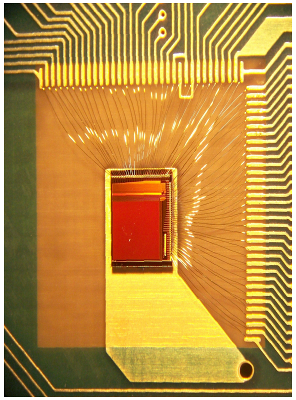
The first beam test of a monolithic particle pixel detector in high-voltage CMOS technology

Ivan Peric, Christian Takacs,
Jörg Behr, Franz M. Wagner, Peter Fischer

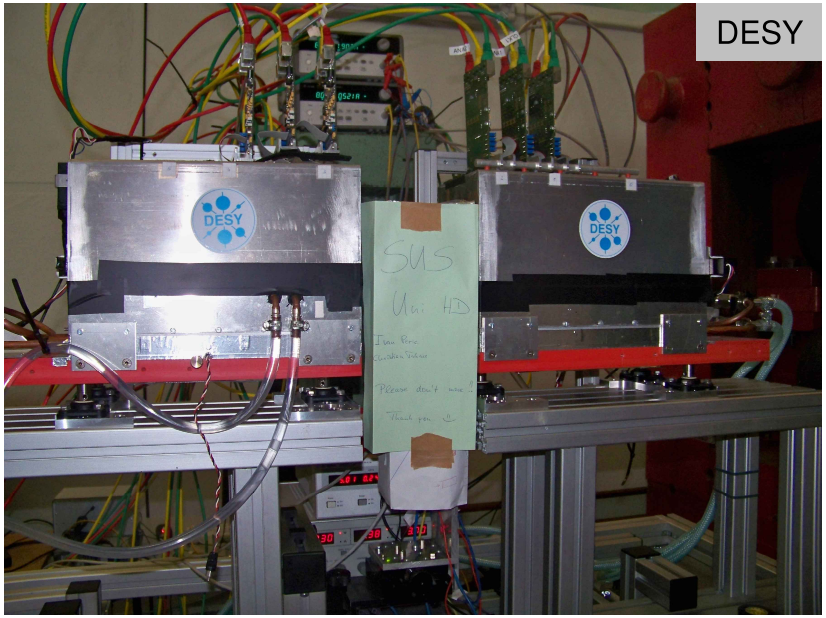
University of Heidelberg

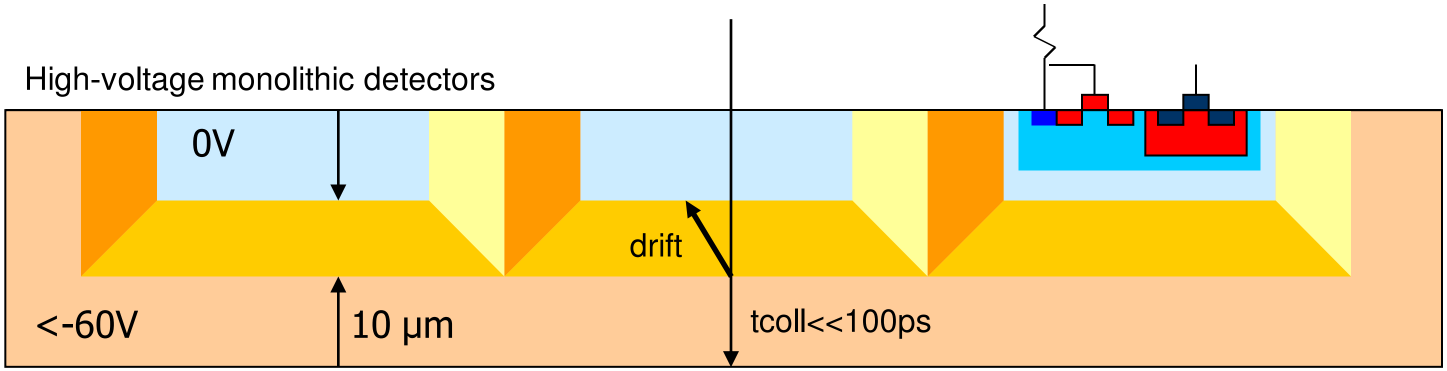
This work draws on the results from an ongoing research project
commissioned by the Landesstiftung Baden-Württemberg

- Monolithic pixel detectors in high-voltage CMOS technology
- **Main features**:
- Easy to implement (standard CMOS technology used), radiation hard and fast
- Allow in-pixel signal processing (CMOS)
- Can be very thin (thinner than 50 μm)
- Possible applications: particle tracking in the case of high occupancy and harsh radiation environment such as in LHC (upgrade)



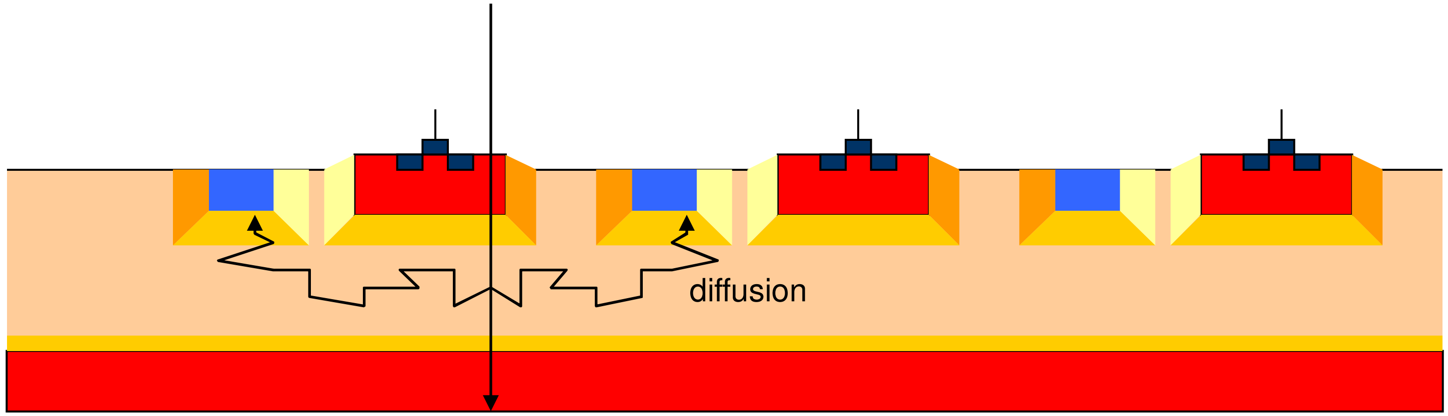
- First test beam results
- First irradiation results





1. Idea – use **high-voltage P/N junctions** as sensor
2. Idea – **place the (CMOS) electronics inside the N-well**

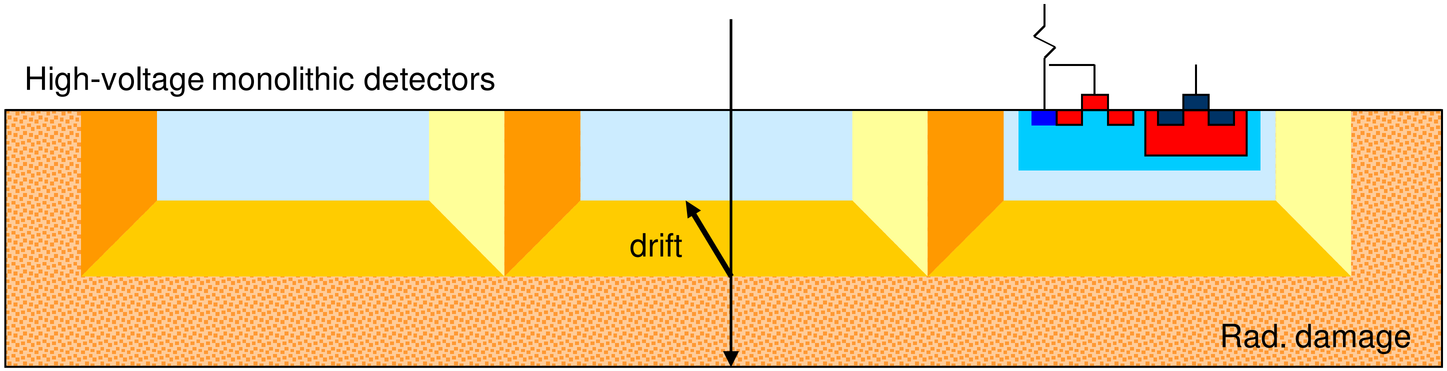
☺ Collection speed
☺ Radiation hardness



MAPS (as comparison)

High-voltage monolithic detectors

High-voltage monolithic detectors



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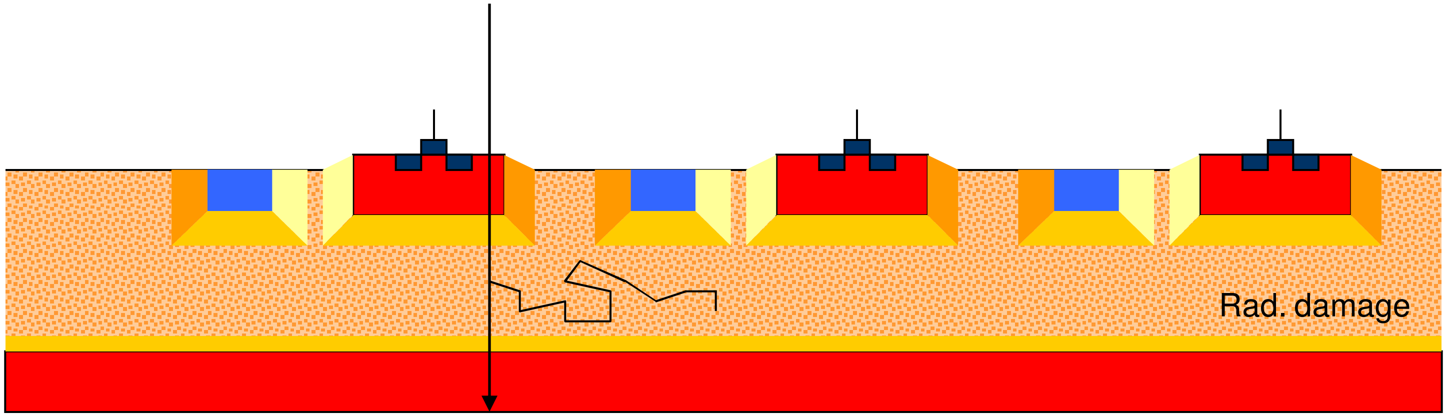
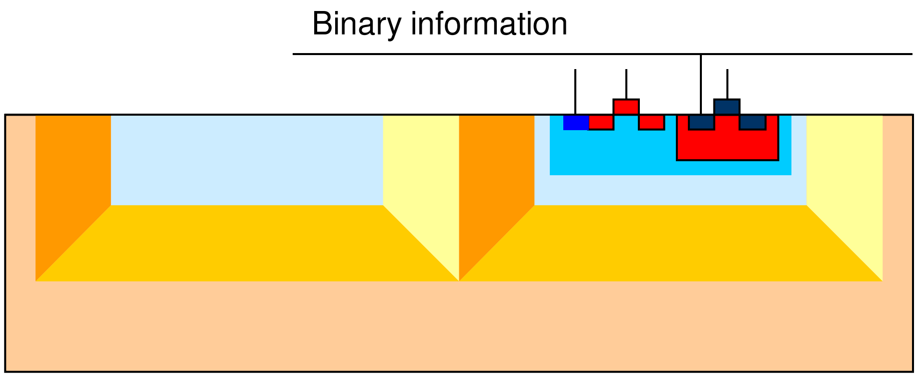
☺ Collection speed
☺ **Radiation hardness**

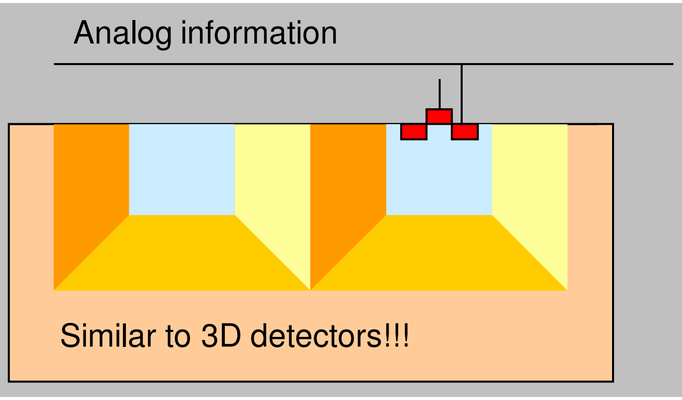


MAPS (as comparison)

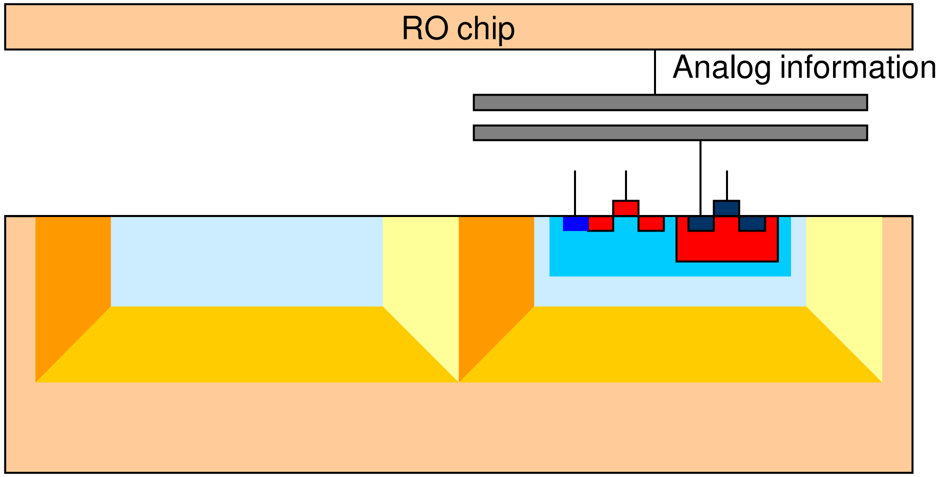
Type A
Binary readout



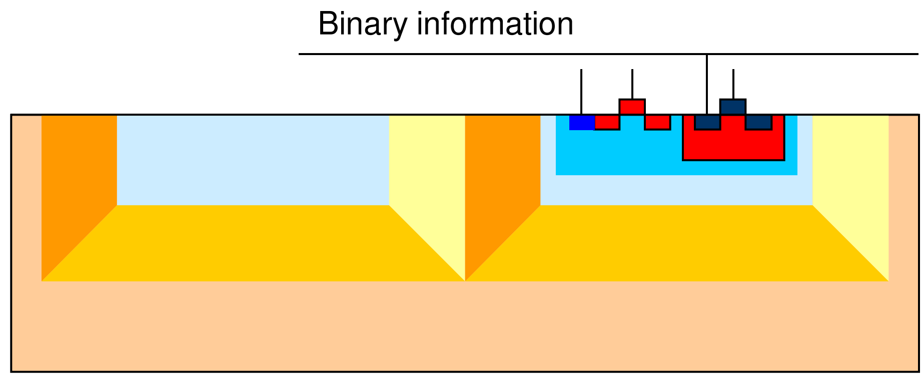
Type B
Analog readout
Rolling shutter addressing



Type C
Capacitive readout

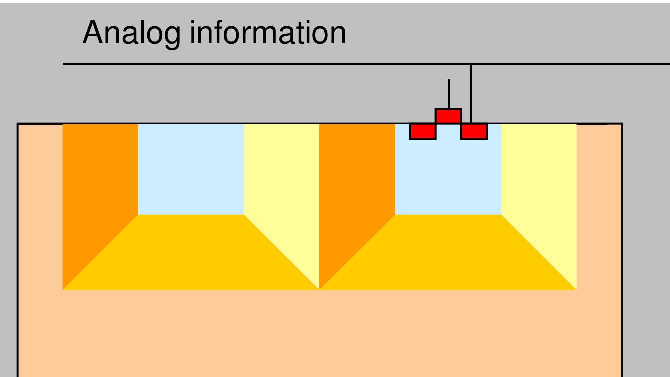


- ☺ In-pixel signal processing
- ☺ **Time measurements possible** (fast readout)
- ☺ Leakage current compensation (+ rad. hardnes)
- ☹ Larger pixels
- ☹ Larger capacitance
- ☹ Static current consumption

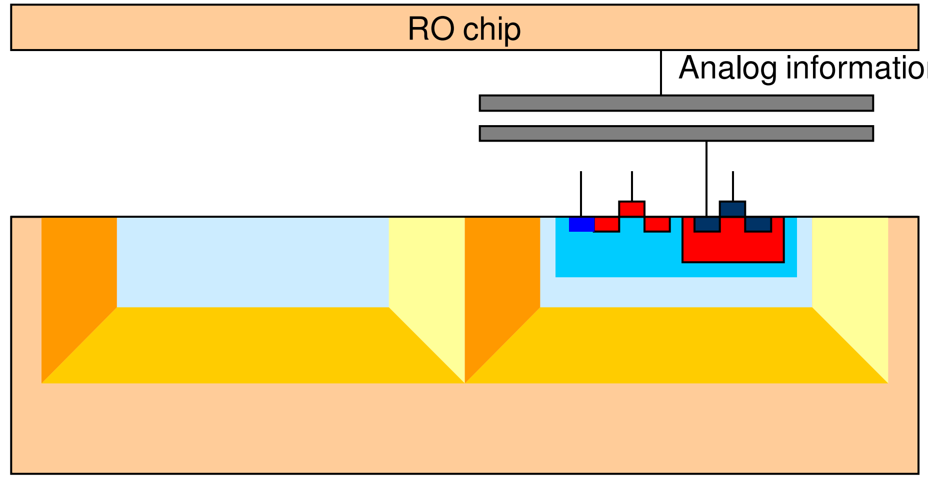


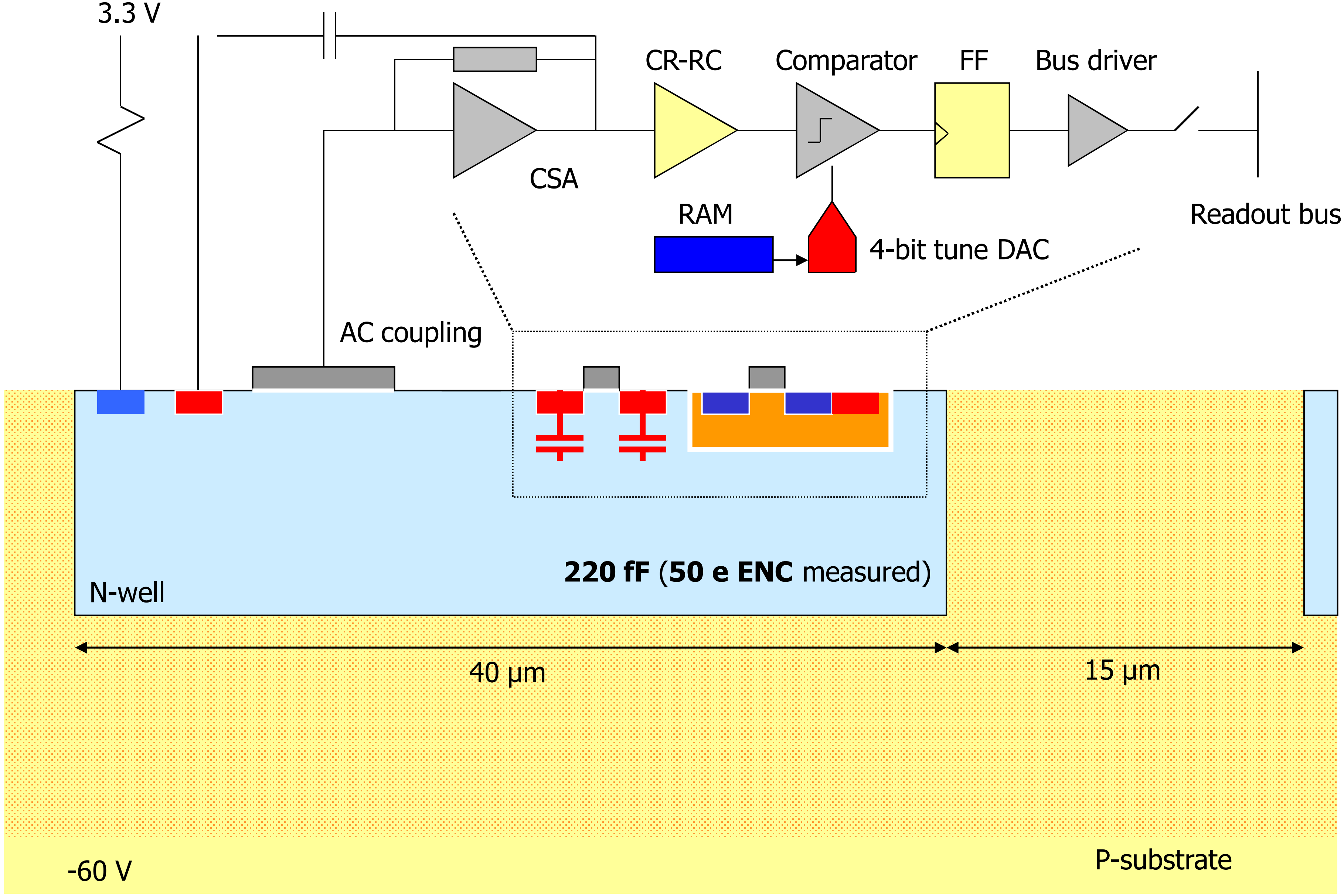
- ☺ **Smaller pixels**
- ☺ Smaller capacitance
- ☺ No static current consumption
- ☹ Time measurements not possible
- ☹ Leakage current added to signal (- rad. hardnes)

Testbeam!!!

