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: 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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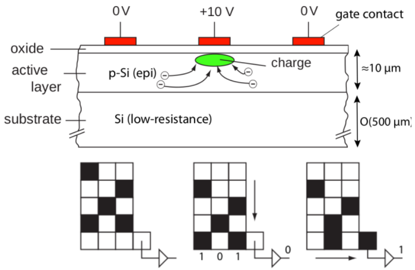
- **CCDs**
- Hybrid pixels
- Monolithic Active Pixels
  - DEPFET
  - CMOS MAPS



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

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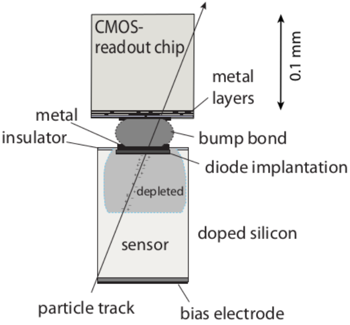
- CCDs
- **Hybrid pixels**
- Monolithic Active Pixels
  - DEPFET
  - CMOS MAPS



Two wafer: one for the sensor and one for the ASIC then microconnected

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- Hybrid pixels
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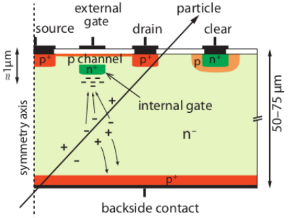
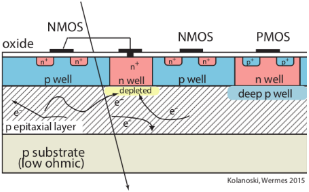
  - DEPFET
  - CMOS MAPS



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



Hybrid vs monolithic

Hybrid pixels

1. module area∼10 cm^2
2. rate capability∼GHz/cm^2
3. sensor and ASIC can be optimized separately
4. are more radiation hard

1. pitch∼50-100 μm
2. point resolution∼10-15 μm
3. thickness∼250 μm
4. bump bonding delicate and expensive

Multiple Scattering!

Monolithic active pixels

1. pitch∼10-50 μm
2. point resolution∼5-10 μm
3. thickness∼2550 μm
4. low power consumption
5. good S/N ratio

1. module area∼cm^2
2. rate capability ∼100 MHz/cm^2

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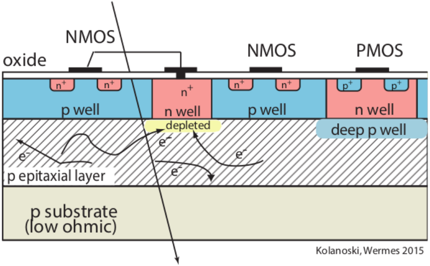
Outline

- 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



$\lesssim$5 µm electronics

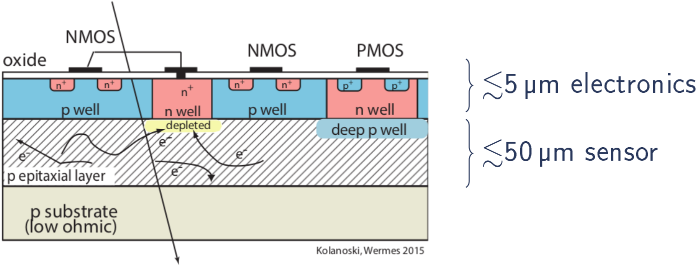
$\lesssim$50 µm sensor

Signal produced by a particle:

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

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

CMOS Monolithic Active Pixel Sensors

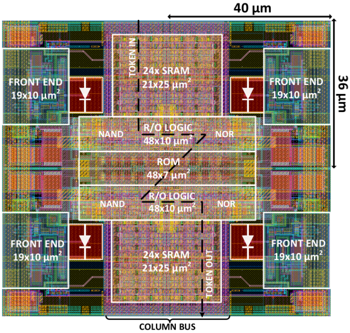


- High resistivity ρ allows for full depleted epi-layer
  Depleted-MAPS at sufficiently low bias V: $d \propto \sqrt{\rho V}$
- $V = Q/C \rightarrow$ if the sensor capacitance C is sufficiently low:
  - High **gain** for the first amplification stage
  - High signal and good **S/N** performances

Front end electronics

Pitch∼50 µm → **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.

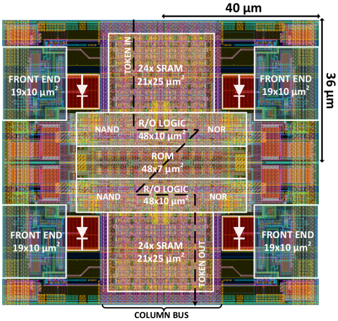


The pixel area include the:

- Analog front end
- Digital readout

Analog	Digital
Triggered	Triggerless
Buffer	No buffer
Rolling shutter	Sparsified

Front end electronics



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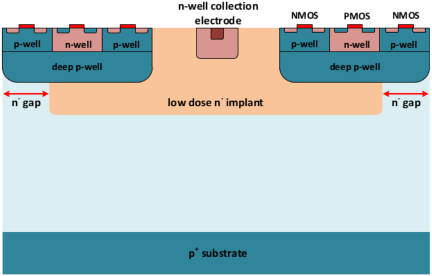
Outline

