Evaluation of the new version of the DECAL CMOS MAPS

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Outline

- **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

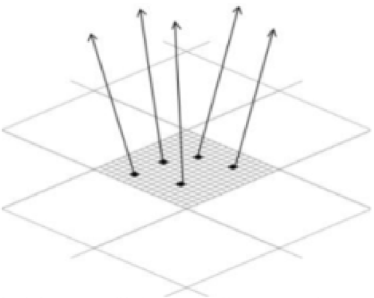
  - High rate test under Cu XRF spectrum

  - The DECAL sensor fabricated in the TowerJazz modified process

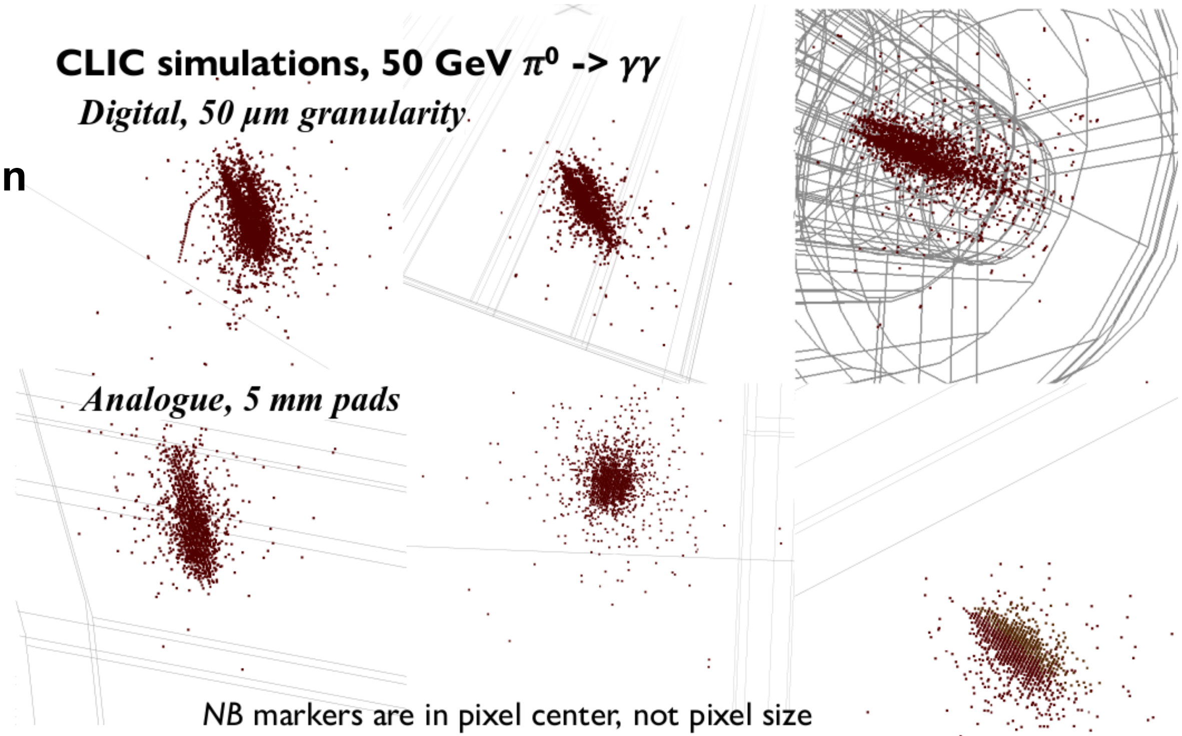
  - Conclusions and Outlook

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

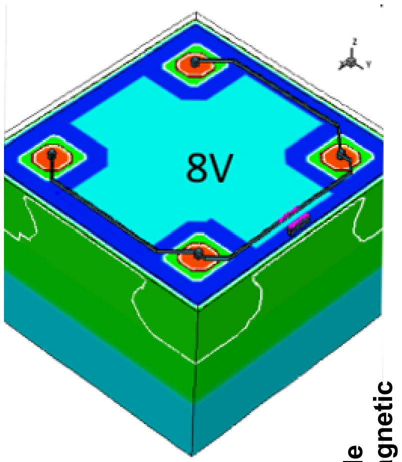


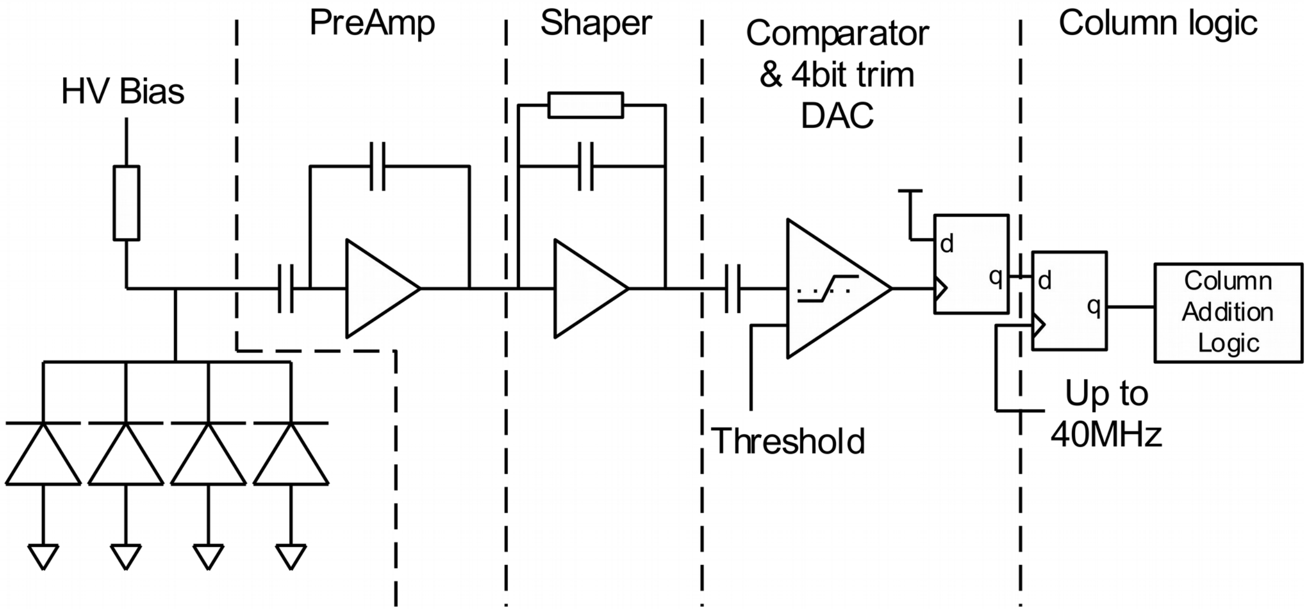
P. Freeman et al., DECAL: A reconfigurable CMOS sensor for pre-shower, outer tracking and digital EM calorimetry in future colliders, CPAD instrumentation Frontier workshop, March 2021

The DECAL sensor

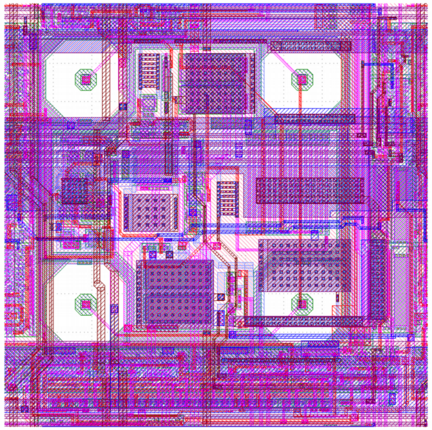
- **Monolithic Active Pixel Sensor designed and fabricated in the standard TowerJazz 180 nm CMOS imaging process on 18/25 µm epitaxial Si**
- **Sensor matrix consists of 64x64 pixels with pitch of 55x55 µm**
  - Four collection nodes, low capacitance, optimum cross talk reduction, expect good signal/noise
  - 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

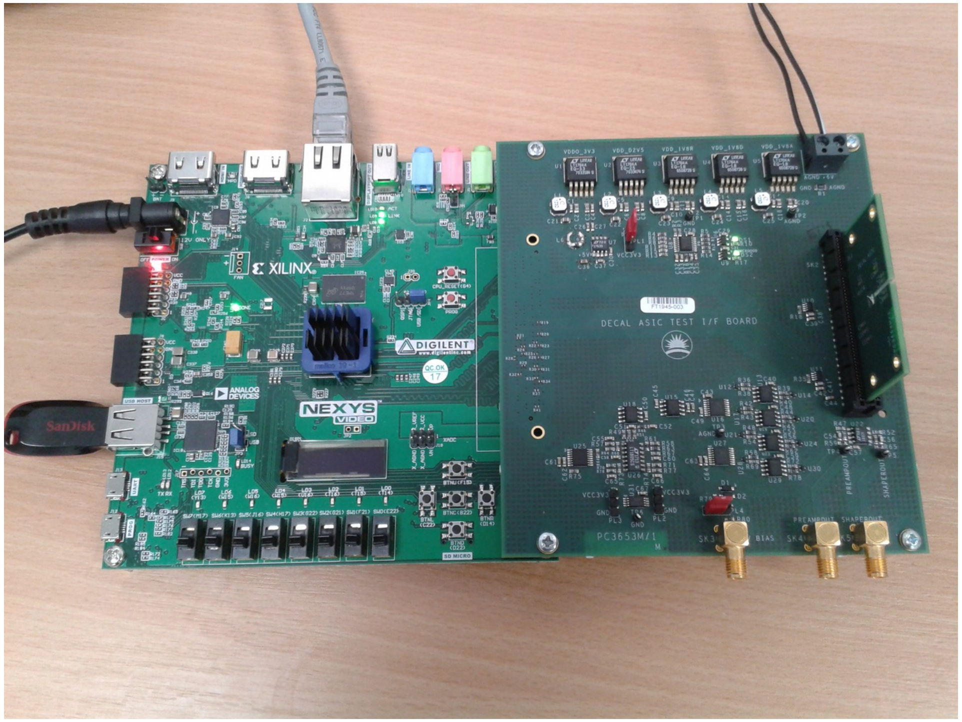


P. Allport et al., First tests of a reconfigurable depleted MAPS sensor for Digital Electromagnetic Calorimetry, Nucl. Inst. and Meth. A, 958:162654, April 2020

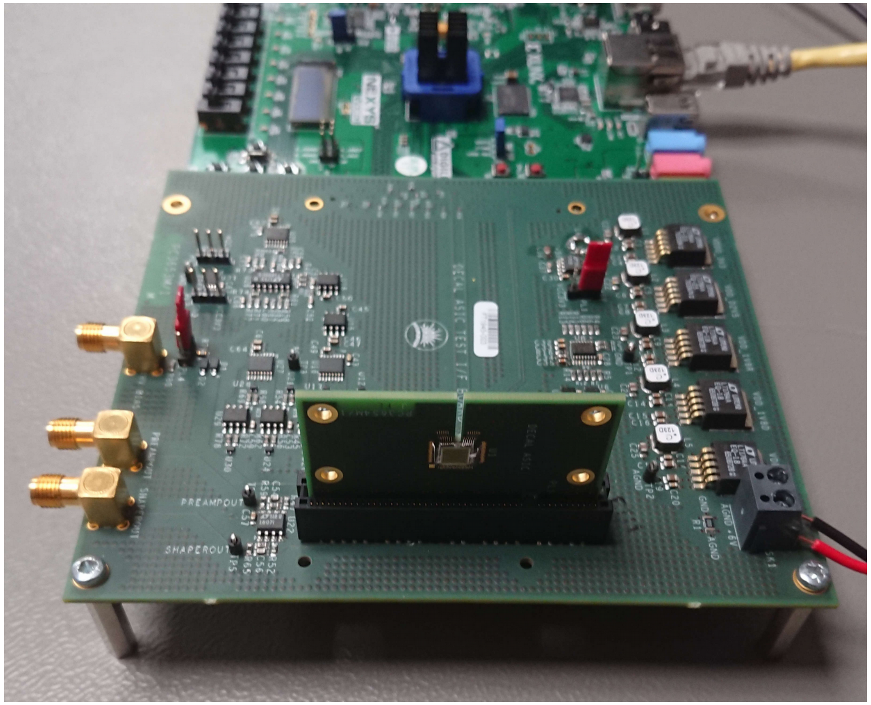
Data acquisition system and software

- **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**

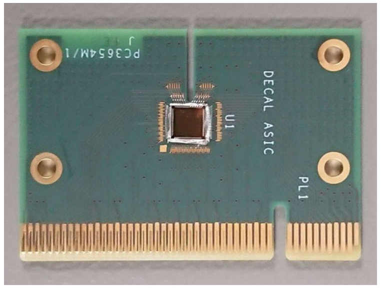
DECAL Hardware



DECAL ASIC plugged in the motherboard



DECAL ASIC and MAPS sensor

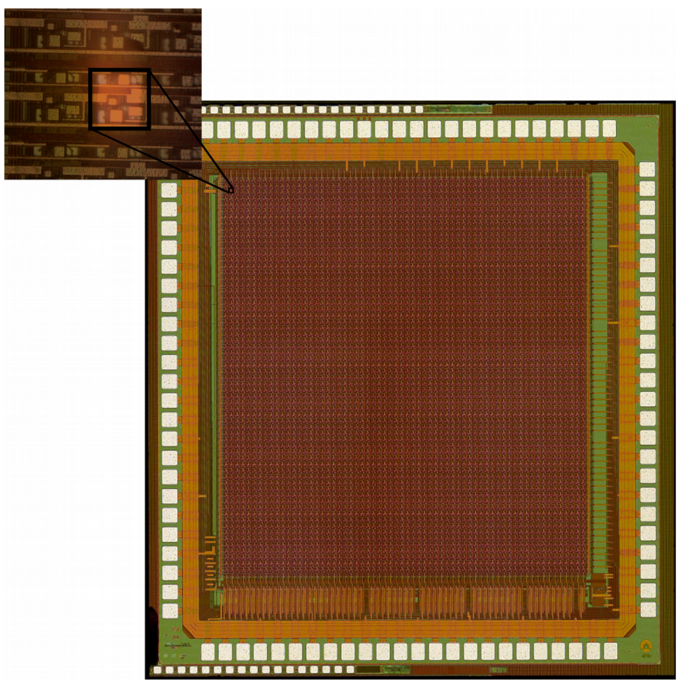


Analogue pixel test

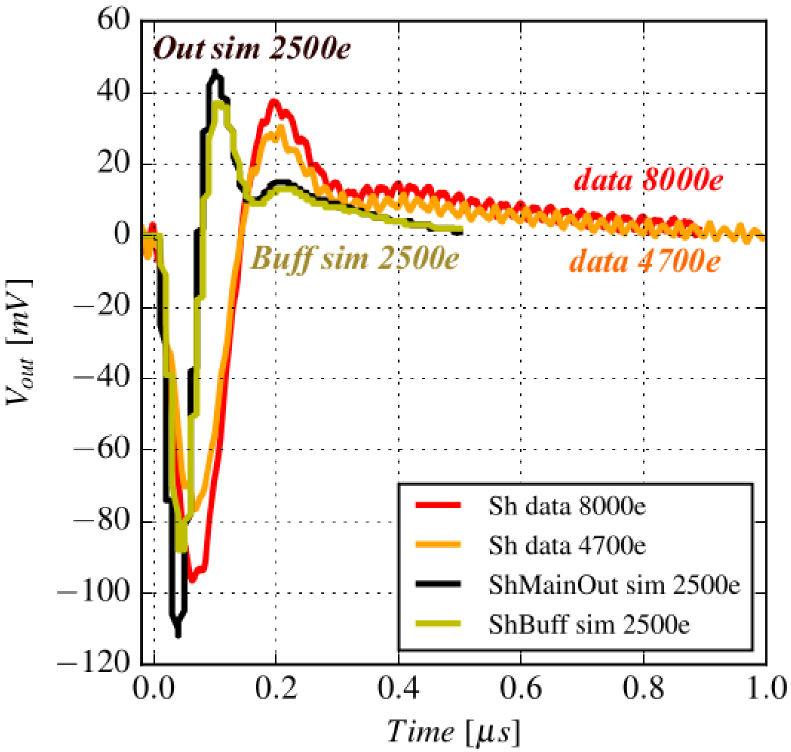
- Laser illuminations with a TriLite laser (pJ/pulse) in the IR wavelength (1064 nm)
- Calculation of the equivalent injected charge in the 18 μm epi of the DECAL Si sensor for a laser spot of 10x10 μm^2 using a Si diode

Sensor layout and laser illumination at the pixel in the top left corner 2^{nd} row 2^{nd} column

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



Shaper signal compared to simulations

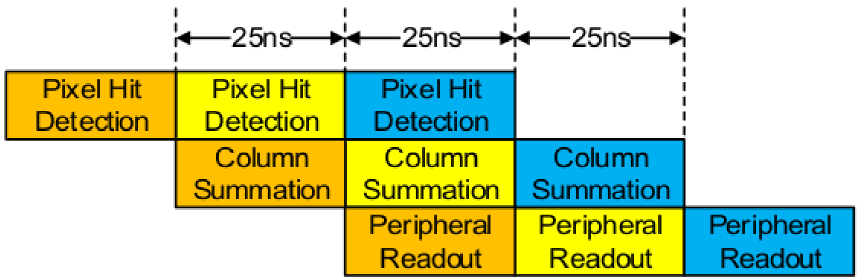


Agreement is observed in the rising time between the measured and simulated signal illuminating at the top left collection node of the analogue pixel
The injected charge estimated to be 2 or 3 times higher than the simulated charge value

Pixel & readout logic

- To achieve data rate of 40 MHz pixel column sum has to be complete within 25 ns

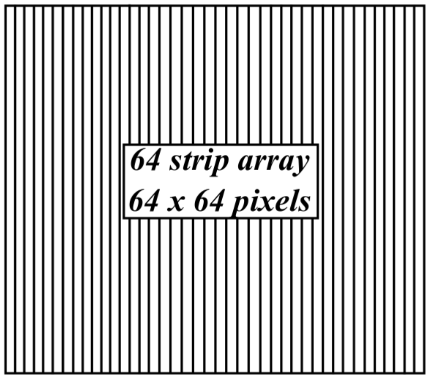
S. Benhammadi et al., DECAL: A Reconfigurable Monolithic Active Pixel Sensor for use in Calorimetry and Tracking, Proceeding of Science, (TWEPP 2019), (040), 2019



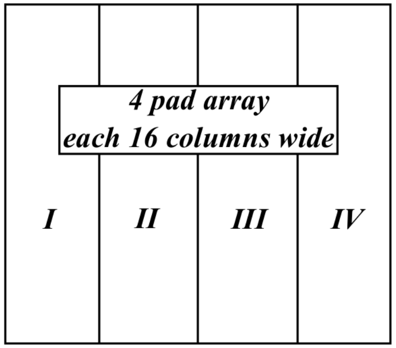
- The readout logic is configured either for strip or pad mode
- Strip mode outputs per pixel column
  - Sum of hits
- Pad mode outputs per pad area
  - Sum of hits

- Overflow flag if max total counts exceeded

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



- Pad mode (16x64 pixel array)
  - 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

