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ELT-HIRES the High Resolution Spectrograph for the ELT: the IFU-SCAO module

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ABSTRACT

The first generation of ELT instruments will include an optical-infrared High Resolution Spectrograph, conventionally indicated as ELT-HIRES. This paper describes the optical design and overall architecture of the Integral Field Unit (IFU) that will fed the spectrograph. The module have the possibility to change the spaxel dimension thanks to a series of reflection mirrors and using a fast tip tilt mirror the position of the re-imaged foci on the fiber bundles can be adjusted looking at the focus image that is visible using a fiber viewer IR camera.

Keywords: Ground-based instruments, high resolution spectrographs, infrared spectrographs

1. INTRODUCTION

The European Extremely Large Telescope (ELT) will be the largest ground-based telescope at visible and infrared wavelengths. The flagship science cases supporting the successful ELT construction proposal were the detection of life signatures in Earth-like exo-planets and the direct detection of the cosmic expansion re-acceleration. It is no coincidence that both science cases require observations with a high-resolution spectrograph. The HIRES-ELT instrument foresees an observing mode that delivers integral field high resolution spectroscopy with spatial sampling down to the diffraction limit of the ELT telescope. The IFU module presented here is sub-system of the front-end of HIRES-ELT that includes two module, namely:

- SCAO module. It is the wavefront sensor, based on a pyramid beam-splitter, that provides the guiding on the reference star and the analysis of the incoming wavefront. The expected performances of the SCAO correction are presented in XXXXXXXX.
- IFU module. It is the module that transforms the incoming f/17.7 light beam from the telescope to the appropriate f/numbers to feed the spectrometer fibers-array with the required spatial scale. The module have the possibility to change the spaxel dimension thanks to a series of reflection mirrors and using a fast tip tilt mirror the position of the re-imaged foci on the fiber bundles can be adjusted looking at the focus image that is visible using a fiber viewer IR camera. The two modules are optically separated by a dichroic window.

2. OVERALL CONCEPT OF THE ELT-HIRES INSTRUMENT

The IFUSCAO module collects the light coming from the ELT and it will injected it into the optical fibers bundle.
The module is composed by two different subsystems optically separated by a dichroic window:

- SCAO module. It is the wavefront sensor, based on a pyramid sensor, that will provide the guiding on the reference star and the analysis of the incoming wavefront.
- IFU module. It is the module that will transform the incoming f/17-7 light beam to the appropriate f/# to feed the microlenses placed on the input side of the fibers, arranged in a squared configuration.

The IFU-SCAO is located into the Nasmyth derotator structure as visible in Figure 1: it is a gravity variant box of 1250x1150x750 mm where the two subsystems are placed one over the other.

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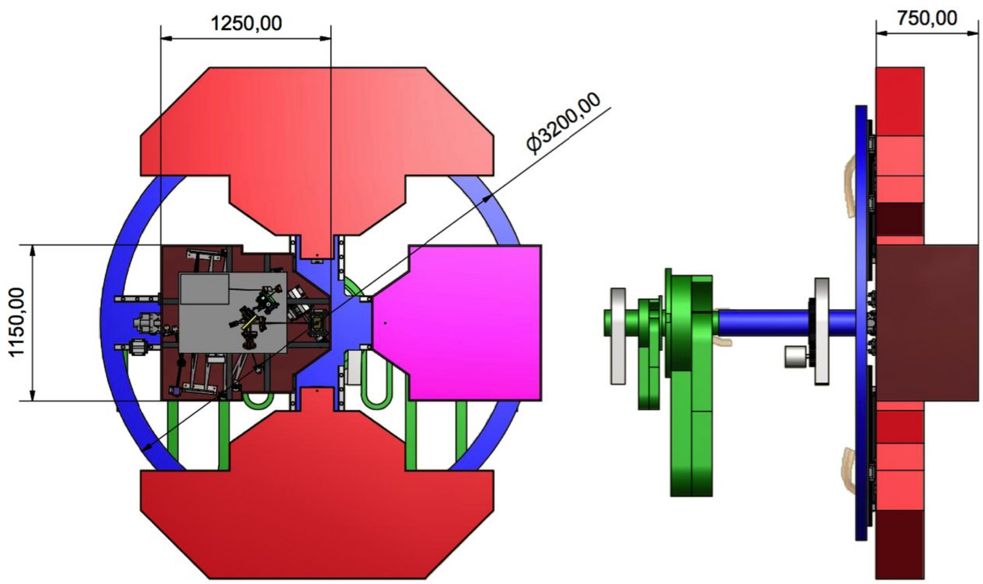


Figure 1 The IFU-SCAO mudole is located into the Nasmyth Derotator structure
The box is placed on a translation stage, visible on the left side of the brown box, to have the possibility to be used alternatively with the other modules, in red and pink in figure.

