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MOSAIC: the ELT Multi-Object Spectrograph

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ABSTRACT

Following a successful Phase A study, we introduce the delivered conceptual design of the MOSAIC[1] multi-object spectrograph for the ESO Extremely Large Telescope (ELT). MOSAIC will provide R~5000 spectroscopy over the full 460-1800 nm range, with three additional high-resolution bands (R~15000) targeting features of particular interest. MOSAIC will combine three operational modes, enabling integrated-light observations of up to 200 sources on the sky (high-multiplex mode) or spectroscopy of 10 spatially-extended fields via deployable integral-field units: MOAO[6] assisted high-definition (HDM) and Visible IFUs (VIFU). We will summarise key features of the sub-systems of the design, e.g. the smart tiled focal-plane for target selection and the multi-object adaptive optics used to correct for atmospheric turbulence, and present the next steps toward the construction phase.

Keywords: Spectrograph, Adaptive Optics, Optical Fibres, Multi-Object, ESO Extremely Large Telescope

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1. INTRODUCTION

The workhorse instruments of the current 8-10m class observatories are multi-object spectrographs (MOS), providing comprehensive follow-up of ground-based and space-borne imaging data. With the advent of even deeper imaging surveys from, e.g., HST, VISTA, JWST and Euclid, many science cases require complementary spectroscopy with high sensitivity and good spatial resolution to identify the objects and to measure their astrophysical parameters. The light-gathering power of the 39m ELT and its spatial resolution, combined with MOSAIC, will enable the large samples necessary to tackle some of the key scientific drivers of the ELT project, ranging from studies of stellar populations out to the highest-redshift galaxies.

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2. SYSTEM CONCEPT DESCRIPTION

The MOSAIC instrument has been conceived as a multi-purpose MOS for the ELT. With an extremely wide range of science cases[5], the top-level science requirements are understandably equally broad. Calling for a mixture of modes with either high multiplex ('High Multiplex Mode'-HMM) or high spatial resolution ('High Definition Mode'-HDM) leads to a number of design constraints which shape the overall instrument concept. In particular, the requirement to achieve a multiplex of 200 in HMM essentially pre-determines that MOSAIC shall be a fibre-fed instrument. Further, the high cost of detectors (especially in the NIR) and spectrograph optics of sufficient quality places a very high emphasis on realizing a design that shares spectrograph hardware between the different modes. In order to minimize complexity, this constraint then means that the HDM must also be fibre based. Thus, the MOSAIC concept is for an entirely fibre-fed spectrographic instrument.

The spectral range of the instrument is from 0.46 to 1.8 µm, with a break at 0.8-0.9µm between a system optimized for visible and a system optimized for NIR. The original requirement of 380nm for the short-wavelength cut-off had to be changed to 460nm due to the poor transmission of the ELT in the blue. Six separate bands provide R=5,000 coverage over the full bandwidth (three in visible, and three in NIR), with selected smaller bands available at higher resolution of R ~ 15,000. In line with the top-level science requirements, the instrument is designed to operate one mode in one band at a time. This places an emphasis on maximizing the achievable multiplex, resulting in four base modes of operation, each of which has a number (4-5) of spectral sub-modes (See Figure 1). The instrument is designed to use as much of the ELT FOV as possible (>Ø7').

Due to the large plate scale offered by the ELT (> 3 mm/arcsecond) and the non-telecentricity of the telescope optical design, a number of compromises are required to realize a practical and affordable MOS instrument design for the ELT. In particular it has been necessary to:

- divide the focal plate into tiles, each of which has a tilt and offset optimized to limit local field and pupil curvature within that tile. This approach reduces the clustering capability of the instrument
- divide the individual pick-offs into multiple fibre spaxels in order to efficiently couple light into the fibres and produce an optical design that is feasible and affordable.

The instrument concept is illustrated graphically in Figure 1.

