SHARK (System for coronagraphy with High order Adaptive optics from R to K band), a proposal for the LBT 2nd generation instrumentation

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ABSTRACT

This article presents a proposal aimed at investigating the technical feasibility and the scientific capabilities of high contrast cameras to be implemented at LBT. Such an instrument will fully exploit the unique LBT capabilities in Adaptive Optics (AO) as demonstrated by the First Light Adaptive Optics (FLAO) system, which is obtaining excellent results in terms of performance and reliability. The aim of this proposal is to show the scientific interest of such a project, together with a conceptual opto-mechanical study which shows its technical feasibility, taking advantage of the already existing AO systems, which are delivering the highest Strehl experienced in nowadays existing telescopes.

Two channels are foreseen for SHARK, a near infrared channel (2.5-0.9 um) and a visible one (0.9 – 0.6 um), both providing imaging and coronagraphic modes. The visible channel is equipped with a very fast and low noise detector running at 1.0 kfps and an IFU spectroscopic port to provide low and medium resolution spectra of 1.5 x 1.5 arcsec fields.

The search of extra solar giant planets is the main science case and the driver for the technical choices of SHARK, but leaving room for several other interesting scientific topics, which will be briefly depicted here.

Keywords: planet finding, coronagraphy, pyramid sensor, adaptive secondary, extreme adaptive optics, large binocular telescope

1. INTRODUCTION

The Large Binocular Telescope, with its First Light Adaptive Optics (FLAO) systems, recently (first scientific light in May 2010, see [4], [15], [12], [13], [14] and [33]) opened a new frontier for the astronomical AO on the 8-10m class

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telescopes. The combination of the pyramid based sensor (see [16], [30], [31], [11], [36] and [3]), together with the high dynamic and spatial resolution of the Adaptive Secondary Mirror (see [34] and [32]) provides performance never reached on this class of telescopes by previous natural or laser guide star systems. In particular we are referring to the extremely low residual wavefront error (below 100nm RMS) routinely reached by the FLAO systems working with bright guide stars. This amount of residual translated into the first high contrast AO corrected images in NIR, with SRs>90% in K and H bands and better than 60% in J (see [29]). Currently the FLAO system is the only one able to deliver a contrast (without coronagraphic techniques) higher than 10^4 in H band at a distance of ~350mas (see Figure 1) and even better in K band. The high level of AO correction also delivers a good image correction at shorter wavelengths reaching SR of 45% in R band.

Also on the seeing point of view, Mount Graham has shown a behavior remarkably good (see [26] e [20]), with an average estimated seeing of about 1” achieved during the commissioning of FLAO and, furthermore, with several nights in which the seeing has been lower than 0.8” and sometimes as good as 0.3” in V Band.

The excellent Strehl performance is opening to a variety of unexplored science cases (see [4], [15] and [33]), the main of which being of course planet finding. The challenge of direct imaging planet detection is in the high contrast necessary between the star and the planet at very small separations. The contrast achieved in NIR and the performance reached at visible wavelengths with FLAO at LBT are the starting point for proposing a new facility designed for high contrast imaging.