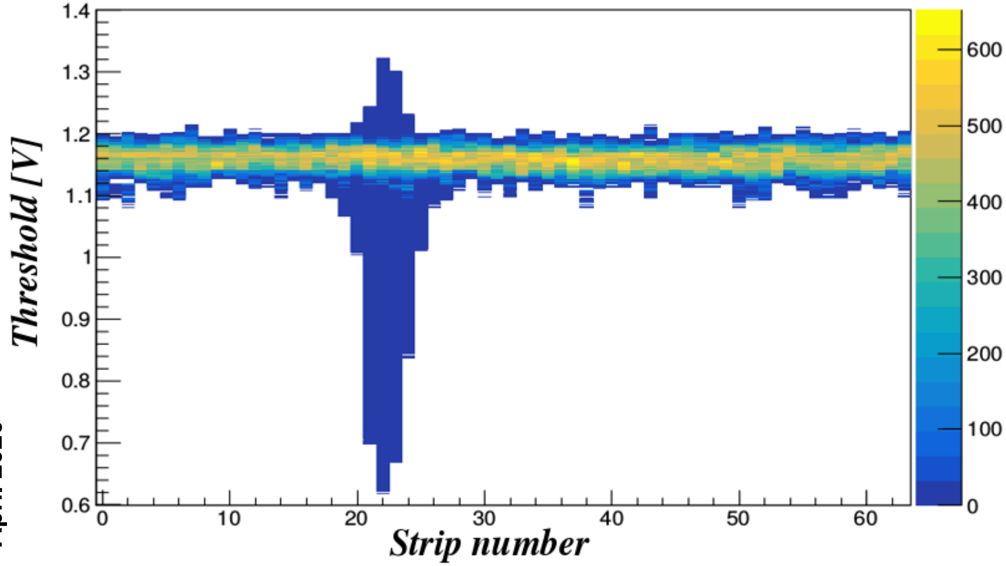


Threshold scan results

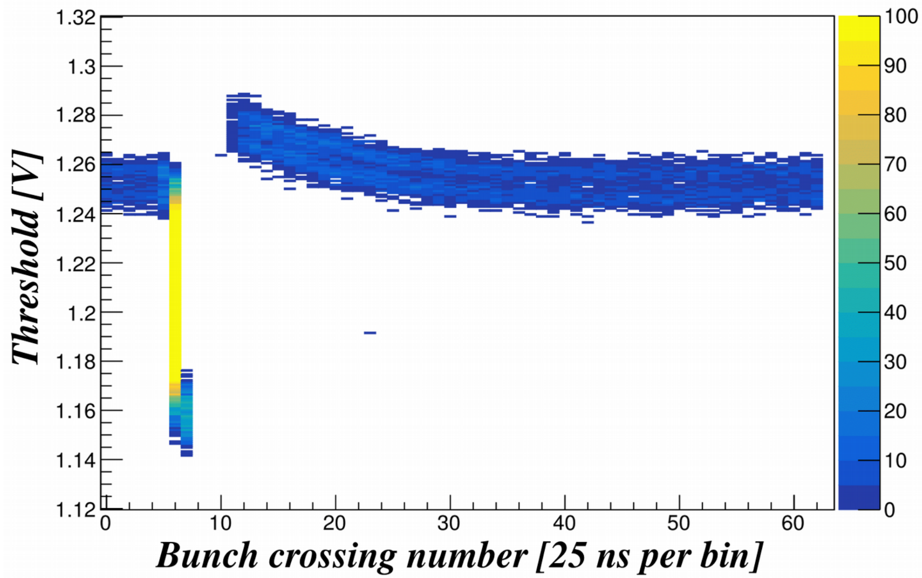
- The performance of digital pixels is evaluated performing threshold scans
  - Rate of hits in each pixel allows to test the full chain from analogue to digital
  - Threshold scan in strip mode with unmasked pixels and global chip configuration
  - Laser illuminations with a diode laser and pulse frequency 100 kHz

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 voltage as a function of strip number



Threshold voltage as a function of bunch crossing number



- Defocused beam, hits recorded from around 10 strips, as the laser illumination causes 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

Digital functionality under laser illumination

- **Comparison of the summing logic in strip and pad mode under identical laser illumination conditions**

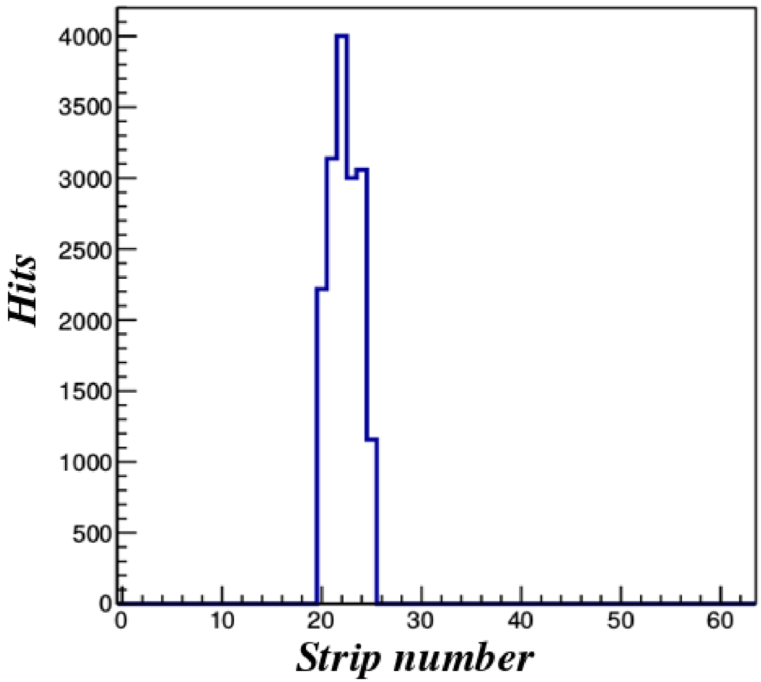
  - With defocused laser beam 6 strips are fired at a global threshold value of 1 V

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

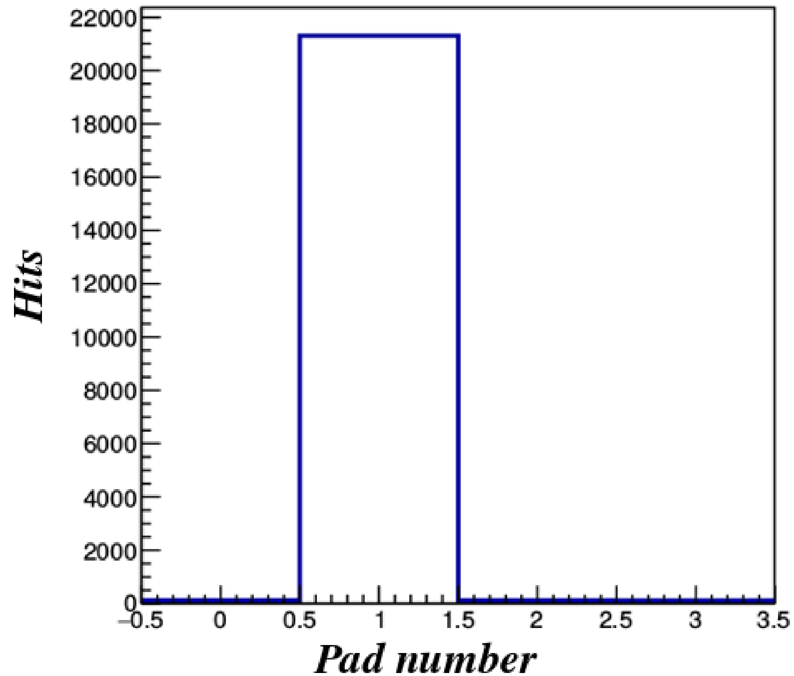
  - The strips, number from 20 to 25, fired in strip mode, correspond in pad number 1

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

Strip mode



Pad mode

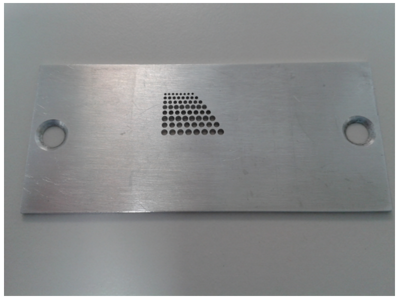


The sum of hits for the 6 strips is smaller than the total number of hits in pad number 1, as in pad mode the max hits per strip can be up to 15. However in strip mode there is more information where each hit occurred due to higher granularity

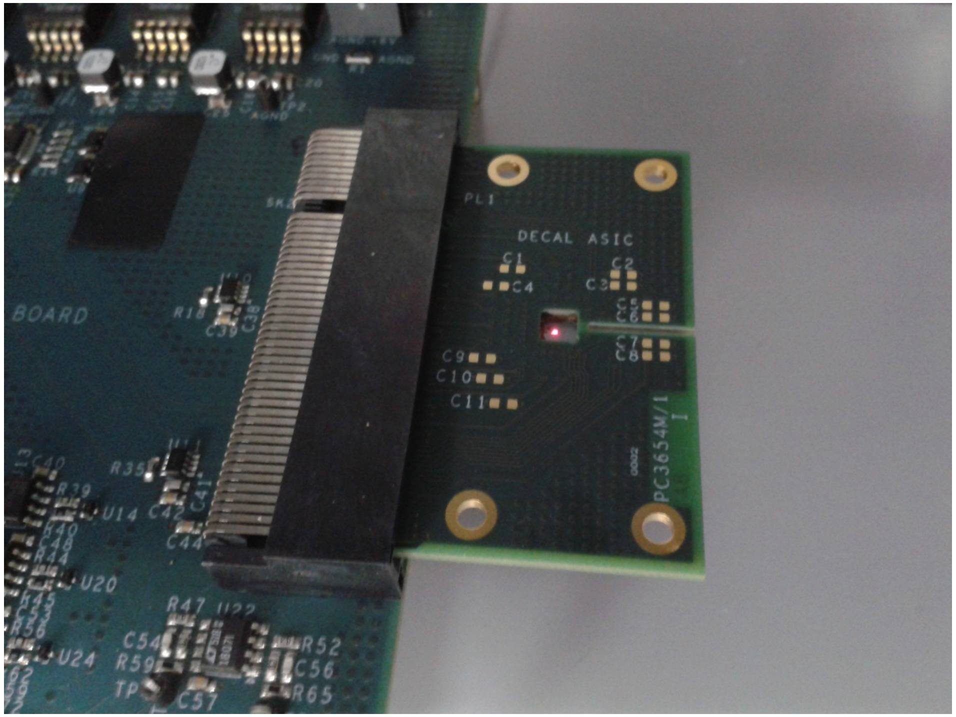
Strip vs Pad mode as a function of illumination area

- 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

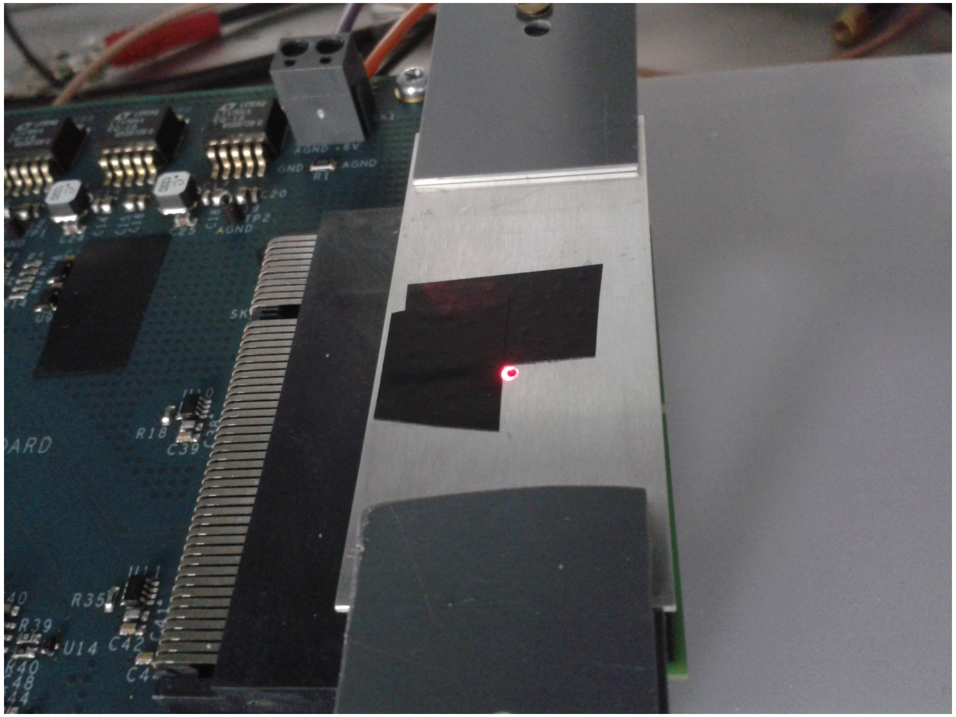
Al aperture



Picture of the boards and the ASIC under test without the Al aperture



Picture of the boards and the ASIC under test with the Al aperture



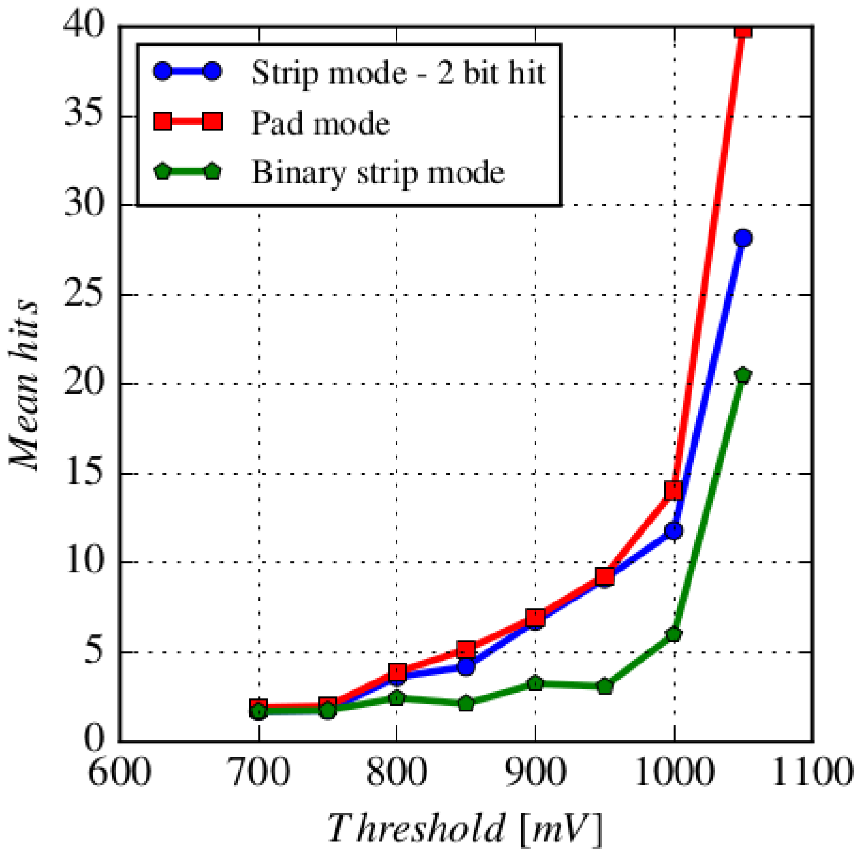
Strip vs Pad mode as a function of illumination area

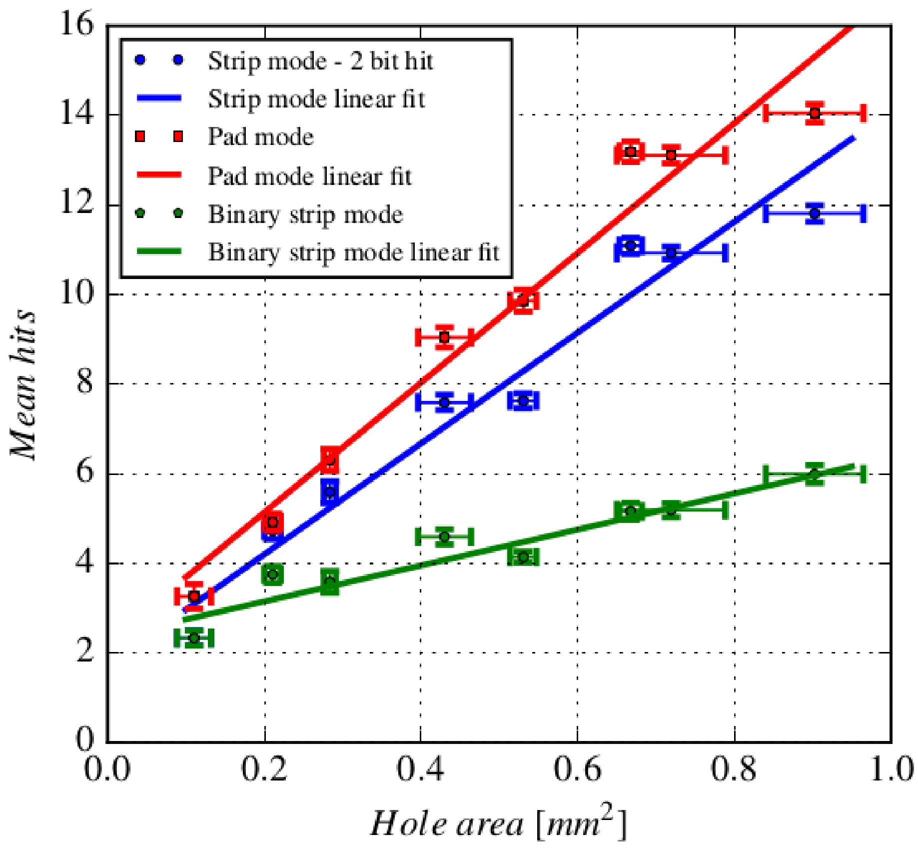
- **Illumination under identical laser conditions for hole diameter in the range of 400 – 1100 µm**
  - Linear behavior is observed as a function of hole area, as both strip and pad mode are operated below saturation

Mean value of hits as a function of threshold voltage for strip and pad mode for hole diameter 1.1 mm

Mean value of hits for threshold voltage 1V for strip and pad mode 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



