ALPIDE – Pixel Detector

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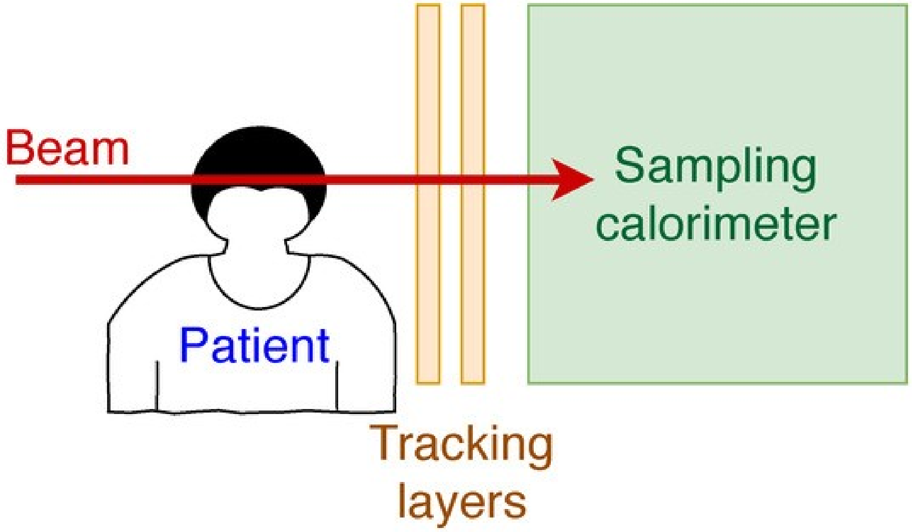
Lecture week
on imaging with particles at UiB
23-28 Sept. 2019

Bergen pCT - Design

- **Conceptual design**

Ref. Universe 2019, 5(5), 128; https://doi.org/10.3390/universe5050128



- **Extremely high-granularity sampling calorimeter**
  - ➔ for tracking, range and energy-loss measurement

- **Technical design** (Sampling Calorimeter)
  - ➔ Planes of ALPIDE pixel detector as active layers and
  - ➔ aluminum (3.5 mm thick) as absorber

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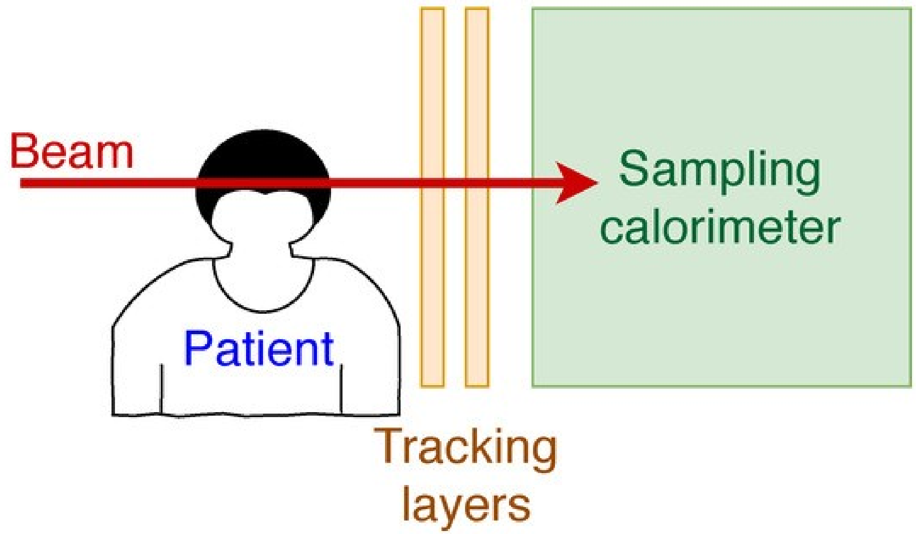
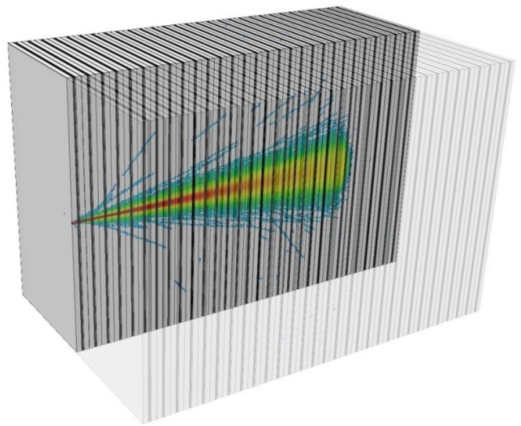


Simulated ion-beam shower in digital calorimeter



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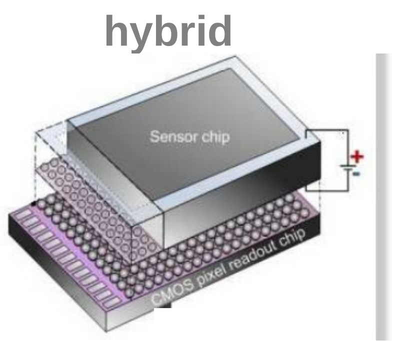
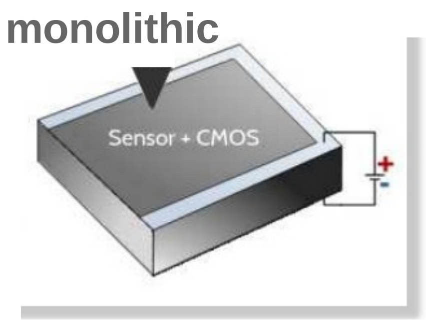
  - aluminum (3.5 mm thick) as absorber

ALPIDE - Introduction

- ALPIDE - ALice PIxel Detector
- Developed for Inner tracking detector of ALICE experiment at LHC, CERN
  (ALICE is Heavy ion physics experiment – Quark-Gluon plasma studies, early stage of universe)
- Monolithic Active Pixel Sensor (MAPS) chip
- MAPS - image sensor where each picture element (pixel) has
  - → photo-detector + active amplifier + memory (pixel are µm in size)
- Monolithic – sensor and electronics in same silicon

  (hybrid: sensor and readout electronics separated)



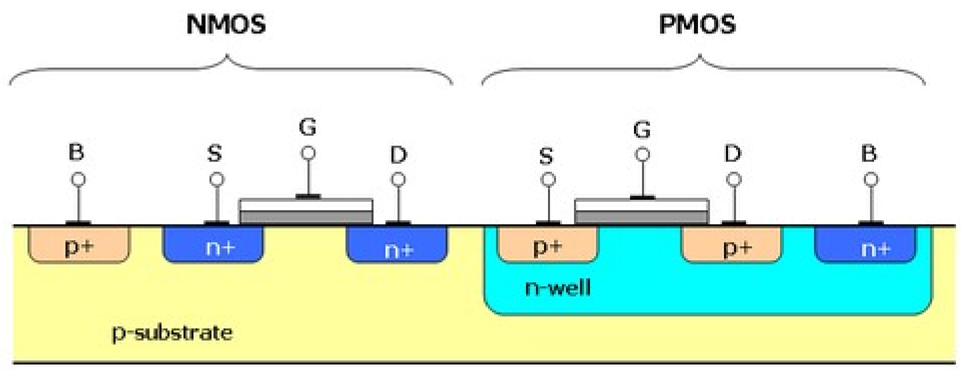


- Produced using CMOS technology

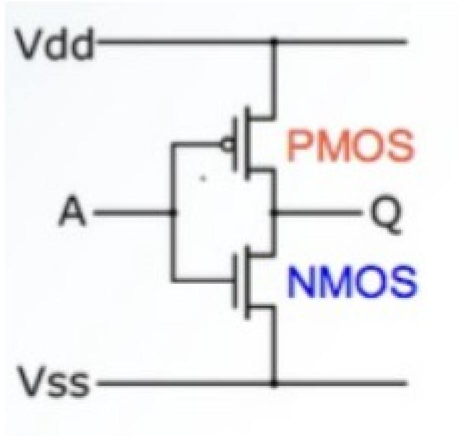
What is CMOS?

- CMOS → Complementary Metal Oxide Semiconductor
- Semiconductor fabrication process uses pairs of n-channel MOSFET (NMOS) and p-channel MOSFET (PMOS) for logic functions
- CMOS technology is used for fabrication of Integrated Circuits

(Microprocessors, Micro-controllers, memory chips etc.)



Cross-section of two transistors in a CMOS gate, in an N-well CMOS process



CMOS inverter

(High – in → Low – out and vice versa)

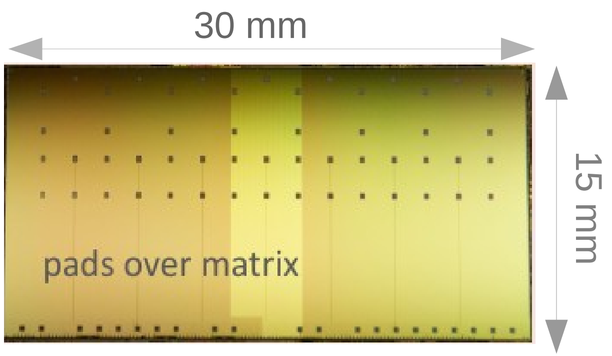
(MOSFET → Metal Oxide Semiconductor Field Effect Transistor)

ALPIDE Specifications

- Produced by Tower jazz in 180 nm semiconductor manufacturing process

  (180 nm is the least distance between the transistors produced on the Si wafer)

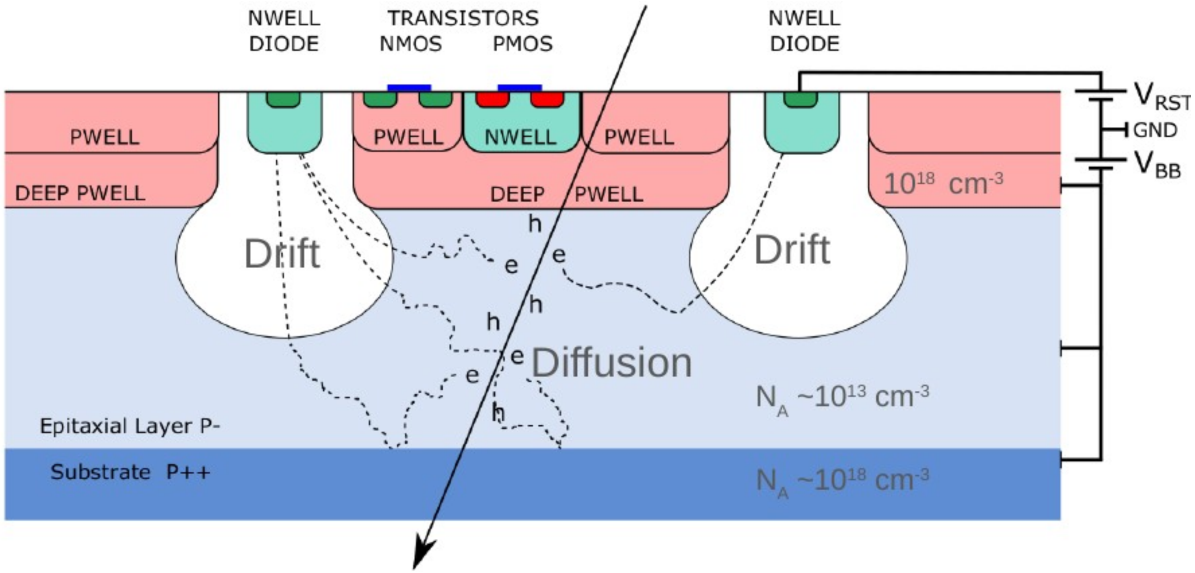
- Dimensions
  - Chip size 15 mm x 30 mm
  - Chip thickness 50 µm or 100 µm
  - No. of Pixels 512 x 1024 pixels (~ 0.5 M)
  - Pixel size ~ 27 µm x 29 µm



- In pixel amplification and discrimination and three data registers (1 bit each)
- Global shutter (STROBE), triggered or continuous readout, 1.2 Gbit/s speed link
- Zero suppressed readout: only hit pixels info. processed
- Performance
  - Efficiency > 99% for MIPs, Heavy ions
  - Max particle rate 100 MHz / cm^2
  - Fake-hit rate < 10^{-8} hit/event/pixel
  - Spatial resolution ~ 5 µm
  - Power consumption 300 nW/pixel

MIPs: Minimum Ionizing Particles

ALPIDE – Working Principle



- N-well diode, p-type epitaxial layer (~25 µm) and substrate
- Diode size (2-3 µm) – very small than pixel size – low capacitance – high S/N
- Possible to reverse bias (up to -6 V)
- Drift e- reaching the collection diode induce a current signal at the input of transistors
- Deep PWELL shields NWELL of PMOS transistors
  – allows full CMOS circuitry in active area

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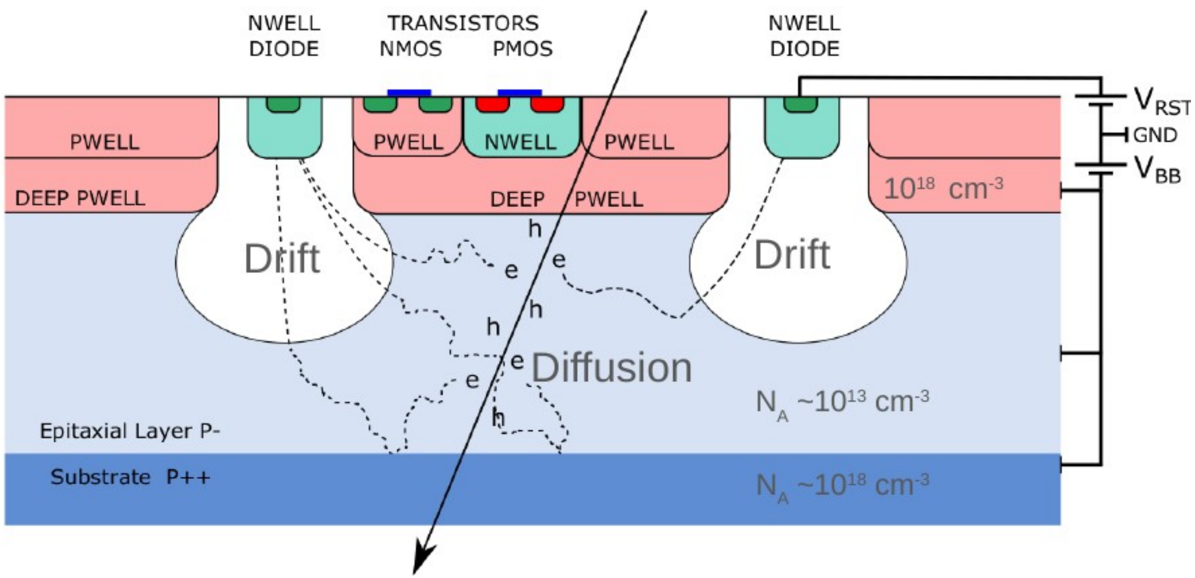

