The CFHT MegaCam 40 CCDs camera: cryogenic design and CCD integration.

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ABSTRACT

MegaCam is an imaging camera with a 1 square degree field of view for the new prime focus of the 3.6 meter Canada-France-Hawaii Telescope. In building the MegaCam mosaic we encountered unprecedented challenges from both the large size of each CCD device (2K x 4.5K with 13.5 micron square pixels each) and the large size of the mosaic in which 40 devices have been assembled in a nearly 4-buttable edge manner on a cold plate. The CCD mosaic flatness of ± 16 µm has been optically checked at its nominal functioning temperature. The CCD mosaic is cooled at 153 K with a cryogenic unit; a close cycle pulsed tube with a power of 90 W at 140 K. A cold capacity, allows a slow warm-up during cooling shutdowns and a thermal dispatching leads to a temperature uniformity better than 3 K on the whole mosaic. The camera cryostat is designed in order to have easy access to the CCDs. The vacuum needed to avoid CCD contamination, leaded us to the use of low out-gassing materials in the cryostat. The instrument was delivered to the observatory on June 10, 2002 and first light is scheduled in October 2002.

Keywords: Wide-field imaging camera, CCD mosaics, CCD metrology, pulse tube, cryocooler, vacuum.

1. INTRODUCTION

MegaCam[1] is an imaging camera with a 1 square degree field of view for the new prime focus of the 3.6 meter Canada-France-Hawaii Telescope[2]. This instrument[3] will mainly be used for large deep surveys ranging from a few to several thousands of square degrees in sky coverage and from 24 to 28.5 in magnitude. The camera is built around a CCD mosaics approximately 30 cm square, made of 40 large thinned CCD devices for a total of 20 K x 18 K pixels.
The camera can be divided in three main parts: the integration of the CCD devices, the thermal and the mechanical aspects:
* The CCD mosaic; from the pavement of the 40 2K x 4K buttable CCDs on the cold plate to their connection with Kapton flex circuit to a custom made vacuum proof connector allowing a direct plug of the controller boards.
* The realization of the thermal path from the cryogenic unit, a close cycle pulsed tube with a power of 80 W at 150 K, through the cold capacity, allowing a slow warm-up during cooling shutdowns, to the thermal dispatching leading to a temperature uniformity better than 0.5 K on the whole CCD mosaic.
* The mechanical aspect of the realization of a highly integrated cryostat, from the cold plate fixations, taking into account the thermal dilatation and loss, through the thermal shielding and the vacuum consideration, with low out-gassing materials, to the cryovessel concept designed for easy access and maintenance of the CCDs.
To describe the camera this paper will follow the thermal flow, going from cold to hot. First explaining the cold generator and the cold path to have CCD at 153 K then after having a presentation of the CCD mosaic we will go to the hot parts that is the cryovessel and its components. A view of the camera mounted on its structure is shown in figure 1.