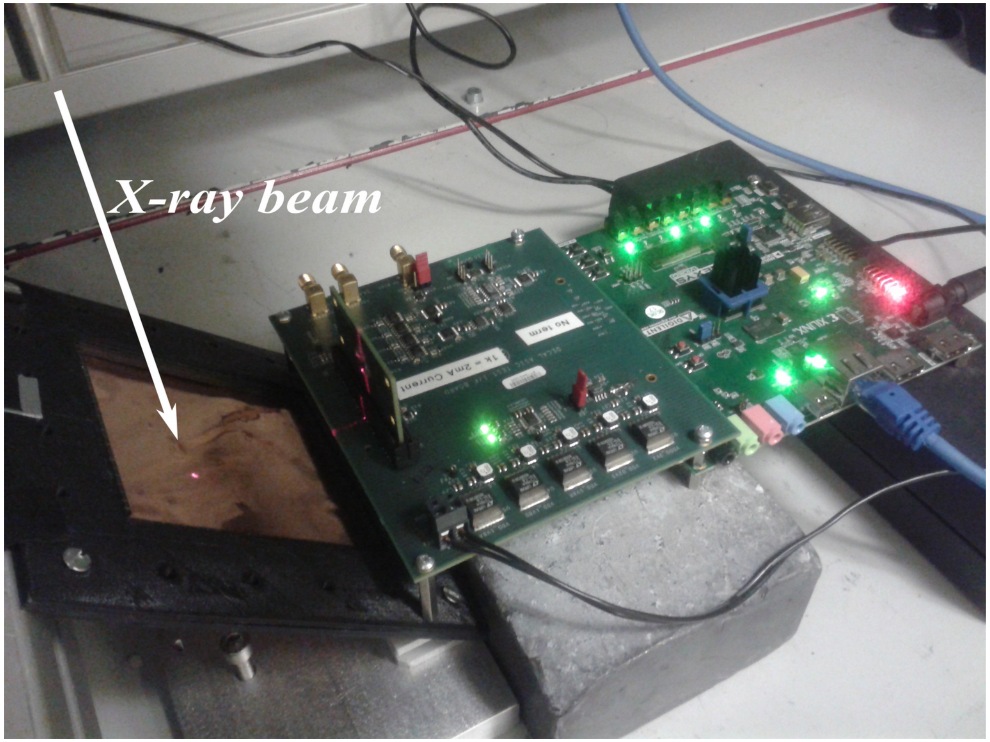


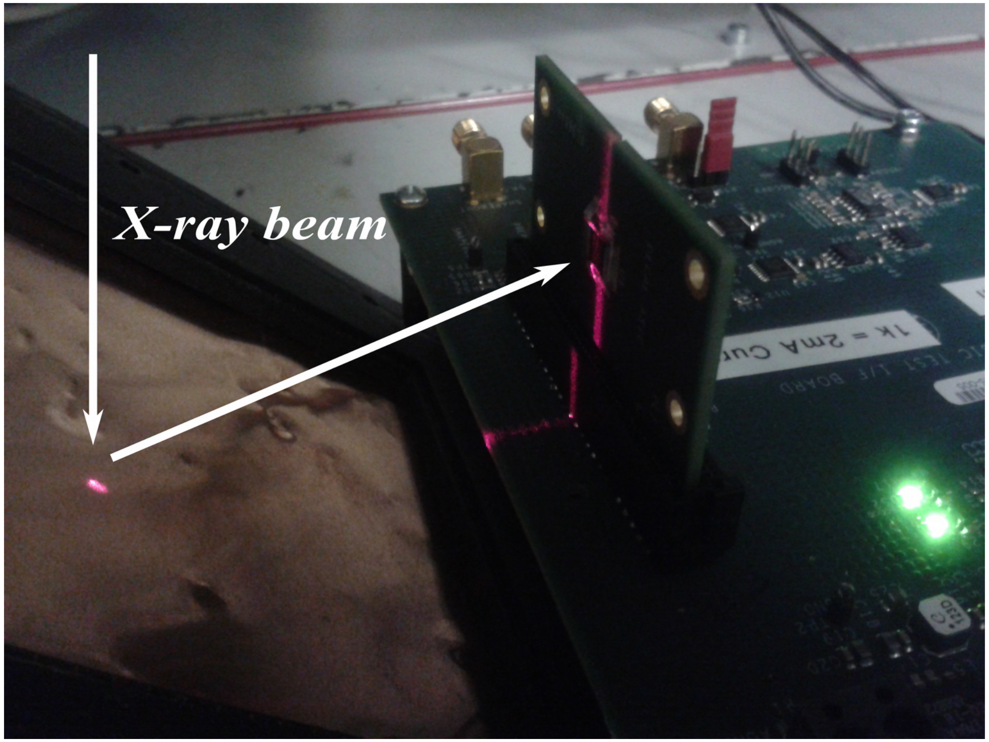
DECAL sensor test using monochromatic X-rays

- **Target material Cu used**

  - High voltage 60 kV and tube current 50 mA

  - Alignment is performed using a red laser

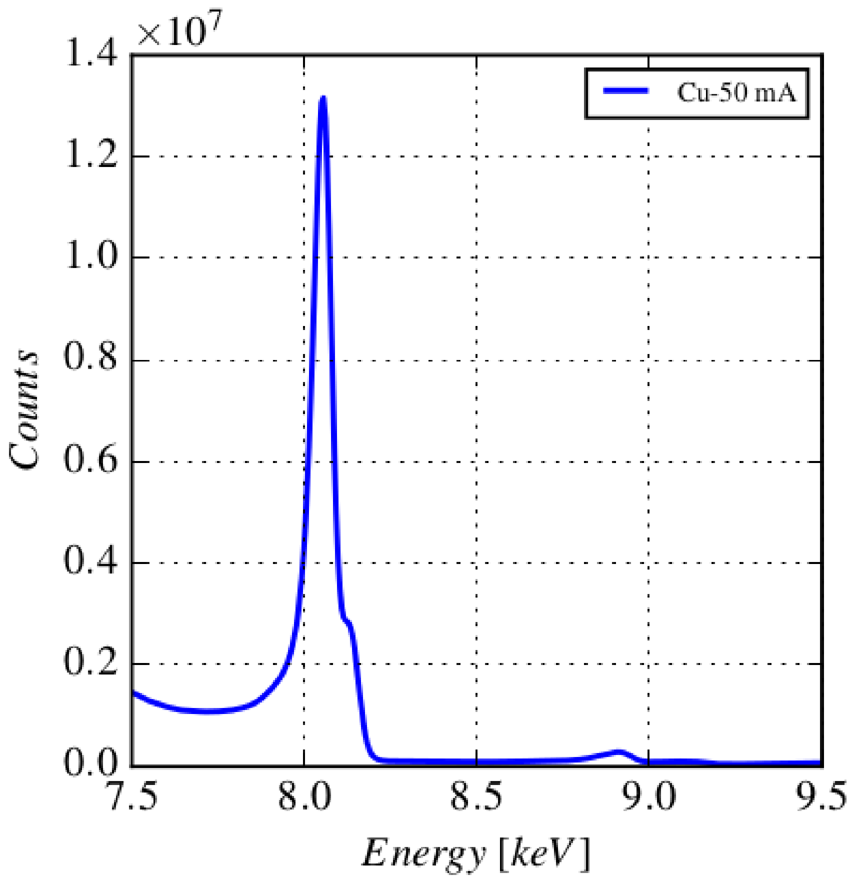




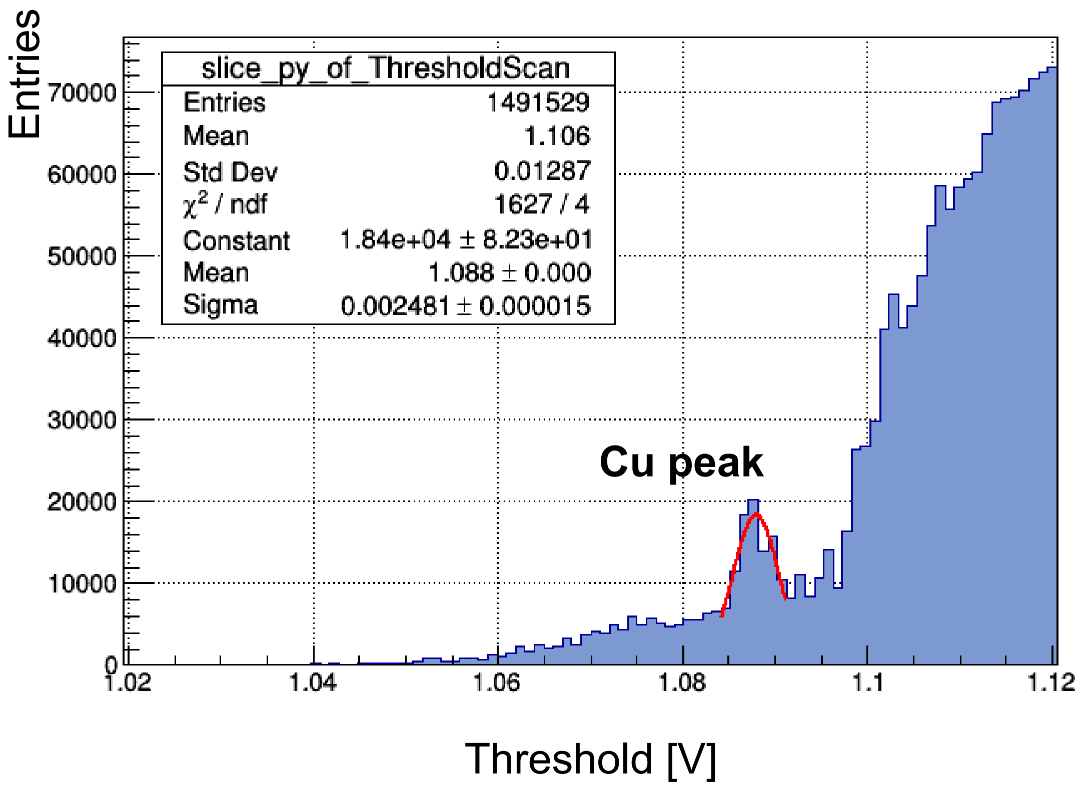
The Cu XRF K_α peak

- **The Cu XRF K_α peak detected with the DECAL sensor during long term threshold scans**

Energy spectrum of Cu measured with the HEXITEC detector manufactured at RAL



Cu XRF K_α peak in the DECAL sensor

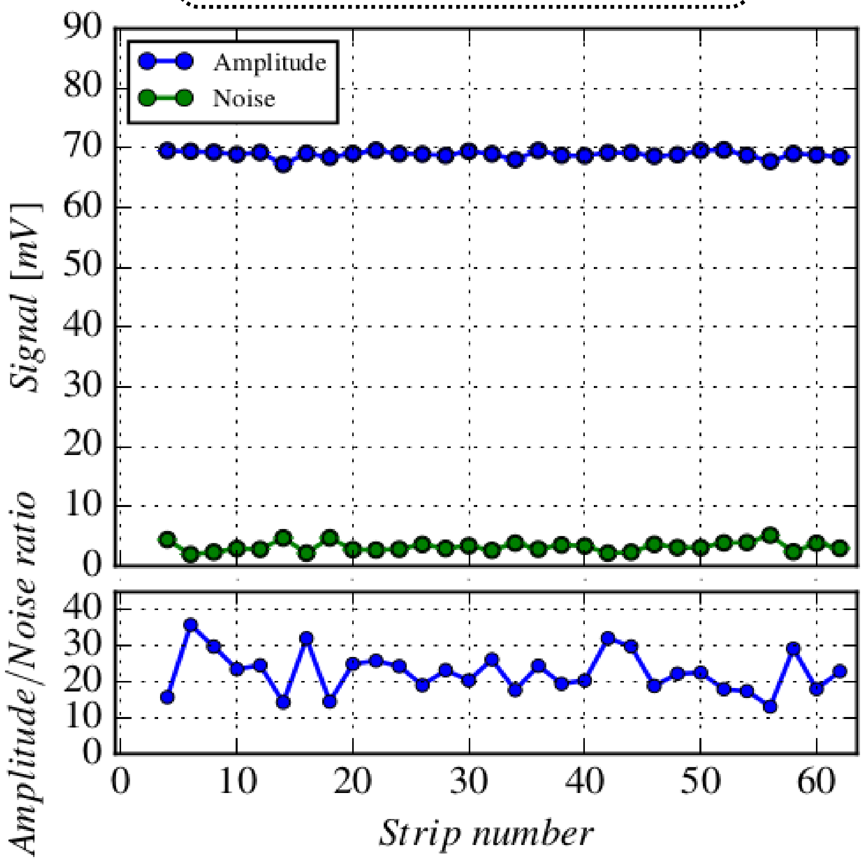


Equivalent Noise Charge vs strip number

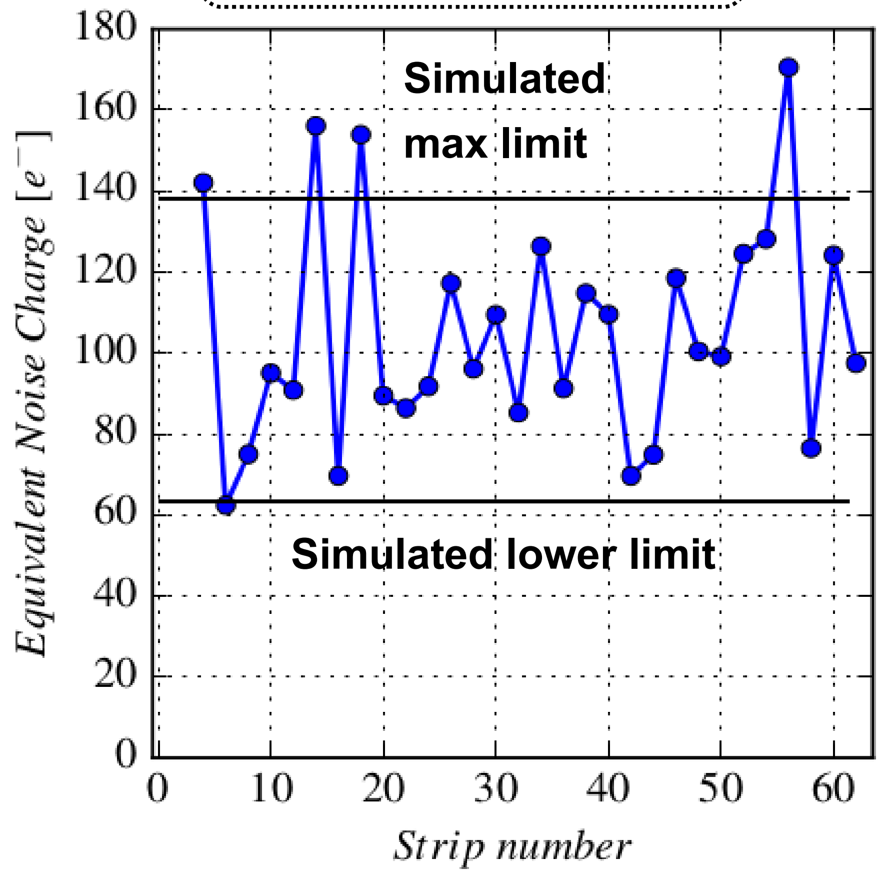
- For the K_α peak E = 8.05 keV and eps = 3.6 eV/e-h in Si pair
- Electrons generated, E_{gen} = E/eps, ≈ 2236 e^-
- Conversion gain, f = 32 [e^-/mV]
- Equivalent Noise Charge = f·peak sigma

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

Amplitude and noise of the Cu peak vs strip number



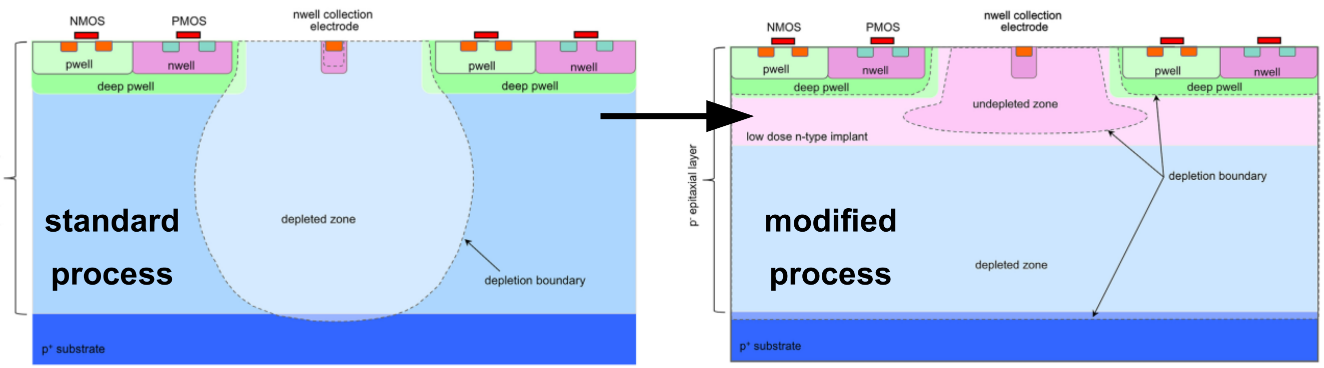
ENC extracted using the Cu peak vs strip number

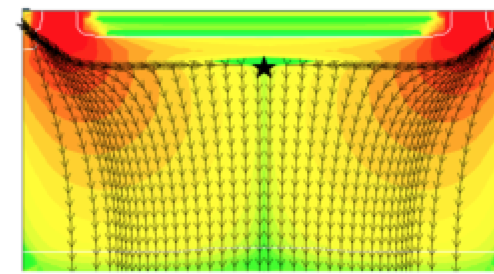


The TowerJazz 180 nm CMOS modified process

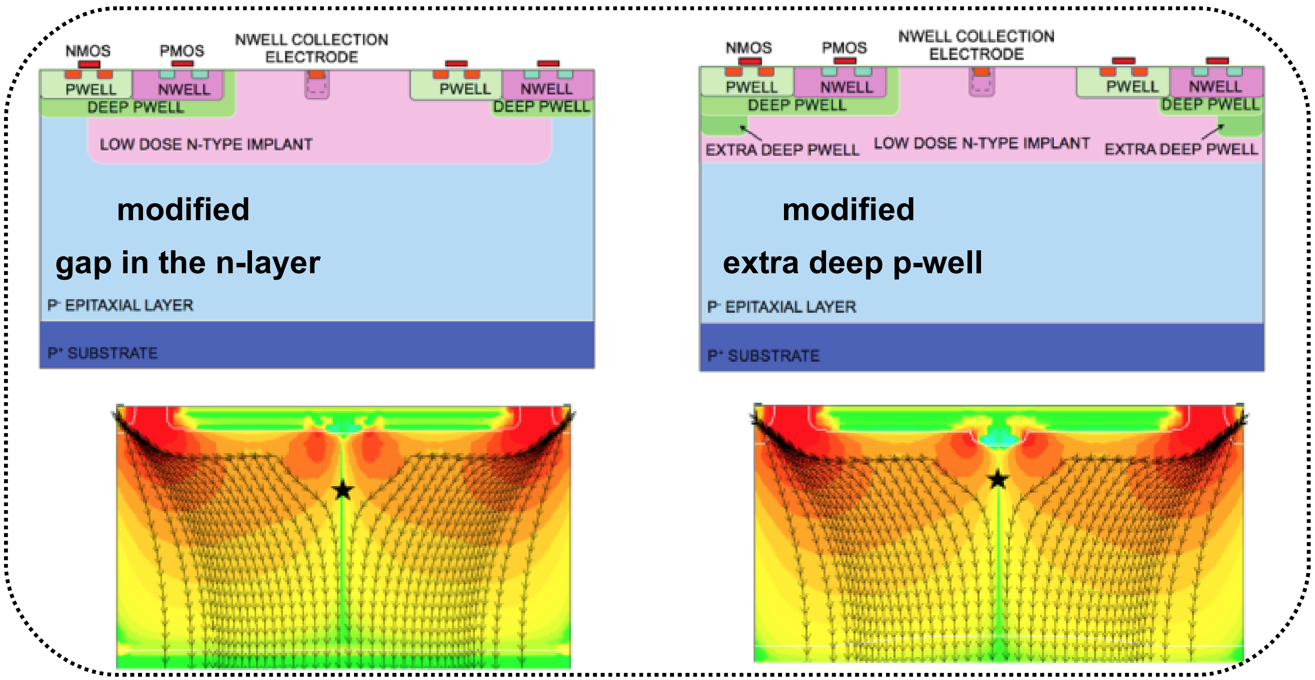
- The first version is referred to as an addition continuous n^- layer design for each pixel
- The second version consists of two variants (gap in the n- layer and extra deep p-well) which expected to shape the electric field so the charge carriers produced are steered more directly towards the collection electrode in the pixel center

W. Snoeys et al., A process modification for CMOS monolithic active pixel sensors for enhanced depletion, timing performance and radiation tolerance, Nucl. Inst. and Meth. A 871 (2017) 90-96





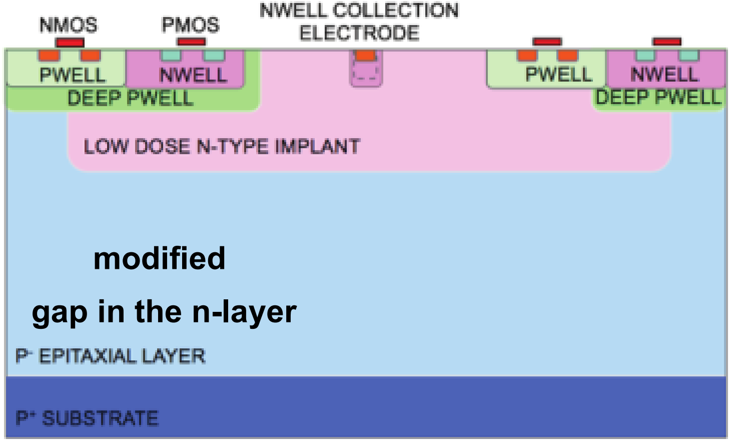
H. Pernegger, Depleted CMOS sensors for HL-LHC, Proceeding of Science, (VERTEX 2018), (041), 2018



