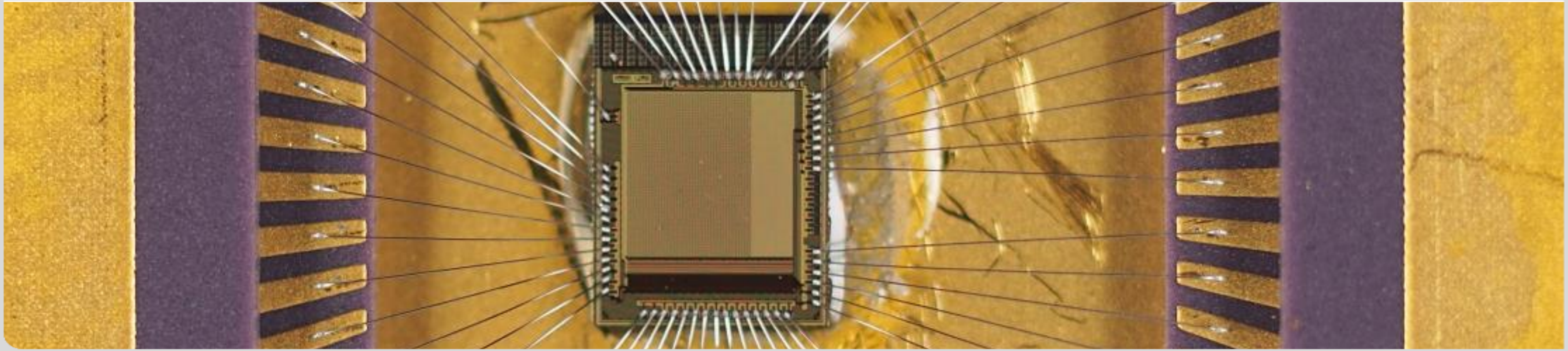
Assessment, radiation tests and design specifications for a novel CMOS monolithic pixel detector integrated on a transmission electron microscope setup

Andrea Ferretti ESR 13 – WP5
Horacio Mateos ESR 4 – WP2

Smart Sensor Technologies and Training for Radiation Enhanced Applications and Measurements (STREAM) is a project funded by the European Commission under the Horizon2020 Framework Program under the Grant Agreement no 675587. STREAM began in January 2016 and will run for 4 years.

ASIC and Detector Laboratory (ADL) - KIT
Thermo Fisher Scientific



Introduction

Andrea Ferretti

- Start: June 2017
- Supervisor: Dr. Luigi Mele
- Place: Thermo Fisher Scientific
- Project: Integration and assessment of novel radiation-hard monolithic CMOS APS for Transmission Electron Microscopy imaging

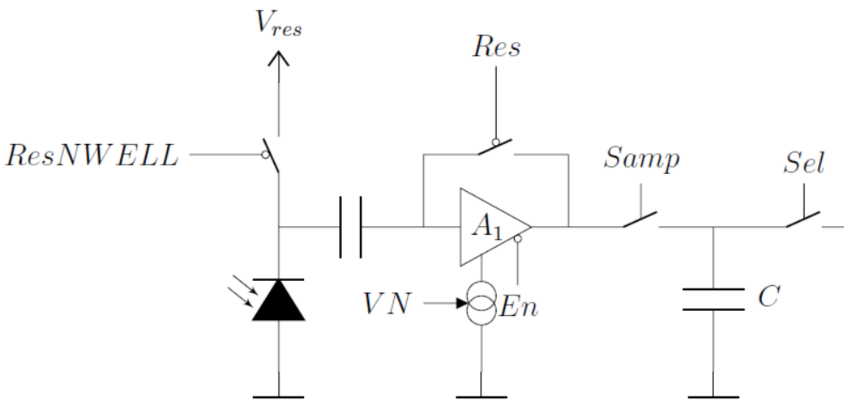
Horacio Mateos

- Start: september 2017
- Supervisor: Prof. Dr. Ivan Peric
- Place: Karlsruher Institute für Technologie
- Project: Test, design and improvement of image sensors for electron microscopy

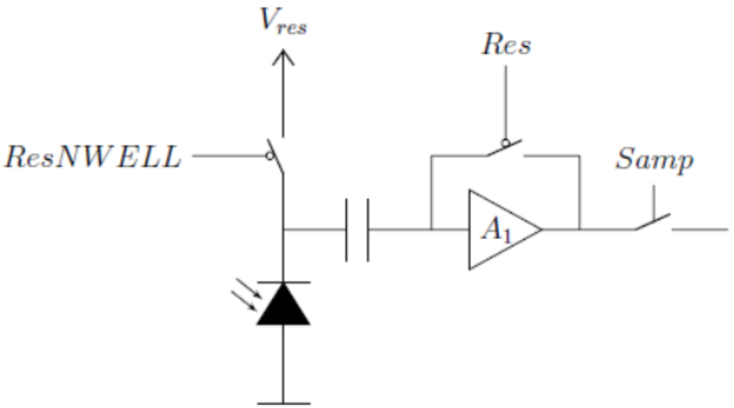
Pixel flavors

- There are 2 types of pixels:
  - Current Pixels – more complex, with CDS
  - Voltage Pixels – simple ones, no CDS

Current Pixels

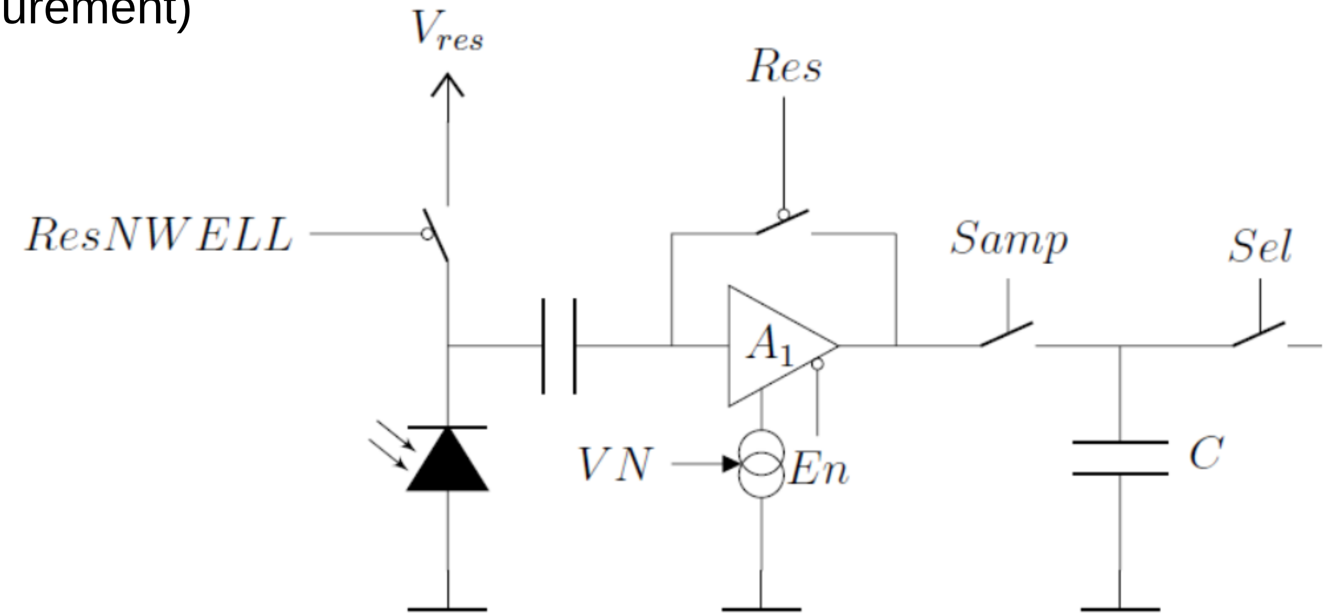


Voltage Pixels

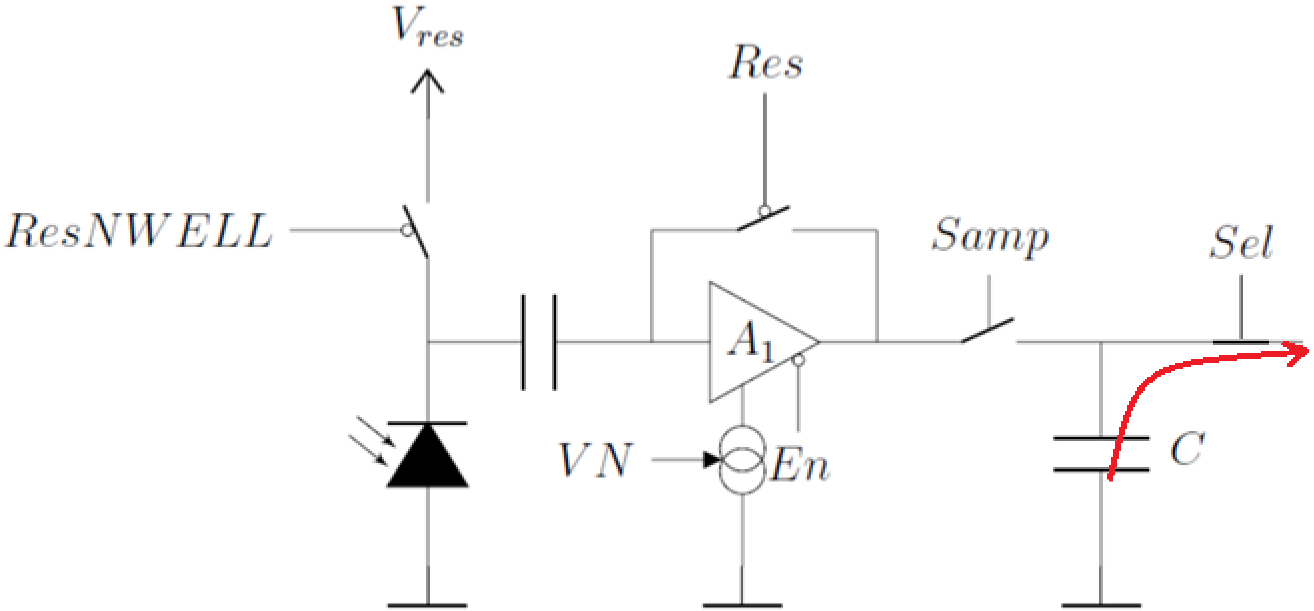


Current Pixels – How it works?

