COMETH*: a CMOS pixel sensor for a highly miniaturized high-flux radiation monitor

Outline:

- Design review
- **Test results of the first prototype**
- Conclusions & Perspectives

*: **Co**unter for **M**onitoring the **E**nergy and **T**ype of charged particles in **H**igh flux

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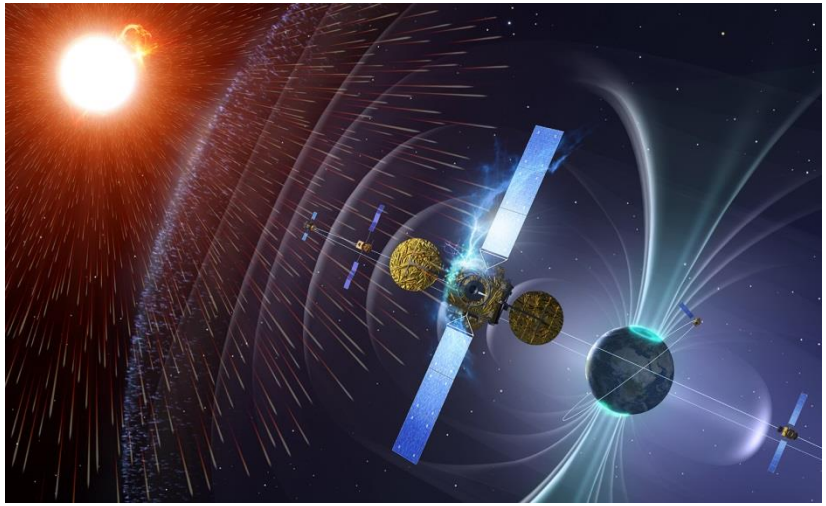
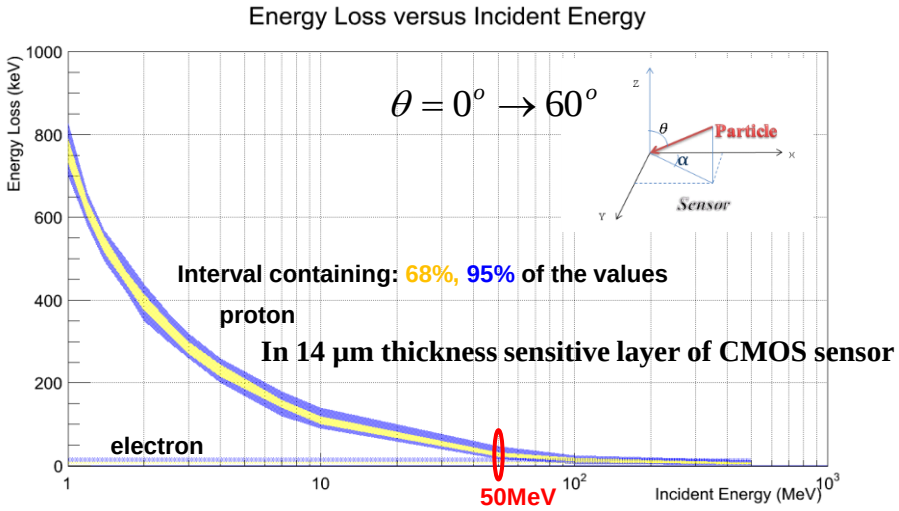
Application targets



- Space radiation environment (Medium Earth Orbit):
  - **Various particle species**: electrons, protons, X rays (effects ignorable), various heavy ion species (~1%);
  - **High flux density** (average number in different orbit):
    - Electrons: $10^4 \rightarrow$ several 10^7 particles/cm^2/s
    - Protons: $10^3 \rightarrow 10^4$ particles/cm^2/s
  - **Large energy range**:
    - Electrons: 100 keV–7 MeV;
    - Protons: 100 keV– 400 MeV;

- **Targets:**
  - ✓ Count individual particles
  - ✓ Distinguish particle species & energies
  - ✓ Provide real-time data
- **Desired feature:** low power, mass, volume and unit cost

