Evaluation of the DECAL Fully Depleted monolithic sensor for outer tracking and digital calorimetry

I. Kopsalis[1], P. Allport[1], S. Benhammadi[2], R. Bosley[1], J. Dopke[2], L. Fasselt[5], S. Flynn[1], P. Freeman[1],

C. Issever[4,5], L.Gonella[1], N. Guerrini[2], K. Nikolopoulos[1], P. Phillips[2], T. Price[1], I. Sedgwick[2], E.G. Villani[2],

M. Warren[3], N. Watson[1], H. Weber[5], F. Wilson[2], A. Winter[1], S. Worm[1,4], Z. Zhang[2]

[1]School of Physics and Astronomy, University of Birmingham, United Kingdom
[2]STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
[3]Department of Physics and Astronomy, University College London, United Kingdom
[4]Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany
[5]Department of Physics, Humboldt University of Berlin, Germany

Outline and Overview

- **Motivation digital EM calorimetry**

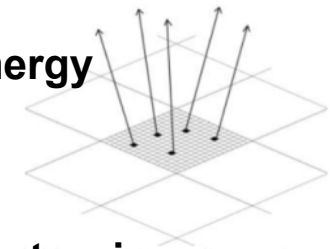
- **DECAL sensor: Towards a reconfigurable Depleted MAPS**
  - **The Monolithic Active Pixel Sensor**
  - **Data acquisition system and software**
  - **Analogue pixel test**
  - **Threshold scan results**
  - **Digital functionality**

- **The DECAL Fully Depleted sensor fabricated in the TowerJazz modified process**
  - **Digital equalization matrix**
  - **Performance tests with monochromatic X-rays and Sr-90 source**

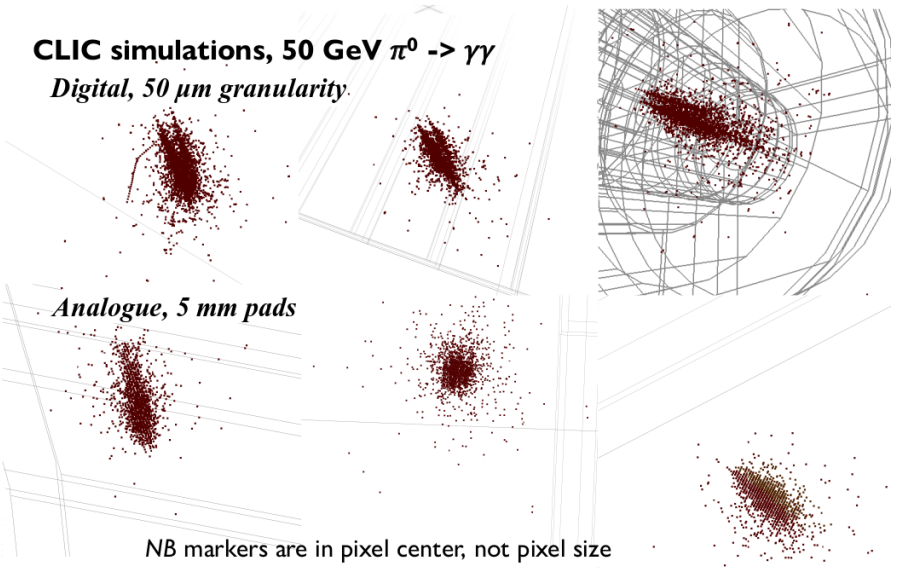
- **Conclusions and outlook**

Motivation digital EM calorimetry

- **Digital SiW EM calorimetry with Monolithic Active Pixel Sensor**
  - Basic idea: count the number of pixels above threshold to estimate the shower energy
- **Small pixel size to avoid saturation (more than 1 hit/pixel) in high density showers**
- **Production costs of CMOS may decrease with growing market**
- **Full-system complexity and costs can be lower due to integration of sensor and electronics**



- **Potential to improve reconstruction if increased granularity can be exploited (50 µm crossed strips vs 5 mm pads)**
  - On-going simulation work with $\pi^0 \rightarrow \gamma\gamma$ reconstruction

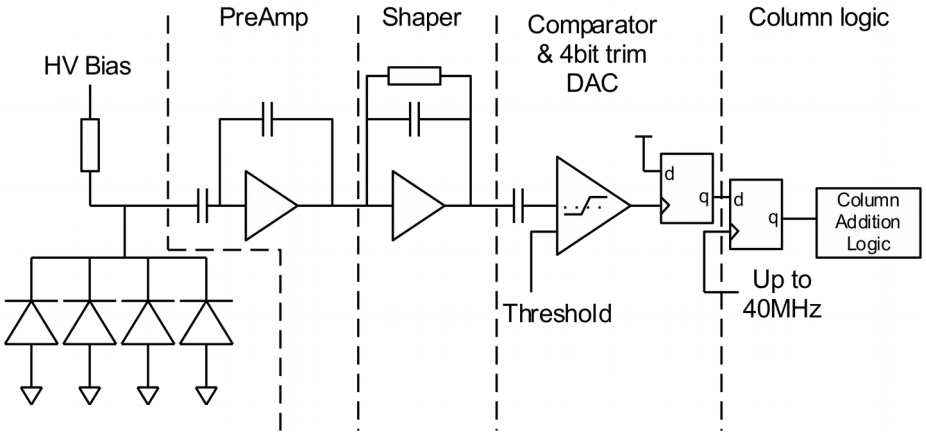


P. Freeman et al., DECAL: A reconfigurable CMOS sensor for pre-shower, outer tracking and digital EM calorimetry in future colliders, CPAD instrumentation Frontier workshop, March 2021

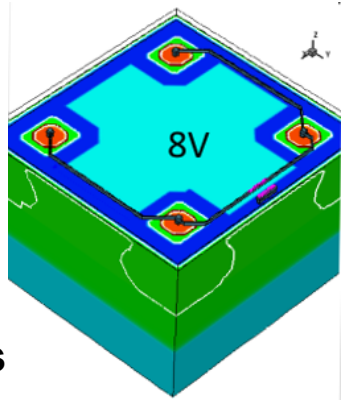
- **MAPS prototypes in 150 nm and 180 nm CMOS imaging process also demonstrate good radiation hardness**