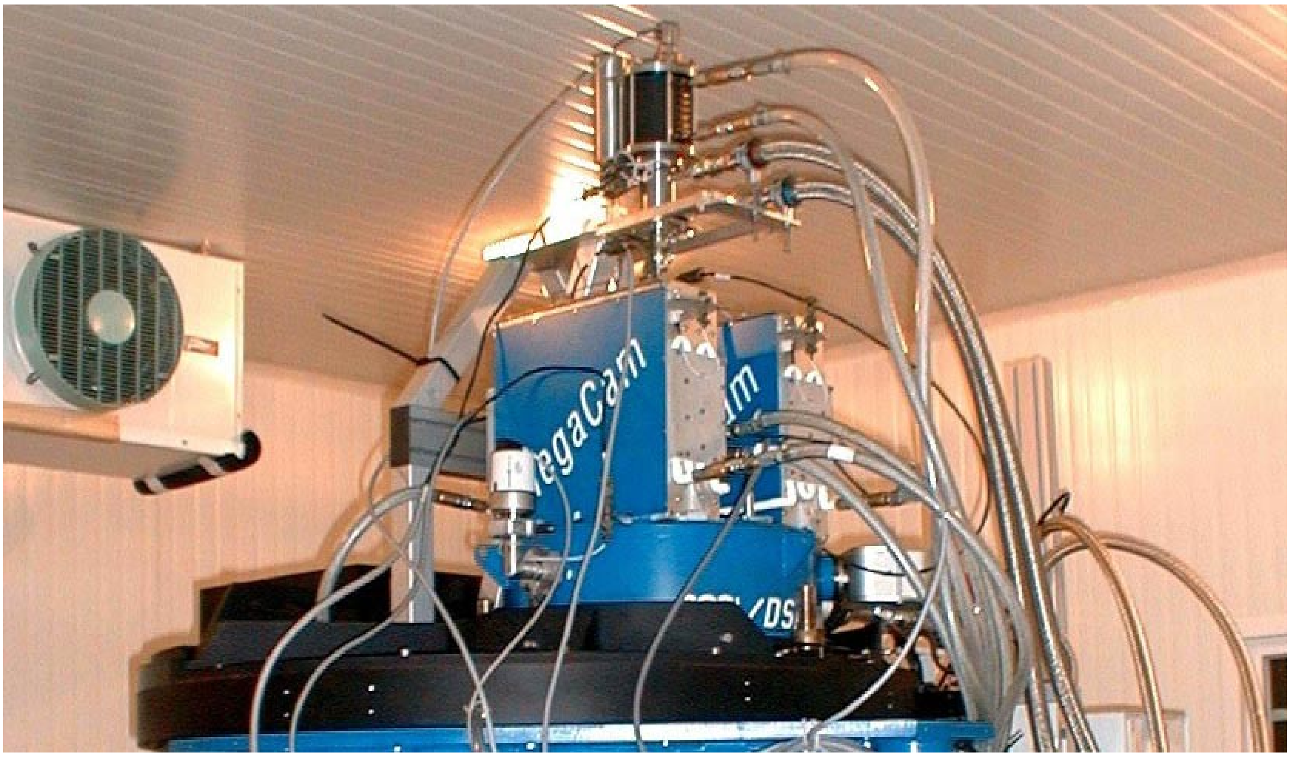


figure 1. **The camera cooled down with its electronics boxes**

2. THE CAMERA COLD PATH

2.1 The cryocooler

To cool down the CCD mosaic to 153 K a closed cycle cold generator is used. This cryocooler consists of a compressor, a rotating valve, a helium buffer and a pulse tube. The He compressor is located on the floor near the telescope and a glycol circulation drives of its power dissipation. From this compressor two He flexible lines of 40 meters, high pressure and low-pressure return, run on the telescope to the rotating valve situated above the camera. The rotating valve step motor creates from the high (21 bars) and low pressure (10 bars) a pressure wave inside the pulse tube at a frequency of 7 Hz. The fixation of the rotating valve on the instrument structure is done trough dampers to absorb induced vibration (figure 1). The only mechanical moving parts of the cryocooler on the telescope are found on the rotating valve, which can be easily dismounted for maintenance without touching the camera. Two 20 cm long He lines do the connection between the rotating valve and the pulse tube.
In the pulse tube it is the oscillating gas flow itself that ensures the cooling effect. With only helium gas flow and no moving parts, the pulse tube is a vibration-free cryocooler. The maximum cold power available is 90 W at 140 K, it can be manually changed with a by-pass on the compressor by adjusting the value of the low-pressure He return. The cold end of the pulse tube, situated in the cryostat under vacuum, is attached to a part called the cold capacity.
Both rotating valve and pulse tube have an external glycol circulation to extract their power dissipation (400 W).

2.2 The cold capacity; a cold dispatcher, filter and capacity.

Inside the cryostat stands the cold capacity made of 10 Kg of aluminum coated with 50 micron of nickel to reduce out-gassing pollution. The cold capacity is attached to the top flange of the cryostat by 4 rods made of fiberglass epoxy to reduce the thermal losses. During the 1.5 hours for the installation of the instrument from its set-up area on the floor to the telescope the helium lines shall be disconnected, therefore the cooling process is stopped Thus the role of the cold capacity is to drive the cold toward the CCD cold plate and to keep the CCD mosaic temperature under 160 K in order to avoid water out-gassing which starts to appear above 170 K. As the power of the pulse tube is dependent on the inclinations, the cold capacity also acts as a filter versus thermal power variation of the pulse tube (± 2 W) when the telescope moves. On the cold capacity a thermal probe (PT 100) and 2 heaters (2 x 12W) are glued to measure the temperature and to make a quick warm up of the camera. The connection to the periphery of the cold plate is done from the cold capacity by copper braids to obtain a thermal uniformity on the plate. The thermal resistance of those braids can be adjusted by varying the numbers of braid mounted. The final version is done with two sets of 3 braids that give a temperature of 120 K on the cold capacity to obtain the 140 K on the cold plate and 153K on the CCD mosaic (figure 2).

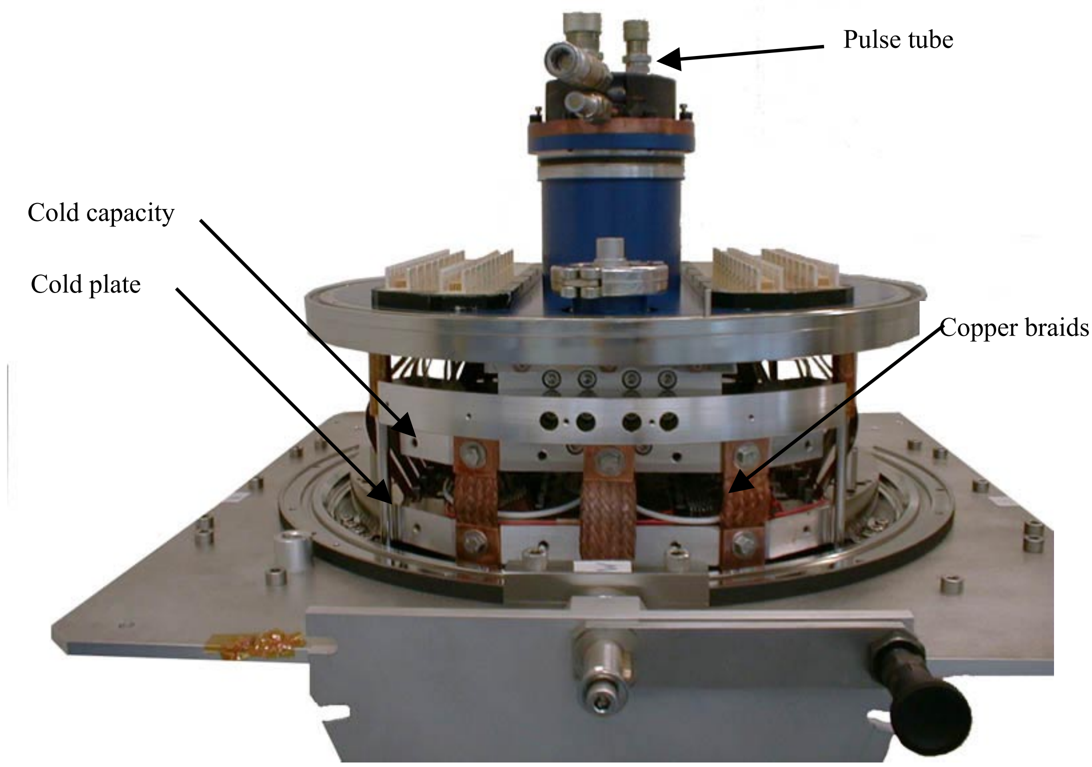


figure 2. **View of the cold path**

3. THE COLD PLATE

3.1 Cold plate design

The cold plate on which the CCD devices are attached has to satisfy a number of constraints and must provide:

- Precise machining at the locations of the CCD attachments,
- Square holes for the CCD connectors,
- Access, despite the 40 CCD flat cables to the outside world, to the copper braids,
- Good temperature uniformity across the whole mosaic surface,
- Good vacuum behavior with no out-gassing,
- Low differential expansion coefficient compared to the CCD packages,
- Important specific heat coefficient to facilitate the temperature regulation and more important to protect the CCDs from too fast a temperature change,
- Reasonable total weight and machining cost.

