

Manual for X-ray setup and module qualification

ETH Pixel Group

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The ETH pixel group is equipped with a Seifert X-ray tube which has been used for the X-ray qualifications of modules for the phase 1 upgrade of the CMS pixel detector. This note documents the use of the setup and the procedure to test layer 1 (L1) and layer 2 (L2) modules.



Figure 1: Picture of a L1 module



Figure 2: Picture of a L2 module

1 Operation of the X-ray setup

The test setup (see Figure 3) is centred around an X-ray tube which has a chromium (Cr) anode. The radiation produced by the tube can either be used directly to obtain high photon rates or directed towards one of five metallic targets that produce a monochromatic but less energetic beam. The available targets are Iron (Fe), Copper (Cu), Molybdenum (Mo), Silver (Ag) and Tin (Sn).

Samples are tested in a climatic chamber where air humidity is kept low and which can be cooled down to a desired temperature (up to -15°C to -20°C depending on the state of the Peltier elements and the water flux used for cooling).

A Keithley power supply is allocated to the setup which is used to provide a depletion voltage to the modules.

A PC is available for the execution of tests.



Figure 3: Picture of the X-ray testing setup including the X-ray tube, the control for the climatic chamber, the Keithley, the PC and the water supplies.

1.1 Operation of the X-ray tube

One should be cautious when operating the X-ray tube since it produces highly energetic photons which can be harmful. A regulation describing the risks of using the X-ray setup can be found in Appendix A and should be read and signed by every user of the setup.

- Open valve entirely for X-ray cooling (3 on Figure 4).
- Switch on X-ray machine (3 on Figure 5).
- (Re)close the door of the X-ray setup housing, press round, green **START** button (4 on Figure 5).
- Turn key to **ON**.
- Warm up X-ray tube by selecting **F7**. Enter the required current and voltage settings by selecting **F2**, **F4 or F6**. One shouldn't operate the tube with very small currents and large voltages as well as the other way around. Suggested values are 60 kV and 30 mA for warming up the tube. Press **Enter** when finished, then **START** (square green one, 5 on Figure 6). This will take up to 30 minutes depending on when the tube was last operated at this or a higher voltage. If the voltage is not set, check green interlock button (4 on Figure 5) and the door and press **CL** to delete the error message.
- To control X-ray tube settings during operation, use the **id3003** programme which is installed on the PC. With this, the X-ray generator can be switched

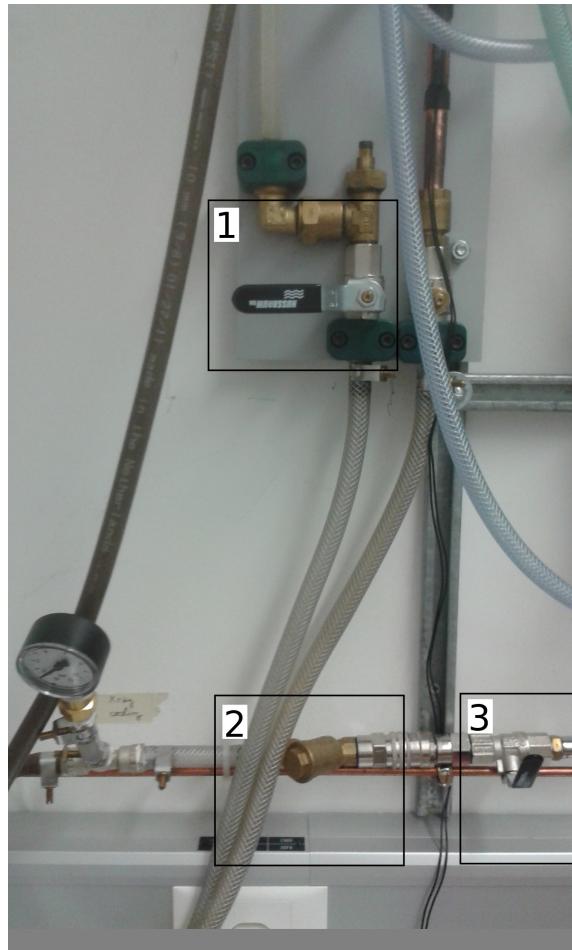


Figure 4: Picture of the water supply for the X-ray setup. Water supply 1 feeds the climatic chamber, supply 3 is used by the X-ray tube and filtered by 2.

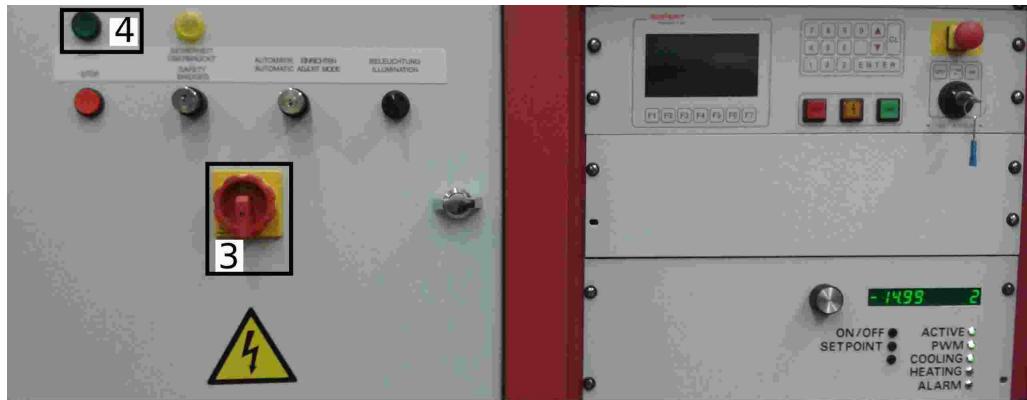


Figure 5: Picture of the command board which enables to operate the X-ray tube and the climatic chamber.

on and off, the voltage and current settings can be adjusted, and the shutters opened and closed. Shutter 1 directs the beam to the targets, shutter 3 directs it to the modules. Some examples:

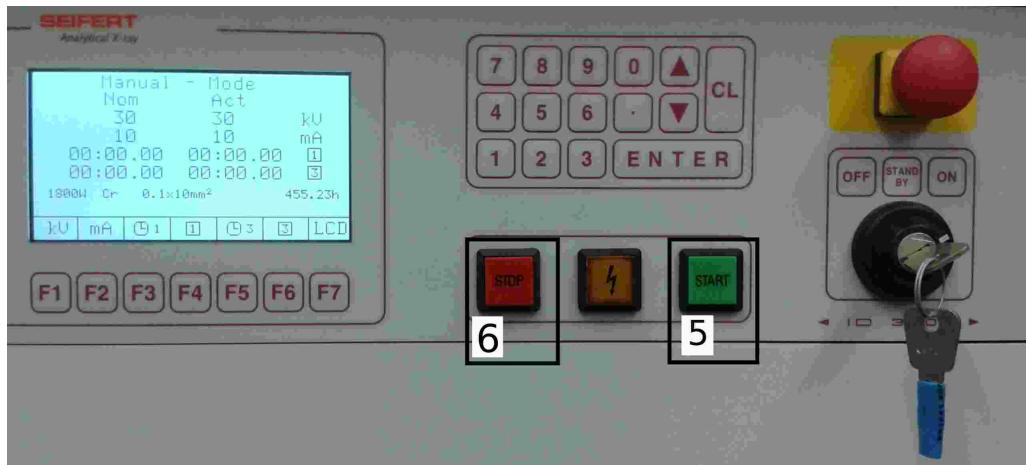


Figure 6: *Detailed picture of the control panel of the X-ray tube generator.*

```
$ id3003.py open shutter 1
$ id3003.py close shutter 1
$ id3003.py set hv on
$ id3003.py set hv off
$ id3003.py set voltage 30
$ id3003.py set current 10
$ id3003.py get voltage
$ id3003.py get current
```

- When taking a break, close the shutter and turn off high voltage. Turn key to **STAND BY**.

After use, turn off the setup as follows:

- Close the shutter, turn off the high voltage.
- Press **STOP** (6 on Figure 6).
- Turn key to **OFF**.
- Turn off X-ray machine (3 on Figure 5).
- Close water valve.

1.2 Targets for monochromatic X-ray beam

The setup is equipped with a movable holder that holds five metallic targets used to create a monochromatic beam.

- To change the target during operation, the **xrf** programme is needed. Available targets are Zn, Cu, Mo, Ag, Sn. Some examples:

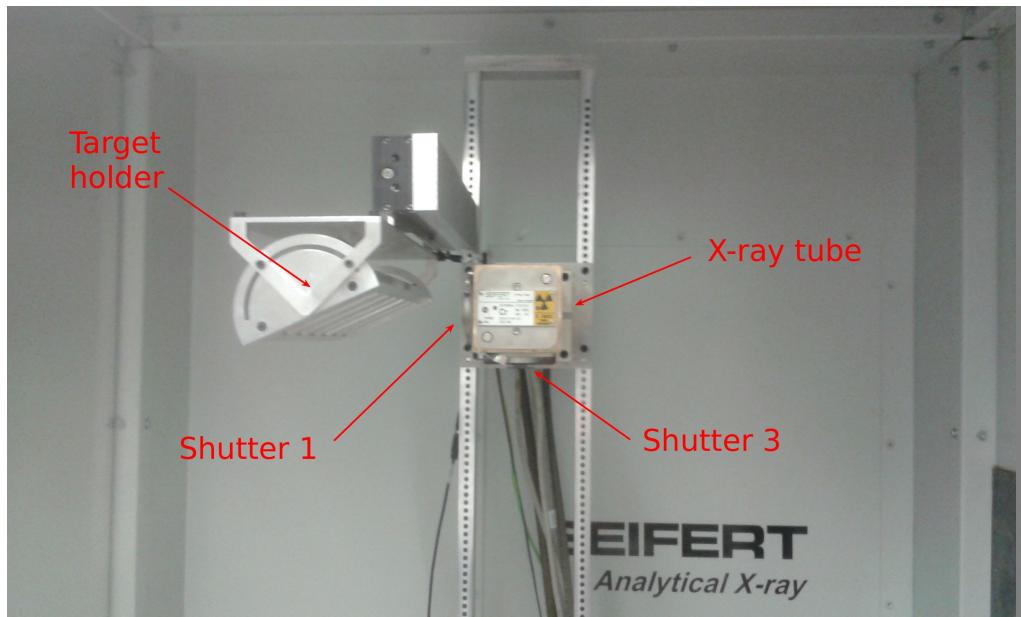


Figure 7: Picture of the target holder and the two shutters of the X-ray beam.

```
$ xrf Ag
$ xrf Mo
$ xrf Sn
$ xrf Screen
```

1.3 Climatic chamber

The climatic chamber creates an temperature and humidity controlled environment to test modules. The chamber is continuously flushed with dry air to keep the humidity low. Six Peltier elements¹ are used to cool down the chamber to up to -20°C.

- Open valve for climatic chamber cooling (2 on Figure 4) until the pressure is about 2 bar (check with left barometer in the X-ray setup). The water pressure is relevant as the minimum temperature to which the chamber can be cooled down to depends strongly on it.
- Switch on cooling with the **ON/OFF** button
- Choose set point by pressing the **SETPOINT** button while turning the knob at the same time until the desired temperature is reached.
- After use turn the cooling off by pressing the **ON/OFF** button and closing the water valve.

¹Type C2-50-1514 from www.tellurex.com

1.4 Keithley

The Keithley power supply is used to provide a depletion voltage to the sensors of the modules.

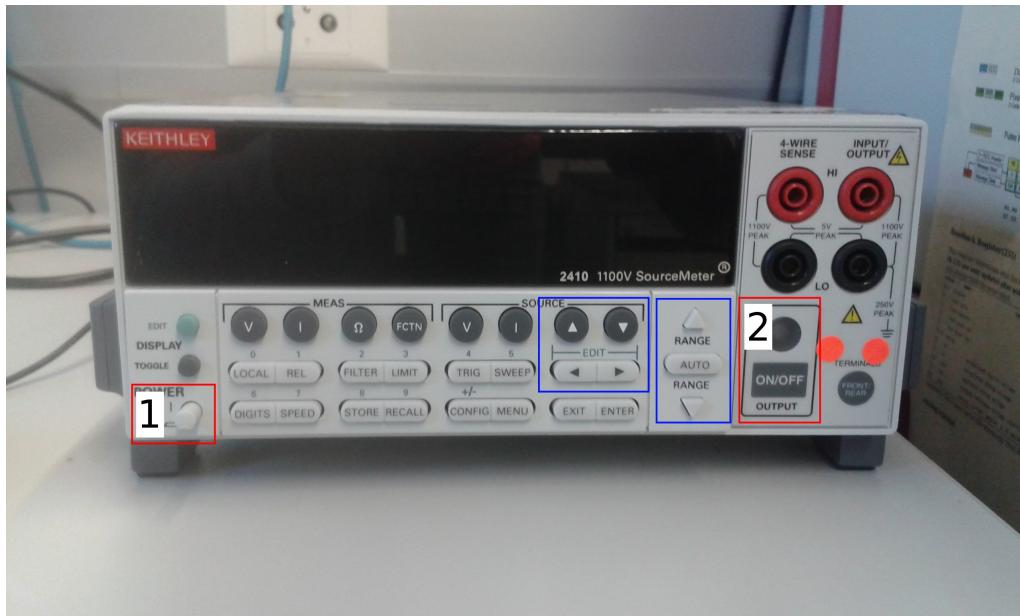


Figure 8: Picture of the Keithley power supply.

- Turn on Keithley by pressing 1 on Figure 8.
- Choose the desired bias voltage with the buttons marked in blue on Figure 8.
- Apply bias voltage to the module by pressing 2 on Figure 8.

1.5 Troubleshooting

Here are some issues that can occur during the use of the X-ray setup:

- **Door of the X-ray setup is not closed properly: "Emergency stop" appears on the display when one tries to start the tube.** Make sure to properly close the door and to press the green **START** button (4 on Figure 5) before retrying.
- **Climatic chamber is not reaching low temperatures.** Try adjusting the water flow. If this does not help, one or several Peltier elements might be faulty. Replace them using the description in Appendix B.
- **Error message saying that the water flow is too low.** If it was forgotten to open the water valve, do this and start over. Otherwise, the flow is too low due to dirty filters. Check external filter on the wall (2 on Figure 4) first which is easier to clean. Unscrew and clean the filter with water and dry air. If this does not solve the issue, one needs to clean the built-in filter in the X-ray tube

casing. This is a very delicate operation due to the sensitive berillium windows in the tube. It should only be performed by an experienced person who has done this before. Instructions can be found in Appendix C.

- **Targets do not move.** Scroll the targets to the "back" position manually.
- X-ray tube in December 2016 is at the end of its lifetime, so it will likely stop working in the near future. The ETH pixel group is in possession of a replacement tube. Appendix C explains how to access to the tube for it to be exchanged.

2 Module testing setup

The setup for testing L1 and L2 modules differs slightly. It is possible to test up to two L1 or four L2 modules at the same time.

