# Manual for X-ray setup and module qualification

ETH Pixel Group

January 10, 2017

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 that has a chromium (Cr) anode. The radiation produced by the tube can either be used directly to obtain high particle 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 can be 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 computer 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.

- 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 have very small values for currents with 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 operated the last time at this or a higher voltage. If the voltage is not set, check green interlock button (4) and the door, press **CL** to delete the error message.
- To control X-ray tube settings during operation, use the **id3003** which is installed on the computer. With this, the X-ray generator can be shut on and off, the voltage and current settings can be adjusted, and the shutter opened and closed. Shutter 1 directs the beam to the targets, shutter 3 directs it

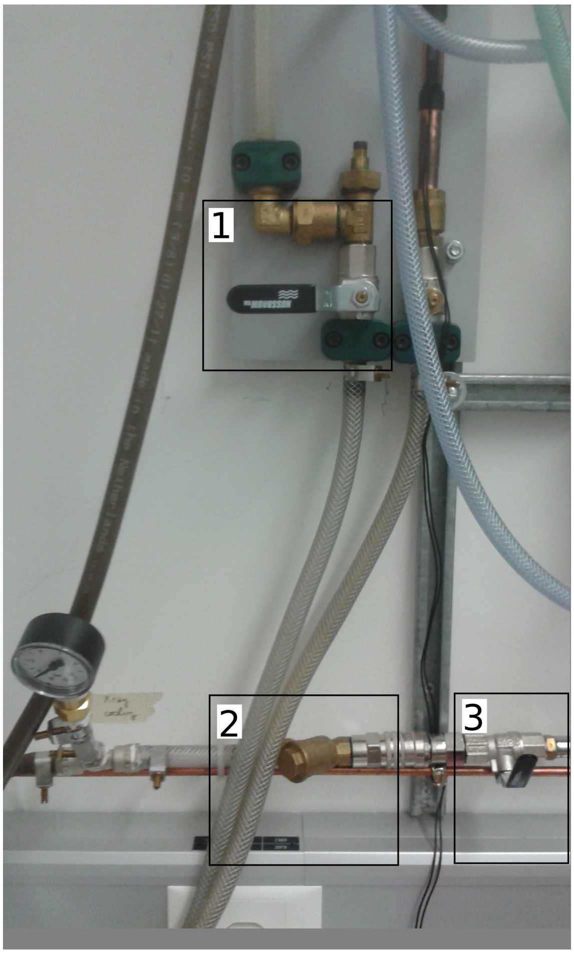



Figure 4: *Picture of the water supply for the X-ray setup. Water supply 1 feeds the climatic chamber, supply 3 is used by the X-ray tube and filtered by 2.*


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

directly to the modules. Some examples:

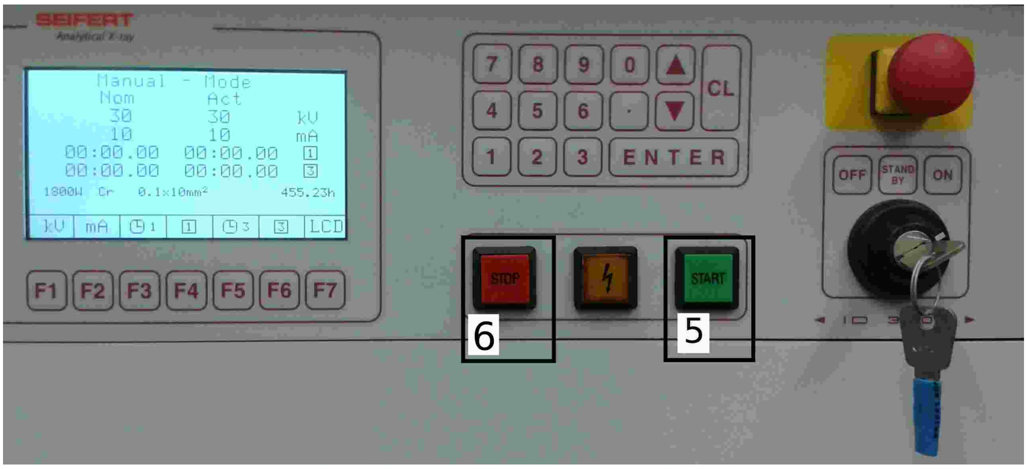



Figure 6: *Detailed picture of the control panel of the X-ray tube generator.*

```
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, turn off high voltage and close the shutter. Turn key to **STAND BY**.

After use, turn off the setup as follows:

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

## 1.2 Targets for monochromatic X-ray beam

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

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

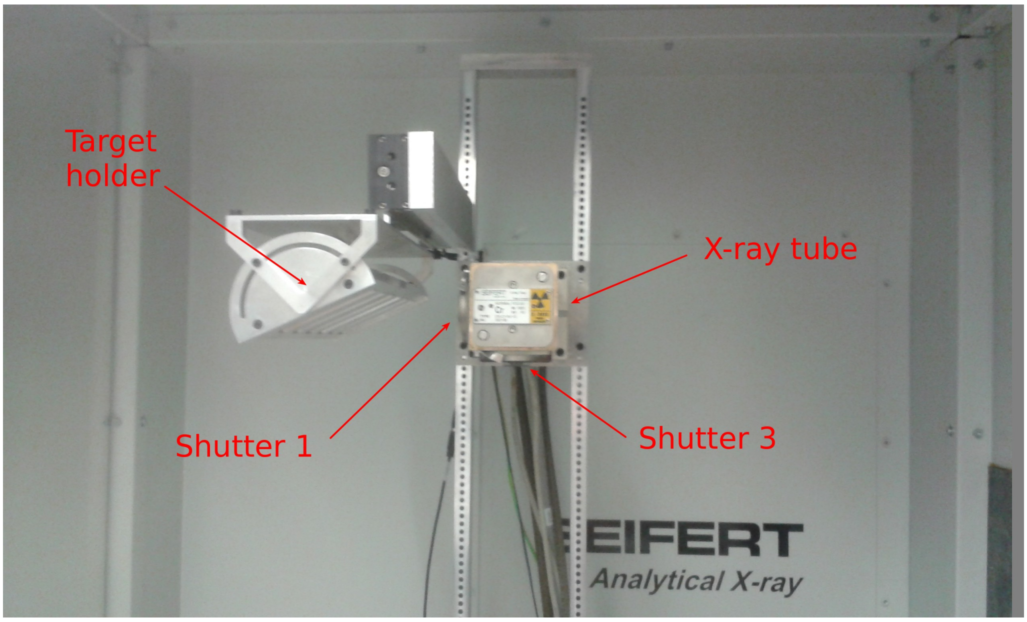



Figure 7: *Picture of the target holder and the two shutters of the X-ray beam.*

```
xrf Ag
xrf Mo
xrf 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 nitrogen to keep the humidity low. Six Peltier elements [1] are used to cool down the chamber to up to -20°C.

- Open valve for module 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 box can be cooled down to depends on it.
- Switch on cooling with the **ON/OFF** button
- Choose setpoint by pressing button **SETPOINT** while turning the knob at the same time.
- After use turn the cooling off by pressing the **ON/OFF** button and closing the water valve.

[1]Type 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 desired bias voltage with the buttons marked in blue on Figure 8.
- Apply bias voltage to module by pressing button 2 on Figure 8.

## 1.5 Troubleshooting

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

- 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 green **START** button (4) 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 A.
- 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. This should only be performed by someone who has done this before. Instructions for it can be found in Appendix B.

- 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 B 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.

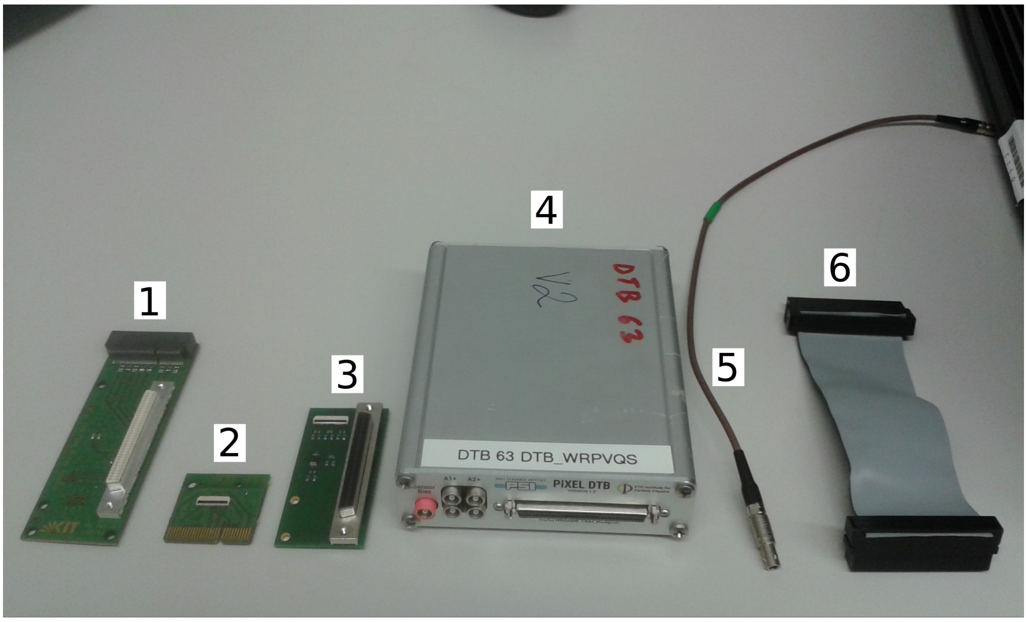



Figure 9: *Picture of the material needed for L1 and L2 modules. 1 is the module adapter for L2 modules, 2 the adapter card for L2 modules, 3 the module adapter for L1 modules, 4 the Digital TestBoard, 5 the LEMO cable, 6 the flatband cable.*

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

- One Digital TestBoards (DTBs) 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

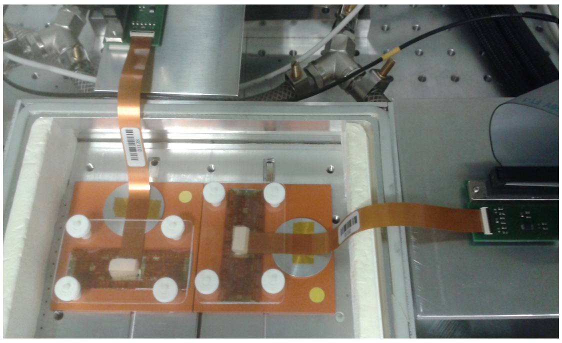


Figure 10: *Picture of the placement of two L1 modules in the climatic chamber*

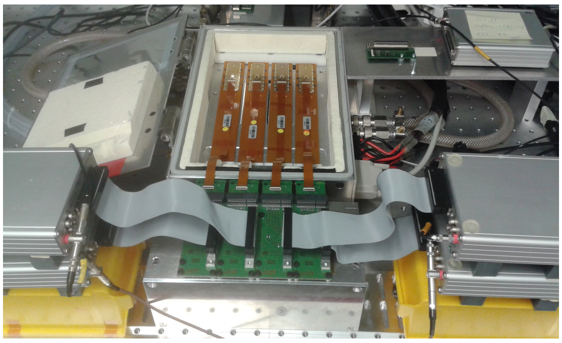


Figure 11: *Picture of the placement of four L2 modules in the climatic chamber*

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.The modules need to be placed under the window covered with aluminium foil Note that the modules should be placed underneath the window in the cover 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 softwares 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 code and information to the software can be found in Appendix H.

