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MOSAIC at the ELT: a unique instrument for the largest ground-based telescope

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ABSTRACT

MOSAIC is the Multi-Object Spectrograph (MOS) for the 39m Extremely Large Telescope (ELT) of the European Southern Observatory (ESO), with unique capabilities in terms of multiplex, wavelength coverage and spectral resolution. It is a versatile multi-object spectrograph working in both the Visible and NIR domains, designed to cover the largest possible area (∼40 arcmin^2) on the focal plane, and optimized to achieve the best possible signal-to-noise ratio on the faintest sources, from stars in our Galaxy to galaxies at the epoch of the reionization. In this paper we describe the main characteristics of the instrument, including its expected performance in the different observing modes. The status of the project will be briefly presented, together with the positioning of the instrument in the landscape of the ELT instrumentation. We also review the main expected scientific contributions of MOSAIC, focusing on the synergies between this instrument and other major ground-based and space facilities.

Keywords: Spectroscopy, multi-object spectroscopy, fiber spectrographs, ELT, galaxies, reionisation, intergalactic medium, stellar populations, multi-messenger astronomy

1. INTRODUCTION

The ESO's 39 meter Extremely Large Telescope (ELT [*]) will start its scientific operations on Cerro Armazones (3046m altitude; Atacama desert, Chile) in 2028. MOSAIC[†] [‡] is one of two first-generation instruments in the ELT roadmap, together with ANDES, arriving at the telescope after the first-light instrumentation (namely HARMONI, METIS, MICADO, and MORFEO).

MOSAIC is a versatile multi-object spectrograph optimized for a large number of science cases needing multiplex capabilities (see e.g.[1,2]). It is intended to provide unique observational capabilities at the ELT, with multi-object observations at moderate spectral resolution, making use of the entire Field of View (FoV hereafter) available at the ELT (∼40 arcmin^2). MOSAIC is built on the legacy of three former E-ELT phase A instrument studies, EAGLE,[3] OPTIMOS-EVE,[4] and OPTIMOS-DIORAMAS.[5] MOSAIC completed its own Phase A conceptual study with ESO in 2016-17.[6] The project was restructured in 2021-22 to prepare for the preliminary design phase. During the current B1 phase the MOSAIC architecture has been optimized to reduce the risk and the required budget, while preserving its scientific performance and taking into account the available mass, volume and power budget on the Nasmyth platform where it will be located. The characteristics and performance of the instrument presented in this article result from the studies conducted since the begining of the Phase B1 in March 2023.

In Sect. 2 we present an overview of the instrument, including the main characteristics and expected performances of MOSAIC. The status of the project and the positioning in the landscape of the ELT instrumentation are presented in Sect. 3. Sect. 4 summarizes the main Science Cases of MOSAIC and briefly describes some of the possible synergies with other facilities. Conclusions are given in Sect. 5.

2. INSTRUMENT OVERVIEW

MOSAIC will cover the optical and near-infrared domains with three observational modes, according to the following characteristics:

- The MOS-VIS mode will provide integrated spectra for ∼140 objects at the same time, covering the ∼0.39-0.95 μm optical range in a single shot. The spectra will be obtained using on-sky apertures of diameter 0.7 arcsec, with spectral resolving power R>4000. Alternatively, it will possible to observe ∼60 (goal 65) objects at higher spectral resoluton R∼19000 within four narrower windows of specific interest (see below);

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[*] https://elt.eso.org/

[†] http://www.mosaic-elt.eu/

[‡] https://elt.eso.org/instrument/MOSAIC/

- The MOS-NIR mode will provide integrated spectra for ∼180 objects at the same time, covering the ∼0.95-1.8 μm near-infrared range in a single exposure. The spectra will be obtained using on-sky apertures of diameter 0.6 arcsec, with spectral resolving power R>4000. Alternatively, it will be possible to observe ∼180 objects at higher spectral resolution R∼18000 within one narrower window of specific interest (see below);
- The mIFU mode will offer Integral Field Units for parallel observations of up to 8 extended objects, covering the same wavelength range as the MOS-NIR mode. The individual FoV of each IFU will be ∼2.2 arcsec in diameter, with hexagonal shape. Each spaxel (also hexagonal) will be 150mas on-sky, providing coarser spatial resolution compared to HARMONI, but optimised to reach higher surface brightness sensitivity for faint extended sources.

