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Document Title

LPNHE CCD Test Bench for LSST – *Description*

Change History Log

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1

Introduction

1.1 Purpose and scope of this document

The IN2P3 contribution to the LSST camera construction includes an in cash contribution to the project for the purchase of the LSST science sensor. Associated to this direct funding contribution, IN2P3 through the LPNHE laboratory is providing an “in kind” contribution in the form of a sensor testing facility and the associated manpower able to:

- perform the reception tests of a fraction or all if needed, of the LSST CCD production as a “sister lab” of BNL
- do detailed studies of the CCD + LSST electronic optimization , as part of French contribution to the science raft. As part of this activity the French group will be providing support to BNL on the usage/running of the LSST REB .
- perform specific studies of the CCD behavior beyond the reception test scope, with the goal to identify any CCD or readout behavior that will leave a signature in the science data that should be removed. Part of this work will go beyond the need of the camera construction and will be part of the preparation of the science analysis inside the Sensor Anomalies Working Group (SAWG) of the LSST Dark Energy Science Collaboration (DESC).

The main goal of this document is to describe the LSST sensor test facility at LPNHE and present its key performances. This presentation will underline the capability of the facility to fulfill the sensor reception testing of the LSST CCD production with a setup equivalent to the BNL Test Stand 3 (TS3) facility. Associated to this presentation background, this document will :

- list the considered plans associated to the sensor reception and testing at LPNHE within the overall LSST raft production
- identifies all the requirements documents used for the design of the LSST sensor test facility at LPNHE.
- focuses on the hardware of the LPNHE test facility associated to sensor testing, including safety and reliability. The plan to guaranty the availability of the facility will be presented. The aspects common to all sensor test facilities, like slow control system, data analysis or data base filling, will be mentioned only to precise interface issues with the LPNHE facility when needed. Specific environements, harware or controles capabilities going beyond the sensor testing (readout optimisation with LSST electronics, CCD characterisation beyond the reception tests) are also described in this document.
- underlines how the LPNHE reception test facility compares to the reference one at BNL for the same tasks, in particular TS1 (Test Stand 1 : Receiving and Inspection , see LCA-10049) and TS3 (Test Stand 3 : Sensor Electro-Optical Testing , see LCA-10051). It will also address the inter-calibration issue between all sensor test facilities (vendor, BNL and LPNHE)

1.2 Applicable Documents and Reference Documents

Table 1.1: The following documents are applicable and form a part of this design document:

| Ref # | Document Number and Title |
|-------|--|
| [1] | LCA-10103, <i>LSST CCD Electro-optical testing methods</i> |
| [2] | LCA-10140. <i>Specification for FITS Images from Electro-Optical Tests</i> |
| [3] | LCA-128. <i>Technical Specification: LSST Back-Illuminated n-channel CCD with Extended Red Response.</i> |
| [4] | LCA-10049 <i>Test Stand 1 design: Receiving and Inspection</i> |
| [5] | LCA-10051, <i>Test Stand 3 design: Sensor Electro-Optical Testing</i> |
| [6] | LCA-279-A, <i>LSST Camera Contamination Control Plan</i> |
| [7] | LCA-10032-A, <i>LSST Camera Electro-static Control Plan</i> |
| [8] | LCA-10102-B, <i>LSST Sensor Handling</i> |

Table 1.2: The following documents are cited for reference only, and do NOT form a part of this design document:

| Ref # | Document Number and Title |
|-------|---|
| [10] | <i>40 CCDs of the MegaCam wide-field camera: procurement, testing, and first laboratory results</i> P.Borgeaud et al. ,Proc. SPIE Vol. 4008, p. 356-367 http://irfu.cea.fr/Sap/Phys/Sap/Activites/Projets/Megacam/Presentations/megacam_spie2000_4008_48.pdf |

1.3 Acronyms and Definitions

1.3.1 Acronyms

Table 1.3: Acronyms

| Acronym | Definition |
|---------|--|
| CCD | Charge-Coupled Device |
| CCS | LSST Camera Control System |
| REB | Raft Electronics Board |
| BNL | Brookhaven National Laboratory |
| LPNHE | Laboratoire de Physique Nucleaire et des Hautes Energies |
| SLAC | SLAC National Accelerator Laboratory |

1.3.2 Definitions

Table 1.4: Definitions

| Term | Definition |
|-----------------|--|
| Packaged Device | A device that has completed the full assembly process including connector installation and package assembly. |
| Tested Device | A device that has been tested to meet the EO and mechanical requirements in the Technical Specification. |
| Science Device | A packaged and tested unit meeting all requirements in the Technical Specification. |

1.4 Specifications

1.4.1 Sensor reception test : work flow overview

The main purpose of the sensor testing in Paris are :

- Contribute to the sensor reception test as part of the IN2P3 “in kind” contribution to the LSST camera construction
- Make available to the project a CCD reception test facility on top of the BNL facility, able to backup on the CCD testing front the BNL facility if the need to reduce the load on BNL appears during the raft construction.

The considered baseline in this document for the LPNHE contribution to the sensor reception is:

- Step 1 : All sensors in a given batch (20-23 sensors) have been qualified by the vendor and are accepted for test as such by LSST.
- Step 2: For the first article and the following first batch, BNL will performs standard reception test on all sensors, prior to send a fraction (20%) of them for testing at LPNHE. This Step 2 will allow to fully qualify the reception test procedure by cross checking the results from the different sensor test facilities (Vendor, BNL and LPNHE).
- Step 3.1: 20% of a sensors batch are sent to LPNHE (4 sensors for a batch of 20)
- Step 3.2: the remaining sensors (80%) are sent to/kept at BNL
- Step 4: Sensor reception tests are performed on the sensors received at LPNHE (20% of a batch) to give a quick feedback on any drift in the e2v production quality. After tests (between 5 to 10 days for 4 sensors) the sensors are sent to BNL.

The sensors will be mounted on raft at BNL and then further tested. As backup, the IN2P3 manpower, and the LPNHE sensor facility at LPNHE, will be able to qualify full batch of sensors at the same rate than the one listed above (goal 1 week-day per sensor) .

1.4.2 Requirement for LPNHE sensor test facility

The LPNHE sensor test facility using the testing method described in LCA-10103, *LSST CCD Electro-optical testing methods* should measure the compliance of the LSST sensors to the requirements listed in LCA-128. *Technical Specification: LSST Back-Illuminated n-channel CCD with Extended Red Response*. On top of these requirements which are common to the two foreseen LSST sensor test facilities, the LSST facility at LPNHE should be able to :

- Receive, test and send to BNL at least 20% of the LSST sensor production.
- monitor the sensor production with a fast feedback to the project. This imply that the LPNHE test facility, will guaranty its availability during the full LSST production, with a goal of 2 days between the reception of a sensor and its expedition to BNL. For 4 sensors, corresponding to 20% of a batch, the goal will be to receive, test and send the sensors in 5 week days, with a requirement of 10 days .
- allow a useful feedback on the vendor production, in case of a detected problem on a sensor, the LPNHE sensor test facility will allow sensor characterization beyond the need of the sensor reception test itself. In particular it will allow precise spot/psf studies.

- go beyond the standard LSST sensor handling requirement (see LCA-279, LCA-10032 and LCA-10102 for ESD and cleanliness requirement) to further minimize the “human factor risk” with a design including the objective to facilitate/optimize the requested human intervention.

For this purpose, the LSST facility at LPNHE will include 3 main operations:

- The sensor reception at LPNHE (LPNHE Sensor Reception: LSR) will be equivalent to the BNL TS1 (see LCA-10048)
- The sensor qualification test at LPNHE (LPNHE Sensor Qualification : LSQ) will be equivalent to the BNL TS3 (see LCA-10051) .
- The re-packaging and sensor expedition to BNL (LPNHE Sensor Expedition: LSE) will follow in practice steps close to TS1.

All these steps LSR, LSQ and LSE, and associated setup will be described in this document.

Requirements related to key components for sensor testing at LPNHE are listed in the next subsections

Controller / sensor readout

The current LSST baseline for the sensor test readout is to use a Archon controller (see LCA-10051). Using a commercial controller, in particular for the first article, will guarantee its availability, independently of the status of the LSST raft electronic development. Still on the long term, following the DEScam sensor test production, LSST has an interest to use its final controller for the production sensor test. Such system, hopefully equivalent for sensor acceptance test point of view to the Archon controller, will have at least two interests:

- As the sensors behavior cannot be fully disentangled of the readout system used, in particular on noise and Xtalk, using the final readout system will provide information on CCD easier to extrapolate to the final LSST environment, information useful to debug the raft as they are run for the first time.
- During the LSST camera construction, the LPNHE team will contribute to the sensor readout hardware and software. For this reason this team will also provide support to BNL (and to SLAC and summit at a later stage) on the raft electronic, including ASICs , FPGA micro-code, LSST electronic&ccd interaction, and CCD & ASICs diagnostic using LSST electronic. To use and develop the LPNHE team expertise by doing the sensor qualification test with a LSST REB, will optimize LSST manpower usage and improve the support and knowledge on the LSST electronic.

So if using the REB for the sensor qualification could be a goal on the long term, it cannot be granted at this stage of the project. that the REB will be fully qualified/operational for the sensor reception, in particular for the first article. For this reason we will develop a cryostat able to interface to the Archon controller and to the REB outside/inside the cryostat. This will allow the cryostat to be compatible with the reception test baseline , and keep the door open for using LSST electronic for sensor qualification at LPNHE.

The compatibility of the LPNHE setup with the LSST readout electronic is requested anyway, as we should be able to perform in this facility CCD/LSST electronic optimisation/development. Notice that due to its noise level and the large fan system included in it, the LSST acquisition system associated to the LSST CCD readout electronic should be located outside the clean room.

Cryostat & optical bench configuration

At LPNHE for cost , space and flexibility reason, we will implement a single optical bench to perform all testing requesting light. Still to guaranty the needed testing capacity, two fully equipped cryostats will be used on the test bench:

- This will allow to have a full backup in case of cryostat failure
- The setup should be also able to run with both cryostats to speed up the test and reach the goal of testing 4 CCD in 5 week days or less: filling one cryostat with a CCD or performing metrology without light (Dark, Bias) , as the other cryostat is on the optical bench for sensor testing with light .
- The LPNHE cryostats and setup will accept all the controllers listed in the previous sub-section: LSST-REB/WREB, SAO and Archon/Reflex.
- Use cryo-generator instead of liquid nitrogen for the cold generation: easier to handle and provide a stable source of cooling. The cryo-generators to reduce the noise and avoid possible cleanliness issue, should be located outside the clean room controlled area.
- Use a cryostat with a door / single screw to simplify the cryostat opening/closing

1.5 Optical Test bench overview

The main elements of LPNHE testbench for the LSST sensors are described on fig. 1.1. This testbench will be used for all sensors related work done at LPNHE : sensors reception test, sensor detailed studies, readout optimisation with LSST electronic. The hardware on this testbench, the clean rooms facility where it is located , and the overall performances of the system will be presented in the rest of this document.

As this bench will be used in several different setups (flat illumination, spots, fringes, etc.), and for many different tasks, its control system needs to be modular and very flexible. It will be running by default under a control system developed at LPNHE able to run all its hardware and compatible to all its tasks. This control system is described in this document. For the sensor reception test, for which CCS is the baseline, and for the contribution to the developement/optimisation/qualification of the CCD control software, part of the testbench should also be able to run under the CCS.

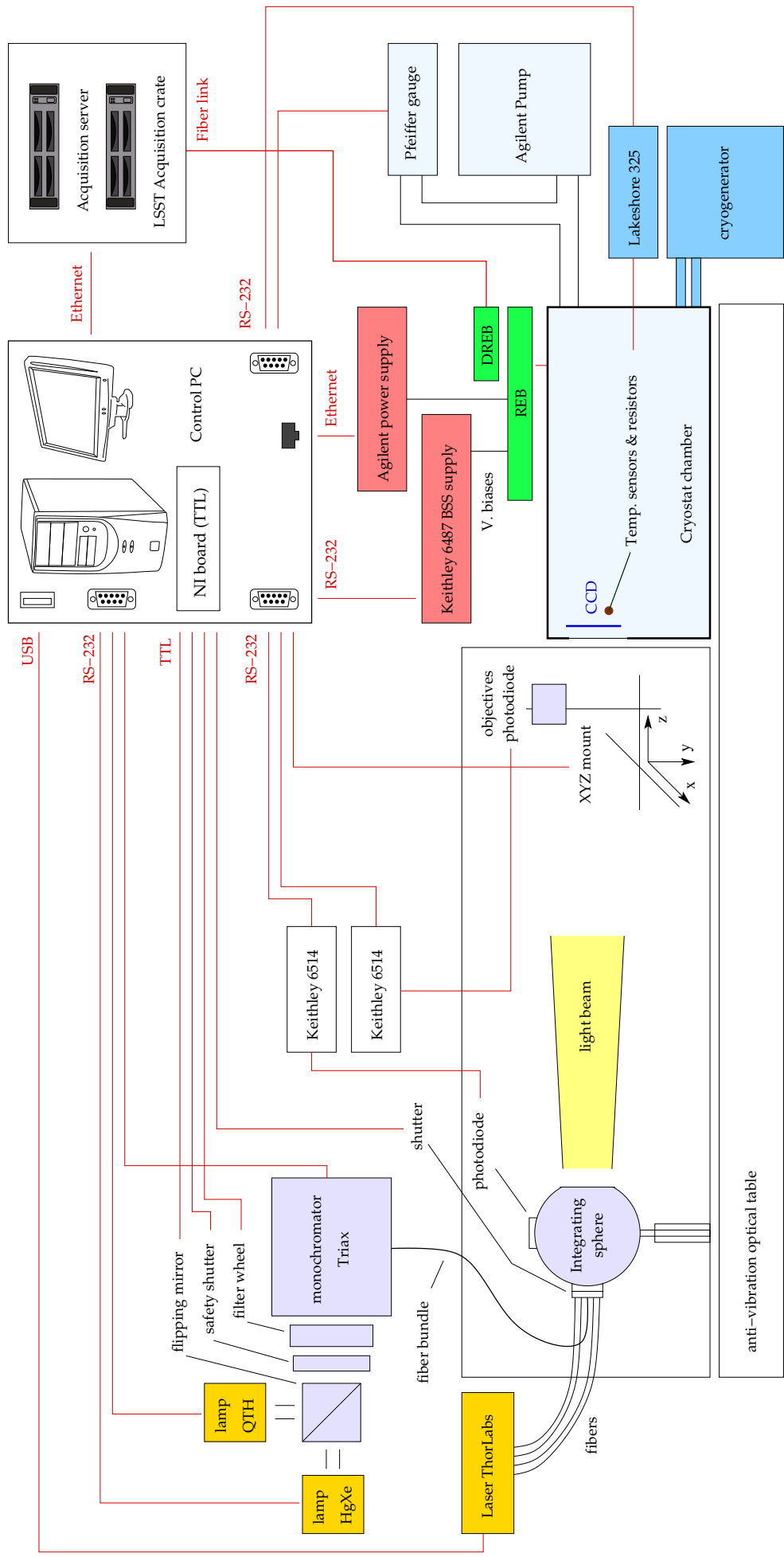


Figure 1.1: Block diagram of the LPNHE testbench for the LSST sensors.

2

Mechanical setup

2.1 Clean Rooms

All the needed operations for the LSST CCD tests are done in two adjacent clean rooms in the basement of the LPNHE, in Paris. The first clean room is a class 10000/ISO-7 room and hosts the optical table, the dark box above it, the light sources, the optical elements, and all the associated instruments (power supply, control electronics, the main test bench computer, etc.).

The second clean room (class 1000/ISO-6) is smaller and adjacent to the first one. This room is dedicated to operations requesting a cleaner environment. All the manipulations inside the cryostat, especially the loading/unloading of a CCD device in a cryostat chamber are done there, under a dedicated class 100/ISO-5 extraction hood (See fig. 2.3).

A special opening (the “guillotine”, see fig. 2.1) between the two rooms allows to place the front door of one cryostat through the wall: the front door may be opened into the ISO-6 clean room directly under the ISO-5 hood, to load and unload CCD in the cryostat without the need to move the cryostat chamber from one room to the other. This opening through the wall is sealed when not used, to avoid any contamination.



