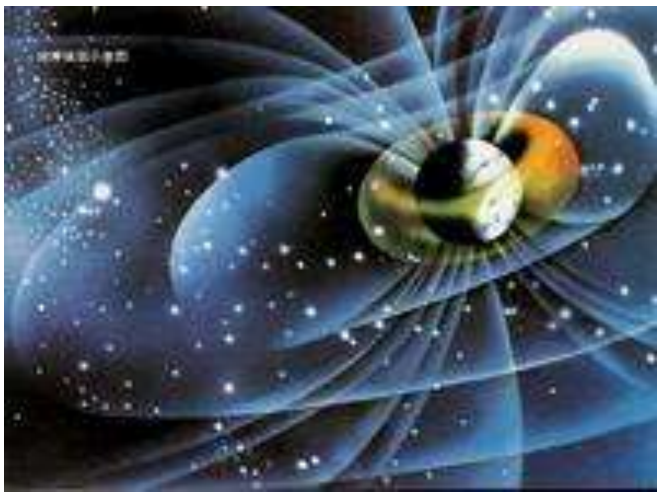
CMOS Pixel Sensor for a Space Radiation Monitor with very low cost, power and mass



Outline:

- ❖ Motivations & Specifications
- ❖ **The first prototype design**
- ❖ Perspectives

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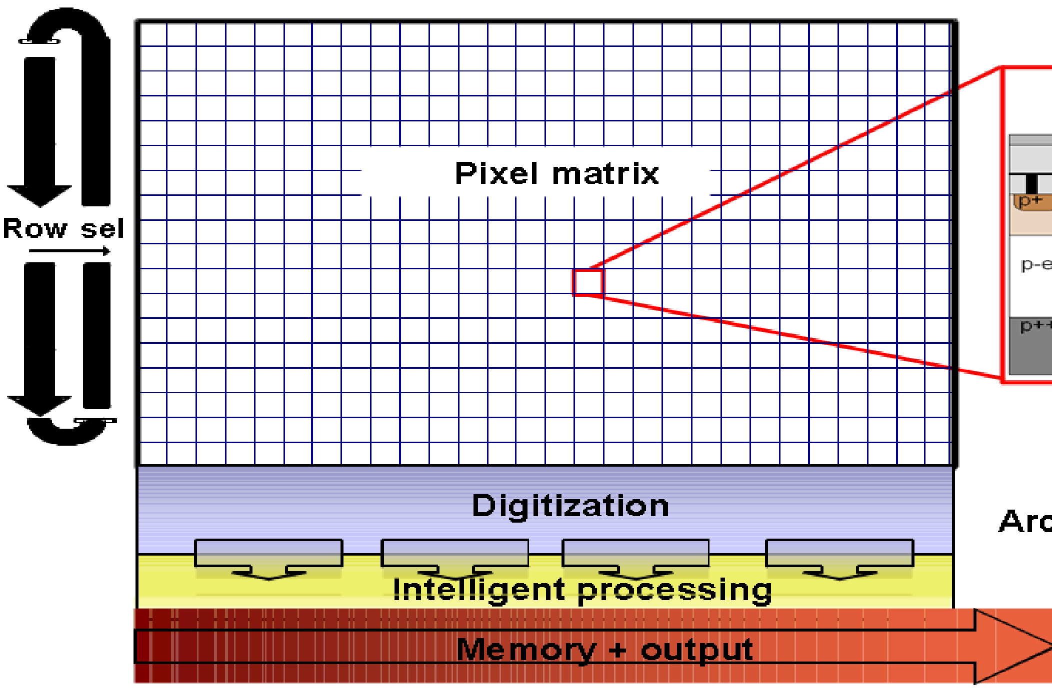
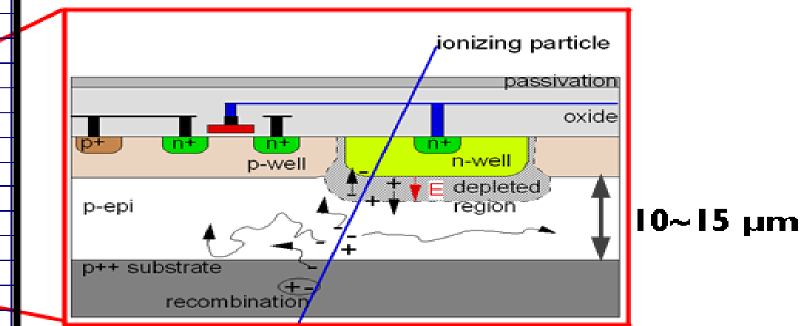
Motivations & Specifications

- *Space radiation environment (Medium Earth Orbit)*
  - ***Electrons:** 100 keV–7 MeV; $10^4 \rightarrow 10^7$ particles/cm^2/s (average number in different orbit)*
  - ***Protons:** 100 keV– 400 MeV; $10^3 \rightarrow 10^4$ particles/cm^2/s (average number in different orbit)*
  - *X rays (negligible in this case);Various heavy ion species (~1%) …*
- *Expected space radiation monitor functionalities*
  - ***Dosimeter***
    - *Measuring the accumulated dose released by those charged particles*
  - ***Particle Rate Meter***
    - *Detect particle flux density with respect to species and energies*
    - *Alerts in case of very intensive radiation fluxes (e.g. during solar storms)*
- *Required features: low cost (highly miniaturized, low power & mass); real-time information*
- *CMOS Pixel Sensor (CPS) used in high energy physics:*

