SAXO+, a second-stage adaptive optics for SPHERE on VLT: optical and mechanical design concept

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ABSTRACT

SPHERE+ is a proposed upgrade of the SPHERE instrument at VLT, which will boost the current performances of detection and characterization of exoplanets and disks, and will serve as a demonstrator for the future planet finder (PCS) of the European ELT. The performance gain will be delivered by a second-stage AO module (SAXO+), including a dedicated wavefront sensor and deformable mirror to remove the residual wavefront errors left by the primary AO loop. This paper is focused on the optical and mechanical implementation of SAXO+ and describes the baseline design concept, selected from trade-off analysis of different options.

Keywords: Extreme Adaptive Optics, Optical Design, Mechanical Design, SPHERE, VLT, ELT, instrument upgrades, SAXO+

1. INTRODUCTION

SPHERE+[1] is a proposed upgrade of the SPHERE[2] instrument at VLT, which will boost the current performances of detection and characterization of exoplanets and disks, and will serve as a demonstrator for the future planet finder (PCS[3]) of the European ELT[4]. The upgrade aims at improving the raw contrast (up to 10^{-5}, goal 10^{-6}) close to the optical axis (at separation of 0.2 as, goal 0.1 as), enabling the observation of fainter and redder targets. The contrast gain will be made possible by a second-stage Adaptive Optics (AO) module (hereafter SAXO+[5]) combined with the currently operating first-stage xAO system (SAXO[6]). SAXO+ will offer moderate spatial sampling (20-30 actuators/sub-apertures) and fast correction frame rate (up to 3 kHz); it will measure and reduce wavefront errors left by SAXO. This paper is focused on the optical and mechanical implementation of SAXO+ within SPHERE. In order to

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preserve the current functionalities, the second-stage opto-mechanical module is designed as a sort of switchable optical by-pass. It is compact, due to space constraints, and offers good accessibility for installation and maintenance. Optical interfaces at the output are left unchanged for the scientific instruments downstream. The module offers two internal pupil images for the second-stage adaptive deformable mirror and a deployable apodizer for coronographic observations. A dichroic beam-splitter feeds the second-stage pyramid-based infrared wavefront sensor. The paper gives an overview of the requirements and of the current baseline concept. A novel concept for the pyramid wavefront sensor (WFS) dynamic modulation device, based on a rotary stage motor, is also presented.

2. REQUIREMENTS

The main requirements of the SAXO+ opto-mechanical module are summarized in Table 1.

Table 1. Main opto-mechanical requirements of SAXO+.

Requirement	**Value**
Science/common path	
Operational	It shall be possible to optically by-pass SAXO+ by a deployable mechanism
Dimensional	Maximum available space in plant ~ 1200 mm × 600 mm Maximum height above SPHERE bench ~ 950 mm Main optical axis of SAXO+ shall be 400 mm above SPHERE optical axis SAXO+ light pick-off between the SPHERE ADC and DTTS beam-splitter
Optical interfaces	Same as SPHERE without SAXO+, in terms of • output focal plane position • focal ratio (F/40) • exit pupil distance (754 mm towards SAXO+) • field curvature (radius 54 mm, concave towards SAXO+)
Wavelength range	0.95 – 2.32 µm
Field of view	15.6 arcsec diameter
Pupil planes inside SAXO+	two pupil planes required, for: • second-stage deformable mirror • deployable apodiser
Diameter of pupil image for DM	~10 mm
Pupil image blur on DM	< 1/10 inter-actuator spacing
Diameter of pupil image for apodiser	3 – 18 mm, for manufacturing reasons
Throughput	> 85%
Dichroic beam-splitter properties	Long-pass preferred
Dichroic beam-splitter position	Close to intermediate focal plane preferred
Polarisation effects	Polarisation vector direction to remain unchanged through SAXO+
Wavefront sensor path	
Wavefront sensor type	Pyramid
Wavelength range	0.95 – 1.1 µm, bright case 0.95 – 1.48 µm (possible extension to 1.8 µm), faint case
Field of view	3 arcsec diameter
Focal ratio on pyramid prism	F/20 – F/40
Tip-tilt modulation	Modulation radius up to ~ 5 λ/D to be confirmed (possible extension to ~ 10 λ/D at slow rate for calibration)
Slow tip-tilt drift compensation	Required (range to be defined)
Pupil registration on WFS detector	Required (range to be defined)
Pupil image diameter on WFS detector	~1.2 mm, corresponding to ~50 pixels for 24 µm pixel pitch
Pupil image blur on WFS detector	<1/10 subaperture

From an operations point of view, it shall be possible to optically feed SAXO+ by an exchange mechanism deploying a pick-off mirror. The light beam shall have to be re-injected downstream SAXO+ into the SPHERE instrument optical path by another deployable mirror. The light pick-off and re-injection group has to be implemented at a specific location inside the instrument bench, i.e., between the Atmospheric Dispersion Compensator (ADC) and the Differential Tip-Tilt Sensor (DTTS) beam-splitter: this location is downstream the primary loop's Deformable Mirror (DM) and WFS and upstream the scientific instruments and, moreover, it offers some clearance for the second-stage module.