In Figure 2 the mechanical design of the IFU-SCAO module is visible. It is composed by the two subsystems: looking at the figure in the bottom part of the box there is the IFU module fed by the transmitted IR light (950-2400 nm) by the dichroic window, while the SCAO module is placed on the top part of the same box and fed by the reflected bluer light (400-950nm).

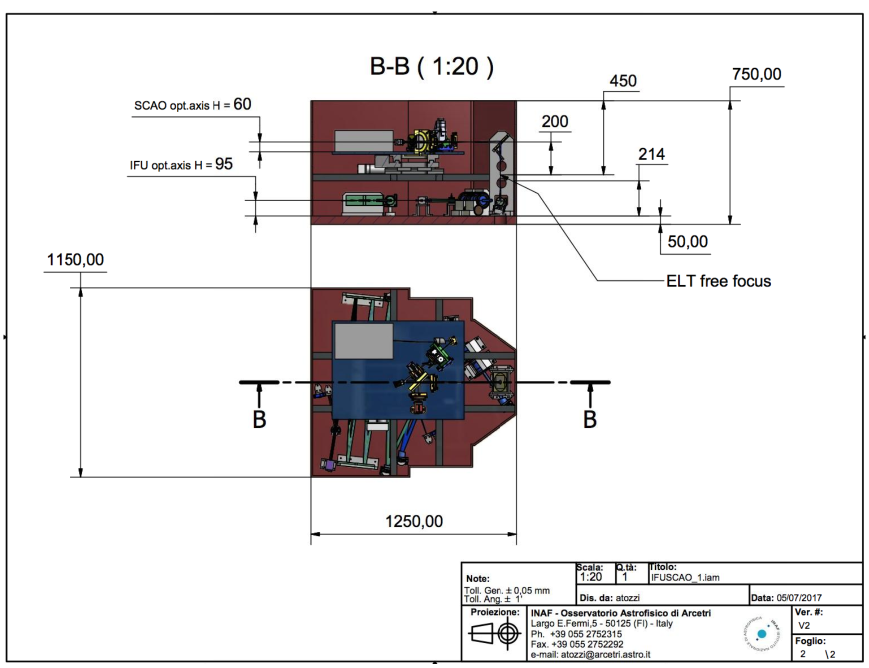


Figure 2 Mechanical design view of the IFU-SCAO module: two separated optical boards hosts the two subsystems.