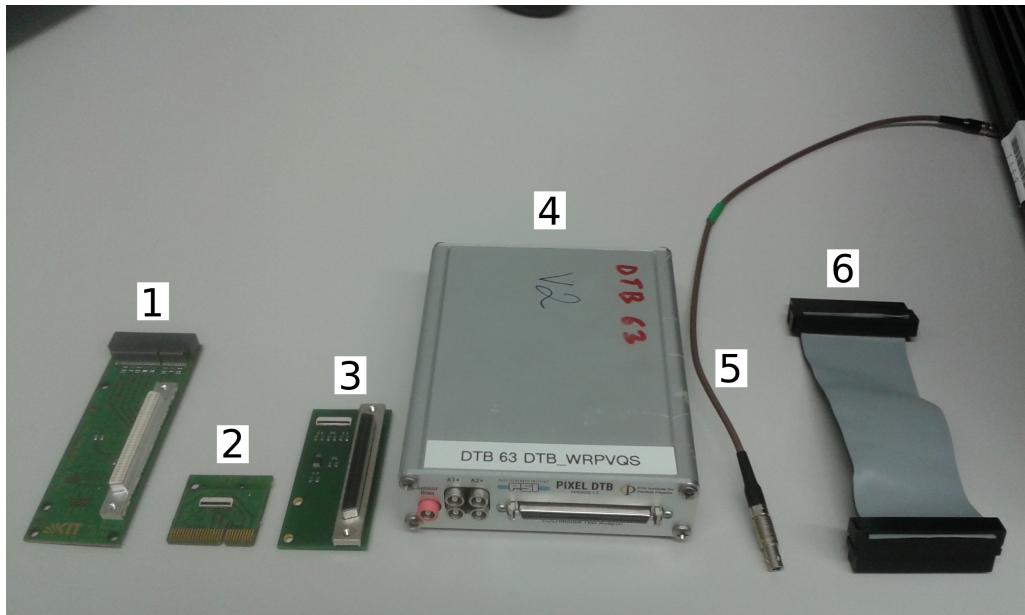


Figure 9: *Picture of the material needed for testing L1 and L2 modules. 1 is the module adapter for L2 modules, 2 the adapter card for L2 modules, 3 the module adapter for L1 modules, 4 the Digital TestBoard, 5 the LEMO cable, 6 the flatband cable.*

In addition to the components of the setup listed above, the material needed for the qualification consists of:

- One Digital TestBoard (DTB) including power and USB cable per module
- One flatband cable and module connector (L1 or L2) per module
- One insert card for each L2 module
- 1 LEMO cable per module connecting the Keithley to the DTB



Figure 10: *Picture of the placement of two L1 modules in the climatic chamber* Figure 11: *Picture of the placement of four L2 modules in the climatic chamber*

Two L1 modules fit in the climatic chamber. Figure 10 shows their orientation. Four L2 modules can be positioned with the available fixations in the climatic chamber as can be seen in Figure 11. Note that the modules should be placed underneath the window in the door of the climatic chamber which is covered with aluminium foil.

3 Programs used for the qualification

The testing of L1 and L2 has been almost completely automatized. For this, three different software are used. The tests are performed with **pXar**, **elCommandante** operates the different components of the setup and **MoReWeb** analyses the results of the qualification. Links to the code and information to the software can be found in Appendix I.

3.1 pXar

pXar is the software that communicates with the modules via the DTB. All tests needed for the X-ray qualification are implemented in this software. In order to start **pXar**, one needs to specify a folder that contains start parameters for the module. These include DAC settings for every ROC, trimbit settings for each pixel, TBM settings as well as other files containing for example information on the test parameters. More details on these files can be found in Appendix F.

3.2 MoReWeb

MoReWeb is a software that analyses the results of the X-ray qualification and which produces an *.html* file displaying the characteristics of the module. Furthermore it automatically assigns a grade to the module based on the defined grading criteria.

3.3 elCommandante

In order to automatize the testing, a software named **elCommandante** was developed. It is able to stir all devices including the X-ray tube settings, opening and closing the different shutters, switching the targets, and controlling the Keithley in addition to starting **pXar** which executes the tests. Since all these settings need to be adapted depending on which test is being executed, **elCommandante** saves a lot of work in that perspective. Furthermore, the files containing the test results are put by **elCommandante** into a format that can be analysed directly by **MoReWeb**.

The only device that is not controllable with **elCommandante** is the climatic chamber, so the temperature has to be set manually before the test.

4 Specific testing conditions for L1 modules

L1 modules have several issues that prevents using the same qualification procedure than for L2 modules.

Since the power consumption of L1 modules is excessively high at low thresholds leading to many read-out errors, the modules are tested at a threshold of Vcal 80 (4000 e⁻) instead of 35 (1500 e⁻).

The noise of the PROC600V2 is quite high when all pixels are unmasked and when exposed to radiation, in particular for the edge and corner pixels, which size is twice or four times the usual pixel size. This is why the two corner pixels 0,79 and 51,79 are masked on every ROC. Otherwise, the high noise of those pixels would thwart the entire readout of the module. In addition to this, the threshold of all other edge pixels is increased even further than 80 Vcal. Furthermore, no grading on the noise of L1 modules is applied.

Due to this high threshold and because the ADC response of the pulse height is not stable when exposed to radiation, the Vcal Calibration is not performed for the modules. It would be possible to get an approximative calibration by trimming the module to a lower threshold and masking every second row and every second column to limit the noise. Then, the PH calibration algorithm would have to be rewritten such that it takes into account the jumps in the ADC. This jump seems more important for uneven rows, so it is recommended to mask those.

Furthermore, the power delivered by the DTB is in some cases not enough when measuring the efficiency at 400 MHz cm⁻¹ of L1 modules. This leads to a high number of read-out errors in that test. In such cases, one can remove the test from the test folder. In the CMS detector, the power supplies can deliver more power than the DTB such that it should not be an issue for operation.

5 Performing the X-ray qualification

This section describes the steps required to perform an X-ray qualification, from the setting up of all needed configuration files to the handling of the devices.

5.1 Starting the X-ray qualification

5.1.1 Staring the necessary devices

- Put the modules to be tested (up to 4 L2 or 2 L1 modules) in the X-ray setup as described above.
- Execute points 1 to 5 from Section 1.
- Turn on Keithley (only button 1 on Figure 8).
- Turn on climatic chamber and set the cooling to 17°.
- Verify that all DTBs are powered.

5.1.2 Setup directory for start parameters

In order to start the qualification, pxar needs configuration parameters for the module. They can be copied from the Fulltest at 17°C from the Full Qualification (FQ). With these, it is not necessary to trim the module and to optimize its pulse height again which saves time.

To prevent having too large files containing the results of the qualification, one can remove unneeded .root and .log files from the FQ. For instance, one can use the script `python ./clean_parameters_folder.py -d Mxxx` which is located in the home directory of the *production* user. Mxxx designates the module name.

5.1.3 elComandante configuration

- Two different versions of elComandante are used for module configuration such that the configuration files do not have to be changed every time between the FQ and the X-ray qualification. Therefore, use the elCommandante version: `/home/production/elComandanteXray/`
- Check the elCommandante.ini and elCommandante.conf files located in the `/home/production/elComandanteXray/config` directory. In particular, verify the test chain in the elCommandante.ini file. This differs for the qualification of L1 and L2 modules. For L2 modules, the test chain should be

```
[Tests]
Test = PixelAlive@17>GainPedestal@17>RetrimHotPixels@150MHz/cm2>
{HRData@50MHz/cm2, HRData@150MHz/cm2, HRSCurves@100MHz/cm2,
XraySpectrum@Zn, XraySpectrum@Mo, XraySpectrum@Ag, XraySpectrum@Sn,
CalDelScanAndSaveDacs@4mA25kV>{HREfficiency@50MHz/cm2,
HREfficiency@100MHz/cm2, HREfficiency@150MHz/cm2,
HREfficiency@200MHz/cm2, HREfficiency@250MHz/cm2}}
TestDescription = XrayQualification
```

and for L1

Table 1: Correspondence between test names in **ElCommandante** and in **pXar**

ElCommandante test	pXar test	Modifications
RetrimHotPixel	trimhotpixels	5s delay before test
HRData	phrun	5s delay before test
HRSCurves	xnoisemaps ²	
XraySpectrum	phrun	30s delay before test
CalDelScanAndSaveDacs	caldelscan ²	Save DACs after test
HREfficiency	pixelalive + xpixelalive ²	1s delay between both tests
IncreaseEdgeThr	incedgethr	

```
[Tests]
Test = PixelAlive@17>IncreaseEdgeThr@17>
RetrimHotPixels@150MHz/cm2>RetrimHotPixels@50MHz/cm2>{
    HRData@100MHz/cm2, HRData@300MHz/cm2, HRSCurves@250MHz/cm2,
    CalDelScanAndSaveDacs@100MHz/cm2>{HREfficiency@50MHz/cm2,
    HREfficiency@100MHz/cm2, HREfficiency@150MHz/cm2,
    HREfficiency@200MHz/cm2, HREfficiency@250MHz/cm2,
    HREfficiency@300MHz/cm2, HREfficiency@400MHz/cm2}}
TestDescription = XrayQualification
```

Note that the names of the tests in the chain are not the same than the corresponding tests in **pXar**. This is due to the fact that some modifications are applied the tests in the X-ray qualification, such as delays before their execution or saving the acquired DACs. These modifications do not alter the outcome of the tests. Table 1 shows which **pXar** test is executed for each test in the test chain.

Furthermore, note that one can specify the testing conditions in the test chain, such as the target used for the *XraySpectrum* tests and the X-ray hit rate which reflects in different X-ray tube settings.

Examples of the elCommandante.ini and elCommandante.conf files for L1 and L2 modules X-ray qualification can be found in Appendix E.

5.1.4 Starting the qualification

- Use elComandante from

/home/production/elComandante**Xray**/elComandante

²Please note that these tests are implemented differently for L1 and L2 module tests. The test procedure remains the same for both types of modules. Tests for L1 modules are found in the XPixelAlive2 tab of **pXar** and for L2 in the HighRate one. Make the necessary modifications in the **home/production/ElCommandanteXray/config/tests/** files.

- Run

```
$ ./el\_comandante.py
```

- Scan modules with scanner from left to right, press enter for an empty position or if the module is the same than in the previous test. The module names can also be inserted manually in the elCommandante.ini file.

5.2 Finishing the qualification

5.2.1 Analysing the data

These steps summarize the actions needed to finish the X-ray qualification. Steps 4-6 are not necessary but were performed during the 2015-2016 production to keep track of all test results.

- Check the test list in the **elComandante** output (below "Final cleanup after all tests ..."). The status code should always be 1. A status code of $\neq 1$ or a red color means that a test has failed.
- Copy files from local directory (eg. /usr/local/data/) to a location where all test results are kept. Copying the .tar files and extracting them is faster than copying the full uncompressed directory.
- Analyse the tests with MoReWeb as follows³:

```
$ ./home/production/MoReWeb/Analyze/Controller.py
```

- Update MoReWeb overview on our group's webserver. For this, use the script **/home/production/synchronize_webserver.sh**. This might need to be adapted.
- Write an Elog entry with the results of the qualification.
- Upload results to the Pisa database as follows:

```
scp -P 23481 -i /data/Equipment/labcomputer/eth-pisa-key.rsa  
M1148_Full....tar eth@cmspixelprod.pi.infn.it:/home/eth/dropbox/
```

5.2.2 Switching off the setup

- Remove modules from the climatic chamber and store them in a safe place.
- Switch off the DTBs, the climatic chamber and the Keithley.
- Perform the last four steps in Section 1.1 to switch off the Xray tube.

³Two versions of MoReWeb are installed: **MoReWeb** and **MoReWebL1**. Modify the command as needed. Remember to specify the path to the data directory in the configuration file for **MoReWeb**.

5.3 Troubleshooting

- The DTBs are not detected by the computer, leading to the typical error message "Unable to detach testboard". USBview is very slow or might not list all connected DTBs. Run the script `/home/production/reset_usb.sh` (as root) or restart the PC (only after agreement from the group).
- Hot Pixel Re-trimming takes very long or finds more hot pixels than usual. The high voltage might not be applied or a wrong `testParameters.dat` file (for instance from an old pXar version) is used.
- The Keithley is not turned on by elComandante. Check if the `port` option in the section `keithleyClient` in the `elComandante.conf` file is pointing to the correct device. Find the device by running the command `findkeithley` on production user. This device number can reset after reboot!

6 Description of the tests performed during the X-ray qualification

6.1 Module parametrization

At the very beginning of the X-ray qualification, two tests of the Full Qualification are repeated.

- PixelAlive: Since the module is handled between both qualifications, a PixelAlive test is performed as a quick verification that no major damage occurred during the handling.
- GainPedestal: The calibration between PH in ADC units and in Vcal units is also repeated since it is very sensitive to environmental features such as temperature which can change slightly between the setups of the FQ and of the X-ray qualification. It is important that this calibration is accurate as it is used for the Vcal Calibration which will be described later. Since the Vcal calibration is not performed for L1 modules, the GainPedestal test is omitted for L1 modules.

6.2 Incedgethr - only for L1 modules

6.2.1 Purpose

It is known that the corner pixels and edge pixels are much noisier than the inner ones on the PROC600V2. This is why the threshold of those pixels is further increased before performing tests during which all pixels are enabled.

6.2.2 Methodology

This test only affects the edge pixels. The trim bit of those pixels are either increased by 8, or set to 15 if the resulting trim bit would be higher than 15. In addition, the trim bit of the corner pixels is automatically set to 15.

6.2.3 Output

This test does not produce any output.

All subsequent tests are performed under X-radiation.

6.3 Trimhotpixels

6.3.1 Purpose

Some pixels become very noisy when the module is exposed to radiation. This is why in this test, noisy pixels are identified and their threshold increased or the pixel masked if the maximum trimbit has been reached.

6.3.2 Methodology

During this test, the module is exposed to X-radiation. Hits are accumulated for a given time and a hit map is acquired. After this, the measured hit rate in each pixel is evaluated and compared to a threshold rate which is set. If the measured rate is higher than that threshold, the trimbit of that pixel is increased by one and the test is repeated either until the pixel is not crossing the threshold any more or until the trimbit value has reached 15. In this case, the pixel is flagged as noisy and masked. It is accounted for the different size of the edge pixels in the comparison of the measured rate and the threshold rate.

6.3.3 Output

Figure 12 shows the hit map that was acquired. The pixel colored in red has a X-ray hit rate which is higher than the set threshold and is therefore retrimmed. Figure 13 confirms that the trim bit value of this pixel has been increased by 8.

6.4 PHrun

6.4.1 Purpose

This test aims to verify the readout uniformity of each column of the module by checking if the measured hit rate increases as expected with higher X-ray rates and also if the readout is stable over time.

6.4.2 Methodology

This test has all pixels enabled at the same time and acquires a hit map of all incoming X-rays. To prevent the data and timestamp buffers to overflow which can

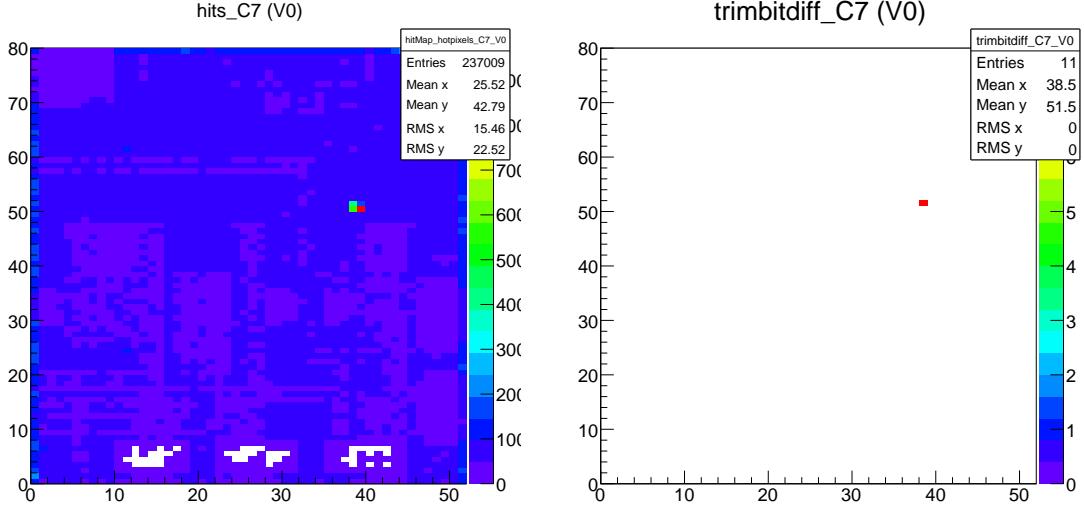


Figure 12: ROC map showing the number of hits acquired per pixel.

Figure 13: ROC map showing the difference between the original trimbit value and the value set after the test.

happen at higher X-ray rates, data acquisition is stopped whenever more than 70% of the buffers are occupied. Data acquisition is resumed once the data in those buffers has been read out.

