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CUBES: application of image slicers to reformat the field for two spectral resolving powers

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ABSTRACT

The Cassegrain U-Band Efficient Spectrograph (CUBES) is a high-efficiency spectrograph designed for observations from 305 to 400nm. It will be integrated at a Cassegrain focus of the Very Large Telescope (VLT). The image slicer technology is applied to reformat the field of view reducing the spectrograph entrance slit etendue and minimising the spectrograph volume and weight without slit losses.

Two image slicers will provide CUBES with two spectral resolving powers: $R \geq 20{,}000$ for high resolution (HR) and $R \geq 5{,}000$ for low resolution (LR). Both image slicers are composed of two arrays of six spherical mirrors. For the HR mode, a rectangular field of view of 1.5arcsec by 10arcsec is reorganised into a slit of 0.19mm × 88mm; for the LR mode, a field of view of 6arcsec by 10arcsec is reformatted into a slit of 0.77mm × 88mm, with slicer mirrors of width 0.5mm and 2mm, respectively.

CUBES is currently in the Preliminary Design Phase (Phase B). This communication presents the Conceptual (Phase A) design and the main performance for the HR and LR image slicers addressing the following technological challenges: compact layout with the minimum number of optical components to optimise throughput, near diffraction limited optical quality, telecentric design with overlapped exit pupils for all slices of the field of view, distribution of the slicer mirrors to reduce shadows and selection of the best substrate for the very short wavelengths at which CUBES will operate.

Keywords: CUBES, VLT, image slicer, re-formatter, high resolution spectroscopy, low resolution spectroscopy

1. CUBES

CUBES[1] was proposed to provide UV ground-based spectroscopy. As explained in Bristow[1] et al. (2014), a gain in sensitivity using CUBES over UVES[2], is at least two magnitudes at 350nm and up to three magnitudes at 320nm and shorter wavelengths. In the same paper, three critical components were identified in order to achieve high efficiency: the detector, the grating and the image slicer. This manuscript is focused on this last component.

Some of the top level requirements are: a spectral resolution, R, of the order of 20,000, with the possibility to offer more than one spectral resolving power in a spectral range between 305 and 400nm (goal 300-420nm). The instrument will be equipped with its own calibration and acquisition system. It shall be optimised in throughput, with an efficiency higher than 40% between 305-360nm (goal > 45% with >50% at 313nm) higher than 37% between 360-400nm (goal > 40%) and > 37% for the rest of spectral range. These are the latest values for the top level requirements.

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CUBES will be installed at a Cassegrain focus of the Very Large Telescope (VLT). The project is currently in Phase B and it is expected to be available for the astronomical community in 2028.

2. REQUIRED RESOLUTIONS

Several scientific applications will benefit from the gain in sensitivity and the spectral resolution in the UV that will be provided by CUBES. For the definition of the top level requirements, the following main science cases were considered:

- Galactic science, enabling the analysis of elemental abundances in different galactic sources and the study of stellar nucleosynthesis, including: Beryllium, iron-peak elements, heavy elements and CNO abundances.
- Solar system and planetary science, in particular the search for water in the asteroid belt or the measurement of the N2/CO ratio in comets.
- Extra-galactic science, including the study of the missing baryonic mass in the high-redshift circumgalactic medium and the cosmic UV background.

Initially, one spectral resolving power of R≈20,000 was defined. During Phase A, the project decided to offer two spectral resolution modes of R≥20,000 for the high resolution mode (HR) and R≥5,000 for the low resolution mode (LR), increasing the instrument capabilities and the range of science cases that could benefit from CUBES. This decision implied the need for two independent image slicers, one per resolution mode, with the characteristics defined in Section 3.

