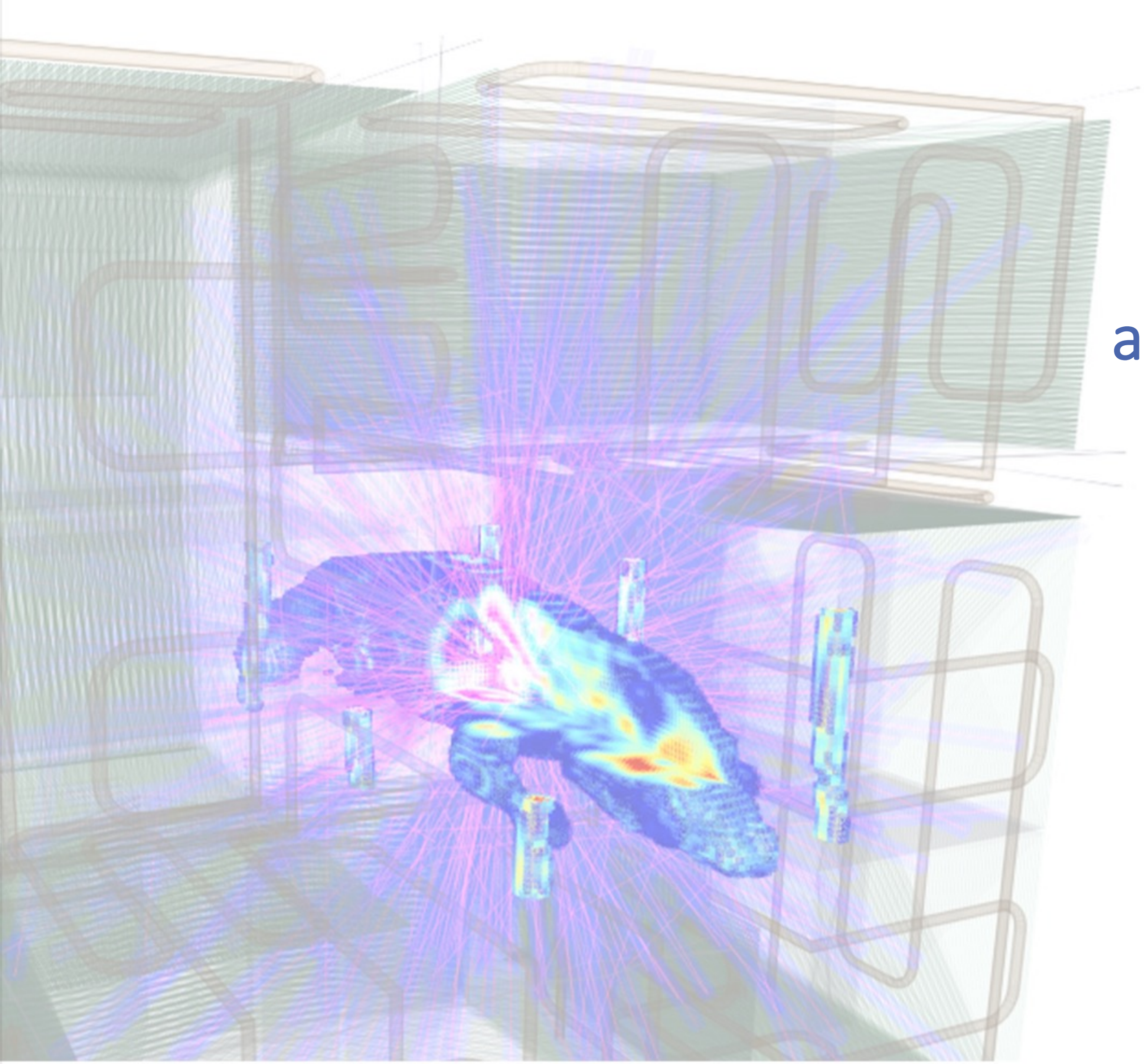


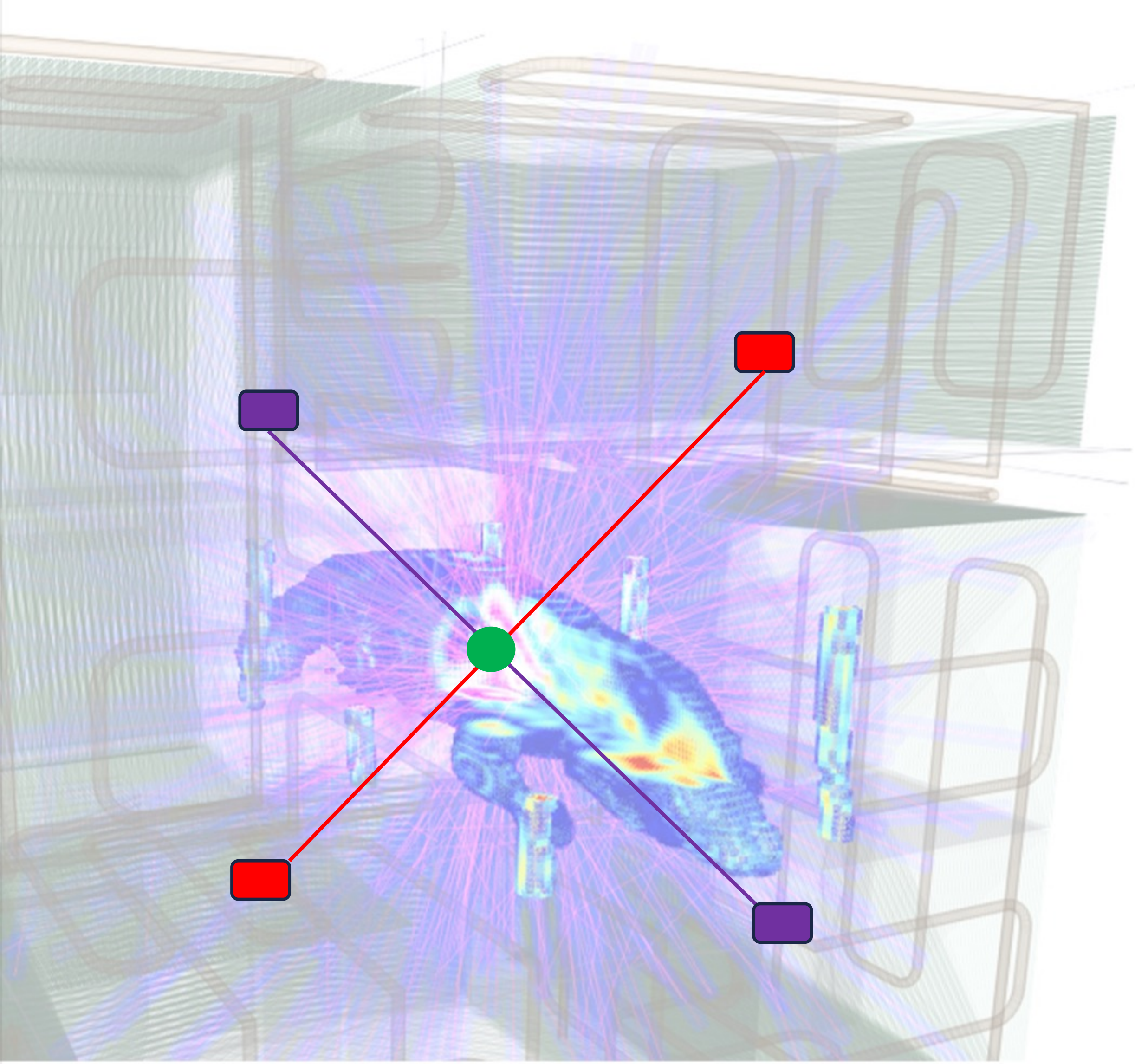
100μmPET

a ultra-high-resolution silicon-pixel-based small animal PET scanner

R.Cardella, on behalf of the collaboration

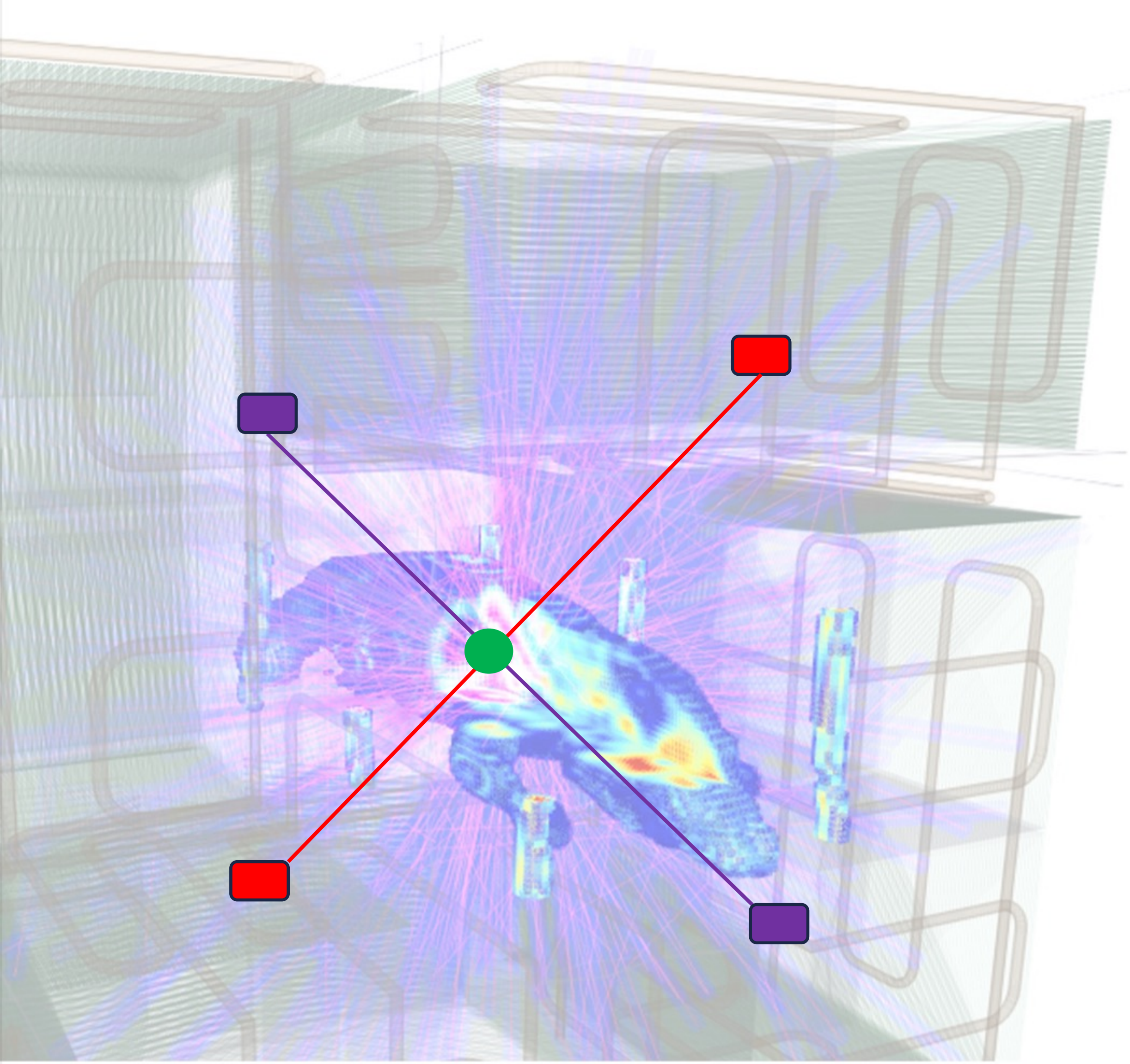
Swiss National Science Foundation
EPFL
Université de Genève
UNI LU

Université de Genève
Faculty of Science
Department of Nuclear and Particle Physics



- Radiotracer injected into the body
- Cells with abnormal metabolic behavior will show an excess of radiotracers
- Positron emission -> e- e+ annihilation
- Detect 2 back-to-back Gamma at 511 keV
- Reconstruct image from Line of Response (LoR)

Atherosclerosis plaques in mouse
Pre-clinical scanner



- Radiotracer injected into the body
- Cells with abnormal metabolic behavior will show an excess of radiotracers
- Positron emission -> e- e+ annihilation
- Detect 2 back-to-back Gamma at 511 keV
- Reconstruct image from Line of Response (LoR)

Image quality and Acquisition time:

- Spatial Resolution
- Noise event rate vs. True coincidence rate
- -> Small time window and low jitter

