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ELT-HIRES the High Resolution Spectrograph for the ELT: Fiber Link

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ABSTRACT

ELT-HIRES is the high resolution and ultra-stable Echelle spectrograph for the ELT. It has been conceived as a modular instrument provided with two independent spectrometers (the baseline design) and a possible extension to four, each of them optimized to cover a fixed spectral range. The role of the fibers is essential to provide the required ultra-stability. Placed at the Nasmyth focus of the ELT, the HIRES fiber link transfers the light from the focal plane to the spectrographs. Each observing modes will be use a unique and independent group of fibers (bundle). The HIRES modular design makes it possible to have new observing modes just with the addition, removal or change of the specific bundles. From a functional point of view the HIRES fiber link subsystem performs some other important tasks, such as dicing the field of view, improving the system stability and providing a uniformly illuminated slit for spectrographs. It is a key subsystem for the instrument and represents a significant technological challenge. The technical requirements, conceptual design and technologies to be used are discussed in this paper. The current status of the subsystem, and future plans are also addressed.

KEYWORD LIST

Extremely Large Telescopes, High Resolution Spectroscopy, High Stability, Optical Fibers, Fiber bundles, Optical Scramblers, Fiber Links.

1. INTRODUCTION

Scheduled for first light in 2024, the European Extremely Large Telescope (ELT) will be the largest ground-based telescope at visible and infrared wavelengths. This telescope will be located at Cerro Armazones in Chile, taking advantage of the favourable site conditions and existing infrastructure. The flagship science cases supporting the successful ELT construction proposal were the detection of life signatures in Earth-like exoplanets and the direct detection of the cosmic expansion re-acceleration and it is no coincidence that both science cases require observations with a high-resolution spectrograph.

Over the past few decades high-resolution spectroscopy has been a truly interdisciplinary tool, which has enabled some of the most extraordinary discoveries spanning all fields of Astrophysics, from Exoplanets to Cosmology. Astronomical high-resolution spectrometers have allowed scientists to go beyond the classical domain of astrophysics

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and to address some of the fundamental questions of Physics. In the wide-ranging areas of research exploiting high-resolution spectroscopy, European scientists have been extremely successful, thanks to the exquisite suite of high-resolution spectrographs that ESO provides to its community. UVES, FLAMES, CRIRES, X-shooter and HARPS have enabled European teams to lead in many areas of research.

ESPRESSO[1], which is now joining this suite of very successful high-resolution spectrographs, holds the promise of truly revolutionising some of these research areas. The scientific interest and high productivity of high-resolution spectroscopy is reflected by the fact that more than 30% of ESO publications can be attributed to its high-resolution spectrographs.

However, it is becoming increasingly clear that, in most areas of research, high-resolution spectroscopy has reached or is approaching the "photon-starved" regime on 8-10m class telescopes. Despite major progress on the instrumentation front, further major advances in these fields desperately require a larger photon collecting area. Due to its inherently "photon-starved" nature, amongst the various astronomical observing techniques, high-resolution spectroscopy requires the collecting area of Extremely Large Telescopes.

2. ELT AND HIRES

When defining the ELT instrumentation, ESO commissioned two phase-A studies for high-resolution spectrographs, CODEX and SIMPLE, which were started in 2007 and completed in 2010. These studies demonstrated the importance of simultaneously covering the optical and near-IR (NIR) when performing high-resolution spectroscopy at the ELT.

Figure 1. The Extremely Large Telescope (credit ESO) will be the largest optical telescope in the world, with a primary mirror diameter of 39.5 m. Instruments, will be fed from ports on one of the Nasmyth platforms (here shown left and right). The optical spectrograph of HIRES will be located on one of these platforms, with the NIR spectrograph located below in the Coudé room.

This marked the birth of the HIRES initiative (http://www.hires-eelt.org). With the start of construction of the ELT, the HIRES Initiative has decided to organize itself as the HIRES Consortium and has recruited additional institutes, which expressed their interest in HIRES. The consortium, strongly motivated by the unprecedented scientific achievements that the combination of such an instrument with the ELT will enable, was commissioned to perform a Phase A study by ESO. The Phase A study started in March 2016 and successfully concluded in May 2018.

Currently, ELT-HIRES is the only planned high resolution and ultra-stable echelle spectrograph for the Extremely Large Telescope.[2]

ELT-HIRES is conceived as a modular instrument provided with two independent spectrometers (baseline) and a possible extension to four,[3] each of them optimized to cover a fixed spectral range. Hence, the major scientific Top Level Requirements of the instrument (i.e. high spectral resolution and simultaneous full optical/NIR spectral coverage) can be fulfilled. Moreover, to guarantee the required wavelength stability, mobile parts and sources of kinetic perturbation are reduced to minimum.