Table 1 presents the curent basic settings of MOSAIC in the different observing modes. The current observing modes of MOSAIC differ from the previous ones in several points. On one hand, the addition of an ADC has opened the possibility to cover the full optical wavelength domain in one shot. On the other hand, the cross-over wavelength of the VIS bandwidth has been shifted from 800 to 950 nm allowing for further optimalization of the instrument optics. Also the multiplex in the MOS-VIS mode has been reduced to fit it into one visual spectrograph.

Figure 1 displays an overview of MOSAIC at the Nasmyth Platform of the ELT, showing the three main systems, namely the Front End, the VIS Spectrograph and the NIR Spectrographs. From the high-level system view, the project is organized around these three main systems or “channels”: Front-End, VIS-Channel and NIR-Channel. Further details regarding the optical design of the NIR spectrograph and its camera protype can be found in Floriot et al. (2024; this conference) and Pamplona et al. (2024; this conference). Some interesting details regarding the implementation of the Front-End can be found in El Hadi et al. (2024; this conference).

All MOSAIC modes will be assisted by Ground-Layer Adaptive Optics (GLAO) using both Natural and Laser Guide Stars. All modes are designed to provide high survey speed, that is to minimize the amount of observing time necessary to reach the required signal-to-noise ratio for all targets in the large statistical samples required by the different MOSAIC science cases (see Sect. 4 and[1] for further details). More details regarding the MOSAIC GLAO performance and system architecture can be found in Bharmal et al. (2024; this conference).

While first-light ELT instruments will focus on exploiting the central part of the ELT focal plane, MOSAIC will exploit a much larger area of 40 arcmin^2 (7.4 arcmin in diameter). To provide such a large FoV has been one of the main motivations for the 5-mirror optical design of the ELT. At this scale, one has to take into account the fact that the ELT focal plane is non-telecentric. To overcome this issue, MOSAIC is developed following an original stepped and tiled focal plane design made of 300 segmented tiles, which can be individually oriented in space to provide local telecentricity. Three distinct families of tiles are being designed, corresponding to different sets of optical fibers/pick-off mirror they will carry, each of them addressing different observing modes: 100 tiles will carry optical fiber bundles suited for MOS-VIS observations (either at low or high spectral resolution), 100 wilfield-of-viewl carry optical fiber bundles suited for MOS-NIR (either at low or high spectral resolution), and 100 other tiles will carry bundles suited for either MOS-VIS or MOS-NIR observations. The maximum multiplex capability for each observing mode if given in Table 1. This design will provide MOSAIC with the very interesting capability of observing in parallel different objects within the same FoV, with different modes, within the limit of 300 objects at the same time, corresponding to the total number of tiles. This will boost the observational efficiency of the instrument. The reader can find further details on the positioners and the tiled focal plane in articles by Bharmal et al. (2024; this conference) and Thurneysen et al. (2024; this conference).

Figure 2 presents the transmissions expected for the different observing modes in the VIS and NIR channels, compared to requirements. As seen in this figure, all the modes have transmissions above the requirements. The VIS-channel is optimized for galactic studies: high survey speed and LSF stability; it includes a dual-arm spectrograph with a three-grating exchanger device allowing to select between MOS VIS-LR(blue), MOS VIS-HR B1 and VIS-HR B2 for the blue camera, and MOS VIS-LR(red), MOS VIS-HR R1 and VIS-HR R2 for the red camera, where the different modes correspond to the settings sumarized in Table 1. Each one of the blue and red arms has a set of 2×6k×6k detectors with coatings optimized to achieve the best signal-to-noise ratio. The optical (blue) performance of the ELT has been greatly improved by adjusting the coatings applied

