



UNIVERSITÀ DI PISA

# Characterization of monolithic CMOS pixel sensors for charged particle detectors and for high intensity dosimetry

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# Outline

- ▶ Pixel detectors
- ▶ CMOS Monolithic Active Pixels
- ▶ TJ-Monopix1
- ▶ Characterization
- ▶ Beam test and FLASH-RT

# Outline

- ▶ Pixel detectors
  - ① Pixel detectors: many different types
  - ② Hybrid versus monolithic
- ▶ CMOS Monolithic Active Pixels
- ▶ TJ-Monopix1
- ▶ Characterization
- ▶ Beam test and FLASH-RT

# Pixel detectors: many different types

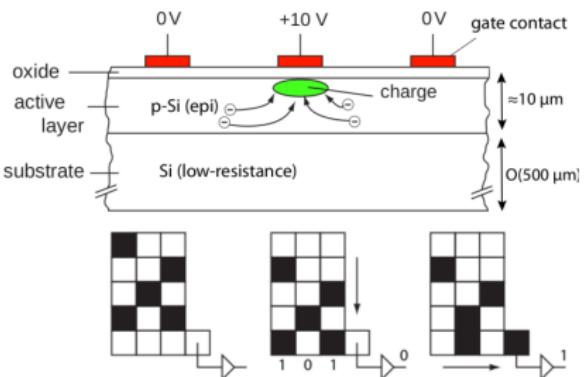
Originally developed for **imaging** applications. Then used for charged particle **tracking**, providing unprecedented resolution to reconstruct decay vertices.

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- ▶ CCDs
- ▶ Hybrid pixels
- ▶ Monolithic Active Pixels
  - DEPFET
  - CMOS MAPS

Readout completely sequential:  
charge moved stepwise into one  
readout node → very slow

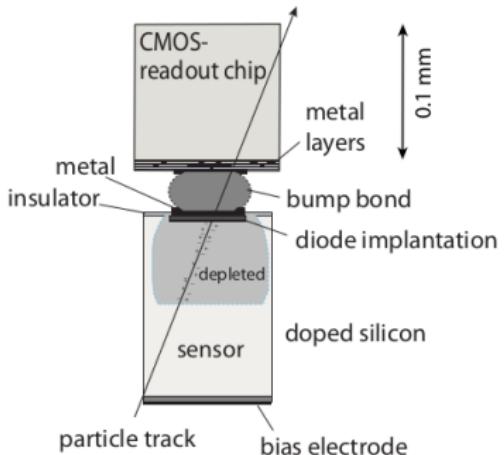


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- ▶ **Hybrid pixels**
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  - DEPFET
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Two wafer: one for the sensor and one for the ASIC then microconnected

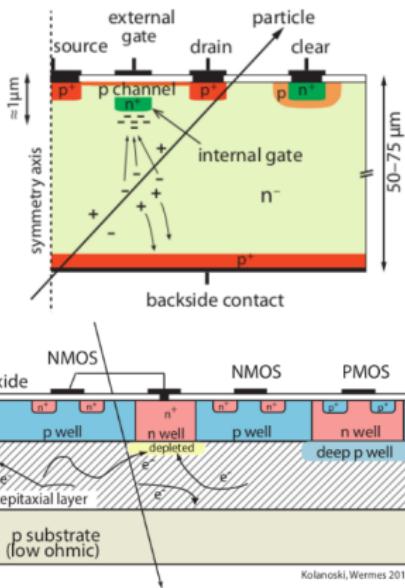


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- ▶ Hybrid pixels
- ▶ **Monolithic Active Pixels**
  - DEPFET
  - CMOS MAPS

One wafer with both the sensor and the electronics: MAPS usage allowed by miniaturization of components



# Hybrid versus monolithic

## Hybrid pixels

- ① module area  $\sim 10 \text{ cm}^2$
- ② rate capability  $\sim \text{GHz}/\text{cm}^2$
- ③ sensor and ASIC can be optimized separately
- ④ are more radiation hard



## Monolithic active pixels

- ① pitch  $\sim 10\text{-}50 \mu\text{m}$
- ② point resolution  $\sim 5\text{-}10 \mu\text{m}$
- ③ thickness  $\sim 25\text{-}50 \mu\text{m}$
- ④ low power consumption
- ⑤ good S/N ratio

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- ② point resolution  $\sim 10\text{-}15 \mu\text{m}$
- ③ thickness  $\sim 250 \mu\text{m}$
- ④ bump bonding delicate and expensive



Multiple Scattering!

- ① module area  $\sim \text{cm}^2$
- ② rate capability  $\sim 100 \text{ MHz}/\text{cm}^2$

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## Monolithic active pixels

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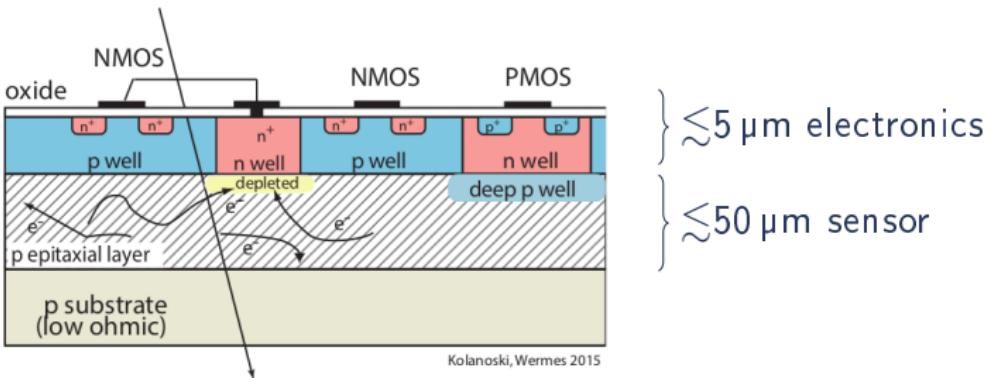
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Multiple Scattering! ↪

# Outline

- ▶ Pixel detectors
- ▶ CMOS Monolithic Active Pixels
  - ① Signal formation
  - ② CMOS MAPS scheme
  - ③ Front end electronics
- ▶ TJ-Monopix1
- ▶ Characterization
- ▶ Beam test and FLASH-RT

# CMOS MAPS: signal formation

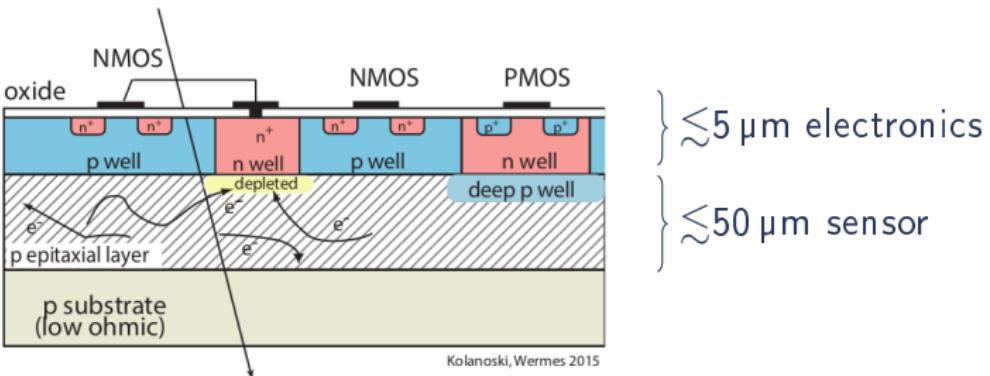


Signal produced by a particle:

- ▶ e/h created by ionization → in Si @ 300 K,  $w_i=3.6 \text{ eV}$
- ▶ by the motion of charge, by drift or diffusion

$$Q_{MIP} \propto d \sim 80 \text{ e}^-/\mu\text{m}$$

# CMOS Monolithic Active Pixel Sensors

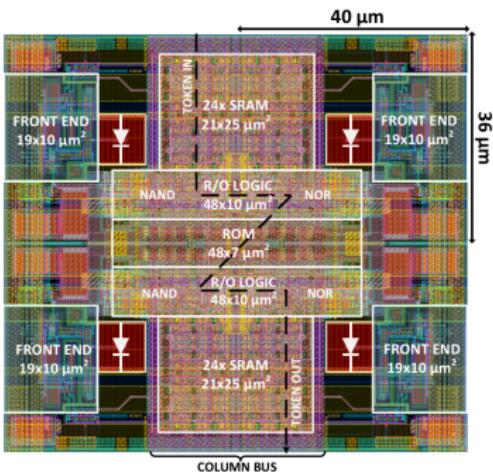


- ▶ High resistivity  $\rho$  allows for fully depleted epi-layer  
Depleted-MAPS at sufficiently low bias  $V$ :  $d \propto \sqrt{\rho V}$
- ▶  $V = Q/C \rightarrow$  if the sensor capacitance  $C$  is sufficiently low:
  - High signal and good **S/N** performances
  - High **gain** for the first amplification stage

# Front end electronics

Pitch $\sim$ 50  $\mu\text{m}$   $\rightarrow$  pixel area economy and dimension of components are extremely relevant.

MAPS usage allowed by miniaturization of components, i.e. TJ-Monopix1 is 180nm CMOS process.



