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SiFAP2: a new versatile configuration at the TNG for the MPPC based photometer

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ABSTRACT

The quality of SiFAP (Silicon Fast Astronomical Photometer) at the TNG has already shown its ability to easily detect optical pulses from transitional millisecond pulsars and from other slower neutron stars. Up to now the photometer based on Silicon Photo Multipliers manufactured by Hamamatsu Photonics (MPPC, Multi Pixel Photon Counter) was mounted (on and manually aligned with) a MOS mask at the F/11 focal plane of the telescope.

In order to have a more versatile instrument with the possibility to remotely center and point several targets during the night we have decided to build a new mechanical support for the MPPCs and mount it on the Namsyth Interface (NI), where originally OIG and later GIANO were hosted.

The MPPC module devoted to observe the target will be placed at the center of the FoV (on-axis), while the reference signal will be collected from a peripheral star in the FoV (Field of view) by means of the MPPC module that will be set at this position by a combination of a linear stage movement and a derotator angle.

At the same time we have introduced the option for a polarimetric mode, with a 3rd MPPC module and a polarizing cube beam-splitter that separates the states between this and the on axis MPPC.

SiFAP has been developed with 3 independent custom electronic chains for data acquisition, exploiting the 3 different outputs (analog, digital, USB pre-processed) provided by the MPPCs modules. The electronic chain fed by the analog output is able to tag a single photon ToA (Time of Arrival) with a time resolution of 25 ns, while the remaining electronic chains can integrate the signal into time bins from 100 ms down to 20 μs. The absolute time is provided by a GPS unit with a time resolution of 25 ns at 50% of the rising edge of the 1PPS (1 Pulse Per Second) signal which is linked to the UTC (Universal Time Coordinated).

Apart from the versatility with the remotely controlled on sky configuration of the MPPCs, the mounting of SiFAP2 at the NI allows for a permanent hosting of the instrument, readily available for observations. The new polarimetric mode will then offer other scientific opportunities that have not been explored so far in high-temporal resolution astronomy.

Keywords: MPPC, Photometer, millisecond pulsar, neutron star, polarization

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1. INTRODUCTION

SiFAP2 (Silicon Fast Astronomical Photometer and Polarimeter, should be SiFAPP thus SiFAP2) is the new improved version of SiFAP[1] which allows for increased versatility and new observing modes. It will be mounted at the F/11 direct Nasmyth focal station of the Telescopio Nazionale Galileo[2] . There will be one MPPC photometer on-axis pointing on target and another MPPC photometer used for reference off-axis which will be moved radially away from the first one with a motorized stage. The whole system will rotate together with the derotator to reach the correct position angle of the object in the sky. This typical observation mode that was available even with SiFAP is improved with the possibility of introducing broad band and neutral density filters in front of the photometers. A 3rd photometer will be mounted perpendicular to the 1st one and the light will be split between the two using a polarizing cube beam splitter. In this configuration there will then be the option to measure linear polarization or circular polarization when inserting a $\lambda/4$ retarder in front of the B/S cube.

2. OPTOMECHANICAL IMPROVEMENTS FROM SIFAP

The first version of SiFAP had been built for the 1.5m telescope in Loiano and succeded in observing and sampling the light curve of several pulsars[3] . At the time of the installation at the TNG the only available focal station was on the TRAM, the translation stage hosting the long slits and MOS masks of Dolores. The optomechanical configuration of SiFAP was completely revised in order to have two MPPC mounted on the support of a MOS mask. The $8.4 \times 8.4\, arcmin^2$ Field of View (FoV) around the target and reference to be observed was transfered into a MOS mask, together with the position of few centering stars. The MPPC were then centered on their relative positions with a centering device. Once mounted on the tram and pointing at the sky, the FoV was centered using Dolores, then the mask was inserted and the MPPC aligned on the sky thanks to the relative position of the centering stars in the FoV[4] .