The DECAL sensor

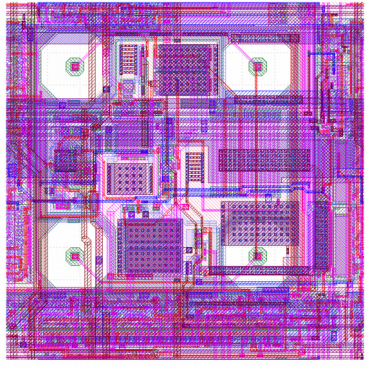
- **Monolithic Active Pixel Sensor designed and fabricated in the standard TowerJazz 180 nm CMOS imaging process on 18/25 μm epitaxial Si**
- **Sensor matrix consists of 64x64 pixels with pitch of 55x55 μm**
  - **Four collection nodes, low capacitance, optimum cross talk reduction, expect good signal/noise**
  - **Operational with 1-2 V bias or higher voltage for faster charge collection**
  - **Pre-amplifier, shaper, comparator, discriminator and trimming logic**
  - **One pixel only with analogue output, data rate 40 MHz for the digital pixels**
- **The digital pixel**



Simulated pixel in TCAD



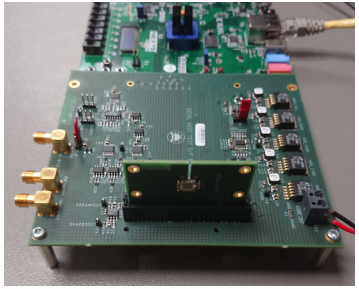
Single pixel gds picture

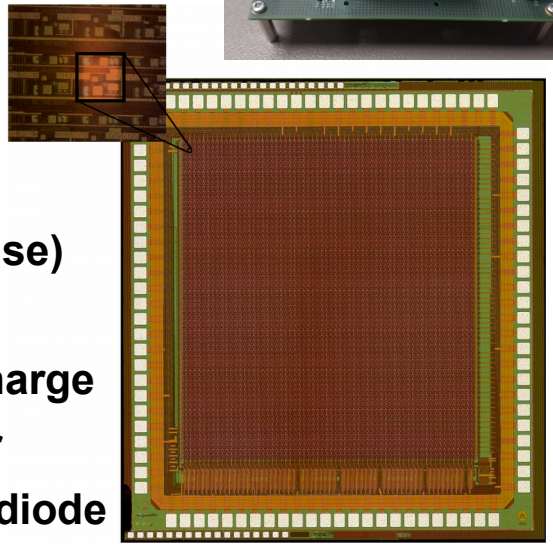


P.Allport et al., First tests of a reconfigurable depleted MAPS sensor for Digital Electromagnetic Calorimetry, Nucl. Inst. and Meth. A, 958:162654, April 2020

Data acquisition system & Analogue pixel test

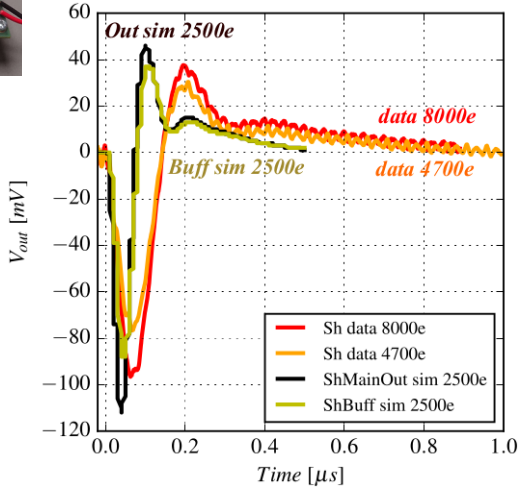
- The data acquisition is done using a NEXYS Video board from Digilent and a specific made DECAL motherboard
  - Ethernet based readout system using the ATLAS ITSDAQ data acquisition software





- Laser illuminations with a TriLite (pJ/pulse) in the IR wavelength (1064 nm)
- Calculation of the equivalent injected charge in the 18 μm epi of the DECAL Si sensor for a laser spot of 10x10 μm² using a Si diode

Shaper signal compared to Cadence simulations

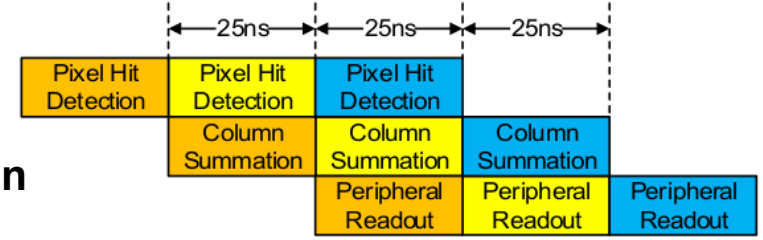


P. Allport et al., First tests of a reconfigurable depleted MAPS sensor for Digital Electromagnetic Calorimetry, Nucl. Inst. and Meth. A, 958:162654, April 2020

Agreement is observed in the rising time between the measured and simulated signal illuminating at the top left collection node of the analogue pixel
The injected charge estimated to be 2 or 3 times higher than the simulated charge value

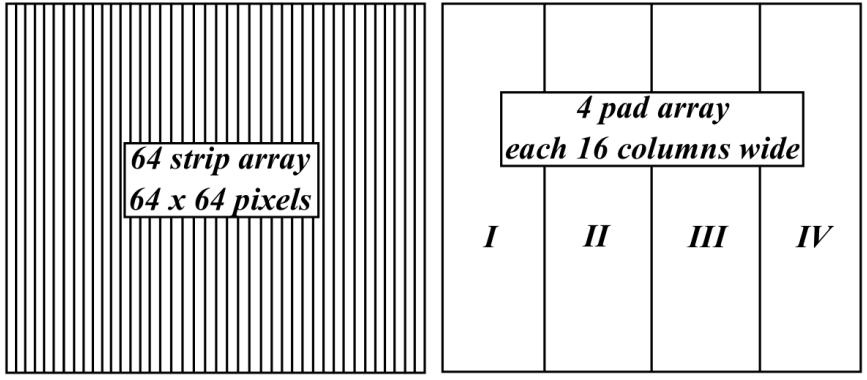
Pixel & readout logic

- To achieve data rate of 40 MHz pixel column sum has to be complete within 25 ns
- The readout logic is configured either for strip or pad mode