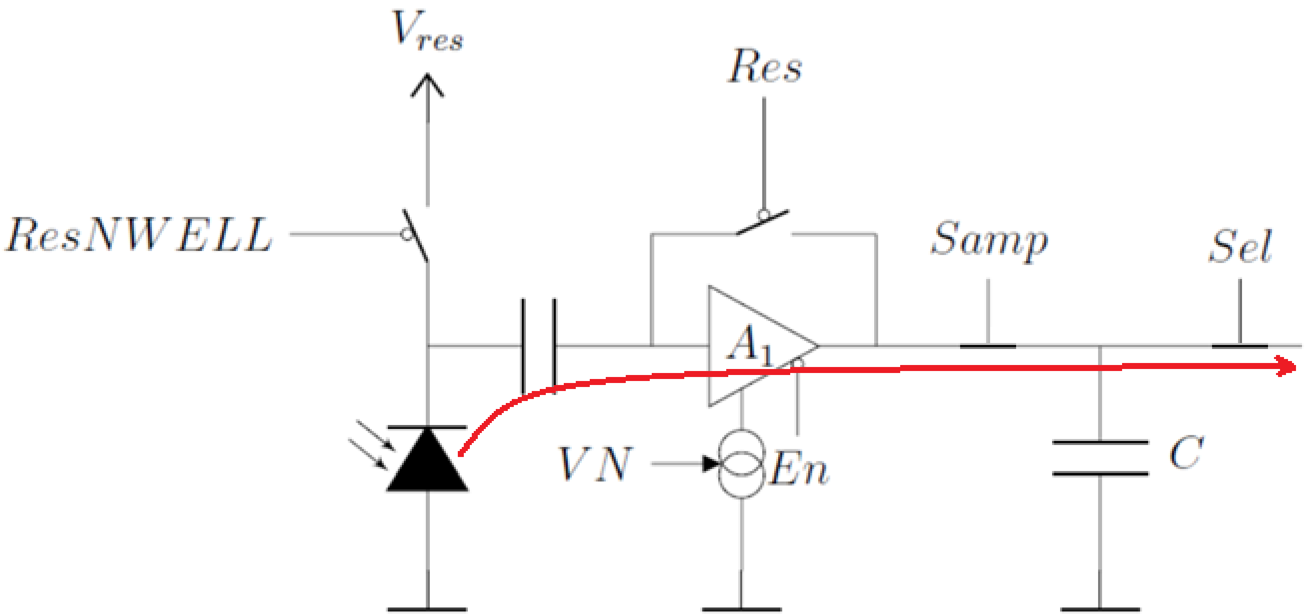
- Capacitor to store charge for Correlated Double Sampling (CDS)
- By using the switches, is possible to sample the pixel current on different states (reset and measurement)



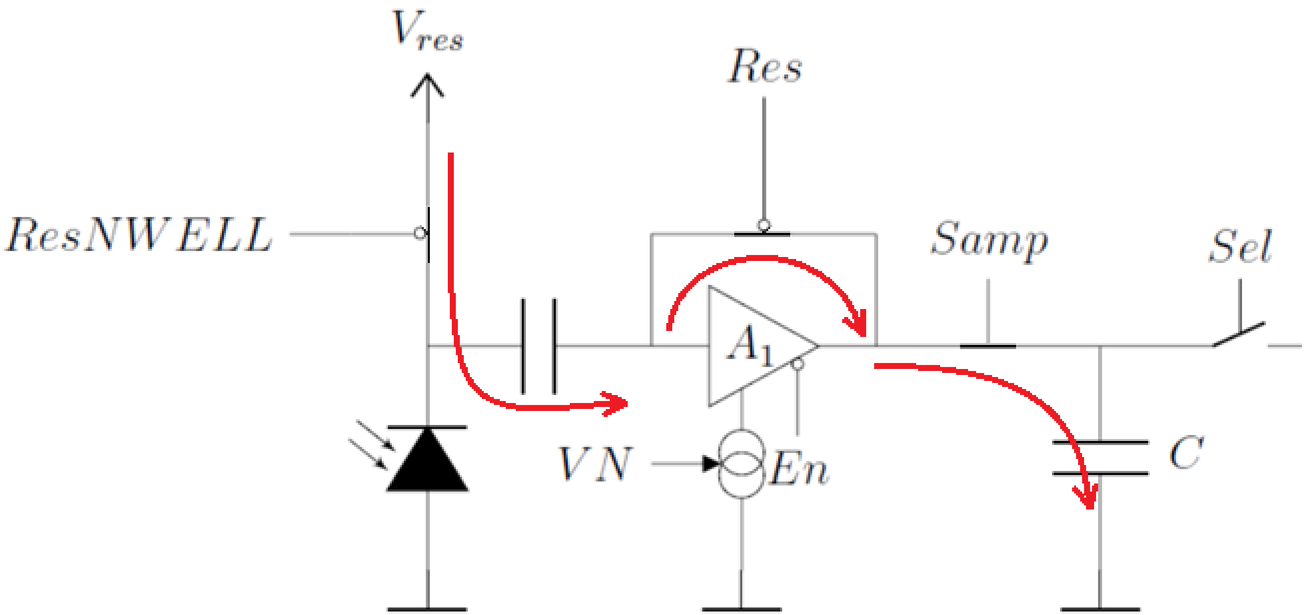
How it works?



How it works?

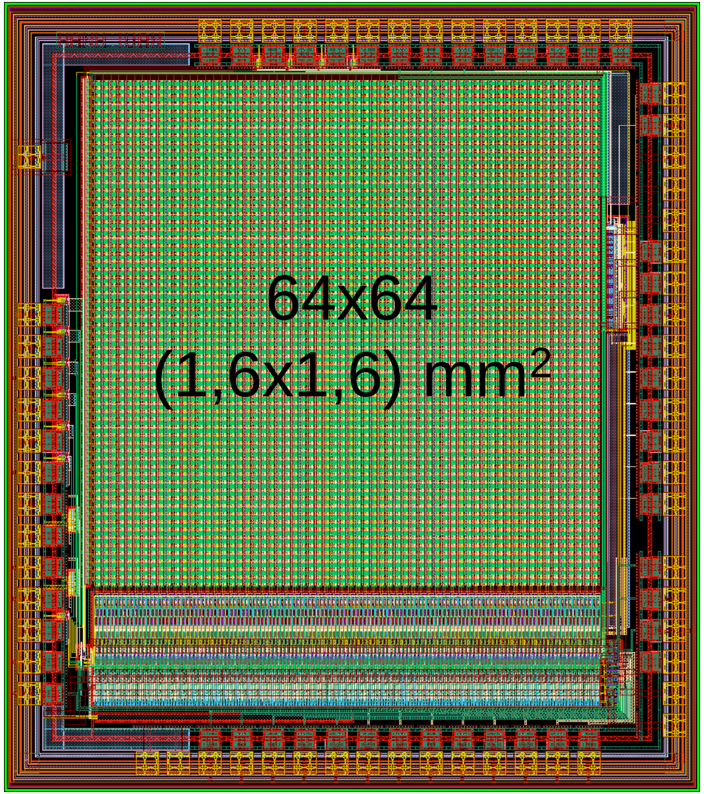


How it works?



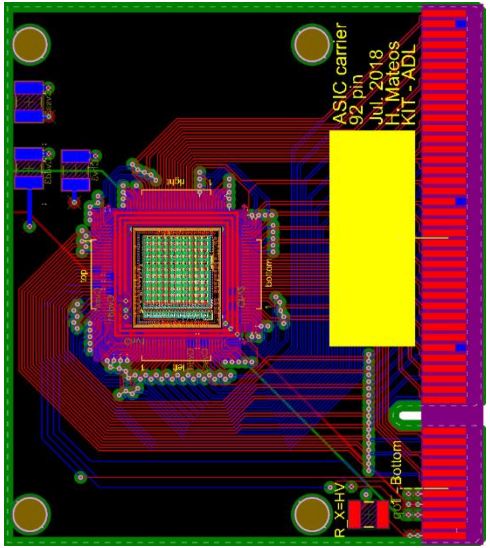
The Sensor

- 180 nm, High Voltage CMOS Technology
- 64x64 pixels (25 µm square pixel)
- 200 µm thick substrate (80 Ω*cm)
- Charge sensitive amplifier
- 128 8-bit ADCs
- Low power consumption
- Fast charge collection (HV)
- Radiation tolerant
- Readout speed ~6 KHz
- Noise floor measured ~ 80e$^-$
- -60V of HV bias

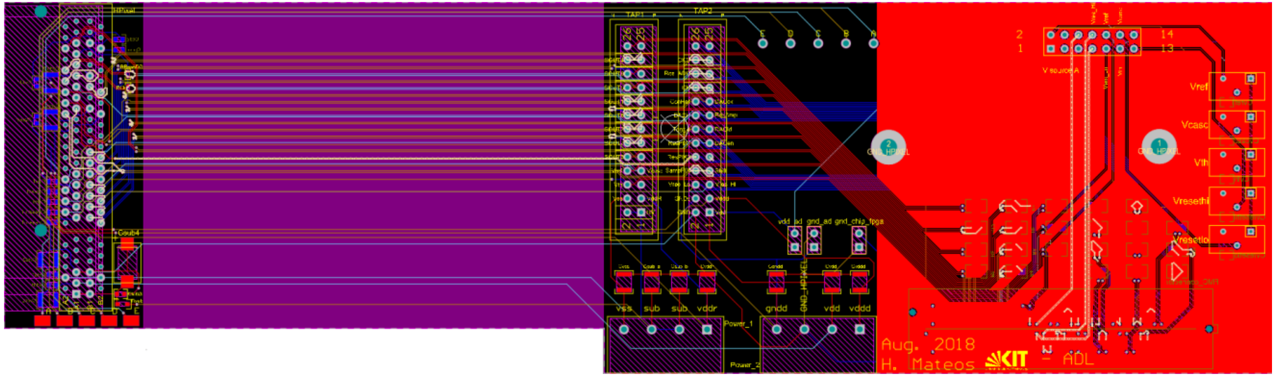


Chip carrier

The sensor carrier PCB

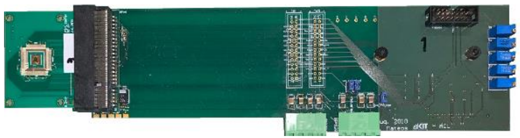


The adapter PCB (FPGA to sensor carrier)



Usage of the Chip

- Interface through Nexys Video (Artix 7)
- Qt/C++ interface on PC
- MatLab + Python for image processing

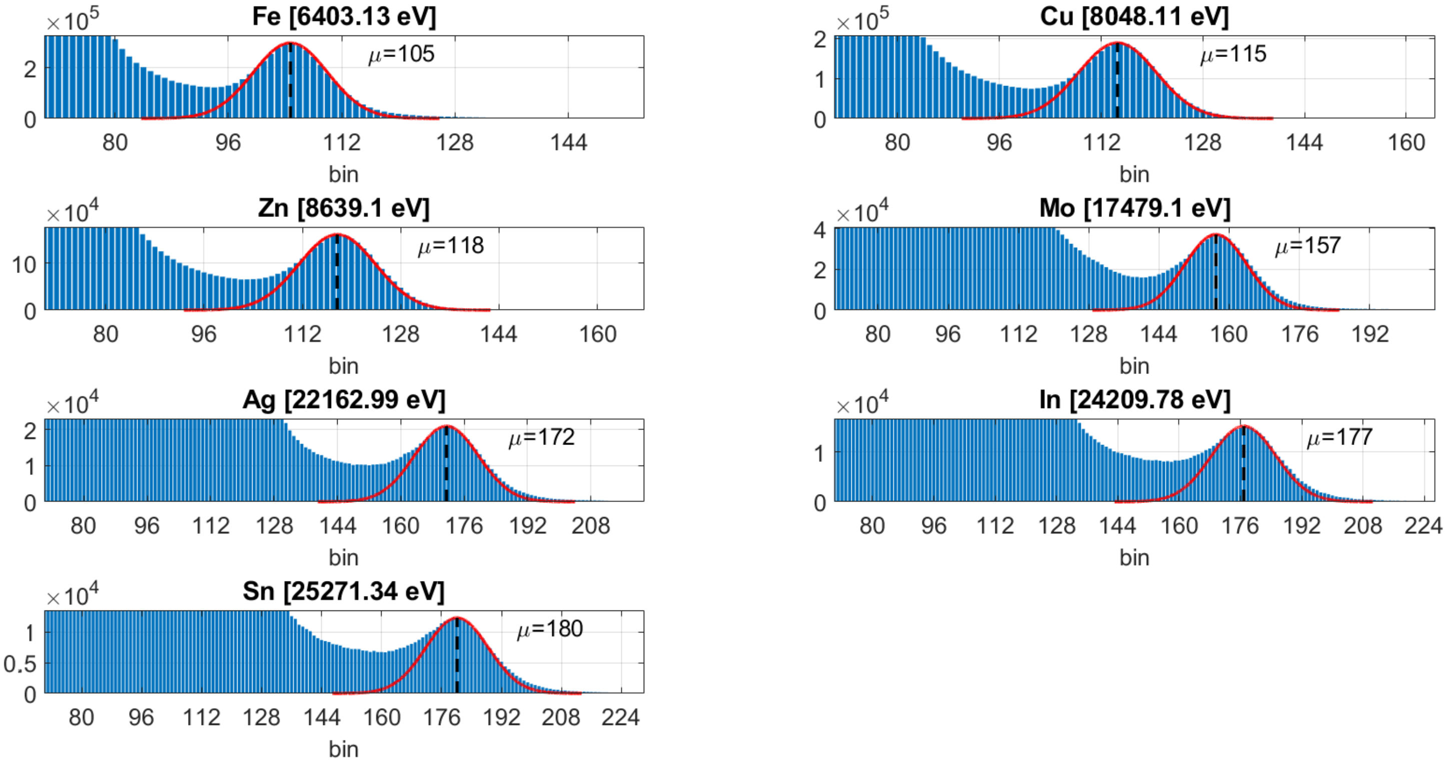


Measurements

- **Successfully tested the functionality of the HPIXEL with X-Rays**
  - The system was able to detect X-rays of 6.4 KeV ~ 25.3 KeV
- Simulations of the chip performed with variable the external voltages and DAC values

- **Successfully tested the functionality of the HPIXEL with electrons**
  - Detected 200 KeV electrons on a Thermo Fisher Tecnai TEM electron microscope in the Eindhoven facility.

