The TT-PET project:
a 30 ps Time of Flight PET scanner
in silicon pixel technology

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On behalf of the **TT-PET collaboration**

The TT-PET project

TT-PET

UNIVERSITÉ DE GENÈVE

A 3-year project started in march 2016 financed by SNSF to produce a PET Scanner for small animals **based on silicon detector technology,** insertable in an MRI machine and with **30ps RMS time resolution**.

Participating institutes:

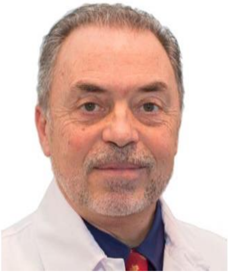
- University of Geneva → Sensor ASIC design and production. Scanner assembly. Image reconstruction.
- University of Bern → Read Out design and production. Flex design and production.
- Hôpitaux Universitaires Genève → Image reconstruction. Scanner test.

In collaboration with:

- INFN of Roma Tor Vergata, IHP microelectronics, Stanford University, CERN - Ideasquare

TT-PET team - University of Geneva and HUG

Giuseppe Iacobucci
- TT-PET Principal Investigator.



Osman Ratib
- HUG/ITMI

Lorenzo Paolozzi
- Sensor design
- Amplifier design

Pierpaolo Valerio
- Electronics design
- Chip design

Emanuele Ripiccini
- Scanner simulation
- Image reconstruction

Daiki Hayakawa
- Sensor simulation
- Image reconstruction

Collaborators at DPNC

Frank Cadoux
- Scanner mechanic assembly
- Scanner thermal management

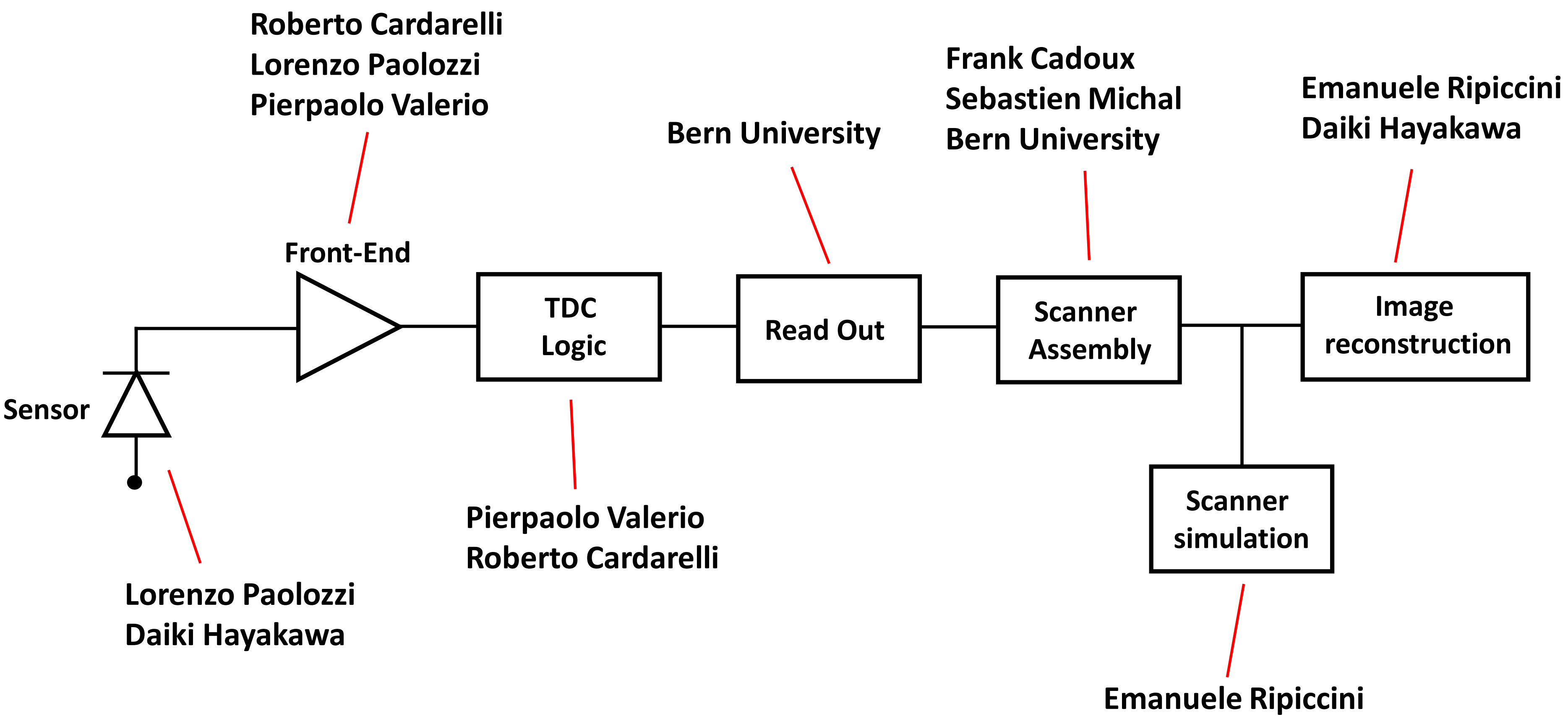
Stéphane Debieux
- Board design
- Electronic support at system level