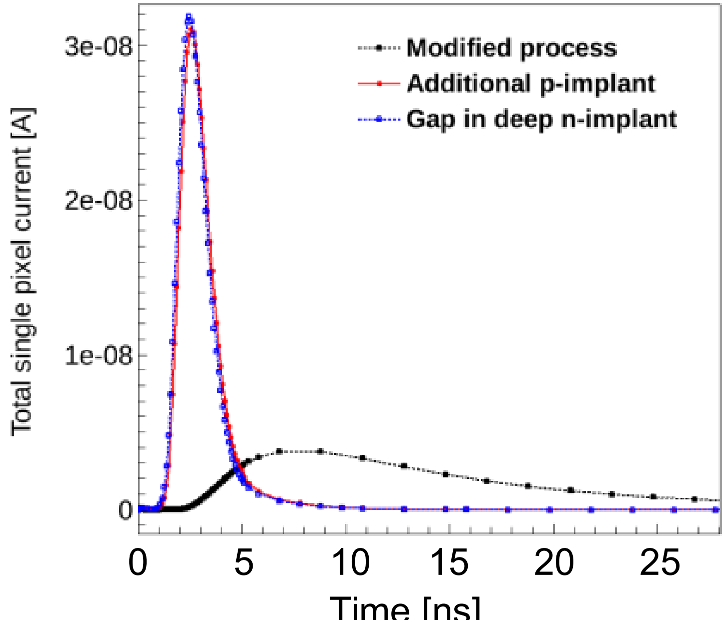
M. Munker et al., Simulations of CMOS pixel sensors with a small collection electrode, improved for a faster charge collection and increased radiation tolerance, Journal of Instrumentation 14 (2019) C05013

The DECAL Full Depleted sensor

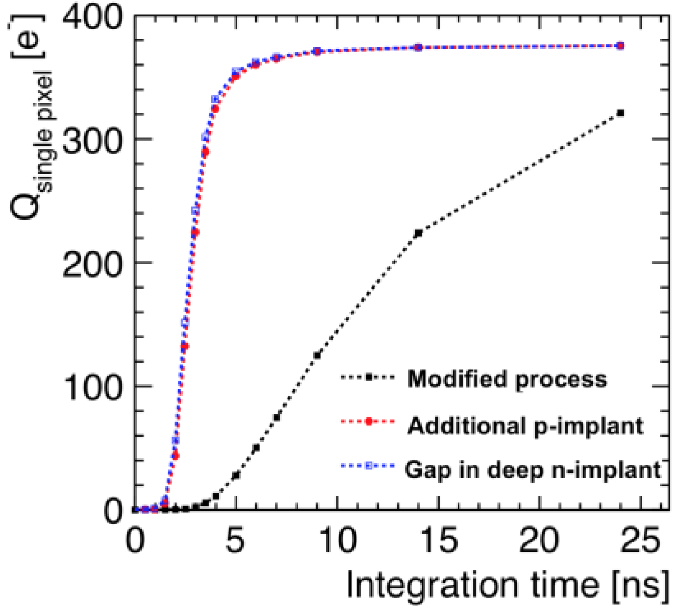
- The second version and the variant with the gap in the n$^-$ layer was chosen for the DECAL FD
- Pixel timing response has been simulated (by CERN groups) with 3D TCAD simulation for a MIP traversing the pixel corner (worst case scenario)
- Faster charge collection has been simulated for the second version (two variants of the modified process)
- Not all the charge is collected within 25 ns for the first version of the continues n$^-$ layer design



Current pulse for different versions of the modified process



Collected charge for different versions of the modified process

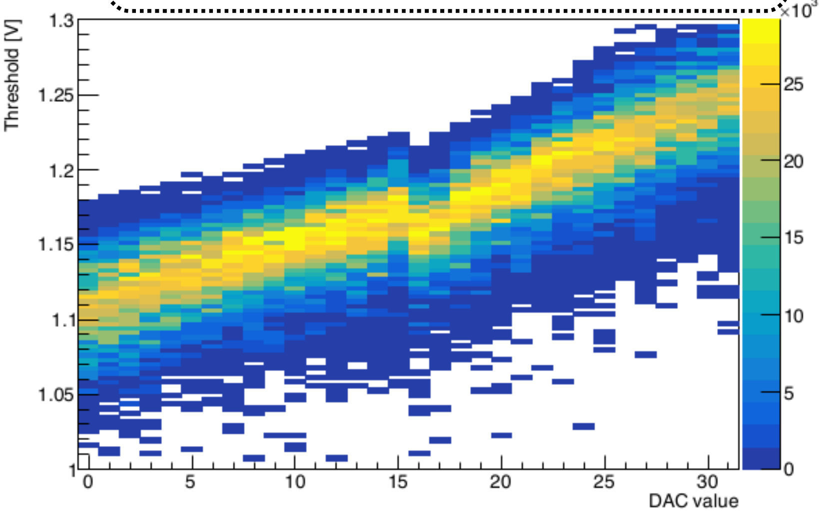


M. Munker et al., Simulations of CMOS pixel sensors with a small collection electrode, improved for a faster charge collection and increased radiation tolerance, Journal of Instrumentation 14 (2019) C05013

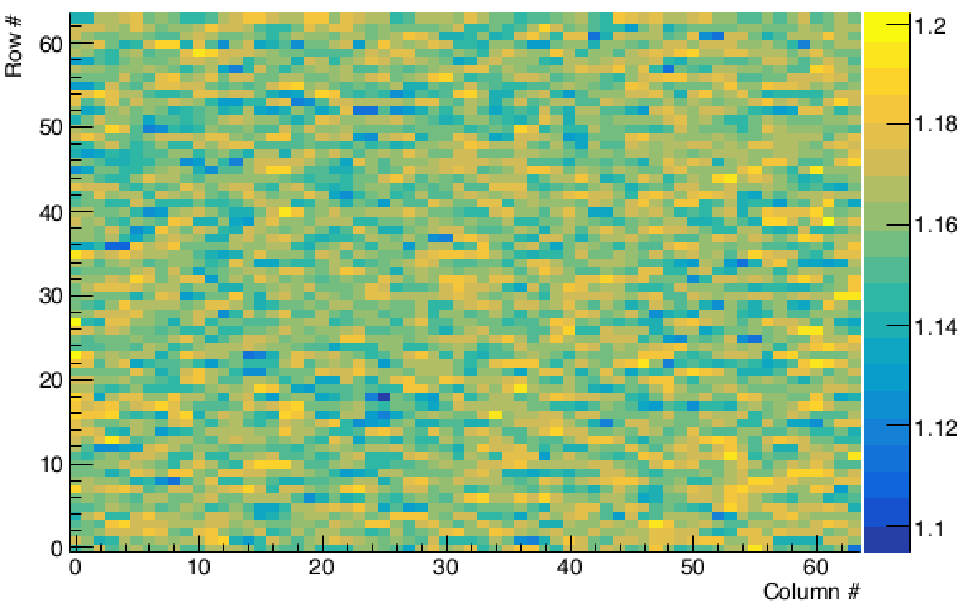
DECAL FD digital functionality

- 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

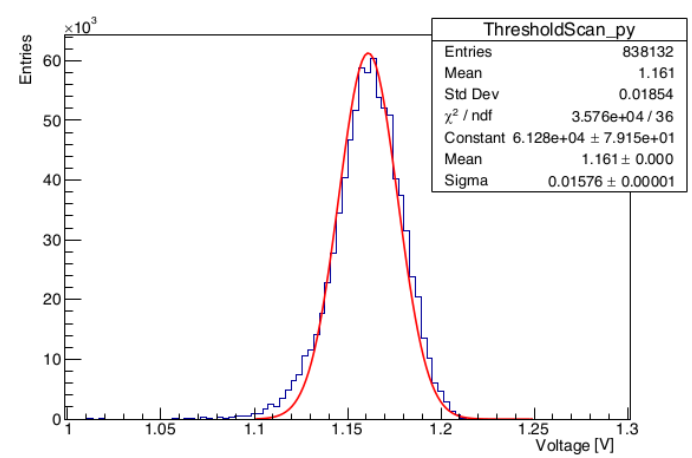
Threshold voltage as a function of pixel configuration



Threshold pixel map



Threshold distribution of a single pixel



Conclusions and Outlook

- **Conclusions**

  - The DECAL sensor prototype fabricated, tested and is 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

  - It can configure 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 measured Equivalent Noise Charge values are in agreement with the expected simulated

- **Outlook and future plans**

  - Evaluate the analogue and digital performance of the DECAL FD under MIP testing, sensor bias voltage and irradiations

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

Thank you for your attention

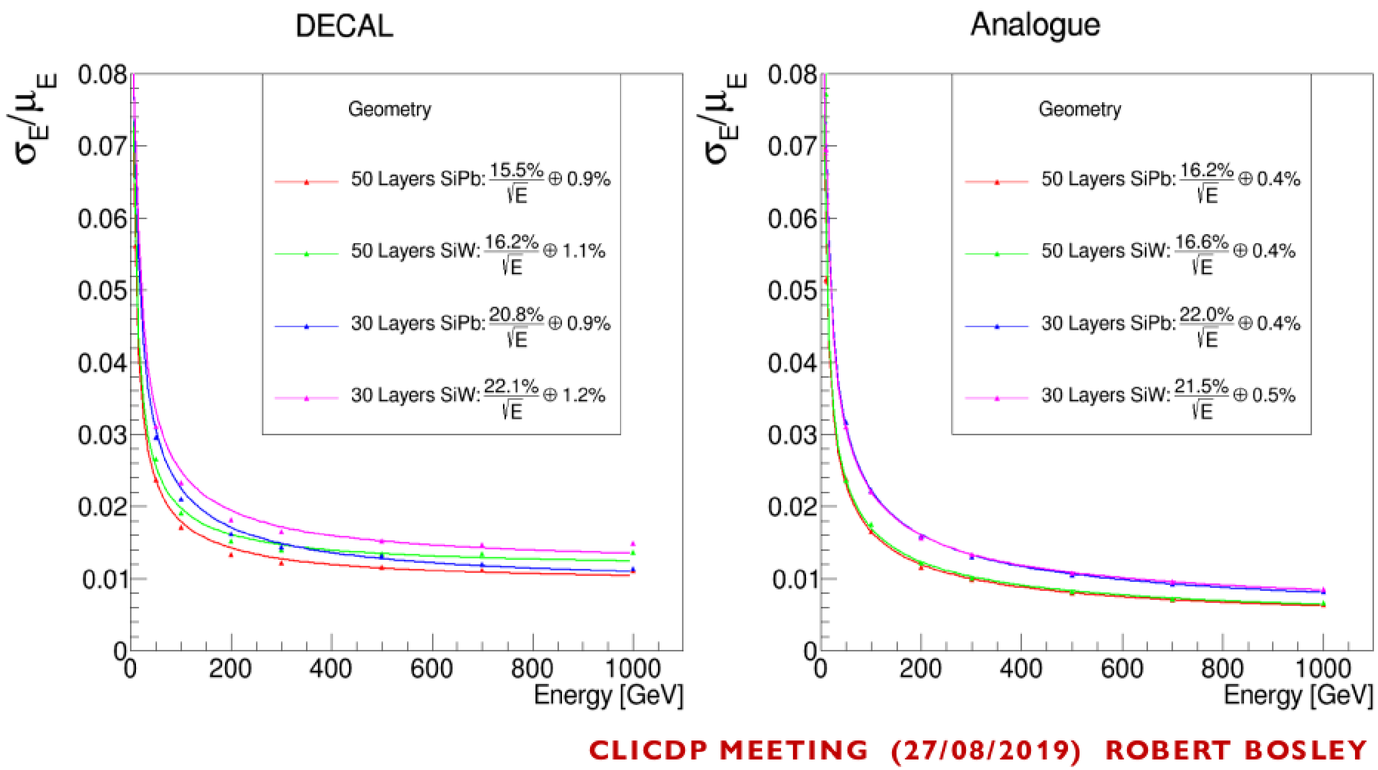
Back up

Simulation results: Energy resolution

- **For single electrons, similar performance of Digital ECAL (with realistic channel threshold per pixel of 480e*) and Analogue ECAL (with perfect performance and full substrate signal per pad) up to around 300 GeV (4T field without pile-up)**

- **Above this energy, saturation (more than one hit per 50μmx50μm pixel) starts to impact performance of digital compared with analogue ECAL**

- **Simulation work focused on reconstruction of $\pi^0 \rightarrow \gamma\gamma$ with PFA**

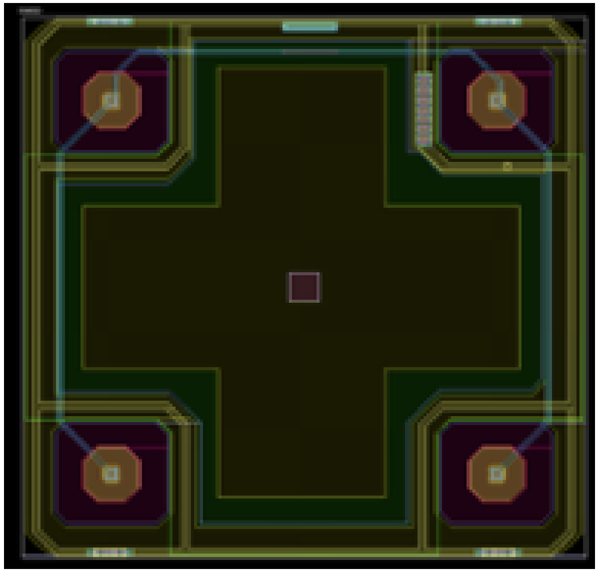


(*6xσ assuming noise of σ = 80 e)

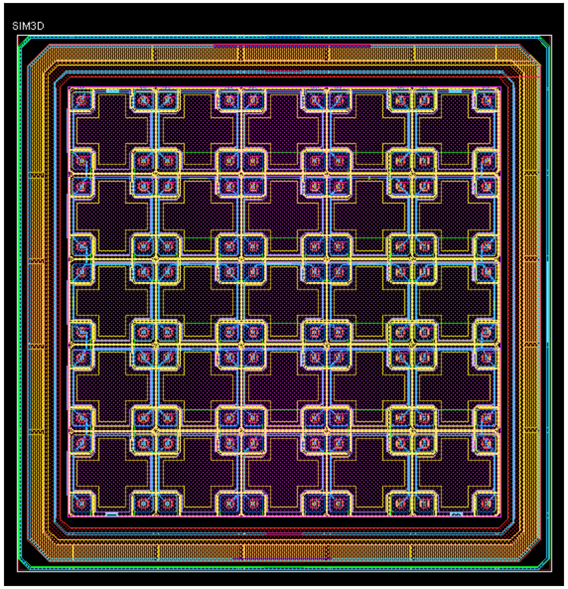
HR-CMOS sensor development

- **HR-CMOS R&D for digital calorimetry and tracking**
  - OVERMOS: A CMOS MAPS project demonstrator
  - DECAL sensor: DMAPS for digital electromagnetic calorimetry, pre-shower and outer tracking
  - TowerJazz Investigator chip & characterization of the TowerJazz modified process

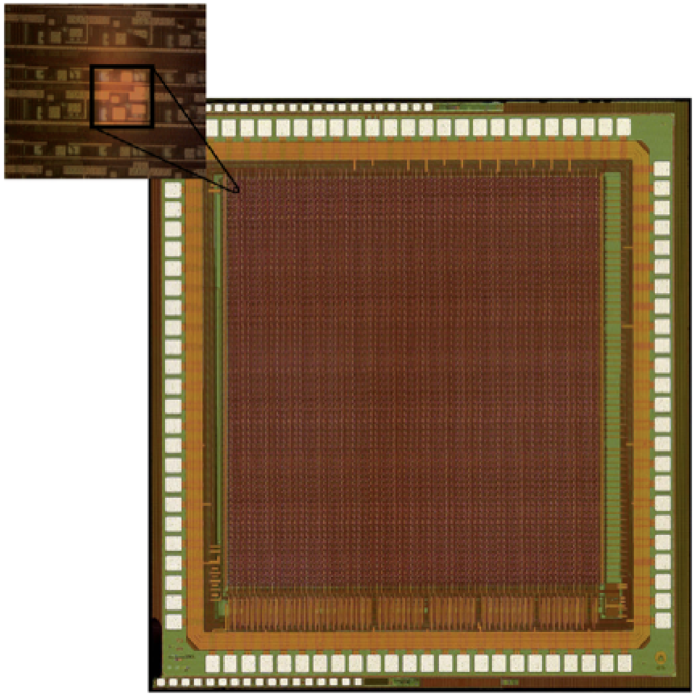
OVERMOS pixel



OVERMOS sensor matrix



DECAL sensor matrix

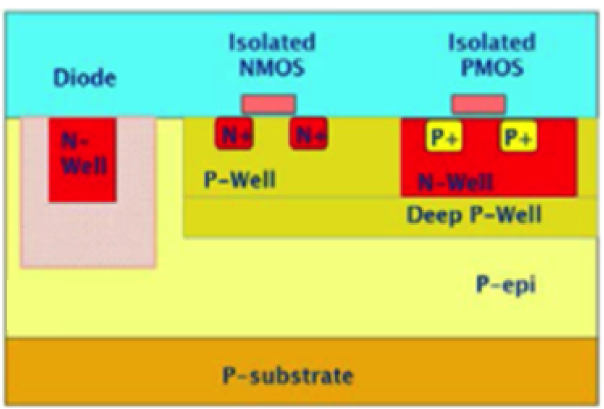


OVERMOS: A CMOS MAPS project demonstrator

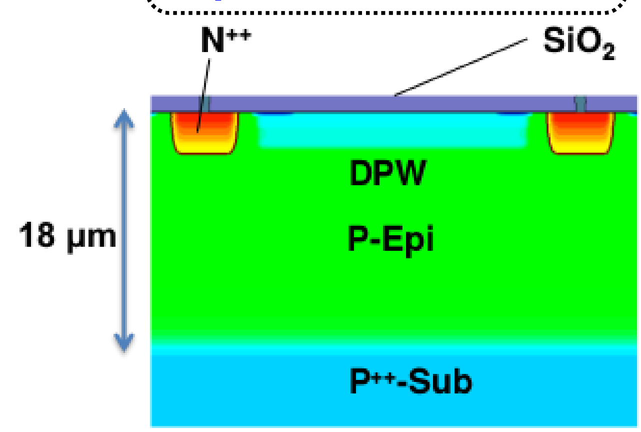
- OVERMOS 1.0 & 1.1 (project support from UKRI - STFC)
  - Designed and fabricated in the standard TowerJazz 180 nm CMOS imaging process on 18 μm epitaxial Si
  - Sensor matrix consists of 5x5 pixels with a pitch of 40x40 μm, multi diode arrangements within pixel, CMOS DPW originally proposed for DECAL of ILC
  - Neutron irradiations from $1 \cdot 10^{13}$ up to $1 \cdot 10^{15}$ n_{eq}/cm^2 at Ljubljana
- OVERMOS characterisation results
  - Measurement campaign and TCAD simulations to understand detailed device response
  - Charge collection results using IR laser illumination on non-irradiated/irradiated structures and comparison with optical TCAD simulations

E.G. Villani et al., OVERMOS – CMOS Hi-Res MAPS detectors for HEP applications, Nucl. Inst. and Meth. A 924 (2019) 78-81