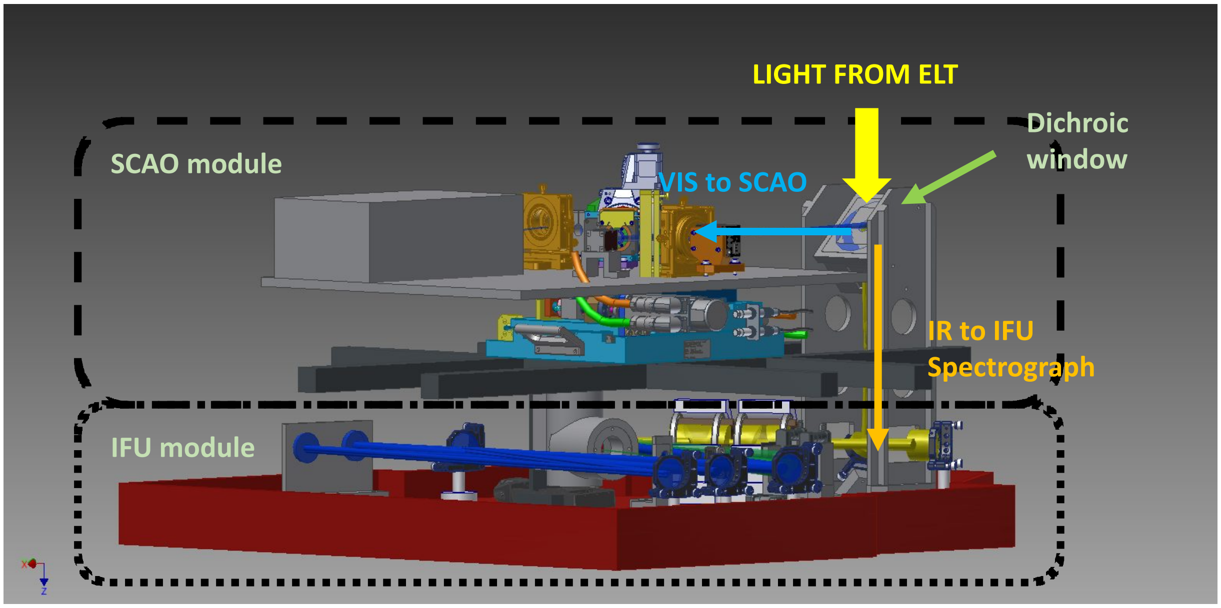


Figure 3 the IFU-SCAO module is separated into two sub modules by the dichroic.

3. IFU MODULE

The IFU module focuses the light from the ELT onto lenslet arrays connected to the fiber bundles corresponding to different observing modes. To minimize costs and simplify manufacturing, these lenslet arrays will be made using the same type of micro-lenses that are used in the front-end and in the spectrometer slit. The HR mode will include 64 micro-lenses organized on a 8x8 pattern while the UHR will consist of 96 micro-lenses organized on a 10x10 pattern with empty corners (see Figure 5).

Parameter	*Value*	*Comment*
Input focus & FOV	f/17.6 D~20"	ELT focus. FOV in reflection for SCAO
Wavelength covarege	950-1800 nm	Extendible to 2400 nm
Output focus IFU100	f/34 D~2"	With 2mm space between lenslets
Scale for mode IFU100	100 mas/spaxel 67 mas/spaxel	IFU100-HR mode (8x8 spaxel) IFU100-UHR mode (10x10 spaxel)
Output focus IFU010	f/340 D~0.2"	With 2mm space between lenslets
Scale for mode IFU010	10 mas/spaxel 6.7 mas/spaxel	IFU010-HR mode (8x8 spaxel) IFU010-UHR mode (10x10 spaxel)
FOV of IFU foci	8X8 spaxels 10x10 spaxels - 4	IFU-HR mode IFU-UHR mode
Interfaces to fibers	Arrays of micro-lenses	

Table 1: IFU scale and modes

In Table 1 the IFU parameters for the two High-Resolution and Ultra-High-Resolution modalities are reported. The two f/numbers values, f/34 and f/340, have been selected to obtain the scale defined by the scientific requirements. Their names (IFU100 and IFU010) refer to the scales (mas/spaxel) in the HR modes.

4. IFU MODULE PHYSICAL DESCRIPTION.

In Figure 4 the IFU module is shown. The tip-tilt selector, based on a Physik Instrument S335 piezo steering mirror, is used to select the IFU010/IFU100 modality and to align the beam on the lenslet corresponding to the HR or UHR mode.