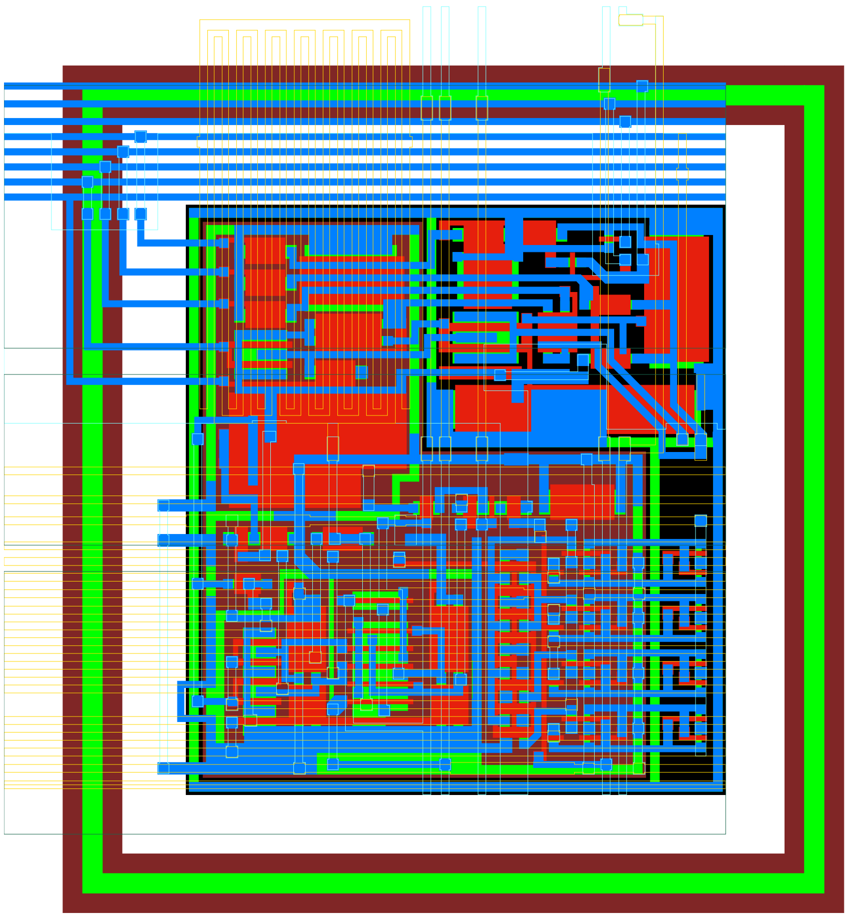


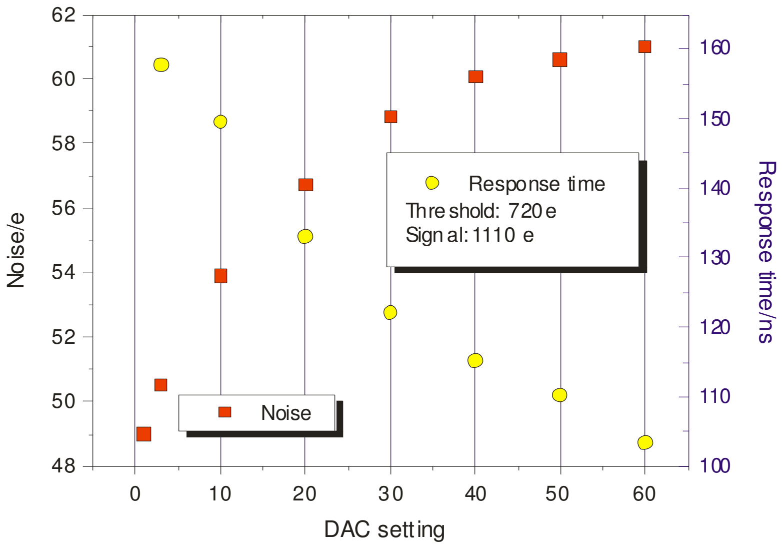
- ☺ Any kind of in-pixel signal processing possible **(hybrid detector**)
- ☺ Radiation tolerant layout can be easily implemented
- ☹ Slightly increased noise because of capacitive transmission




3.3 V
CR-RC
Comparator
FF
Bus driver
CSA
RAM
4-bit tune DAC
Readout bus
AC coupling
220 fF (50 e ENC measured)
N-well
40 µm
15 µm
-60 V
P-substrate

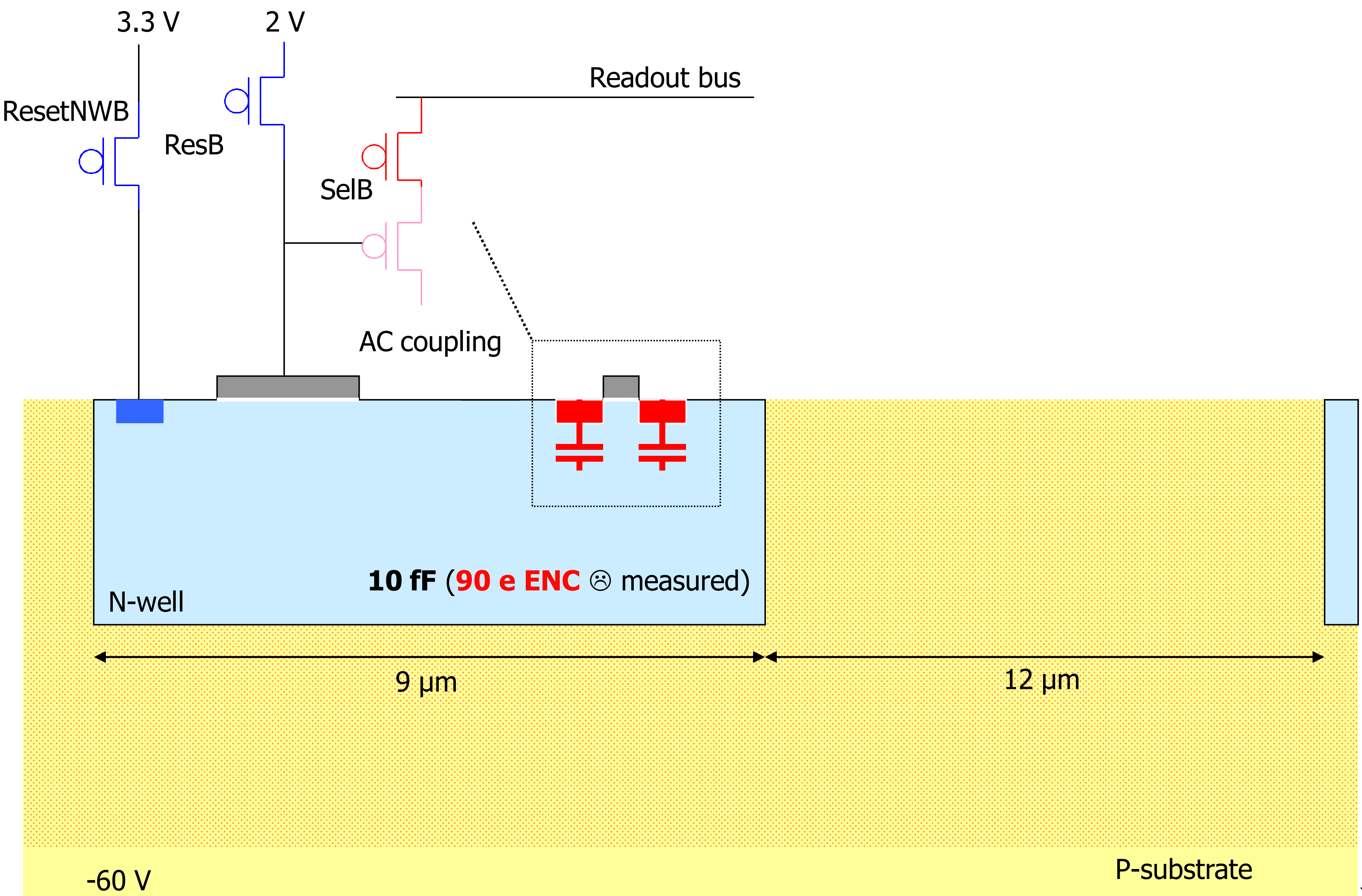
Type A





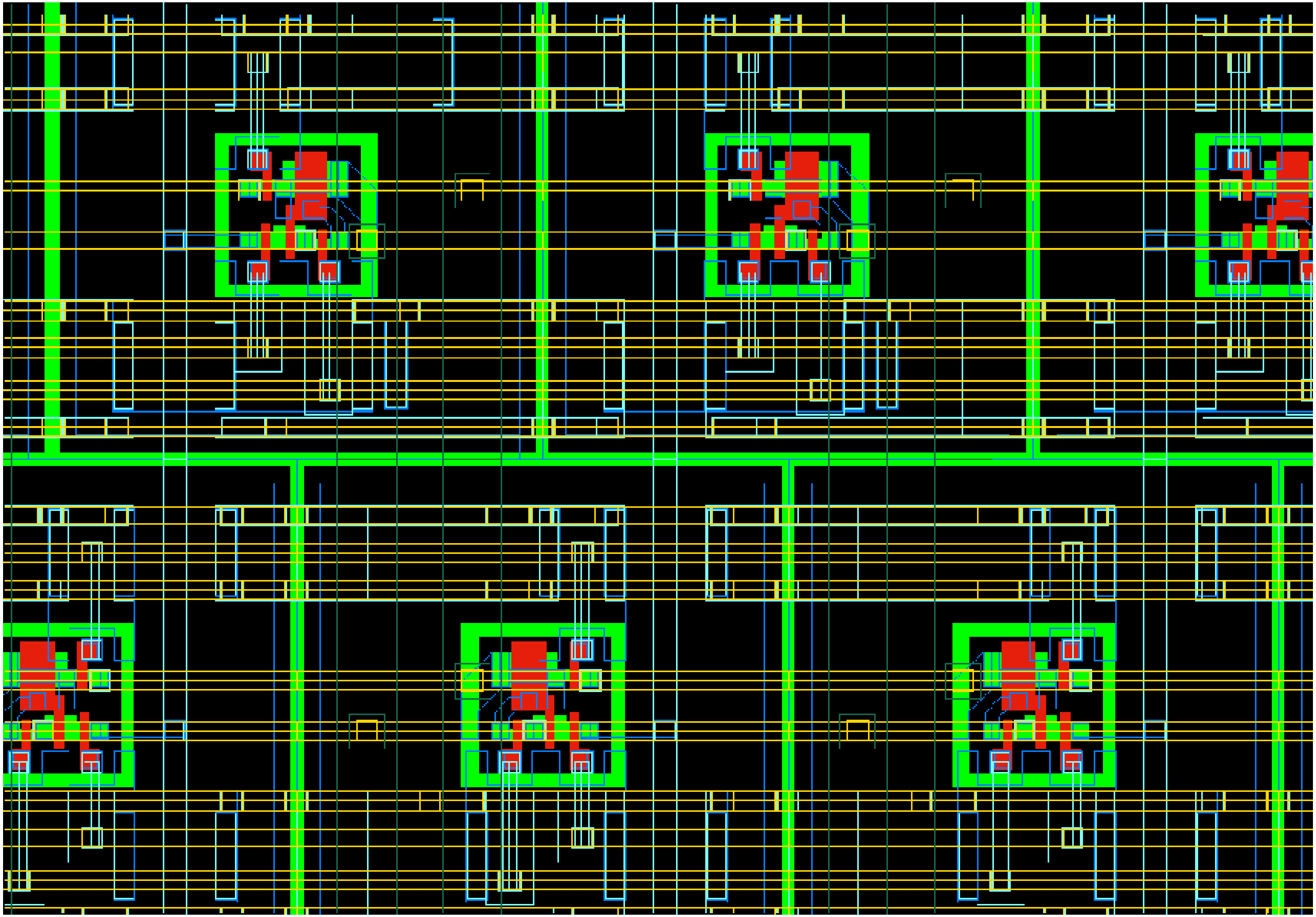
Response time
Threshold: 720 e
Signal: 1110 e
Noise
Noise/e
Response time/ns
DAC setting

Type B

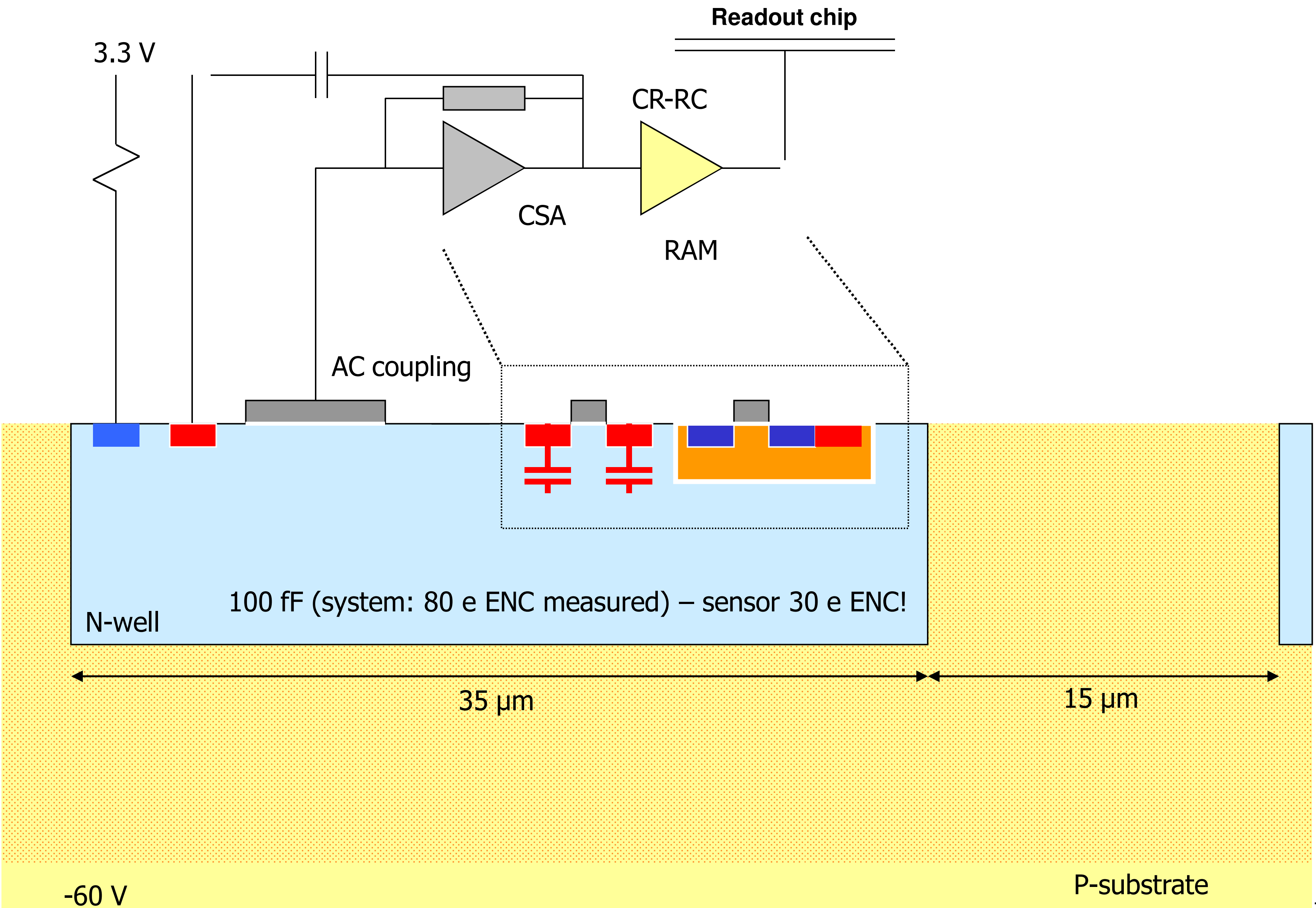


3.3 V
2 V
Readout bus
ResetNWB
ResB
SelB
AC coupling
10 fF (90 e ENC ☹ measured)
N-well
9 µm
12 µm
-60 V
P-substrate

Type B



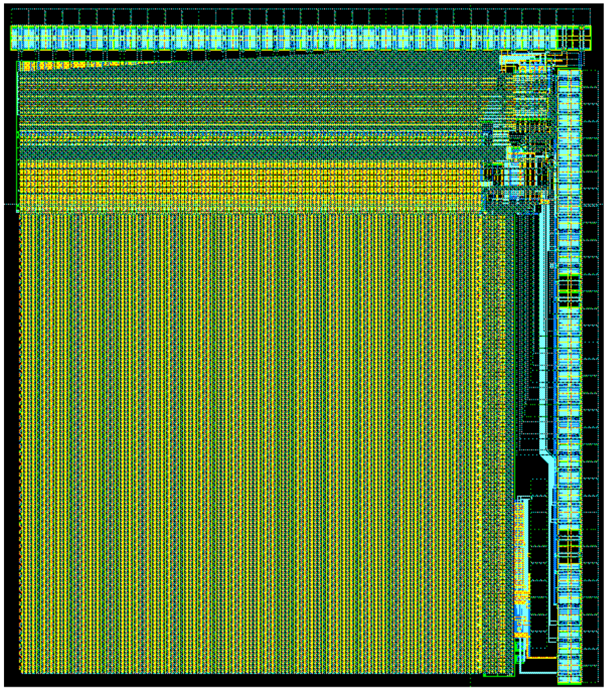
Type C



Readout chip
3.3 V
CR-RC
CSA
RAM
AC coupling
100 fF (system: 80 e ENC measured) – sensor 30 e ENC!
N-well
35 µm
15 µm
-60 V
P-substrate

