Upgrading SPHERE with the second-stage adaptive optics system SAXO+: conceptual design of the opto-mechanical module

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ABSTRACT

SAXO+ is a second-stage adaptive optics module for the SPHERE instrument at VLT. It has been proposed to increase the achievable contrast and improve the current performance of detecting and characterizing exoplanets and disks. It is developed by the SPHERE+ consortium as part of the roadmap activity for the planet finder instrument (PCS) of the Extremely Large Telescope (ELT). This paper describes the optical and mechanical design of SAXO+.
Keywords: Extreme Adaptive Optics, optical and mechanical design, instrument upgrades, SAXO+, SPHERE, VLT, PCS, ELT

1 INTRODUCTION

SAXO+ [1] is a second-stage adaptive optics module for the SPHERE [2] instrument at VLT. It is designed to work in a cascaded Adaptive Optics (AO) architecture together with SAXO [3], the currently operating first-stage AO system within SPHERE. The goal is to increase the contrast close to the optical axis and improve the current performance of detecting and characterizing exoplanets and disks. SAXO+ is developed by the SPHERE+ consortium as part of the roadmap activity for the planet finder instrument (PCS) [4] of the Extremely Large Telescope (ELT) [5].

This paper concerns the SAXO+ optical and mechanical implementation [6][7]. It outlines the main requirements and system choices as well as a description of the optical and mechanical design. The SAXO+ module is very compact. The common path hosts the second-stage Deformable Mirror (DM). A dedicated Wavefront Sensor (WFS) measures the residual wavefront aberrations left by the first-stage AO system.

At the moment of writing, the SAXO+ consolidation phase has been completed and the project is waiting for approval to possibly enter the final design and development phase, until installation and commissioning that we aim for 2027.

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2 REQUIREMENTS AND SYSTEM CHOICES

2.1 General requirements

The time delay error dominates the SPHERE AO error budget. A straightforward approach to reduce the time delay is to run the AO system faster. In practice, this is most easily achievable by a cascaded AO system with a second-stage lower-order AO system (SAXO+ in this case), which corrects a smaller area of the PSF at a higher update rate.
SAXO+ AO performance analysis [8] shows that the SAXO+ performance requirements could be achieved by a DM with about 25 actuators across the pupil diameter and running at up to 3 kHz (the exact frequency depending on the guide star brightness).
A "non-invasive solution" is mandatory for SAXO+: the second-stage module has to preserve all current functions and optical interfaces of the SPHERE instrument. This requirement, along with tight constraints on volume, mass, and fixation holes, impose a very compact opto-mechanical layout, which can be achieved with a small aperture DM, thus requiring a small pupil image. A preliminary optical and mechanical design (section 2.3) indicated a reference size of about 10 mm, or slightly more, for this pupil image, i.e., of the same order of magnitude as other intermediate pupil images inside the SPHERE instrument.
The required Field of View (FoV) for the SAXO+ common path is 16.7 arcsec in diameter.
The overall wavelength range for the common path is 0.95-2.32µm. Two wavelength ranges have been defined for the WFS path on the basis of extensive AO system analysis: 0.95-1.1µm (bright guide star cases) and 0.95-1.45µm (red/faint cases).
The optical design has to preserve the orientation of the polarization vector to ensure compatibility with the current polarimetric capabilities.
In order to benefit from second-stage AO correction, the SPHERE apodizers for coronographic observations (which are upstream of SAXO+, section 2.2) have to be in "open" position when SAXO+ is operated. Therefore, SAXO+ has to offer an intermediate pupil plane for new apodizers, downstream of the second-stage DM. Three apodizers are foreseen, based on the Apodized Pupil Lyot Coronograph approach [9].

