An ultra-stable cryostat for the detectors of ESPRESSO

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ABSTRACT

ESPRESSO, the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations, is a super-stable Optical High Resolution Spectrograph for the combined Coude focus of the VLT. It can be operated by either one of the Unit Telescopes (UTs) or collect the light from up to 4 UTs simultaneously.

ESPRESSO aims to measure radial velocity with an accuracy of 0.1 meter/sec, which is a factor of ten better than its pre-cursor HARPS at 1 meter/sec. In ESPRESSO this translates to the requirement to have a centroid accuracy of spectral lines on the detector sensitive pixels to 2 nanometer RMS.

Given the wide spectral range of ESPRESSO, the optical path is split into two channels, on which two large 92 mm x 92 mm CCDs are used in blue and red version to record the full spectrum. In order to achieve the extremely high (nanometer) stability, ESPRESSO has a fixed optical layout: No moving parts are foreseen inside the spectrograph, so that the Stability and Repeatability of the instrument performance are maximized and any thermal consumption generated inside the spectrograph itself is avoided. The optical bench is placed inside a vacuum vessel hosted in a three level thermal enclosure system, capable to guarantee temperature stability of the order of 0.001 K inside a vacuum environment.

This paper gives a detailed description of the cryostat with the flexible de-coupling of the detector dewar between the instrument vacuum vessel and its optical bench. The design is described, including the measures taken in order to provide an optimal thermal connection and a very accurate mechanical referencing of the large CCD chip. The specific experiment, which has been set-up in order to verify and physically measure the real stability of the detector "pixels" relative to the rest of the world is shown. The results obtained with a similar setup, measuring the stability of the HARPS detector and the preliminary results of the stability of the final ESPRESSO detector system are indicated.

Keywords: accuracy, CCD, cryogenic system, detector cooling, nanometer, nitrogen continuous flow, very high stability

1. INTRODUCTION

The predecessor of ESPRESSO - named HARPS - is in operation at ESO's observatory La Silla already since 2003 with excellent results. The performance limitation is due to slight un-stability of the spectral lines on the detector, which causes a 30cm/sec RMS fluctuation within a period of 30 minutes (Figure 1). The two upper curves show the position of the ThAr spectrum on the CCD for both spectrograph fibres: Fibre A Object and Fibre B Reference. Their position remains stable during several hours, proving the excellent absolute stability of the instrument. During scientific observations fibre A is fed with the star, while fibre B, illuminated by the thorium calibration lamp, measures the drift of the instrument since the last wavelength calibration. The drift value on fibre B is used to correct the stellar radial velocity measured on fibre A. The difference between both fibres shown on the lower curve indicates how precise the drift correction is: The position of both fibres follows each other perfectly at the photon noise level.

Deep investigations and a long series of tests have shown that these fluctuations were directly linked with small thermal variations coming from the cryo-cooling system.

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Those very small variations were only measurable with the detector system integrated into the instrument and moreover only after having reached an already reasonable level of stability of the complete instrument. It is understandable that in the case of ESPRESSO - where the stability requirement is even an order of magnitude higher - it is not reasonable to wait until such a late stage of the development to get full qualification of this very critical aspect. Therefore it was necessary to develop a special strategy in order to perform this type of qualification outside the ESPRESSO instrument at an earlier development stage.

The following section describes in detail the strategy and the test set-up which has been developed in order to perform a complete qualification of the detector system prior to its integration into the spectrograph. This test incudes a detailed assessment of the HARPS replica stability measurement inside the new ultra-stable lab set-up and indicates the preliminary stability range of the ESPRESSO detector system.

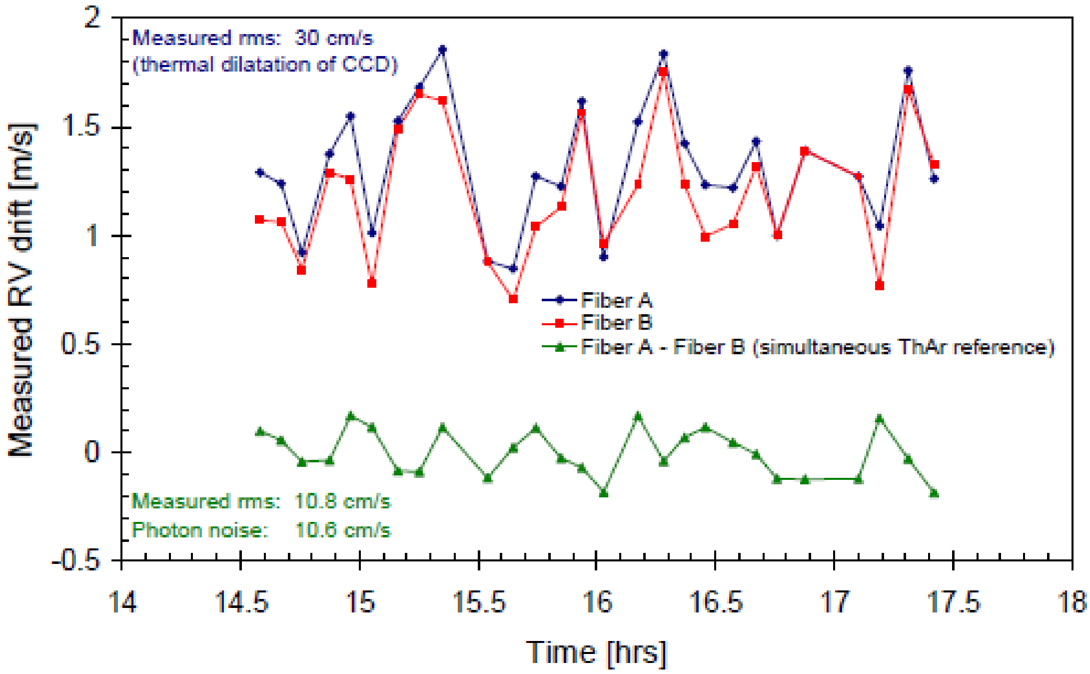

Figure 1. Instability measured on the HARPS detector

2. HARPS DETECTOR CRYOSTAT SET-UP

As precursor of the large high resolution radial velocity spectrograph ESPRESSO, HARPS inaugurated what is commonly used now for these type of instruments: The spectrograph has no moving function at all and is mounted inside a vacuum chamber – the instrument vacuum vessel. The instrument vacuum vessel has an independent vacuum form the vacuum inside the detector cryostat. Figure 2 shows a view of the HARPS detector dewar in connection with the instrument vacuum vessel wall, where the various parts can clearly be recognized.

This very special design with a vacuum insulated spectrograph, requires also some specific thoughts about the design of the detector system and its cryostat. Already at the time of the HARPS design an LN2 continuous-flow cryostat was selected in order to minimize interventions during operation and to and guarantee a longer autonomy, compared to a bath cryostat. A specific version of the traditional ESO continuous-flow cryostat has been designed to satisfy the spectrograph arrangement. Figure 2 shows a view of the HARPS detector Dewar: The two main parts of the detector Dewar (cooling system and detector head) are clearly separated by a third flexible connecting part, which at the same time isolates and connects the two through the instrument vacuum vessel wall. This is done in order to eliminate the temperature critical parts (e.g., LN2 lines, cooling system) from the inside of the instrument vacuum vessel.