Atherosclerosis plaques in mouse
Pre-clinical scanner

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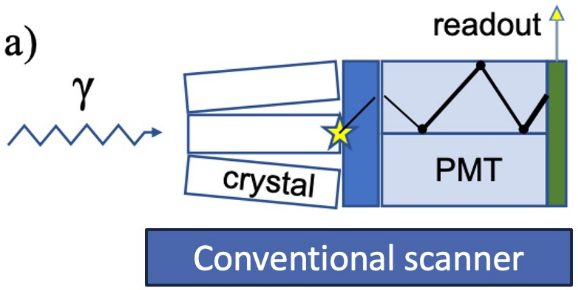
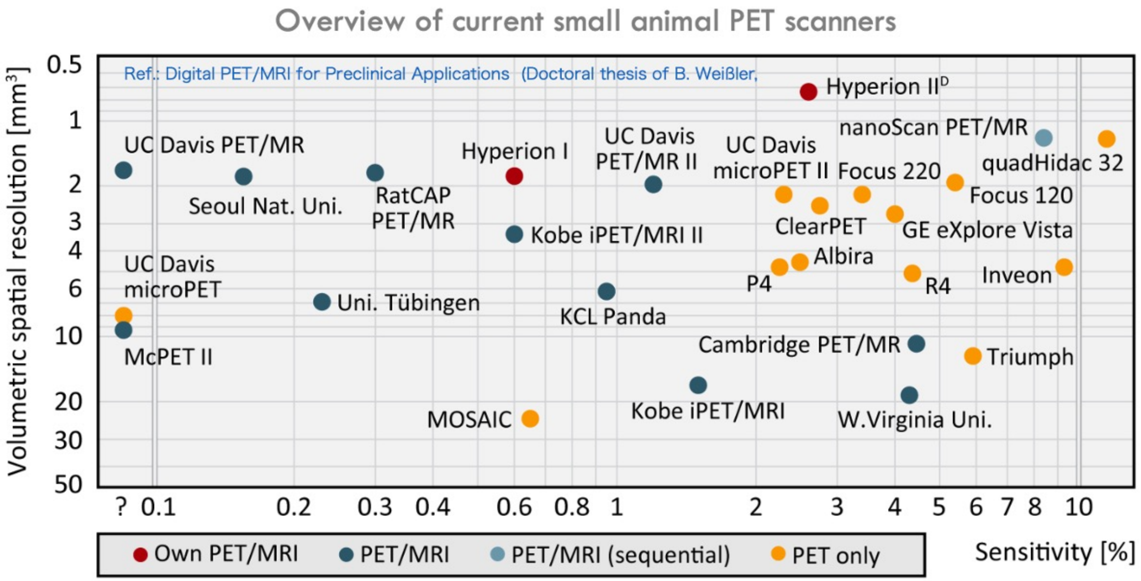
Department of Nuclear and Particle Physics

Best **pre-clinical small animal** scanner combine MRI – CT with PET to achieve resolution of **0.5mm³**





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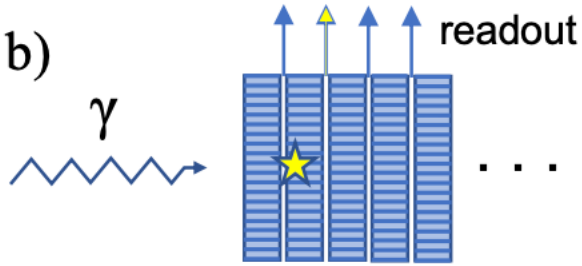
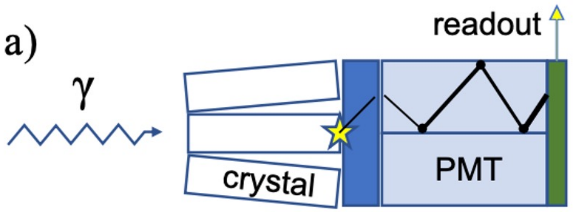
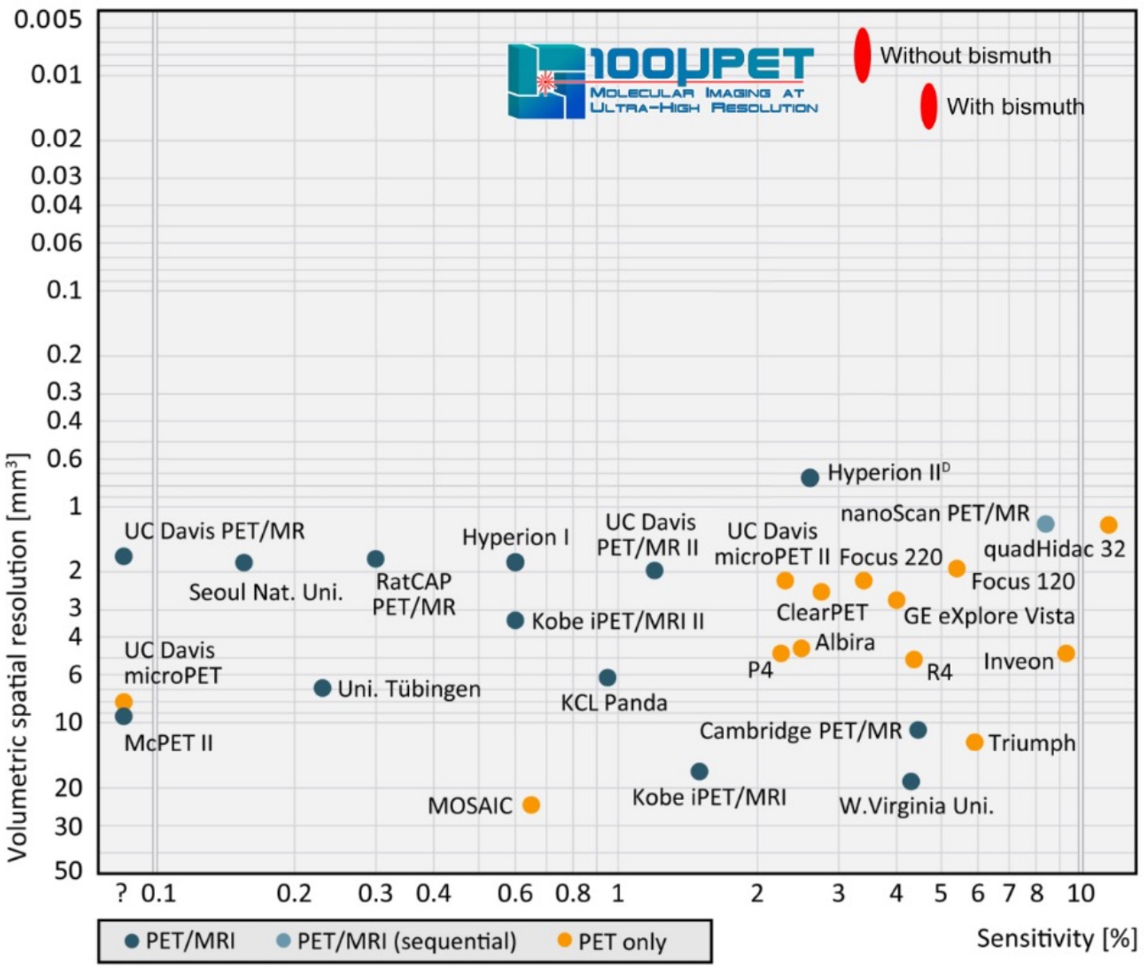


Our proposal (MAPS)
1 order of magnitude better!

Best **pre-clinical small animal** scanner combine MRI – CT with PET to achieve resolution of **0.5mm³**



Conventional scanner



DOI 0.1109/TRPMS.2024.3456241

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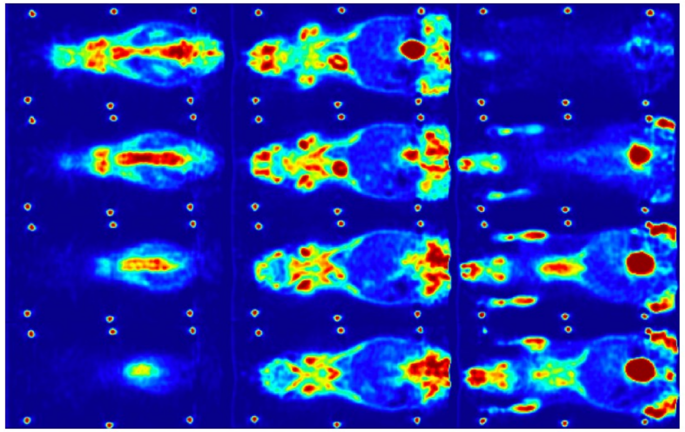
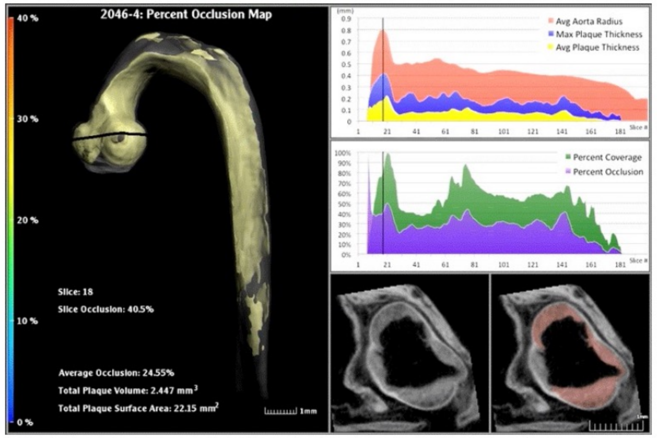
- Mouse phantom from Digimouse PET (background) + atherosclerotic plaque microCT (signal of interest)
  - Injected activity: 30 MBq
  - Measurement time: 20 min
    - Mouse volume = 45 mL ➞ **1.4 x 10^9** background annihilations
    - Plaque volume = 0.006 mL ➞ **8.4 x 10^6** plaque annihilation

Digimouse PET section



+

microCT of atherosclerotic plaque



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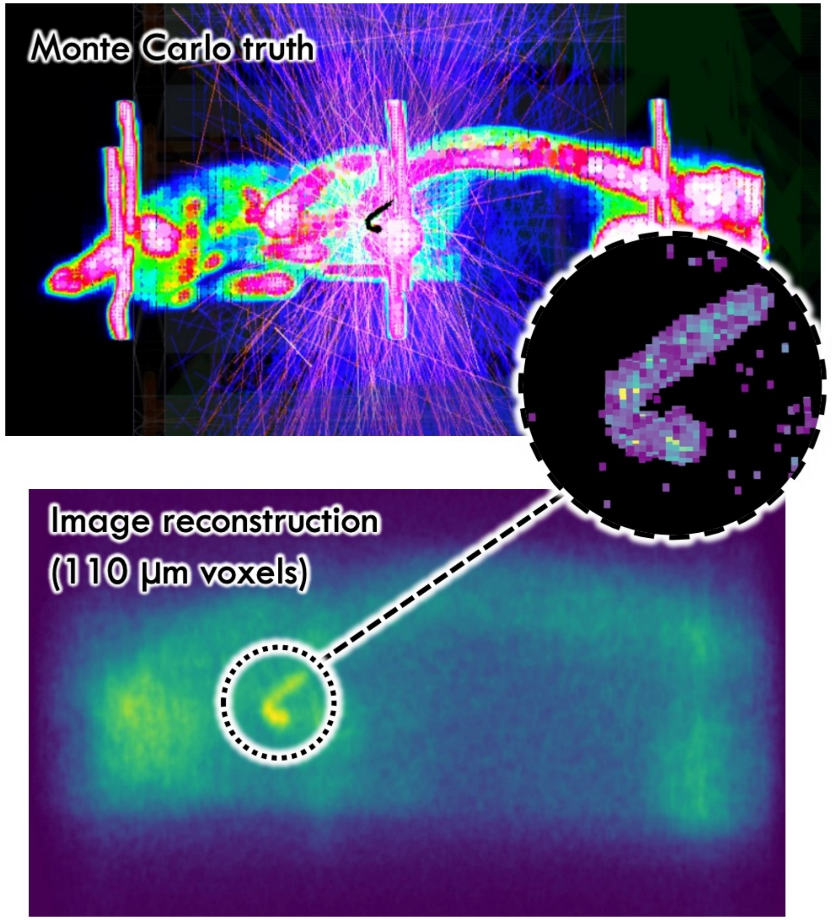

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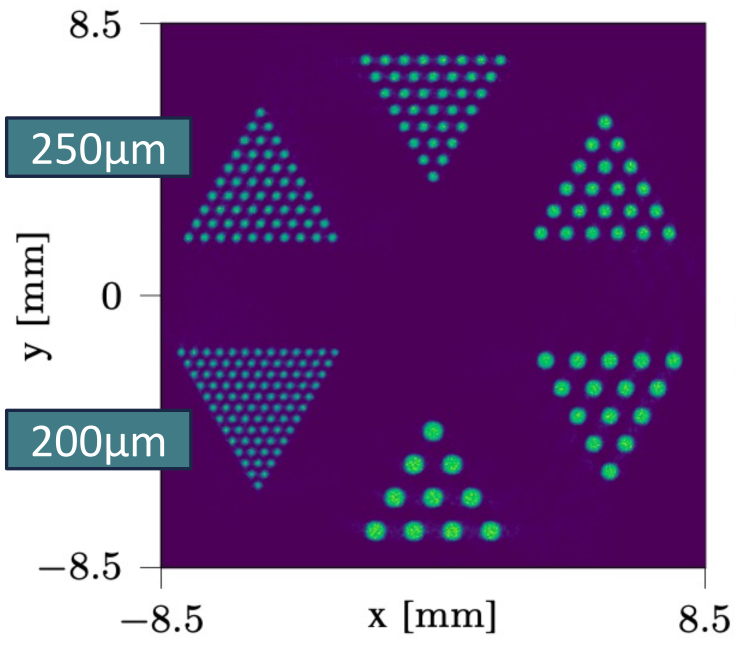
How far can we bring down the spatial resolution?