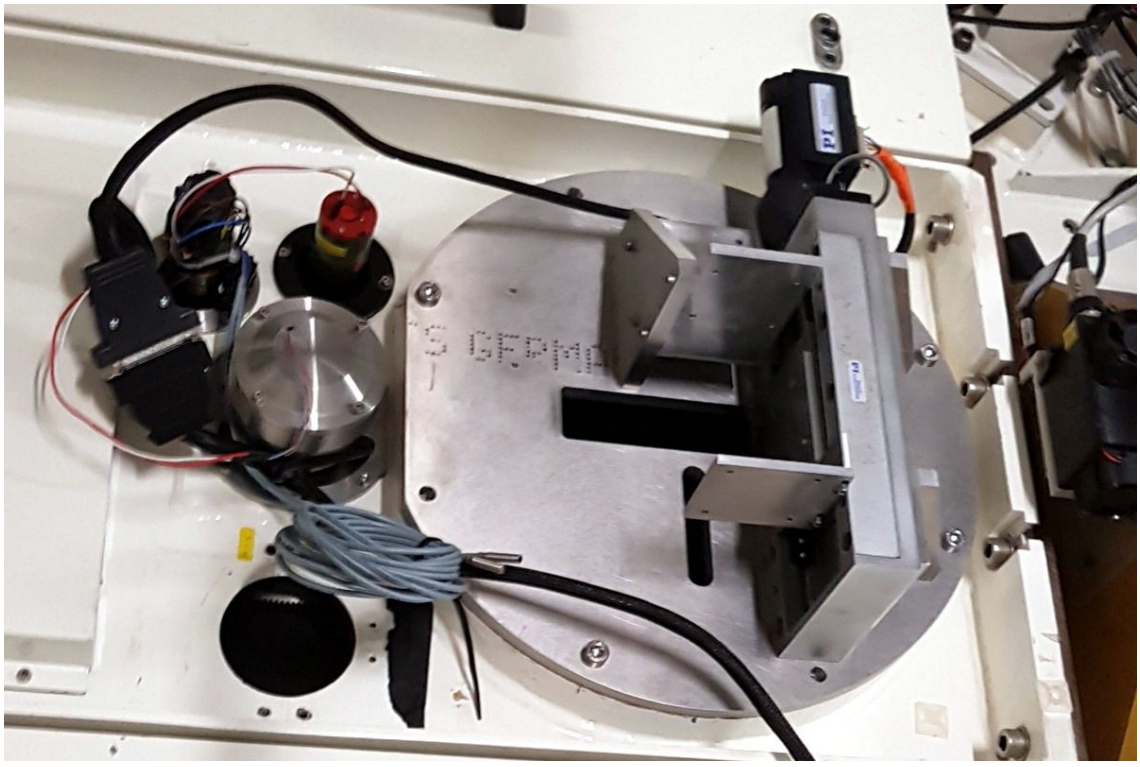

Figure 1. The mechanics of SiFAP2 mounted at the new F/11 focal station during calibration and alignment tests

This observing and alignment strategy was first tested on the Crab pulsar and it demonstrated the feasibility of the method. The following tests, always limited to few hours per night and sometimes a DDT night, allowed

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for several emblematic discoveries like the first detection ever achieved of optical pulsations from a ms pulsar[5] . Optical pulses were observed when such a transitional pulsar[6,7] was surrounded by an accretion disk and showed X-ray pulses. Energy arguments and observations subsequently performed simultaneously to XMM-Newton indicate that optical pulses are most likely powered by the rotation of the magnetic field of the neutron star rather than by accretion of matter (Papitto et al. 2018, in prep.).

This configuration unfortunately had the drawback that it was limited to that particular observing mask; for a new target a new mask had to be machined and the MPPC had to be realigned. Having prepared beforehand several masks for the possible targets of the night, the time needed to perform the change was around half an hour for the mechanical part and few minutes more for the pointing and re-centering of the mask on the new target. A considerable fraction of time when the option to observe is limited to free technical hours. The other limitation was the lack of filters (neutral density or broadband) in front of the detectors. Finally, being a visiting instrument and in that particular focal station, it had to be mounted and dismounted and could not be readily available when needed.

