Fermilab

UNIVERSITÀ DI PISA

DARK MATTER DETECTORS

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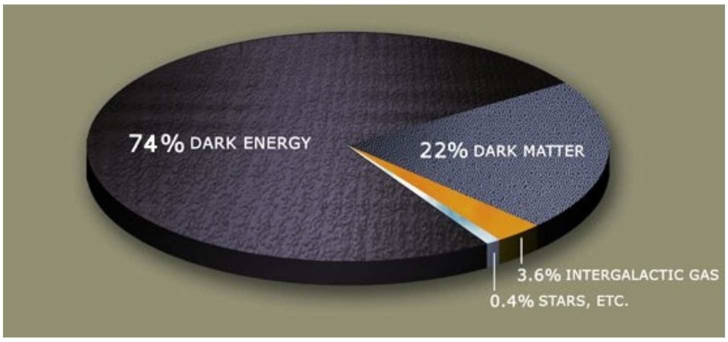
Contents

Chapter 1

Introduction

Scientists believe that we know only a small part of the universe; and this suggests that there is so much to discover !
As can be seen in the next graph we think that only 4 % of the universe is known, whereas the remaining 96 % can be consider *Dark Matter* and *Dark Energy.*
In Fermilab there are some experiments that try to find out more about this matter; one of these is the "DAMIC" experiment.



DAMIC experiment

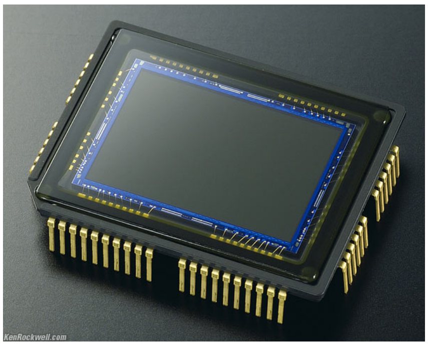
DAMIC means "Dark Matter In CCDs". This project uses indeed CCDs (Charge Coupled Devices) as detectors for dark matter.
These detectors can record a snapshot of the electric charge created by a collision between an incident particle (for example mouns, cosmic rays, or dark matter particles) with the material inside the CCD (in our case the silicon).

Chapter 2

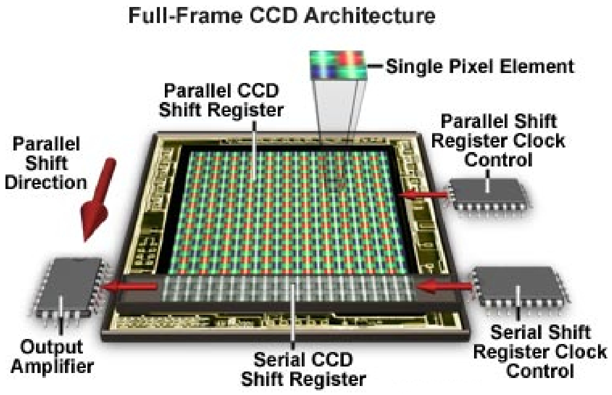
CCDs as detectors

CCD : Overview and working principle

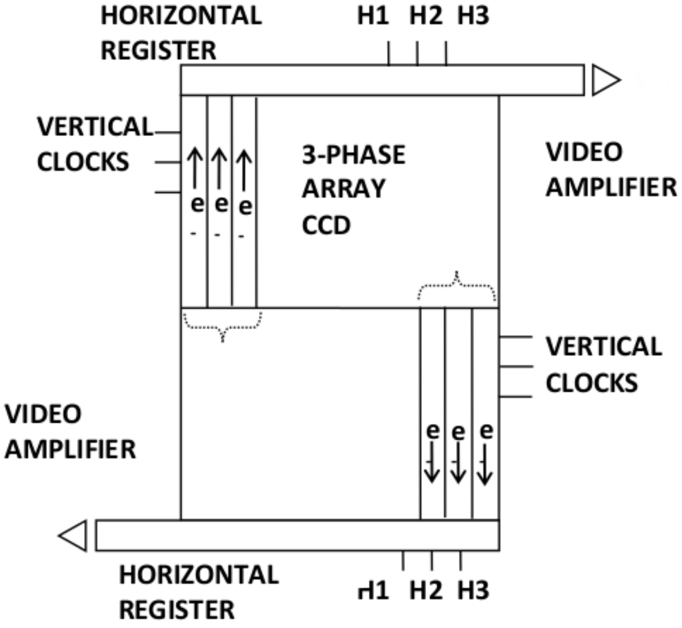
CCD means "Charge Coupled Devices".
This is a light sensitive detector. It consists in a matrix of detectors (that are semiconductors capable of accumulate charge); each detector represents a pixel and the amount of accumulate charge depends on the amount of light which falling upon it.
The next image shows a CCD sensor.



Although a CCD is a light-sensitive detector, using the photoelectric effect it can also detect charged or uncharged particles by other physic effect such as compton, electron scattering, electron or nuclear recoil, etc.
The next image shows a tipical architecture of CCD.

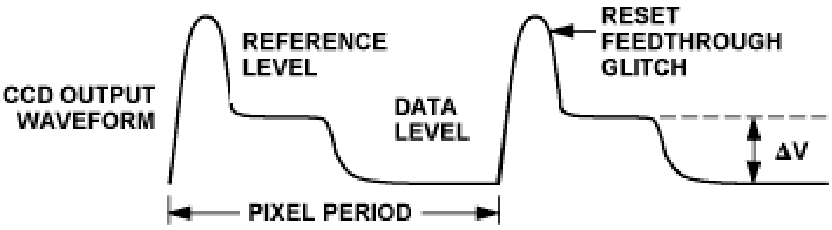


The next image shows an example of CCD architecture.



It's divided in two identical parts, upper and lower part; each one has a detectors array, a register (horizontal register) and an output amplifier.
In the first phase the CCD accumulates charge in the detectors array, in other words it takes a snapshot.
In the second phase the accumulated charge in each row is transferred to the neighboring row and the charge in the first row is transferred to the horizontal register.
In the last phase the charge in the horizontal register is amplified and read out through the output amplifier.

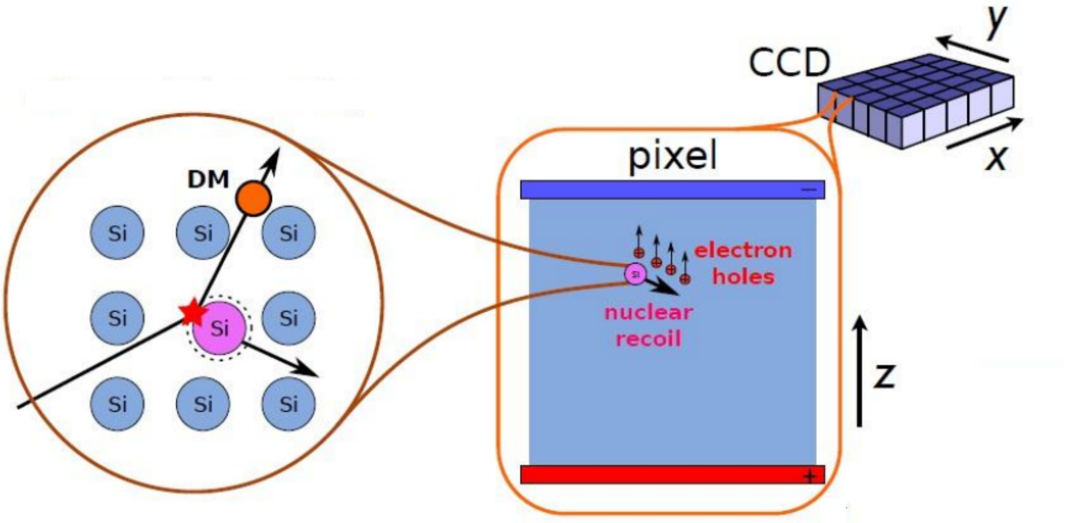
The output waveform can be seen in the next image.