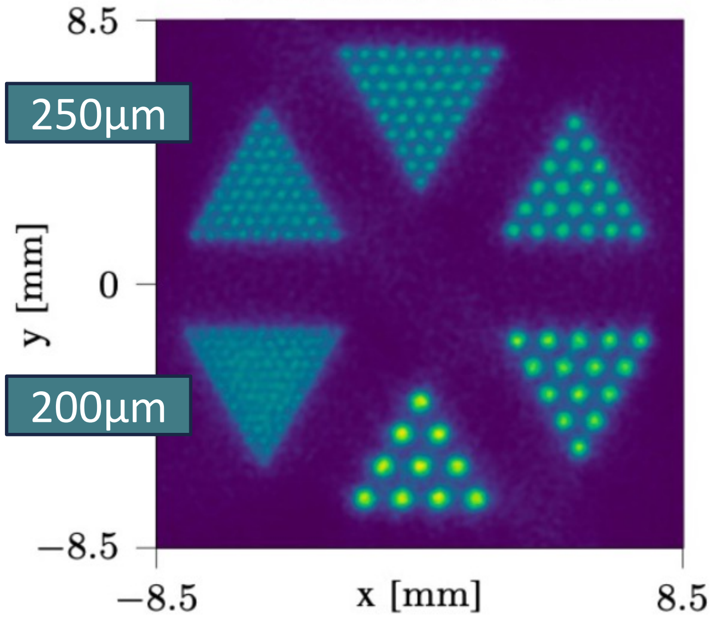
100µm pixel pitch



No acollinearity,
No positron range,
$p = 0.1$ mm, no bismuth,
reconstructed with OSEM

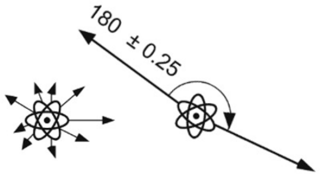
No uncertanty in Gamma emission process

100µm pixel pitch



Positron range: 102µm FWHM for F18

Acolinearity: $90\mu m \approx 4 \cdot 10^{-3} R$



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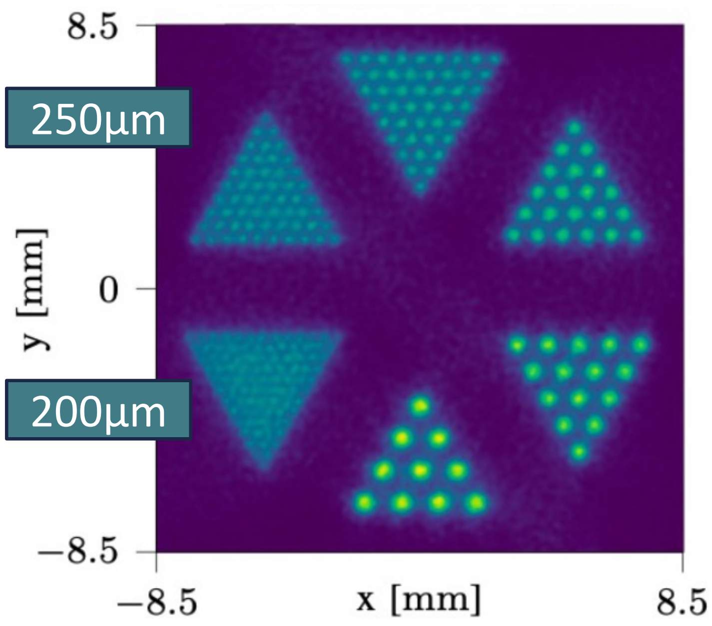
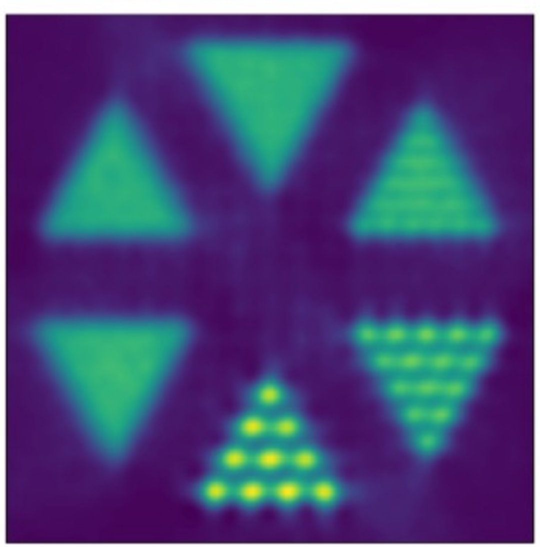
100µm pixel pitch

Reference scanner

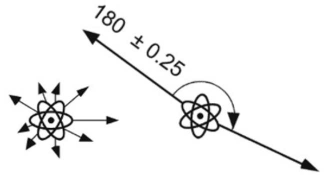




Reference scanner ~ state of the art

Positron range: 102µm FWHM for F18

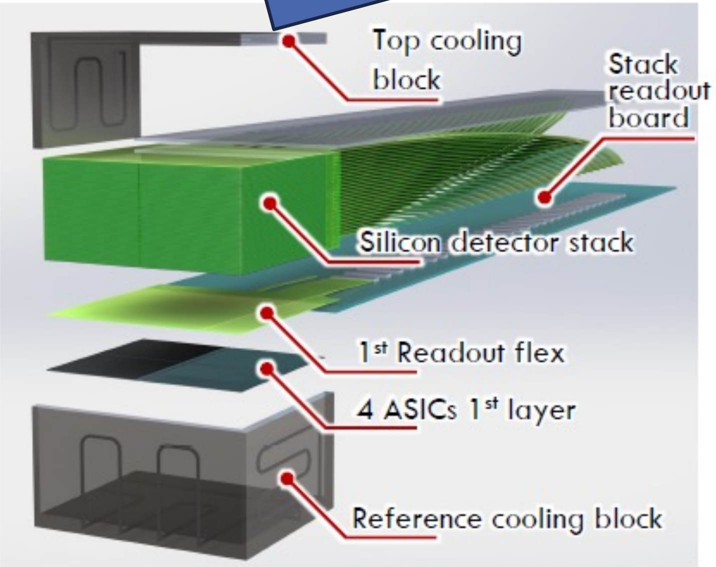
Acolinearity: $90\mu m \approx 4 \cdot 10^{-3} R$

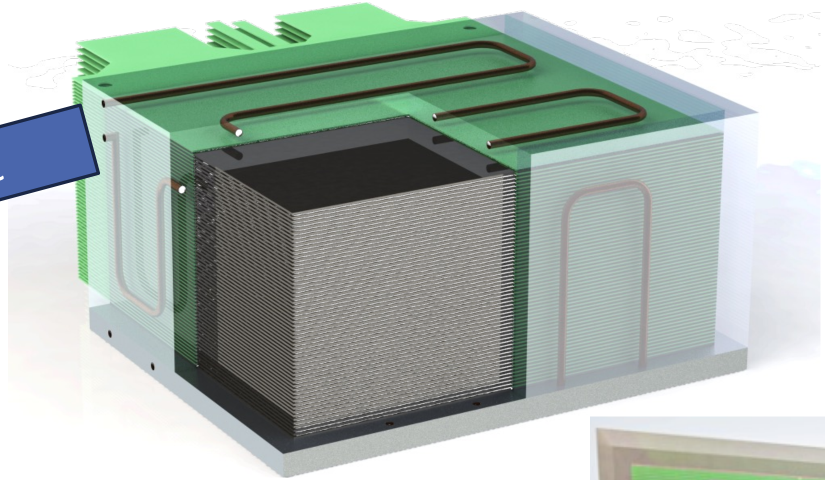


Large improvement with respect to reference scanner

Tower: 60 quad-module layers (240 chips)

Trade-off Sensitivity / Cost





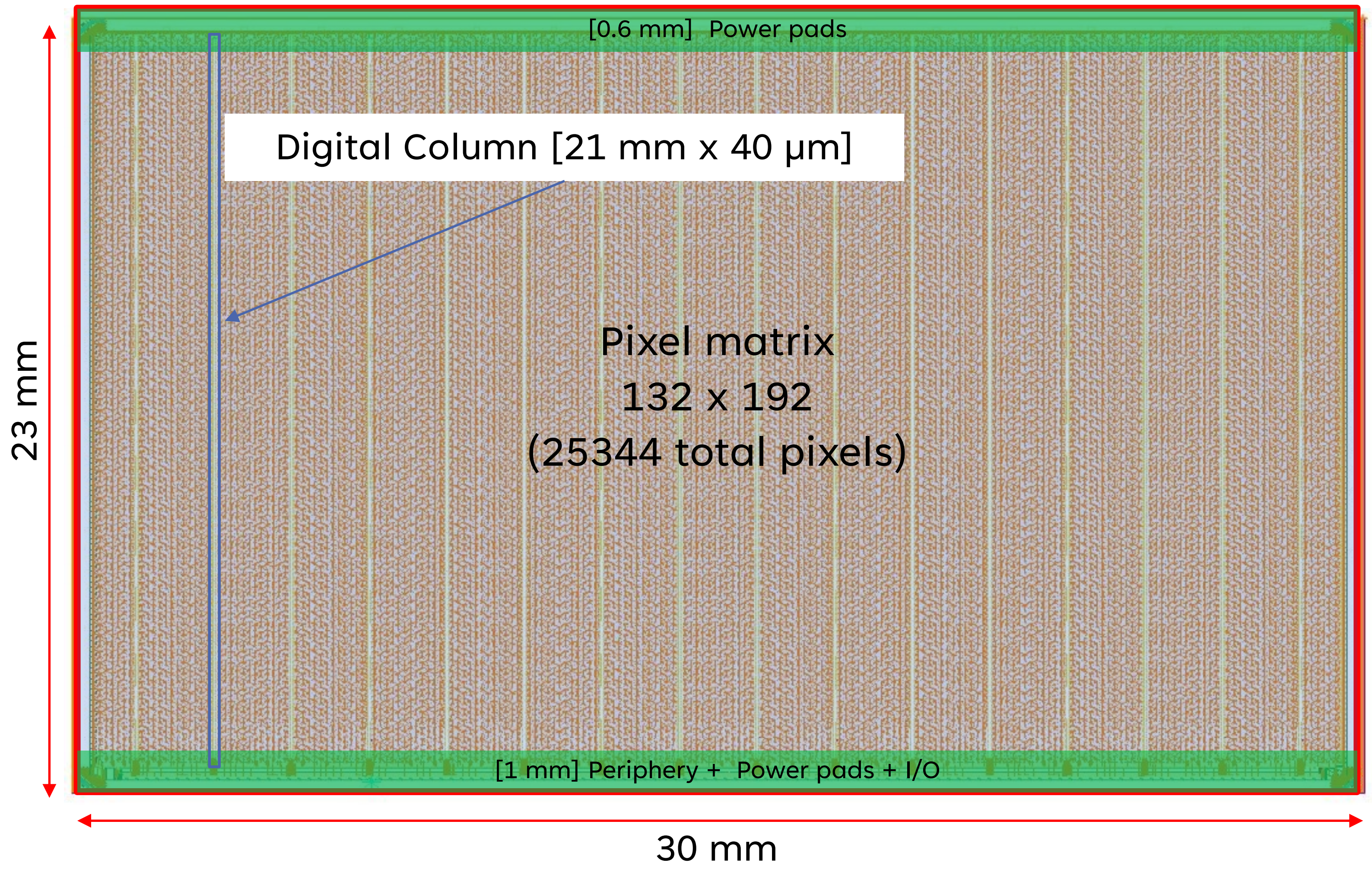
100µPET Scanner:
4 towers (960 chips)

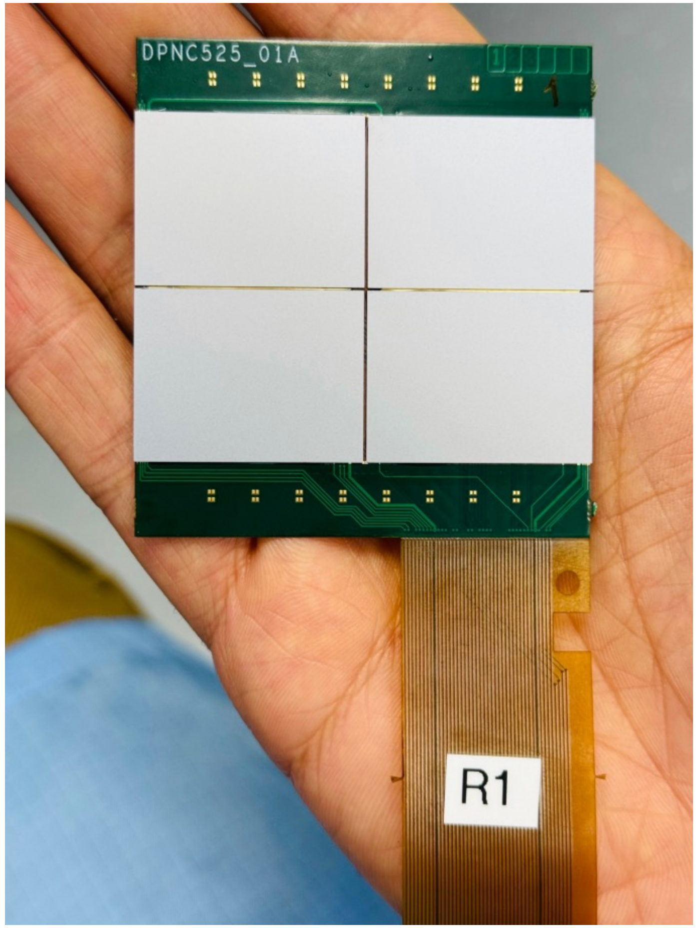
F. Cadoux et al.