- Strip mode (1x64 pixel array) outputs per pixel column
  - Counts above threshold, max 3 hits per column
  - Data rate: 320 Mbits/s x 16 =5.12 Gbits/s

- Pad mode (16x64 pixel array) outputs per pad area
  - 4 pad arrays, max 15 hits in each of four 16 column blocks (240 total counts)
  - Lower rate, about ¼ of the LVDS output channels



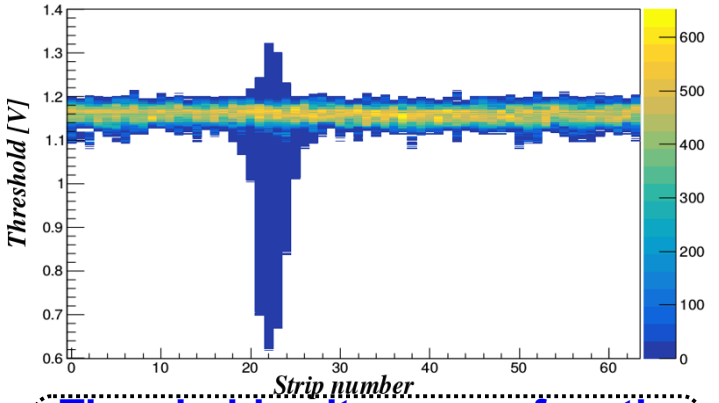
S. Benhammadi et al., DECAL: A Reconfigurable Monolithic Active Pixel Sensor for use in Calorimetry and Tracking, Proceeding of Science, (TWEPP 2019), (040), 2019

Overflow flag if max total counts exceeded

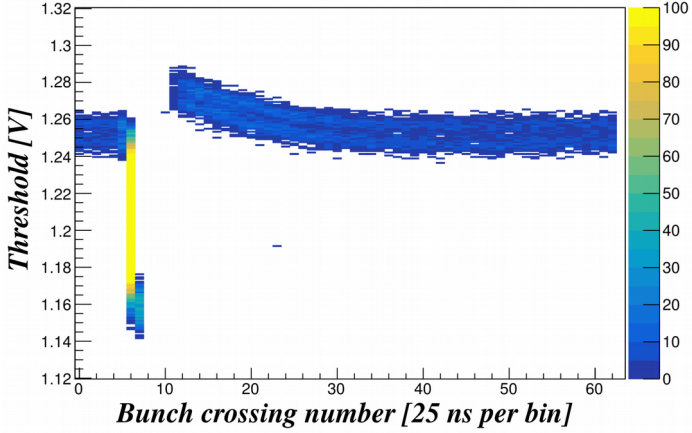
Threshold scans: Digital functionality

- The performance of the digital pixels is evaluated performing threshold scans under laser illuminations with a diode laser and pulse frequency 100 kHz
  - Rate of hits in each pixel allows to test the full chain from analogue to digital
  - Threshold scan in strip mode with unmasked pixels and global chip configuration
- Defocused beam, hits recorded from around 10 strips, as the laser illumination causes the pixel shaper output voltage to drop
- Noise band and a clear signal response reflecting the Gaussian laser beam profile
- Using the laser trigger, the shaper response from a single strip is measured
- Time response of the order of 25 ns

Threshold voltage as a function of strip number



Threshold voltage as a function of bunch crossing number



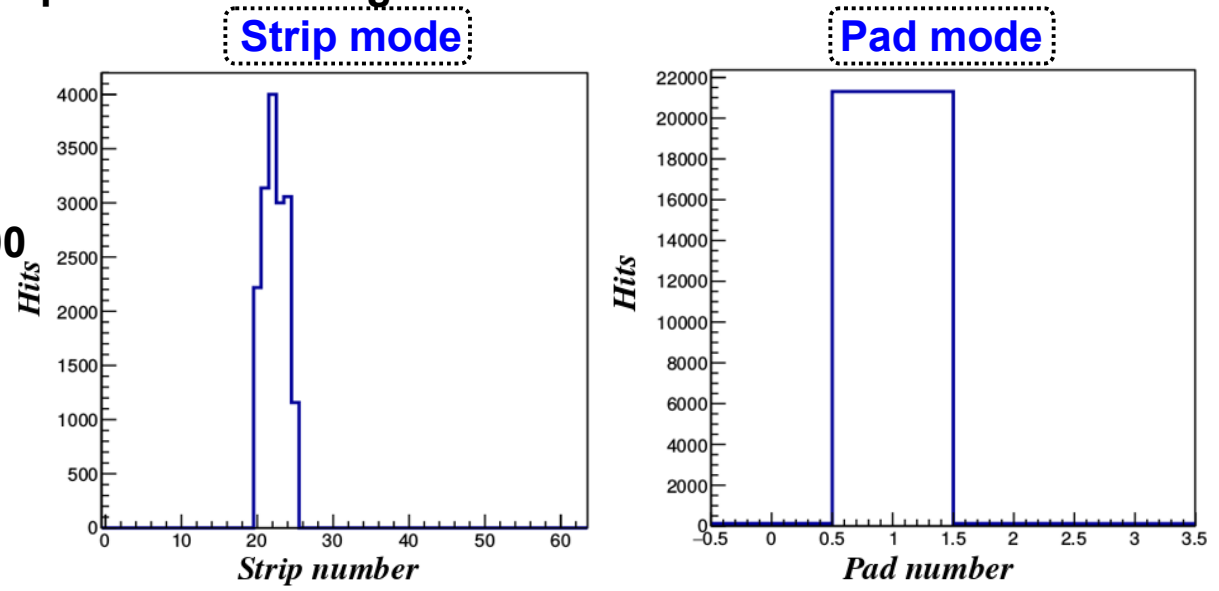
P. Allport et al., First tests of a reconfigurable depleted MAPS sensor for Digital Electromagnetic Calorimetry, Nucl. Inst. and Meth. A, 958:162654, April 2020