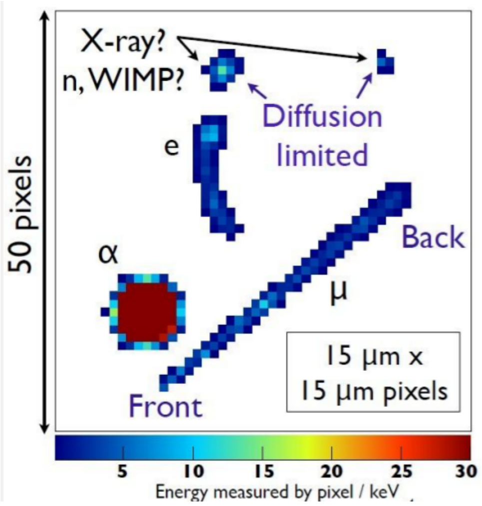
It consists in a sequence of pixel periods separated by a reset pulse.
Each pixel period has two section : a reference interval which represents the zero-value of that pixel, and a data interval which represents the level of that pixel.
At the end of each line there is an *end-of-line* pulse, therefore the sequence starts again to the next line.

How does the detector work?

The next image shows a cross section of a pixel.

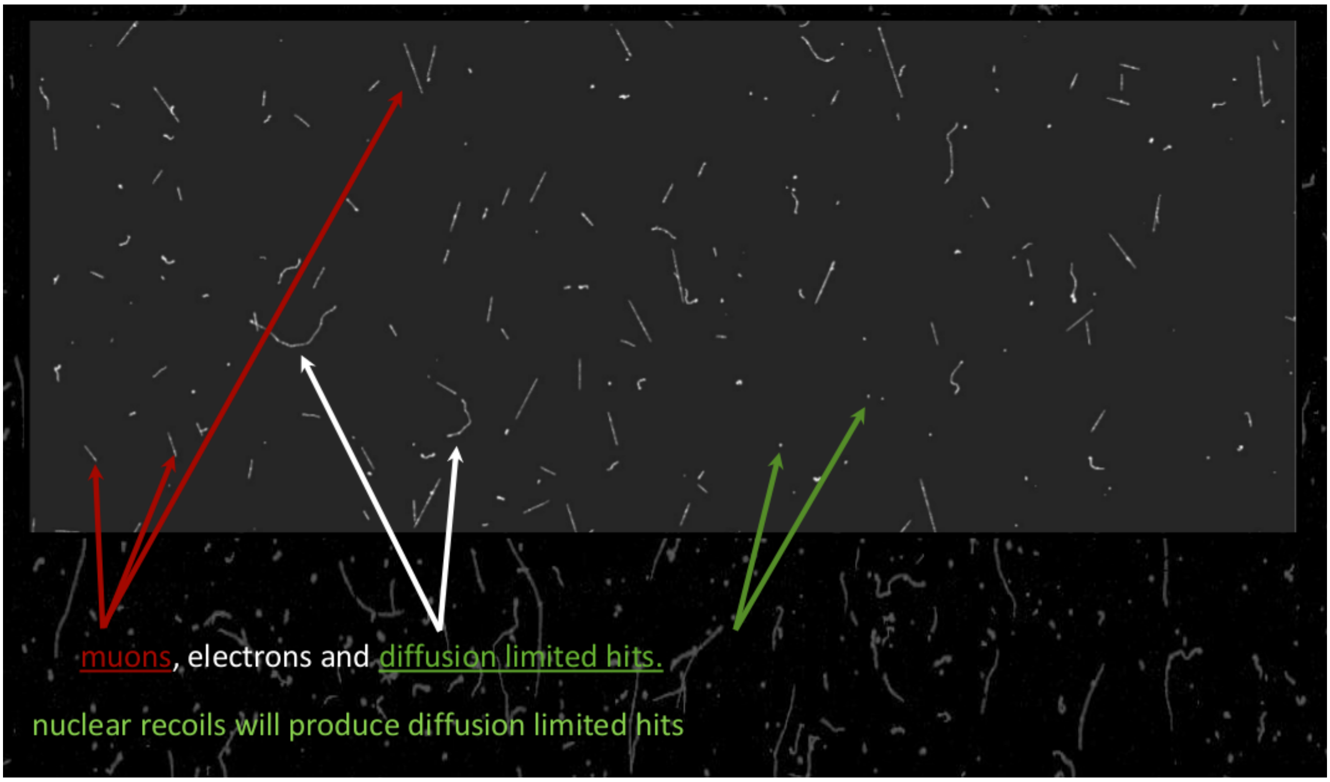


When a particle impacts with the structure of silicon, it can disrupt the crystal lattice of the material and a phonon is generated.
The result image allow us to understand the nature of incident particle. The next image shows the result: for example a moun left a straight trace, an electron left a blend trace ecc ...



Final snapshot

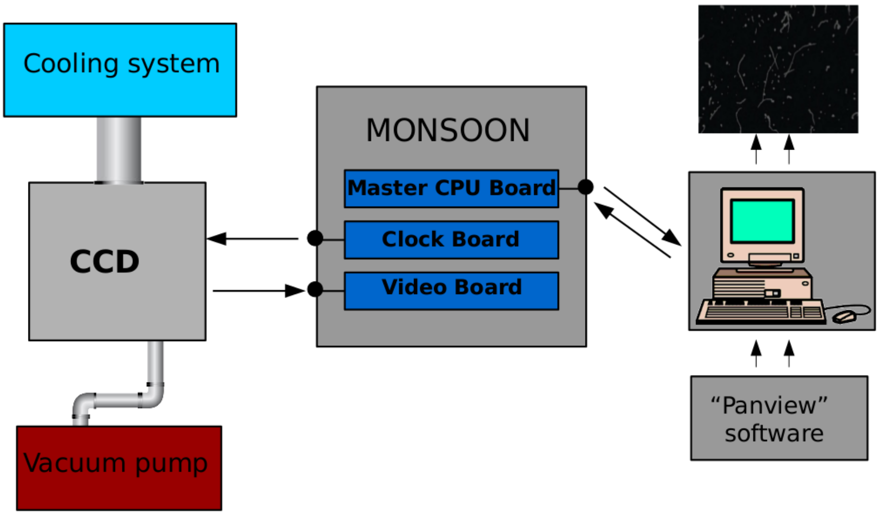
In the next image there's a real snapshot made by our CCD.