2.2 SAXO+ location and light feeding

SAXO+ is positioned downstream of the SPHERE IR ADC and apodizers, and upstream of the Differential Tip-Tilt Sensor (DTTS) beam-splitter. The optical beam for SAXO+ is picked off from the SPHERE optical path and re-injected back into the SPHERE optical path after second-stage AO correction by a deployable pick-off group consisting of two fold mirrors. When the pick-off group is outside the SPHERE main path, SAXO+ is simply skipped, and SPHERE operates normally. The selected zone for the optical beam pick-off group is shown by the red circle in Figure 1.

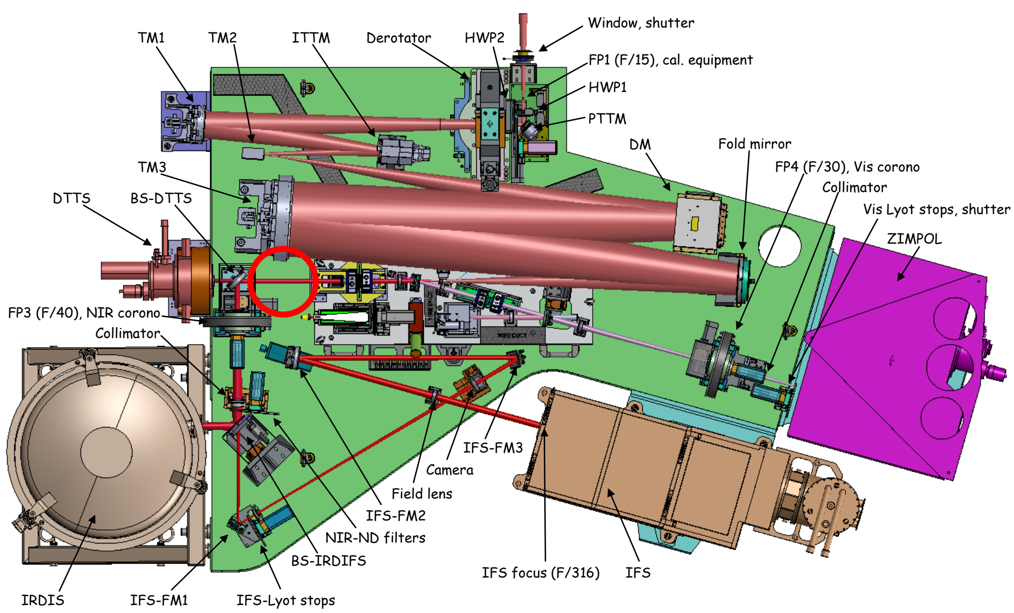

Figure 1. SPHERE bench and optical beam pick-off zone for SAXO+ (red circle).

2.3 Optical layout

The SAXO+ optical layout results from a trade-off study among five preliminary optical designs. The preliminary optical designs were built using paraxial lenses (one lens for each focal plane re-imaging or pupil re-imaging) and flat fold mirrors. Due to the relaxed focal ratios of optical beams, the paraxial lens approximation was verified to be sufficiently representative. All five preliminary designs fulfilled the interface requirements, including realistic sizes for the main devices (WFS camera, DM, etc.).

The main features of the selected baseline design are: compact size, best possible accessibility to crucial devices, and the long-pass dichroic beam-splitter placed nearby an intermediate focal plane.

The trade-off study also gave important indications regarding the size of the pupil images inside SAXO+.

- Pupil image on the DM:
  the diameter of this pupil image is constrained to be about $d \approx 10$ mm in order to meet interface requirements with a design of acceptable complexity; it is possible to change the pupil size by up to about 30% by design re-optimisation, with manageable modifications and without violating interface constraints.
- Pupil image on the tip-tilt modulation mirror (more details on this device are given in section 2.4):
  the pupil image size that fits the preliminary designs is $d \approx 5$ mm. Reducing this size requires a shorter focal ratio of the collimating optics (thus potentially tighter tolerances) and increases the necessary mechanical tip-tilt of the mirror. Increasing this size is marginally possible, it reduces the required mechanical tip-tilt of the mirror, at the expense of a larger mirror mass and inertia.
- Pupil image for the apodizer:
  the size of the pupil image for the apodizer that naturally fits the designs is $d \approx$ 8-10 mm.