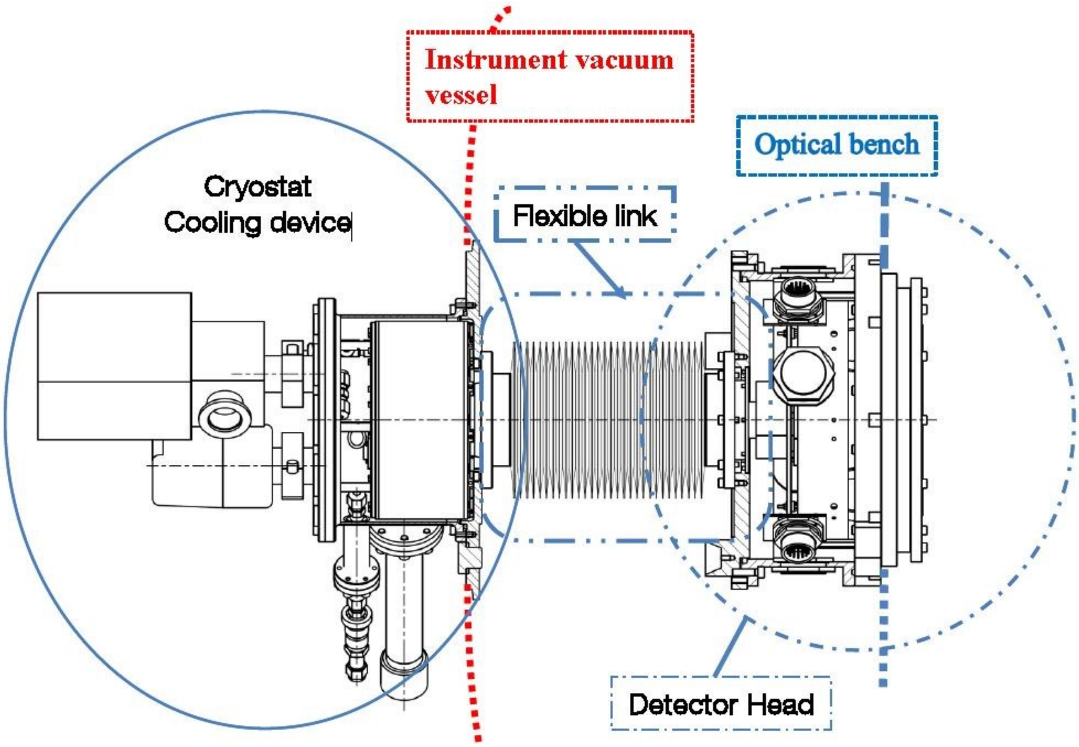

Figure 2. Conventional design of the detector cryostat for high resolution and high stability radial velocity spectrograph HARPS

3. ULTRA-STABLE CRYOSTAT MEASUREMENT SET-UP

3.1 Measurement Set-up design

The very small instability reported in the introduction was measured only after the instrument was commissioned and has been in operation for about one year. Extremely high stability is required in order to detect such small fluctuations, this level of stability can normally only be reached inside the real instrument.

In the case of ESPRESSO - which is designed for an even higher resolution - it was absolutely necessary to find a way of qualifying the detector system independent of the instrument in order to gain time during the development and construction phase. Various alternatives (e.g., capacitive sensors) have been investigated in order to measure the real stability of the detector relative to the external "world". It turned out that performing the measurement with an optical system is the most representative of the real operation. It also enables to investigate other effects inside the silicon layer it-self. Such technique was already used in the past to analyze the spot projection of a single optical fibre to assess the stability of a detector relative to the change of orientation of gravity (e.g. at the stability of the NACO wavefront sensor). Using a single spot will of course never comply with the requested resolution of a few nanometers. A large number of spots are necessary in order to reduce the measurement noise. This leads to the design of a small multi spot projector shown in Figure 3. The projector itself includes a small custom-made integrating sphere. The latter diffuses the light, which illuminates in-turn a chrome coated plate with ~ 25000 etched, randomly distributed pin holes. To achieve the best possible intrinsic stability, the multi-spot projectors are used without any intermediate imaging optics, which potentially alters the measurements. For these reasons the multi-spot projectors are attached to the vacuum housing of the Detector Dewar, extremely close to the sensitive surface of the CCD in order to produce spots of a reasonable size (~5 pixels square).

The complete set-up (Figure 4) is composed of an outer vacuum vessel, accommodating the actual detector head supported via thermal insulation structures and the detector cooling system, both in a configuration almost identical to the one used inside the ESPRESSO instrument. The system is fitted with a number of temperature sensors, several fibre-fed multi-spot projectors with external LED illumination and Lakeshore detector temperature controller.

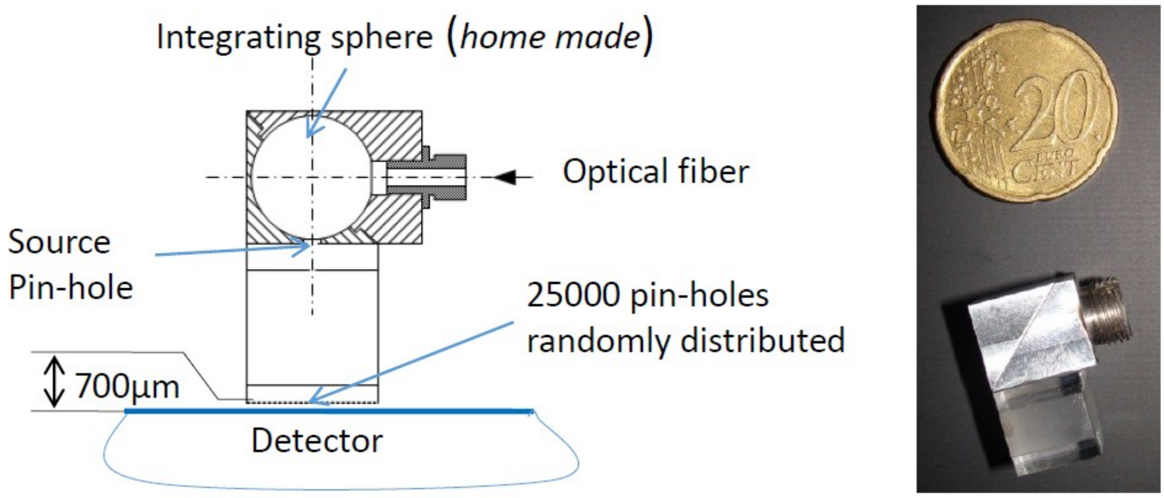

Figure 3. Multi spot projector system (~ 25 000 small spots projected onto the CCD)

An actively cooled cryogenic sorption pump is used on the outer vacuum vessel to keep the vacuum in the vacuum chamber without any disturbing vibrations. (The detector cryostat also has an integrated sorption pump in its own vacuum.) This facility - designed and built with European development funds for the verification of the HARPS instability assumption - will in the long term be used for the testing and qualification of the ESPRESSO detector cryostat stability aspects. In addition to the architecture described above, the complete vacuum vessel is installed inside a thermal enclosure which is thermalized within 0.1K using re-circulation of air. This is very close to the final architecture used for both HARPS and ESPRESSO where especially ESPRESSO is surrounded by multiple thermal enclosures with even better inside temperature stabilization.