Pixel cross section with individual doping layers



Simulated fabrication process in TCAD



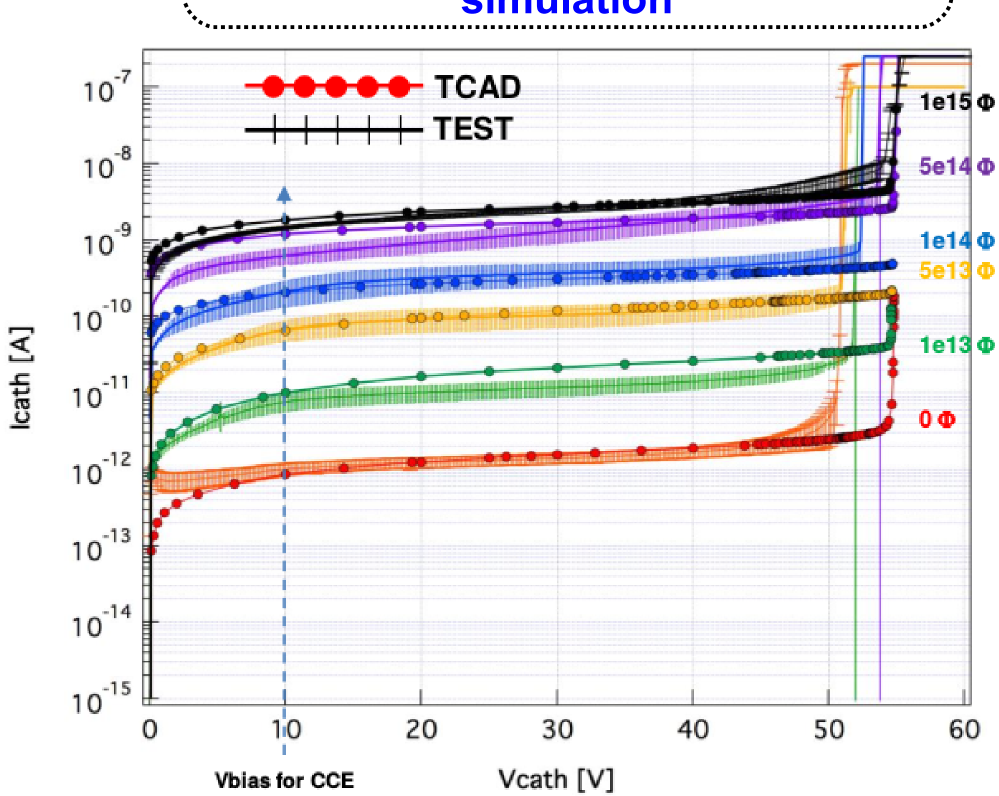
OVERMOS: A CMOS MAPS project demonstrator

- **OVERMOS 1.1 (TCAD simulation of Current vs Voltage as a function of fluence)**

  - Using the Hamburg Penta Trap Model (HPTM) presented in the RD50 workshop, Hamburg (4-6/6/18)

Current vs Voltage results before and after irrad. from data and TCAD simulation

E.G. Villani, TCAD process and device simulation of OVERMOS, a CMOS 180nm MAPS detector, 34th RD50 Workshop, Lancaster (12-14/6/19)



Φ	I_{leak_μ}[A] @10V	I_{leak_TCAD}[A] @10V	Δ%	$^{a}BV_{\mu}$[V]	BV_{TCAD}[V]
0	1.0e-12	0.85e-12	15	50.8	54.79
1e13	7.5e-12	1e-11	-33.3	52	54.6
5e13	6.72e-11	7.47e-11	-11.1	51.2	54.7
1e14	2.1e-10	2.06e-10	1.9	52.4	54.7
5e14	6.21e-10	1.18e-9	-90	53.6	54.8
1e15	1.43e-9	1.83e-9	-28	54.4	54.8

Good agreement between data and TCAD simulation

OVERMOS: A CMOS MAPS project demonstrator

- **OVERMOS 1.1 (TCAD simulation of Charge Collection)**

CC results before irrad. from data and TCAD simulation for 3 pixel hit positions 7, 10, 25

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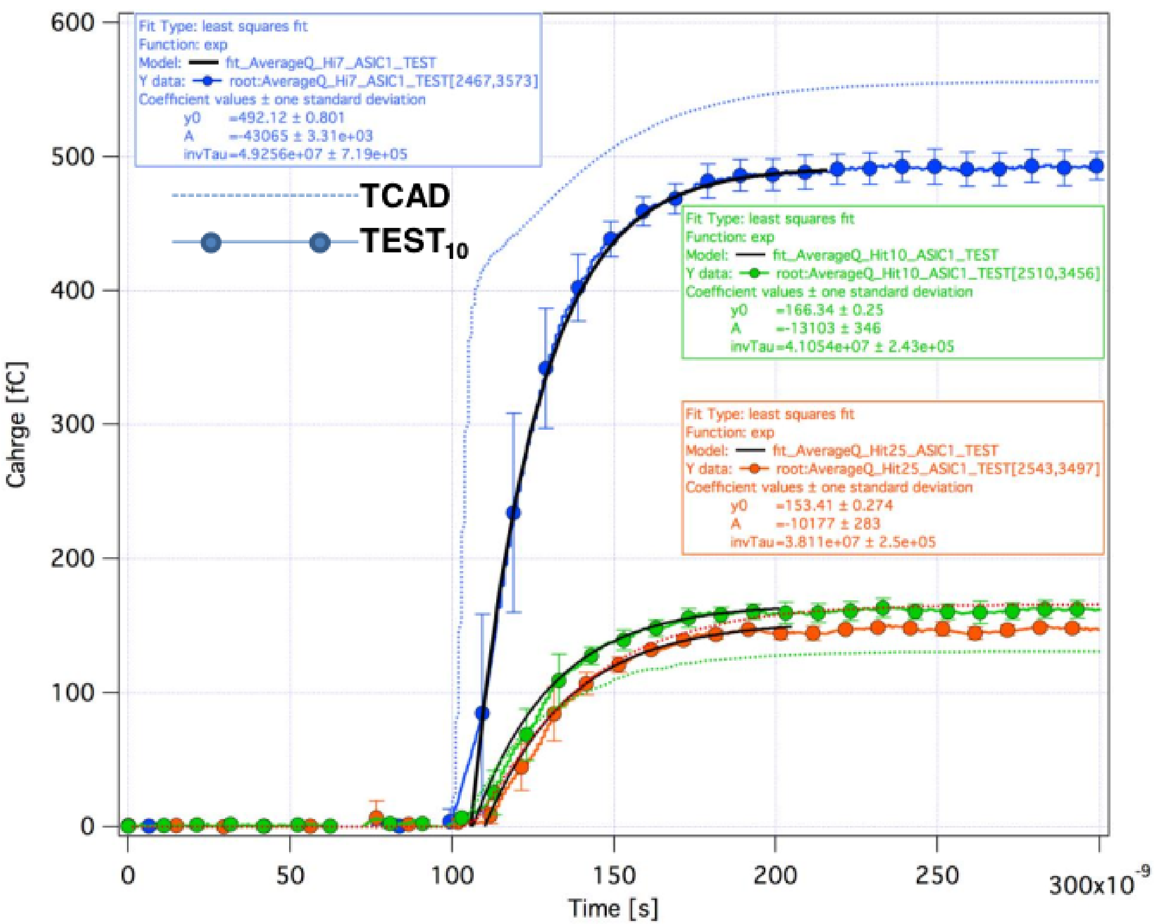
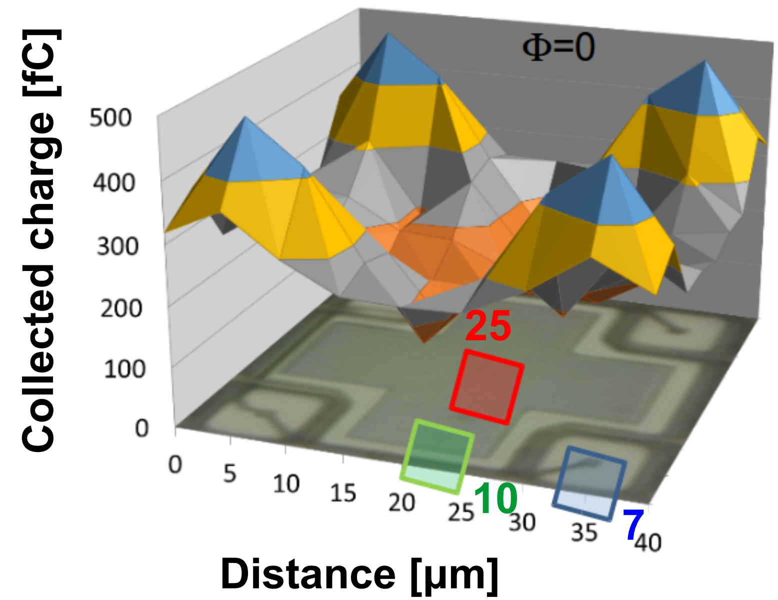


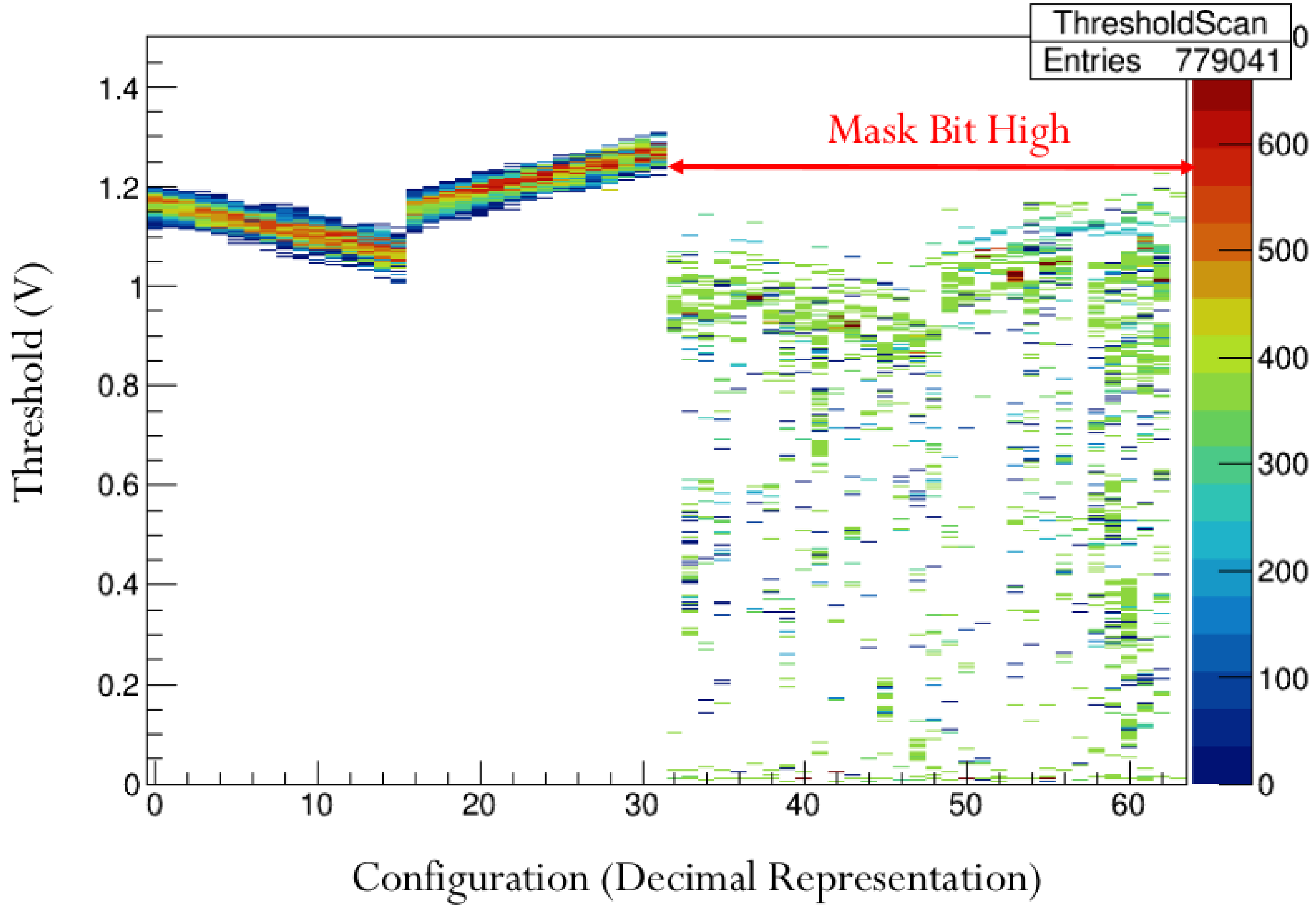


- **Pulse rise time differences between the data and TCAD simulation**
- **The effects of charge amplifier used during the measurements are under investigation**
- **After irradiation the results look similar and the total collected charge is lower for the same pixel hit positions**

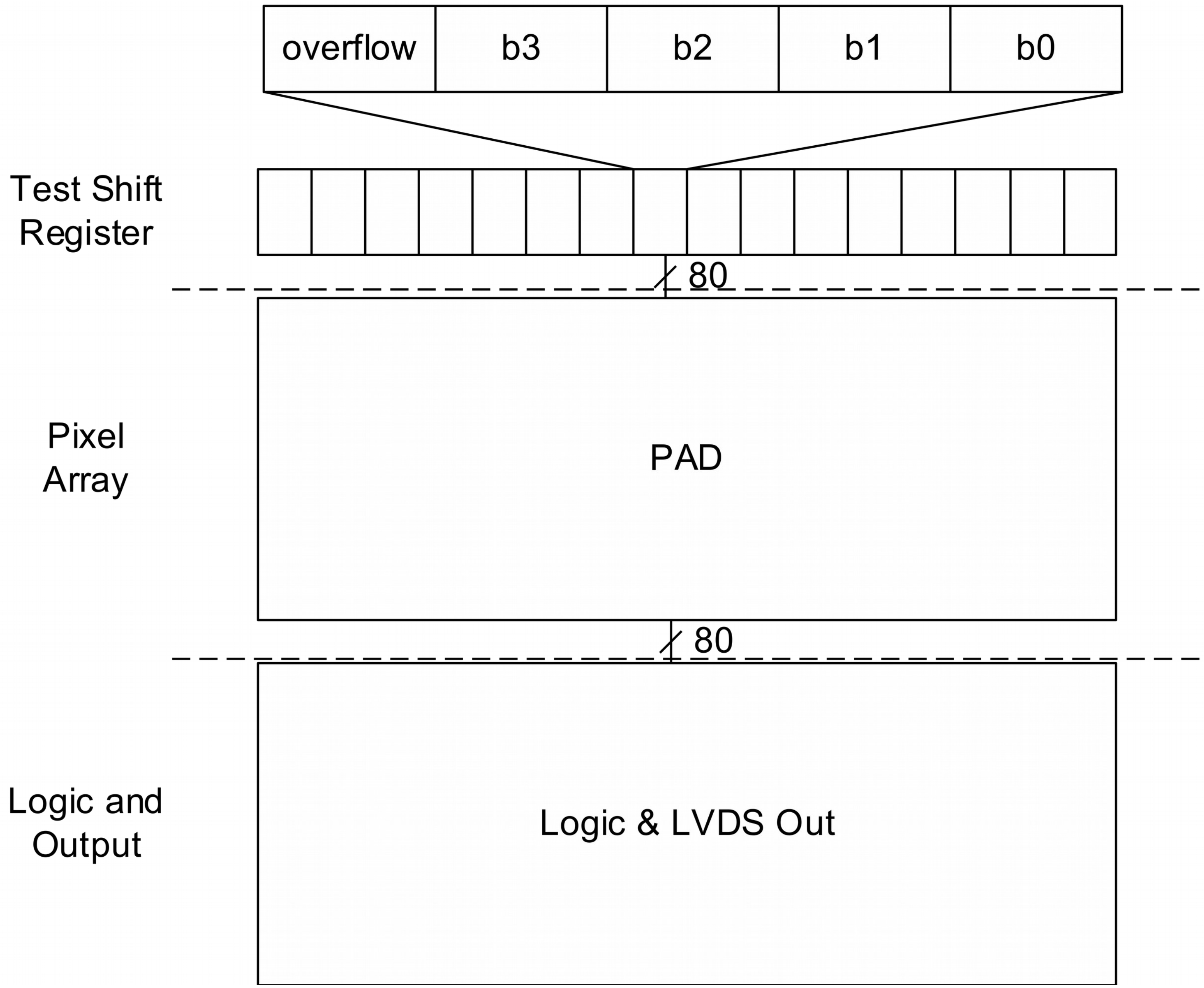
$TEST_{10}$: Average of 10 pixels before irrad.

DECAL: Pixel problem reports

- **Comparator cannot be fully disabled: Corrected an “And” gate was added to disable the comparator**
- **Buffer for calibration clock incorrect: Corrected an “Inverter” gate was added for the calibration clock**



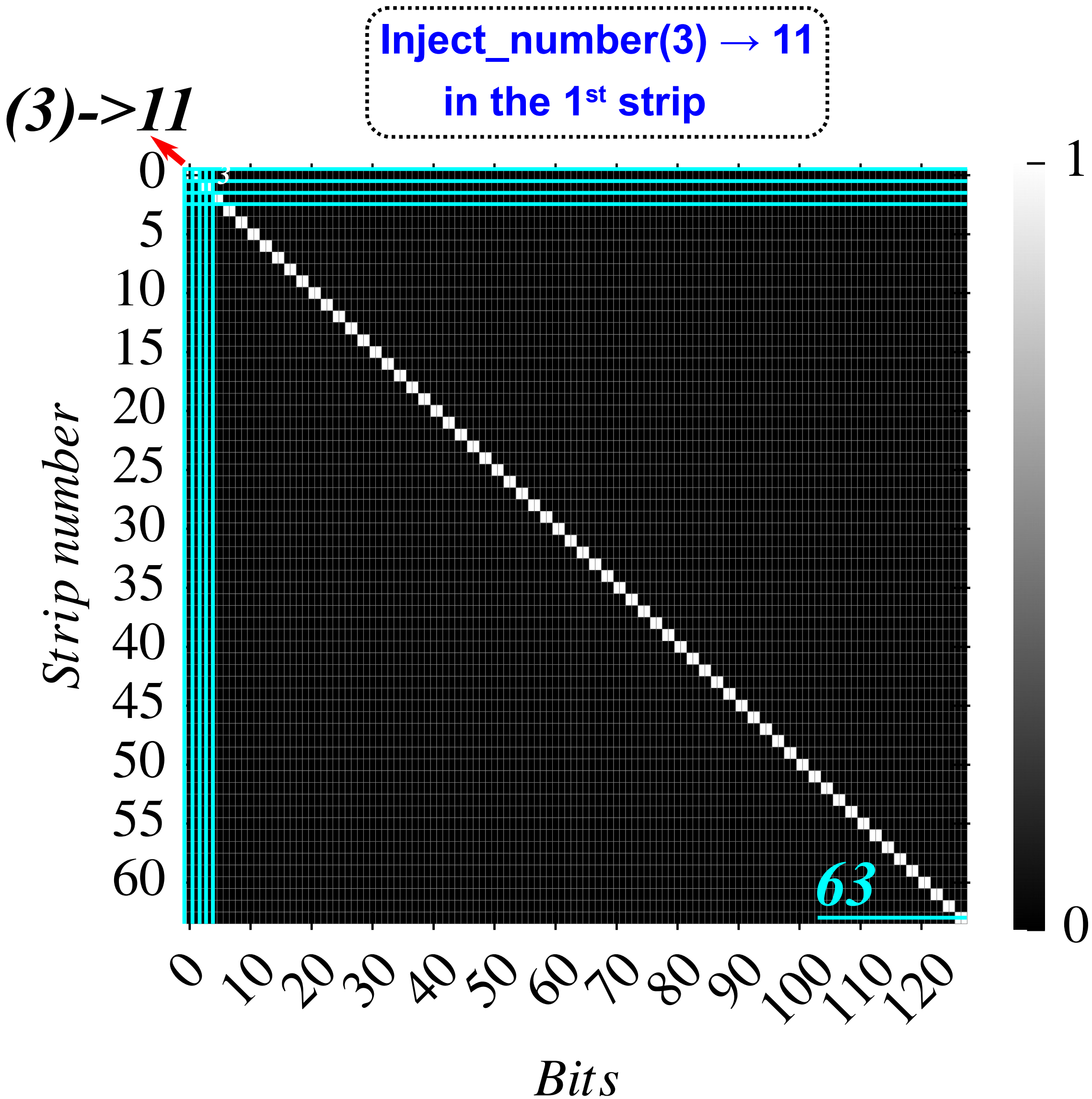
Testing of the digital functionality



Testing of the digital functionality

- **Testing pixel output by**
  - Placing data in the test shift register
  - Running the output
  - Checking if output is correct