2.4 Wavefront sensor

The SAXO+ WFS is based on the pyramid concept [10] as a baseline.

Tip-tilt modulation is a common technique to make the response of a pyramid WFS linear over the expected range of input wavefront distortions. In the consolidation phase of SAXO+, at least three concepts were considered:

a) modulation by a fast tip-tilt mirror in a pupil image plane (this is the standard approach adopted in other existing pyramid-based AO systems [11]);
b) modulation by a tilted mirror, rotated at fast speed around an axis through the mirror centre [6][7];
c) static modulation employing optical devices such as optical diffusers or diffractive optical elements [12][13][14].

Due to their relatively low technology-readiness level, solutions b) and c) were left to further investigation, as they need more research and development effort. Solution a) was chosen as baseline for SAXO+.

A conservative upper limit for the modulation radius, derived by AO end-to-end simulations [8], is $3\lambda/D$ (λ: WFS wavelength, D: telescope pupil diameter). The SAXO+ WFS is required to compensate internally for slow tip-tilt drifts with respect to the SPHERE DTTS, which is the tip-tilt sensor ensuring that the AO-corrected star image is aligned to the coronographic mask of the instrument. This internal compensation is performed as a baseline by the SAXO+ tip-tilt modulation mirror itself, applying a steering command to the modulation trajectory; when the applied offset approaches saturation, the command is offloaded to an XY centring mechanism of the pyramid prism. Given the pupil image diameter on the tip-tilt modulation mirror, the required peak-to-valley rotation is 0.7mrad per axis at a frequency up to 3kHz, and an additional 1.4mrad per axis at slow rate (1Hz) for field steering.

The tip-tilt modulation is synchronized with the camera acquisition by a trigger signal generated by the WFS camera itself, in order to avoid random mismatches between the two periods.

The design FoV of the SAXO+ WFS, and thus the diameter of the field stop at the WFS input, has been determined considering several effects: width of the seeing-limited PSF, allocations for tip-tilt modulation and tip-tilt steering, diffraction effects due to the field stop size, sky background contamination, etc. The resulting FoV diameter is 3.2 arcsec. This value is under revision at the moment of this writing and might be reduced.

AO system analysis indicated an optimal diameter of about 50 pixels for each of the four pupil images produced by the pyramid WFS: this diameter corresponds to about 2 pixels per projected actuator pitch of the second-stage DM. The four pupil images are required to be arranged within the central 128×128 pixels region of the detector.

In addition to the pyramid wavefront sensing scheme, an optional approach based on Zernike's phase-contrast method, named ZELDA [15], will possibly be implemented.

2.5 Remotely-controlled functions

Several remotely-controlled mechanisms are required within SAXO+, apart from the DM, the WFS camera and the tip-tilt modulation device, which have been described in the previous sections. These mechanisms serve essentially two types of functions: exchange of devices and adjustments.

Three exchange mechanisms are required. The first one is for deploying the pick-off group (section 2.1) in the SPHERE optical beam to feed SAXO+, or remove it to restore the SPHERE configuration. An exchange mechanism is required for positioning the dichroic beam-splitters between the common path and the WFS path: at least two positions are needed, to cover the two wavelength ranges of the SAXO+ WFS (section 2.1), one more position is for AIT purposes and two more positions might be needed for the optional ZELDA WFS. The last exchange mechanism is for positioning the apodizers: four positions are needed, three for the apodizers themselves (section 2.1) and one "open" for the observing modes without apodizer.

The two mirrors in the pick-off group (section 2.2) and another fold mirror in the common path are mounted on remotely-controlled tip-tilt adjustments for alignment purposes. This functionality is mainly planned for initial alignment operations, or after major maintenance, and is justified by the need to relax the global mounting tolerances of SAXO+, which would be otherwise too tight, given the limited accessibility to the module within the SPHERE enclosure.