The role of the fibers is essential to provide the ultra-stability of ELT-HIRES. Located at the Nasmyth focus of the ELT, the ELT-HIRES Fiber Link transfers the light from the focal plane to the spectrographs that are firmly placed at Nasmyth Platform (optical) and Coudé Room (NIR) (see Figure 1 and Figure 2).

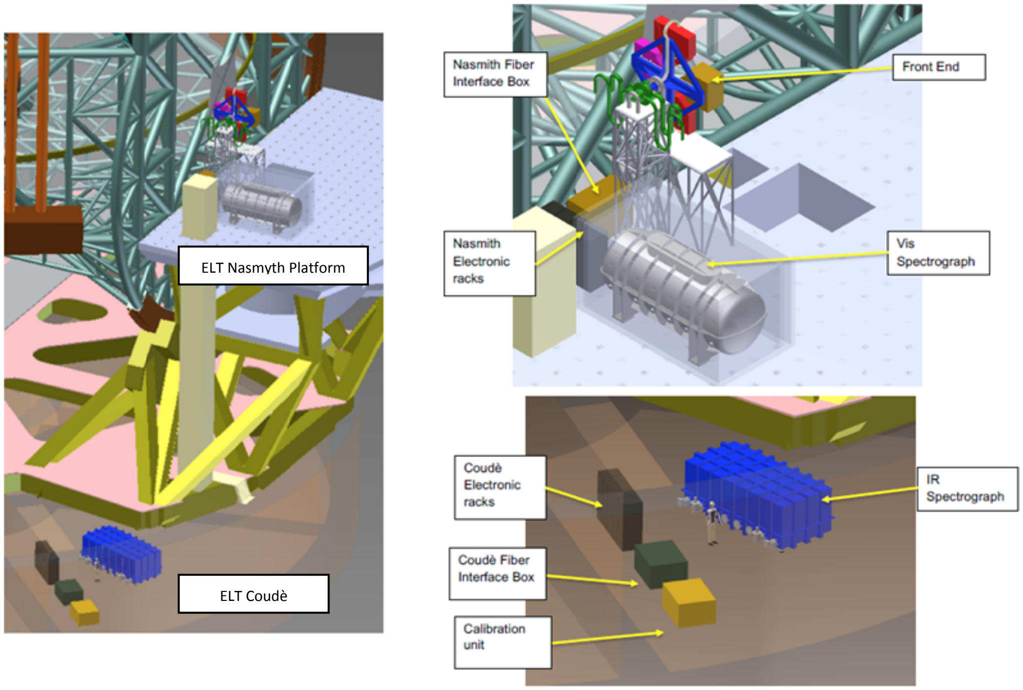


Figure 2. ELT-HIRES distribution (left). System at Nasmyth Platform (top left) and Coudè Room (bottom right).

3. FIBER LINK FUNCTION

The Fiber Link (FL) bundles carries the light from the Front End (FE)[4] focal plane to the spectrographs via the fiber-to-fiber (F2F) interface. Its role in the Functional Architecture of the instrument is shown in Fig. 3.

The observing mode is selected at the level of the FE-FL interface. This modular approach allows the number of observing modes to be increased by adding other bundles of fibers and slits.