X-Ray Measurements



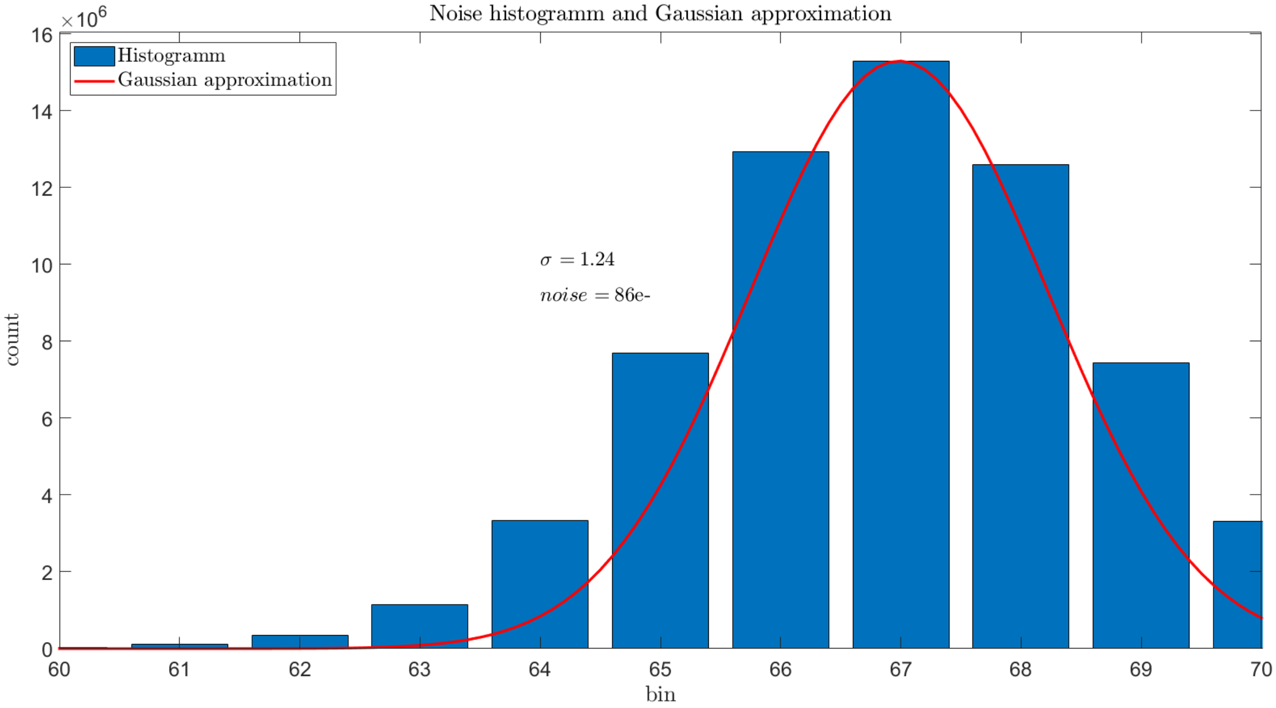
X-Ray Measurements

7 targets (6.4 KeV ~ 25.3 KeV)

Target	Energy [eV]	μ (measured by the chip) [bin]
Fe	6403.13	105
Cu	8048.11	115
Zn	8639.1	118
Mo	17479.1	157
Ag	22162.99	172
In	24209.78	177
Sn	25271.34	180

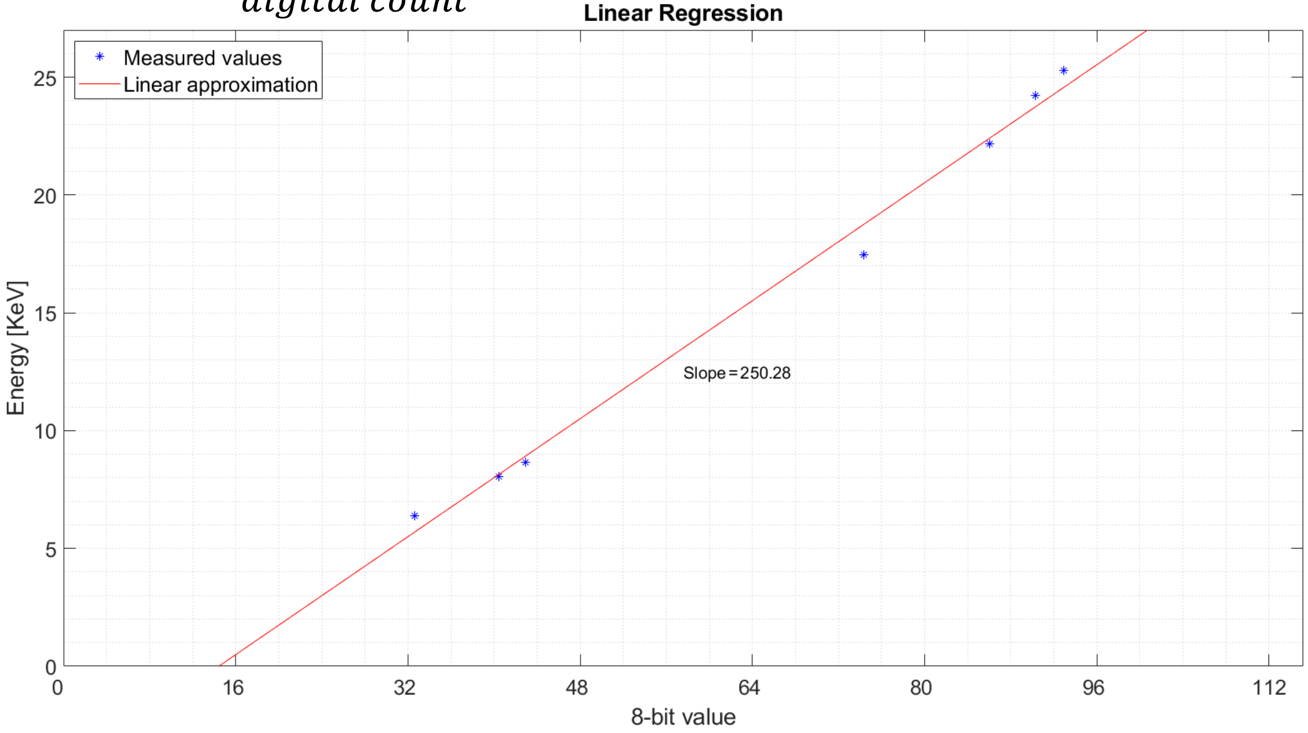
X-Ray Measurements

- Noise levels around 86 e^- (for the lowest energy)



X-Ray Measurements

- Resolution: ~ 250 $\frac{eV}{digital\ count}$ with a theoretical range between 6 KeV ~ 43 KeV



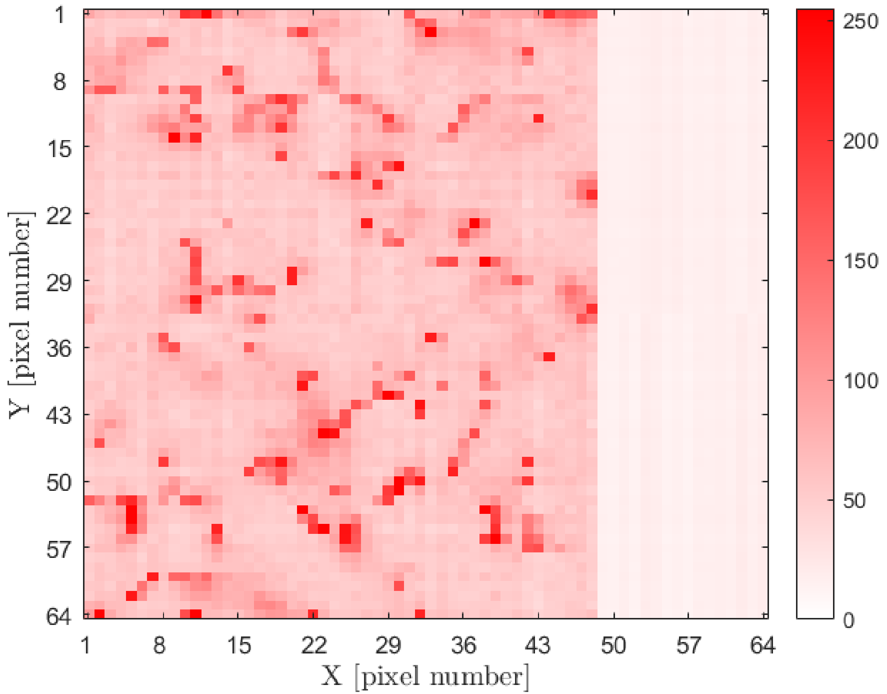
X-Ray Measurements

- After 50 Mrad of total dose, resolution was: ~ 329 $\frac{eV}{digital\ count}$
- After 250 Mrad of total dose, the chip continued working, however, due to the high background noise, it was not possible to calculate the conversion factor.

Electron measurements - preliminaries

- Different Gain settings and High voltage biasing have been used during the tests to verify the configurability of the chip

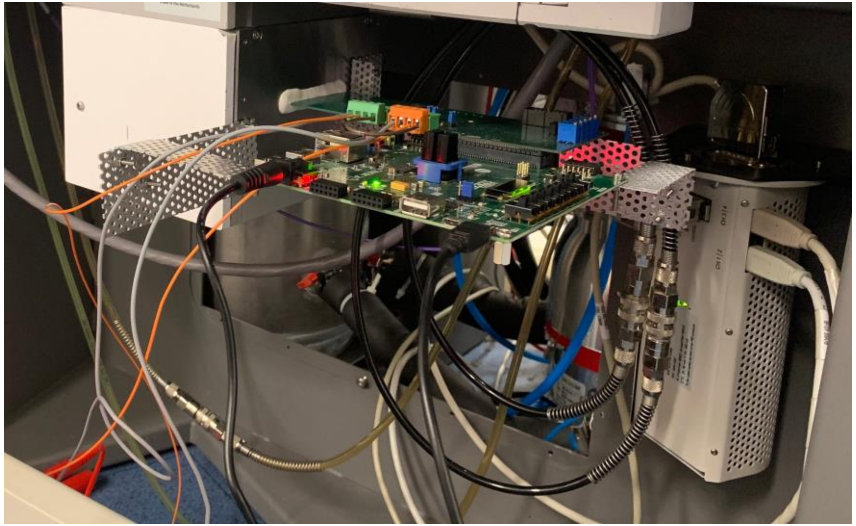
- First tests have been carried out in late January at Thermo Fisher Scientific. Unfortunately, just after some data was gathered the sensor stopped working.