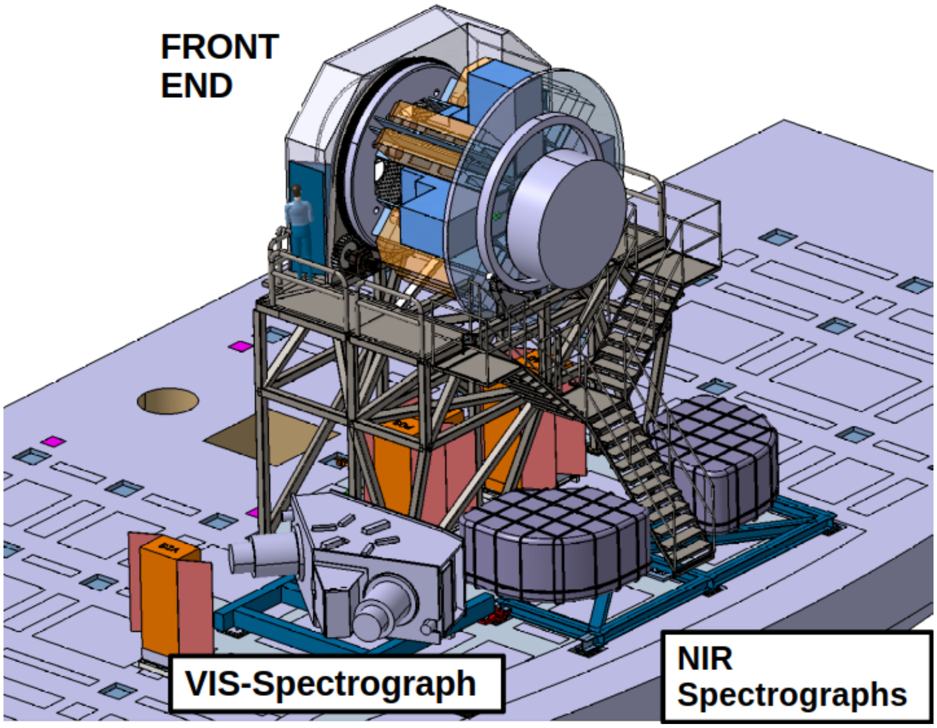

Figure 1. Overview of MOSAIC at the Nasmyth Platform of the ELT (~ 30m×15m). The three main systems are displayed, namely the Front End, the VIS Spectrograph and the NIR Spectrographs.

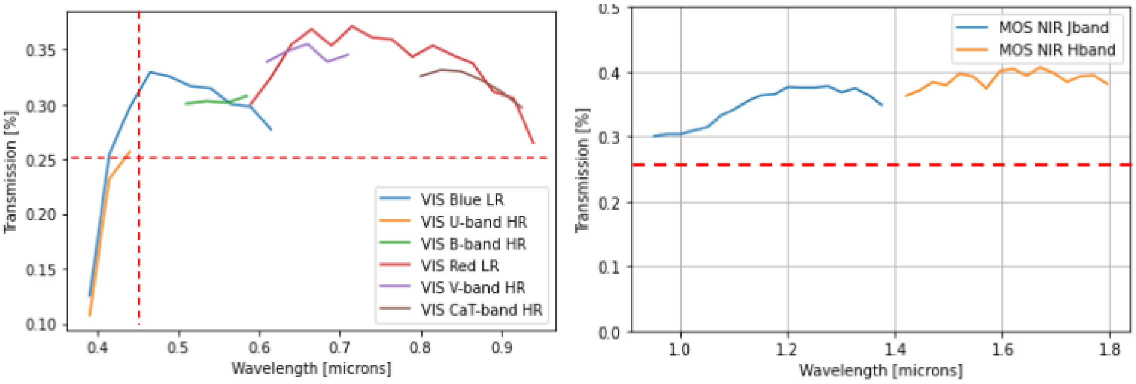

Figure 2. Transmissions expected for the different observing modes in the VIS and NIR channels (left and right respectively), excluding atmospheric and telescope transmissions. The red dashed lines display the transmission requirements.

to the ELT mirrors.[7] The NIR-channel is optimized for faint sources and optimal sky subtraction. It includes two "twin" spectrographs and cryostats, each one consisting of a J and H-band arms and cameras. The H-band arm includes two possible observing settings, NIR-LR and NIR-HR, both in MOS and mIFU modes, where the different modes correspond to the settings sumarized in Table 1. Each one of the cameras has an H4RG 4k×4k detector, meaning eight H4RG detectors in total, working at a temperature of 90K.

Table 1 also presents the expected sensitivity in terms of limiting AB magnitudes[8] for point sources. It is worth noting that the whole VIS and NIR bandwidths are covered in a single exposure in the Low/Mid-resolution modes; however, we cannot observe the same object simultaneously in the two channels. Four High-resolution bands are available in the VIS channel (two of them, one on each arm blue/red, can be observed simultaneaously), and one in the NIR H-band.

Table 1. Basic settings of MOSAIC in the different observing modes. The multiplex capability is given in column 2. The limiting magnitudes given in the last column are indicative, and correspond to the current expectations for a point source observed with signal-to-noise ratio of 5 in 5h total exposure time. In this simulation, the DIT used in the VIS and NIR are 1200 and 300 seconds respectively.