Figure 2.1: The “guillotine” door connecting to the class 10000/ISO-6 room for CCD loading/unloading. Left: seen from the testbench room. Right: seen from the class 10000/ISO-6 room.

The clean rooms are cleaned twice a week to be stay under the cleanness requirements. Dust contamination measurements are performed regularly (See table 2.1 below).

| Room | Dust particle counting (average) | |
|---------------------------|----------------------------------|---------------------------|
| | $\geq 0.5 \mu\text{m}$ | $\geq 5 \mu\text{m}$ |
| Test bench room (ISO-7) | $8533 \pm 5014 /\text{m}^3$ | $200 \pm 298 /\text{m}^3$ |
| CCD transfer room (ISO-6) | $0 /\text{m}^3$ | $0 /\text{m}^3$ |
| Class 100/ISO-5 limit | $352 /\text{m}^3$ | $29 /\text{m}^3$ |
| Class 1000/ISO-6 limit | $3\,520 /\text{m}^3$ | $293 /\text{m}^3$ |
| Class 10000/ISO-7 limit | $35\,200 /\text{m}^3$ | $2\,930 /\text{m}^3$ |
| Class 100000/ISO-8 limit | $352\,000 /\text{m}^3$ | $29\,300 /\text{m}^3$ |

Table 2.1: Dust counting done on 2014-06-24 in the LPNHE clean rooms. Average of 15 measurements done in each room.

2.2 Mechanical structure

The two cryostats, and all the instruments of the test bench sit on a dedicated home made structure from ELCOM elements (see fig. 2.3).).

The cryostats are mounted on rails in order to move on the structure. They can be switched between two positions by using the rails and a rotating platform as shown on fig. 2.2 and fig. 2.3.

When one cryostat is being used for measurements with its front window coupled to the dark box entrance on the optical table, the other one can be brought through the wall so it can be opened and the next CCD to be tested can be loaded inside.

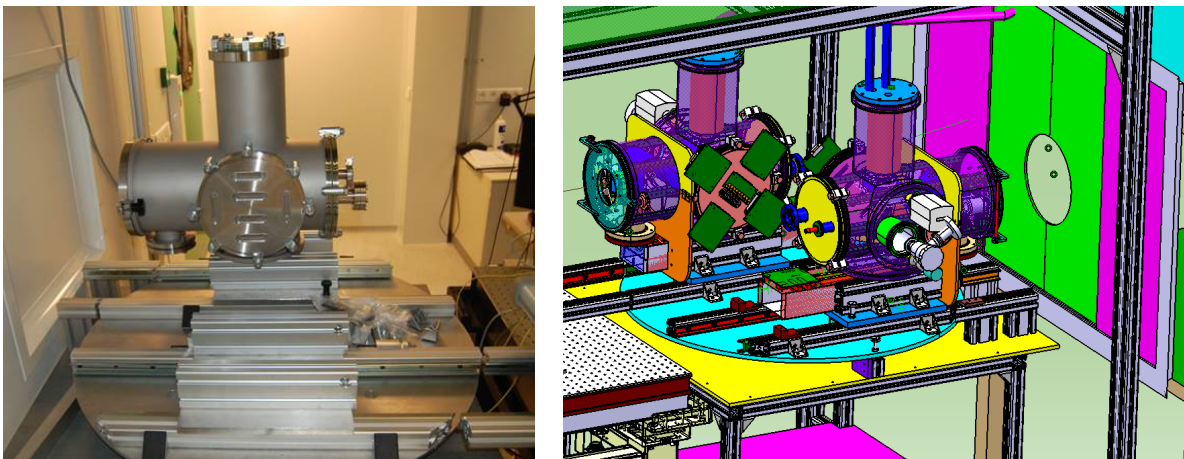


Figure 2.2: Left: picture of one cryostat on the rotating platform. Right: CAD view of the two cryostats on the rotating platform

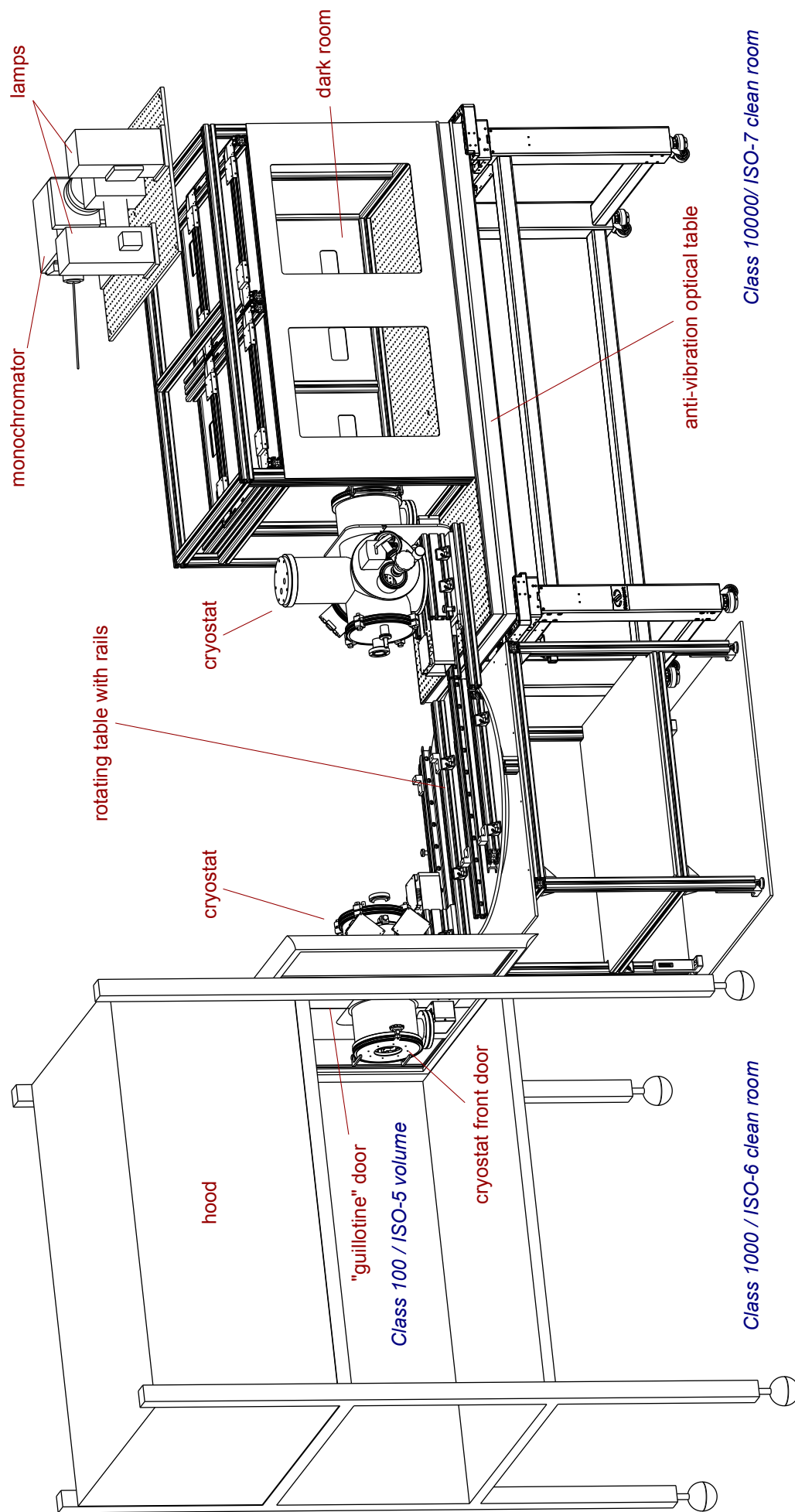


Figure 2.3: The LSST sensor test bench in the two clean rooms. The separation wall and the instruments are not shown.

2.3 Optics mountings

Two optical tables are used. A small one is set on the top of the ELCOM structure and hosts the lamps, the monochromator and the associated filters (see fig. 5.5 in chapter 5.2.1). The main optical table is inside a dark box and host the main optical setup providing light to the CCD for the various tests.

The rails for the cryostat in CCD-test position and the dark box are both set onto an anti-vibration table. This allows to have the whole optical setup floating on air cushions. This way, the optical setup (including the cryostat and the CDD) is mechanically decoupled from the rest of the setup except for the contact of the cryostat with the pump, which can be disconnected. The university compressed air network is providing the necessary flow to maintain the air cushions active.

The dark box sits on a large optical table, regularly padded (every 25 mm) with holes into which one can screw optical elements. More details about the optical elements used are given in 5.1.

2.4 Dark box

The dark box is an home made light-tight black plastic box with two doors for an easy access to the optical setup. It has a few feed-through for various cables and a hole coupled with the cryostat window. The 1×1×2 m dark box and the space for the optical instruments is visible on the right of fig. 2.4.

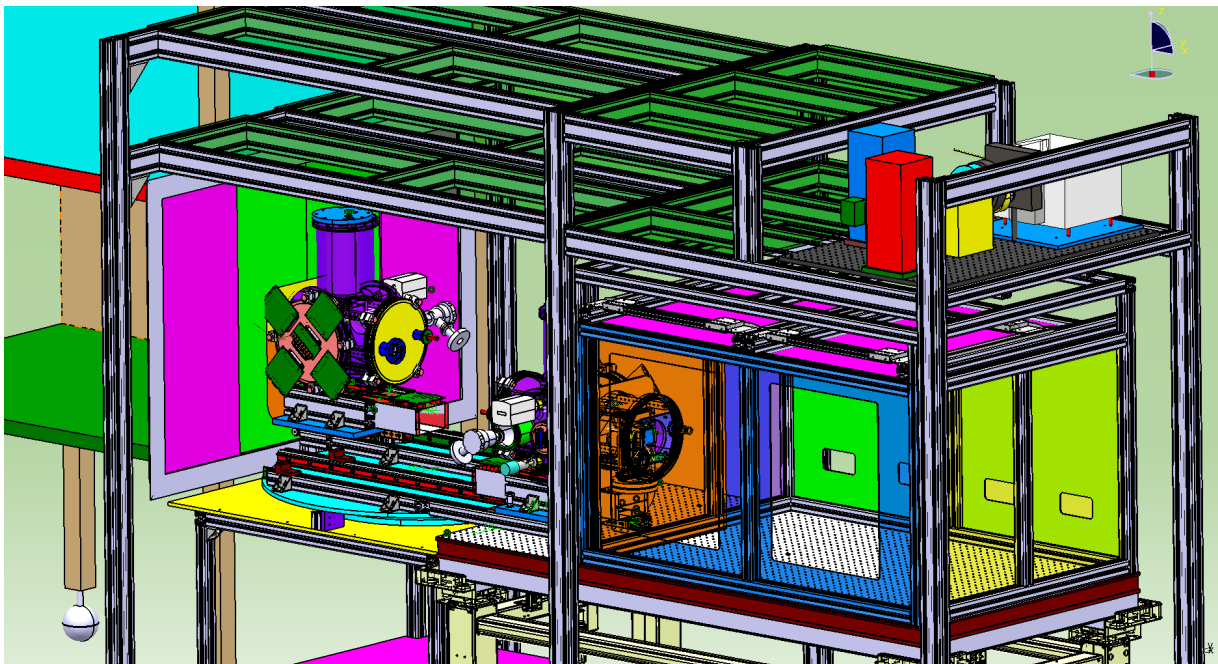


Figure 2.4: CAD view of the test bench, with the dark box sitting on the main anti-vibration optical table. The small optical table with the lamps sits on the ELCOM structure, visible on the top right of the drawing.

3

Vacuum system

3.1 Cryostat chamber

The cryostat used are two identical models custom-made by Neyco. Their specification are ...

Each cryostat is equipped with several ports to allow for all the necessary signal to travel in and out from the device under test to the control and acquisition system (see fig. 3.1).

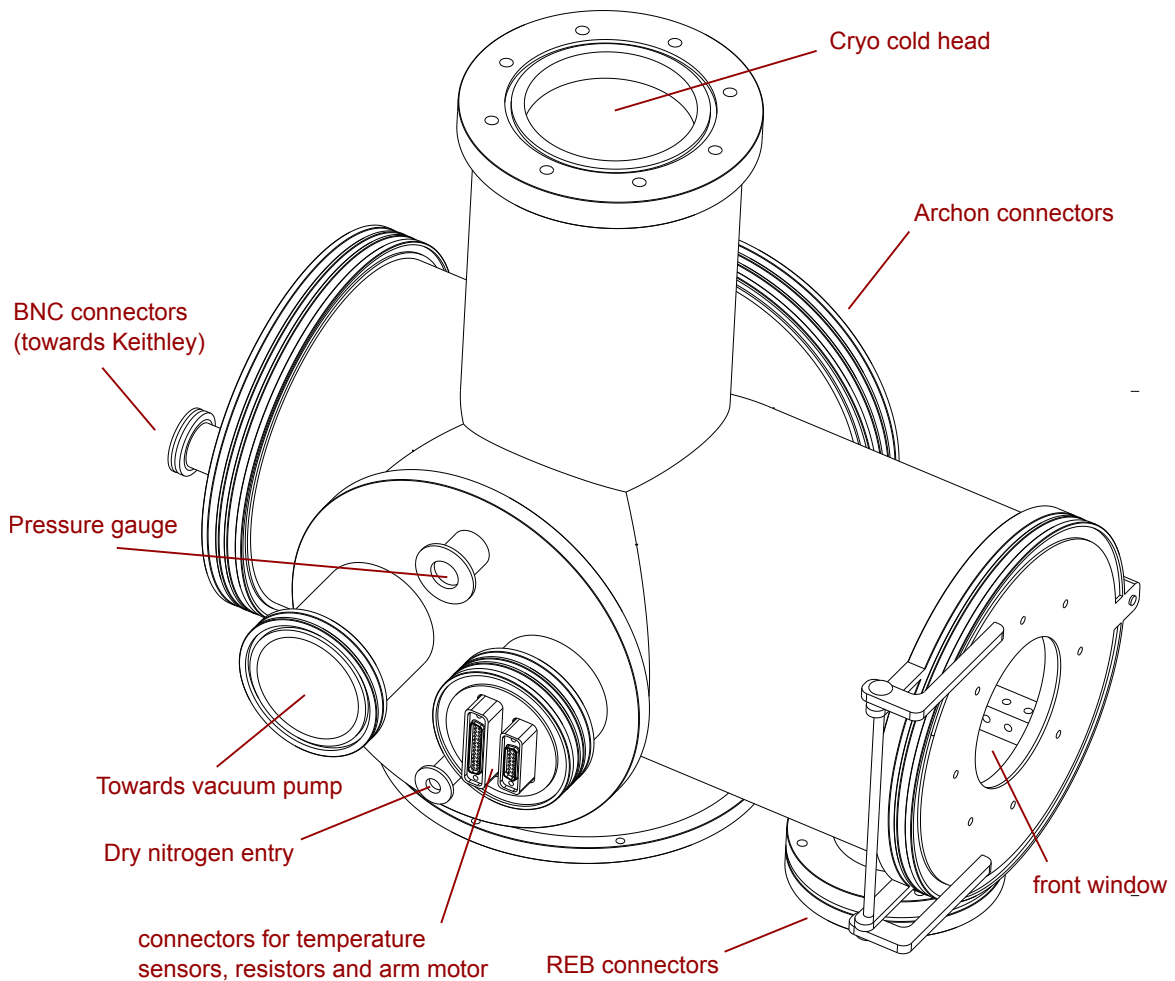


Figure 3.1: CAD isometric view of the cryostat chamber

Each cryostat also has a compressed air controlled valve on the pipe connecting it to the pump. This valve is used to isolate the cryostat from the pump before disconnecting it for a vibration sensitive measurement or in order to maintain the vacuum in the cryostat in case of failure of the pump.

3.2 Pumps and pressure gauges

The vacuum pumps used are two TPS Turbo Pump Systems (model 969-8228) from Agilent Technologies. They are remotely controlled and include a pressure gauge located in the outgoing pipe.