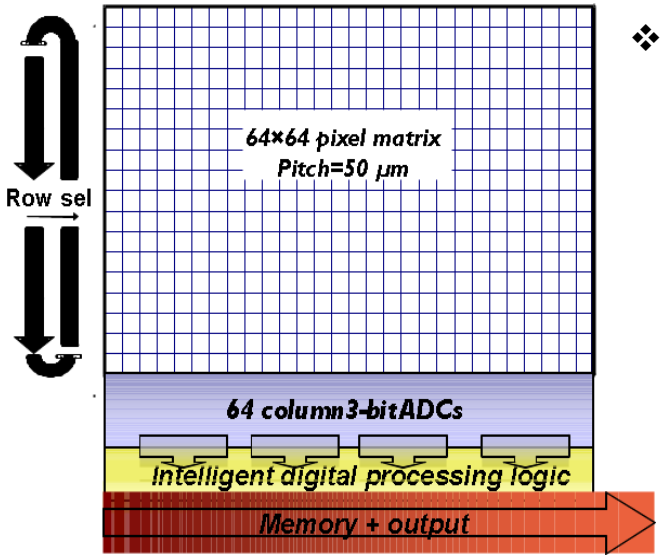
Particles energy loss varies with their species and energies.



Monte Carlo simulation results with Geant4

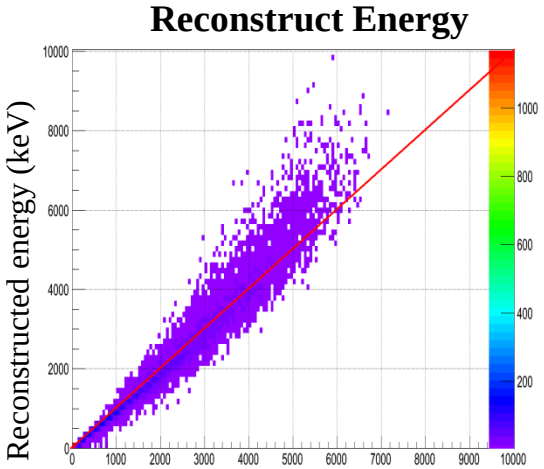
Good measurement of energy loss => determination of incident energy and species.

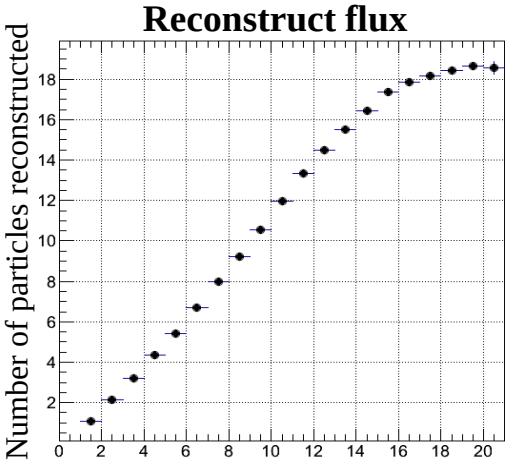
Proposed solution and simulated performances



Proposed CMOS Pixel Sensor architecture developed through MIMOSA series @ IPHC

- **Reconstruction capability** (validated by simulation) [1]**:**
  - **Energy:** a relative value of 10% standard deviation;
  - **Flux:** ~ 10^7/cm^2/second; (not an absolute limit of this architecture)





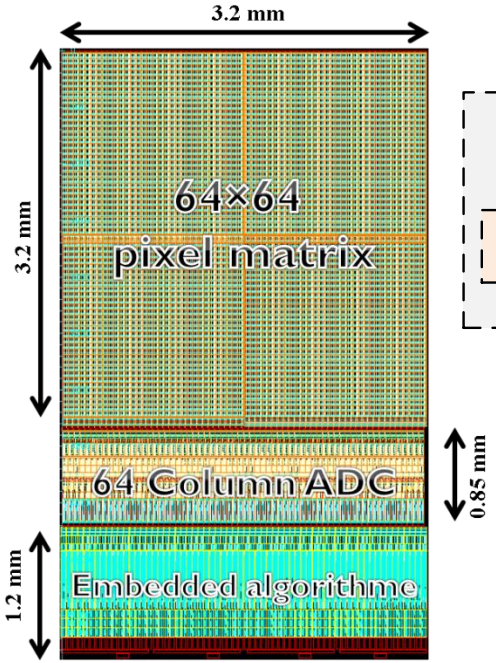
Electrons and protons with mixed energies (1 MeV to 100 MeV)

- Some key parameters used to perform the simulation:
  - **Sensitive area:** 10 mm^2 (pixel matrix)
  - **Operation speed**: 50,000 frames/s
  - **Seed pixel signal range**: ~300 e$^-$ to tens of k e$^-$
  - **ADC**: concerned range from 0 to 4400 e$^-$
    - Threshold (<300 e$^-$);
    - 3-bit, 700 e$^-$ step size.