MODE	N	λ(min) nm	λ(max) nm	R(mid)	R(min)	Sampling pixels	m_{AB}
MOS VIS-LR	140	390	950	5000	4000	>3.57	26.0
MOS NIR-LR	180	950	1800	R>4000 (goal 5000)	>4000	>2.5	26.0-25.4
mIFU-LR	8	950	1800	R>4000 (goal 5000)	>4000	>2.5	25.0
MOS VIS-HR B1	65	390	455	19000	<18000 in few SRE	2.61	23.5
MOS VIS-HR B2		510	595				24.7
MOS VIS-HR R1		610	712				24.2
MOS VIS-HR R2		800	934				24.4
MOS NIR-HR	180	1523	1620	R>18000 (goal 23000)	18000	>2.5	23.8
mIFU-HR	8	1523	1620	R>18000 (goal 23000)	18000	>2.5	23.4

3. STATUS AND POSITIONING IN THE LANDSCAPE OF THE ELT INSTRUMENTATION

MOSAIC completed its Phase A conceptual study in 2016-17.[6] The project was reorganised in 2021-22 to prepare for a preliminary design phase (Phase B). This important milestone was reached in March 2023, with the signature of the Phase B1 Agreement with ESO for a Phase B1 study whose duration is 1.5 years, leading to a Specification and Architecture Review (SAR). The Phase B2 is expected to follow immediately after the SAR, leading to the Preliminary Design Review (PDR) at the end 2025, entering Phase C (final design). Currently the Preliminary Aceptance in Europe (PAE) is expected in 2032, with on-sky operations subject to the first-light instrumentation schedule.

The MOSAIC consortium is responsible for raising funding for both the human resources and hardware procurement. Raising such resources results in a large consortium of $\sim$ 350 members belonging to 31 laboratories from 23 institutional partners spread over 13 countries (Austria, Brazil, Finland, France, Germany, Italy, Netherlands, Portugal, Spain, Sweden, Switzerland, United Kingdom and USA). The consortium is in fact still growing, since new partners are expected to join to complete the project budget in the coming years.

Following the high-level system view described in Sect. 2, each Channel has its own deputy Project Manager and System Engineer. Instead of having a global Assembly, Integration and Testing (AIT) on a unique integration site, the size of MOSAIC is such that we are in the process of exploring a distributed and remote integration at three diferent locations: i) The NOVA optical-infrared laboratory in Dwingeloo (Netherlands) for the VIS-Channel; ii) UCM campus in Madrid (Spain) for the NIR-Channel; and iii) LAM (Marseille) for the Front End and Adaptive Optics parts, named Front-End Channel. If the feasibility is demonstrated, the adoption of a remote AIT will have a positive ecological impact by reducing the travel between the consortium laboratories. Further details on the assessment and routes to reducing the environmental impact of MOSAIC can be found in Janssen et al. (2024; this conference).

Regarding the positioning of MOSAIC in the landscape of the ELT instrumentation, we note that this instrument is unique in providing spectroscopic multiplex capabilities at moderate resolving power (R$\sim$4000-5000), covering the whole electromagnetic spectrum, from the bluest wavelengths (0.39μm) all the way to the NIR (1.8μm). It will be the only ELT instrument providing observations on a wide patrol field ($\sim$40 arcmin^2), with a selection of simultaneaous modes. Indeed, MOSAIC has been optimized to yield the highest survey speed, and to successfuly study the faintest sources thanks to its high surface-brightness sensitivity, as discussed in Sect. 4.

4. THE SCIENCE CASES OF MOSAIC

All MOSAIC partners already agreed to pool the Guaranteed Time Observations (GTO) granted by ESO as a reward for building the instrument and share it to conduct ambitious and transformative surveys. More than 250 scientists from 14 countries are involved in the MOSAIC Science Working Groups (SWG) and Science Team. The team has actively participated into the definition of the MOSAIC architecture as presented in previous sections, by setting the scientific priorities of the observational modes. There is still work in progress in the definition of the simultaneous modes that will be accessible and considered as high-priority.

The large Science Team is organised in five SWGs corresponding to the most prominent MOSAIC science cases (see also the references[1,2]):

- SWG1: First light galaxies and reionisation. MOSAIC will measure UV rest-frame spectra of the most distant galaxies, which is essential to assess their formation history and their role in the reionisation of the Universe. More precisely, MOSAIC is expected to contribute to the spectroscopic study of the first stars, the formation and evolution of the first super-massive black holes and AGN, as well as the study of the metal content of primeval galaxies, and the properties of the first proto-clusters formed in the early universe.