6.4.3 Output

Figures 14 to 21 show the output of the *phrun* test. Figure 14 shows the average pulse height of all hits in a pixel. Ideally there should not be any visible structure. Figure 15 histograms the pulse height of all recorded X-ray hits in all pixels. Figure 16 shows again the average pulse height of all hits per pixel, but the pulse height here is converted to Vcal units. The pulse height of every hit in Vcal units is shown in Figure 17. Figure 18 shows the amount of X-ray hits per pixel. The read-out uniformity over time is verified in Figure 19. One events regroups all hits detected between two triggers, which come every 100 kHz. This line should therefore be as flat as possible. Figure 20 shows the number of hits per column. The first and last column is expected to have about twice the number of hits than the other columns since the pixel size of those columns is larger. Otherwise, the number of hits should be similar for all columns, though there can be some fluctuations due to the structure of the HDI which shields some parts of the module more than others. Figure 21 summarizes the information from the two last plots.

6.5 Xnoisemaps

6.5.1 Purpose

This test aims to measure the electrical noise of each pixel. A similar test is performed in the FQ, but here all pixels are enabled and the module is exposed to X-radiation during the test which is not the case during the FQ.

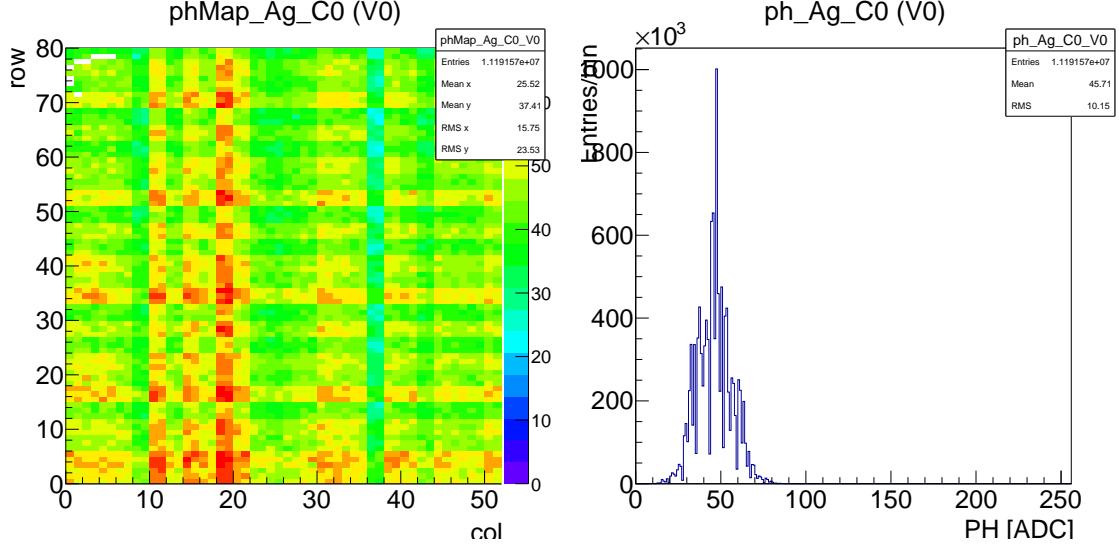


Figure 14: ROC map of the average pulse height of all hits in each pixel

Figure 15: Histogram of the pulse height of every hit recorded by one ROC

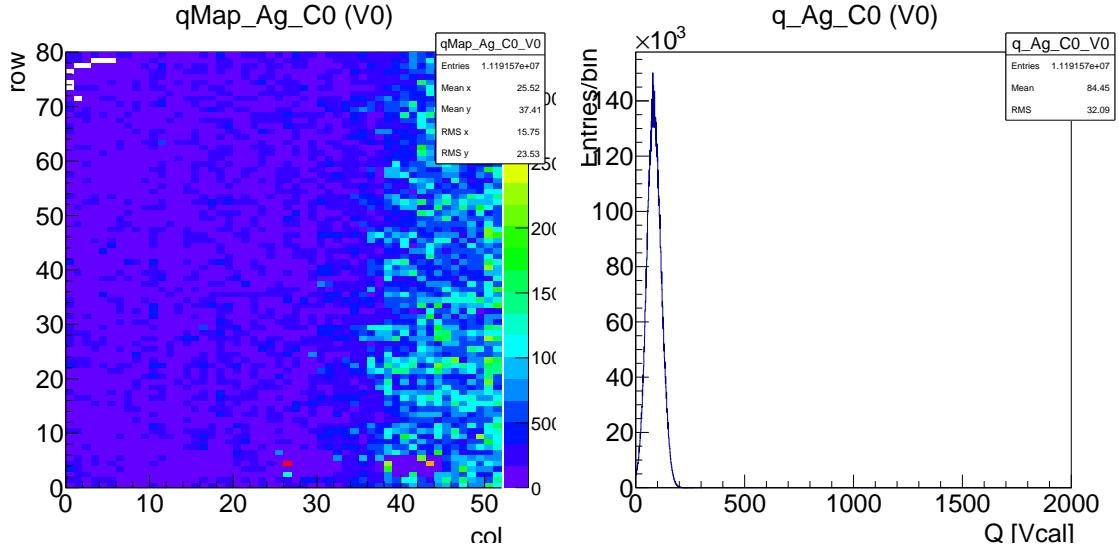


Figure 16: ROC map of the converted average pulse height in Vcal units

Figure 17: Histogram of the pulse height in Vcal units for all recorded hits.

6.5.2 Methodology

This test measures an *SCurve* for every pixel. To obtain it, a fixed number of test pulses are sent to every pixel and the number of correctly read-out pulses is recorded. This is done for many Vcal values around the threshold. The result is fitted with an error function, and the width around the half maximum is interpreted as the noise of the pixel.

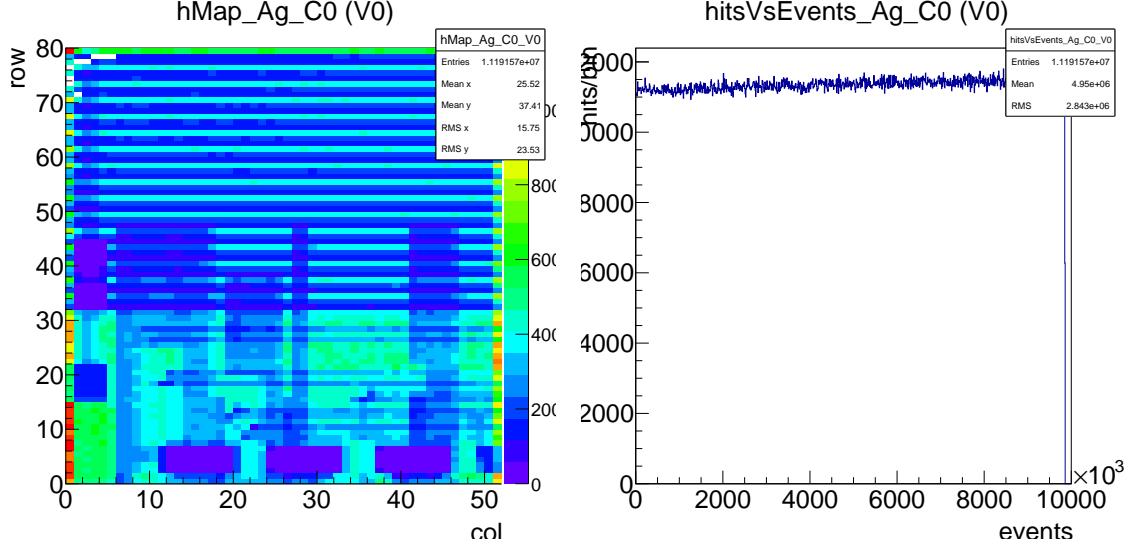


Figure 18: ROC map of the number of hits acquired per pixel.

Figure 19: Histogram showing the number of X-ray hits per event.

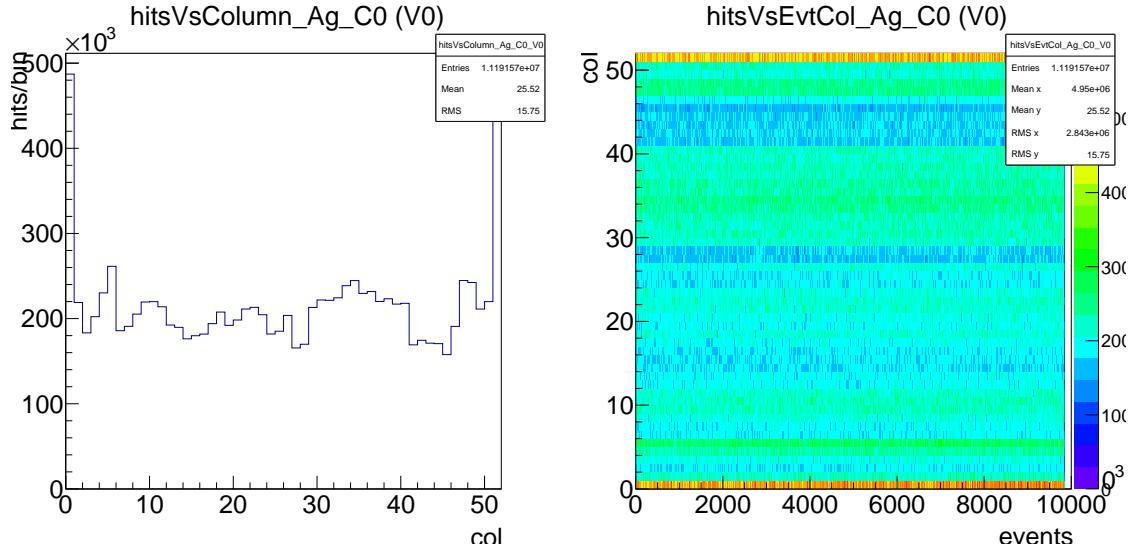


Figure 20: Histogram showing the number of X-ray hits per column.

Figure 21: Map showing the number of X-ray hits per event for every column.

6.5.3 Output

Figure 26 shows the threshold of every pixel, which is histogrammed in Figure 23. Similarly, the noise per pixel is shown in Figure 24 and its distribution in Figure 25. Figures 26 and 27 show the map and the distribution of the "turn-off", which is the point at which the efficiency drop back to less than 50%. Since no "turn-off" is expected when measuring an *SCurve* as a function of Vcal, the "turn-off" is set at the maximum value of the tested DAC.

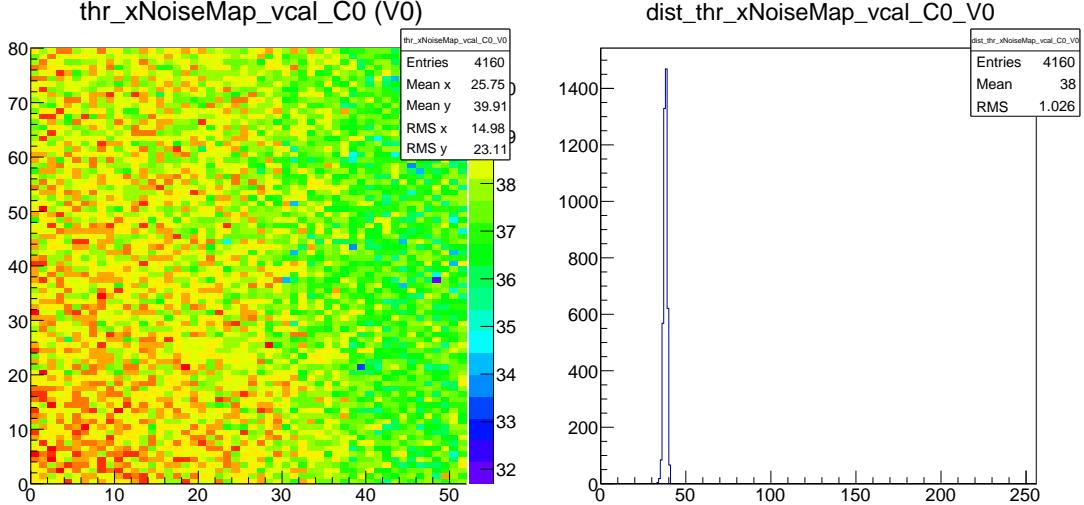


Figure 22: Map showing the measured threshold of every pixel.

Figure 23: Distribution of the threshold of every pixel.

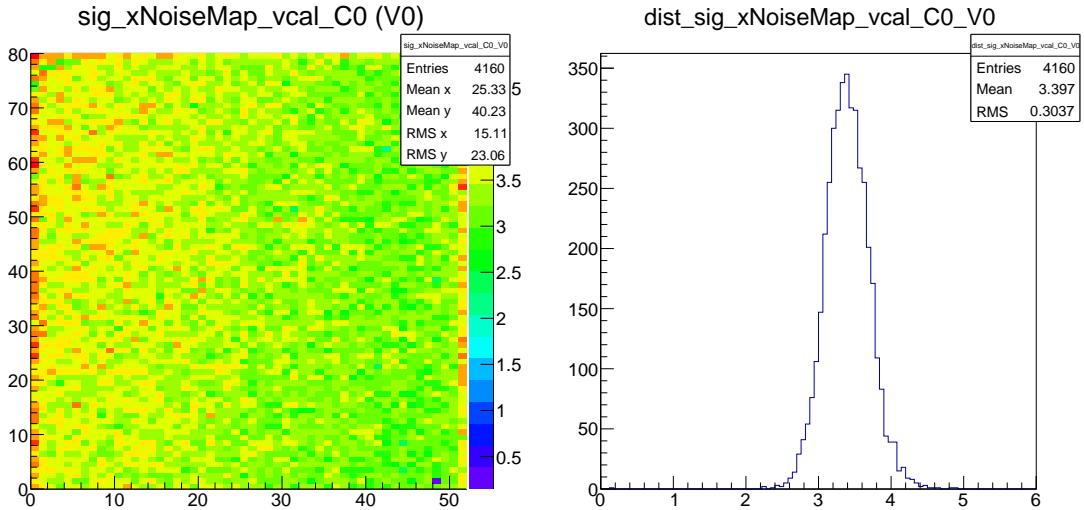


Figure 24: Map showing the measured noise for every pixel.

Figure 25: Distribution of the noise of all pixels.

6.6 Caldelscan

6.6.1 Purpose

The efficiency of a ROC is slightly varying with the CalDel DAC. It is therefore optimized before the efficiency measurement.

6.6.2 Measurement

The first step in the optimization of CalDel is to see for which of its values test pulses can be read out (see Figure 28). To this aim, a set number of test pulses for

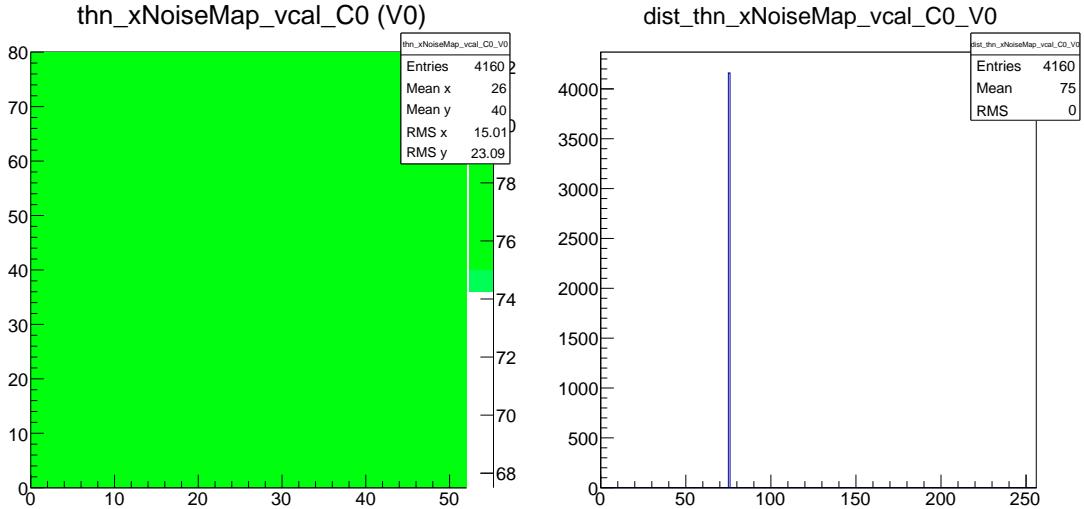


Figure 26: Map showing the measured turn-on threshold for every pixel.

