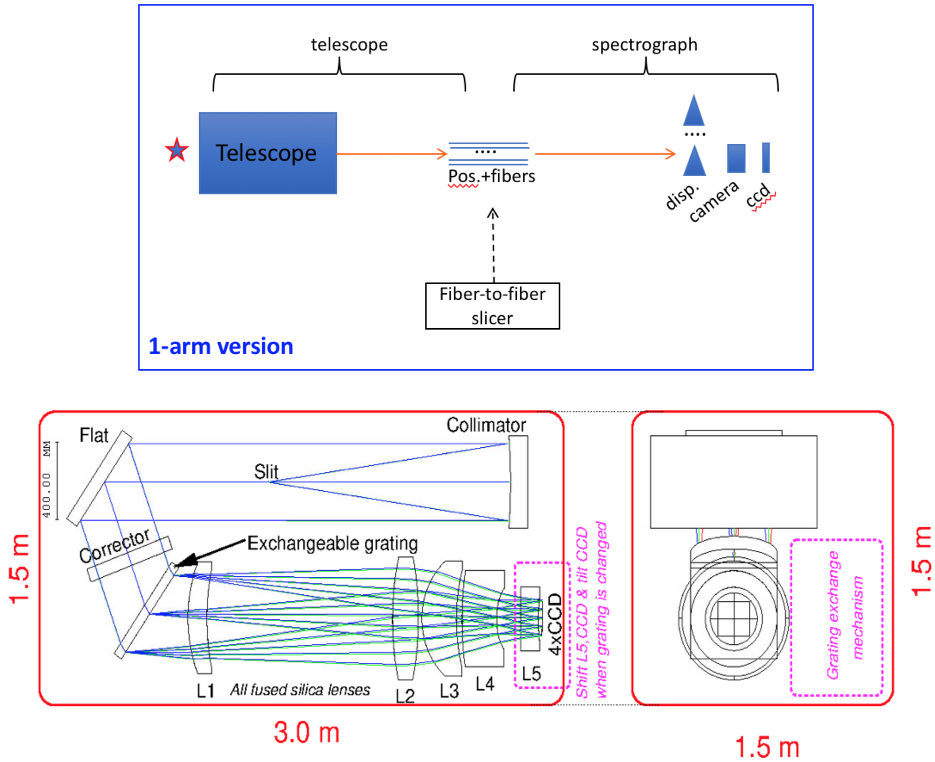


Figure 2. Instrument topology (upper panel) and optical layout (lower panel) of the 1-Arm concept design for HR-MOS

2.2 1-Arm concept design

Figure 2 shows the second solution proposed for the HR-MOS, based on a 1-Arm design. Two different configurations (for a spectral resolution R=80000 and R=60000) have been considered. The main optical specification are summarized in Table 3 for the configuration at R=80000.
In addition to a collimator and a corrector system, the concept design for this solution foresees up to a maximum of 4 exchangeable dispersing elements with no use of an ADC or dichroics, a hard camera lenses based on 5 lenses (with the last one movable accordingly with the grating selection) and a mosaic of 4 CCDs 10Kx10K (9 micron of pixel size). All the elements are positioned in a compact configuration thanks to the introduction of a plane folding mirror.
For R=80000, the 1-Arm solution ensures a S/N ratio of 100 in 1hr exposure for a mag-lim-AB of 15.2. The simultaneous wavelength coverage for a central wavelength λ_c=390 nm, 520 nm, 660 nm, 860 nm will be $\Delta\lambda$= 36 nm, 48 nm, 61 nm, 80 nm respectively.
The crucial optical element for this design is the camera lenses. However, due to the relative slow working f-number, the overall design complexity is relaxed and the performance are good for all the selected wavelength bands and for a so huge focal plane dimension. On the other hand the absence of an ADC, makes the simultaneous spectral acquisition from 390 nm to 860 nm (as central wavelengths) impossible, increasing the observation time for each object under study.

2.3 Hybrid Solution

In order to solve the dichotomy between the 4-Arms and 1-Arm solutions, an intermediate concept design is also under study. Figure 3 shows the instrument topology for this hybrid concept.
Following the optical path, the beam after fiber slicing, is redirect to a collimator system and a single disperser element (Lithographic/Holographic Etched Grating). Then, the light is divided in 3 wavelength bands using

Table 3. 1-Arm concept design specifications.

Minimal Spectral Resolution	80000
Detector size	Mosaic of 4 CCDs, 10Kx10K
Pixel size	9 micron
Number of camera lenses	1
Diam. of collimated beam	400 mm
Slit length	240 mm
Number of wav. bands/grating	4
Blaze angle of gratings	37.5 deg
Simultaneous Spectral coverage ($\Delta\lambda/\lambda_c$)	9%
Central wavelength bands (λ_c)	390nm(U), 520nm(B), 660nm(V), 860nm(I)
Spectral sampling	2.7px
Number of objects	50
Number of slices	31 or 37
Diam fibers on sky	1.2 arcsec
Diam fibers to spectrometer	0.21 arcsec