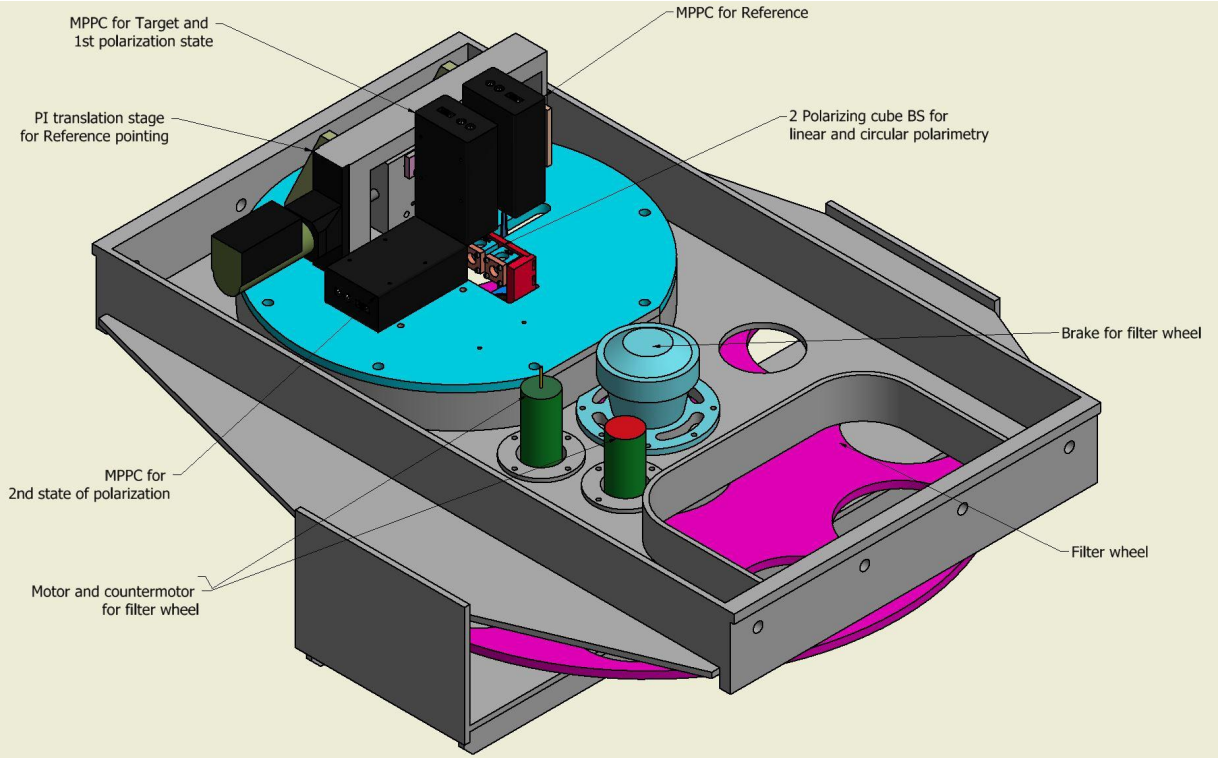

Figure 2. SiFAP2 view from above

The WOW premiale of 2016 allowed to move GIANO,[8] a Near IR high resolution spectrograph, close to HARPS-N[9] for the worldwide unique multi-band high-resolution spectroscopy of GIARPS[10] configuration in the Nasmyth B station: there is thus an empty focal station in the Nasmyth A interface. This focal plane position had originally been foreseen for OIG[11] and later hosted the preslit feeding GIANO with a fiber. We realized that with a new mechanical flange it could be possible to mount a new version of SiFAP that could get rid of the limitation described before. In particular (a) it could be always mounted, (b) it would have a filter wheel in front of the detectors and (c) it would not need a mask for centering. During the design of the system the idea to insert a polarimetric mode arose and it was soon decided that implementing this observing mode was not only easily and economically feasible but highly interesting from the scientific point of view.

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3. SCIENTIFIC DRIVER

High time resolution multi-wavelength observations are crucial at the basis of a complete comprehension of relativistic astrophysical objects, such as neutron stars and stellar-mass black holes. Unfortunately, we cannot take advantage of the complementarity of observational techniques on a sub-second scale since this time domain is presently limited to radio, X-ray and γ wavelengths only.