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

TowerJazz Monopix1

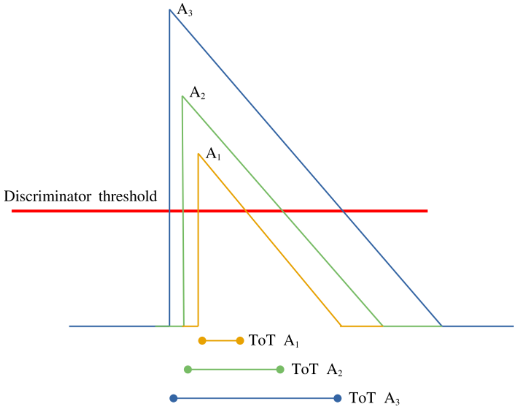
- Designed by ATLAS collaboration
- Produced by TowerJazz, an electronic foundry located in Israel
- Small electrode design: 2 μm with C=3 fF
- The sensor implements a process modification in the epi-layer that allows the creation of a planar junction (ALICE)
- The Front End has 4 flavors, all ALPIDE-like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

Resistivity	>1 kΩcm
Matrix size	1×2cm^2
Pixel size	36×40 μm^2
Max depletion	25 μm
ToT	6-bits
Time resolution	25 ns



TJ-Monopix1 analog output

ToT = **Time Over Threshold**

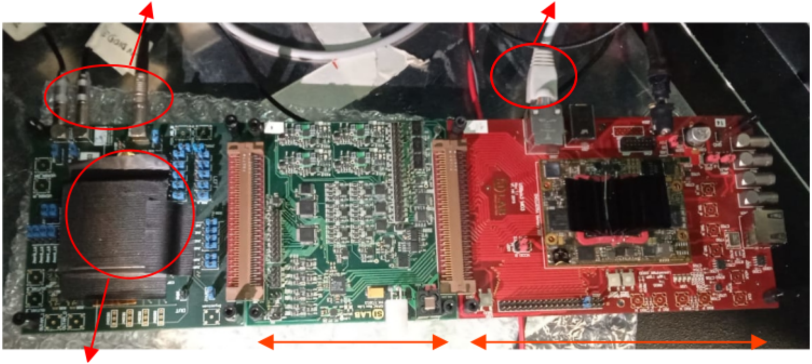


- The reset circuit of the amplifier made with a **PMOS**, guaranties the discharge of the preamplifier with constant slope
- The ToT grows linearly with the pulse amplitude
- Before readout ToT is stored in RAM as a 6-bits variable $\rightarrow$ then the ToT can vary in range 0-1.6 µs

TJ-Monopix1 experimental setup

Bias of the sensor

Connection with the DAQ



DUT
(Device Under Test)

GPAC breakout board

FPGA

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

Threshold and noise

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

The threshold and the noise are **strictly** related with the **FE** settings

What determins 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
$\sim 9\ e^-$	$\sim 270\ e^-$	$\sim 30\ e^-$

Threshold and noise: how to measure them?

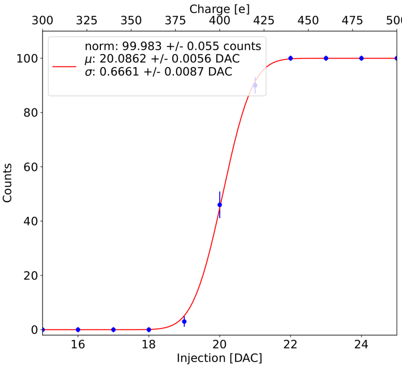
- **Internal injection circuit** allows sending a voltage step V_{inj}[DAC] on an injection capacitance C_{inj} at the FE input
- Scan at different pulse height V_{inj}[DAC] injecting 100 pulses at fixed discriminator threshold

By design:

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

S-curve

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



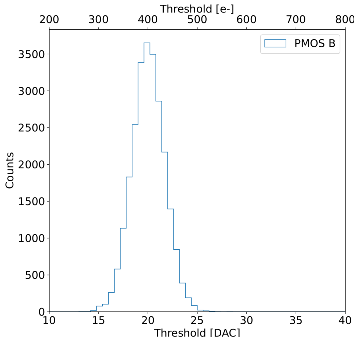
Assuming a gaussian noise:

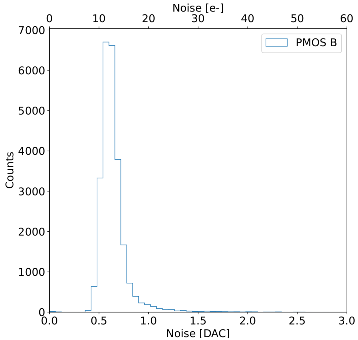
- threshold $\rightarrow$ the 50%
- noise $\rightarrow$ 1/slope

Analytical parametrization of the curve with the *error function*

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

Threshold and noise results





	Measurement	Simulation
μ [e^-]	400.8±0.2	∼270
Δ_μ [e^-]	33.0±0.2	∼30
σ [e^-]	12.26±0.07	∼9
Δ_σ [e^-]	1.50±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 for a reference in charge e^-: $V_{signal,DAC} \rightarrow Q_{signal,e^-}$