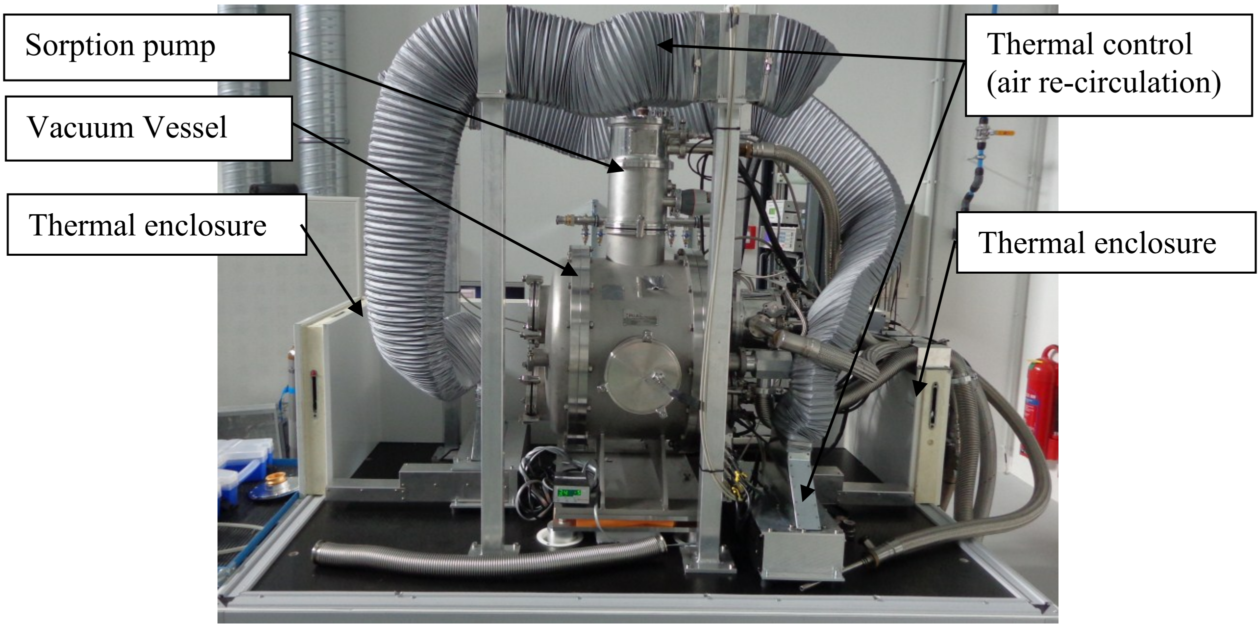

Figure 4. Final set-up in (opened-up) thermal insulation chamber and with cryogenic sorption pump on the (large) vacuum vessel

The ultra-stable cryostat set-up enables continuous optical centroiding stability tests of the detector system. Specifically developed LabVIEW routines allow a permanent x, y and z position tracing of the CCD detector(s) relative to the spot projector images.

In the first case of the HARPS detector system replication (Figure 5), the system is measuring the position of the two CCDs of the detector mosaic (2 x e2v CCD 44-82).

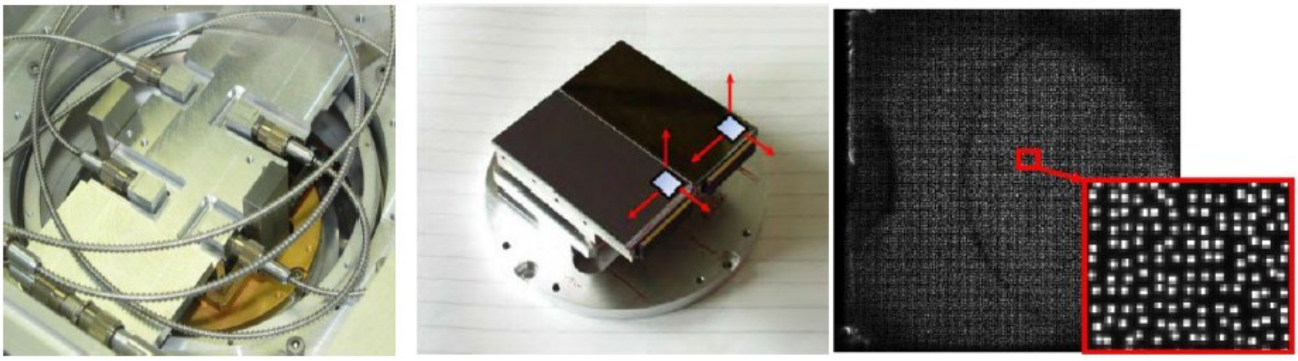

Figure 5. Fibre set-up to feed four multi spot projectors (left), CCD mosaic and projector fields (middle), Resulting image and detail of spot pattern (right)

3.2 HARPS detector system replica measurements in ultrastable set-up

The x, y, z centroid positions of the projected spots onto the CCDs are fully analyzed (Figure 6) in the resulting CCD images after being read out through them. Their differential motion is computed and displayed by a LabVIEW program. The latter records and displays simultaneously the correlated differential measurement graphs of individual temperature and pressure sensors inside the Detector Dewar, as well as additional sensors for ambient and the large vacuum vessel. This complete set of data allows not only to detect the instability and drift of the sensitive surface of the CCD detector, but also to analyze the cause. Knowing the causality allows to trace the source of the image motion and to counteract. Figure 7 shows a measurement recorded during a temperature transition of the CCD mosaic. We can clearly see a drift of the centroid position, which is directly correlated with the temperature change.

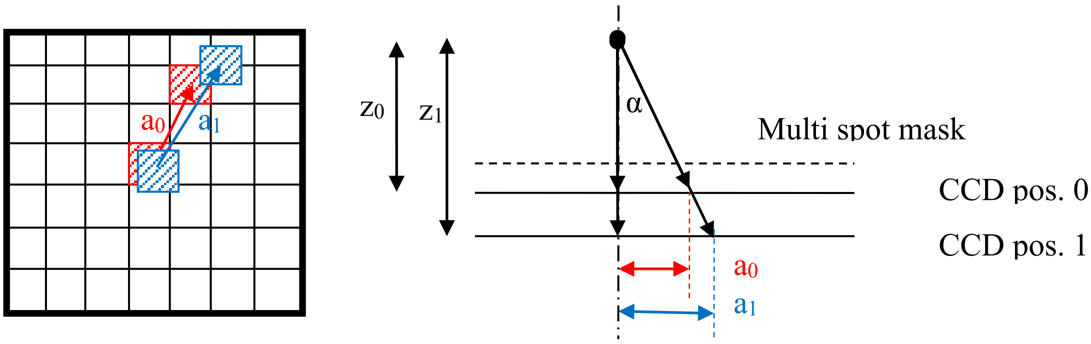

Figure 6. Centroid analysis (Spot pattern divided into 49 sub-windows and computed motion vectors)

Contrary to Figure 7, Figure 8 shows a measurement recorded under extremely stable conditions. This measurement was recorded over a period of about 2 hours and shows a stability better than 5nm PV.

Taking into account that this measurement happened with a CCD mosaic, the required 2nm RMS centroid stability for ESPRESSO is therefore in reach with all the additional selection and design measures taken on its improved set-up, as described in the next section.