Yannick Fravre
- Electronic support at system level

Didier Ferrere
- Scanner assembly support

Mathieu Benoit
- Sensor and guard ring simulation

TT-PET activities



The PET technique

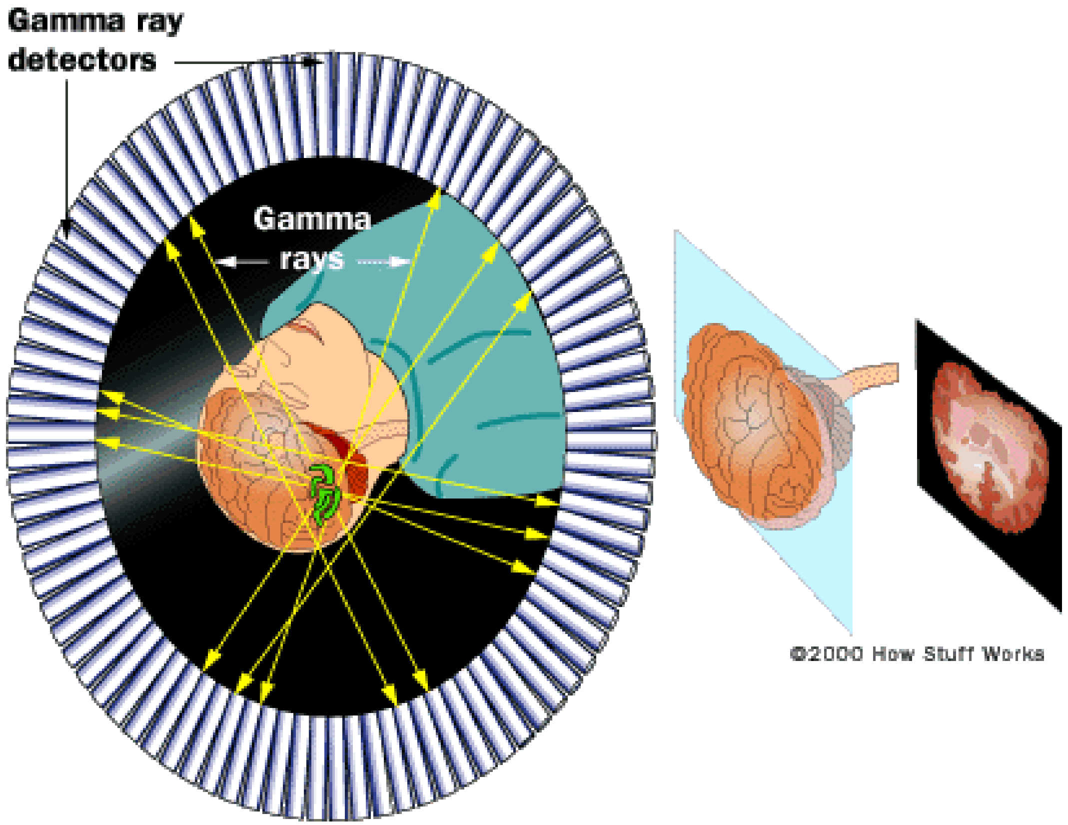
Principle of the Positron Emission Tomography

A functional imaging technique

- A radiopharmaceutical containing a $\boldsymbol{\beta^+}$ **emitting isotope** reaches the target location (ex: tumour cells).

- The positrons annihilate with the nearby tissue, emitting **two back-to-back photons**.

- The photons are detected in coincidence, tracking a **line of response**.



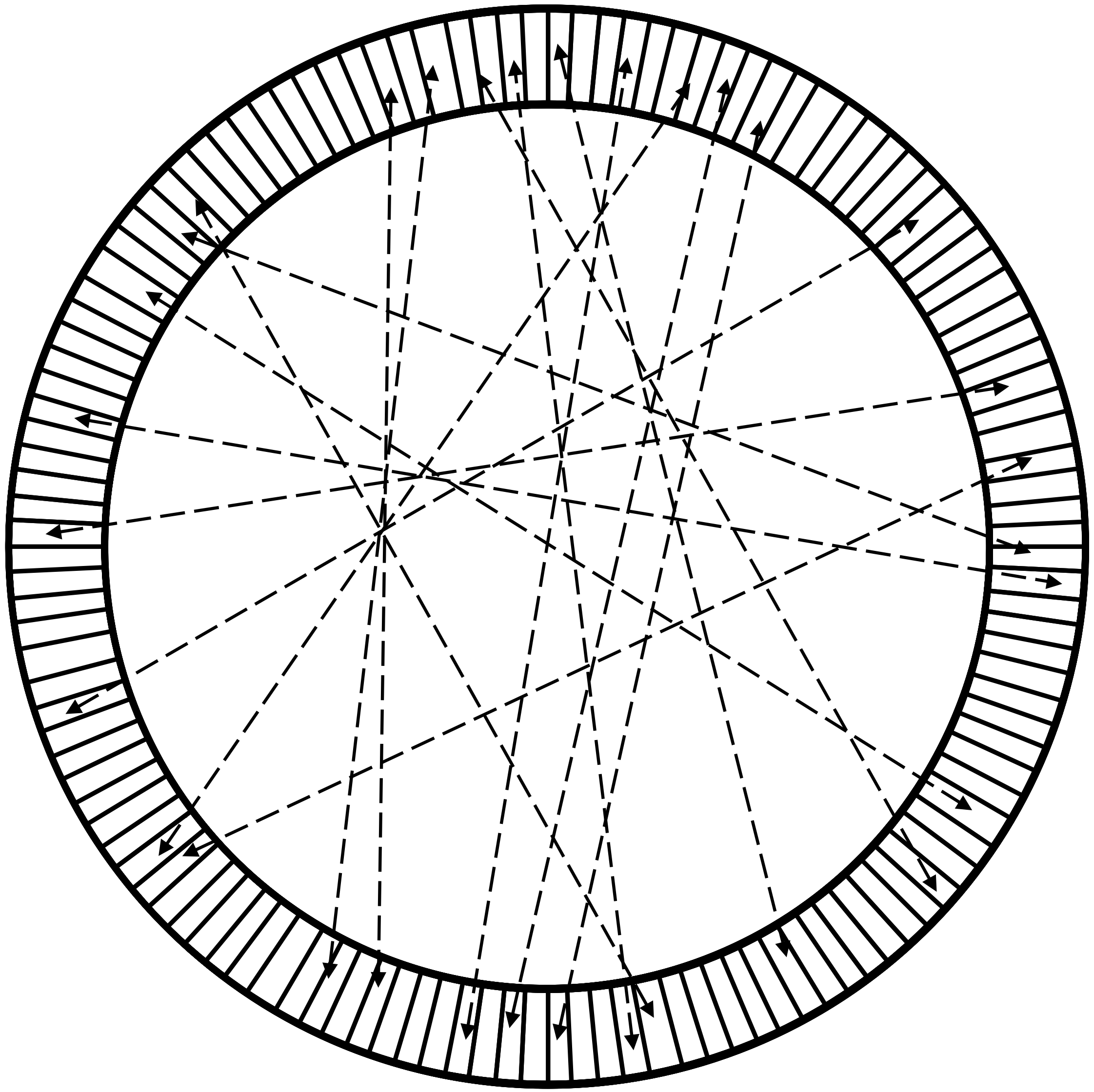
TOF-PET vs Traditional PET

Traditional PET:

- To each photon couple is associated a **line of response**.
- The background events overlap with the signal.