Event size	1 cluster (< (5x5) pixels)
Event rate	10 kHz/cm^2
Equivalent Noise Charge (ENC)	~250 e-
Operation Threshold	**[2000 / 3000] e-**
Time resolution RMS (Qin > 7 ke-)	**200 ps**
ToA	Yes, seed pixel
ToT	Yes, for time-walk correction
Power consumption	**< 100 mW/cm^2**
Pixel pitch	**150 µm**

CMOS monolithic sensor in IHP SG13G2 BiCMOS, **130 nm** process featuring **SiGe HBT**

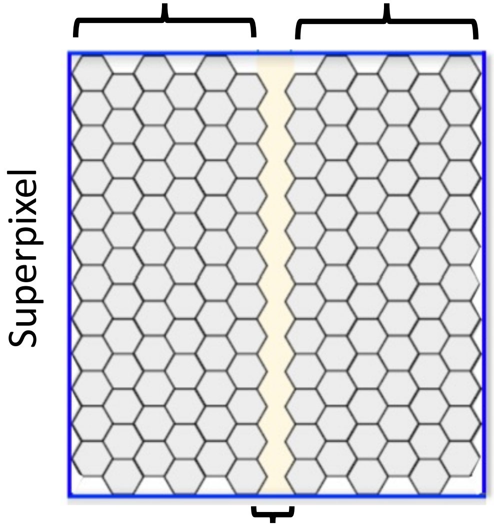
See also talk from L. Paolozzi next Thursday





Submitted for production in October 2023

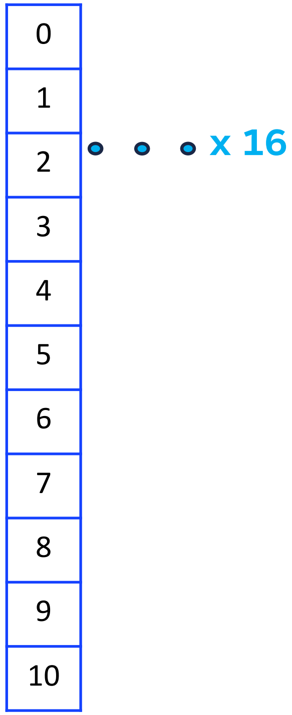
Super Column

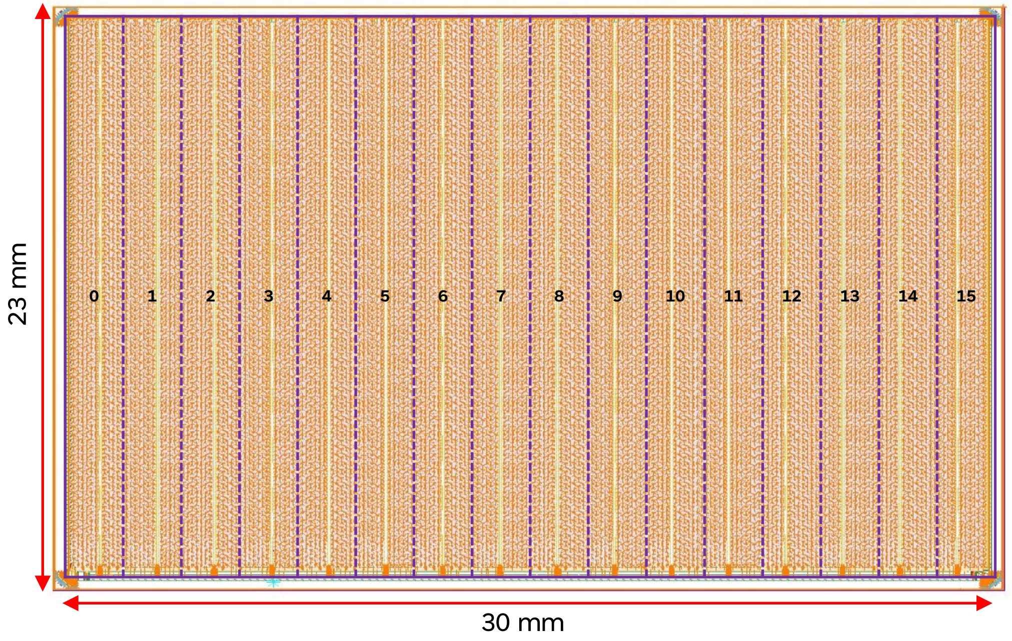


1 x 12 pixels
digital lines and configuration
(non-sensitive region)
1/13 of matrix area (7.7%)

x 11

Super Colum
11 Super Pixels

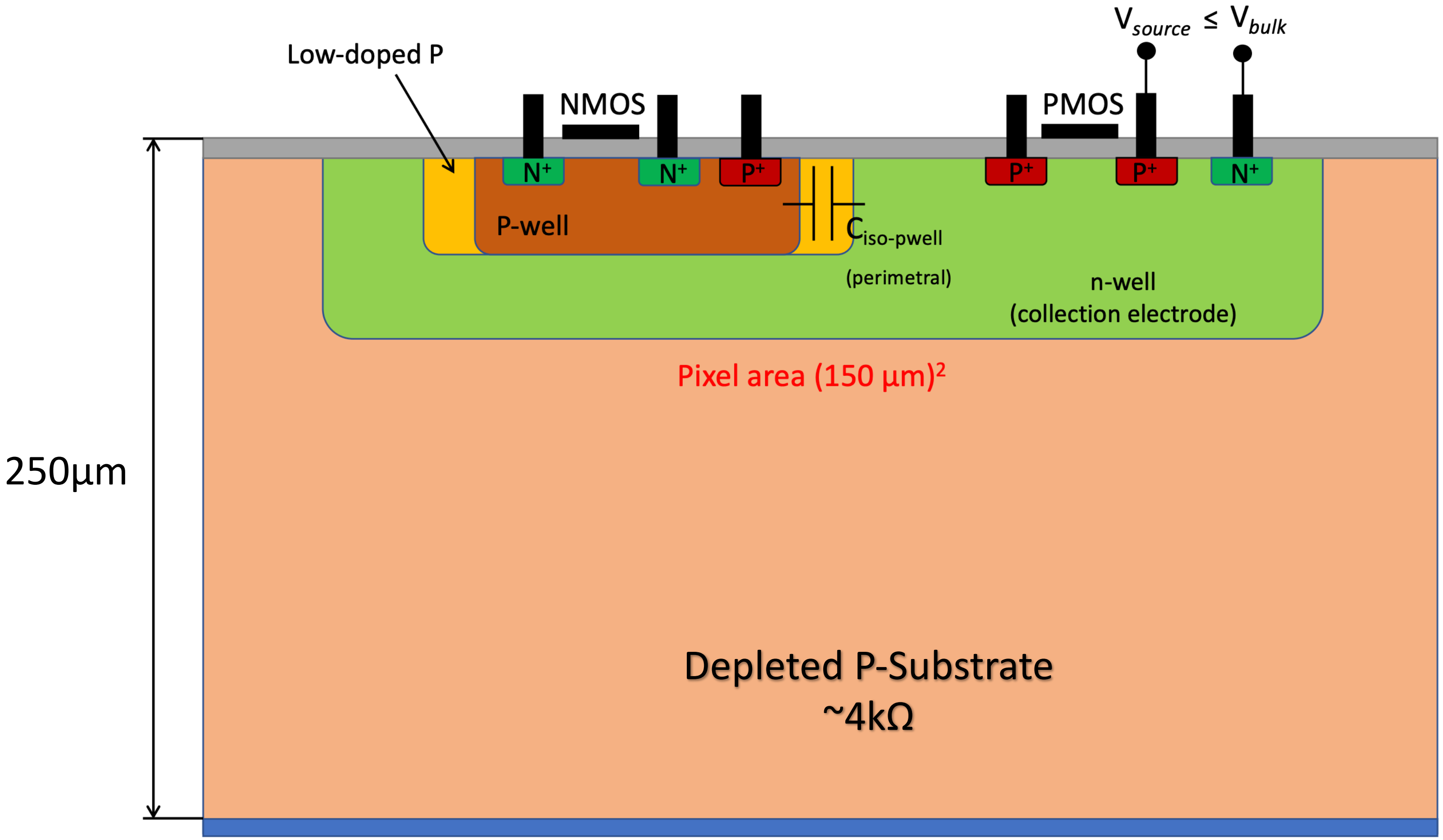




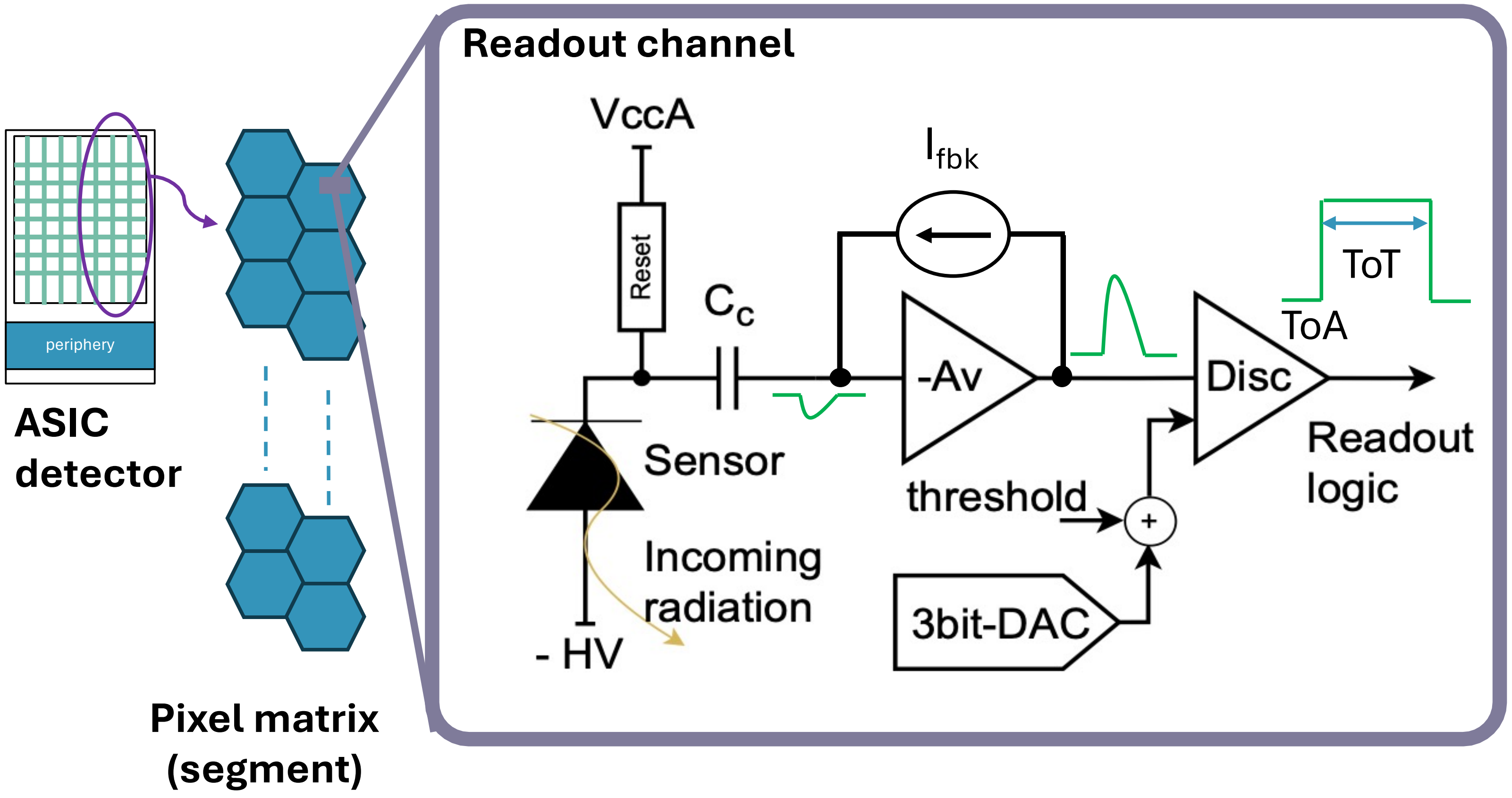
Asynchronous 51-bit bus
No Clock inside the matrix