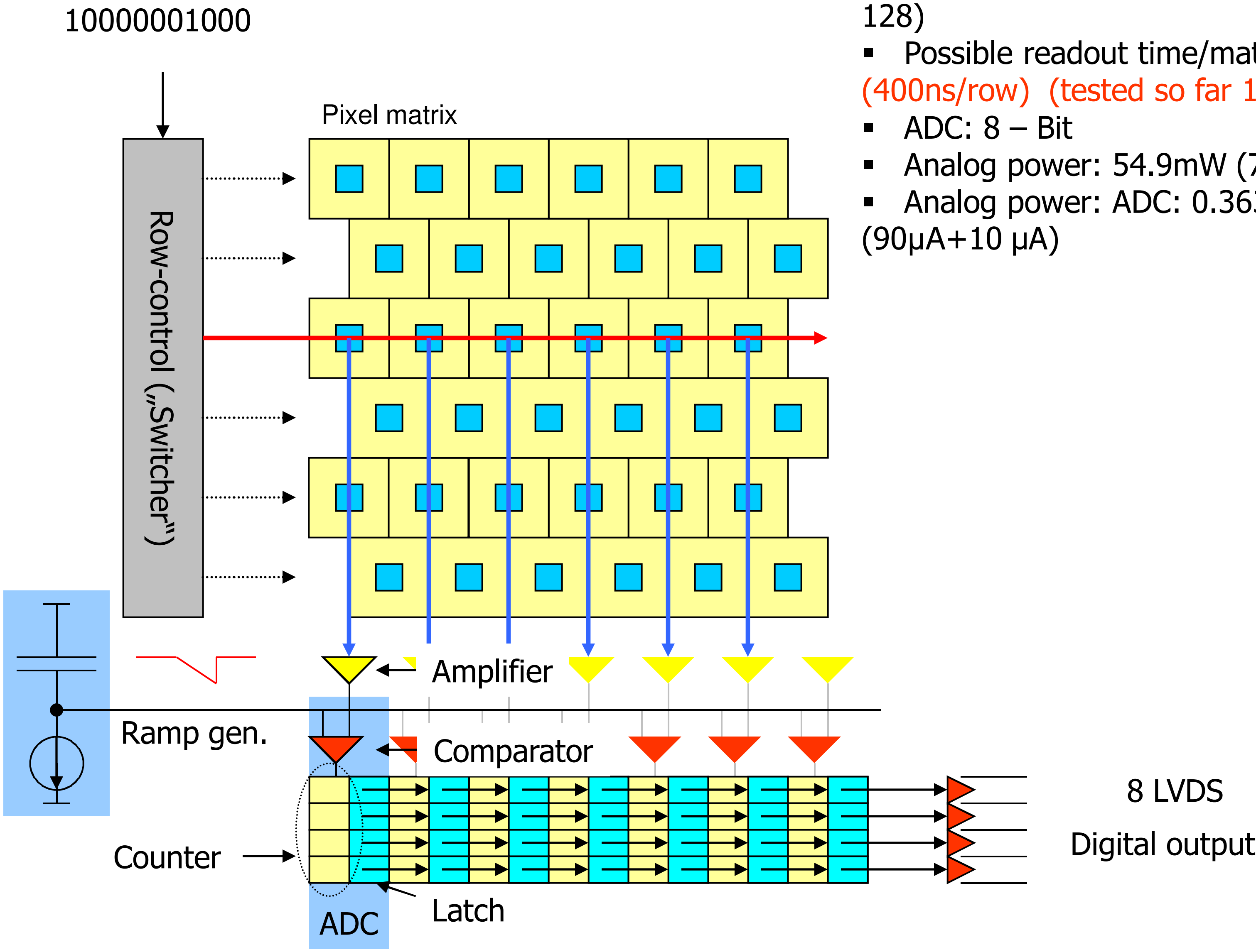
The “Taki” chip

- 128X128 pixel-matrix – pixel size 21X21μm²
- The chip can be easily scaled to 4 or 16 times larger area
- Fast digital readout – designed for ~50 μs frame readout time (164 μs tested)
- **128 end-of-column single-slope ADCs** with 8-bit precision
- Low power design - full chip 55mW (only analog)
- Radiation hard design

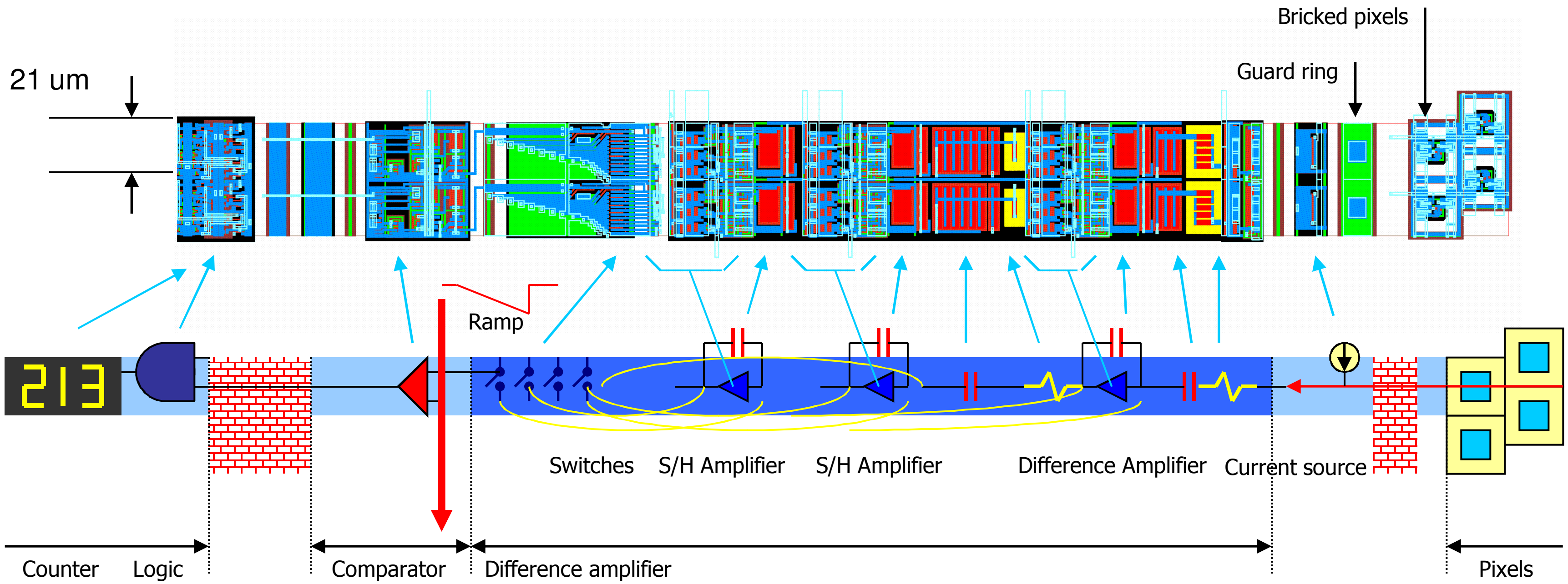


Chip structure

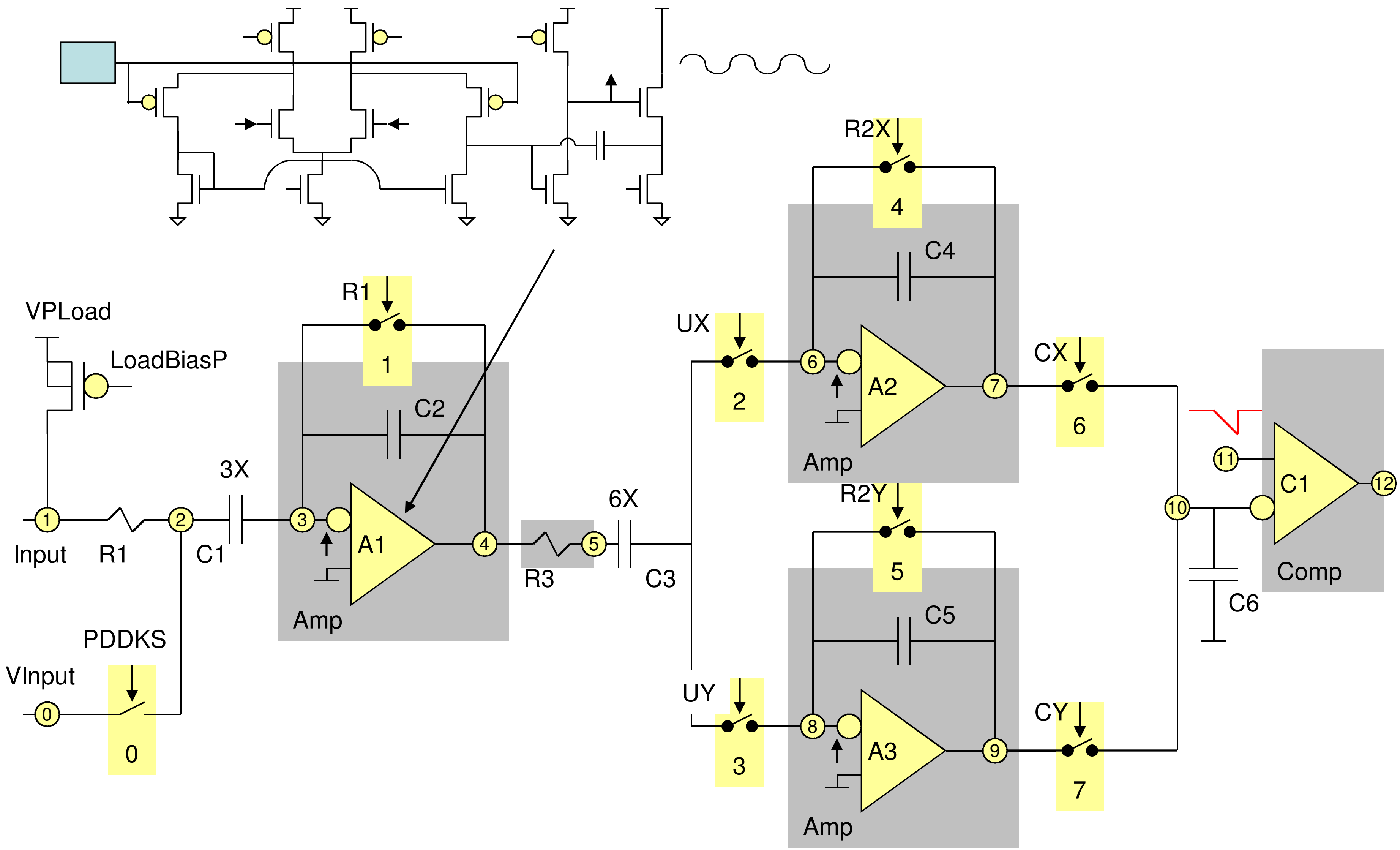
- Pixel size: 21 X 21 µm
- Matrix size: 2.69 X 2.69 mm (128 X 128)
- Possible readout time/matrix: ~50 µs (400ns/row) (tested so far 1.28 µs/row)
- ADC: 8 – Bit
- Analog power: 54.9mW (7.63mW/mm²)
- Analog power: ADC: 0.363mW/ADC (90µA+10 µA)



- Switched capacitor amplifier
- Single slope ADC
- Asynchronous 8-bit counter



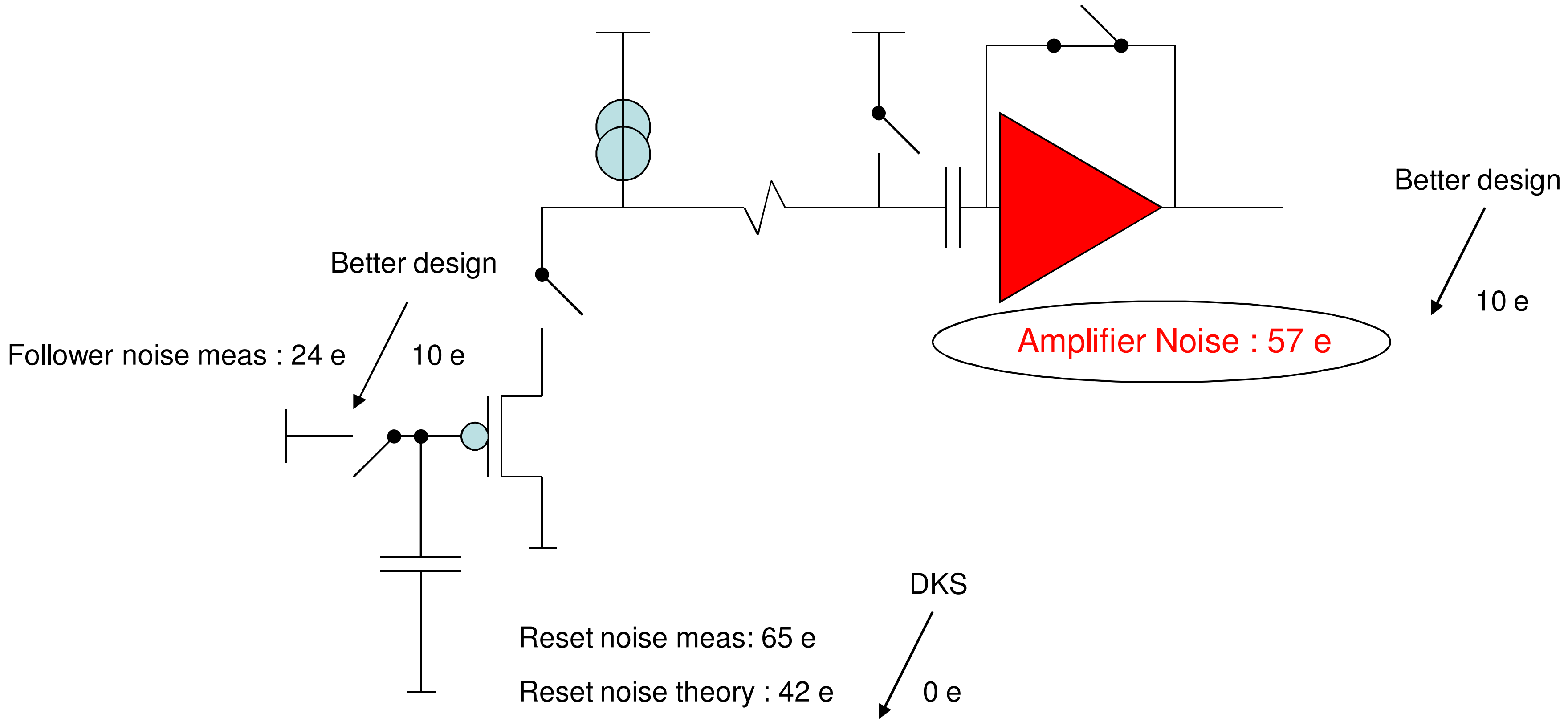
(Problem with the) difference amplifier



The amplifier **oscillates** under standard bias conditions ☹

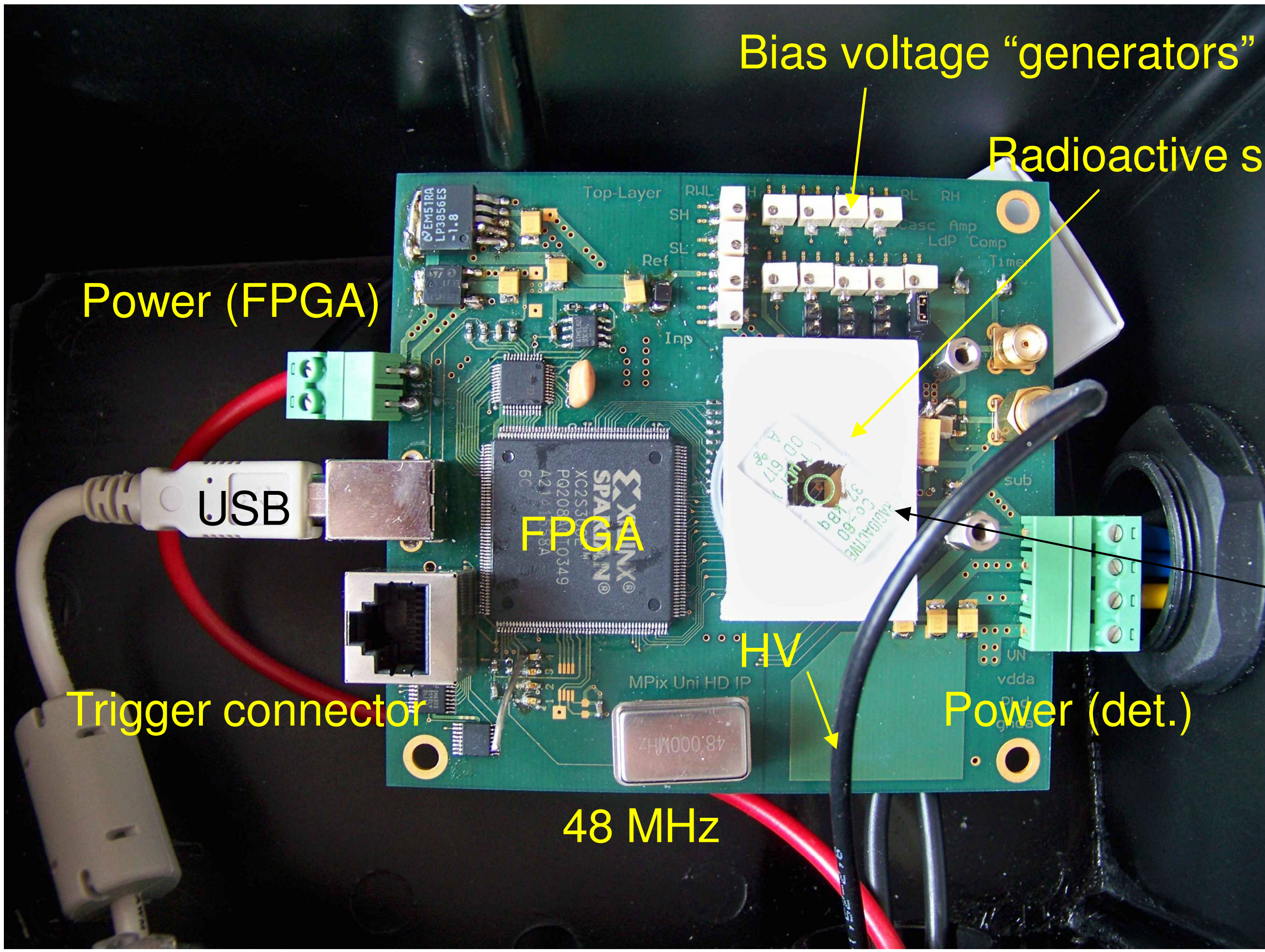
Noise (present and future)

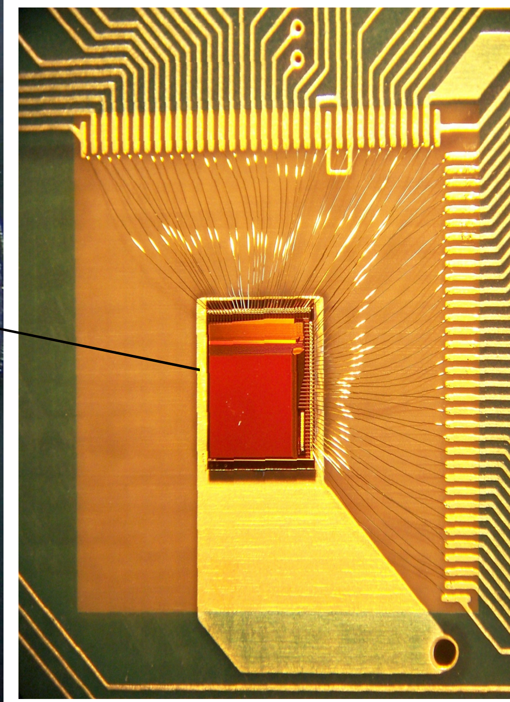
The ENC is mainly caused by the readout electronics