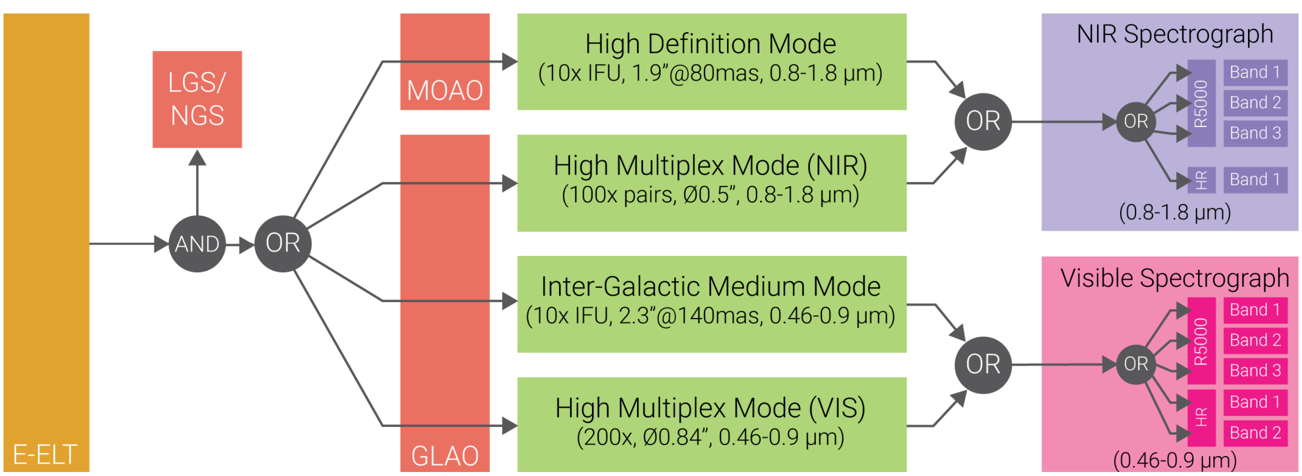


Figure 1: MOSAIC Instrument Concept

In particular, MOSAIC has been designed as a modular instrument, whereby certain blocks of functionality can be grouped together into a module. The full MOSAIC is composed of a series of such modules. This scheme creates a flexible, scalable architecture which means that the cost and capability of the final instrument can be tuned to the available budget and scientific goals. Even functionality of an entire module (such as an HMM mode, as an example) can be removed in this scheme. This is depicted schematically in Figure 2, and the main components are described in the following.

- Base Architecture: the set of components which is required irrespective of the configuration, e.g. main structure etc.
- Focal Plate: The set of positioner systems required to feed the NIR and VIS modules – this is scalable between 40 and 200 science target positioners depending on the configuration.
- NIR Mode Module: A NIR module is centered around a single NIR detector (a Hawaii 4RG), housed in its own spectrograph. A full module would include all the pick-offs, fibres and compensators required for the IFU and HMM modes associated with that detector. The full implementation has 5 such modules.
- Visible Mode Module: An identical concept to the NIR module, but centered around a visible detector (an e2v 6k in the baseline presented here). The full implementation has 5 such modules.