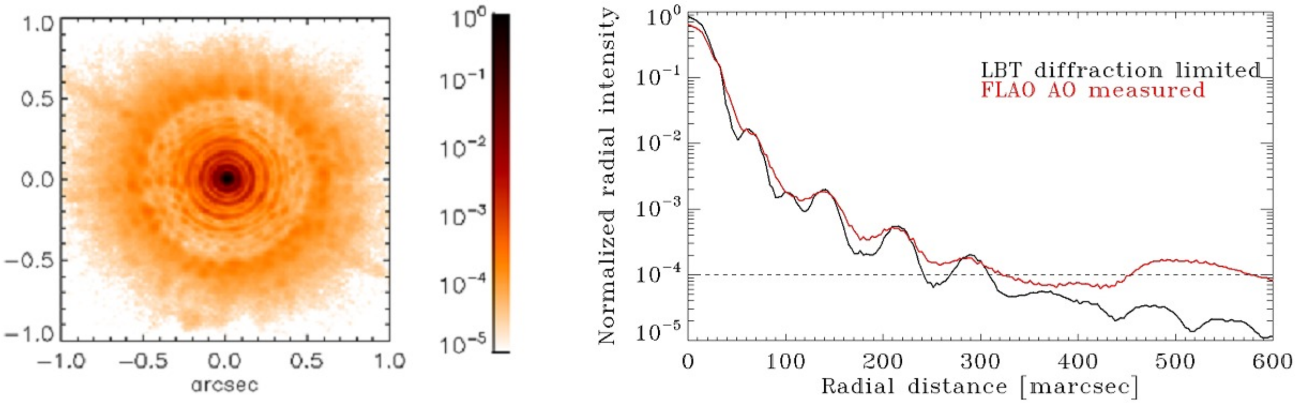

Figure 1. (Left) High-order AO-corrected PSF using a bright star (MR = 6.5) under median seeing conditions (seeing~0.7”±0.1”). (Right) Comparison between the diffraction-limited PSF (black full curve) and the AO-corrected PSF profiles (red full curve). Profiles are normalized to the diffraction-limited peak.

SHARK will have two channels, each of them installed on a different telescope arm, namely the VISible channel (VIS channel in the following) and the Near InfraRed channel (NIR channel in the following), exploring from R to K bands.

The two channels of SHARK are simple and flexible instruments, essentially two cameras for direct imaging (both with a FoV of the order of 20”x20”, even if solutions with wider FoV are under study) but equipped indeed with coronagraphic capabilities. In the VIS channel, the baseline design has a fiber fed IFU, in a 2” region, with spaxel in the range of 40-80 mas and spectral resolution in the range 100-5000.

In both channels polarimetric filters may also be inserted, together with several broad and narrow bands filters.

In its Coronahraphic mode, a simple classical Lyot it is foreseen (see [21]) as baseline coronagraph for both channels. We briefly recall that such a configuration foresees an occulting mask to be positioned onto the focal plane to mask the star light, and a stop onto the pupil plane to undersize the pupil to minimize diffractive effects caused by the focal plane occulting mask.

The classical Lyot Coronagraph is working pretty well with Inner Working Angles (IWA) which are greater than 3-4λ/D (see [16] and [18]), and thus does not allow to go, for example in K band, closer than ~200mas from the star (~80 mas in R band). Of course there are science cases which would benefit a lot from going as close as possible to the central object, and this is why we are carefully evaluating other coronagraphic techniques to be implemented into the system. To achieve this, we do have a design (see following sections) where, both onto the focal plane and onto the pupil plane, there are wheels which can accommodate up to eight masks. We emphasize that alternative coronagraphic techniques will not impact the instrument design, which is kept as the minimum level of complexity required for an imaging camera (above all in the NIR channel, where a re-imaging of the pupil is anyhow necessary to introduce there a cold stop to minimize the thermal background). We will in fact consider only coronagraphic techniques that will require additional masks in the currently available focal plane and/or pupil plane, with the only impact to fill one of the available positions in the correspondent filter wheel, as it will be clear in the section describing the opto-mechanical layout of the instrument.

We point out that the SHARK VIS channel is unique (in every observing mode, i.e. imaging, coronagraphy and spectroscopy) in the current LBT instrument scenario, while the NIR channel is complementary (in its coronagraphic fashion) to other already existing observing facilities. We also emphasize that SHARK is proposed for the LBT 2nd generation instrumentation but, in the proposed configuration, it may co-exist with the currently available instrumentation, being placed at the entrance of LBTI sharing with it part of the wavelength domain. SHARK have been endorsed by LBTO for a Phase A study.