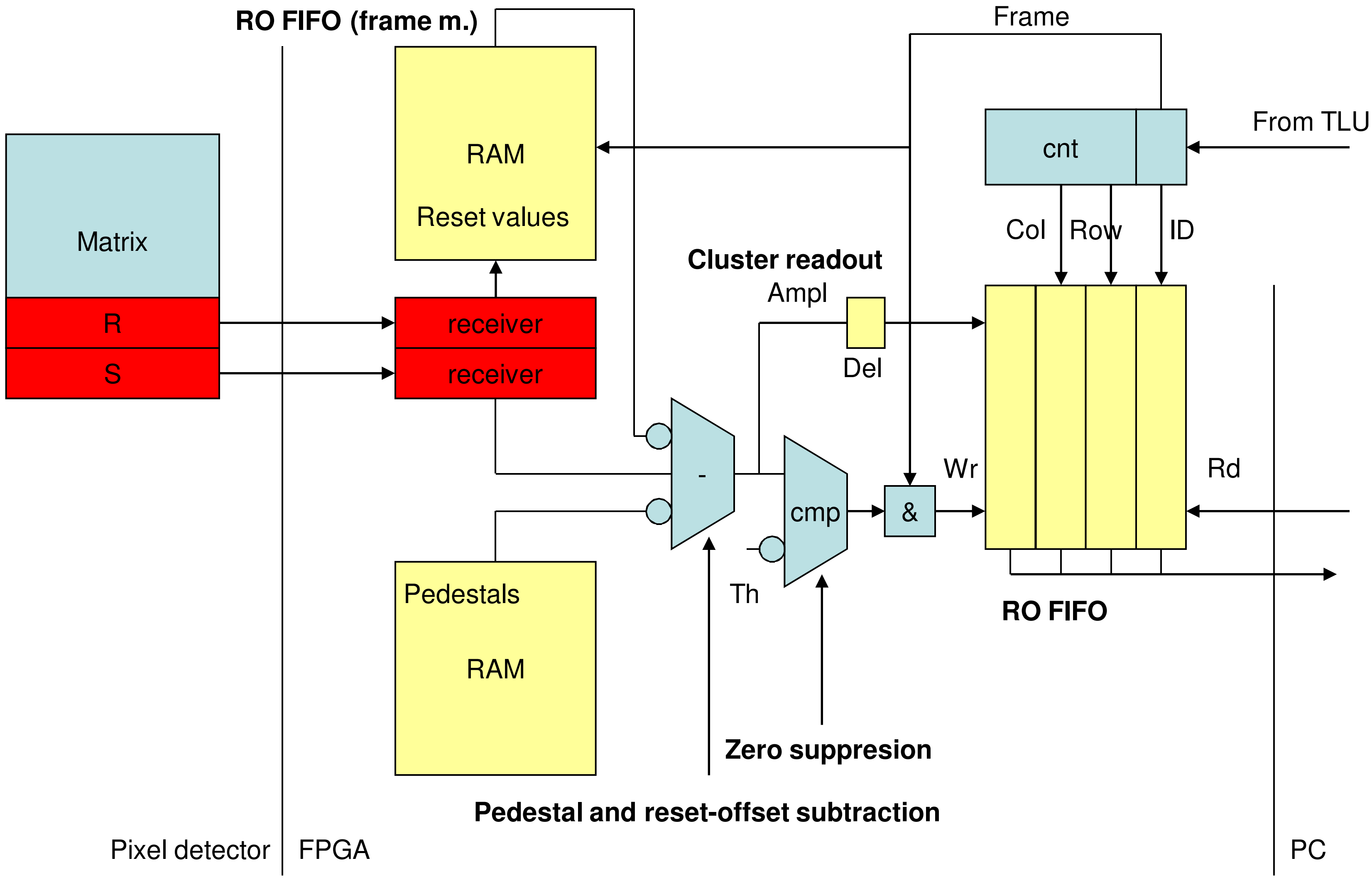


Reducing of ENC from 90 e to 30 e is realistic - > all S/N ratios will be increased by factor 3

- Very simple detector test system – a single PCB
- Only 4 external voltages needed, high voltage is generated by batteries
- USB 1 communication with DAQ PC





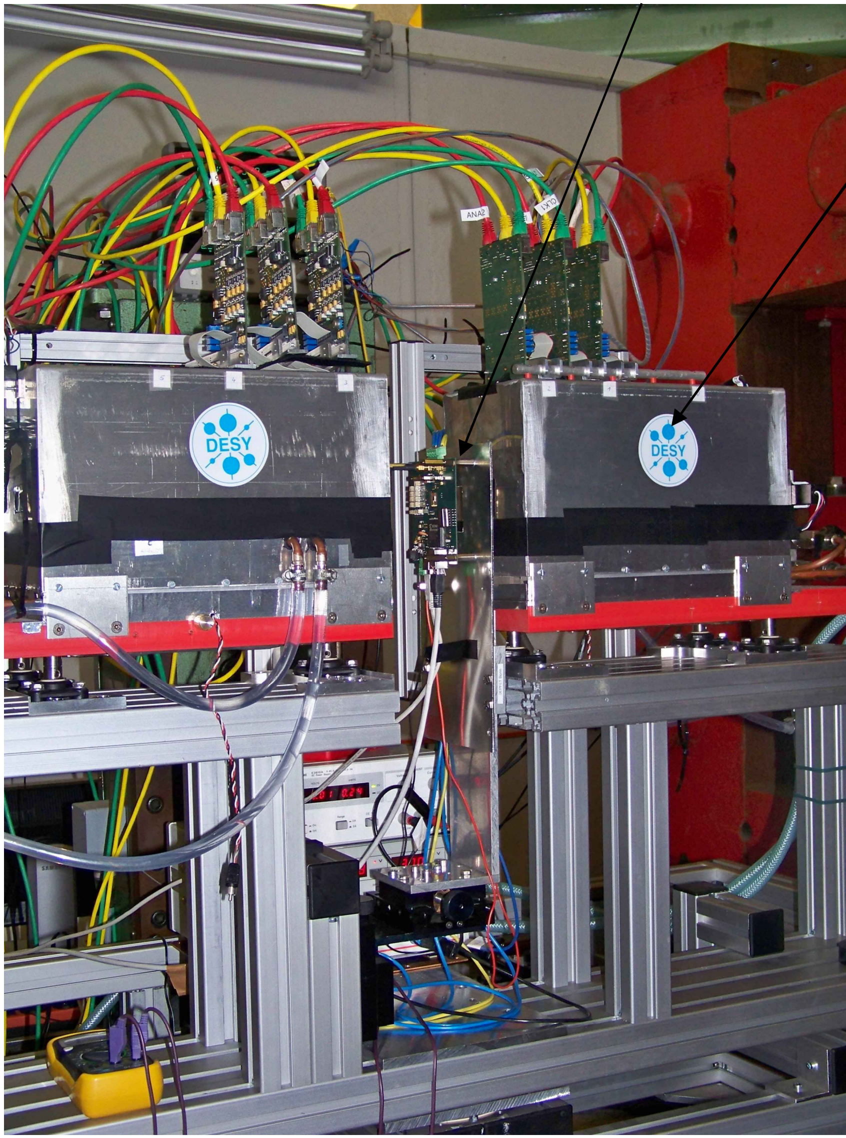


DKS mode, **frame mode-** or **zero suppressed cluster readout**

Test beam DESY

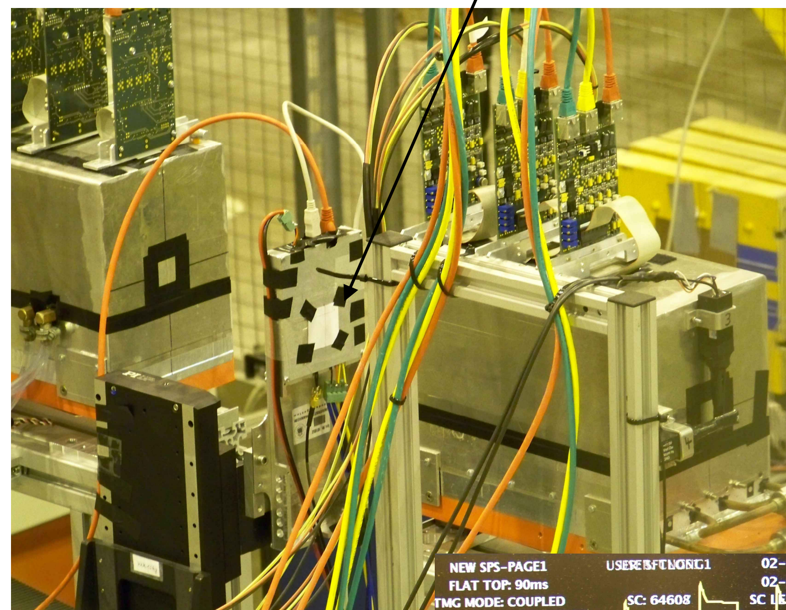
DUT

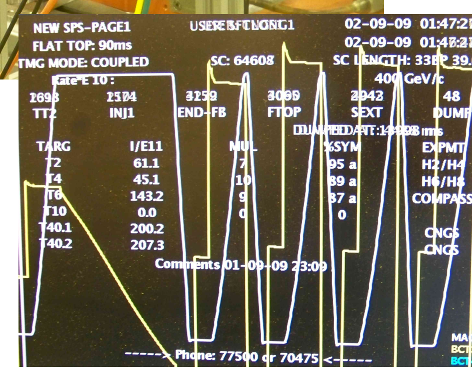
EUDET telescope

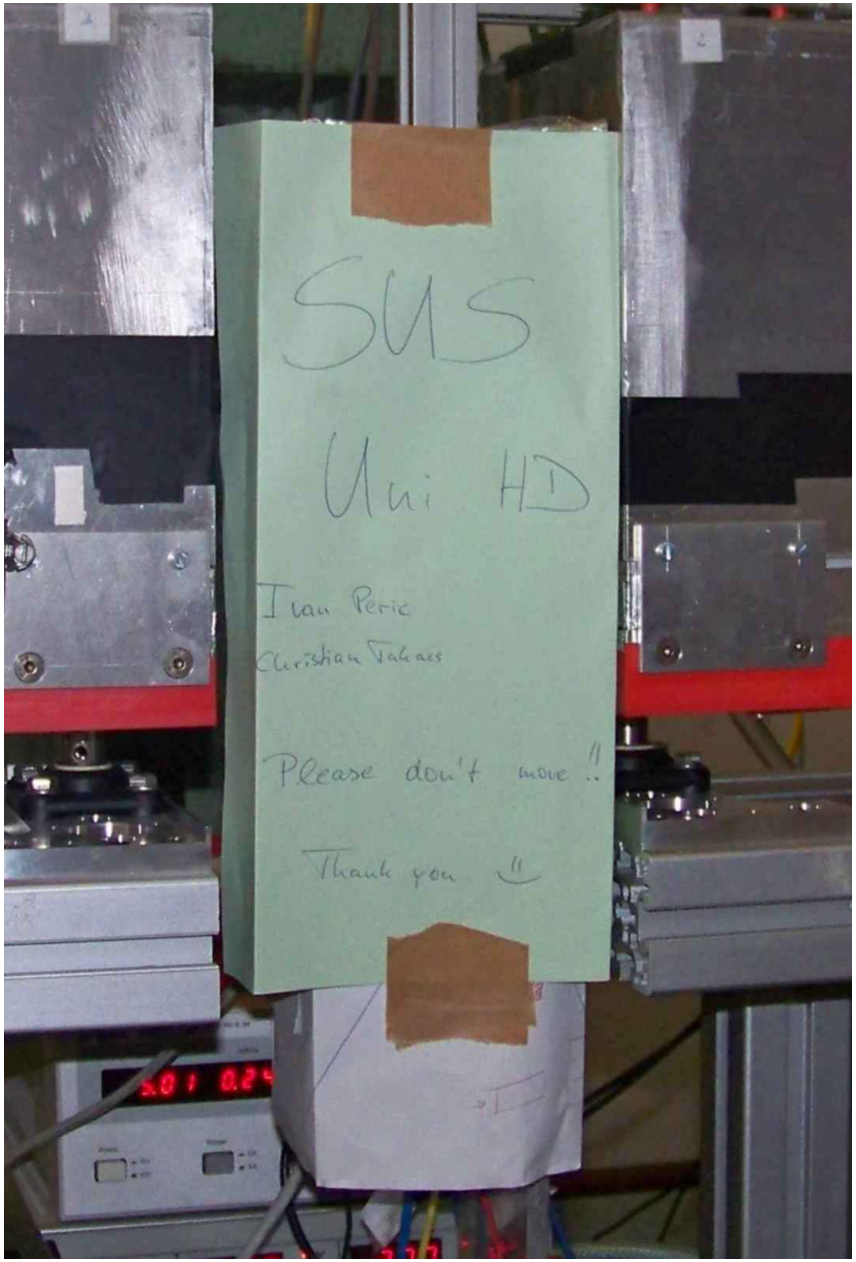


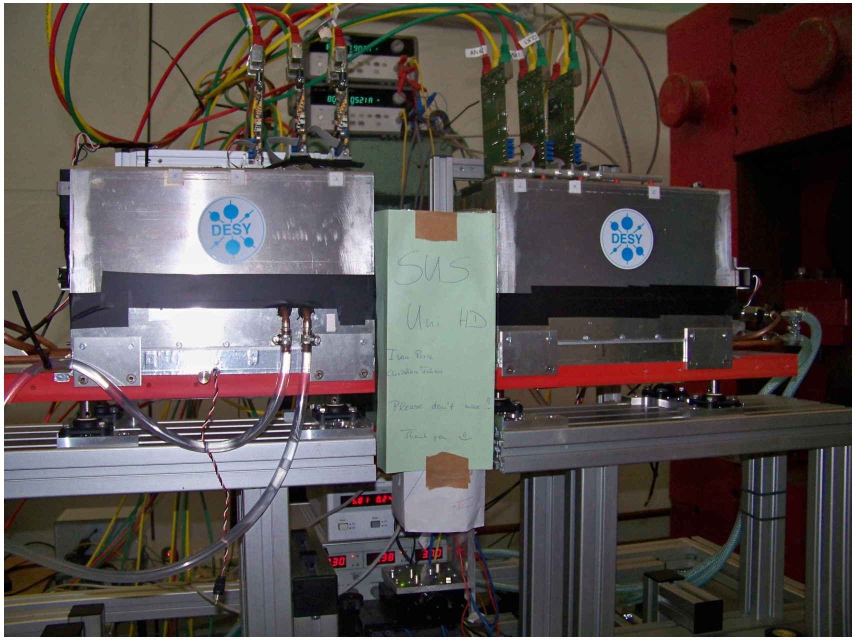
Test beam CERN

DUT

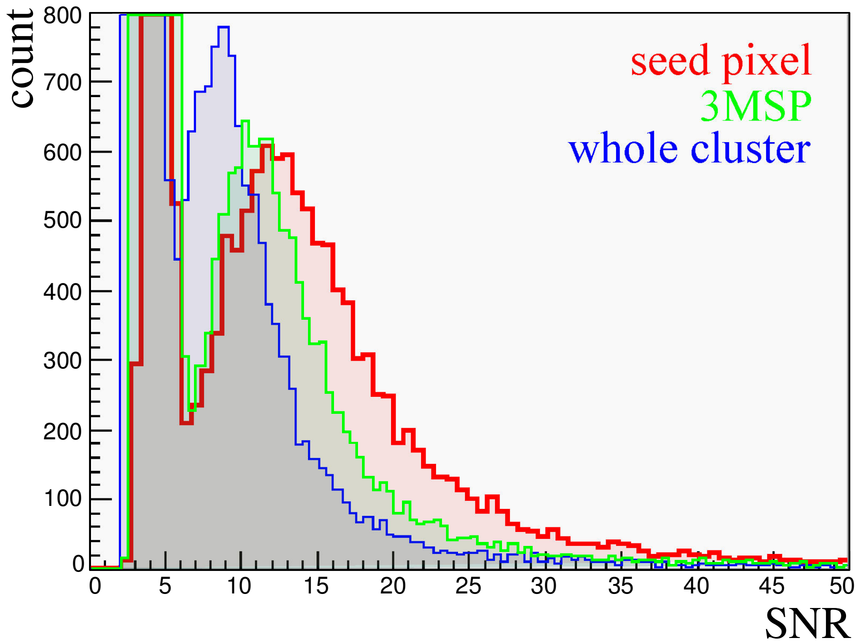




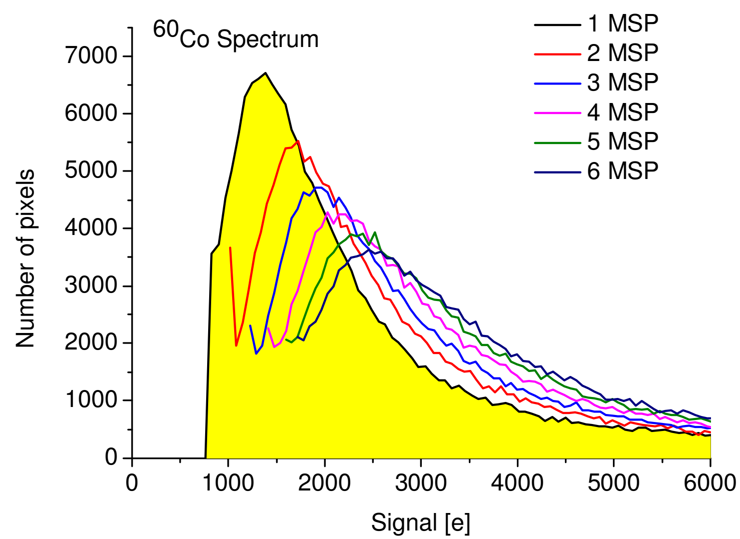

SUS
Uni HD
Ivan Peric
Christian Takacs
Please don't move !!
Thank you


DESY
DESY
SUS
Uni HD

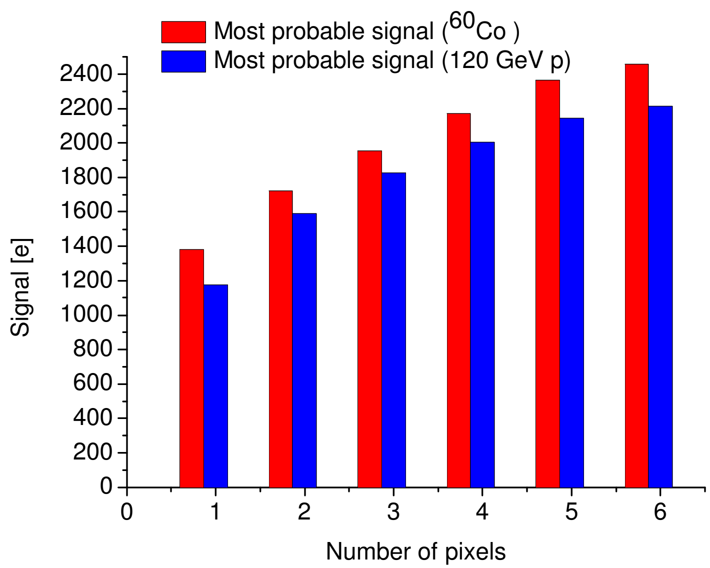
MIP spectrum (CERN SpS - 120GeV protons)

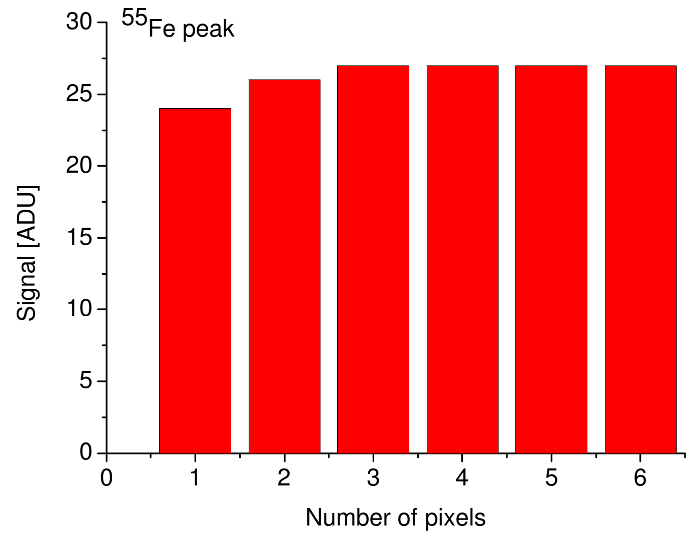


MIP spectrum (^{60} Co)



MIP spectrum (CERN SpS - 120GeV protons**)**
The signal increases from **1200 e** (single pixel) to **2200 e** (6-pixel cluster)
The measured S/N ratio varies from 12.3 (single pixel) to 9.8 (6-pixel cluster)