- SWG2: Inventory of matter. MOSAIC will provide the first exhaustive census of matter at $z\sim3$, by combining measurements of the tomography of cold gas in the intergalactic medium and the circumgalactic medium, and of the dark matter content of $z\sim3$-4 galaxies. The gas properties of the circumgalactic mediumwill be addressed, such as inflows, outflows, metals, and the equation of state. For these needs, both the mIFUs and the high multiplexing capabilities of MOSAIC are important.

- SWG3: Mass assembly of galaxies through cosmic time. This group is focusing in particular on the dynamics of low-mass galaxies. Several key projects are being considered based on the mIFU and multiplex capabilities both in the VIS and NIR domains, such as the analysis of resolved galaxy properties, the study of stellar populations and variations of the Star Formation Histories, from star-forming to quenched galaxies, and the build-up of large-scale structures at redshifts $z>3$.

- SWG45: Stellar populations in and beyond the Milky Way, and Galaxy Archaeology. This group is aiming to unveil the star formation and evolution history of galaxies, and probe low-metallicity stars in a variety of environements. MOSAIC is expected to overcome the current limitations with 8-10m-class telescopes thanks to its higher sensitivity which allows one to probe further down in the color-magnitude diagram, and to explore larger heliocentric distances. In particular, MOSAIC will permit the measurement of physical parameters for dwarf stars where current observations are limited to giant stars.

- SWG6: Transients and multi-messenger astrophysics. MOSAIC could play a fundamentsl role in the identification and characterisation of electromagnetic counterparts. For this science domain, the coverage of the full optical and NIR range (though not simultaneously) is a big improvement compared to the previous architecture. It is worth to note that this science case is not considered as dimensioning for the MOSAIC architecture.

Several important synergies have been identified between MOSAIC and other facilities already available or becoming available in the 2030s, such as the James Webb Space Telescope (JWST[9]), Euclid,[10] MOONS/VLT,[11] Roman Space Telescope,[12] SKA,[13] Athena,[14] or HARMONI/ELT.[15] Indeed, MOSAIC will be a leading follow-up machine for all these experiments and surveys. Some outstanding science cases will be directly impacted. In this respect, we can mention the synergy between JWST, SKA and MOSAIC for the study of galaxies during the epoch of reionization, the 21-cm signal correlated with the spectroscopic mapping by MOSAIC and JWST being used to trace the topology of the process. The complementarity between MOSAIC, MOONS and HARMONI is clear in the studies conducted by the SWG45, the three instruments providing complementary views in dense stellar regions. The studies conducted in the SWG2 and SWG3 will benefit from the combined use of MOSAIC and Euclid, JWST, SKA, and/or MOONS. The dark matter part of the SWG2 science will also strongly benefit from a synergy with HARMONI, which will provide high resolution data for measuring the central dark matter densities, and distinguishing between different dark matter types. Another potentially important synergy is expected with BlueMUSE,[16] arriving at the VLT at the same time as MOSAIC, and optimized for the bluest wavelengths down to 350nm. BlueMUSE will be a potential follow-up instrument for MOSAIC prime targets. PSF[17] and WEAVE[18] are key synergistic (and at some point competing) facilities, susceptible to provide useful target fields and complementary views for all MOSAIC science cases. Last but not least, MOSAIC will be also important for the follow-up of Gravitational Wave sources detected by LIGO and LISA.

The MOSAIC Science Team has started the long process of building these future MOSAIC surveys. This process starts by building Science Reference Projects, which will detail what are the foreseen observations with MOSAIC, along with observational considerations (e.g., possible choise of field, number of visits, calibration requirements, etc.). These will be assembled into the MOSAIC Red Book at the end of phase B and will be used by the consortium to design Core Projects, which will be later arranged into a set of MOSAIC surveys.

5. CONCLUSION

In conclusion, MOSAIC will provide the ELT community with multi-object observations over a large patrol field, covering the optical and near-infrared wavelength range in a highly efficient way. The parameter space covered by MOSAIC in terms of spectral range and resolution, and FoV, makes it a unique instrument in the landscape of ESO/ELT instrumentation by effectively filling the parameter space necessary to make the best possible use of the ELT. MOSAIC provides discovery space by covering such a large wavelength domain, at different spectral and spatial resolution for hundreds of targets in an as large as possible FoV.

MOSAIC is meant to be a multi-tasking instrument for the ELT and, as such, an efficient follow-up machine for the most powerful space missions and ground-based experiments foreseen in the post-2030 landscape (JWST, Euclid, Rubin, Roman, SKA, Athena or LISA among others). The MOSAIC project has anticipated its Preliminary Acceptance in Europe in 2032, with on-sky operations subject to the first light instrumentation schedule.

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