Threshold scans: Digital functionality

- **Comparison of the summing logic in strip and pad mode under identical laser illumination conditions**
  - With defocused laser beam 6 strips are fired at a global threshold value of 1 V

- **The mean value of hits for each strip is approximately 3, the laser repetition was chosen 1000**

- **The strips, number from 20 to 25, fired in strip mode, correspond in pad number 1**

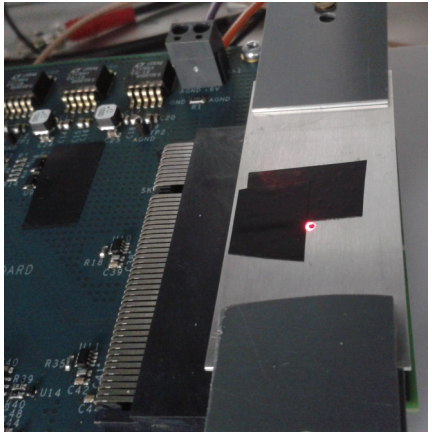


I. Kopsalis and S. Worm, Performance characterisation results of HV/HR CMOS devices, WP6: Novel High Voltage and Resistive CMOS sensors, AIDA-2020-D6.3, CERN 2020

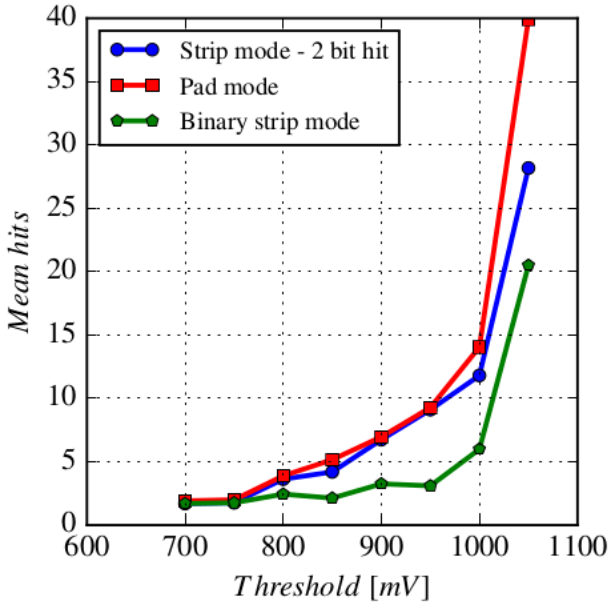
The sum of hits for the 6 strips is smaller than the total number of hits in pad number 1, as in pad mode the max hits per strip can be up to 15. However in strip mode there is more information where each hit occurred due to higher granularity

Strip vs Pad mode as a function of illumination area

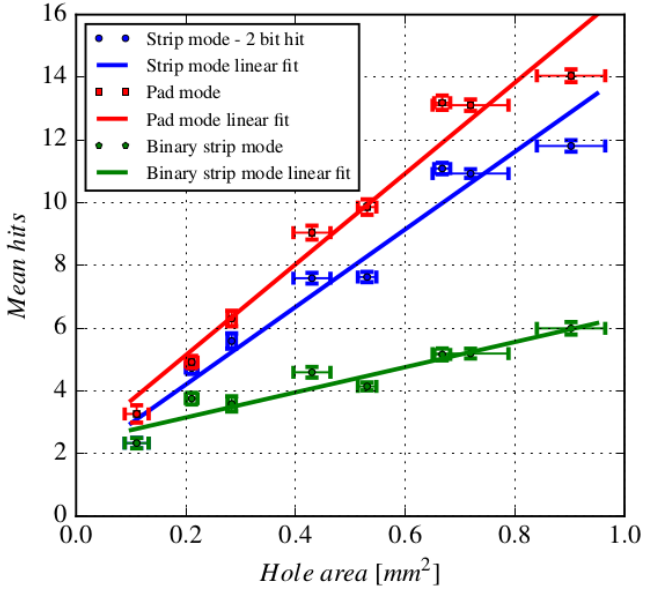
- **Laser illumination using an Al aperture with hole diameter in the range of 400 – 1100 μm**
- **Investigation of the dependence of the mean hits for strip and pad mode on the illumination area**
  - **Linear behavior is observed as a function of hole area, as both strip and pad mode are operated below saturation**



Mean value of hits as a function of threshold for hole diameter 1.1 mm



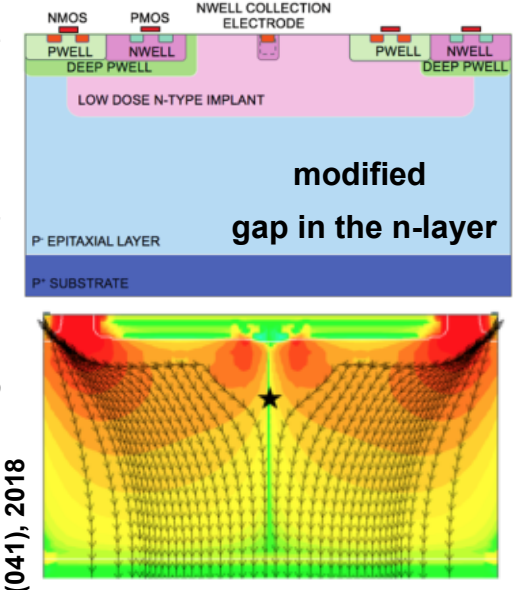
Mean value of hits for threshold 1V for different illumination hole area



P. Allport et al., A reconfigurable CMOS Sensor for Tracking, Pre-Shower and Digital Electromagnetic Calorimetry, Nucl. Inst. and Meth. A, 978:164459, October 2020