The pixel area include the:

- ▶ Electrode
- ▶ Analog front end
- ▶ Digital readout

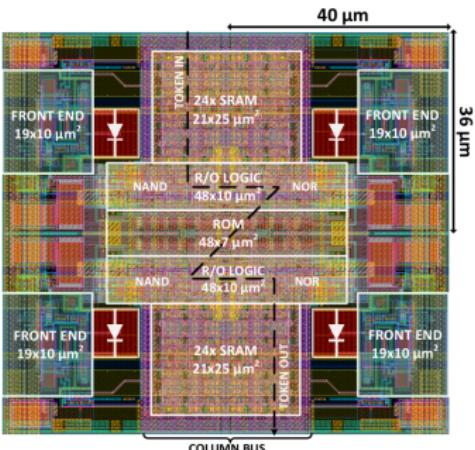
Analog	Digital
Triggered	Triggerless
Buffer	No buffer
Rolling shutter	Sparsified

# Outline

- ▶ Pixel detectors
- ▶ CMOS Monolithic Active Pixels
- ▶ TJ-Monopix1
  - ① TJ-Monopix1 design
  - ② TJ-Monopix1 analog output
- ▶ Characterization
- ▶ Beam test and FLASH-RT

# Front end electronics

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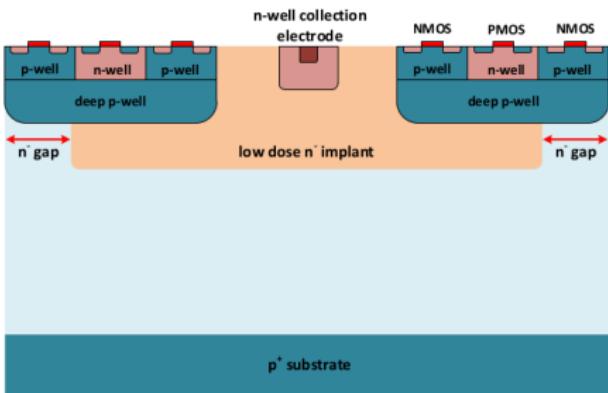
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# TowerJazz Monopix1

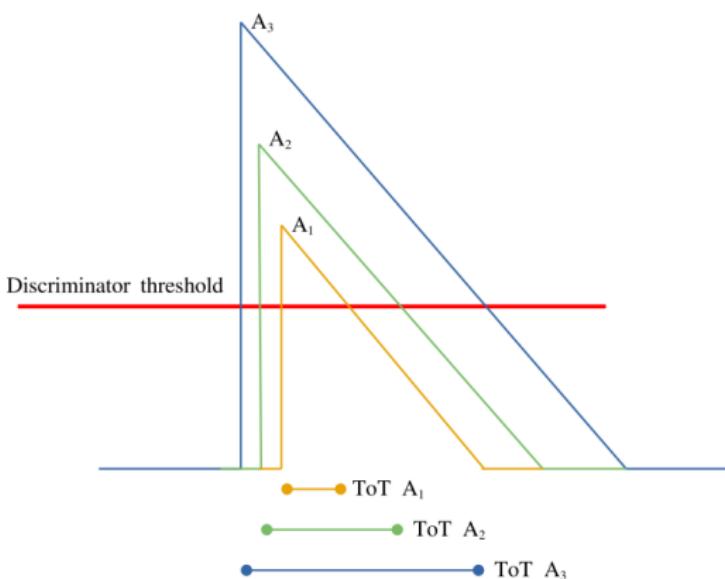
- ▶ Designed by ATLAS collaboration
- ▶ Produced by TowerJazz, an electronic foundry located in Israel
- ▶ Small electrode design:  $2\text{ }\mu\text{m}$  with  $C=3\text{ fF}$
- ▶ The sensor implements a process modification in the epi-layer that allows the creation of a planar junction (ALICE)
- ▶ The Front End has 4 flavors, all ALPIDE-like (ALPIDE chip design by ALICE and used in the ITS2)

Resistivity	$>1\text{ k}\Omega\text{cm}$
Matrix size	$1\times 2\text{ cm}^2$
Pixel size	$36 \times 40\text{ }\mu\text{m}^2$
Max depletion	$25\text{ }\mu\text{m}$
Time resolution	$25\text{ ns}$



# TJ-Monopix1 analog output

ToT = Time Over Threshold



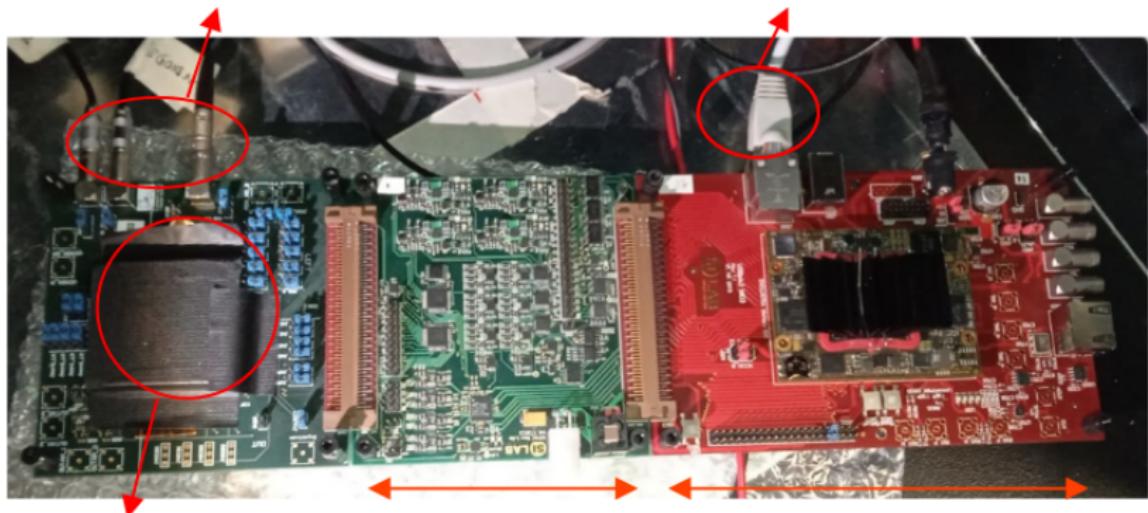
- ▶ The reset circuit of the amplifier made with a **PMOS**, guarantees the discharge of the preamplifier with constant slope
- ▶ The ToT grows linearly with the pulse amplitude
- ▶ Before readout ToT is stored in RAM as a 6-bits variable  
→ then the ToT can vary in range 0-1.6  $\mu$ s

# Outline

- ▶ Pixel detectors
- ▶ CMOS Monolithic Active Pixels
- ▶ TJ-Monopix1
- ▶ Characterization
  - ① Threshold and noise
  - ② Calibration of the ToT
  - ③ Characterization with radioactive sources
  - ④ Study of the readout time
- ▶ Beam test and FLASH-RT

# TJ-Monopix1 experimental setup

Bias of the sensor



DUT  
(Device Under Test)

GPAC breakout board

FPGA

# Threshold and noise

The lower the threshold, the lower the minimum detectable signal, allowing for thinner detector ( $Q_{MIP} \propto d$ ).

What determines the minimum stable threshold?

- ▶ the **ENC** = Equivalent Noise Charge
  - ▶ the **threshold dispersion** among different pixels
- .....

Expected values found by simulation with optimal FE settings

Noise	Threshold	Threshold dispersion
$\sim 9 \text{ e}^-$	$\sim 270 \text{ e}^-$	$\sim 30 \text{ e}^-$

# Threshold and noise: how to measure them?

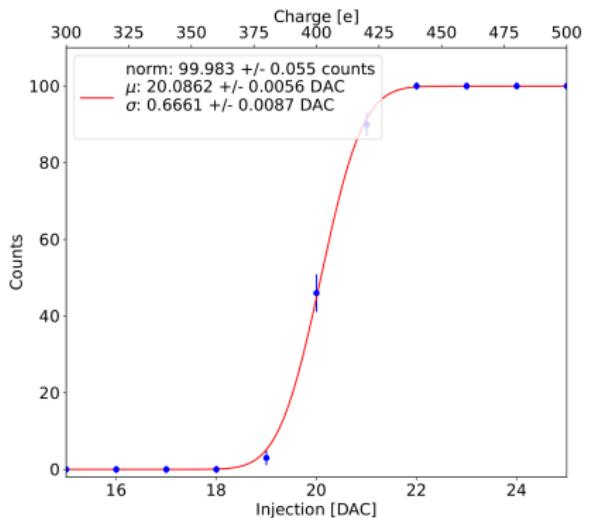
- ▶ Internal injection circuit allows sending a voltage step  $V_{inj}[\text{DAC}]$  on an injection capacitance  $C_{inj}$  at the FE input
- ▶ Scan at different pulse height  $V_{inj}[\text{DAC}]$  injecting 100 pulses at fixed discriminator threshold

By design:

$$C_{inj} = 230 \text{ fF} \rightarrow Q_{inj} = 20 \text{ e}^- / \text{DAC}$$

# S-curve

- Efficiency curve as a function of the injected  $V_{inj}$ [DAC]



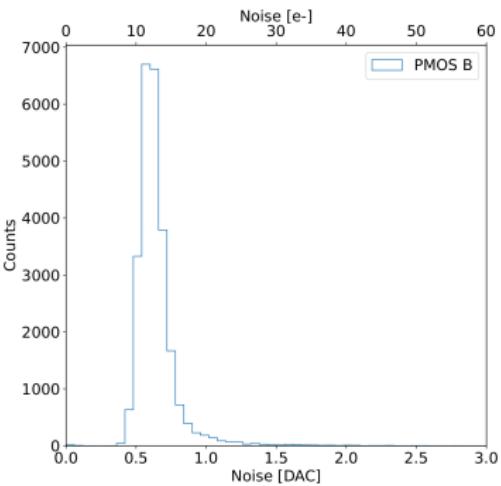
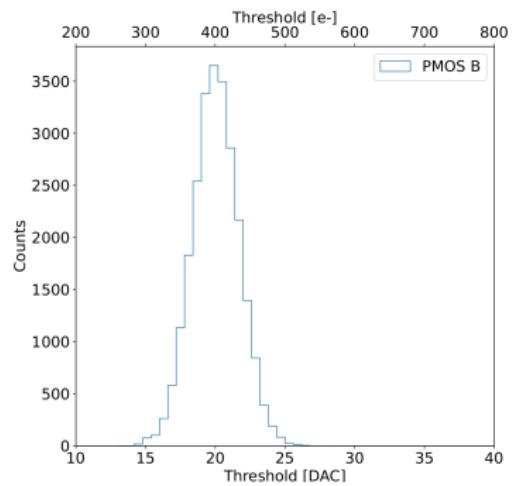
Assuming a gaussian noise:

- threshold → the 50%
- noise →  $1/\text{slope}$

Analytical parametrization of the curve with the *error function*

$$Q_{inj} = 20 \text{ e}^- / \text{DAC}$$

# Threshold and noise results



	Measurement	Simulation
$\mu$ [e $^-$ ]	$400.8 \pm 0.2$	$\sim 270$
$\Delta\mu$ [e $^-$ ]	$33.0 \pm 0.2$	$\sim 30$
$\sigma$ [e $^-$ ]	$12.26 \pm 0.07$	$\sim 9$
$\Delta\sigma$ [e $^-$ ]	$1.50 \pm 0.05$	-

- ▶ Measurement → without optimized FE settings
- ▶ Simulation → with optimized FE settings

# Calibration of the signal

How convert the  $ToT_{signal,clk}$  in electrons?

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- ① Used the **internal injection** circuit for a parametrization of the ToT:  $ToT_{signal,clk} \rightarrow V_{signal,DAC}$
- ② Used radioactive source as a reference in charge  $e^-$ :  
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- ▶  $P_{abs,photo-electric} \sim 58\% \rightarrow \lambda = 29 \mu\text{m}$
- ▶  $w_i = 3.6 \text{ eV in Si @ 300 K} \rightarrow 1616 e^-$

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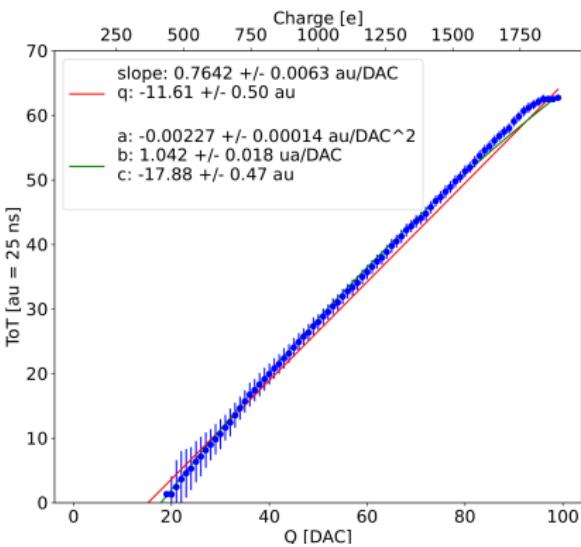
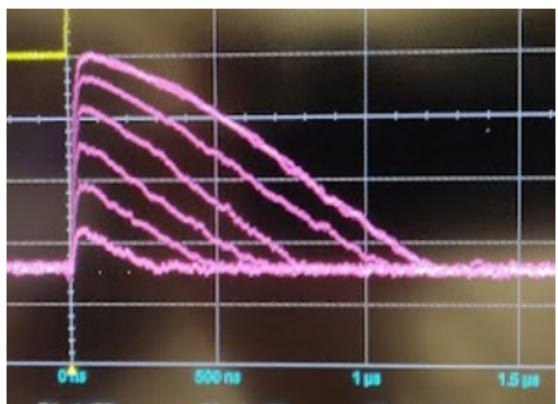


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$$Q_{signal,e^-} = \frac{1616e^-}{V_{Fe55,DAC}} V_{signal,DAC} = \frac{1616e^-}{V_{Fe55,DAC}} \frac{(ToT_{signal,clk} - q)}{\text{slope}}$$

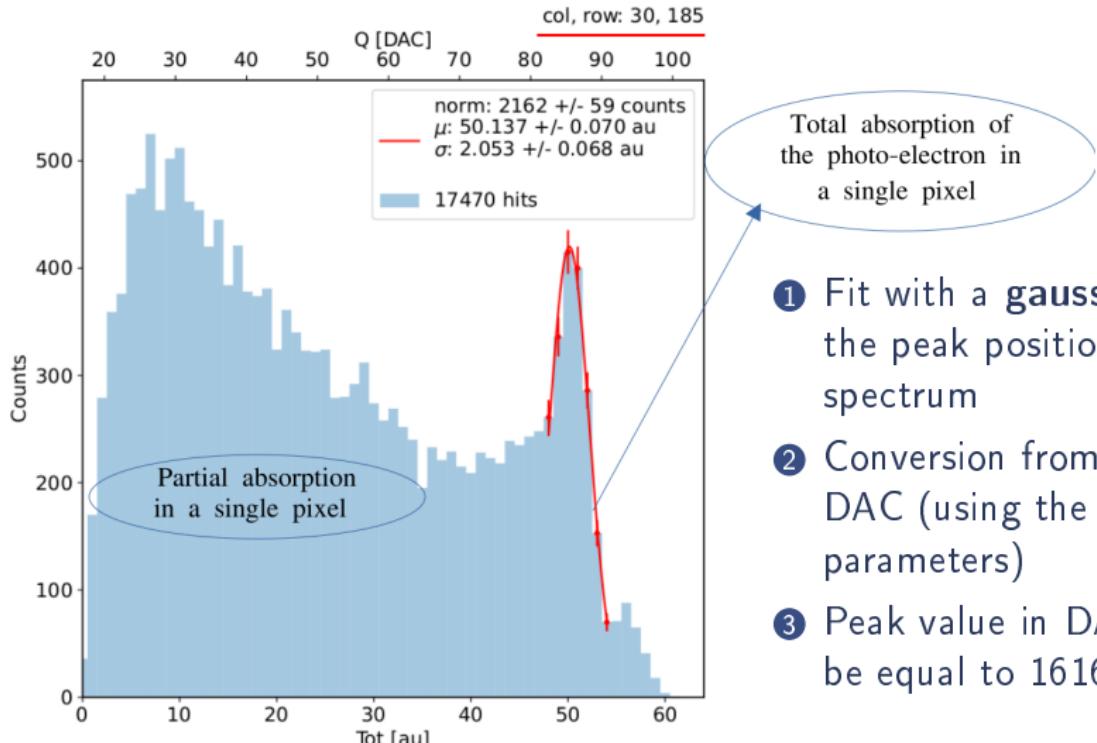
# ToT calibration

- ToT[clock counts] calibration in  $V_{inj,DAC}$  done using the internal **injection** circuit
- Scan in the voltage step height  $V_{inj,DAC}$
- $Q_{inj,e^-}$  depends on the  $C_{inj}$ , different for each pixel:  
$$Q_{inj} = V_{inj} C_{inj}$$

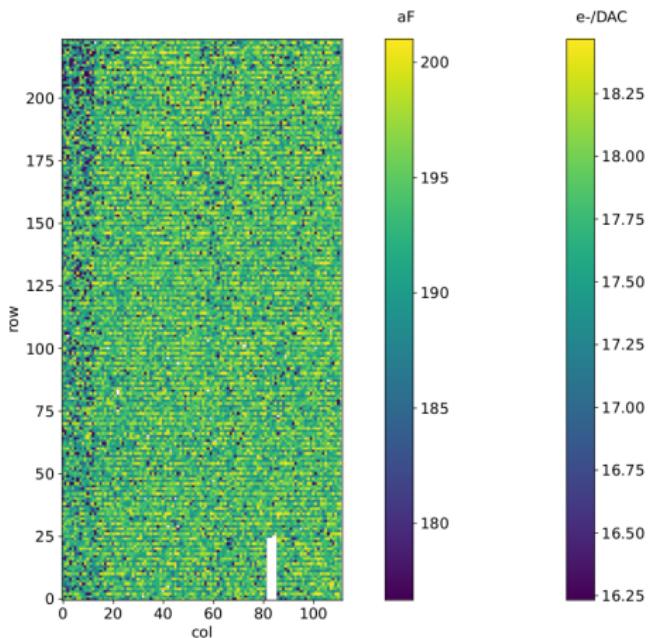


# ToT absolute calibration: $\text{Fe}^{55} \rightarrow \text{Mn}^{55}$ $K_{\alpha}$

## ► Single pixel distribution of the ToT



# Calibration results



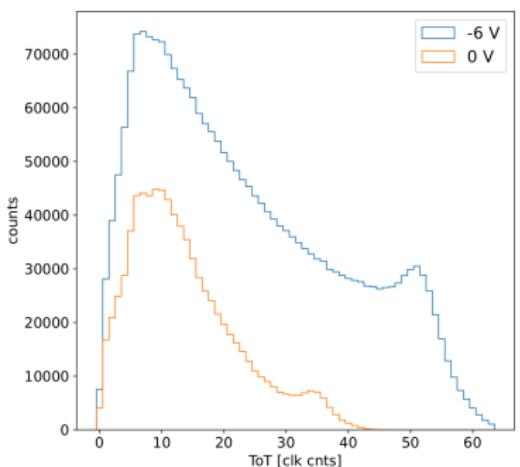
- ▶  $C_{inj}$  is in range 180-200fF (expected 230 fF)
- ▶  $F$  is in range 16.5-18.5 (expected 20.2 e/DAC $^-$ )
- ▶ applying the calibration the threshold and noise are respectively 340 e $^-$  and 10 e $^-$
- ▶ structure on rows probably due to bias line differences in the injection circuit