Figure 27: Histogram of the turn-on threshold of every pixel.

every CalDel value are sent to a single pixel, and the number of test detected pulses is then read out. The valid range of CalDel values contains all DAC values for which the number of detected test pulses is at least 80% of the maximum. For safety and to cope with small variations amongst all pixels of a ROC, the lowest and highest CalDel values are excluded. Once the CalDel range has been found, the efficiency is measured for all pixels for a set of CalDel values within that range. Examples are found in Figures 29 and 30 which show a histogram of the efficiency of all pixels for the first and the sixth CalDel that is tested. The efficiency is the fraction of correctly read-out test pulses. The mean efficiency of all pixels is evaluated for every pixel and plotted in a histogram (see Figure 31). The final chosen CalDel value is the value of that DAC where the efficiency is highest.

6.6.3 Output

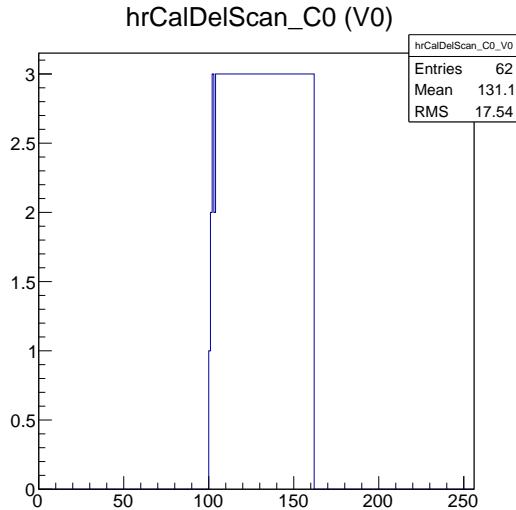


Figure 28: CalDel scan of ROC 0.

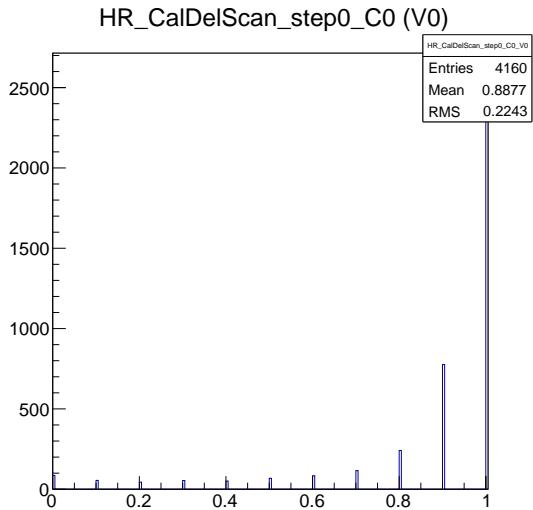


Figure 29: Efficiency of ROC 0 with the first tested CalDel.

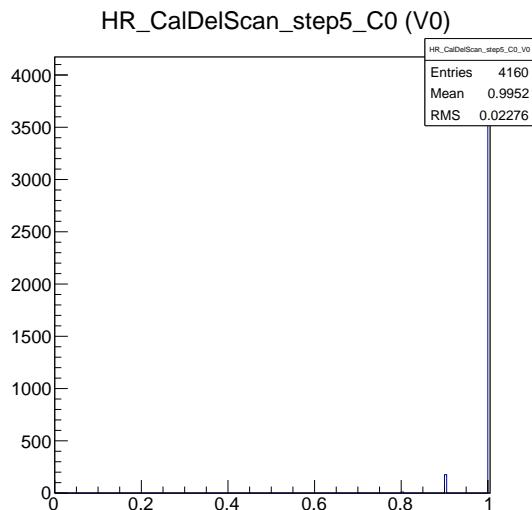


Figure 30: Efficiency of ROC 0 with the sixth tested CalDel.

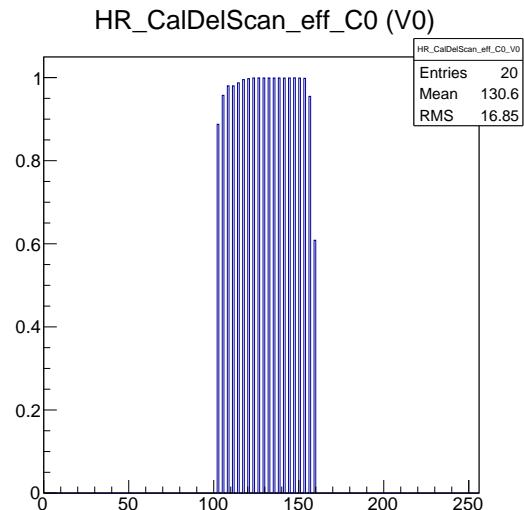


Figure 31: Efficiency of each pixel on the ROC as a function of CalDel.

6.7 Xpixelalive

6.7.1 Purpose

This test aims to measure the efficiency of each pixel at a measured pixel hit rate.

6.7.2 Measurement

This test is performed while exposing the module to X-radiation. A fixed number of test pulses are sent to every pixel, and the number of correctly read-out pulses is recorded (see Figure 32). The efficiency is the fraction of test pulses which is read out correctly and is plotted for every pixel in Figure 34. Due to their larger size and to their usually higher noise, the efficiency of edge pixels is lower for a fixed X-ray rate. This is why the fiducial efficiency is also evaluated (see Figure 35). Here the efficiency of all pixels which are not on the edge of a ROC is shown. At the same time, X-ray hits are read-out by the module, and the number of hits per pixel are evaluated (see Figure 33). The hit rate at which this efficiency was measured is evaluated by counting the number of X-ray hits recorded, and is corrected for the calculated efficiency. Here, one assumes that the efficiency to detect both kinds of hits is the same which is a sensible assumption since both type of hits go through the same read-out chain of the ROC.

6.7.3 Output

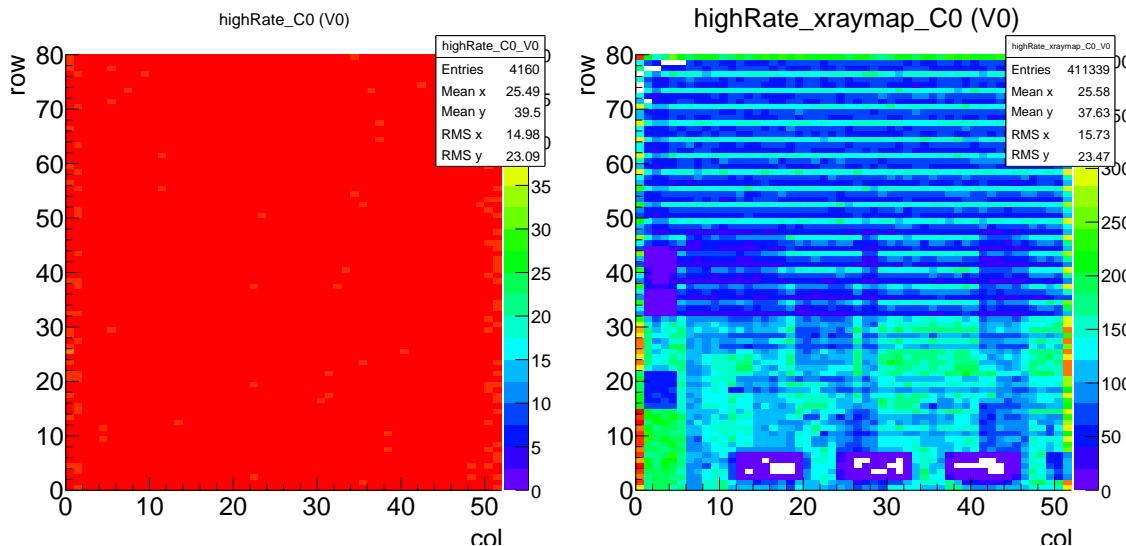


Figure 32: Number of correctly read-out test pulses per pixel.

Figure 33: Hit map acquired during the efficiency measurement.

7 MoReWeb results of module qualification

After analysing the test results, **MoReWeb** produces a webpage with all relevant information for the module. Some of the important features are presented here.

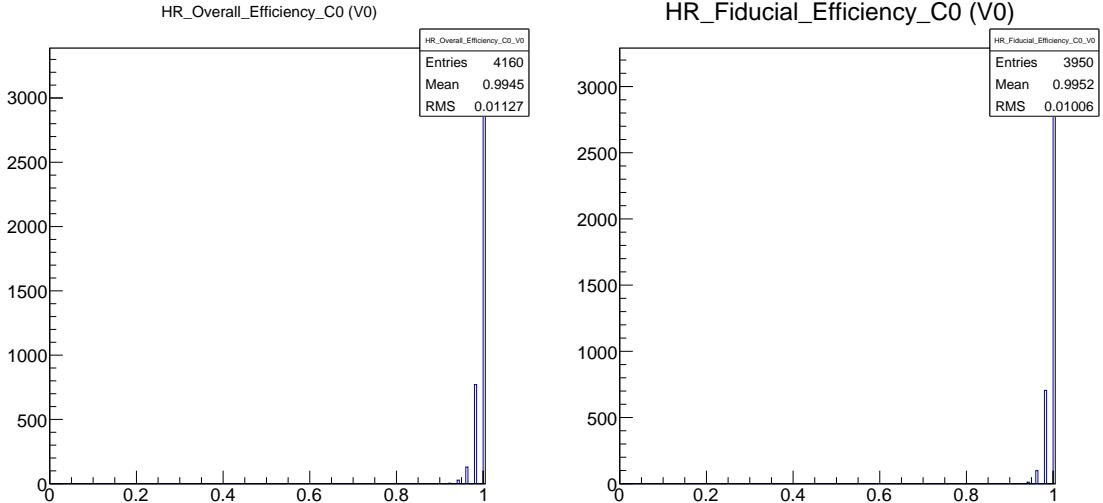


Figure 34: Efficiency distribution of all pixels
 Figure 35: Efficiency of all pixels in the fiducial region (which excludes all edge pixels).

While a grade is automatically assigned by **MoReWeb**, it is nonetheless worthwhile to carefully look at all provided maps in order to detect unusual problems which were not spotted by **MoReWeb**.

7.1 Module overview

This page gives an overview of the most important characteristics of a module. It includes a map of the module showing broken bump bonds, a hit map which shows the number of detected X-ray hits per pixel, maps showing the dead, retrimmed and masked pixels, efficiency maps at different X-ray hit rates and maps showing the noise and the threshold of each pixel. Furthermore a table gives the most important characteristics of every ROC, such as its efficiency, its noise, and its number of defect pixels. Some examples for a good module can be found in Appendix G.

7.2 ROC overview

In addition to the module overview page, results for each individual ROC are shown on a separate page. Here, more information can be found about the efficiency of the chip, its defect pixels, its read out uniformity, and its noise. Some examples for a good ROC can be seen in Appendix H.

7.3 Vcal calibration

Furthermore, MoReWeb provides the results of the Vcal calibration, which is performed for every ROC individually. The calibration is needed to convert the deposited charge which is measured in ROC internal units to electrons. For this, four spectra are acquired with different fluorescent targets during the qualification. Each

spectra is fitted with a sum of two Gaussians. One of these is assumed to fit the signal, the other corresponding to a Gaussian noise. The turn-on due to the trimming is also included via an error function. From this fit, the mean of the signal peak is extracted and converted to a Vcal value using the PH calibration. Since the energy is characteristic of each target as the emitted spectra is monochromatic, one can associate the found Vcal value to a number of electrons, which is the deposited energy divided by 3.6 eV. This is because 3.6 eV is the energy needed to create one electron-hole pair in silicon. Finally, the corresponding electron numbers of all four targets are fitted with a straight line in order to get conversion parameters between Vcal values and a number of electrons. Figure 36 shows the acquired spectrum by a ROC of one of the monochromatic targets. The red line represents the fit. Figure 37 shows the calibration between a pulse height in Vcal units and a number of electrons. The four blue dots represent the values found for each target. Furthermore, **MoReWeb** produces a summary page where the conversion factors of all ROCs are outlined.

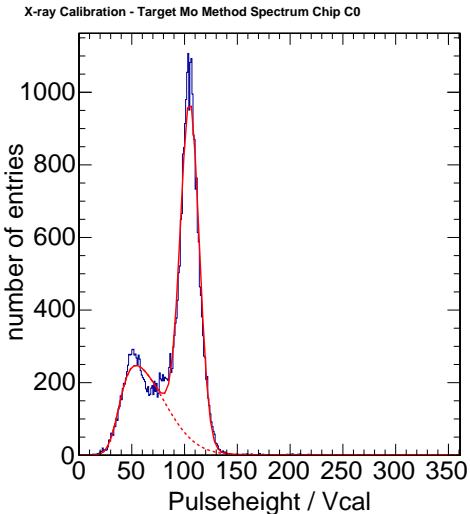


Figure 36: Molybdenum spectrum acquired by a ROC. The fit function is shown in red.

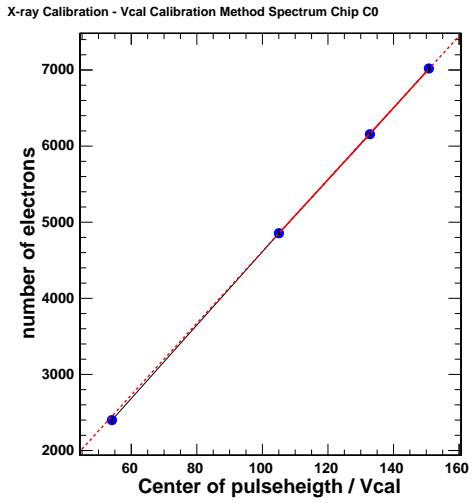


Figure 37: Vcal calibration of a ROC.

8 Results

This section summarizes the results of X-ray qualifications of both L1 and L2 modules during the 2015-2016 production of the Phase I upgrade of the BPix detector of CMS. An overview of the full production status can be obtained with **MoReweb** using the command

```
$ ./Controller.py -p
```

8.1 Modules for Layer 2 (L2)

311 modules in total were tested in the X-ray qualification. Out of these, 242 received grade A, 39 grade B and 30 grade C, leading to a yield of 90.4% (note that modules with severe defects that were discovered in the FQ are not tested in the X-ray qualification and do not appear in the results shown here). The total yield goes down to 81.0% when including results from the FQ.

- Noise: The noise for every pixel is shown in Figure 38. While the black line corresponds to all pixels, the coloured lines correspond to the grade of the module in which the pixel lies. Here, green is for modules graded A, orange for modules graded B and red for modules graded C. Modules with a detector grade (A or B) have with almost only pixels with a noise lower than 400 e^- . The noise of some pixels has been measured to be up to 900 e^- , but those modules were graded C. Most of those pixels can be associated to two modules with different severe defects. Here higher noise was not the main reason for the downgrade of those modules. It can also be seen that the test failed for a minority of pixels which can be recognised by the bin at noise 0e^- . This however also only concerns grade C modules and is therefore not problematic.
- Efficiency: Figures 39 and 40 show the interpolated efficiency per ROC at 50 MHz and at 120 MHz, which is the expected rate for L2 modules. It can be seen that the efficiency globally decreases for higher rates, but that it remains well above 98% for all ROCs.
- Vcal Calibration:

Figures 41 and 42 show the offset and the slope of the Vcal calibration for each tested ROC. The distribution of the offsets is centred close to zero as expected. The slope has a mean of around $47\text{e}^-/\text{Vcal}$ independently of the grade of the module. The slope has a spread of about $2.1\text{e}^-/\text{Vcal}$.

8.2 Modules for Layer 1 (L1)

132 modules in total were tested in the X-ray qualification. Out of these, 97 received grade A, 7 grade B and 28 grade C, leading to a yield of 78.8% (note that modules with severe defects that were discovered in the FQ are not tested in the X-ray qualification and do not appear in the results shown here).