- **The test is complete for both strip and pad mode with the logic setup differently**

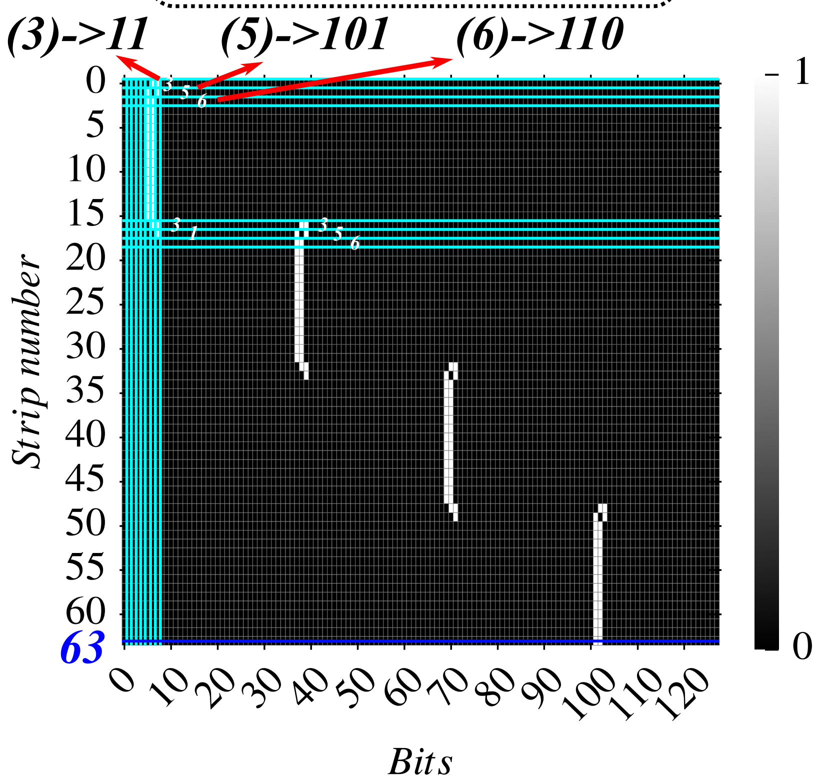


Strip mode works as specified in the design

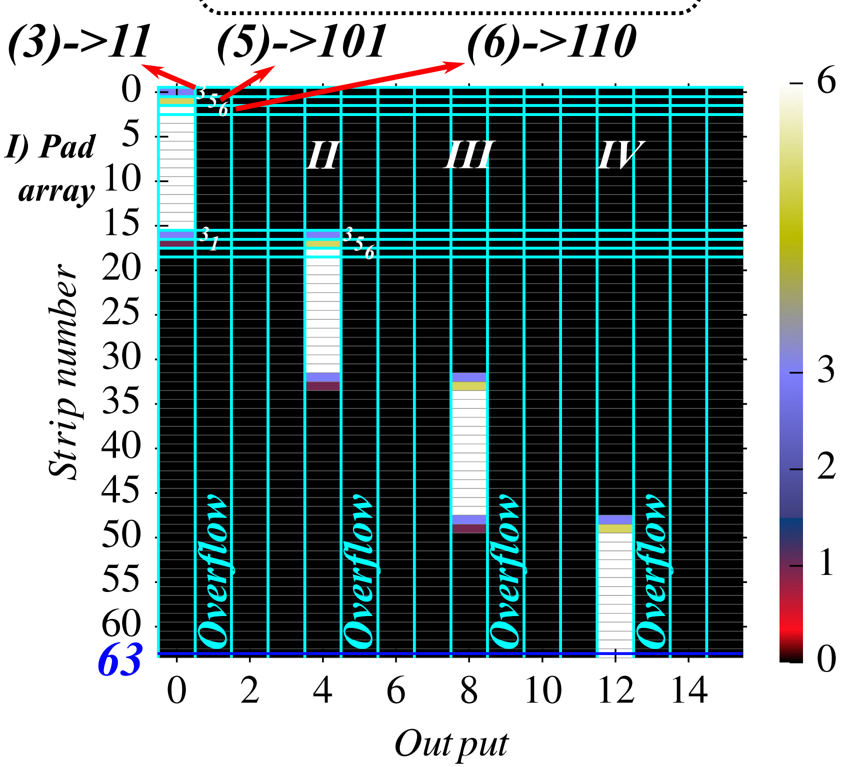
Digital functionality in pad mode

- **Operate the ASIC in pad mode**
  - Inject_number(3), (2), (1) and shifting along the strips
  - Compare the inject_number(3), (2), (1) vs the sum of each output block

Inject_number(3), (2), (1) in the 1st, 2nd and 3rd strip



Inject_number(3), (2), (1) and sum



The summing logic of the pad mode obviously is presented after printing the data on the decimal system, overflow is expected as $\sum_{i=0\rightarrow15} col_i[4]$
Pad mode works as specified in the design

Digital functionality in pad mode

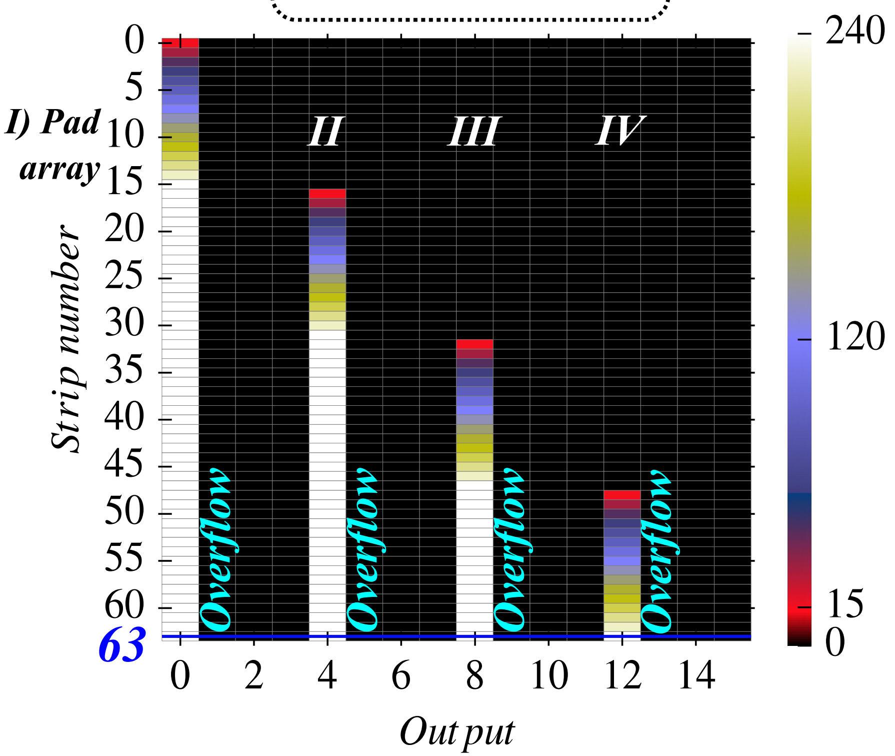
- **The desired behavior**

  - Lower 4 bit of every column get added up (hence expected maximum is 240 for 16 column blocks)

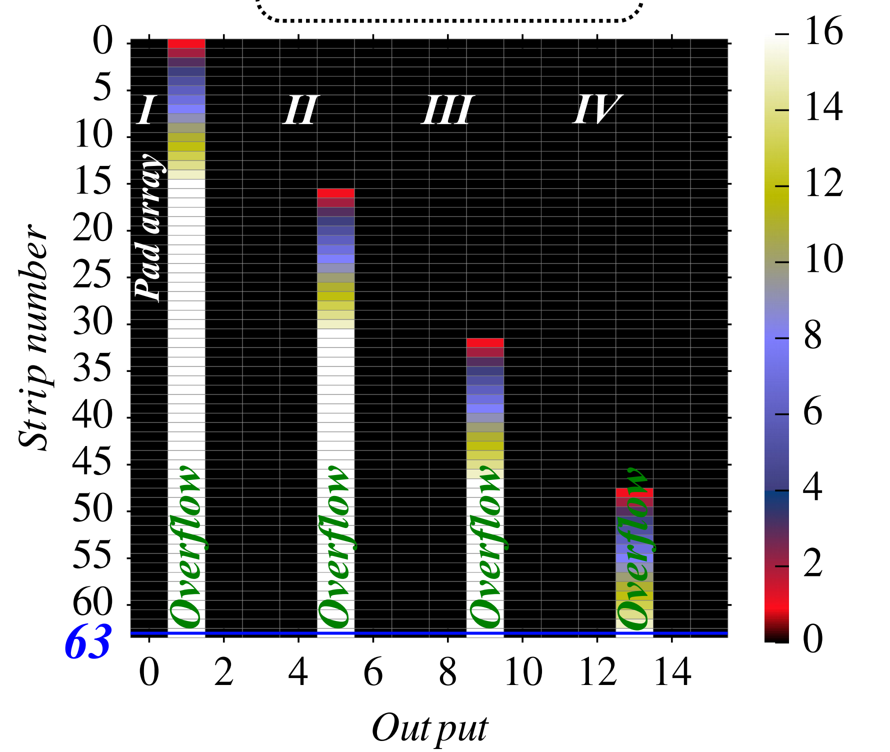
  - Highest bits get summed in overflow: Inject_number(15) should only act on sum and inject_number(16) should only stimulate an overflow output

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

Inject_number(15) and total sum



Inject_number(16) and total sum

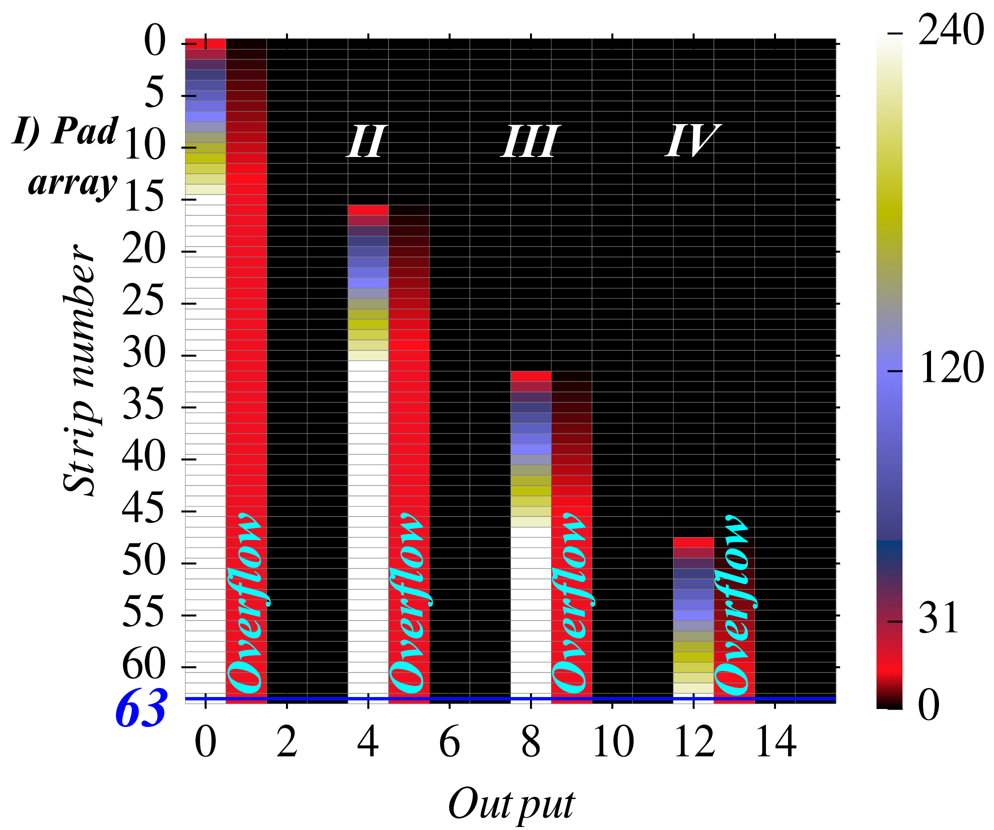


The observed maximum number is 240 and overflow is observed after the inject_number(16) with sum zero of the output blocks

Digital functionality in pad mode

- **Overflow performance observed as expected according to design specifications**

  - Inject_number(31)

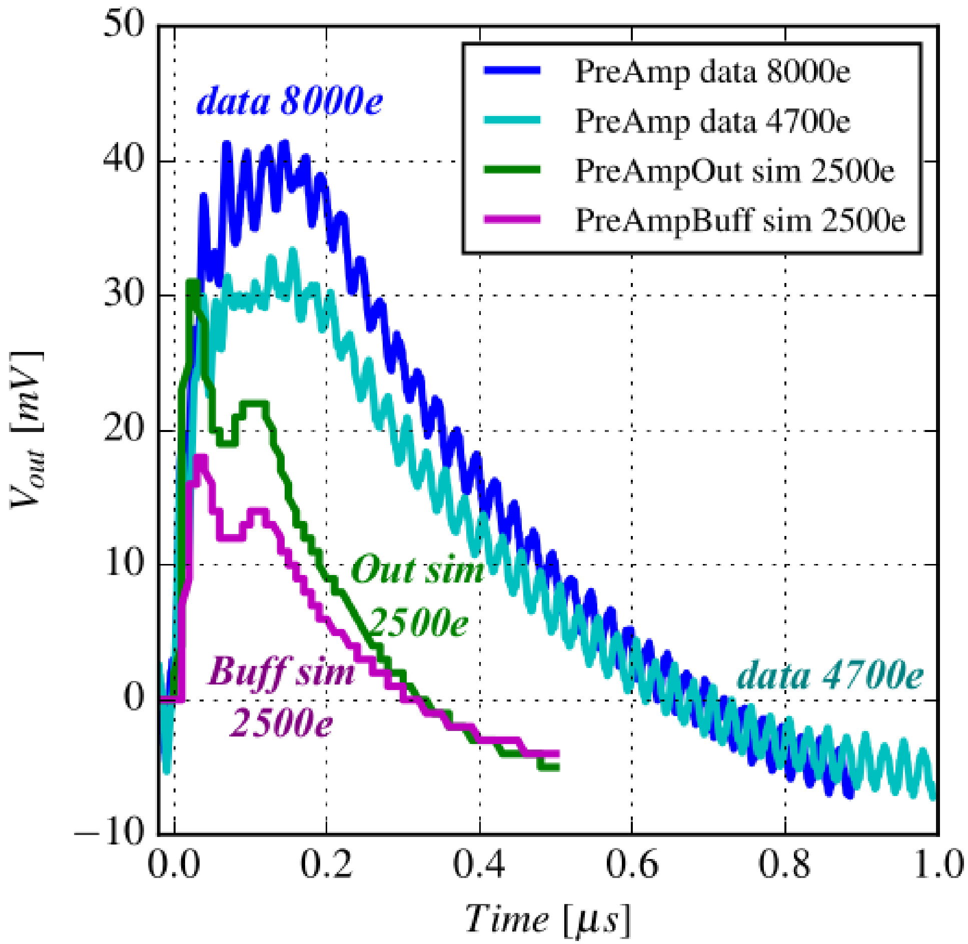


The sum is the same whilst the overflow turns on for inject_number(31) as expected
The overflow next to each output block appears with the maximum number 16 which is resulting from 31-15 = 16
The maximum injected number is 31

Analogue pixel test: Pre-amplifier signal

- **Comparison of the Pre-amplifier signal for different injected charge values and V_{bias} = 2 V to Cadence simulations with charge collection time 10 ns and V_{bias} = 5 V**

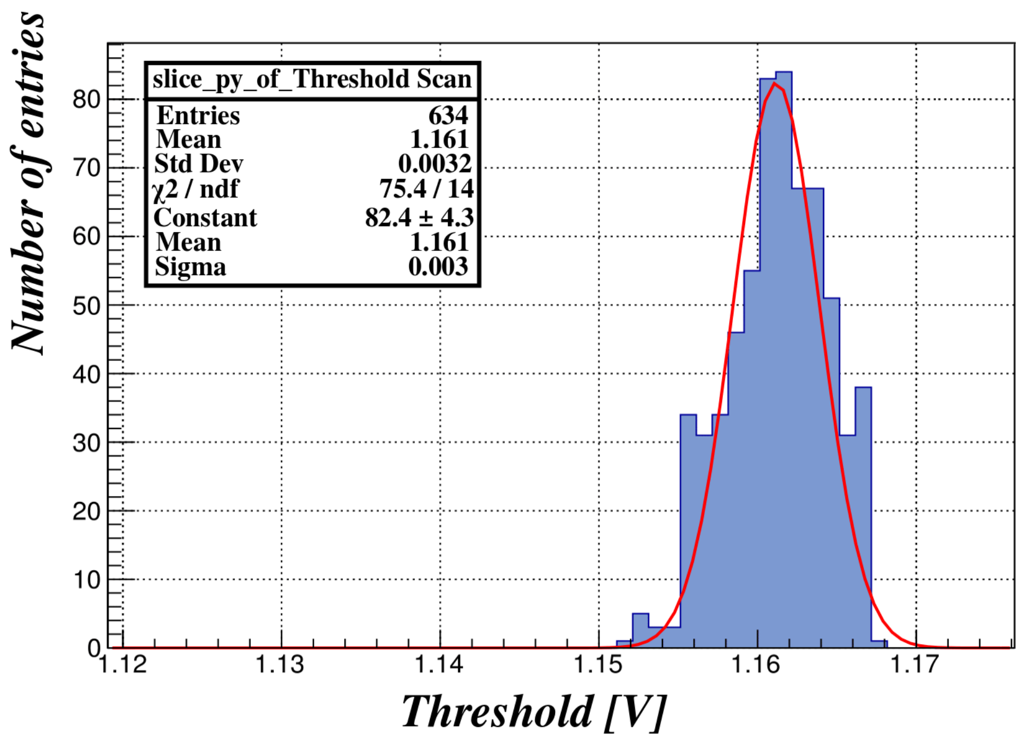
PreAmp signals compared to simulations



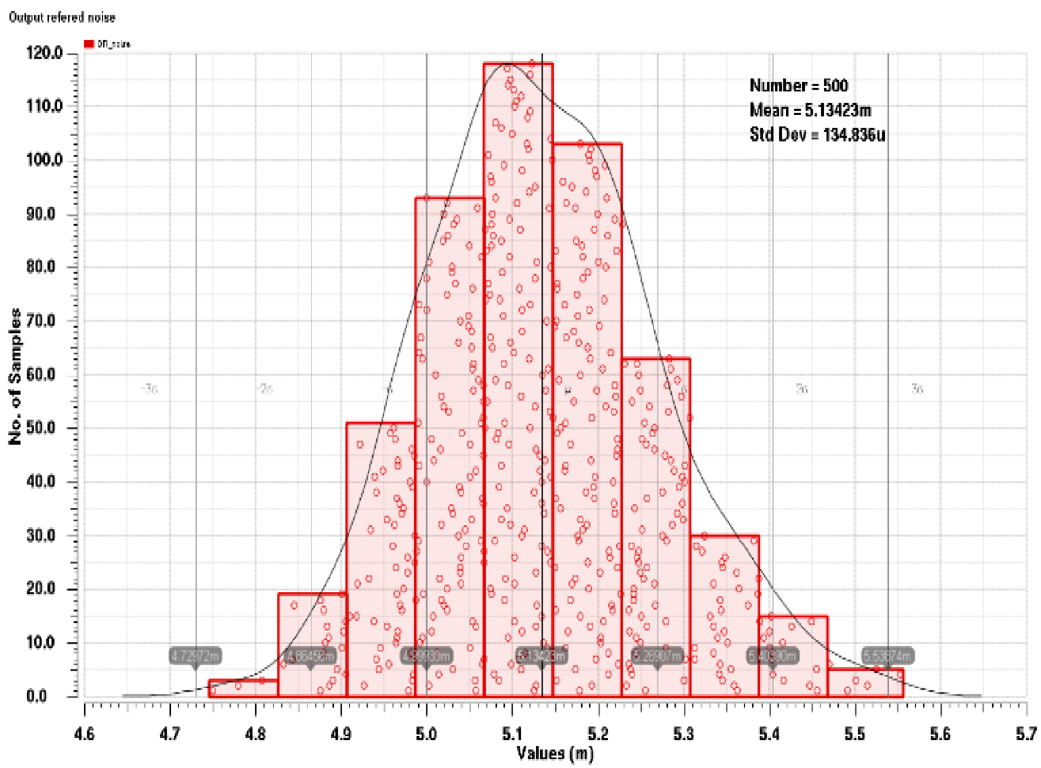
Single pixel noise

- **For laser switched off**
  - **The single pixel noise ≈3 mV, measured at the output of the shaper**
  - **The simulated pixel noise is ≈5 mV**