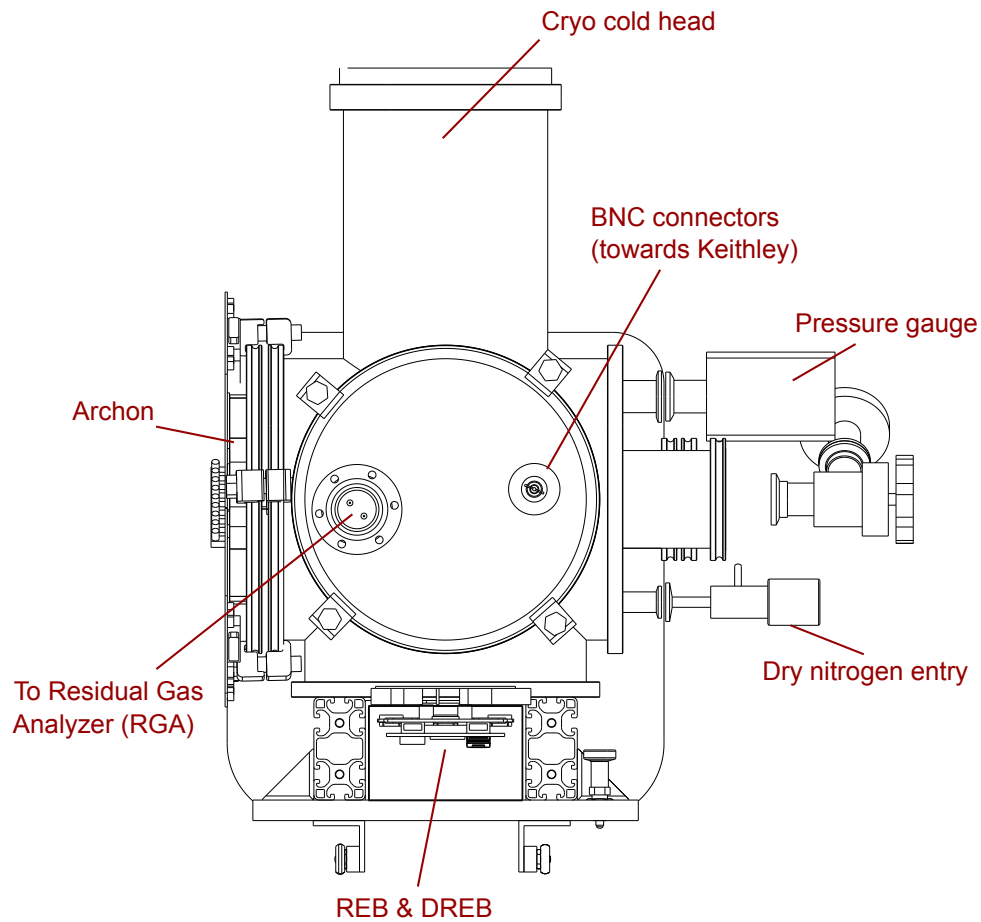


Figure 3.2: Back view of the cryostat chamber

They are located on each side of the rotating platform and must be disconnected and reconnected to the cryostat at each switch or for vibration sensitive measures.

The cryostat pressure is also monitored with a pressure gauge (Pfeiffer PKR251). This permanent monitoring allows an external electronic device to disable the cooling in case of a vacuum leak.

Pumping from the atmospheric pressure to 10^{-5} mbar takes approximately 24 hours (see fig 3.3).

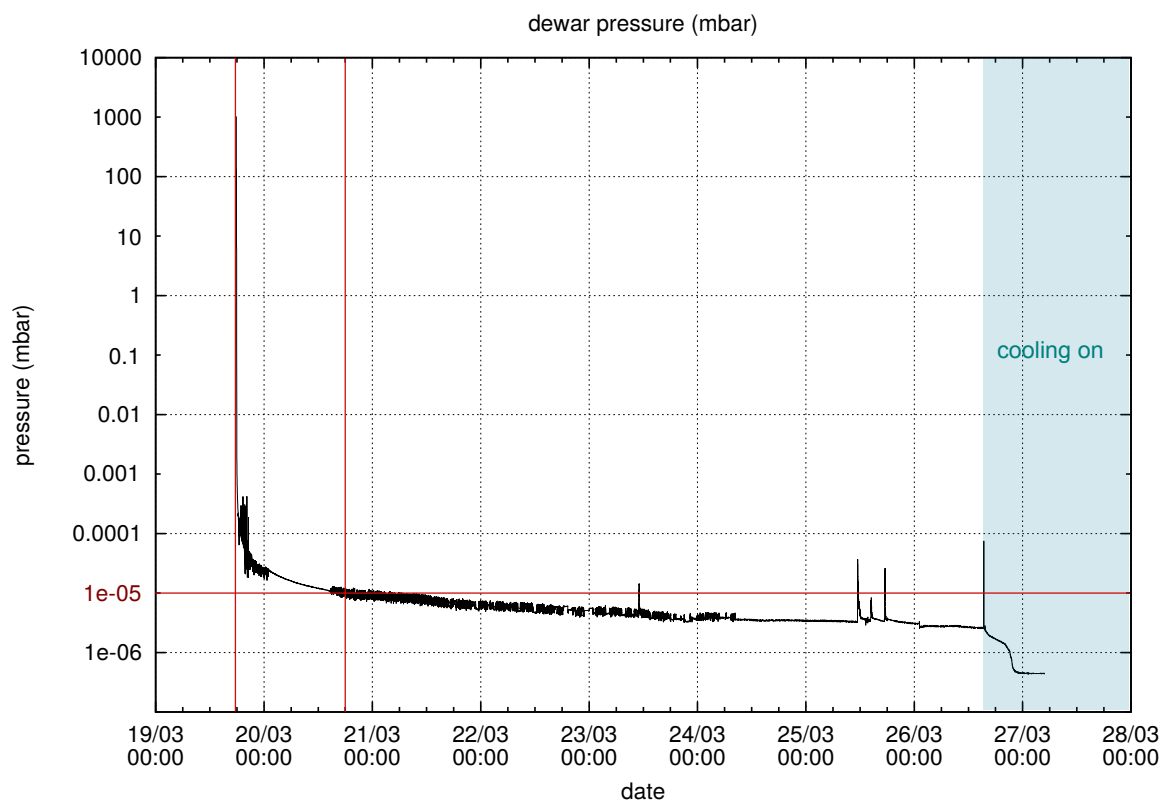


Figure 3.3: Pressure measurement inside the cryostat chamber while it is being pumped down to vacuum and then cooled down

3.3 X-Ray arm

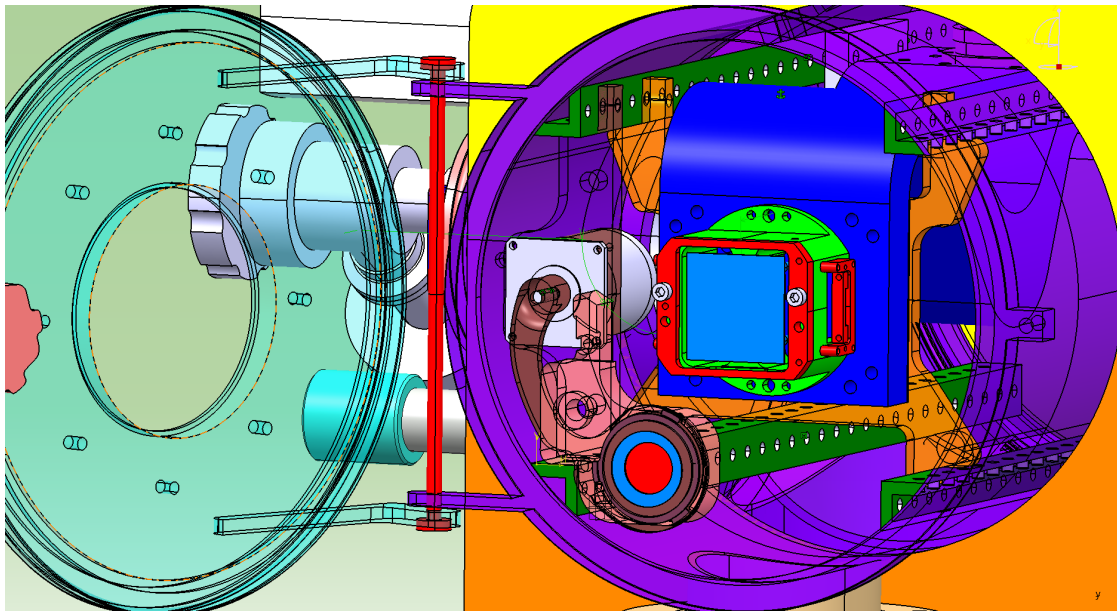


Figure 3.4: CAD view of the cryostat: focal plane details with door open

Some tests require the use of an X-ray source (^{55}Fe) figured as a red disc with blue ring support on the drawing of fig 3.4. In order to bring it in front of the CCD device, the source is mounted on an aluminium arm (brown on the drawing). The arm is moved via a step motor (light grey on the drawing) model VSS 42 from Phytron, high vacuum (HV) qualified and remotely controlled.

4

Thermal system

4.1 Cooling

Each cryostat chamber has its own cryogenerator: the cryogenerators used are two identical Orca(TM) models from Advanced Research Systems, Cryogeny (arscryo.com), with a mixed refrigerant Joule Thompson cooler. The fluid selected for our application is the MR-125, which is rated for above 125 K, and has a peak refrigeration capacity of 30 W at 160 K.

In order to avoid unnecessary noise in the test room, the two cryogenerators are deported outside of the room, the cold fluid being brought to the the cryostats via long flexible pipes (superflex hose, 50 ft, 1/2 inch) passing through air-tight wall feed-through.

The flexibles are connected to the cooling head at the top of the cryostat. They are long enough to be kept connected while switching the cryostat from one position to the other, and their position prevents them from getting caught during the cryostat movements.

4.2 Cold finger/cold plate

The cold connection from the head of the cryocooler to the CCD is a 2 cm thick, 12 cm wide and 30 cm long copper cold finger, made of stacked layers for flexibility. There is an indium foil between the copper and the cooling head at the top of the cryostat (copper mass is in dark blue on drawings of figure 3.4 and wave-shaped on fig 4.1). The CDD itself (bright blue on the drawing) is mounted on a metallic jig (bright green with red parts), which is mounted on the front of the copper plate.

4.3 Temperature control & monitoring

For each cryostat, the temperature is monitored via two temperature sensors (PT1000), one at the front and one at the back of the copper thermal conductor. The sensors are read via a Lakeshore temperature control unit (Lakeshore 325). Heating is done by two heating resistors (HTR-50 from Lakeshore, 50 Ω and 50 W heating power each) in aluminium casings screwed behind the copper conductor at the level of the CCD support.

Using the sensor and the heating resistor, the temperature is regulated using a PID feedback loop with a target and parameters that are remotely adjustable.

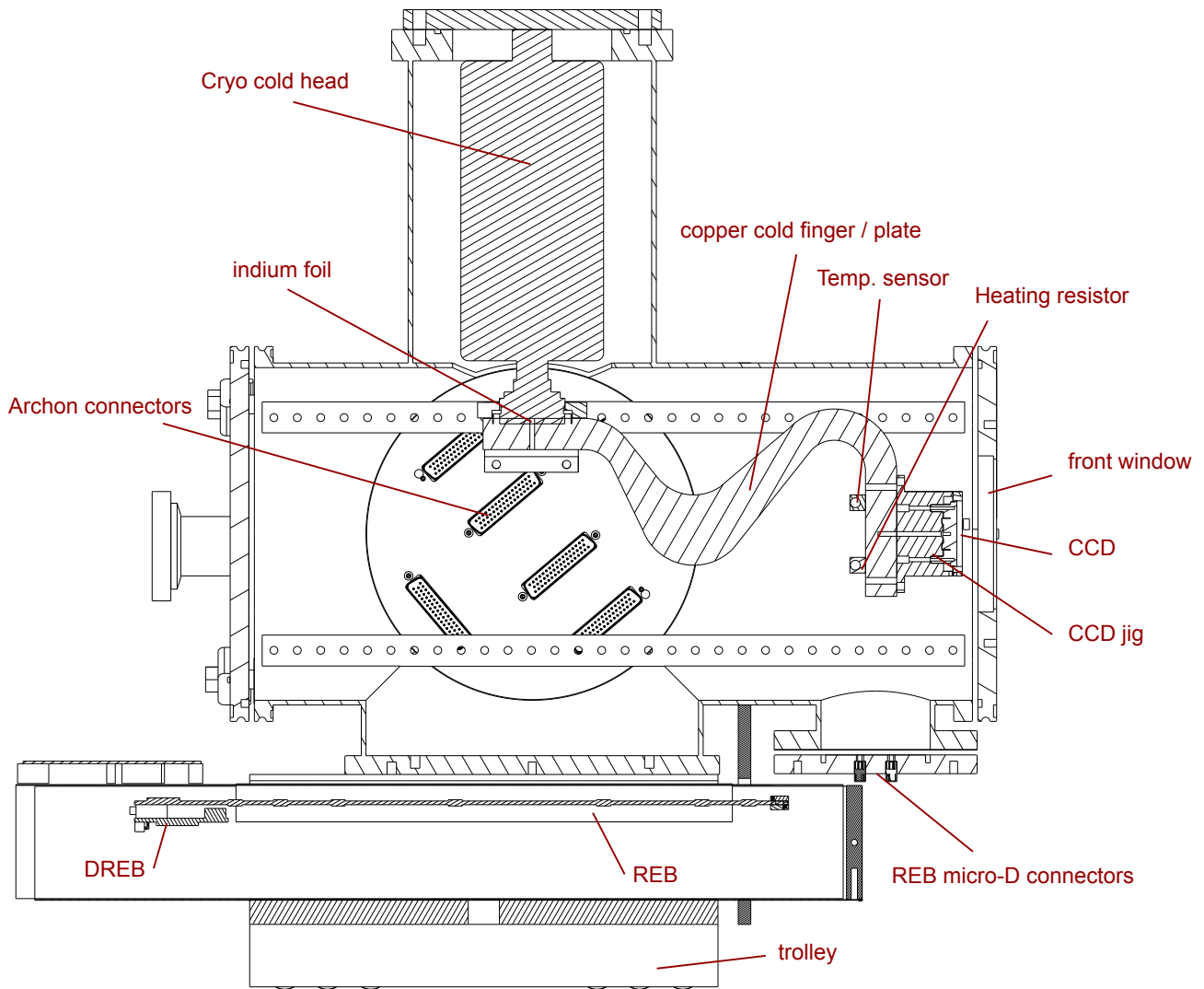


Figure 4.1: Cryostat chamber (cut)

4.4 Performances

The free-run cooling performance of the system is depicted on figure 4.2, it takes about 6 hours to cool to -100°C . The minimum temperature in the front side is around -142°C . The natural reheating is depicted on figure 4.3, the controlled temperature in the front side is -122°C , in these conditions we need around 40% of the controller's heating available power (25 W).

The stability of the front side temperature over 36 hours is shown on figure 4.4.

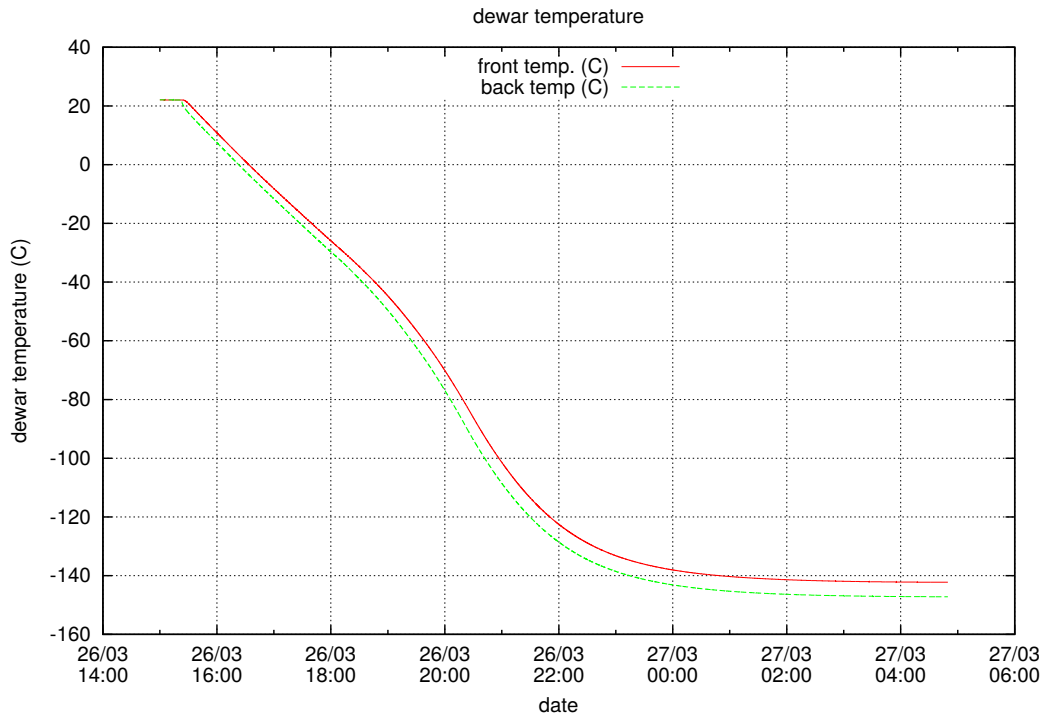


Figure 4.2: Cooling performance of the system.