⇨ more statistics is necessary to identify the excess emission point.

⇨ **Larger radioactive dose.**



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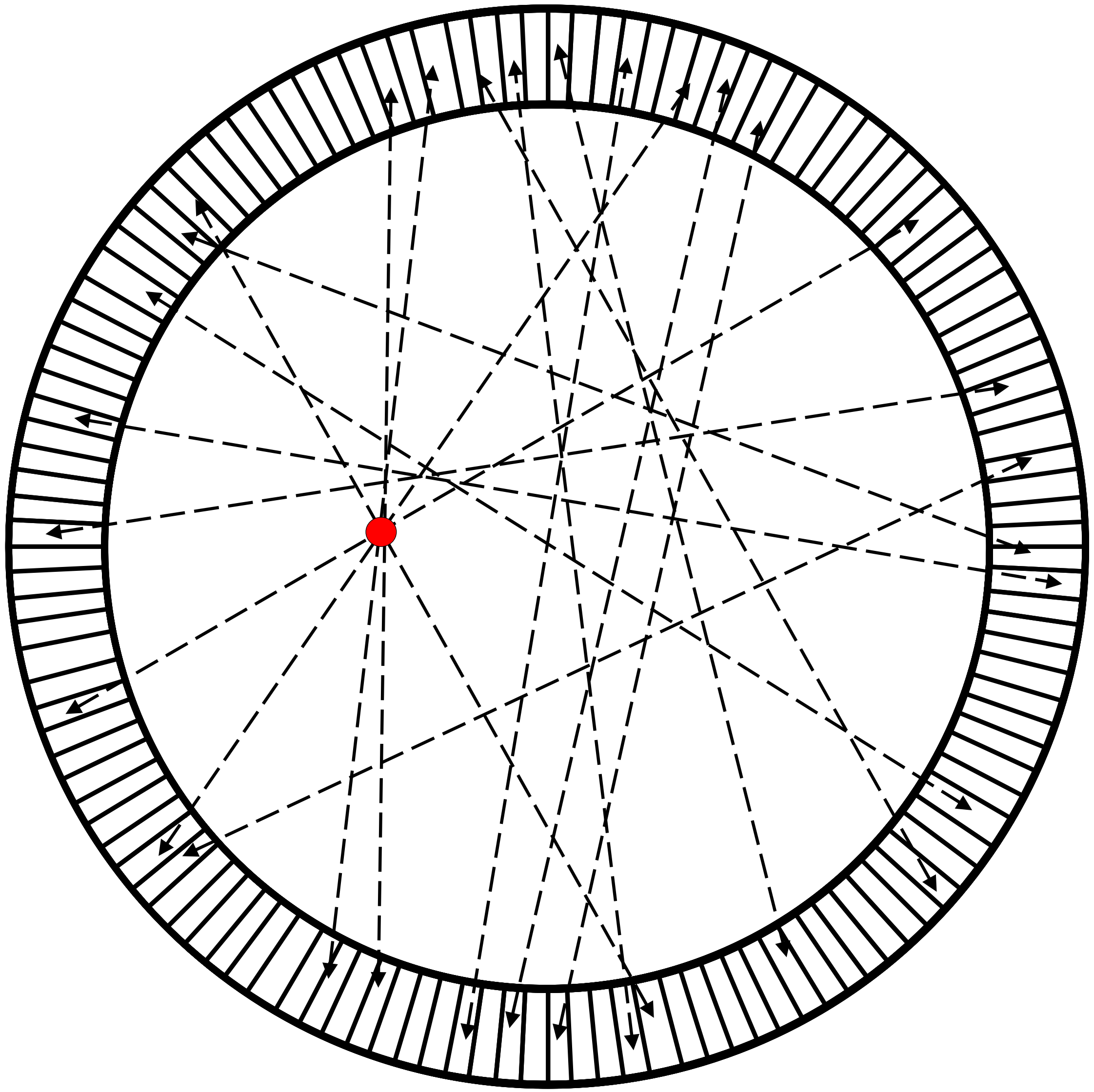