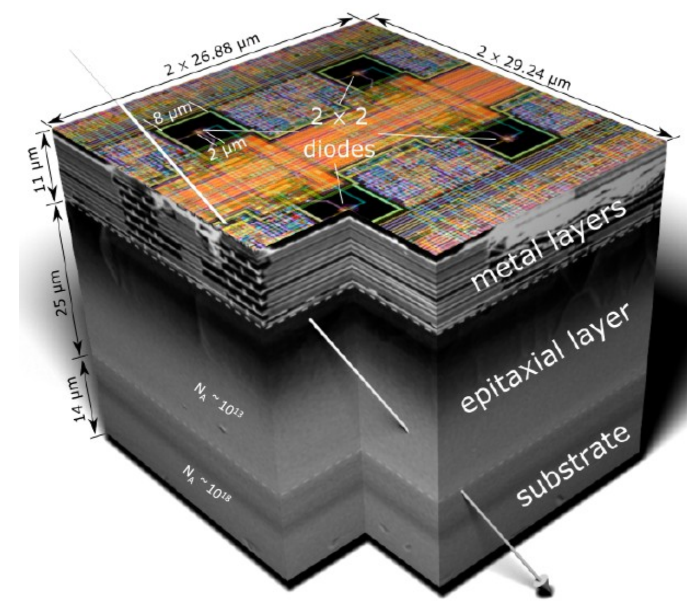

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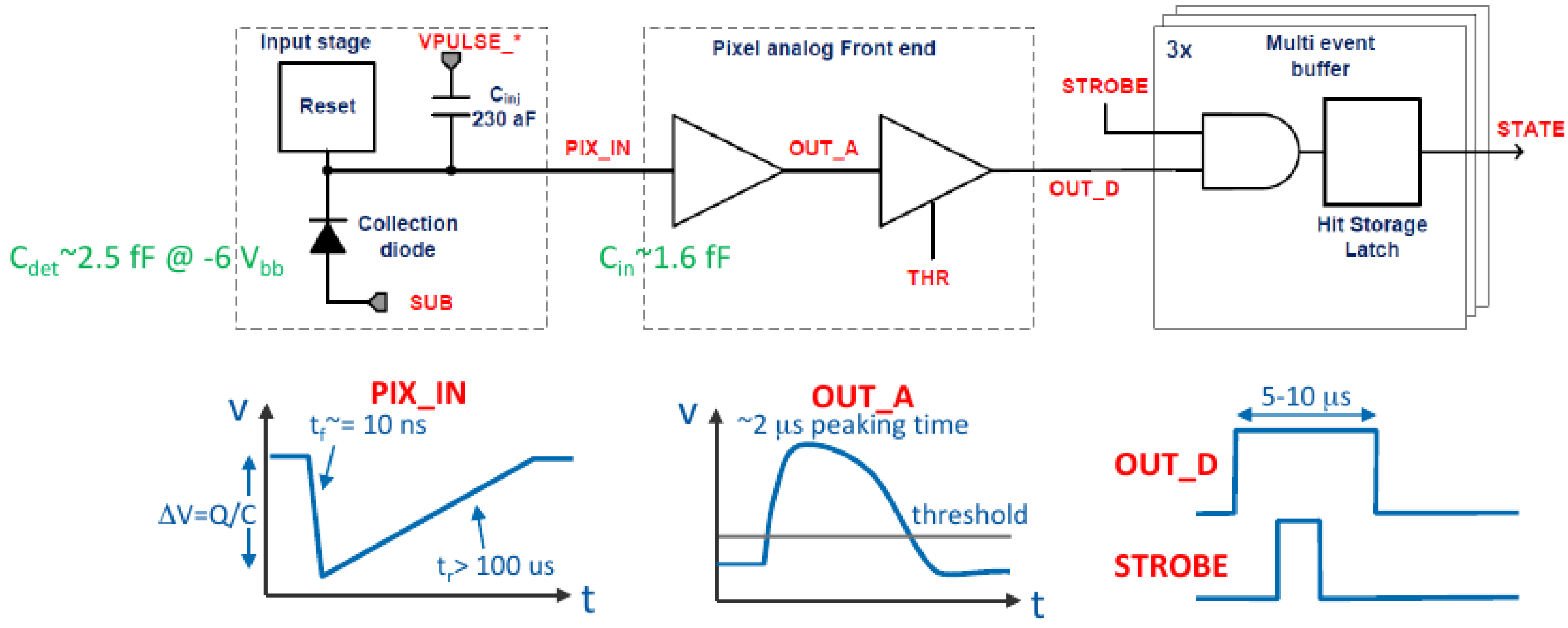
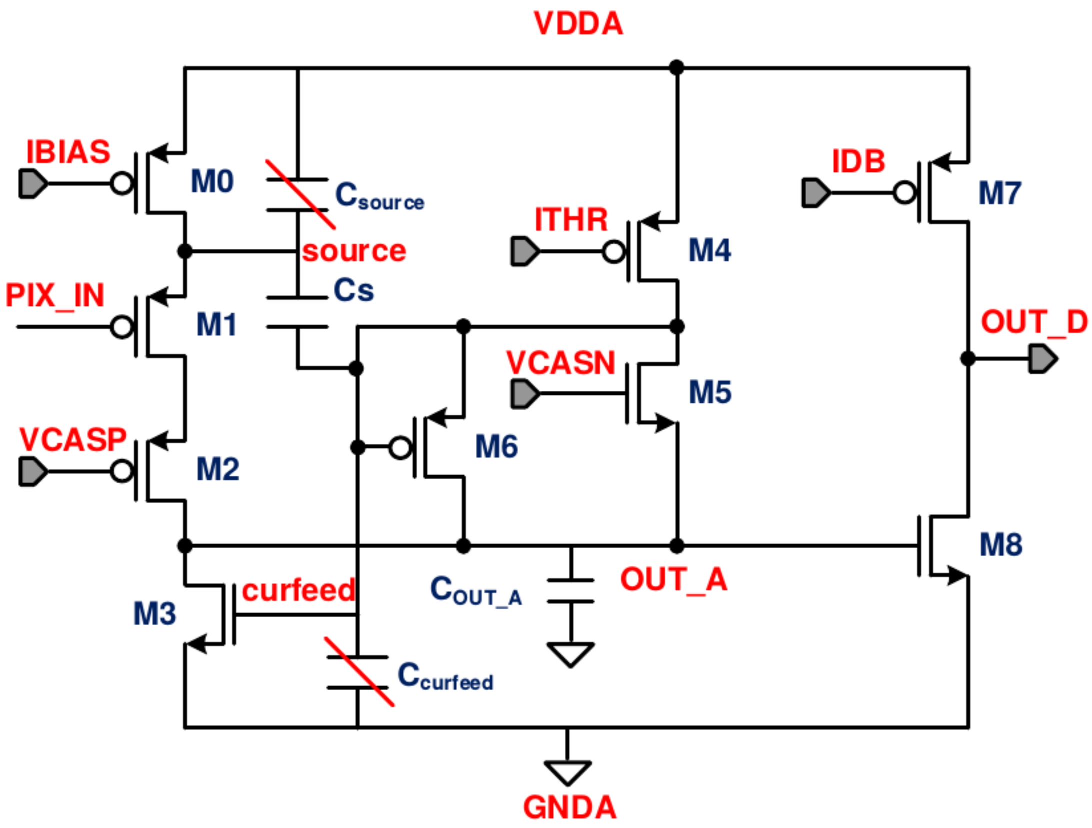
ALPIDE – Signal Processing at Single Pixel Level



- OUT_A: Upon particle hit front-end forms a pulse with 1 to 2 µs peaking time
- OUT_D: Global threshold for discrimination forms binary pulse (OUT_D)
- STATE (Latch): Global shutter (STROBE) latches the discriminated hit in memory

ALPIDE – Front-End Scheme



- Nine transistors
- List of DAC parameters:

(control pulse shape, threshold etc.)

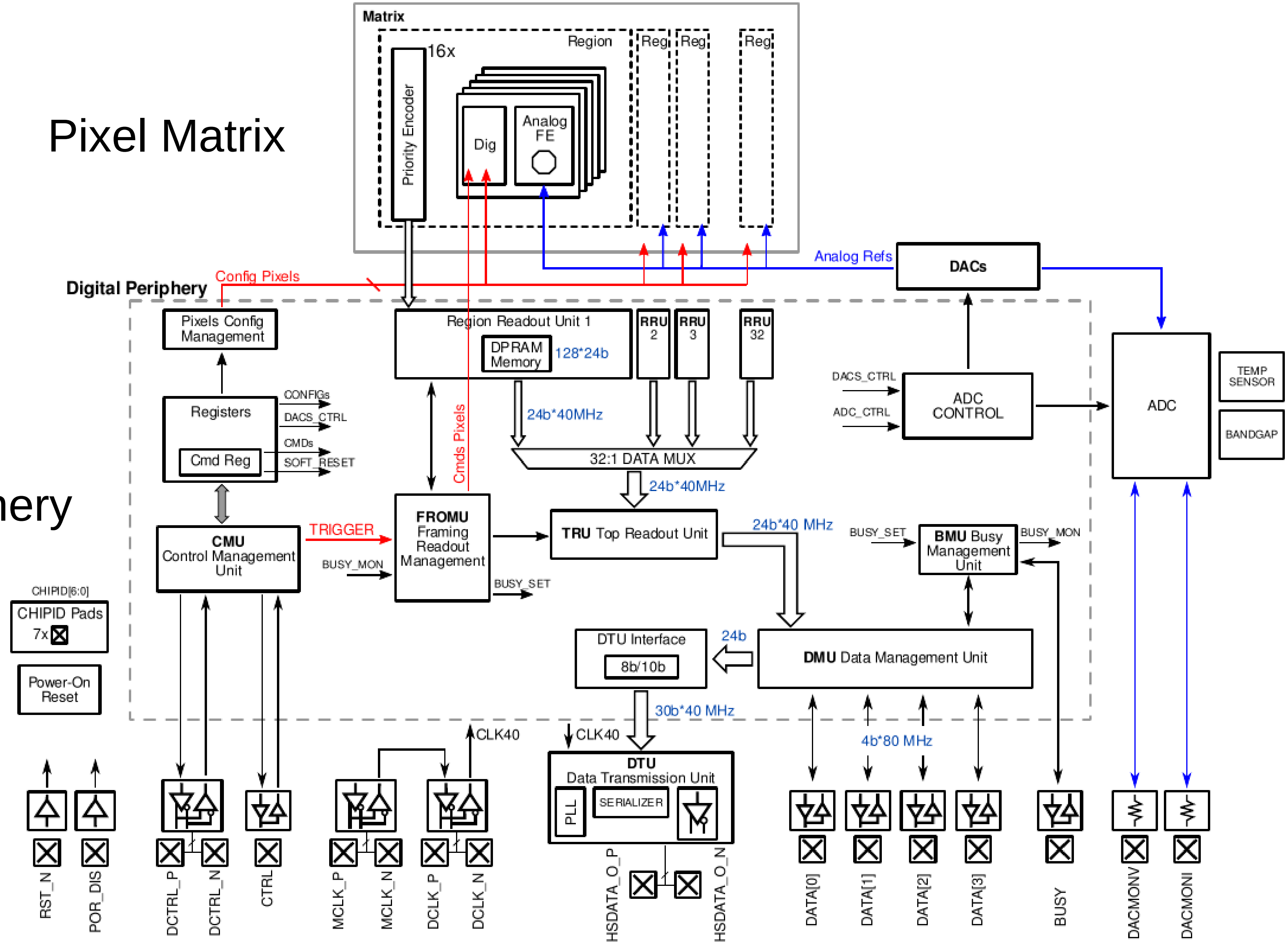
VRESETP
VRESETD
VCASP
VCASN
VPULSEH
VPULSEL
VCASN2
VCLIP
VTEMP

IAUX2
IRESET
IDB
IBIAS
ITHR

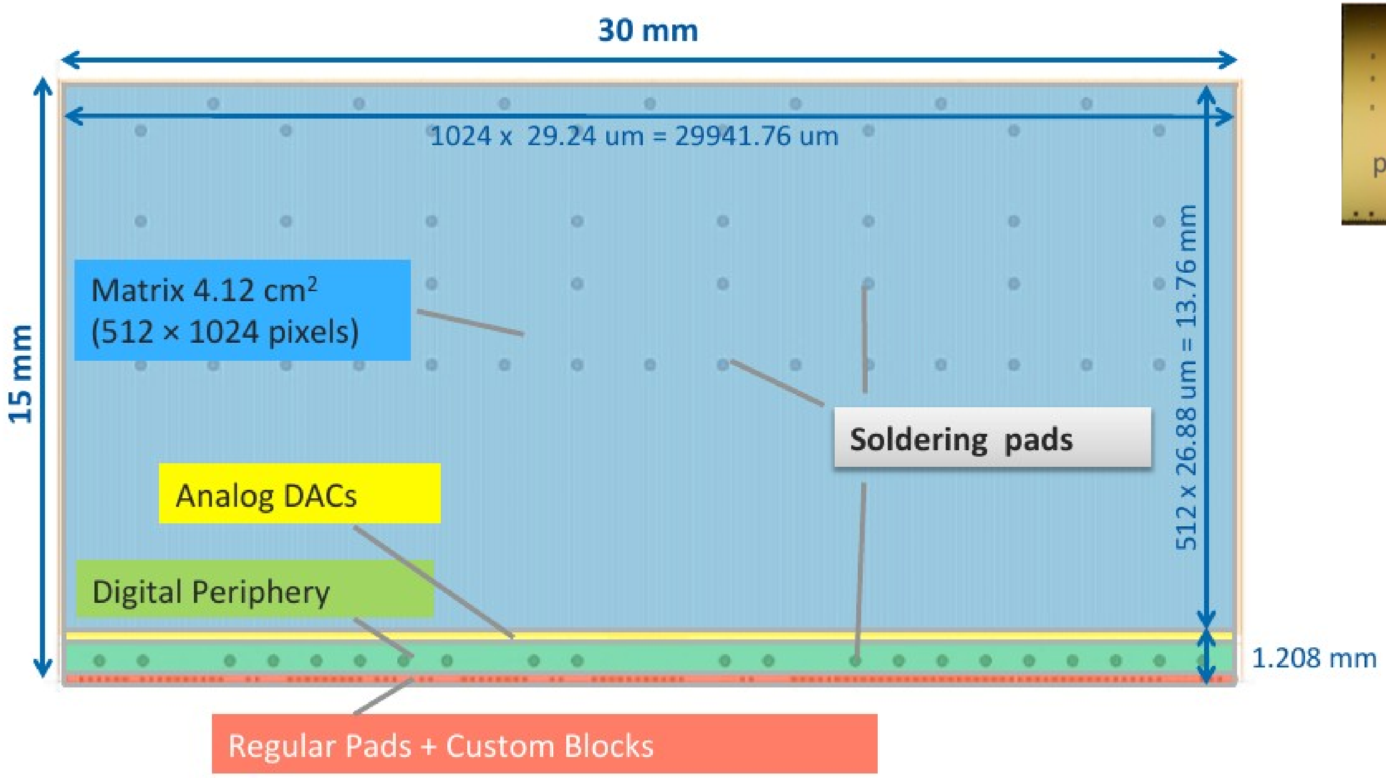
ALPIDE – Detailed Block Diagram

Pixel Matrix

Digital Periphery

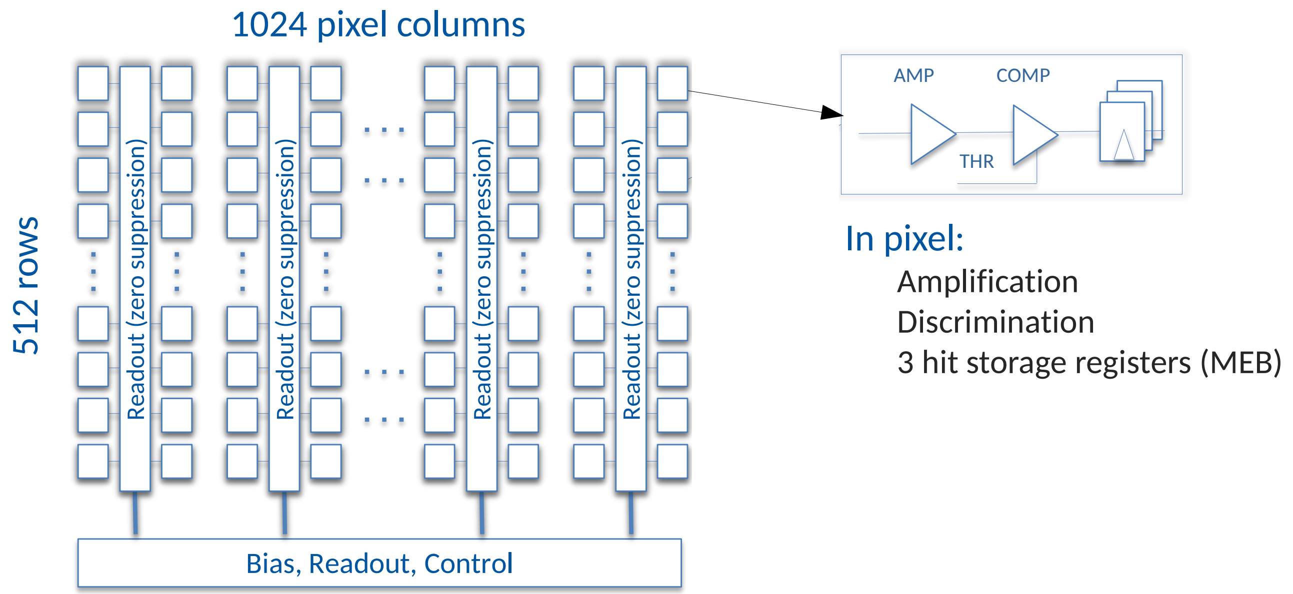


ALPIDE – Simplified



- **Pixel Matrix** (32 readout regions x 16 dcol/region: 512 dcol in total)
- **Digital Periphery** (several modules and DACs)
  - Region Readout Unit (x32), Frame and Readout Management Unit, Busy Management Unit, Data Formatting, Management and Transmission Unit
  - 11b ADC for DAC controls, Temp sensors etc.