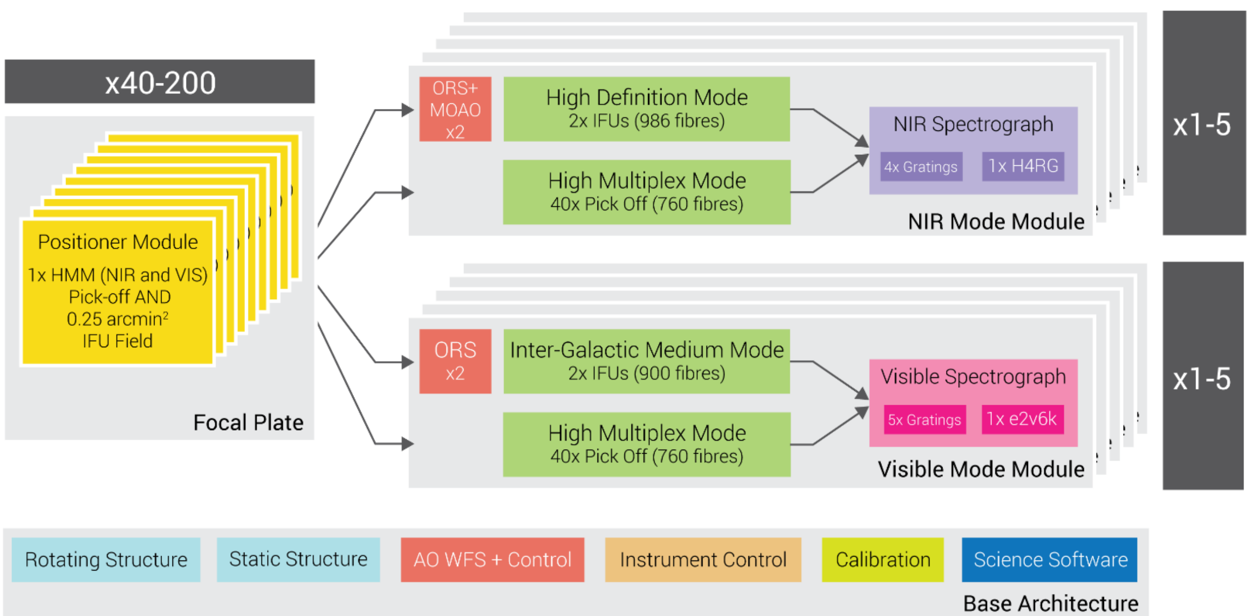


Figure 2: MOSAIC Modular Concept.

3. ARCHITECTURE OVERVIEW

The Full Instrument Architecture is shown in Figure 3 and also in Figure 4. It clearly shows that the instrument is divided into two parts that, due to the all fibre design, are mechanically independent from each other: a rotating structure containing all fibres and pickoffs and a static structure comprising the set of visible and near-infrared spectrographs and the majority of the electronics and control components.