# Changing the bias

Acquisitions with:

- ▶ Injection
- ▶  $\text{Fe}^{55}$  source

	-6 V	-3 V	0 V
Threshold [ $e^-$ ]	$350 \pm 35$	$368 \pm 35$	$420 \pm 35$
Noise [ $e^-$ ]	$10.9 \pm 1.4$	$10.9 \pm 1.4$	$14.4 \pm 1.8$



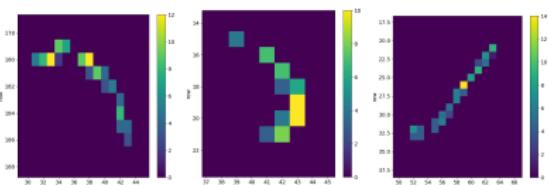
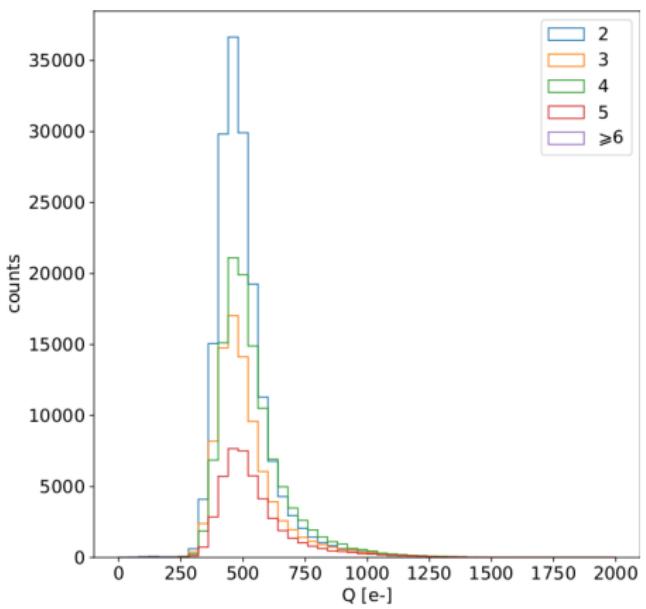
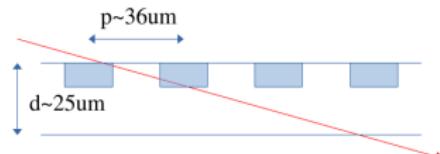
Reducing the bias from -6 V to 0 V  
reduction of the below quantity in the  
 $\text{Fe}^{55}$  spectrum:

- ① ToT value of the peak  $\sim 30\%$
- ② N of events under the peak  $\sim 60\%$
- ③ hit rate  $\sim 60\%$

1 is due to the reduction in the gain, 2  
and 3 are due to the decrease in the  
depletion thickness

# Acquisition with $\text{Sr}^{90} \rightarrow \text{Y}^{90} \beta^- \rightarrow \text{Zr}^{90} \beta^-$

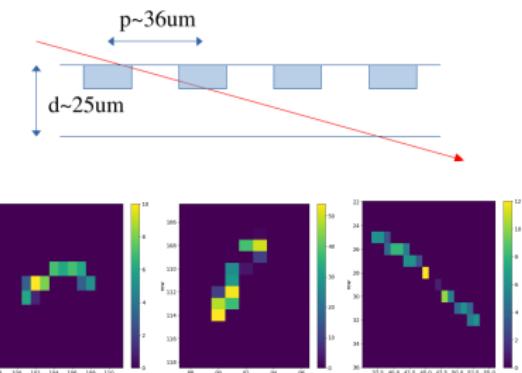
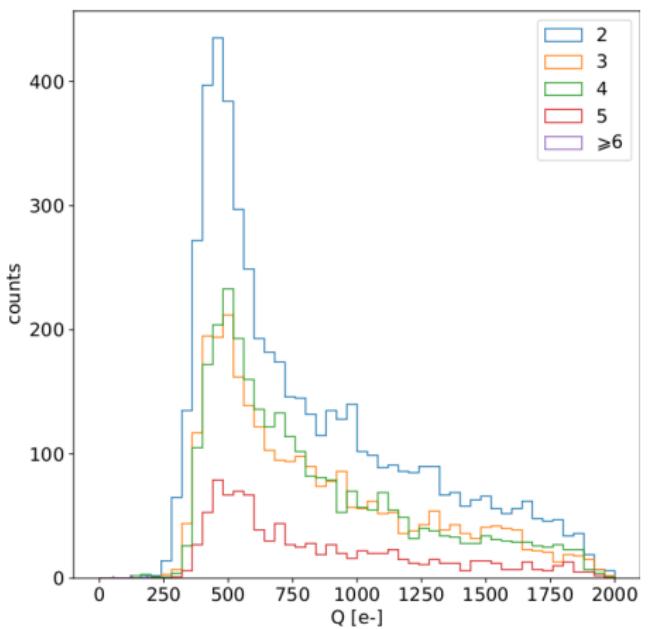
- Q released per pixel for different cluster sizes



- $E_{e,max} = 2.3 \text{ MeV}$
- Q in cluster is proportional to the cluster size
- small variation of Q per pixel because of large angle electrons
- charge sharing among pixels

# Acquisition with cosmic rays

- Q released per pixel for different cluster sizes

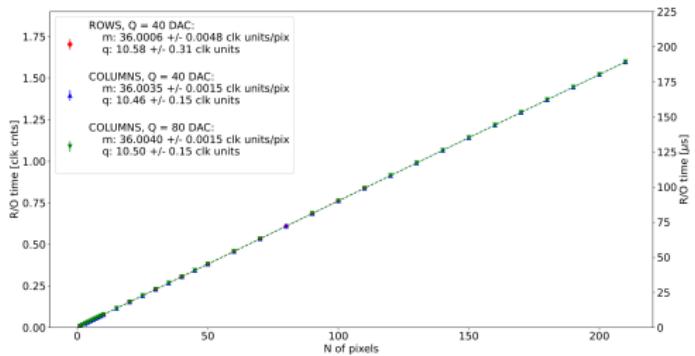


- $Q$  in cluster is proportional to the cluster size
- broad distribution due to the more various sample of particles and energies

# Readout time

Used the internal **injection** circuit that allows injecting pulses at different rate

- ▶ Readout is completely sequential: one serializer @ 40 MHz
  - each hit is a 27-bits data packet → the single pixel readout time is at least 675 ns
  - next prototype version, TJ-Monopix2, has a faster serializer 640 MHz that improves the readout speed
- ▶ No memory on pixel



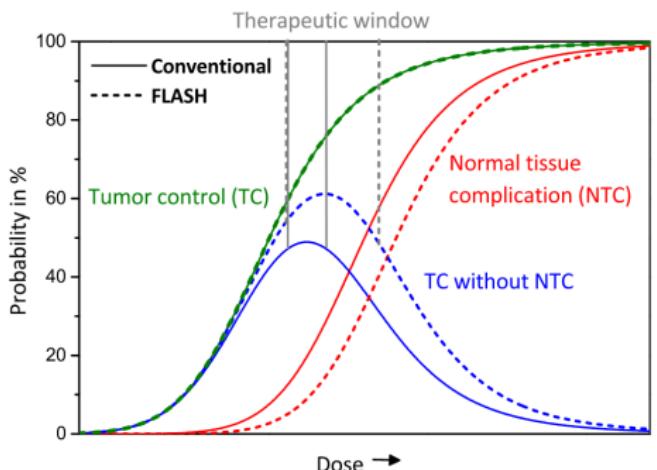
Readout time slightly depends on the FE status and is at least 31 clk cnts = 775 ns per pixels

# Outline

- ▶ Pixel detectors
- ▶ CMOS Monolithic Active Pixels
- ▶ TJ-Monopix1
- ▶ Characterization
- ▶ Beam test and FLASH-RT
  - ① Motivation: FLASH radiotherapy
  - ② Possible application of MAPS in FLASH-RT
  - ③ Test on the beam: experimental setup
  - ④ Test on the beam: preliminary results

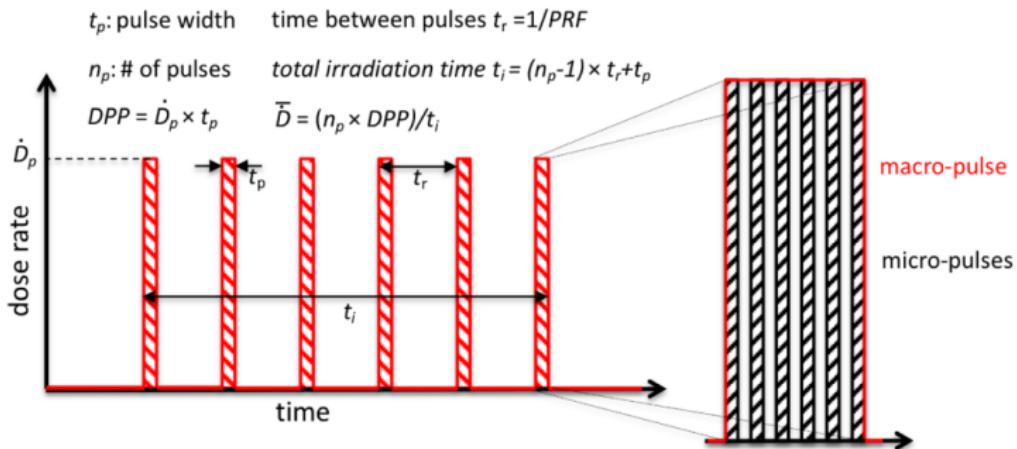
# FLASH radiotherapy

- ▶ Radiotherapy takes advantage of the damage caused by the ionization of energy loss by particles to damage ill tissue
- ▶ FLASH-RT consists in delivering a high dose in a very short time: this seems to be reducing the toxicity of radiation on healthy tissues having the same efficacy on tumor, then increasing the therapeutic window