3. IMAGE SLICERS

The image slicers for CUBES are used as field re-formatters. They reorganise a bi-dimensional entrance field of view, which is smaller than those associated to spectrographs that use image slicers as Integral Field Units (IFU), into the spectrograph entrance slit. For the HR mode, a rectangular field of view of 1.5arcsec by 10arcsec is reorganised into a slit of 0.19mm × 88mm, while for the LR mode, a field of view of 6arcsec by 10arcsec is reformatted into a slit of 0.77mm × 88mm. Thus, the image slicers change the geometrical shape of the entrance field of view, keeping the coverage of the same effective area on the sky; they define the spectrograph entrance slit width, directly linked to the instrument spectral resolving power; they avoid light losses, they place the exit pupils on the spectrograph grating and reduce the etendue, enabling smaller opto-mechanical components and thus, a lighter instrument, especially important due to its location at a Cassegrain focus.

In order to optimise the throughput, the layout adopted for the image slicers presents only two arrays of mirrors: a slicer mirror array and a camera mirror array, as shown in Figure 1, with each array having six mirrors. Spherical curvature has been selected for all the optical components. This is found to be sufficient to obtain the required optical quality while reducing the complexity of manufacturing, alignment and tests, as well as reducing the cost. The layouts of the image slicers are conceptually the same, but with different technical parameters, which leads to the different spectrograph slit widths at their outputs.

A fore-optic system magnifies the telescope field of view providing a larger linear image size, which enables to increase the width of the slicer mirrors and facilitate manufacturing. The slicer mirror array has a linear size of 20mm length by 3mm width for the HR mode and 20mm length by 12mm width for the LR mode. These arrays are composed of six rectangular mirrors of 0.5mm width by 20mm length for the HR mode and 2mm width by 20mm length for the LR mode, all with spherical curvature. The width of the slicers mirrors, placed at the output focus of the fore-optics system, corresponds to 0.25arcsec for HR and 1arcsec for LR. Each one of the six slicer mirrors present a different tilt angle around the X and Y axes. Thus, each one of them reflect a slice of the entrance field of view in a different direction, towards a camera mirror. The slicer mirrors produce an intermediate pupil image between the slicer and the camera mirrors. The camera mirror array is composed of six spherical mirrors with rectangular shape, whose dimensions are 10mm by 16.4mm for HR and 12mm by 16.4mm for LR. Each camera mirror produces an image of their associated slice of the field, called slitlet, and constitute a fraction of the spectrograph entrance slit, which is composed of six aligned slitlets and five gaps between them of 8.36mm each. These gaps facilitate the overlapping of the six pupils on the grating position and avoid potential cross-talk between slitlets. The six exit pupils, one per slice of the field, overlap along the Z axis (direction of light propagation) and in the XY plane (of the diffraction grating aperture).

The length of the slit is the same in both cases, 88mm, this has been defined within the maximum (around 90mm) allowed by the spectrograph in order to provide good optical quality. The width of the slit is 0.19mm for the high resolution mode and 0.77mm for the low resolution mode. In the Phase A layout, each mirror has a different radius of curvature. Both image slicers produce the same magnification, 0.38. The length of the image slicers, defined from the slicer mirror array to the camera mirror array is 350mm. There is an offset of 20mm between the input optical axis (centred in the slicer mirror array) and the output one (centred in the generated slit), to avoid the exit beam returning towards the same input direction. This offset has been defined as a compromise between the optical quality and the available space for the mechanical mounts and the slit mask. The optical designs of the image slicers are shown in Figure 1. A more complete description can be found in Calcines[3] et al. (2022).