The following remotely-controlled adjustments are foreseen in the WFS path. The pyramid prism is mounted on XYZ translation stages: the XY axes (orthogonal to the optical axis) are needed for centring the pyramid on the guide star image and possibly for offloading large steering commands as anticipated in section 2.4, while the Z axis (along the optical axis) is for nulling defocus on the pyramid. The objective forming the four pupil images is also mounted on XYZ translation stages: the XY axes are for registering the positions of the pupil images on the detector, while the Z axis is for focusing the pupil images. According to the analysis conducted so far, the Z-axis adjustments, once set during installation and initial alignment, are only needed to compensate for seasonal thermal effects. One of the two XY axes of the pyramid can also be used as exchange mechanism, to replace the pyramid and the focal plane mask required by the optional ZELDA WFS (this functionality, if confirmed, requires adequate stroke for this axis).

Of course, manual adjustments also have to be implemented for the alignment of optical components and various devices: these degrees of freedom will only be used during Assembly, Integration and Test (AIT) activities.

3 OPTICAL DESIGN

Figure 2 and Figure 3 show an optical functional block diagram and an optical model of SAXO+.

A deployable fold mirror picks off the optical beam from the SPHERE optics to feed SAXO+. After passing through SAXO+, the optical beam is re-injected back into the SPHERE optical path by another deployable fold mirror, while preserving the SPHERE optical interfaces at the output focal plane. For opto-mechanical reasons, the two fold mirrors, and a lens to re-image the focal plane, are mounted on the same deployment mechanism. When the deployable group is out of the optical beam, SAXO+ is skipped.

The science/common path (red rays) consists of four doublet lenses. The first doublet lens, L1, forms a pupil image on the SAXO+ DM. The second doublet lens, L2, forms an intermediate focal plane where a dichroic beam-splitter splits the WFS path (in reflection) from the common path (in transmission); the beam-splitter is positioned in such a way to leave clearance around the reflected focal plane in the WFS path for positioning, if necessary, a deployable calibration source. The third doublet lens, L3, forms a pupil image for the deployable apodizers. Finally, the fourth doublet lens, L4 (mounted on the deployable pick-off group described above) forms the output focal plane. The optical beam in the common path is folded by five mirrors, one of which is the DM.

The WFS path (yellow rays) consists of a doublet lens WFS-L1, which forms a pupil image on the tip-tilt modulation mirror, a doublet lens WFS-L2, which forms a telecentric focal plane on the pyramid prism and a three-lens pupil imaging objective WFS-L3 which forms four pupil images on the WFS camera.

Instead of cemented doublets, air-spaced lenses have been assumed to avoid any risk related to thermally induced stress, light absorption by glue, etc.

The pyramid prism consists of two prisms made of different materials, to reduce chromatic effects on the pupil images, following the approach implemented in other existing AO systems [16].

From an optical point of view, the design could host, as a second option, the ZELDA WFS (section 2.4), which requires the pyramid prism to be replaced by a focal plane phase mask (through an exchanger mechanism). The pupil imaging objective WFS-L3, which is designed to accept four optical beams from the pyramid to form four pupil images, could also accept a single beam from the ZELDA WFS to form a single pupil image at the centre of the detector.

A preliminary analysis of environmental effects (temperature and pressure) and alignment tolerances (both for global mounting and internal alignment) was performed during the consolidation phase, in order to derive preliminary requirements for the mechanical design addressed in the next section.