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$Fe^{55} \rightarrow Mn^{55} + \underbrace{K_\alpha\ (5.9\,\text{keV},\ 24.4\%)}$ or K_β (6.5 keV, 2.9%)

- $P_{abs,photo-electric}$ ~58% → λ=29 µm
- w_i=3.6 eV in Si @ 300 K→ 1616 e^-

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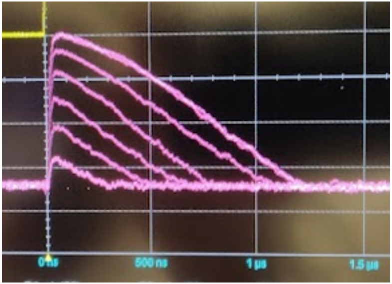
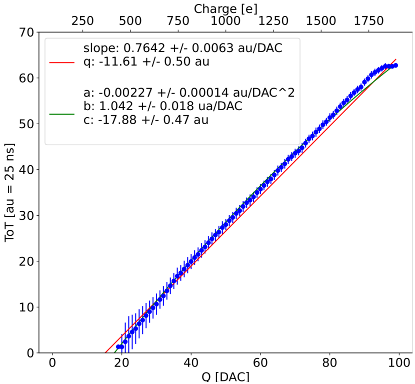
$$Q_{signal,e^-} = \frac{1616e^-}{V_{Fe55,DAC}} V_{signal,DAC} = \frac{1616e^-}{V_{Fe55,DAC}} \frac{(ToT_{signal,clk} - q)}{slope}$$

ToT calibration

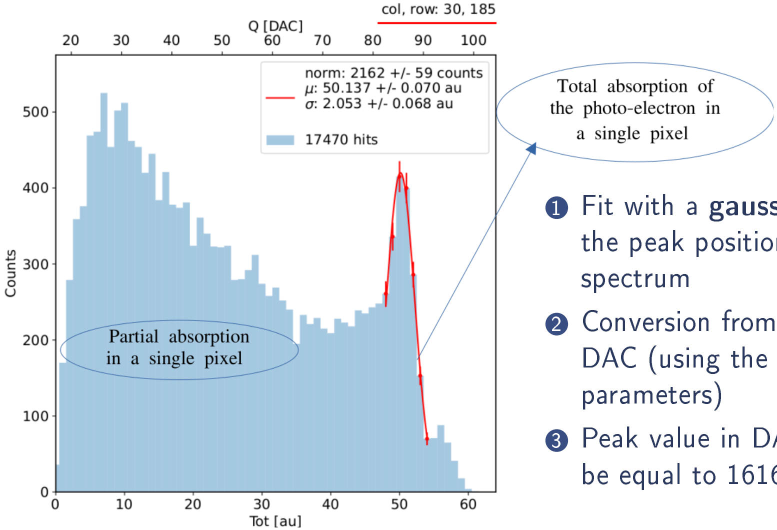
- ToT[clock counts] calibration in $V_{inj,DAC}$ done using the internal **injection** circuit
- Scan in the voltage step height $V_{inj,DAC}$
- Q_{inj,e^-} depends on the C_{inj}, different for each pixel: Q_{inj}=$V_{inj}C_{inj}$





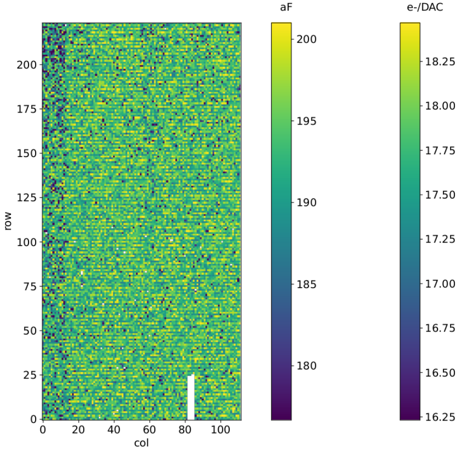
ToT absolute calibration: $Fe^{55} \rightarrow Mn^{55}\ K_\alpha$

- Single pixel distribution of the ToT



1. Fit with a **gaussian** to find the peak position in the spectrum
2. Conversion from ToT to DAC (using the line parameters)
3. Peak value in DAC fixed to be equal to 1616 e^-

Calibration results



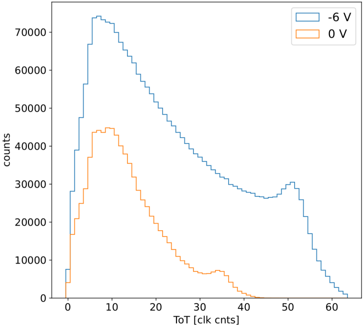
- C_{inj} is in range 180-200fF (expected 230 fF)
- F is is range 16.5-18.5 (expected 20.2 e/DAC^{-})
- structure on rows probably due to bias line differences in the injection circuit
- applying the calibration the threshold and noise are respectively 340 e^{-} and 10 e^{-}