High granularity, Tiny size, large readout speed (~10k Frame/s), Good radiation tolerance (>100k Rad & 10^{12}neq/cm^2), low power consumption (~100mW/cm^2)

How CMOS Pixel Sensor works





Architecture developed through MIMOSA series @ IPHC

- 100% fill-factor
- Miniaturized: sensor and signal processing integrated in the same silicon wafer
- Low cost: standard commercial CMOS technology
- Low power dissipation: rolling shutter operation mode
- Almost dead time free: very short reset time
- Sensitive: signal collected by the sensing diode as low as 200 e^- $ENC \approx 10\ e^-$ $SNR \approx 20$
- High granularity

Why CMOS pixel sensor?

- **Granularity of pixel sensor**: *perform like many small detectors*
  - *High flux detection capability*

    Many particles (>100/cm^2)/ frame
    High frame rate (> 10k Hz)
    } *Very high counting rate (> 10^6/cm^2/s)*

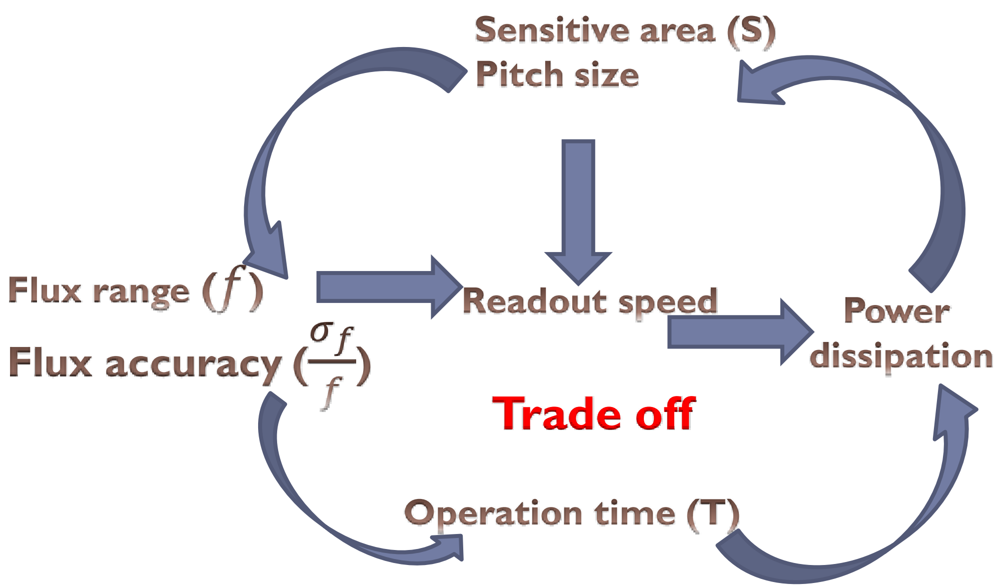
  - *Identify particles based on their energy deposition*

    Total charge spreads over several pixels
    Charge measurement for each pixel
    } *Sensitivity from single pixel signal*
    Dynamic from clustered pixels signal

- **CMOS monolithic sensor: smart**

Integrate intelligent digital processing logic → directly give the information we need → real time information possible

Choice of sensor ***sensitive area***, ***pitch size*** *and* ***readout speed***



Flux estimation:

- relative uncertainty is:
  $$\frac{\sigma_f}{f} = \frac{1}{\sqrt{fST}}$$
- Working hypothesis: low cost, miniaturize

  10 mm² sensitive area

Operation time (T)	$\frac{\sigma_f}{f} = 10\%$	$\frac{\sigma_f}{f} = 1\%$
Flux 10^3 part./cm²/s	1 s	100 s
Flux 10^7 part./cm²/s	0.1 ms	10 ms

Choice of sensor ***sensitive area***, ***pitch size*** *and* ***readout speed***

❖ Probability of misjudgment by hits pile-up

Frame time (speed)	Pixel pitch	Clusterize in pixels	P(N≥2)
☺ 100 μs	20 μm	3×3	0.07%
		5×5	0.47%
	50 μm	3×3	2.18%
		5×5	13.02%
50 μs	50 μm	3×3	0.59%
		5×5	3.98%
☺ 20 μs	50 μm	3×3	0.10%
		5×5	0.72%
		6×6	0.002%

Considering the power dissipation

$$P(N > N_{MAX}) = 1 - \sum_{N=0}^{N=N_{MAX}} \frac{\lambda^N e^{-\lambda}}{N!}$$

N: the hits quantity in the same cluster in the same frame

λ: probability of particle hits in the cluster in one frame

Considering the worst situation:

- flux= 10^7 *particles/cm*^{2}/s for electron
- flux= 10^4 *particles/cm*^{2}/s for proton

≤20 hits per frame

Occupancy ≤ *10%*

Final choice:

Area=10 mm^2 pitch= 50 μm

64×64 pixels Frame<20 μs

Device simulation

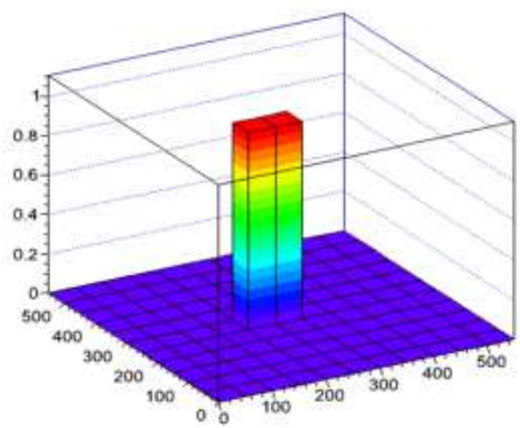
- 4 steps: translate requirements from measurements ⟶ sensor design
  - Geant4: Energy deposited in sensitive area (Monte carlo simulation)
  - Private model of CPS response: Energy deposited ⟶ signal over pixels
  - Digitization of pixel: signal over 3 bits
  - Clusterization algorithm: embedded data processing

Range of expected signal on seed pixel: 300 e- to 120k e-

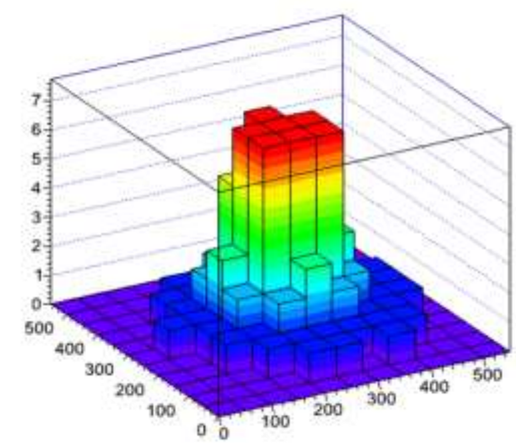
3-bit ADC:
LSB: 700e-; Range: 200e- to 4400e-