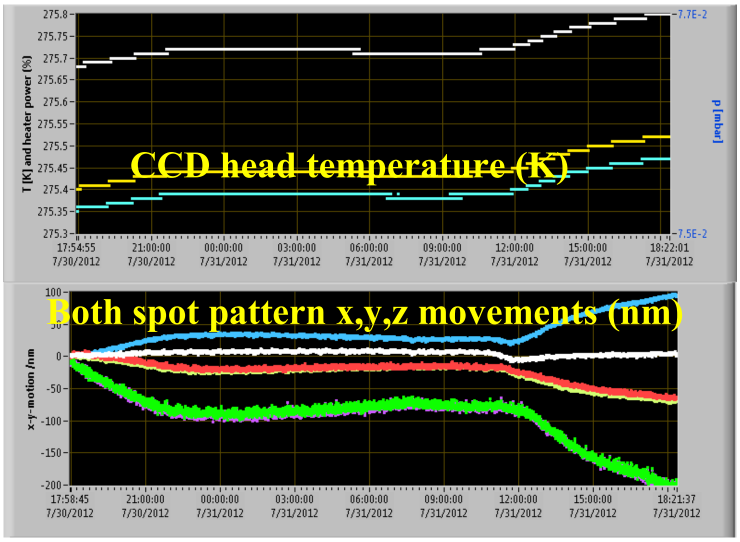

Figure 7. Centroiding stability, showing an obvious drift of the CCD detector positions, correlated with their temperature changes

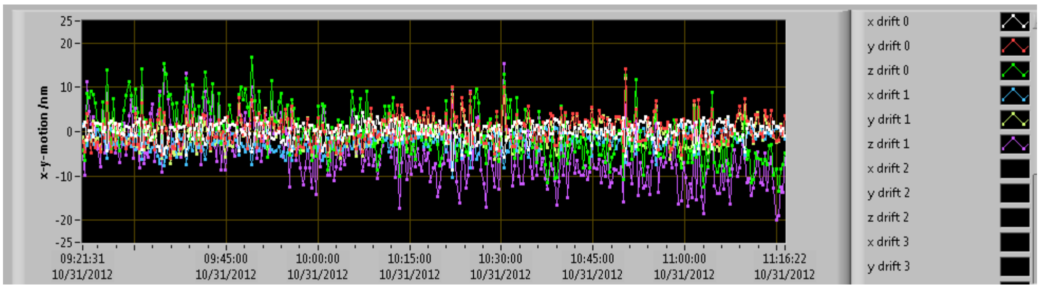

Figure 8. Very stable centroid measurements x, y, z of both detectors < 5nm peak to valley over time.

4. DESIGN OF THE ESPRESSO CRYOSTAT

4.1 Improvement of the cryostat head and cooling unit

The ESPRESSO cryostat (Figure 9) has been designed following the architecture of the HARPS cryostat with a number of substantial improvements. The first design change was not related to the performance, but was a re-location of the various electrical and vacuum ports towards the back of the cryostat module in order to simplify the installation of the Detector Dewar into and onto the instrument vacuum vessel. The new design allows an installation of the fully assembled, vacuum leak tested and evacuated detector cryostat onto the instrument vacuum vessel, whereas before it was necessary to split detector head and cooling system to first close the instrument vessel. On this operation also the delicate sealing operation of the detector cryostat internal LN2 tubes had to be done in-situ after the installation on the instrument vessel.

The following changes have been made on the ESPRESSO cryostat in order to improve its stability / accuracy performances:

- A small bubble has been implemented on the LN2 inlet. This device acts as a very primitive phase separator for nitrogen. On one hand it prevents liquid drops to reach the heat exchanger which would create some sudden temperature drops, and on the other hand the collected energy is used to efficiently cool the sorption pump.
- The LN2 main cooler has been improved, it is five times heavier in order to provide a larger thermal inertia and to be less sensitive during opening of the LN2 regulation valve (which controls the LN2 flow periodically). The heat exchanger is supported on the vessel via a thermal insulating structure and connected via the thermally

"weak" spring loaded connection towards the cold bench. This again in order to thermally decouple the critical detector stability from instability of the cooling system.

- The complete system is fitted with a three level temperature closed-loop control marked (1), (2) and (3) in Figure 9. Stage (1) controls the temperature of the LN2 heat exchanger (~ ± 0.1K) switching directly the nitrogen circulation flow. The subsequent stage (2) stabilizes the temperature of the cold bench (~ ± 0.01K), which supports the CCD chip interface carrier. This control is implemented by heating the bench and measuring its temperature with a Pt100 temperature sensor. Finally Stage (3) is the closest to the CCD chip it-self and aims to stabilize the temperature of the CCD chip extremely accurate (~ ± 0.001K). A temperature sensor is fitted directly to the CCD package for this control loop. Note that this accuracy is less straight forward than on an IR detector, simply due to the higher power consumption of the CCD, the non-continuous readout, and the sheer size of the detector being a multiple of an IR detector. The implementation of the thermal coupling of the CCD chip and other measures are described in more detail within the next sections. Zirconium Oxy-Nitride temperature sensors are used to measure the temperature accurately with high resolution around the operating temperature of about 153 K.