Changing the bias

Acquisitions with:

- Injection
- Fe^{55} source

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



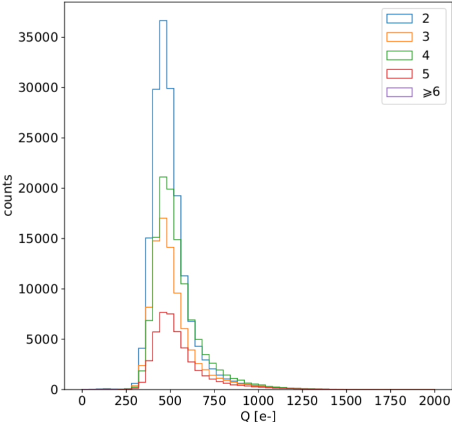
Reducing the bias from -6 V to 0 V reduction of the below quantity in the Fe^{55} spectrum:

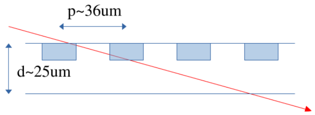
1. ToT value of the peak ∼30%
2. N of events under the peak ∼60%
3. hit rate ∼60%

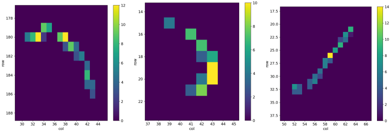
1 is due to the reduction in the gain, 2 and 3 are due to the decrease in the depletion thickness

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

- Q released per pixel for different cluster sizes



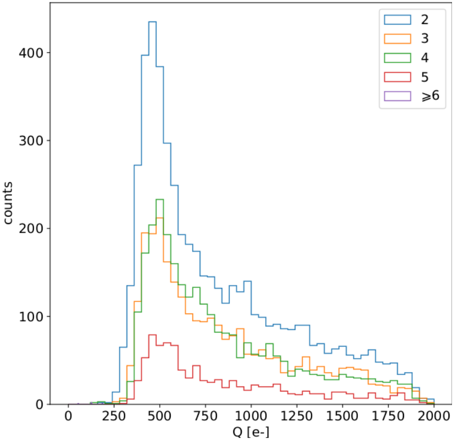


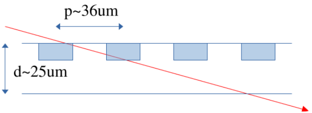


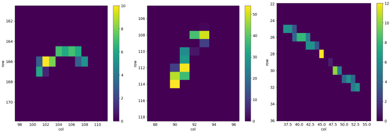
- $E_{e,max}$=2.3 MeV
- Q in cluster is proportional to the cluster size
- small variation of Q per pixel because of large angle electrons
- charge sharing among pixels

Acquisition with cosmic rays

- Q released per pixel for different cluster sizes





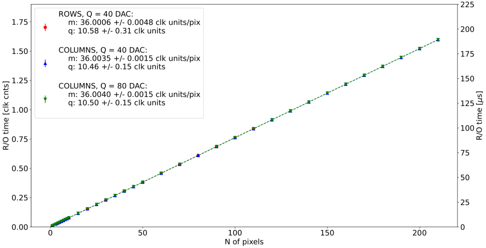


- Q in cluster is proportional to the cluster size
- broad distribution due to the more various sample of particles and energies

Readout time

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

- No memory on pixel
- 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 removes the limitation in the readout speed



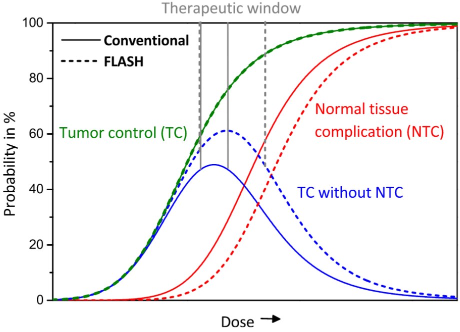
Readout time **slightly** depends on the FE status and can be reduced down to 31 clk cnts = 775 ns per pixels

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

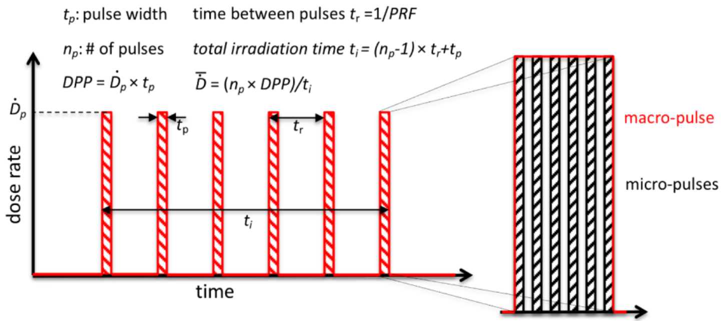
FLASH radiotherapy

- 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 toxiticy of radiation on healty tissues, 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	$\lesssim$500 ms
Dose Per Pulse	0.3 Gy	1-10 Gy
Pulse width	3 μs	~2 μs