Digital Periphery

TDCs, DACs, Bandgap, LVDS drivers, config registers



- In-pixel electronics
  - Affects input capacitance
- Non-isolated PMOS
  - Need to reduce in-pixel digital circuits
  - 360fF pixel capacitance



OR-tree chain

On-chip TDC

- Time of Arrival (ToA)
- Time over Threshold (ToT)

ToT $\propto Q_{in}$ → Time-walk correction

A. Picardi et al.

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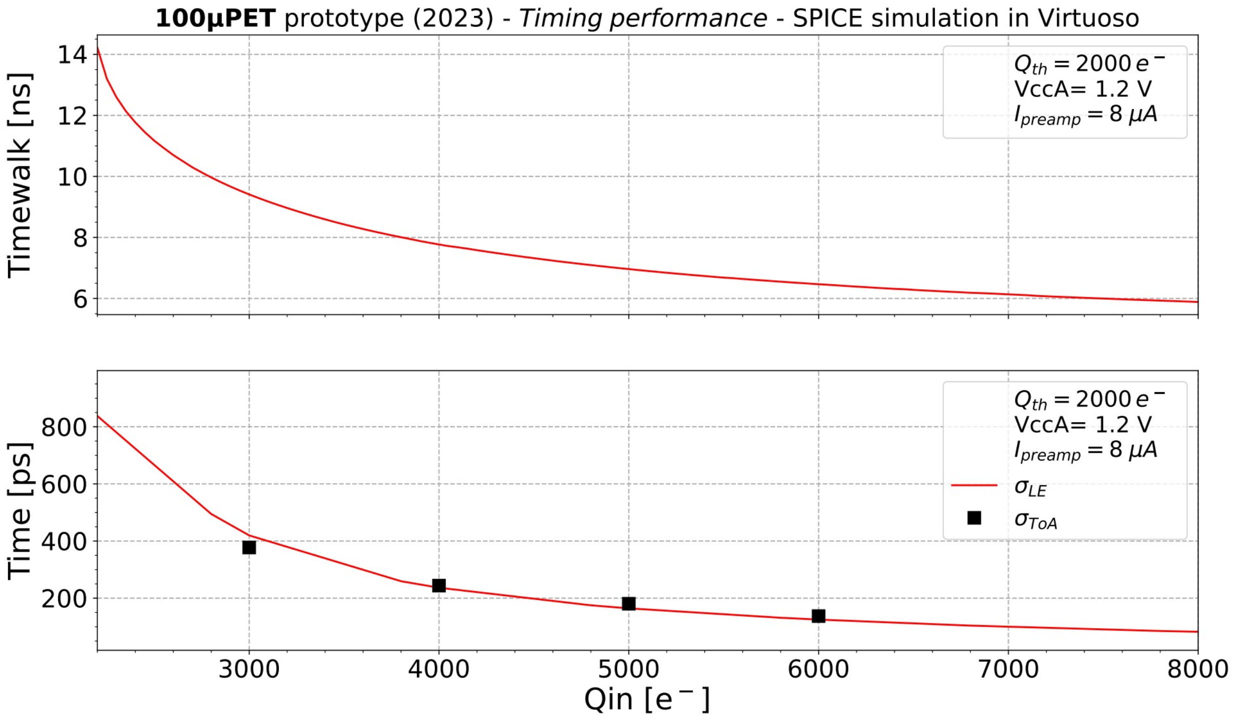
Good time resolution to select **coincidence events** from noise

Use 1 ns time window
"4D-Tracking"



Excellent timing performance with very low power consumption.

Want to see what SiGe can do with little increase in power consumption?
Don't miss the talk from L. Paolozzi next Thursday

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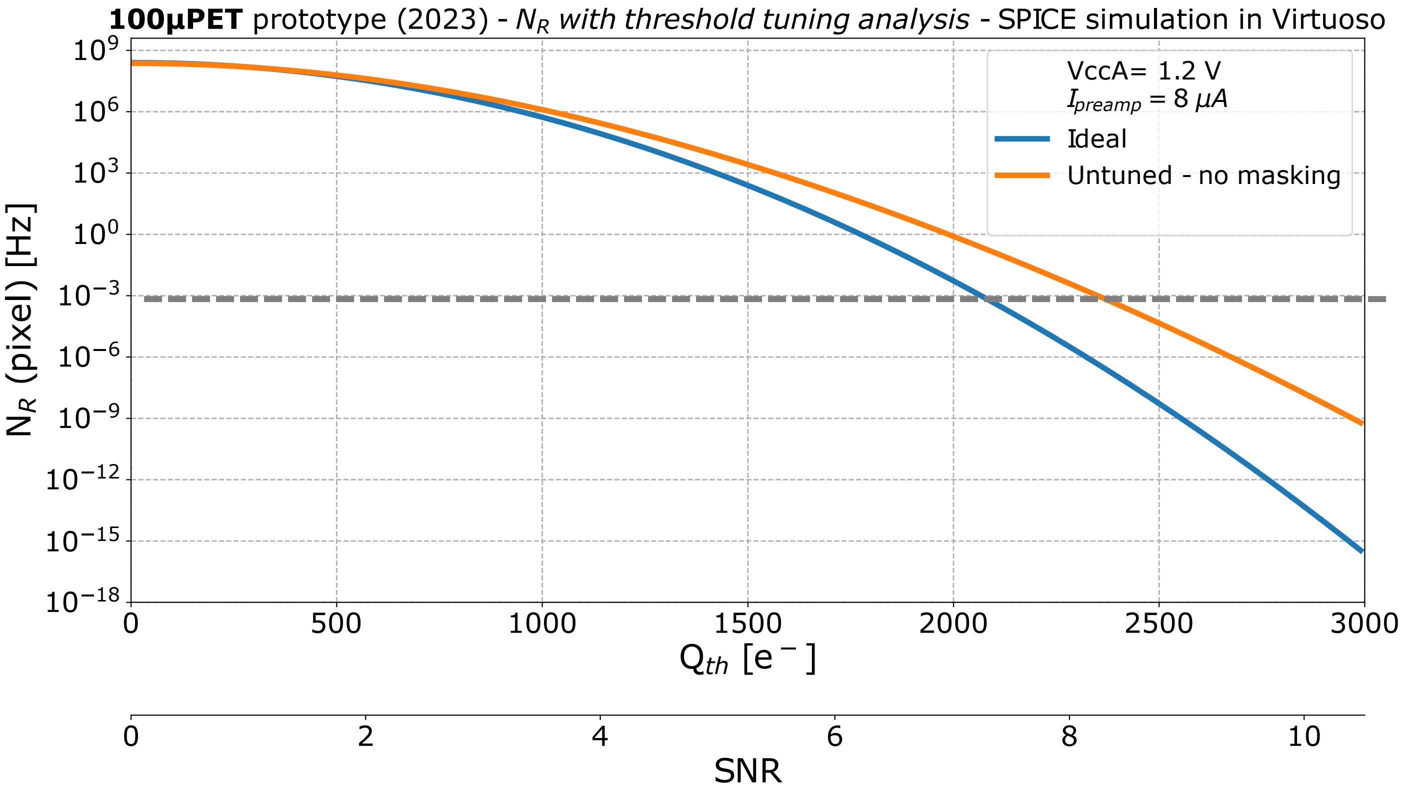
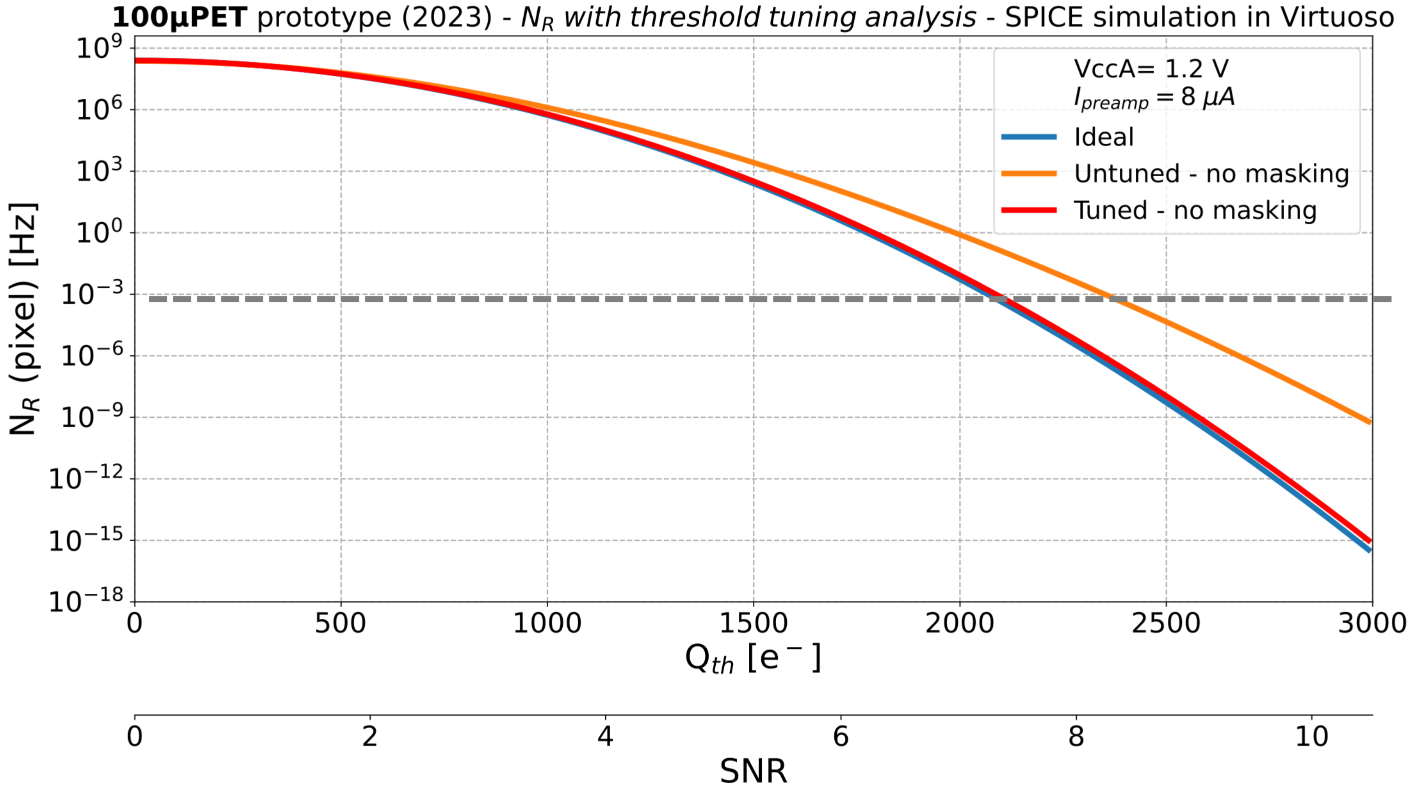
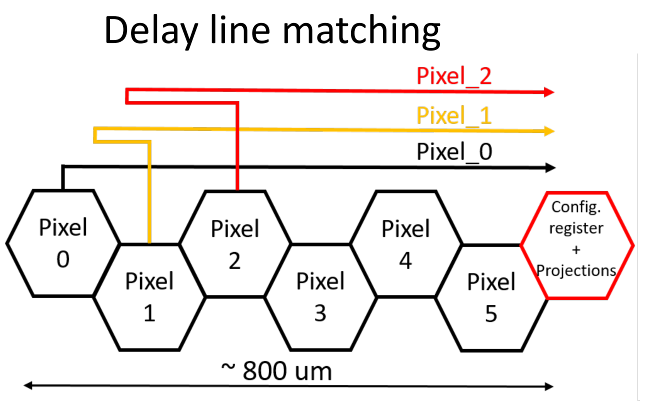
$$N_R = f_{n0} \cdot e^{\frac{-Q_{th}^2}{2 \cdot ENC^2}}$$

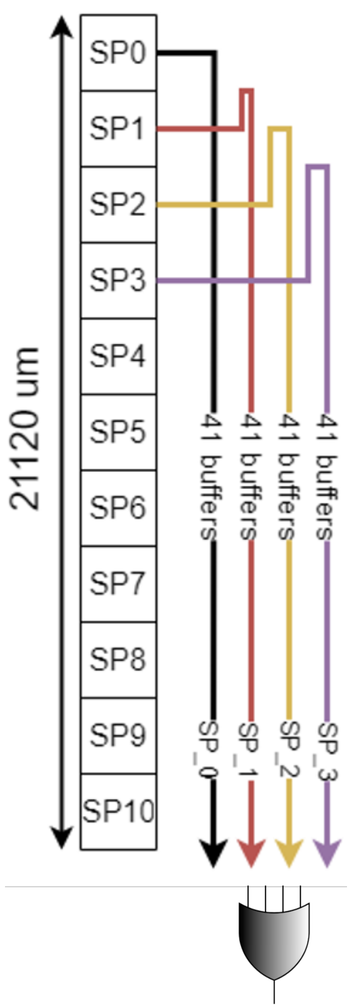


Mismatch worsens the Noise Rate. With threshold tuning, we can achieve the required Noise Rate