## 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 the 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 E.

## 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 a 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 that the test temperature has to be set manually before the test.

## 4 Specific testing conditions for L1 modules

L1 modules have several problems that prevents using the same qualification procedure than for L2 modules. Since the power consumption of L1 modules is excessively high leading to many read-out errors at low thresholds, 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 for every ROC. Otherwise, the high noise of those pixels handicaps the entire readout of the ROC. In addition to this, the threshold of all other edge pixels is increased even further than the 80 Vcals. Furthermore, no grading on the noise of L1 modules is applied.

Due to this high threshold and because the ADC response of the pulse hight is not stable under rate, 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 is more important for uneven rows, so it is recommended to mask those.

Furthermore, the power consumption of L1 modules is in some cases higher than it can be delivered by the DTB when measuring the efficiency at $400\,\mathrm{MHz\,cm^{-1}}$. 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 situ, 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 of 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 Start 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).
- 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. These can be copied from the FullTest@17 from the FQ. With these, it is not necessary to trim the module again and to optimize its pulse height 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.

Examples for the elCommandante.ini and elCommandante.conf files for L1 and L2 module qualification can be found in Appendix D.

### 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 for 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
```

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 | |

and for L1:

```
[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 are not the same than the corresponding names in pxar for those tests. This is due to the fact that some modifications are applied to some of those tests in the 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 these test chains, such as the target used for the XraySpectrum tests and the X-ray hit rate which reflects in different tube settings.