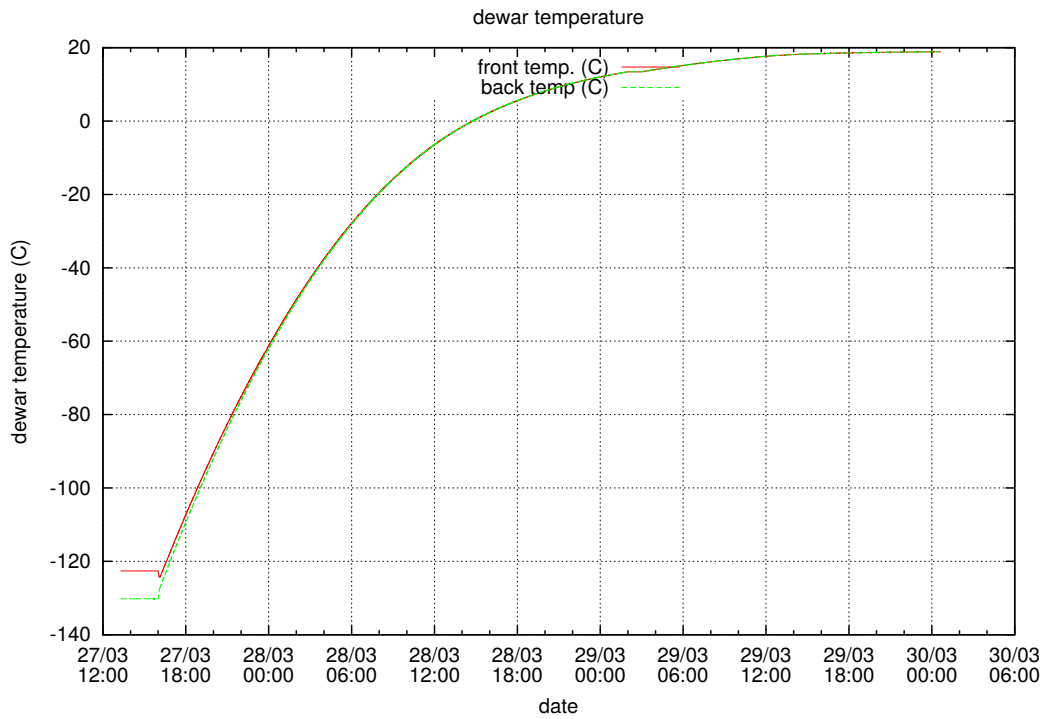


Figure 4.3: Natural reheating after the cooling system was shot down.

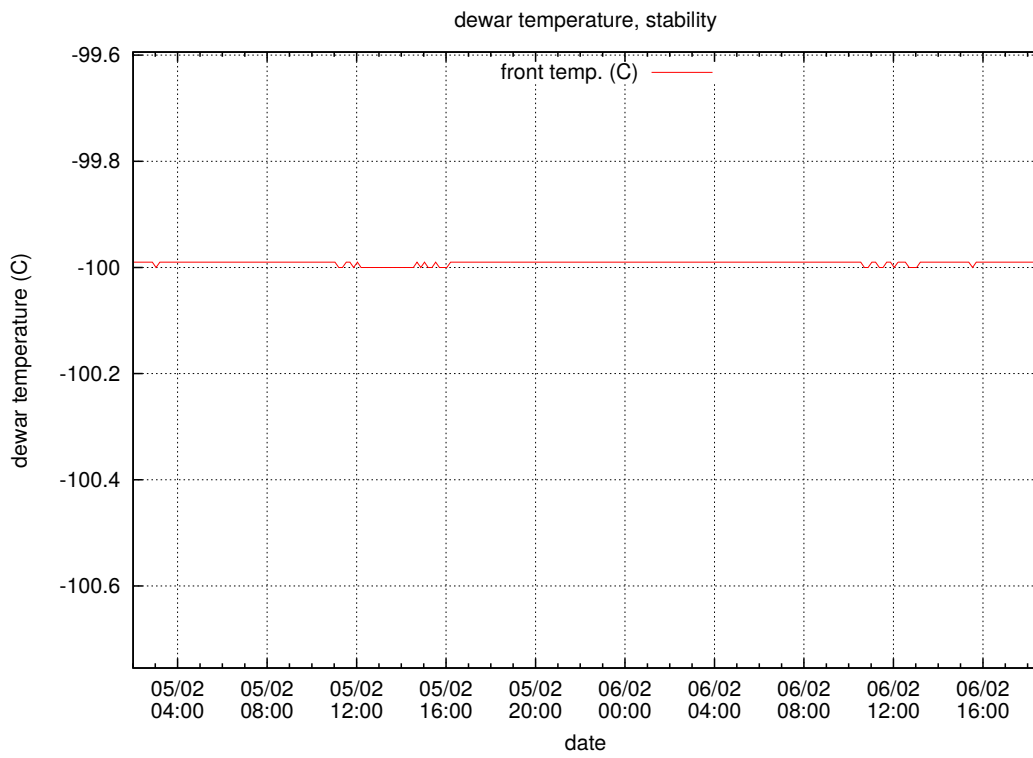


Figure 4.4: Stability of the front side controlled temperature

5

Optical systems

5.1 Light sources

5.1.1 Quartz Tungsten Halogen Lamp (QTH)

The lamp is a 250 W model 6334NS from Newport, a visible and near infrared source with a smooth spectral curve and stable output. The approximate flux is 10000 Lumens and has a 3400 K color temperature. The lamp is housed in a Newport 66991 universal QTR/IR lamp housing, and we use a Newport 300W radiometric power supply model 69931. Furthermore, the flux for this lamp is stabilized by a Newport digital exposure controller model 68950 using a thermo electric cooled light sensor model 71582 from Newport. The achieved controlled power is around 230W. The spectral irradiance for the lamp is shown on figure 5.1

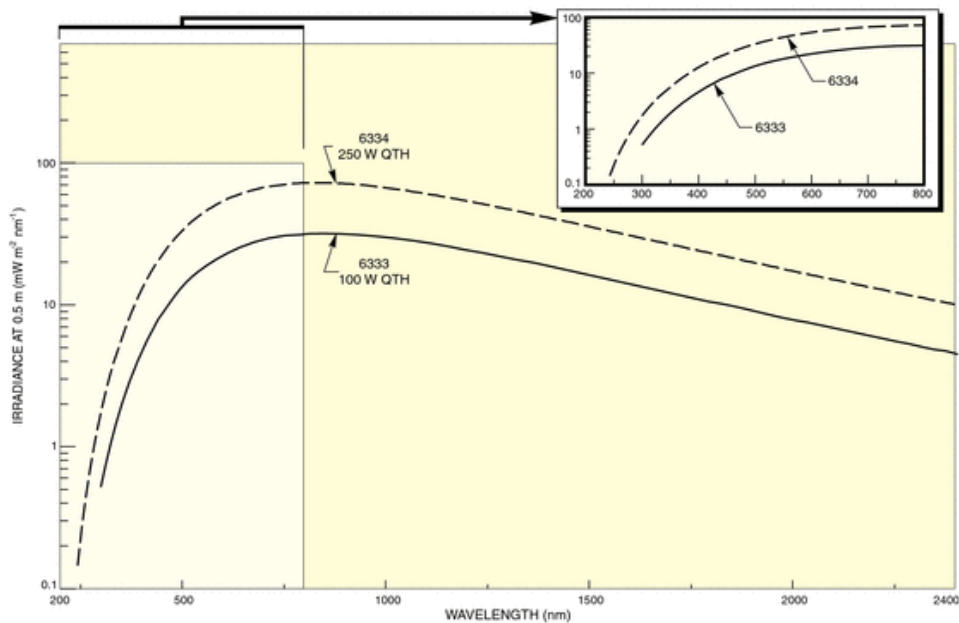


Figure 5.1: Spectral irradiance of QTH model 6334NS lamp from Newport.

5.1.2 Hg(Xe) Arc Lamp

The lamp is a 500 W Hg(Xe) from Newport, model 66142, housed in a Newport 66901 universal arc lamp housing. The power supply is a model 69911 from Newport. The spectral irradiance for the

lamp is shown on figure 5.2

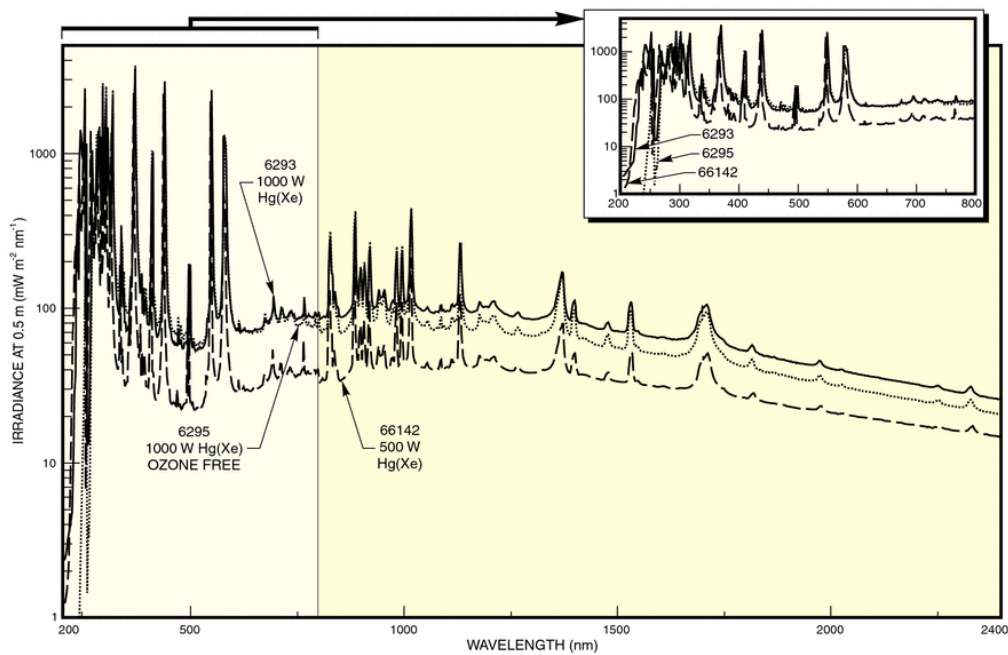


Figure 5.2: Spectral irradiance of the Hg(Xe) model 66142 lamp from Newport.

These light sources are fed to the monochromator through a security shutter and filter wheel, the source selection is performed via a flipping mirror as depicted on figure 5.5. The wavelength selection setup is described in section 5.2.1.

5.1.3 Laser diodes

The laser device (Laser MCLS Series Multi Channel from ThorLabs) has four laser diodes with the following wavelengths: 406 nm, 635 nm, 808 nm and 980 nm: their characteristics are given in table 5.1.

Each diode output is sent through an adapted 2 m fiber to the integrating sphere (see 5.2.2). To produce micrometric spots on the CCD the fibers may also be directly connected to a collimator in front of various pinholes (see 5.4.3).

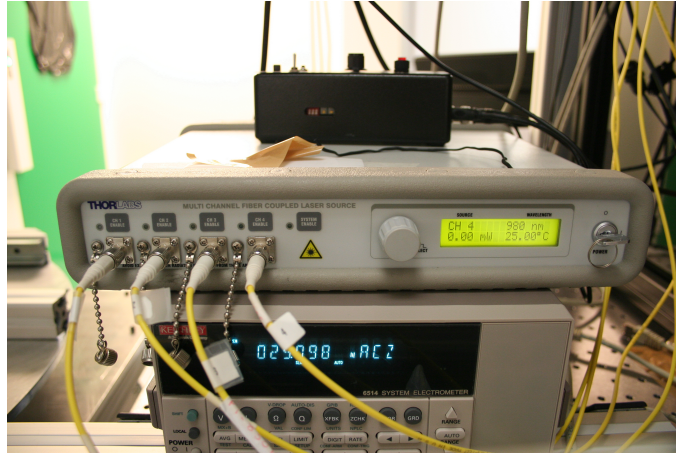


Figure 5.3: 4-channels fiber coupled laser source from Thorlabs. Front panel, with the adapted attached fibers.

| Channel | Wavelength | serial | | current | output power | on CCD |
|---------|------------|-----------|---------------|----------|--------------|--------|
| 1 | 406 nm | — | laser thresh. | 18.60 mA | ??? | ??? |
| | | | max. | 35.20 mA | 4.78 mW | ??? |
| 2 | 635 nm | 100726-10 | laser thresh. | 43.80 mA | ??? | ??? |
| | | | max. | 64.20 mA | 3.92 mW | ??? |
| 3 | 808 nm | 101118-01 | laser thresh. | 23.60 mA | ??? | ??? |
| | | | max. | 66.00 mA | 6.94 mW | ??? |
| 4 | 980 nm | 101105-32 | laser thresh. | 32.60 mA | ??? | ??? |
| | | | max. | 56.80 mA | 8.30 mW | ??? |

Table 5.1: Laser diodes properties. For each laser diode, the current can be modulated from zero to the specified maximum current value. Below the lasing threshold, the diode behaves like a LED; above, it starts lasing.

5.1.4 LEDs

In the LSST requirements, several measurements should be made with a 500 nm light source. To get a very stable light source, we plan to also use a Golden Dragon LV W5AM (505 nm, 58 lm/W) with a home-made stabilized current source (up to 10^{-4} relative precision) copied from the DICE project.

A wavelength tunable and flux adjustable light source based on 32 LEDs from 300 to 1200 nm, with precise pulse capabilities, derived from the DICE source, is currently under development at LPNHE; we plan to use it on the LSST test bench.

5.2 Optical devices

5.2.1 Wavelength selection setup

To choose the light source entering the monochromator we use a beam steerer from Newport (model 77765), it is a flipping mirror driven by a small DC motor. The mirror switching is controlled by a TTL signal. The beam transmission is controlled by an electronic safety shutter from Newport (model 71445), driven also by a TTL signal. Then the motorized filter wheel (Newport model 74040) allows us to choose among six filters (See table 5.2). The filtered beam enters the monochromator (Triax 180,

with gratings listed below in table 5.3, soon replaced by a Newport Cornerstone 260) and the output is fed into the integrating sphere through a fiber bundle (Thorlabs BF20LSMA02). Figure 5.5 depicts the wavelength selection setup.

| Wheel position | manufacturer | reference | effect |
|----------------|--------------|------------|------------------------|
| 1 | Newport | 10CGA-305 | FH: $\lambda > 308$ nm |
| 2 | L.O.T. Oriel | 550FH90-25 | FH: $\lambda > 560$ nm |
| 3 | L.O.T. Oriel | 850FH90-25 | FH: $\lambda > 853$ nm |
| 4 | — | — | — |
| 5 | — | — | — |
| 6 | — | — | — |

Table 5.2: Filters loaded in the filter wheel.

| Grating | groves/mm | blaze wavelength | calibration offset |
|---------|-----------|------------------|--------------------|
| G0 | 1198 | 500 nm | 3576 |
| G1 | 1198 | 750 nm | 3525 |
| G2 | 509 | 1500 nm | 3612 |

Table 5.3: Gratings specifications in the Triax 180 monochromator.