- Noise: The noise for every pixel is shown in Figure 43. The same colour code applies than for the Figures concerning L2 modules. Here, one can clearly see that the noise for L1 modules is much higher than for L2 modules, the mean noise is at around 350e^- , but some pixels have a noise up to 1000e^- . Due to this, no grading on the noise is applied for L1 modules.
- Efficiency: Figures 44 and 45 show the interpolated efficiency per ROC at 150 MHz and at 300 MHz, which is the expected rate for L1 modules. The efficiency at 150 MHz is close to 100% for all ROCs. The outlier comes from one module with a not yet understood issue on one of the ROCs. At 300 MHz, the

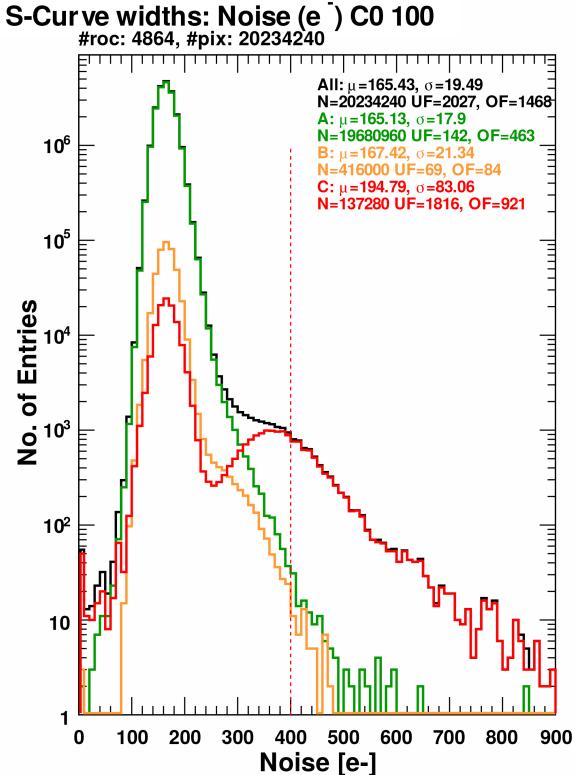


Figure 38: *Noise of every pixel of layer 2 modules. The green histogram corresponds to pixels on modules graded A, the orange one to modules graded B and the red one to modules graded C. The black line corresponds to the distribution of all pixels regardless of the grade.*

efficiency is on average slightly lower than at 150 MHz. Some ROCs however have a higher efficiency which is in some case even larger than 100%. This can be explained by the fact that these values are extrapolated from a fit on the measured efficiency values for each double-column, and the fit failed in those cases. For a few ROCs, the efficiency is lower than 98%.

8.3 Reasons for downgraded modules

This section only lists defects which were observed during the X-ray qualification. Only the three most important reasons are presented here. The list of grading criteria are shown in Appendix D.

8.3.1 Double-column defects

Most of the modules failing the X-ray qualification fail due to one or in a few cases two defective double-columns (DCs) on one or multiple ROCs. 16 (5%) L2 modules and 22 (17%) L1 modules have such problems with defective DCs. This high percentage for L1 modules was already reduced by introducing an electrical

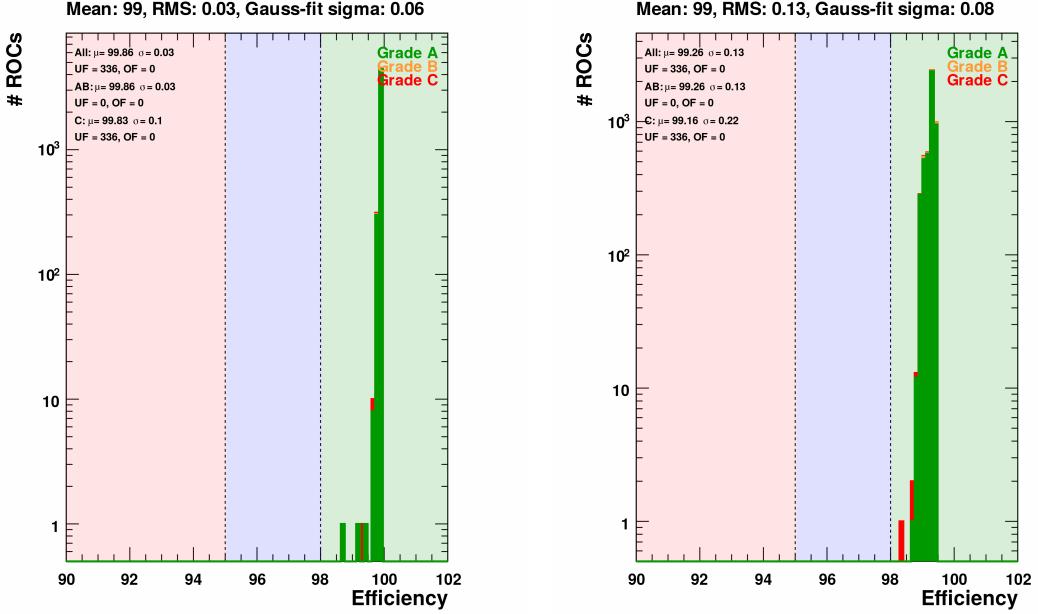


Figure 39: Efficiency of all ROCs at 50 MHz.

Figure 40: Efficiency of all ROCs at 120 MHz.

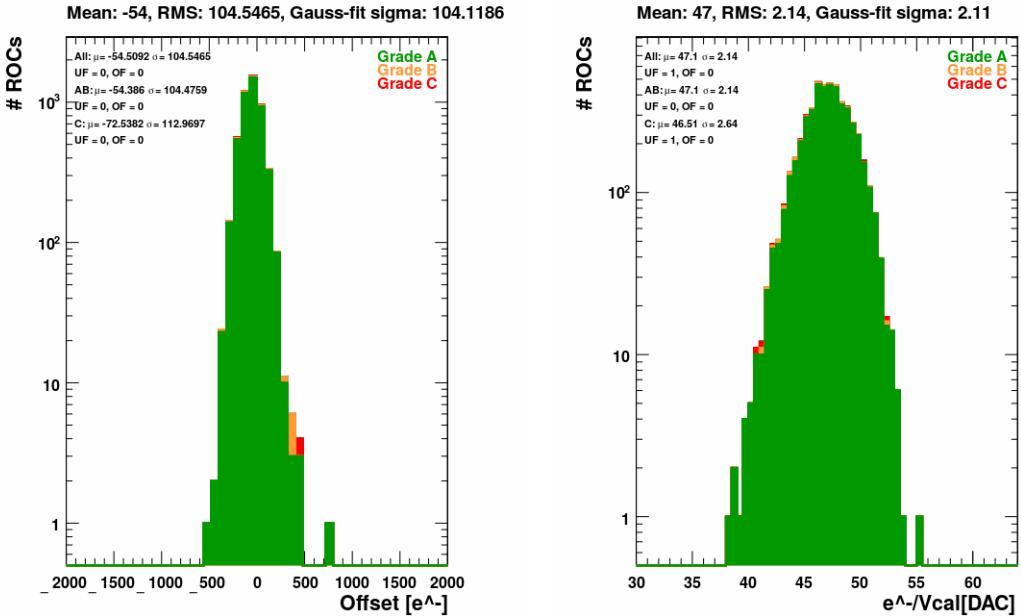


Figure 41: Offset of the Vcal calibration. Figure 42: Slope of the Vcal calibration.

DC test in the wafer test which already sorted out a large fraction of ROCs with DC problems. Various types of DC defects have been observed. For some modules it can be noticed by an absence of hits either on the hitmaps, or when calibrate signals are used, or sometimes also for both. For some modules, these defects can

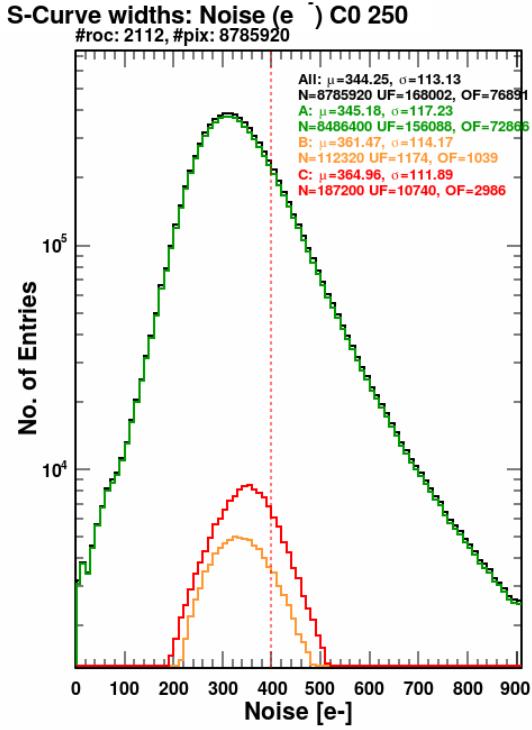


Figure 43: *Noise of each pixel of layer 1 modules. The green histogram corresponds to pixels on modules graded A, the orange one to modules graded B and the red one to modules graded C. The black line is the sum of all pixels.*

be associated to defective timestamp or data buffers, but this is not the case for all modules. Other cases include address decoding issues that only appear when all pixels are enabled at the same time. One example can be seen in Figures 46 and 47 where one double-column does neither see X-rays nor internal calibrate signals when it is exposed to radiation. In this case, the problem could be traced back to defective timestamp buffers.

8.3.2 Bump bonding defects

Another reason of failure is the number of broken bump bonds (BB) which means that the connection between the read-out chip and the sensor is broken. This concerns 5 L2 and 2 L1 modules. Furthermore, 37 L2 modules are downgraded to B due to a bad BB quality. In order to further constrain the number of bad bump bonds, no module with more than 200 BB defects was selected to be installed in the detector. Figure 48 shows a module map where lighter colours designate pixels where the bump bonds are defective for several modules. Here, the linear structures come from modules with a defective DC which is misinterpreted as broken BBs. This map shows that most of the BB defects appear on the edges and the corners of ROCs, forming so-called "church windows".

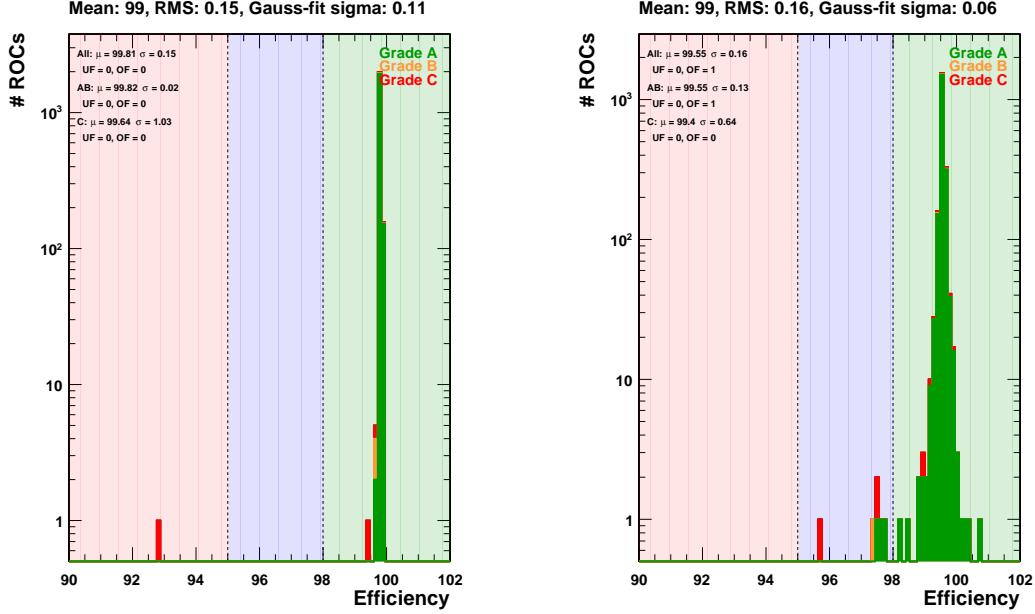


Figure 44: Efficiency of all ROCs at 150 MHz.

Figure 45: Efficiency of all ROCs at 300 MHz.

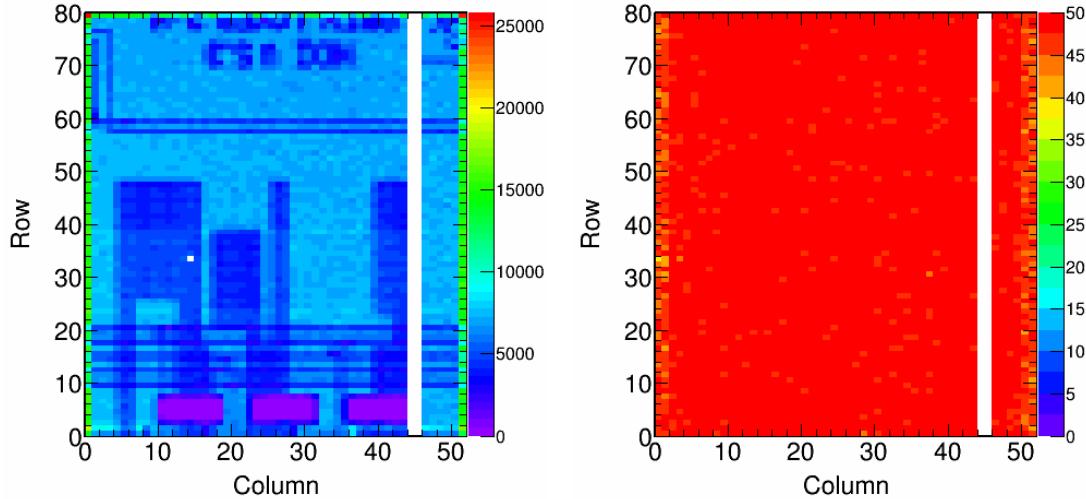


Figure 46: Hit map of a ROC with a defective DC.

Figure 47: Number of correctly read out test pulses per pixel (out of 50) for the same ROC at an X-ray hit rate of approximatively 150 MHz cm^{-2} .

8.3.3 Defective HDI

Six L2 modules were rejected due to a defective batch of HDIs which was used for those modules. For these HDI, the resistance of the ground line is too high, such that the delivered analog current for ROCs further away from the TBM is not sufficient

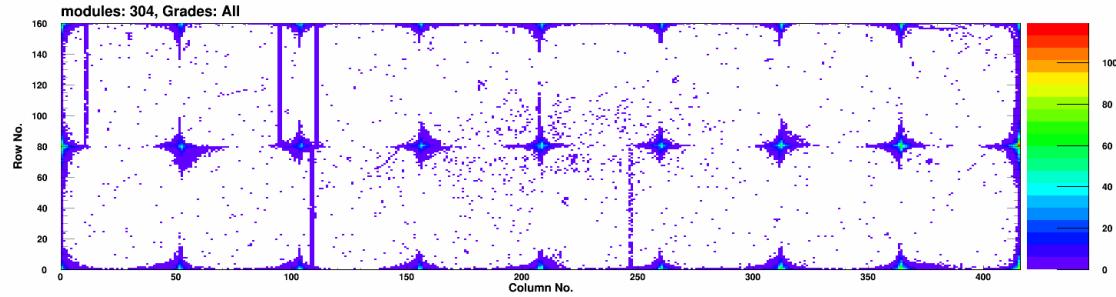


Figure 48: *Overview of all bump bonding defects for the L2 module production.*

for operation. This issue should not appear again as this is now tested in the HDI qualification.

Appendices

A Regulation for the use of the X-ray setup

Regulation for the use of the ISO-Debyeflex 3003 X-ray device at the Institute for Particle Physics, ETH Zürich

General

The Institute for Particle Physics operates a 3500 W / 60 kV X-ray generator from the company General Electric for the testing of detectors in the laboratory HPK C25. This device can produce ionising radiation, its use is therefore regulated by the law for radiation safety. All personnel working with this device must be trained for its operation and informed about its potential dangers. The regulations which are issued by the officer of radiation safety must be followed. The officer of radiation safety is available for questions and the solutions of problems concerning radiation safety.

Danger potential

The X-ray tube produces bremsstrahlung with a (anode dependant) characteristic energy spectrum of up to 60 keV. Without filtering and shielding this can lead to a dose output of several mSv per minute at a distance of 20 cm. Therefore the potential of danger from the tube is considerable. For this reason the equipment is built with inherent protection. It cannot - except for grossly negligent manner - be operated without shielding. The dose output at the outer surfaces of the shielding is below 1 µSv per hour.