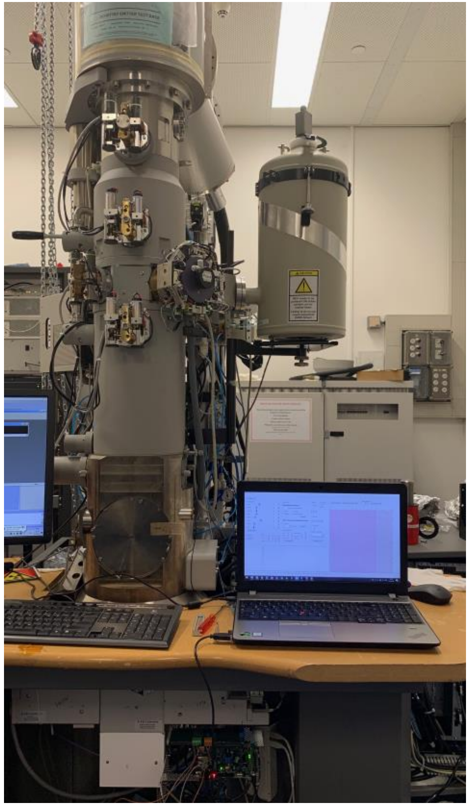


200 keV electrons

Electron measurements – preliminaries

- Integration on TEM tool with custom feedthrough board
- Faraday Cup and TEM aperture used to calibrate the electron beam and calculate the electron density/pix
- Test Chip 1: Sensor uniformly irradiated
- Test Chip 2: Focused beam on pixel matrix





Electron measurements – preliminaries

Integration on TEM tool with custom feedthrough board:

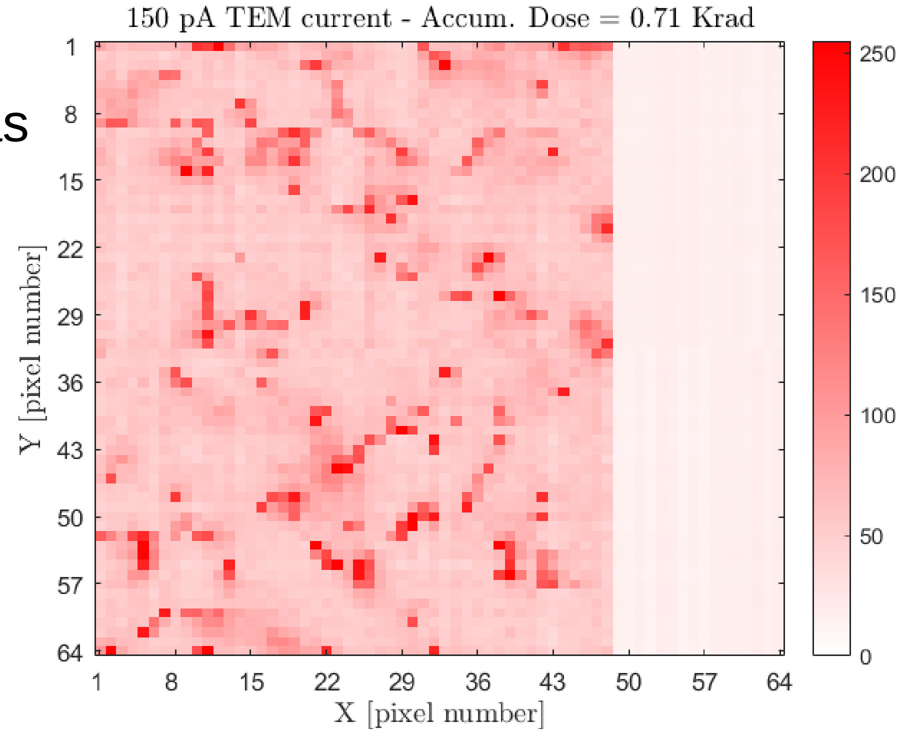
- KIT design - Thermo Fisher specs
- Lead flange slot and epoxy compliant(vacuum seal)
- Tested at Thermo Fisher

Calibration of the electron beam to calculate the electron density/pix:

- Fluo-Screen of TEM is not accurate, Faraday Cup is
- Map Fluo-Screen values to measured Faraday Cup values
- Mapped values and ratio between the Faraday Cup area Microscope set aperture used to derive electron current density per pixel

Electron measurements – test chip 1

- The chip was able to detect single electrons
- The readout block stops to work when the ionizing radiation dose was around 78 kRad
- Background noise
  - before irradiations: 47 ADC counts
  - after last working measurement (61.42 kRad accumulated dose) was 65 ADC counts



Electron measurements – test chip 1

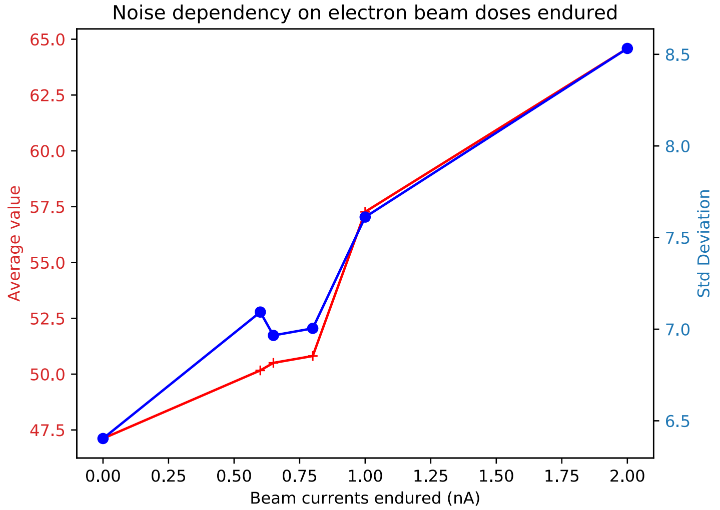
HPIXEL sensor pixels come in two flavours:

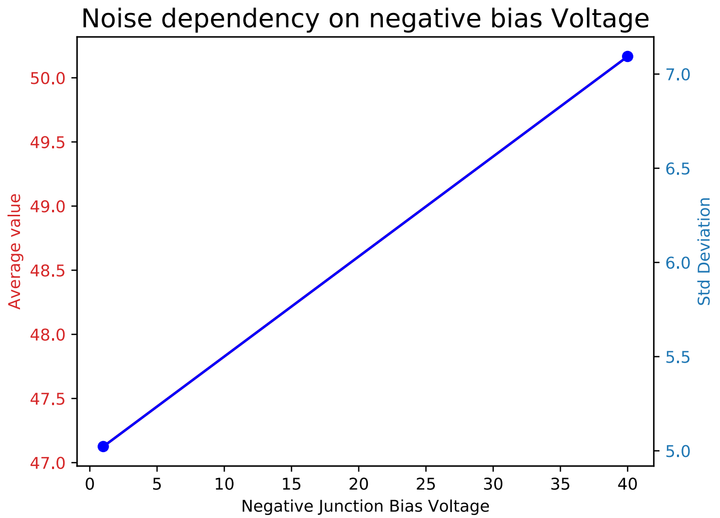
- Current pixels [columns 0-48]
- Voltage pixels [columns 48-64] (simple ones, no CDS)

All the further analysis was carried out on background corrected data

Electron measurements – Noise analysis Chip1

Dark Noise – mostly Fixed Pattern Noise

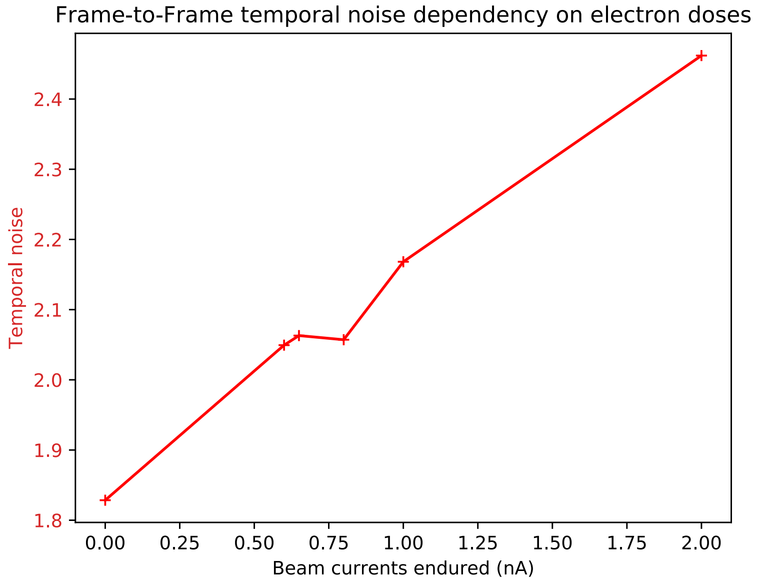




Both pixel types are considered together, a more thorough analysis would involve splitting the analysis

Electron measurements – Noise analysis Chip1

Dark Temporal Noise – Frame-to-frame standard deviation

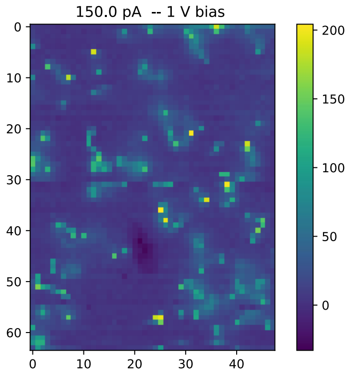


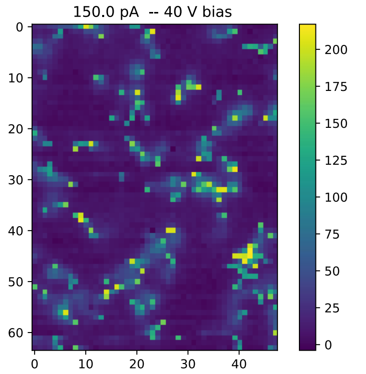
Both pixel types are considered together, a more thorough analysis would involve splitting the analysis