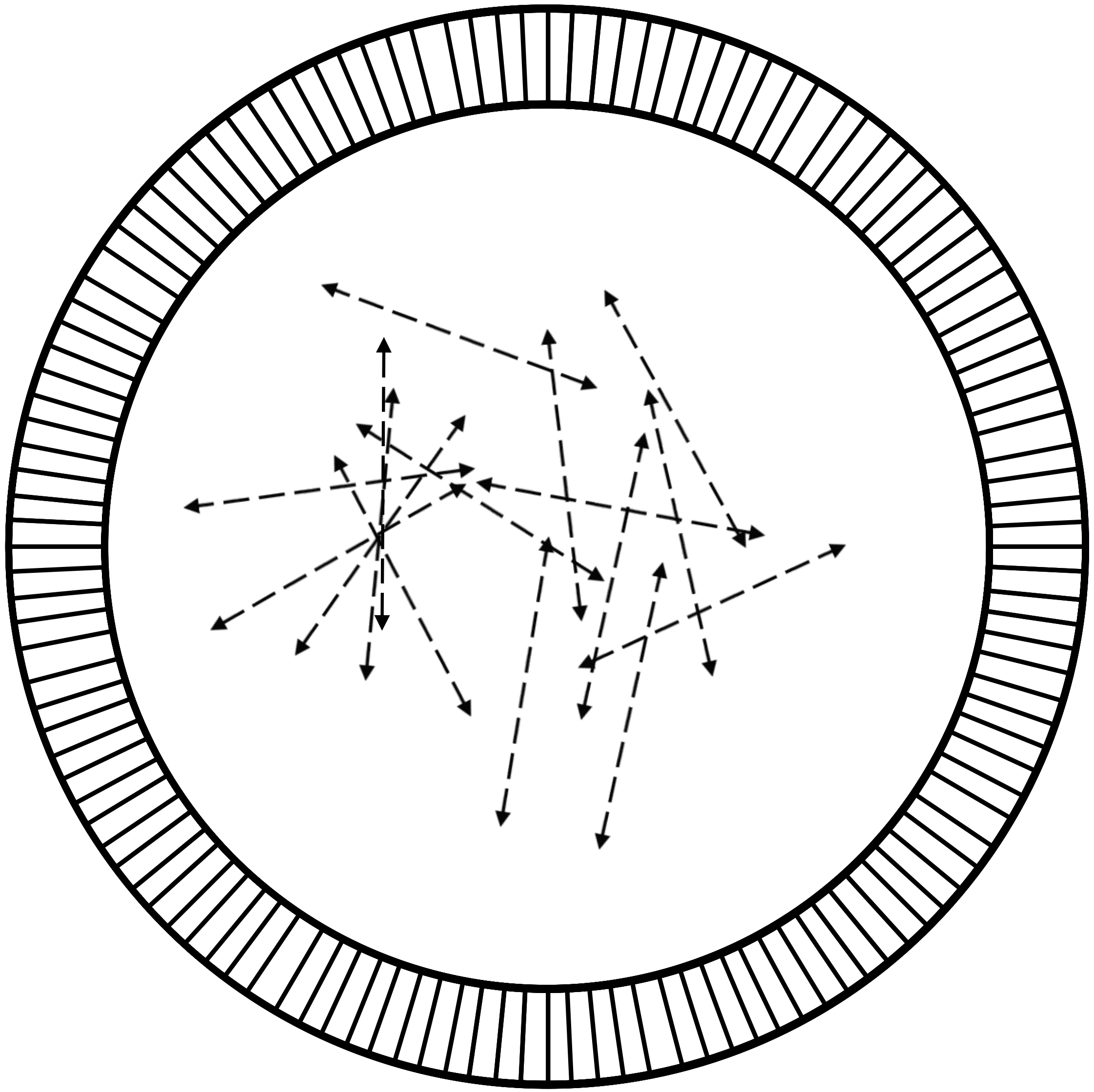
TOF-PET vs Traditional PET

Traditional PET:

- The emission point is **identified along the line of response**.

⇨ Reduction of the fake coincidences.

⇨ **Better scanner sensitivity.**



TOF-PET vs Traditional PET

Traditional PET:

- The emission point is **identified along the line of response**.

⇨ Reduction of the fake coincidences.