Operating regulations

Only trained personnel may operate the device. Unauthorised persons have no admittance to the room, it must be locked while not in use. Before starting the operation of the device it must be ensured that the shielding is correctly closed. The shielding is equipped with a safety interlock which will turn off the high voltage of the device immediately when it is opened. Nevertheless the opening of the device without turning off the controlling device or closing the shutters of the tube housing is strictly forbidden. The manipulation of the safety interlock is considered grossly negligent. If operating conditions are significantly changed (e. g. position of the X-ray tube), the dose rate at the surface of the cabinet has to be remeasured by a suitable X-ray dose rate meter.

Operating instructions

In order to work with the device the following safety mechanisms must be considered. The high voltage will not turn on unless the X-ray cabin safety system is activated by pressing the green, round (not square) 'Start' button and closing its doors. Additionally the emergency stop button must be in a released state. When this is established more safety mechanisms prevent the opening of the electrical shutter: the circuit breaker connected to the corresponding shutter must be closed and the shutter safety switch mechanically (not manually) pressed. Lastly the mechanical shutter must be held open mechanically. Any neglected safety mechanism will prevent the emission of an X-ray beam. In order to actually start the high voltage the square 'Start' button must be pressed and to open a shutter it must be selected on the screen using the function keys. The 'Stop' button turns off the high voltage and closes all shutters. At all times the emergency stop button can be pressed which will stop the X-ray emission in any case.

Individual responsibility

Every individual is responsible that the safety measures mentioned above are followed for their own safety as well as the safety of others.

Agreement

I hereby confirm that I have been informed about the regulations for the use of the X-ray device ISO Debyeflex 3003.

Surname:

First name:

Place, date:

Signature:

B Replacement of Peltier elements in the climatic chamber

These steps summarize the necessary work to replace a Peltier element in the X-ray setup.

- Unscrew the plate holding the temperature monitor (Shown on Picture 5 - careful, cables are attached to it).
- Verify which Peltier elements are faulty by only connecting one Peltier at a time (see Figure 49). If it is faulty, the Peltier element will not draw any current as seen on the power supply.
- Remove the water supplies and the serial adapter from the right side of the climatic chamber.
- Unscrew the top frame (see Figure 50 - upper screws on the sides).
- Remove the front, back and right side panels (see Figure 51 and 52).
- Remove the cooling plate. The temperature sensor must be unplugged for this (see Figure 53).
- Unscrew the Peltier element connector (see Figure 54), unplug the temperature sensor on the copper block if access is needed to the Peltiers in the back.
- Take out all the Peltier elements, remove the thermal grease, and replace the broken ones.
- Apply thermal grease on the copper block at the dedicated spots, put the Peltiers on top (see Figure 55 and 56).
- Reconnect the Peltier elements.
- Put thermal grease on top of the Peltier elements.
- Reconnect the temperature sensor.
- Rescrew the cooling plate and all the other parts of the climatic chamber.



Figure 49: Verification of the functionality of the Peltier elements.

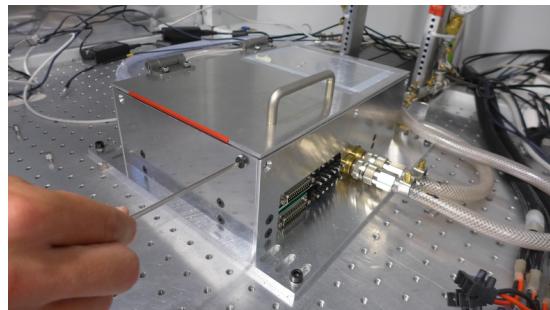


Figure 50: Unscrewing of the walls of the climatic chamber.

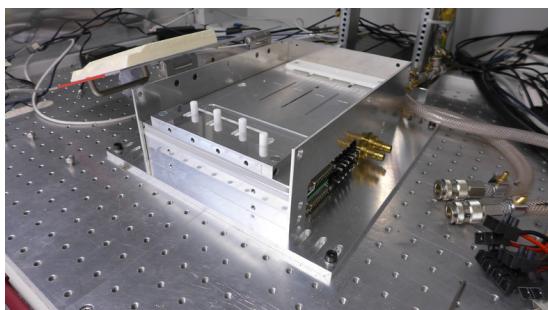


Figure 51: Picture of the opened climatic chamber I.



Figure 52: Picture of the opened climatic chamber II.



Figure 53: Picture of the climatic chamber with removed base plate.

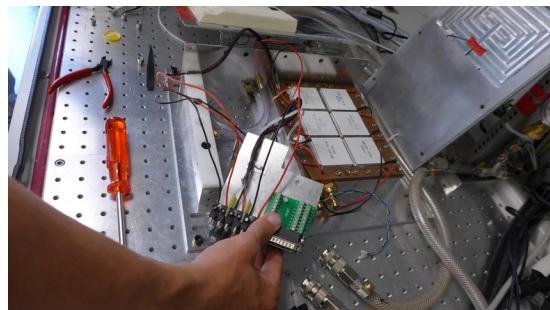


Figure 54: Picture of the Peltier element connector

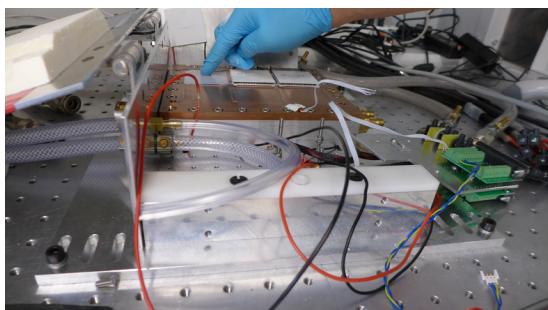


Figure 55: Thermal grease application on the Peltier elements.



Figure 56: Picture of all Peltier elements in the climatic chamber.

C Cleaning of the X-ray filter

Before performing this operation, make sure that the dirty filter is actually the cause of the problem. To do this, turn off the ID3003 program, hold the "Enter" button, turn the key to "Stand By" and select item 02 "Preset flow rate" which will show the water flow. It should be around 6l min^{-1} . If the flow is below 3.5l min^{-1} , the system will not start any more, and the filter has to be cleaned.

WARNING:

Only unmount the tube if you know what you are doing. Read the manuals. This instruction alone does not qualify you for doing the operation. If you have doubts, call the reseller company Fisch and Partner!

Handle tube carefully, do not touch beryllium windows. If they get wet, carefully dry them WITHOUT exerting force to them. Water on the windows causes them to corrode.

Beryllium is poisonous when in contact with skin and VERY brittle! Note that there are 4 windows in total.

- Close water return and supply at the ceiling of the lab (in this order to prevent static pressure) and the inlet at the wall. Empty hoses by dis-attaching them far away from the setup and empty them in a bucket. Remove devices below x-ray tube as they may get wet.
- Carefully unscrew the tube base plate from the mounting rack (2 big diagonal slotted screws) and catch the water which will start leaking out. The tube with the base plate is pressed towards the power connector in the back with a spring, one has to hold it and be careful otherwise it might pop out.
- Pull out the tube very carefully without bumping it against the housing of the tube. The tube is at very low pressure and can implode if it breaks. Danger by flying shards! Place it in a safe place. It is fine to lay it onto the glass cylinder. Do not touch the beryllium windows, if they get wet, carefully dry them without exerting force to them (e.g. suck the water with the corner of a soft tissue). Detach the base plate from the tube by unscrewing 4 hex screws as shown in Figures 59 and 60. Two of these screws are hidden in the holes of the front plate. Figure 61 shows the front plate which was unscrewed from the X-ray tube.
- The filter is in a casing below on the base plate (see Figure 62). Remove the filter cap carefully (it has a $\sim 0.5 \times 10$ mm slit on the top). Corrosion might make the cap stick to the baseplate. If needed, use two screw drivers to lever the cap off without harming the baseplate itself. Then remove the filter from the filter cap by carefully pressing it out e.g. with the blunt side of a cutter.

- Clean filter with water and by blowing pressurized air against the flow direction (available e.g. in the workshop). Figures 57 and 58 show the filter before and after cleaning.
- Place filter back into its casing, make sure that it is sitting at the end of the cap. Figure 63 shows the filter and its casing.
- Screw base plate to the tube. There is only one configuration where all 4 screws fit.
- Make sure the tube housing is absolutely dry! Remember that you will apply 60 000 V to the tube. Flushing the volume with dry air can speed up the process.
- Re-insert the tube including the base plate into the case. Again avoid any collision with the housing. It has to be pressed against the power connector. Tighten the 2 diagonal screws.
- Evaluate the success of the operation by measuring the water flow again.

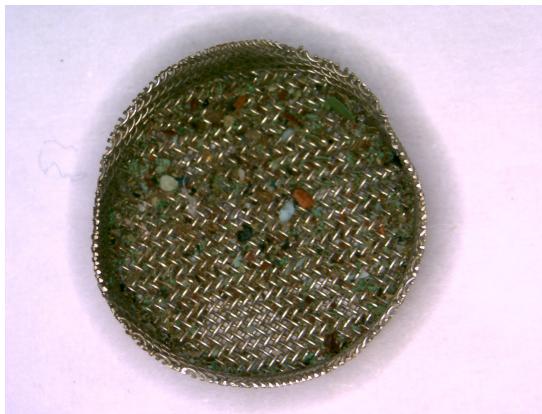


Figure 57: Picture of the filter before cleaning.

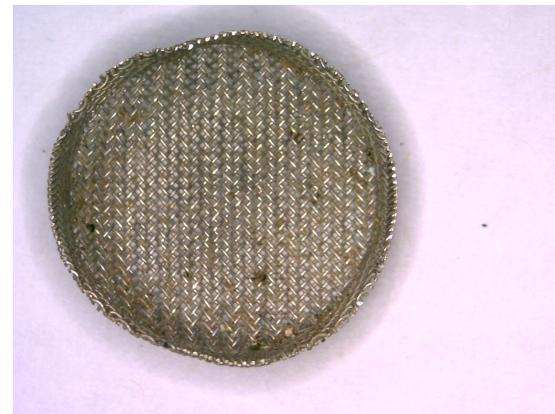


Figure 58: Picture of the filter after cleaning.



Figure 59: Unscrewing of screws that hold the front plate I.



Figure 60: Unscrewing of screws that hold the front plate II.



Figure 61: Front mount plate detached from the X-ray tube.



Figure 62: Casing of the filter removed from the front plate.



Figure 63: *Filter and its casing.*

D Grading criteria for L1 and L2 modules X-ray qualification

After the X-ray qualification, a grade A, B or C is assigned to every ROC on a module, where A are almost perfect ROCs, B are ROCs with some minor defects that can still be used in the detector, and C are ROCs which are not to be installed. The global module grade is the worst of the grades of all the ROCs on the module. A ROC can be downgraded either due to one of its performance parameters or due to a too high number of defective pixels. When more than 42 pixels on a ROC are defective, the ROC is graded B, if there are more than 168, it is graded C. Furthermore, no module with more than 200 bump bond defects are accepted. The performance parameters leading to a downgrade are shown in Table 3 and the reasons for a pixel being defective in Table 2.

Table 2: List of reasons for a defective pixel.

defective pixel if:	
Bump defects	pixel is alive but no hits in bitmap
Noise [e ⁻]	>400
Hot pixel	can't be re-trimmed and has to be masked

Table 3: Performance parameters of a ROC leading to a downgrade

	B	C
Average noise ⁴ [e ⁻]	> 300	> 400
Efficiency 120/300 ⁵ MHz cm ⁻¹	< 98%	< 95%
Column uniformity problems	-	≥ 1
Readout uniformity problems	-	≥ 1

E ElCommandante configuration files

The only files that need to be modified are the `./config/elComandante.conf` and the `./config/elComandante.ini` files. The first of those is used to indicate which port is occupied by the different devices steered by `elComandante`. In the second one, details about which tests are to be executed and under which conditions (temperature, X-ray hit rate) should be indicated. Please note that for readability reasons some lines in the following examples are split into several lines. For testing, this change needs to be reverted.

E.1 L1

`elComandante.ini`:

```
[ModuleType]
TB0 = M1106
TB1 = M1140
TB2 =
TB3 =

[Modules]
TB0 = M1106
TB1 = M1140
TB2 = M2358
TB3 = M2359

[CoolingBox]
CoolingBoxUse = False

[Cycle]
nCycles = 2
highTemp = 17
lowTemp = 15

[Environment 4mA25kV]
XrayCurrent = 4
XrayVoltage = 25
Temperature = 17
```

⁴only for L2 modules

⁵120 MHz cm⁻¹ for L2 and 300 MHz cm⁻¹ for L1 modules

```
XrayTarget = None

[Environment 25MHz/cm2]
XrayCurrent = 3
XrayVoltage = 18
Temperature = 17
XrayTarget = None

[Environment 50MHz/cm2]
XrayCurrent = 5
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 75MHz/cm2]
XrayCurrent = 7
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 100MHz/cm2]
XrayCurrent = 10
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 125MHz/cm2]
XrayCurrent = 12
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 150MHz/cm2]
XrayCurrent = 15
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 175MHz/cm2]
XrayCurrent = 17
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 200MHz/cm2]
XrayCurrent = 20
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 225MHz/cm2]
XrayCurrent = 22
XrayVoltage = 30
Temperature = 17
XrayTarget = None
```

```

[Environment 250MHz/cm2]
XrayCurrent = 25
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 300MHz/cm2]
XrayCurrent = 30
XrayVoltage = 30
Temperature = 17
XrayTarget = None

[Environment 400MHz/cm2]
XrayCurrent = 30
XrayVoltage = 34
Temperature = 17
XrayTarget = None

[Environment 500MHz/cm2]
XrayCurrent = 30
XrayVoltage = 40
Temperature = 17
XrayTarget = None

[Environment Ag]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Ag

[Environment Ba]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Ba

[Environment Br]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Br

[Environment Cu]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Cu

[Environment Fe]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Fe

```

```

[Environment Mo]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Mo

[Environment Sn]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Sn

[Environment Zn]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Zn

[Environment Xrf]
XrayCurrent = 30
Temperature = 17
XrayVoltage = 60
XrayTarget = Mo

[IV]
Delay = 2
Step = 10
Stop = -200
Start = 0

[Keithley]
BiasVoltage = -150
KeithleyUse = True

[LeakageCurrent]
Duration = 60

[LowVoltage]
LowVoltageUse = False

[OperationDetails]
Operator = production
Hostname = toblerone.ethz.ch
TestCenter = ETHZ

[Test HREfficiency]
testParameters = Ntrig=50

[Test PhOptimitation]
testParameters = saturationvcal=100

[Test Trim]
testParameters = Vcal=80

[Test XraySpectrum]

```

```

testParameters = runseconds=30

[TestboardUse]
TB0 = True
TB1 = True
TB2 = False
TB3 = False

[Test HRData]
testParameters = runseconds=20

[Test HRSCurves]
testParameters = DacLo=15,DacHi=75,Ntrig=50

[Test RetrimHotPixels]
testParameters = trimhotpixelthr=200,runsecondsHotPixels=1,savetrimbits=1 \
,maskuntrimmable=1

[Test RetrimHotPixelsNoRate]
testParameters = trimhotpixelthr=10,runsecondsHotPixels=5,savetrimbits=1 \
,maskuntrimmable=1

[Test Scurves]
testParameters = ntrig=50,DAC=vcal,DacLo=25,DacHi=150,dumpOutputFile=1 \
,dumpProblematic=1

[Tests]
Test = PixelAlive@17>IncreaseEdgeThr@17>RetrimHotPixels@150MHz/cm2> \
RetrimHotPixels@50MHz/cm2>{HRData@100MHz/cm2,HRData@300MHz/cm2, \
HRSCurves@250MHz/cm2,CalDelScanAndSaveDacs@100MHz/cm2> \
{HREfficiency@50MHz/cm2,HREfficiency@100MHz/cm2,HREfficiency@150MHz/cm2, \
HREfficiency@200MHz/cm2,HREfficiency@250MHz/cm2,HREfficiency@300MHz/cm2, \
HREfficiency@400MHz/cm2}}
TestDescription = XrayQualification

[Xray]
XrayUse = True

[VerifyTestParameters]
CheckExistence = False

[BarcodeReader]
BarcodeReaderUse = True
Fill = Both
CorrectModuleNames = True

[Alerts]
AlertsUse = True

[VerifyDACs]
dacs = vicolor==100,phscale>0,phoffset>0,vcolorbias==100,ctrlreg==16,vdig==8

[PostProcessing]
run = /usr/local/data/clean_xray_folder.py -f -d {directory}