### 5.1.4 Starting the qualification

- Use elComandante from

  **/home/production/elComandanteXray/elComandante**

- Run

[2]Please 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 necessary modifications in the ./ElCommandanteXray/config/tests/ files.

```
$ ./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. Otherwise, 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 a good overview 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 .tar files and extracting them is faster than copying the full uncompressed directory.
- Analyze the tests with MoReWeb.
- Update MoReWeb overview on the groups 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.

## 5.3 Troubleshooting

**Problem:** The DTBs are not detected by the computer, typical error message: Unable to detach testboard. USBview is very slow and might or might not list all connected DTBs
**Solution:** Run the script **/home/production/reset_usb.sh** (as root) or restart computer (only after agreement from the group).

**Problem:** Hot Pixel Re-trimming takes very long or finds more hot pixels than usual
**Solution:** Might be missing HV or wrong testParameters.dat file (for instance from an old pXar version).

**Problem:** The Keithley is not turned on by elComandante
**Solution:** Check if the **port** option in section **keithleyClient** in **elComandante.conf** 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 setup 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 also 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 that the inner ones on the PROC600V2. This is why the threshold of those pixels is further increased during 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-ray 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 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 double column of the module by verifying 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 acquired a hit map of all incoming X-rays. To prevent the buffers to data and timestamp buffers to overflow

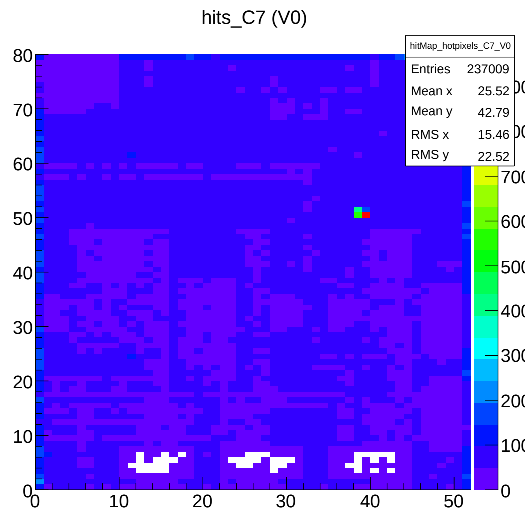



Figure 12: ROC map of the number of hits acquired per pixel

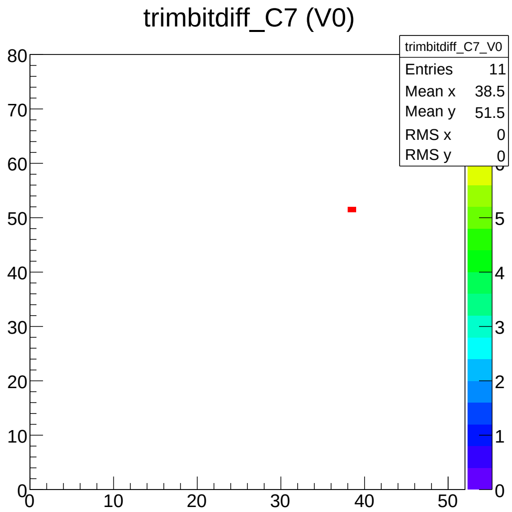



Figure 13: ROC map showing the difference between the original trimbit value and the value set after the test

which can 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 HRData test. Figure 14 shows the average pulse height of all hits in a double column. 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 in the FQ.

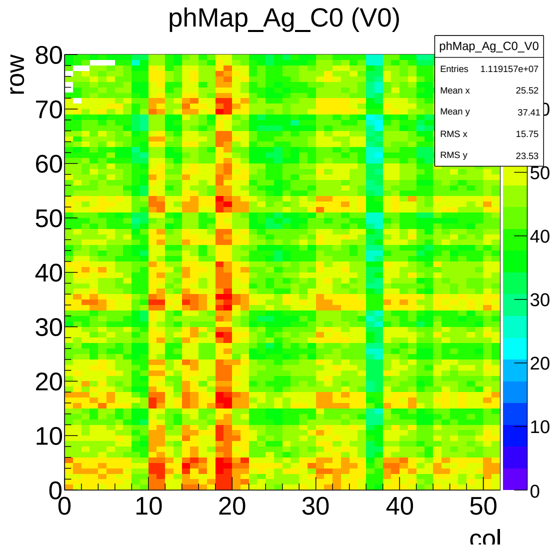



Figure 14: ROC map of the average pulse height of all hits in each pixel

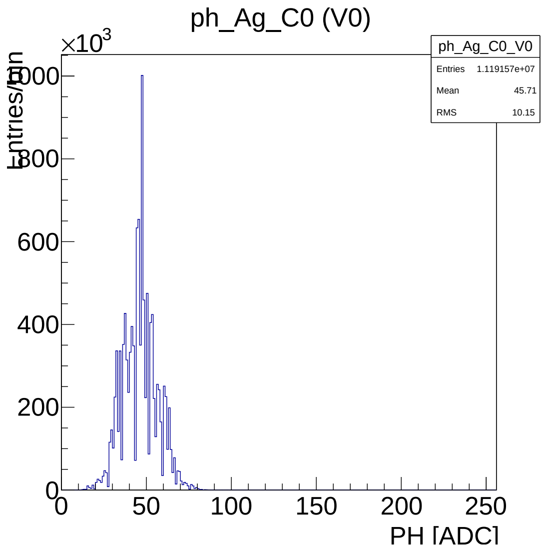



Figure 15: Histogram of the pulse height of every hit recorded by one ROC

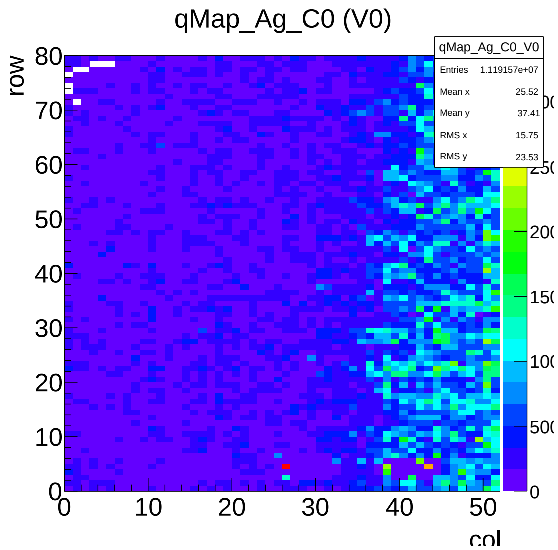



Figure 16: ROC map of the converted average pulse height in Vcal units

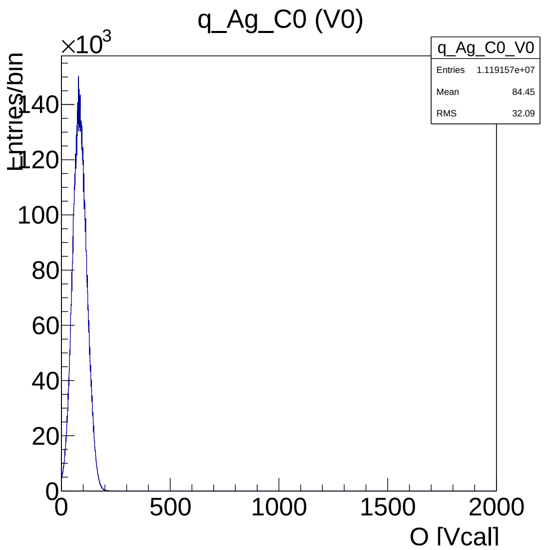



Figure 17: Histogram of the pulse height in Vcal units for all recorded hits.