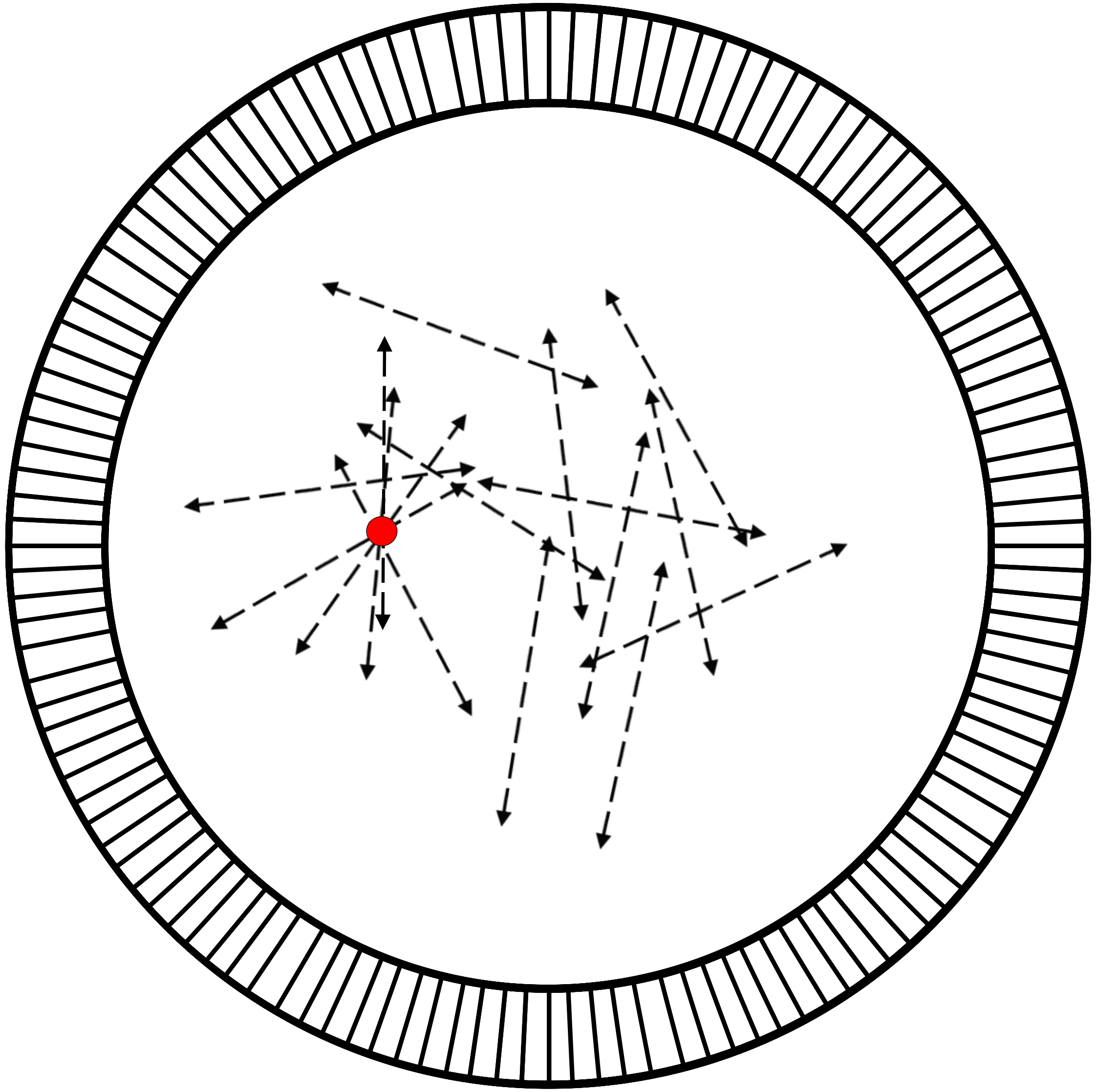
⇨ **Better scanner sensitivity.**

- Best time resolution available on the market:

$$\sigma_t \cong 130ps$$

- Target time resolution for TT-PET:

$$\sigma_t = 30 \text{ ps RMS}$$



The DOI measurement

Depth of Interaction measurement:

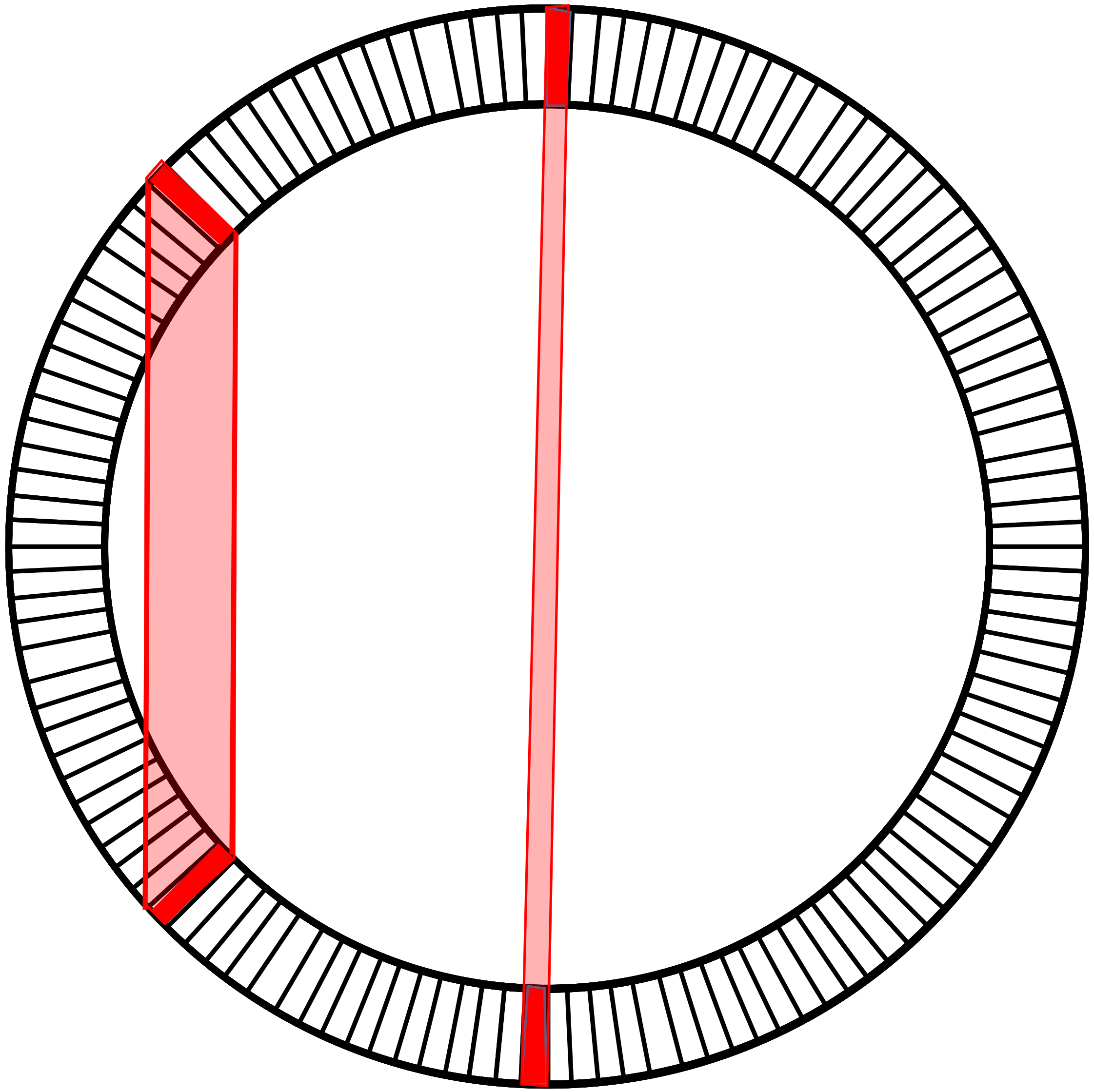
- Uncertainty on the photon interaction point inside the sensor in the radial direction.

⇨ Degradation of the time resolution.

⇨ Degradation of the space resolution along the radial direction.