2. SHARK SCIENCE CASE

Shark in its direct imaging mode is essentially an imager, and opens to a wide variety of science topics which can be explored in the proximity of the AO reference star, due to the isoplanatic angle problem. The very good correction that the LBT AO system is doing also at visible wavelengths (reaching, as already mentioned, SR of 45% in R band) opens to a number of unexplored (at least in the Northern Hemisphere) targets (see [5], exploited with the Magellan visible AO in the Southern sky), which makes the visible arm of SHARK particularly attractive and unique. In its coronagraphic mode, SHARK is designed for the detection of extra solar planets, which is a very exciting scientific argument of the modern Astronomy, but also very challenging because of to the very demanding resolution and contrast required on the scientific images. Only recently, combination of eXtreme Adaptive Optics (XAO) with suitable diffraction (coronagraphs) and speckle subtraction techniques (Angular Differential Imaging – ADI, Spectral differential imaging – SDI, Polarimetric Differential Imaging) allowed reaching the correct regime to detect giant planets around young, nearby stars. Previous discoveries in this field have been possible only by using non-direct-imaging techniques, such as transits and radial velocity measurements, which revealed a large number of planets and planetary systems very different from the solar one, improving our knowledge on the planets formation and evolution issue.

The limits of such techniques are on the limited distance at which the planet detection is possible (a few astronomical units), on the limited sample of the stellar types which is possible to analyze (essentially old, chromospherically quiet and slowly rotating stars), and the difficulty in characterizing discovered planets (only possible for transiting planets).

Direct imaging will give the possibility both to analyze the outer regions of planetary systems around stars in a wide range of masses and to characterize photometrically and spectroscopically the detected planets.

Since the performance of the AO system is obtaining the best results at longer wavelengths (due to the direct wavelength dependence of the Fried diameter), the natural application of Coronagraphy is in the IR domain, where the achieved Strehl is giving remarkable contrast which are, as already said, necessary for the faint companion detection.

The mechanism of formation of planetary systems, where the outer regions are among the most critical to understand, is of great interest for such an instrument. Current available data mainly concern planets at small separations. Searches for planets at large separations have been performed in the last years; in this region, the highest sensitivity is obtained by using high contrast imaging techniques focused on young stars. Close-in or old planets mainly shine through reflected light, but such planets are expected to be projected very close to the central star and are difficult to be detected. Young stars should then be preferred because planet intrinsic luminosity is mainly powered by gravitational contraction and rapidly declines while the planet ages. These objects are better observed in the NIR (1-2.5 micron). Up to now, only two systems (HR8799 and β Pic) have been discovered with characteristics typical of planetary systems. While both of them are extremely interesting objects, a wider statistics is clearly crucial to constrain the models and characterizing the discovered planets. Detection of multiple systems and of orbital motion allows a discussion of the dynamical properties of the system. In addition, there is evidence that the smallest (young) planets do not follow the same relation between colors and spectral types found for Brown Dwarfs, the L-T transition possibly occurring at a lower temperature.

Given the characteristics of LBT AO-Systems with respect to those of both SPHERE and GPI, we expect 1-2 magnitude fainter targets to be reachable, and this will allow observing many more nearby small mass stars and solar type stars in star-forming regions at close distance (e.g. Taurus at 140 pc). The proposed instrument will allow to study with LBT the earliest evolution of giant planets and their link with the circumstellar disks, then providing specific clues to the formation mechanism.

Several other very interesting topics can be pursued with SHARK in its coronagraphic fashion. The circumstellar environment of a young star where planets are believed to form consists of an accretion disk and the associated stellar jets. The study of proto-planetary disks is fundamental to comprehend the formation of our own solar system as well as of extra-solar planetary systems. To understand how matter aggregates to form the building blocks of planetary bodies, new need to investigate not only the evolution of the disk itself, but also the role of jets in shaping its structure. This requires observing the system at high angular resolution as close as possible to the parent star, where the interplay between the accretion and ejection of matter dominates the dynamics. SHARK at LBT will offer a unique opportunity to investigate these phenomena.