- ▶ FLASH-RT is still **under test!**
  - medical aspect
  - bio-physics aspect
  - instrumental aspect

# Electron FLASH radiotherapy



	CONV-RT	FLASH-RT
Dose rate	0.03 Gy/s	40 Gy/s
Intra pulse dose rate	100 Gy/s	$10^6$ Gy/s
Treatment duration	~minutes	$\leq 500$ ms
Dose Per Pulse	0.3 Gy	1-10 Gy
Pulse width	3 $\mu$ s	$\sim 2$ $\mu$ s

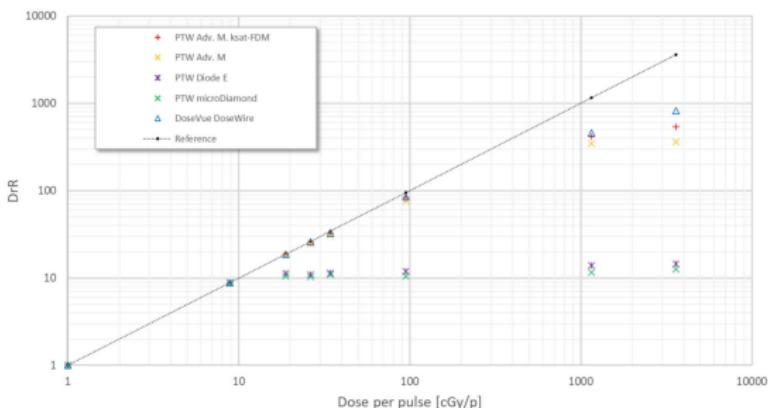
Assuming water as the dosimetric reference material

# FLASH-RT: need for detectors

All online detector types show saturation problems at such high intensity

Different types of detector with different characteristics are required:

- ▶ dosimeters
- ▶ beam monitors



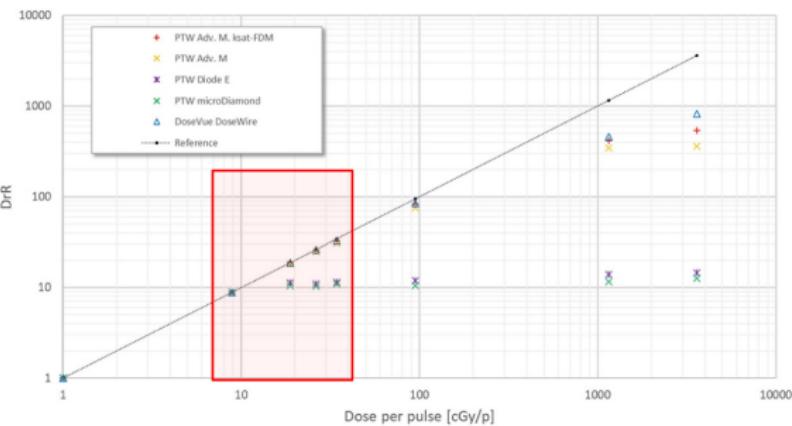
*Di Martino et al. 2020*

# FLASH-RT: need for detectors

All online detector types show saturation problems at such high intensity

Different types of detector with different characteristics are required:

- ▶ dosimeters
- ▶ beam monitors
- ▶ detectors for diagnostic



*Di Martino et al. 2020*

$$N_A = 0.2\text{--}1.2 \times 10^9 / \text{cm}^2 @ \text{Dose Per Pulse} = 0.07\text{--}0.4 \text{ Gy}$$

# Possible applications of MAPS

① **Dosimeters**: very difficult because of saturation effect.

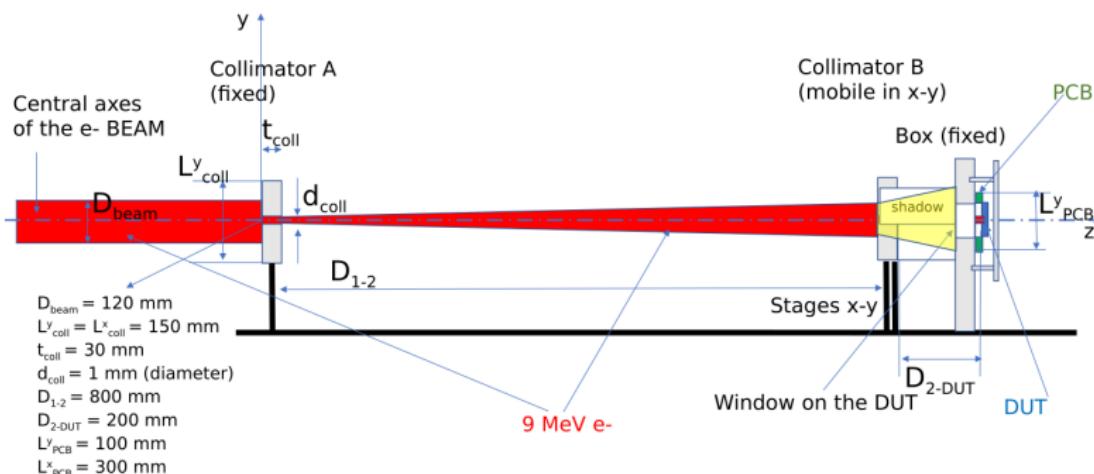
Need to:

- divide the charge of one pulse in microbuckets
- reduce the FE charge sensitivity by large factor
- use a fast FE and a fast readout

② **Beam position monitors**: very thin detectors ( $\sim 50 \mu\text{m}$ ) that do not disturb the beam

- **Very High Energy Electrons FLASH-RT** that uses pencil beams, in this case the pixels are saturated but it does not matter

# Beamtest: experimental setup scheme

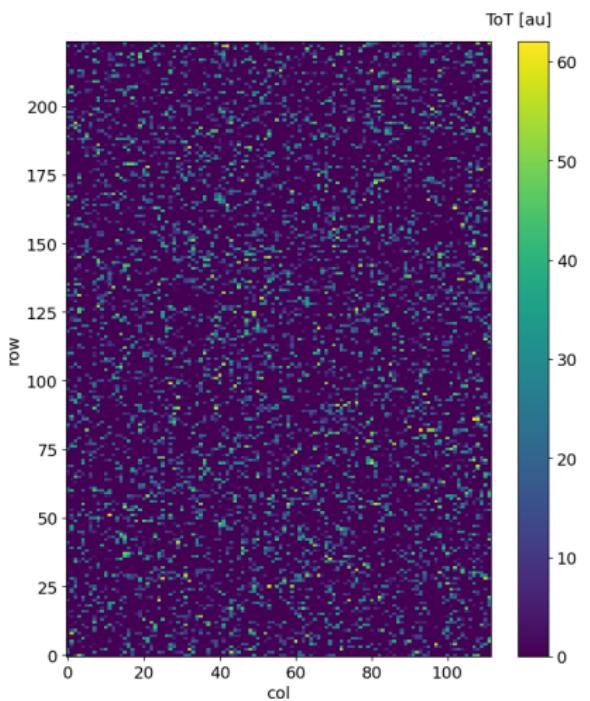


- ① Collimator A: to reduce fluence on the DUT of  $4 \cdot 10^{-4}$
- ② Collimator B: to illuminate only a small portion of DUT to see the beam border

# Beamtest: experimental setup

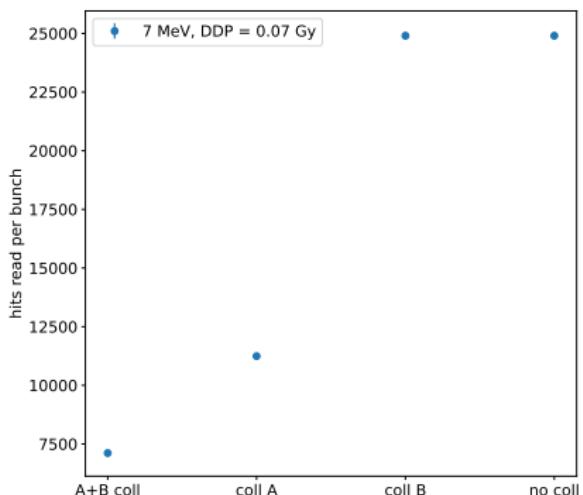


# Preliminary results



- ▶ Underestimation of the Bremsstrahlung produced by electrons that stop in the collimators
- ▶ High background in data
- ▶ Need a simulation to better understand the data

# Preliminary results



- ▶ Saturation of the readout system occurs without collimators
- ▶ Expected because of the typical readout time of TJ-Monopix1

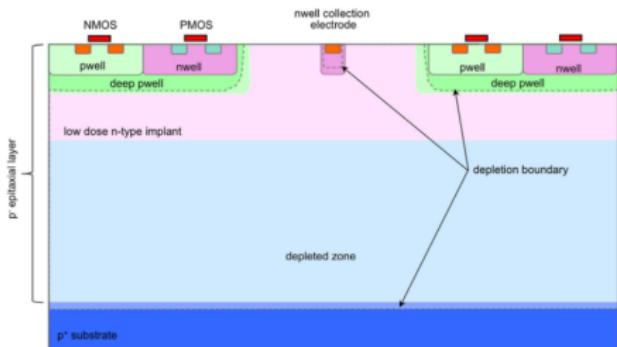
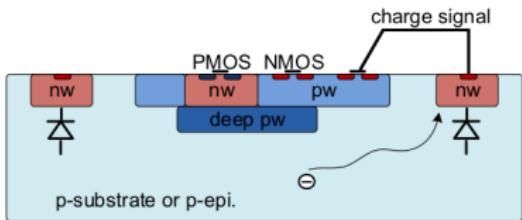
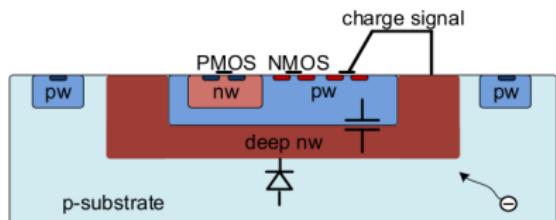
# Conclusions