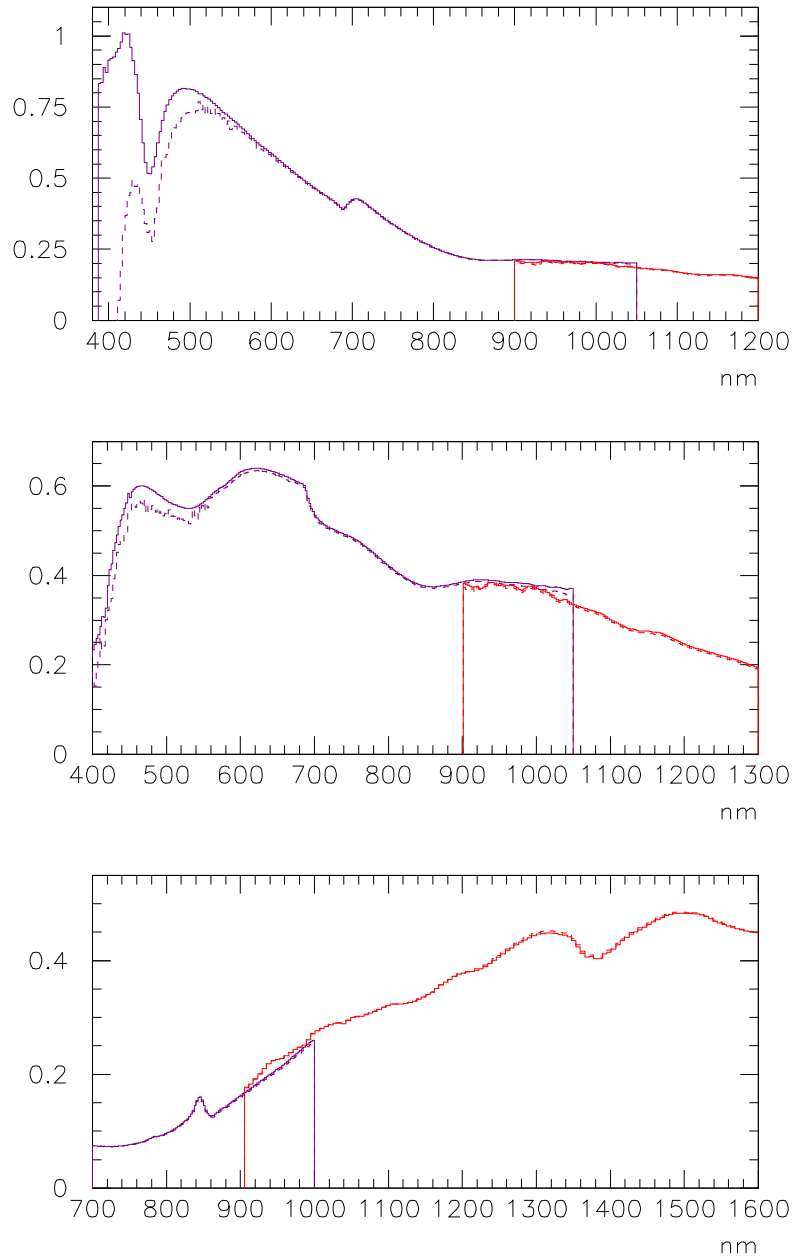


Figure 5.4: Approximate grating transmission. A blackbody spectrum was used at two different temperatures, hence the different estimates. Two photodiodes were used, a Si photodiode (left part of the spectrum), and an InGaAs photodiode in the near infra-red.

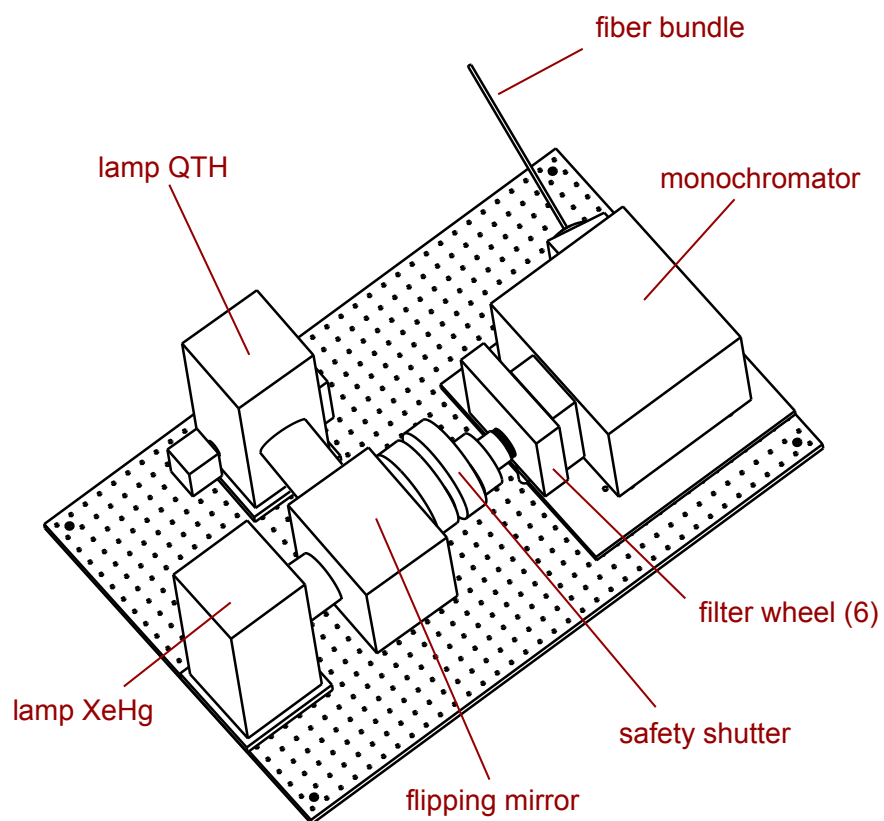


Figure 5.5: Wavelength selection setup. A flipping mirror allows to choose between the QTH and the Hg(Xe) lamps. The light beams then goes through a safety shutter, a filter wheel (with filters to cut higher orders) and a monochromator. The resulting light beam is then fed into the integrating sphere through a fiber bundle.

5.2.2 Integrating sphere

To produce a flat illumination on the cryostat chamber window and thus on the CCD inside, we use a 6 inch integrating sphere (Edmunds model 58586) with two 1 inch ports and a 2.5 inch exit port.

The light coming from the laser diodes or the lamps through fibers or a dedicated fiber bundle (7 multimode fibers, 400-2200 nm) is injected through the 1 inch lateral entrance port of the sphere. A Melles-Griot 04IES211 shutter is fixed there to be able to modulate (up to 1/30s) the illumination duration. The fibers and the shutter are attached to a dedicated home made light injection system (see below).

The Melles-Griot shutter is controlled by a shutter controller 04-ISC-850 driven by TTL signals sent either by the National Instrument board (see below) or by the REB itself (clock line 17) in order to have a more precise exposure duration.

A FDS10x10 photodiode (Thorlabs) of 100 mm² is attached on the top 1 inch port, in order to monitor the light flux inside the integrating sphere by measuring in real time its output current with a picoammeter (model Keithley 6514).

Sphere support

During our tests, it appears that the positioning of the Edmunds integrating sphere on the optical table was not reliably reproducible when done with standard optical elements. To solve this problem we designed and printed (in ABS) a special support made of two parts: a *bowl* perfectly fitted to the outside shape of the integrating sphere, and a *foot* which can be screwed in the optical table. This greatly improved the reproducibility of the sphere positioning (fig 5.6).

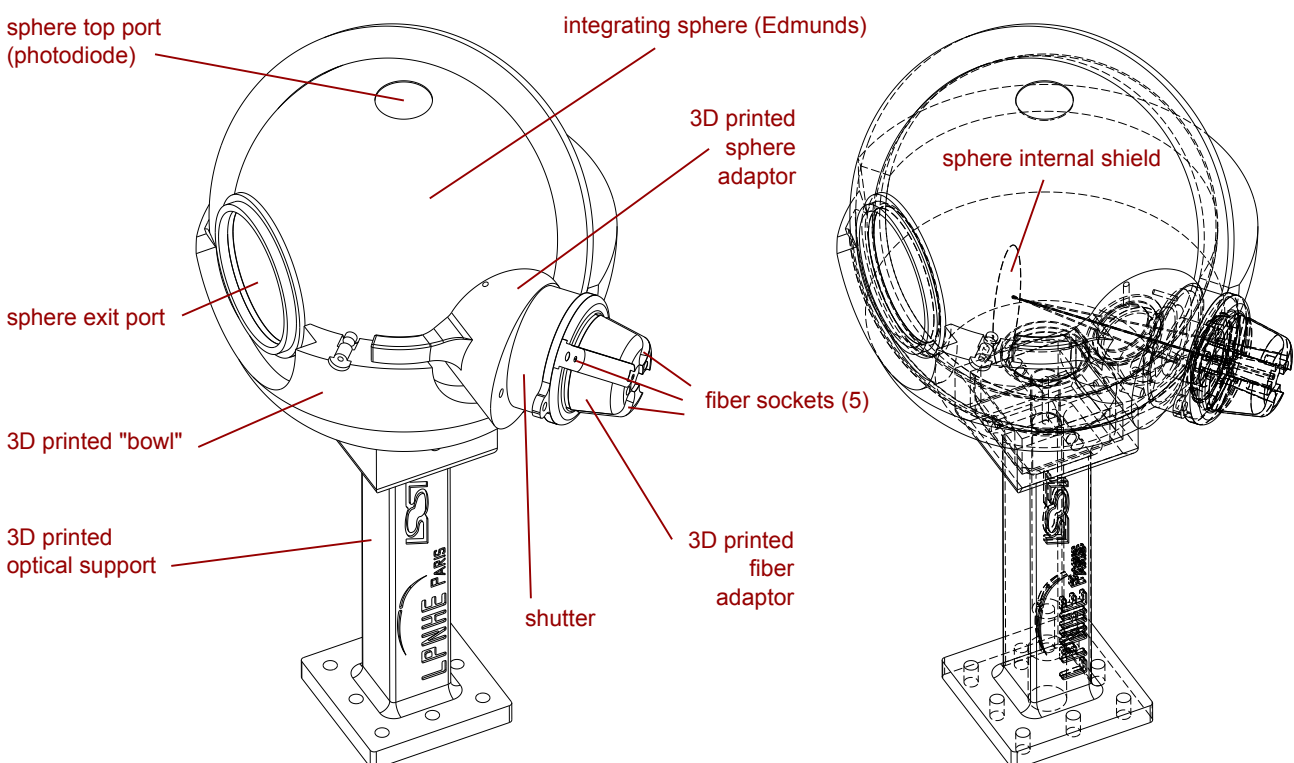


Figure 5.6: Integrating sphere with its special support and the light injection system. The 3D printed support (the adjusted bowl and the foot) greatly improve the stability and the repeatability of the optical setup.

Light injection system

To be able to use either one of the 4 laser output or the lamps light flux without needing to regularly disconnect and reconnect the fibers to the integrating sphere, we decided to fix the 4 fibers and the fiber bundle to a unique fiber socket designed for that purpose.

It appears that feeding the integrating sphere by connecting the fibers without any consideration about the injection angles does not produce an output beam with sufficient uniformity, and the resulting beam properties (shape, position of the maximum, etc) are strongly dependent on the injection angle through the entrance port of the sphere.

To obtain a good uniformity of the sphere output beam, we designed a special light injection system for the integrating sphere. The Edmunds 58586 integrating sphere has an internal shield to forbid any light ray to go directly from the entrance port to the exit port. We designed our injection system to ensure that the light beams coming from the 4 fibers (from the 4 laser diodes) and from the fiber bundle (from the lamps and monochromator) converge on this internal shield, to increase the number of reflections inside the sphere. This greatly improve the resulting output beam uniformity, and reduce the dependency of the output beam structure on the injection angle. On the area corresponding to the CCD, the illumination uniformity is better than 1% (see fig. 5.8).

Our injection system is made of two 3D printed ABS elements: an adaptor to fix the shutter on the sphere 1 inch port, and a special multifiber socket attached on the entry of the shutter. See fig. 5.6 and 5.7.

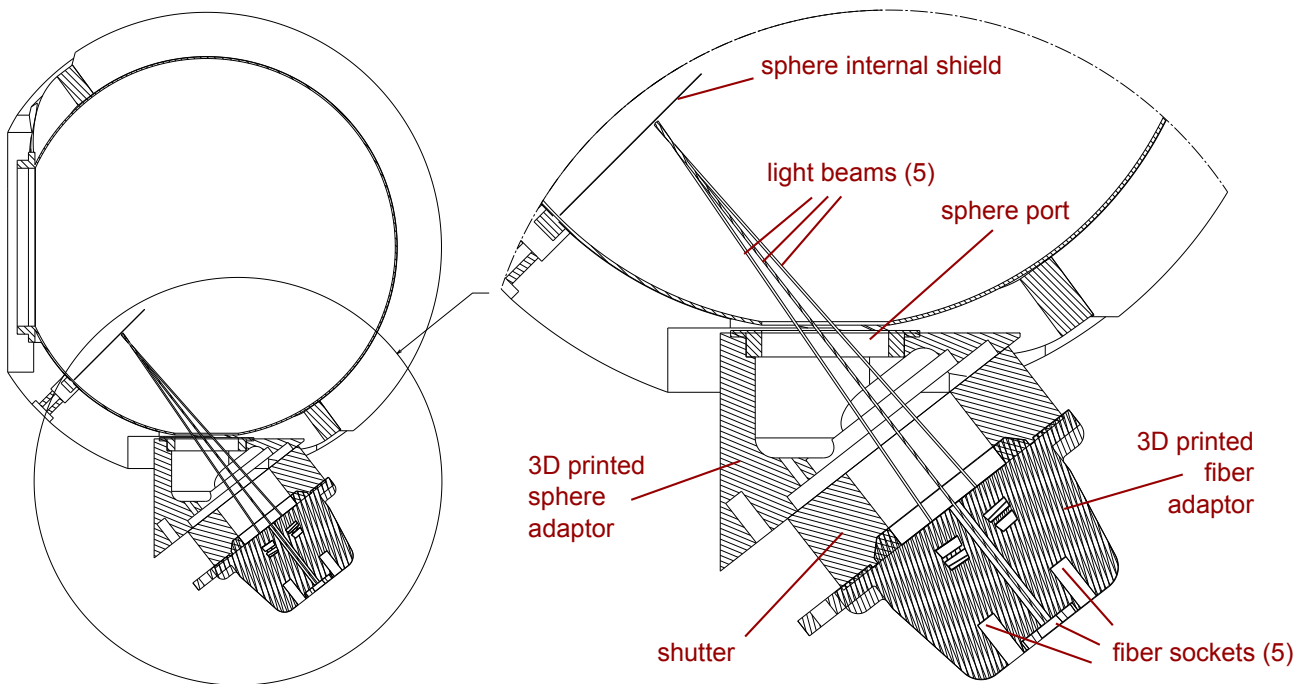


Figure 5.7: Integrating sphere light injection system. The light beams coming from the 4 fibers (from the 4 laser diodes) and from the fiber bundle (from the lamps and monochromator) converge on the sphere internal shield, to increase the number of reflections inside the sphere, and thus improve the resulting beam uniformity.