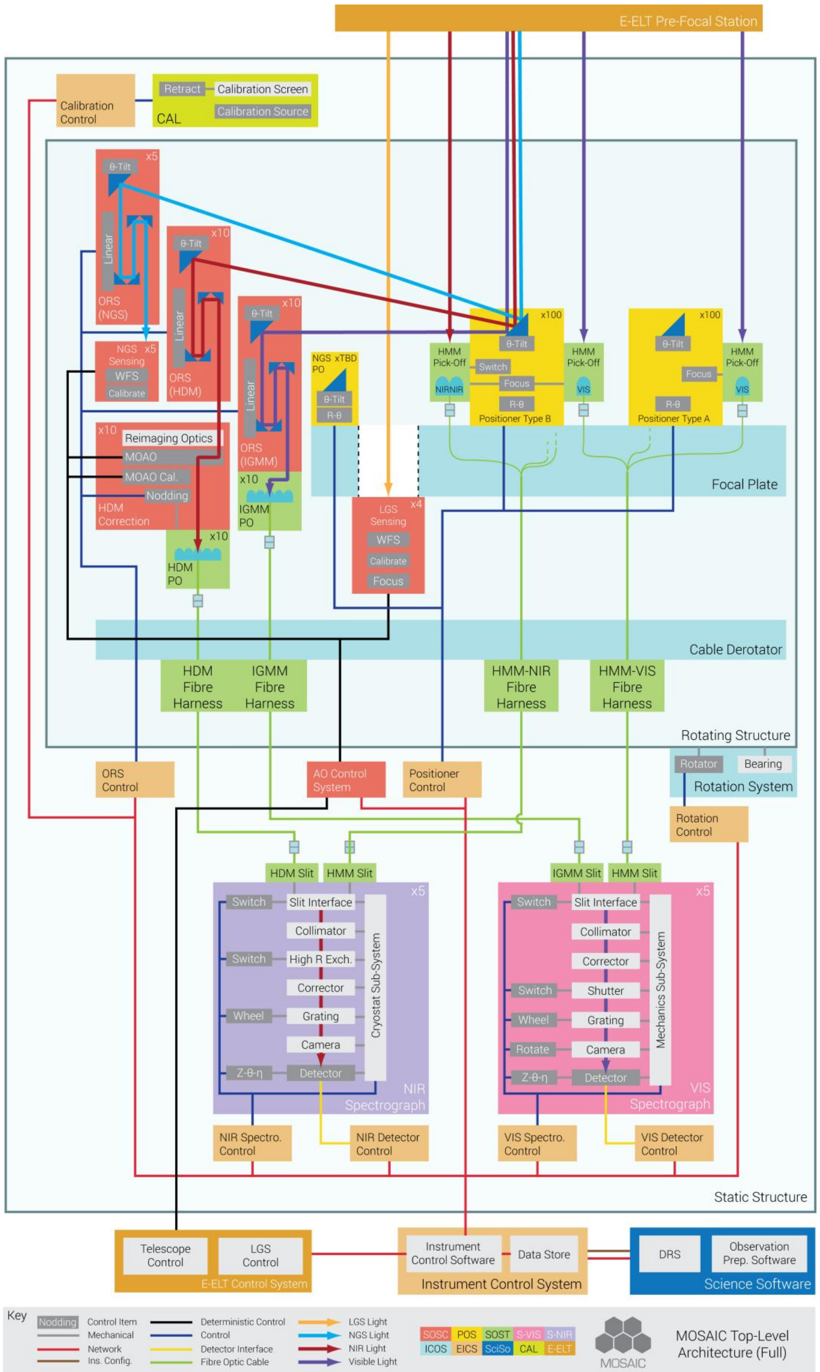


Figure 3 Instrument Architecture Overview Diagram

4. SYSTEM DESIGN DESCRIPTION

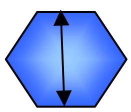
4.1 End-to-End Optical Architecture

This chapter describes the optical interfaces in the whole system, starting at the output of the ELT, and ending at the spectrograph detector. The optical architecture is quite different for HMM modes and for IFUs modes (HDM in the Near Infra Red and VIFU in the visible):

- in the case of HMM, light is transmitted from the focal plate to microlenses, fibres and slits that feed the visible or infrared spectrographs
- in the case of HDM, light is picked-off with a mirror and delivered outside of the focal plate and is directed into the Optical Relay Module by a beam steering mirror. Because the position of the targets in the focal plate lead to different optical paths, a path-length compensation system is implemented that permits the correction of optical path differences Within the Optical Relay Module a pupil image is formed on a DM to provide open-loop adaptive optics correction. Finally light is refocused to create a 2 arcsecond focal plane with the same optical properties as the ELT focal plane. From this point, we recover the same architecture as the HMM (pupil injection into fibres that are re-arranged in slits to feed a spectrograph).
- For VIFU, the architecture is similar to HDM's in terms of light extraction and optical path compensation. However the DM is replaced with a flat mirror as no adaptive optics correction is required for this mode.

For all modes, the FOV is sampled by an hexagonal arrangement of microlenses with pupil injection in fibres. This hexagonal configuration is optimal to minimize the fibre injection angles. A circle would be perfect but would cause severe sampling losses in the field. The value of the spatial sampling at the microlens level should be understood as the distance between the opposite sides of the hexagon, often referred to as the *width* of an hexagon:

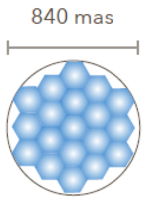
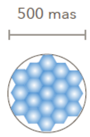
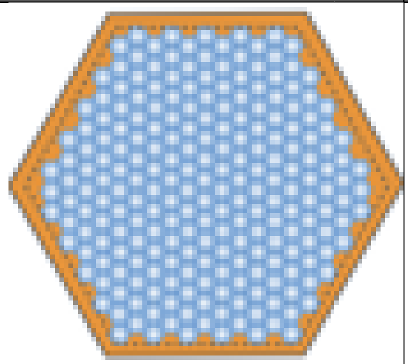
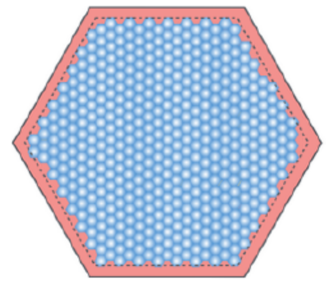
Sampling:



For all modes, except HDM, the spatial microlenses "sampling" does not correspond to an effective required sampling, but is sharper than the requirement: in those three cases (HMM-VIS, HMM-NIR, VIFU) the sampling is only performed to minimize the local field, i.e. the beam etendue, to be able to work with reasonable size optics at the spectrograph level. The signals from several microlenses are summed at detector level in order to get the required spatial resolution. Even though this approach is costly in detector pixels, it is a way to cope with the large plate scale of the ELT without working with excessively fast and large spectrograph optics which would be prohibitively expensive.

The total aperture sizes and sub-samplings, in milliarcseconds, at either in the ELT focal plane (HMM-VIS or -NIR) or after an optical relay (HDM and VIFU) are summarized in Table 1.

Table 1: Comparison of aperture and sampling sizes for the various MOSAIC modes.