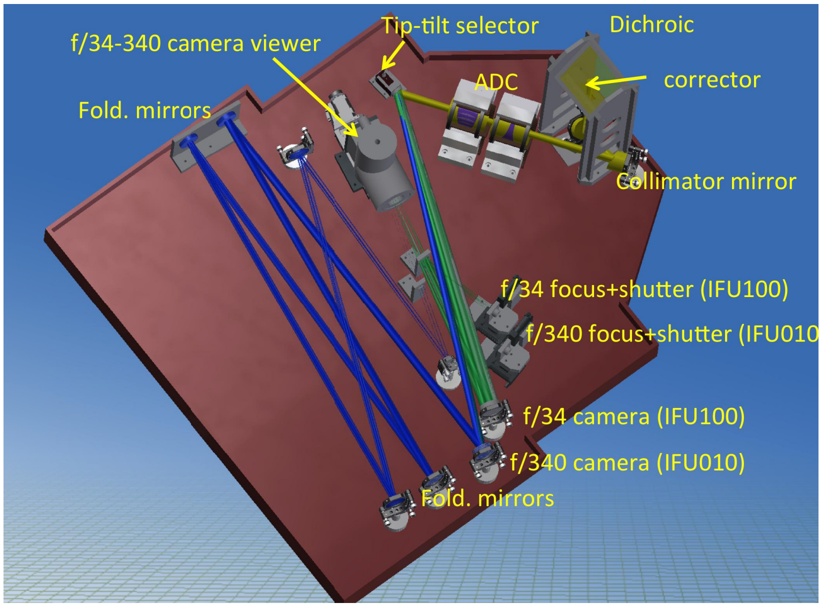


Figure 4 IFU module with the two optical branches: f/340 (IFU010) and f/34 (IFU100).

In front to the two fiber bundles, one for the HR and one for the UHR modality, there is a shutter that permits to cover with a black foil of metal one or both bundle.

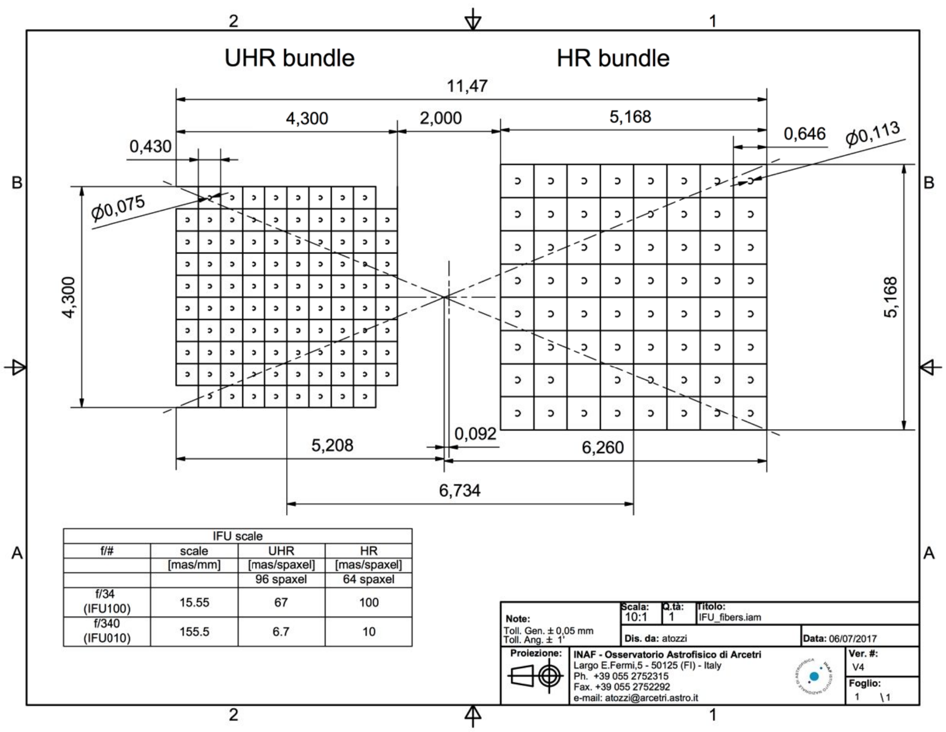


Figure 5 On the left the UHR fiber bundle: 10x10 lenses of 430 micron side, fiber core 75 micron.
On the right the HR fiber bundle: 8x8 lenses of 646 micron side, fiber core 113 micron.

For each IFU focus, f/340 and f/34, it will be placed the fiber termination module where the two UHR and HR bundles will be placed rearranging them for example as shown in Figure 5: the maximum dimension, that is represented by the diagonal that in case of a space between lenslet of 2 mm is 12,407 mm. The four lenses at the corners in UHR mode, will not be present (96 microlenses).
The switching of the star between the two modalities, HR and UHR, may be done moving the Tip Tilt steering mirror of the appropriate angle to have a displacement on the focal plane of 6.734 mm, that is the center to center distance of the two fiber bundles.

Two beam splitters permit to have a direct image of the pointed object on a single SWIR camera (for example a commercial InGaAs camera identical to those used in the front-end interfaces). Thanks to the folding mirrors it is possible to arrange them to have on the same plane of the SWIR camera the two transmitted focal planes: IFU010 and IFU100.

In Table 2 the list of motorized axis for IFU module is reported. There are three linear stages for focusing: one for each fiber bundle and one for the camera viewer.