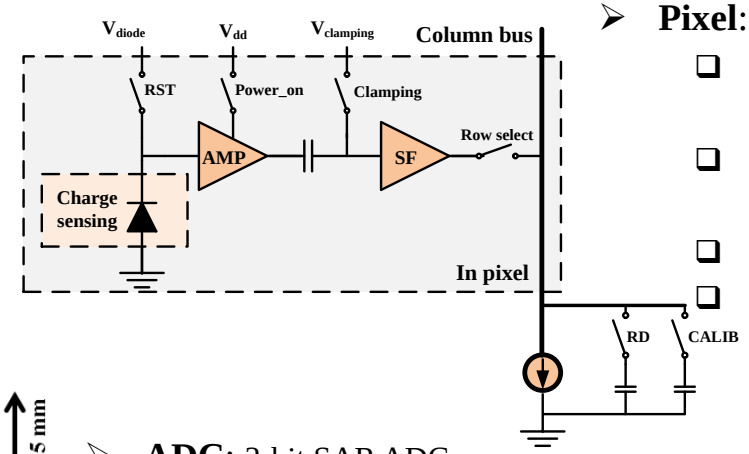
- **Cluster size:**
  - **Electrons:** 2 to 3 pixels in average (confirmed by test);
  - **Protons:** cluster size is inversely proportional to energy. Low energy proton may possibly trigger 9×9 pixels.

[1] Y.Zhou *et al.*, JINST 7 (2012) C12003.

Key parameters during COMETH design (1/2)

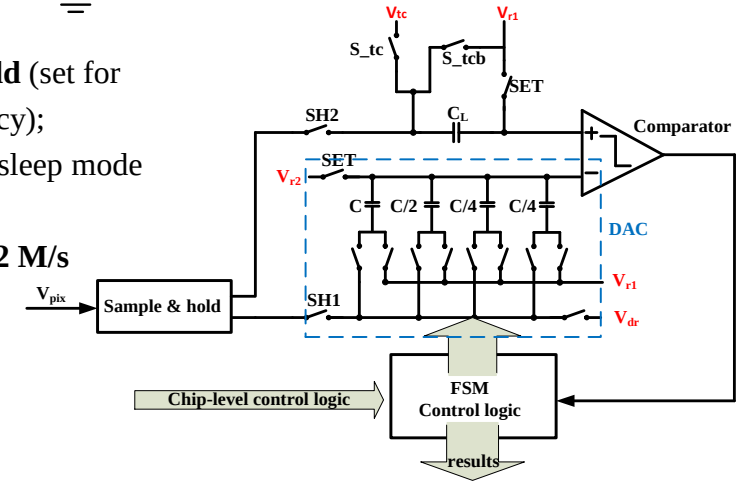


Layout of COMETH: 16.8 mm² (0.35 µm process)



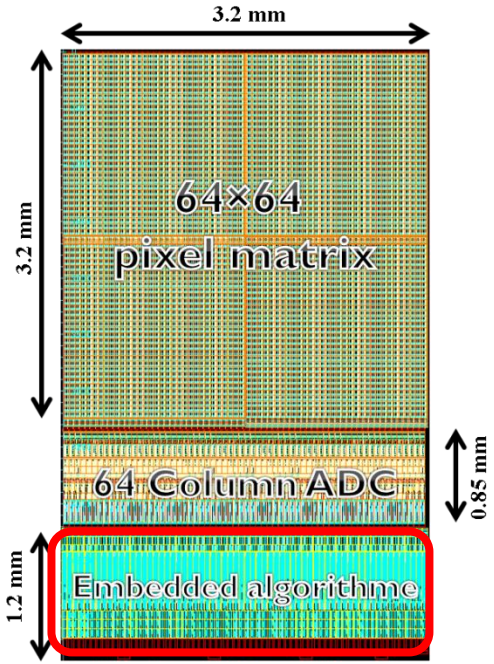
- **Pixel**: signal collection and amplification
  - Amplify the signal while limit the noise;
  - **Linear response** for the signal range from **0 to 4400** e^-;
  - Processing time for each pixel: **240 ns**;
  - Power dissipation: 130 µW for a single pixel, 130×64 µW for matrix (rolling shutter mode).