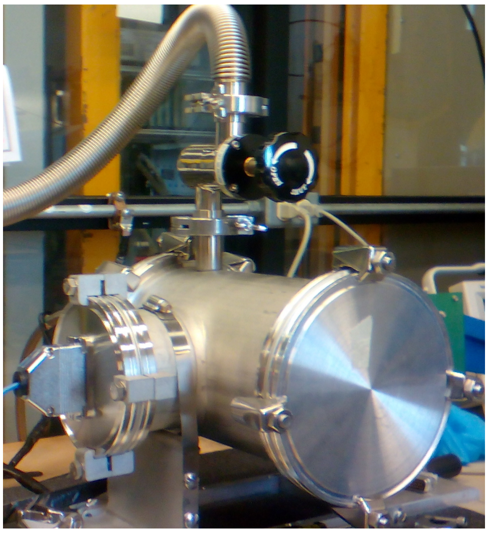
Chapter 3

The setup

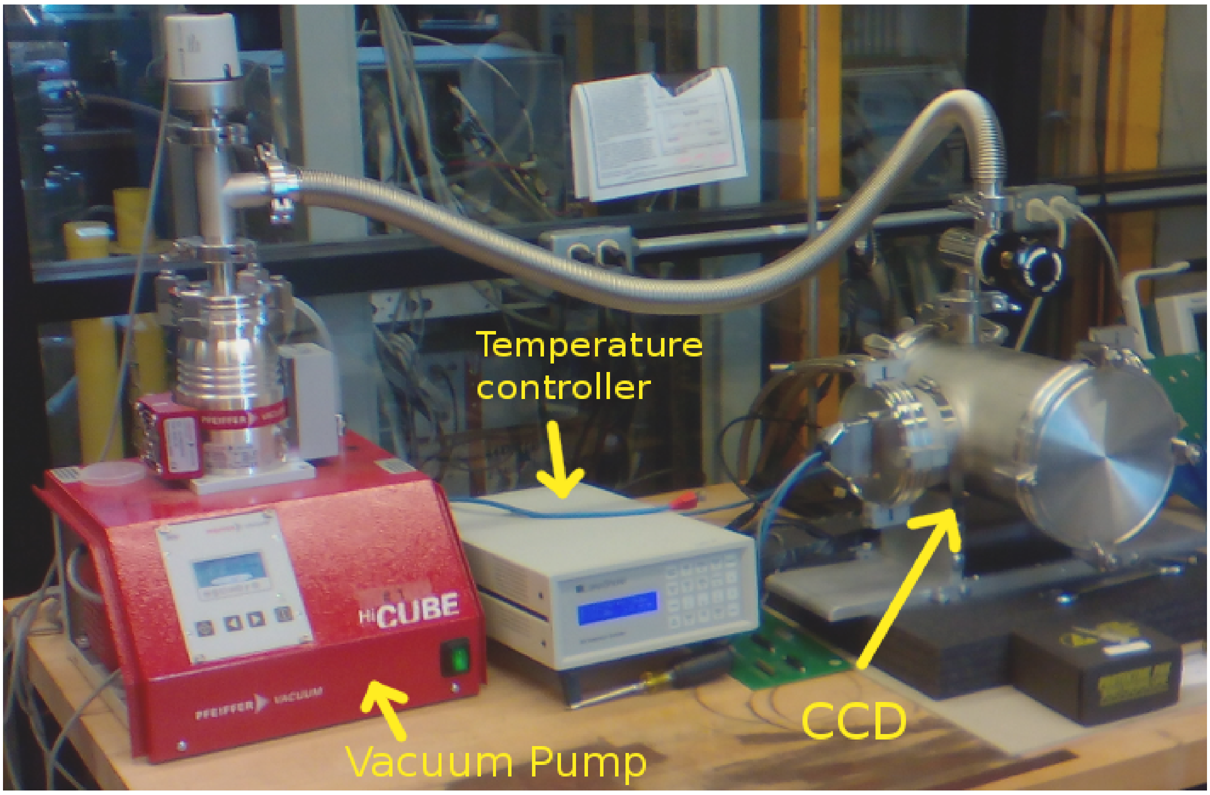
The system is located in the SiDet building (”Silicon Detector Facility”) in Fermilab. In the next figure will show a block diagram of our system.



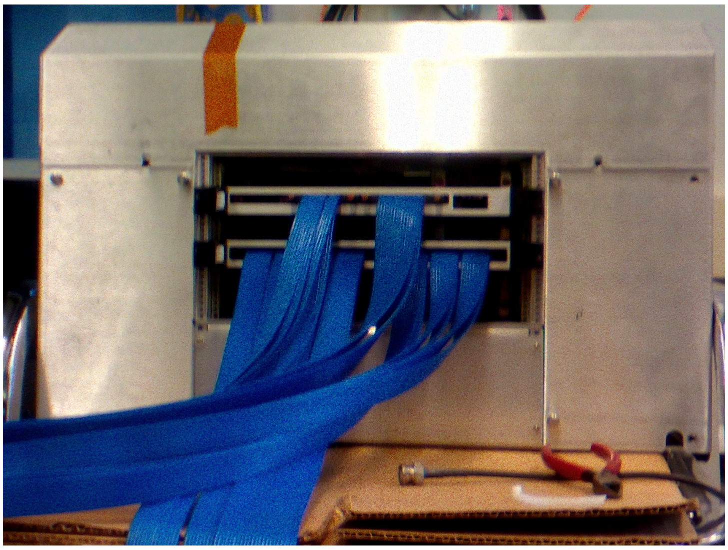
The CCD (next photo) is the heart of the system. It’s cooled at about -150 °C.
It has a resolution of 8 megapixel, divided in 4096 rows and 2048 colums.
It’s kept in a dark box, to avoid the presence of the ligth.



There is also a vacuum pump to avoid the ice formation inside the CCD that could be dangerous.
In this photo we can see the entire system located in a SiDet laboratory.



The CCD communicate with an electronic system called "MONSOON" (next image), developed by Fermilab in collaboration with some universities.

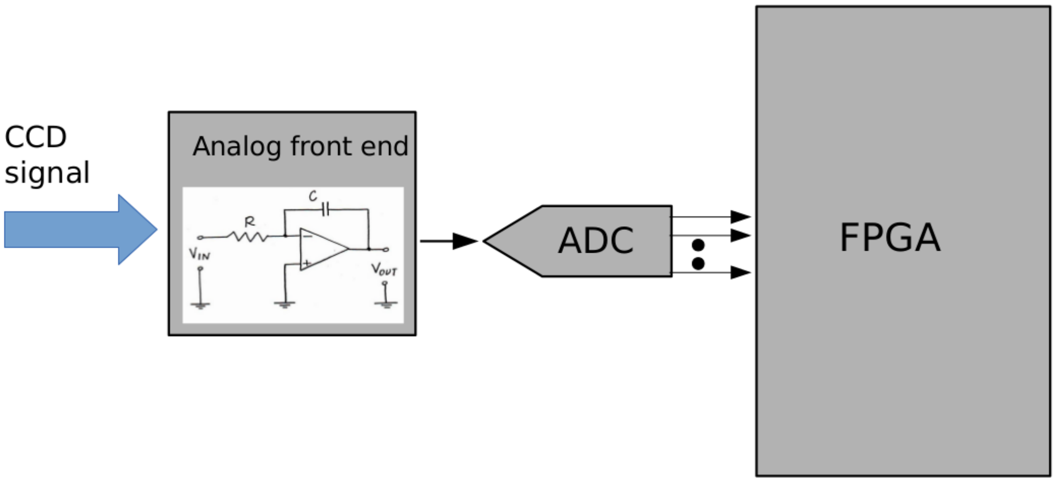


Monsoon has 3 electronics boards inside : Master CPU Board, clock board and video board.
The Master CPU Board controls the system and communicates with the external personal computer (used to send commands by user).
The Clock Board provides the suitable clock signals to the CCD.

With the *PANVIEW* software we can send commands to the system, for example "take a snapshot", or change some parameters (integration time or the reading area).
Finally we can see and analize the result image with specific software (for example *DS9*).

Monsoon System : Acquisition board

In the next image can be seen the acquisition system.



It has an analog front end which amplifies the signal and then integrates it.
After the analog system there is an analog to digital converter ("ADC") which provides the digital data to the FPGA ("Field Programmable Gate Array").
The analog front end performs also the **Correlated Double Sampling** technique, useful to calculate the values of the pixels.

Chapter 4

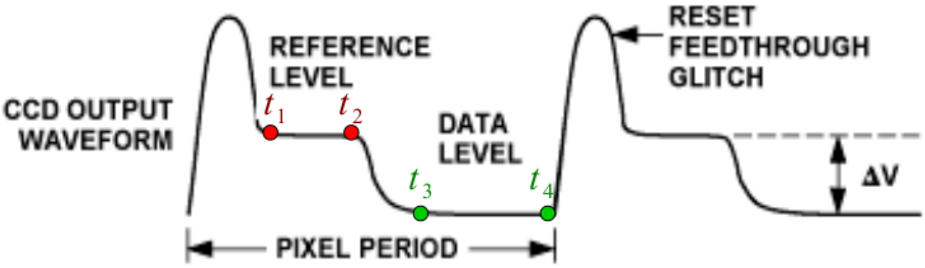
Our purposes

GOAL : Substitute the analog integrator system with a digital system which implements the Correlated Double Sampling throught an FPGA.