3.2 Choice of the cold plate material

Extensive studies have been pursued to choose the material satisfying the above requirements: we studied Copper, Aluminum alloy, Silicon carbide, Invar, Beryllium and Aluminum nitrure, allowing the thickness to vary between 10 and 30 mm. Copper was rejected because the thickness (therefore the weight) needed to be too important in order to meet the specification for the flatness of the mosaic. Beryllium is much too difficult (therefore too expensive) to handle

and machine. SiC is also difficult to machine (specially making square holes). We could not find a provider for a piece of AlN the size of the cold plate. Invar was not used because of its low thermal conduction.
We chose Aluminium because it was the simplest solution for supply and machining thus lowering the cost. The thermal conduction (λ = 240 W / m. K) and the specific heath (Cp = 900 J / K. Kg) are good, the Young Modulus (E = 72 GPa) is not critical for us since the load on the cold plate is small and the aluminium is lightweight. The main weakness of aluminium is its Coefficient of Thermal Expansion (α = 24 ppm / K), ten times larger than Invar of the CCD package. We can work around this obstacle if we accept the fact that while cooling down the gap between each CCD package diminish (from 600 to 500 micron) and if we paid enough attention to their fixing on the cold plate to avoid constrain (thus deformation) on the CCD. Also the attachment of the cold plate on the hot flange must allow the cold plate to shrink (see section 5). An other disadvantage of aluminum is it's out-gassing; it was reduced (factor 100) by having a Nickel coating on all exposed surfaces.
The cold plate is shown on figure 2. For each CCD, 8 holes are necessary: a big square hole for the CCD connector, 2 holes for the studs that are used to lower the CCD package, 2 holes for the accurate positioning of the CCD package, 3 holes for the screws. Also several holes are made for the attachments. The dimension of the cold plate is Φ 400 mm for a thickness of 25 mm (figure 3).

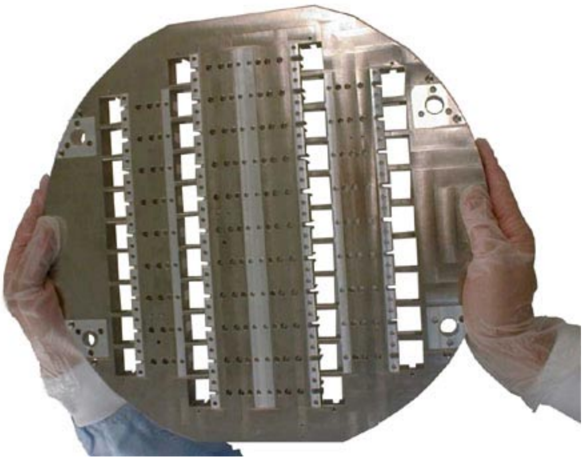


figure 3. **View of the cold plate**

Thermal uniformity

A finite element model was used to study the thermal uniformity and the mechanical deformation of the cold plate (figure 4). Since the flex cables connecting the CCDs to the CCD controller are perpendicular to the cold plate thus making 4 walls, the cold is brought to the periphery of the plate, using 6 copper braids.

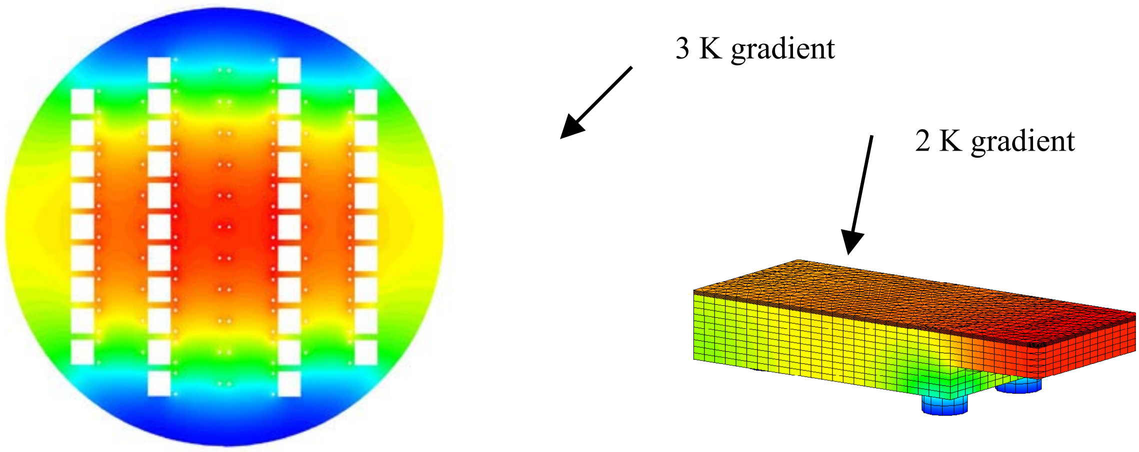


figure 4. **Thermal uniformity model of the cold plate and of the CCD**

The thermal dissipation of the 40 CCDs in nominal functioning mode is 5 W. The gradient across the cold plate is only 2.7 degrees. Most of the CCD packages have a temperature probe mounted of them. The dispersion of the temperature of the CCD packages is shown in the table 1 with a cold plate cooled to 140 K. This dispersion includes the dispersion of the temperature probes themselves and the dispersion in the mounting of these probes on the packages, resulting in a dispersion of the thermal connection between the probes and the packages. The intrinsic temperature homogeneity of the cold plate is therefore much better than the one measured in table 1.
In the CCD the glue between the Silicon and its INVAR package has a poor thermal conductivity and while making the gradient more important between the Silicon and the package it lowers the thermal gradient on the Silicon surface. This is important for the CCDs are cooled only by their three shims attached on the cold plate. This thermal aspect of the CCD was studied with a finite element model (figure 3). The thermal contact resistance between the cold plate and the CCD gives gradient of 10°C for a fixation torque of 0.5 N/m on each of the CCD mounting shims.