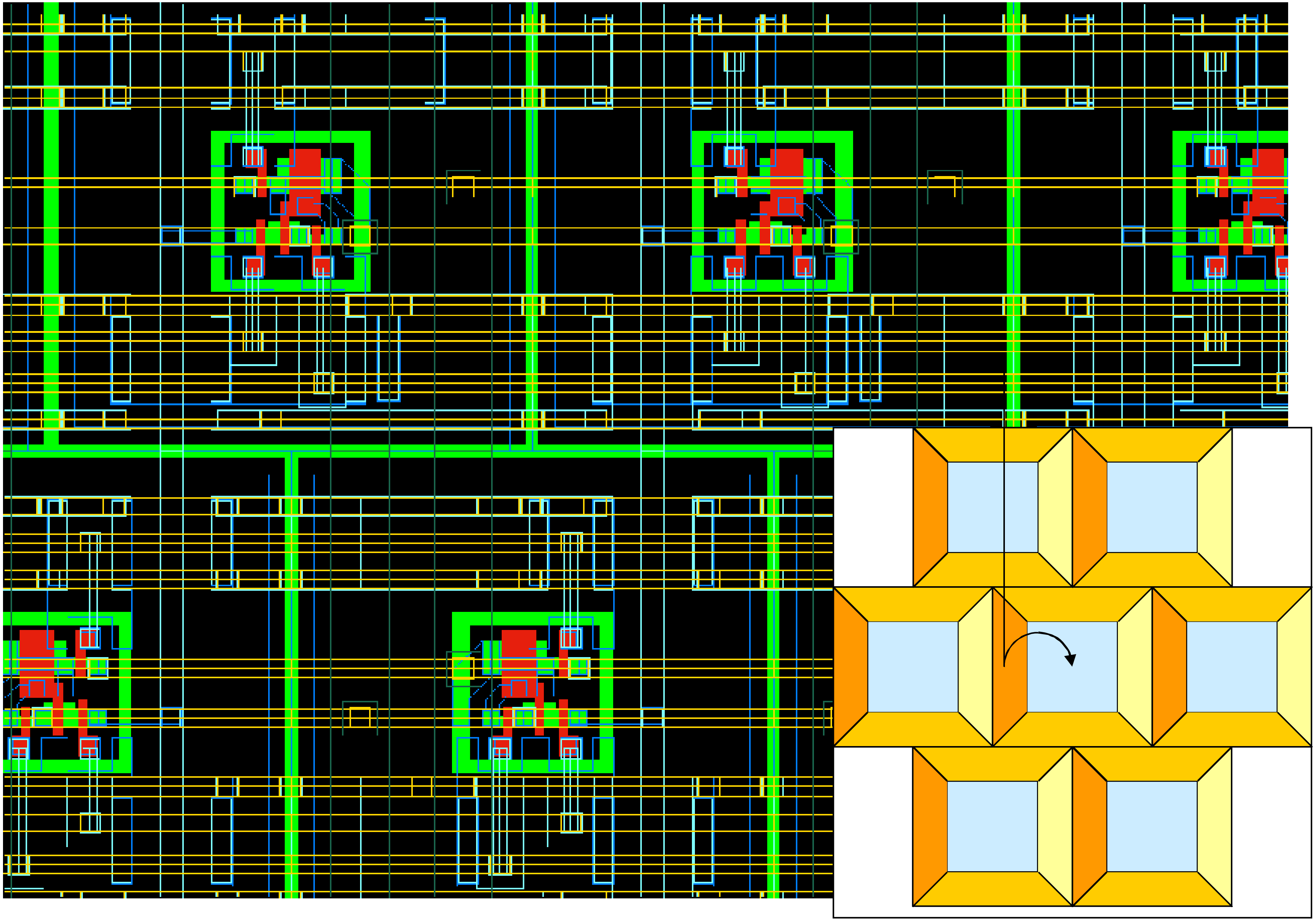


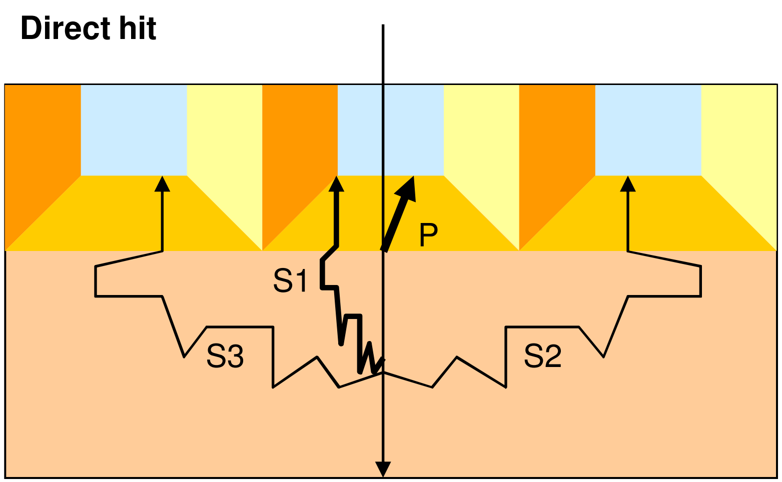


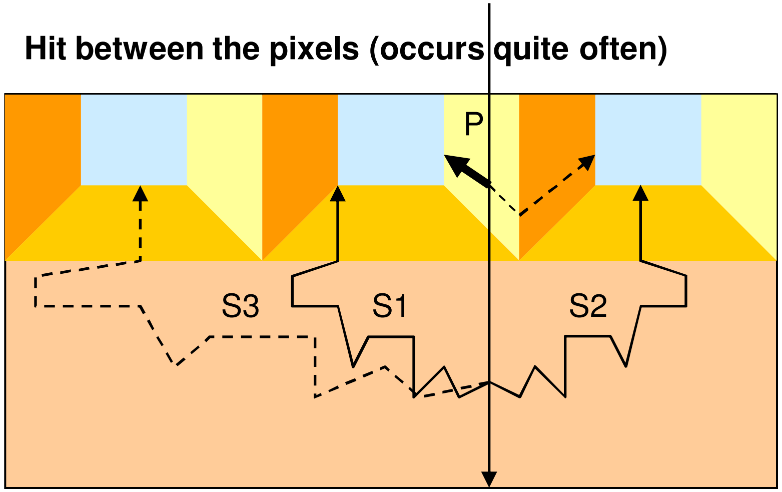
Comparison between **^{60}Co** and **120GeV proton** spectra
^{60}Co signals higher by 10% - expected from theory due to lower particle energy
Seed pixel sees about 50% of the total signal
The next MSP sees only 25% of the seed pixel signal
Cluster size is 6 pixels
Moderate charge sharing (the seed gets the most)
Do we expect this? – the gaps between n-wells are large, the most of the particles hit the gaps

As comparison **^{55}Fe**
Seed pixel sees about 90% of the total signal
Cluster size is 3 pixels
No charge sharing

6 pixel cluster

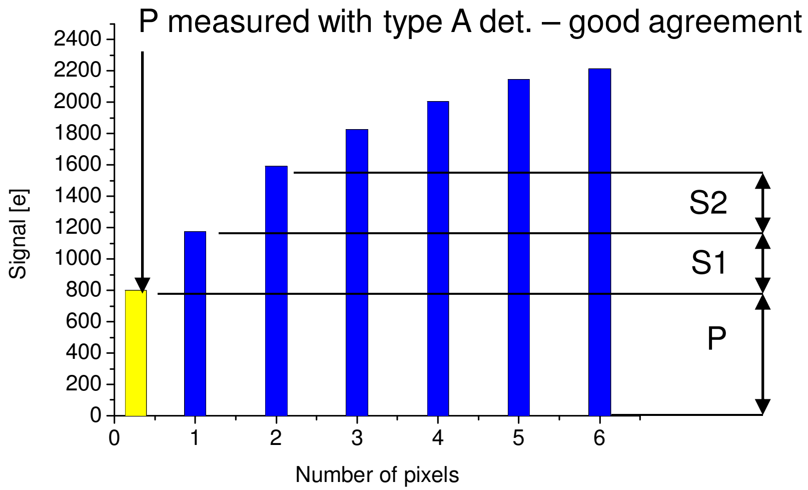


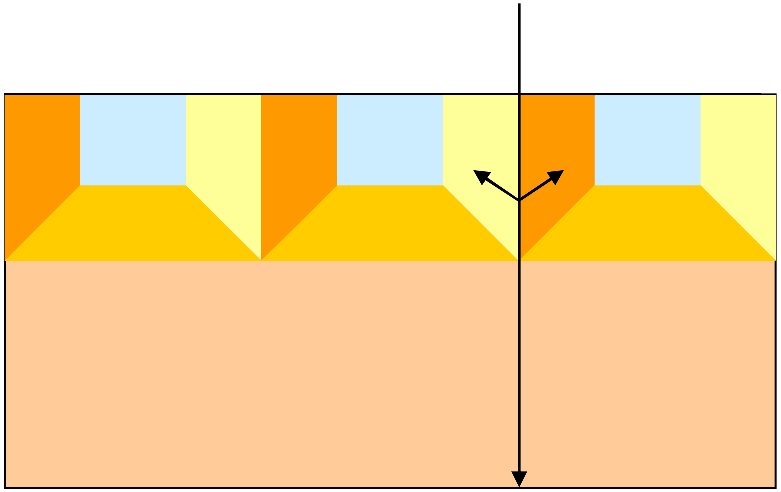


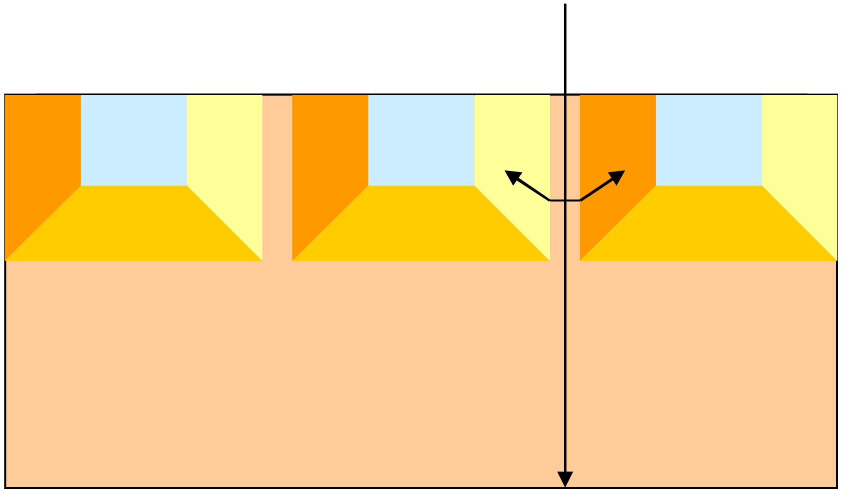


The **drift** leads to the **primary signal** P – this signal portion is **not shared** between pixels, it is collected in the pixel next to the particle hit point

The **diffusion** of the electrons generated in the non-depleted bulk is the secondary signal mechanism



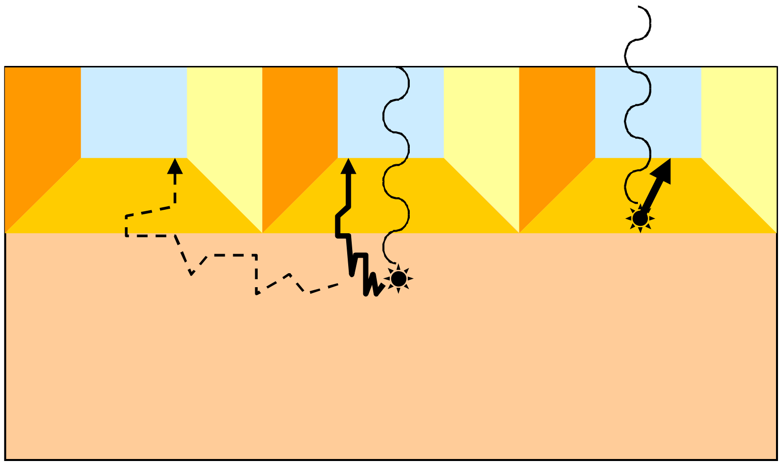




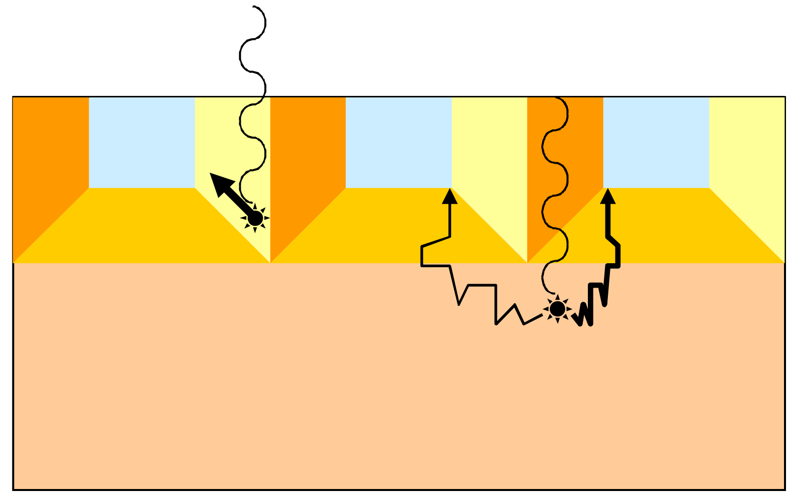
Is there sharing of primary signal?
Such clusters could be lost after applying the **seed cut**…

Do we have gaps with zero E-field? (Moreover, they could be insensitive to particles)

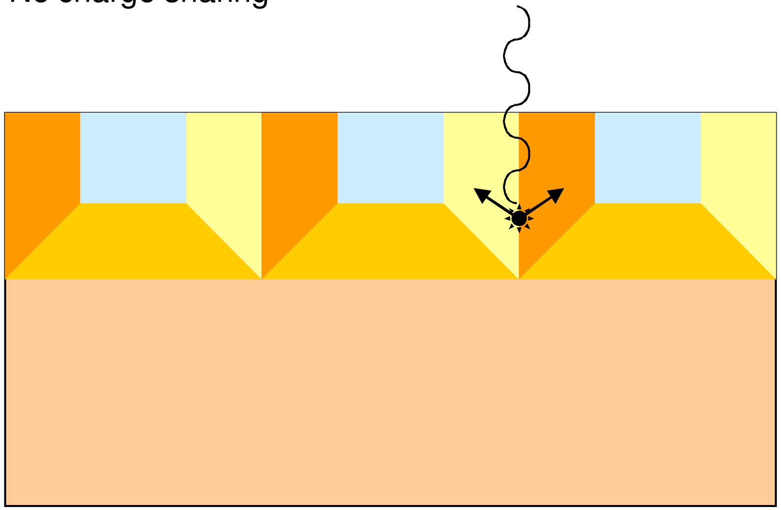
Fe-55 (explanation of the measured spectra)



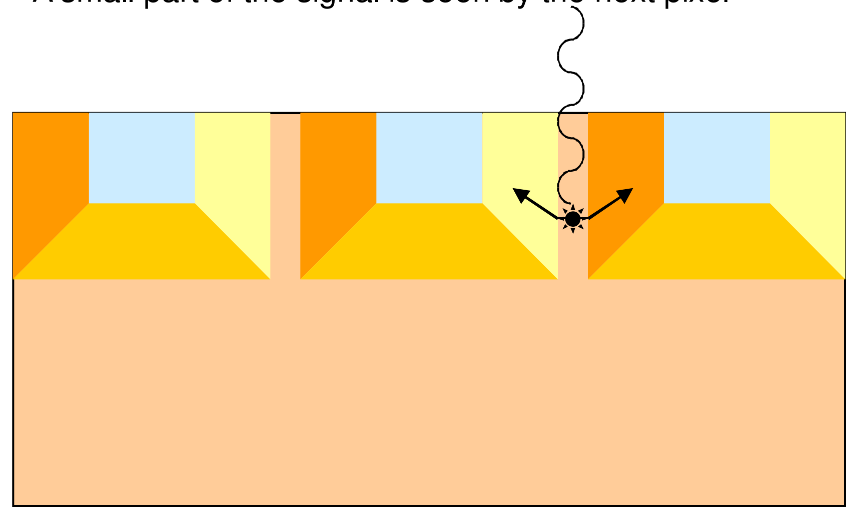
No charge sharing



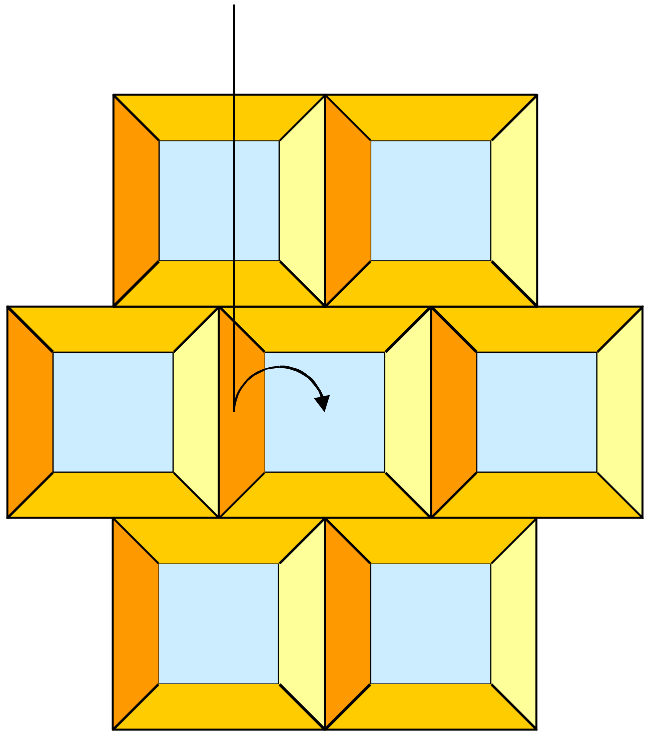
A small part of the signal is seen by the next pixel

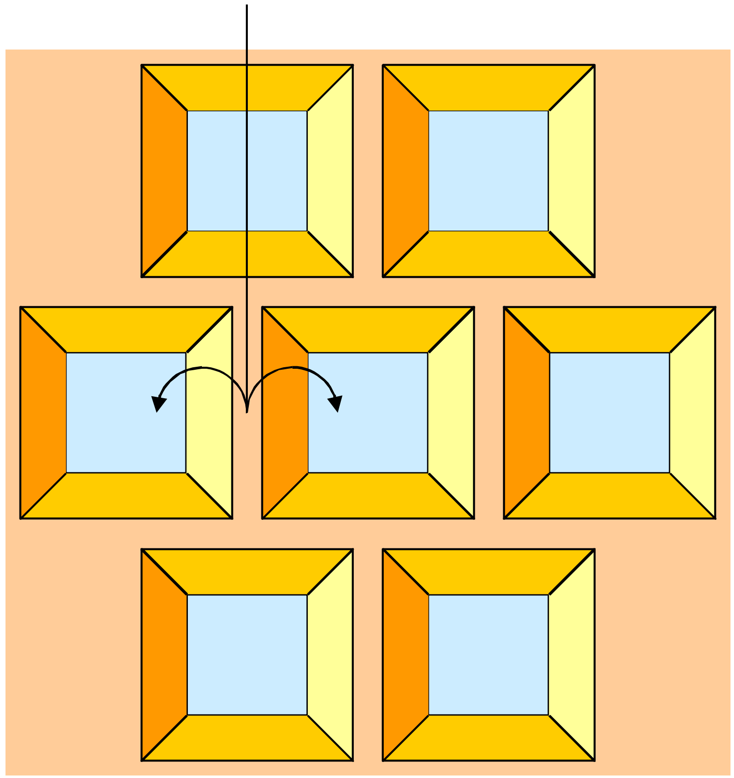


Seen very seldom



Seen very seldom





Do we have gaps with zero E field?