Mode	HMM-VIS	HMM-NIR	VIFU	HDM
Aperture (shown to scale)				
Inner Diam	727 mas	433 mas	2 arcsec	1.72 arcsec
Outer Diam	840 mas	500 mas	2.31 arcsec	1.9 arcsec
Microlens sampling	168 mas	100 mas	138 mas	80 mas
Actual spatial resolution	840 mas	500 mas	276 mas	160 mas
Fibres/ Object	19	19	221	493

The HMM-VIS and VIFU modes are fed in to the same visible spectrograph. Similarly HMM-NIR and HDM are harmonized to feed the same NIR spectrograph. This harmonization is evaluated only at the spectrograph entrance slit level. At that point, the spectrograph sees an identical slit (same width, same length, same F/#) for two different modes, even though it can correspond to different sampling on the sky. This happens because the injection constraints, the pupil shear budgets and the F-ratio of the fibre injection are different for all modes, and can be optimized together to harmonize the slit parameters and enable the use of only one kind of visible spectrograph, and one kind of NIR spectrograph.

4.2 Overview and mechanical concept design

Following from this system architecture and the optical end-to-end architecture described in Section 4.1, the concept mechanical instrument design is shown in

Figure 4.

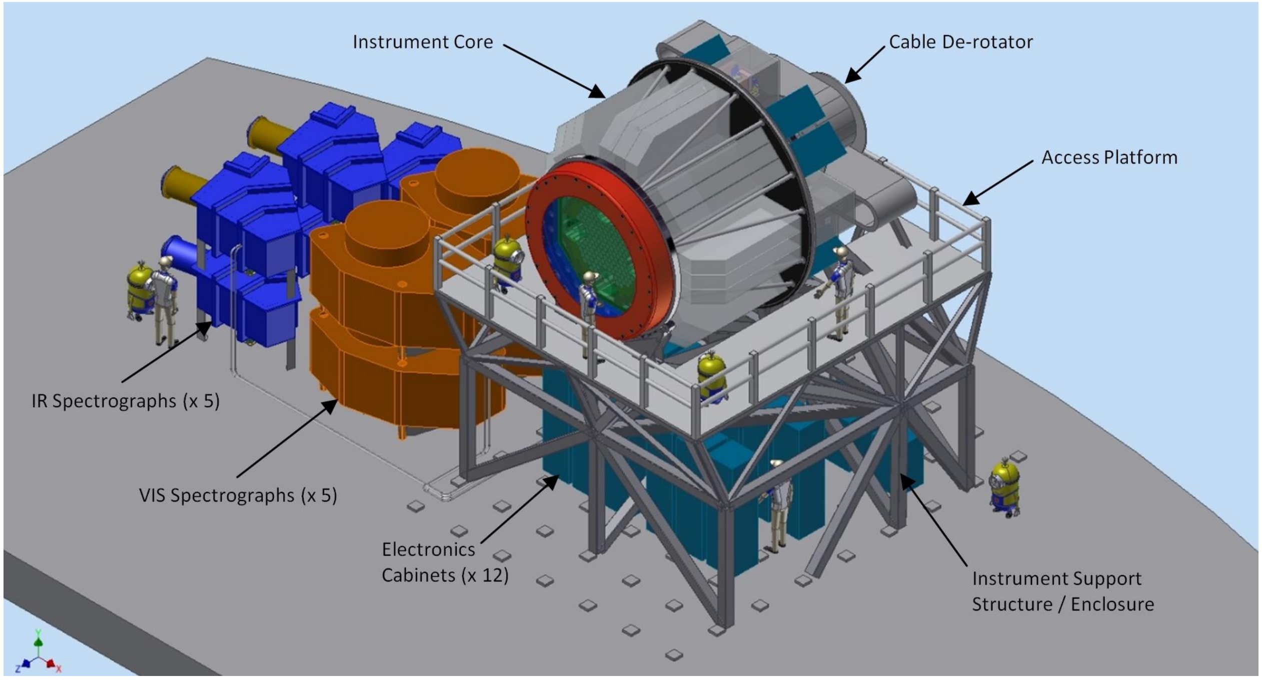


Figure 4: Overview of the concept mechanical design for MOSAIC.