For space constraints reasons, the second-stage module has to be implemented on a plane above the main bench and, in any case, it has to be as compact as possible.

Optical interfaces have to be the same with and without the second-stage module.

Two pupil planes are required inside the module: one for the second-stage DM and one for a deployable apodiser, for the coronographic modes of SPHERE.

Inside the module, a dichroic beam-splitter (or more than one, with different wavelength ranges) has to be implemented to split the light between the science/common path and the second-stage WFS path.

A number of requirements closely related to the AO functionalities of the module derive from the system architecture, which is the scope of other papers in this conference[1][5]. These requirements are summarized in the following.

The pupil image for the second-stage DM shall have a diameter of about 10 mm, compatible with MEMS-type DMs with inter-actuator spacing of the order of few 1/10 mm. The number of actuators across the pupil is still under investigation at system-level, therefore the pupil image diameter might have to be increased by about 30%.

The WFS shall be based on the pyramid approach[7], therefore the WFS path shall include a focal plane for the pyramid prism, a pupil re-imaging lens with convenient back-focal length for the camera and a pupil registration mechanism.

Moreover, the WFS path shall include a wavefront Tip-Tilt Modulator (TTM) which requires an accessible pupil image. Tip-tilt modulation is also addressed in section 4.

3. PRELIMINARY DESIGN

3.1 Optical design

Several optical designs have been produced, in order to explore different solutions regarding overall layout and volume, accessibility to the module and to its components, position and configuration of the dichroic beam-splitter, etc. The current working baseline has been selected by comparison of five designs, all matching the interface and performance requirements described in section 2.

The selected baseline is the most compact one among all the explored designs options in terms of overall volume. Two crucial components, i.e., the DM and TTM, are located close to the outer enclosure of SPHERE, for better accessibility. A long-pass configuration for the dichroic beam-splitter has been preferred, in order to simplify coating design and manufacturing. The dichroic beam-splitter is located close to an intermediate focal plane: this position has been preferred in order to have a readily available focal plane at the entrance of the wavefront sensor path for calibration purposes.

An optical functional block diagram for the selected design is shown in Fig. 1. The optical beam through the SPHERE optics may be picked-off by a deployable fold mirror in order to feed SAXO+, and then re-injected into the SPHERE optical path, with the same optical interface, by another deployable fold mirror. For opto-mechanical reasons, the two fold mirrors, plus a lens to re-image the focal plane, are mounted on the same deployment mechanism (section 3.2). When the deployable group is out of the optical beam, SAXO+ is simply skipped.

A full optical model is shown in Fig. 2. All the elements labelled "lens" in the block diagram are air-spaced doublets, with the exception of the lens between the pyramid prism and the final pupil images in the WFS path, where an air-spaced triplet solution has been adopted in order to guarantee enough back-focal distance for the WFS camera. All the lenses are designed with high-transmission materials in the near infrared.

The diameter of the pupil image on the DM is about 10 mm, which matches the requirement of section 2. It is straightforward to modify the design in order to adapt this diameter to a specific DM model or to enlarge it by about 30%, if that will be the outcome of the on-going system-level analysis. The pupil image on the tip-tilt modulator is 5 mm, allowing the use of compact devices for this function.

The optical performance of this design is excellent. The nominal polychromatic Strehl Ratio is of the order of 99% both at the output focal plane and on the pyramid focal plane inside the WFS path; the optical quality of the pupil images is well within the requirement of 1/10 of the relevant pitch/subaperture size. An error budget will have to be developed, in agreement with the system level, accounting for manufacturing and alignment tolerances and dynamic effects (e.g., thermo-elastic variations depending on temperature).