Noise consideration

Sensor digital performance with vertically impinging

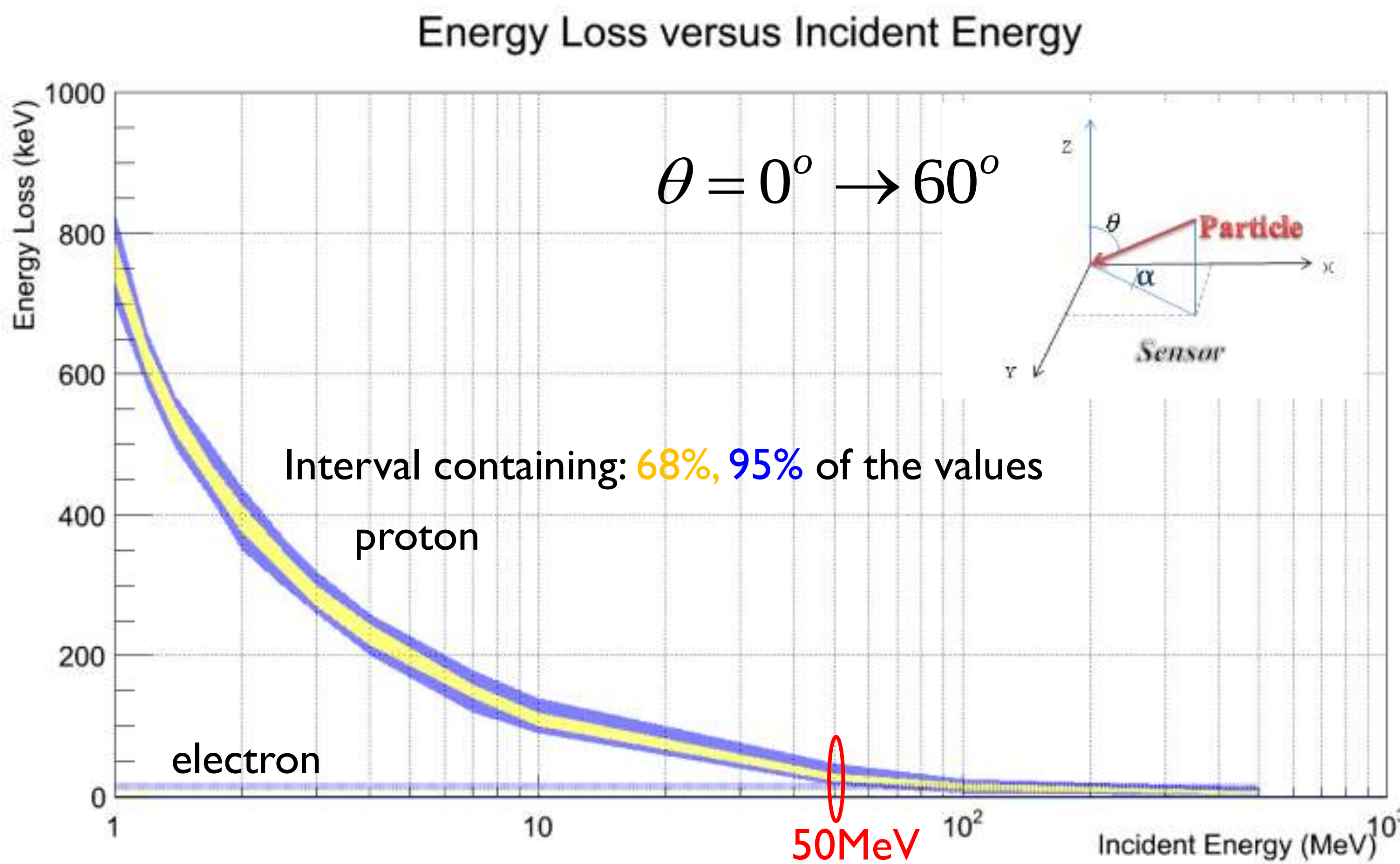


500 keV electron



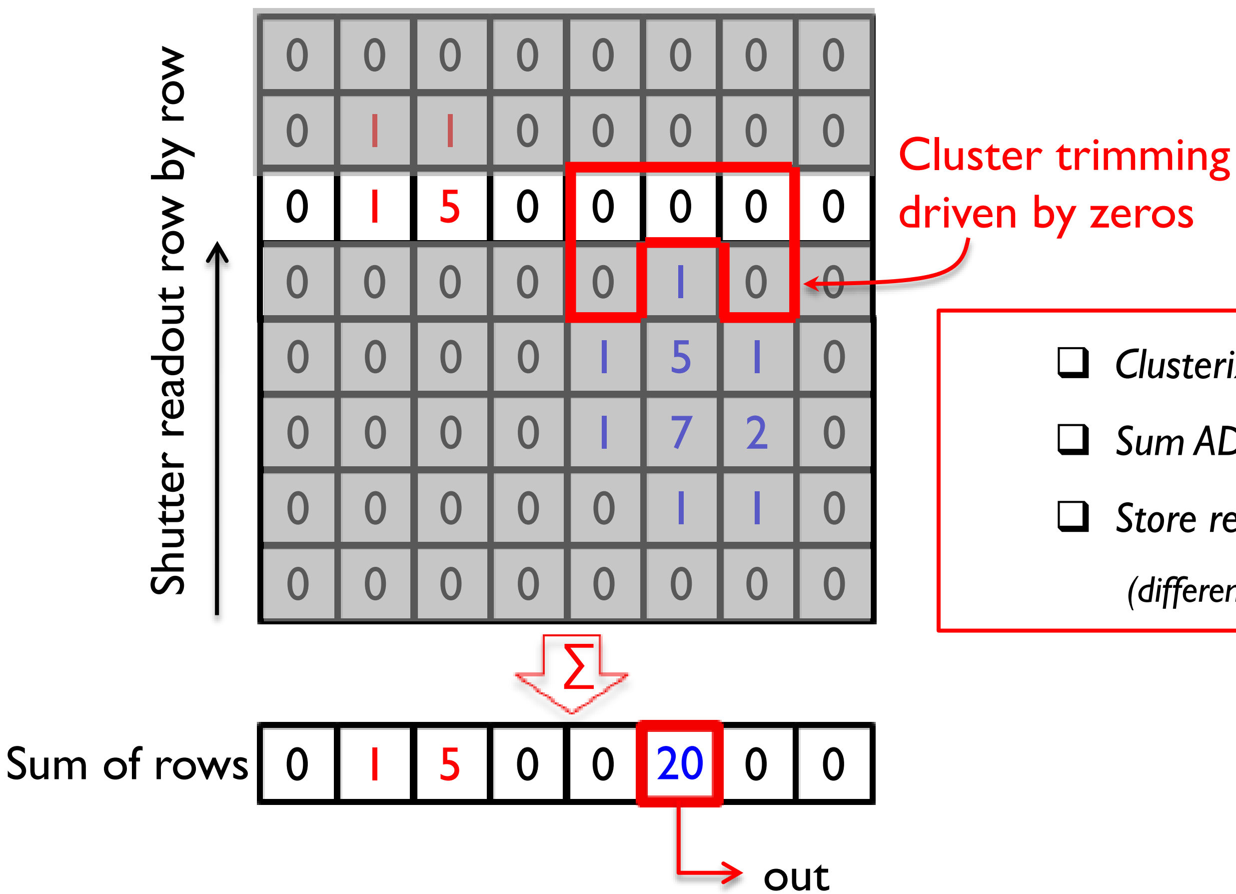
1 MeV proton

Device simulation



Device simulation