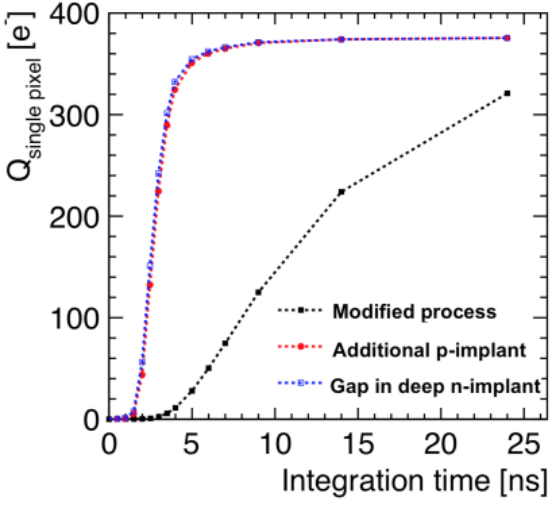
The DECAL Fully Depleted sensor

- **TowerJazz 180 nm CMOS modified process**
  - **The first version is referred to as an addition continuous n⁻ layer design for each pixel**
  - **The second version of two variants (gap in the n- layer and extra deep p-well) which expected to shape the electric field so the charge carriers produced are steered more directly towards the collection electrode in the pixel center**
- **The second version and the variant with gap in the n⁻ layer was chosen for the DECAL FD**
- **Pixel timing response has been simulated (by CERN groups) with 3D TCAD simulation for a MIP traversing the pixel corner**
- **Faster charge collection has been simulated for the second version (two variants of the modified process)**



H. Pernegger, Depleted CMOS sensors for HL-LHC, Proceeding of Science, (VERTEX 2018), (041), 2018

Collected charge for different versions of the modified process

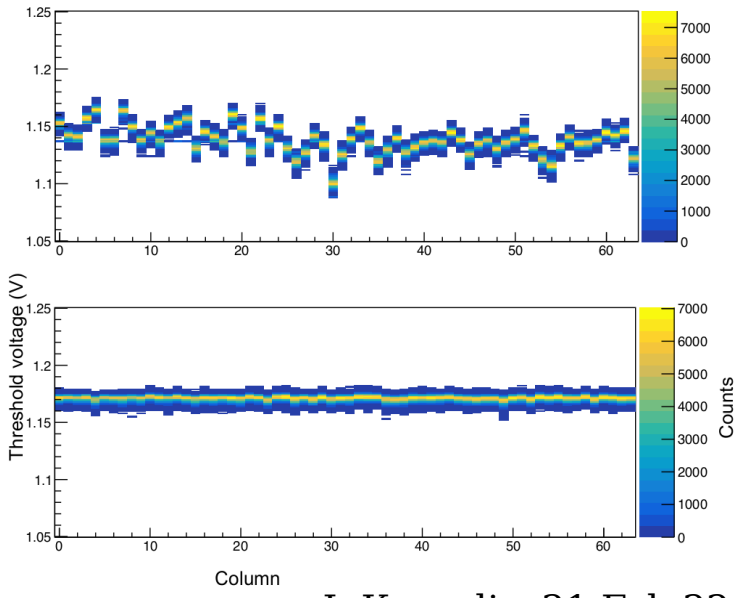


M. Munker et al., Simulations of CMOS pixel sensors with a small collection electrode, improved for a faster charge collection and increased radiation tolerance, Journal of Instrumentation 14 (2019) C05013

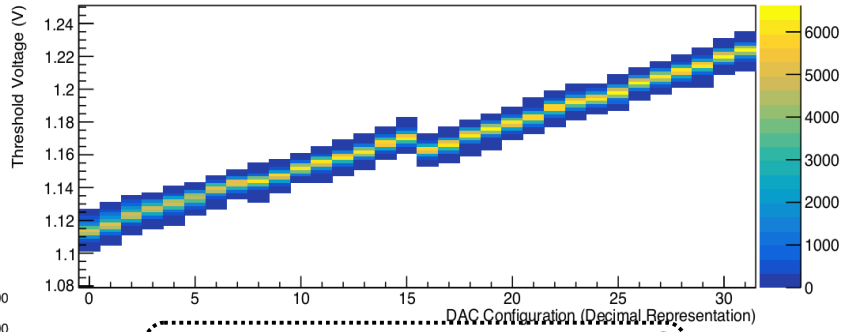
DECAL FD digital functionality

- With the DECAL FD possibility of configuration of all pixel columns and full depletion of the sensor under bias voltage on p-epi
- Threshold scan in single pixels → threshold pixel map and in principle threshold trimming of the pixel matrix
- 5 bits pixel trimming with a maximum shift of ≈150 mV
- Example of trimming of a single row for all columns at threshold of 1.17 V

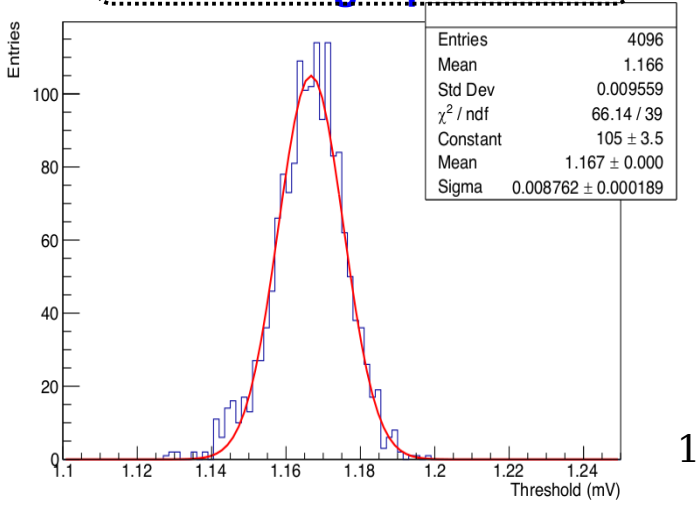
Threshold voltage before & after trimming of a single pixel row