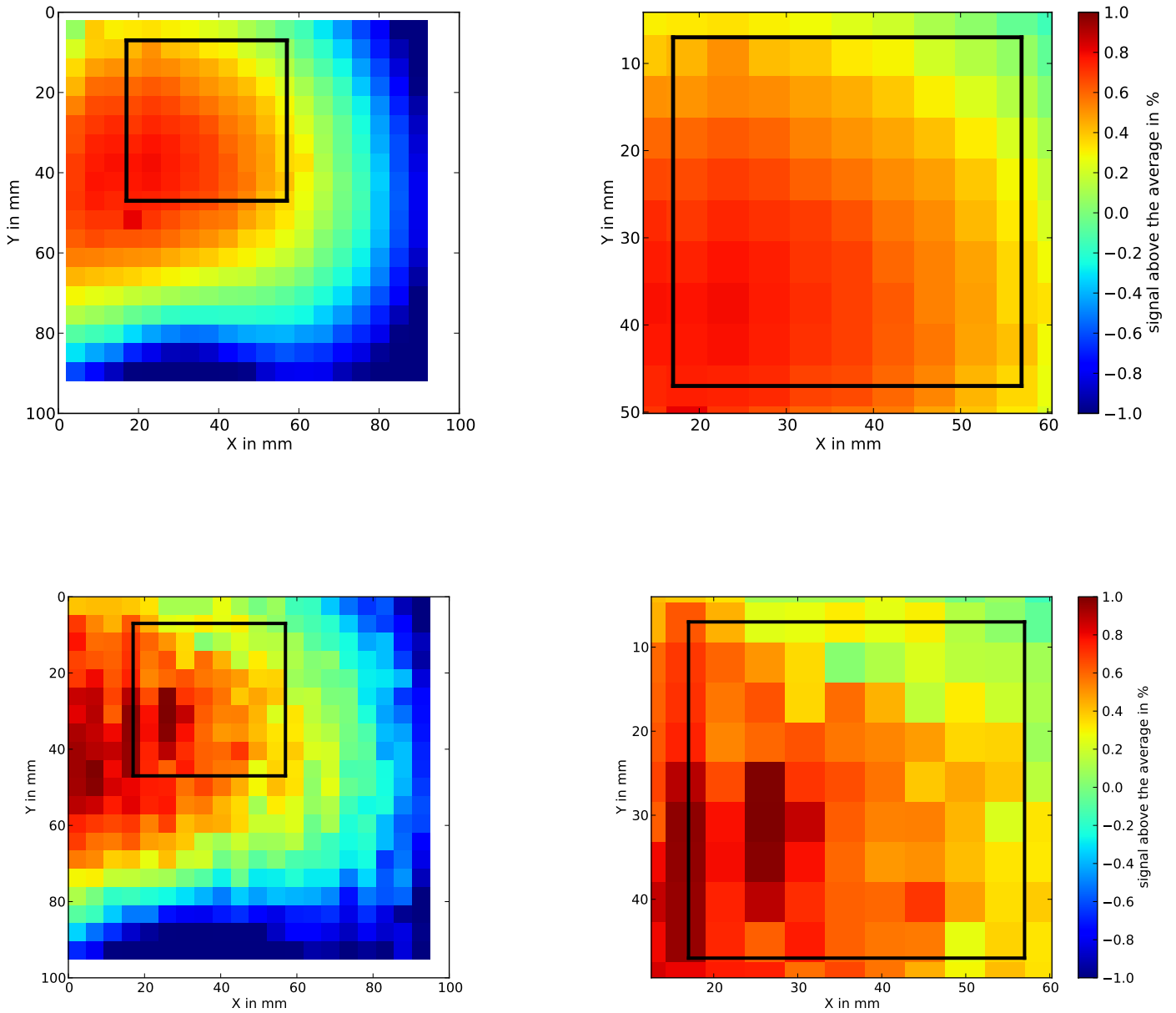


Figure 5.8: Illumination maps ($100 \text{ mm} \times 100 \text{ mm}$) of the beam produced by the integrating sphere with our light injection system. These maps are done with a photodiode fixed on the XYZ mount (see section 5.2.3), in front of the cryostat window, xx cm ... from the CCD plane. The black square indicates the position of the CCD. Top: illumination map with the QTH lamp on and the monochromator set on $\lambda = 500 \text{ nm}$: left: the whole map, right: a zoom on the CCD area. Bottom: illumination maps with the laser channel 1 (406 nm) turned on.

5.2.3 XYZ mounting

In order to be able to precisely move several optical elements in front of the CCD, we installed a motorized XYZ mounting in the dark box, in front of the cryostat window.

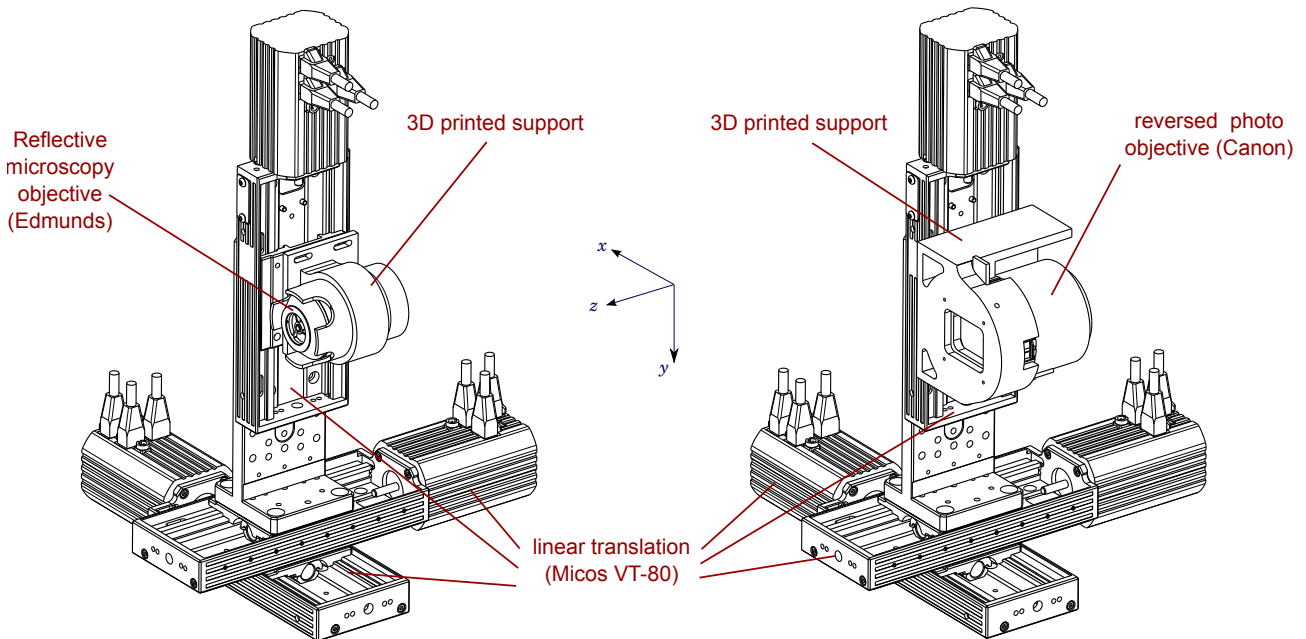


Figure 5.9: Motorized XYZ mounting, in two configurations. Left: with the reversed microscopy objective to produce micrometric light spots. right: with a remotely controlled Canon objective to image microscopy patterns on the CCD. It is also used to map the integrating sphere beam with a Hamamatsu photodiode attached (not shown).

This XYZ mounting is made up of three Micos Pollux VT-80 linear translation motors of 100 mm range, fixed with ELCOM elements and an adapter (see fig 5.9 and 5.10). These 3 motors have a displacement resolution better than $0.2 \mu\text{m}$, with a very good repeatability.

On the upper part a 3D printed plate is fixed: on this plate, several optical elements can be attached:

- A reflective objective for microscopy (ref: Edmunds 59884), encased in a home made 3D printed support, can be fixed there. Used with several micrometric pinholes and a the light beam coming from a fiber, it allows to project a subpixel light spot on the CCD, and to focus and move it (see below, section 5.4.3).
- A FDS10x10 photodiode connected to a picoammeter Keithley 6514 can be fixed on the XYZ support, in order to map the output beam of the integrating sphere and characterize the mean intensity and uniformity in a plane parallel to the CCD (fig. 5.8).
- A Canon objective (50mm f/1.8 II) can also be fixed on the XYZ support, in order to project and focus light patterns (obtained by sending the integrating sphere beam through several transmission patterns) on the CCD (see 5.4.4). The Canon focusing lens is remotely controlled by a home made circuit based on an Arduino Nano.

When unused, the XYZ support can be automatically parked in a “park” position where it does not interfere with other measurements.

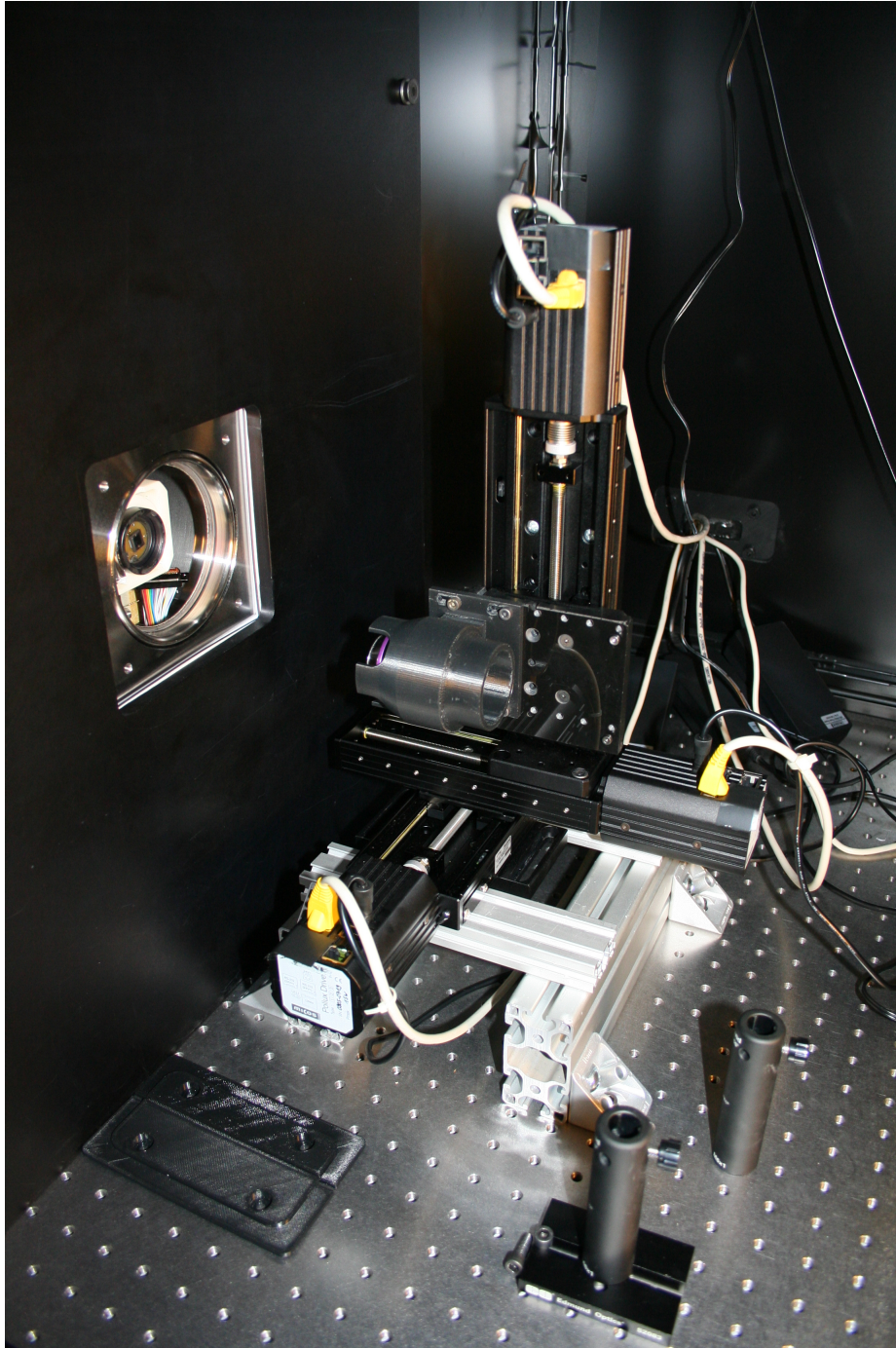


Figure 5.10: The Micos Pollux XYZ mounting and the Edmunds microscope objective to produce subpixel spots on the CCD. On this picture, the XYZ mounting is parked.

5.2.4 Fringe projector (Michelson interferometer)

In order to do MTF measurements on the CCDs, we use a Michelson interferometer (see fig 5.11) to project fringes on the CCD sensor, with controlled fringe spacing and fringe orientation.

The Michelson interferometer is made of a cube beamsplitter and two 2-inch mirrors, each one fixed on a motorized corner mount: the precise position and angle of each of the two interferometer mirrors are controlled by three piezo motors (New Focus Picomotor, Newport 8852). Each group of three motors is controlled through a three-axis picomotor driver (Picomotor Driver Module Newport 8763-Kit), through an ethernet connection.

A dedicated home-made software allows to automatically get interferences fringes on the focal plane with the requested fringe spacing and orientation.

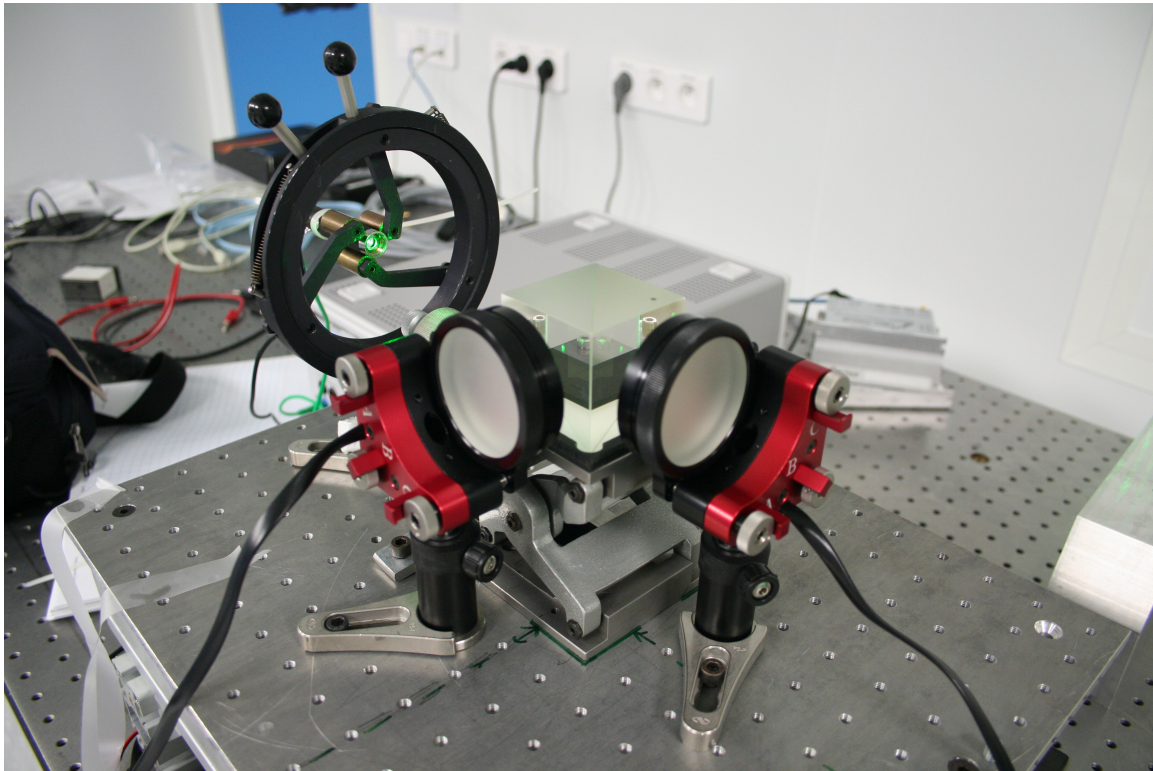


Figure 5.11: The Michelson interferometer used as a fringe projector.

5.3 Flux measurement systems

5.3.1 Photodiodes

In order to measure and monitor the light flux intensities, several photodiodes are used on the test-bench. Their output current is measured by two dedicated Keithley 6514 multimeters/electrometers used as picoammeter.

A FDS10x10 photodiode (Thorlabs) is fixed on the top 1-inch port of the integrating sphere to continuously monitor the light flux in the sphere (see fig. 5.6).

To measure the resulting flux on the CCD, a second photodiode from Hamamatsu, calibrated by the DKD (soon to be replaced by a NIST calibrated photodiode), can be placed inside the cryostat chamber, in a special jig, at the exact position of the CCD (see fig. 5.12).

By intercalibrating the sphere photodiode and the photodiode at the CCD place, this setup allows to predict the absolute light flux received by the CCD. This is mandatory to measure CCD QE.

5.3.2 Small CCD camera for tests

To validate several illumination measurement methods we use a small amateur astronomer CCD camera (Imaging Source DMK 41AU02.AS) with its optics removed. This a 1/2" CCD (Sony ICX205AL, progressive scan) of 1280 x 960 pixels, 8-bits, read continuously, from 15 FPS to 60 minutes exposure.