### 6.5.2 Methodology

This test measured 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.

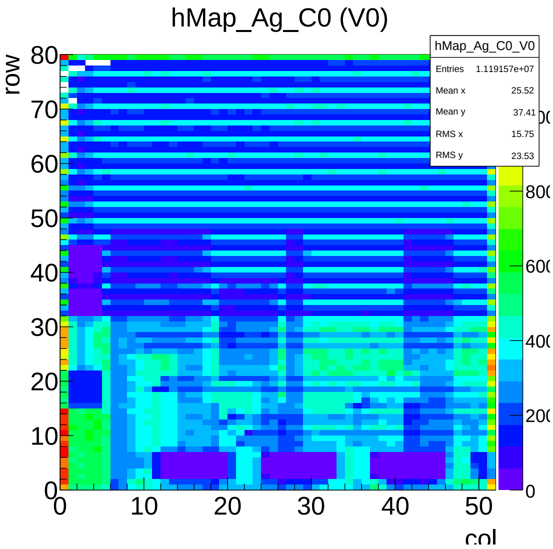



Figure 18: ROC map of the number of hits acquired per pixel.

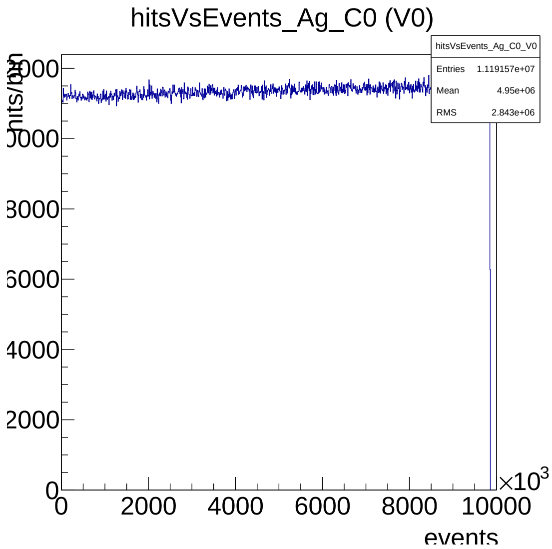



Figure 19: Histogram showing the number of X-ray hits per event.

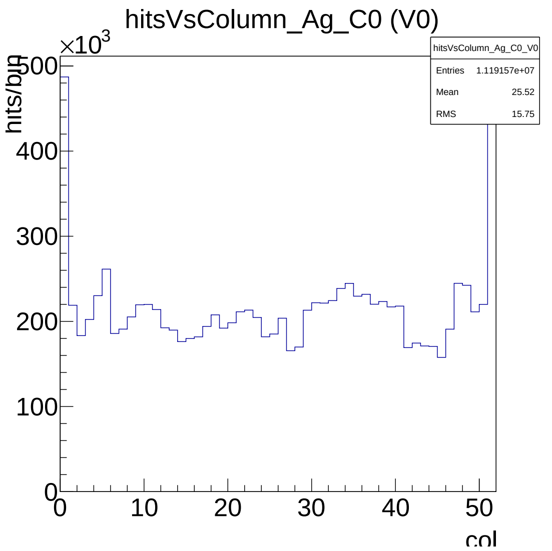



Figure 20: Histogram showing the number of X-ray hits per column.

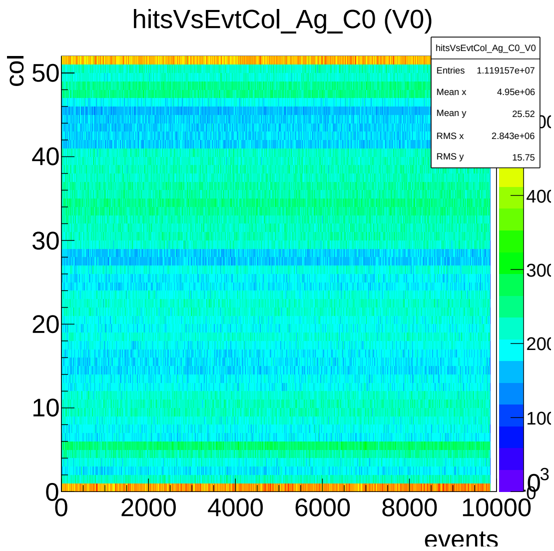
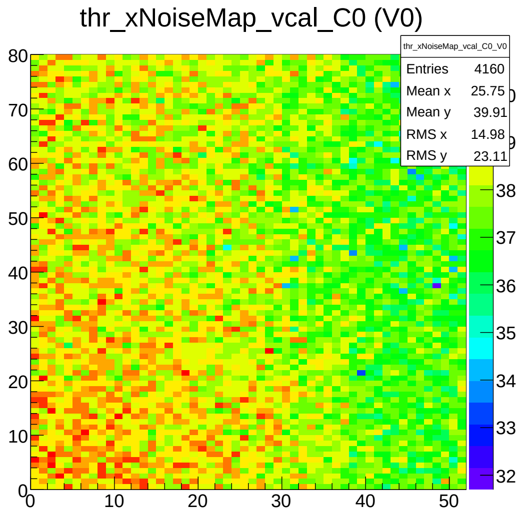



Figure 21: Map showing the number of X-ray hits per event for every column.

### 6.5.3 Output

While the noise was already measured during the Full Qualification, it is remeasured here since it increases when all pixels are enabled (which is not the case in the FQ) and when the module is exposed to radiation. The noise measurement is performed in a similar way.



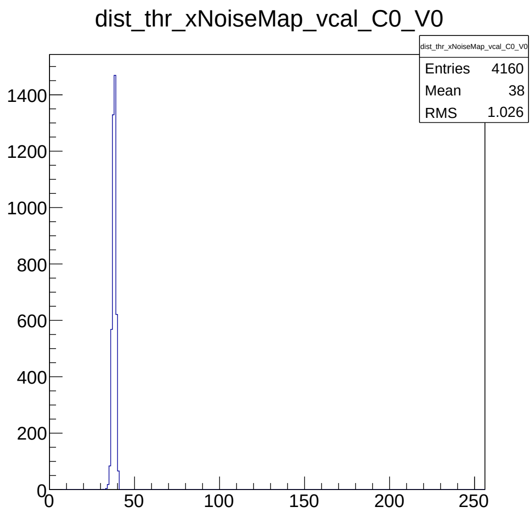
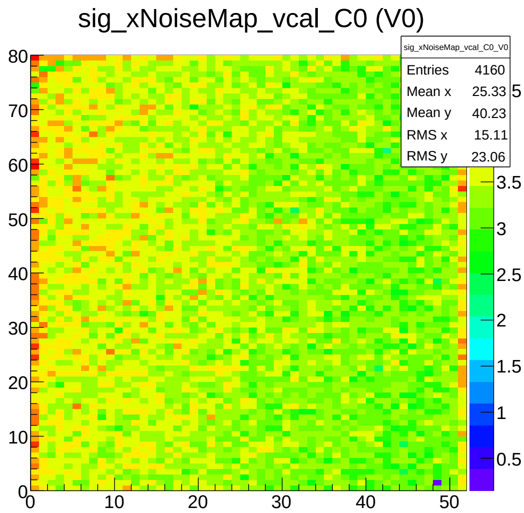




Figure 22: Map showing the measured threshold for every pixel.

Figure 23: Histogram of the threshold of every pixel.



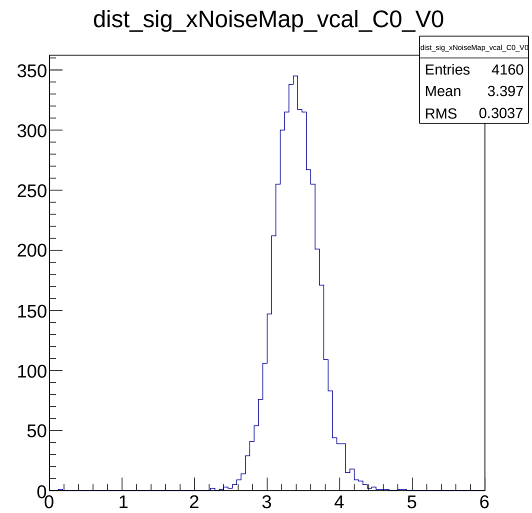




Figure 24: Map showing the measured noise for every pixel.

Figure 25: Histogram of the noise of every pixel.

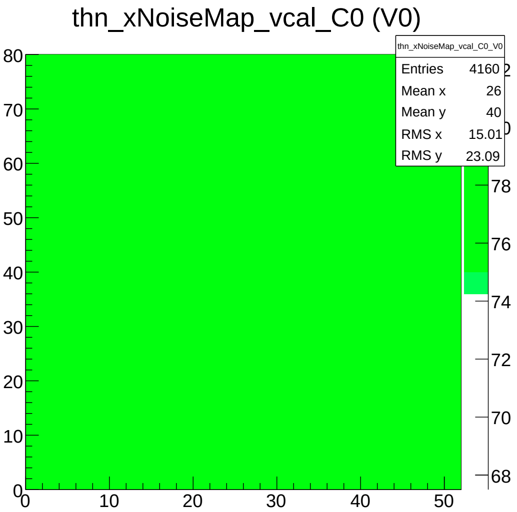
## 6.6 Caldelscan

### 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 pulses for



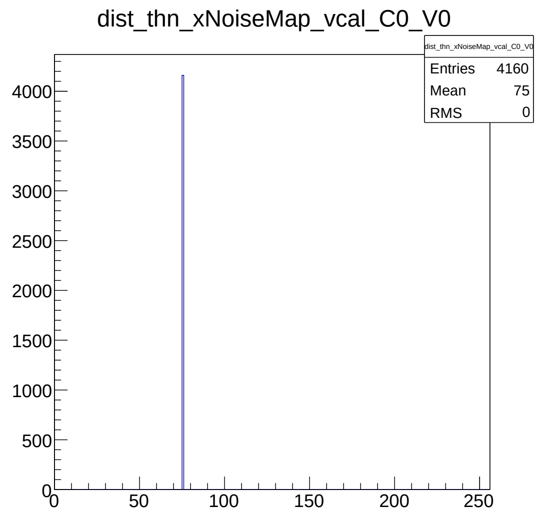




Figure 26: Map showing the measured turn-on threshold for every pixel.

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

every CalDel value are sent to a single pixel, and the number of detected pulses is then read out. The valid range of CalDel values is then 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

## 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 fro 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

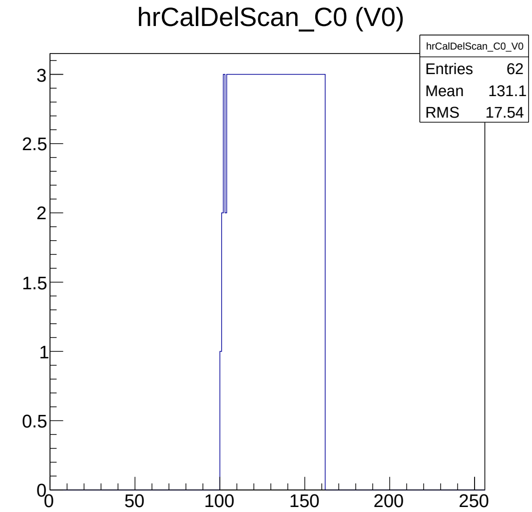



Figure 28: CalDel scan of ROC 0

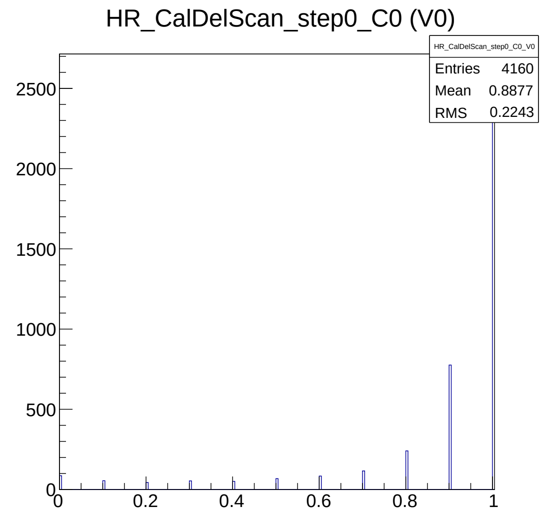



Figure 29: Efficiency of ROC 0 with first tested CalDel

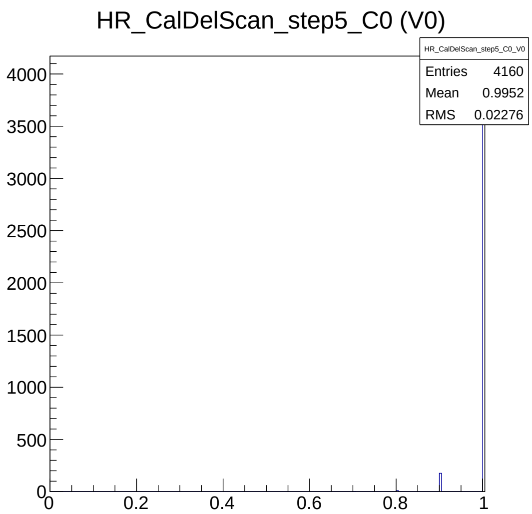



Figure 30: Efficiency of ROC 0 with sixth tested CalDel.

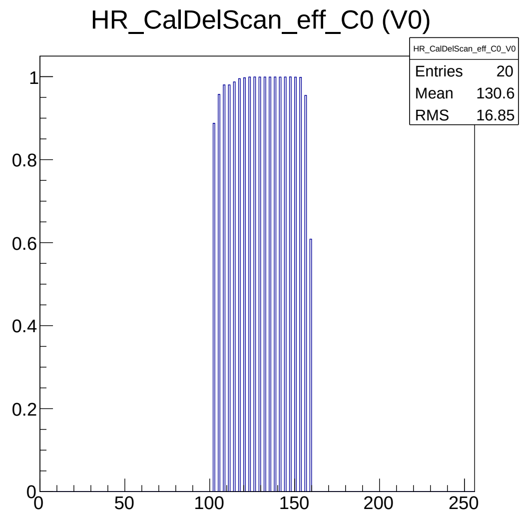



Figure 31: Efficiency of each pixel on the ROC as a function of CalDel.

time, X-ray hits are read-out by the module, and the number of hits per pixel are evaluated (see Figure 33). This is needed to evaluated the pixel hit rate at which the efficiency was measured. The calculation is not done by pxar, but by MoReWeb and is explained in section

#### 6.7.3 Output

This test is performed at different rates to measure the efficiency of each ROC. The test sends a set number of calibrate signals to each pixels while the chip is exposed to radiation. Evaluating the fraction of correctly read-out calibrate signals

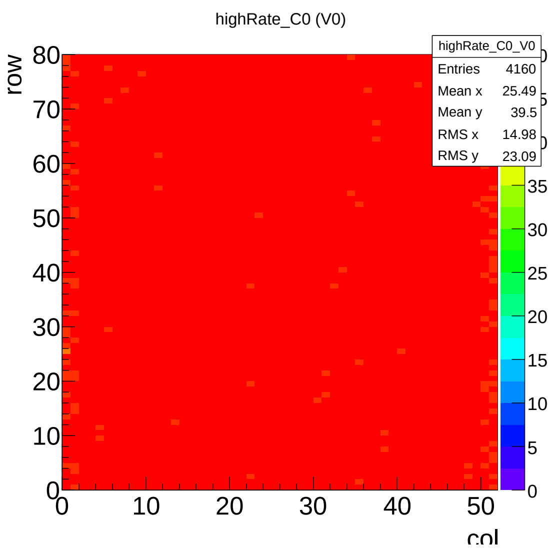



Figure 32: Number of correctly read-out test pulses per pixel.

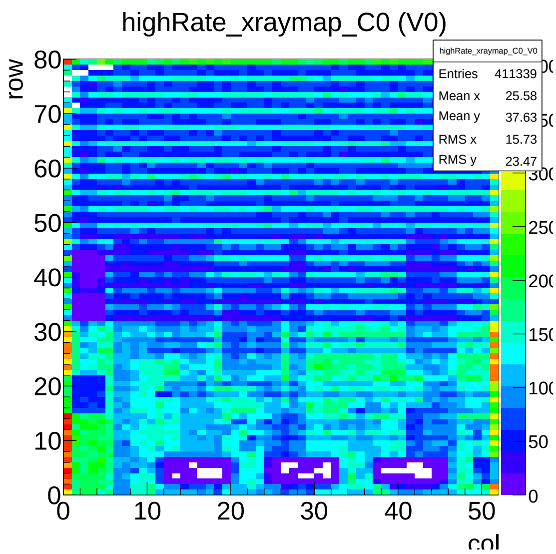