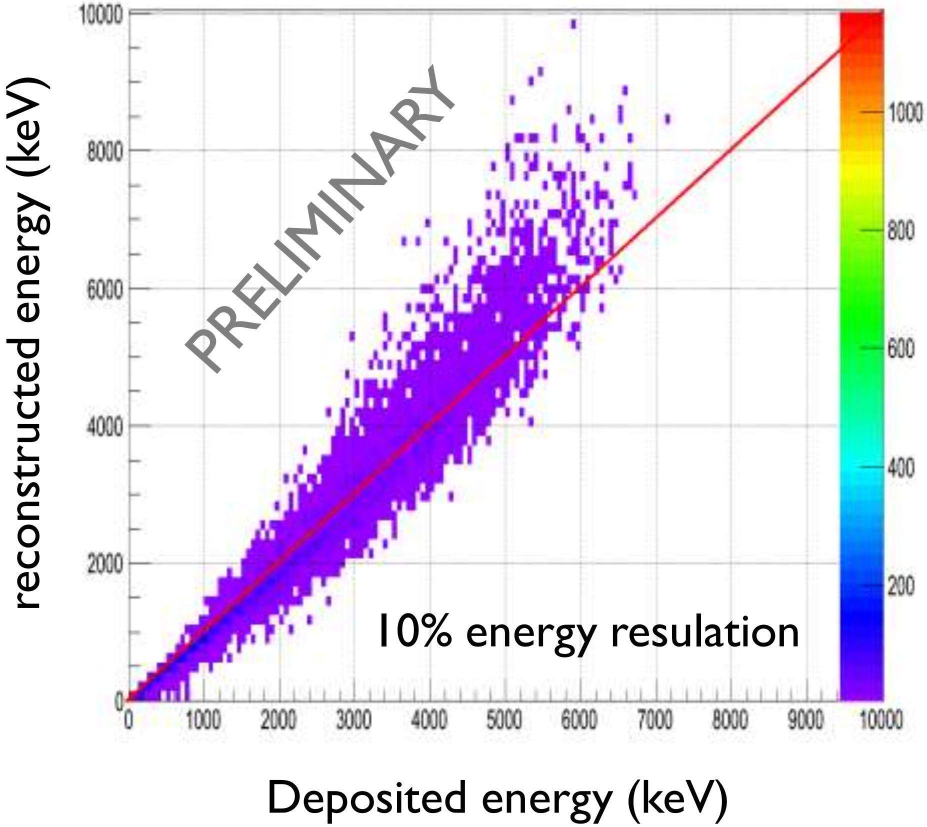
Clusterization algorithm: *embedded data processing*



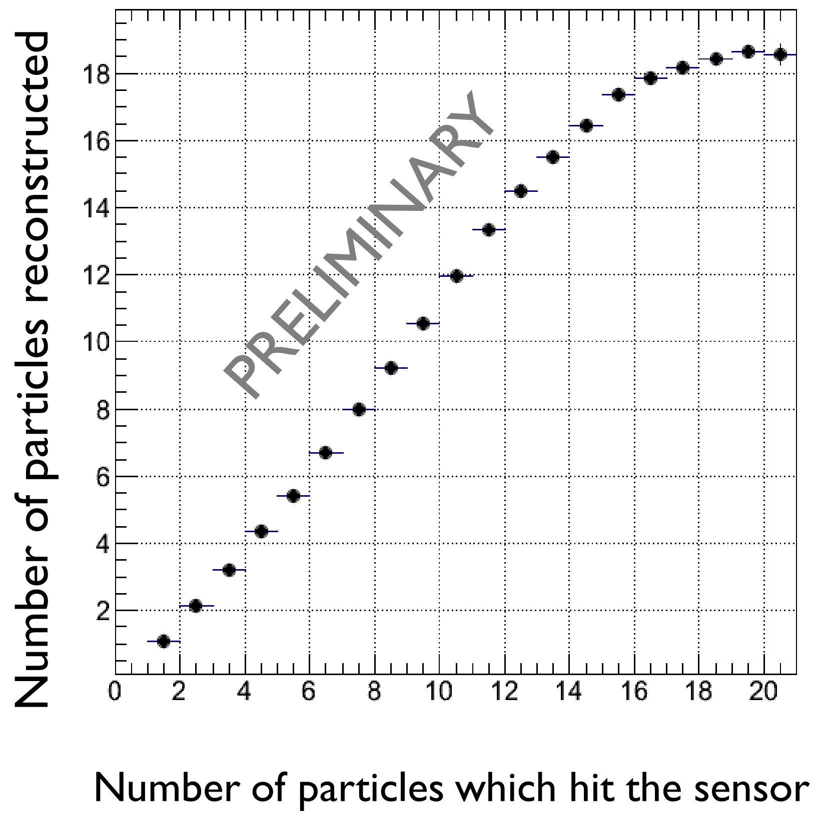
- *Clusterization*
- *Sum ADC counts in each cluster*
- *Store results in each memory*

  (different energy & species particles)