CDS : Correlated Double Sampling

The *Correlated Double Sampling* is a method to measure electrical values and removing the undesired offset.
It's also a noise reduction technique (in the image processing).

The next image shows the waveform of the CCD output signal (as seen in the previous chapters).



The CDS integrates the signal in two intervals (data interval and reference interval) and then **subtract** them; in other words it does the average of data interval minus the average of reference interval.

$$CDS_i = \frac{1}{T}\int_0^T [Data_i(t) - Ref_i(t)]dt$$

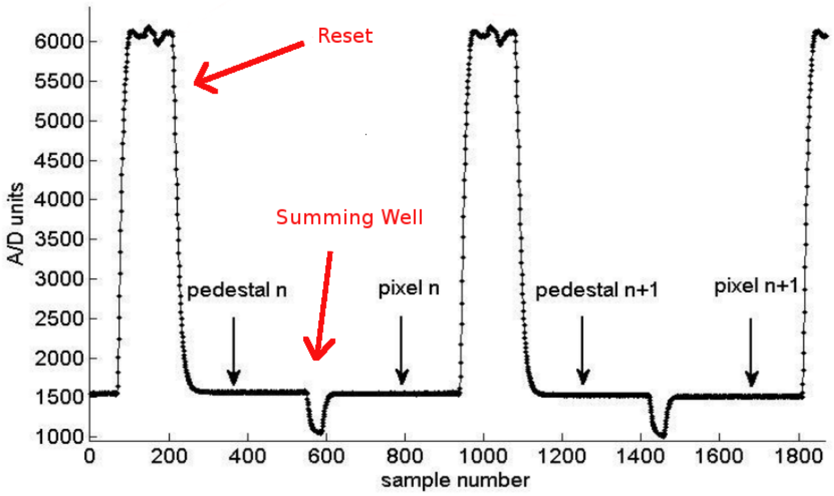
Therefore :

$$CDS_i = \frac{1}{T}[\int_{t_3}^{t_4} x_i(t)dt - \int_{t_1}^{t_2} x_i(t)dt]$$

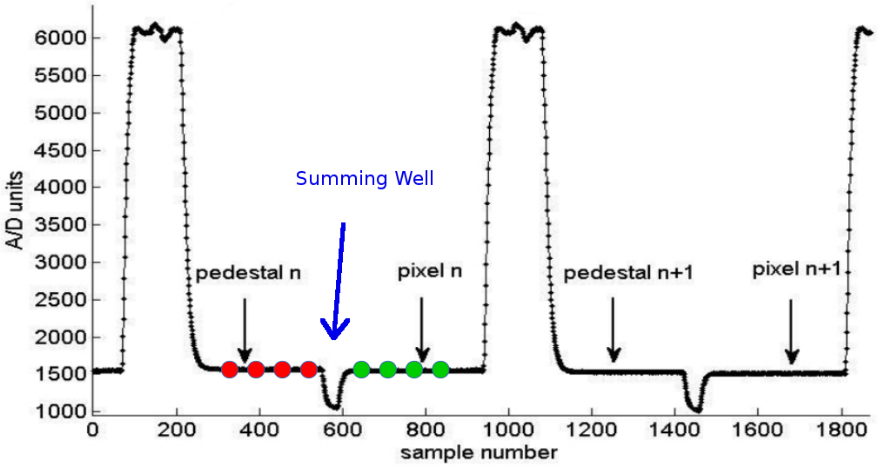
Digital Correlated Double Sampling

As already mentioned, our goal is substitute the analog system with a digital system. Since we are going to work with **digital samples**, we have to use the Digital Correlated Double Sampling.

How does it work?
In digital domain we have this kind of signal :



First of all we have to take N-samples of pedestal section and N-samples of pixel section during the observation time, as close as possible to the summing well pulse, as can be seen in the next figure.



When we get the right samples, we can processing the data and calculate the values of pixels using the digital correlated double sampling :

$$CDS_i = \frac{1}{N_s}[\sum_{N_s} pixel_i(N_s) - \sum_{N_s} pedestal_i(N_s)]$$

FPGA : Field Programmable Gate Array

As mentioned above, our goal is substitute the analog system with a digital system. To do this we are going to use an FPGA ("Field Programmable Gate Array").
We use the evaluation board Xilinx ML-605, equipped with Virtex-6 *"XC6VLX240T-1FFG1156"* FPGA (next figure).

Since the ML-605 hasn't an Analog to Digital Converter ("ADC") on board, we have to use an external ADC.
We use an **Analog to Digital Converter** board developed by FNAL ("Fermi National Accelerator Laboratory") and ESE ("Electronics Systems Engineering"); it has the following characteristics :

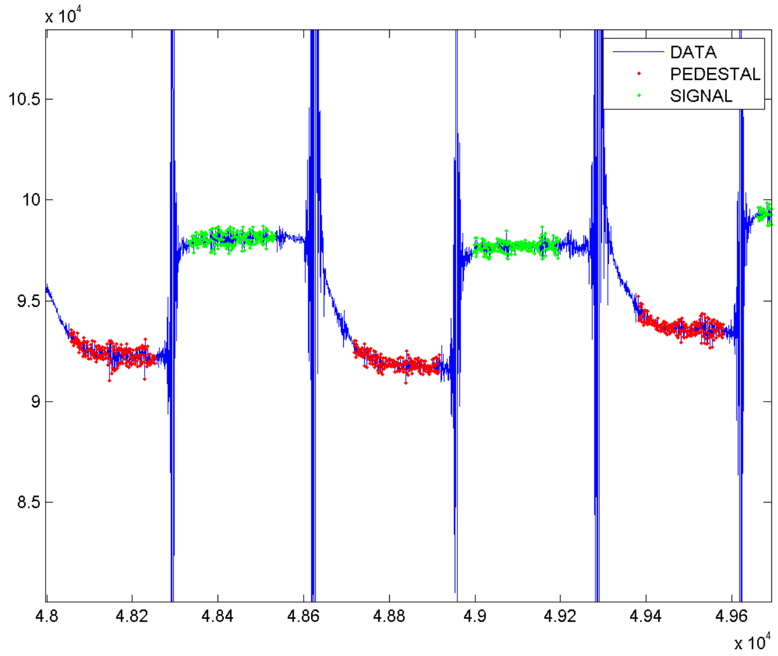
- 8 Channels
- Low noise
- Resolution : 24 bit
- Sampling Frequency : 2.5 MHz
- Programmable FIR ("Finite Inpulse Response") filter

Chapter 5

Data analysis

In this chapter will discuss how to analyze the collected data.
As already seen, with the FPGA we sampling directly the CCD output signal. Then the collected data are transferred to the computer by the ethernet port and finally saves in the hard disk of computer.
Now we can use the Matlab software to do the analysis.