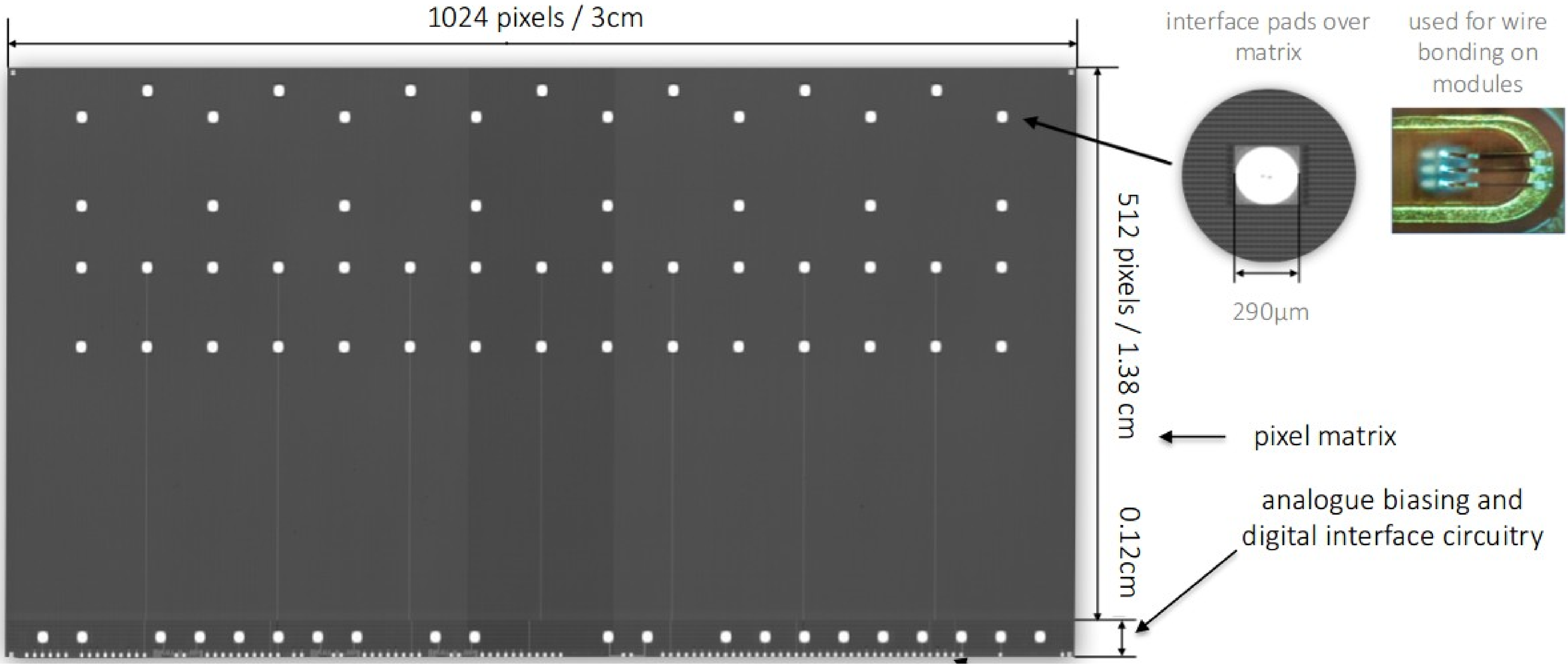
Matrix Readout



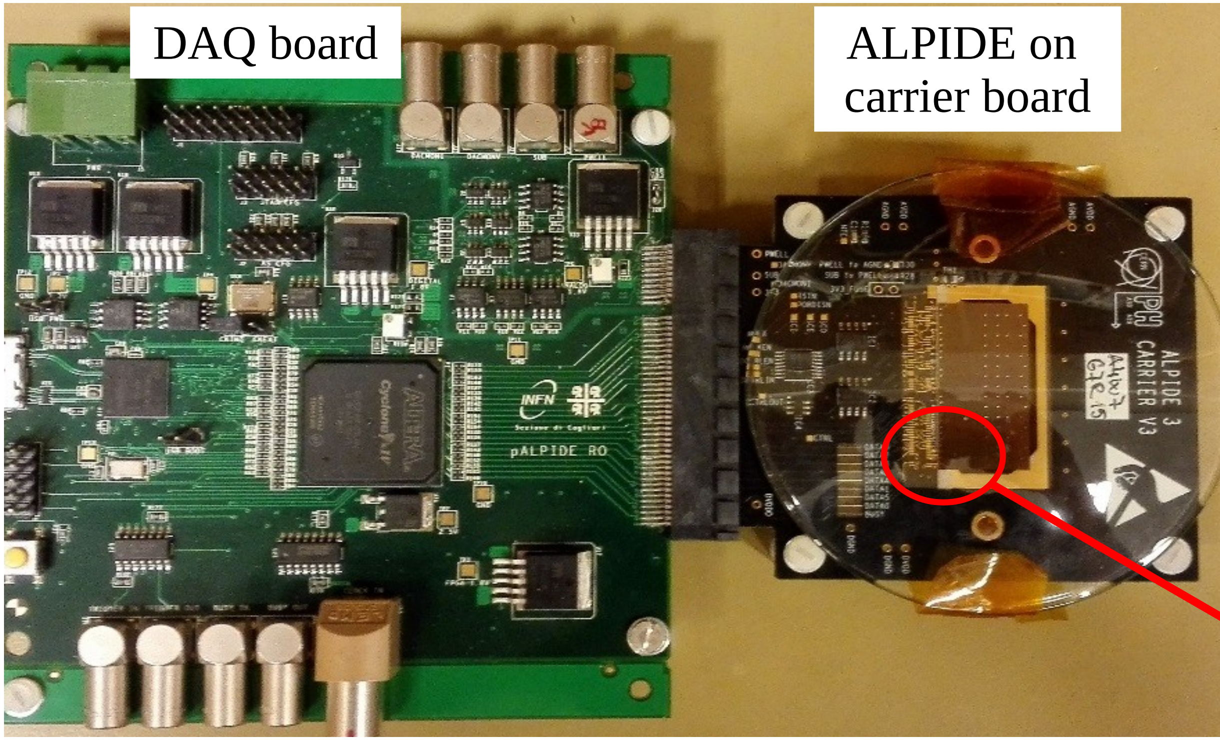
- Readout pixel state register – priority encoder circuit arranged per double column.
- Sequentially provide address only of hit pixels – zero suppression, fast readout
- Every clock cycle the hit pixel with the highest priority is readout and then reset, so that the next one can be treated in the next clock cycle until all hit pixels have been read out.
- The readout is controlled at the chip periphery with a signal synchronous with the clock

ALPIDE – Interface Pads

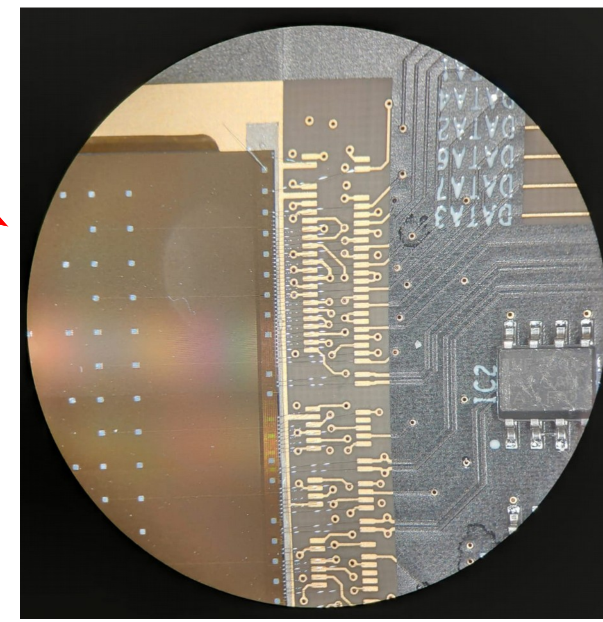
Two possible connections schemes:
(1) Pads over the matrix and (2) Pads at the periphery

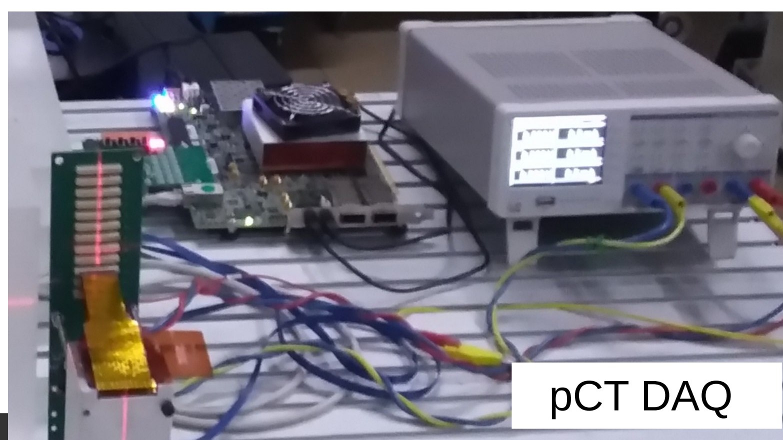


ALPIDE – Data Acquisition



Small pads at the periphery used for bonding





ALPIDE – Threshold and Noise

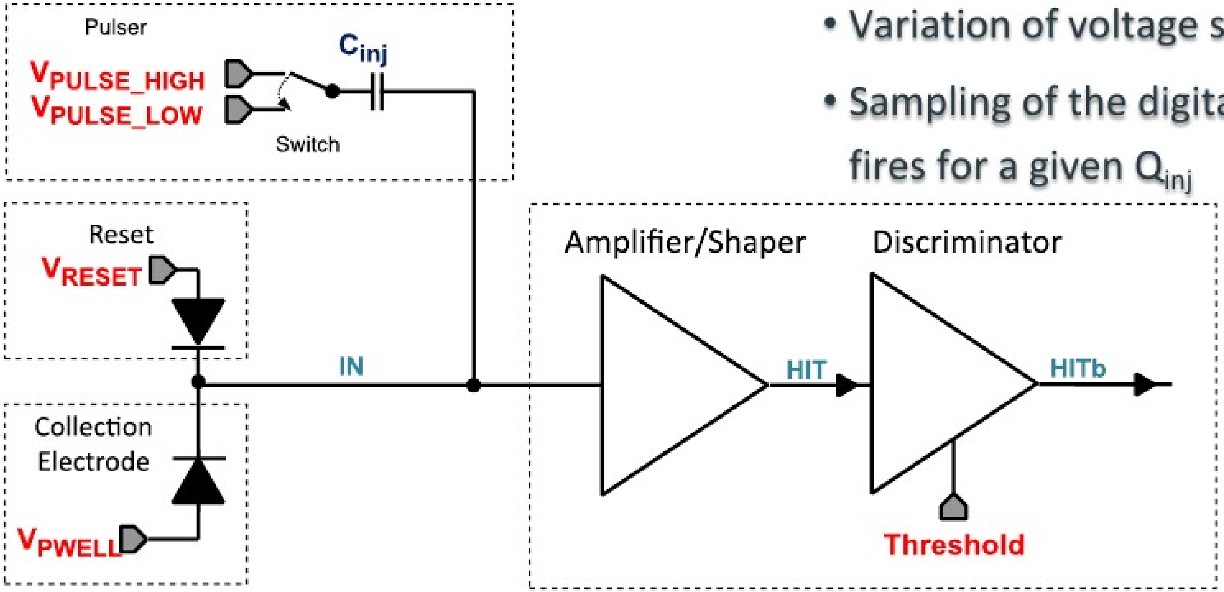
How to measure the pixel threshold?

The challenge:

- Measure an analogue property in absence of analogue outputs

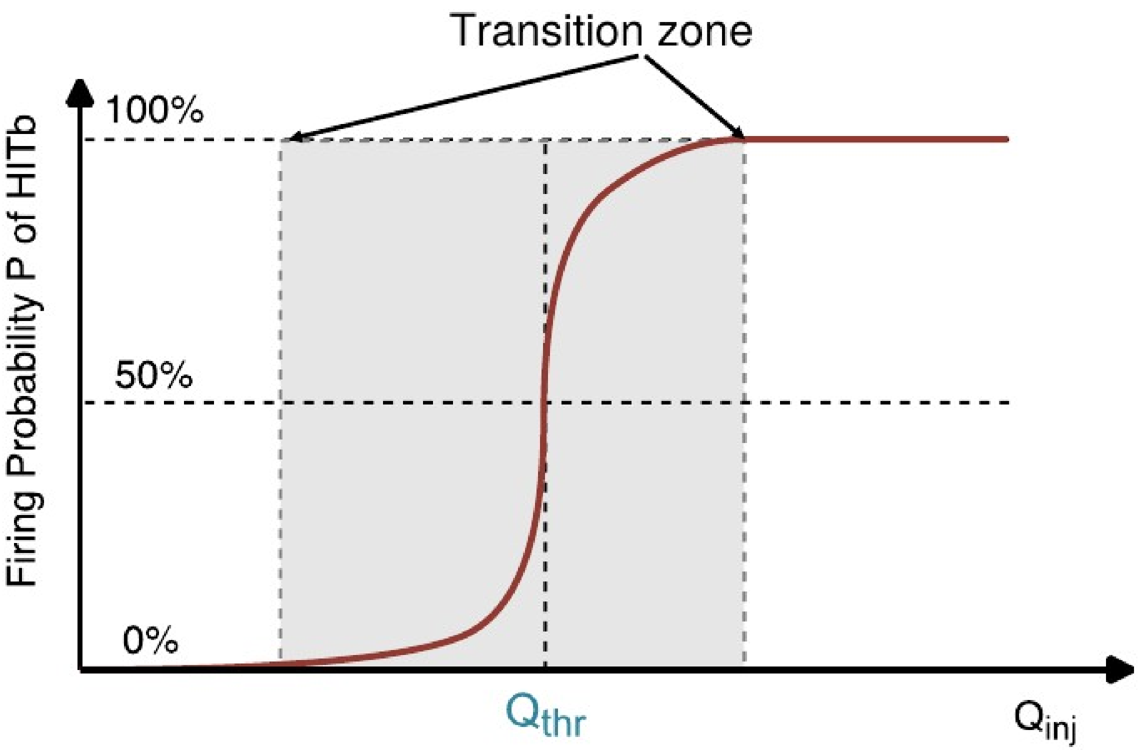
The solution: 'S-Curve scan'

- Pulsing the pixel input IN using a capacitor C_{inj}: by applying a voltage step using a switch
- Injected charge: $Q_{inj} = C_{inj} * (V_{PULSE\_HIGH} - V_{PULSE\_LOW})$
- Variation of voltage step using on-chip DACs
- Sampling of the digital output HITb, counting how often a pixel fires for a given Q_{inj}



ALPIDE – Threshold and Noise

The S-Curve (for single pixel)



$$P(q) = \frac{1}{2} \cdot \mathrm{Erf}\left[\frac{q - Q_{thr}}{\sqrt{2} \cdot \sigma}\right]$$

Charge Threshold Q_{thr}:

- charge for which the pixel fires 50% of the time

Thermal Noise σ

- Transition zone width / steepness of the S-Curve

Determination of the parameters:

- Fitting the S-curve function to the data: gives threshold and noise
- Numerical derivation + finding the maximum: threshold only, but simple and fast

ALPIDE – Threshold and Noise

The S-Curve (for single pixel)