Mismatch worsens the Noise Rate. With threshold tuning, we can achieve the required Noise Rate





TDC [LSB 150 ps]

Simulation results

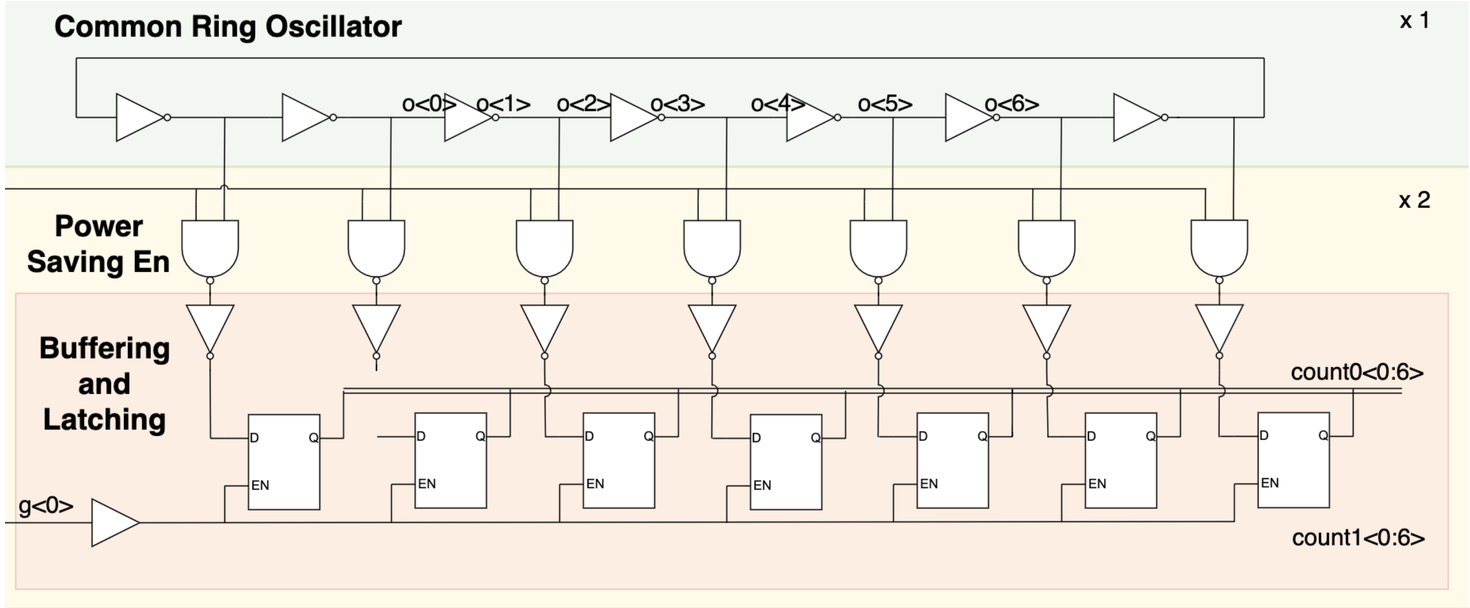
Max skew	67 ps
Mismatch rms	11 ps
Jitter rms	0.5 ps
T. coeff.	0.6 ps/C
V. coeff.	7.3 ps/mV

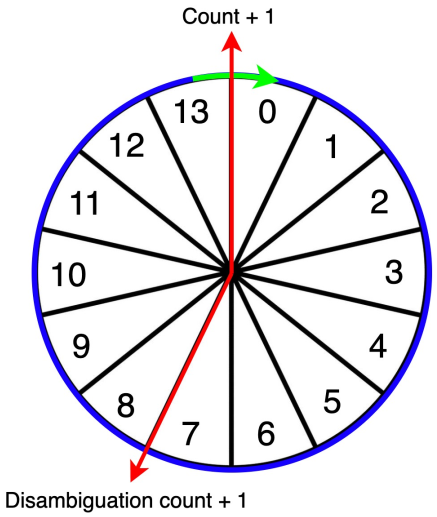
No pixel-to-pixel delay calibration required

11 Super-Pixel output fast-OR

1 TDC channel/Super Column

L. Iodice et al.





Supercolumn independent Flash-TDC with 7-stages free-running ring oscillator.

- States of the oscillator encode the fine-time: expected **LSB = 150ps.**
- Course timing with a counter on stage 0 and disambiguation bit on stage 1.
- **Reference** and **Calibration's** channel signals are generated per Supercolumn.
- Reference : Synchronization with DAQ for coincidence with an internal counter at readout clock frequency (50MHz).

- We are building a small-animal PET with ultra-high resolution
  - All silicon (**MAPS**): 960 sensors to build the full scanner
  - Design validated with simulations
  - **Volumetric** resolution between **0.01 mm³ and 0.02 mm³**
  - **Sensitivity** from **3%** to **5.5%**

- Currently building a **thermal Mock-up scanner** to validate cooling and assembly
  - NCP assembly validated with mock-ups

- MAPS submitted in October 2023
  - 130nm SiGe BiCMOS
  - Asynch readout
  - 150µm pitch, 200 ps time resolution, 2ke$^-$ ENC 280-e @ <100mW cm^2

The people

100μPET
Molecular Imaging at Ultra-High Resolution

The 100μPET project

Giuseppe Iacobucci
- project P.I.
- System design

Lorenzo Paolozzi
- Sensor design
- Analog electronics

Didier Ferrere
- System integration
- Laboratory test

Antonio Picardi
- ASIC Design (Analog)
- Front-end

Martin Walter
- P. I.

Michäel Unser
- P. I.

Yannick Favre
- Board design
- RO system

Stéphane Débieux
- Board design
- RO system

Franck Cadoux
- Mechanical design

Thanushan Kugathasan
- Lead chip design
- Analog

Pablo Jané
- Nuclear Medicine
- PET imaging
- Translational imaging

Aleix Boquet-Pujadas
- Signal/image processing
- Physical modeling

Roberto Cardella
- ASIC Design (Digital)
- Sensor Design

Mateus Vicente
- System integration
- Laboratory test

Jihad Saidi
- Laboratory test
- Data analysis

Luca Iodice
- ASIC Design (Analog)
- TDC

Vincent Taelman
- Molecular biology
- Radiopharmacy

EPFL

Sergio Gonzalez-Sevilla
- System integration
- Laboratory test

Terry Baltus
- Board design
- RO system

Sèbastien Cap
- Board design
- RO system

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UNIVERSITY OF LUCERNE

Carlo A. Fenoglio
- ASIC Design (Digital)
- Firmware

Théo Moretti
- Laboratory test
- Data analysis

Stefano Zambito
- Laboratory test
- Data analysis

Matteo Milanesio
- Laboratory test
- Data analysis

Chiara Magliocca
- Laboratory test
- Data analysis

Leonardo Cecconi
- Chip Design
- Firmware

Jordi Sabater
- Detector simulation
- Laboratory test

Rafaella Kotitsa
- Sensor simulation

Andrea Pizarro
- Laboratory test
- Data analysis

Ivan Semendyaev
- Laboratory Tests
- Data Analysis

Main research partners:

Roberto Cardarelli
INFN Rome2 & UNIGE

Holger Rücker
IHP Mikroelektronik

Marzio Nessi
CERN & UNIGE

Matteo Elviretti
IHP Mikroelektronik

Funded by:

Swiss National Science Foundation

erc European Research Council
Established by the European Commission

Sinergia

ATTRACT

UNIVERSITÉ DE GENÈVE UNITEC

Thank you for your attention

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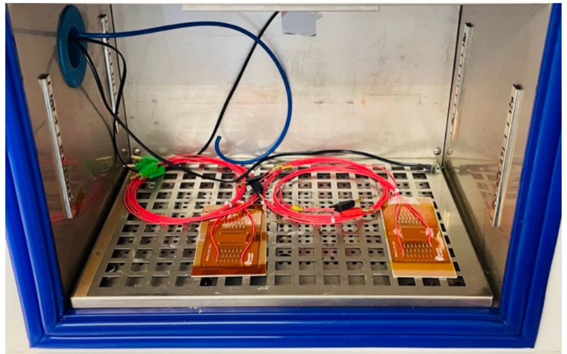
Backup slides

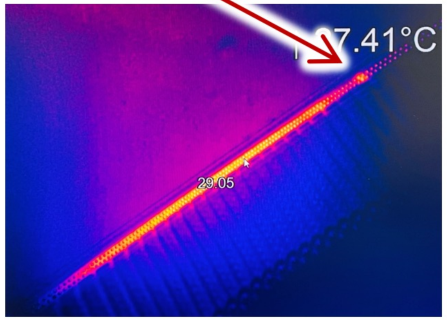
Au studs with NCP bonding was chosen for the assembly

- 100% yield connection among hundreds of pads
- (Direct) Current stress-tests to verify bonding failure
  - Limit DC to 200 mA, avoiding local heating exceeding Tg of the glue (60-80 °C)
    - Visible permanent defects (hot spots – higher bonding resistance) after reaching 300 mA
- 100 TCs from +5 to +60 °C
  - No effect on connections