Item	Use	model
Tip Tilt	Mode Selection & guiding	1 Piezo stage S335 PI
ADC	Atmospheric dispersion corrector	2 Faulhaber AM1540
Focus Guider	Focus stage for the guider camera	1 PLS85 PI
Shutter IFU010	Shutter for selection bundle	1 M111-DG PI
Shutter IFU100	Shutter for selection bundle	1 M111-DG PI
Focus fiber IFU010	Focusing stage for bundle & shutter	1 M112-DG PI
Focus fiber IFU100	Focusing stage for bundle & shutter	1 M112-DG PI

Table 2: IFU Motor axis list

5. IFU MODULE OPTICAL DESCRIPTION

In Figure 6 the Zemax optical layout is shown: there are four configurations, two for the IFU100 and two for IFU010. For each f/number there is a beam splitter that reflects the major part of the light to the fibers bundle, while it transmits some percent to a InGaS IR camera module for the guiding.

The optical description is divided into its functional parts: dichroic and its corrector, collimator, Atmosferic Dispersion Corrector (ADC), TipTilp steering mirror, cameras and fiber viewer and guiding system.

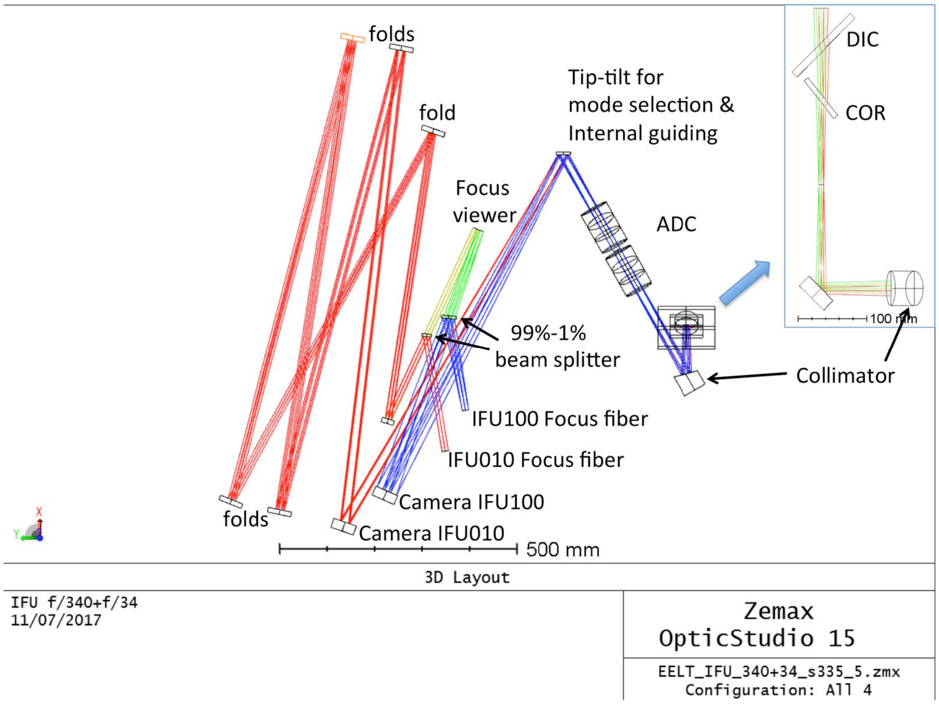


Figure 6: Optical layout of the IFU module. Different colours are referred to different configurations. Red and blue are the feeding, yellow and green the alignments.

- Dichroic and corrector.

These two windows work together and the system permits to have the outcoming chief ray perfect aligned with the free one: there is only a focal shift of 5.35 mm along the optical axis itself.

Table 3 Dichroic and Corrector optical specifications

Element	Description
Dichroic (DIC)	200 mm before the ELT focus, tilted by 45 degrees Material: Infrasil 301 Physical size 120 x 120 mm (TBC), clear aperture 115 x 115 mm (TBC) Centre Thickness is 10 mm, wedged by 21,7 ± 0,5 arc-min 1st surface flat, $\lambda/10$ PV, S/D 40/20 with dichroic coating as follows R_{min}>98% over 700 nm - 950 nm (AOI = 45±4 degrees) T_{min}>98% over 950 nm - 2450 nm (AOI = 45±4 degrees) 2nd surface flat, $\lambda/10$ PV, S/D 40/20 with A/R coating as follows: R_{max}<1% over 950 nm - 2450 nm (AOI = 45±4 degrees)
Corrector (COR)	65.0 mm from 2nd surface of Dichroic-1 (centre to centre distance), tilted by -96.43 degrees with respect the 2nd surface of DIC there is the first surface of the Corrector.