Figure 33: Hit map acquired during the efficiency measurement.

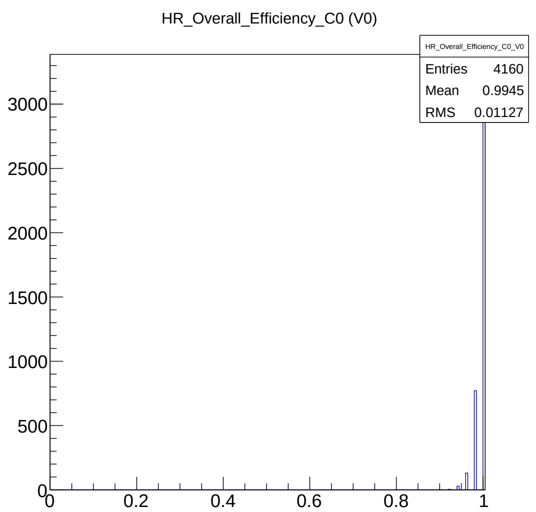



Figure 34: Efficiency distribution of all pixels

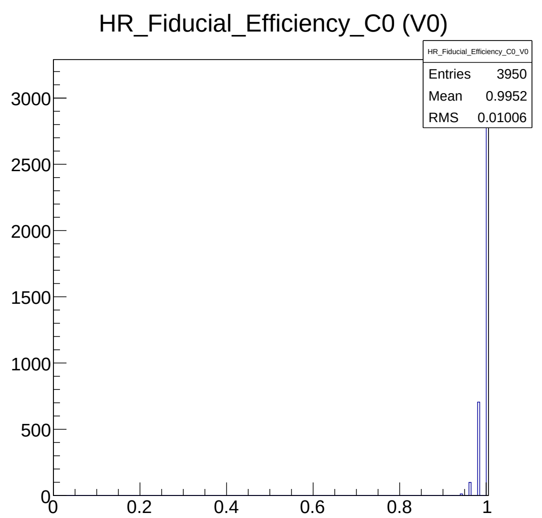



Figure 35: Efficiency of all pixels in the fiducial region (which excludes all edge pixels).

gives the efficiency. 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 both type of hits go through the same read-out chain of the ROC.

# 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. 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 seen in Appendix F.

## 7.2 Chip

In addition to the module overview page, results for each individual chip 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 of a good module can be seen in Appendix G.

## 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 which is assumed to be the signal, the other corresponds to a Gaussian noise with constant and linear terms. 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.

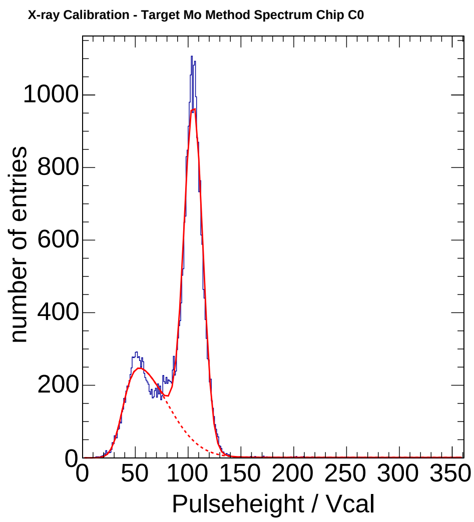



Figure 36: Molybdenum spectrum acquired by a ROC. The fit function is shown in red.

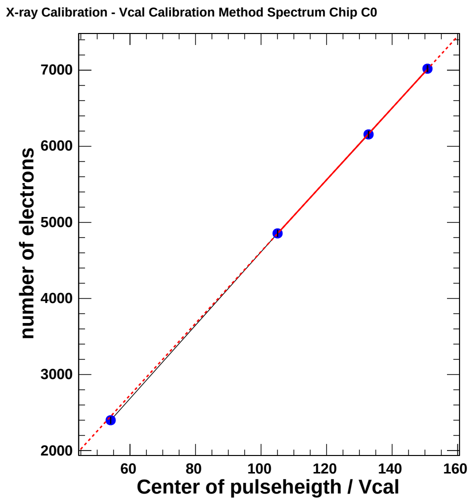



Figure 37: Vcal calibration of a ROC.

# 8 Results

This section summarizes the results of X-ray qualifications of both L1 and L2 modules of 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 only very few exceptions 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.

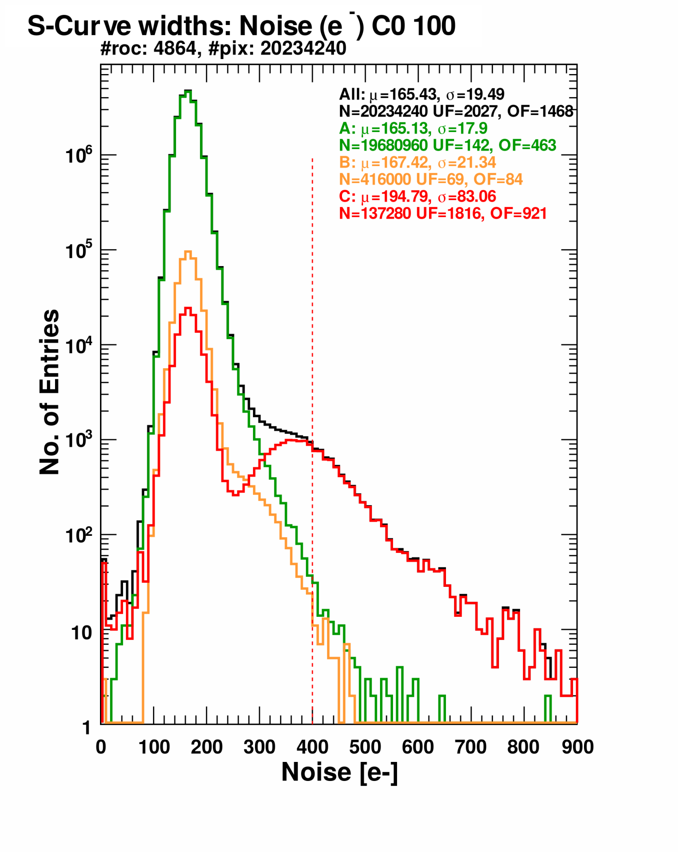



Figure 38: *Noise of each pixel of layer 2 modules. The green histogram corresponds to pixels on modules graded A, the orange one to modules graded B and the red one to modules graded C. The black line is the sum of all pixels.*

- 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 $47e^{-}$/Vcal independently of the grade of the module. The slope has a spread of about $2.1e^{-}$/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).

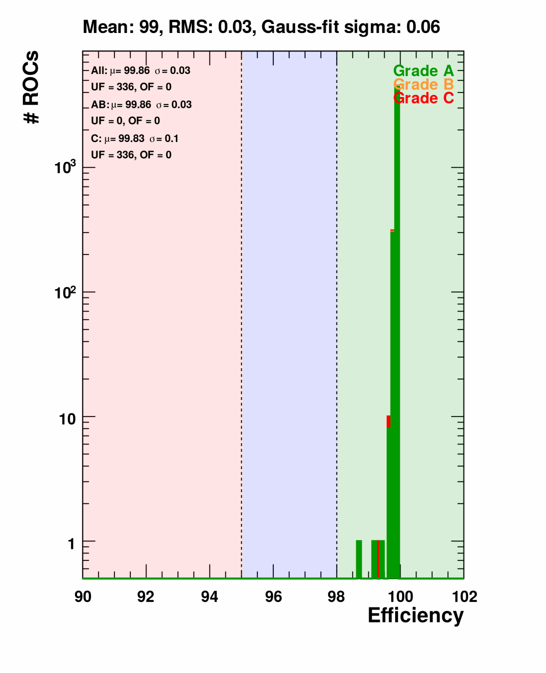



Figure 39: Efficiency of all ROCs at 50 MHz. The color designated the grade of the module to which the ROC belongs to. Green stands for grade A, orange for grade B and red for grade C.

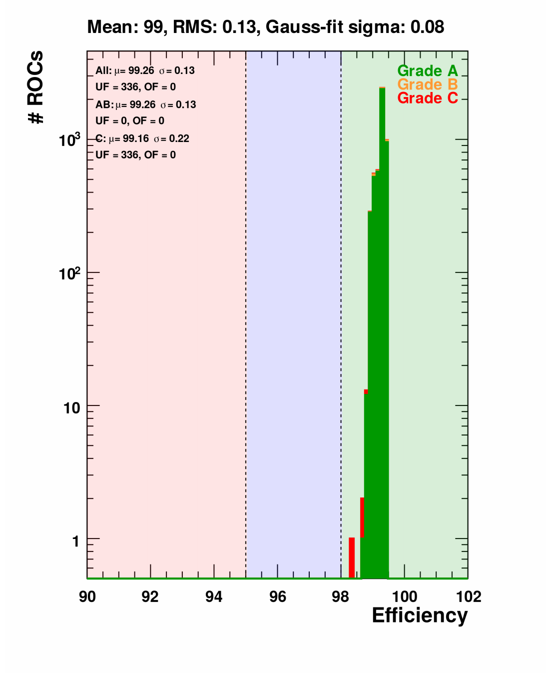



Figure 40: Efficiency of all ROCs at 120 MHz. The color designated the grade of the module to which the ROC belongs to. Green stands for grade A, orange for grade B and red for grade C.

- Noise: The noise for every pixel is shown in Figure 43. 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. 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 performed 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 efficiency is on average slightly lower than at 50 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

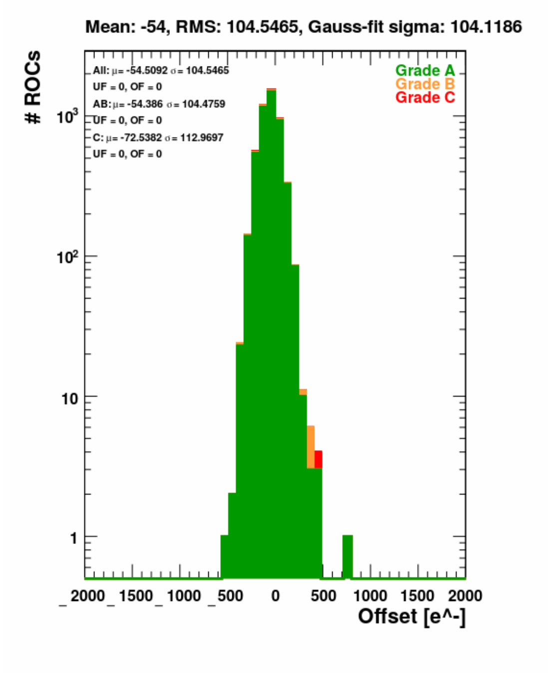



Figure 41: Offset of the Vcal calibration. The color designated the grade of the module to which the ROC belongs to. Green stands for grade A, orange for grade B and red for grade C.

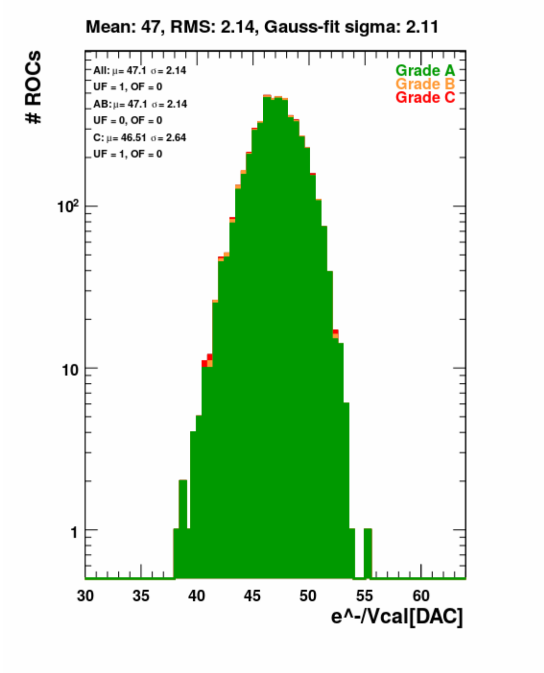