- **ADC**: 3-bit SAR ADC
  - **Tunable threshold** (set for detection efficiency);
  - **Power efficient** (sleep mode without hit);
  - Sampling rate: **4.2 M/s**



- **COMETH**:
  - Operation speed: **~65, 000 frames/s** (> 50 k frames/s used in simulation);
  - Unfired pixels > 97% up to flux as high as $10^7/cm^2/s$
  - Power dissipation (VDD = 3.3V): ~ **100 mW**;

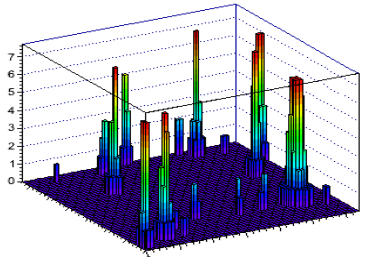
Key parameters during COMETH design (2/2)



Layout of COMETH

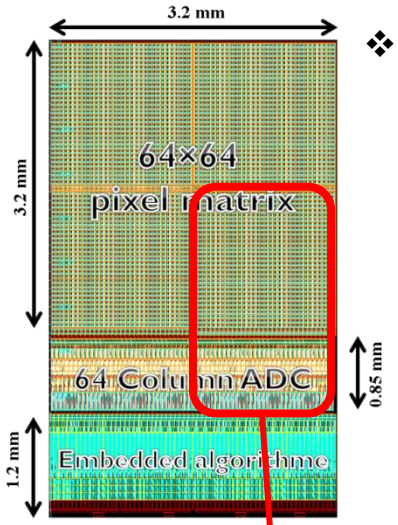
- **Features:**
  - Size: 1.2×3.2 mm²;
  - Power dissipation: **56.7 mW** (3.3 V power supply, estimated by using CADENCE EPS);
  - Main clock frequency: 25 MHz;

- **Digital processing stage**: embedded reconstruction algorithm, described using Verilog (hardware description language) and synthesised with the same 0.35 µm process.
  - **Purpose** (determined by operation on board a satellite)**:**
    - Suppress the data amount: relax the data transmission stress;
    - Process the data: provide high level information itself, remove signal treatment power aside the sensor;
  - **Functionalities:**
    - Clusterization;
    - Summation;
    - Separation;
    - Counting;

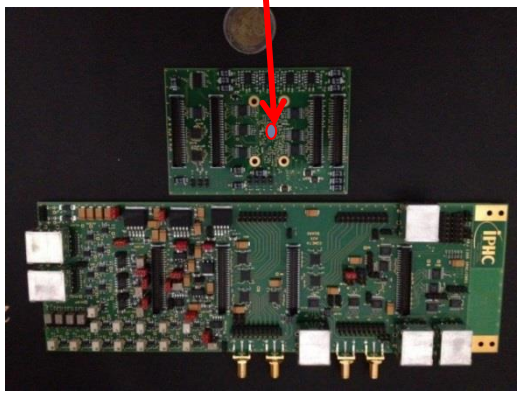


  - **Performances** (checked by a full simulation of the layout against many inputs)
    - Capable to reconstruct most of cluster cases, except some tricky clusters with two adjacent dead pixels.
    - Outputs: 4 channels; **65 k bits/second/channel**;
    - Data transmission sparsification factor: **0.24‰** (compared to ADC outputs transmission)