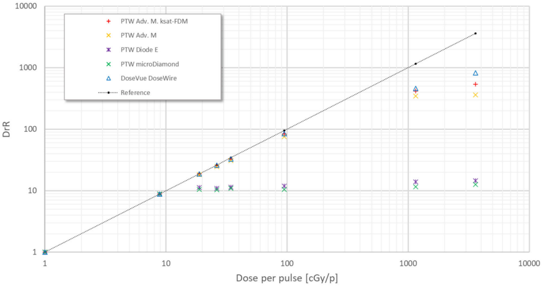
Assuming **water** as the dosimetric reference material

FLASH-RT: need for detectors

All online detector types show saturation problems at such high intensity

Different types of detector with different charateristics are required:

- **dosimeters**
- **beam monitors**
- detectors for diagnostic



Di Martino et al. 2020

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

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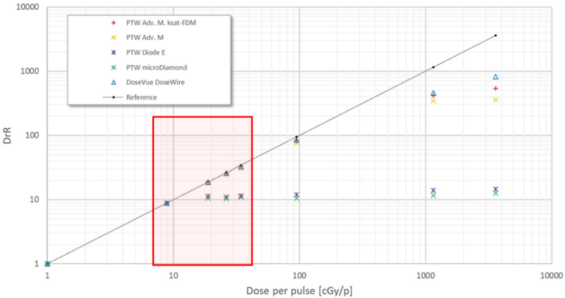

Di Martino et al. 2020

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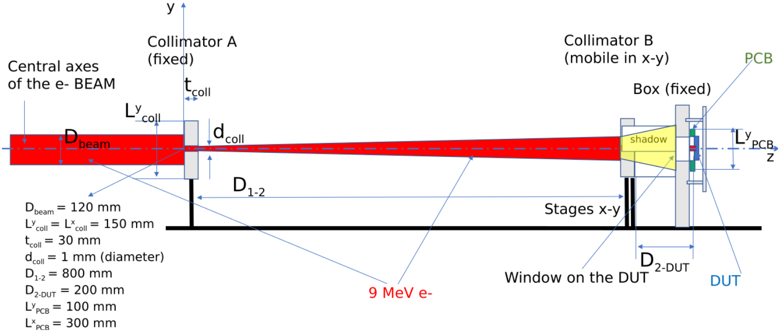
Possible applications of MAPS

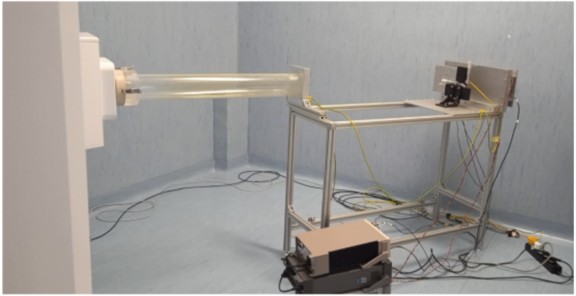
1. **Dosimeters**: very difficult because of saturation effect. Need to:
    - divide the charge of one pulse in microbuckets
    - reduce the FE charge sensitivity by large factor
    - use a fast FE and a fast readout
2. **Beam position monitors**: very thin detectors ($\sim$50 μm) that do not disturb the beam
    - **Very High Energy Electrons FLASH-RT** that uses pencil beams, in this case the pixels are saturated but it does not matter

Test on the beam: experimental setup

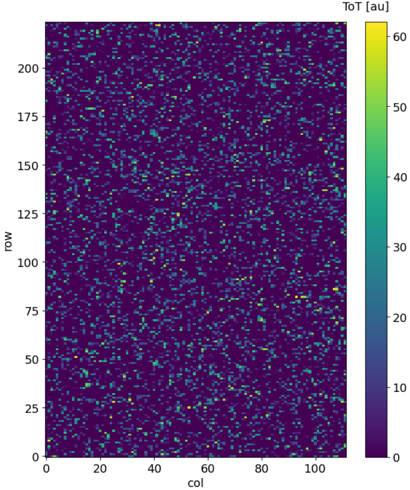


1. Collimator A: to reduce fluence on the DUT of $\mathbf{4\ 10^{-4}}$
2. Collimator B: to illuminate only a small portion of DUT to see the beam border

Test on the beam: experimental setup

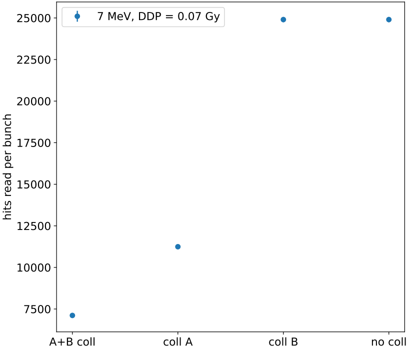


Test on the beam: preliminary results



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

Test on the beam: preliminary results



- Saturation of the readout system occurs without collimators
- Readout logic has been tested with high hit rate