Specifically SHARK should allow us to get both high-contrast images of circumstellar disks with optical/near-IR coronagraphy and coronagraphic imaging of stellar jets.

Also in the extra-galactic field the unique capabilities of SHARK in terms of spatial resolution and contrast enhancement may be successfully applied: to study the feeding/feedback mechanism in nearby sources, the AGN-host relations as well as Dumped Ly-α systems (DLAs) and the quantum space-time degradation at high redshift. In this context the goals are:

- to discover and fully characterize the AGN close pairs
- to constrain the Black Hole feeding mechanism (e.g. supernovae driven winds vs gravitational asymmetries) in local Seyfert galaxies
- to trace, in bright quasars, molecular outflows powerful enough to clean the inner kpc and quench the star formation (SF) by mapping dust lanes on scales down to hundred pc, and investigating whether outflows are dusty or rather the AGN feedback has already swept the ISM. Color maps and IFU follow-up of SF regions in the galaxy nucleus and disk, will allow to constrain the SF rate, the age, and the metallicity
- to study the galaxies associated with DLAs, hence to understand the connection between dense cold gas in the cosmic web and galaxy evolutionary mechanisms at high z

The possibility to observe at the same time the target in VIS and NIR wavelengths, using both imaging and coronagraphic modes (and the VIS IFU mode), combined in ways which are dependent on the target, is giving to the astronomer a flexibility not present in similar instruments worldwide.

3. SHARK AT THE TELESCOPE

The basic idea is to have the two SHARK channels installed one for each LBT arm. There is a preliminary agreement with the LBTI PI (Phil Hinz) for which SHARK might be installed at the entrance foci of LBTI, as it is shown in Figure 2, using two deployable dichroics to feed the two SHARK channels. In this way, on the VIS side, the IR light is totally transmitted to LBTI, while on the NIR side, only the wavelengths higher that K band would reach the LBTI focus. The dichroics may be positioned just before the entrance window of LBTI, the latter transmitting the IR light to the interferometric focus and reflecting the VIS light to the Pyramid WFS. Such a dichroic, on the VIS channel would pick-up only a certain amount (to be decided) of the VIS light, to feed with the rest the WFS, while on the NIR channel is picking up only the J, H and K bands, letting all the visible light and the wavelength higher than K to go through. With this setup, SHARK will provide possible contemporary observations from R to K bands. Such a flexible configuration with several combined binocular observing modes is reflecting the request coming from the principal science cases, for which contemporary observations in the VIS and NIR domain are required.

In the following, after doing a few considerations on the possible coronagraphic solutions, we show the conceptual opto-mechanical study of the NIR and VIS channels.

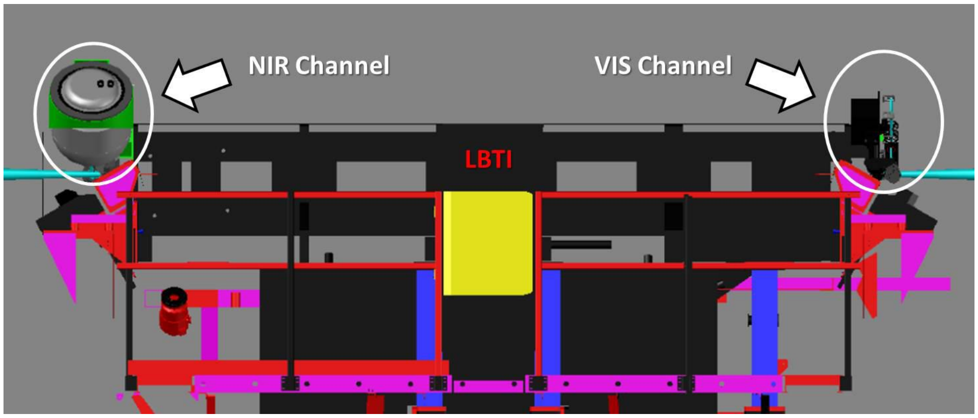

Figure 2: a possible installation of the two SHARK channels at the LBTI entrance foci

4. THE OPTO-MECHANICAL CONCEPT

As already shown in Sec. 3, the two SHARK channels, the VIS and the NIR ones, will be installed one for each LBT arm. In this section we describe the opto-mechanical layout of the two channels, starting with the NIR one.