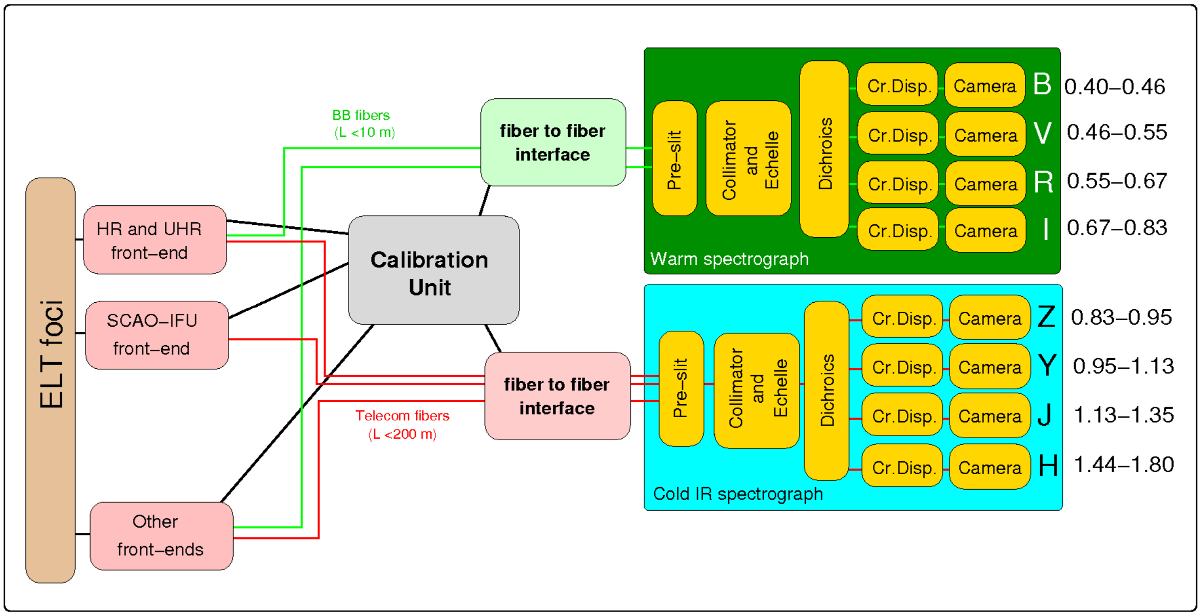


Figure 3. The ELT-HIRES Functional Architecture, with light split between two spectrographs, optical at the top and NIR at the bottom.

Several bundles are provided so as to cover all scientific observing modes. Most of the science cases require seeing-limited observations (either maximizing the throughput or the accuracy). Some science cases require spatially resolved spectroscopy by means of an adaptive optics (AO)-assisted integral field unit (IFU) at high spectral resolution or some multi-object spectroscopy at medium spectral resolution and/or some spectro-polarimetric capabilities.[5][6] There are specific bundles to cover all them.

Thus, the idea is to provide a unique and independent group of fibers (bundle) for each different observing mode. The modular design makes it possible to have new observing modes just with the addition, removal or change of the specific bundles.

From a functional point of view the ELT-HIRES FL subsystem performs some other important tasks as dicing the field of view (FoV), improving the system stability and providing a uniformly illuminated slit for spectrographs. It is a key subsystem for the instrument and it represents a challenge, due to the size and number of fibers that are required.

The ELT-HIRES Fiber Link comprises not only of fibers but also optics, mechanics and feedthrough devices. As it is the connection between other functional subsystems in the instrument, interface design and control systems are key issues from the system point of view.

3.1 The ELT-HIRES FL functions

- To Dice the field using a Field Dicer.
- To convert the F/20 FE beam in a F/3.5 beam and inject it into an optical fiber that is used to transport the light to the spectrograph.
- To improve the system stability in the observing modes optimized for accuracy. It stabilizes the illumination of the source at the entrance of the spectrograph and provides a uniformed illuminated slit for spectrographs.

- To transfer light from FE to the spectrograph via the F2F interface. For the modes optimized for accuracy it also provides simultaneous calibration light.
- To transfer light from CU to the FE.

3.2 Bundles for each Observing Modes

At this point the ELT-HIRES FL supports at least 12 Observing Modes:

- Observing mode B1: High throughput high resolution single aperture
- Observing mode B2: High throughput high resolution double aperture
- Observing mode B3: High throughput Ultra-high resolution single aperture
- Observing mode B4: High throughput Ultra-high resolution double aperture
- Observing mode B5: High accuracy high resolution single aperture
- Observing mode B6: High Accuracy high resolution double aperture
- Observing mode B7: High accuracy Ultra-high resolution single aperture
- Observing mode B8: High accuracy ultra-high resolution double aperture
- Observing mode A1: SCAO mode high resolution
- Observing mode A2: SCAO mode ultra-high resolution
- Observing mode A4: Polarimetry High resolution mode
- Observing mode A5: Polarimetry Ultra-High resolution mode

	Spectroscopy										Polarimetry	
Observing Mode	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**A1**	**A2**	**A4**	**A5**
Resolution	100K	100K	150K	150K	100K	100K	150K	150K	100K	150K	100K	150K
FoV on sky (arcsec^2) (per bundle)	~1.4	~0.68	~1	~0.46	~1.4	~0.68	~1	~0.46			~0.68	~0.46
Number of bundles	1	2	1	2	1	2	1	2	1	1	2	2
Total number of fibres	64	64	96	96	64	64	96	96	64	96	64	96
Req.	Maximum Throughput				Maximum Accuracy				AO assisted IFU		Double Scrambler	

Table 1. ELT-HIRES observing modes (OMs) and bundles definition

3.3 Bundles description

Fiber Link subsystem is conceptually divided into 3 main parts: Input Bundles, Fiber to Fiber Interface and Output Bundle. Each part is linked to a certain functional requirement. Thus:

- The “Input Bundles” include the Field Dicing subsystem, implemented in order to improve the resolution-throughput product. Field Dicing is the main mode of operation in ELT-HIRES, with an IFU[8] and Pupil Dicing as probable alternatives to consider in future phases.