Tests performed

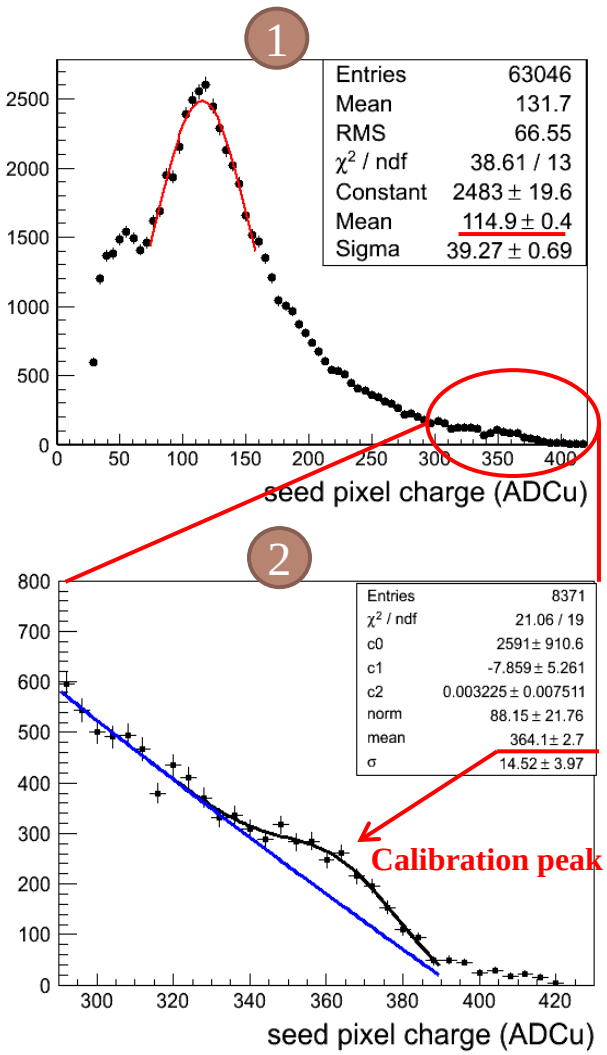


Reduced scale prototype with 32×32 pixels and 32 column ADCs



- **Pixel matrix:** was tested with 3 types of source and without any source for noise distribution.
  - **^{55}Fe** : X-rays with high probability of 5.9 keV photon energy which translates into 1640 e^- generated in silicon. Used for calibration.
    - CVF (charge to voltage conversion factor);
    - CCE (charge collection efficiency) combined with cluster size;
  - **Beta particle source**: energy range from several keV to 220 MeV, mean value around 128 MeV.
    - Cluster size for electrons;
    - Seed pixel collected charge (used for ADC threshold determination);
    - SNR (signal to noise ratio) of the smallest signal in COMETH application.
  - **Infrared** (1063 nm) **laser illumination**: frequency and intensity controlled by electrical signals; spot (5µm) average position adjustable in both x, y, z directions with 1 µm resolution.
    - Pixel response linearity;
    - Sensing diode reset and recovery efficiency;
- **ADCs:** were tested with external voltage biases replacing the pixel outputs
  - Threshold tunable functionality;
  - Power dissipations for with signal/ without signal;
  - Transfer function;
  - Noise performances: DNL, ILN, Temper Noise, Fixed Pattern Noise between columns.

Calibration test: ^{55}Fe



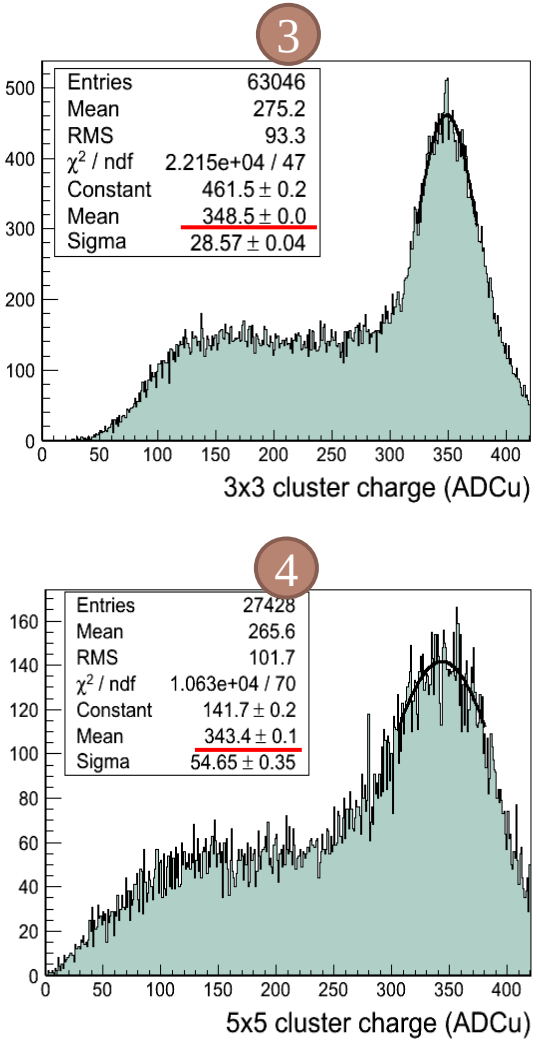
➢ **CCE** (seed pixel):
115/364 = **(31.6±0.5)%**