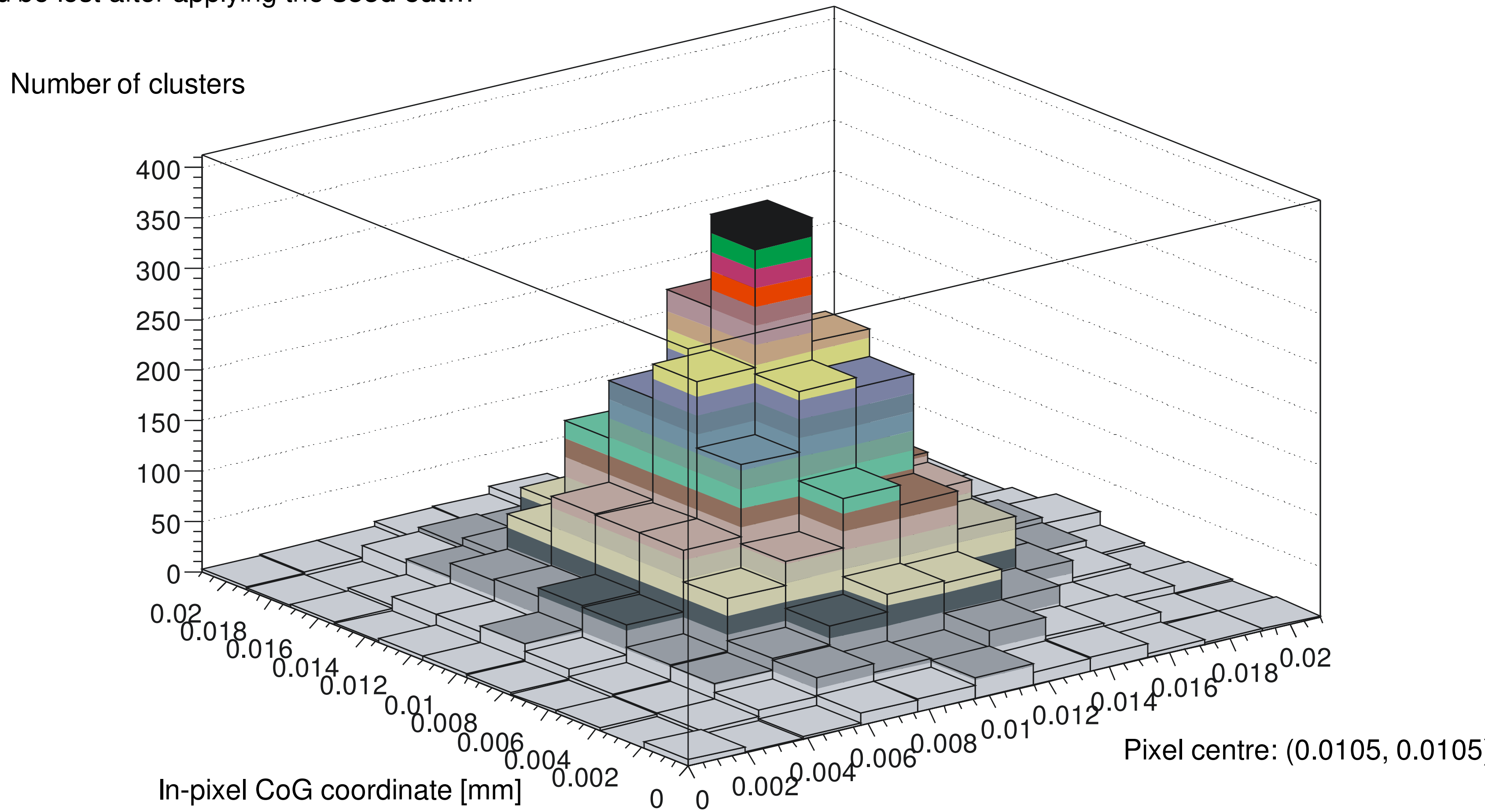
If yes, there will be a certain number of clusters with **two equal seeds**
COG correction should be then 0.5 pixel size

CoG correction distribution in pixel frame of reference

The COG correction distribution is not homogenous inside a pixel due to **reduced charge sharing** – the small CoG correction values occur more frequently

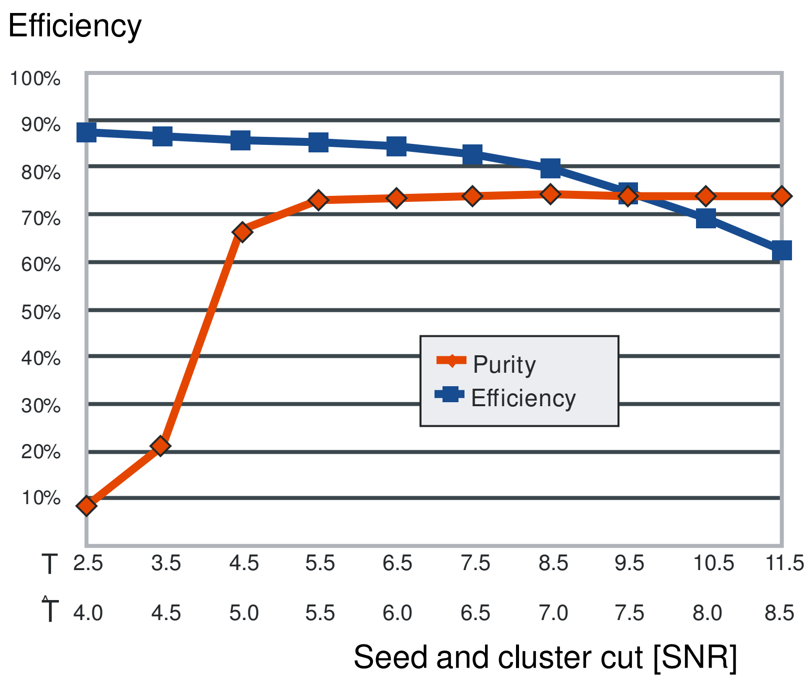
Large CoG values occur very seldom => there are no *sensitive* gaps with E=0 but… the gaps could be insensitive

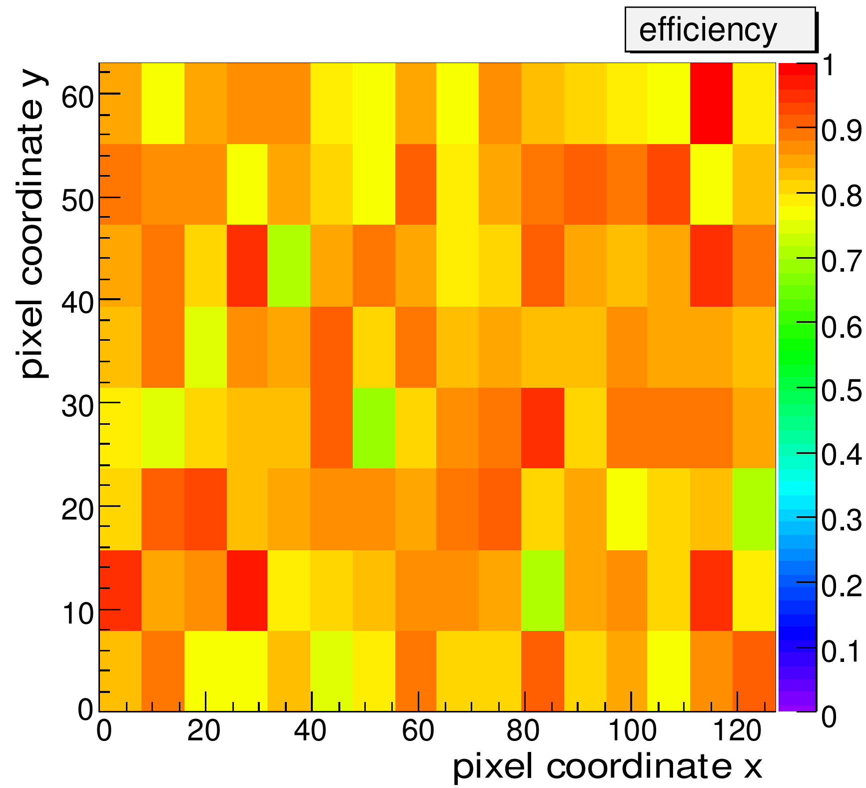
Or the clusters with **two equal seeds** could be lost after applying the **seed cut**…

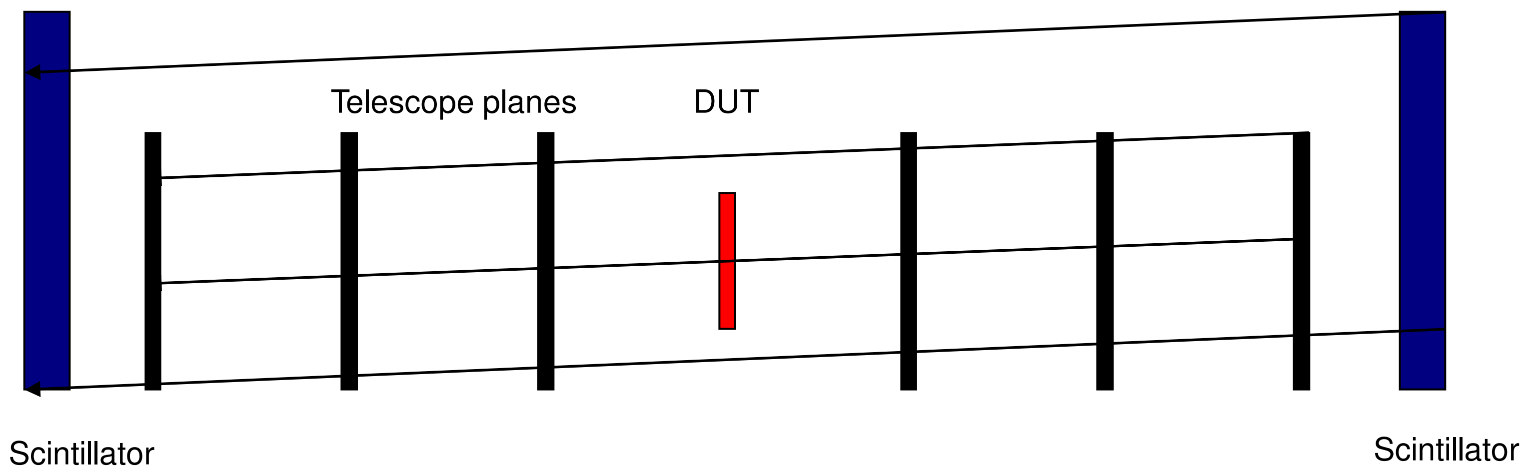


Efficiency

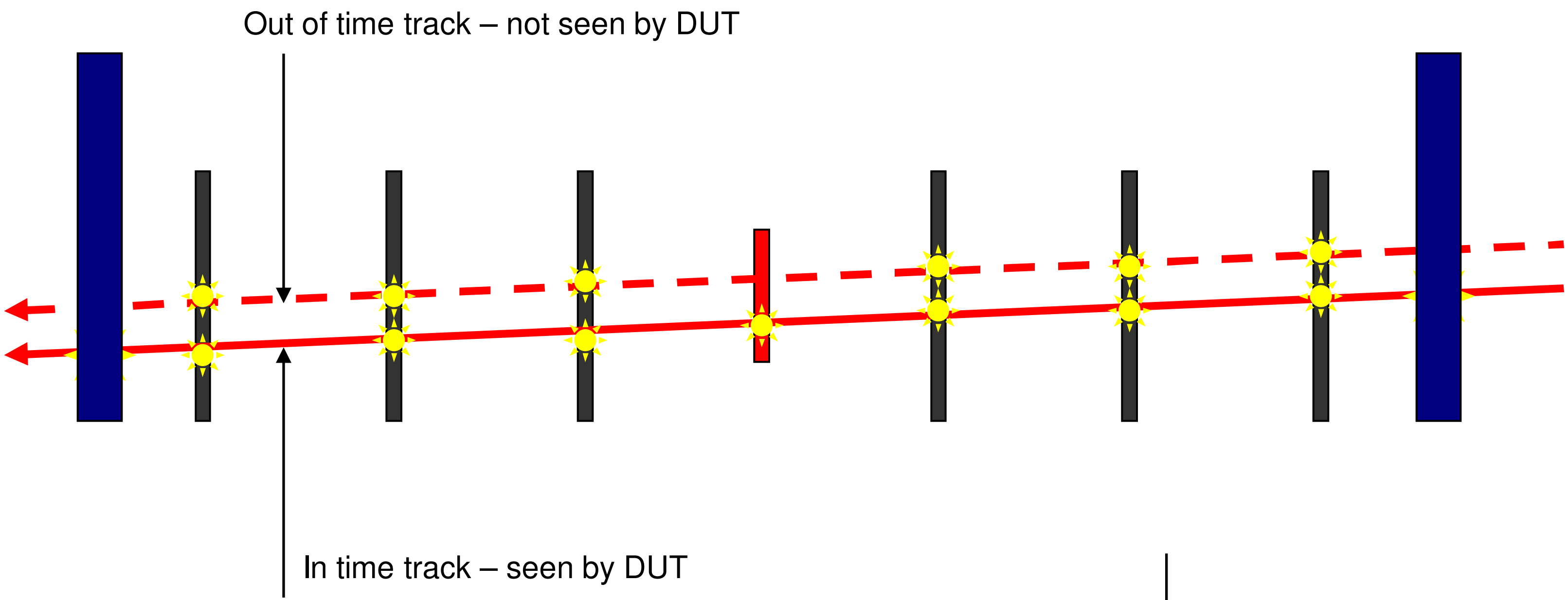
Efficiency is the answer but…
Efficiency is homogenous over the matrix area and saturates at **86% for low seed/cluster thresholds**