- The “Fiber to Fiber Interface” (into the so-called “F2F Boxes”, Figure 4) connects the bundles coming from the FE to those going to the spectrometers. For the observing modes that require high accuracies it includes sub-systems that stabilize the illumination for the spectrographs (scrambling of the light). As the device where the fibers are split, it could include any mechanism, shutter or interface that is required.
- “Output Bundles” connected to linear arrays of micro-lenses that act as entrance slits. Each slit is generated with the fibers of a particular bundle that determines the observing mode.

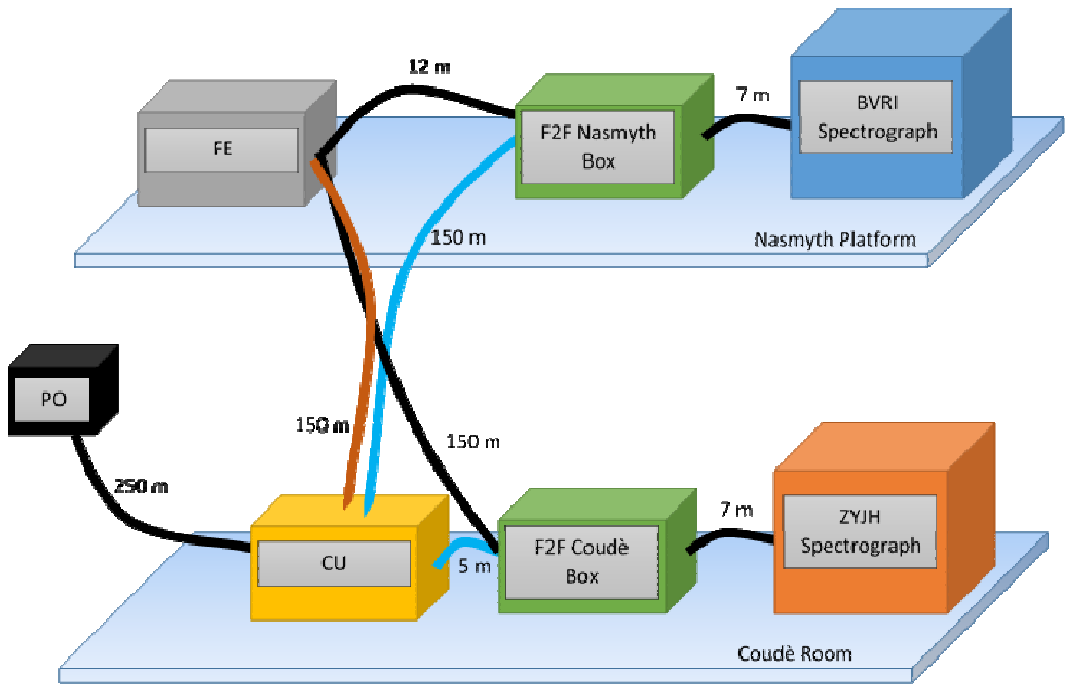


Figure 4. Functional distribution of the FL bundles. Projected fiber length is indicated.

Legend: FE -> Front End Subsystem [4], PO -> Polarimeter [5][6], CU -> Calibration Unit [7], F2F -> Fiber to Fiber

3.4 Field Dicers at Front End interface

The input of the fiber link turns a F/20 beam coming from the FE into a F/3.5 beam that is injected into the optical fiber bundle.

For most OMs, it also dices the FoV (according to the scientific requirements) and projects the image of the pupil onto the input end of the fiber.

The arrays of microlenses (Field Dicing) will be composed of different number of hexagonal lenses, which will be close packed to form a large hexagonal pattern.

A hexagonal arrangement has been selected to fit the circular FoV. If a square FoV is required, it would be more convenient to choose a square arrangement (also standard in fabrication).