Electron measurements – Current pixels Chip 1

Frames

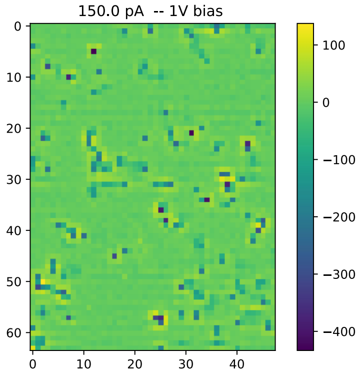
150 pA

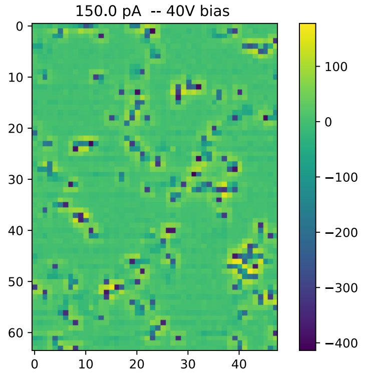




40V bias show sharper events, both on the original frames and LoG

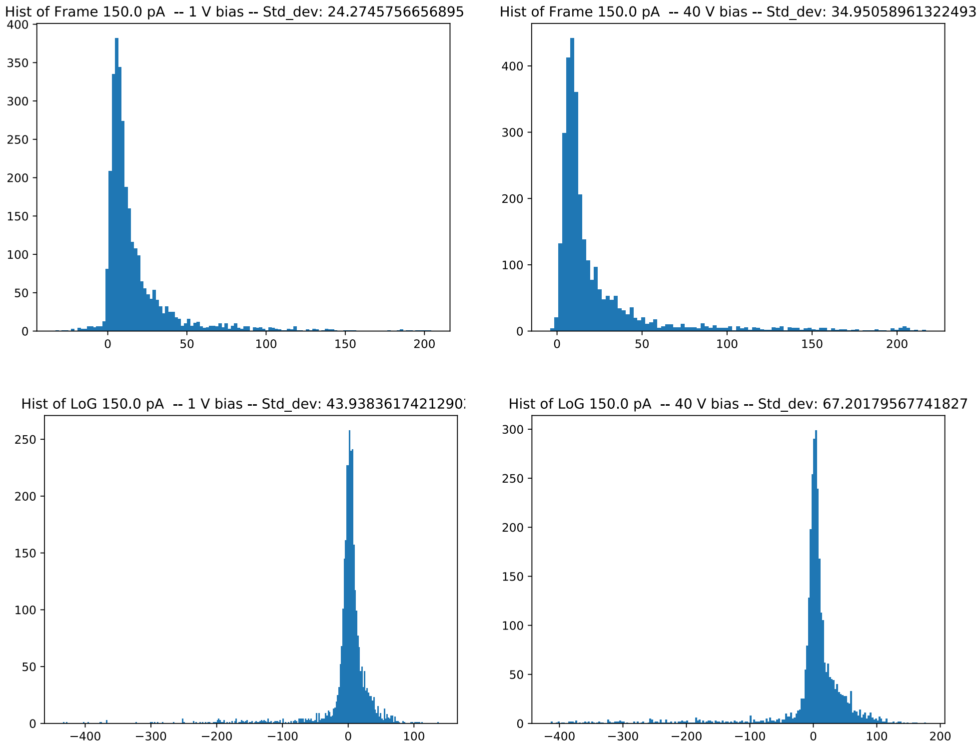
LoG





Laplacian of Gaussian with $\sigma = 0.6$ used to locate electron events

Electron measurements – Current pixels Chip 1



Even at low 150 pA current beam (294 e/pix/s roughly) there is already a difference. 40V counts more high-value pixels
and a higher average overall due to greater collection

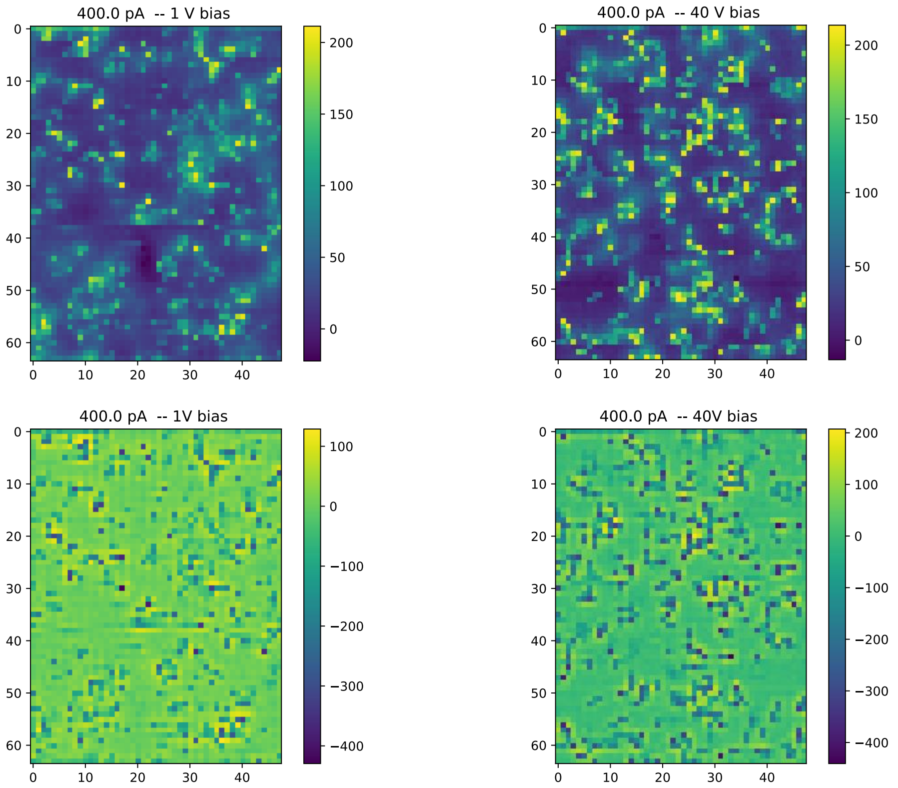
Laplacian of Gaussian histograms show higher negative values too

Electron measurements – Current pixels Chip 1

Frames

400 pA

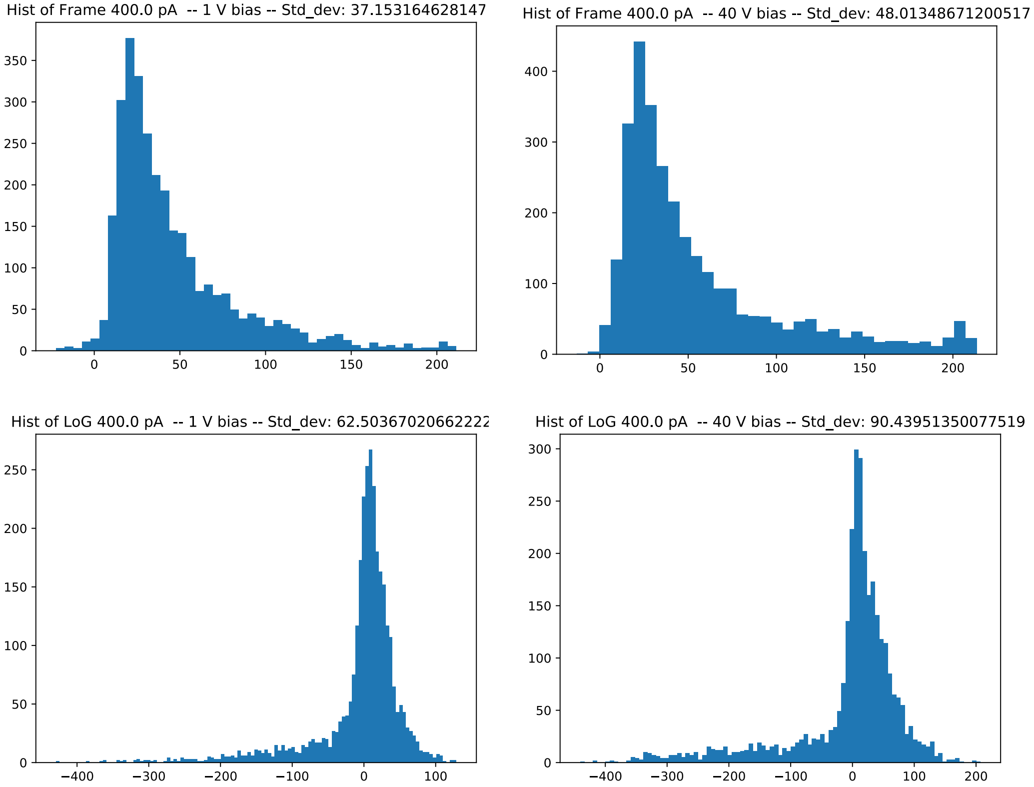
LoG



40V bias show sharper events, both on the original frames and LoG

Laplacian of Gaussian with σ = 0.6 used to locate electron events

Electron measurements – Current pixels Chip 1



400 pA current beam (800 e/pix/s roughly) – difference in distributions increases

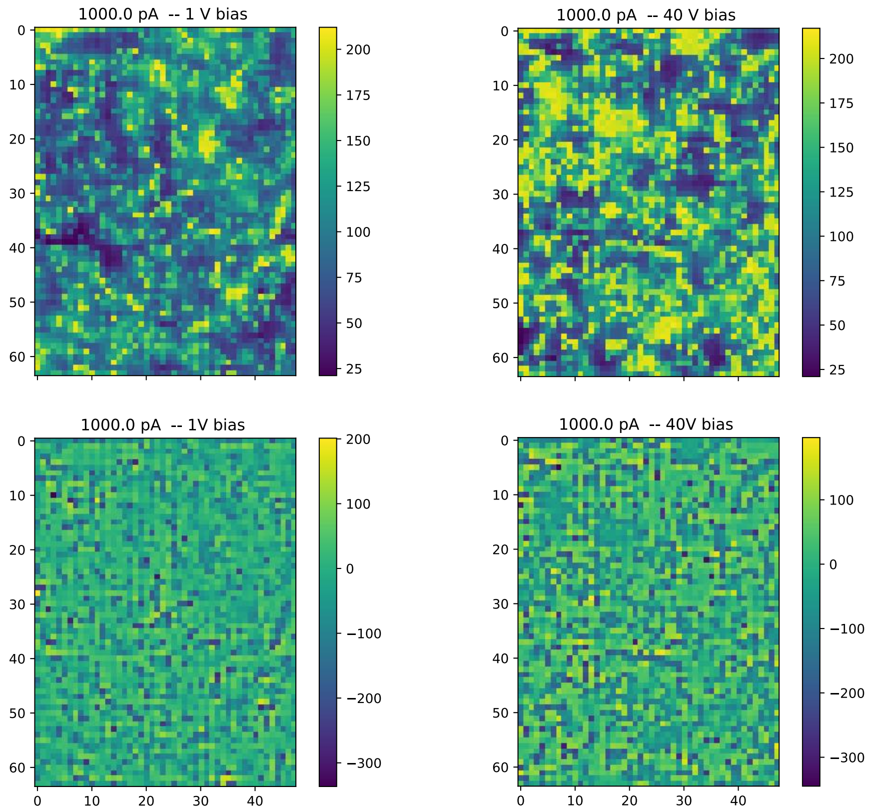
Laplacian of Gaussian histograms show higher negative values too

Electron measurements – Current pixels Chip 1

Frames

1 nA

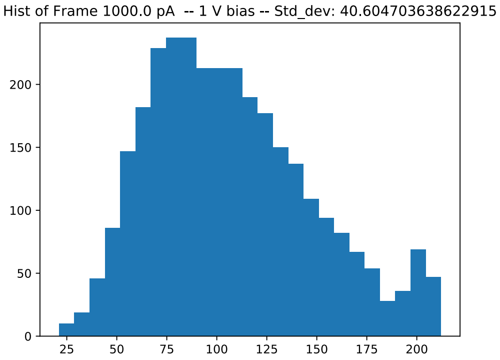
LoG

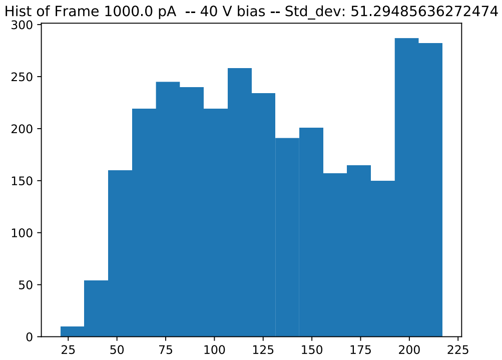


40V bias show sharper events, both on the original frames and LoG

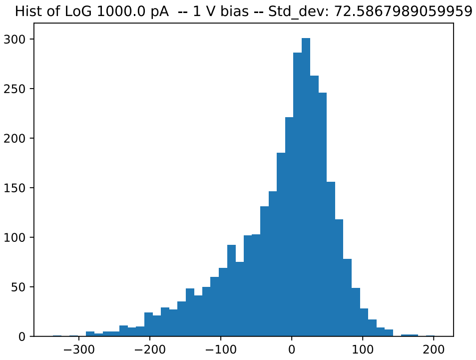
Laplacian of Gaussian with σ = 0.6 used to locate electron events