	Material: Infrasil 301 Physical size 50 x 50 mm, clear aperture 45 x 45 mm Thickness 7,40 mm, wedged by 54,55 ± 0,05 arc-min (in the direction opposite to wedge of Dichroic-1) Both surfaces flat, λ/10 PV, S/D 40/20 A/R coating on both surfaces as follows: R_{max}<1% over 950 nm - 2450 nm (AOI = 43±4 degrees)

- Collimator.

The collimator if an off-axis parabolic mirror. It generates a collimated beam with the pupil image in between the two triplets of prisms that compose the ADC.

Table 4 Collimator optical specifications.

Element	Description
Collimator (COL)	200 mm after the transmitted focus there is the off-axis parabola mirror. Material: Fused Silica (TBC) Physical size 50 mm diameter (TBC), clear aperture 48 mm (TBC) Centre Thickness is 67 mm Radius of curvature is 486,4 mm ± 0,5 mm, Conic constant is -1 Parental focal length is 243,2 mm ± 0,5 mm Zonal radius = 125,0 mm ± 0,1 mm surface, λ/10 PV, S/D 40/20 with AR coating R_{min}>98% over 950 nm - 2440 nm (AOI = 30±4 degrees)

- ADC.

The ADC consists of two identical groups of three prisms. It provides diffraction limited compensation of the atmospheric dispersion up to a zenith distance of 70 deg.

Table 5 ADC optical specifications.

Element	Description
Atmospheric Dispersion Corrector (ADC)	204 mm after the center of COL there is the first surface of ADS. . Physical size 50 mm diameter (TBC), clear aperture 48 mm (TBC), center thickness for each prism is 30 mm ± 0,1 mm, in/out surfaces of the two couple of prisms are 90° with respect the chief ray. 1st surface prism angle is 7° 24’ 90” ± 30”, material 1st prism is ZnS 2nd surface prism angle is 14° 42’ 07” ± 30”, material 2nd prism is BaF_2 3rd surface prism angle is 21° 51’ 05” ± 30”, material 3rd prism is CaF_2 4rd surface prism angle is 5° 08’ 50” ± 30” surface, λ/10 PV, S/D 40/20 with AR coating R_{min}>98% over 950 nm - 2440 nm (AOI = 30±4 degrees)

In Figure 7 the spot diagrams for the two different zenithal angles 0° and 70° are reported for the case f/34 (IFU100).

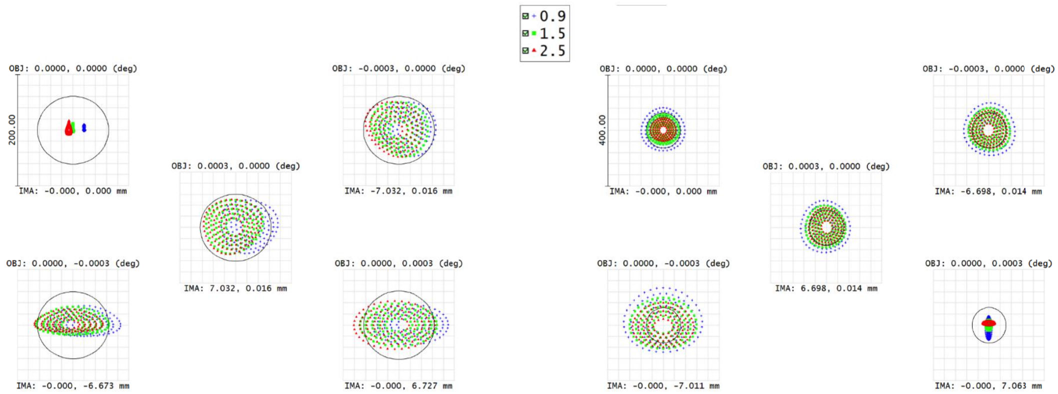


Figure 7 Spot diagram for Z=0° (left) and Z=70° (right). Represented field are 0,0 and (+/-1.1”;+/-1.1”).