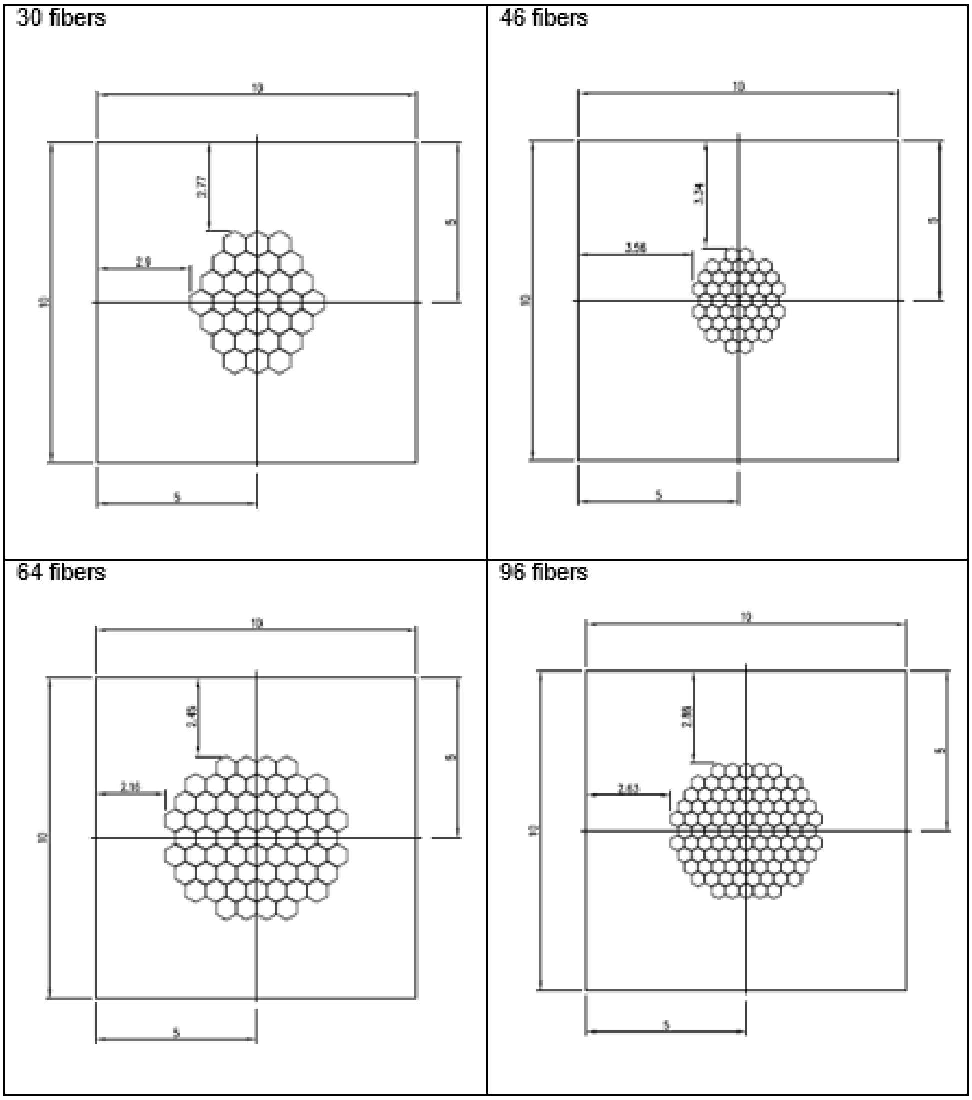


Figure 5. FE mechanical interface (sketch). Units: mm.

In the particular case of polarimetry, it will also provide an F/20 output beam, quasi-telecentric (to minimize injection losses). That will be the optical interface with FL subsystem.

Considering polarimetry requirements, length, size, material and arrangement of the fibers for polarimetry are the same as in B2 and B4. Also part of the optics affecting the bundles is coincident with B2 and B4 –modes for spectroscopy. The difference between spectroscopy and polarimetry bundles is in the F2F Interface; polarimetry requires Double Scrambling optics for Modal Noise Reduction.

On the Polarimetry Arm, at the FE-FL interface, there will be the following bundles: (e= extraordinary beam / o= ordinary beam).

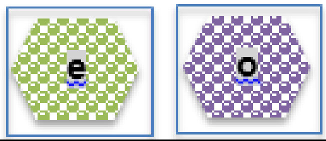
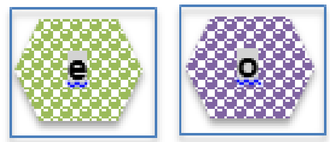
OM11	OM12
30 + 30 fibres	46 + 46 fibres
	

Figure 6. FE fiber distribution for polarimetry (A4 & A5) in Tab. 1

The separation between bundles will be determined by polarimeter optical design. This separation is expected to be > 10mm. There are no special requirements for the mechanical interface, it is considered to be the same as the rest of the bundles.

3.5 Connectors

Standard connectors will be used to join “input bundle” and “output bundle” when maximum throughput is the goal (i.e. OMs with no requirement on high accuracy). There are some custom solutions and many commercial options for multi-fibre schemes.

Figure 7. Glenair MIL-spec multi-fibre connector. 48-fibre versions are commercially available. It uses a modular design. The connector is built up of individual ceramic ferrule 'pin' inserts (shown in the picture below the connector halves).