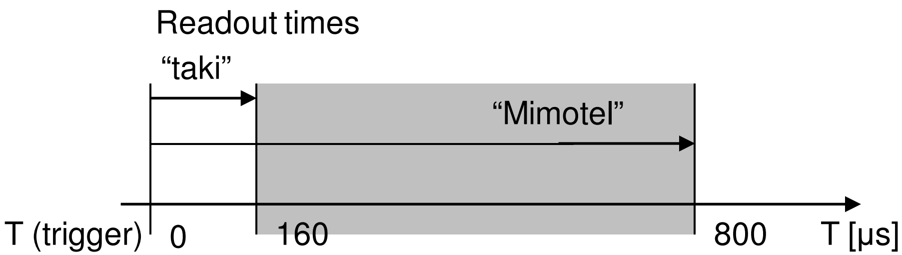


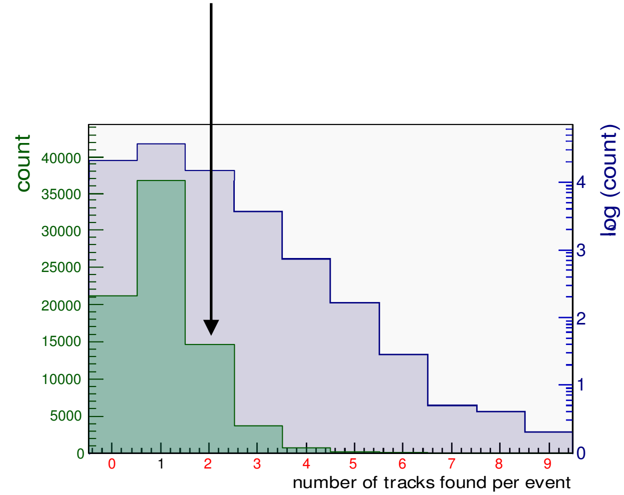



Telescope planes
DUT
Scintillator
Scintillator

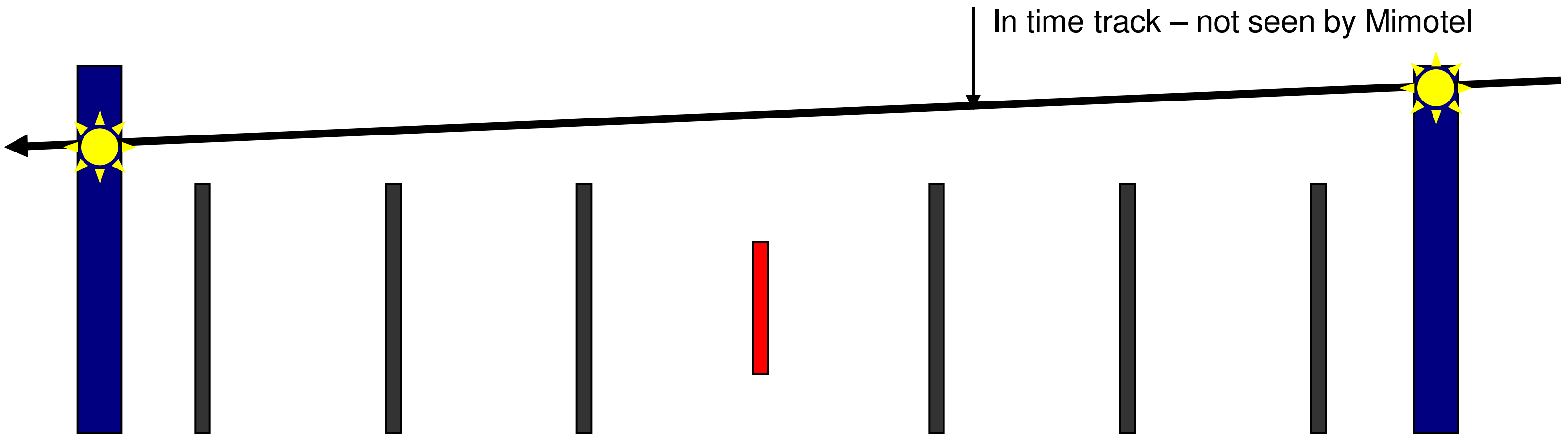
(Irregular events) double track event

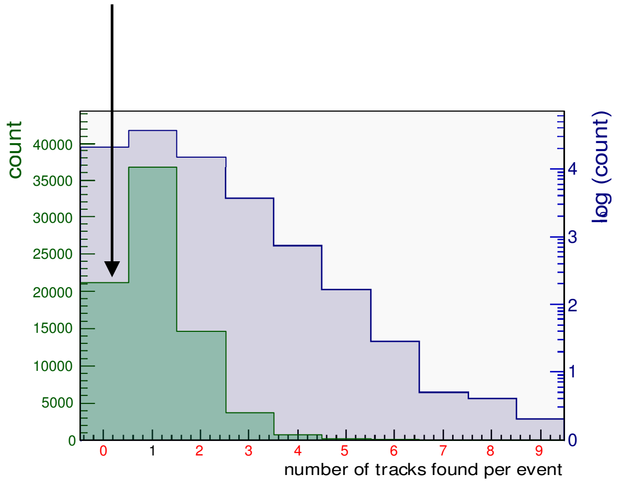




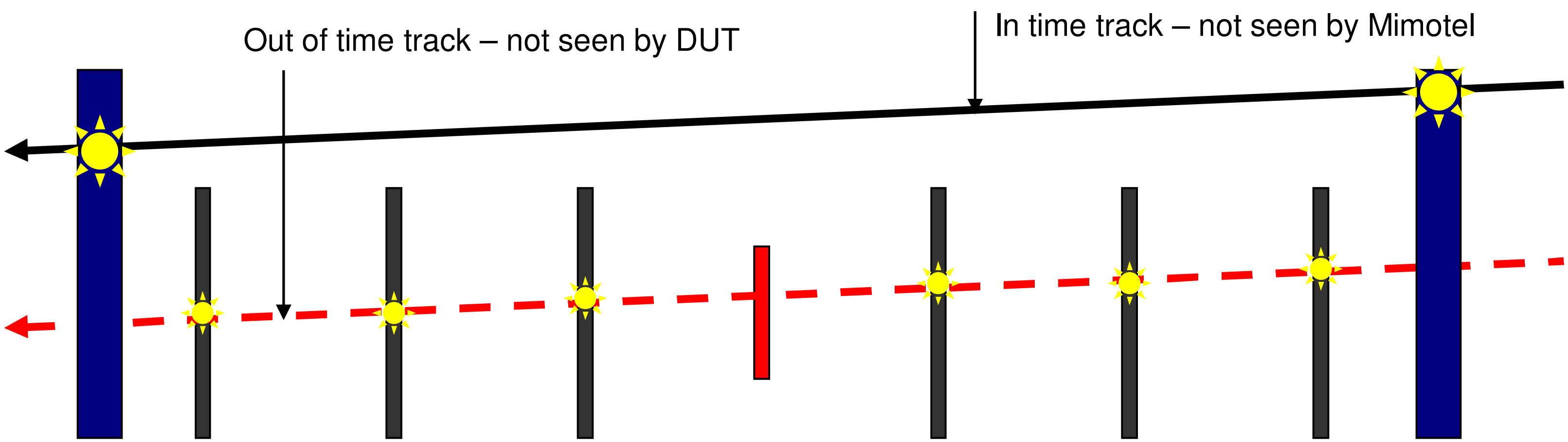


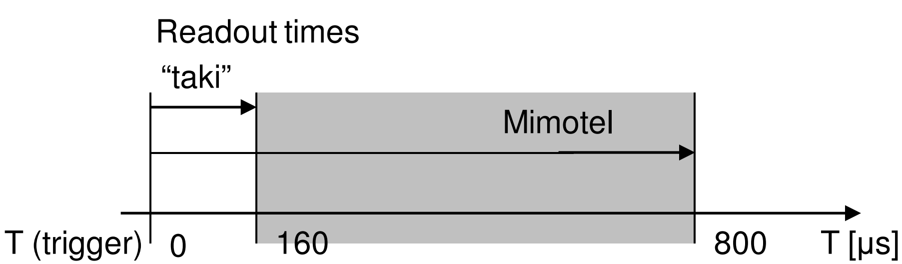
(Irregular events) empty event

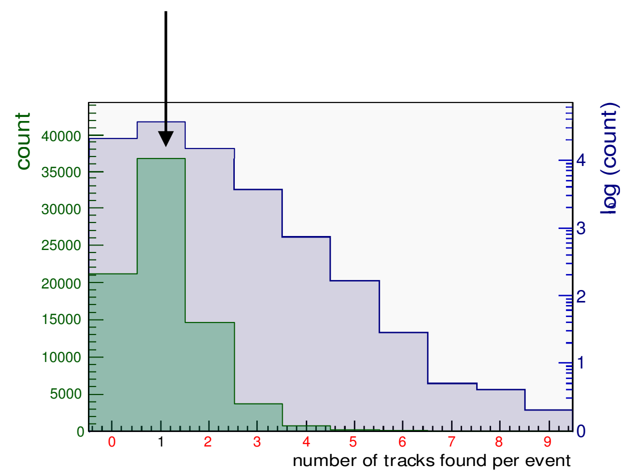




(Irregular events) double track event seen as a single track event



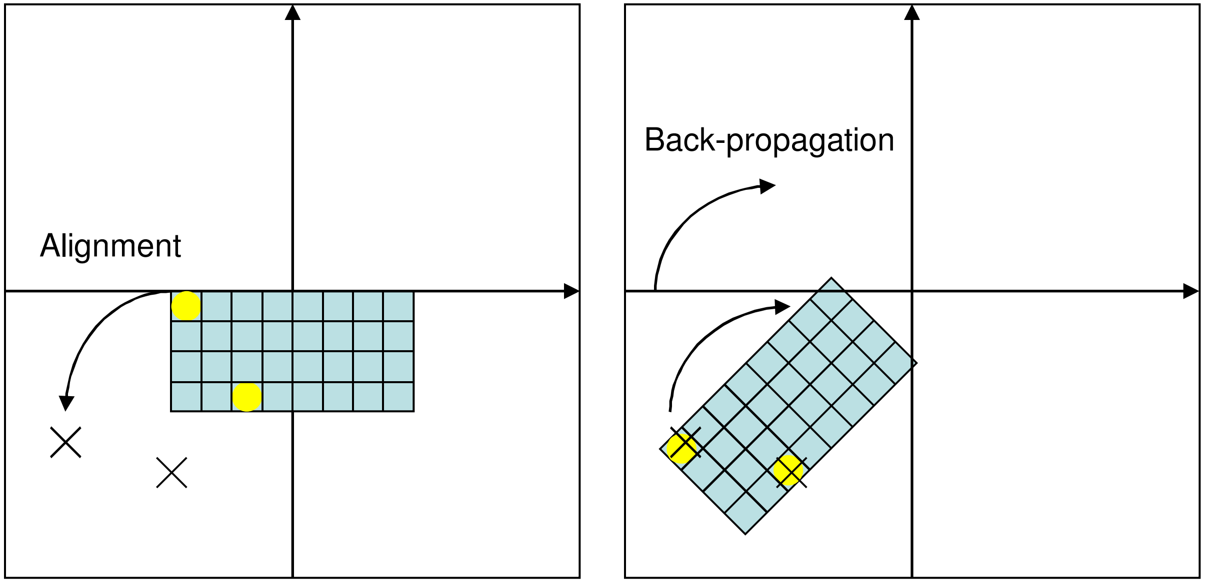


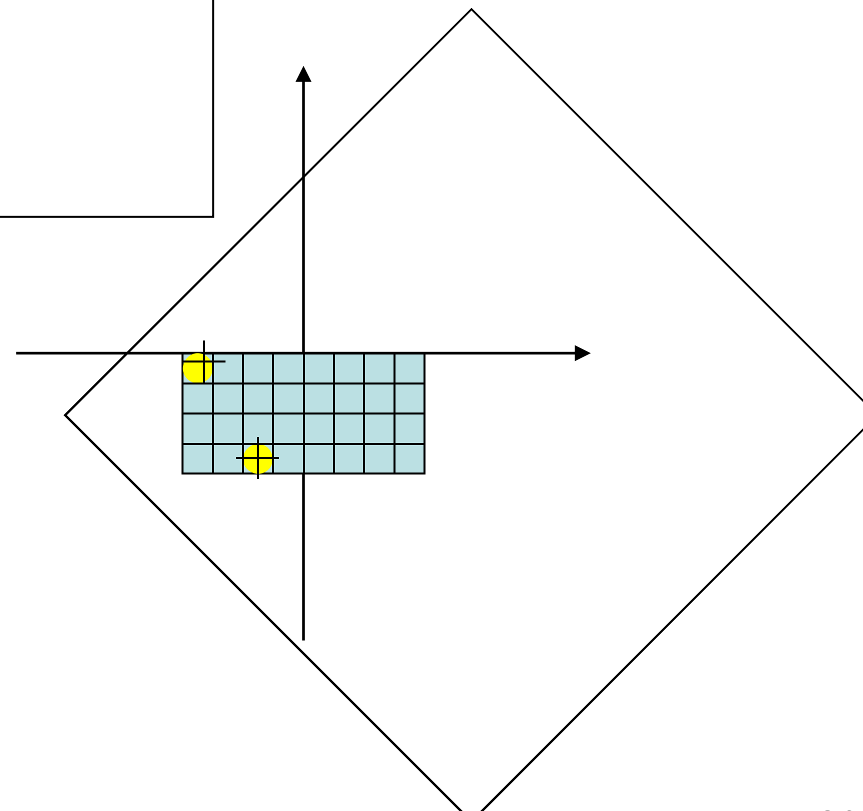


Efficiency (conclusions)

- Efficiency lower than 100% probably due to **timing** issues
  - Readout of telescope and DUT **are not synchronous**
  - DUT integration (readout) time **164 μs**
  - Telescope integration time = **800 μs**
  - Large cluster and **track multiplicity** in telescope
  - multiple tracks in telescope due to high beam intensity and long integration time
  - Small cluster multiplicity in DUT due to shorter integration time
- Some “out of time” particles hit the telescope **after the trigger moment** (during the readout) – the **particles are not seen by the DUT due to wrong timing**
- **Neglecting of all multiple track events increases efficiency from 72% to 86%**
- Problem: **A part of scintillator outside the telescope area**: some out of time tracks are seen as single tracks by telescope. **If we were** able to filter these out of time tracks too, **we would** probably measure a better efficiency

In-pixel measurements – back-propagation

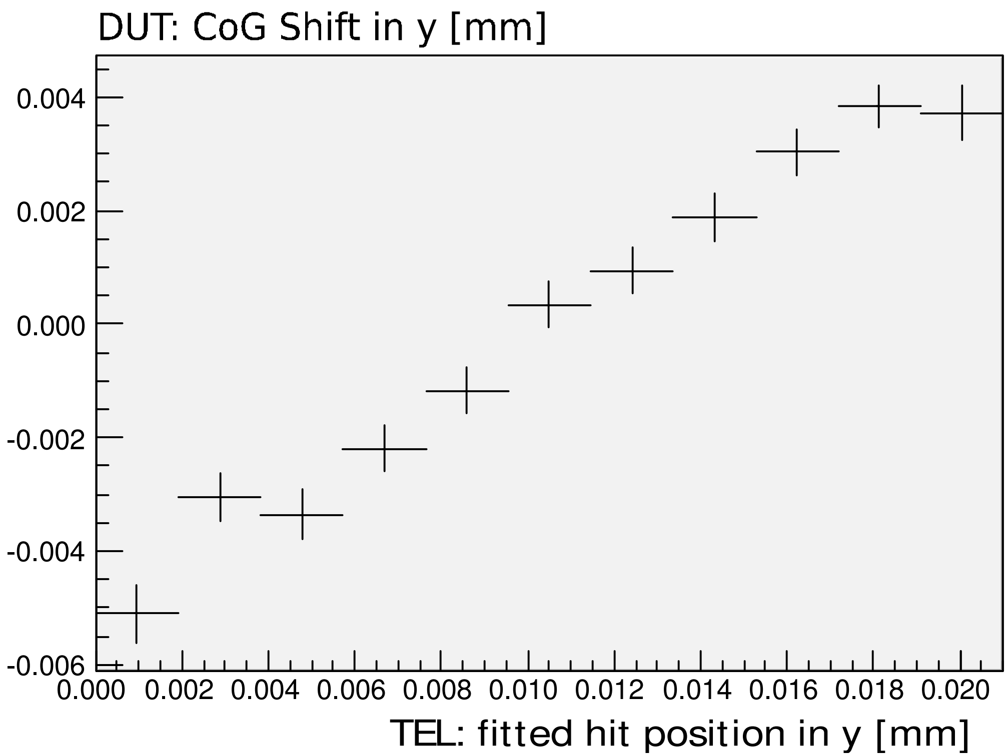




Excellent spatial resolution of the EUDET telescope allows the investigation of DUT properties as function of the **in-pixel hit point**
We performed series of such n-pixel measurements
The fitted coordinate is back-propagated to the DUT frame of reference and DUT pixels frame of reference

In-pixel CoG

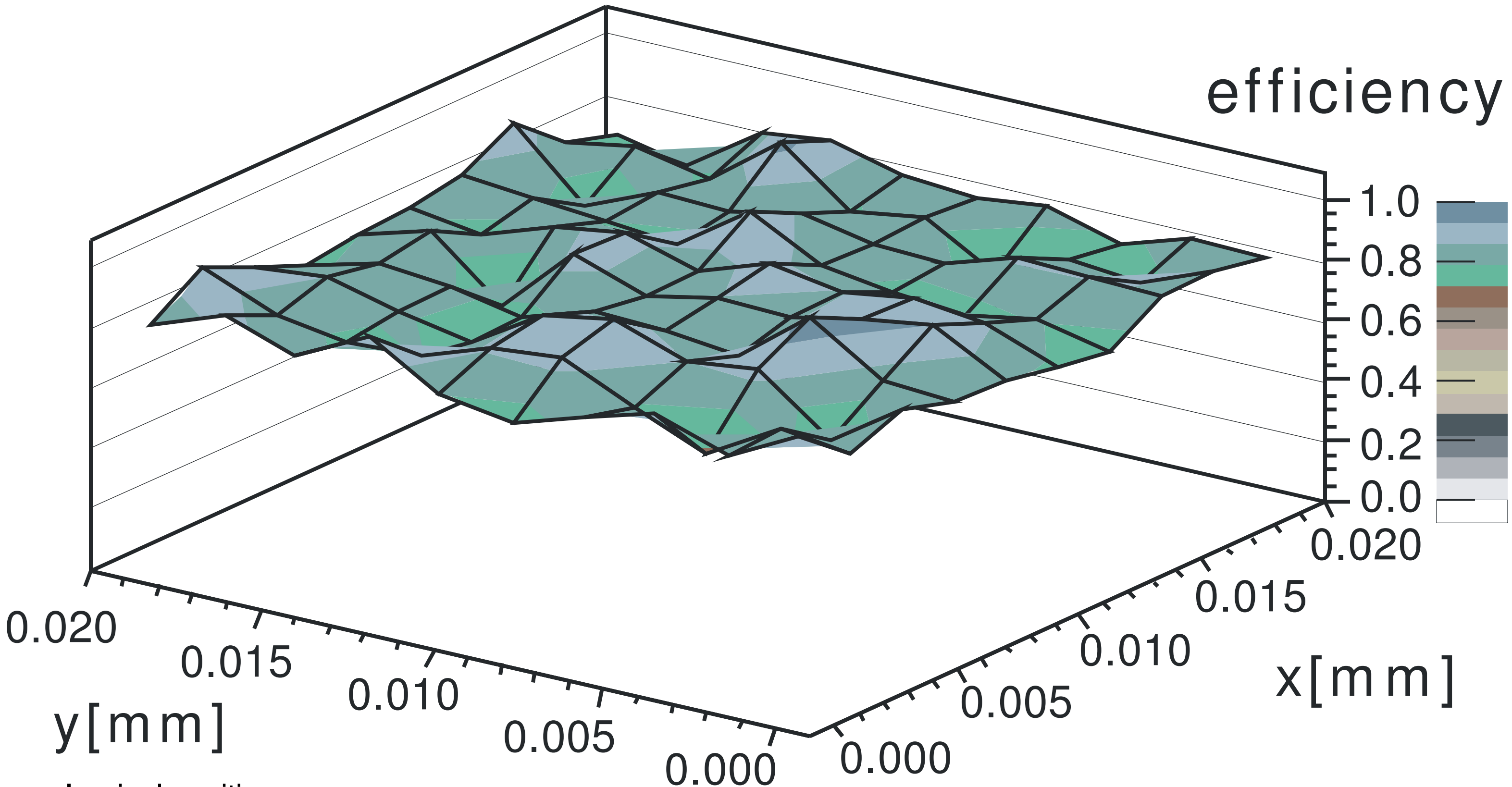
- **CoG correction works** but the **slope is too small** (by factor ~ 3) probably due to **absence of charge sharing** (primary signal) and noise (Eta-correction does not lead to better results)
- **Good check of the back-propagation tool**



In-pixel position

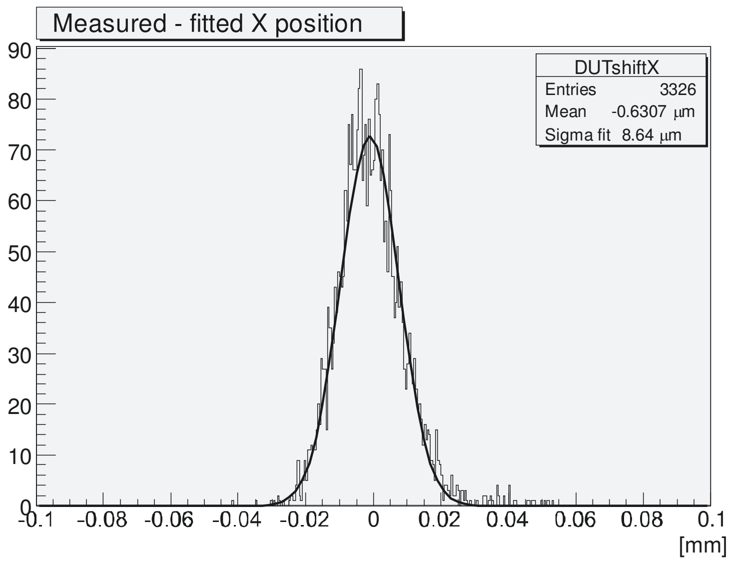
Pixel centre: 0.0105 mm

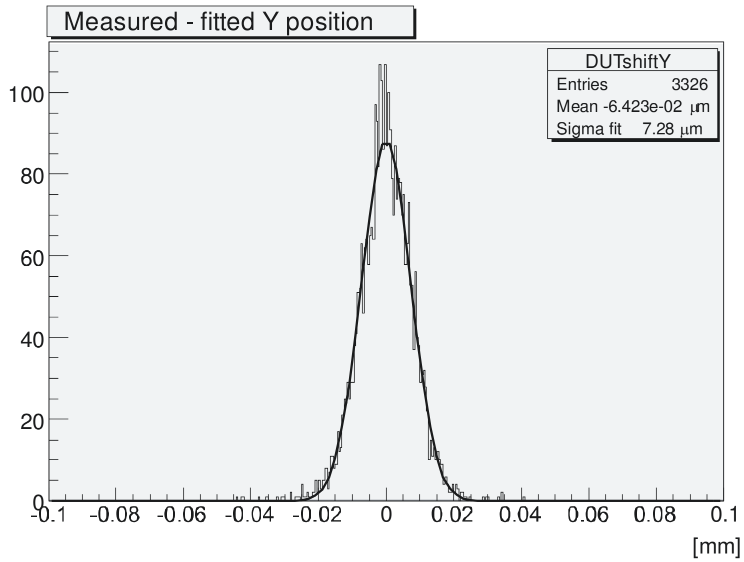
There are no insensitive regions! => There are no E=0 gaps!



In-pixel position
Pixel centre: (0.0105, 0.0105)

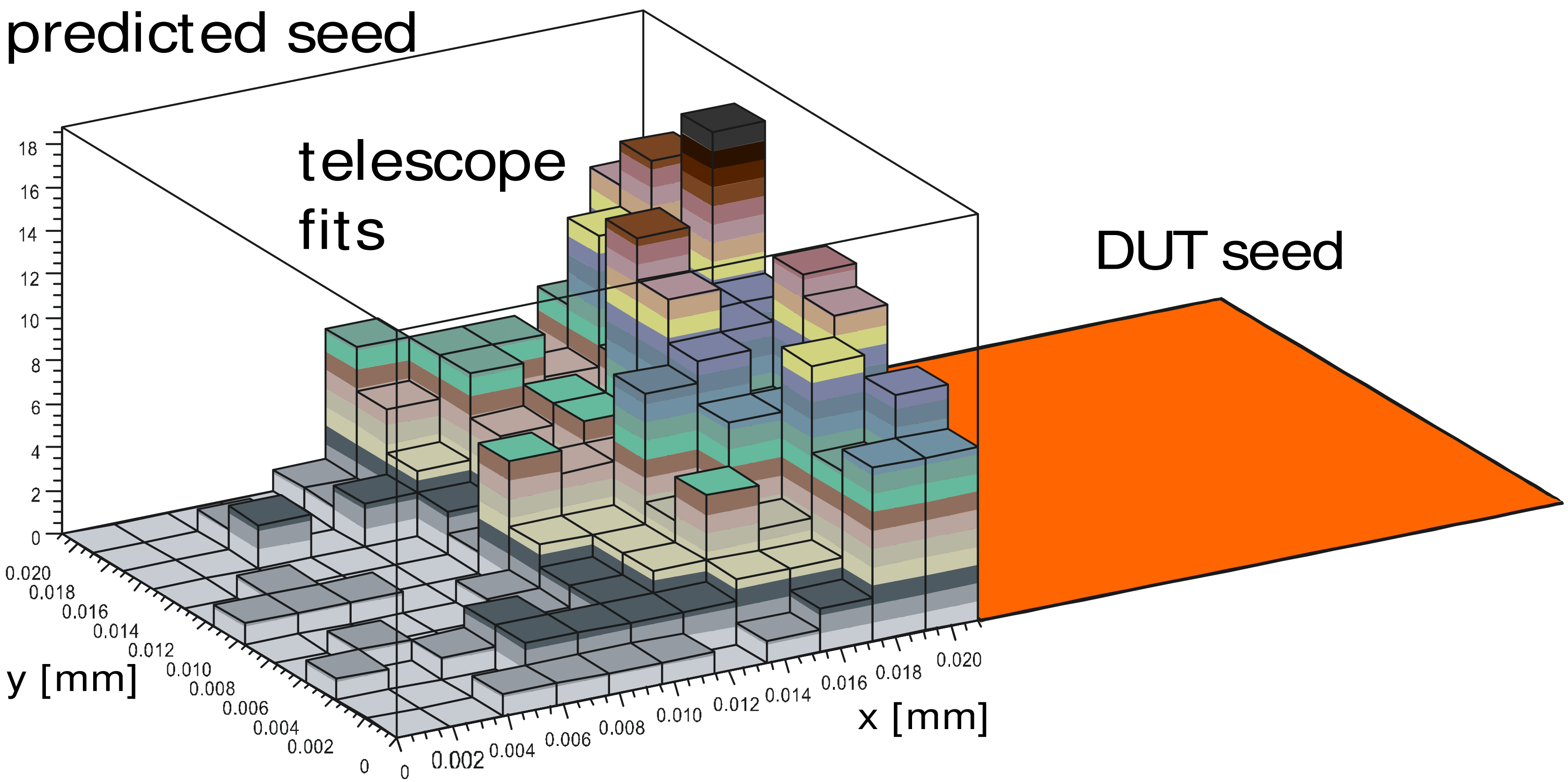
- Spatial resolution
- Sigma residual **X: 7.3 µm**
- Sigma residual **Y: 8.6 µm**
- The **difference** is probably caused by the **bricked pixel geometry** – still not understood completely, simulations will be done
- The spatial resolution is **not as good as in the case of standard MAPS** due to **absence of charge** sharing in the case of primary signal
- It is not completely clear why is the resolution worse than 21 µm /sqrt(12) = 6.1 µm
- The residual is sometimes larger than the pixel pitch.