```

elCommandante.conf:

```
[defaultParameters]
M3501 = M3501
M3502 = M3502
M3503 = M3503
M3504 = M3504

[Directories]
baseDir = ../
testDefinitions = $configDir$/tests/
moduleDB = <!Directories|baseDir!>/moduleDB/
subserverDir = <!Directories|baseDir!>/subserverDATA/
dataDir = /usr/local/data/
jumoDir = <!Directories|baseDir!>/coolingBox/
keithleyDir = <!Directories|baseDir!>/keithleyClient/
defaultParameters = /home/production/pxarL1/data
scriptDir = <!Directories|baseDir!>/analysisClient/scripts/

[TestboardAddress]
TB0 = DTB_WWXJGB
TB1 = DTB_WWV6Z5
TB2 = DTB_WWXTQT
TB3 = DTB_WWV6Z5

[subsystem]
Ziel = 127.0.0.1
Port = 12334
coolingBoxSubscription = /jumo
keithleySubscription = /keithley
psiSubscription = /psi
xraySubscription = /xray
analysisSubscription = /analysis

[jumoClient]
port = /dev/ttyJUMO
programName = coolingBoxClient.py

[keithleyClient]
port = /dev/ttyUSB1

[lowVoltageClient]
lowVoltageType = yoctorelay

[xrayClient]
xrayDevice = /dev/ttyID3003
xrayType = id3003
xrfDevice = /dev/ttyZaber
xrfType = zaber
xrfTargets = Zn:0,Cu:25320,Mo:50640,Ag:75960,Sn:101280,Ba:126600,Br:151920
turnOffHV = False
beamOffBetweenTests = False

[psiClient]
psiVersion = /home/production/pxarL1/bin/pXar
```

```
[Transfer]
host = cmspixel.pi.infn.it
port = 23481
destination = /home/eth/dropbox
user = eth
checkForTars = False
```

E.2 L2

elCommandante.ini:

```
[ModuleType]
TB0 = M2241
TB1 = M2246
TB2 = M2243
TB3 = M2245

[Modules]
TB0 = M2241
TB1 = M2246
TB2 = M2243
TB3 = M2245

[CoolingBox]
CoolingBoxUse = False

[Cycle]
nCycles = 2
highTemp = 17
lowTemp = 15

[Environment 4mA25kV]
XrayCurrent = 4
XrayVoltage = 25
Temperature = 17
XrayTarget = None

[Environment 25MHz/cm2]
XrayCurrent = 3
XrayVoltage = 18
Temperature = 17
XrayTarget = None

[Environment 50MHz/cm2]
XrayCurrent = 6
XrayVoltage = 18
Temperature = 17
XrayTarget = None

[Environment 75MHz/cm2]
XrayCurrent = 7
XrayVoltage = 20
Temperature = 17
```

```
XrayTarget = None

[Environment 100MHz/cm2]
XrayCurrent = 8
XrayVoltage = 22
Temperature = 17
XrayTarget = None

[Environment 125MHz/cm2]
XrayCurrent = 9
XrayVoltage = 23
Temperature = 17
XrayTarget = None

[Environment 150MHz/cm2]
XrayCurrent = 10
XrayVoltage = 24
Temperature = 17
XrayTarget = None

[Environment 175MHz/cm2]
XrayCurrent = 11
XrayVoltage = 25
Temperature = 17
XrayTarget = None

[Environment 200MHz/cm2]
XrayCurrent = 12
XrayVoltage = 26
Temperature = 17
XrayTarget = None

[Environment 225MHz/cm2]
XrayCurrent = 13
XrayVoltage = 27
Temperature = 17
XrayTarget = None

[Environment 250MHz/cm2]
XrayCurrent = 15
XrayVoltage = 26
Temperature = 17
XrayTarget = None

[Environment 300MHz/cm2]
XrayCurrent = 18
XrayVoltage = 26
Temperature = 17
XrayTarget = None

[Environment 400MHz/cm2]
XrayCurrent = 24
XrayVoltage = 26
Temperature = 17
XrayTarget = None
```

```

[Environment 500MHz/cm2]
XrayCurrent = 30
XrayVoltage = 26
Temperature = 17
XrayTarget = None

[Environment Ag]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Ag

[Environment Ba]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Ba

[Environment Br]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Br

[Environment Cu]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Cu

[Environment Fe]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Fe

[Environment Mo]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Mo

[Environment Sn]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Sn

[Environment Zn]
XrayCurrent = <!Environment Xrf|XrayCurrent!>
Temperature = <!Environment Xrf|Temperature!>
XrayVoltage = <!Environment Xrf|XrayVoltage!>
XrayTarget = Zn

```

```

[Environment Xrf]
XrayCurrent = 25
Temperature = 17
XrayVoltage = 60
XrayTarget = Mo

[IV]
Delay = 2
Step = 10
Stop = -200
Start = 0

[Keithley]
BiasVoltage = -150
KeithleyUse = True

[LeakageCurrent]
Duration = 60

[LowVoltage]
LowVoltageUse = False

[OperationDetails]
Operator = production
Hostname = toblerone.ethz.ch
TestCenter = ETHZ

[Test HREfficiency]
testParameters = Ntrig=50

[Test PhOptimitation]
testParameters = saturationvcal=100

[Test Trim]
testParameters = Vcal=35

[Test XraySpectrum]
testParameters = runseconds=60

[TestboardUse]
TB0 = True
TB1 = True
TB2 = True
TB3 = True

[Test HRData]
testParameters = runseconds=100

[Test HRSCurves]
testParameters = DacLo=15,DacHi=75,Ntrig=50

[Test RetrimHotPixels]
testParameters = trimhotpixelthr=200,runsecondsHotPixels=1,savetrimbits=1, \
maskuntrimmable=1

```

```

[Test RetrimHotPixelsNoRate]
testParameters = trimhotpixelthr=10,runsecondsHotPixels=5,savetrimbits=1, \
maskuntrimmable=1

[Test Scurves]
testParameters = ntrig=50,DAC=vcal,DacLo=25,DacHi=150,dumpOutputFile=1, \
dumpProblematic=1

[Tests]
Test = PixelAlive@17>GainPedestal@17>RetrimHotPixels@150MHz/cm2> \
RetrimHotPixels@50MHz/cm2>{HRData@50MHz/cm2,HRData@150MHz/cm2, \
HRSCurves@100MHz/cm2,XraySpectrum@Zn,XraySpectrum@Mo,XraySpectrum@Ag, \
XraySpectrum@Sn,CalDelScanAndSaveDacs@4mA25kV>{HREfficiency@50MHz/cm2, \
HREfficiency@75MHz/cm2,HREfficiency@100MHz/cm2,HREfficiency@125MHz/cm2, \
HREfficiency@150MHz/cm2,HREfficiency@200MHz/cm2,HREfficiency@250MHz/cm2}}
TestDescription = XrayQualification

[Xray]
XrayUse = True

[VerifyTestParameters]
CheckExistence = False

[BarcodeReader]
BarcodeReaderUse = True
Fill = Both
CorrectModuleNames = True

[Alerts]
AlertsUse = True

[VerifyDACs]
dacs = vicolor==100,phscale>0,phoffset>0

```

elCommandante.conf:

```

[defaultParameters]
M3501 = M3501
M3502 = M3502
M3503 = M3503
M3504 = M3504

[Directories]
baseDir = ../
testDefinitions = $configDir$/tests/
moduleDB = <!Directories|baseDir!>/moduleDB/
subserverDir = <!Directories|baseDir!>/subserverDATA/
dataDir = /usr/local/data/
jumoDir = <!Directories|baseDir!>/coolingBox/
keithleyDir = <!Directories|baseDir!>/keithleyClient/
defaultParameters = /data/moduleParameters/
scriptDir = <!Directories|baseDir!>/analysisClient/scripts/

[TestboardAddress]

```

```

TB0 = DTB_WS6UZ0
TB1 = DTB_WWXTQT
TB2 = DTB_WXENWR
TB3 = DTB_WWV6Z5

[subsystem]
Ziel = 127.0.0.1
Port = 12334
coolingBoxSubscription = /jumo
keithleySubscription = /keithley
psiSubscription = /psi
xraySubscription = /xray
analysisSubscription = /analysis

[jumoClient]
port = /dev/ttyJUMO
programName = coolingBoxClient.py

[keithleyClient]
port = /dev/ttyUSB1

[lowVoltageClient]
lowVoltageType = yoctorelay

[xrayClient]
xrayDevice = /dev/ttyID3003
xrayType = id3003
xrfDevice = /dev/ttyZaber
xrfType = zaber
xrfTargets = Zn:0,Cu:25320,Mo:50640,Ag:75960,Sn:101280,Ba:126600,Br:151920
turnOffHV = False
beamOffBetweenTests = False

[psiClient]
psiVersion = /home/production/pxar46Xray/bin/pXar

[Transfer]
host = cmfspixel.pi.infn.it
port = 23481
destination = /home/eth/dropbox
user = eth
checkForTars = False

```

F Configuration files for pXar

Table 4 lists all files that are required by **pXar** in order to start. In the table, # designates the Vcal value to which the module was trimmed, if it has not yet been trimmed, # is blank. The ROC number is represented by *, and & stands for the TBM core (0a, 0b for L2 modules, 0a, 0b, 1 and 1b for L1 modules).

These files can automatically be generated by **pXar** as explained on the corresponding *twiki* page whose link can be found in Appendix I.

Table 4: List of all necessary start parameter files of **pXar**.

File name	Amount	Purpose
configParameters.dat	1	pXar configuration (module composition, voltages...)
dacParameters#_C*.dat	nRocs	DAC parameters
defaultMaskFile.dat	1	Contains pixels that are to be masked
moreTestParameters.dat	1	Other test parameters
phCalibration_C*.dat	nRocs	Stores PH for a set of Vcal values for all pixels
phCalibrationFitErr#_C*.dat	nRocs	Parameters of Error function fit of PH calibration
readbackCal_C*.dat	nRocs	Stores values of readback calibration
tbmParameters_C&.dat	2*nTBMs	Timings for the TBM
tbParameters.dat	1	Settings for the DTB
testParameters.dat	1	Test parameters
trimParameters#_C*.dat	nRocs	Trimbit configuration for each pixel

G MoReWeb results - Module overview

This section shows some results of an excellent L1 and L2 module as seen on the module overview page of **MoReWeb**. Figure 64 shows a L2 ROC overview table, which gives the most important information about each ROC. For L1, the table would look similar, except that the noise is considerably higher, and that the efficiency is evaluated at 150 MHz cm^{-1} and at 300 MHz cm^{-1} . Figures 65 and 66 show a heatmap respectively of a L1 and a L2 module. One can clearly distinguish the difference between both due to the position of the Molex connector and the position and number of TBMs. Figures 67 and 68 give the threshold of each pixel for a L1 and a L2 module. One can see that the threshold is higher for L1 modules as expected, and that the threshold is further increased for the edge pixels. Figures 69 and 70 show the noise of each pixel of a L1 and a L2 module. Here as well one notices the much higher noise for a L1 module. Figure 71 shows the efficiency of every pixel without exposing the module to radiation. This map looks similar for both types of modules. Figure 72 shows the efficiency of a L2 module at a X-ray rate of 250 MHz cm^{-1} . Here, one can clearly see the loss of efficiency, especially in the edge columns of each ROC. For a L1 module, the efficiency should still be above 98% at this rate.

H MoReWeb results - Chip overview

This section shows some Figures of well working ROCs on L1 and L2 modules. Figures 73 and 74 show the efficiency of a L1 and a L2 ROC as a function of pixel hit rate. To obtain this Figure, the *xpixelalive* test is performed at different rates. In each test, the average efficiency of all pixels of a DC is measured as well as the average hit rate, leading to one point in the graph per DC. Clearly, the efficiency is higher at comparable rates for the L1 ROC. Figure 75 allows to verify the uniformity of the ROC as a function of time and for all columns. Here the number of hits

Chips		Summary ROCs															
Overview		ROC	Grade	Def	DC	Eff 50	Eff 120	Eff chi2	Rate "50"	Rate "150"	BB def	R/O	Unif.	Thr [e-]	"100"	Noise "100"	Noisy pix
Module		Chip 0	A	2	0	99.82	98.94	0.7	26.2	79.1	2	0/0	0	1957	180	0	
Grade		Chip 1	A	0	0	99.85	98.92	0.56	25.8	79.0	0	0/0	0	1950	182	0	
Manual Grade		Chip 2	A	0	0	99.83	98.99	0.63	21.0	65.5	0	0/0	0	1924	160	0	
ROC Grades A/B/C		Chip 3	A	0	0	99.87	99.29	0.65	40.7	121.2	0	0/0	0	2102	174	0	
Total Pixel Defects		Chip 4	A	1	0	99.86	99.30	0.45	40.1	119.6	1	0/0	0	2077	173	0	
Bump Bonding Defects		Chip 5	A	0	0	99.85	99.25	0.7	51.0	149.8	0	0/0	0	2143	176	0	
Noisy Pixels		Chip 6	A	0	0	99.87	99.31	0.61	47.3	139.5	0	0/0	0	2119	176	0	
Hot Pixels		Chip 7	A	0	0	99.86	99.25	0.86	46.8	137.3	0	0/0	0	2124	164	0	
ROCs with r/o problems		Chip 8	A	0	0	99.83	99.00	0.88	43.0	127.3	0	0/0	0	2088	167	0	
ROCs with unif. problems		Chip 9	A	0	0	99.86	99.30	0.59	42.4	126.6	0	0/0	0	2081	173	0	
Efficiency 50/120		Chip 10	A	0	0	99.89	99.30	0.51	38.6	114.7	0	0/0	0	2037	170	0	
Mean Noise		Chip 11	A	0	0	99.82	98.96	0.65	35.8	107.9	0	0/0	0	2056	173	0	
ROC 15		Chip 12	A	0	0	99.82	98.99	0.57	33.2	100.2	0	0/0	0	2029	168	0	
ROC 13		Chip 13	A	0	0	99.85	99.23	0.61	19.2	60.1	0	0/0	0	1959	165	0	
ROC 14		Chip 14	A	0	0	99.84	99.24	0.43	22.3	68.7	0	0/0	0	1957	166	0	
ROC 12		Chip 15	A	0	0	99.84	98.91	0.45	21.6	65.9	0	0/0	0	1951	168	0	

Figure 64: Table summarizing the characteristics of every ROC on a L2 module.

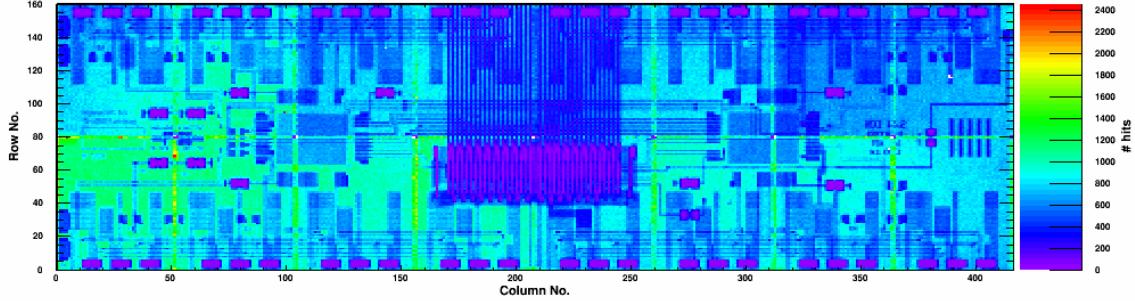


Figure 65: Map of a L1 module showing the number of hits per pixel.