Mean (K)	stdev	min	max
143.4	1.3	140.2	146.2

Table 1: **Distribution of the temperature of the CCD packages**

Temperature regulation

A series of heaters (24 W in total) and 3 thermal probes (PT 100) have been glued to the cold plate for the regulation of the temperature. Figure 5 shows the evolution of the temperature of the cold plate in normal use: we put the MegaCam instrument on a swiveling bench and simulated several nights of observations (including different inclinations of the instrument from 0 to 60 degrees, and different external temperatures from 0 to 10 C), separated by days of “rest”. The regulated power dissipated by the heaters varies with the zenithal angle of the instrument (since the efficiency of the pulse-tube based cooling system varies with the inclination of the pulse tube) and with the heat radiation from the outside world but the cold plate temperature stays extremely stable, with a dispersion around the nominal value of only 0.04 K. The thermal regulation and control of the camera is assured by a PLC design CEA[4].

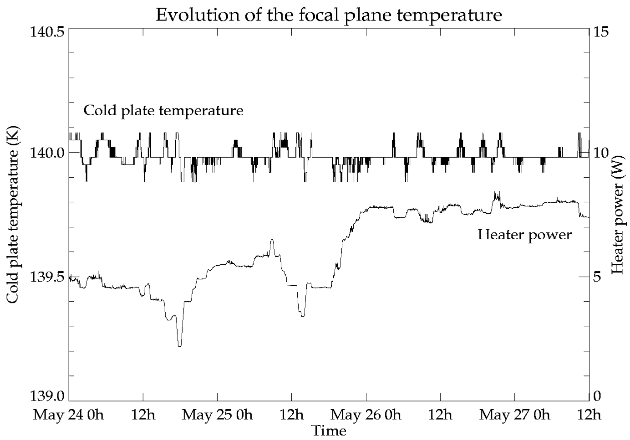


figure 5. **Evolution of the focal plane temperature**

4. THE CCD MOSAIC PAVEMENT

We intended to build the array in a “plug and play” way so that any CCD device could be plugged anywhere in the mosaic with no further mechanical adjustment. This allows one, for example in the case of a failure of a CCD in the center, to replace it by a spare device, or one located in one of the corners without any danger for the neighboring devices. This plug and play approach required a strong collaboration with the CCD manufacturer, which had to deliver 40 quasi-identical packages.

The CCD package

The CCD Invar package has three height defining pins whose lengths are adjusted with shims. The accuracy of the machining of the shims and the flatness of the CCD chips themselves is such that the height of the package (from the lower surface of the shims to the surface of the silicon) is 14.001 mm with a standard deviation of 6 microns. The packages rest on 7 very precisely machined strips on the cold plate (figure 6). The precision of the machining of these strips is such that they are fully contained between two parallel planes separated by no more than 10 micron.
The x and y position of each CCD package on the mosaic is defined by two positioning studs with an accuracy of ±12 micron. The specification for the position of the CCD itself within its package was to have the first and last column, as well as the top and bottom row of pixels at a distance of 50 micron from the edge of the package. This could not be checked by looking at the pixels since we use backside illuminated devices and we checked it by measuring the position of the silicon substrate.
The gaps between adjacent CCD package devices, when the plate is at room temperature, has been measured at 0.6 mm on three sides and 3.3 mm on the 4th side (to give room to the pads connecting the CCD to its connector). The distance between the edge of the first pixel to the sawn edge of the silicon is 100 ± 10 µm at the top edge and 210 ± 10 µm at the sides (manufacturer data), a further margin of 50 µm from the edge of the silicon to the edge of the metal package allows to protect the CCD against damage.
Knowing these values, the distance between two adjacent CCD pixels is 1.1 mm at the sides, 0.9 mm at the top edge and 5 mm between a top edge and the connector side, which gives a filling factor for the whole mosaic of 93 %.

Mounting a CCD package

Each CCD package also has two long studs that are used to lower the package from above the mosaic without any risk of touching the neighboring devices. This allows one to safely remove and replace a faulty device, as illustrated in figure 6.