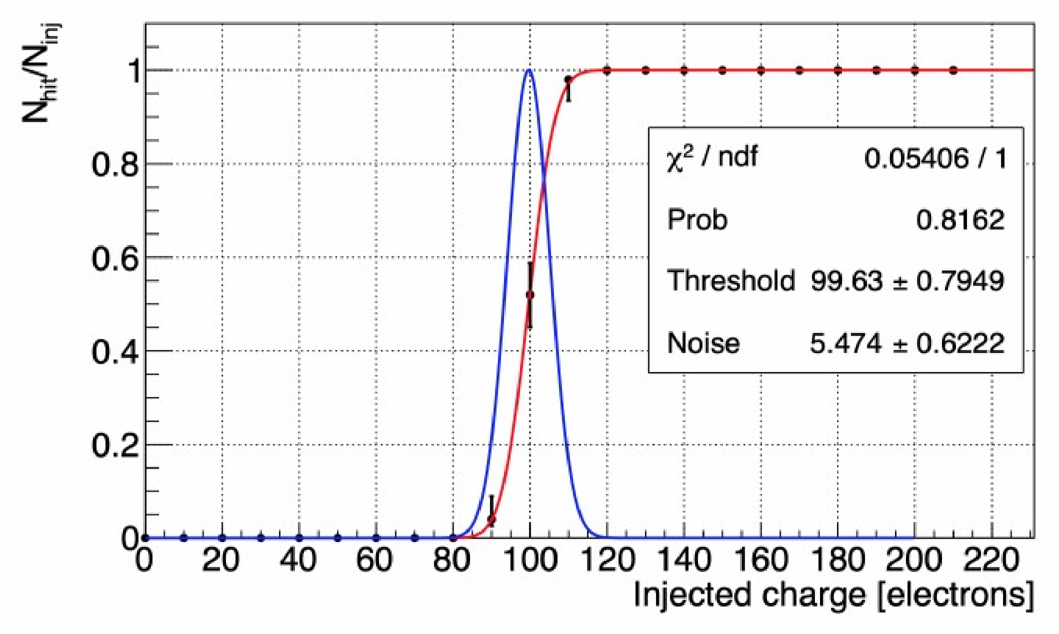


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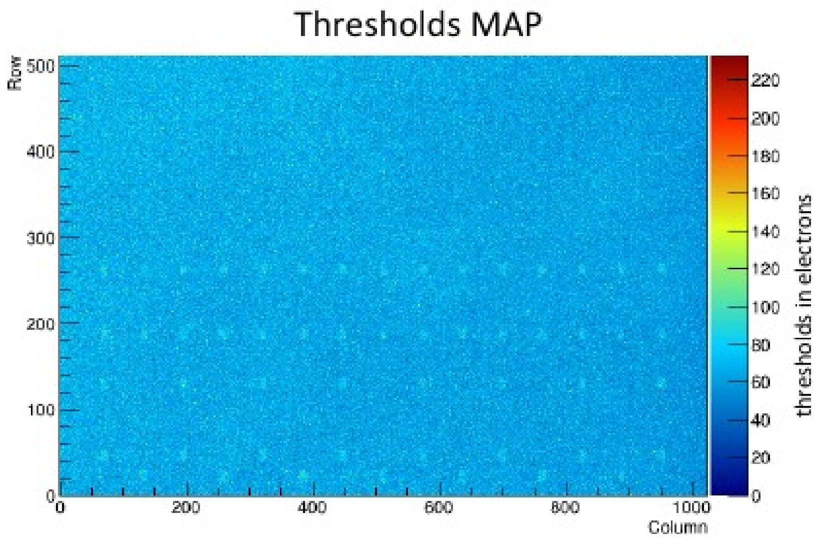
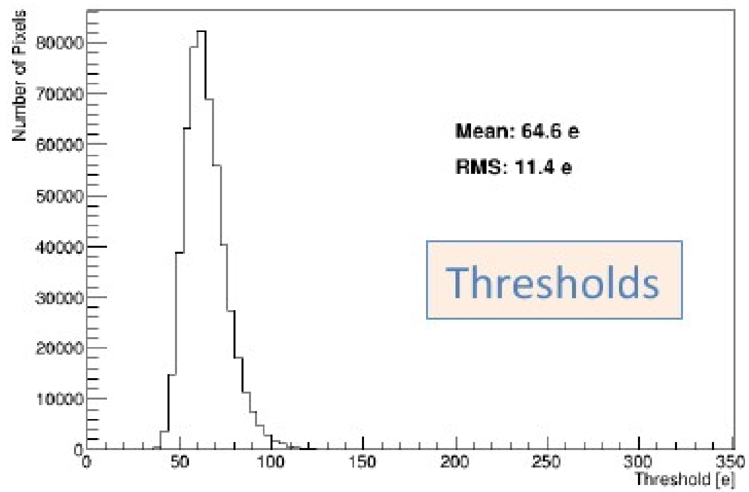
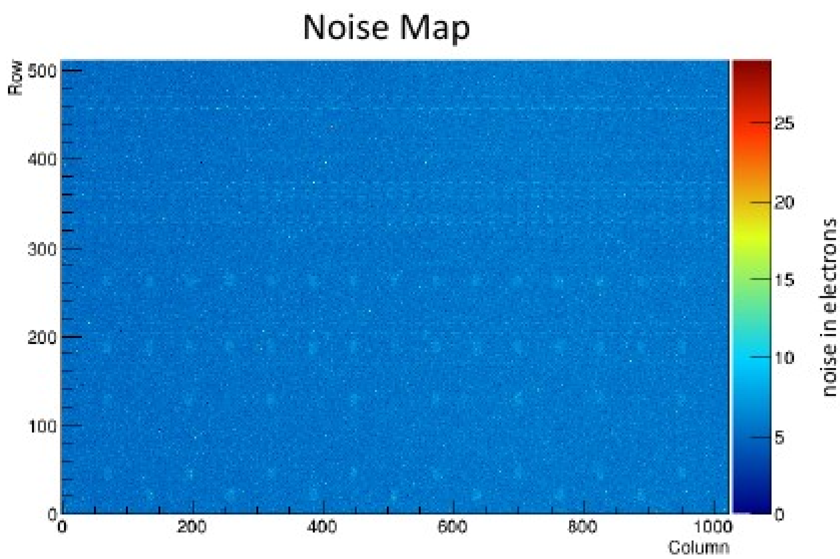
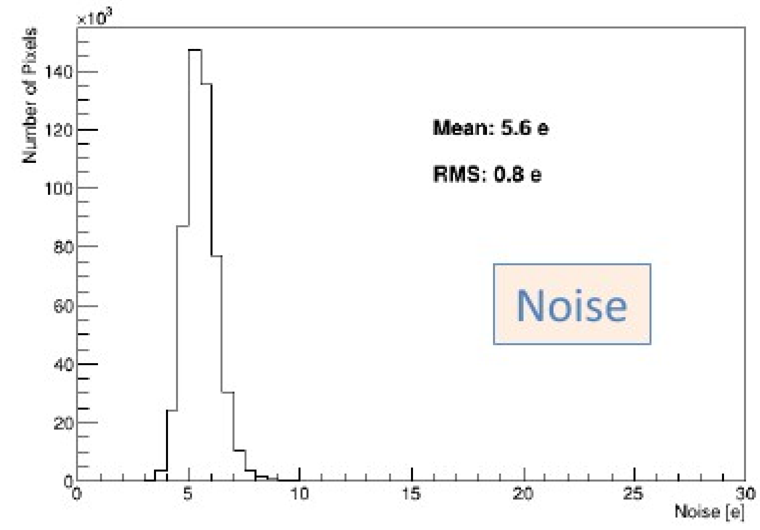
Figure taken from PhD thesis M. Suljic

ALPIDE – Threshold and Noise





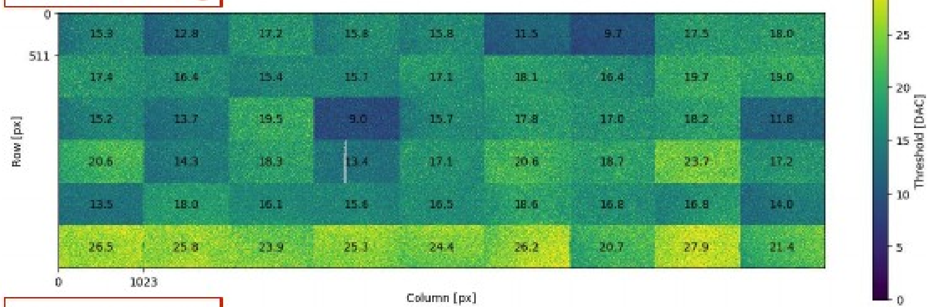




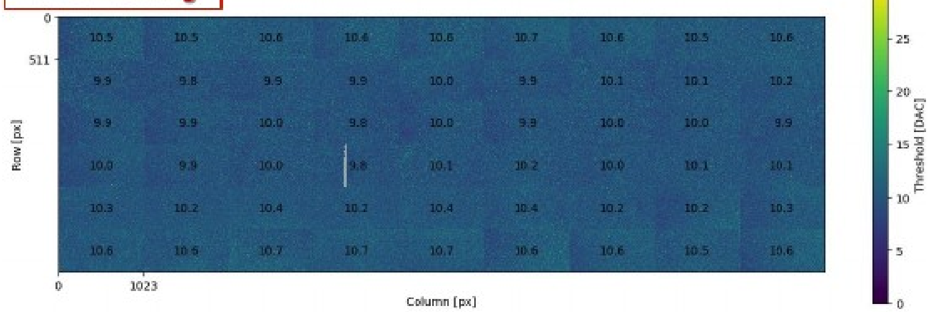
ALPIDE - Threshold Tuning

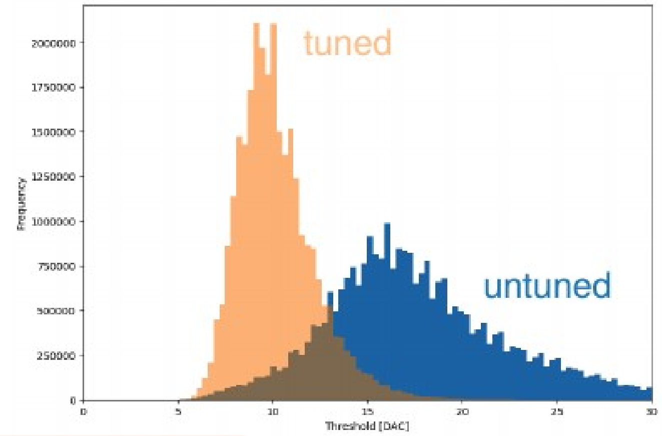
Threshold Tuning 54 alpides

Before Tuning

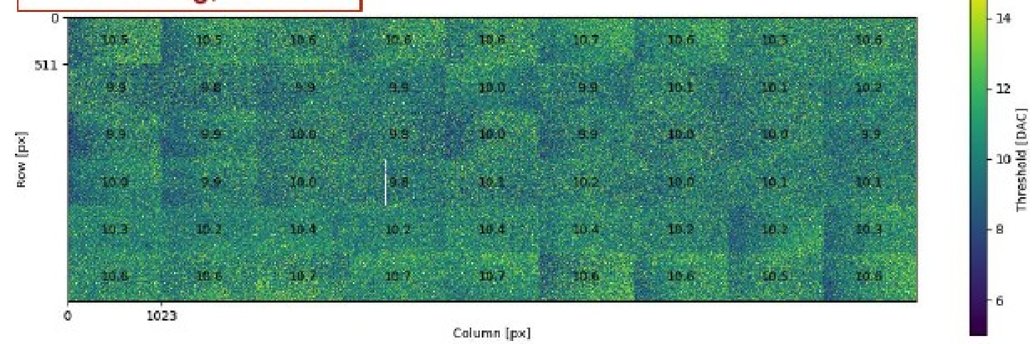


After Tuning



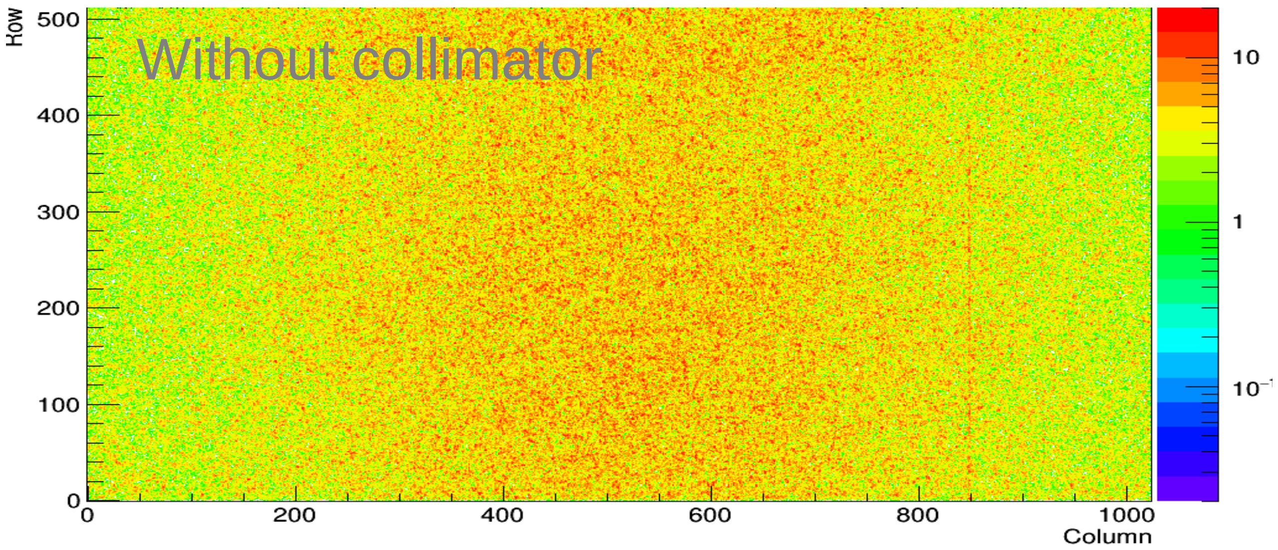


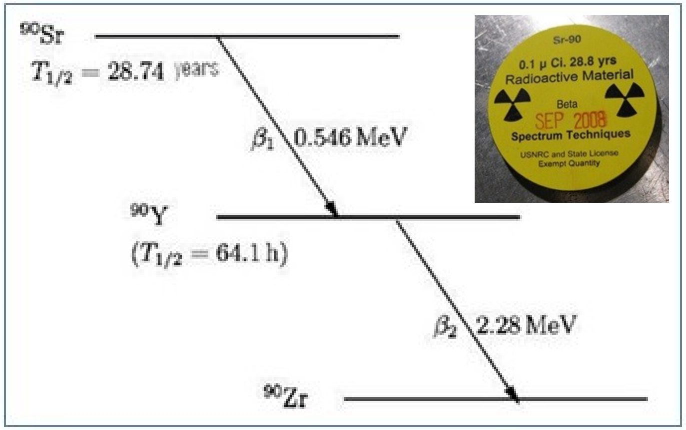
After Tuning, zoomed

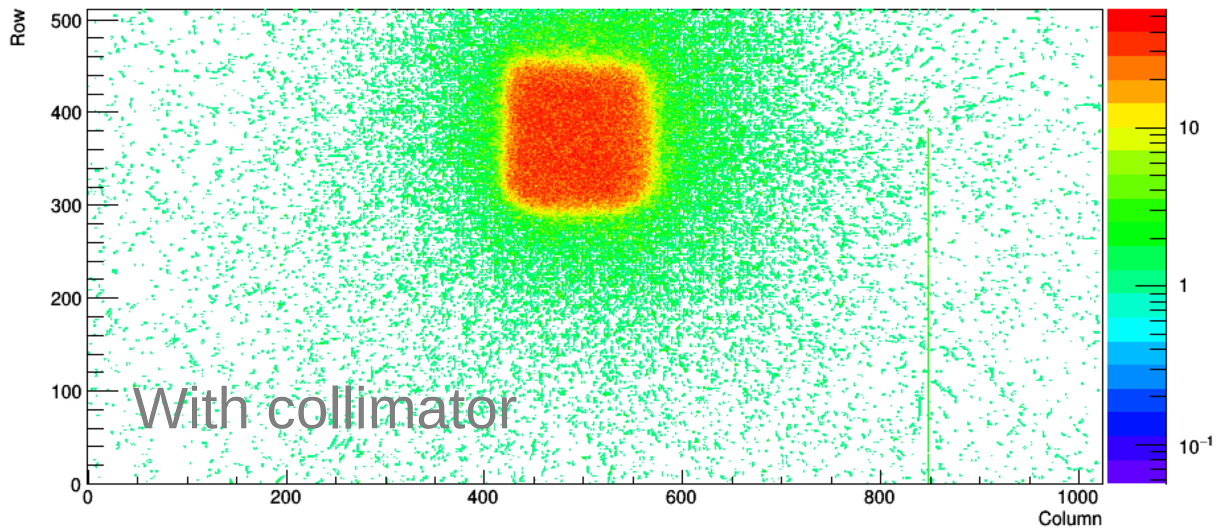


- Adjustment front-end parameters to equilibrate the charge threshold of all chips