- DOI measurement for TT-PET:

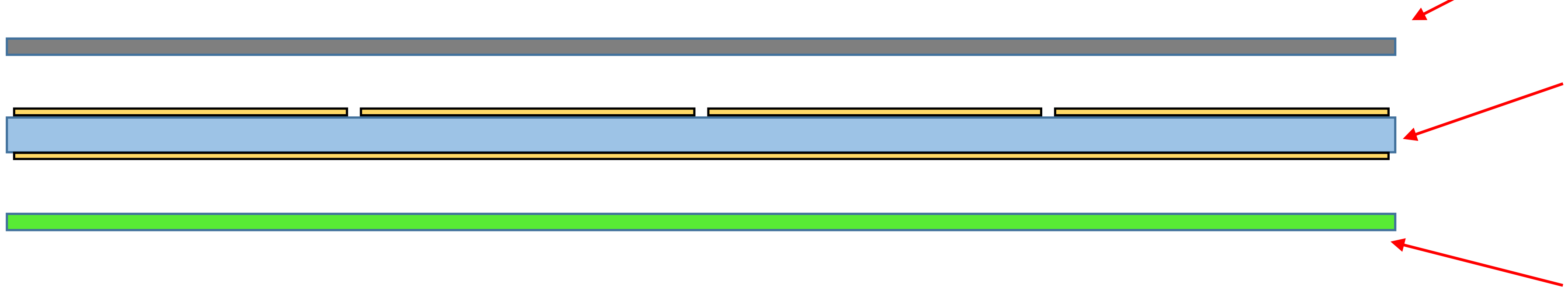
$$\Delta r < 250\ \mu m$$



The TT-PET scanner

Basic detection element

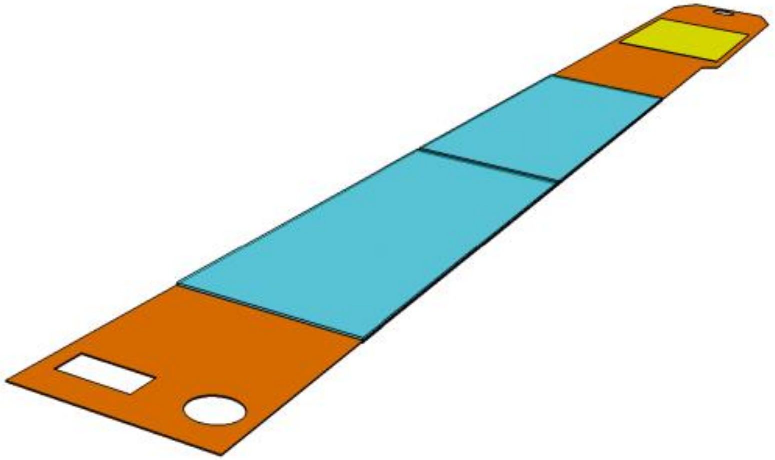
Module



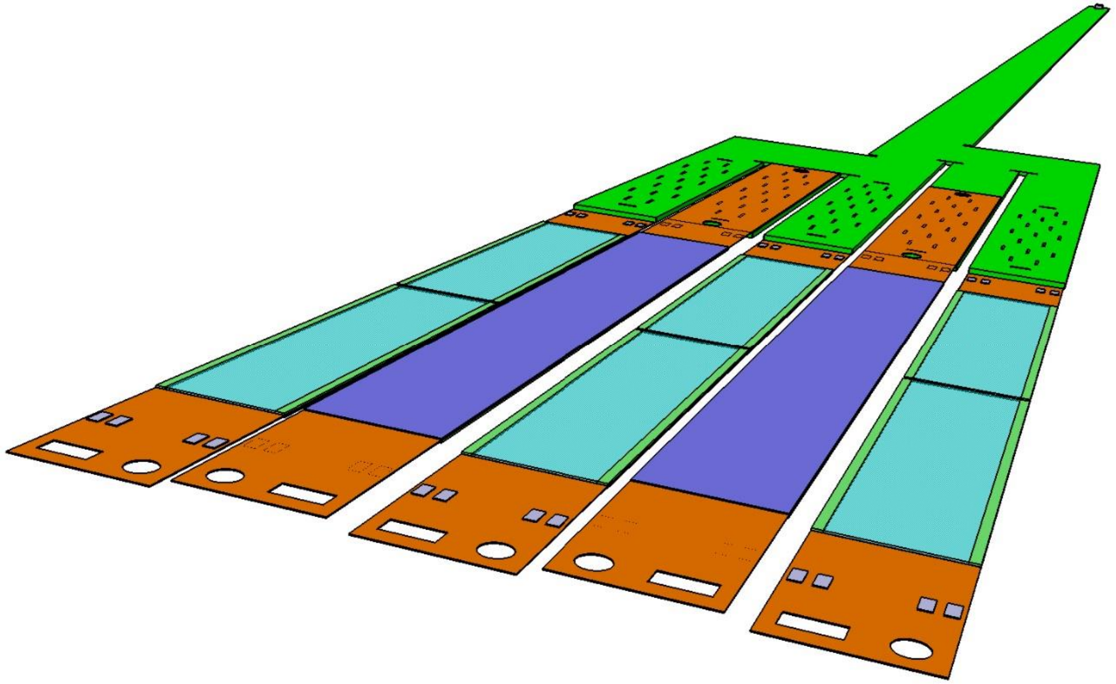
- **Polyimide flex circuit.**
  55 μm thickness
- **Monolithic pixel sensor:**
  100 μm thickness
- **Lead converter**
  50 μm thickness