The Instrument Core (i.e. the rotating structure) is mounted on a platform (the Instrument Support Structure, ISS) in order to meet the ELT interface specification of a focus centre 6 m off the Nasmyth platform. We expect to make extensive use of the volume beneath the support structure for accommodating non-rotating MOSAIC hardware, for example the equipment racks for the control electronics. The spectrograph hardware is located to the side.

Rotating Structure

As illustrated in the architecture block diagram, the rotating structure houses the focal plate and positioners, IFU and NGS WFS path-length compensation system (with µDM for the HDM mode) and the LGS WFS, as well as the DM and WFS drive electronics cabinets. The mechanical layout of the rotating structure is shown in more detail in Figure 5.

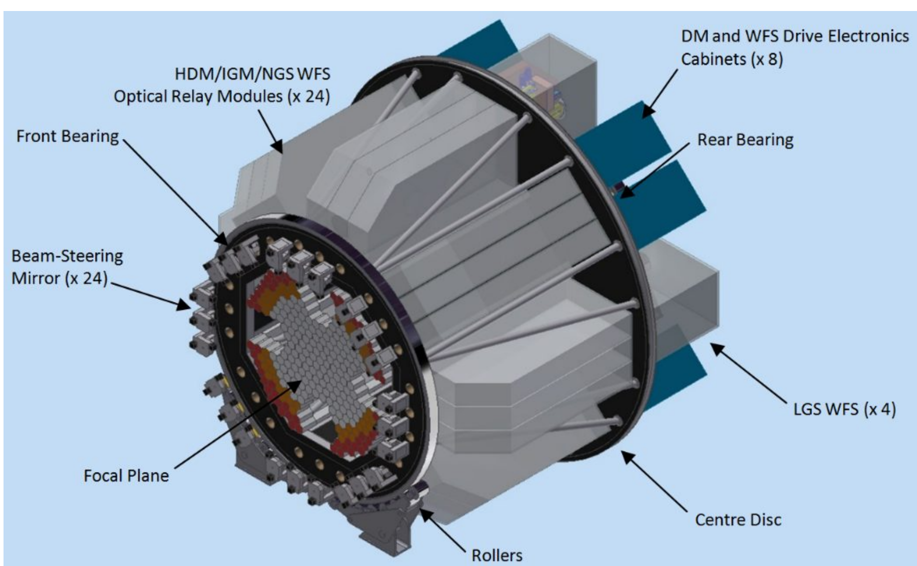


Figure 5: Detail of the MOSAIC Rotating Structure

In particular, it was decided to mount the LGS WFS *behind* the focal plate since i) LGSS rotation with the field is required in any case and ii) it reduces the diameter of the rotating structure resulting in a mechanically more stable arrangement.

The positioner system for MOSAIC is based on tiles arranged on a stepped focal plate. This results is required for non-telecentricity compensation for the ELT. The tile features a multi degree of freedom pick-off mirror which acts as a pick-off for IFU and NGS modes and a HMM-fibre pick-off on an additional focus stage. The range of the HMM-arm is greater than the pick-off mirror, being able to approach near to the centre of an adjacent tile. In 'Type A' tiles, only a HMM-VIS pick-off is present, while in Type-B tiles both a HMM-VIS and 2 HMM-NIR pick-offs, mounted on a cross-beam switch exchange mechanism are included (i.e. only every second tile mounts a HMM-NIR pick-off).

The focal plate arrangement, in terms of tiles, is illustrated in Figure 6. The Optical Relay Modules[8] (ORM) are arranged around the periphery of the focal plate and the pick-off mirror of the positioner is used to direct a field (HDM, IGMM or NGS) towards an appropriate ORS.

Not shown in the figure, but likely required, are additional Type C tiles (that is, tiles with only the pick-off mirror) implemented around the periphery of the technical field to allow for NGS capture for wavefront sensing over the full 10 arcminute field.