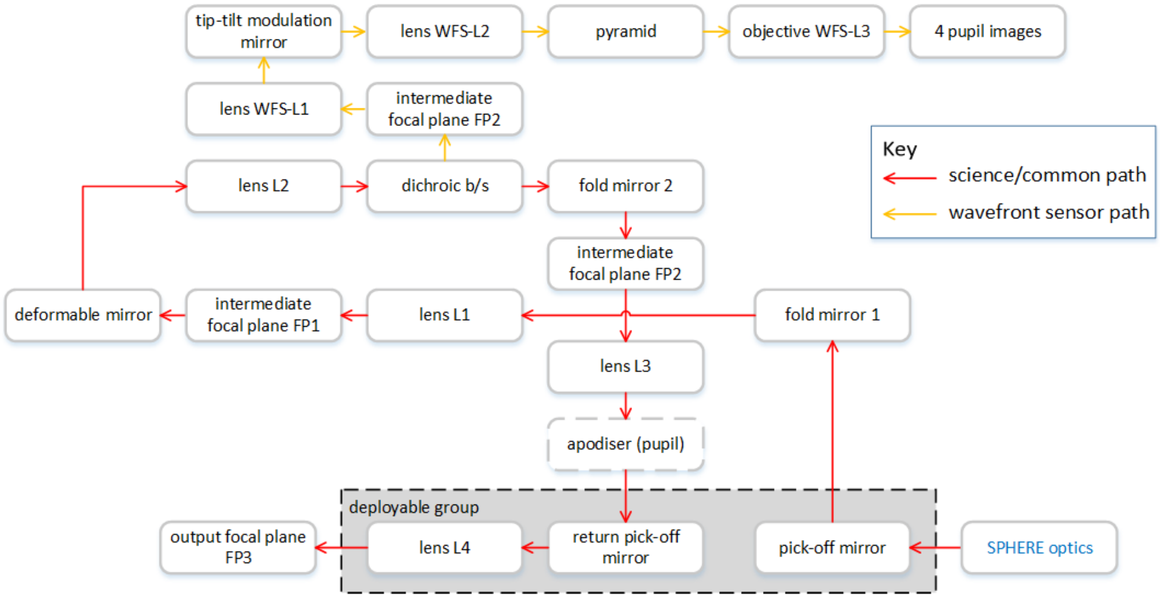

Figure 2. SAXO+ optical functional flow diagram.