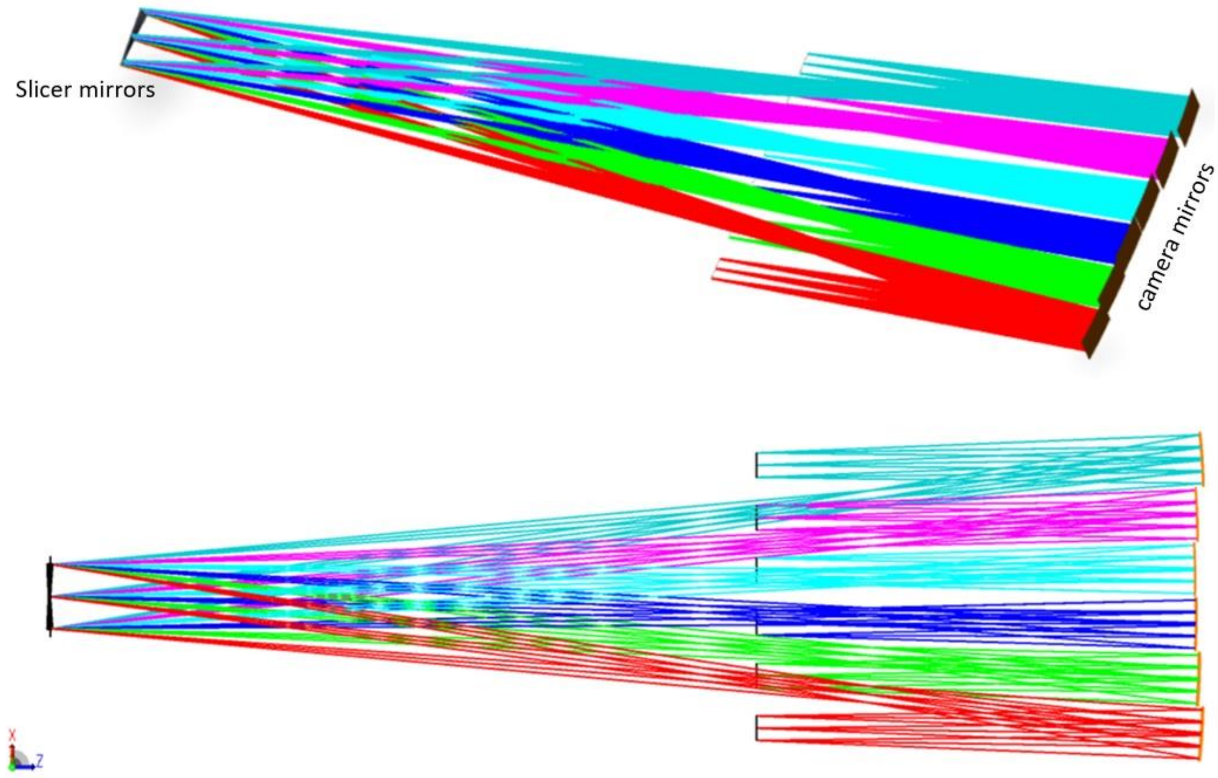

Figure 1. Optical layout of the two image slicers composed of an array of slicer mirrors and an array of camera mirrors. The six spherical camera mirrors generate an image of their associated slices of the field of view. The tilt angles around the X and Y axes enables the distribution of the slitlets, in this case, generating a straight slit for the spectrograph.

The optical quality obtained at the spectrograph slit position is presented in Figure 2, which is mostly diffraction limited except for the extreme slices (Configurations 3 and 4). In this picture, each column represents a slitlet, defined by seven field points and the circle is the Airy disk, which defines the diffraction limit.

Figure 2. Optical quality obtained for the HR (top) and LR (bottom) image slicers. Each column represents a slitlet defined by seven field points. The circle is the Airy disk, showing the diffraction limit. Configurations 3 and 4 corresponds to the slices with the largest off-axis distances.

At the slitlets position a slit/field mask will be used to define the spectrograph entrance slit. The concept is presented in Figure 3, showing the slit dimensions for both resolution modes (HR, LR), the six slitlets and the gaps between them. This mask will also help to avoid potential stray light. A pupil mask at the intermediate pupil position (between the slicer and camera mirrors) was initially evaluated but only the slit mask is being considered in the current design. This, together with the baffles defined in the spectrograph, seem enough at this stage, but this will be confirmed by the detailed stray light analysis.