Signal extraction

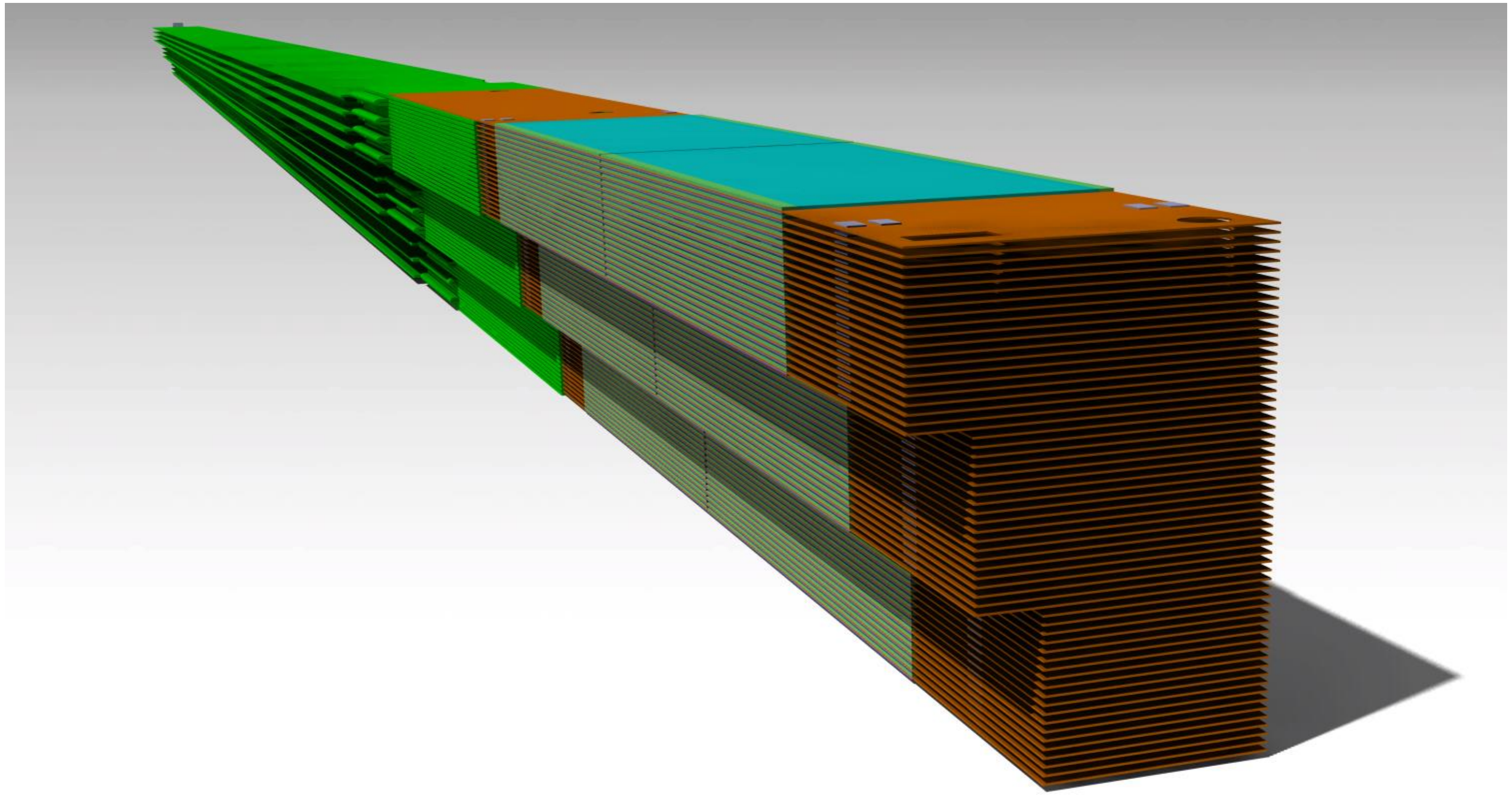
Two chips are bump bonded on a "module flex"



A group of 5 module flexes are then connected to a "data flex", which sends the data to the read out with a lower density of interconnections.



Scanner "cell"



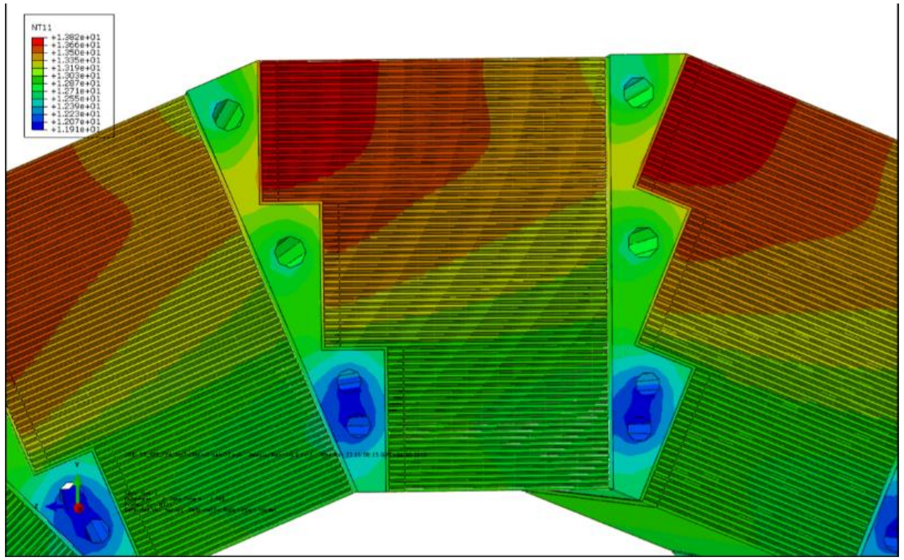
- A scanner cell is a stack of 60 modules, tightly coupled.
- Total cell thickness will be approximately $\mathbf{1.5}\ \boldsymbol{cm}$.
- Cell assembly will be possible thanks to the new DPNC flip-chip machine.
- Designed by the DPNC mechanical engineering group.