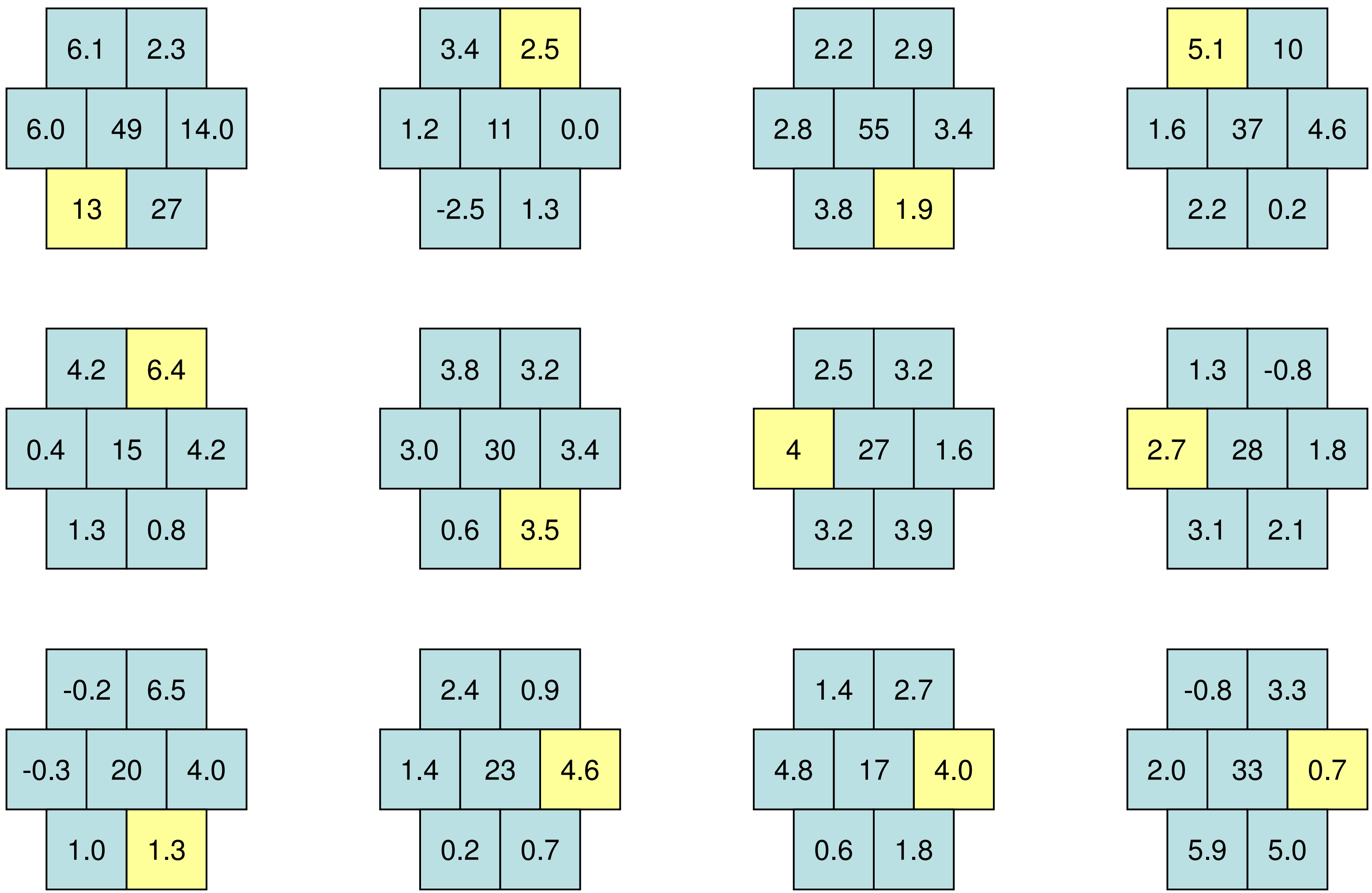
Seed pixel – fitted hit point mismatch

- The back-propagation (in pixel measurements) show that the **fitted hit** point (measured by the telescope) is sometimes **outside** (in the next pixel) of the **seed pixel**.
- This **mismatch worsens the spatial resolution**
- The fitted hit point – seed pixel mismatch occurs more probably when fitted point is near the pixel boundary
- **The mismatch seems, however, not to be caused by the electronic noise**

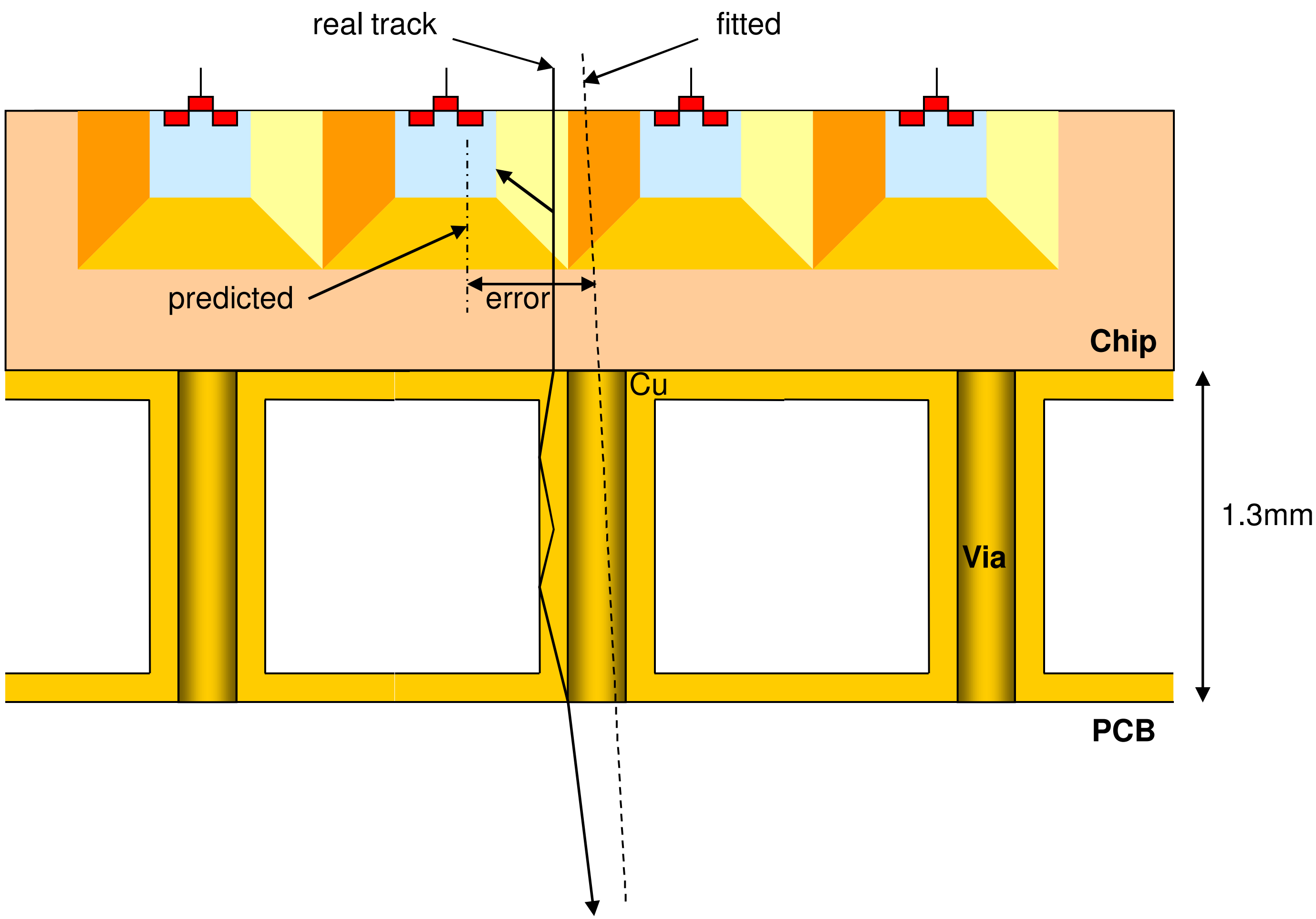


Seed pixel – fitted point mismatch (clusters and their pixel S/N)

A few clusters when the fitted point is outside the seed pixels are shown – the **seed pixel amplitude (S/N amplitude) is always very high** – there is little chance that we have chosen the wrong seed due to electronic noise.



The mismatch seems to be caused by the measurement-setup uncertainties, e.g. mechanical instability, **multiple scattering** on PCB “vias”.



Summary (test beam)

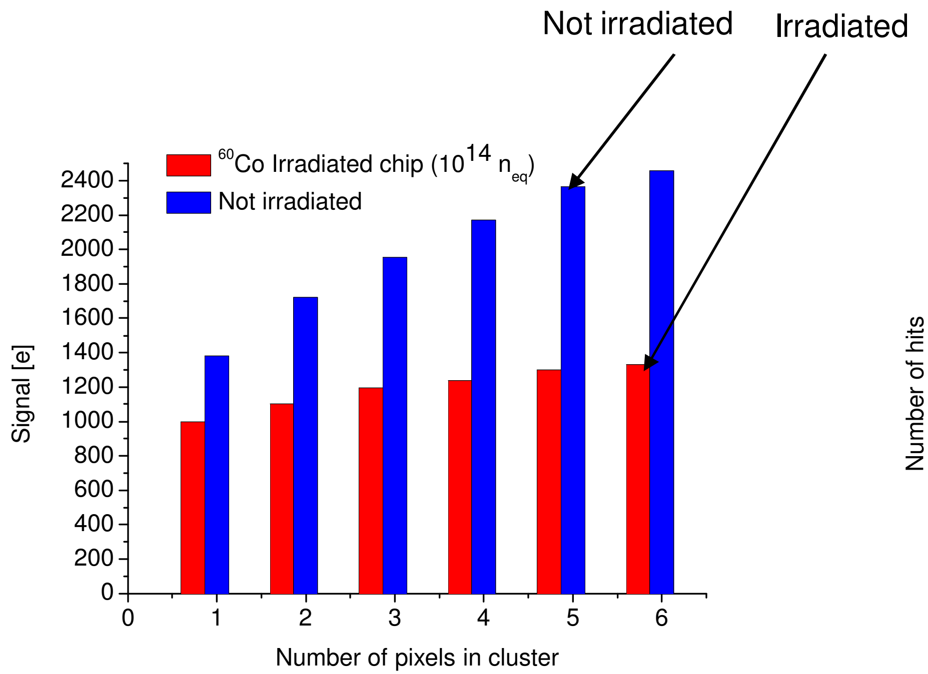
- Efficiency: 86%
- Purity: 72%
- Sigma X-residual 8.6 µm
- Sigma Y-residual 7.3 µm
- S/N ratio seed: 12.3
- S/N ratio cluster (6 pixels): 10
- **There is little charge sharing – the seed pixel receives 50 % or more of the total signal**
- **There are no insensitive regions**
- **Spatial resolution worse than expected probably due to MS, to be understood**

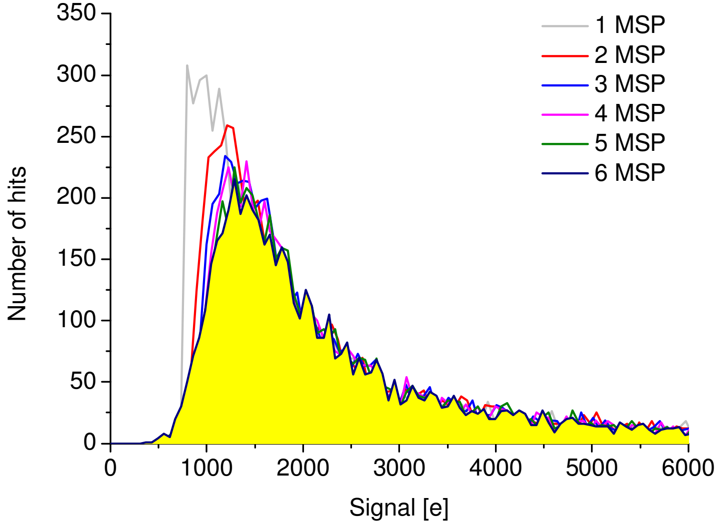
Irradiation with neutrons has been performed by **Franz M. Wagner** at FRM II - **"Forschungsneutronenquelle Heinz-Maier-Leibnitz"** http://www.frm2.tum.de/

After irradiation to **10^{14} n_{eq}** the **seed "MIP" (most probable ^{60}Co) signal is 1000 e** and the **cluster signal is 1300 e –** the real MIP is by about 10% lower

The measurement has been performed at **0C**

Leakage current / pixel increases from **350 fA to 130 pA**

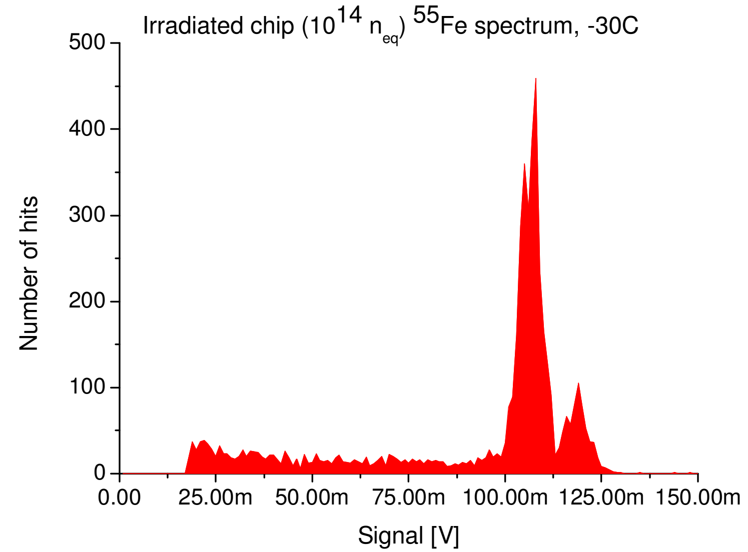


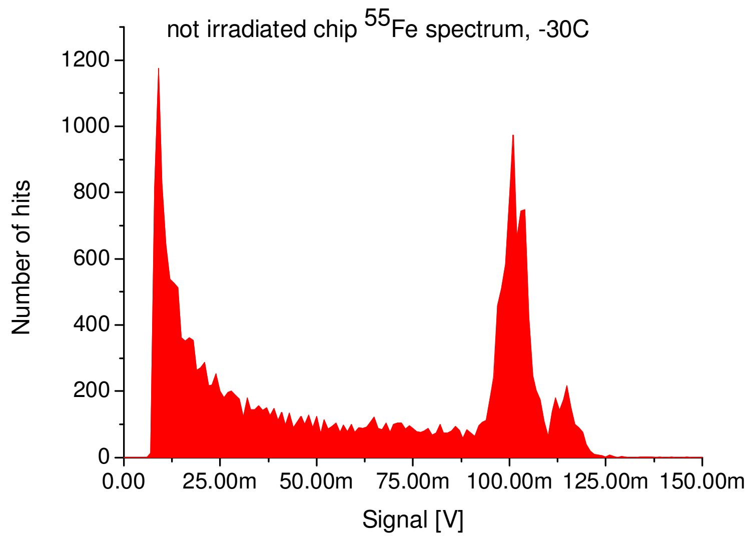


Irradiation with neutrons (10^{14} n_{eq}) – noise (Type C)

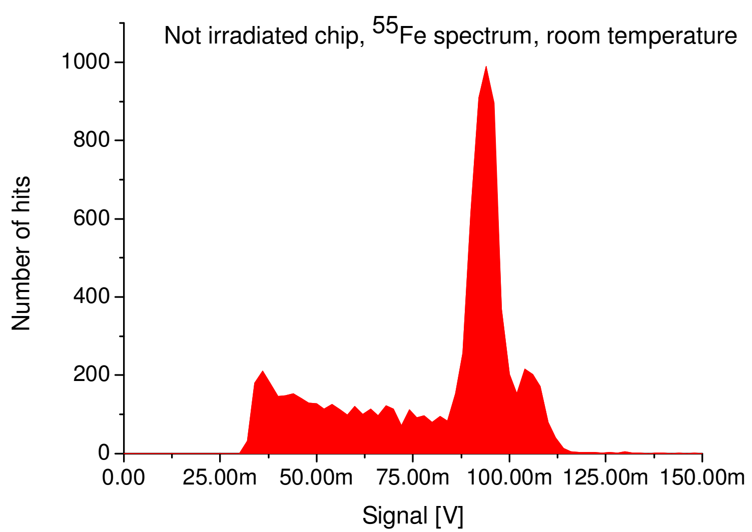
- **Type C** detector, **^{55}Fe spectrum**
- **Excellent noise performance after irradiation**
- No clustering possible with this detector

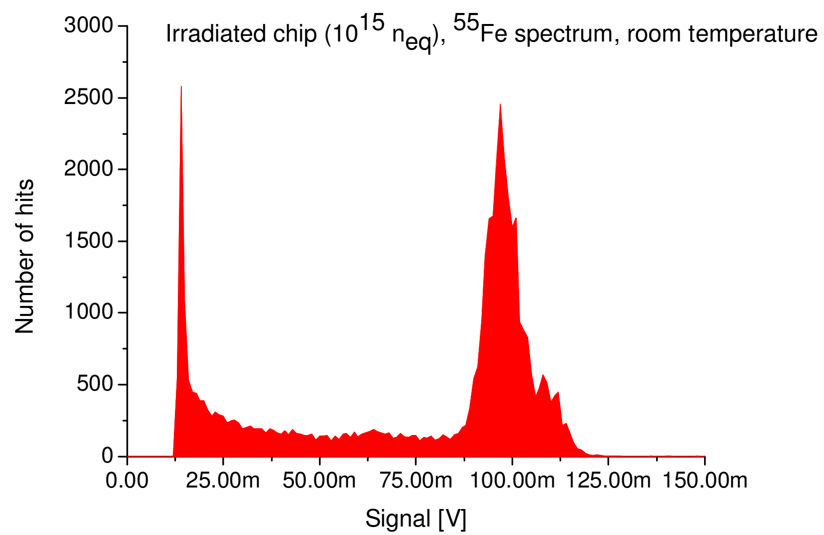
Irradiated to 10^{14} n_{eq}, - 30C, noise about 30 e





Irradiated to 10^{14} n_{eq}, room temperature, noise about 60 e





Summary

Type B (10 fF detector capacitance, **21 µm x 21 µm pixel size**)

- **Signal**:
  - **not irradiated: 1200 e (seed) to 2200 e (cluster) (MIP)**
  - Irradiated to **10^{14} n_{eq} : 1000 e (seed) to 1300 e (cluster) (^{60}Co)**
- Noise: **90 e** (not irradiated) – **the high noise is the result of non-optimal design, will be reduced by new design (the chip has already been submitted)**
- Type A (**220 f** detector capacitance, **55 µm x 55 µm pixel size**)
- **Signal**:
  - Not irradiated: **1700 e** (MIP) (good agreement with type B)
  - Noise **55 e** at **110 ns shaping time**
- Extrapolations for type A:
- **Signal after 10^{14} : 1200 e (MIP)**
- *Signal after 10^{15} : 800 e*
- Type C (**100 f** detector capacitance, **50 µm x 50 µm pixel size**)
  - Noise after **10^{14} n_{eq} : 60 e** (longer shaping times) (**room T**)
  - Radiation hardness of more than **2 MRad** tested
- Future plans: irradiation to at least **10^{15} n_{eq} and 50 MRad**

Thank you