The astrophysical objects that can in principle be better understood at high time resolution have been presented by Shearer[12], with the further advantages of polarimetry discussed by Collins[13]. In addition to the arguments of these authors, here we note that efforts devoted to the development of high time resolution instrumentations working in the optical range, possibly with polarimetric capability, are necessary to export our knowledge of magnetized plasmas from laboratories to astrophysical environments. Sub-seconds optical and near infrared photo-polarimetry and possibly spectro-polarimetry would open the possibility to understand how fundamental physical mechanisms, such as shocks, plasma instabilities or magnetic reconnections, work at the astronomical scales and contribute to very relevant observed phenomena, e.g. stellar flares.

4. CUSTOM ELECTRONICS FOR HIGH SPEED PHOTOMETRY

The electronics coupled to the photometers has demonstrated to be reliable for our scientific purposes and no improvements for the acquisition electronics are foreseen for SiFAP2. You should refer to[1] for a detailed description of the system. We just remember here that SiFAP has been developed with 3 independent custom electronic chains for data acquisition, exploiting the 3 different outputs (analog, digital, USB pre-processed) provided by the MPPCs modules. The electronic chain fed by the analog output is able to tag a single photon ToA (Time of Arrival) with a time resolution of 25 ns, while the remaining electronic chains can integrate the signal into time bins from 100 ms down to 20 μs. The absolute time is provided by a GPS unit with a time resolution of 25 ns at 50% of the rising edge of the 1PPS (1 Pulse Per Second) signal which is linked to the UTC (Universal Time Coordinated).

5. OPTOMECHANICAL DESIGN AND CONFIGURATIONS

The new configuration of SiFAP2 considers a fixed MPPC mounted on the optical axis and intended for the target. The scale at the F/11 focus is of 187 μm per arcsec, and being the active area of the MPPC 1.3 $\times$ 1.3 mm^2, it will have a FoV of roughly 7 $\times$ 7 arcsec^2. The size of the FoV is important anyway only because it relaxes the centering error: these MPPCs, even though bidimensional with 20x20 APD do not produce images. Pointing of the target will be done with the TCS and centering will be checked with the A&G probe. During the commissioning phase a reference mark will be find on the A&G camera which corresponds to the centering of the star into the on-axis MPPC. Once in tracking the A&G probe will be used for guiding off-axis.
Pointing of the reference star will be in polar coordinates from the target. A translation stage will move another MPPC radially, away from the target MPPC, covering the distance r between target and reference. The derotator of the telescope will then move the whole system to the correct position angle, PA.
Once the photometers are locked into target and reference, there are three possible observing modes:

- high speed photometry with target and reference;
- linear polarization photometry;
- circular polarization photometry.

To resume, in order to configure the system for this observing modes there are 4 axes to be controlled (apart from the TCS axes) and they are detailed in the following and in Table 5.5.

5.1 Pointing of target (AR, DEC): authomatic

Pointing of the target is achieved with the pointing of the telescope. Centering will be performed through a reference mark on the guiding camera. Coordinates will be given to the telescope from a catalog. No dedicated controller is needed here but info will be displayed on the SiFAP2 GUI.

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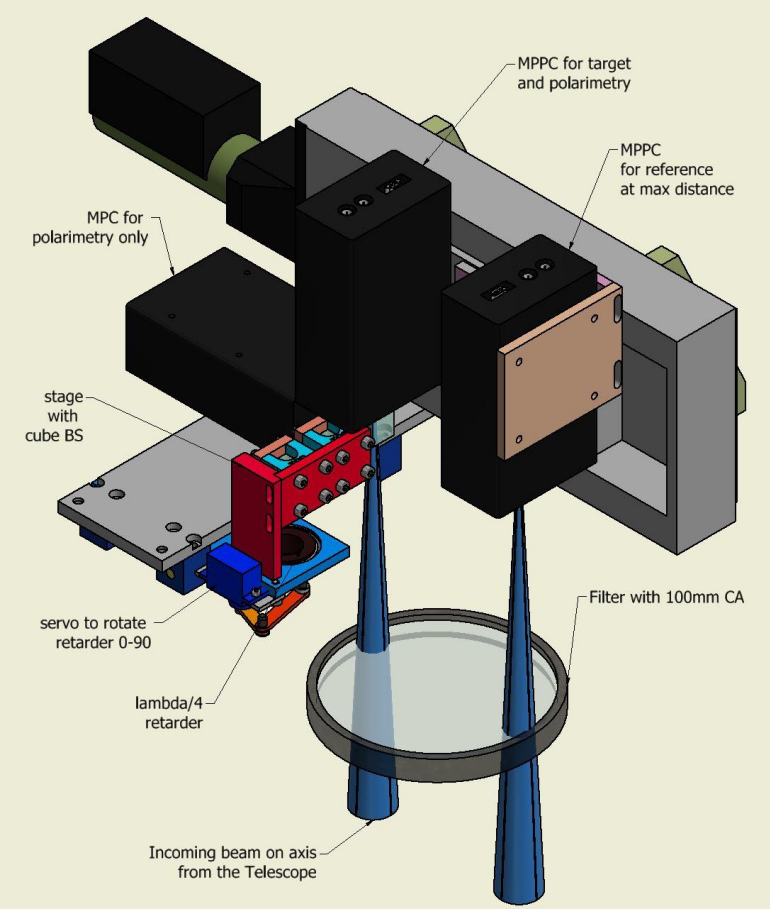