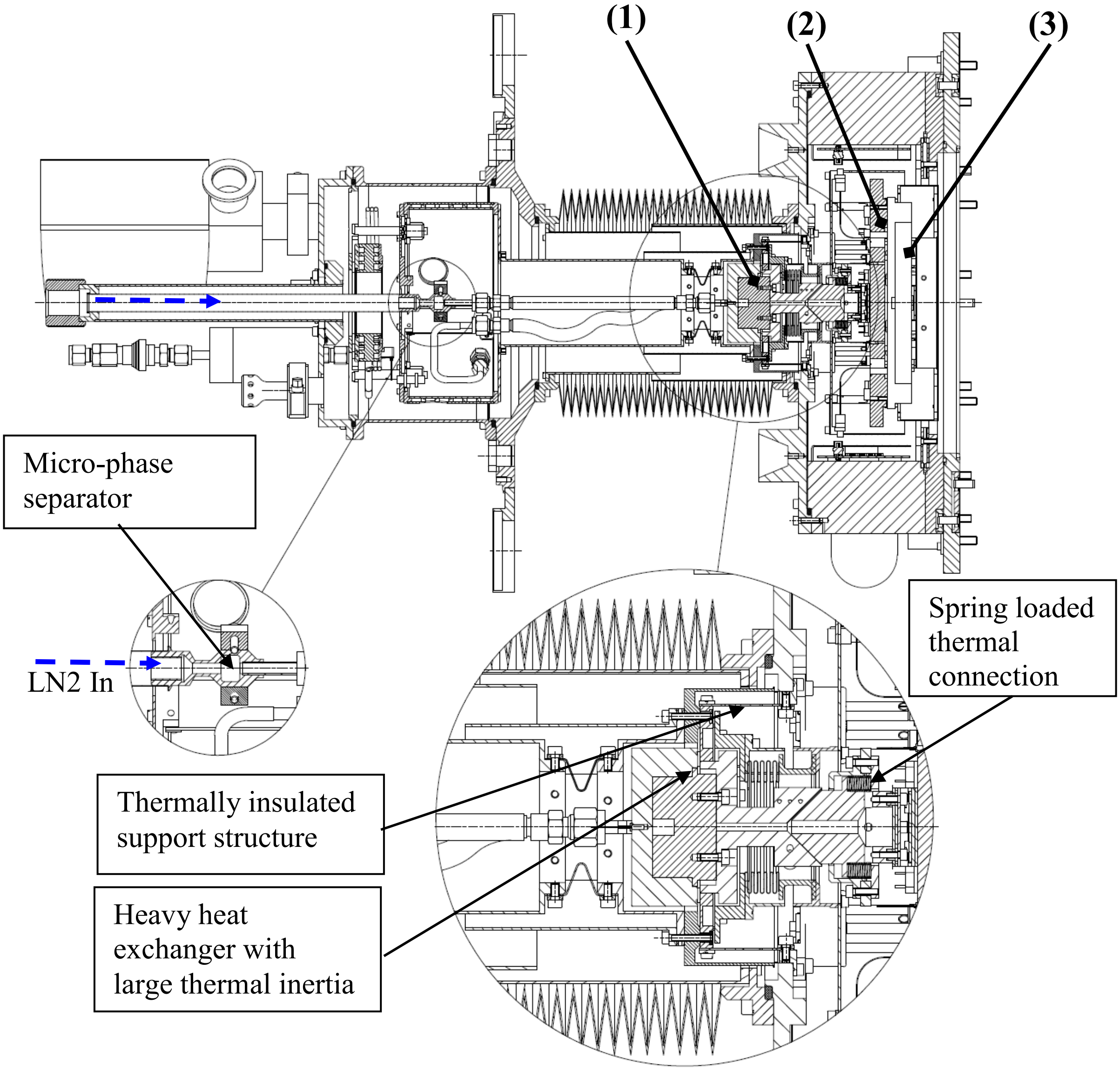

Figure 9. Improvements implemented in the ESPRESSO detector cryostat for even higher measurement accuracy

4.2 Selection of the detector chip, improved detector package

For ESPRESSO a detector format of about 90 x 90 mm^2 is required for each spectrograph channel. In order to overcome the limitations with a CCD mosaic (like in HARPS), where each CCD can move independently of the other due to the expansion of the mosaic plate, a monolithic CCD was requested for ESPRESSO. The search for those dealt with the largest CCDs available on earth, limited by the typical 6 inch wafer format of scientific CCD production.

The use of CMOS and hybrid detectors was examined due to their operational benefits with non-destructive readout and less power consumption, but they were simply not advanced far enough to satisfy the required combination of size, efficiency and stability and required binning.

A detector package material study to compare different materials was done in order to simulate via finite element analysis the physical deformation and the temperature distribution on the CCD chip itself, examining different cooling connections and different load cases in electrical operation.

Amongst others, Silicon Carbide was identified to be one of the best package material candidates, due to its excellent match of CTE to Silicon at the CCD operating temperature and its high thermal conductivity. This material however is brittle and threads may not be implemented directly inside this material. The precise location of all provisions inside the package may change slightly during its manufacturing, due to the sintering process of the Silicon Carbide material.

Long before the ESPRESSO detectors materialized, considerations to improve the CCD package of the smaller 4k x 4k MUSE detectors had already taken place at ESO, which resulted in several suggestions forwarded to CCD suppliers.

Amongst those were:

- improve the structural stiffness of the CCD package
- apply a solid material thickness below the CCD chip for improved thermal conductivity and homogeneity across large detectors
- find a way to internally cool large devices, not relying onto the threaded studs and spacers, typically made of invar, which are bad thermal conductors
- have a provision for a centering pin inside the CCD package / position this mechanism as accurately as possible
- center the CCD silicon die with respect to its central pin accurately inside its package

Following these points and competitive tendering, ESPRESSO is equipped with an e2v CCD 290 of 9k x 9k format with 10 µm pixelsize and 16 outputs. Both standard (blue) and high resistivity (red) version are used inside ESPRESSO.

The SiC CCD package design combines structural stiffening and optional additional cooling possibilities through its integrated ribs. It has enabled to interface the inner structure of the detector package with its four ribs to individual cooling connections (Figure 10 & 12). The central thread is used to mount a ball-shaped pin, interfacing to a bearing in the cryostat chip carrier (Figure 10 & 12), in order to allow symmetrical expansion around the centre.

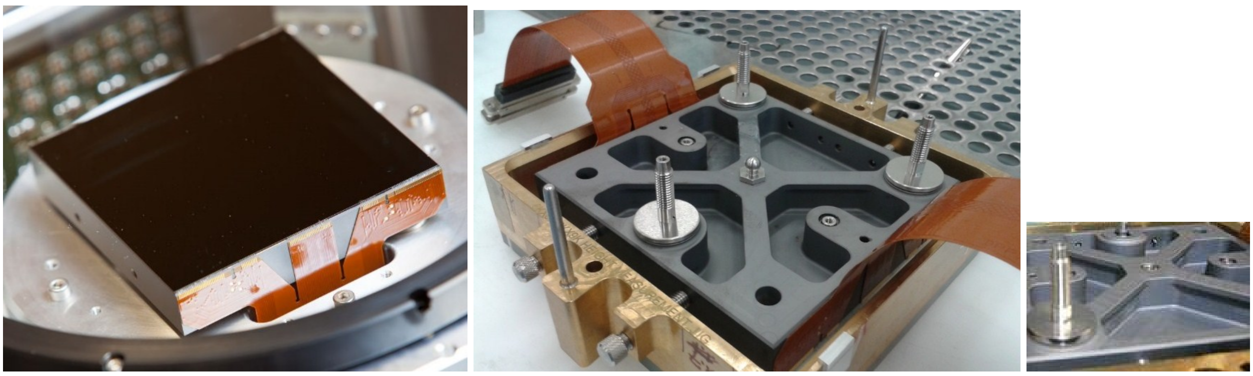

Figure 10. Top and Bottom view of the e2v 9k x 9k CCD package (left and middle), detail of ribs (right)

4.3 Electrical operation of the CCD

In order to optimize the stability behavior between different sets of exposures the clocking of the CCD needs to be optimized as well. Figure 11 shows the goal to have a more equalized power consumption during all phases of operation.

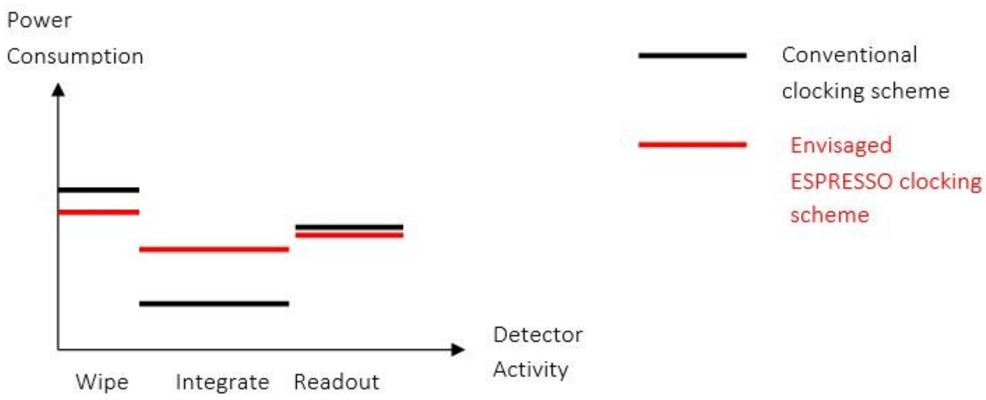

Figure 11. Conventional CCD clocking scheme versus envisaged ESPRESSO clocking scheme