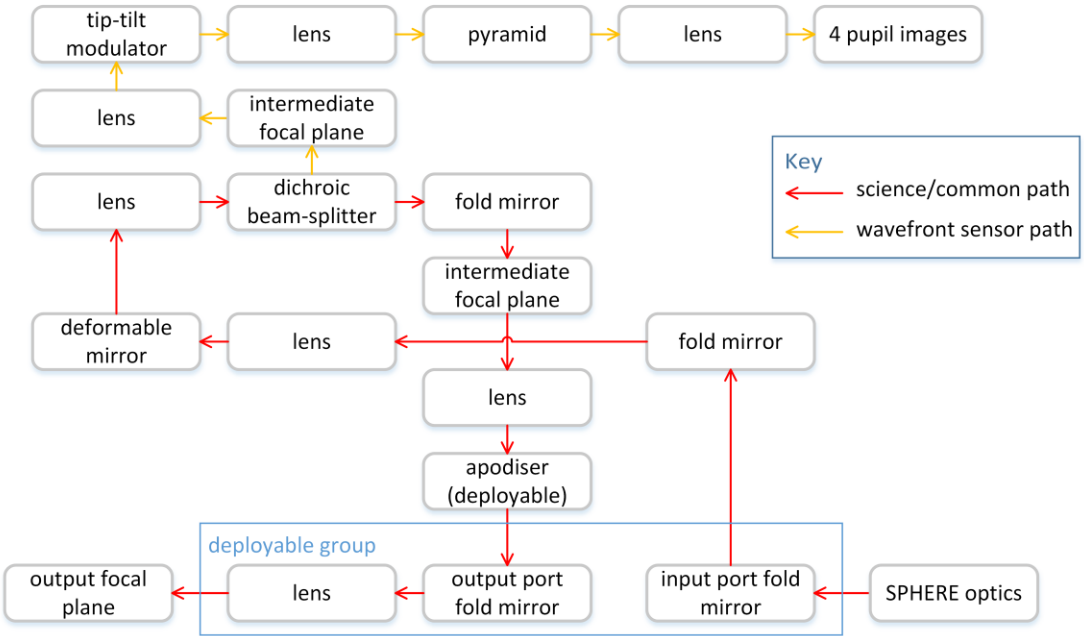


Figure 1. Optical block diagram of SAXO+. The starting block is “SPHERE optics” at the bottom-right. With this choice, somehow unconventional, the order of the blocks in this conceptual diagram approximately reflects the order of the elements in the optical model shown in Fig. 2 and in the mechanical models shown later in the paper.

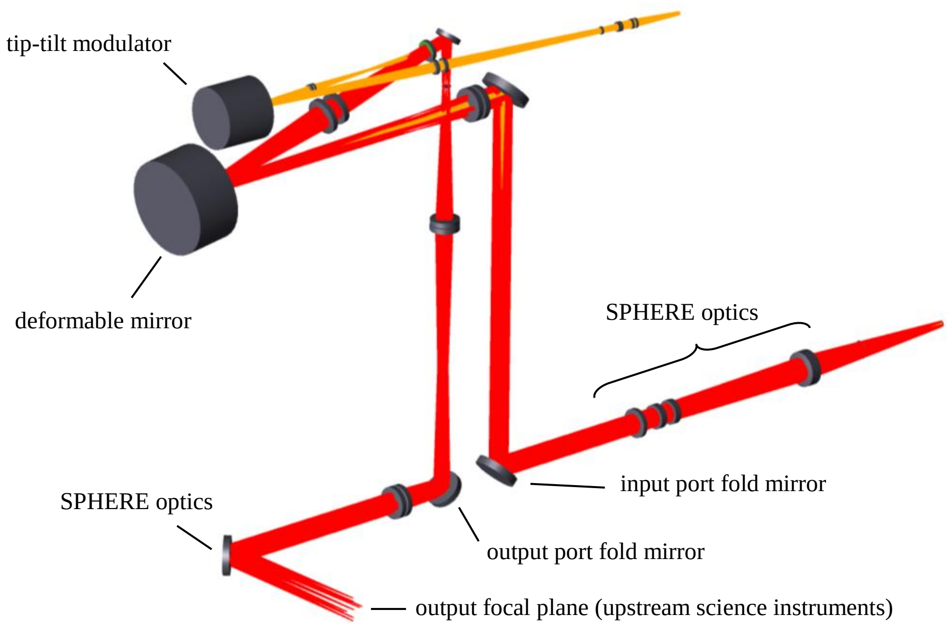


Figure 2. Second-stage AO module optical design.

3.2 Mechanical implementation

The choices related to the mechanical implementation within the SPHERE instrument enclosure have to be evaluated in a constrained context to fulfil all the requirements concerning the actual SPHERE interfaces and budgets, minimizing the impact on the existing instrument operations. For this reason, SPHERE will not be dismounted from the Nasmyth platform and the second stage AO bench will be integrated in the instrument bench by using only already existing threaded holes. To keep the active damping support element working in its operating range, the global center of gravity and mass budget of the optical bench shall be as close as possible to the previous specifications and each variation must be carefully evaluated. Temperature stability inside SPHERE enclosure has to be maintained without introducing sources that might induce unwanted convection effects.

The preliminary design that we present in this paper, still under definition and subject to change, is the result of a first trade-off among different designs under evaluation and it is compatible with the actual interfaces requirements and constraints. The allocation of the additional electronic cabinets is still under evaluation.