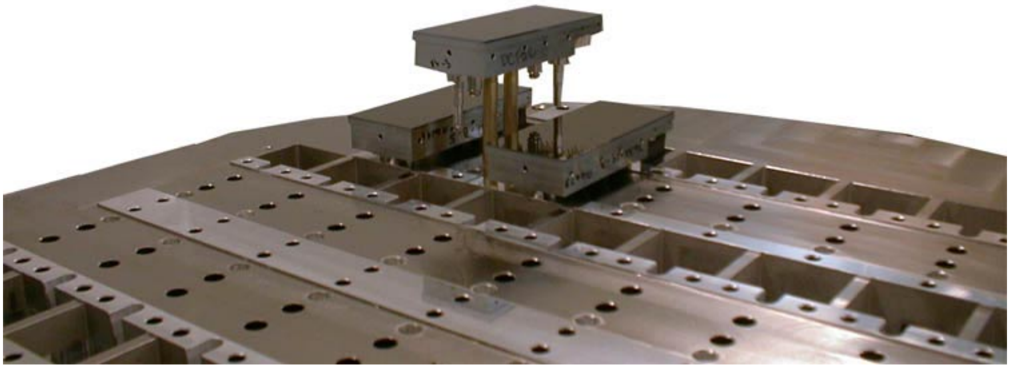


figure 6. **Removal of a CCD from the mosaic**

Flatness measurements

In order to respect the MegaPrime image quality error budget, the flatness of the whole mosaic at 0 degree zenith angle should be ± 32.5 µm including the CCD array deviation from the best fit plan and from the deflection of the cold plate.
We have independently measured the flatness of each individual CCD before their assembling on the cold plate and the 7 rows of strips of the cold plate on witch the CCDs are mounted
After the population of the CCD mosaic, the measurement of the flatness was performed in two steps: first at room temperature with a microscope based system which has an accuracy of 3 µm (figure 7, left), and then at the operating temperature (153 K) through the window (figure 8), using a triangulation method and a laser beam (figure 7, right). The final result of this measurement is showed in figure 9 respectively for the width and length side. The flatness of the CCD mosaic at cold temperature is ± 16 µm, which is much better than the requirement.