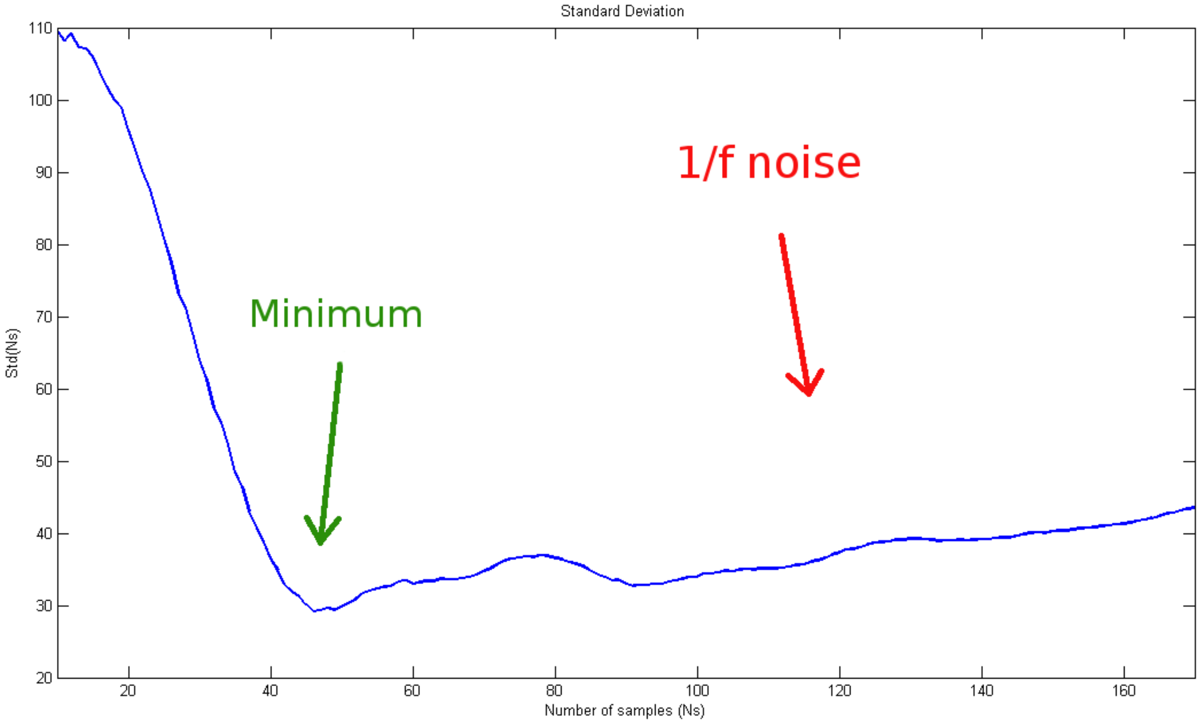
The first step is recognize the reset and summing well impulse; to do this we can use a script which find the peaks.
The next step is recognize the **pedestal** and **signal** interval, as can be seen in the next image.



The last step is calculate the value of each pixel (green part - red part) by means of digital correlated double sampling.

Standard deviation and noise measurement

In this section we are going to measure the noise of the system.
To do this we read only few lines of the CCD and then we calculated the standard deviation of the pixels, for several integration time (which means number of samples taken closely to the summing well impulse).
In the next image can be see the resulting plot.



In the plot we can see the minimum value, which is for **45 samples**.

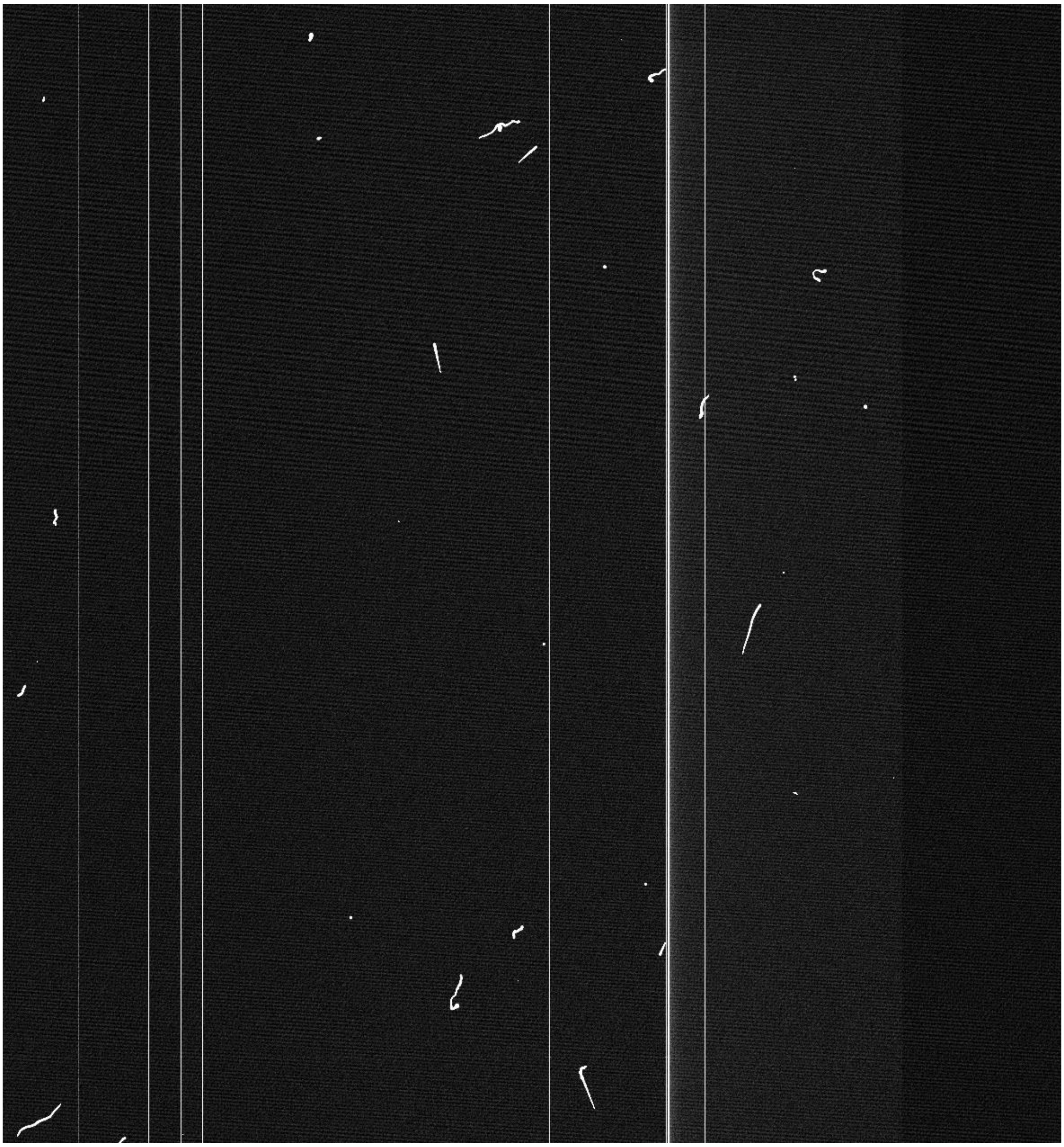
If we increase the number of samples the **1/f noise** (or ”pink noise”) problem may arises and this is a limitation to achieve lower energy detection in cosmology and other areas of physics and engineering.