Device simulation: algorithm performances

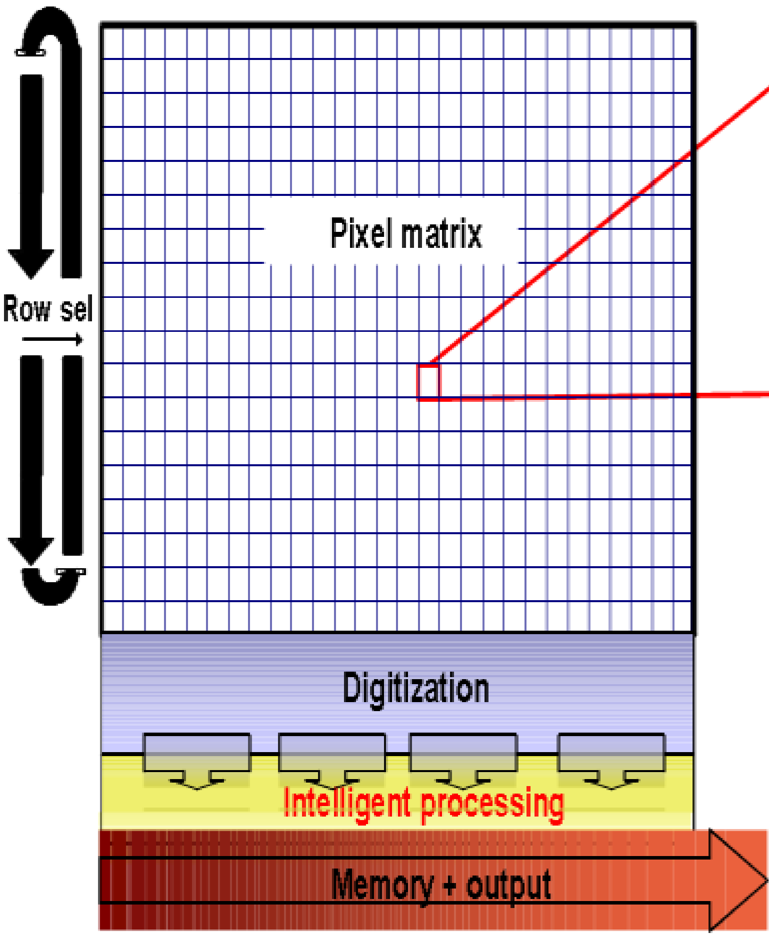


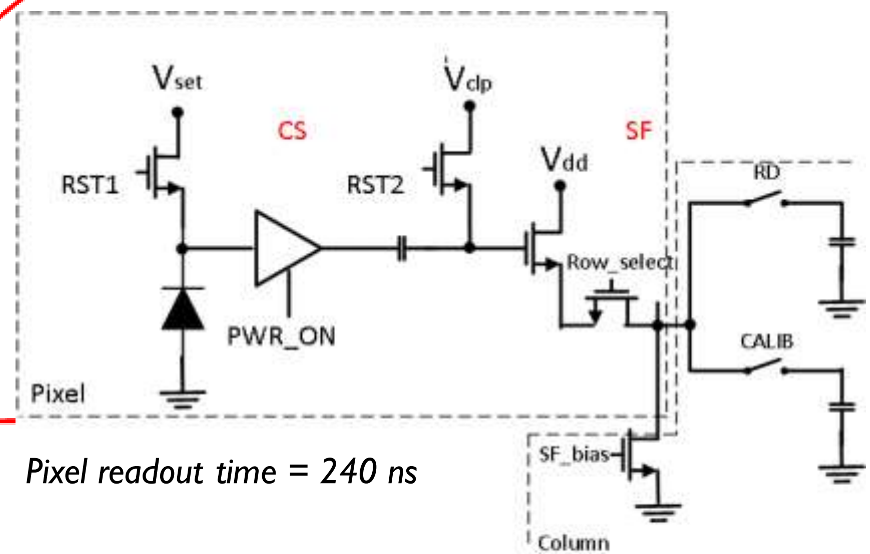
20 particles in a frame with mixed energies (from 1 MeV to 100 MeV)



Depends strongly on the energy distribution of the incoming particles. Low energy particle <10 MeV, large cluster