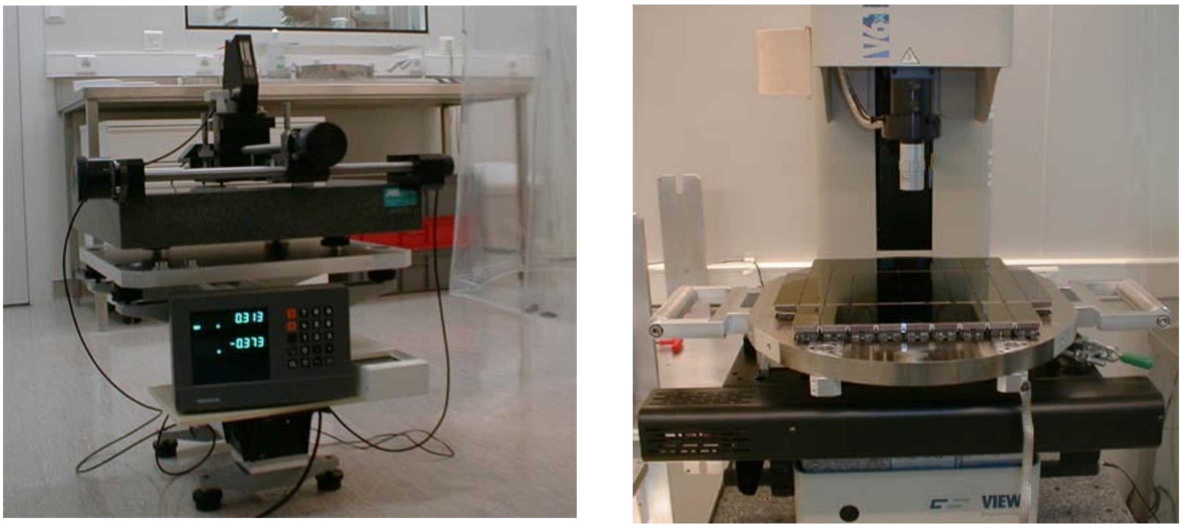


figure 7. **The CCD mosaic metrology tools**

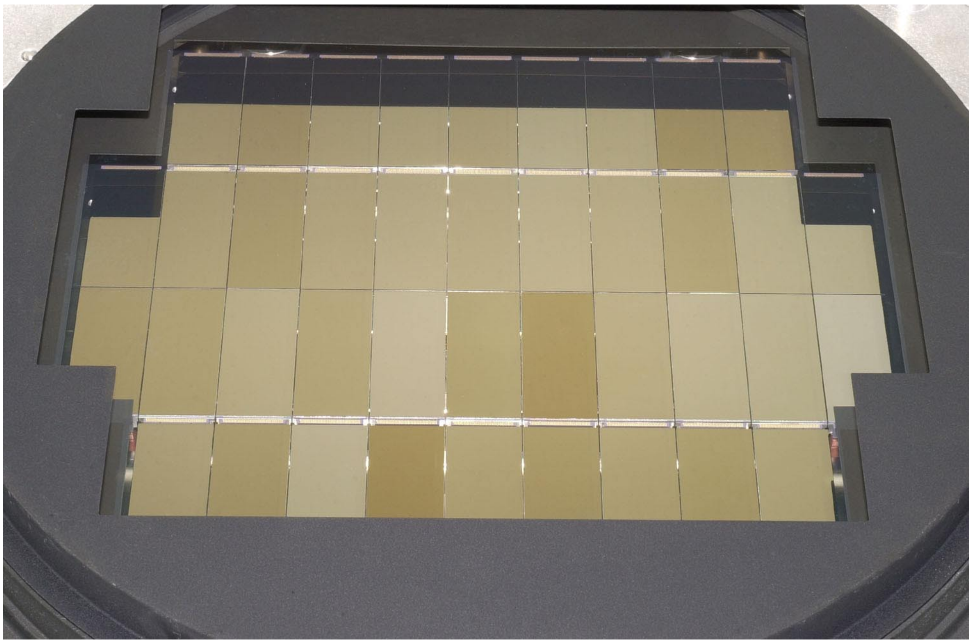


figure 8. **View of the MegaCam 40 CCDs mosaic through the window.**

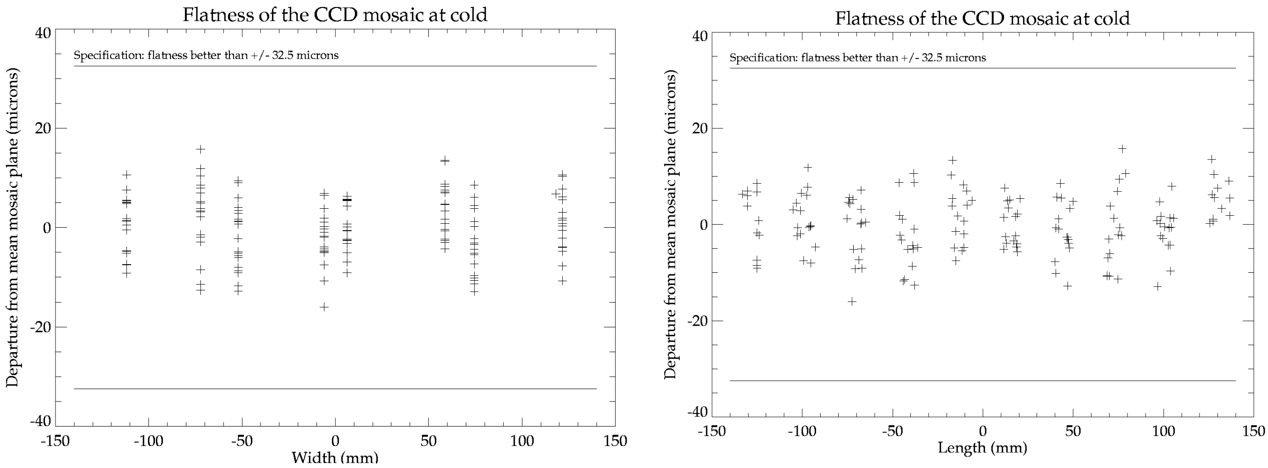


figure 9. **CCD mosaic width and length flatness metrology.**

CCDs connections

There are no electronics components inside the cryostat: this avoids out-gassing, simplifies the camera assembling, reduces the thermal dissipation, and facilitates the maintenance given that access is outside. There is no disadvantage since the controller boards are directly plugged on the cryostat hermetic connectors. A 15 cm long Kapton 4 layer flex circuit connects each CCD to the connectors. The thermal loss through the 40 flex circuit is less than 5 W and the out-gassing of the flex is reduced with the use of the Kapton material (figure 10).

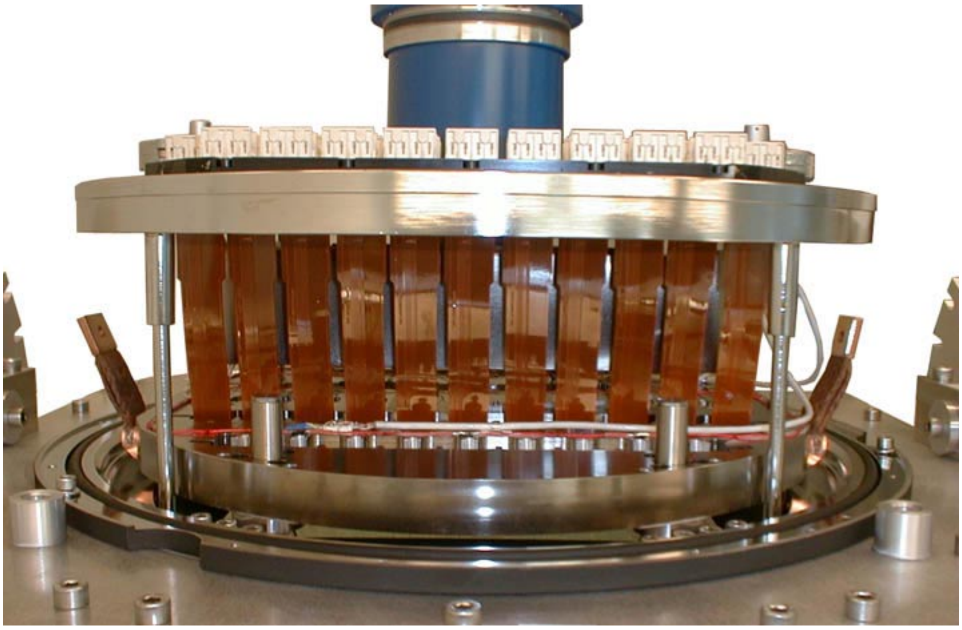


figure 10. **View of the 1st row of the flexes Kapton cable**

5. THE CRYOSTAT

Cold plate attachment to the cryostat

The cold plate is mounted on the cryostat flange with 4 special titanium clips to counterbalance the mechanical stress from the contraction of the cold plate during the cool down or warm up phases. While allowing the cold plate to shrink (1mm shrink on a 400 diameter) when cooled the clips prevent the plate displacement due to the inclination of the telescope. We have used a finite element model to study the thermal gradient and the mechanical aspects (constrain, deformation, 1st eigen value above 1000 Hz). These clips are inserted in heat insulators held in the flange in order to minimize heat conduction losses through conduction (figure 11).