Threshold voltage as a function of pixel configuration



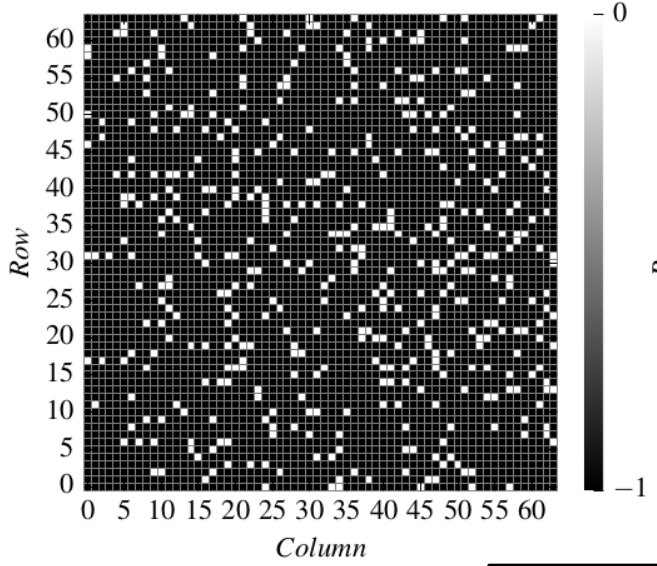
Threshold distribution of a single pixel



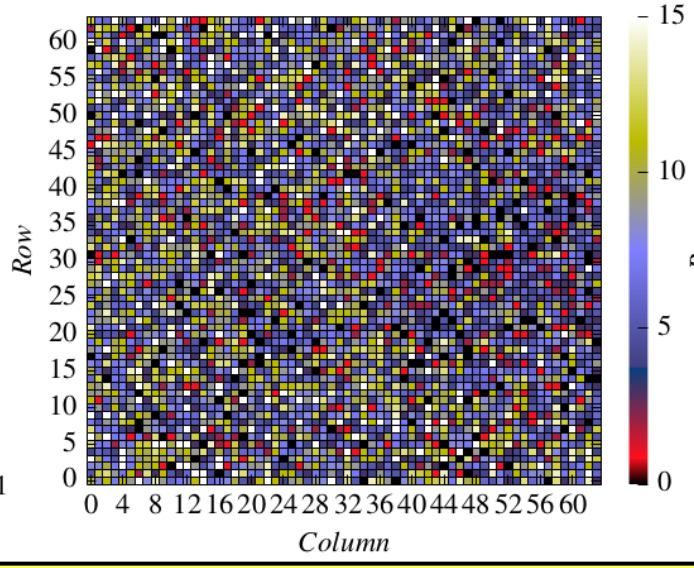
DECAL FD equalization pixel matrix

- **Trimming of the 64x64 pixel matrix to a fixed threshold voltage ~ 1.17 V**
- **All pixels responding, no masked pixels, no observable systematic threshold voltage non-uniformity across the pixel matrix**