Front-end readout electronics (1/3): pixel





Pixel readout time = 240 ns

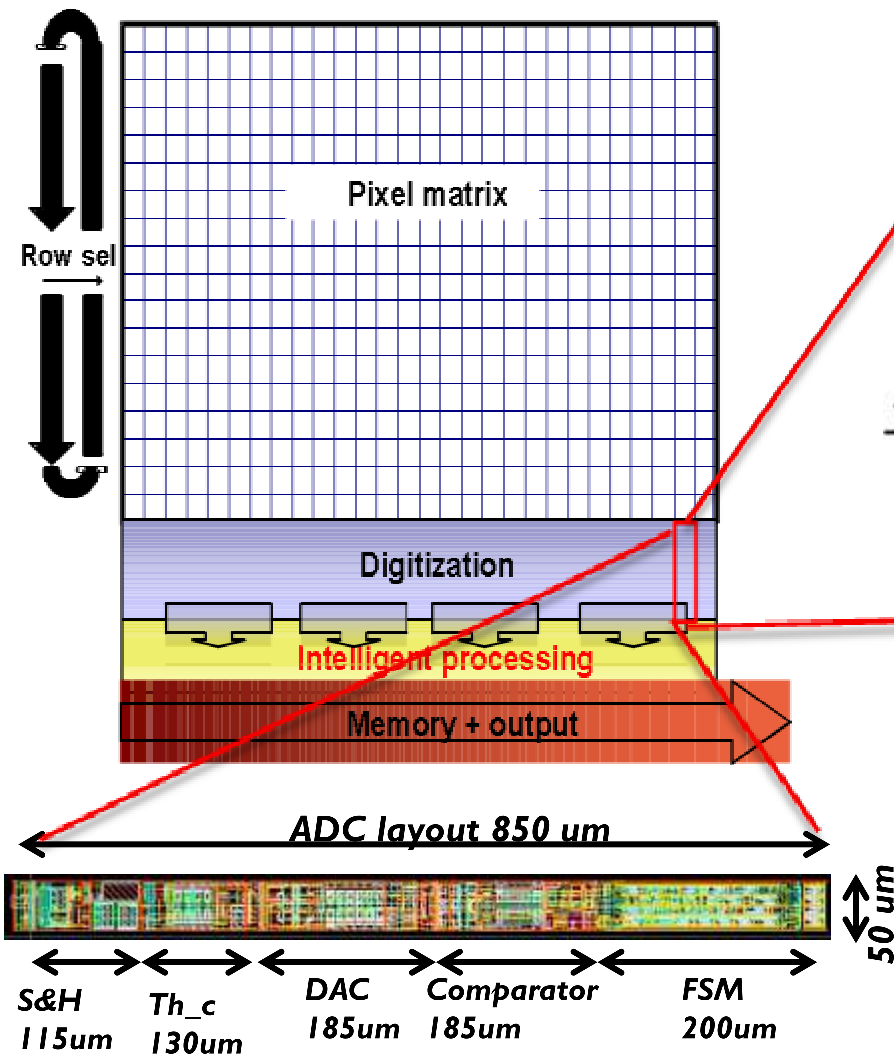
Schematic of the pixel

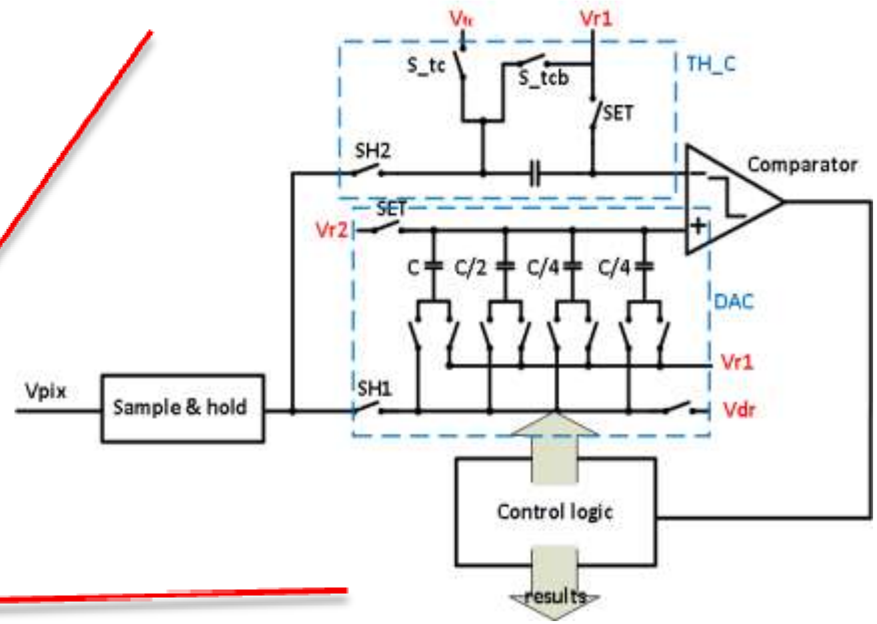
Charge to Voltage conversion Factor):

$$CVF \approx 60uV/e^{-}$$

- All NMOS
- Pixel level CDS (correlated double sampling)
- Relative linear response (300 e^{-}, 10k e^{-})
- Enough SNR (Signal to Noise Ratio) for efficiency: 300 e^{-} /14 e^{-} ≈ 21

Front-end readout electronics (2/3): Column level ADC





The dedicated 3-bit successive approximation ADC

- *Column level CDS*
- *Adjustable I/O characteristic*
- *Special state for reducing power consumption*
- *Particular layout size: 50×850 um²*