4.1 NIR Channel Opto-Mechanical layout

The NIR channel of SHARK will provide both direct and coronagraphic imaging, over a FoV of about 20” x 20” (almost 30” on the diagonal). The current optical design is described in Figure 3, and it is based on a classical two off-axis parabolas design, with the aim of maximizing the optical quality on the FoV (SR>97.7%) and minimizing the instrument dimensions. All the optics used inside the instrument are below 40mm in diameter, demanding in terms of optical quality but commercially available. The overall NIR channel can rotate on a mechanical bearing to compensate for field rotation.

Just before the input focal plane, there is a deployable ADC, to correct for atmospheric diffraction.

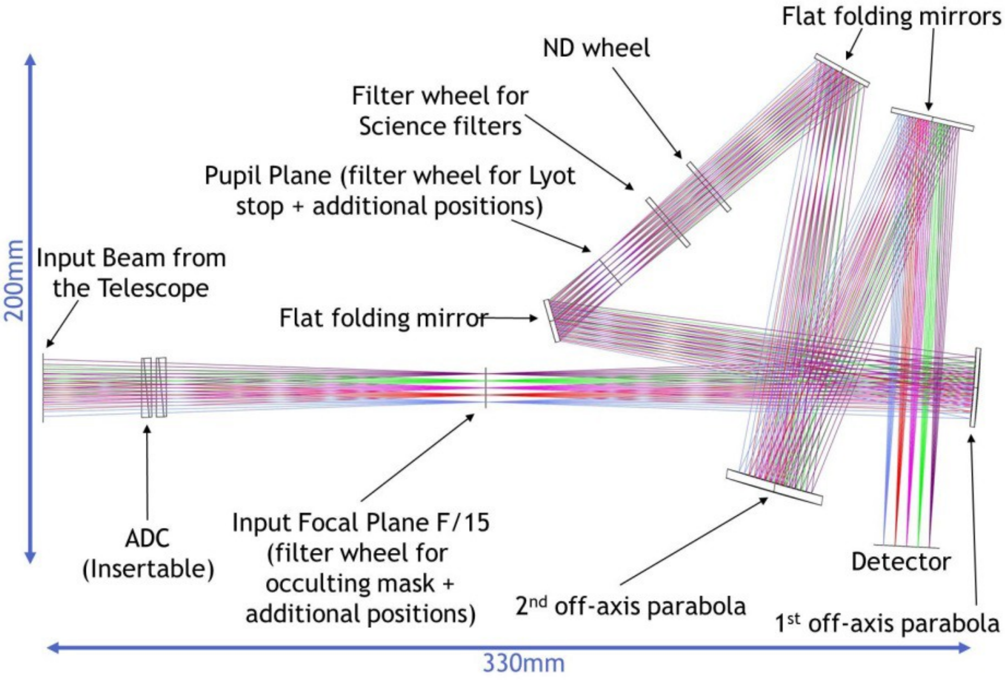

Figure 3: the SHARK NIR Channel optical design

On the input focal plane, a filter wheel can select between different occulting masks.

Onto the pupil plane, a selector can switch between the Lyot mask and the "empty" position (to provide direct NON-Coronagraphic imaging on the detector). Six additional masks positions are available here, for a total of eight.

A filter wheel is positioned just after the pupil plane (7 positions available), giving the possibility to insert broad and narrow band filters.