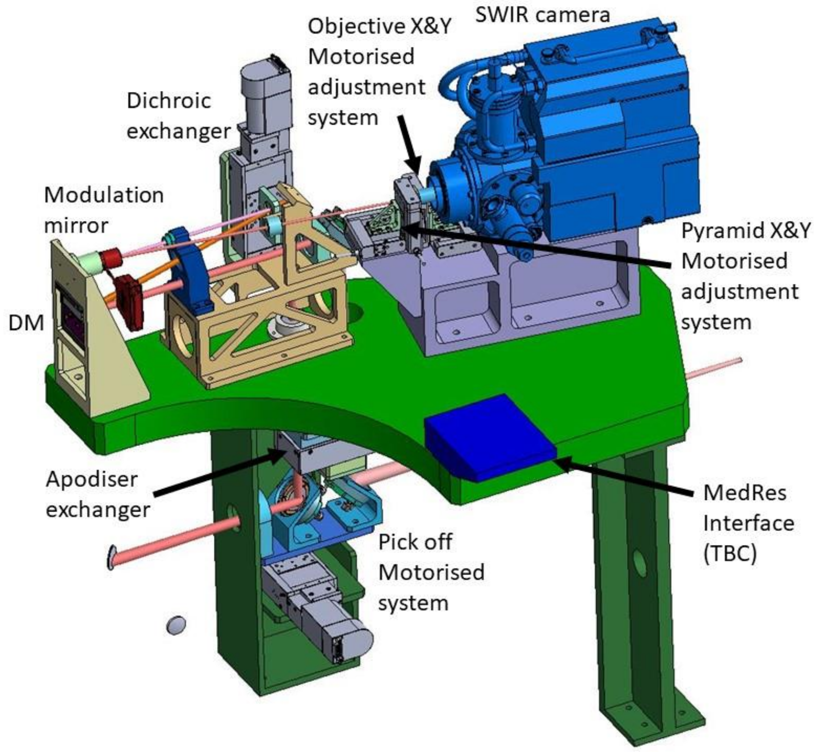
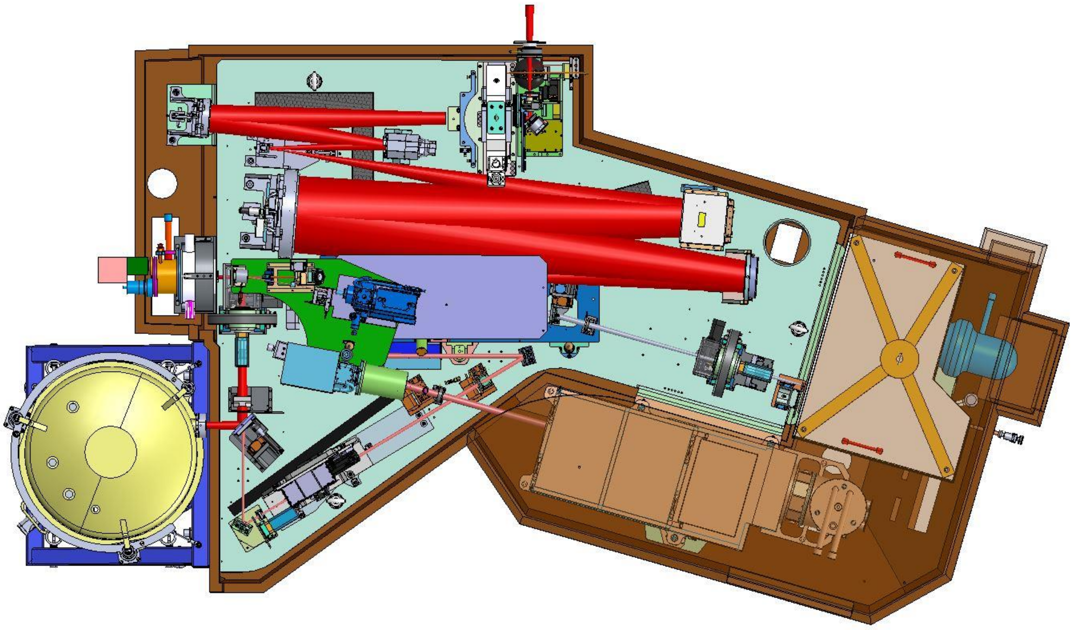


Figure 3. Second stage AO preliminary design with optics mountings (alone).