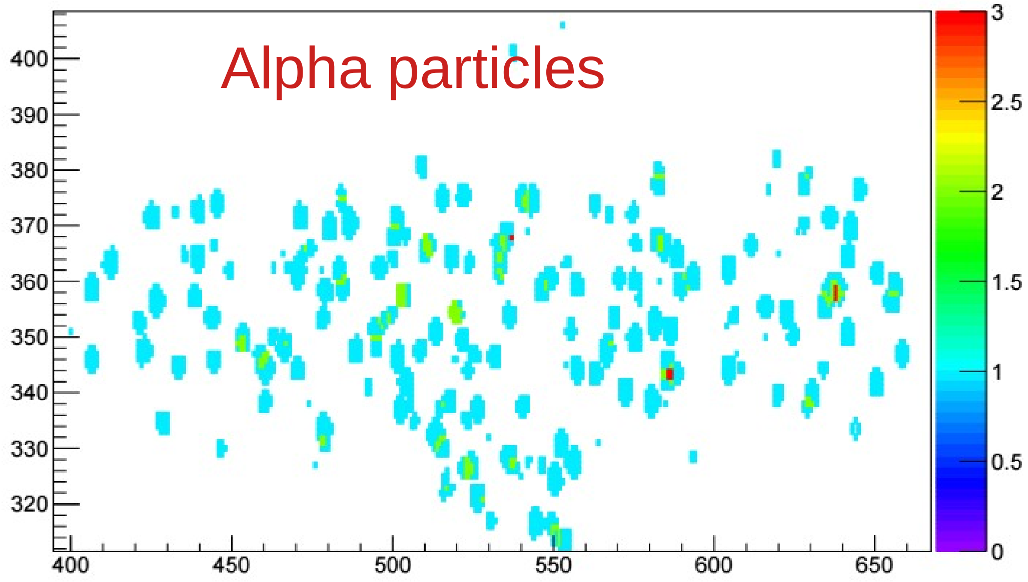
ALPIDE - Response to Electrons

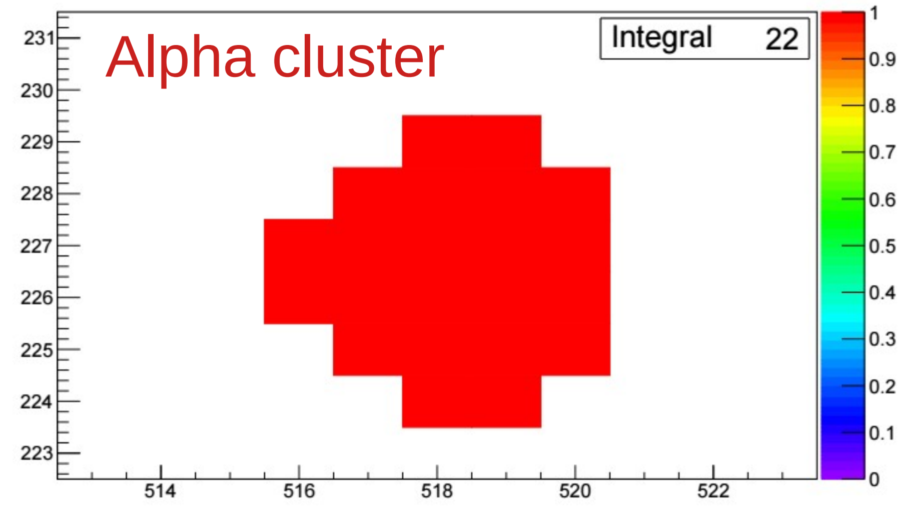


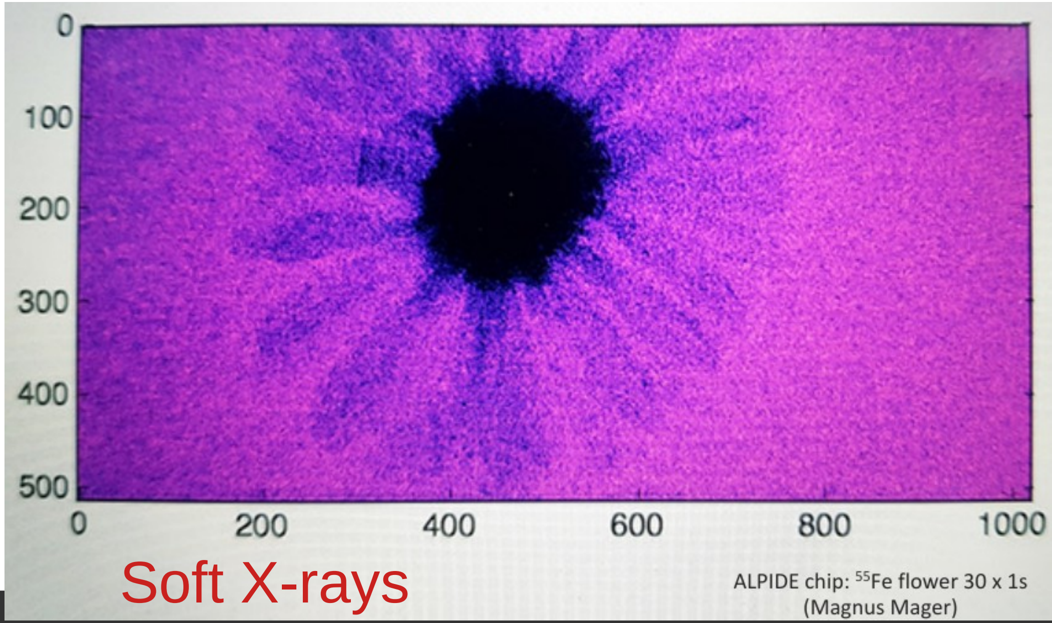




ALPIDE - Response to Alphas and Soft X-rays



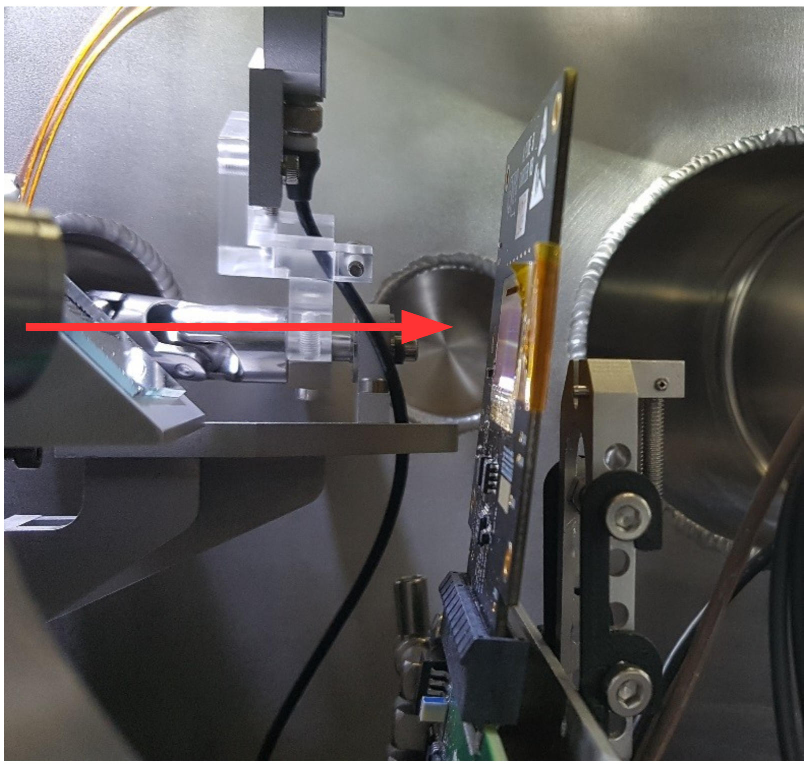




Micro Beam Test

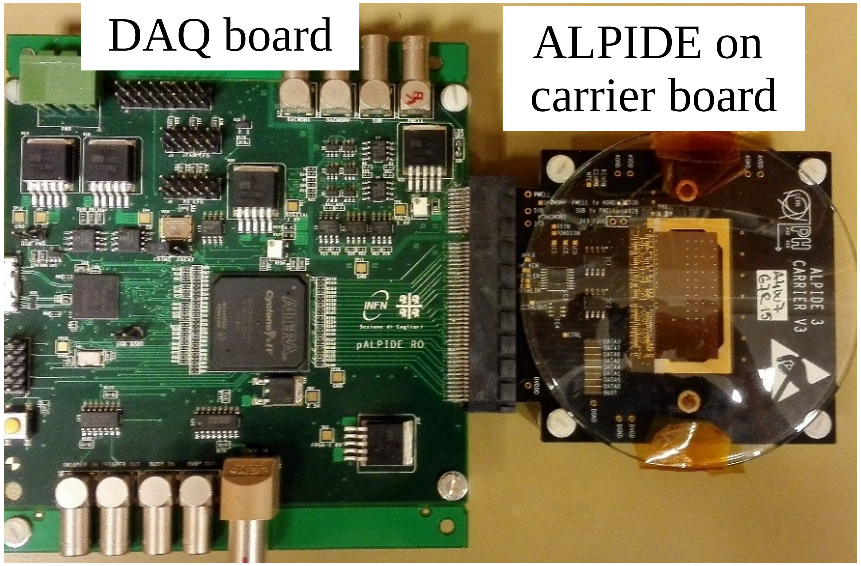
Aim: Study the effect of beam position on cluster size

Test done at Australia Nuclear Science and Technology Organization (ANSTO) in Australia



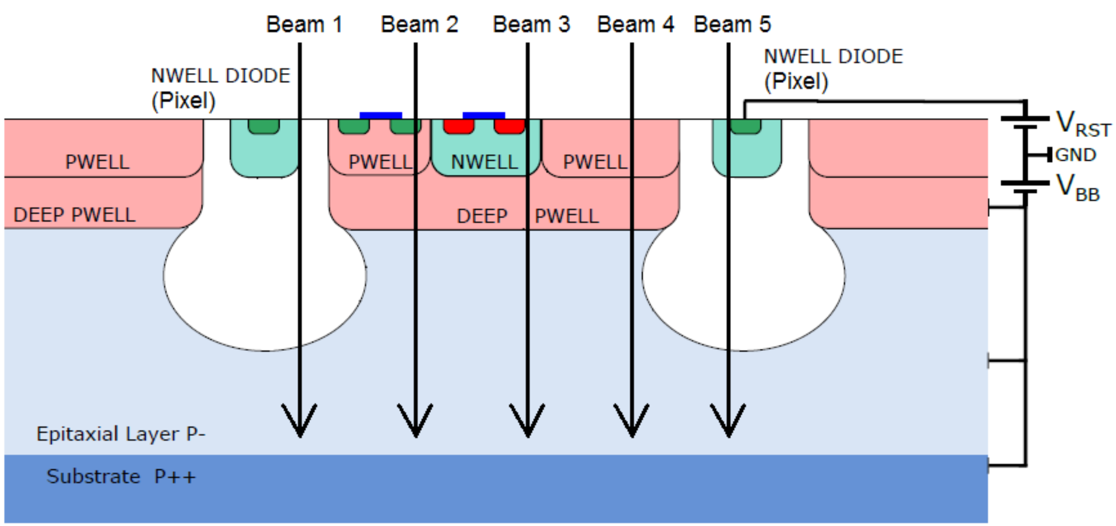
ALPIDE inside the vacuum chamber
ALPIDE tilted by ~ 5^0
Beam direction shown by Red arrow

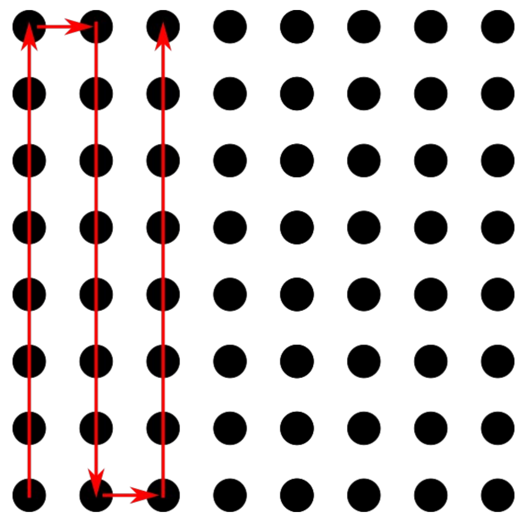
- Test parameters
  - Ion beam — Helium-4
  - Energy — 10 MeV (± 0.1 MeV)
  - Beam size — 1 µm
  - Rate — 2 k to 10 k ions/sec
  - Trigger freq. (period) — 100 kHz (10 µs)
  - Bias Voltage — 0 V and -3 V



Micro Beam Test

- ALPIDE surface was raster scanned
  - Spot size 1 µm
  - Area 128 x 128 µm²
  - Dwell time 200 ms / spot
  - Single pixel size 27 µm x 29 µm

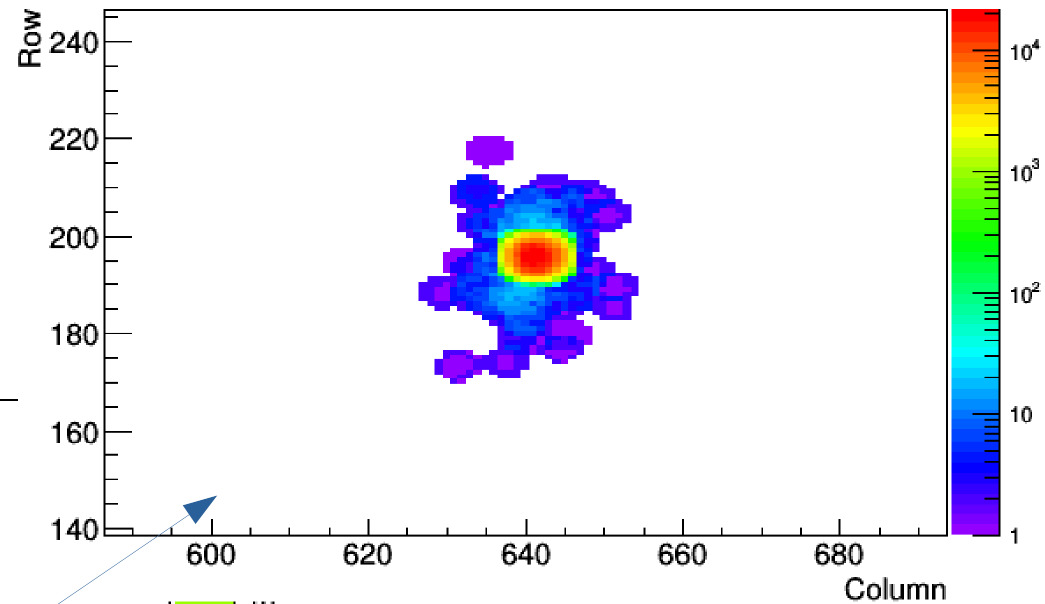


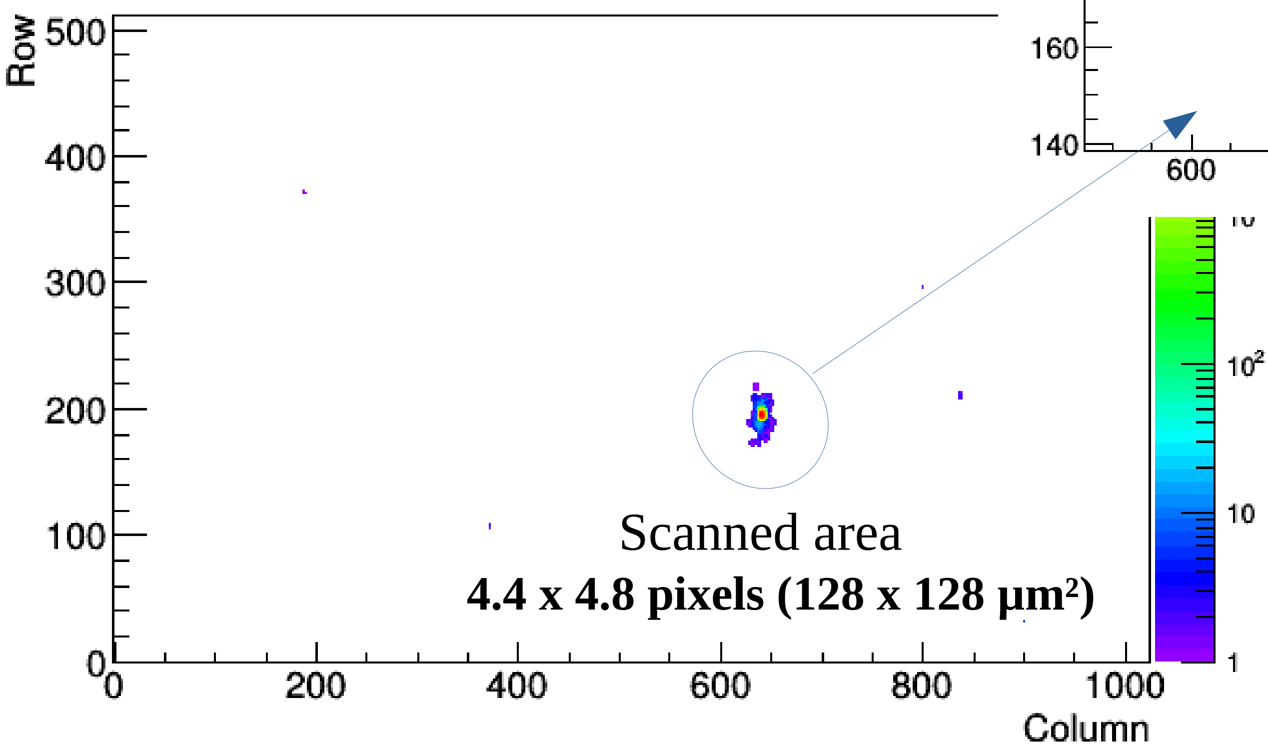


Dot – beam spot
Red arrow – beam spot moving direction
Dwell time – the time spent by beam on a dot