Just after, another filter wheel (7 positions in total) will allow the insertion of different neutral density filters, to allow observations of very bright targets. This wheel might possibly accommodate also a few polarized filters or additional science filters, for science cases for which only faint target observation is required.

The 2nd off-axis parabola and a couple of folding mirrors are directing the beam toward the HAWAII II detector, on which the spatial sampling is 2 pixels on the J Band diffraction limit PSF, i.e. Nyquist sampled in J.

The possibility to make polarimetry (both in direct imaging and coronagraphy) using polarized filters to be inserted onto the optical path is under study, as well as the possibility of doing low resolution spectroscopy by using a long slit and a grism to be inserted onto the focal plane and on the collimated beam respectively. At this stage, both solutions might be easily implemented (of course if requested by the science cases) adding in the currently available filter wheels the proper optics required.

In Figure 4 there are two views of the NIR channel opto-mechanical study, which of course foresees cryogenic dedicated gears and stepper motors, initialized through dedicated limit switches.

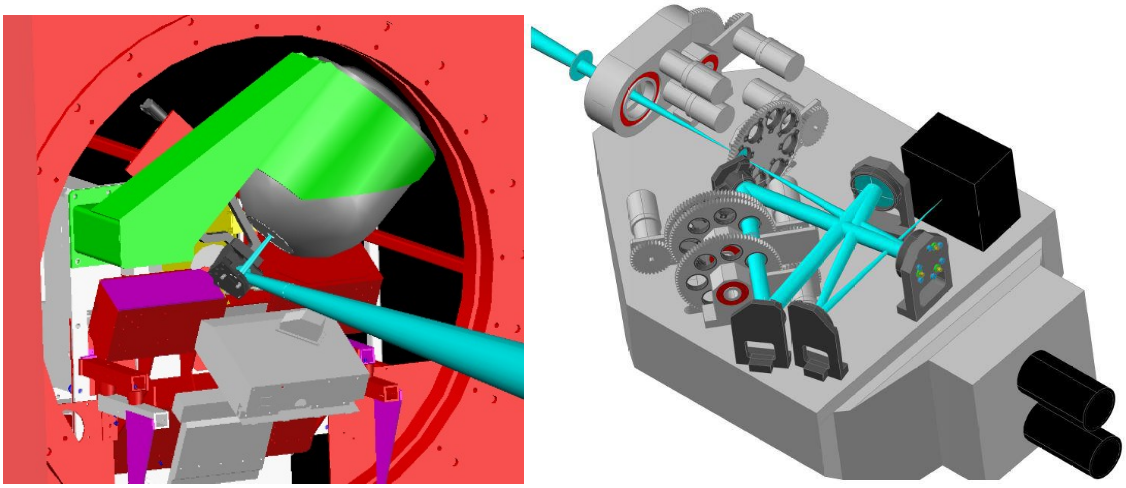

Figure 4: on the left side the SHARK NIR channel installed at the LBTI entrance focus; on the right side a view of the Opto-Mechanical concept of the SHARK NIR bench.

The Cryogenic tank, shown in Figure 4 left side, can contain in this preliminary design 20 liters of Nitrogen, ensuring a duty cycle for the refill of more than 24 hours. The refilling valves have been oriented in a way that the maximum angle with respect to the zenith position is 45 degrees, independently from the telescope position, to avoid Nitrogen spilling out.

The detector foreseen is a Hawaii 2RG HgCdTe detector, of which only one quadrant is used in the current design, meaning that we will use 1024 x 1024 pixels of 18µm size. The housing will be customized, and the dimension currently considered in the opto-mechanical design is an upper limit of similar system already in use.