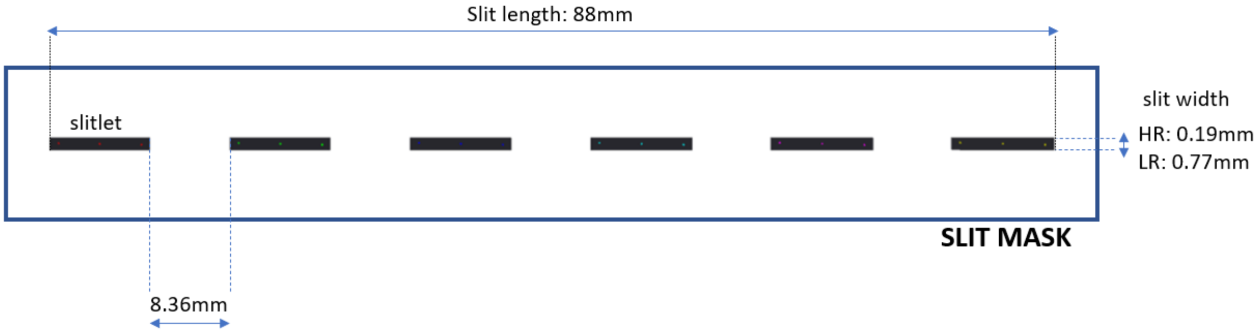

Figure 3. Sketch showing the concept for the slit mask that will be place at the image slicer output defining the entrance slit for the spectrograph.

Due to the short wavelengths at which CUBES will operate, glass slicer mirrors are considered, since a better surface roughness is achievable compared to other materials. For the Phase A design, the material considered was Zerodur. In Phase B, the preferred choice is Fused Silica, which matches better the CTE of Invar, which will be used for the mechanical parts in the image slicer assembly. The full image slicer will be manufactured in Fused Silica, with the two arrays of mirrors assembled on a Fused Silica baseplate to avoid thermal effects. Each image slicer is an independent module (see Figure 4), composed of the following components: slicer mirror array, camera mirror array, slit mask and baseplate. The HR and LR image slicers will be placed on a motorised translational stage, allowing the observer to select the appropriate image slicer for their observations.

4. THE IMAGE SLICERS IN THE OVERALL INSTRUMENT LAYOUT

The CUBES instrument is composed of two sub-systems[4]: the pre-slit and the spectrograph. The pre-slit sub-system consists of a fore-optics system that re-images the telescope image on the slicer mirrors with the appropriate plate scale. Its optical path includes an ADC for atmospheric dispersion corrections, a slit viewer, which is part of the Acquisition and Guiding (A&G), a calibration unit, the option of a fibre link connection to UVES[2] and the image slicers (HR and LR). A sketch of these sub-systems is shown in Figure 4 and these are discussed in more detail in Zanutta et al. (2022)[4]. Further details about the spectrograph design are presented in Zanutta[4] et al. (2022) and Cristiani[5] et al. (2022).