➢ **CCE** (9 pixels):
348/364 = **(95.6±0.5)%**

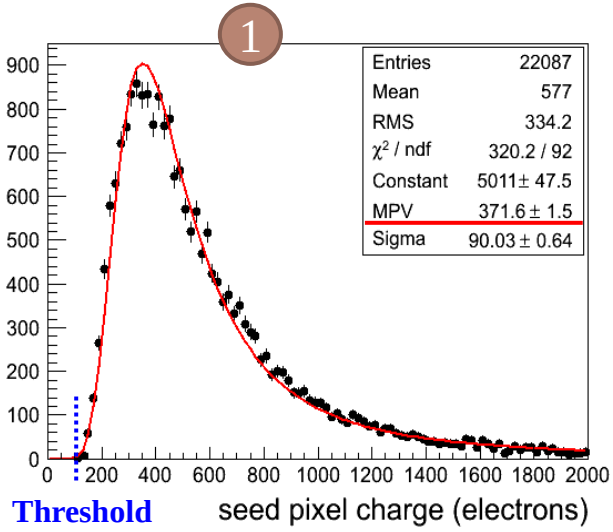
❑ **Satisfactory high CCE for the sensor with 50 µm pitch size, 4.3×4.3 µm² sensing diode located in the center of each pixel.**

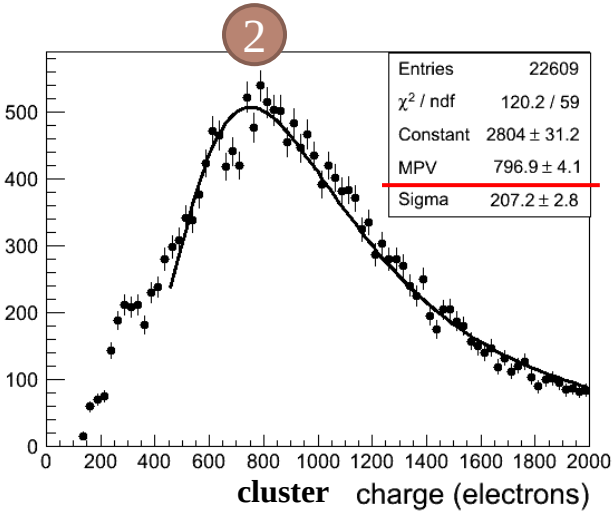
➢ **CCE** (5×5 cluster):
343/364 = **(94.3±0.5)%**

➢ **Seed pixel calibration peak**:
364 ADC unit; 4.5 e⁻/ADC unit;
➢ **CVF**: ~33 µV/e⁻