- ▶ CMOS MAPS test setup prepared in the INFN clean room
- ▶ Prototype TJ-Monopix1 characterized with:
  - Internal injection
  - Radioactive sources ( $\text{Fe}^{55}$ ,  $\text{Sr}^{90}$ )
  - Cosmic rays
  - Electron-beam for FLASH-RT
- ▶ Parameters in reasonable agreement with expectations
  - Threshold, noise and dispersion measured somewhat larger than simulation done with optimized FE settings
  - Readout time corresponds to simulations
  - Saturation effects in FLASH-RT test not surprising with current readout scheme
- ▶ Future developments
  - Test setup already active on TJ-Monopix2
  - Detailed measurements provide input for future chip design for Belle II upgrade (Obelix)
  - More detailed simulation and understanding required for FLASH-RT applications

# Backup

# MAPS sensor types

- Large fill factor ( $\sim 100\text{-}200 \text{ fF}$ ) or small fill factor ( $<5 \text{ fF}$ ), depending on the deep p-well structures



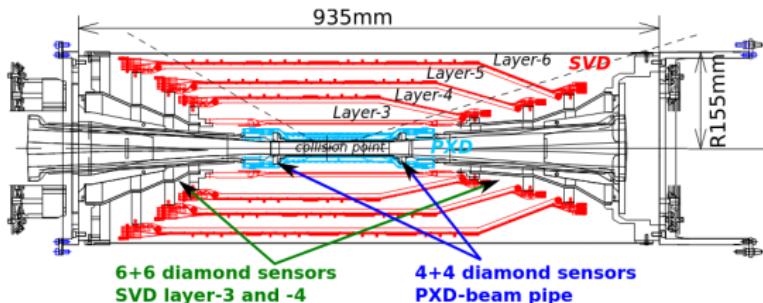
- Process modification with a low dose planar implant, whose main investigator is ALICE

# Belle2 vertex detector

Thin detector needed for a precise reconstruction of B-decay vertices

VXD made by:

- ▶ PXD → 2 DEPFET layers
- ▶ SVD → 4 strip layers



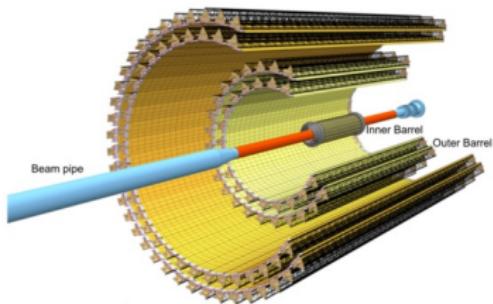
Replacement of VXD with **VTX**, proposed for LSH2. VTX should be made of 5 layers of CMOS MAPS

- ▶ improvements in the track and vertex resolutions
- ▶ reduction in the material budget
- ▶ higher background tolerance because of the smaller sensor (pixels than strips)

# ALPIDE - ALice PIxel DEtector

ALICE ITS2 upgraded in 2019-20

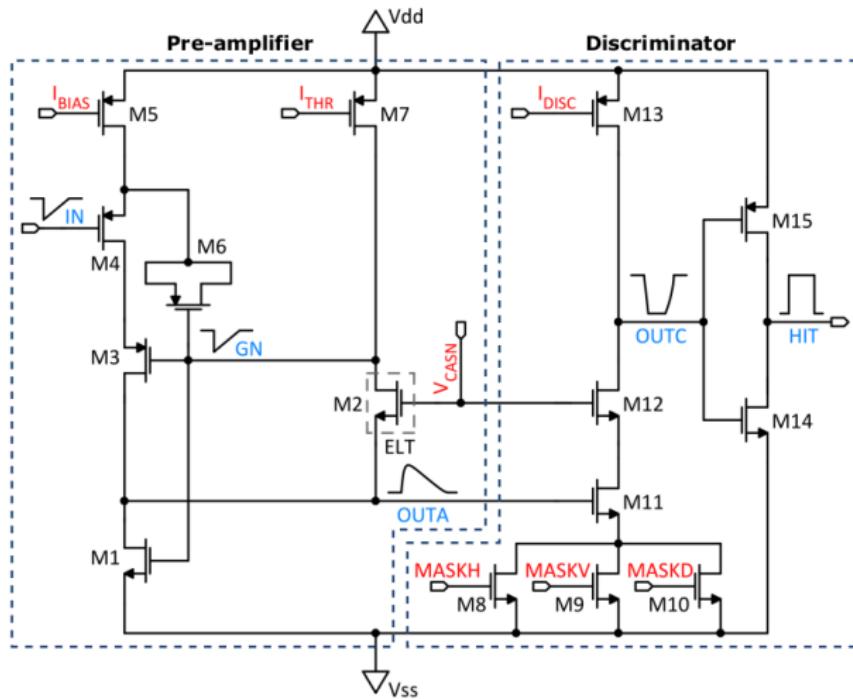
The **sensor** uses high resistivity p-type epi-layer, TowerJazz in  $0.18\text{ }\mu\text{m}$ . It is the first large area  $\sim 10\text{ m}^2$  MAPS detector with sparsified readout. Many MAPS have an **ALPIDE-based Front End** (i.e. TJ-Monopix1, ARCADIA)



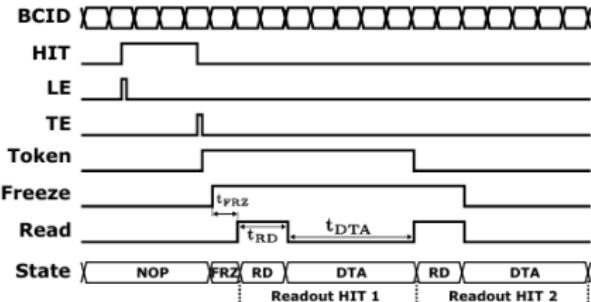
- ▶ position resolution  $\sim 5\text{ }\mu\text{m}$  (pixel dimension  $27 \times 29\mu\text{m}^2$ )
- ▶  $X_0/\text{layer}$  reduced from 1.14% to 0.3%
- ▶ tracking efficiency of low- $p_T$  ( $p_T \sim 0.1\text{ GeV}/c$ ) improved by a factor 6

# ALPIDE front end

ALPIDE like: circuit implemented in TJ-Monopix1



# TJ-Monopix1 readout sequence



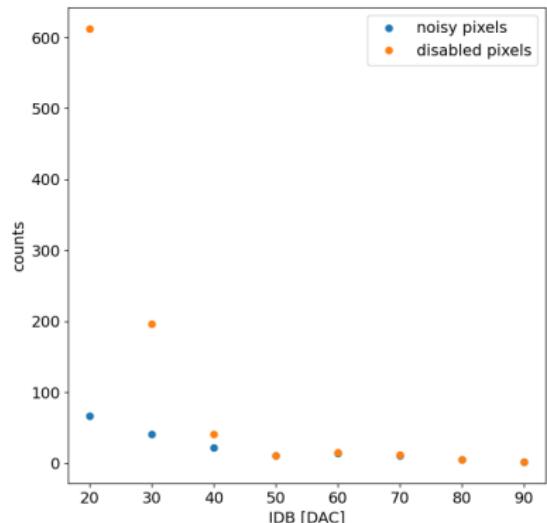
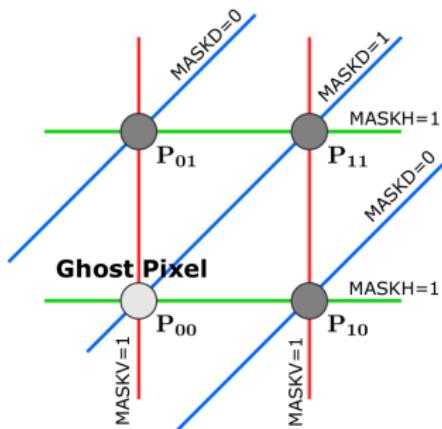
**BCID** = Bunch Crossing  
identification is the clock  
of the timestamp

- ▶ The **token** manage the priority chain
- ▶ The **freeze** is a global signal and is used to lock the matrix during the readout.  
Pixels without any hit can store new data but they cannot access the priority chain until the freeze stops
- ▶ The **read** is used to indicate when the pixel can access the data bus

# TJ-Monopix1: noisy pixels

The masking algorithm uses 3 coordinates to mask a pixel:

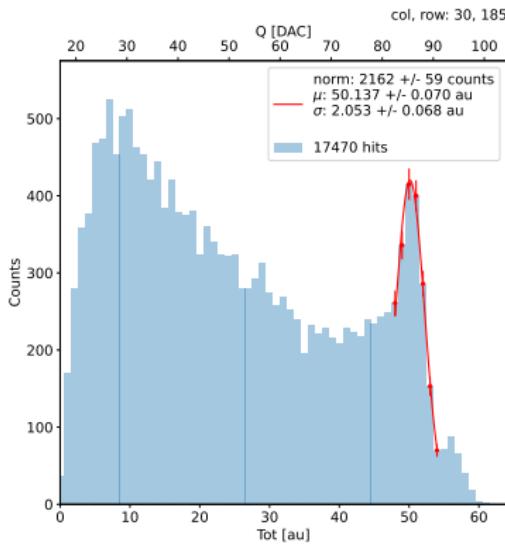
- ▶ MASKV → column of the pixel
- ▶ MASKH → row of the pixel
- ▶ MASKD → diagonal of the pixel