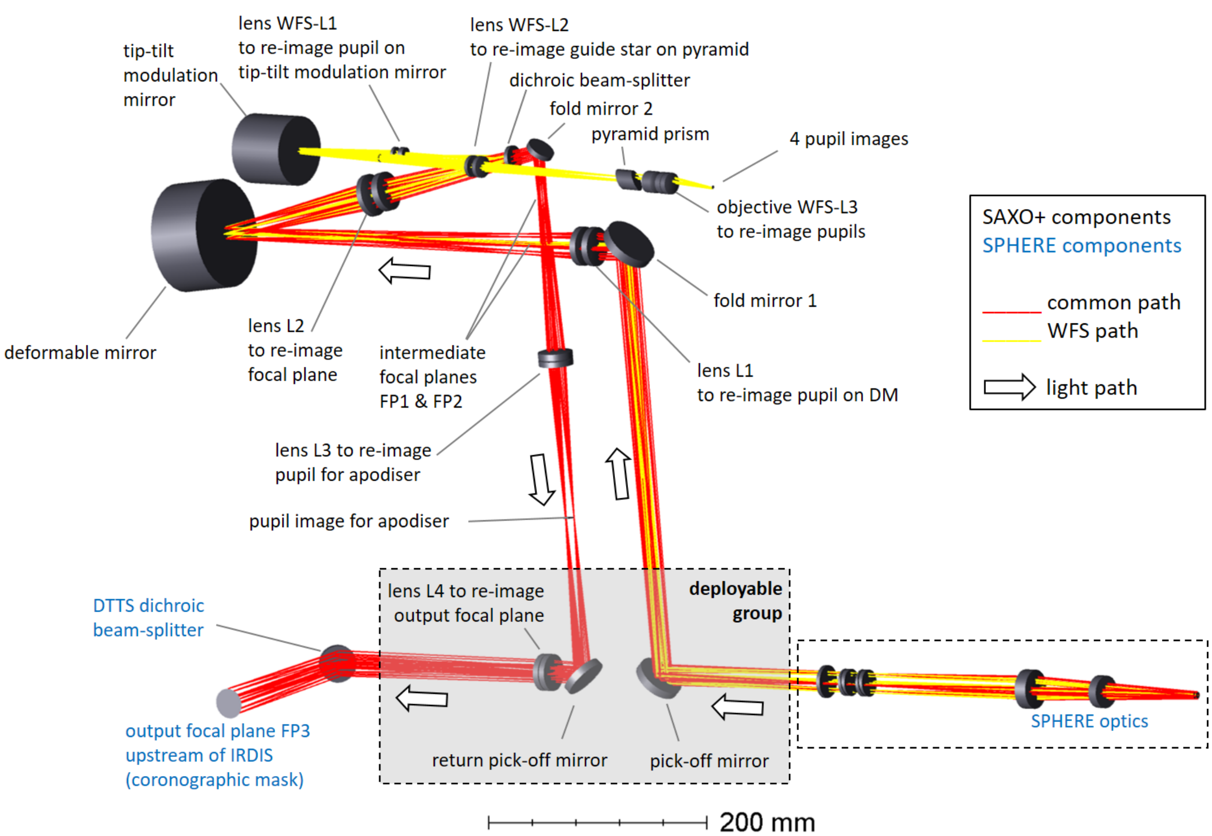

Figure 3. SAXO+ optical model.

4 MECHANICAL DESIGN

The preliminary mechanical design does not show obvious showstoppers. The main components are located on a platform over the SPHERE optical path. Since it is impossible to drill new holes on the SPHERE bench, the main challenge is that this structure must be stiff enough with only two legs. The structure will be made of aluminium 5083 as the SPHERE bench to avoid any thermal differential effect. The additional mass on the SPHERE bench must be limited and located close to the centre of gravity to avoid any perturbation on the active damping. The total added mass for SAXO+ on the SPHERE bench is expected to be below 100 kg.
The next two figures show the overall opto-mechanical layout and two details of the WFS path, respectively.

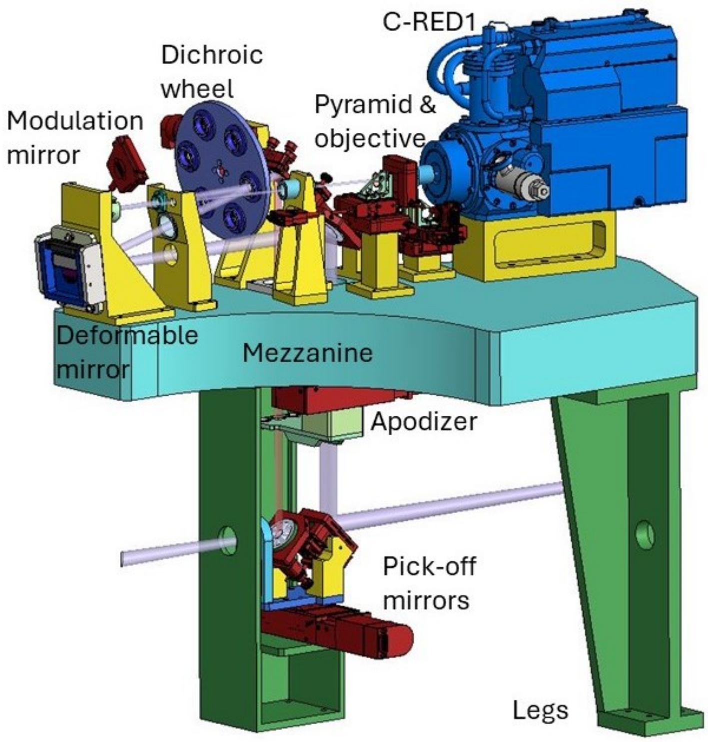

Figure 4. SAXO+ opto-mechanical design.