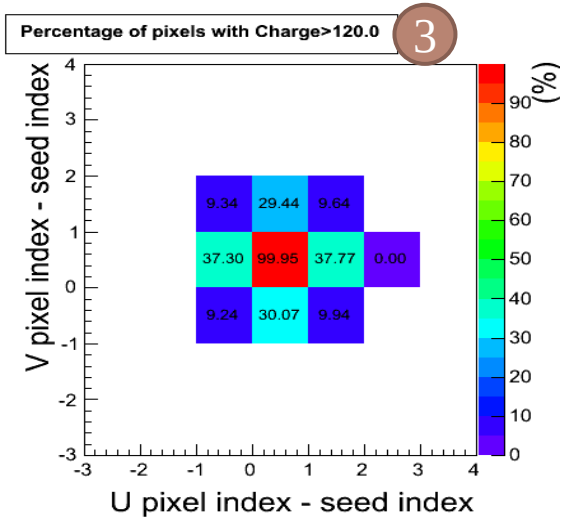


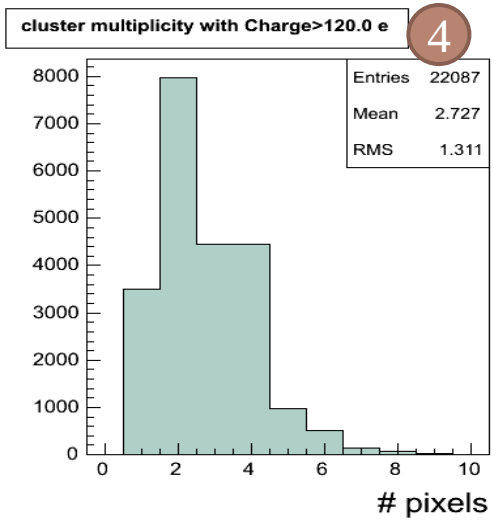
Beta source test





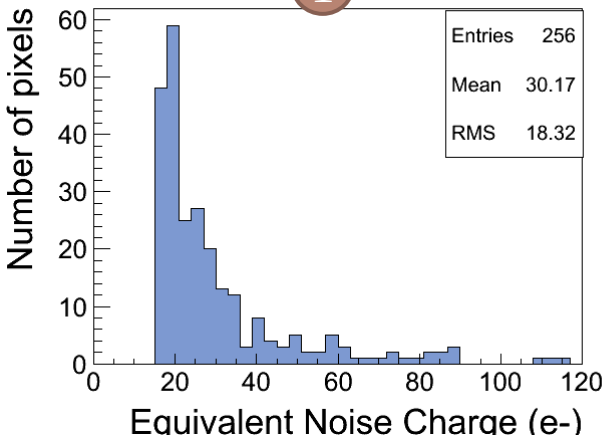
- **Seed pixel MPV** (Most probably value): **372±1 e⁻**
- **Threshold** (determines the **detection efficiency**): **120 e⁻** for **99.95%**
- ❑ **Confirm the simulated sensor response to electrons: Most probably 2 to 3 fired pixels for each hit.**
- **Cluster MPV:** around 2 times seed pixel MPV
- Most of the charges are collected by the **5 crossed pixels**;
- Most of the clusters contain **2 to 3 pixels** higher than threshold;





Noise and infrared laser illumination test

1



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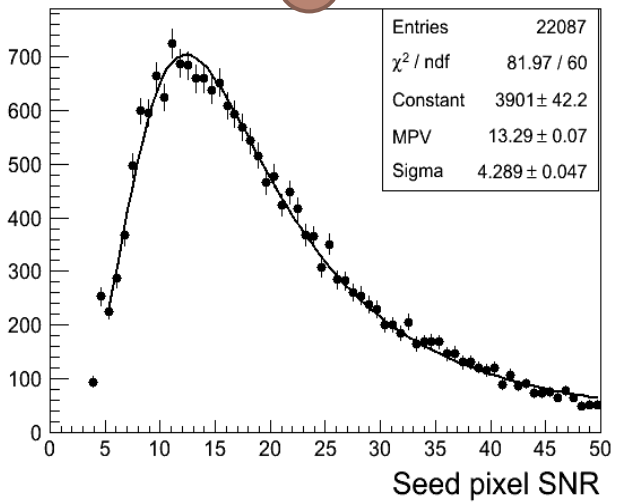