The conventional readout scheme consists of the operations: Wipe - Integrate – Readout. In the wipe operation all parallel and serial registers need to be clocked continuously, typically at faster pace than during the readout. During the integration time, the serial registers are typically idle, whereas the parallel register is static with one or two phases integrating at high rail. The output amplifiers are typically powered on during all of these operations.
Consequently the power consumption of the device during these modes differs (see **Error! Reference source not found.**11, conventional clocking scheme) and the temperature control loop has to compensate for it. This situation is critical for ESPRESSO, as on the scale of the required accuracy, delays in the control loop will lead to slight temperature variation and herewith also to potential stability problems for positional accuracy. Whereas serial register and CCD outputs are distributed at top and bottom section of the device, the actual pixel grid which should have the maximum operational stability, is the parallel register.
The envisaged clocking scheme in ESPRESSO will therefore try to equalize this power consumption as best as possible by introducing dummy clocking during integration into serial and possibly parallel registers.
Readout modes and exposure times on ESPRESSO may change between fast and slow mode, but there is an idle time between three and eight minutes when changing the object and switching between fast and slow mode, in which dummy readouts are possible, which will be implemented.

4.4 Improved detector mount inside ESPRESSO detector head

Despite all improvements, the chip with its extraordinary large light sensitive surface (92 x 92 mm^2) is much more difficult and critical to interface and cool as the previous smaller generation detectors like in HARPS. Figure 12 shows details of the chip mounting inside the detector head.

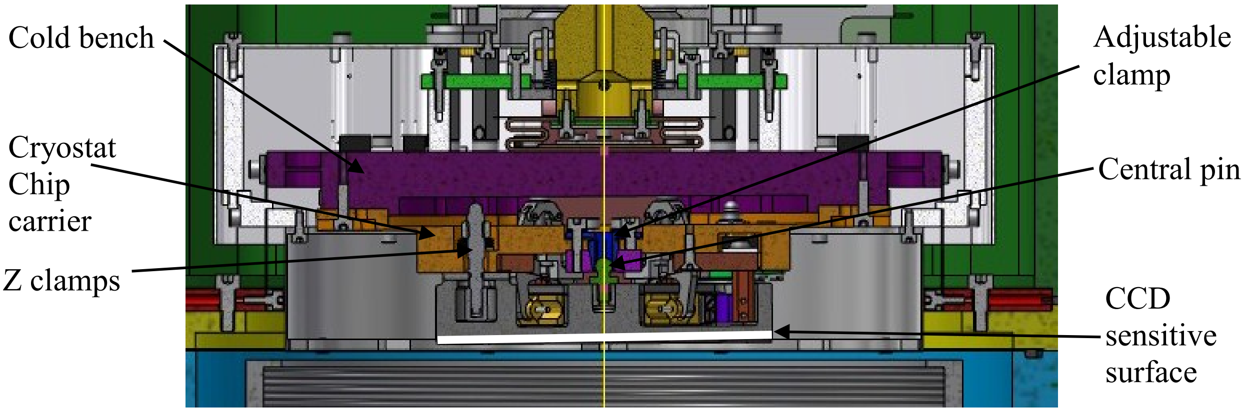

Figure 12. Cut view of the Detector Head (mounting of the CCD chip), CCD facing downwards

The x, y position is defined by an invar spherical pin (added to the CCD package by ESO) whose position is fixed relative to the cryostat chip carrier by means of an adjustable clamp. Along z (vertical in Figure 12) the CCD is elastically fixed (but pushed against the cryostat chip carrier as mechanical reference), using the three threaded fixation legs (with precision spacers to compensate for the tilt) provided by the CCD package.
The three fixation legs (Z clamps) are attached with a limited clamping force (~1x weight of the package per clamp) in order to allow for differential thermal expansion (in x and y) without inducing deformation of the sensitive surface of the CCD. This force is far too low to ensure an efficient heat sinking of the CCD. For this reason four thermal clamps (Figure 13 & 14) are added to provide a well distributed cooling across the large area chip.

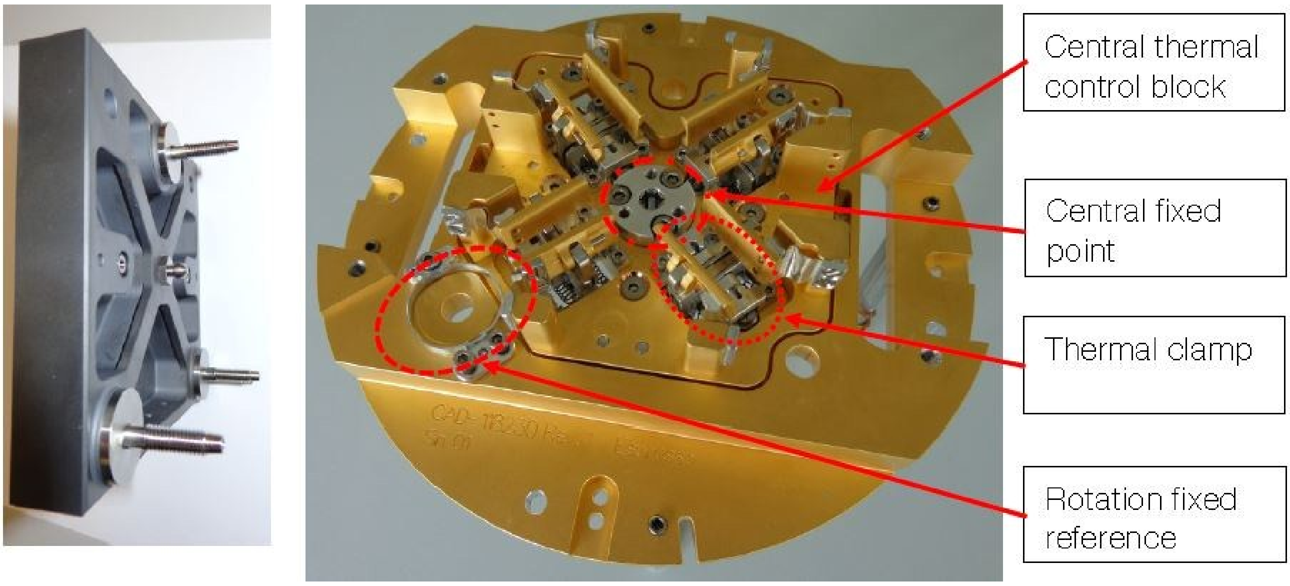

Figure 13. SiC CCD package with central pin inserted (left); Detail of the mounting of the CCD chip on the cryostat chip carrier (right)