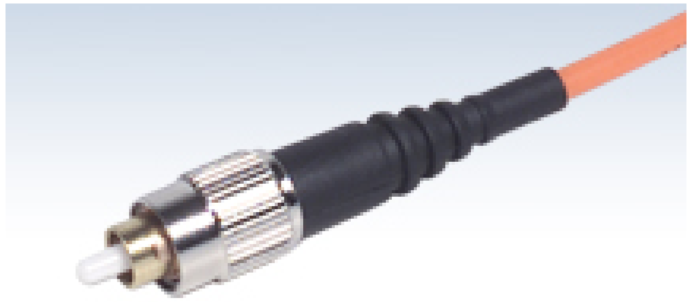


Figure 8. FC/PC connector type. This type of connector is commercially available and used in ESPRESSO [13]

3.6 Feedthrough

There are two interfaces between the FL subsystem and spectrographs, these are: the fiber feedthrough and slits. According to the ELT-HIRES design, the bundles of fibers will pass through the dewar/cryostat wall so as to form the interface for the slit.

The ELT-HIRES feedthroughs will be mechanical and continuous. There are several options from commercial vendors for multi-fibre schemes and some designs are being developed inside ELT-HIRES Team in parallel so as to achieve a better “in house solution”.

Figure 9. An example of a commercial connector. Here pin-style sub-connectors are incorporated into a complete vacuum feedthrough.

3.7 Scrambler

An important function of the Fiber Link subsystem is improving the system stability for the observing modes requiring high accuracy, thus avoiding variations the illumination of the spectrograph pupil or in the fiber image on the detector. Scrambling is an intrinsic attribute of real optical fibres by which, the light distribution at the fiber entrance is partially scrambled at the output end. However this effect is not perfect and some information of spatial light distribution is preserved. It can be distinguished two different manifestations of this property: Near-Field (NF) scrambling is associated with variations of illumination of the image of the fiber and the Far-Field (FF) scrambling which is associated with the distribution of image light into the pupil. Both effects should be treated differently.

The ELT-HIRES optical scrambler may be a challenge (the flux variation between the fibers of ELT-HIRES is an issue when high radial velocity precision is required). Its development will be based on other instruments solutions [12][13][14][15], but some innovative alternatives may be considered so as to optimize the performance of the system. The phase A analysis included the study of:

- The use of rectangular fibers to mix the light of several fibers into a single one.
- Pupil illumination to feed the input bundles at FE.
- A fiber bundle double scrambling scheme.

In the following phases of the project, the advantages (spectral accuracy, stability, repeatability) and disadvantages (light losses, costs) of these solutions will be evaluated. In addition, prototype tests will be developed.

3.8 Slits

Each bundle forms a slit that is part of the "slit unit" feeding each spectrograph. This subsystem feeds the spectrograph with a telecentric beam (FL optical beam).

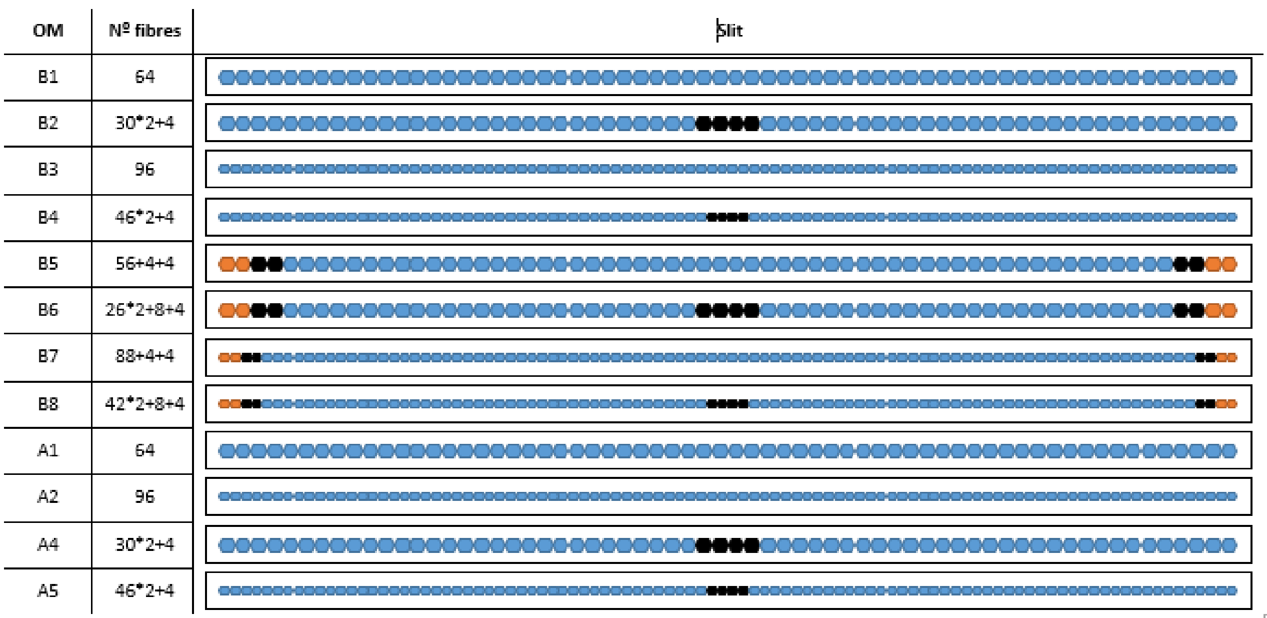


Figure 10. Distribution of the fibers at slit interface, with the relevant observing modes (OM) described in Table 1. Here, the calibration fibers are in orange, black points are dark fibers (non-illuminated) used to physically separate light coming from different objects.