- TipTilt

Tip Tilt mirror is a 25.4 mm diameter flat mirror placed 100 mm after the ADC and placed on a Physik Instrumente piezo steering platform model S-335 that works in closed loop up to ±15 mrad: that it means 4 degree as optical defection angle. It will be used not only to switch between the two optical configuration IFU100 and IFU010 but also to align the target on the correct position in the focal plane, having 0.2 micro-radians (0.3” of TT mechanical deflection) of closed-loop resolution with a TT angle over PSF displacement scale that is 9mm/0.1°.

- Camera

Here as “camera” we are referring to the optical groups that allow to feed the fiber bundles. The two camera optics are based on a reflective sphere. The use of one or another camera is selected by the TipTil mirror.

Table 6 Camera optical specifications.

Element	Description
Collimator f/34 (CAM_100)	900 mm after the transmitted focus (800 mm after TT) there is the collimator based in an on axis spherical mirror. Material: Fused Silica (TBC) Physical size 55 mm diameter (TBC), clear aperture 52 mm (TBC) Centre Thickness is 50 mm Radius of curvature is 1067 mm ± 1 mm, Conic constant is 0 Surface, λ/10 PV, S/D 40/20 with AR coating R_{min}>98% over 950 nm - 2440 nm (AOI = 20±3 degrees)
Collimator f/340 (CAM_010)	1000 mm after the transmitted focus (900 mm after TT) there is the collimator based in an on axis spherical mirror. Material: Fused Silica (TBC) Physical size 55 mm diameter (TBC), clear aperture 52 mm (TBC) Centre Thickness is 50 mm Radius of curvature is 6502 mm ± 5 mm, Conic constant is 0 Surface, λ/10 PV, S/D 40/20 with AR coating R_{min}>98% over 950 nm - 2440 nm (AOI = 4±3 degrees)

- Fibers/Guiding

A flat beam splitter is used to have some percent of light projected onto a IR camera used as viewer: the folding mirrors of f/340 mode permit to have on the same detector the two focus planes, this to avoid the use of a double infrared camera. The reflected beam if used to feed the fibers placed on the same focal plane.

Table 7 Slit Viewer Beam Splitter optical specifications

Element	Description
Beam Splitter (BS010-BS100)	200 mm before the f/360 and 250 mm before the f/36 focus, there is the beam splitter tilted of 10° and 15° tilted respectively. Material: Infrasil 301 Physical size 40 mm of diameter (TBC), clear aperture 38 mm (TBC) Centre Thickness is 6 mm 1st surface flat, λ/10 PV, S/D 40/20 with dichroic coating as follows R_{min}>98% over 950 nm - 2450 nm (AOI = 12.5±4 degrees) T_{min}<98% over 950 nm - 2450 nm (AOI = 12.5±4 degrees) 2nd surface flat, λ/10 PV, S/D 40/20 with A/R coating as follows: R_{max}<1% over 950 nm - 2450 nm (AOI = 12.5±4 degrees)

The encircle energy value for the IFU100 case is shown in Figure 8: we have approximately 90% energy in 320 um spot diameter for the different incoming fields.