ADC conversion time = Pixel readout time = 240 ns

Front-end readout electronics (3/3): layout

0.35 um process, 3.3 V supply voltage

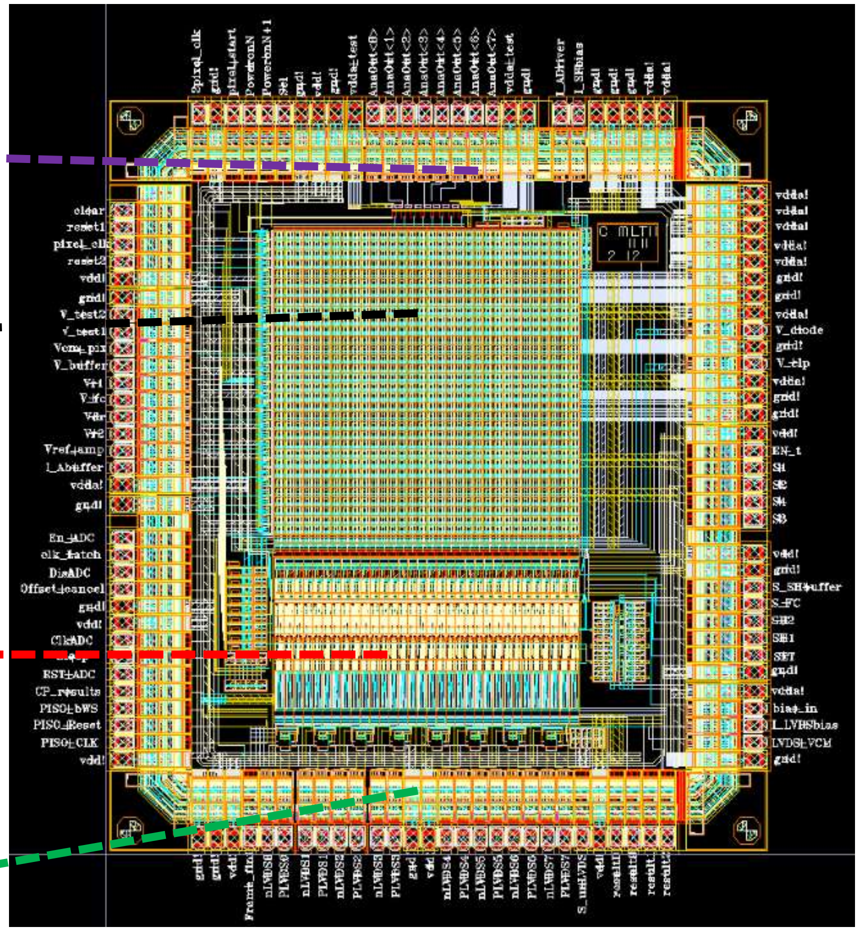
Area: 3.5×4 mm²

Analog Outputs

32×32 Pixel matrix
1.6×1.6 mm²
& sequence

32 Column 3-bit ADCs
& MUX

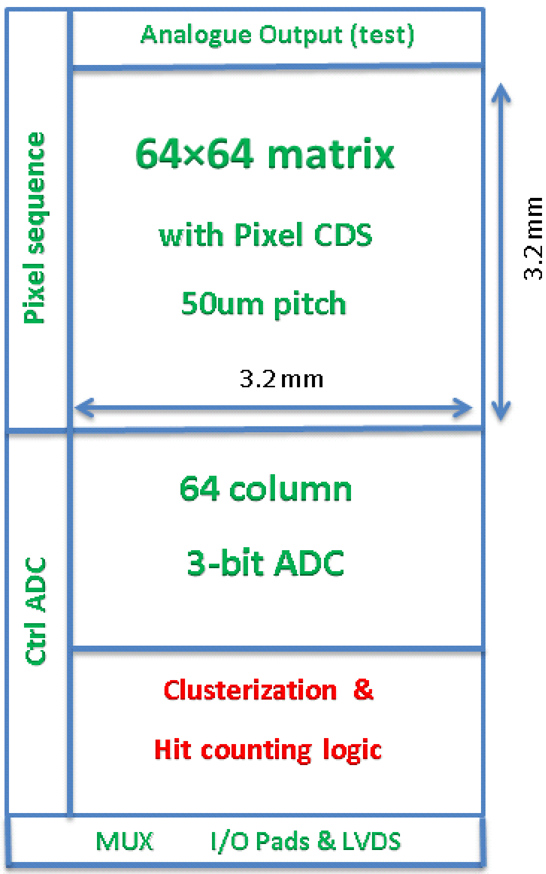
Digital Outputs



- ***Power dissipation:***
  - *~130 uW/pixel*
  - *~700 uW/ADC with hit*
  - *~600 uW/ADC without hit*
  - *64×64 pixel + 64 ADCs: ≈ 50 mW*

- ***Timing***
  - *One row: 240 ns*
  - *One frame (32 rows): 7.68 μs*

Perspectives



Floor plan of the future final smart sensor

- *2012-2013*
  - *Reception of 1st prototype at mid-september 2012*
  - *Test*
  - *Design of Clusterization & Hit counting logic*
- *End of 2013: 1st full validated architecture*
  - *Weight: few grams*
  - *Size: 5×15 mm^2 (estimated)*
  - *Measurement: 10^3-10^7 part./cm^2/s with 10% relative uncertainty in 1 second*
  - *e^-& p^+ separated up to 50 MeV*

Additional e^-/p^+ separation can be achieved by using several sensors with different shieldings

Application would not be limited in space radiation detection