3.9 Fiber bundles

The key elements of the FL are obviously optical fibers. They allow the transport of light in an efficient way from one place to another and, when necessary, they can be used to improve the stability of the image of the object by scrambling effects. Depending on the OM, one or two bundles are required, these bundles are shown in Table 1.

The fiber size will be defined by throughput conservation. The magnification needed for the conversion of F/# determines the size of the fibers for each of the modes of observation. Taking into account the beam injection aperture for the fibers, F/3.5, and the sky-project width of the spectrometer slit (0.170 arcsec for R=100,000 and 0.113 arcsec for R=150,000), the size of the fibers core will be: 123 and 75 microns. In the high accuracy modes octagonal fibers will be used to optimize the NF scrambling. Fibers with square and octagonal cores are currently manufactured and this type of fiber presents very good NF scrambling capabilities.

Another feature to consider is the focal ratio degradation (FRD). There are several causes of the FRD (manufacturing techniques, use of adhesives, bending in the fibers, roughness at fibers end etc.) All these causes must be minimized during the manufacturing process of the bundles. Whilst uncommon for telecommunications purposes, there are manufacturers who have optimized their manufacturing processes to minimize microbends and stress on its fibers. Choosing epoxies and gluing processes minimizes stresses and a correct routing of protective external elements in the fiber bundle can minimize FRD effects. Finally, the use of telecentric beams (as in ELT-HIRES) and the correct alignment of the fibers inside the bundles also minimizes the effects of FRD.

All the proposed science bundles are provided with input optics to dice the image of the FoV in the FE focal plane. These optics will also inject the light into the fibers, by fitting each dice of FoV into a fiber core. Calibration fibers (used for simultaneous calibration in some of the observing modes) will work in the same way and are going to be part of the final bundle.

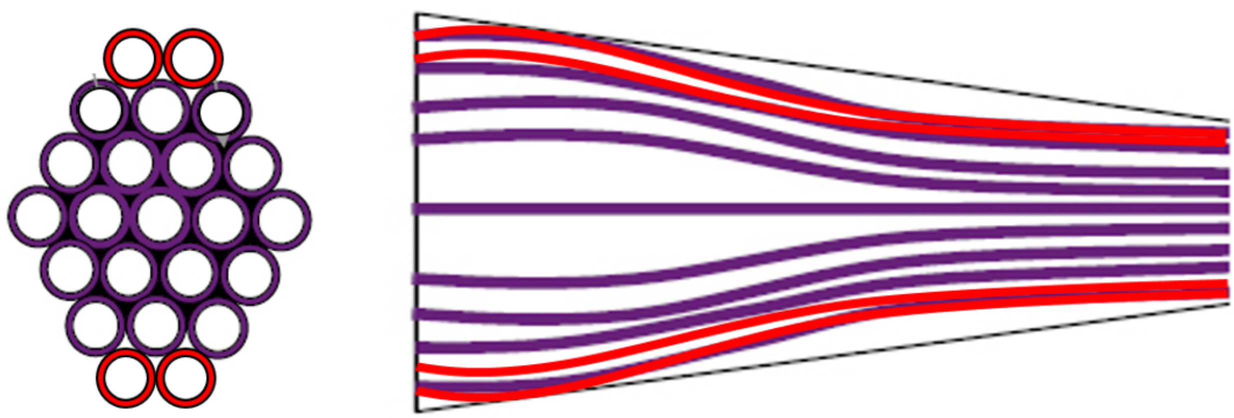


Figure 11. Example of how fibers for science (purple) and for simultaneously calibration (red) could be distributed along the bundles. Calibration fibers will be placed out of the science FoV at FE focal plane (left) and on the final ends of the slits at spectrograph entrance (right)

Each OM is linked to a particular bundle. This way, the requirements for each OM will be fulfilled by the provision of particular devices along the bundle.

The preliminary cable design builds on that already successfully implemented in FMOS, PFS and DESI.[16] Here, stranded cables are used where the tensile load is supported by high strength core. Each fiber has slack built in per unit length (of the order of ~2%) that ensures the minimal stress due to cable bending (known as ‘racetracking’).