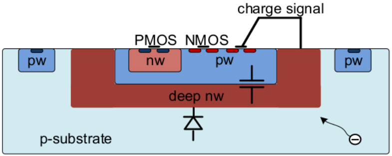
Conclusions

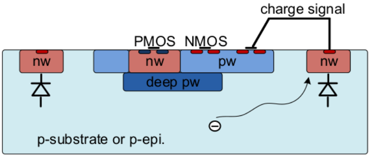
- CMOS MAPS test setup prepared in the INFN clean room
- Prototype TJ-Monopix1 characterized with
  - Internal injection
  - Radioactive sources (Fe^{55}, Sr^{90})
  - Cosmic rays
  - electron-beam for FLASH-RT
- Parameters in reasonable agreement with expectations
  - Threshold, noise and dispersion somewhat larger than expected

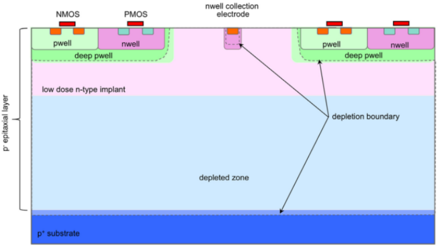
Backup

MAPS sensor types

- **Large fill factor** (∼100-200 fF) or **small fill factor** (<5 fF), depending on the deep p-well structures





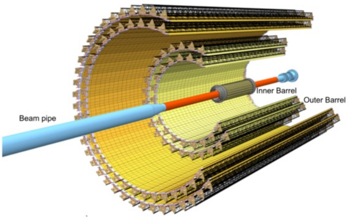


- **Process modification** with a low dose planar implant. whose main investigator is ALICE

ALPIDE - ALice PIxel DEtector

ALICE ITS2 upgraded in 2019-20

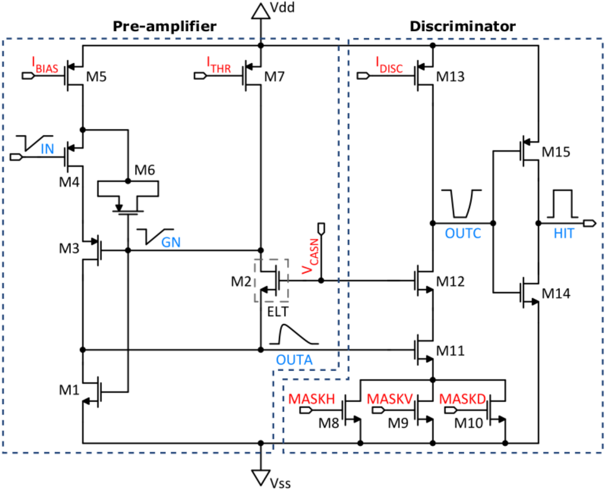
The **sensor** uses high resistivity p-type epi-layer, TowerJazz in 0.18 µm. It is the first large area $\sim$10 m^2 MAPS detector with sparsified readout. Many MAPS have an **ALPIDE-based Front End** (i.e. TJ-Monopix1, ARCADIA)



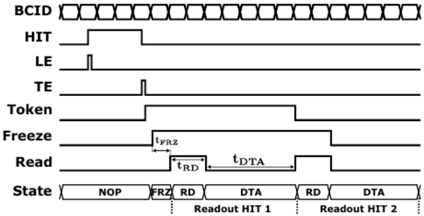
- position resolution $\sim$5 µm (pixel dimension 27×29µm^2)
- X_0/layer reduced from 1.14% to 0.3%
- tracking efficiency of low-p$_T$ (p_T $\sim$0.1 GeV/c) improved by a factor 6

ALPIDE front end

ALPIDE like: circuit implemented in TJ-Monopix1



TJ-Monopix1 readout sequence



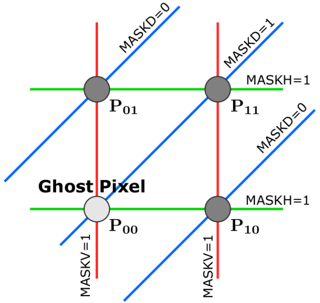
BCID = Bunch Crossing identification is the clock of the timestamp

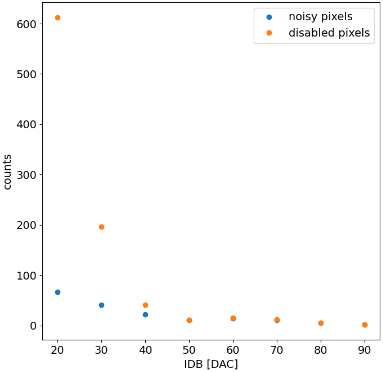
- The **token** manage the priority chain
- The **freeze** is a global signal and is used to lock the matrix during the readout.
  Pixels without any hit can store new data but they cannot access the priority chain untill the freeze stops
- The **reed** is used to indicate when the pixel can access the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

TJ-Monopix1: noisy pixels

The masking algorithm uses 3 cordinates to mask a pixel:

- MASKV $\rightarrow$ column of the pixel
- MASKH $\rightarrow$ row of the pixel
- MASKD $\rightarrow$ diagonal of the pixel