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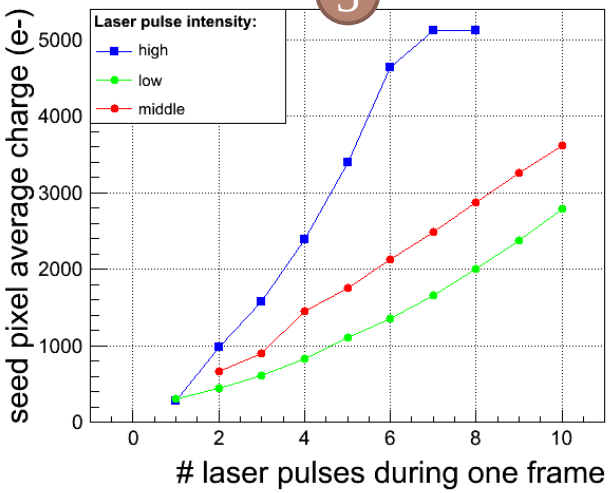
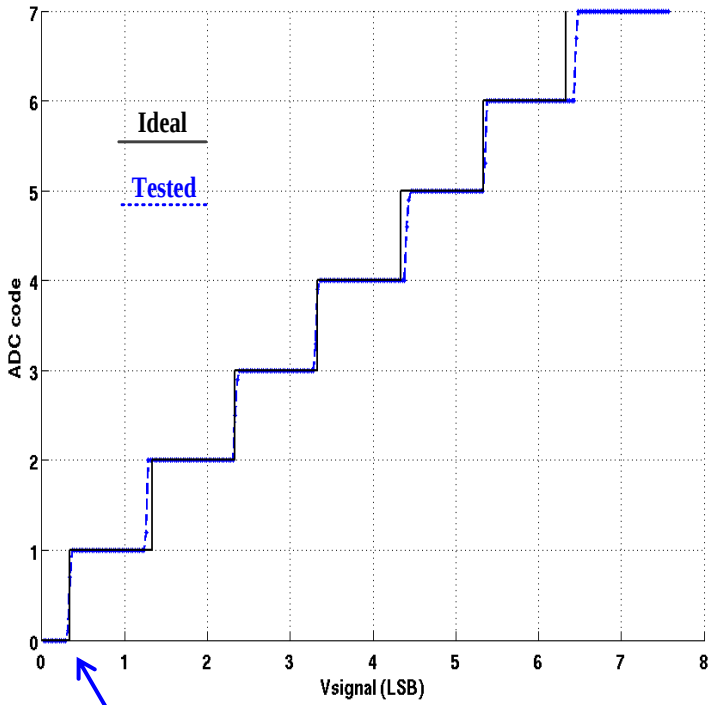
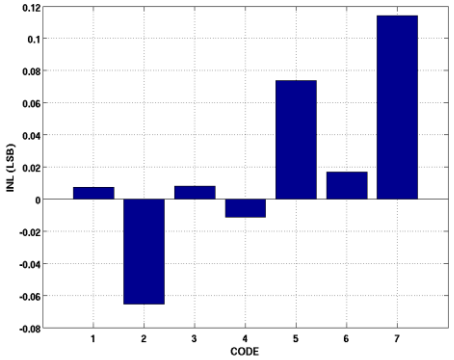


- Laser illumination test:
  - **Linear response range**: 0 to 4600 e^-; (satisfy the expectation 0 to 4400 e^-)
  - Sensing diode **fast reset and recovery** from large signals also confirmed by large intensity and various frequency illumination.
- Noise:
  - **ENC**: 30 e^-;
  - **SNR** (for electrons, the smallest signal in COMETH application): 13 for MPV

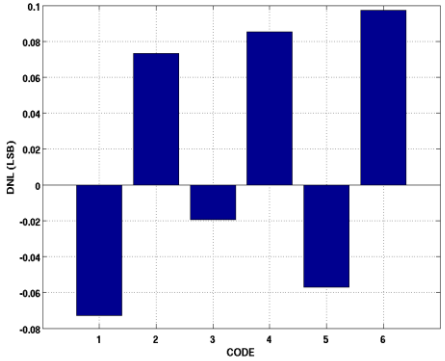
ADC test



Single ADC transfer function



INL



DNL

- Noise:
  - INL and DNL for a single ADC are less than ±0.12 LSB
  - Temper noise (rms): 0.02 LSB;
  - Fix pattern noise between 32 columns (rms): 0.21 LSB (need to be improved in next version)

- Threshold tunable to meet the detection efficiency

$1LSB = 700\ e^- = 700\ e^- \times CVF = 23.1\ mV$

- Single ADC power dissipation:
  - With signal: 759 µW;
  - Without signal: 532 µW;
  - Average: 539 µW (3% fired pixels)

Conclusions & Perspectives

- Tests of the first prototype:
  - Good CCE with x-ray source demostrates detection efficiency with 50×50 µm^2 pixel;
  - Beta source tests confirm the simulated response and the sensitivity of this sensor technology to electrons;
  - Small electron triggered cluster size validates the counting capability to high flux;
  - The linear pixel response for the signal range concerned and ADC performances give confidences in the ability for the embedded digital processing;

- **Perspectives**:
  - Calibrate sensor response to protons with further tests;
  - Improve the electronics' performances: reduce the pixel's noise and ADC FPN between columns; further optimize the system power dissipation;
  - More comprehensive simulations to evaluate the capabilities of the embedded algorithm (eg. High flux density inputs with various cluster size and shapes).

All these elements make us confident that the radiation counter with very low mass and power can indeed reach the expected performances up to the 10^7 particles/cm^2/s flux.

Thank you for your attention