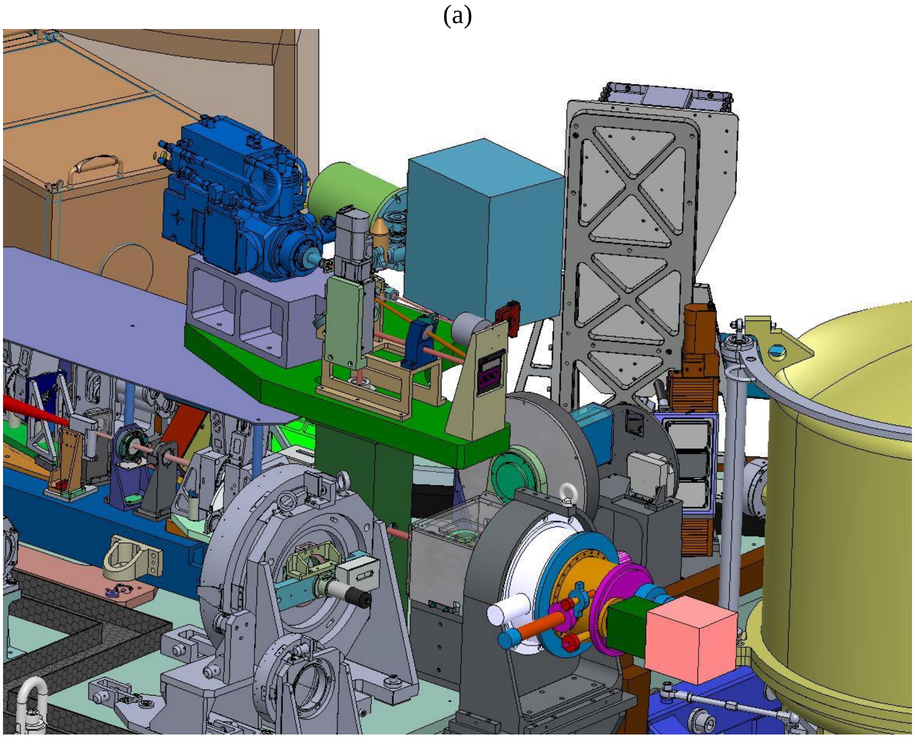
Since the SPHERE optical bench is already crowded, the current baseline choice relies on the implementation of an upper level over the existing instrument. A schematic view of the SAXO+ bench is depicted as a stand-alone unit in Fig. 3. A pick-off mirror is mounted on a motorized stage and inserted in the existing SPHERE optical beam to feed the second stage AO. Other translations stages are foreseen for apodiser and dichroic exchange mechanism. In order to compensate for thermal expansion/contraction effects on the beam alignment, the pyramid WFS centering will be tuneable in X and Y directions (i.e., orthogonal to the local optical axis) and a second X and Y adjustment in needed also for the triplet objective in front of the SWIR camera to compensate for slow pupil mis-registration effects.

The SAXO+ platform (depicted in green in Fig. 3) is mounted on two pillars fixed on the main SPHERE bench using the available fixation points. The accessibility to critical components which need fine tuning or regular maintenance operations, like the DM or the modulation device, has to be carefully considered in the design trade-off operation. An overall top view of the SPHERE bench, including the SAXO+ allocation, is depicted in Fig. 4. The second stage AO system is positioned close to the instrument center of gravity to limit changes on the active positioning system of the bench.

In order to maximise the thermomechanical stability, the new structure will be made by the same aluminium alloy as the SPHERE bench. Additional enclosure feedthrough will be as small as possible to limit the impact on insulation performances.



(a)



(b)

Figure 4. SPHERE optical bench with second stage AO. The MedRes [9] instrument is also visible. a) Top view; b) Side view.

4. WAVEFRONT MODULATION

The SAXO+ residual wavefront measurement is performed by a pyramid WFS operating in a wavelength range spanning 0.95 – 1.1 µm extensible to 1.48 µm (and possibly 1.8 µm, to be confirmed) in the case of faint star science case. Due to its limited linear range, this kind of WFSs often relies on wavefront tip-tilt modulation[7][8]. Classically this modulation is dynamically introduced by the means of a tip-tilt mirror conjugated to the pupil plane, but, in literature, some reference to implementations without modulating devices can be also found[14][15][16] (these cases are discussed later in section 4.3).

The SAXO+ preliminary requirements on wavefront modulation, all to be confirmed, can be summarized as follows:

- The reference star Point Spread Function (PSF) shall reproduce a repeatable circular pattern on the tip of the pyramid prism with a maximum 10% error on the circle geometry and a maximum 1% error on its repeatability in a frequency range spanning 100Hz up to ~ 3kHz;
- The modulation device shall be able to reach a maximum amplitude of 10 λ/D. This modulation radius translates into ~ 2 mrad mechanical amplitude (~ 0.1°). The maximum amplitude should not be necessary in high temporal frequency regime;
- The modulation device shall be able to reach a minimum amplitude of 2-3 λ/D at the maximum modulation frequency (~ 3kHz).