Figure 3. The main optomechanical components of SiFAP2 without the supporting flange.The 3 MPPCs can be seen together with the 2 polarizing cube BS and the retarder.

5.2 Pointing of reference (AR, DEC): authomatic

The reference star will be pointed at converting its AR/DEC coordinates into polar coordinates offsets from the target (r,theta):
(a) The distance (r) to the target will be controlled using a M155.10 Physik Instrumente translation stage. The minimum distance is defined by the size of the photometers (35mm), while the maximum distance is limited by the range of motion of the PI stage, as it can be seen in Fig.4. Anyway the maximum usable distance is defined by the filters diameter (with CA 100mm) as it is shown in Fig.5 nd in Fig.3. This means that, at the F/11 scale of $187\mu m$ per arcsec, the distance of the reference to the target must be between roughly 3 and 8 arcmin. The PI stage will initialize and be able to move with a repeatibility in position much better than 0.1 mm. The system is designed in order that it will activate each of the limit switches on the PI without any collision with other moving parts.
(b) The angle (theta) on sky should be reached using the derotator as we said before. At the maximum distance (r) of 100 mm the error of 0.1 mm on the detector would correspond to an error on the angle (theta) of $2 \cdot 10^5 \cdot 0.1/100 = 200$ arcsec, which is easily achieved with the pointing performances of the derotator. The coordinates of the reference star will be chosen from a catalog but both r and theta will be calculated and displayed by the GUI. A command will be given by the user in order to allow the movement of the derotator.

5.3 Filter setting: user selected

The filter wheel (FW) has 10 positions (1 open, 9 filters) with the optical axis at 215 mm from the rotation axis. This means the precision of positioning of the FW must be $0.1/215 \cdot 2 \cdot 10^5 = 90\,\text{arcsec} = 0.03\,\text{deg}$. The

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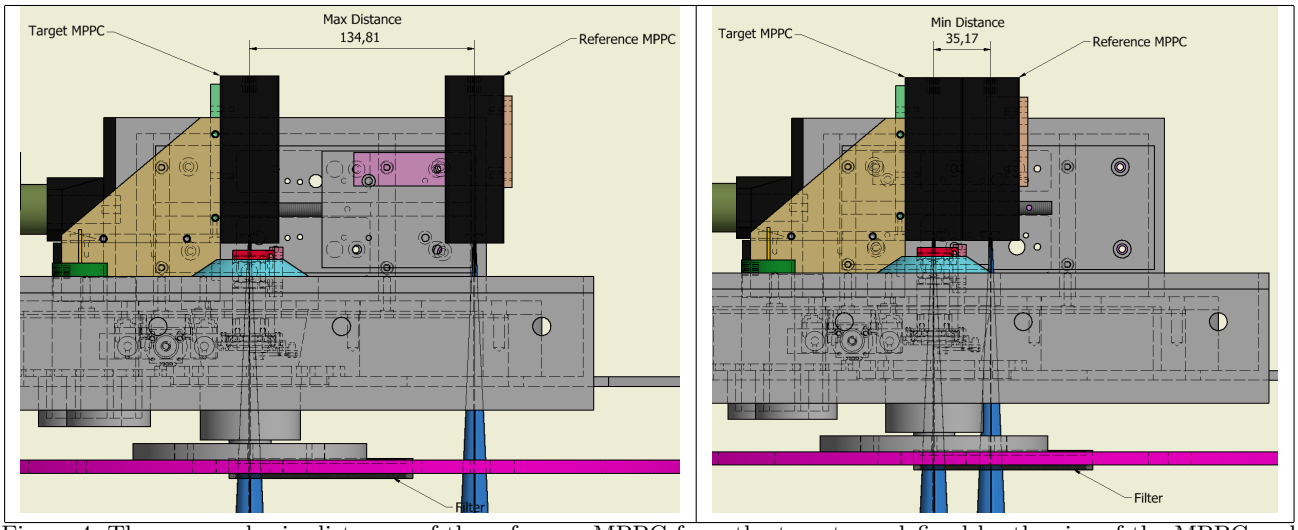