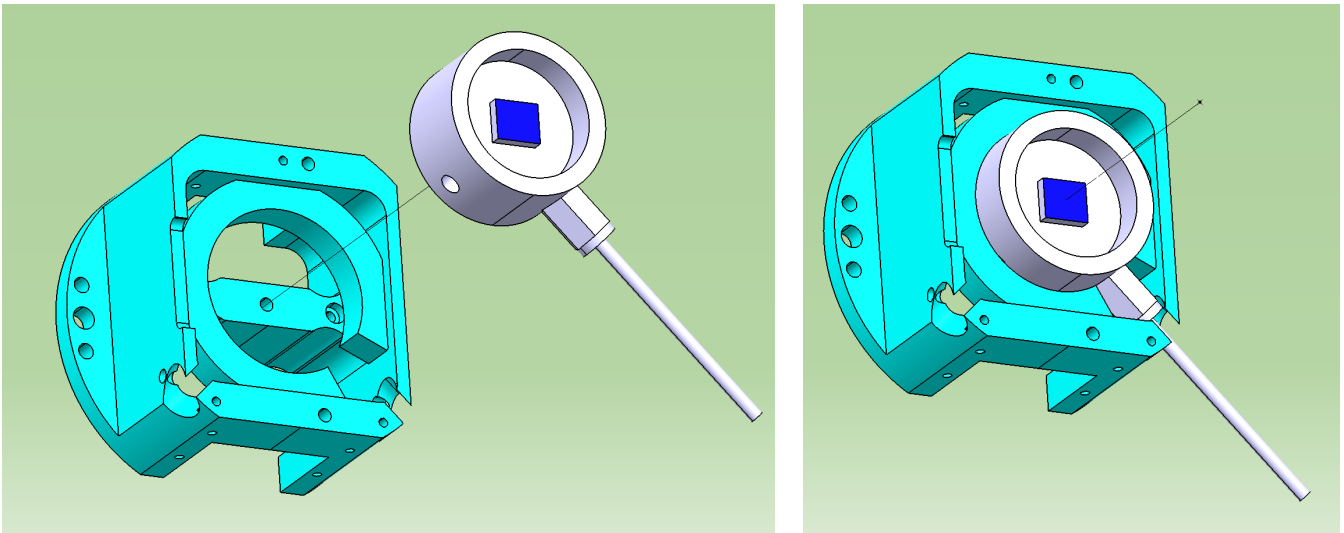


Figure 5.12: For light flux metrology in the cryostat, we designed a special jig to host the calibrated Hamamatsu photodiode at the exact place occupied by the CCD.

5.4 Optical setups

In this section, we describe the different optical setups available on the testbench for CCD qualification and tests.

5.4.1 Dark frames

Dark frames are done with a dedicated metallic cover placed on the cryostat chamber window. When doing dark frames, the cryostat chamber does not need to be placed against the dark box; that way, it is possible to take dark frames with one CCD while the other one is used on the dark box with various illuminations.

5.4.2 Flat frames

For flat illumination frames, the cryostat chamber is tightly fitted against the opening of the dark box. The output beam of the integrating sphere directly illuminates the CCD (for its uniformity, see fig. 5.8).

5.4.3 Spots

To study charge diffusion, measure the MTF and the brighter-fatter effect, we produce micrometric subpixel light spots on the CCD. To do so, we send the output of a fiber through a pinhole, and focused the resulting beam on the CCD with a reflective microscopy objective (Edmunds 59884) used in reverse. The objective is attached on the XYZ mount in order to be able to focus and to move the spot on the CCD surface.

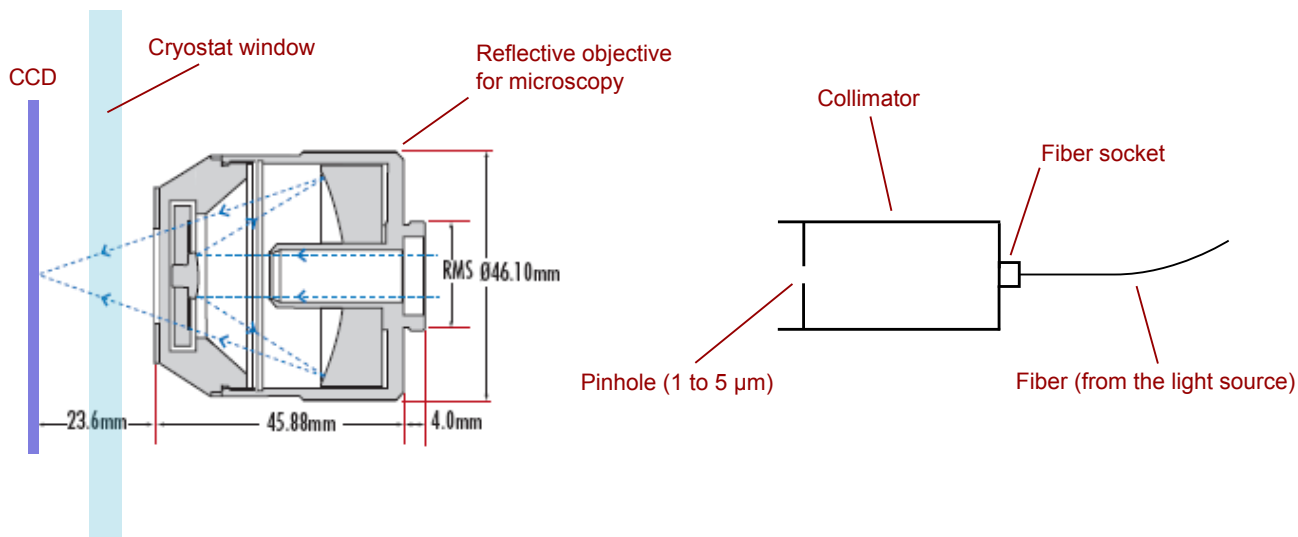


Figure 5.13: Optical setup to produce subpixel light spots on the CCD. The Edmunds 59884 microscopy objective is attached on the XYZ mount in order to be able to focus and to move the spot on the CCD surface.

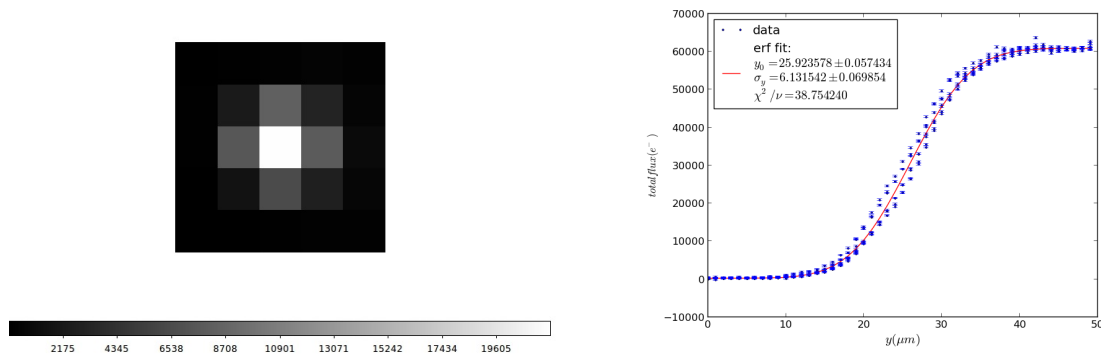


Figure 5.14: Left: example of a spot produced on a E2V 250 CCD. Right: Virtual Knife Edge measurement (VKE) done with this setup on the same E2V CCD by moving the spot across the frontier between pixels.

5.4.4 Fringes & regular illumination patterns

To produce fringes, we use the Michelson interferometer (fig 5.11) described in section 5.2.4, with the fiber bundle output as the light source.

We also have a second way to produce regular illumination patterns, by sending the light beam from the integrating sphere through a microscopy transmission pattern, and imaging it on the CCD with a Canon objective (50mm f/1.8 II) attached on the XYZ support (fig. 5.9). The Canon focusing lens is remotely controlled by a home made circuit based on an Arduino Nano, to properly focus the resulting pattern image on the CCD.

5.4.5 X-ray frames

X-ray frames are done with the cryostat cover in place to close the cryostat. The X-ray source is a ^{55}Fe radioactive source from AREVA/CERCA-LEA; its activity is 200 kBq (2011-02-11).

The ^{55}Fe source is mounted on an aluminium arm (fig. 3.4). The arm is moved via a step motor (light grey on the drawing) model VSS 42 from Phytron, high vacuum (HV) qualified and remotely controlled.

For X-ray exposures, the source is moved in front of the CCD in several positions to illuminate the whole surface of the CCD. It is then parked during the CCD readout.

6

Electronics

6.1 Power supplies and connections

The E2V LSST CCDs come with two flex cables bonded to the CCD with 37-pin nanoD connectors at the other end. On the test bench however, to avoid damaging the bonding or connectors, these nanoD connectors are fixed on the CCD jig, with a nanoD to (male/plugs) microD pigtail on each side. For the ITL CCD, there is a plug on the CCD, so we must add a custom-made extension from this plug to two microD connectors with pinout that is compatible with E2V.

The REB is the Raft Electronics Board of LSST. Two versions have been produced up to now, as well as a version of the WGREB (Wavefront Guider Raft Electronics Board). On the CCD test bench, we use these boards as the CCD controller. The figure 6.1 shows a schematics of the connections from the CDD to the REB. The CCD-side connection on the REB are two (female/sockets) nanoD connectors, as they are designed to be connected directly to the CCD. On the bench, we have a pigtail extender from the REB nanoD to two microD feedthrough on the underside of the cryostat (male inside, female outside). There are also two microD to microD (female to female) pigtail extenders inside the cryostat to plug on the pigtails from the jig.

The power supplies to the REB come in on one HE10 connector for with four positive voltages (5 V digital power supply, 32 V bias supply, 9 V and 24 V rail supplies), and one BNC cable for the negative back-substrate bias (-70 V nominal), which is simply transmitted through the board. The digital signals are transmitted through a mini-SAS shielded cable (8F36-AAA105-0.50 by 3M) to the RCM translation board. This board requires a separate 12 V power supply, and translates the digital signals to and from the optic fiber link to the acquisition board (COB) on the XTCA crate.

To allow controlled shutdown of the CCD in the event of a general power cut, the common power supply providing the 4 positive REB voltages and the 12 V RCM power supply are all on UPS.

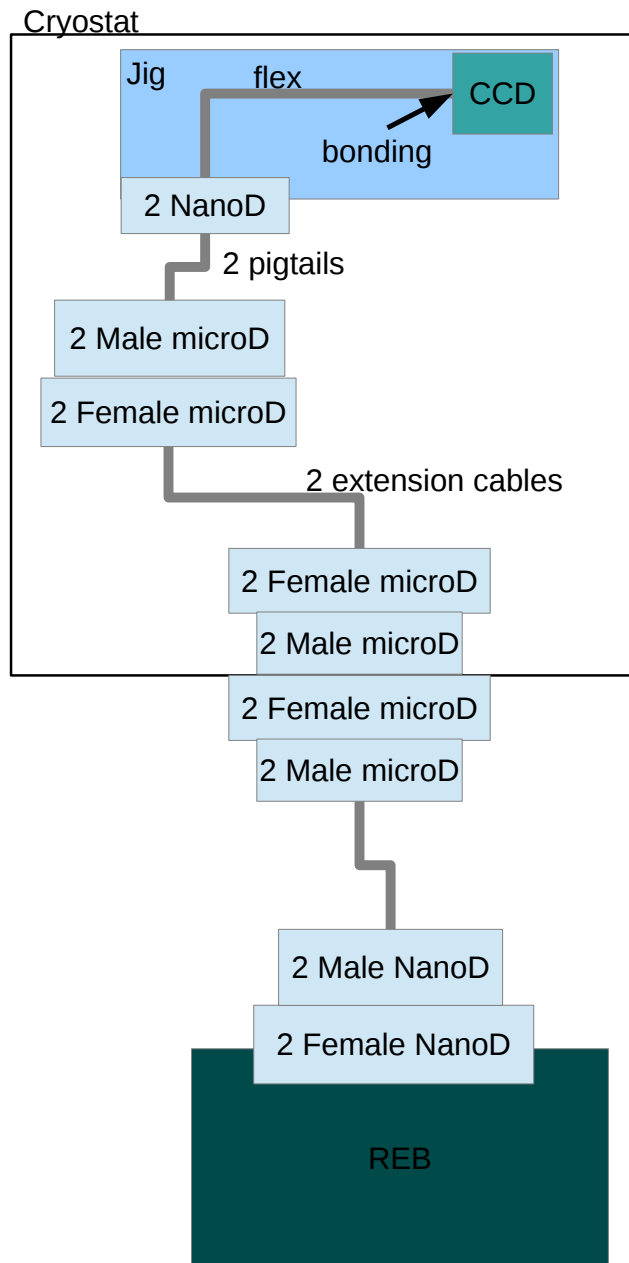


Figure 6.1: Scheme of the connections

6.2 CCD operations

6.2.1 CCD Control

The control of the CCD is done by driving the two CABACs (Clock And Biases ASIC for CCD) on the REB. REB1 and REB2 carry version 0 of the CABAC, and WREB will be upgraded to version 2 before being connected to a CCD. Specifications and user's manual of the CABAC are available as LSST Camera controlled documents:

- LCA-10046, CABAC0 Specifications and Design
- LCA-10928 CABAC1 User's Manual
- LCA-11548, CABAC2 Implementation

CABAC2 raw calibration results are available on LSST eLog (https://dbweb4.fnal.gov:8443/ECL/lstt_camera/).

6.2.2 CCD readout

The analog part of the CCD signal processing is done by two ASPICs (Analog Signal Processing Integrated Circuit) on the REB. Each has eight input channels. REB1 carries version 2 of the ASPIC, REB2 and WREB carry version 3 with a possibility to upgrade to version 4. Specifications and user's manual of the ASPIC are available as LSST Camera controlled documents:

- LCA-10932, ASPIC2 User's Manual and Performances
- ASPIC3 Specification, Design and User's Manual
- LCA-10887, ASPIC3 Testing Report

The conversion to digital signals is done by 18-bit ADCs.

7

Control software

7.1 Control PC

All the test bench instruments are controlled by a dedicated Linux box (Ubuntu 14.04) called *lpnlsstbench*.

Most of the available instruments are connected via RS-232 (or RS-232 over USB) to *lpnlsstbench*. To avoid problems with RS-232 to USB convertors, like device confusion when connecting/disconnecting devices, we used two PCI Multiport serial controller (from Brain Boxes) which provide each 8 RS-232 ports. With the native one, we have 17 RS-232 ports to connect all our devices.

A few instruments are connected by USB. The Agilent power supply is controlled through an ethernet link, as well as the New Focus Picomotor motors.

The filter wheel, the safety shutter, the integrating sphere shutter and the flipping mirror are controlled by TTL signals generated by a PCI National Instrument board located inside the *lpnlsstbench* linux box.

7.2 Software overview

This testbench is used for several CCD tests and sensors studies: the LSST sensors production testing, for the optimization of the CCD clocking sequences, but also for to study the bright-fatter effect, charge diffusion between pixels, and so.

As this bench is aimed to be used in many setups (flat illumination, spots, fringes, patterns, maps, etc.), and for many different tasks, its control system needs to be modular and very flexible.

For the large majority of the available instruments and devices on the LSST sensors testbench, we already wrote several years ago dedicated control software in C++, with Qt as the underlying library. Qt offers facilities for the GUI as well as the RS-232 serial port. We adapted these existing programs (by adding XML-RPC remote functions) to integrate them with the Python scripting environment. For a few instruments, we also wrote and recycle native Python drivers.

We devised a modular software architecture which allows us to integrate all the existing control software in a high level scripting environment (see fig. 7.1), but at the same time, it is still possible to control any instrument independently without using the whole software, which is very practical during tests or for debugging purposes.