4.1 Tip-Tilt mirror option

Most of the AO existing systems based on modulated pyramid wavefront sensing rely on fast piezo-electric tip-tilt systems actuating a mirror. This choice has the advantage to be based on reliable standard existing commercial components and to have a limited heat emission at ‘usual’ loop frequencies (500-1000 Hz). The case of SAXO+ represents a challenge both in terms of loop speed and modulation amplitude. In order to fulfil the system needs, a possible solution, adopted by other systems with similar requirements, is to use classical piezo-electric elements, which can be assimilated to electric capacities, and to improve the speed by working in high voltage regime, providing wave signals with a high-end generator in open-loop control. One important drawback of this choice is that working in open-loop requires a deep knowledge of the system and frequent calibration.

The development of custom systems based on piezo-electric tip-tilt actuators is also possible, but expensive.

4.2 Rotary stage option

We propose in this paper to develop a fully custom solution based on a mirror mounted on a high-speed rotating motor with a magnetic actuation for the mirror tilt control. The incontestable advantage of this solution is its mechanical simplicity: the actuation relies indeed on a pure rotation, while the classical tip-tilt modulation is based on the combination of two or three push-pull actuators. On the other hand, the required rotation speed in the case of SAXO+ is of the order of 3000 round/s that corresponds to 180 000 rpm (round per minute) minimum, that represents a challenging value for electrical motors.

The first prototype under development is based on a motor with classical ball bearing. This motor can reach 500 000 rpm without any charge and its lifetime without load is around 1000 hours. The bearing or rotor can be easily replaced during ordinary maintenance operations. Other solutions based on air or magnetic bearing instead of standard ball bearing are under evaluation to increase the system lifetime.

The principle of the proposed concept is depicted in Fig. 5. A voice coil around the mirror (coloured in green) associated with the magnets at the mirror’s back controls the mirror angle. The magnetic field created by the coil, which can be precisely controlled, induces a tilt around the flexible pivot due to the magnets placed in opposition on each side of the pivot. Due to the distance between the pivot and the optical surface of the mirror, a small defocus is induced by the tilt. Considering a tilt of 0.1° (that corresponds to the maximum required modulation radius of about 10 λ/D) this defocus is about 10 nm PtV.

A water-cooling system cools down the motor and the voice coil for stability reasons. The coils control will be initially done with a standard power supply to find the good range of current needed to produce the desired mirror tilt angles. The system is protected and contained by a cap (depicted in blue in Fig. 6 and 7) for safety reasons in case of break at high speed.

The mirror holder (light blue, Fig. 7) is a single part obtained by additive manufacturing in titanium alloy. This technology allows us to perform all the required functions in one light part in order to assure low inertia compatible with very high rotation speed and flexibility requirements. A deformable shaft enables the tilt angle variation to adapt the modulation diameter.

The complete system, without cooling connectors, is quite compact (~ 45x45x54 mm) and a first quotation indicates that its cost should be reduced w.r.t. the classical tip-tilt piezo-electric alternative.

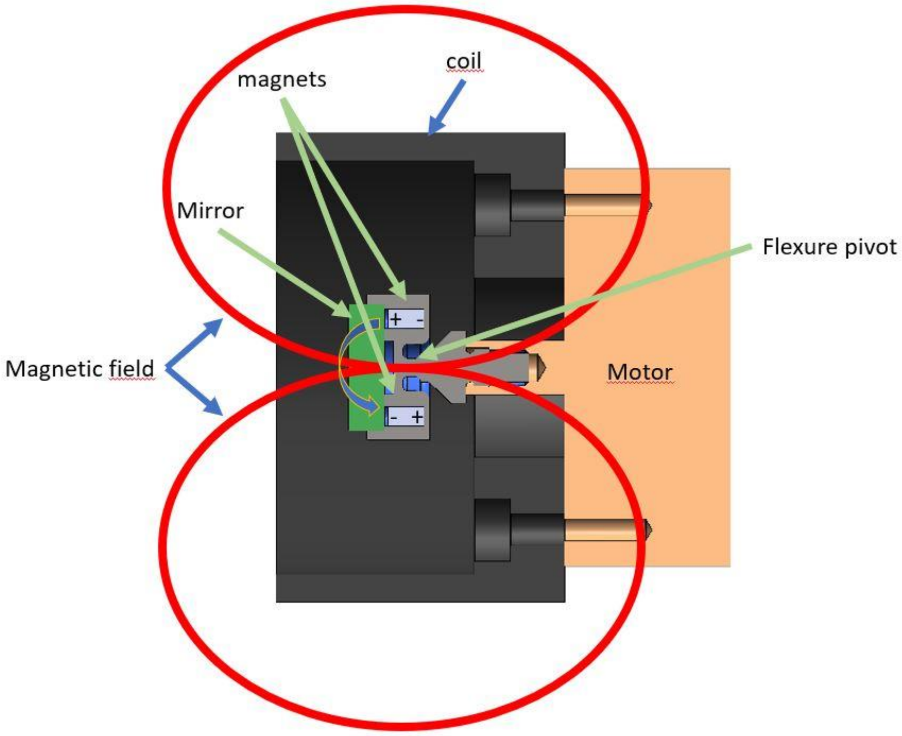


Figure 5. Schematic view of the system.