Measured pixel noise



Simulated pixel noise



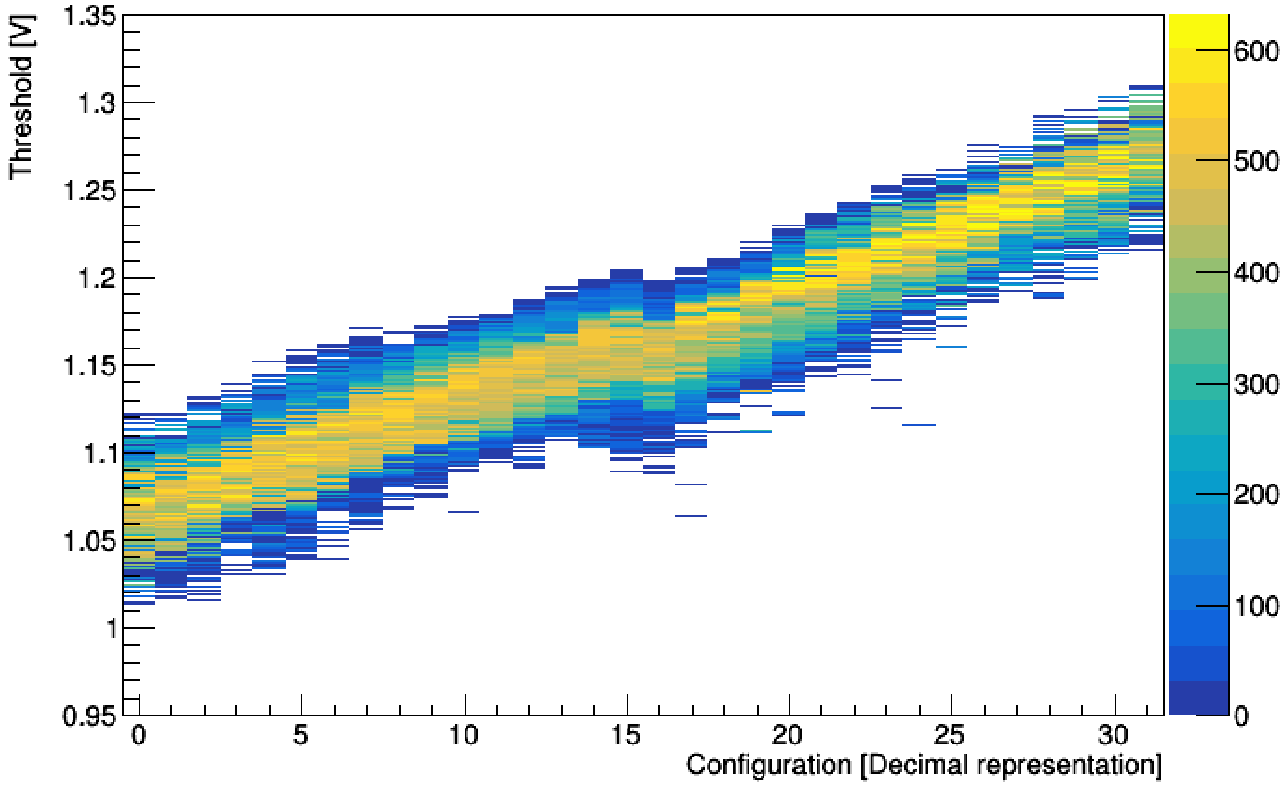
Threshold pixel trimming

- Trimming logic of a 5 bit calibration DAC
  - The DAC itself is a binary weighted current mirror where the current is applied through a 31 kΩ resistor
  - This voltage is then sampled in either polarity by a capacitor in the path of the signal from the shaper, allowing the threshold to be tuned

Threshold voltage as a function of pixel configuration

- The maximum 32 value in the x-axis, verifies the pixel threshold tuning from 5 bits

- A smooth gradient in the noise level with a maximum shift of ≈200 mV.



Strip vs Pad mode

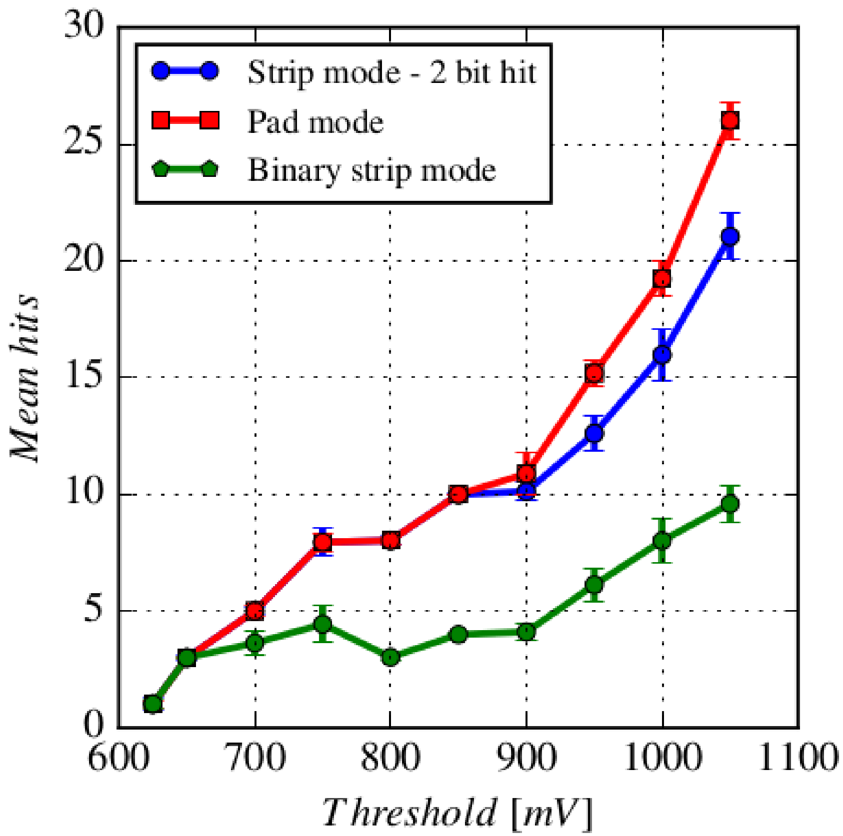
- To verify the difference in the integrated counts a test is performed that measures the number of hits per laser pulse as a function of threshold

- The strip and pad mode agree up to ≈10 hits before the strip mode starts to undercount

- In strip mode with 2 bit hit information, max 3 hits per strip per laser pulse are recorded
  - Mode suitable for particle tracking

- In pad mode, higher number of hits per pad per laser pulse is recorded
  - Mode suitable for digital calorimetry

Mean value of hits as a function of threshold voltage for strip and pad mode



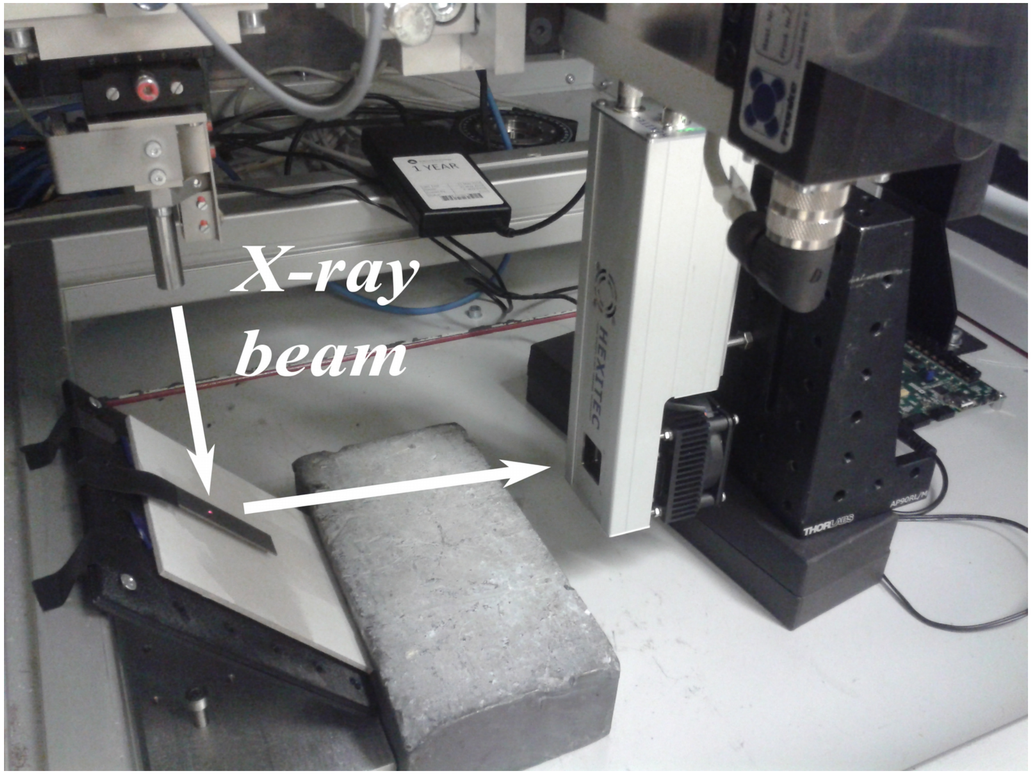
P. Allport et al., First tests of a reconfigurable depleted MAPS sensor for digital electromagnetic calorimetry, Nucl. Inst. and Meth. A (2019), doi.org/10.1016/j.nima.2019.162654

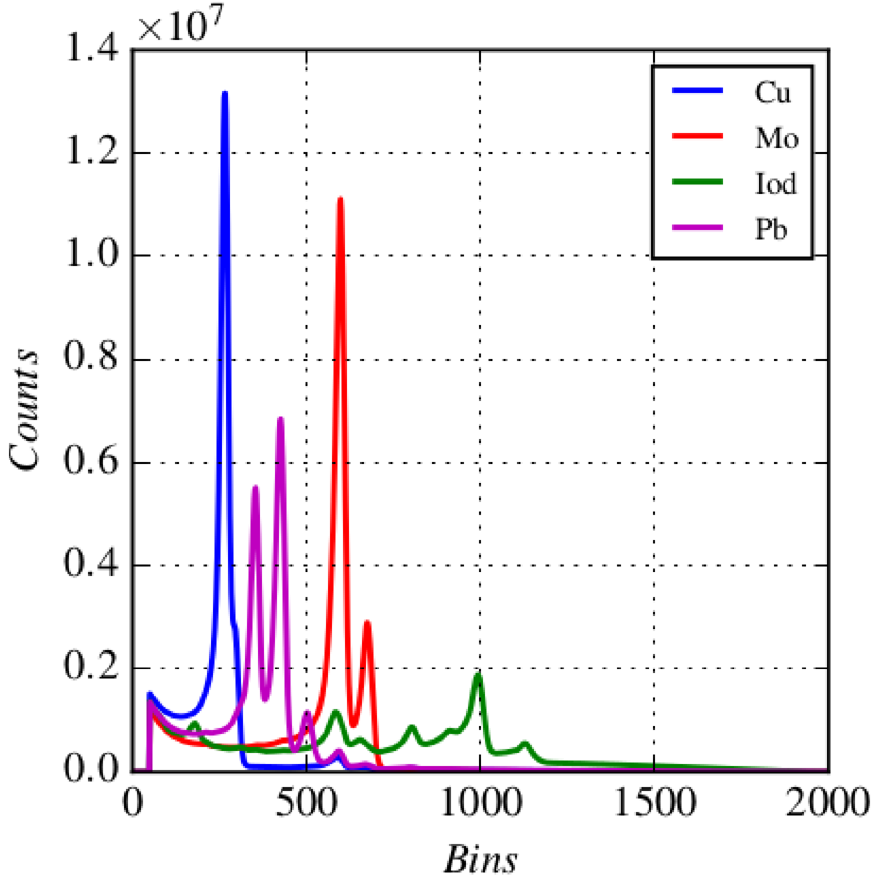
The HEXITEC detector

- **The HEXITEC detector manufactured from the Technology Department at RAL was used to measure the X-ray fluorescence spectrum**

HEXITEC under test, the alignment performed using the red laser

Measured spectra for Cu, Mo, Iodine and Pb

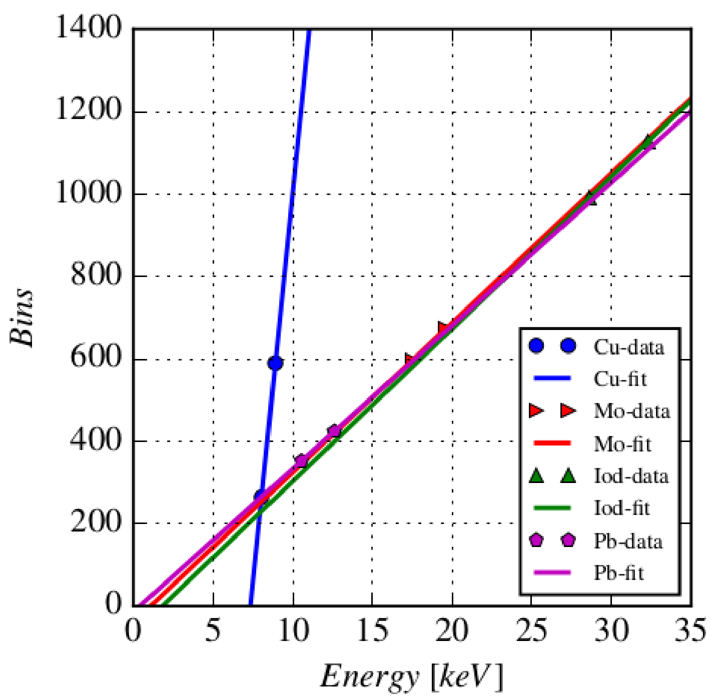




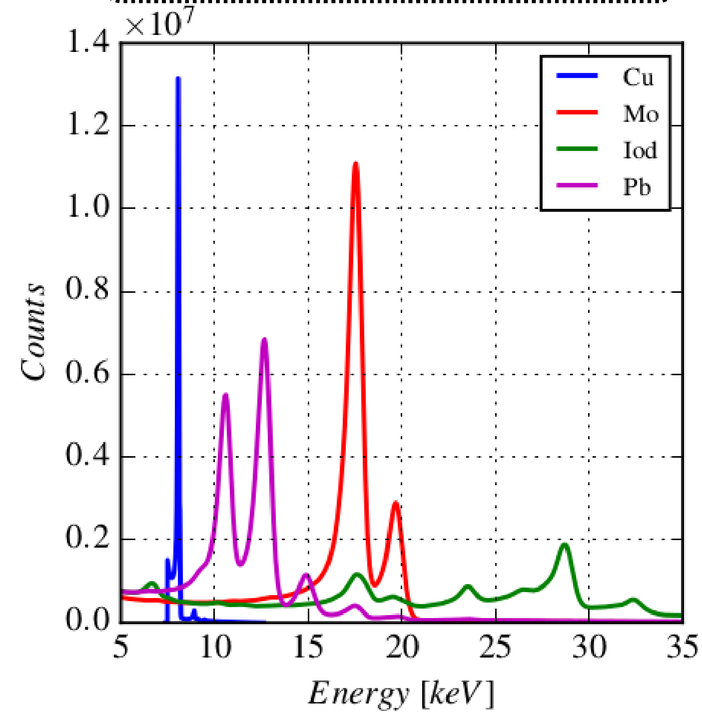
The HEXITEC detector

- **Converting bins to energy using the K_α and K_β energy values from literature***

Bins to energy dependence for the 4 targets



Energy spectra for Cu, Mo, Iodine and Pb



	Cu	Mo	Iod	Pb
$K_{\alpha 1}$ [keV]	8.05	17.48	28.61	-
$K_{\beta 1}$ [keV]	8.91	19.61	32.29	-
$L_{\alpha 1}$ [keV]	-	-	-	10.55
$L_{\beta 1}$ [keV]	-	-	-	12.61