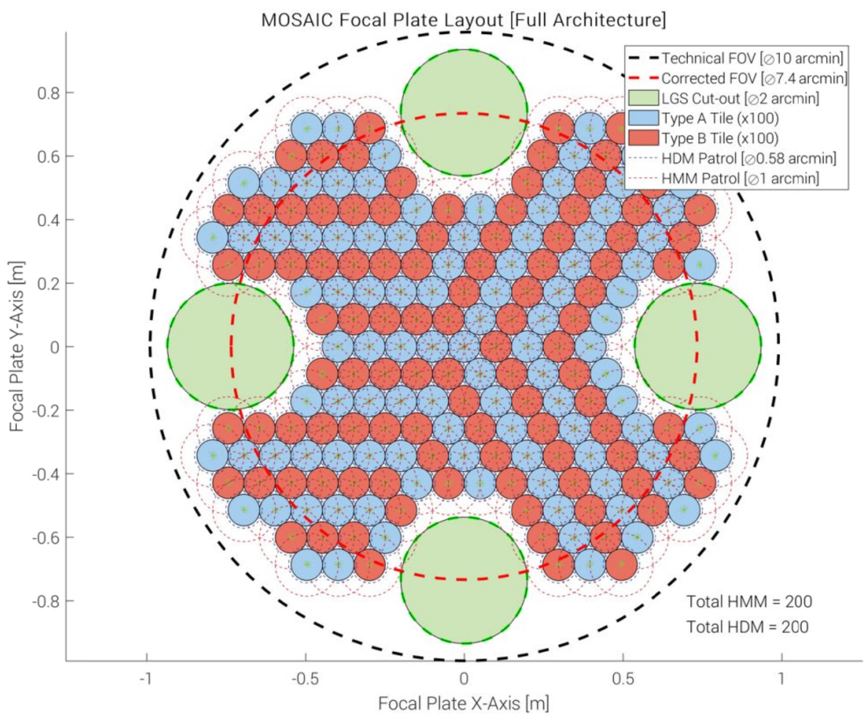


Figure 6: MOSAIC Focal Plate Layout

The signal correction system for MOSAIC is responsible for providing the corrections to the field required for achieving the science requirements. In particular this includes the Adaptive Optics System, but also the Optical Relay Modules which receives the IFU and NGS fields and corrects for pointing and focal length.

The fibre system transports light from the focal plate (or re-produced focal plate at the output of an ORS) to the spectrographs via the cable de-rotator. In the case of HMM modes, this means a distributed series of microlens pick-offs attached to the various positioners. For the IFU modes, it means microlens IFU arrays at the output of an optical relay (plus μDM in the case of HDM mode).

It is expected that all pick-offs will be pig-tailed with a connector in order to de-risk the AIT process. This allows the bulk of the fibre run through the de-rotator to be a separate module from the focal plate. Similarly, the slit assemblies within the spectrographs will also be pig-tailed with connectors to allow de-coupling of the assembled spectrographs form the cable de-rotator – again for AIVT purposes.

The spectrograph systems- both VIS[9] and NIR – interface with the output slit formed from the SOST fibres. Slit-exchange mechanisms allow selection of the mode of operation (HMM or IFU), and grating exchange mechanisms allow selection of the bands. The optical designs of the two spectrograph concepts are reproduced in Figure 7 and Figure 8. The two figures are shown with approximate relative scale.

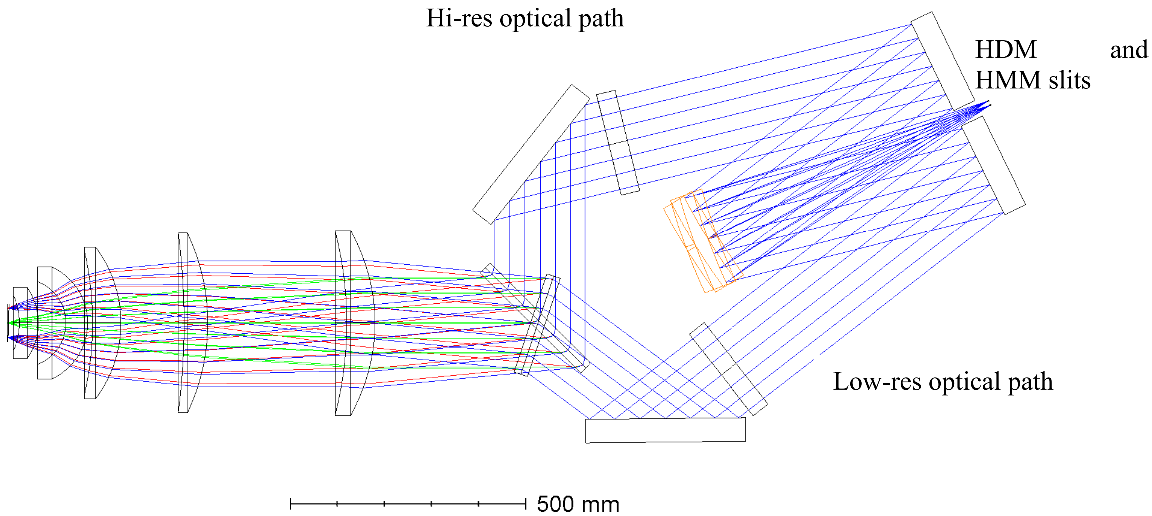


Figure 7: Optical Design of the NIR Spectrograph.