Scanned Area

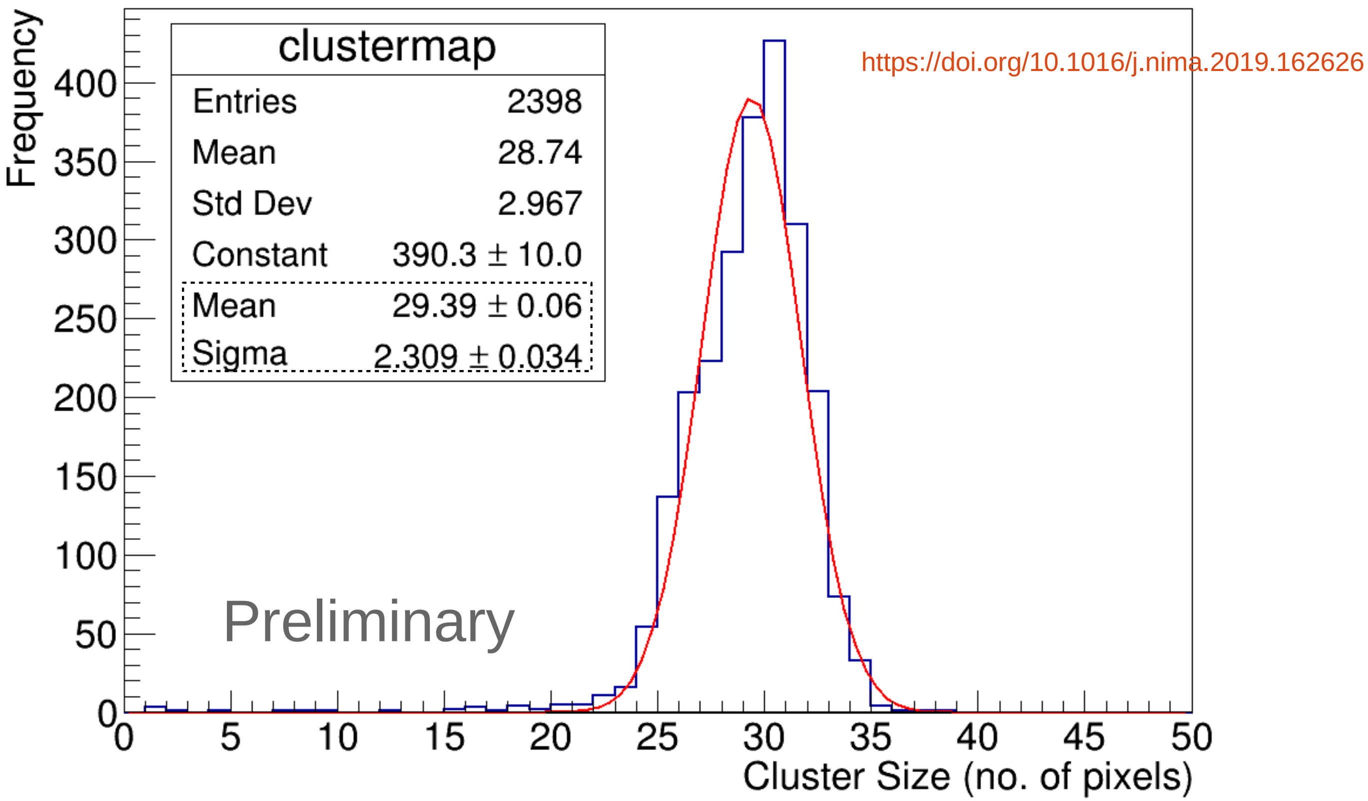
- He4 beam energy 10 MeV
- Beam freq. 10 kHz
- Dwell time 200 ms/spot
- Bias voltage 0 V





Cluster Size: High LET Micro Beam

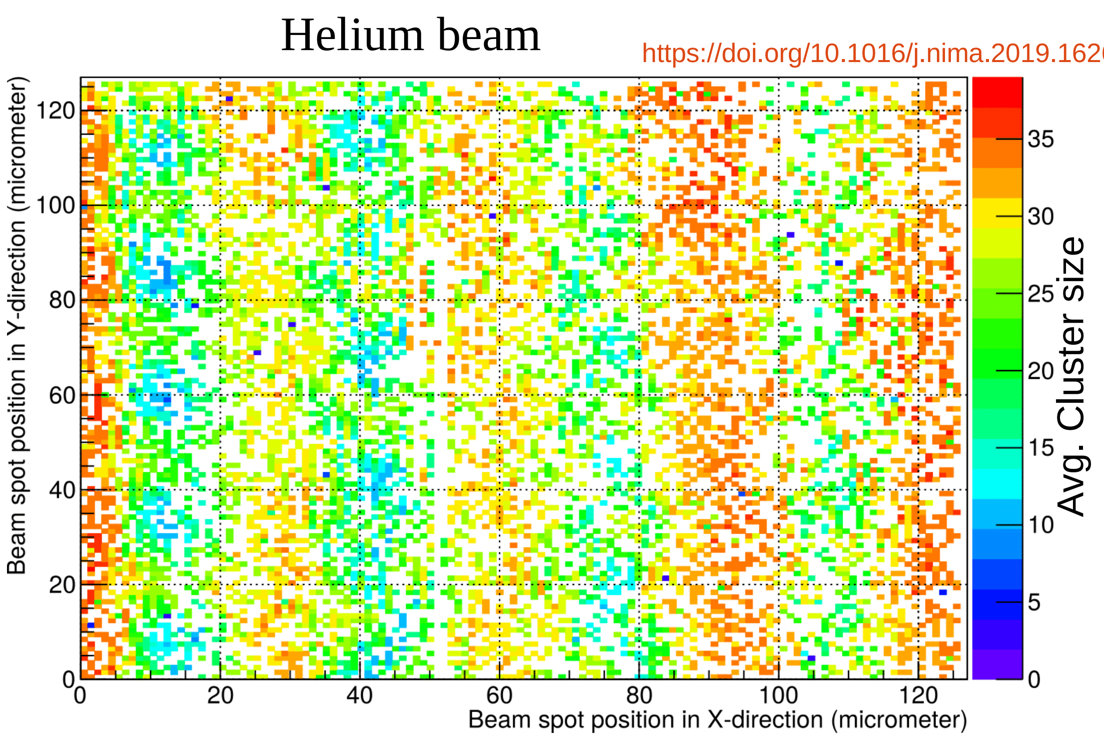
Data set selected for few spots



Possible to record heavy ions with ALPIDE!

LET: Linear Energy Transfer

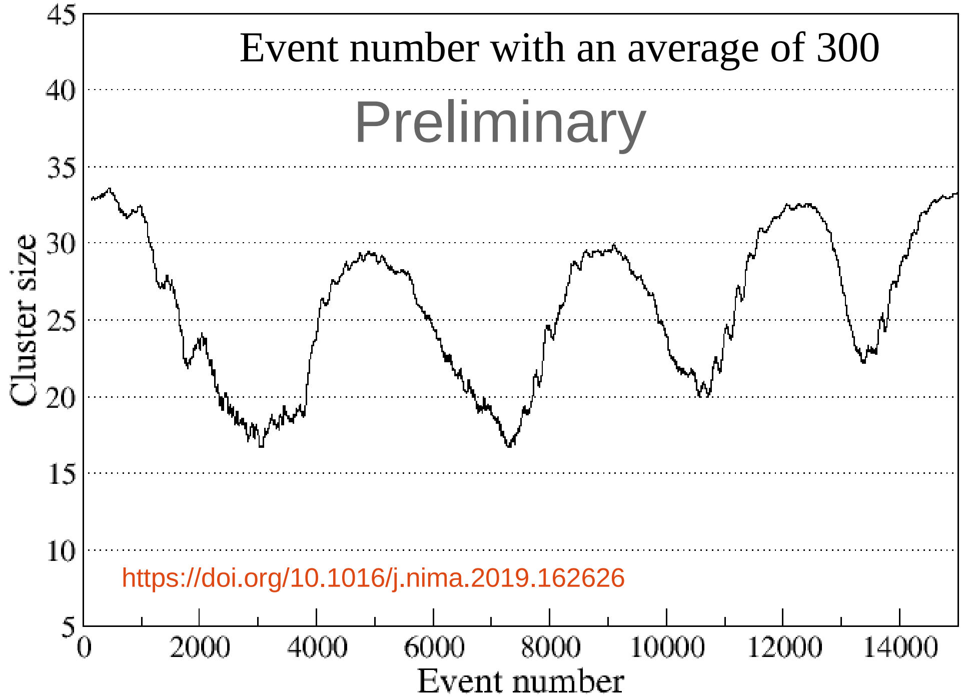
Cluster Size Map



- Clusters are dependent on the beam position
- Clusters are rather constant in vertical bands visible on various X-values
- Clusters could be smaller
  when the beam is positioned in the vicinity of collection diode than in its periphery
- No direct impact on particle tracking: cluster center is used for particle tracking

Avg. cluster size vs. Event number

Event number → X - position → Irradiation time

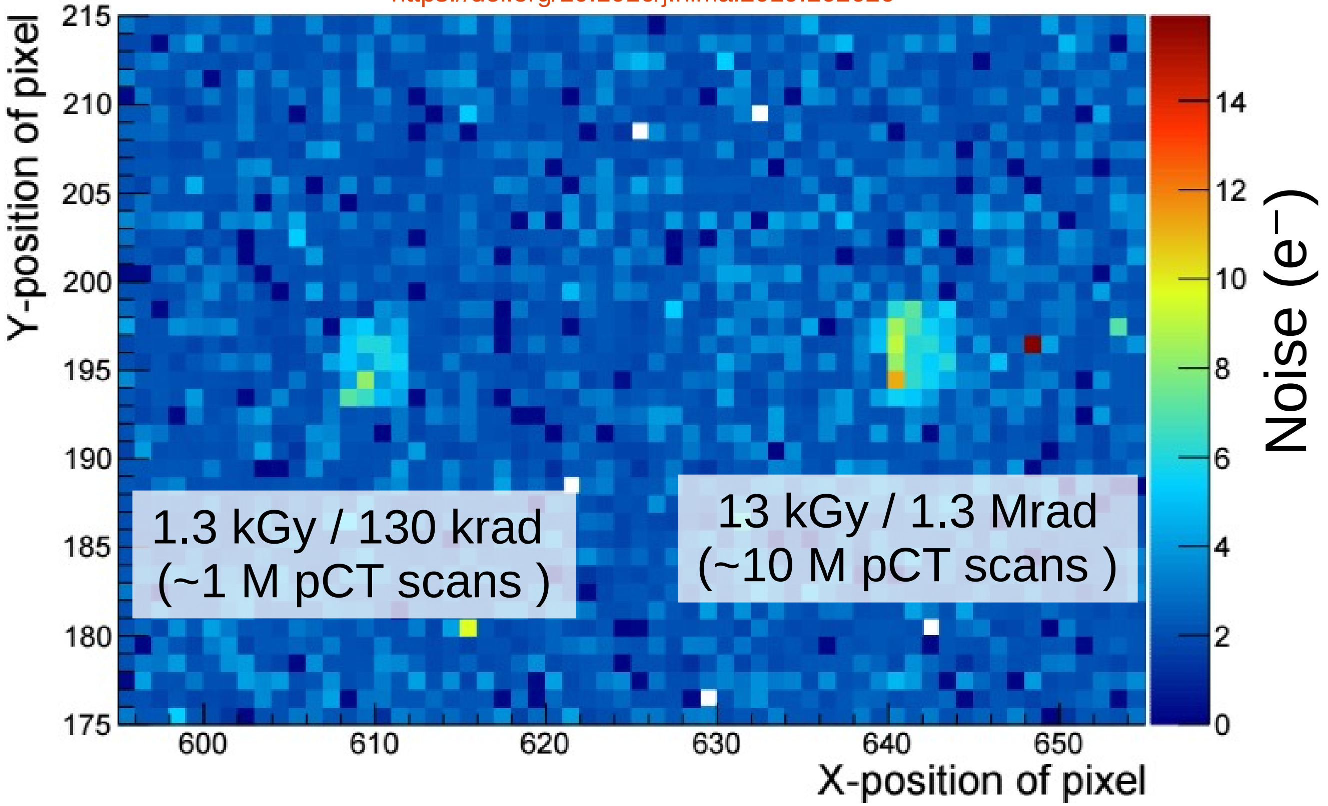


- Beam moving from left to right, across the columns
- Oscillating pattern:
  - Some areas are slightly more sensitive than others due to process variations
  - Rise in temperature, chip was in vacuum – cooling required (~ 20^{0} C)
  - Small increase in noise due to irradiation

Noise Map: Irradiated ALPIDE

- Scanned two places in ALPIDE:
  - 2 kHz beam freq. (at Right) and 10 kHz beam freq. (at Left)

https://doi.org/10.1016/j.nima.2019.162626

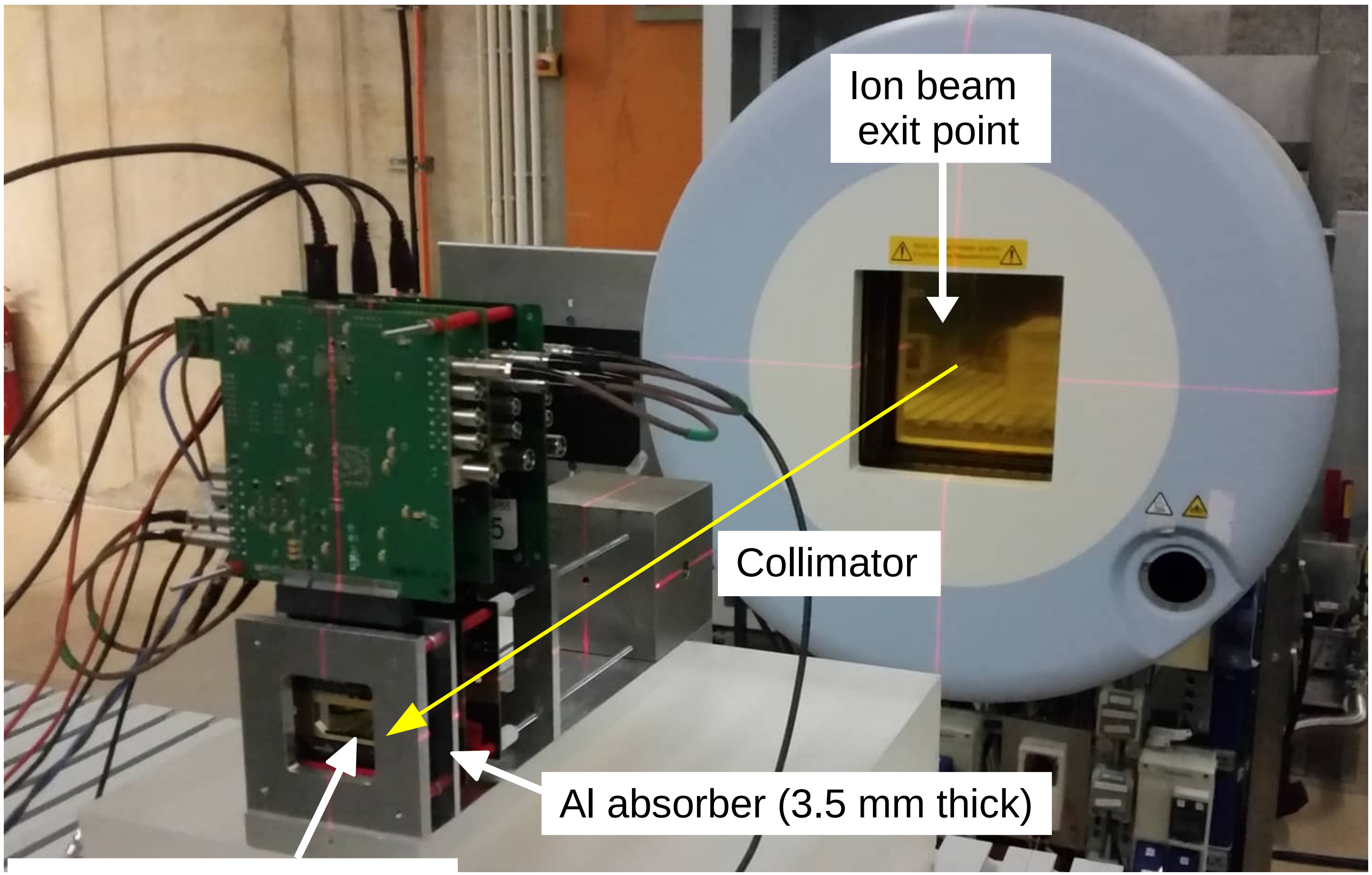


- Increase in noise but ALPIDE was working → No serious issues!!