4.2 VIS Channel Opto-Mechanical Layout

We briefly describe also the VIS arm of SHARK, which has a layout very similar to the one of the NIR channel, the main difference being the use of a moveable mirror to allow direct imaging (bypassing the coronagraphic path) of the whole field of view (about 20x20 arcsec) on the camera detector. In this configuration (direct imaging) the light coming from the telescope is passing only through the ADC (also removable) and through a flat mirror, as it can be seen in Figure 5 (where the flat mirror is not inserted in the optical path, and it is called “direct imaging selector mirror”).

When the first flat mirror is not inserted (as shown in Figure 5), the coronagraphic optical layout is based on two off-axis parabolas giving a 5 x 5 arcsec corrected field of view (Strehl > 99%). Two filter wheels, one in the focal plane and one in the pupil plane, allow for the selection of occulting masks and pupil stops. This configuration has been developed for the Lyot coronagraph, but can also make use of Vortex, shaped pupil coronagraphs and Phase masks. A third wheel after the pupil plane is foreseen for science filters.

The field rotation may be provided by means of a direct camera rotation due to its light weight (<1kg). This solution has the advantage to minimize variation of the non-common path aberrations. The camera will also be installed on a motorized focus adjustment, not shown in the image. It is foreseen to use a fast low noise sCMOS camera with a 2500 x 2000 pixels detector and a very small pixel size of 6.5 µm. This device can expose subfields of 256x256 pixels at about 1000 fps with 1e- rms noise level allowing to image bright sources with high dynamics and to freeze the speckles.

Figure 5 shows an overall view of the compact (450x400 mm) VIS channel, for which it is also foreseen a spectroscopic mode (also not shown in the image) through a fiber fed IFU mode, which will be accomplished by moving the camera away in the “extra-focal” direction and inserting onto the focal plane the optical fiber bundle. The latter interfaces the VIS channel focal plane to an external slit spectroscope (located in a convenient location at a certain distance from the instrument) allowing to obtain multi spectral images of a 2x2 arcsec subfield with spatial resolutions of about 40-80 mas. The spectral coverage is in the range of 600-950 nm while the spectral resolution is mainly related to the flux of the sources and to the spectroscope final design, with probably a couple of selectable different spectral resolutions ranging from a few hundreds to a few thousands.

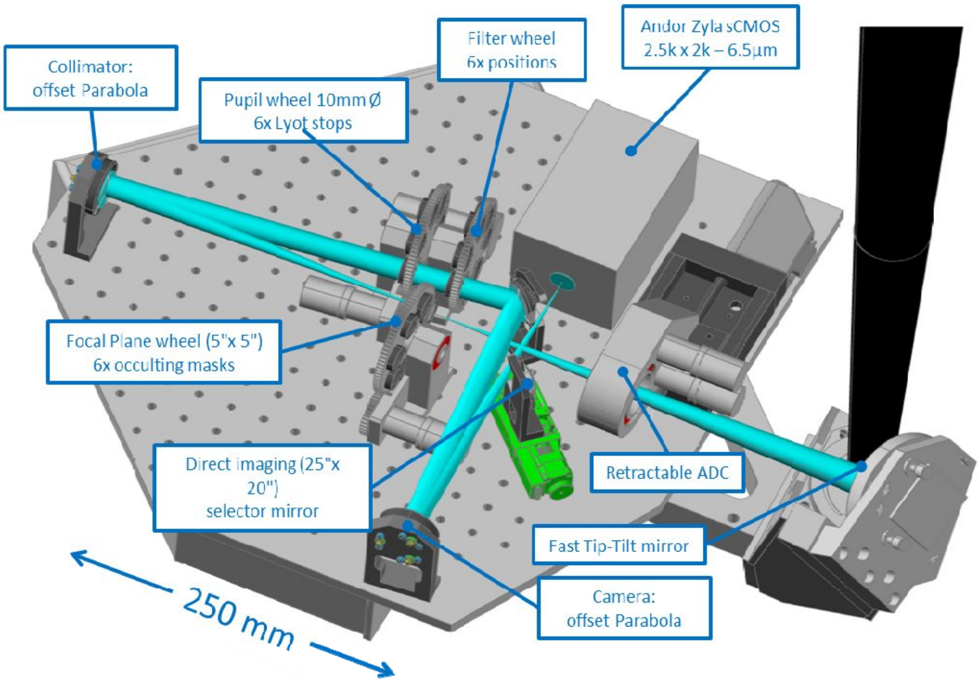

Figure 5: CAD render of the assembled VIS channel, in green the mobile relay mirror used to exploit direct imaging on its right there is the insertable ADC optics. The pitch of the holes on the optical breadboard is 25 mm.