As regards the noise consideration, the minimum value of standard deviation we measured is about 25 ADU (”Analog-Digital Units”). The gain of electronic system is about 13.2 (see next sections) ; so we can calculate the noise of the CCD in electrons :

$$Noise = \frac{25}{13.2} \approx 1.89\ e^{-}$$

Image generation

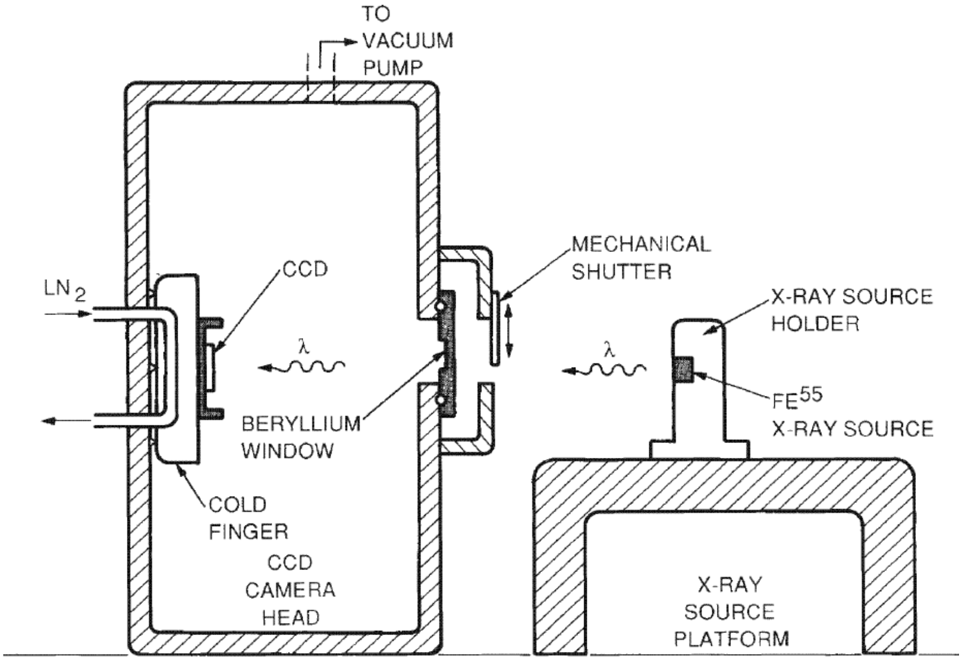
In this section will see the processed image in Matlab; this figure show it.



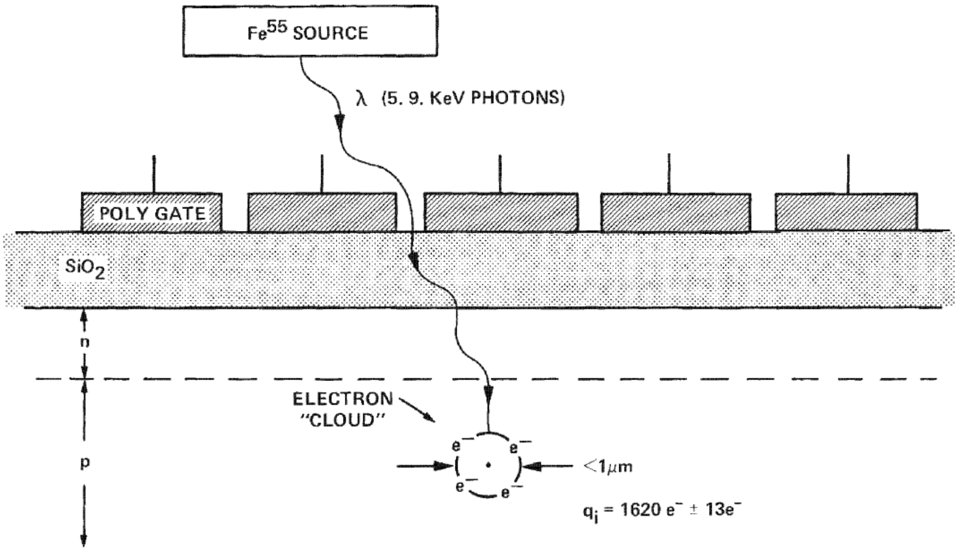
This image is created by means of a complex Matlab script, which reads the saved datafiles that contain the data came from the FPGA, finds and separates the lines interval and then looking for the summing well peaks for each line. The values of each pixel has been calculated by means of digital correlated double sampling with 45 samples taken (the lower noise condition).
In the image we can see many tracks (electrons, muons etc . . .).
The vertical lines are due to horizontal register problems in the CCD and the dark right side of the image represents the *overscan*.

X-Ray calibration

Unfortunately the current CCD technology does not permit accurate measurement of small charge units therefore we have to use an alternative calibration technique that use **x-ray illumination**.
We used the Fe^{55} soft x-ray source which has become a standard in measuring CCD characteristics.
In the next figure can be see the system that we are used, where an x-ray source is placed in front of the CCD sensor.

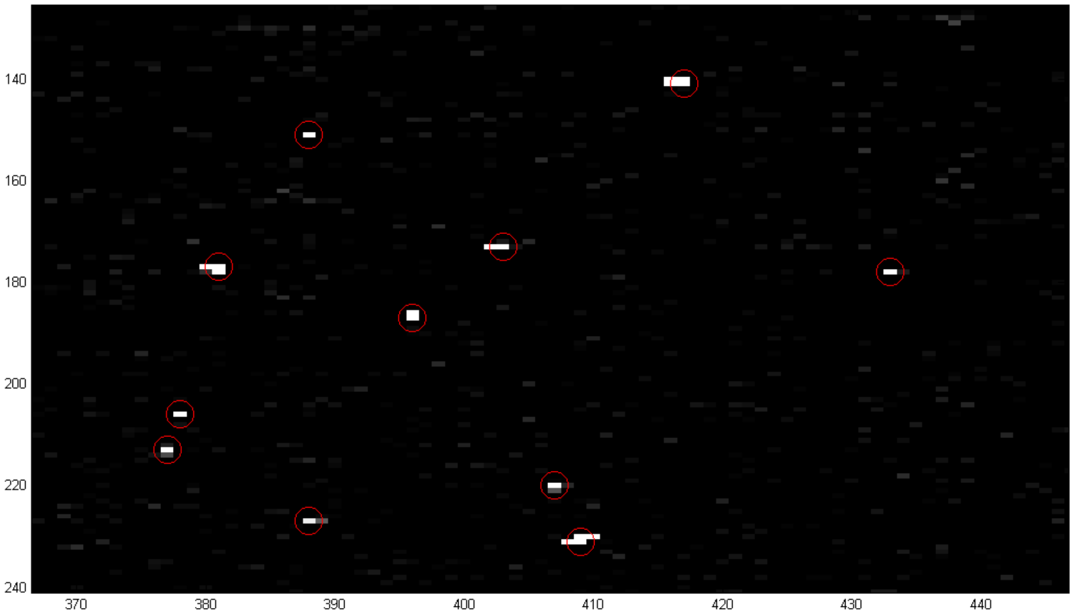


The soft x-ray photons (1 to 100 Å) have much higher energy than visibile light photons. This energy is absorbed by silicon and multiple e-h pairs are generated.
In contrast to the visible light case, the electrons are generated in a very small cloud diameter, essentially a near-perfect point source, as can be seen in the next figure.

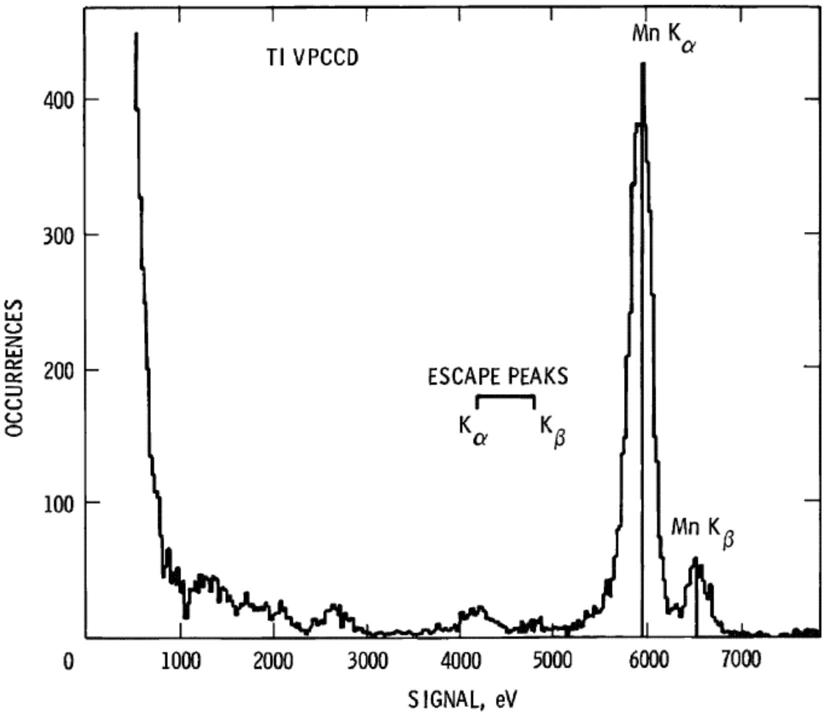


Ideally the charge accumulated from a single x-ray photon would be confined to a single pixel with no charge in the surrounding pixels, but in fact the generated charge is diffuses into neighboring pixels to form **clusters**.
The size and the shape of these clusters is an indicator of CCD performance.
The next image shows our Fe^{55} calibration image.