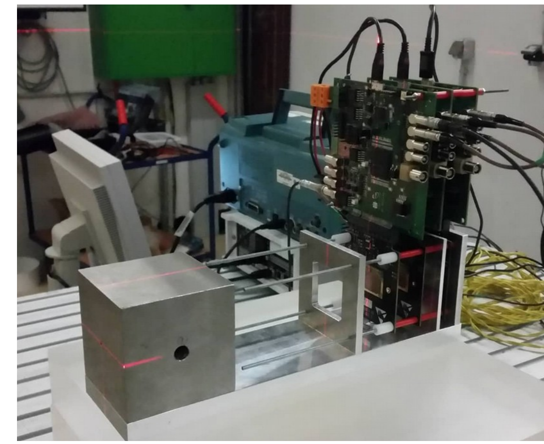
ALPIDE Telescope Experiment at HIT, Heidelberg

Aim: Ion tracking, clusters vs. ion energy (LET)

Test setup at Heidelberg Ion-Beam Therapy Center (HIT)

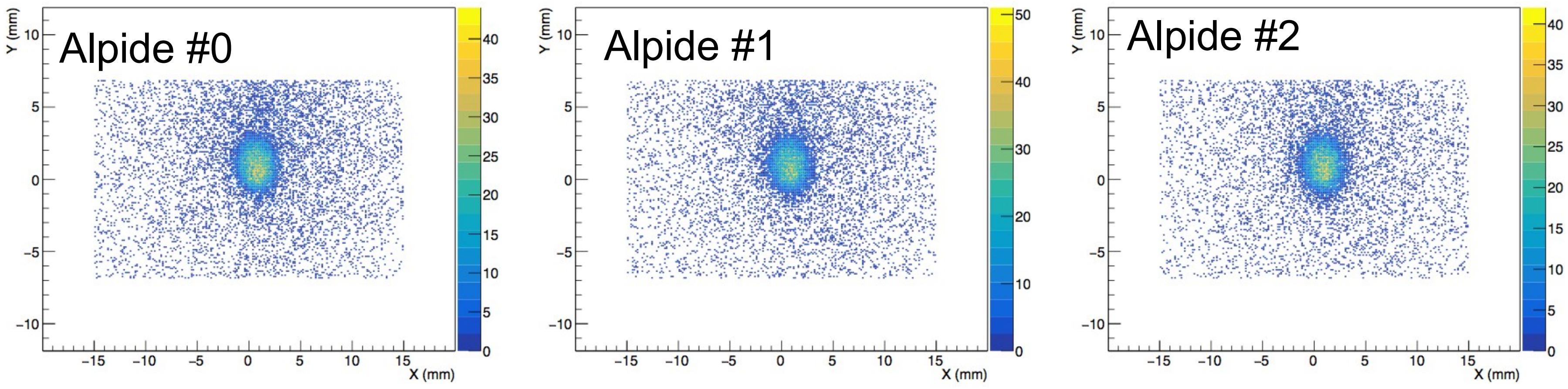


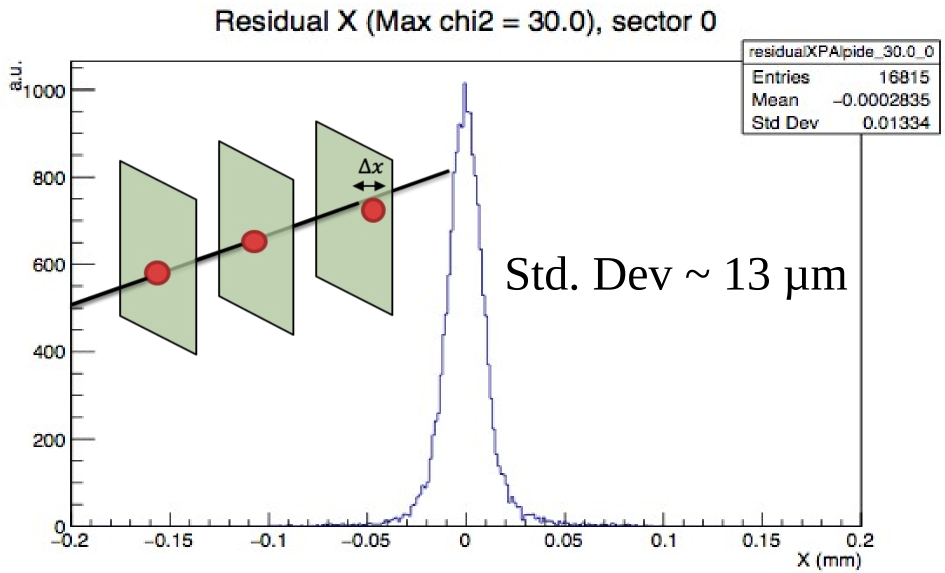
Telescope – 3 ALPIDE



Beam energy (MeV/u)	
Helium	Proton
50.57	48.12
100.19	200.11
150.11	221.06
200.38	
220.5	

Beam Alignment

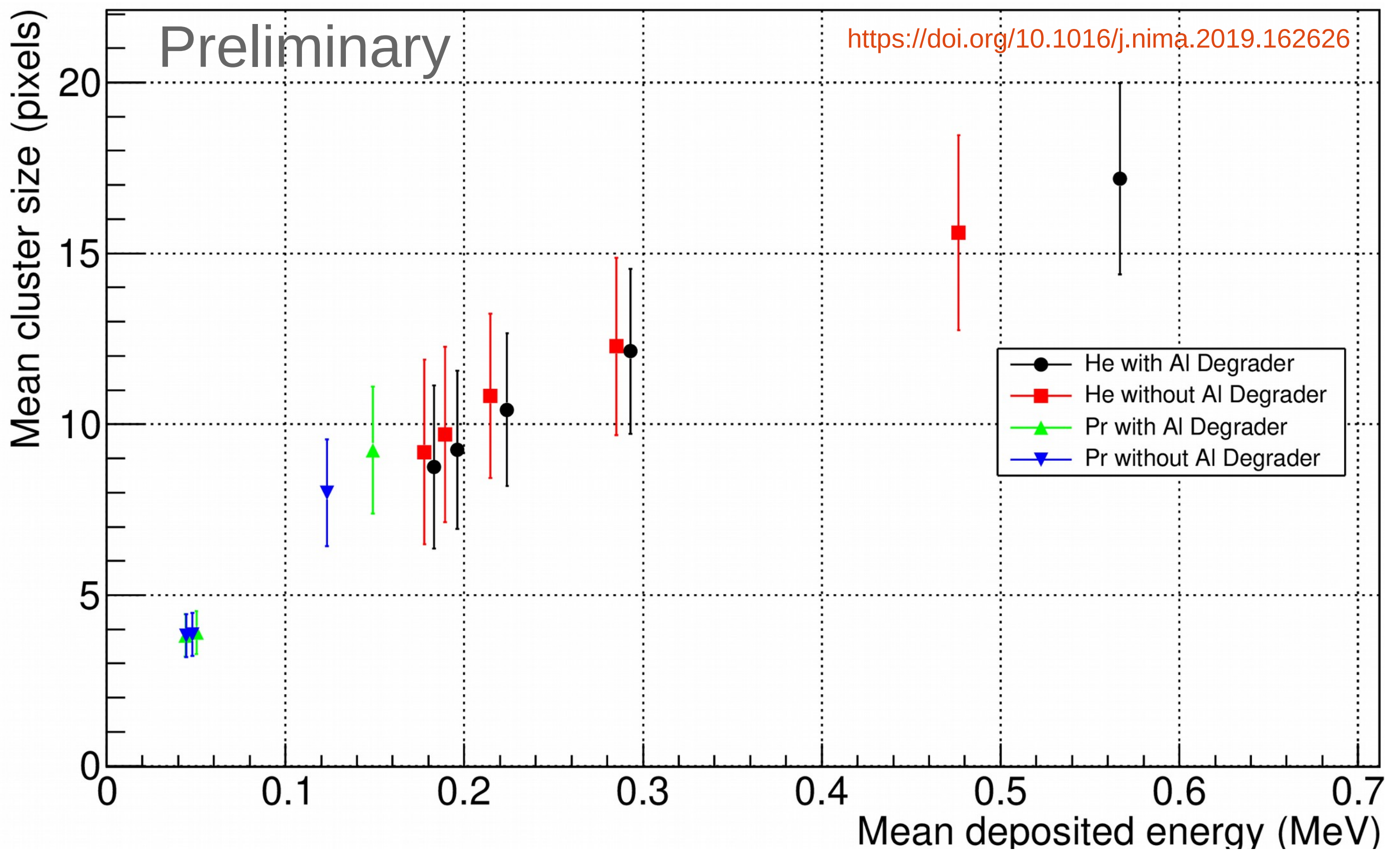




- Energy 220.5 MeV/u (FWHM = 10.1 mm)
- ^{4}He rate ~ 80 kHz
- Time frame 10 μs
- Collimator 3 mm

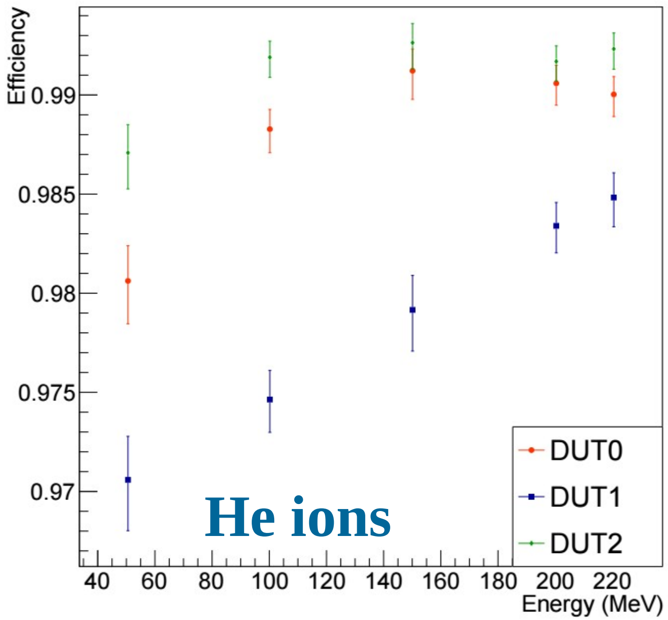
Cluster Size vs. Energy Loss in ALPIDE w/o Absorber

For proton and helium in layer3

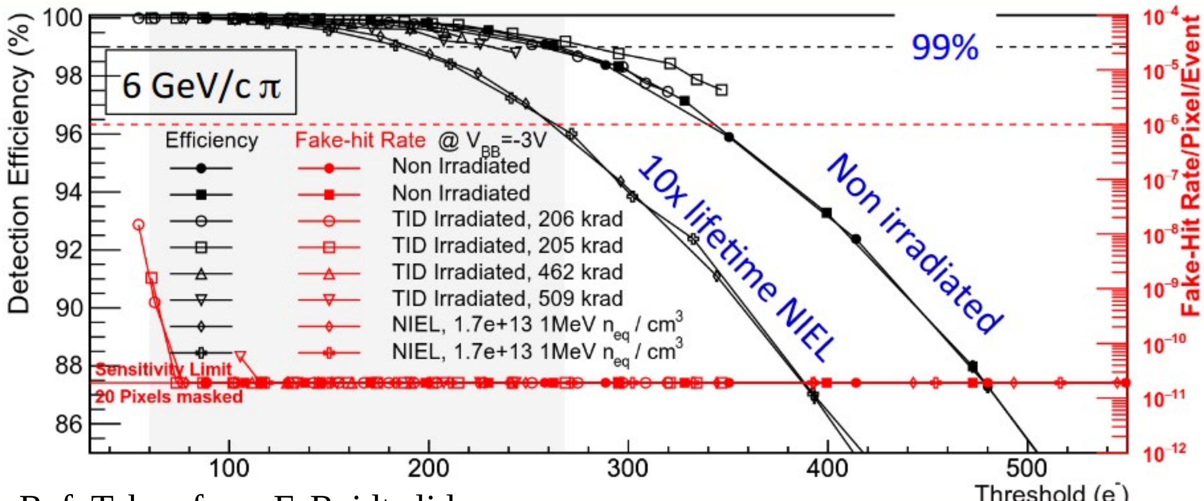


- Tracking of He and p beam is possible down to 50 MeV/c w/o absorber
- Cluster size decreases in proportion with LET
- Proton clusters are smaller than Helium as expected