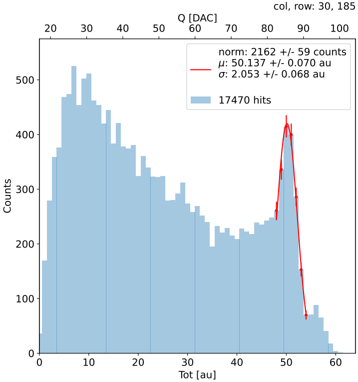




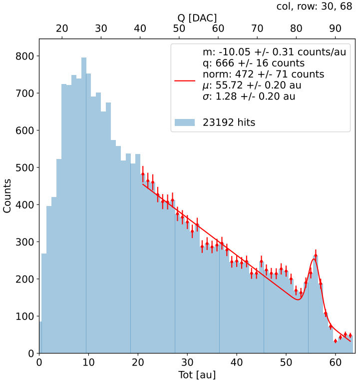
IDB = discriminator threshold

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

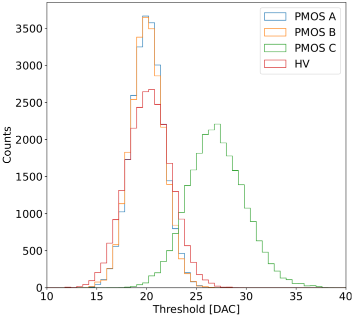


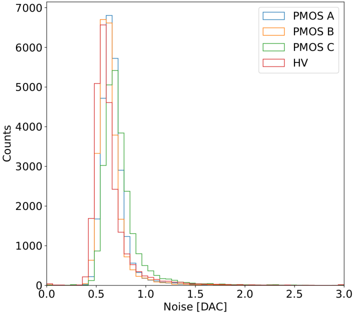
Partial deep p-well



Full deep p-well

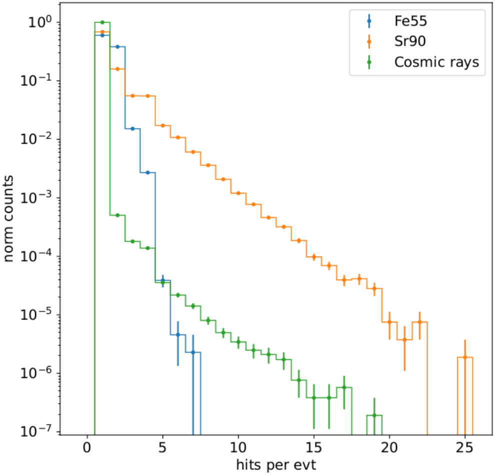
Threshold and noise results with different FEs





	PMOS A	PMOS B	PMOS C	HV	simulation
μ [e^-]	401.7±0.2	400.8±0.2	539.7±0.6	403.9±0.2	∼270
Δ_μ [e^-]	32.9±0.1	33.0±0.2	55.5±0.4	44.7±0.2	∼30
σ [e^-]	13.01±0.06	12.26±0.07	13.9±0.1	11.7±0.1	∼9
Δ_σ [e^-]	1.61±0.04	1.50±0.05	1.91±0.07	1.58±0.07	-

Acquisition with sources: Fe^{55}, Sr^{90}, cosmic rays

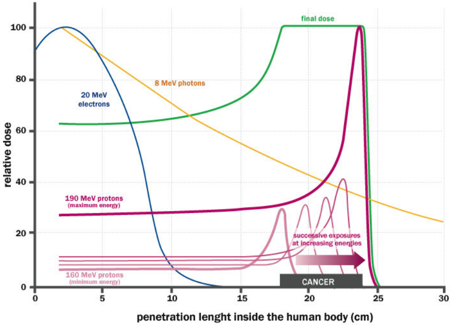


- Fe^{55} photon produces smaller clusters: pure charge sharing
- Sr^{90} and cosmic rays go across more pixels

Radiotherapy

Many different sources:

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



Test on the beam: ElectronFLASH

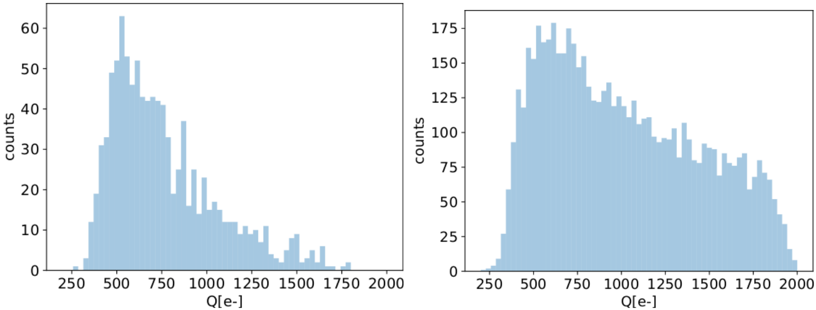
ElectronFLASH is the new accelerator for research on FLASH-RT placed in S. Chiara hospital in Pisa

Accelerator charateristics:

- linear accelerator
- bunched beam
- two energy configurations 7-9MeV
- 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