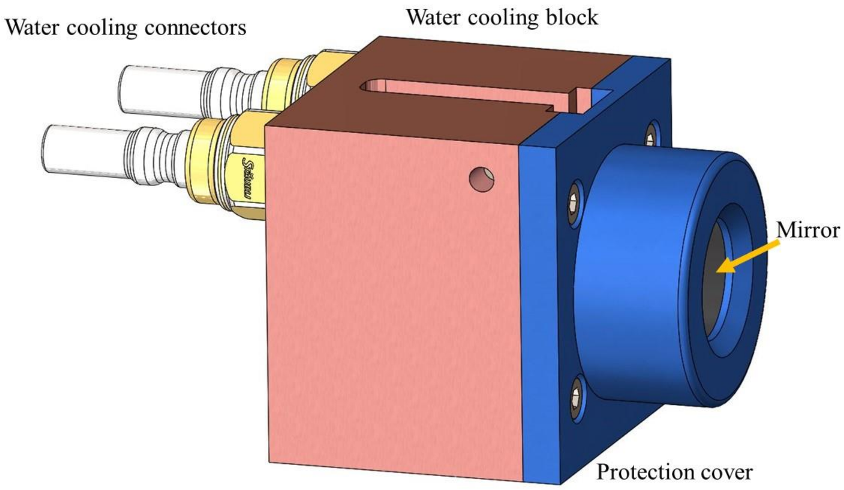


Figure 6. Modulation mirror system based on rotary stage.

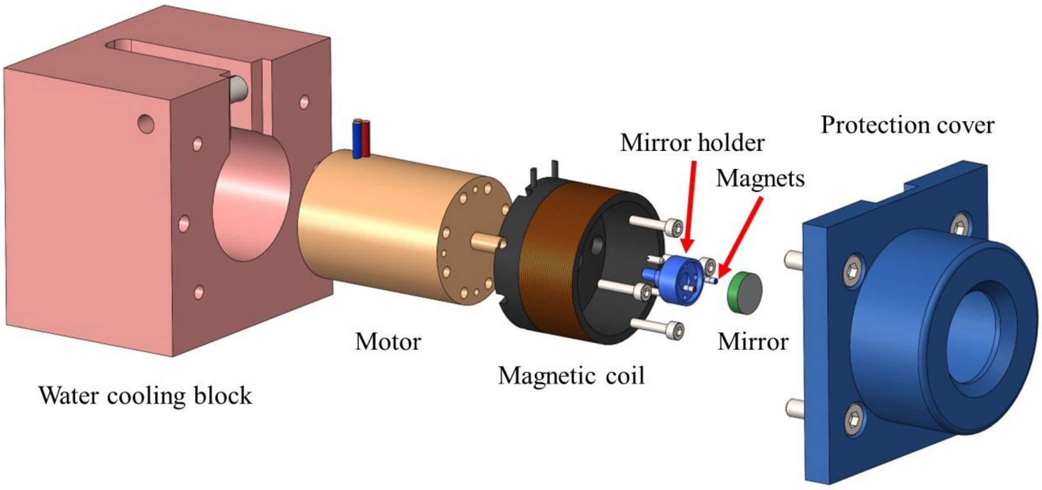


Figure 7. Prototype exploded view.

In Fig. 8 is apparent that a first Finite Element Analysis validates the low level of constrain (<50MPa for a material with a RP_{02}>500MPa) in the mirror holder with a first eigenfrequency over 3000 Hz.
The first prototype is under manufacturing, and first results are expected for next autumn.