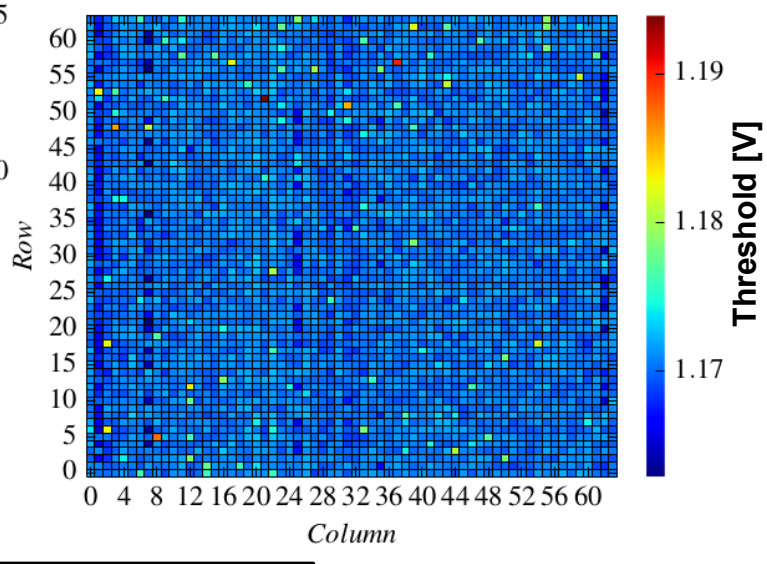
Polarity bits 64x64 pixels



DAC configuration (Decimal representation) 64x64 pixels



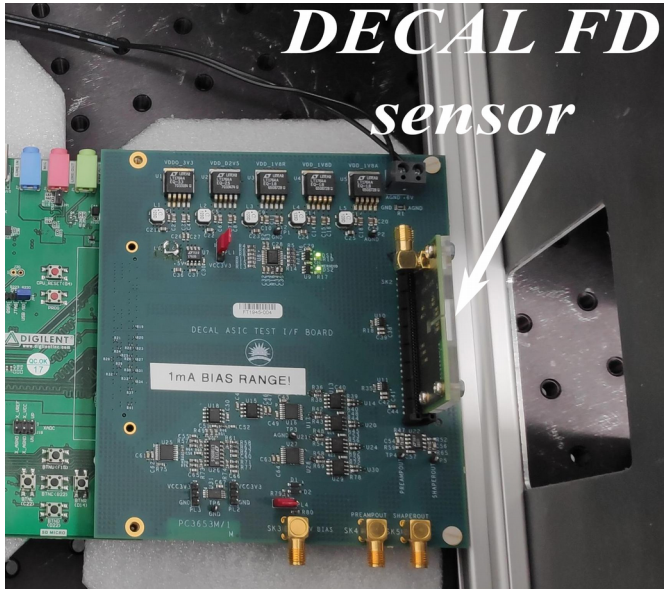
Threshold uniformity 64x64 pixels

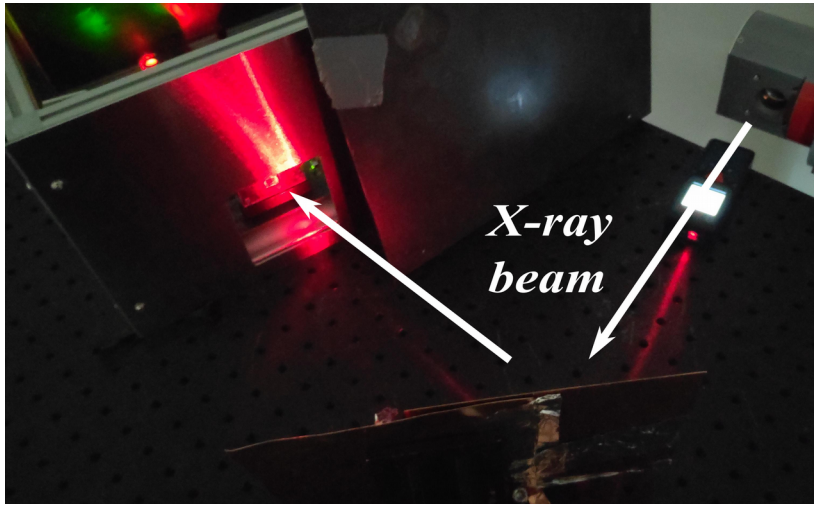


Threshold uniformity across all pixels is possible

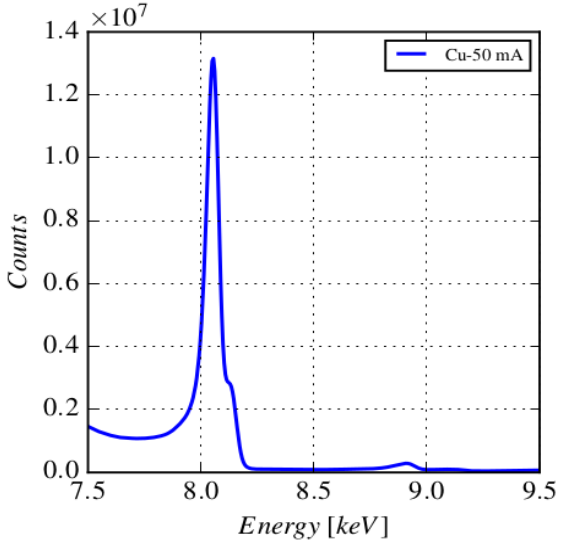
DECAL FD test with monochromatic X-rays

- **Monochromatic X-rays by illuminating with an X-ray tube target material Cu**
- **Sensor test with high rate photons of the Cu XRF spectrum, K_α peak E = 8.05 keV and eps = 3.6 eV/e-h in Si pair**
  - Electrons generated, E_{gen} = E/eps, ≈ 2236 e^-, conversion gain and ENC is extracted





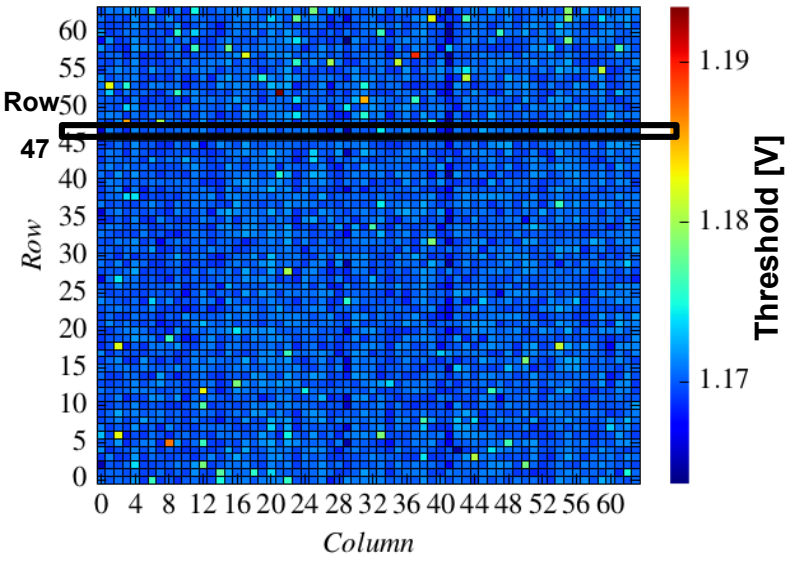
Energy spectrum of Cu measured with the HEXITEC detector



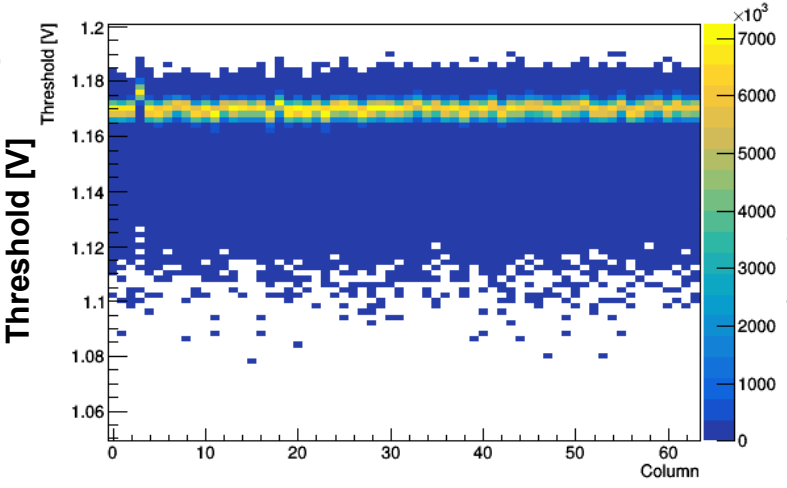
DECAL FD test with monochromatic X-rays

- **Uniform threshold voltage of the pixel matrix and long term threshold scan of a single row**

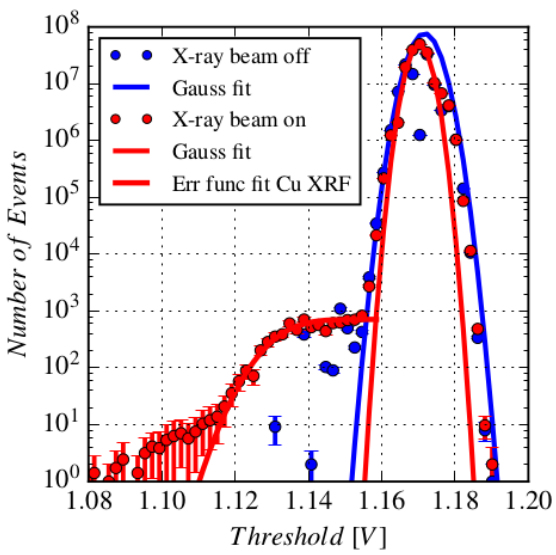
Threshold uniformity under X-ray illumination