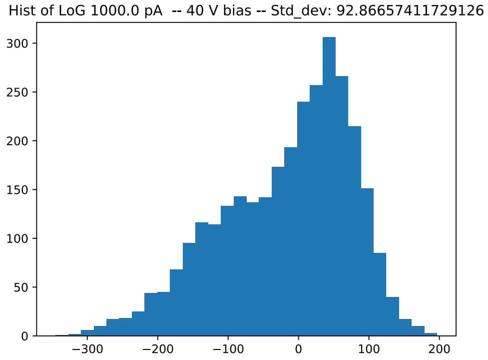
Electron measurements – Current pixels Chip 1





1 nA current beam (1800 e/pix/s roughly) – difference in distributions increases



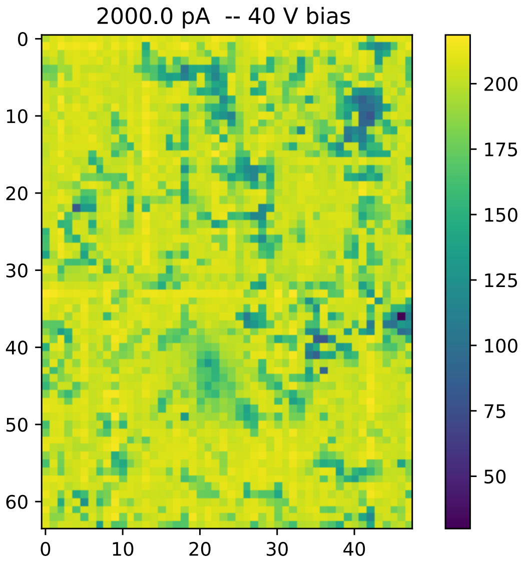


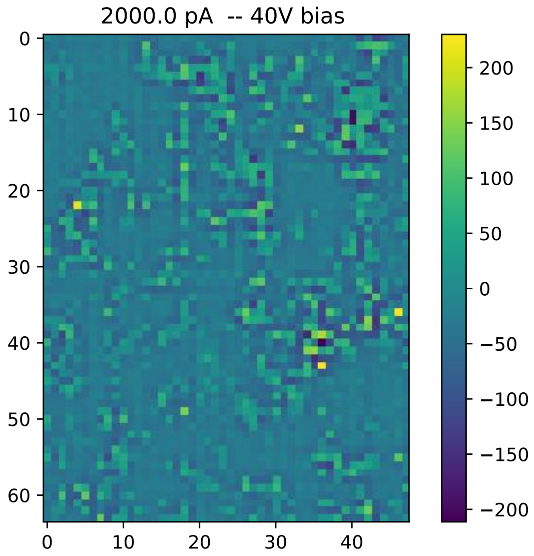
Laplacian of Gaussian histograms show higher negative values too

Electron measurements – Current pixels Chip 1

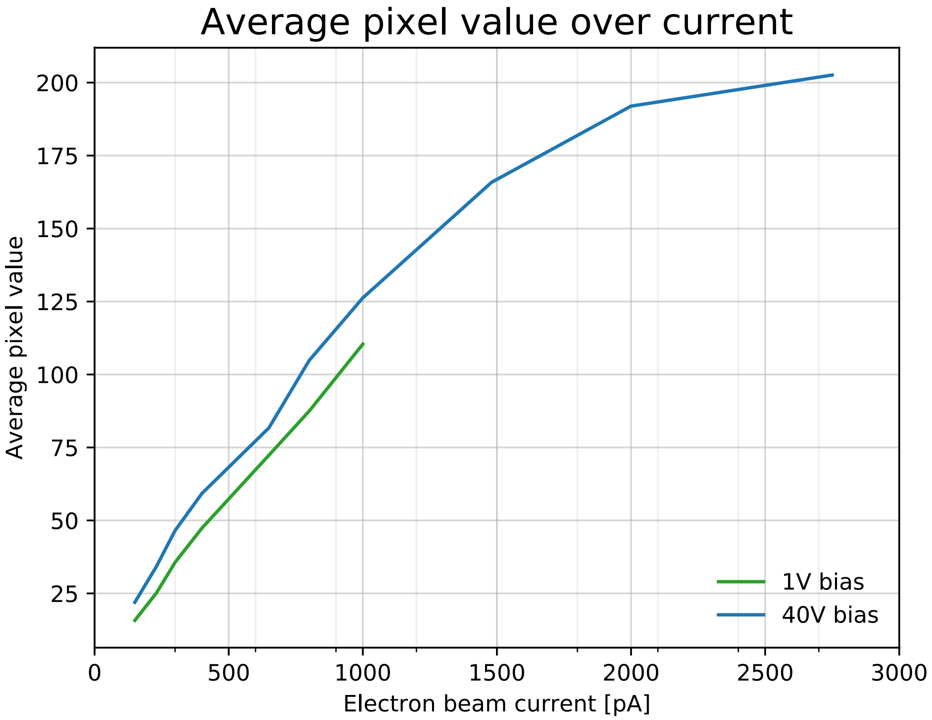
2nA – 3600 e/pix/s
roughly uniform
illumination

LoG





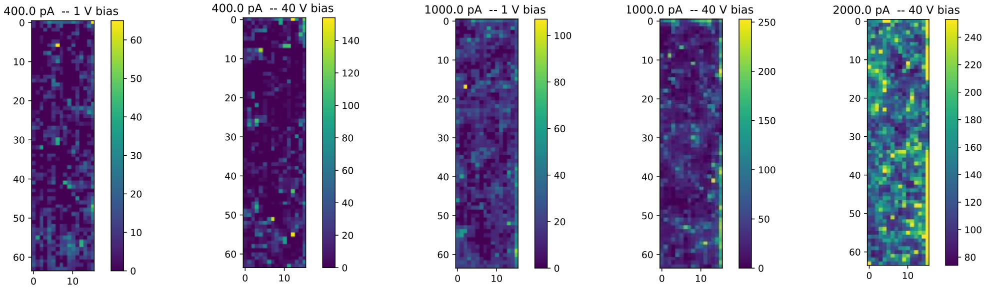
Electron measurements – Current pixels Chip 1



Collection improves with higher BIAS

Electron measurements – Voltage pixels Chip 1

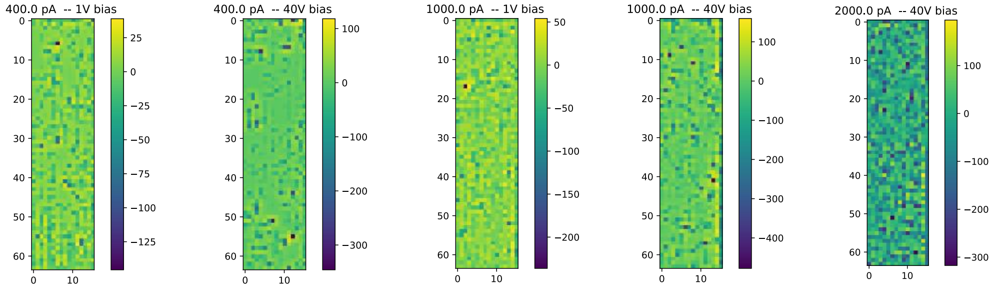
Frames



Voltage pixels saturate much later than current pixels

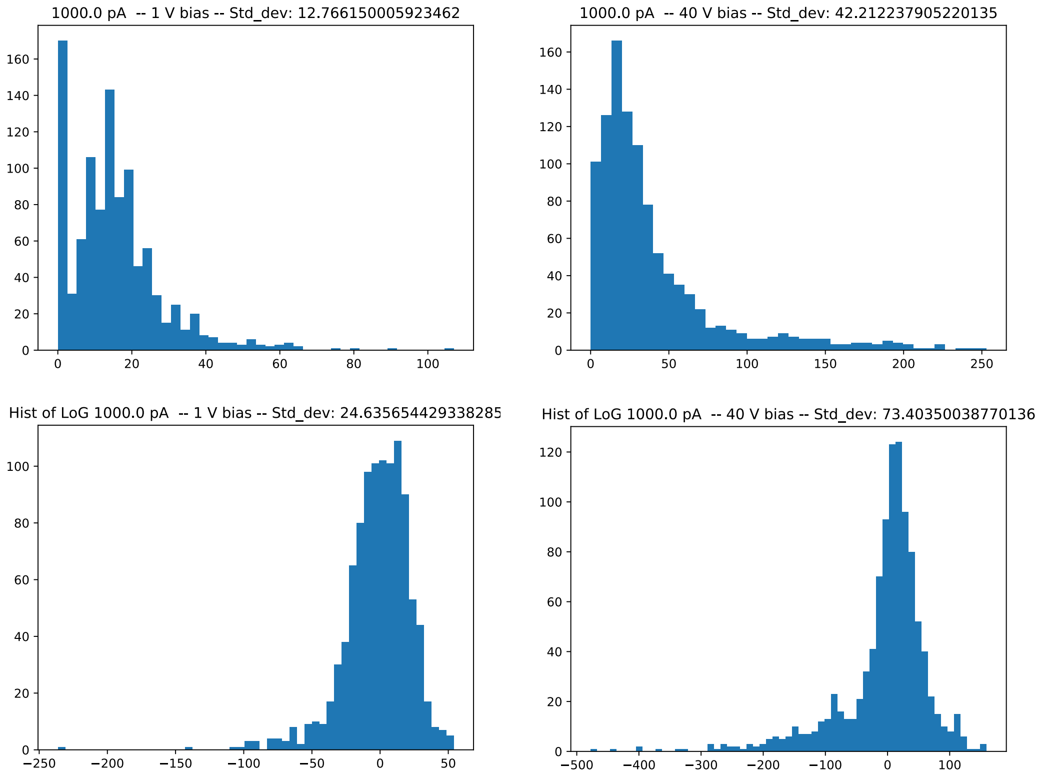
400 pA
1 nA
2 nA

LoG
σ = 0.6



40V bias show sharper events, both on the original frames and LoG

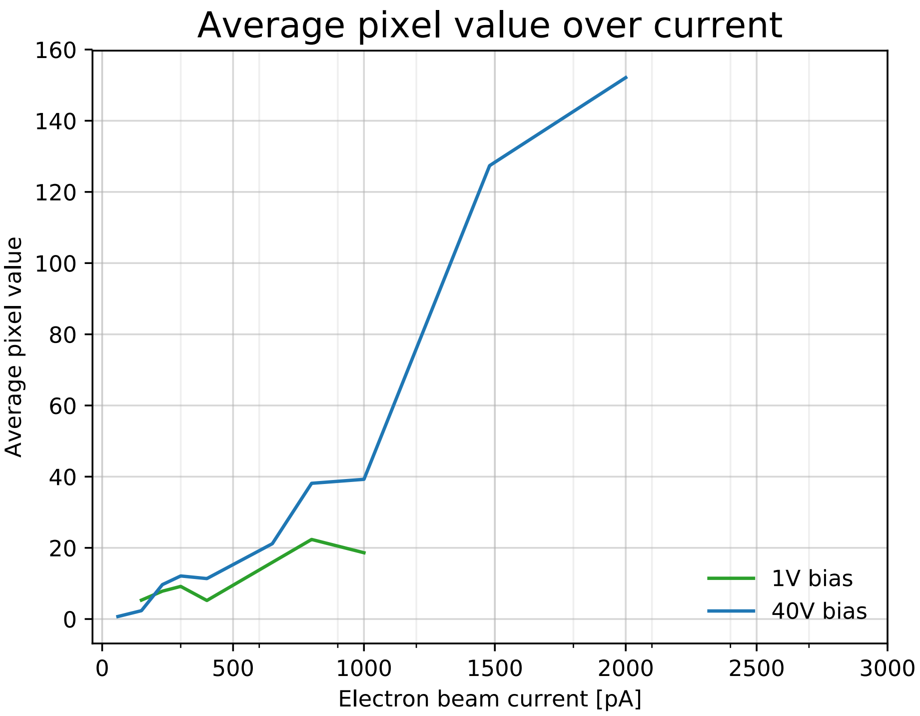
Electron measurements – Current pixels Chip 1