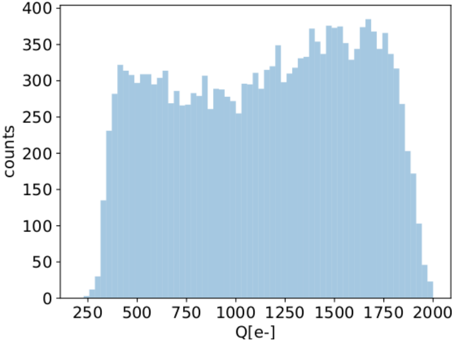
- With **both** the collimators, DPP=0.07 Gy, t_p=4 μs, PRF=1 Hz



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

Test on beam: preliminary results

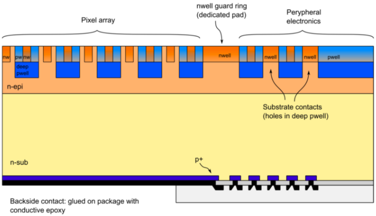
- **Without** any collimator, DPP=0.04 Gy, t_p=4 μs, PRF=1 Hz
- MIP are expected to release 2000 e^-, and because of rollorver are expected to be 300-400e^-



- 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

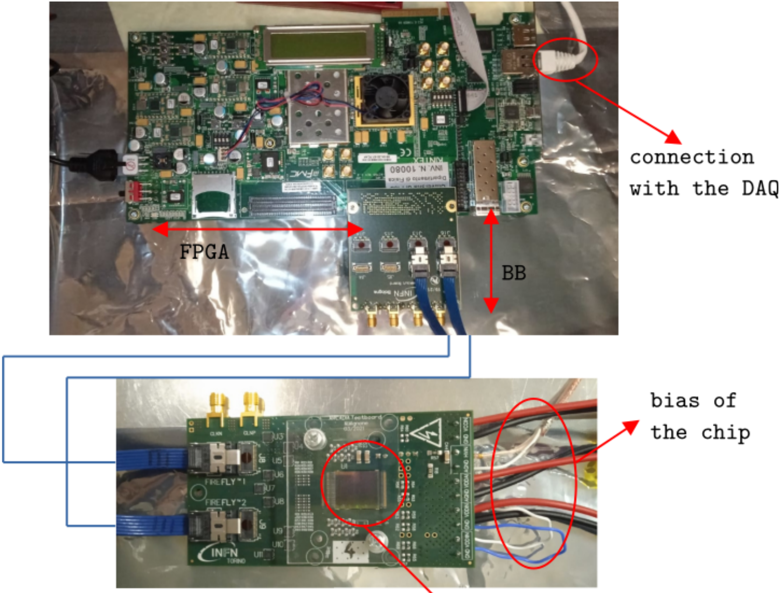
ARCADIA MD1



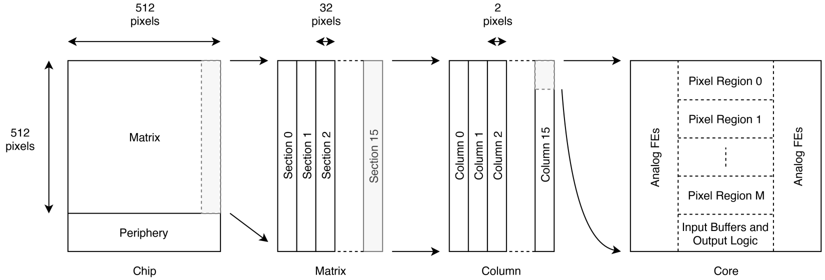
Parameter	Value
Matrix size	$1.28 \times 1.28\ cm^2$
Pixel size	$25 \times 25\ \mu m^2$
Depth	$48/100/200 \mu m$
Electrode size	$9 \times 9 \mu m^2$
Power consumption	$\sim 10 mW/cm^2$
Output signal	digital

- n-doped epitaxial layer

ARCADIA MD1: experimental setup



ARCADIA MD1: matrix division



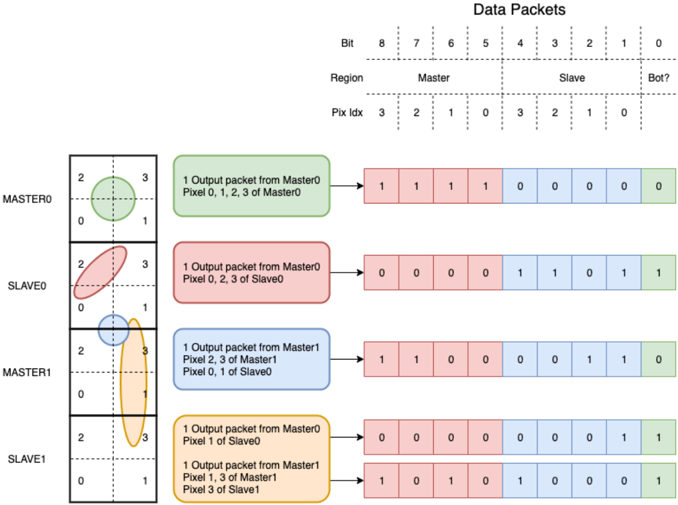
The matrix contains 512×512 pixels divided in:

- 16 sections containing 512×32 pixels
- 512×2 double columns
- cores of 32×2 pixels
- regions containing 4×2 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	hitmap

ARCADIA MD1: clustering

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



ARCADIA MD1: clustering