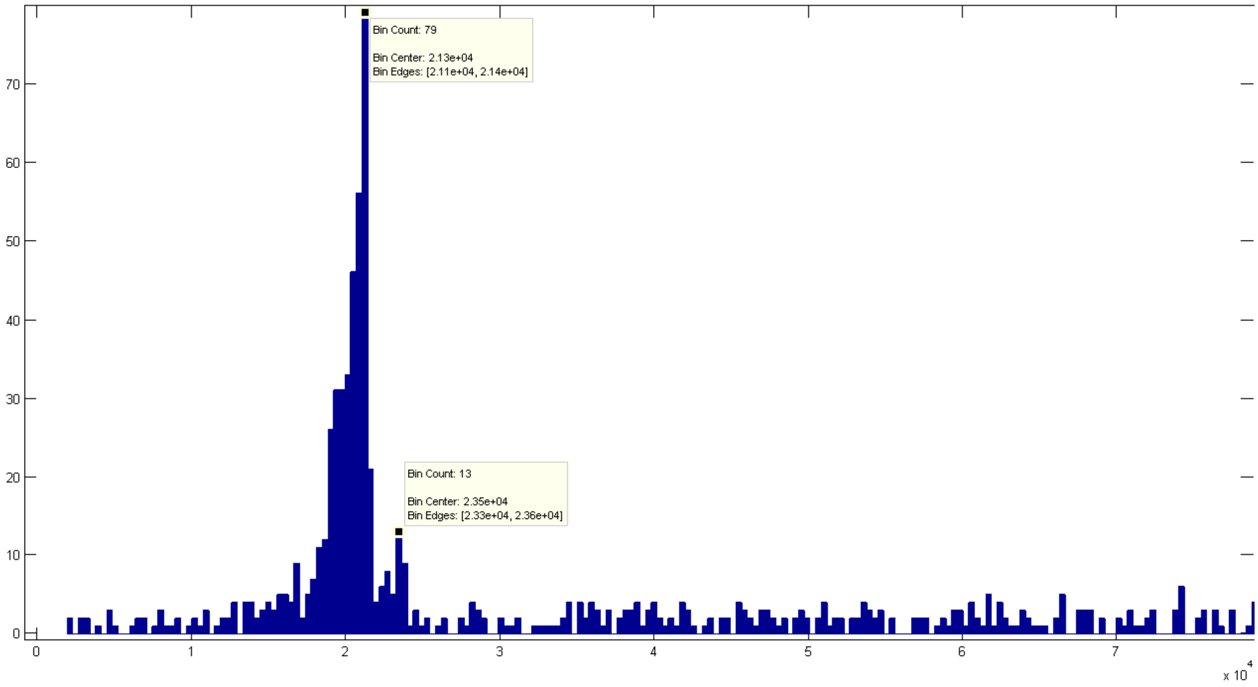
Once we have quite x-ray points, we can looking for the clusters. To do this it was written a Matlab script that finds the position of each bright pixel and then groups these pixels in clusters, as can be seen in the next image.



The next step is measure the **total energy** of each cluster, or rather the energy of each detected x-ray, and make an histogram that will show us the distribution of the all measured energies.
So we sum the values of each cluster and put these value in a vector (energy vector) and then we make the histogram of this vector.
From the histogram we expect to see two main peaks, called K_α and K_β.



The next image shows our histogram.



We found in our histogram :

- K_α : 2.13e4 ADU
- K_β : 2.35e4 ADU

We know the tabulate values of K_α and K_β emission lines for the x-ray source :

- $K_{\alpha - Fe_{55}} = 1620\ e^-$
- $K_{\beta - Fe_{55}} = 1778\ e^-$

So, if we compare this standard values with the values of K_α and K_β emission lines for the x-ray source found, we can calculate the gains :

$$Gain_1 = \frac{2.13e4}{1620} = 13.15$$

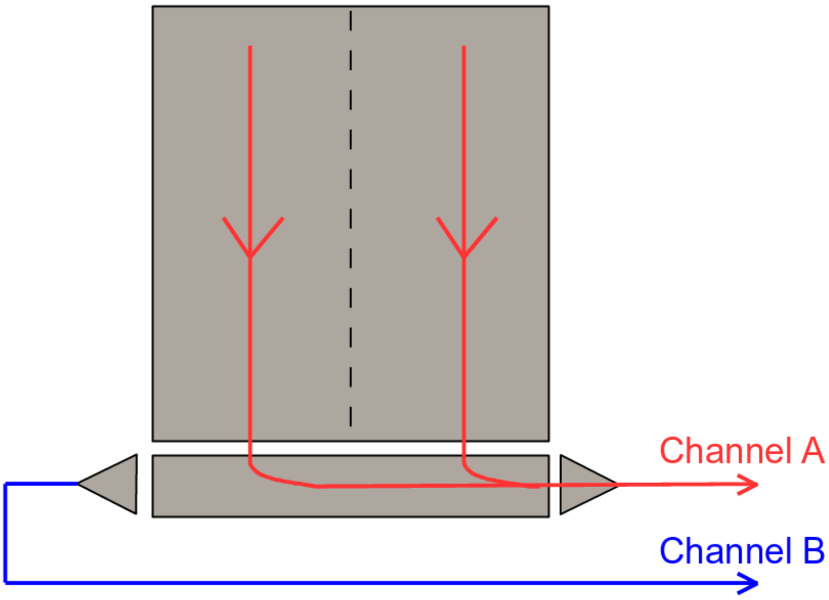
$$Gain_2 = \frac{2.35e4}{1778} = 13.22$$

As we expected the values are similar; so we can conclude that the gain is about 13.2 ADU/e^-.