***X-ray data booklet, Lawrence Berkeley National Laboratory, University of California Berkeley, USA (2009)**

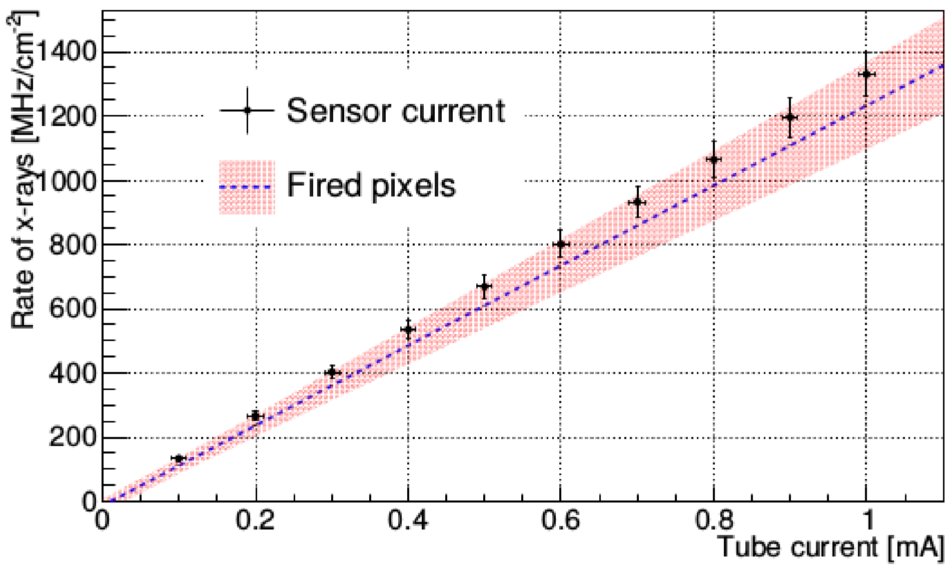
Rate of X-rays

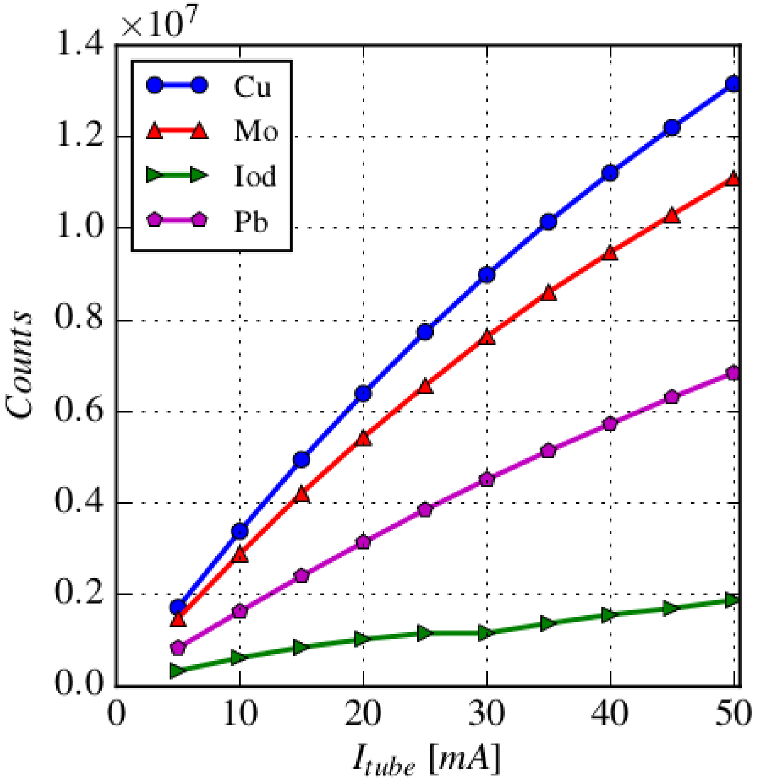
- **Rate of X-rays measured with the CMS chip a few years ago in HH**

High rate test of the PSI46, the CMS frond-end chip, for the Pixel Phase I upgrade

Measured counts with the HEXITEC detector as a function of tube current for Cu, Mo, Iod and Pb target material

M. Centis Vignali, Silicon sensors for the upgrades of the CMS pixel detector, PhD thesis, University of Hamburg, DESY-THESIS-2015-052



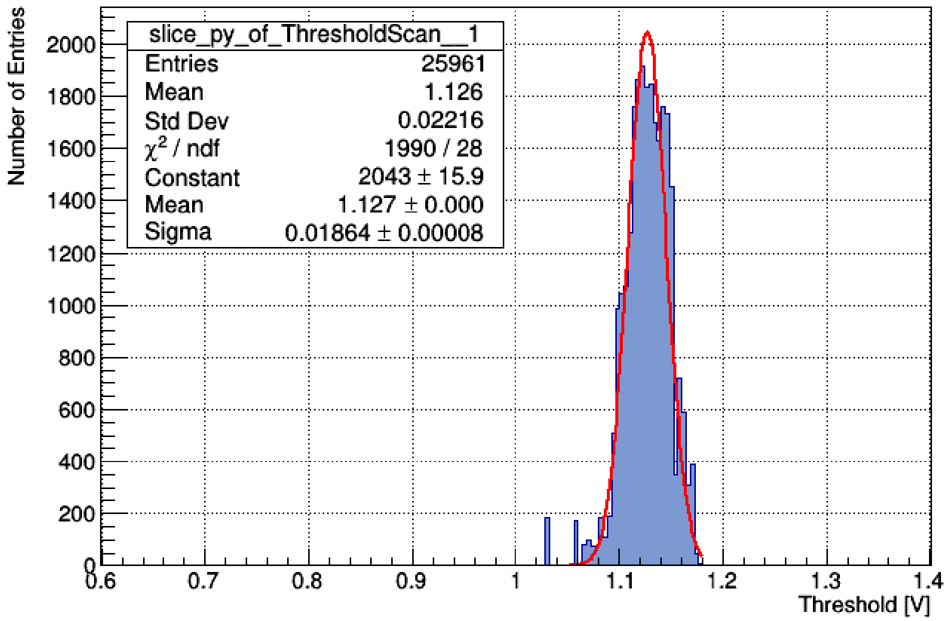


For a photon flux of 10^7 photons/s, the rate of X-rays in the DECAL sensor is ≈ 40 MHz/cm^2

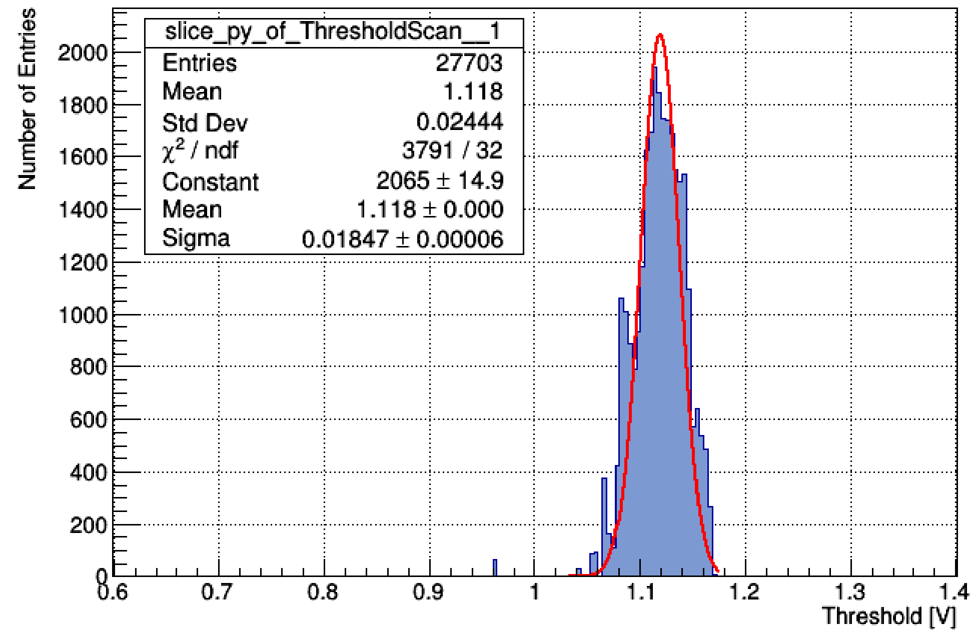
DECAL sensor test using monochromatic X-rays

- **Test under Cu XRF spectrum**

X-ray tube off



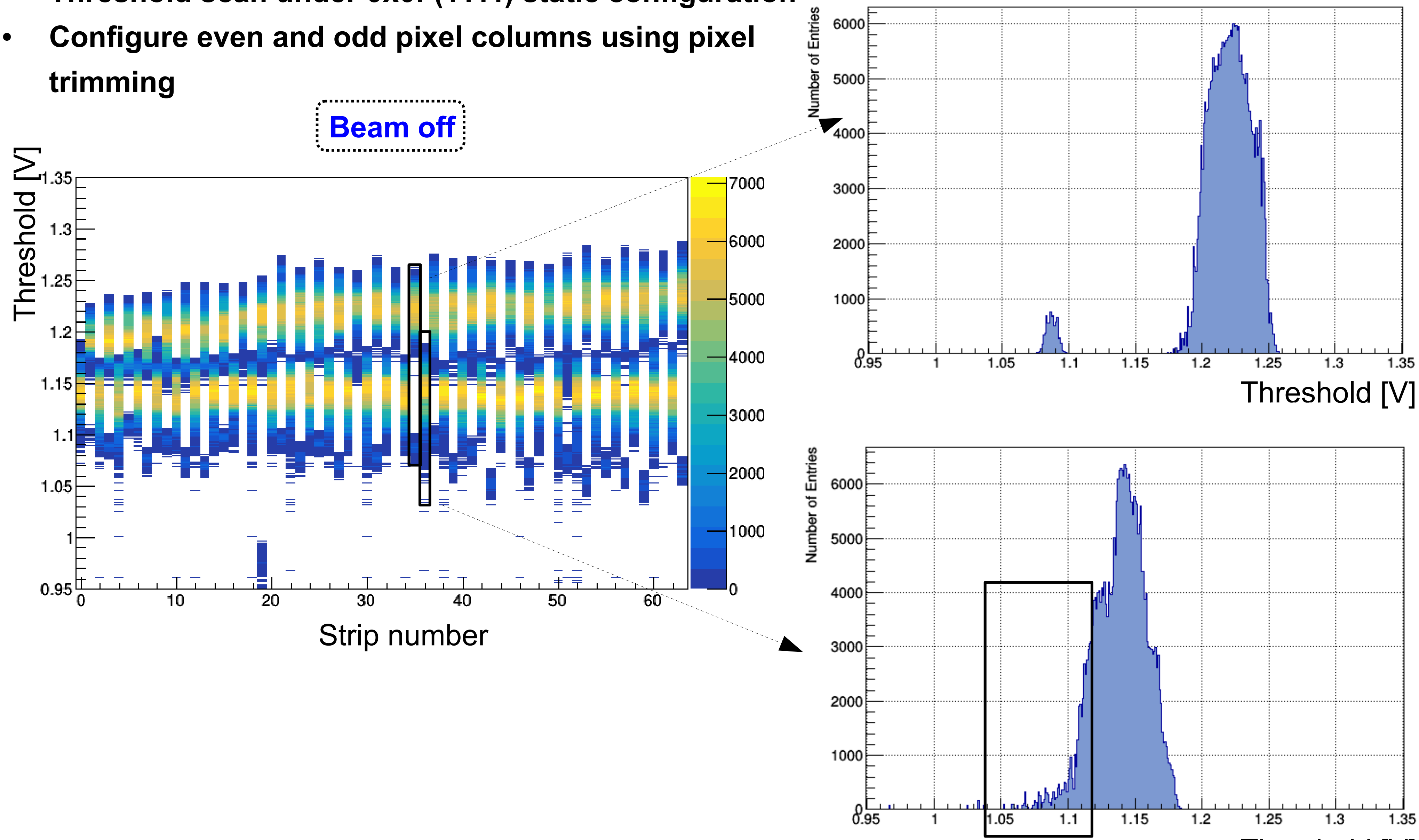
X-ray tube on



A difference of 10 mV is observed in the threshold mean value when the sensor is operated under X-rays compared to normal environment

The scan in order to detect the Cu XRF K_α peak

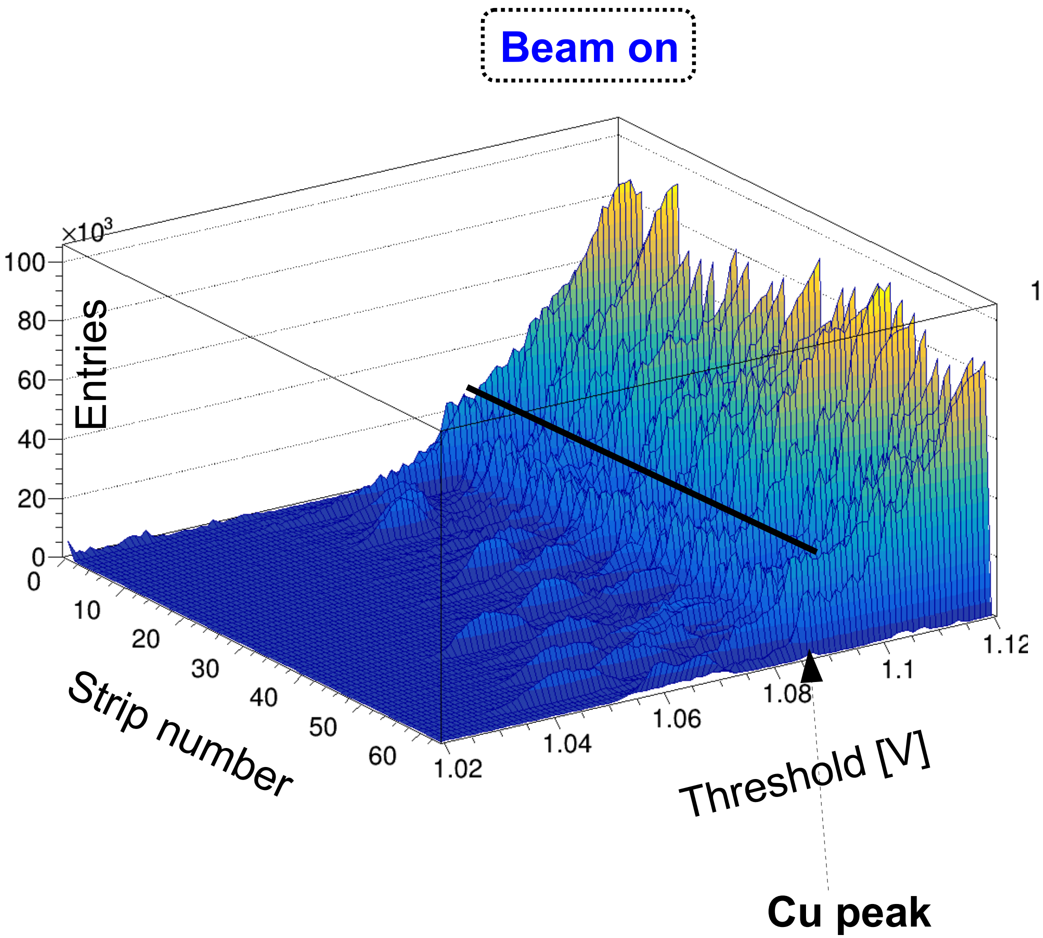
- **Threshold scan under 0x0f (1111) static configuration**
- **Configure even and odd pixel columns using pixel trimming**

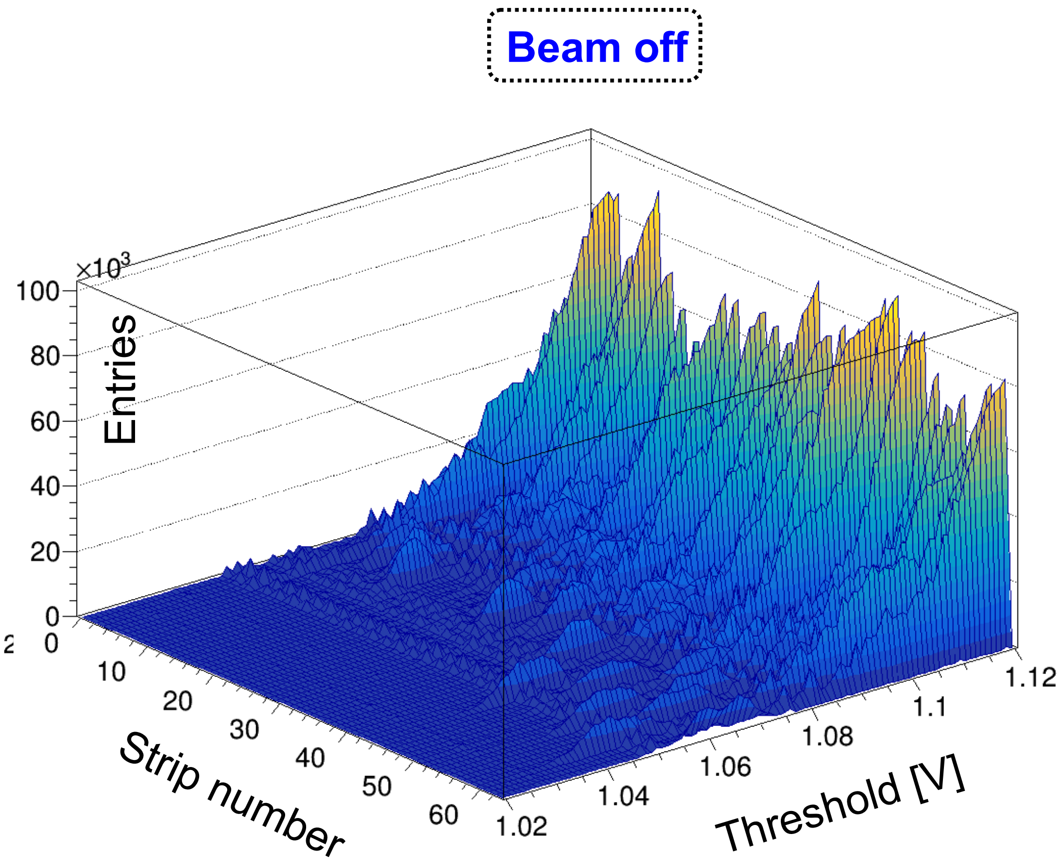


The tail where the Cu K_α peak possibly appears when the beam is on

The tail for beam on & off

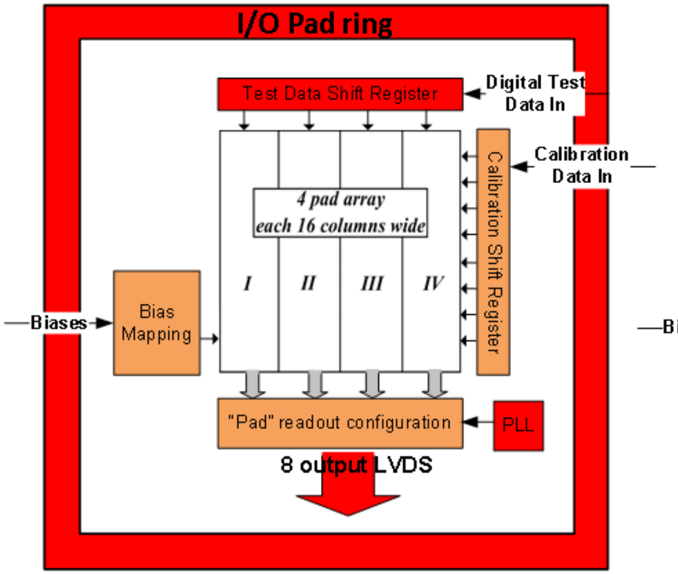
- **Tail for all even strips**

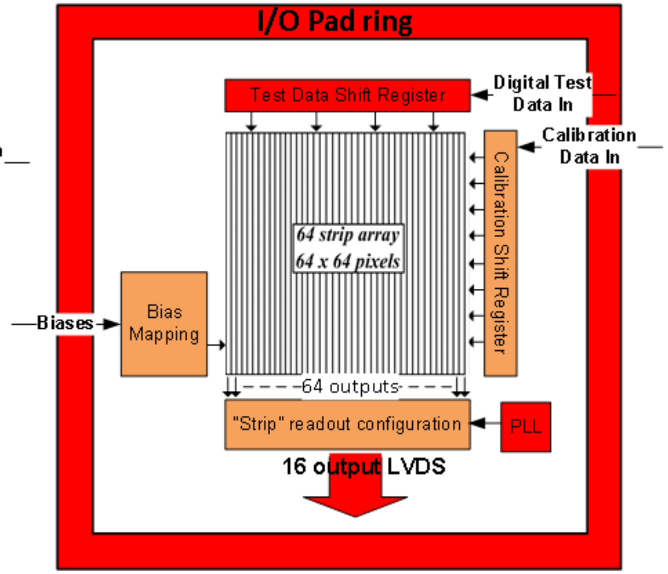




The DECAL sensor in the TJ modified process

- Necessary modifications in the sensor design





- Pixel:
  - Fix problem report
  - Fully depleted layer with gap is the design goal
- PLL: Significant layout modifications
- LVDS drivers: Significant layout modification
- Pad ring: Major modifications (new library cells + FD modifications)
  - Create 1 pad for HV bias
  - Create 1 pad for -20V substrate
- Guard ring: Moderate layout modification
- Top level: Required significant layout modification on Y axis