1 nA current beam (1800 e/pix/s roughly) – 40V counts again more high-value pixels and a higher average overall due to greater collection

Laplacian of Gaussian histograms show higher negative values too

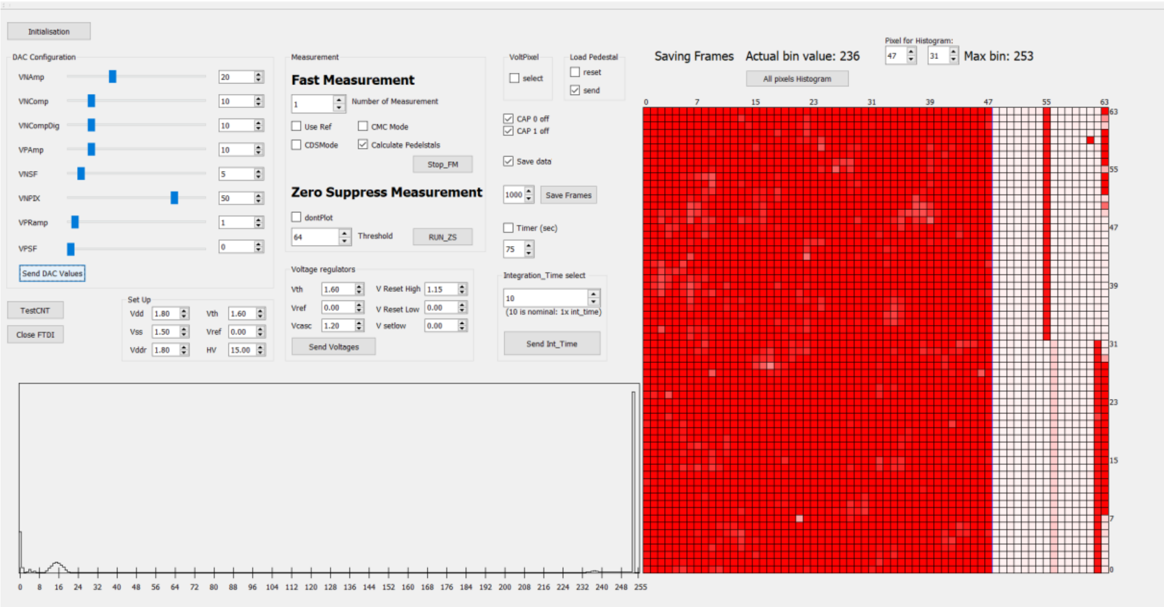
Electron measurements – Current pixels Chip 1



Collection improves with higher BIAS

Electron measurements – Breakage of chip 1

Chip 1 broke at 2.75 nA step in uniform illumination

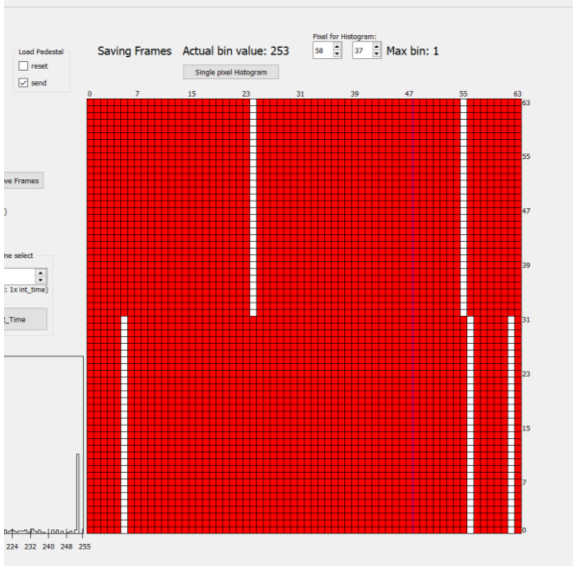


Column patterns in the image and pixel being either at saturation (255) or dark (0) suggest that failure might be related to the DIGITAL section.

I personally blame ADCs as they are arranged in a column-sharing flavour. Top-half/bottom-half differences also point to ADCs which are shared in a similar manner

Electron measurements – Breakage of chip 1

Other examples:



Steps to calculated the number of electrons/pixel endured:

- Multiply current dose by area factor between the aperture and single pixel (find current density/pixel)
- Integrating current over time of each measure
- Summing doses from all the steps (current + earlier)

Each pixel endured a total of 13.1 * 10^6 electrons

Electron measurements – Breakage of chip 1

Each pixel endured a total of 13.1 * 10^6 electrons

Assuming electrons lose all the energy in the 200µm thick substrate (energy loss ~ 0.75 KeV/µm in Si), it is easy to figure the energy in J/Kg by simply :

$$\frac{(N_{electrons} * E_{electron})}{MASS_{pixel}}$$ [J/kg]

Then dividing by 10^5 gives the dose in MRad.

The calculated radiation that each pixel endured before collapse is **~80 kRad**

Electron measurements – Test Chip 2

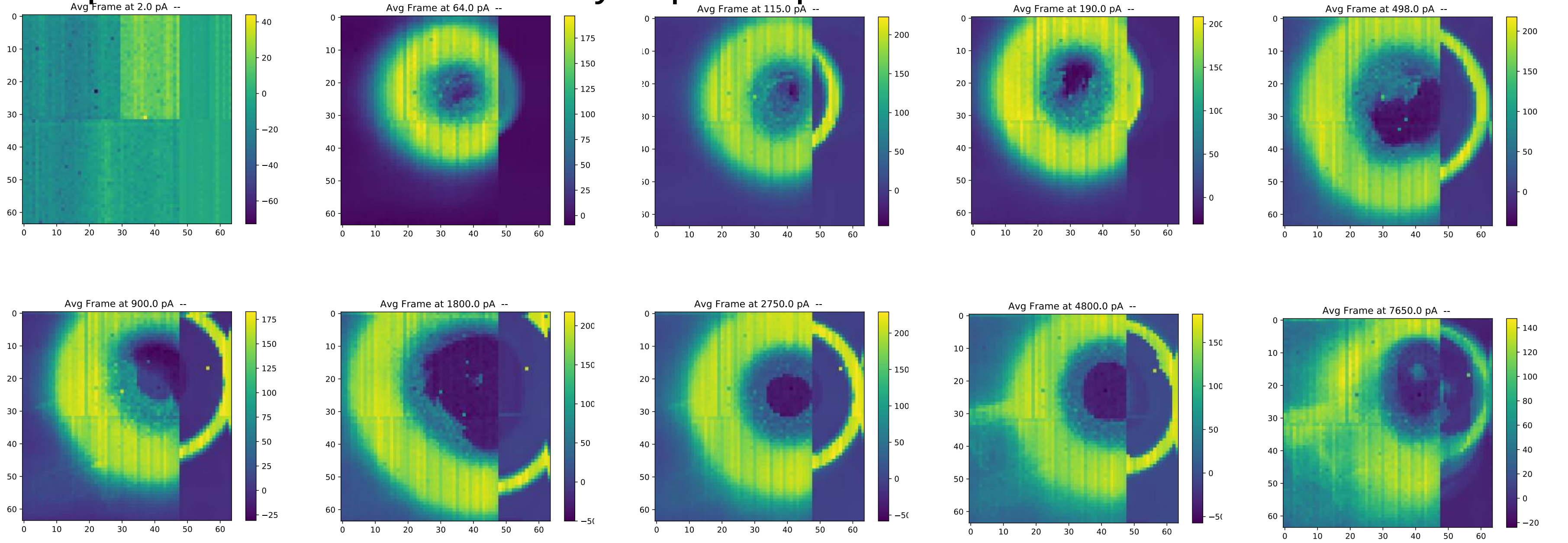
Chip 2 is tested with focussed beam at different Electron currents

- The goal is to focus the beam on the pixels only to test their radiation hardness, trying to avoid illuminating the digital circuitry

Electron measurements – Test Chip 2

Testing with focussed beam at different Electron currents

Wrap-around effect on extremely exposed pixels



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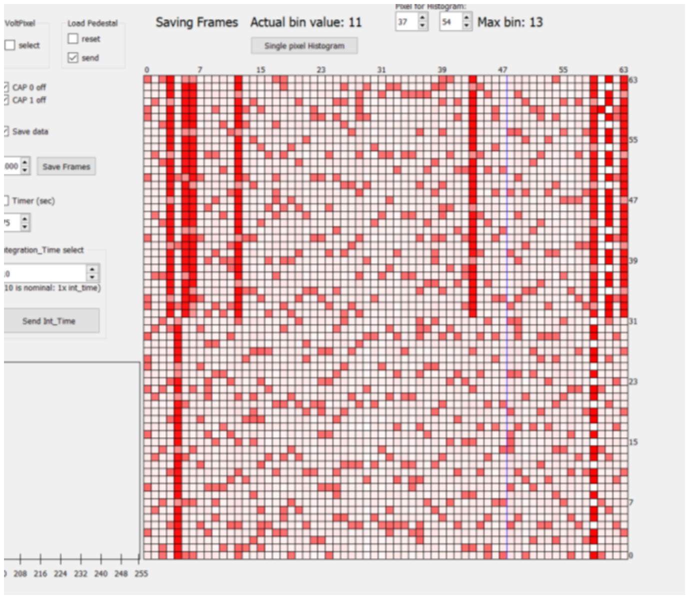
Thermo Fisher Scientific

Electron measurements – Test Chip 2

- At 7.65 nA Chip 2 was not functional anymore. Stripe/column patterns seem to point again to a digital failure.
- However pixel noise had already grew significantly at the first steps.(next)
- From the calculations, chip pixels have endured a factor of ~1000 larger doses compared to chip 1’s pixels and collapsed around **~70MRad/pixel**

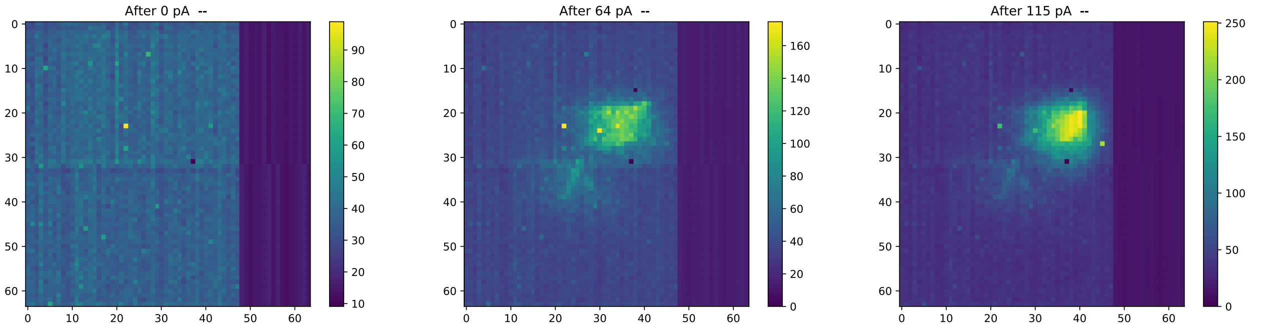


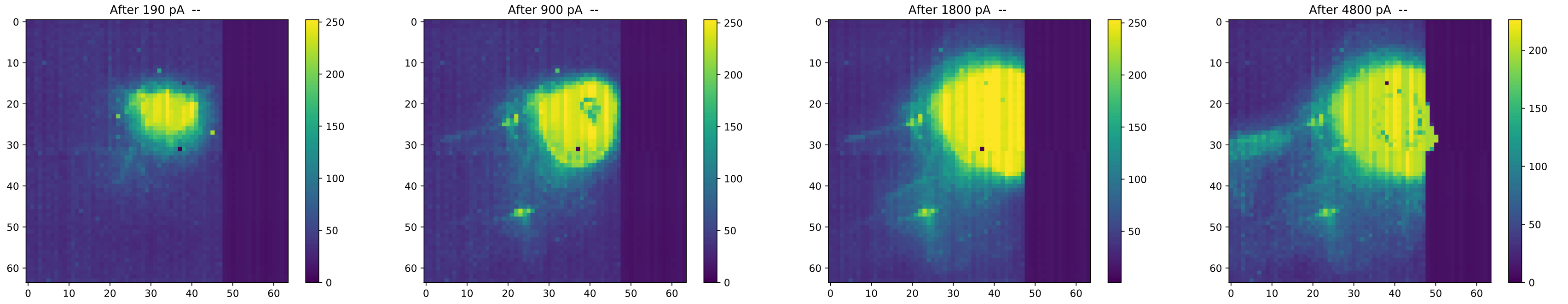
Electron measurements – Test Chip 2

Evaluation of Damage:

Average Dark Noise map after each beam current increase step

Chip is already compromised after 64 pA focused beam

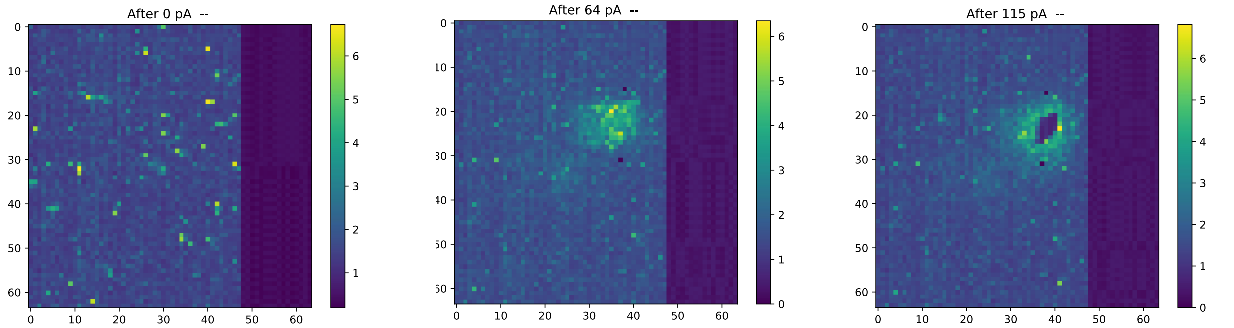


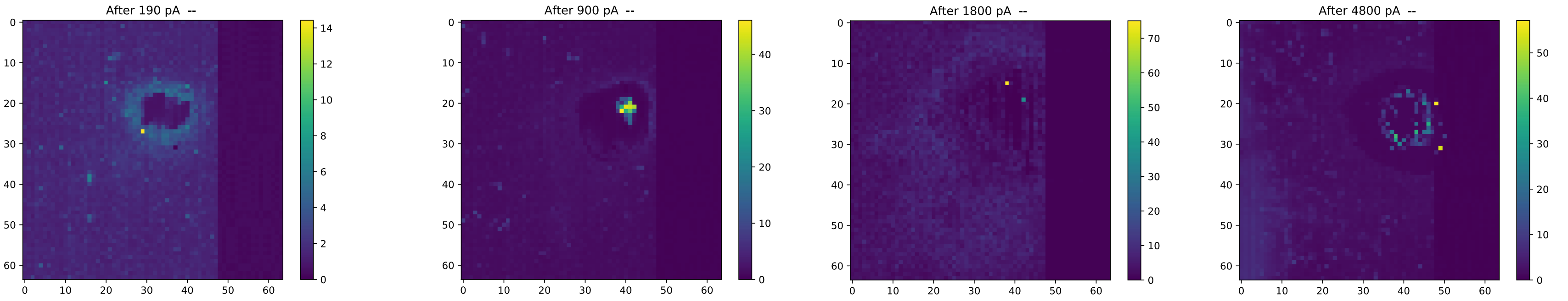


Electron measurements – Test Chip 2

Evaluation of Damage:

Temporal Dark Noise map after each beam current increase step

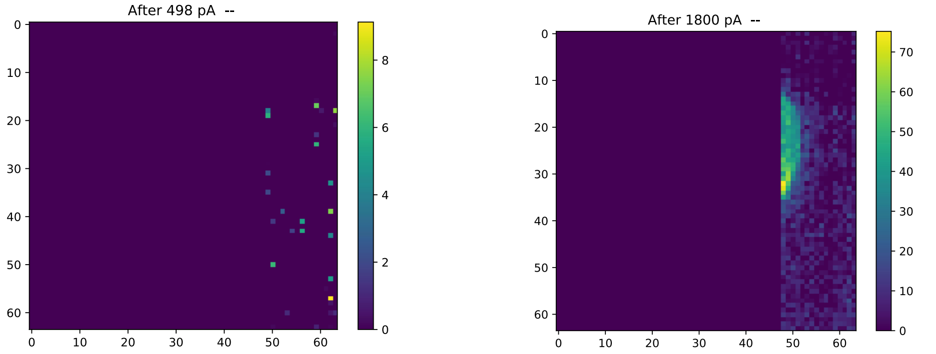




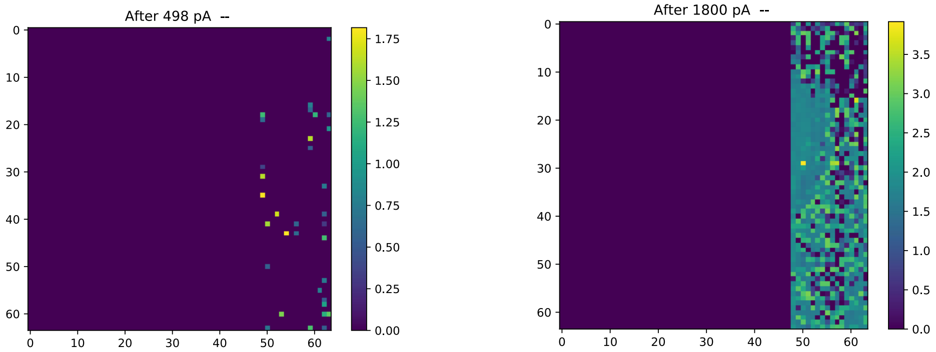
Electron measurements – Test Chip 2

Evaluation of Damage on Voltage Pixels, they seem more radiation hard:

Average Dark Noise map

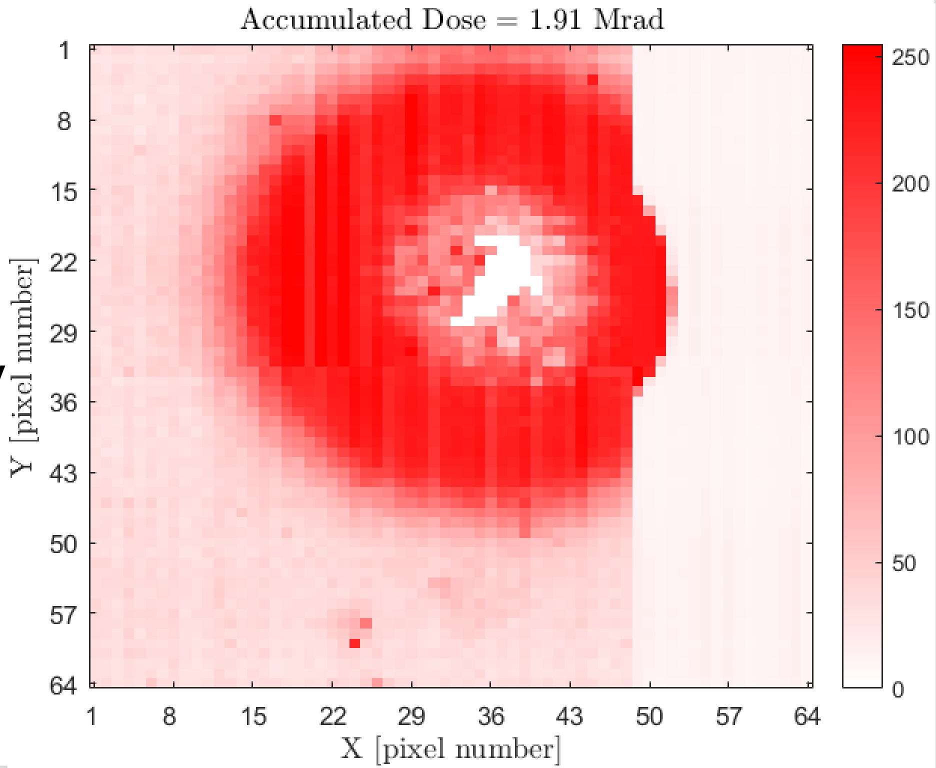


Dark Temporal Noise map



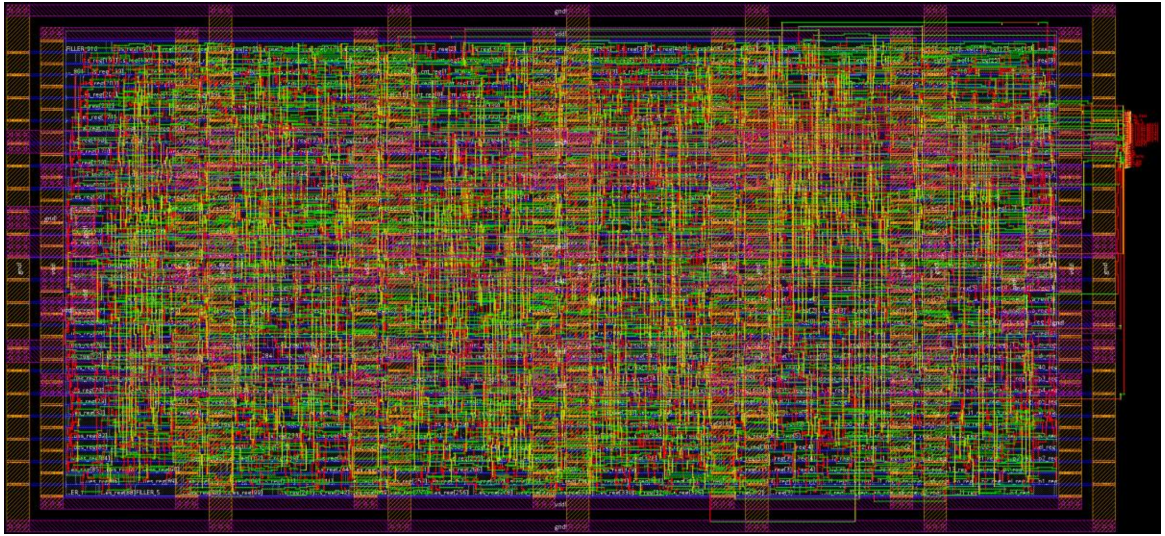
Electrons measurements – Chip2 conclusions

- After 3.5 MRad, the pixels at the center of the spot were saturated without the beam on.
- After ~63 MRad the chip stopped working
- The voltage pixels seem inherently more radiation tolerant
- Example image from the GUI



Redesign digital part

- Investigation to make it radiation tolerant
- Possibly, decrease noise
  - By reducing amount of digital lines in/out



Next steps

- Near future:
  - Full test against photon and electrons radiation
  - Finish the design a new chip version

- Long term:
  - Test the new version of the chip
  - Improve PC interface to do clustering

Thank you!