The installation of the VIS channel is foreseen on the side of the LBTI input port, as already shown in Figure 4. In Figure 6 there is a more detailed view of the possible installation area on the LBTI side, where a deployable arm will allow the insertion of a dichroic, picking up a fraction of the order of 50% of the visible light to be folded toward SHARK, leaving the rest to go through for the wave front sensing operations. All the infrared light is untouched, giving in principle the possibility to operate LBTI and the VIS channel of SHARK at the same time.

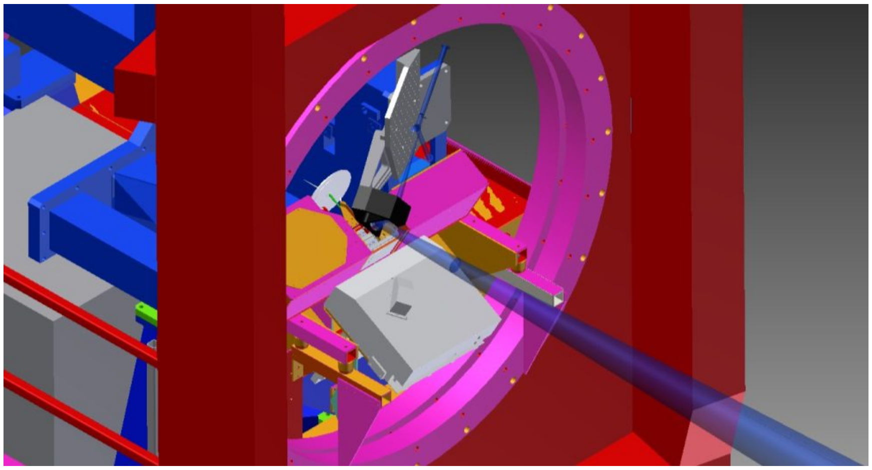

Figure 6: The VIS channel installed on the side of LBTI. The mounts of the optical components are not shown for the sake of clarity.

5. CONCLUSIONS

SHARK is an instrument designed for high contrast imaging, that will exploit the extreme adaptive optics correction provided by the Pyramid based LBT AO systems. Both the NIR and the VIS channel are essentially imagers, designed in a way they can easily turn into coronagraphic facilities and, in the case of the VIS channel, also into a spectroscopic instrument. This flexibility will allow to take full advantage of the LBT binocular capabilities and, in combination with the excellent LBT AO performance, will give clear opportunities to obtain primary science goals.

Furthermore, LBT is planning to improve even more the performance of the AO systems upgrading the speed of the adaptive secondary mirrors and increasing the WFSs sensitivity by using L3-CCDs, and for this reasons we expect 1-2 magnitude fainter targets to be reachable with respect to other similar instruments not taking advantage of the Pyramid gain (see [31]).

The impact on the SHARK science would be obvious, allowing LBT to observe, in the NIR domain, many more nearby small mass stars and solar type stars in nearby star-forming regions (e.g. Taurus at 140 pc), complementing somehow the surveys of SPHERE and GPI.

In the VIS domain instead, SHARK will be one of the few instruments providing direct imaging, coronagraphy and spectroscopy on diffraction limited targets, and this fact will open the possibility to make outstanding new science, the most challenging and attractive of which might be exploring the possibility to observe exceptionally bright exoplanets orbiting around nearby stars.

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