Figure 4. The max and min distances of the reference MPPC from the target are defined by the size of the MPPC and the ROM of the Translation stage

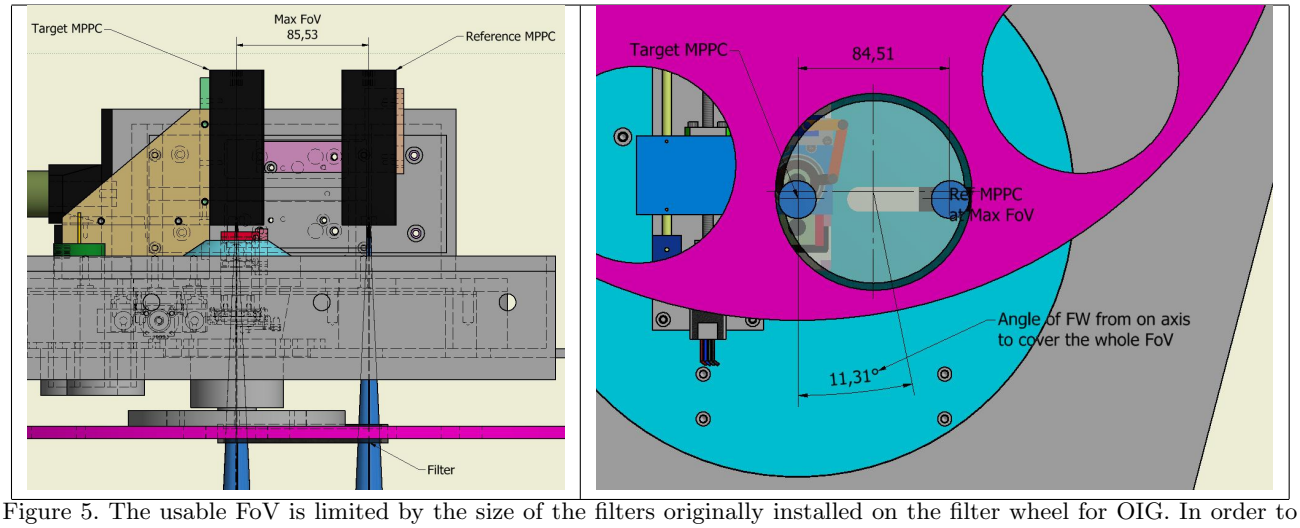

Figure 5. The usable FoV is limited by the size of the filters originally installed on the filter wheel for OIG. In order to feed both MPPC with the same filter the wheel will be rotated to the angle allowing the maximum distance between the 2 detectors

FW has 2 mechanical stops (no continuous rotations) and needs proximity sensors for initialization. During observations the position of the FW is not on-axis but displaced in between target and reference in order to cover both sensors with the same filter. We could decide to have and adaptive positioning depending on the distance (r) between target and reference and place the filter always at the midpoint, but to simplify we decided to define a new fixed position which keeps the target at the minimum distance from one edge of the filter without vignetting and the reference covered on the whole range of movements (roughly like on-axis plus half filter width). This position it can be seen that corresponds to the on-axis + 11.31 deg as in Fig. 5 right or in Fig. 3. The filter wheel position will be defined by the chosen filter from a drop down menu with filter names like [U-johnson],[z-Gunn], [ND2], etc. (The whole set of broad- and narrow-band filters available for OIG can be seen here http://www.tng.iac.es/instruments/filters/). Before and after the movement of the wheel, obtained with a system of motor and counter motor acting on the gear of the wheel to minimize backlash, a brake will be opened and closed in order to maintain the position of the filter even with small unbalances.