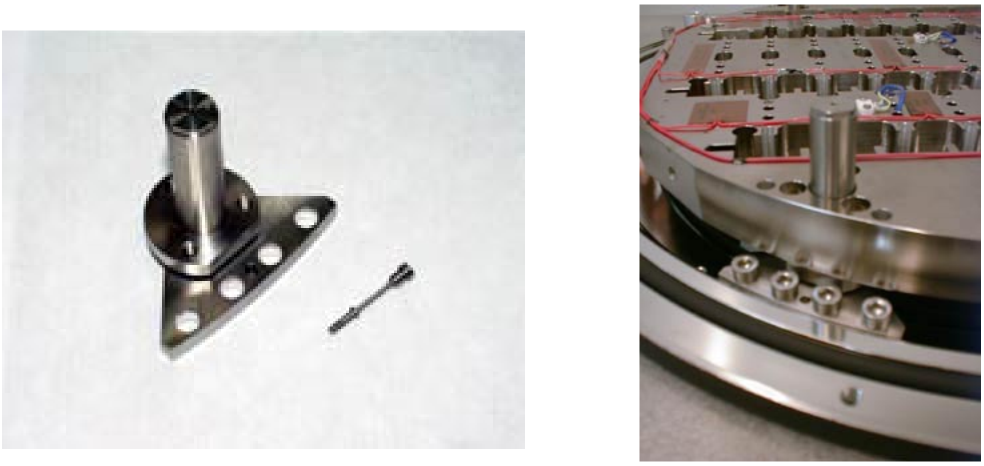


figure 11. **The clips used to mount the cold plate**

Thermal screens

To insulate the cold element included in the cryovessel from the outside room temperature several thermal screens are used in preference to MLI to minimize out gassing.
The front screen between the mosaic and the window is made of a 1 m thick Cu sheet cut out to act as an optical aperture. Four copper braids coming from the cold capacity cool it. To prevent out-gassing and optical reflection it is black painted with a paint used in space application that withstand cold cycle and has a low out-gassing value.
The two screens surrounding the cold elements are made of a 1 mm thick Cu sheet folded in half cylinder and have a 50 microns nickel coating to prevent out-gassing and to have a good emissivity value to lower the thermal losses by radiation (figure 12). They are fixed to the cold capacity and have holes in front of the vacuum entrance of the cryovessel (pump and gauge).

Windows

The window is made of a 25 mm thick, 400 mm diameter glass (type BSL7Y) with a coating to prevent reflection. The thickness was determined by the security factor i.e. 6 at see level and 10 at the summit. The central deformation due to vacuum is 72 microns. The main thermal losses of the camera is due to radiation of the windows on the CCD i.e. 21 W of the 38 W total thermal losses (figure 8).

Cryostat body

The cryovessel is composed of 3 parts, the top and bottom flanges and the body. Those parts are made in stainless steel with an internal electrolytic polish to reduce their emissivity factor and baked before assembly to reduce their out-gassing.
On the bottom flange the cold plate is mounted with the titanium clips, after the front screen and the window are mounted. On the top flange are mounted the pulse tube, the two connectors for CCDs and the two connectors for thermal control (heaters and sensors), and the cold capacity.

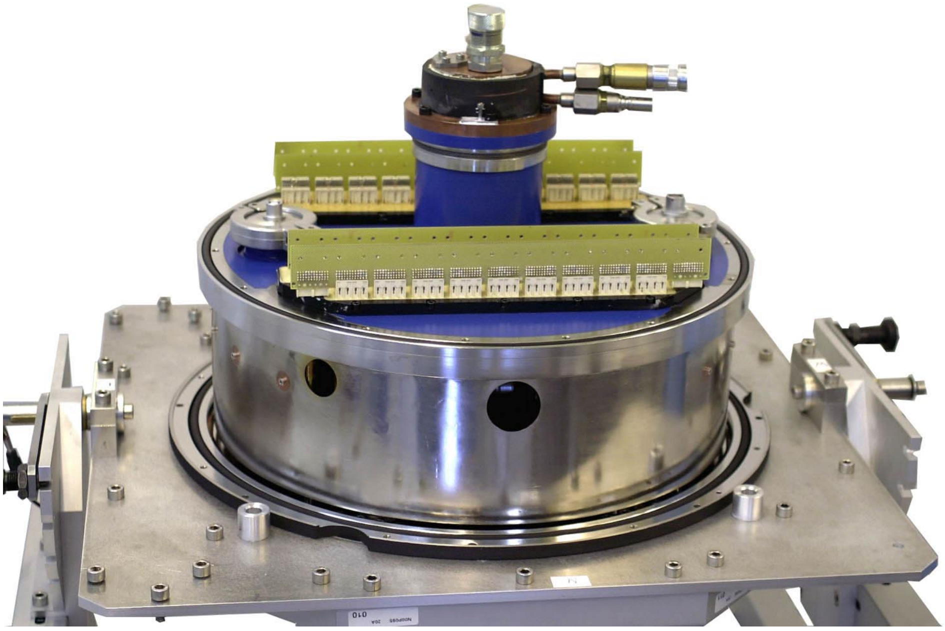


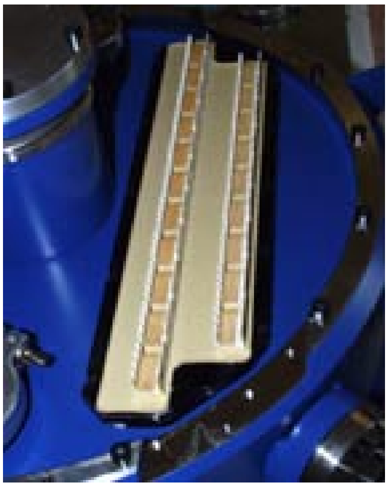
figure 12. **Thermal screens in the cryostat**

Once both flanges are separately equipped the top one sit on the bottom one through 4 stainless steel rods that maintain it a bit lower than its nominal value. Then the cabling operations are done between them i.e. sensor and heater, Kapton flex circuits, copper braids. When all connections are tested good the surrounding screens are mounted. The last operation is the brought down of the cryovessel body first fixed to the bottom flange and then fixed to the top one thus lifting it by a few centimeter to reduce the bending of the CCDs flex circuit (figure 10). This unusual cryovessel assembling design (body after the flanges) allows an easy access to the inside of the cryostat especially for the CCDs connection. All the integration of the MegaCam camera has been done in a class 100 clean room. (figure 13)

figure 13. **Lowering of the cryostat body in the class 100 clean room.**

CCD connectors and electronics boxes[5]

Since no electronics is located inside the cryostat and to avoid further flex between the connectors and the controllers board we have made a special hermetic connector that allows on its external face a direct plug of the CCD controller boards. There is one of those connectors implanted on each side of the pulse tube. They are made of a 3.2 mm printed circuit board accommodating 20 4*12 pins connectors on the internal face and 20 2*20 pins on the external face, both connectors are tied by printed wires. This board is then glued with conductive silver glue in a aluminum flange and drowned with epoxy glue on both side. The internal face is varnished with non-conductive low out-gassing varnish. Before connecting the CCDs flexes to their internal connectors a ground cap is mounted on the external face and removed just before plugging the board (figure 12). The leak of those connectors is under 1 10^{-9} mbar/ l. s. (figure 14).