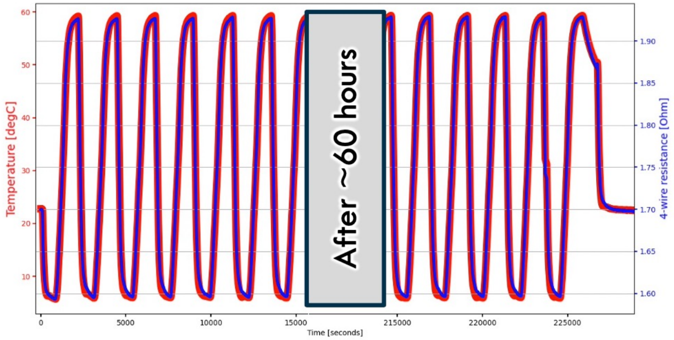
Bonded samples inside climate chamber



Bonded assembly and IR thermal image during DC injection



Temperature and resistance measurement during TC



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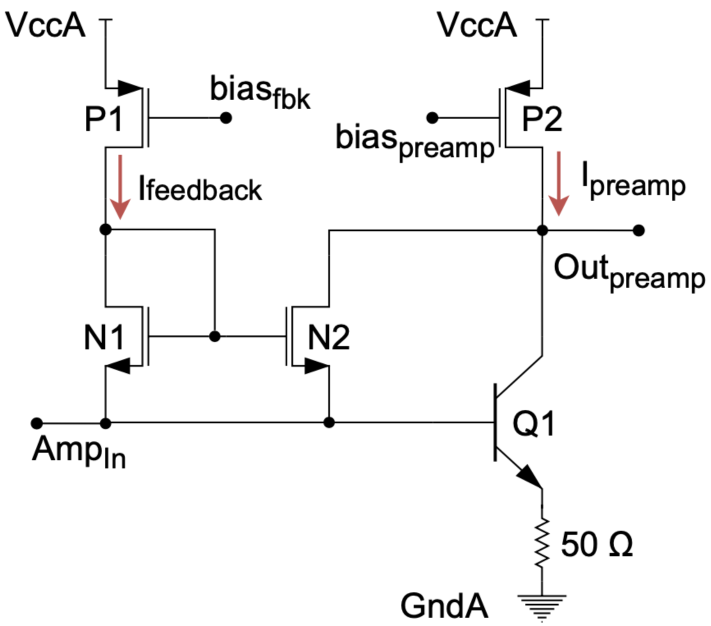
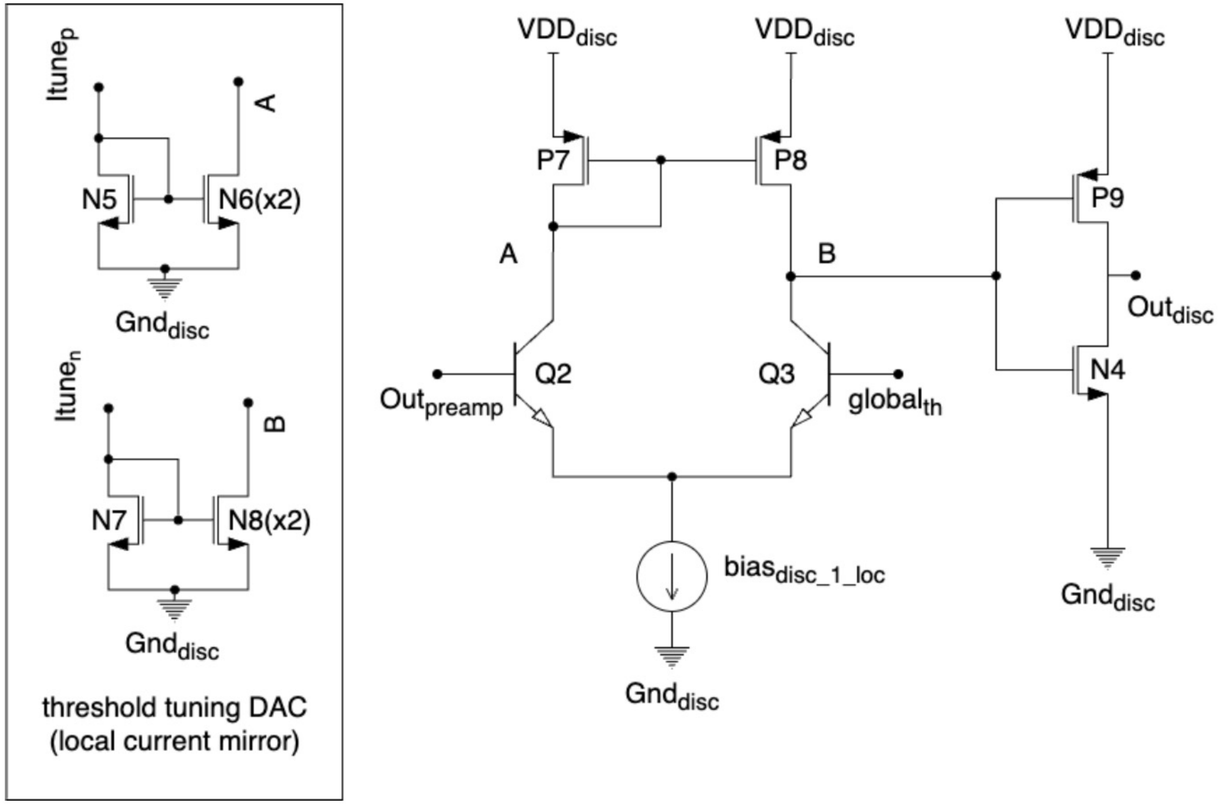
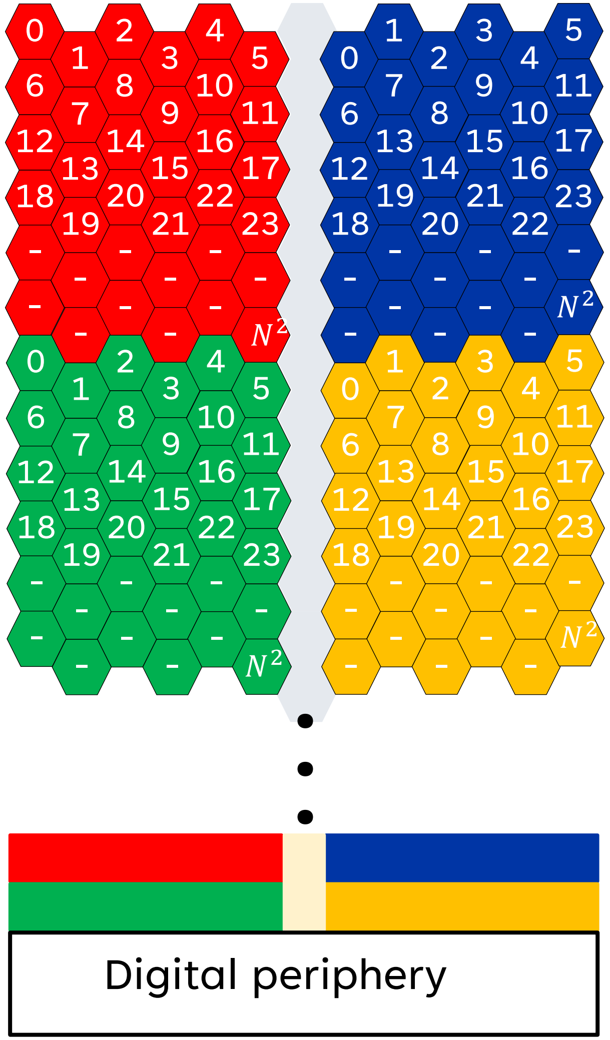
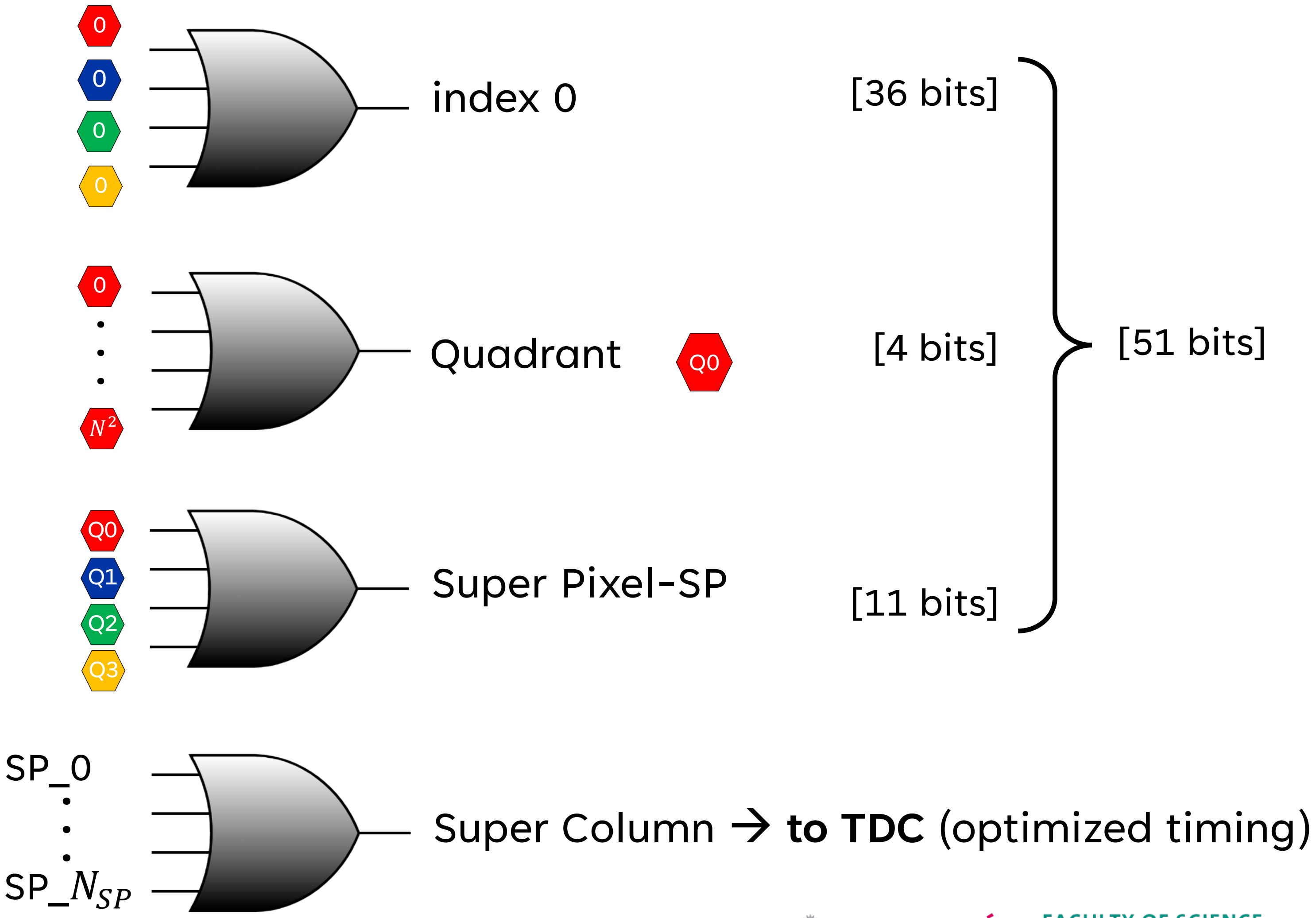
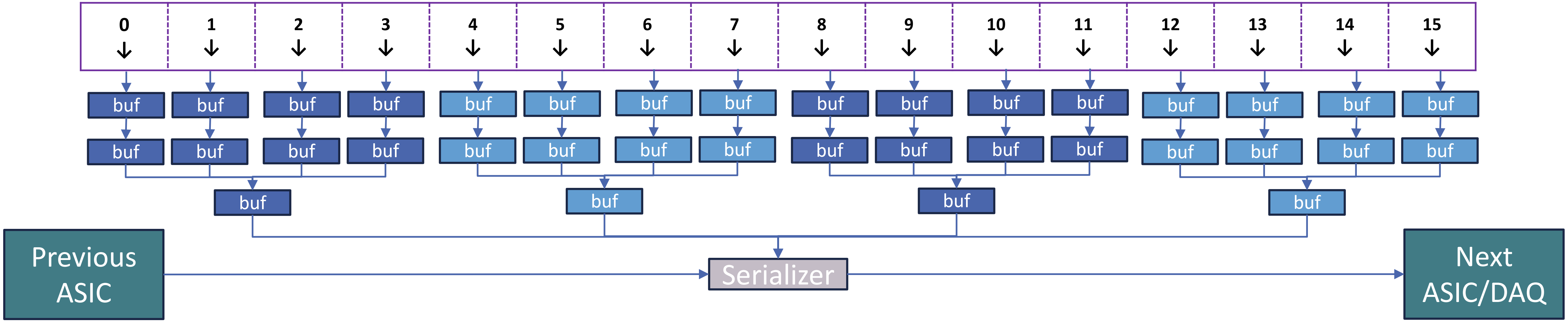


Figure 72 – Preamplifier schematic.




Digital periphery


index 0
[36 bits]
Quadrant
Q0
[4 bits]
[51 bits]
Q0
Q1
Q2
Q3
Super Pixel-SP
[11 bits]
SP_0
SP_N_{SP}
Super Column → **to TDC** (optimized timing)



Each super-column provides pixel address and TDC data:
event size of **143 bits**.

Each super-column data is processed **in parallel** and **independently** in the periphery
3-level buffer minimizes data loss at the target event rate.

Read-out speed 50 Mb/s (with **50 MHz clock**)

- Max read-out event rate 350 k events/s,
- Chips can be daisy-chained to reduce the number of outputs to DAQ.
- Maximum expected rate for quad module (24 cm^2 x 10 kHz/cm^2) = 240 k events/s

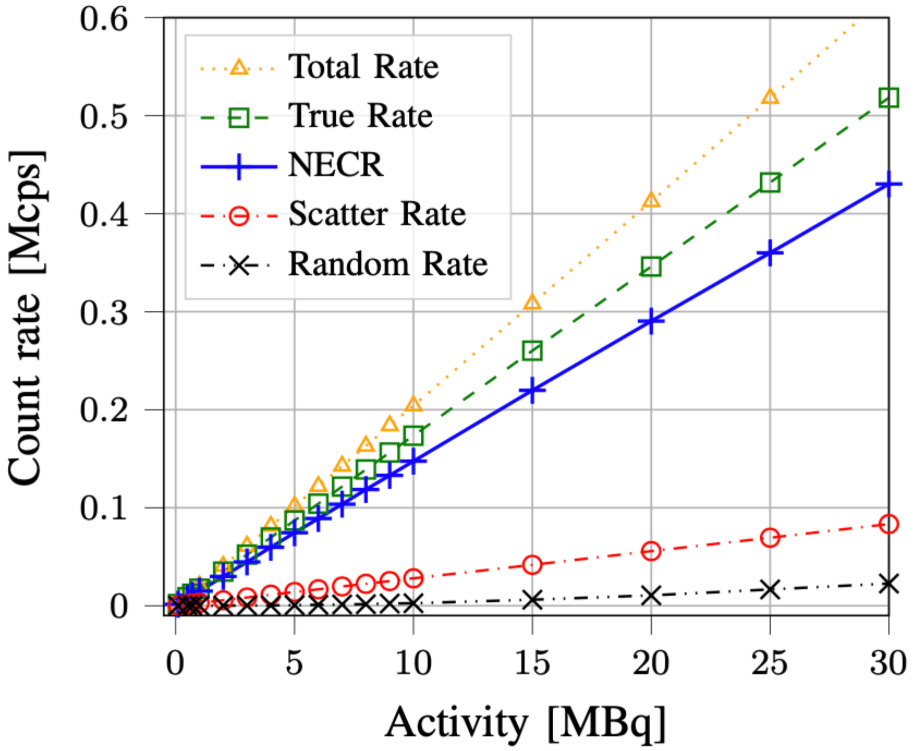


Fig. 17. Count rate as a function of activity with a window of 1 ns. (The timing resolution is of 0.3 ns.)