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5.4 Polarization modes

As explained before SiFAP2 will have 3 possible observing configurations: simple high speed photometry, linear and circular polarization. Polarimetry is based on the dual beam swapping strategy[14,15] .

Mechanical configurations for linear and circular polarimetry can be seen in Fig. 6. These observing modes will be chosen by the user with a button from the GUI; a stepper motor with lead screw will move an optomechanical stage with two polarizing cube Beam Splitter as in Fig. 6. The cube BS can be seen also in Fig. 3. For linear polarization only a polarizing cube BS is needed, while for the circular polarization the cube is optically after a retarder. The cube BSs will split the light into the 2 polarization states and feed the MPPC of the target and a 3rd MPPC that is mounted perpendicular to the target one, on the other side with respect to the reference MPPC. The derotator of the telescope will perform the Beam swapping.
There are then two identical polarizing cube BS by Bernard Halle with 10 mm side and they are mounted into custom supports for easy handling and mounting. They will be pre-aligned in the optical laboratory in order to be optically equivalent and do not laterally shift or tilt the incoming beam. The shift in focus introduced by the cubes will be adjusted with a movement of M2. The system is designed in order to be able to move without colliding onto other movable components and activate each limit switch at the extremes of its ROM.

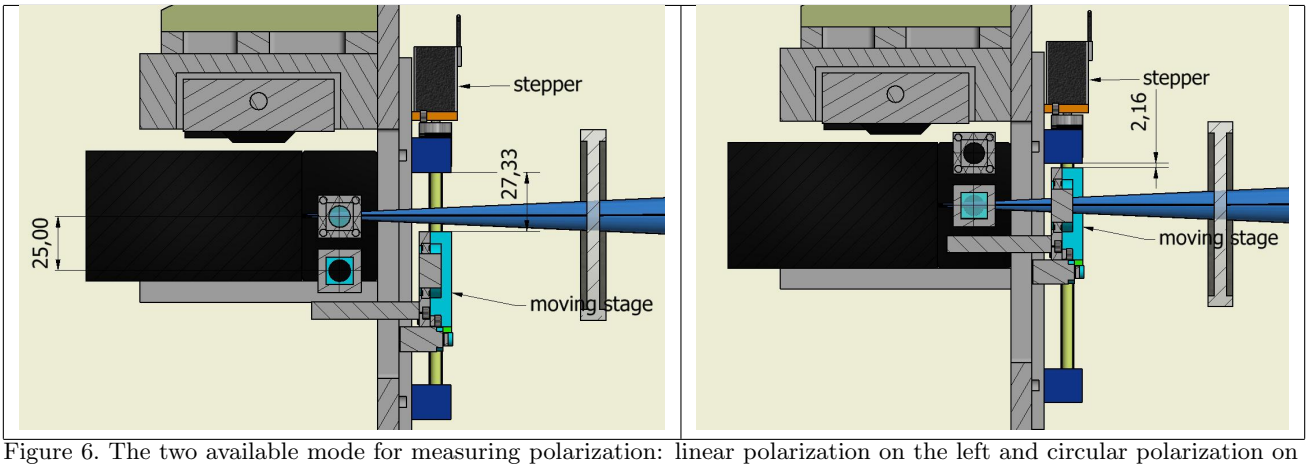

Figure 6. The two available mode for measuring polarization: linear polarization on the left and circular polarization on the right, with the $\lambda/4$ retarder in front of the BS cube.

5.5 Retarder mode

When the circular polarization is set there is a $\lambda/4$ retarder from Bernard Halle with 10 mm clear aperture before the polarizing cube BS. Beam swapping will be obtained by rotating the retarder between positions separated by 90 degrees with a micro servo actuator.