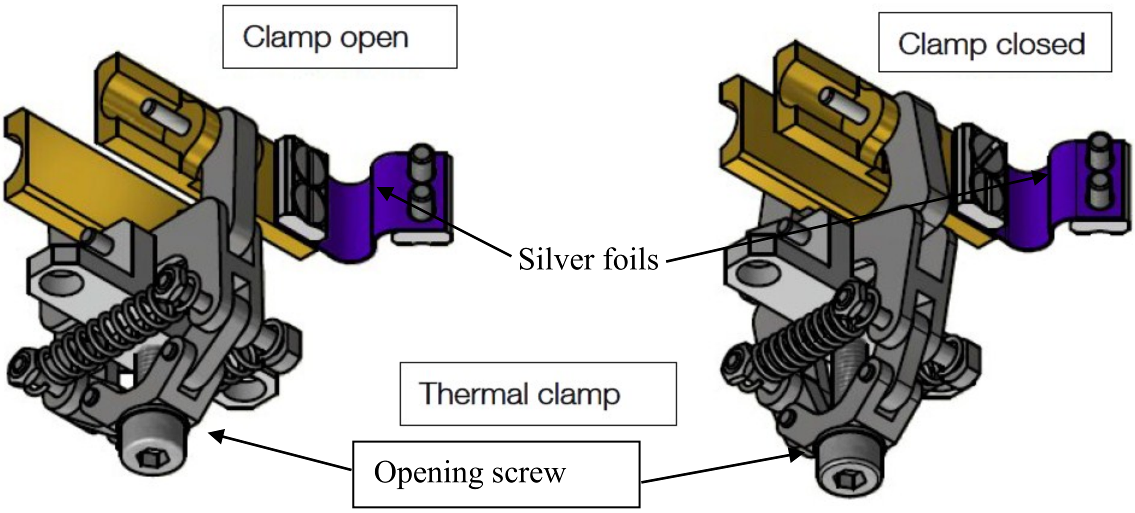

Figure 14. Thermal clamps opened and closed

The thermal clamps (Figure 14) are directly linking the radial ribs of the SiC package to the massive central thermal control block, made of copper. Silver foils are used in order to guarantee an optimal thermal conductance to the cryostat chip carrier. During installation of the CCD these clamps are fully opened by inserting the opening screw. The same applies to the adjustable central clamp as well as the rotation reference. The CCD is installed and attached to the cryostat chip carrier, using the three Z clamps. Their spring compression is defined using a torque limitation key. The other clamps are then closed by removing the opening screws. All clamping forces are pre-defined in order to unload the staff executing this delicate operation.

The measurements of the final temperature have shown a dependence of the thermal gradient between the cryostat chip carrier and the CCD package itself, depending on the clamping forces of the thermal clamps. The gradient can be reduced from 14 K to 8 K at 153K by increasing the clamping force from 10 N to 50 N. These clamps are directly squeezing the ribs and as they are fully floating relative to the rest of the mechanics, the clamping force can be increased considerably without any risk of deformation of the CCD sensitive surface. Here the structural stiffness improvement of the package works to our benefit.

5. PERFORMANCE EVALUATION OF THE ESPRESSO SYSTEM

5.1 Test set-up

A third ESPRESSO cryostat has been procured and fully prepared with a specific detector head including the extension to host the multi-spot projectors and the associated fiber feed through in close proximity to the CCD. Figure 15 shows the setup ready for the measurement. The system was equipped with three spot projectors and has been installed in the (ultra-stable) test vacuum vessel. The resulting images as read out by the CCD are shown in Figure 16.

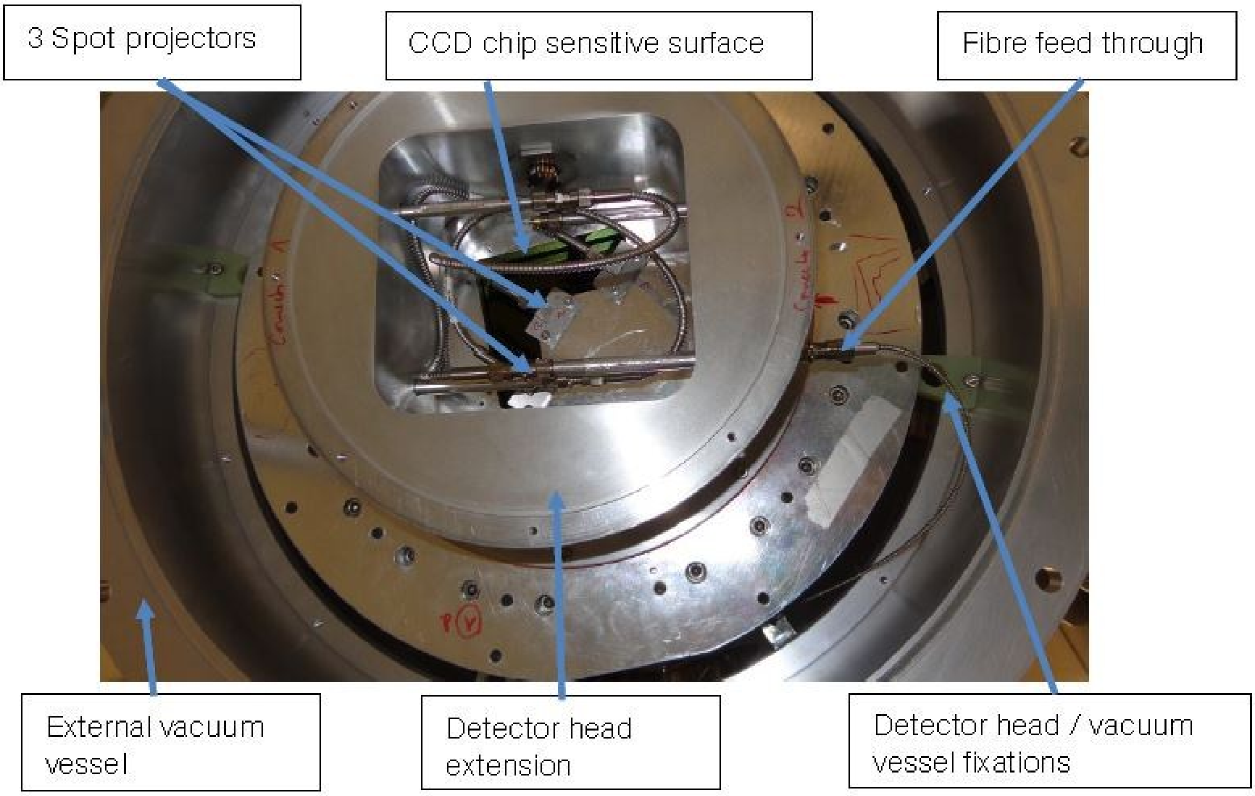

Figure 15. Multi-spot projector set up for the assessment of the stability of the ESPRESSO CCD and its improved cryostat inside the ultra-stable set-up

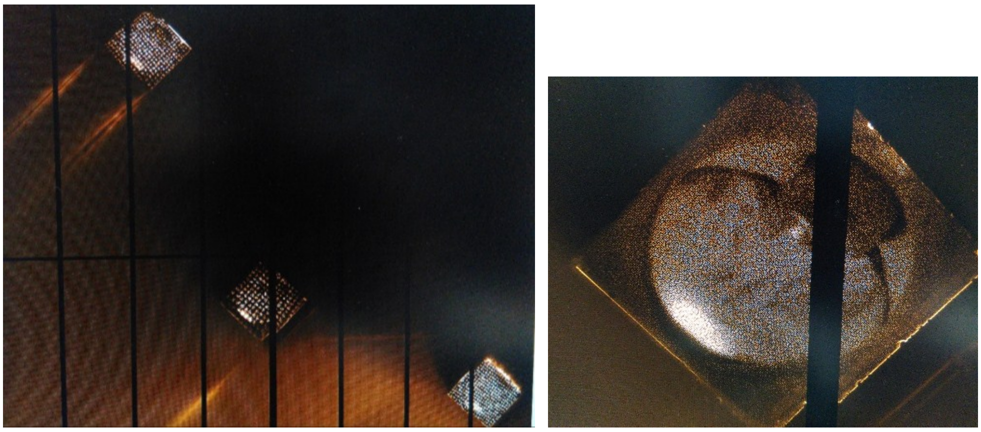

Figure 16. Readout image of all three multi-spot spot projectors on 9k x 9k ESPRESSO CCD (aliasing due to monitor and screenshot) (left), close-up of one projector image, overlapping two readout sections (right)