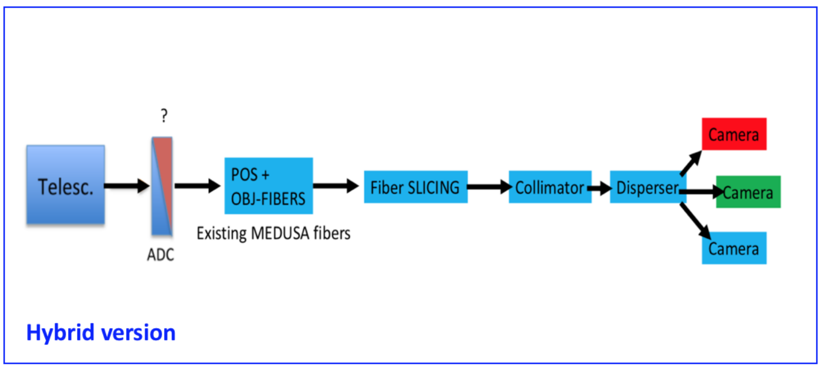


Figure 3. Instrument topology of the Hybrid concept design for HR-MOS.

dichroics and imaged in 3 different ccds by the 3 camera lens.
Albeit this layout can ensure in total a large simultaneous wavelength coverage, a critical point of this layout is that the 3 wavelength bands are not independent. Moreover, the location of the dichroics after the disperser, makes optically more difficult the design forcing the camera lens to be quite far away. The main optical specification are summarized in Table 4 for the configuration at R=80000.

3. FIBER SLICING

For the 1-Arm design in particular, but also extendable to the 4-Arm design, the possibility to introduce a fiber slicer has been considered. Two main models are under evaluations (see Figure 4). The first concept refers to the multi-fiber links presented in the OPTIMOS-EVE study for the E-ELT.[5] The second concept uses an on-axis parabola as a collimator and an array of hexagonal off-axis mirrors to slice the light from a central large fiber in several small fibers with microlens.
The introduction of a fiber slicer could have a great strategic advantages with respect for example to a pupil image slice, usually located into the spectrograph, after the collimator and before the dispersers. Fibers can

Table 4. Hybrid concept design specifications.

Minimal Spectral Resolution	80000
Diam fibers on sky	1.2 arcsec
Diam fibers to spectrometer and F/#	53 micron - F/5
Number of objects	132
Number of slices	19 (hexagonal pack)
Coll F/#	10
Coll focal length	2800 mm
Collimated beam size	280x280 mm
Slit length	294 mm
Blaze angle of gratings	48.7 deg
Grating line density	641.7 l/mm
Camera F/#	2.2
Camera focal length	606 mm
Detector size	9Kx9K
Pixel size	10 micron
Spectral sampling	2.3px

be organized and changed with no limitation in future. Moreover, the fiber slicer is a completely independent component with respect the spectrograph or the positioner. This means that from an organizational point of view, the overall instrument has the possibility to be separated into functional parts: focal plane positioner, fiber slicer and light transportation and spectrograph.

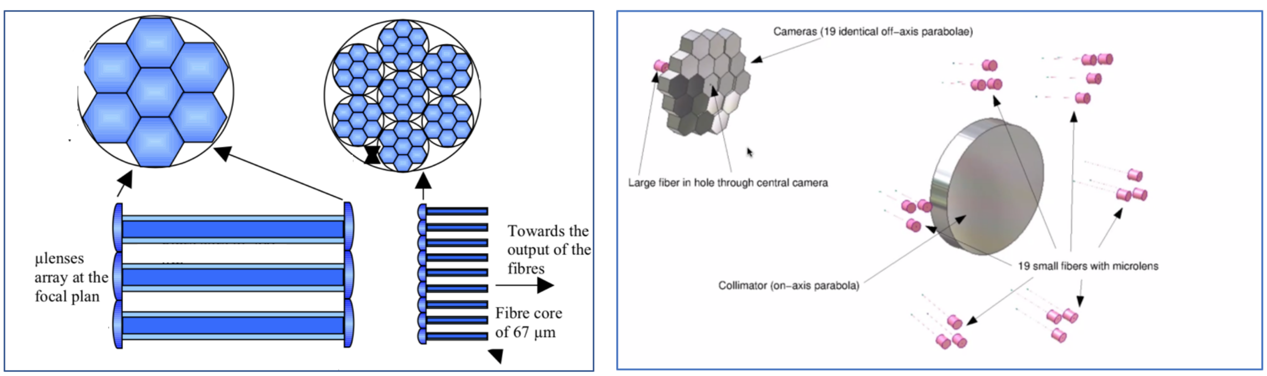


Figure 4. Possible concept designs for the Fiber Slicer. Left panel: Solution presented for OPTIMOS-EVE study for the E-ELT (Credits to Isabelle Guinouard (GEPI)). Right panel: Slicing based on an on-axis parabola as a collimator and an array of hexagonal off-axis mirrors to divide the light from a central large fiber in several small fibers with microlens.

4. CONCLUSIONS

The concept of a high resolution spectrograph (HR-MOS) for the VLT has been investigated, both for the science and technological aspects. Such a project will be a workhorse instrument in the future in the context of Galactic and Local Group science. Two main concept designs have been discussed in order to meet the scientific requirements based on a 4-Arms solution and a 1-Arm solution. An intermediate design has been also proposed. A trade-off (see Table 5) is on ongoing to evaluate the performance of each solution.

Table 5. Trade-off Table

	4-Arms Design	1-Arm Design	Hybrid Design
ADC	yes	NO	?
Slicer	Pupil	Fiber	Fiber
Dispersing elements	4	1	1
Disperser dimensions	challenging	commercial	feasible
Dichroics	yes	No	yes
Camera lenses	4 simple	1 feasible	3 simple
Detector	4 (separated)	1 (mosaic)	3 (separated)
Total Dimensions	huge	feasible	TBD
Simultaneous wav. coverage	larger	smaller	larger

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