Long term threshold scan pixel row 47



Pixel row threshold distribution



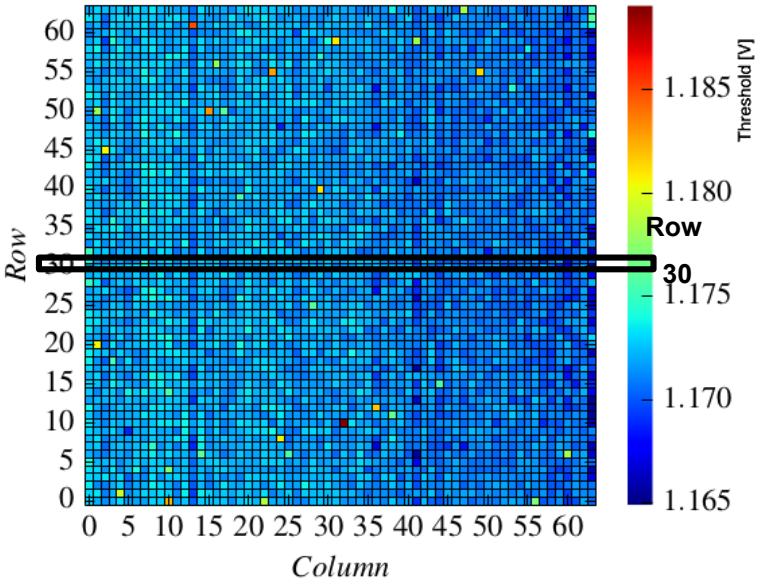
- **Error function fit in the signal detected below the global threshold**
- **Conversion gain, f = 59 [e⁻/mV]**

	Mean [V]	Sigma [mV]
Beam off Gauss	1.172	3.3
Beam on Gauss	1.170	2
Beam on Err func	1.132	10.2

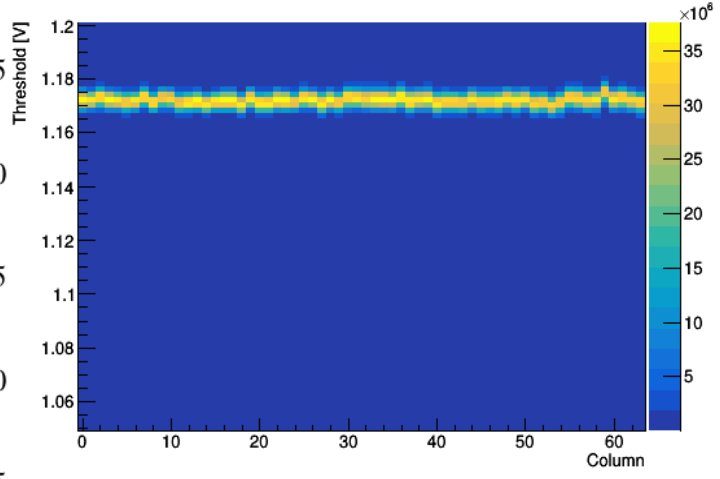
DECAL FD test with Sr90 source

- **Uniform threshold voltage of the pixel matrix and long term threshold scan of a single row with a Sr90 source of 160 MBq activity**

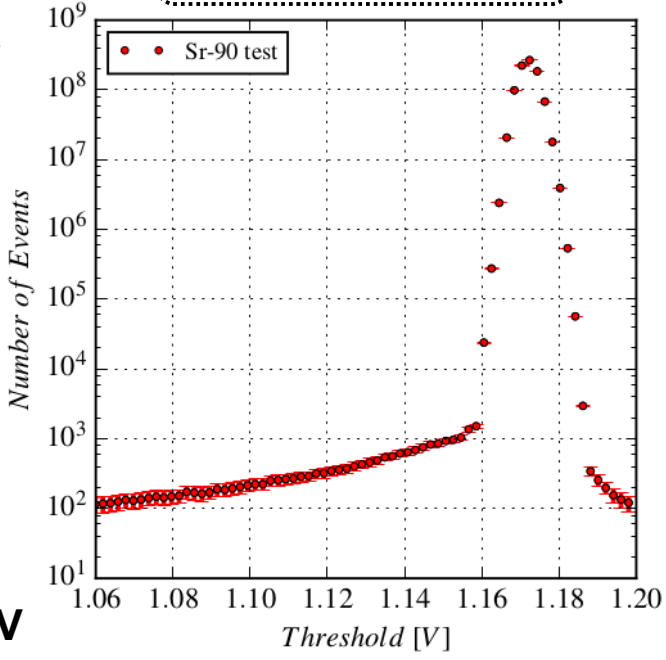
Threshold uniformity under Sr-90 exposure



Long term threshold scan pixel row 30



Pixel row threshold distribution



- Events recorded for thresholds below the global threshold ~ 1.17 V

- Evidence of MIP detection sensitivity

Conclusions and Outlook

- **Conclusions**
  - **Two DECAL sensor prototypes (standard & modified TJ process) fabricated, tested and are being explored as candidate sensor for a digital EM calorimeter**
  - **Analogue pixel test: Good agreement is observed in the rising time of the shaper signal between the measured and simulated data using the Cadence toolkit**
  - **Threshold scan: Digital pixel functionality is confirmed performing threshold scans under laser illumination**
  - **Configuration up to six bits which gives the advantage of high granularity on the pixel trim and the sixth bit is used for pixel mask flag which de-activates the in-pixel comparator**
  - **The above advantage improves substantially the pedestal and noise scans**
  - **The DECAL FD shows threshold uniformity (>85% of pixels within 1 mV range), the conversion gain is extracted performing test with monochromatic X-rays**
- **Outlook and future plans**
  - **Investigate the MIP sensitivity of the DECAL FD before and after irradiation**

Thank you for the attention