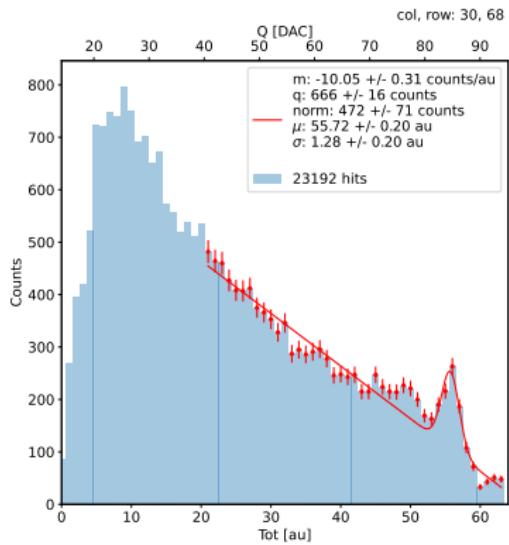
IDB = discriminator threshold

# Different collection properties

2 different **dose profile** in the sensor: Reduced Deep P-Well (RDPW) and Full Deep P-Well (FDPW) with different charge collection efficiency

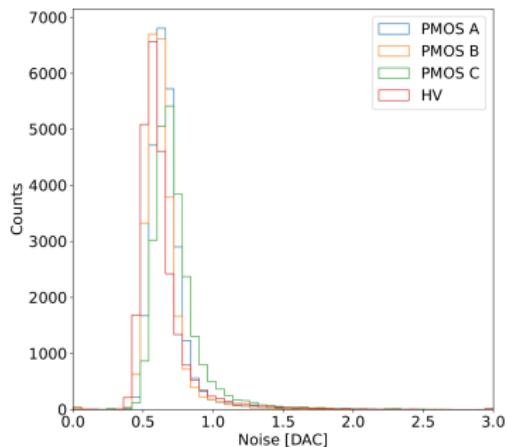
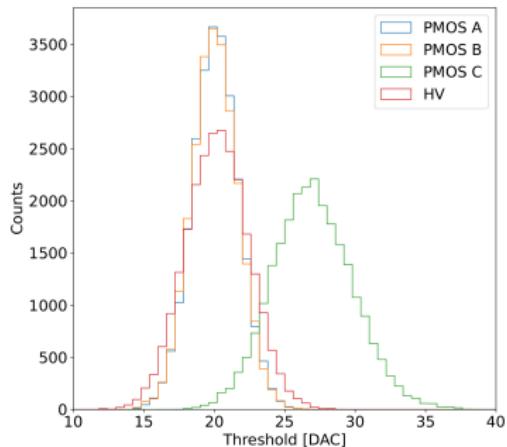


Partial deep p-well



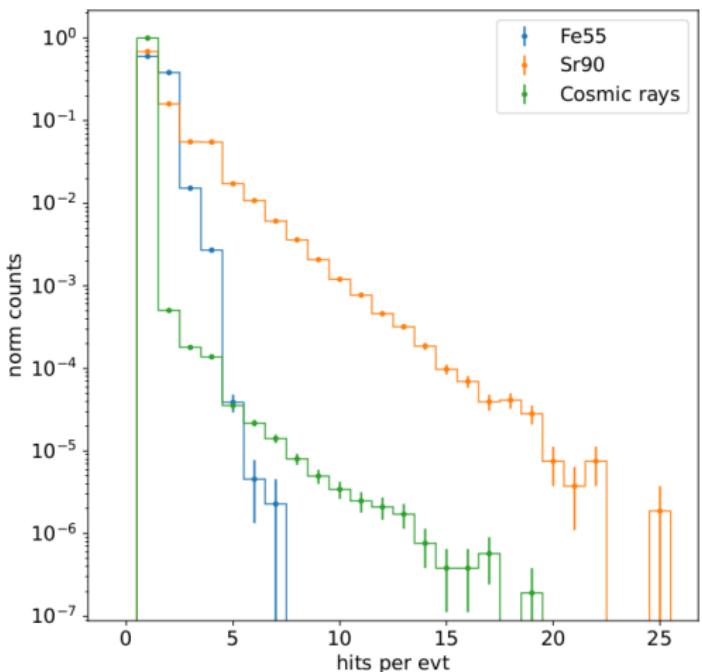
Full deep p-well

# Threshold and noise results with different FEs



	PMOS A	PMOS B	PMOS C	HV	simulation
$\mu$ [ $e^-$ ]	$401.7 \pm 0.2$	$400.8 \pm 0.2$	$539.7 \pm 0.6$	$597.7 \pm 0.3$	$\sim 270$
$\Delta\mu$ [ $e^-$ ]	$32.9 \pm 0.1$	$33.0 \pm 0.2$	$55.5 \pm 0.4$	$66.1 \pm 0.3$	$\sim 30$
$\sigma$ [ $e^-$ ]	$13.01 \pm 0.06$	$12.26 \pm 0.07$	$13.9 \pm 0.1$	$17.3 \pm 0.1$	$\sim 9$
$\Delta\sigma$ [ $e^-$ ]	$1.61 \pm 0.04$	$1.50 \pm 0.05$	$1.91 \pm 0.07$	$2.3 \pm 0.1$	-

# Acquisition with sources: $\text{Fe}^{55}$ , $\text{Sr}^{90}$ , cosmic rays

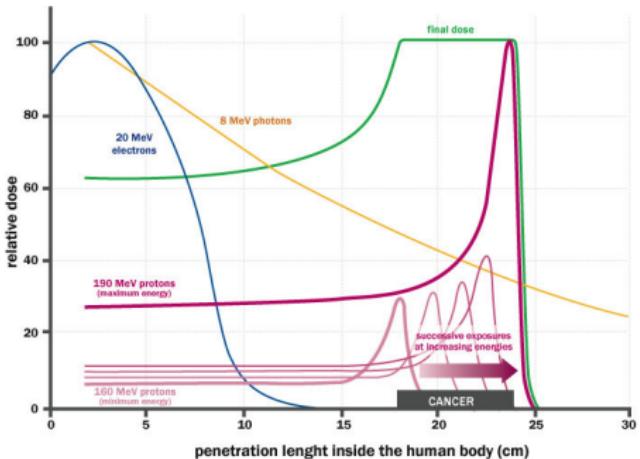


- ▶  $\text{Fe}^{55}$  photon produces smaller clusters: pure charge sharing
- ▶  $\text{Sr}^{90}$  and cosmic rays go across more pixels

# Radiotherapy

Many different sources:

- ▶ hadrons → Bragg peak
- ▶ photons → exponential absorption
- ▶ electrons →  $\sim 10$  MeV or VHEE  $\sim 100$  MeV



# Test on the beam: ElectronFLASH

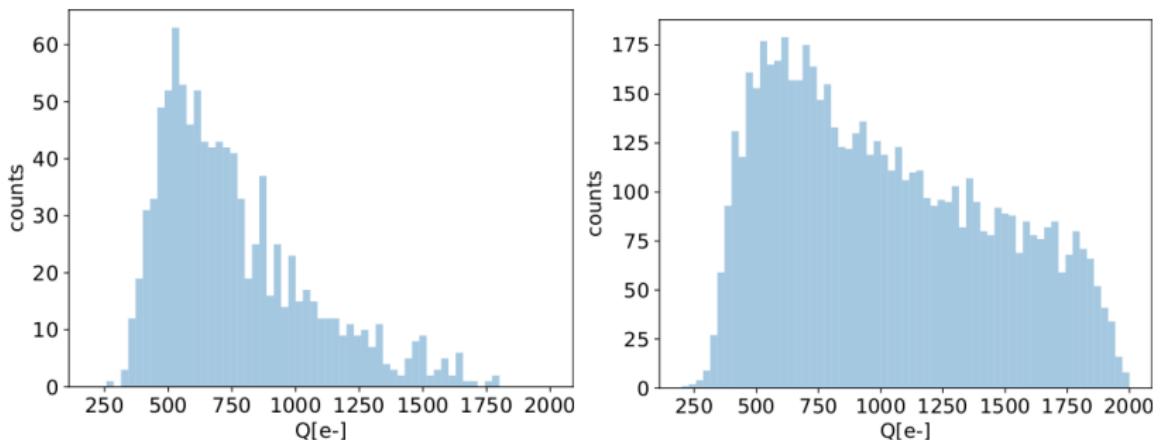
ElectronFLASH is the new accelerator for research on FLASH-RT placed in S. Chiara hospital in Pisa

Accelerator characteristics:

- ▶ linear accelerator
- ▶ bunched beam
- ▶ two energy configurations 7-9 MeV
- ▶ can reach ultra high intensity (over 5000 Gy/s)
- ▶ beam parameters can be configured independently from each other
- ▶ equipped with a set of plexiglass applicators (diameters in range from 1 cm to 12 cm) which are used to produce a uniform dose profile