$$NECR = \frac{T^2}{S+T+KR}$$

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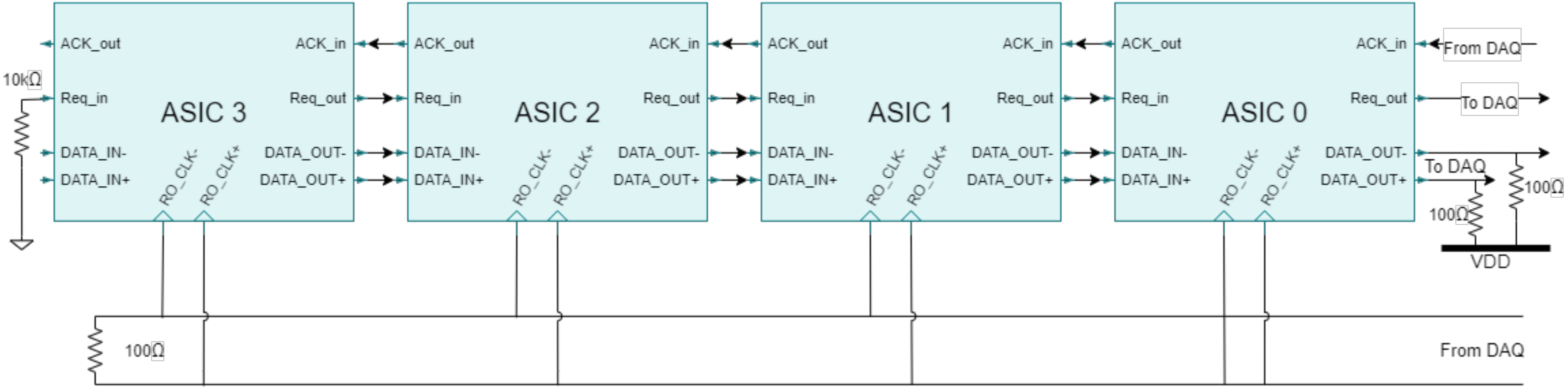
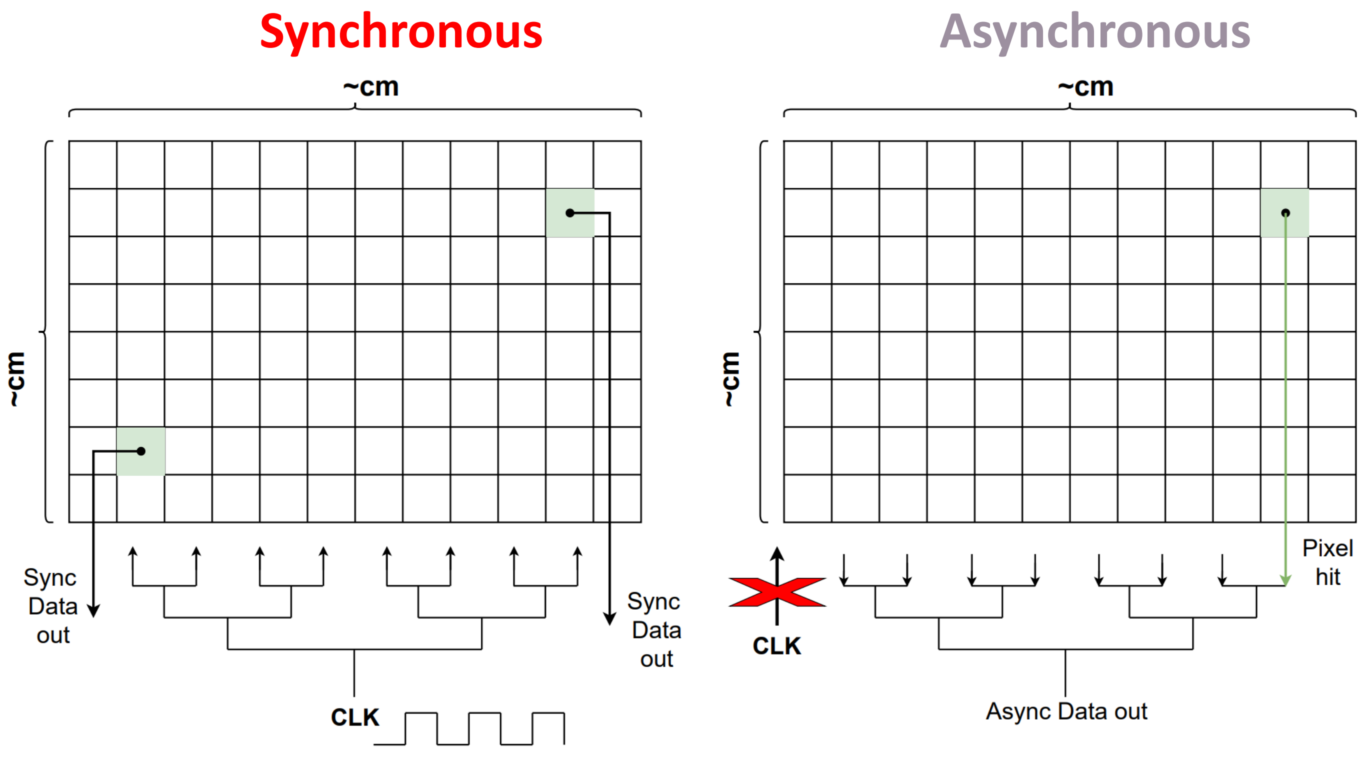


- 4-chip daisy chain
- Priority given to the left-most chip (furthest from DAQ)
- First chip request to GND
- DAQ acts as last unit in the chain.

- In pixel sensor applications, especially for **large area pixel sensors** with a density of thousands of pixels, one of the challenges is an efficient information readout that meets the recent trends of stringent timing specifications.

→ Two different approaches:



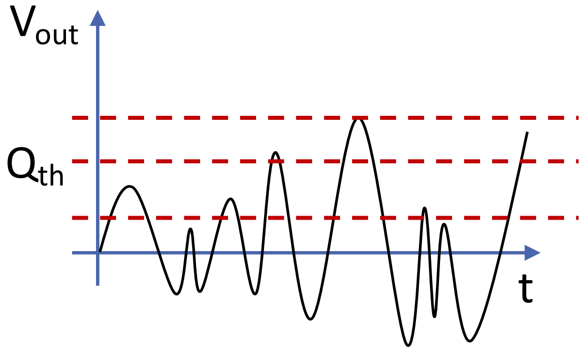
Synchronous

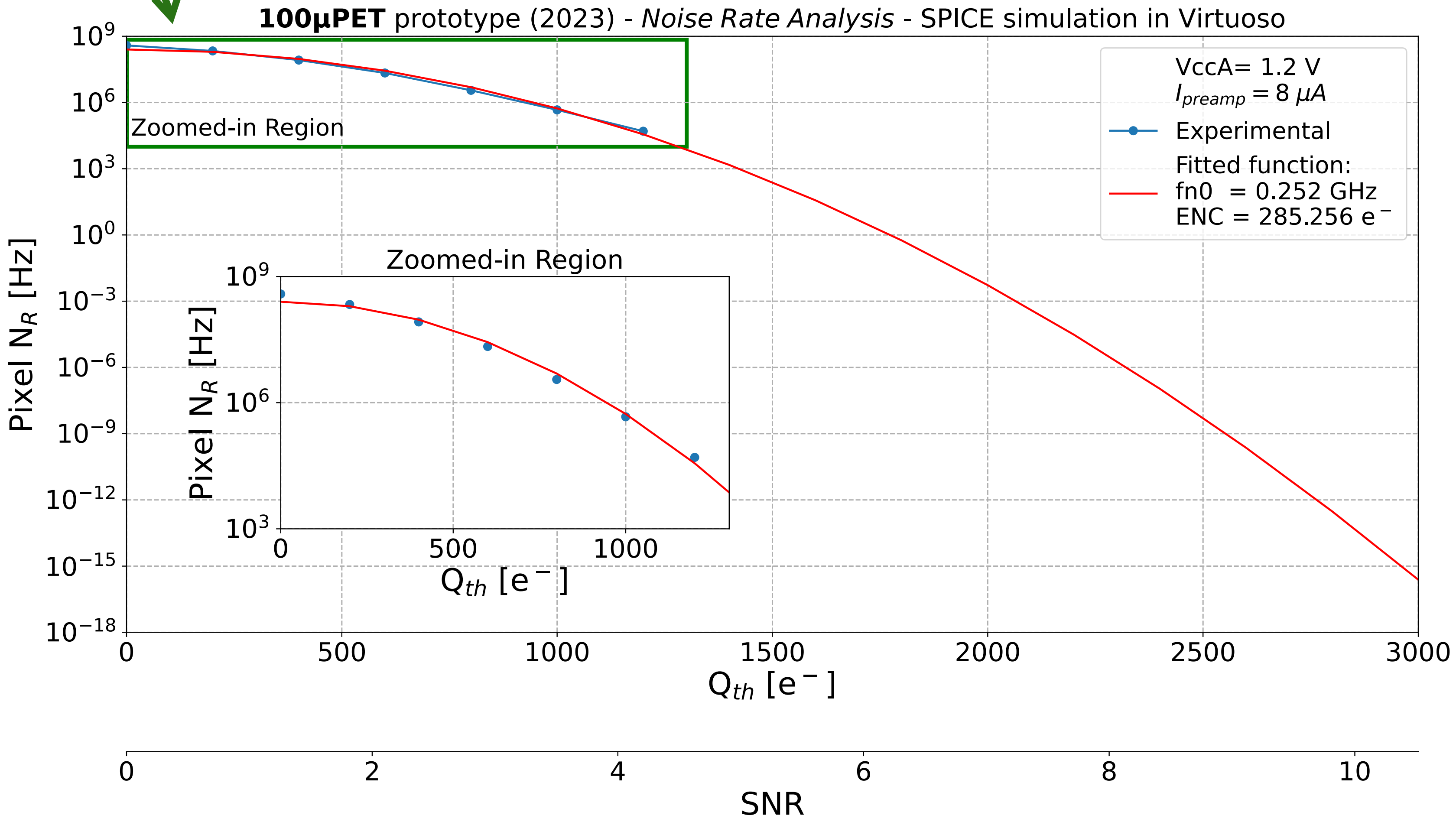
- Clock distributed across the chip
  - ➢ High power dissipation
  - ➢ Noise on the power supply
  - ➢ Stringent skew constraints on the clock tree

Asynchronous

- No clock distributed across the chip
  - ➢ Lower power dissipation
  - ➢ Less noise on the power supply
  - ➢ Stringent skew constraints on the outputs

$$N_R = f_{n0} \cdot e^{\frac{-Q_{th}^2}{2 \cdot ENC^2}}$$





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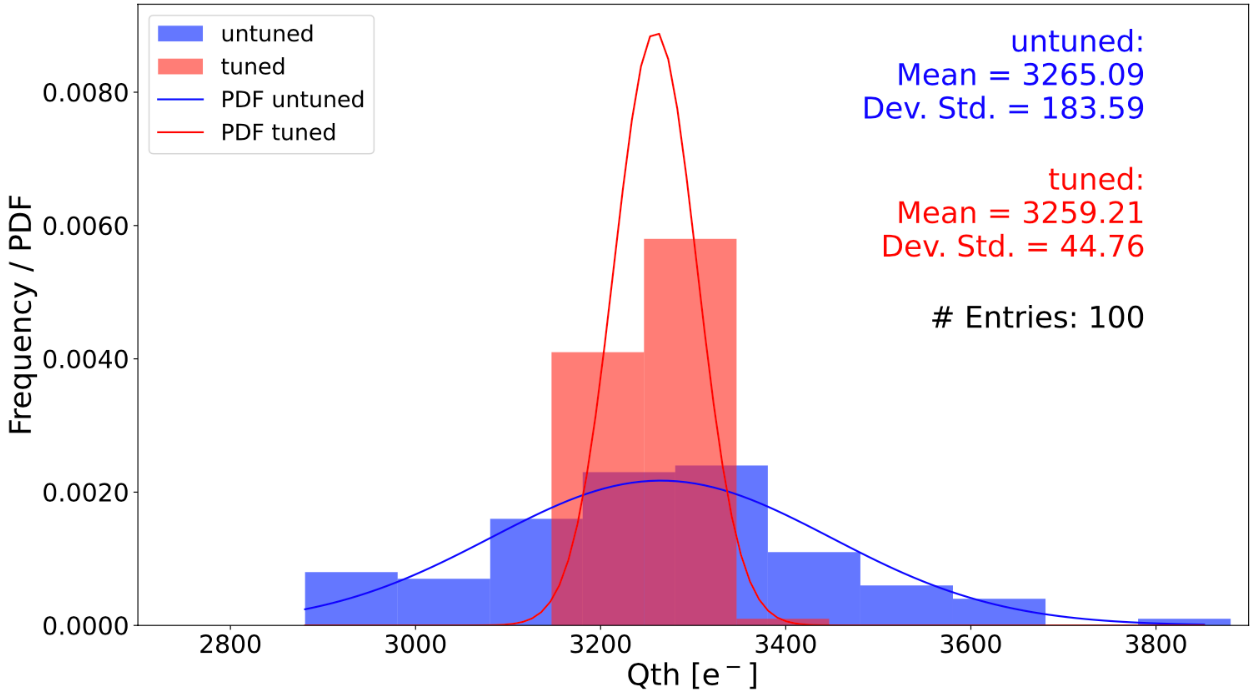

Figure 74 – Simulation - Mismatch compensation technique: frequency and the probability density function (PDF) of charge threshold mismatch of both untuned and tuned configurations.(Qth=3000 e^{-}, # montecarlo = 100)