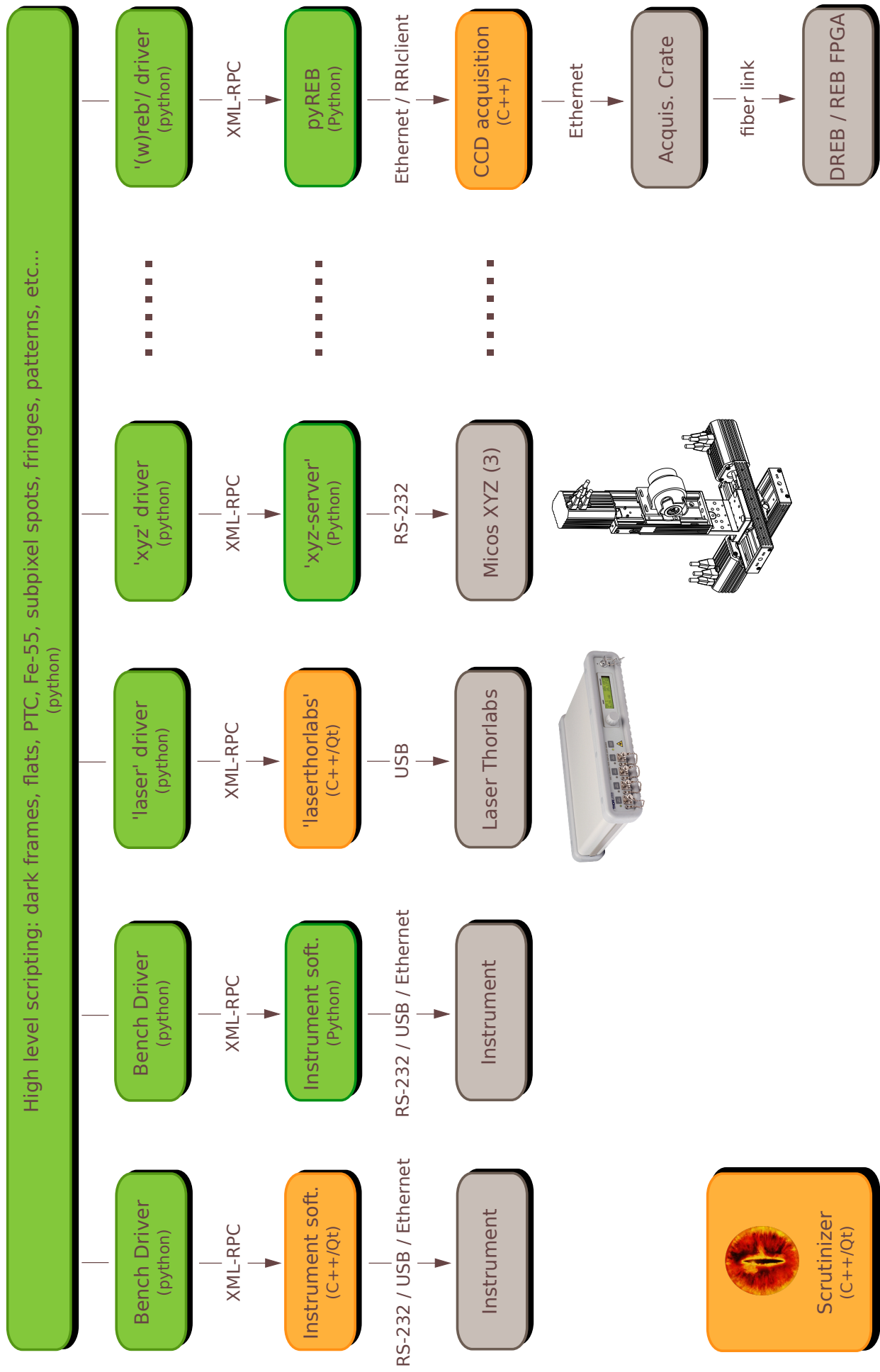


Figure 7.1: Architecture of the control software for the LPNHE testbench. This figure gives the general scheme and as an example, it shows how this scheme works for two instruments: the 4 channels fiber coupled laser source (Thorlabs) and the XYZ mounting (Micos).

7.3 Control of the testbench instruments

Table 7.1 gives the exhaustive list of the test bench instruments (except the REB/WREB) and describes how each instrument is controlled and integrated in the test bench software. For each instrument, column “Software” indicates its control software; column “Driver” gives the name of the corresponding Python driver for high level scripting facilities (see below). Figure 7.2 shows a few examples of the instrument control interfaces.

| Instrument | Link | Device | Software | XML-RPC | Driver |
|---|---------|---|--------------------|---------|----------------|
| <i>Cryostat Control</i> | | | | | |
| Lakeshore-325 (0) | RS-232 | /dev/ttyS7 | lakeshore | 8091 | 'lakeshore0' |
| Lakeshore-325 (1) | RS-232 | /dev/ttyS8 | lakeshore | 80- | 'lakeshore1' |
| Agilent Pump (0) | RS-232 | /dev/ttyS12 | agilentpump | 8093 | 'agilentpump0' |
| Agilent Pump (1) | RS-232 | /dev/ttyS13 | agilentpump | 8094 | 'agilentpump1' |
| Pressure Gauge Pfeiffer | RS-232 | /dev/ttyS6 | pfeiffer | 80- | 'pfeiffer' |
| Phytron Motor (0) | RS-232 | /dev/ttyS14 | phytron | 80- | 'arm0' |
| Phytron Motor (1) | RS-232 | /dev/ttyS15 | phytron | 80- | 'arm1' |
| <i>Power Supply</i> | | | | | |
| Agilent Power S. | TCP/IP | lpnws5205 | agilentpowersupply | 8092 | 'agilentpower' |
| Keithley 6487 (BSS) | RS-232 | /dev/ttyS11 | keithley-server | 8301 | 'bss' |
| <i>Light Sources</i> | | | | | |
| Oriel QTH lamp | RS-232 | /dev/ttyS2 | oriel | 8089 | 'QTH' |
| Oriel Hg(Xe) lamp | RS-232 | /dev/ttyS3 | oriel | 8085 | 'XeHg' |
| Laser Thorlabs 4-channel | USB | /dev/laser | laserthorlabs | 8082 | 'laser' |
| <i>Optical setups</i> | | | | | |
| Monochromator Triax | RS-232 | /dev/ttyS0 | triax | 8086 | 'triax' |
| Flipping Mirror | NI Card | DIO 3 | ttd | 8086 | 'ttd' |
| Filter Wheel | NI Card | DIO 0, 5, 6 | ttd | 8086 | 'ttd' |
| Safety Shutter | NI Card | DIO 2/AIO 3 | ttd | 8086 | 'ttd' |
| Melles Shutter | NI Card | DIO 4/AIO 2 | ttd | 8086 | 'ttd' |
| XYZ mounting Micos Pollux | RS-232 | /dev/ttyS16 /dev/ttyS17 /dev/ttyS18 | xyz-server | 8201 | 'xyz' |
| Picomotor (Michelson) | TCP/IP | - | picomotor | 80- | 'michelson' |
| Canon objective control | USB | /dev/canon | canon-server | 8251 | 'canon' |
| Camera 41AU02.AS | DMK USB | /dev/video0 | dmk | 8100 | 'dmk' |
| <i>Flux/current measurements</i> | | | | | |
| Keithley 6514 DKD photodiode | RS-232 | /dev/ttyS1 | keithley-server | 8211 | 'DKD' |
| Keithley 6514 photodiode | RS-232 | /dev/ttyS3 | keithley-server | 8212 | 'PhD' |

Table 7.1: Instruments and devices of the test bench: connections and control software.

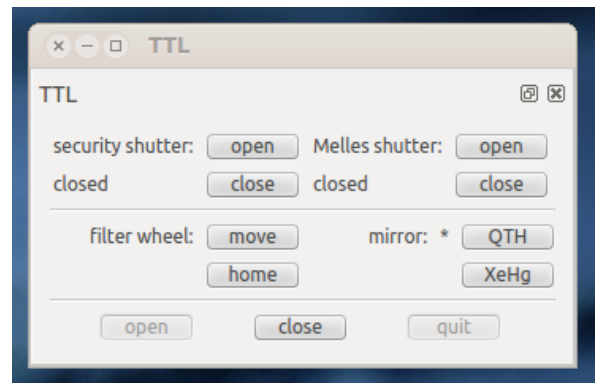
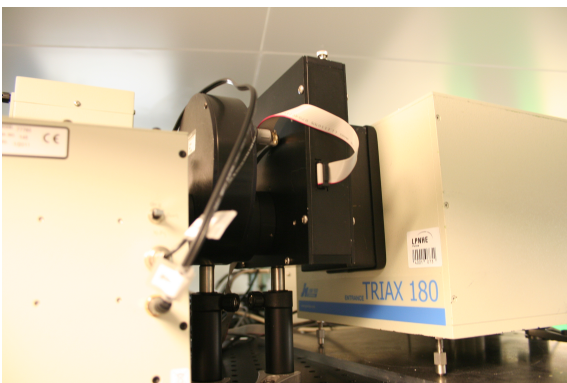
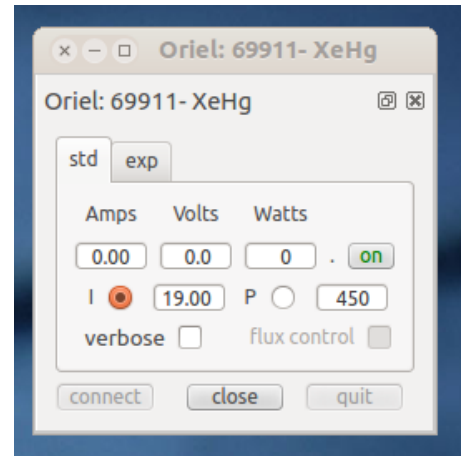
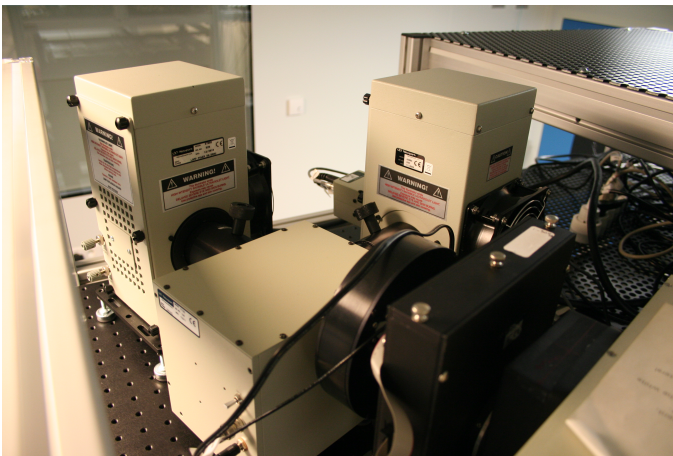
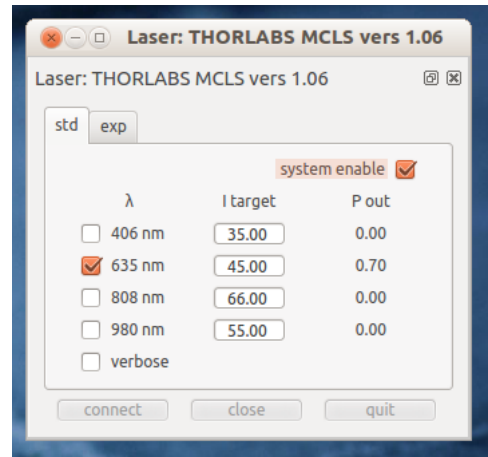


Figure 7.2: A few examples of the C++/Qt control panels and the corresponding instruments. Top: The Thor-Labs lasers and the C++/Qt GUI `laserthorlabs` to control it. Middle: the two lamps (QTH and Xe(Hg)) and the flipping mirror, and the `oriell` control panel for the Xe(Hg) lamp. Bottom: The safety shutter and the filter wheel and the `tll` panel.

7.4 REB/WREB slow control

In this section, we describe the various pieces of software we are using for the slow control of the REB/WREB and the CCD sensor. These codes are prototypes only aimed for this testbench: they are useful to experiment and prototype new features to be included later in the CCS (notably for the sequencer programming, the optimization of the CCD readout, and the diagnostic facilities).

The REB/WREB is driven through the LSST acquisition crate by using remotely the `rriClient` and `imageClient` tools.

To simplify the REB slow control and at the same time keep the flexibility needed for our sensor studies, we wrote a dedicated Python module `PyREB` for the REB slow control. The `PyREB` module essentially rely on the `rriClient` program to read/write at the REB FPGA subaddresses, and on `imageClient` to get the resulting CCD frame. The low level read/write operations are done by successive calls to `rriClient`:

```
R = reb.REB(reb_id = reb_id)
a = R.read(0x02)
l = R.read(address = 0x20, n=4) # read 4 words and returns a list
R.write(address = 0x21, 0x3e45)
```

Various methods are provided to do REB operations: programming the sequencer, launching the sequencer subroutines, configuring the CABAC voltages, configuring the ASPIC, etc. Amongst its many features, the `PyREB` module allows to dump the sequencer program from the FPGA memory, to disassemble it, to slightly alter the sequencer configuration, and so on.

Here is an example on how to slightly alter the clocking scheme in-between two frame readout:

```
# taking a frame
R.run_subroutine('acquisition', exposuretime = 5.0)

# alter the clock sequence for the line transfer (slot 2)
func_line_transfer = R.dump_function(2)
func_line_transfer.timelengths[2] -= 10 # decrease duration of slice #2
# send back the modified function into the FPGA memory
R.send_function(2, func_line_transfer)

# taking another frame
R.run_subroutine('acquisition', exposuretime = 5.0)
```

These features are very useful for the optimization of the CCD readout.

The “PyREB” software package is described in details in a separate document: “PyREB: A Python module for LSST REB control” XXX-XXX.

7.5 Software integration and scripting

Scripting facilities are critical for the various sensor studies and tests we will run on this testbench.

For the integration of the various software elements, our solution is to combine the existing C++/Qt or Python instrument control programs with some Python glue, and use the XML-RPC protocol to remotely control the C++/Qt or Python instrument software from the scripts (See fig. 7.1).

This solution has the advantage that all the instruments do not need to be physically connected to the same computer. This setup is very flexible: depending of the tests/measurements to do, only the needed subset of instruments will be activated.

The high-level scripts are run through a `ipython` master console running on the test bench control PC. The main Python object is a `lsst.testbench.Bench` singleton, on which the various instrument drivers are attached once they are activated by a call to the `Bench.register(...)` method

(see below). On request, each instrument driver can provide all the instrument informations to store them as FITS keys in the data headers.

Here is an example of a minimal script commanding the REB and the laser Thorlabs to take flat illuminations:

```
import os, os.path
import time
import lsst.testbench

B = lsst.testbench.Bench() # create a Bench singleton

B.register('laser') # connect to the laser    -> B.laser
B.register('reb')   # connect to the REB     -> B.reb
B.register('ttl')   # connect to the NI board -> B.ttl

# Configure the REB
sequencer = B.reb.Sequencer.fromxmlfile("sequencer.xml")
B.reb.send_sequencer(sequencer)

# launching a clear 10 times
B.reb.run_subroutine('clear', repeat = 10)

# taking a bias
time.sleep(1)
B.reb.run_subroutine('bias')

# Turn on the laser, channel 2, current = 45 mA
B.laser.select(2) # select one of the 4 laser diodes
B.laser.setCurrent(45.0) # 45 mA
B.laser.enable()

# print on screen the meta information from all the instruments
print B.get_meta()

# taking an exposure of 5s
B.reb.run_subroutine('acquisition', exposuretime = 5.0)

# Turn off the laser
B.laser.disable()
```

The high-level testbench software is described in details in a separate document: "LSST Testbench at LPNHE: User's Manual" XXX-XXX.

8

Safety

8.1 Cryogeny & vacuum.....

The thermal regulation of the CCD in the cryostat is controlled with a LakeShore. The cryostat pressure is also monitored with a pressure gauge (Pfeiffer); an external electronic device disabled the cooling in case of a vacuum leak. Both instruments are controlled by two C++/Qt programs.

8.2 CCD Safety: *Central Scrutinizer*

To insure the safety of the CCD

program monitoring the critical variables for each cryostat chamber: temperature, pressure.

If losing vacuum or sudden reheating -> take over, stop any running high level scripting, and run a shutdown sequence :

shutdown the biases on the CCD (in the proper order), turn off the cooling...