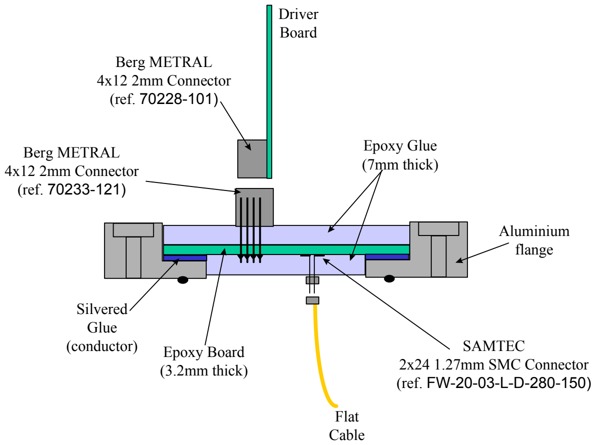


figure 14. **CCDs connectors external view and design**

Vacuums aspect

The cryostat is equipped with a vacuum gauge a DN40 valve and a ionic pump.
In order to avoid thermal losses by convection and contamination of the CCD a vacuum better than 2.10^{-5} mbar must be reached inside the cryostat. When the instrument is mounted on the telescope the vacuum must be held without any mechanical pumping unit available. To reach this goal we have paid attention to all out-gassing materials inside the cryostat; moreover before cooling down after an opening, the camera is baked out. This baking consists of: several boiled nitrogen scavengings, the cryostat is then connected to a Zeolite canister and warmed up at 50 °C, finally the cryostat is pumped downed until a vacuum of 5.10^{-6} mbar is reached. Once the cold is done the pulse tube acts as a cryogenic pump and the vacuum reachs 4.10^{-6} mbar without mechanical pump. The advantage of having an external Zeolite trap when baking is that the pollution is removed and the vacuum quality stays good until the cryostat is opened. To conserve the vacuum quality when the camera is cold and the pulse tube is off, i.e. instrument being mounted on the telescope or power faillure, a small ionic pump powered by an UPS is connected to the cryostat. The ionic pump is also active when the pulse tube is on for it eliminates different gases than the cryogenic pump. Figure 15 shows the vacuum pressure in the cryostat with the CCD mosaic at 153 K and the ionic pump on: the vacuum is stable around 2.10^{-6}. In figure 15 the vacuums variation is due to external temperature brought from 10°C to 0°C in the climatic room.

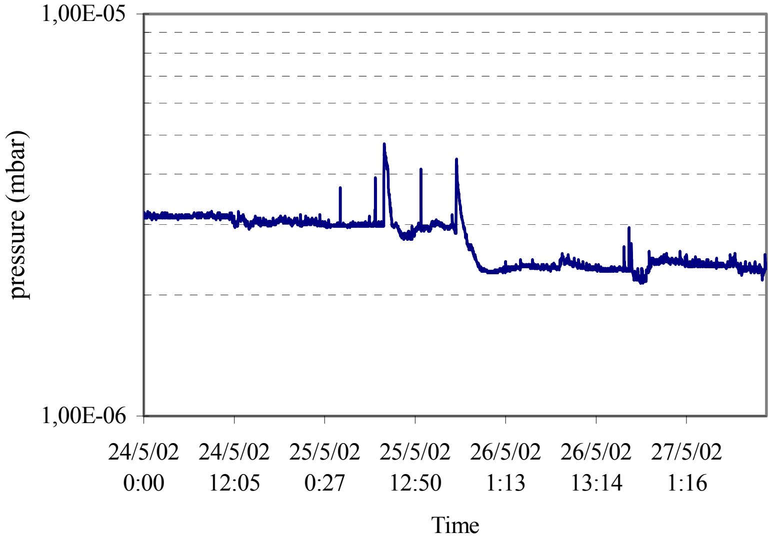


figure 15. **Static vacuum in the cryostat**

6. CONCLUSION

The camera was delivered to the CFHT in June 2002. It was installed in a laboratory and cooled down with the CFHT team, everything worked out nominally and all the CCD devices were alive. The know-how was passed from the CEA team to the CFHT team for they will maintain and operate the instrument. The camera we be installed with the MegaCam structure[6] on the telescope by the beginning of October to have its first light.

REFERENCE

1. MegaCam home page http://www-dapnia.cea.fr/Phys/Sap/Activities/Projets/Megacam/index.htlm
2. MegaPrime home page http://www.cfht.hawaii.edu/Instruments/Imaging/Megacam/index.htlm
3. O. Boulade et al., "MegaCam, the new Canada-France-Hawaii Telescope wide field imaging camera", in Instrument Design and Performance for Optical/Infrared Ground Based Telescopes, M. Iye and A. F. Moorwood, eds, Proc. SPIE **4841**, 2002.
4. J-Y Roussé et al., "The CFHT MegaCam control system: new solutions based on PLC, WorldFIP fieldbus and java softwares", in Instrument Design and Performance for Optical/Infrared Ground Based Telescopes, M. Iye and A. F. Moorwood, eds, Proc. SPIE **4841**, 2002.
5. J. de Kat et al., "The electronic controller of the 40 CCDs MegaCam mosaic," in Scientific Detectors Workshop, J. Beletic and P. Amico, eds, 2002.
6. S Aune et al., "The CFHT MegaCam filter, shutter and roll pitch mechanisms", in Instrument Design and Performance for Optical/Infrared Ground Based Telescopes, M. Iye and A. F. Moorwood, eds, Proc. SPIE **4841**, 2002.