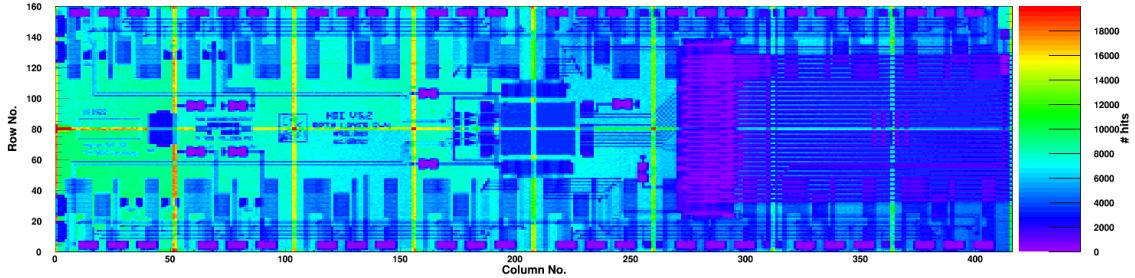


Figure 66: Map of a L2 module showing the number of hits per pixel.

per event should remain constant, and there should not be large differences in the number of events for all columns. Small variations are expected due to the larger size of pixels in columns 0 and 52 and due to some features on the HDI which can shield part of a ROC. Figure 76 shows the scaled ratio of the number of X-ray hits collected per column for two different X-ray rates. This should be close to one for all columns. Figures 77 and 78 show the noise of the L1 and the L2 ROC when

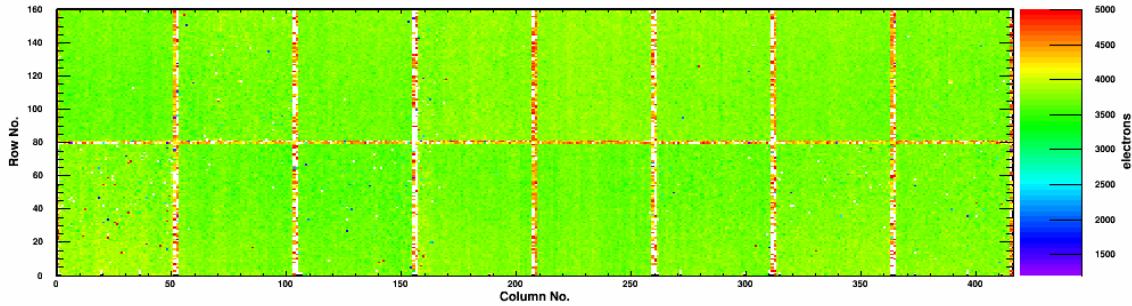


Figure 67: *Map of a L1 module showing the threshold of each pixel.*

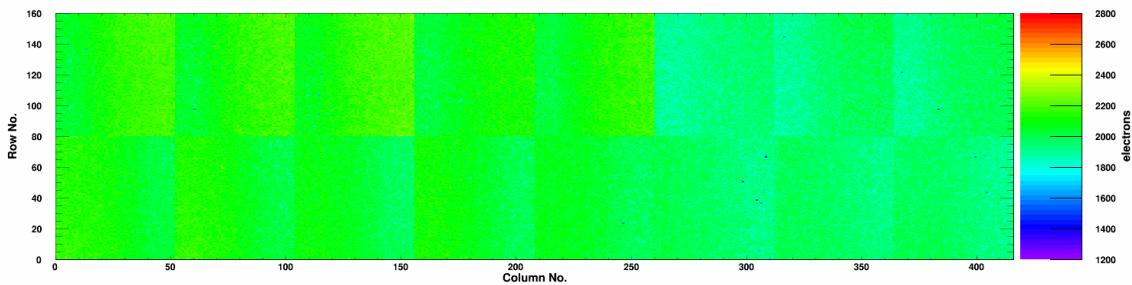


Figure 68: *Map of a L2 module showing the threshold of each pixel.*

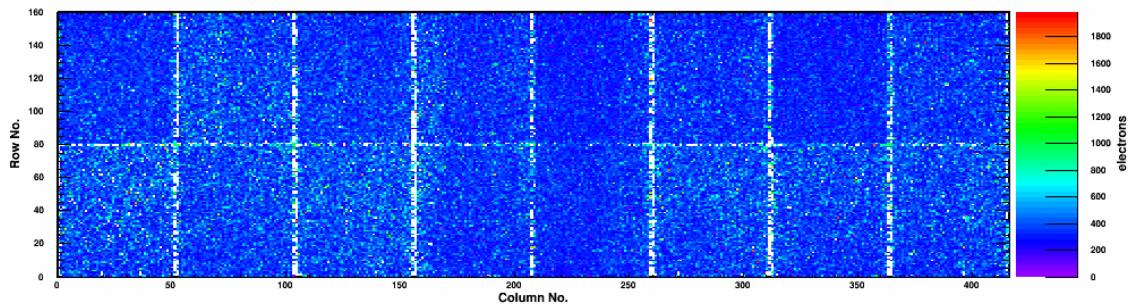


Figure 69: *Map of a L1 module showing the noise of each pixel.*

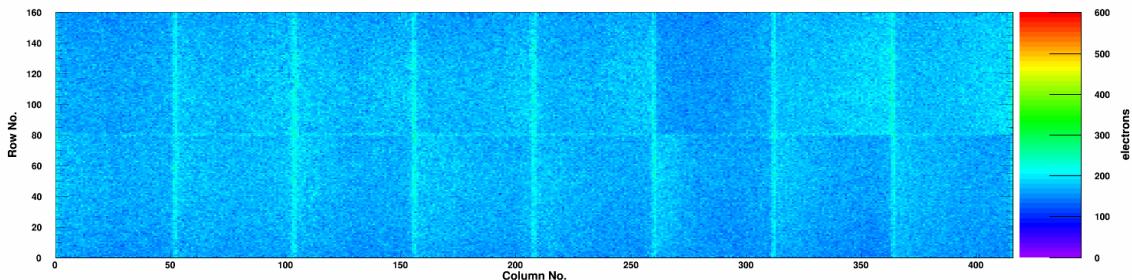


Figure 70: *Map of a L2 module showing the noise of each pixel.*

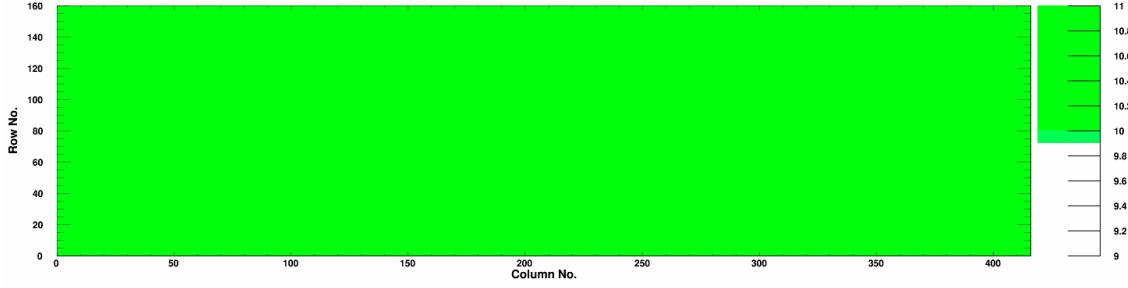


Figure 71: *Map of a L2 module showing dead or inefficient pixels (without exposing the module to radiation).*

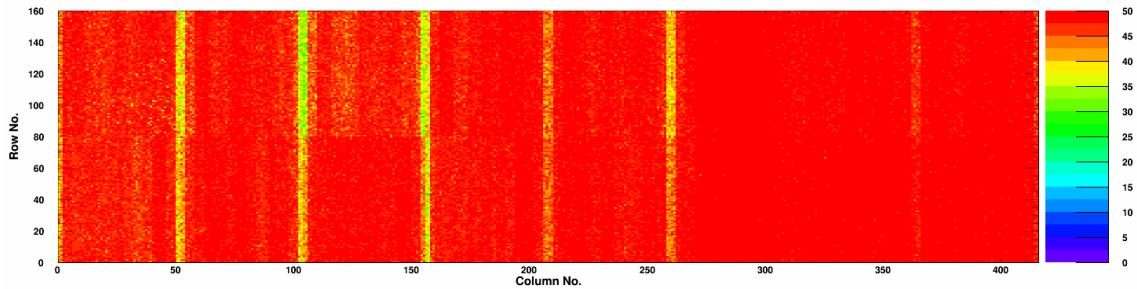


Figure 72: *Map of a L2 module showing the efficiency of each pixel when exposing the module to X-radiation.*

exposed to radiation. It is obviously much higher for the L1 ROC than it is for the L2 ROC. No grading is applied on the noise of L1 ROCs.

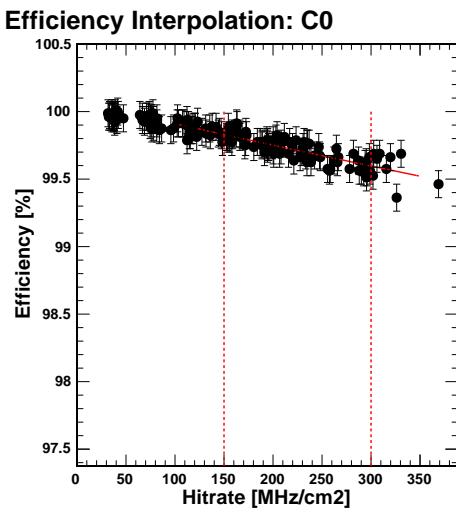


Figure 73: Efficiency of a L1 ROC as a function of particle hit rate.

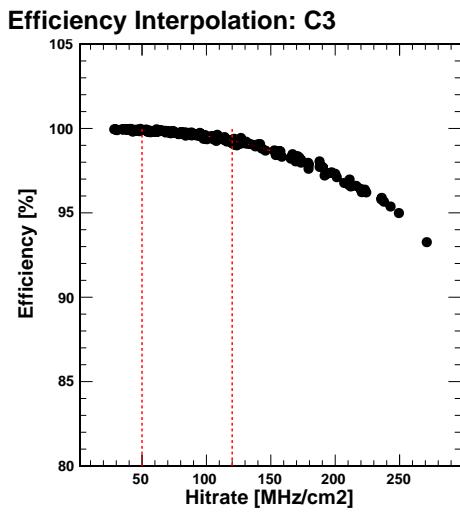


Figure 74: Efficiency of a L2 ROC as a function of particle hit rate.

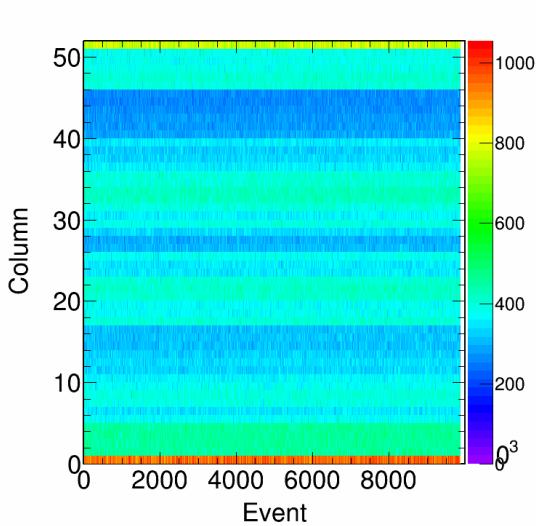


Figure 75: Number of X-ray hits per event per column.

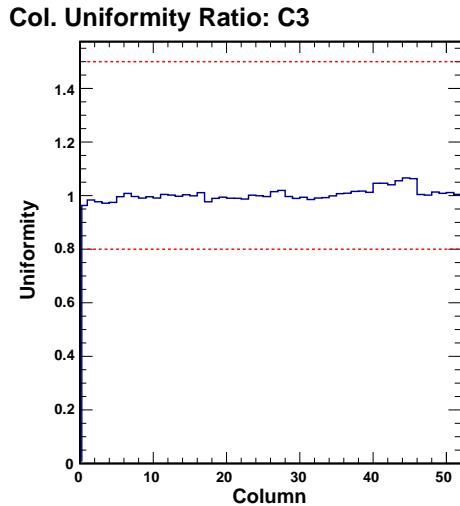


Figure 76: Scaled ratio between the number of X-ray hits acquired at two different X-ray rates.

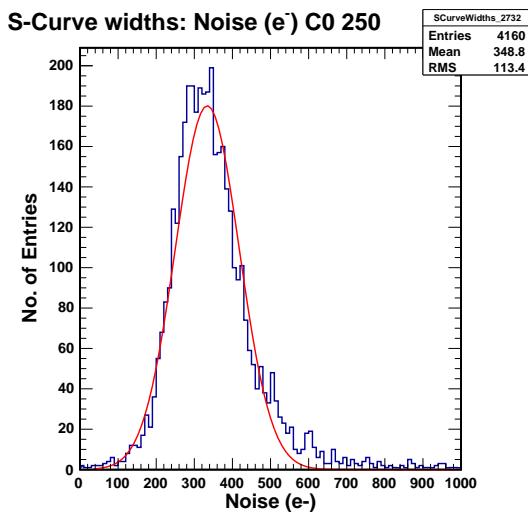


Figure 77: Noise of a ROC on a L1 module when exposed to radiation.

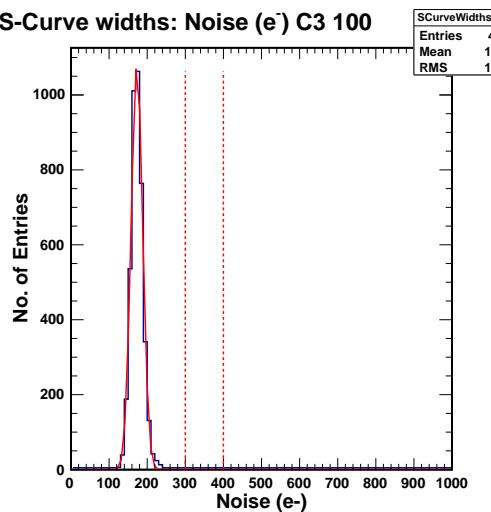


Figure 78: Noise of a ROC on a L2 module when exposed to radiation.

I Links to relevant documentation

- ETH Pixel Group webpage: Links to the results of the 2015-2016 production can be found here.
<https://cmspixel.phys.ethz.ch/>
- ETH labs control: This webpage allows to control different parameters such as temperature and humidity in all ETH labs.
<http://cmspixel2.ethz.ch:8080/>

- **pXar** twiki: This webpage gives some information on how to install and use **pXar**.
<https://twiki.cern.ch/twiki/bin/viewauth/CMS/Pxar>
- **pXar** github: The source code for **pXar** can be found here.
<https://github.com/psi46/pxar>
- **elCommandante** twiki: This webpage gives some information on how to install and use **elCommandante**.
<https://twiki.cern.ch/twiki/bin/viewauth/CMS/ElComandante>
- **elCommandante** github: The source code for **elCommandante** can be found here.
<https://github.com/psi46/elComandante/>
- **MoReWeb** twiki: This webpage gives some information on how to install and use **MoReWeb**.
<https://twiki.cern.ch/twiki/bin/view/CMS/MoReWeb>
- **MoReWeb** github: The source code for **MoReWeb** can be found here.
<https://github.com/psi46/MoReWeb>
- Phase 0 detector module qualification: Gives results from the qualification of modules for the phase 0 detector.
<https://cmospixel.phys.ethz.ch/moduleTests/moduleDB/prodTable.php?Serie=00>
- PSI Phase I webpage: Information on all components of the modules is available here.
<http://cms.web.psi.ch/phase1/>
- Pisa Database: This database lists all test results from the phase I production in 2015-2016.
<http://cmospixelprod.pi.infn.it/index.html>
- Specification of BPix modules: Some information on the tests of individual components of modules is shown here.
<https://twiki.cern.ch/twiki/bin/viewauth/CMS/BPixSpecs>
- Other links: This twiki links to many other pages related to the Phase I upgrade project.
<https://twiki.cern.ch/twiki/bin/view/CMS/CMSPixelPhase1>