Figure 42: Slope of the Vcal calibration. The color designated the grade of the module to which the ROC belongs to. Green stands for grade A, orange for grade B and red for grade C.

criteria are shown in Appendix C.

### 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 was already reduced by introducing an electrical 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 either on the hitmaps, or when calibrate signals are used, or sometimes also for both. For some modules, these defects can 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 bad bump bonds (BB) which means that the connection between the read-out chip and the sensor is broken. This concerns

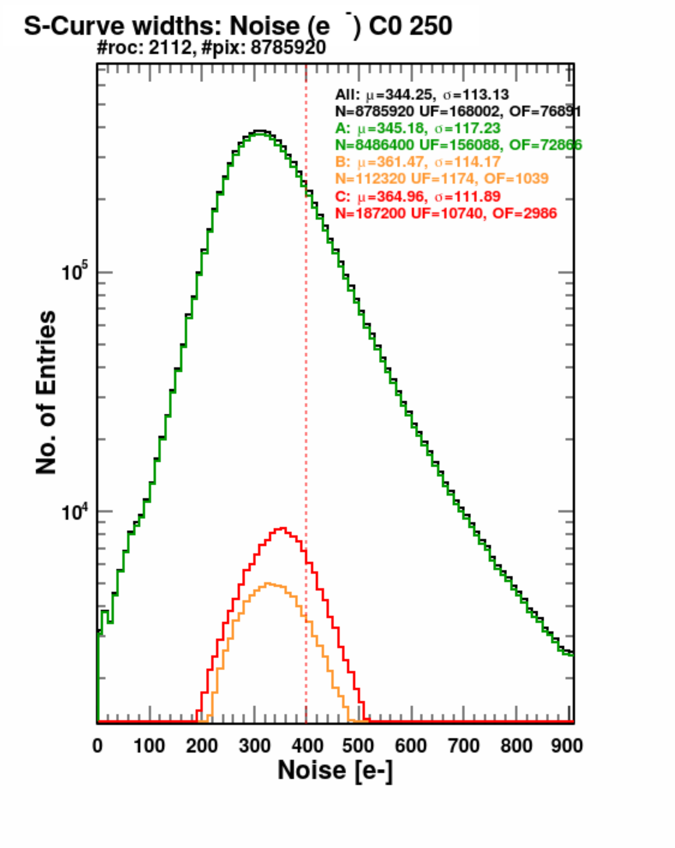



Figure 43: *Noise of each pixel of layer 1 modules. The green histogram corresponds to pixels on modules graded A, the orange one to modules graded B and the red one to modules graded C. The black line is the sum of all pixels.*

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 BB. This map shows that most of the BB defects appear on the edges and the corners of ROCs, forming so-called "church windows".

### 8.3.3 Defective HDI

Six L2 modules were rejected due to a defective batch of HDIs which were used for those modules. For these HDI, the resistance of the groundline was too high, such that the delivered analog current for ROCs further away from the TBM is not sufficient for operation. This issue should not appear again as this is now tested in the HDI qualification.

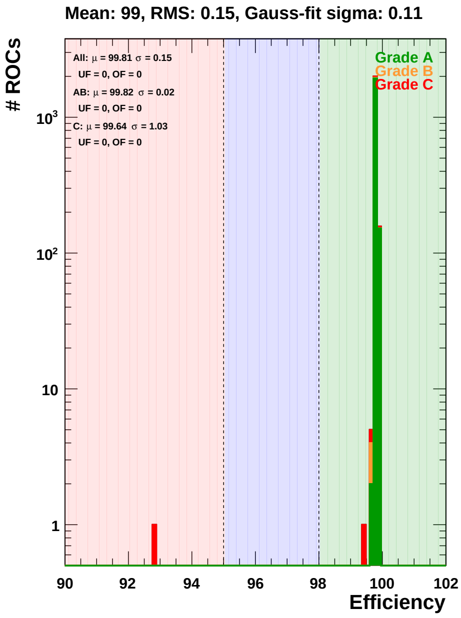



Figure 44: Efficiency of all ROCs at 150 MHz. The color designated the grade of the module to which the ROC belongs to. Green stands for grade A, orange for grade B and red for grade C.

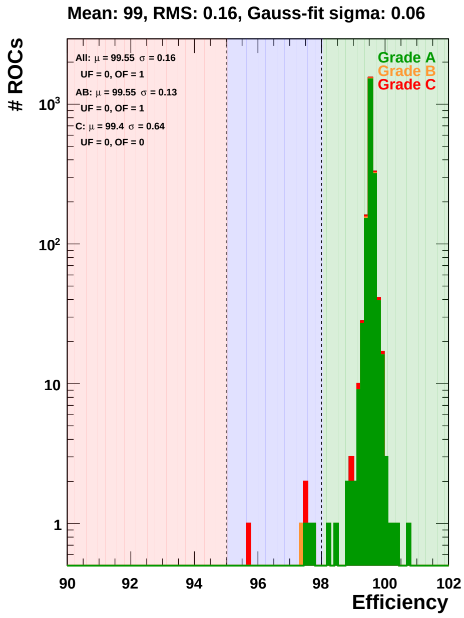



Figure 45: Efficiency of all ROCs at 300 MHz. The color designated the grade of the module to which the ROC belongs to. Green stands for grade A, orange for grade B and red for grade C.

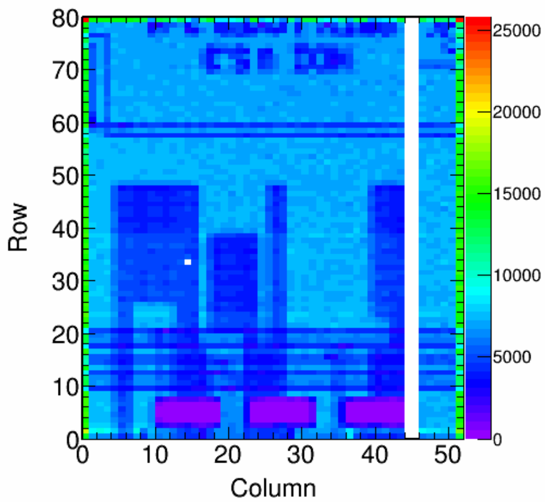



Figure 46: Hit map of a ROC with a defective DC.

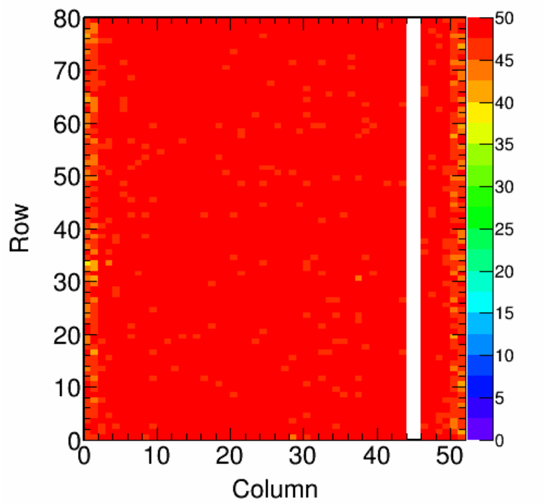



Figure 47: Number of correctly read out test pulses per pixel (out of 50) for the same ROC at an X-ray hit rate of approximatively 150 MHz cm$^{-2}$.

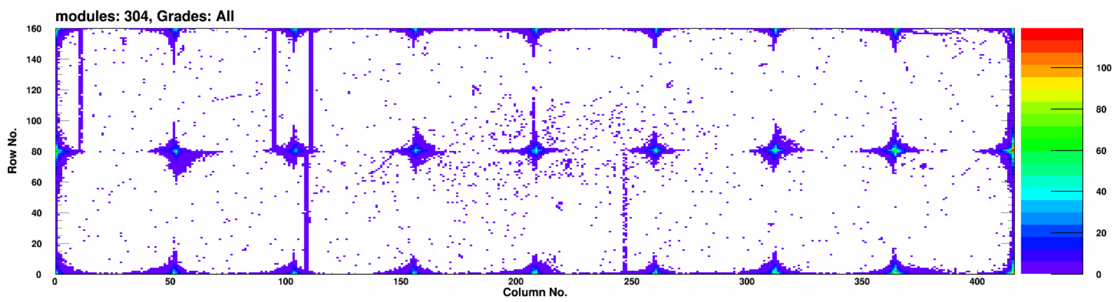



Figure 48: *Overview of all bump bonding defects for the L2 module production.*

# Appendices

## A 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 water supplies and serial adapter from the right side of the climatic chamber.
- Unscrew top frame (see Figure 50 - upper screws on the sides).
- Remove front, back and right side panels (see Figure 51 and 52).
- Remove cooling plate. The temperature sensor must be unplugged for this (see Figure 53).
- Unscrew Peltier element connector (see Figure 54), unplug temperature sensor on 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.

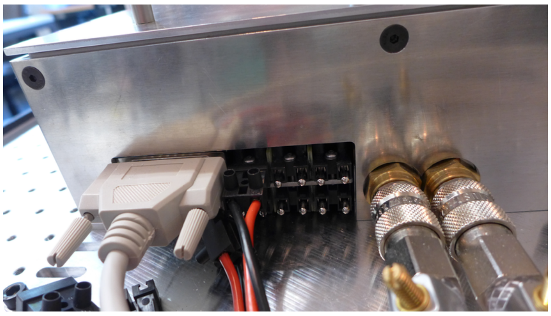