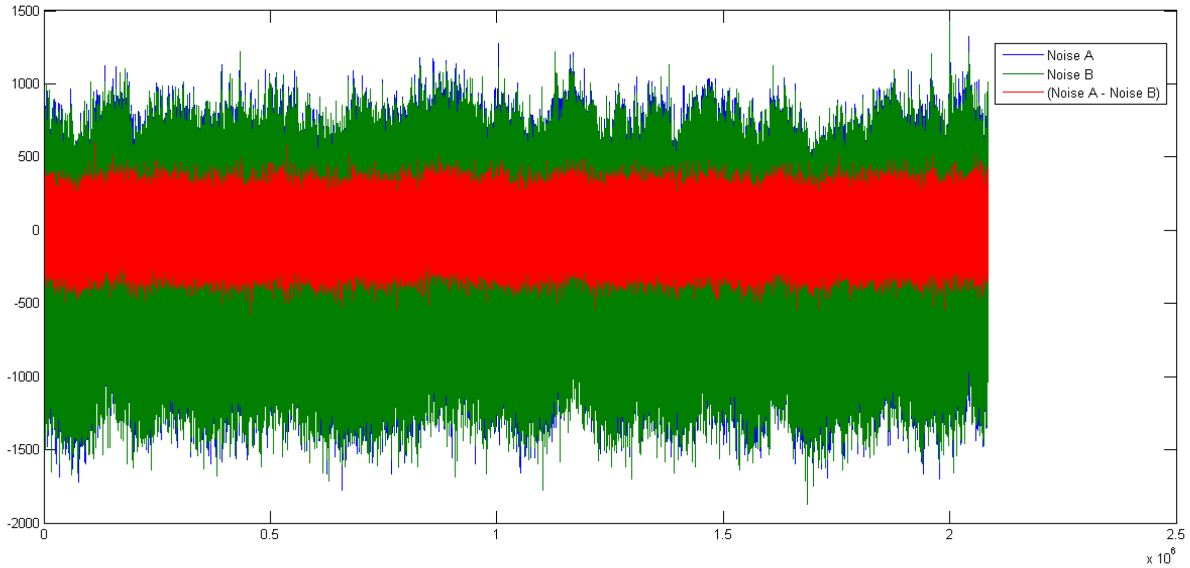
Chapter 6

Noise improvement

Our future purpose is try to improve the noise performance in the CCD.
In our CCD the entire image is only transferred into one of the horizontal registers (lower or upper), so the signal comes out from only one amplifier. In the other amplifier instead there'll be only the noise of CCD.
In the next image can be seen the output configuration of our CCD.



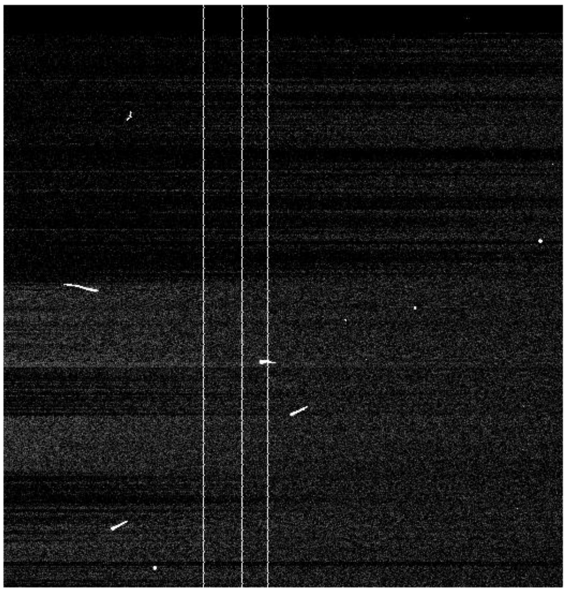
If we do an acquisition from the FPGA without any clocks in the CCD, we'll get only the noise of the system.
In the next figure we can see the only noise acquisition plot of the two CCD channels : Channel A and Channel B (in blue and green).



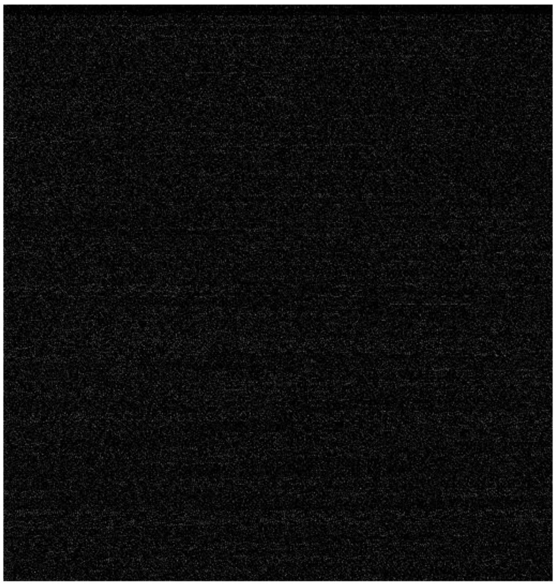
They appear not enought stable (there are some fluctuations), but, we can see these noise are **CORRELATED**; so if subtract them we obtained the signal in red, which is more stable and less wide.

Future plans

As mentioned above, the noise of the two channel are correlated, so we could acquire both the Channel A(the good image) and Channel B (the noise), as can be seen in the next image, and then we could subtract them (A-B) in order to achieve better noise performance.

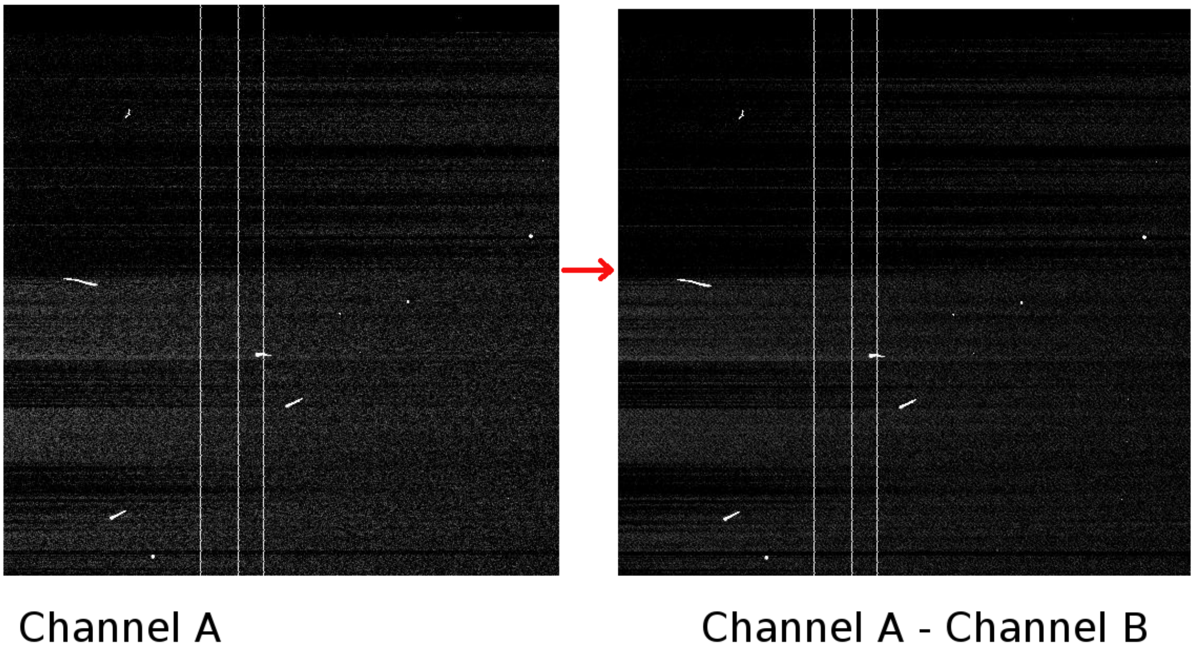


Channel A



Channel B

In the next figure can be seen that the right image is less noisy than the left one.



Conclusions

The dark matter world is one of the most fascinating fields we are going to discover and study.
The large part of the universe is still unknown and full of secrets; this is a good reason to go on with our experiments !

In this report it was explained what are our goals and what we have done. By measuring the noise performance in our digital system we obtained very good results, and this means that we can proceed with the substitution of the old analog system. The next goal is try to take advantage of *digital signal processing* for improving the noise performance beyond the correlated double sampling below 1/f limit.

Bibliography

[1] James R. Janesick, *Scientific Charge-Coupled Devices*, SPIE Press, 2001.

[2] G. Cancelo, *Advances in CCD Sub Electron Noise Techniques and Applications*, 8^{th} Patras Workshop, 2012.

[3] Gustavo Cancelo*, Juan Estrada, Guillermo Fernandez Moroni, Ken Treptow, Ted Zmuda, *Low noise readout techniques for Charge Coupled Devices (CCD)*, TIPP (Technology and Instrumentation in Particle Physics), 2011.