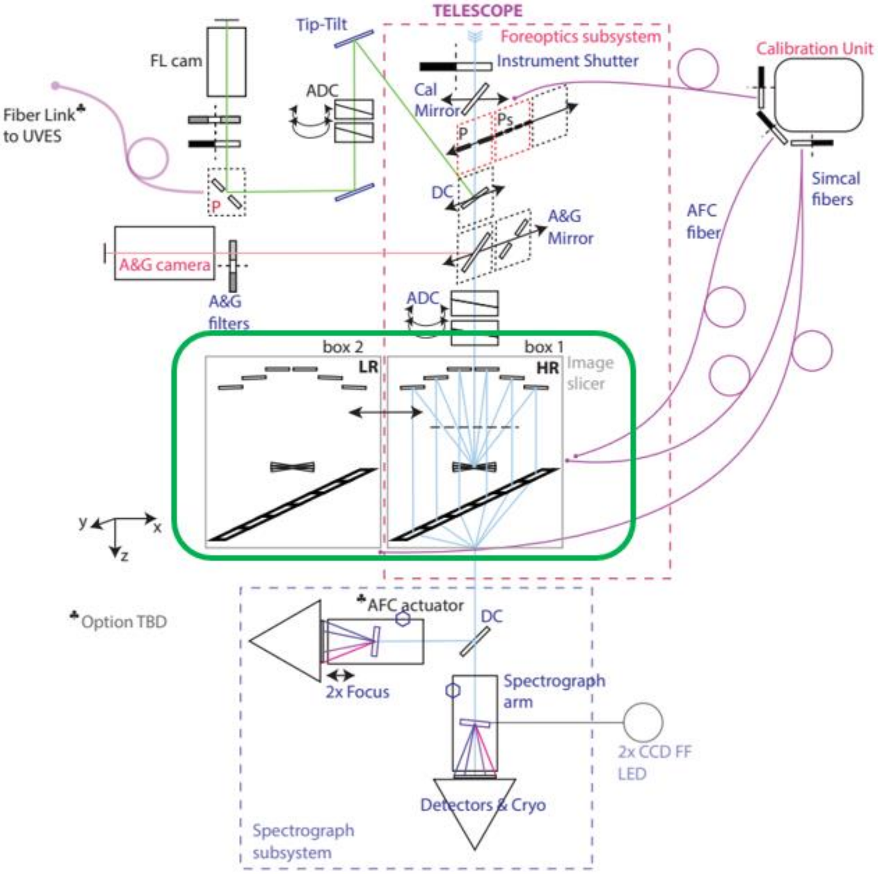

Figure 4. Sketch of the different subsystems of CUBES. The two independent boxes for the two image slicers are highlighted. These will be assembled on a motorised translational stage that will place the desired image slicer in the instrument optical path.

5. CONCLUSIONS

This manuscript presents the conceptual (Phase A) design of two image slicers for the instrument CUBES, the Cassegrain U-Band Efficient Spectrograph, designed for high-efficiency observations from 305 to 400nm. CUBES is currently in the Preliminary Design Phase (Phase B) and it will be installed at a Cassegrain focus of the Very Large Telescope (VLT) in 2028.

Two image slicers are considered for CUBES, providing two spectral resolving powers: R≥20,000 for high resolution (HR) and R≥5,000 for low resolution (LR).

The image slicers are used as field reformatters, reducing the spectrograph entrance slit etendue without slit losses and minimising the size and weight of the component and thus, that of the instrument, making it suitable to be installed at a Cassegrain focus.

The image slicers will be manufactured in glass as two separate modules for HR and LR. Each one of them is composed of an array of six spherical slicer mirrors, an array of six spherical camera mirrors and a slit mask that defines the spectrograph entrance slit. Both modules will be integrated on a motorised linear stage, which will place the desired image slicer in the instrument optical path, enabling the user to select the observation mode.
The considered solution presents low technical complexity. The width of the slicer mirrors are 0.5mm and 2mm for high and low resolution, respectively.

The presented designs have successfully passed the Phase A review. The designs are being optimised for the Preliminary Design Review, scheduled by the end of 2022.

REFERENCES

[1] Bristow, P., Barbuy, B., Macanhan, V., Castilho, B., Dekker, H., Delabre, B., Diaz, M., Gneiding, C., Kerber, F., Kuntschner, H., La Mura, G., Reiss, R., Vernet, J., "Introducing CUBES: the Cassegrain U-band Brazil-ESO spectrograph", Proc. SPIE 9147 (2014).

[2] D'Odorico, S., Cristiano, S., Dekker, H., Hill, V., Kaufer, A., Kim, T-S., Primas, F., "Performance of UVES, the echelle spectrograph for the ESO VLT and highlights of the first observations of stars and quasars", Proc. SPIE 4005 (2000).

[3] Calcines, A., Wells, M., O'Brien, K., Morris, S., Seifert, W., Zanutta, A., Evans, C., Di Marcantonio, P., "Design of the VLT-CUBES image slicers: Field re-formatters to provide two spectral resolutions", Experimental Astronomy, paper accepted (2022).

[4] Zanutta, A., Cristiani, S., Atkinson, D., Baldini, V., Balestra, A., Barbuy, B., Bawden P. Macanhan, V., Calcines, A., et al, "CUBES Phase A design overview – The Cassegrain U-Band Efficient Spectrograph for the Very large Telescope", Experimental Astronomy, paper accepted (2022).

[5] Cristiani, S., et al, "CUBES, the Cassegrain U-Band Efficient Spectrograph", Proc. SPIE 12184-9 (2022).