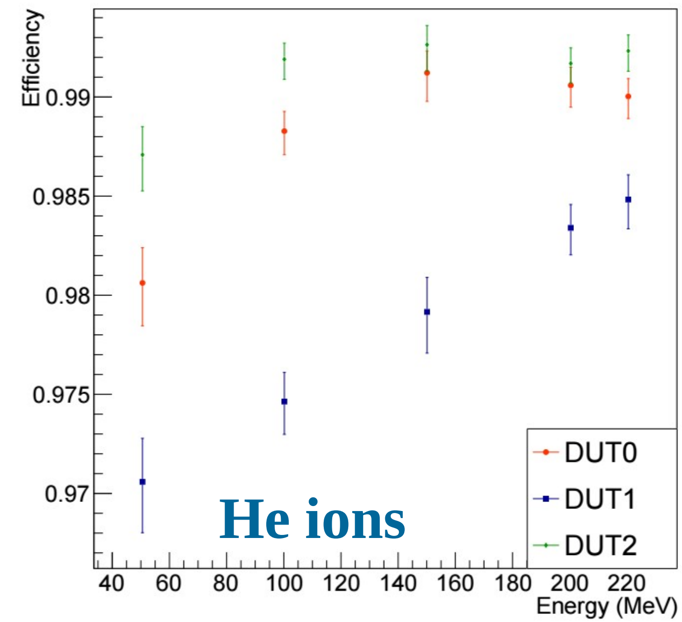
Detection Efficiency



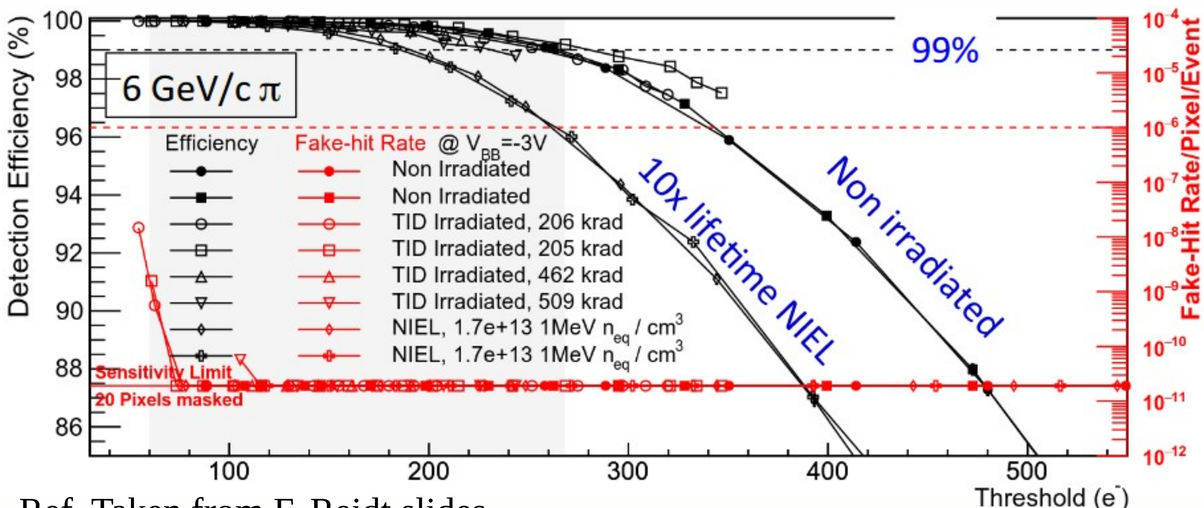
Detection Efficiency



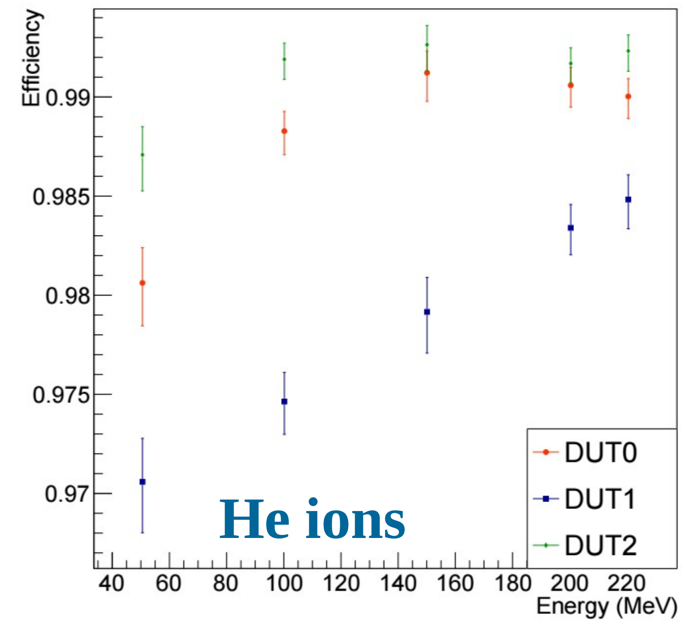
Ref. Taken from F. Reidt slides



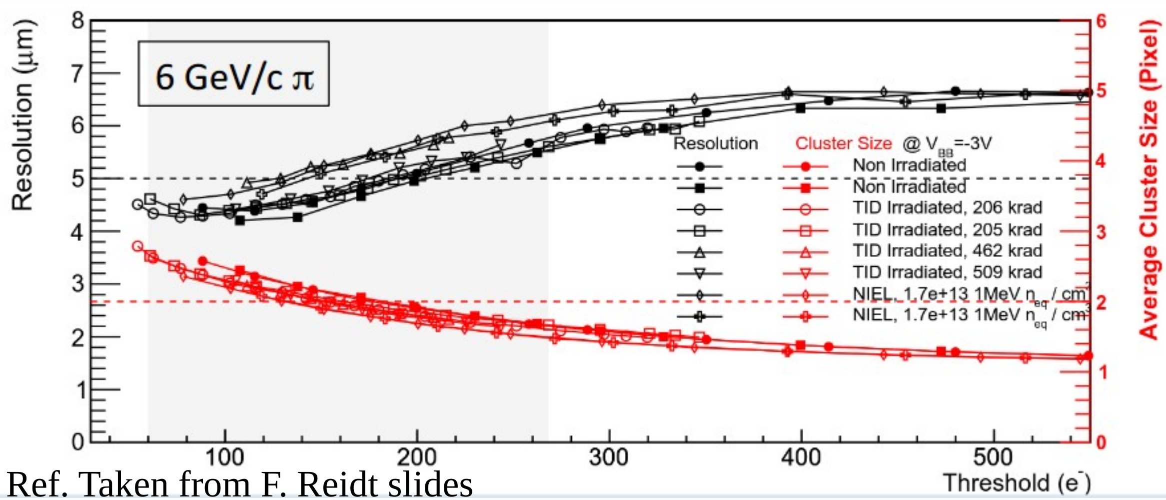
Detection Efficiency



Ref. Taken from F. Reidt slides



Position Resolution pions

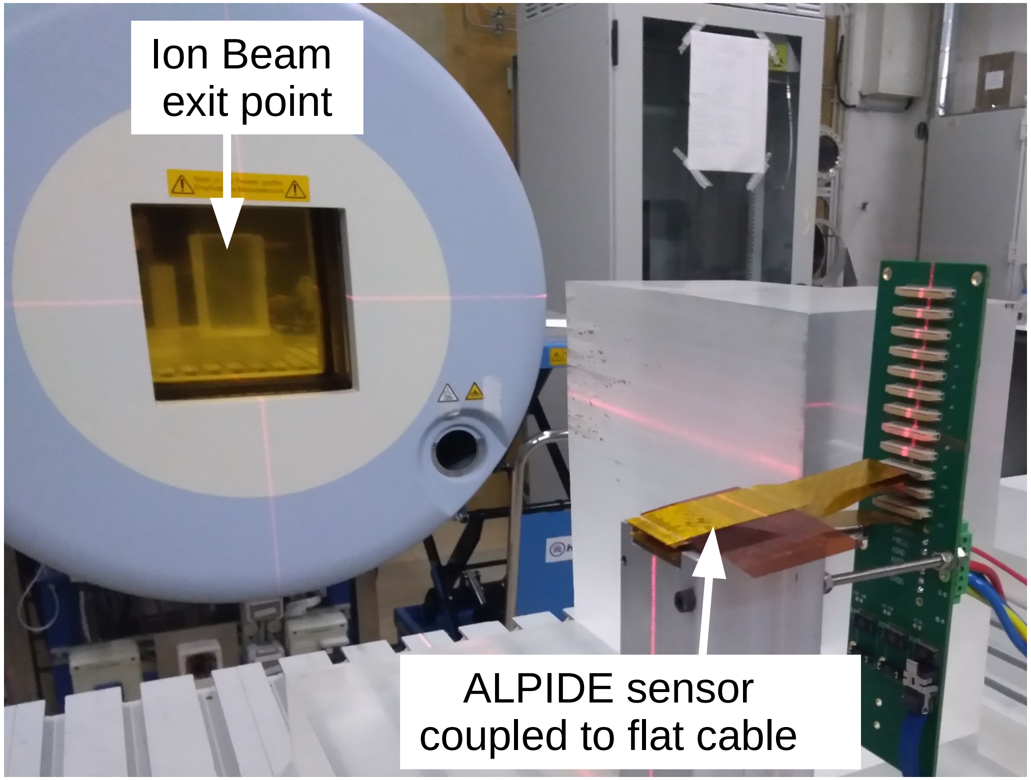


Ref. Taken from F. Reidt slides

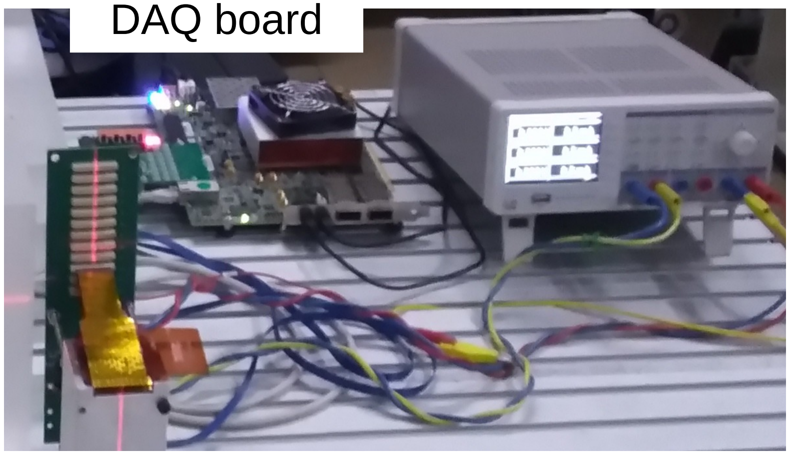
Single ALPIDE Experiment at HIT Heidelberg

Aim: Lateral scan of ALPIDE – capture ion tracks for high LET ion beam

Heidelberg Ion-Beam Therapy Center (HIT)



Carbon beam energy: 140.4 MeV/u

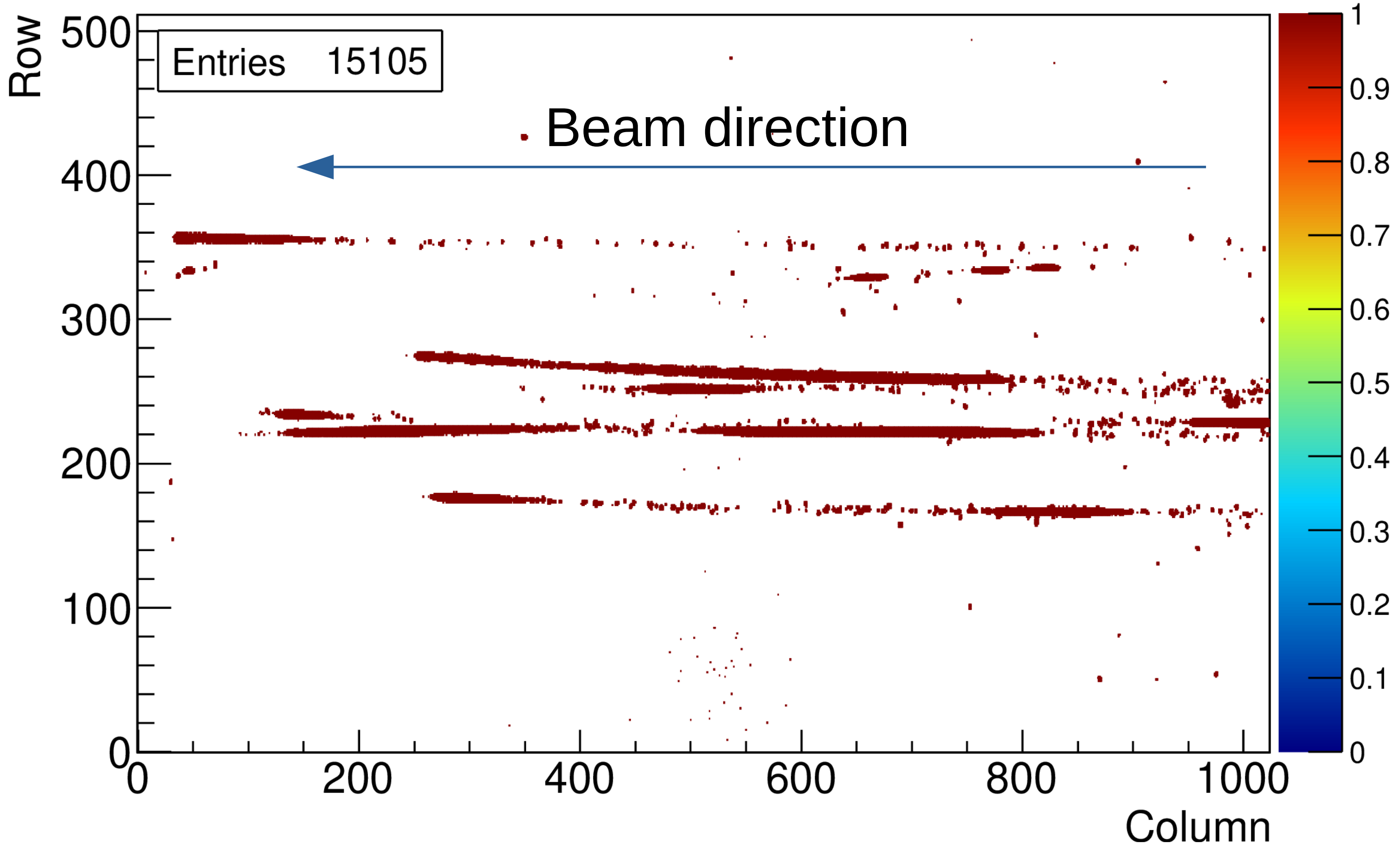


Range of Carbon
in ALPIDE (50 µm thick) ~ 2.5 cm

The ALPIDE chip was kept at few meters away from the beam exit
to stop the beam in sensitive volume of the chip – Record high multiplicity events

Hitmap: Carbon Ions

Hitmap of 1 time frame or 1 event = 485 μs

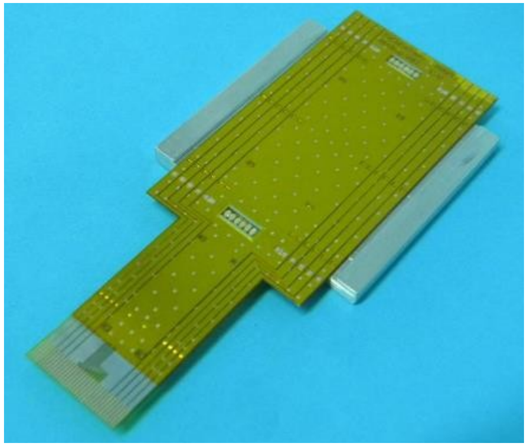


Possible to record high multiplicity event !

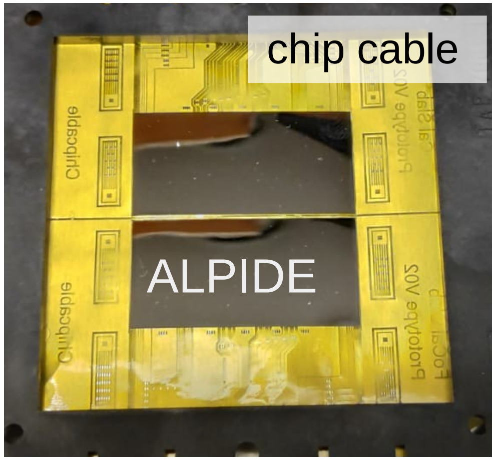
Mounting Sensors on Flexible Cables

Intermediate prototype: chip cable with two ALPIDEs

Back side



Front side

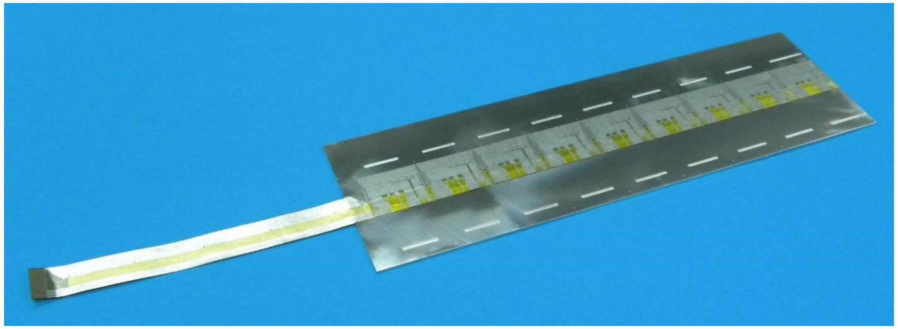


- ALPIDE mounted on thin flex cables:
  Aluminum-polyamide dielectric
  (30 um Al, 20 um plastic)

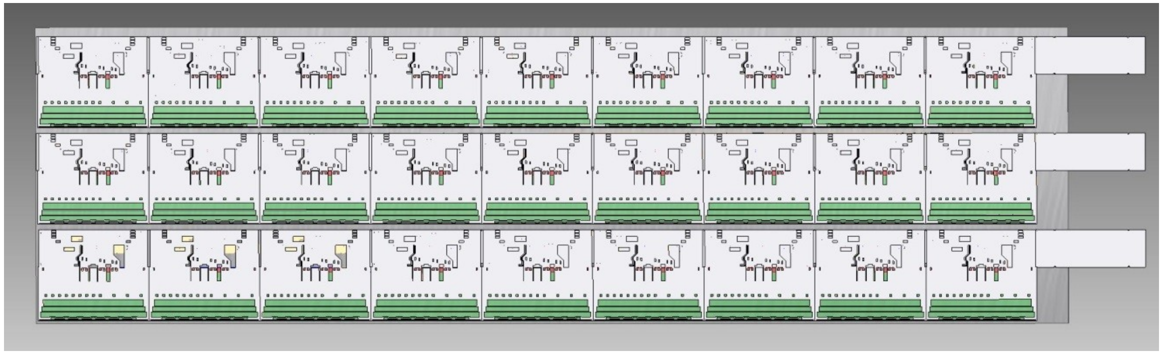
- Design and production:
  Utrecht University, The Netherlands and
  LTU, Kharkiv, Ukraine

Final system

Flexible carrier board modules (1 x 9 chips)



Schematic: Flexible carrier board modules (3 x 9 chips)



Thank you!

Dose Calculations: full 3D scan

Assuming proton beam of 150 MeV energy given to the complete system with an average density of 2.67 g/cm³ and 400 cm² area of the scanner.

The dose on average per scan is

= [200 Million protons * 150 MeV proton beam energy] / [400 cm² * 20 layers (from range of 150 MeV protons) * 0.3945 cm/layer * 2.67 g/cm³] = $4.8e^{-3}$ J / 8.43 kg

= ~ 1 mGy per scan

Hence, 1.3 kGy dose corresponds to about 1 M pCT scans. A new text is added in the revision (line 128-129).