# Test on beam: preliminary results

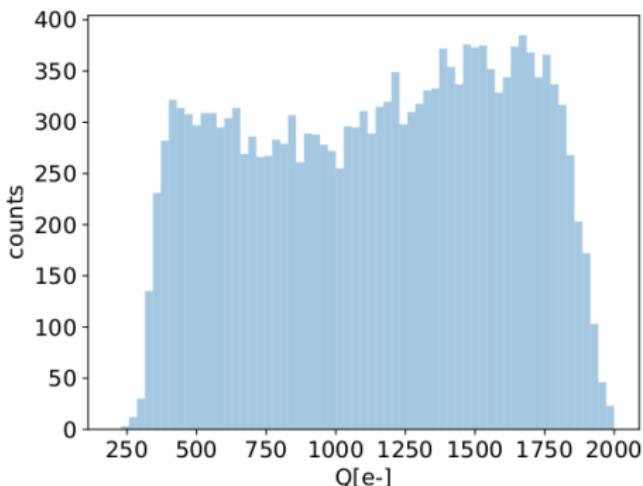
- With **both** the collimators,  $DPP=0.07\text{ Gy}$ ,  $t_p=4\text{ }\mu\text{s}$ ,  $PRF=1\text{ Hz}$



- the collimators do not shield the detectors from all particles
- probably photons are produced by electrons in Al collimators
- for each accelerator pulse, 2 readout "cycle"

# Test on beam: preliminary results

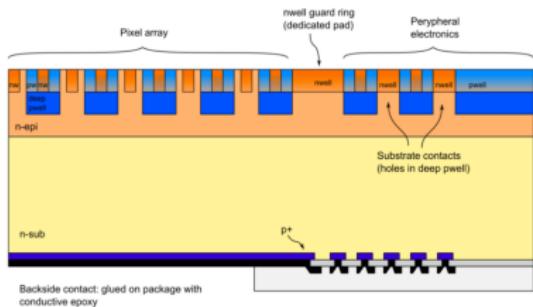
- ▶ Without any collimator, DPP=0.04 Gy,  $t_p=4\ \mu\text{s}$ , PRF=1 Hz
- ▶ MIP are expected to release 2000  $e^-$ , and because of rollover are expected to be 300-400  $e^-$



- ▶ ToT converted in charge
- ▶ pixels turn on in N clock counts
- ▶ after each pulse an induced signal on the whole matrix

Need for a simulation to understand the data

# ARCADIA MD1



- ▶ produced by LFoundry (Italy)
- ▶ 110 nm CMOS technology
- ▶ n-doped epitaxial layer

Parameter	Value
Matrix size	$1.28 \times 1.28 \text{ cm}^2$
Number of pixels	$512 \times 512$
Pixel size	$25 \times 25 \mu\text{m}^2$
Depth	$48/100/200 \mu\text{m}$
Electrode size	$9 \times 9 \mu\text{m}^2$
Power consumption	$\sim 10 \text{ mW/cm}^2$
Output signal	digital

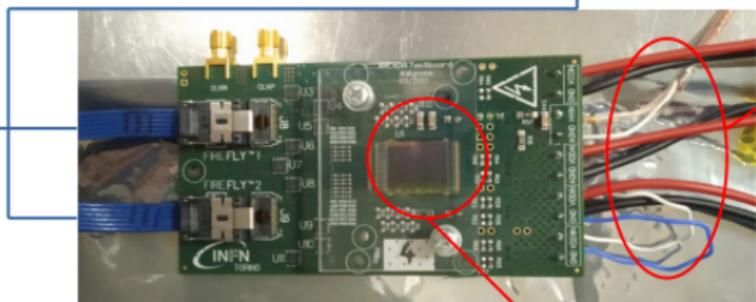
# ARCADIA MD1: experimental setup



connection  
with the DAQ

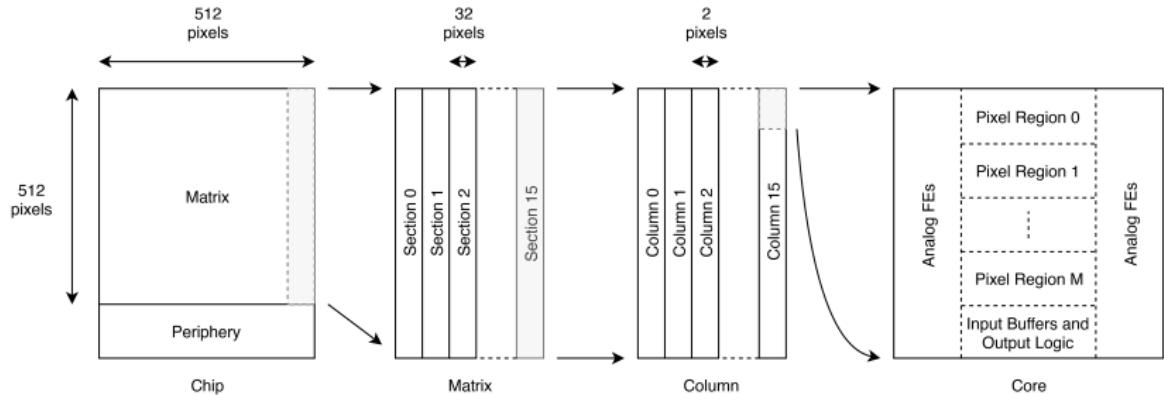
FPGA

BB



bias of  
the chip

# ARCADIA MD1: matrix division



The matrix contains  $512 \times 512$  pixels divided in:

- ▶ 16 sections containing  $512 \times 32$  pixels
- ▶  $512 \times 2$  double columns
- ▶ cores of  $32 \times 2$  pixels
- ▶ regions containing  $4 \times 2$  pixels → regions can be master or slave

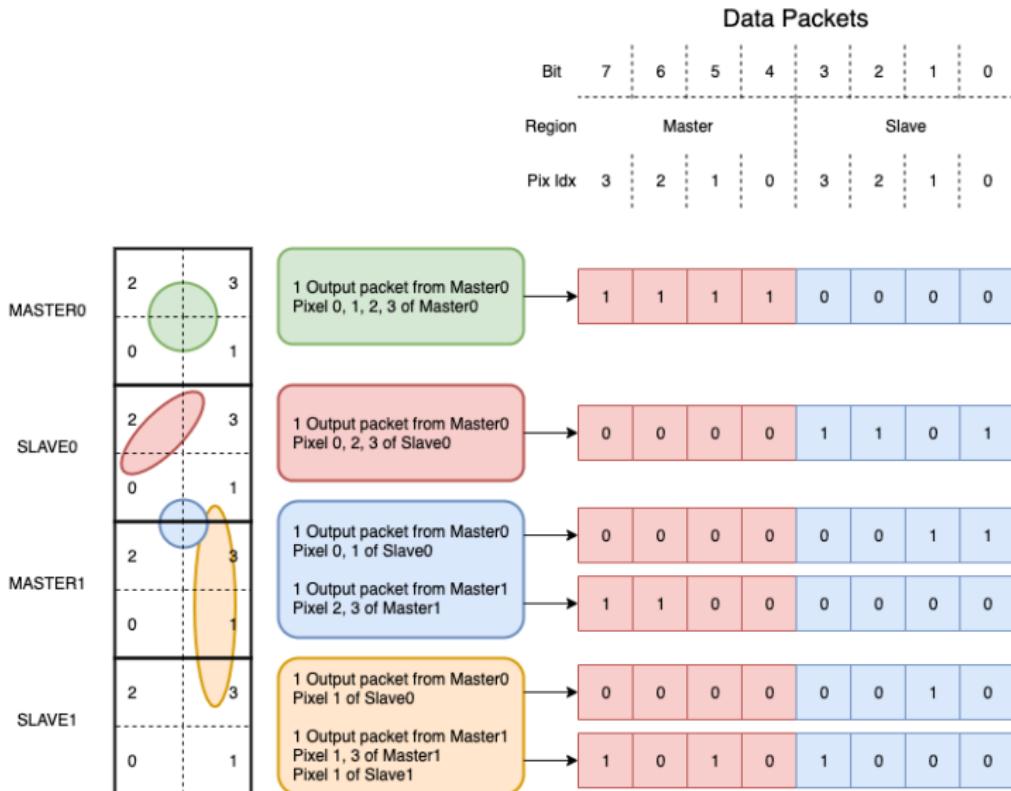
Bits	Meaning
31:24	timestamp
23:20	section index
19:16	column index
15:9	pixel region
8:0	bitmap

# ARCADIA MD1: clustering

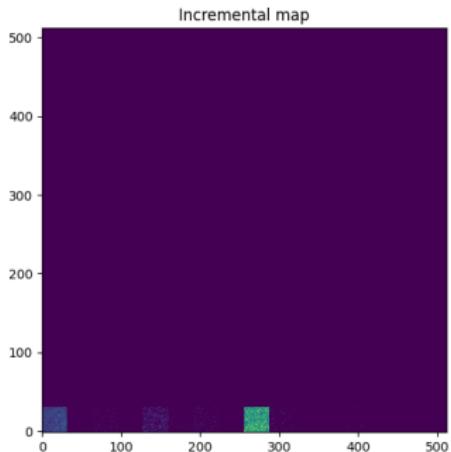
Clustering allows transmit less data packet, *Master* regions can decide what *slaves* data to transmit



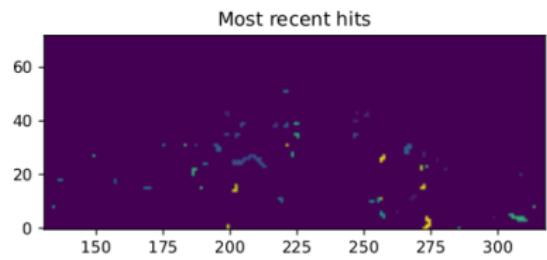
# ARCADIA MD1: clustering



# ARCADIA measurement with radioactive sources



$\text{Fe}^{55}$



$\text{Sr}^{90}$