5.2 Results

At the time of writing this report the test system is ready to be put into operation inside its thermal enclosure, this means the first results should start to be available during the summer. This is slightly later than originally planned, but still in-line with the actual schedule of ESPRESSO. The set up will also be used in order to optimize the read-out and operation of the CCD it-self for equalized power consumption throughout different operation modes of the detector.
In the end the combination of all measures on CCD package, mechanical design for the improved mount, cryogenic considerations, three stage thermal control system optimization and CCD operational aspects will be the key to reach an even better performance than measured for the HARPS replica in the ultra-stable set-up.

6. INFRARED APPLICATION

Several projects of high-resolution spectrographs for precise radial velocity measurement are actually under development. Amongst them, CARMENES (the Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Echelle Spectrographs) has been designed by a Spanish/German consortium for the largest telescope of the Calar Alto observatory. As the name states, CARMENES consists of two arms, built into two separate vacuum vessels. The optical spectrograph is using a copy of the ESPRESSO cryostat which cools a 4k x 4k CCD, housed in an ESO MUSE detector head. This adaptation was considerably facilitated through the high level of standardization applied on the detector cryogenic systems at ESO.

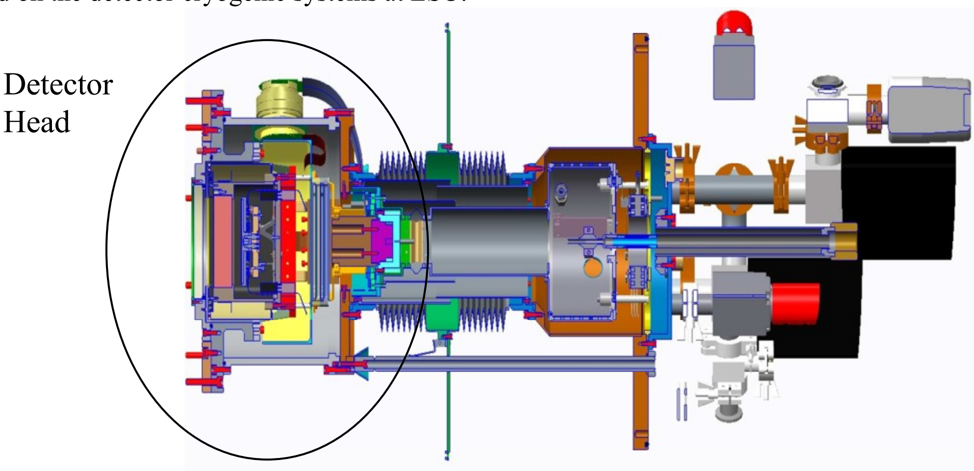

Figure 17. Cut-view of the Infrared version, developed for CARMENES NIR

More challenging was the use of a similar cryostat design to cool the mosaic of 2 HAWAII 2RG which record the InfraRed spectrum in the focal plane of the NIR spectrograph. A specific detector head directly interfaced to the vacuum flange of the cryostat has been used to host the mosaic. The heat sinking of the mosaic base plate is directly provided by the LN2 heat exchanger via a reasonably high conductance braid.

The thermal stabilization of the NIR detector is performed as usual by a small set of heaters on the mosaic base plate. These heaters are powered via a Lakeshore temperature controller, which measures the temperature with a Silicon diode attached to the same mosaic base plate. The latter allows a temperature stability of a few milliKelvin. As shown in Figure 18, small regular variations can be seen, which are caused by the on/off switching of the LN2 flow. Contrary to the ESPRESSO system described above, this cryostat has only two levels of temperature control: The LN2 heat exchanger and the detector mosaic base plate. Nevertheless this stability is largely compatible with the technical specification of the CARMENES instrument.

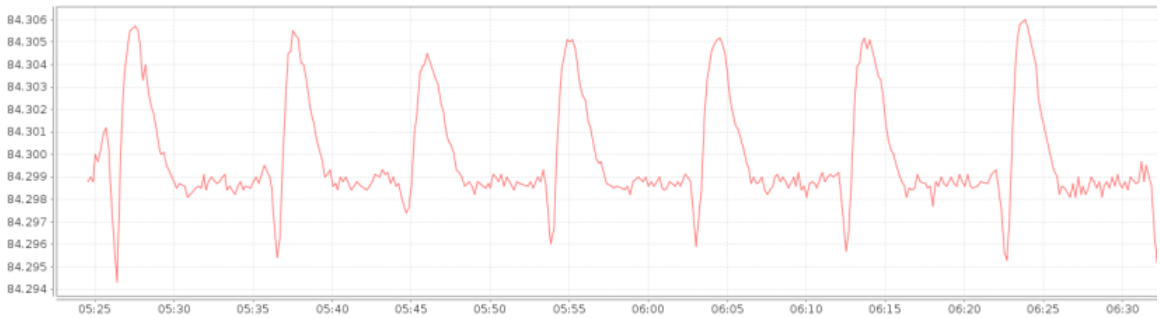

Figure 18. Detector stability recorded on the CARMENES NIR spectrograph

ACKNOWLEDGEMENTS

This project would have not been possible without the excellent collaboration with all levels of the very talented and innovative ESPRESSO consortium (https://obswww.unige.ch/wordpress/espresso/project/consortium/), which is largely based on many individuals having already initiated and built ESPRESSO's pre-cursor, the HARPS instrument.
The EU funding grant contributed to develop the ultra-stable test facility.
Our thank also goes to the technical and scientific staff on La Silla and within the HARPS scientific user community, who enabled us to analyze and process HARPS data in order to identify stability related shortcomings on very small level, but essential for the improvement in ESPRESSO.

REFERENCES

[1] http://www.eso.org/sci/facilities/develop/integration/
[2] Feautrier, P., "NAOS visible wavefront sensor," Proc. SPIE 4007, 396-407 (2000).
[3] Pasquini, L., Avilla, G., et al., "FLAMES: a multi-object fiber facility for the VLT" Proc. SPIE 4008, 129-140 (2000).
[4] Henault, F., Bacon, R., et al., "MUSE optomechanical design and performance," Proc. SPIE 5492, 909-920 (2004).
[5] Rupprecht, G., Pepe, F., Mayor, M., et al., "The exoplanet hunter HARPS: performance and first results," Proc. SPIE 5492, 148-159 (2004).
[6] Vitalli, F., Lizon, JL., et al., "The REMIR cryogenics restyling," Proc. SPIE 6269, 626-634 (2006).
[7] R. Bacon et al., 2010, "The second-generation VLT instrument MUSE**",** Proc. SPIE, 7735-7
[8] Lizon, J.L., Accardo, M., "LN2 continuous flow cryostats: a compact vibration free cooling system for single or multiple detector systems", Proc. SPIE, 7739, 7739E