Figure 49: Verification of the functionality of the Peltier elements.

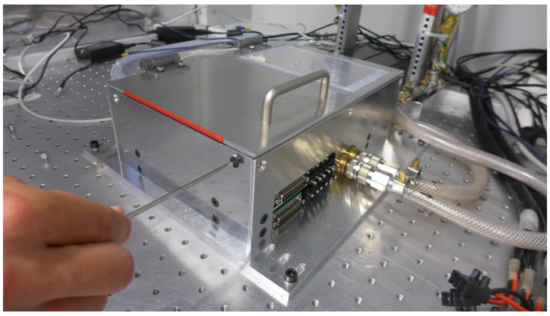


Figure 50: Unscrewing of the walls of the climatic chamber.

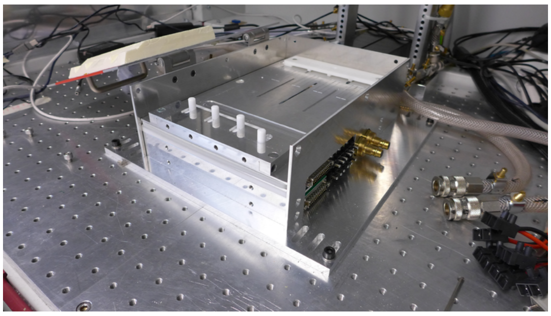


Figure 51: Picture of the opened climatic chamber I.

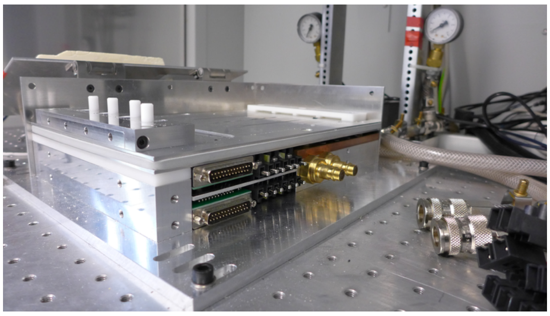


Figure 52: Picture of the opened climatic chamber II.

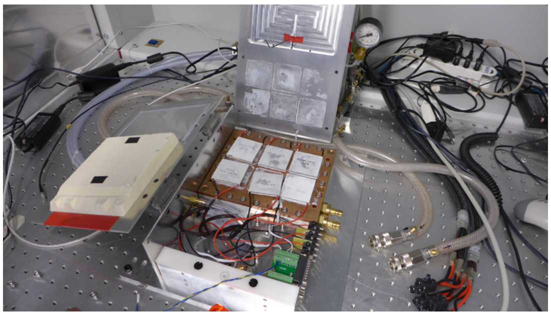


Figure 53: Picture of the climatic chamber with removed base plate.

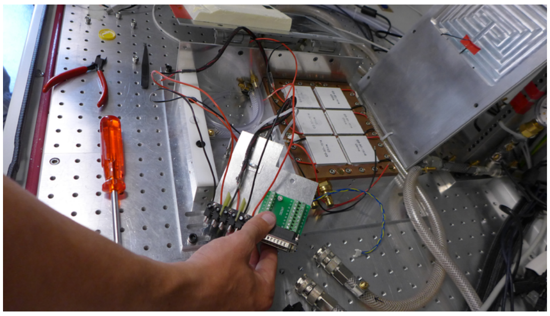


Figure 54: Picture of the Peltier element connector

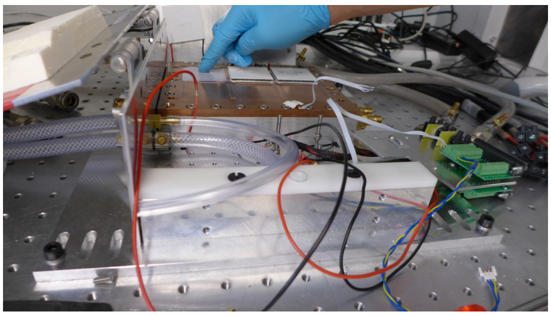


Figure 55: Thermal grease application on the Peltier elements.

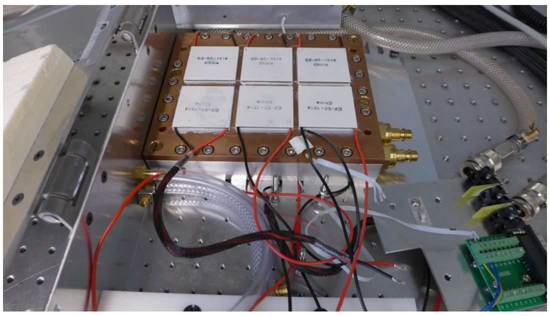


Figure 56: Picture of all Peltier elements in the climatic chamber.

# B 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 ID3003 program off, hold the "Enter" button, turn the key to "Stand By" and select 2. Then select item 02 "Preset flow rate" which will show the water flow. It should be around $6\,\mathrm{l\,min^{-1}}$. If the flow is below $3.5\,\mathrm{l\,min^{-1}}$, 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 it may get wet.empty the tubes.

- 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 if 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.

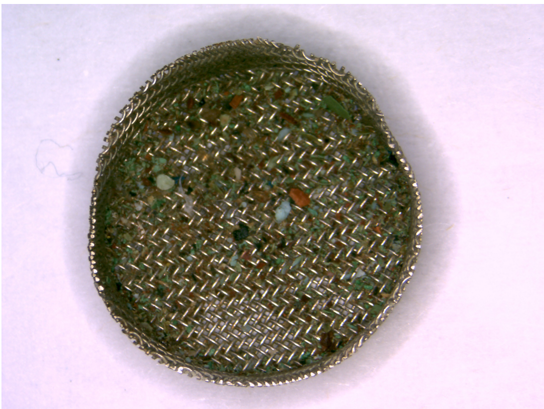


Figure 57: Picture of the filter before cleaning.

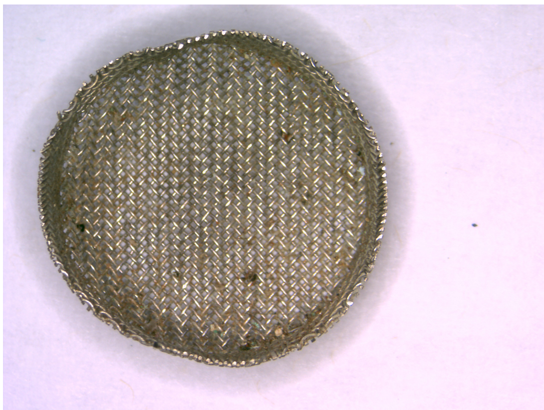


Figure 58: Picture of the filter after cleaning.

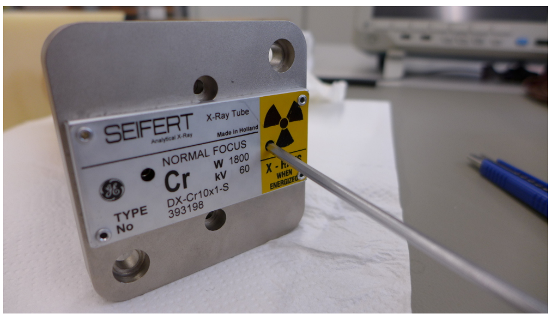



Figure 59: Unscrewing of screws that hold the front plate I.


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

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

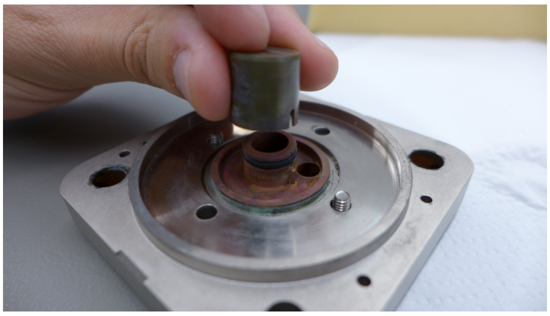


Figure 62: Casing of the filter removed from the X-ray tube.

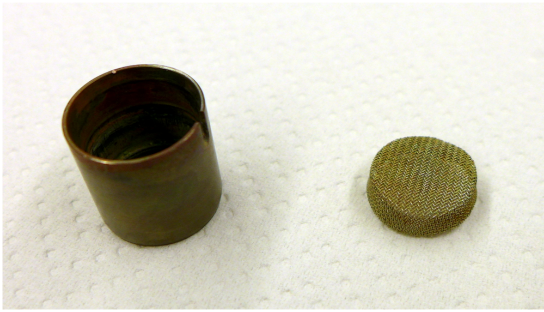


Figure 63: *Filter and its casing.*

# C 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 were accepted. The performance parameters leading to a downgrade are shown in Table 2 and the reasons for a pixel being defective in Table 3.

Table 2: Performance parameters of a ROC leading to a downgrade

| | B | C |
|---|---|---|
| Average noise [3] [$e^-$] | $> 300$ | $> 400$ |
| Efficiency 120/300 MHz/cm2 | $> 98\%$ | $> 95\%$ |
| Column uniformity problems | - | $\geq 1$ |
| Readout uniformity problems | - | $\geq 1$ |

Table 3: List of reasons for a defective pixel.

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

# D 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 elCommandante. In the second one, one should indicate details about which tests to execute and under which conditions (temperature, X-ray hit rate). Please note that for readability reasons some lines are split into several lines. For testing, its needs to be written in one line

## D.1 L1

elCommandante.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
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
```