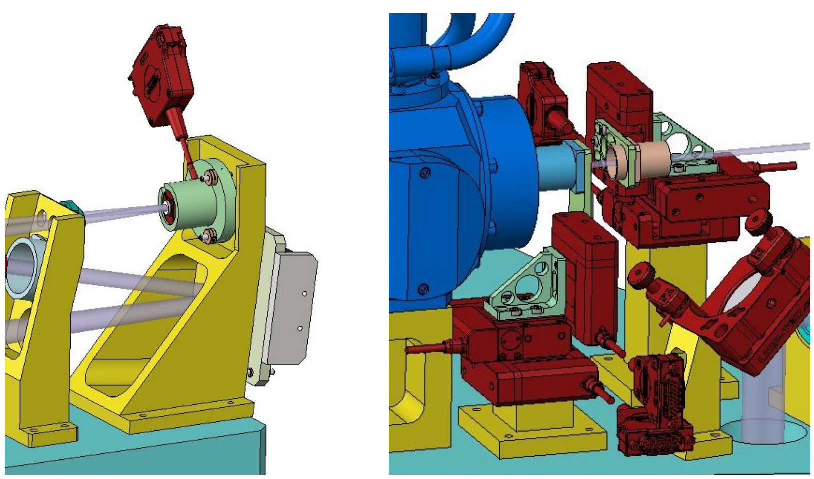

Figure 5. Left: tip-tilt modulation device. Right: WFS pyramid and objective.

The two mirrors in the pick-off group are mounted on a translation stage, moving parallel to the mirror's surfaces. The output doublet lens moves also along with the two mirrors. A 50 mm aluminium frame translation stage with 1 µm unidirectional precision has been selected for this exchange mechanism.
The two mirrors in the pick-off group and fold mirror 1 (see Figure 2 and 3) are mounted on tip-tilt motorized mounts for alignment purposes and other maintenance operations. The chosen piezoelectric motorized mounts can hold a defined position once reached. Adjustment of these tip-tilt degrees of freedom will have to be performed based on error signals provided by the available sensors in the instrument, i.e., SAXO+ WFS camera, SPHERE DTTS and IRDIS (the latter offers both focal plane and pupil imaging modes).
The apodizer exchange mechanism is similar to the pick-off group mechanism and shares the same type of translation stage to limit the number of references and spare parts.
The DM mount is equipped with precise and stable static adjustments in the six degrees of freedom.
The dichroic beam-splitter wheel is mounted on a precise rotation stage and allows six positions. Due to tight positioning specifications, each dichroic beam-splitter must be aligned with a manual tip-tilt adjustment.
The tip-tilt modulation device is mounted on a fine static tuning system for precise alignment during AIT.
The pyramid and the pupil imaging objective need to be precisely positioned in the optical beam: during operations, in XY, i.e. orthogonal to the optical axis, and for seasonal compensations, along the Z axis. Very compact translation stages have been chosen, matching perfectly the available volume and limited stroke.
If the implementation of the optional ZELDA WFS will be confirmed, a mechanism for exchanging the pyramid prism and the focal plane phase mask will have to be implemented here. The most straightforward solution seems to be a slight modification of the pyramid's holder and XYZ adjustment. The holder size should be extended to support both the pyramid and the focal plane mask, and the stroke of one axis in the XY centring mechanism should be increased to also act as an exchange mechanism for switching the pyramid and the focal plane mask.
The C-RED One infrared camera by First Light Imaging SAS is by far the heaviest element in SAXO+ and needs to be connected to a liquid cooling circuit and, for maintenance purposes, to a vacuum pipe. It can be adjusted in position on the bench, while the vertical position can only be adjusted by shimming.

5 FUTURE DEVELOPMENTS

The optical and mechanical design shown in this paper successfully passed the consolidation phase review, which was held at ESO on 18-19 April 2024.
In order to achieve the final design level, the optical design will have to be finalized after consolidating all system-level requirements.
System budgets will also have to be consolidated, and the preliminary environmental and tolerance analysis, carried out during the consolidation phase, will be finalized accordingly, including optics manufacturing errors.
The mechanical design will have to be developed in every detail; in particular, Finite Element Analysis will optimise the support structure to reach the best stiffness/mass ratio.

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