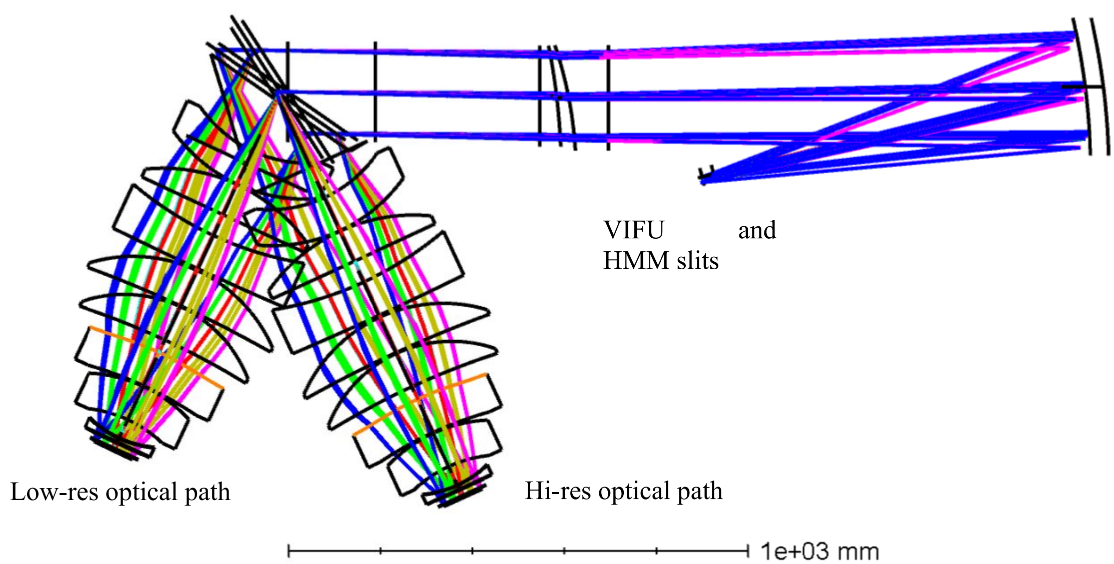


Figure 8: Optical Design of the VIS Spectrograph, showing two camera positions for the LR and HR modes

5. TOWARDS THE FABRICATION PHASE

Multi-IFUs assisted with MOAO in NIR (for example measuring high redshift rotation curves) and in VIS (observing red-shifted UV absorption lines) are unique in efficiently generating an inventory of all phases (dark matter & multi-phase gas) of matter. They are very competitive when compared to slit-fed spectrographs, given the known issues with

sky-subtraction, light concentration and aperture losses. MOSAIC will be the most efficient ELT instrument for follow-up on JWST, for example uncovering the sources of reionization. It will exploit the gain in telescope size and can be implemented with a moderate demand on the AO systems implemented in the telescope. We also argue that, besides the indispensable follow-up of the many faint sources discovered by JWST, MOSAIC will be important in providing targets for other ELT instruments. We expect it to become the work-horse instrument for identifying the counterparts of future, very distant Gravitational Wave events detected by LISA/Virgo, as well as with ATHENA, since all these experiments depend on high multiplex optical spectrographs for source and distance identification. We lastly note that the MOSAIC risks are well understood, since the instrument design is free from untested technology and low in complexity.
Given a Phase B starting point in early 2019 with design activities and prototyping activities to last 3 to 4 years. We are confident to enter the building Phase in 2023, get AITV[11] and, finally, delivery to ESO in 2027 and on sky instrument commissioning in 2028.

Considerably more detail about many aspects of the MOSAIC instrument were presented separately at this SPIE Conference[1,2,3,4,5,6,7,8,9,10,11,12].

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