## D.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_WS6UZO
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 = cmspixel.pi.infn.it
port = 23481
destination = /home/eth/dropbox
user = eth
checkForTars = False
```

# E 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. * stands for the ROC number, and & for the TBM core (0a, 0b for L2 modules, 0a, 0b, 1a, 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 H.

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 |

# F MoReWeb results - Module overview

This section shows some results of an excellent L1 and L2 module 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 $150\,\mathrm{MHz\,cm^{-1}}$ and at $300\,\mathrm{MHz\,cm^{-1}}$. Figures 65 and 66 show a hitmap 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 $250\,\mathrm{MHz\,cm^{-1}}$. 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.

# G 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. 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 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

Chips

**Overview**

--- select ---

Summary

| | |
|---|---|
| Module | M2356 |
| Grade | A |
| Manual Grade | None |
| ROC Grades A/B/C | 16/0/0 |
| Total Pixel Defects | 3 |
| Bump Bonding Defects | 3 |
| Noisy Pixels | 0 |
| Hot Pixels | 0 |
| ROCs with r/o problems | 0 |
| ROCs with unif problems | 0 |
| Efficiency 50/120 | 99.85/99.14 % |
| Mean Noise | 171 e- |

Summary ROCs

| 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chip 0 | A | 2 | 0 | 99.82 | 98.94 | 0.7 | 26.2 | 79.1 | 2 | 0/0 | 0 | 1957 | 180 | 0 |
| Chip 1 | A | 0 | 0 | 99.85 | 98.92 | 0.56 | 25.8 | 79.0 | 0 | 0/0 | 0 | 1950 | 182 | 0 |
| Chip 2 | A | 0 | 0 | 99.83 | 98.99 | 0.63 | 21.0 | 65.5 | 0 | 0/0 | 0 | 1924 | 160 | 0 |
| Chip 3 | A | 0 | 0 | 99.87 | 99.29 | 0.65 | 40.7 | 121.2 | 0 | 0/0 | 0 | 2102 | 174 | 0 |
| Chip 4 | A | 1 | 0 | 99.86 | 99.30 | 0.45 | 40.1 | 119.6 | 1 | 0/0 | 0 | 2077 | 173 | 0 |
| Chip 5 | A | 0 | 0 | 99.85 | 99.25 | 0.7 | 51.0 | 149.8 | 0 | 0/0 | 0 | 2143 | 176 | 0 |
| Chip 6 | A | 0 | 0 | 99.87 | 99.31 | 0.61 | 47.3 | 139.5 | 0 | 0/0 | 0 | 2119 | 176 | 0 |
| Chip 7 | A | 0 | 0 | 99.86 | 99.25 | 0.86 | 46.8 | 137.3 | 0 | 0/0 | 0 | 2124 | 164 | 0 |
| Chip 8 | A | 0 | 0 | 99.83 | 99.00 | 0.88 | 43.0 | 127.3 | 0 | 0/0 | 0 | 2088 | 167 | 0 |
| Chip 9 | A | 0 | 0 | 99.86 | 99.30 | 0.59 | 42.4 | 126.6 | 0 | 0/0 | 0 | 2081 | 173 | 0 |
| Chip 10 | A | 0 | 0 | 99.89 | 99.30 | 0.51 | 38.6 | 114.7 | 0 | 0/0 | 0 | 2037 | 170 | 0 |
| Chip 11 | A | 0 | 0 | 99.82 | 98.96 | 0.65 | 35.8 | 107.9 | 0 | 0/0 | 0 | 2056 | 173 | 0 |
| Chip 12 | A | 0 | 0 | 99.82 | 98.99 | 0.57 | 33.2 | 100.2 | 0 | 0/0 | 0 | 2029 | 168 | 0 |
| Chip 13 | A | 0 | 0 | 99.85 | 99.23 | 0.61 | 19.2 | 60.1 | 0 | 0/0 | 0 | 1959 | 165 | 0 |
| Chip 14 | A | 0 | 0 | 99.84 | 99.24 | 0.43 | 22.3 | 68.7 | 0 | 0/0 | 0 | 1957 | 166 | 0 |
| 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.*

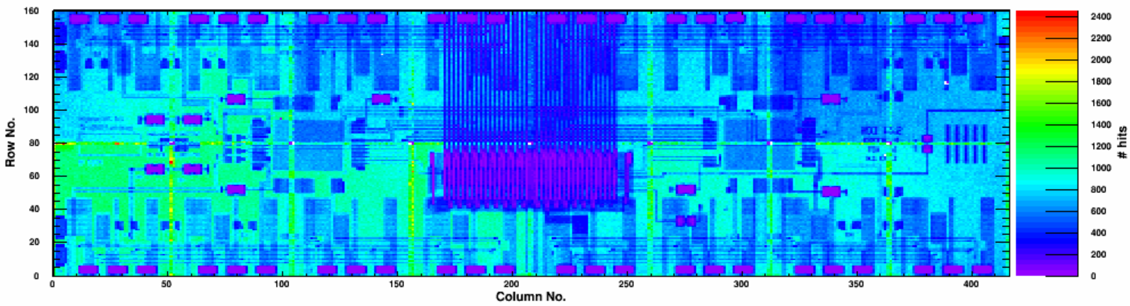



Figure 65: *Map of a L1 module showing the number of hits per pixel.*

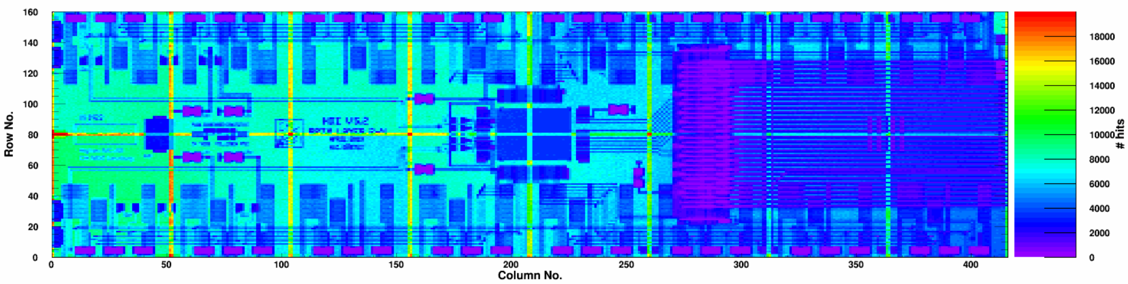



Figure 66: *Map of a L2 module showing the number of hits per pixel.*

to some features on the HDI which can shied 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 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.

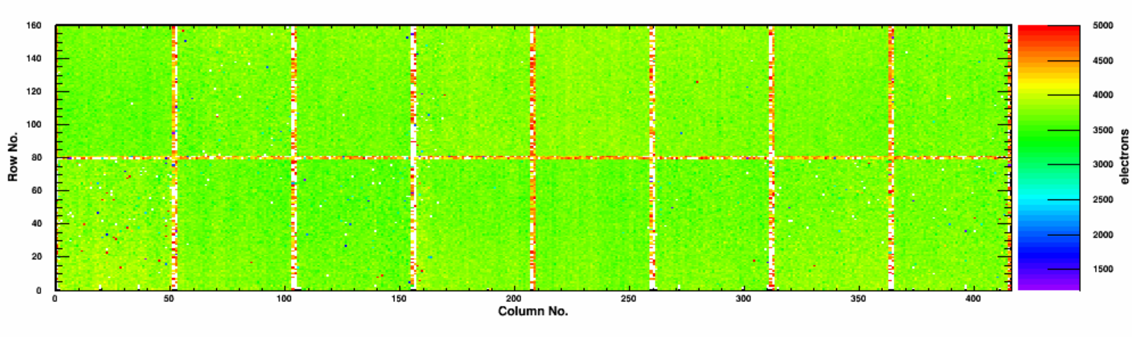



Figure 67: *Map of a L1 module showing the threshold of each pixel.*

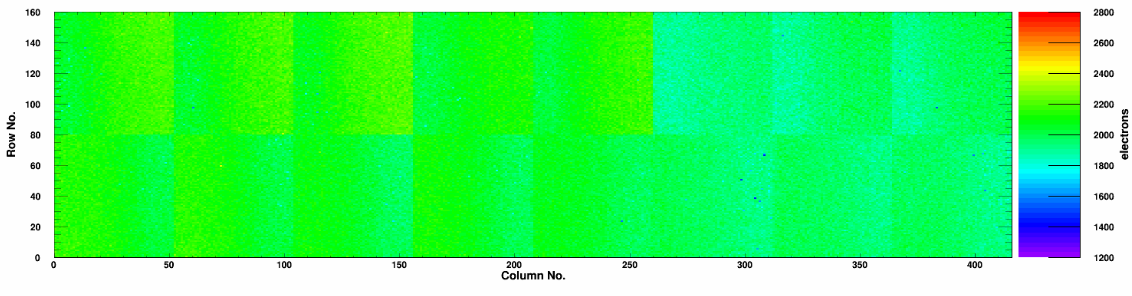



Figure 68: *Map of a L2 module showing the threshold of each pixel.*

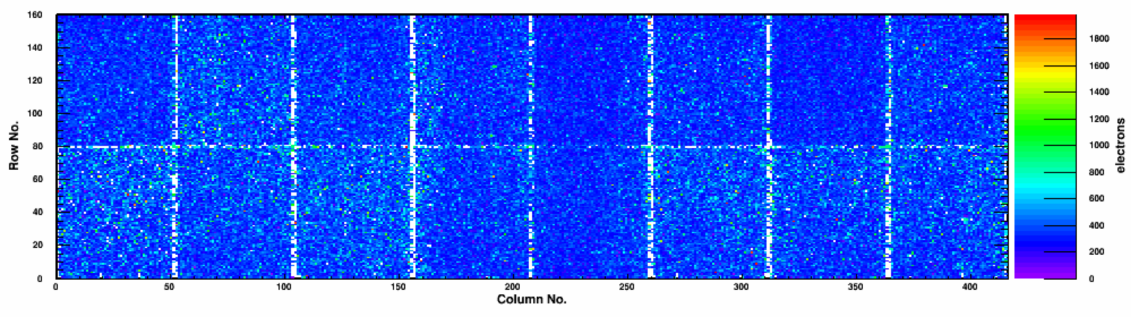



Figure 69: *Map of a L1 module showing the noise of each pixel.*

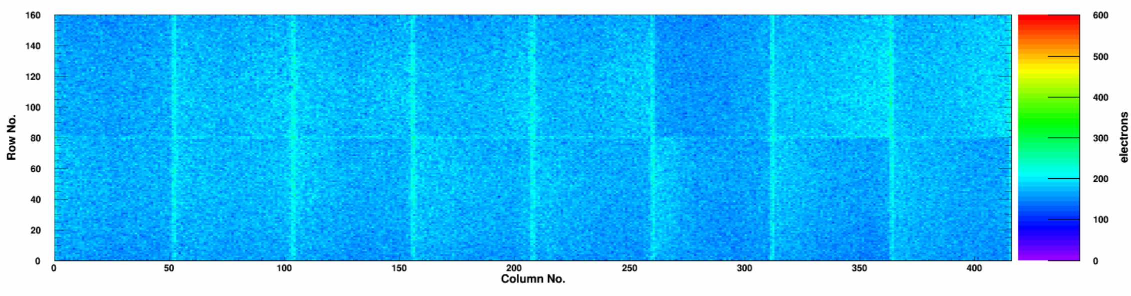



Figure 70: *Map of a L2 module showing the noise of each pixel.*

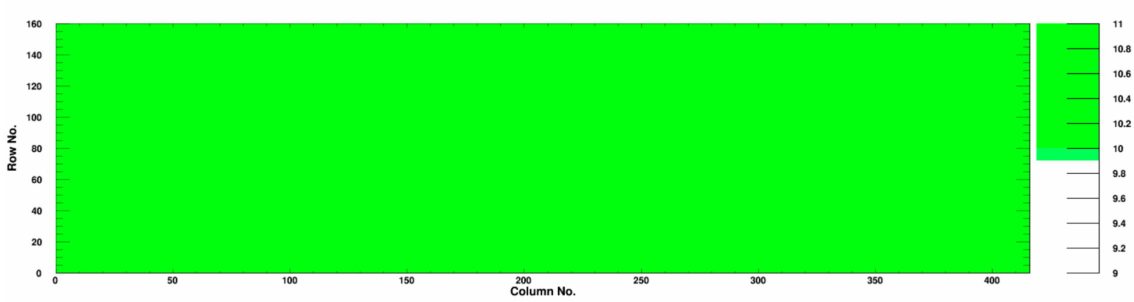



Figure 71: *Map of a L2 module showing dead or inefficient pixels (without exposing the module to radiation).*

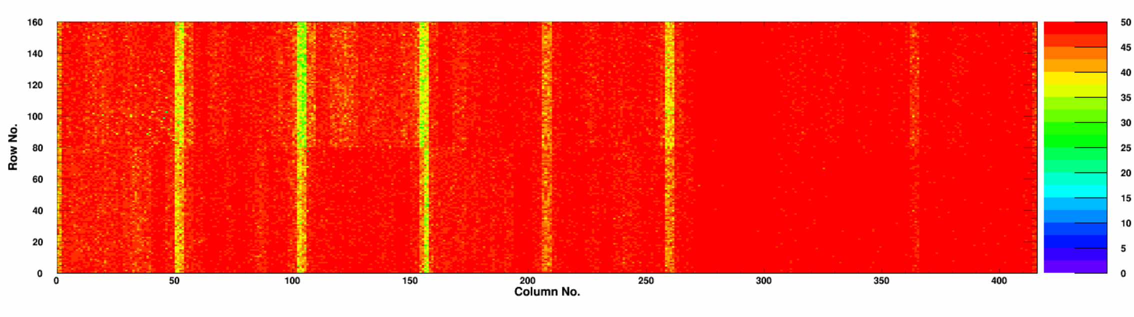



Figure 72: *Map of a L2 module showing the efficiency of each pixel when exposing the module to X-radiation.*

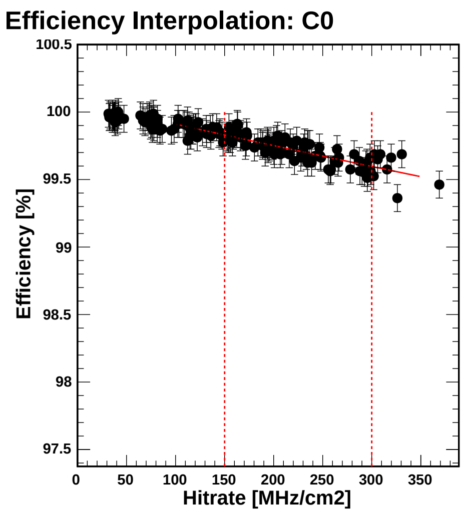



Figure 73: Efficiency of a L1 ROC as a function of particle hit rate.

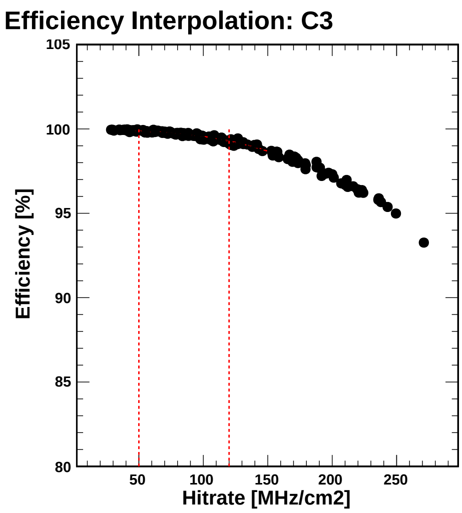



Figure 74: Efficiency of a L2 ROC as a function of particle hit rate.

# H Links to relevant documentation

- ETH Pixel Group webpage: Links to the results of the 2015-2016 production can be found here.

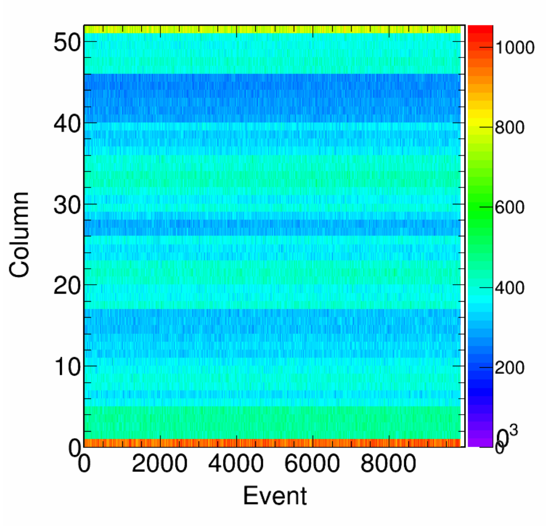



Figure 75: Number of X-ray hits per event per column.

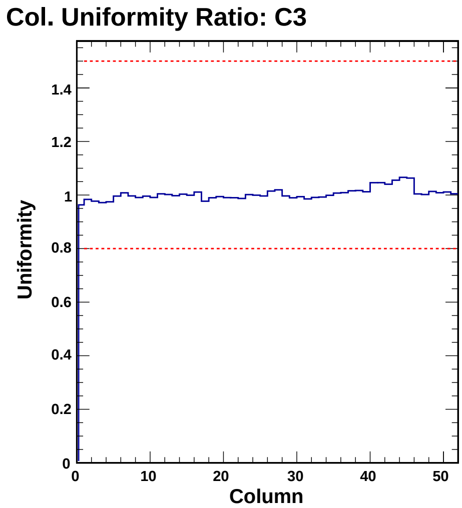



Figure 76: Scaled ratio between the number of X-ray hits acquired at two different X-ray rates.

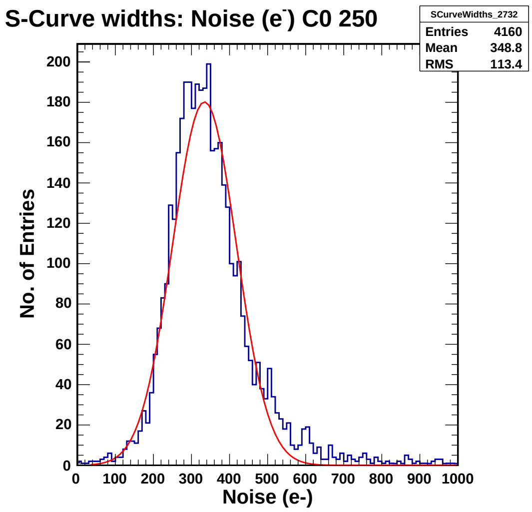



Figure 77: Noise of a ROC on a L1 module when exposed to radiation.

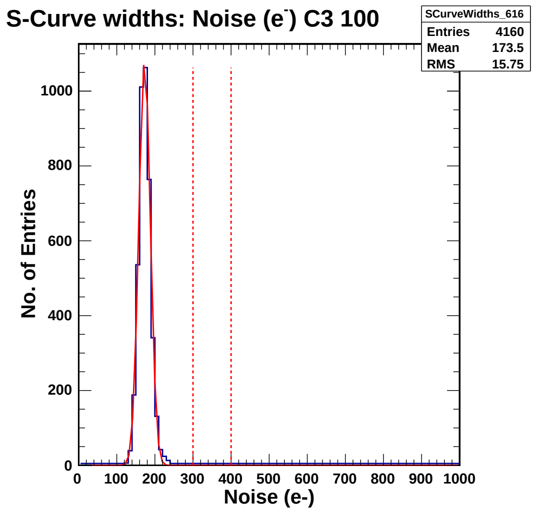



Figure 78: Noise of a ROC on a L2 module when exposed to radiation.

`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: Here, results from the qualification of modules for the phase 0 detector can be found. https://cmspixel.phys.ethz.ch/moduleTests/moduleDB/prodTable.php?Serie=00
- PSI Phase I webpage: Information on all components of a module 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://cmspixelprod.pi.infn.it/index.html
- Specification of BPix modules: Some information of tests of individual components of modules 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