Axis name	Control axis	range	positions	Error/repeat	Lim. Sw/brake
Ref pointing (r)	PI 155	100 mm	continuous	0.1 mm	2
Filter wheel	2motors/enc	360 deg	10 (filt.names)	0.03 deg	2 + brake
Polarization	stepper	50 mm	3 (no,lin,circ)	0.1 mm	2
Retarder	servo	90 deg	2 (0,90)	0.1 deg	0

Table 1. Resume of the 4 new axes controls needed for the SiFAP2 system

6. CONTROL SOFTWARE AND USER INTERFACE

While we are using an engineering GUI developed under LabView for the AIV phases of the instrument in the laboratory and at the telescope (a screenshot can be seen in Fig. 8), the control software final version will be developed in two blocks:

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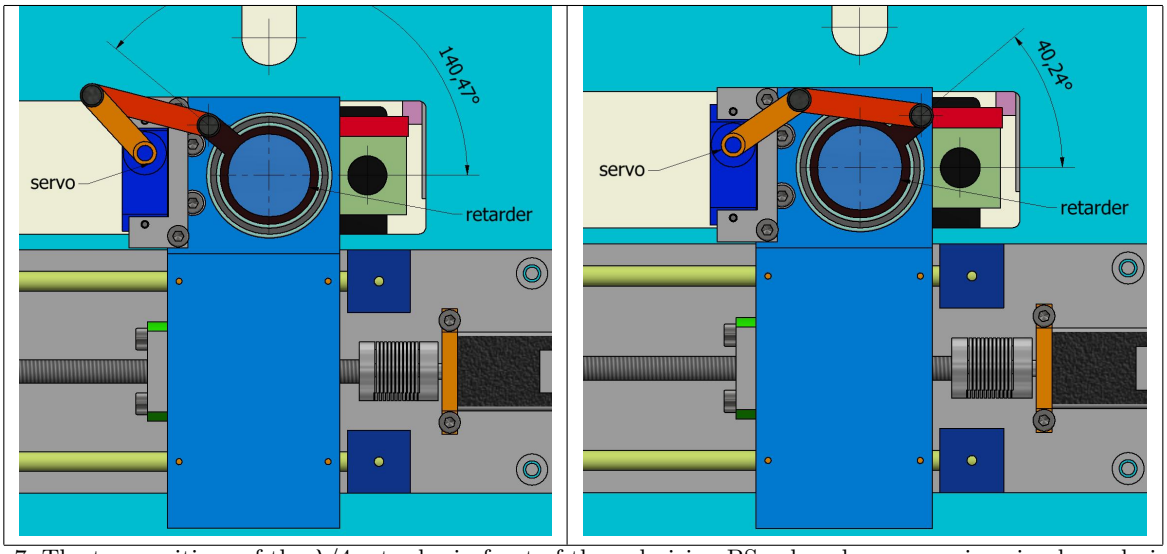

Figure 7. The two positions of the $\lambda/4$ retarder in front of the polarizing BS cube when measuring circular polarization.



Figure 8. SiFAP2 engineering graphical user interface for the axes controls.

- The back-end, a control service written in Java that will control the instrument setup, axes movements logic, command execution and telemetry logging. Also, this service will make possible the integration with another telescope systems via a restful API. For example the pointing of the target and the changing in position angle of the derotator will make need of the possibility to interact with the TCS.
- The front-end: A web interface that can be used from any device with a modern web browser (including computers, tablets, smartphones or embedded devices) allowing the user to perform the normal system operations and the maintenance tasks.

7. CONCLUSIONS

SiFAP2 is now undergoing a campaign of alignment and testing in the laboratory and on the sky and we foresee it to be available for the first night-time observations by the end of summer 2018. In this new configuration it will maintain the main functionalities as the previous version but it will gain in easiness of use and setup, in versatility and will provide new observing modes with filters and linear and circular polarimetry.
It will still be considered as a visitor instrument anyway and observations limited to DDT and spare technical time.
Once the capabilities of this instrument are consolidated with the science that is producing in such a limited

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observing time, our hope is to obtain more funds and improve it with a more robust electronics and a user friendly GUI for the temporal data acquisition. Only after it will be available to the astronomical community as a proprietary instrument of the TNG, with possibility to apply for regular observing time, an produce top level science as we expect.

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