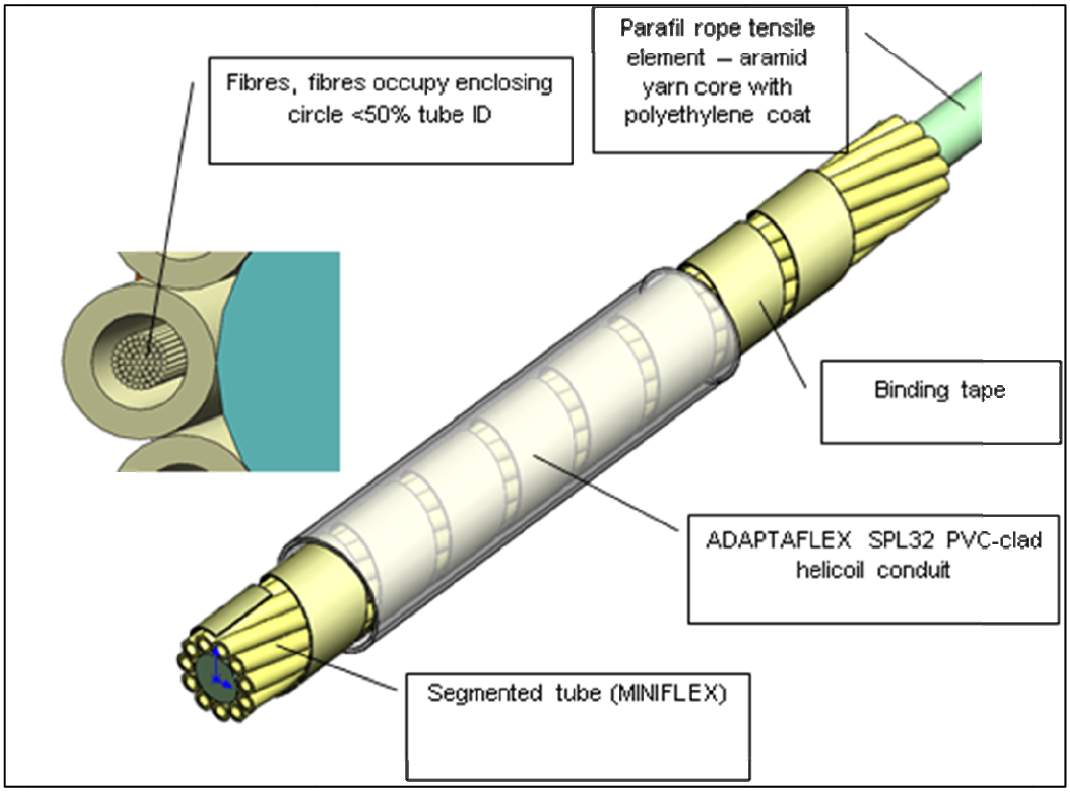


Figure 12. The concept for stranded cables for the ELT-HIRES FL subsystem. This design is used to reduce stresses on the fibers due to bending.

Past studies have shown bends should be avoided below a 30 cm - 40 cm radius (PFS prototype: 32 mm OD cable carrying several hundred fibres having 128 micron core).

Cable twisting is also something to be avoided for a stranded construction. Special care should be taken during installation to monitor and correct any twists that are applied. If cable twisting is necessary or unavoidable, a maximum limit of ± 180 degrees over several metres would minimize problems.

The precise safe values for bending and twisting are cable-specific and a prototype would need to be tested to provide accurate figures.

The diameter of the cables (bundles) would be around 32 mm, which approximately yields a total cable weight of around 2 tons.

4. CONCLUSIONS

ELT-HIRES is the high resolution and ultra-stable Echelle spectrograph for the Extremely Large Telescope (ELT). It is a modular instrument and in the baseline design, light is split into two independent spectrometers, one covering the optical and the other the near infra-red. There is also scope for a possible extension to four spectrographs, by adding an ultraviolet and K band spectrographs. The role of the fibers is essential to provide the required ultra-stability for these spectrographs.

In this paper we have discussed functions and the design of the Fiber Link subsystem, which will transfer the light from the focal plane of the ELT to the spectrographs. A particular portrayal of each bundle has been included and all the main parts of the subsystem have been described. These include the functional architecture, a description of the observing modes and the effect on their fiber bundles, the field dicer, which allows the light to enter the fibers, the fiber connectors and feedthrough system, preliminary ideas for a scrambling system, the output slits at the spectrograph and specifications of the fiber bundles.

ACKNOWLEDGEMENTS

This work has been developed thanks to the valuable contribution of several teams that have been working for years so as to improve the use of fibers for astronomy. As it is usual and advisable in any technological project, the ELT-HIRES Fiber Link has taken advance of this research and heritage.

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