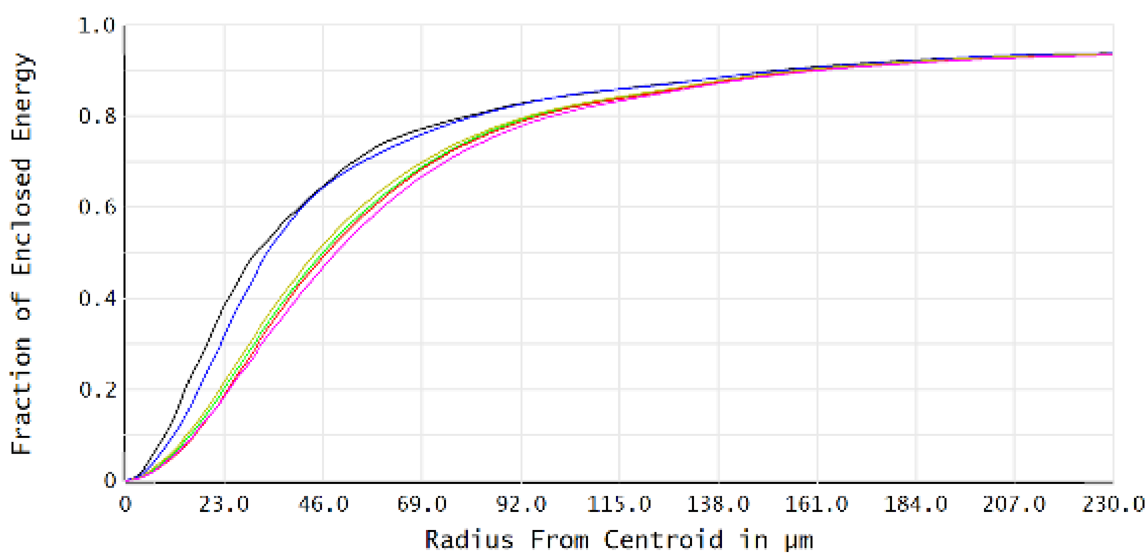
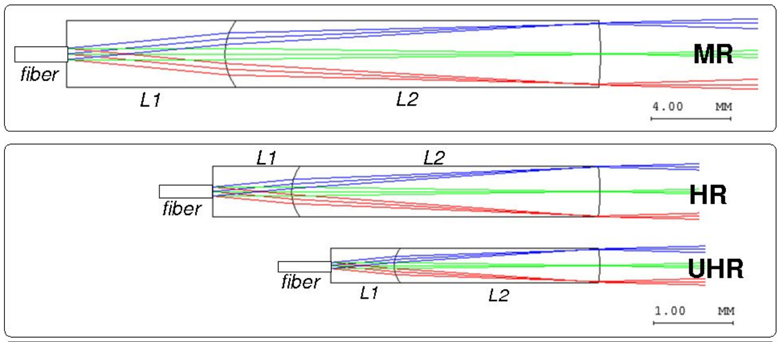


Figure 8 Encircle energy for PSF f/34 (IFU100) case.

6. MICROLENSES DESIGN

In front to each fiber a microlens is placed: on the two f/# foci a double IFU will be placed as visible in Figure 5. The dimension of the lenses in the HR and UHR modes are respectively of 646 um and 340 um. The lenses will be squared to permit the possibility to mold them side by side forming a monolithic microlens array. The scope of these lenses is to collect the desired field of view incoming to the lens into the core fiber dimension that in smaller and is around a commercial value of 113 um diameter. At the same time the fiber will be illuminated not by the focus but by a pupil image: the lenses are calculated to have a pupil image placed on the fiber with the correct diameter.



Name	L1 (t,R in mm)	L2 (t,R in mm)	F# fiber	F# lens	Ø core (mm)	D lens (mm)	Maximum light losses for all fields and wavelengths
HR	SBSL7 t=1.00 R1 flat R2=0.510 K2=-4.0	SLAM55 t=4.00 R1=0.510 K1=-4.0 R2=2.407	F/3.5	F/20	0.113	0.646	4%
UHR	SBSL7 t=0.80 R1 flat R2=0.350 K2=-4.0	SLAM55 t=2.60 R1=0.350 K1=-4.0 R2=1.71	F/3.5	F/20	0.075	0.430	5%
MR	SBSL7 t=8.0 R1 flat R2=2.80 K2=-3.0	SLAM55 t=19.0 R1=2.80 K2=-3.0 R2=15.1	F/3.5	F/20	0.570	3.40	2%

Main parameters of micro-lenses (glued doublets) for the HIRES ZYJH spectrometer module.
L1, L2: t=thickness, R=radius of curvature, K=conic constant. Fiber is glued to first (flat) surface of L1.
F# fiber : nominal aperture of light beam at the fiber; beams are telecentric .
F# lens: nominal aperture of light beam at the micro-lens; beams are telecentric.
Ø core: diameter of fiber core.
D lens: size of the lens.
Includes light losses produced by blurring of images, by deviations from telecentricity, and by variations of the beam apertures. Maximum values among all fields and wavelengths; average values are smaller.

Figure 9 Layout, rays-tracing and main parameters of the micro-lenses.

7. ACKNOWLEDGEMENTS

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