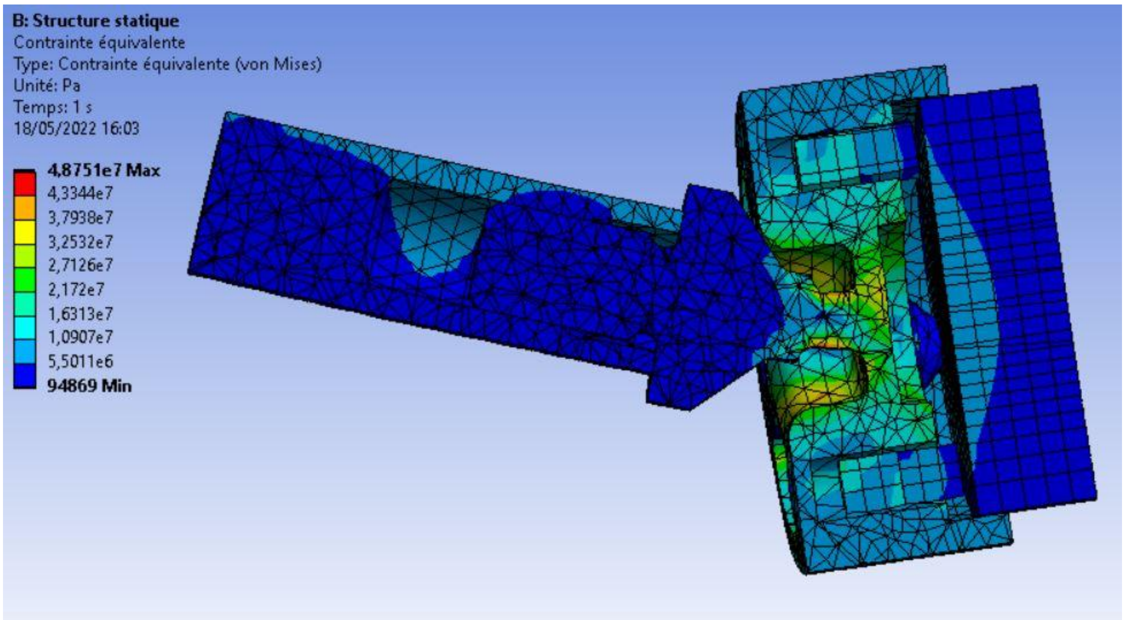


Figure 8. Prototype constrain simulation result.

4.3 Static modulation options

The possibility to introduce a static modulation pattern on the tip of the pyramid WFS by the means of a light diffusing plate placed in an intermediate pupil plane has been proposed by Ragazzoni et Al. [14] and then tested by LeDue et Al.

using a holographic diffuser[15]. It has been speculated also that residual aberrations from the AO cycle could act as a sort of natural dynamic modulation[10][11] and a few existing WFSs are based on this concept[12][13]. These WFSs work in the visible bandwidth, while the AO correction is optimized for the Near Infra-Red scientific channel, letting the guide star PSF to be only partially corrected by the AO cycle. Another interesting work on wavefront sensing based on static modulation is reported in Marafatto et Al.[16] which proposed to use an holographic diffuser to diffract part of the light in a ring shape around the pin of the pyramid WFS and to let the undiffracted light reaching the pin of the pyramid to contribute to the high sensitivity regime of the WFS.

The advantages of the static approach are numerous, from the gain in opto-mechanical simplicity (with the exception of the need of a possible exchange mechanism for different modulation amplitudes/patterns), to the weak maintenance needs and the low cost. On the other hand, this approach is still a bit immature in the SPHERE update context, since it has never been implemented in AO instrumentation with high performance requirements, like xAO systems and it therefore requires a deep investigation and prototyping. The current approach is to study different static modulation patterns by the means of numerical simulations and to investigate and eventually prototype different implementation solutions. The modulation patterns currently under study include:

1. Diffused light distributed into specific cone angles determined by the modulation radius[14][15]: this light distribution can be produced by the means of simple diffusing elements in transmission or reflection (e.g. polished/sand blasted diffusers) or by the means of holographic diffusers (DOE) which allow a more accurate shaping of the intensity distribution on the focal plane but suffer from chromaticity. Another possibility is to use an array of micro-lenses with a pitch much smaller than the sub-aperture size projected on the DM.
2. Ring-like light distribution shape with radius equivalent to the modulation radius[16]: this light distribution mimics the tip-tilt dynamic modulation effect on the PSF and it can be obtained statically by the use of a diffractive axicone (DOE) with ring's thickness equivalent to the diffraction-limited spot size;
3. Multiple-beam 2D splitting of a single beam into several beams (e.g. 2x2), each with the characteristics of the original beam (except for its power and angle of propagation): this light distribution can be obtained by the means of diffractive beam splitters (or dot generator, DOE). A diffractive beam splitter can generate 2-dimensional beam matrix, depending on the diffractive pattern on the element.

Some critical points that must be carefully investigated concern: i) the efficiency of transmitting elements, either holographic or not - most of the light (ideally > 98%) should pass through the optical element to be used for wavefront measurement not to degrade the instrument performance in limiting magnitude; ii) the static modulation device should introduce very small wavefront error in the first Zernike orders (< 500) in order not to limit the WFS dynamical range; iii) chromatic effects when dealing with DOE.

5. FUTURE DEVELOPMENTS

The preliminary optical and mechanical design of SAXO+ shown in this paper demonstrates the opto-mechanical feasibility of a second-stage AO module inside the SPHERE instrument. The design will be developed and finalized, following the consolidation of the requirements. In parallel to the development of the system budgets, manufacturing and alignment tolerances will be estimated; appropriate budgets, or even compensators if necessary, will have to be defined for dynamic effects such as thermo-elastic variations due to temperature changes.

The development of modulation concepts for the pyramid WFS is already in progress, in order to fulfill the requirements which are rather demanding with respect to already existing systems. Simulations and prototyping activities will be crucial to identify the most effective solution.

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