The TT-PET scanner

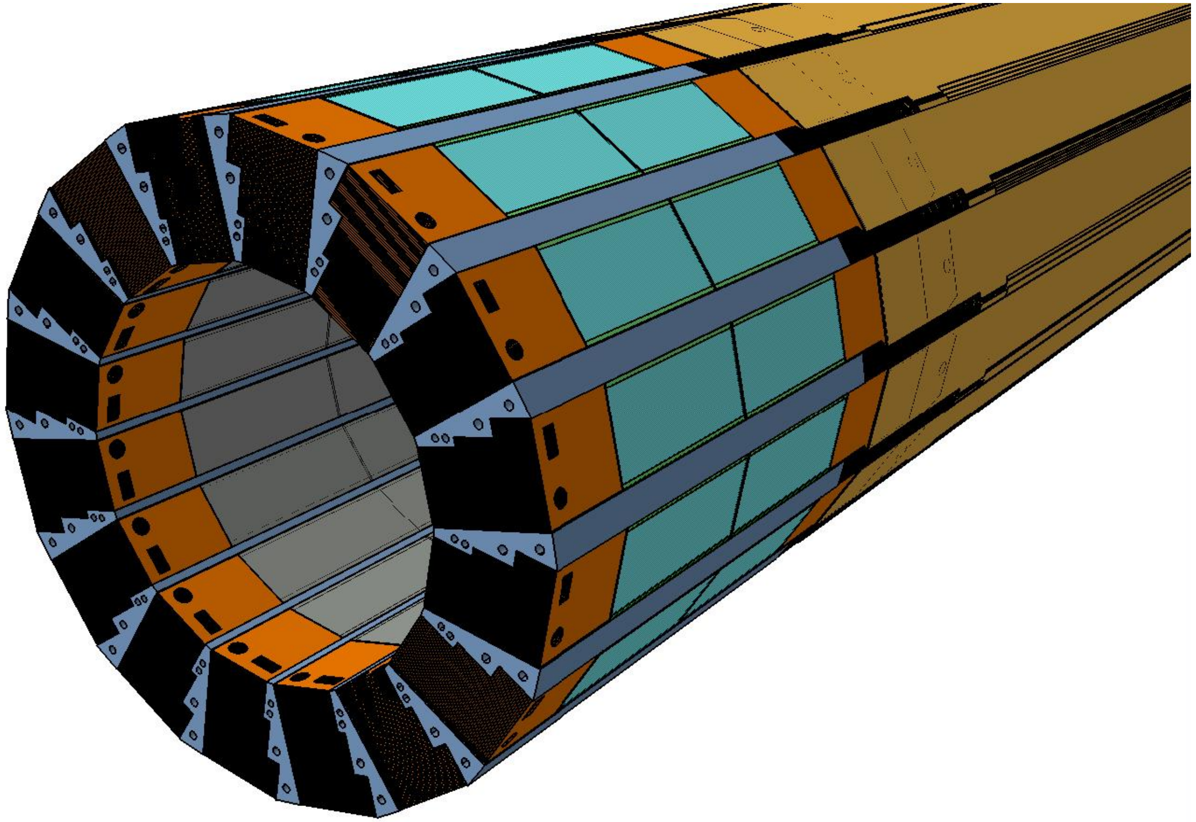
More than 1 Mpixel.

High density of silicon pixel sensors

- Sensor power budget $< 80\ mW/cm^2$
- Active cooling: $\Delta T < 1^{o}$ C in the sensitive volume

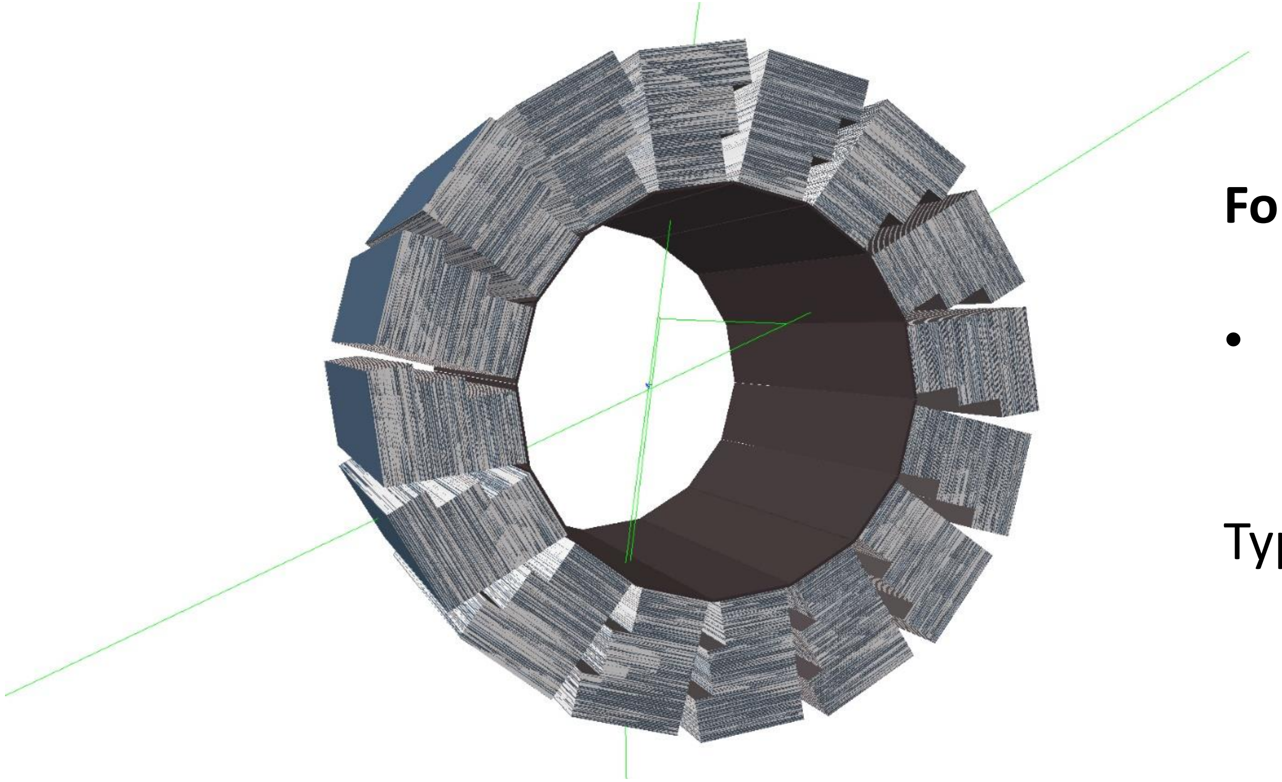


Simulation by F. Cadoux



The TT-PET scanner

A Geant4 simulation has been developed to predict the scanner efficiency to $511\ keV$ photons, the expected detection rate per chip and the scanner space resolution.



For 1.5 cm cell thickness

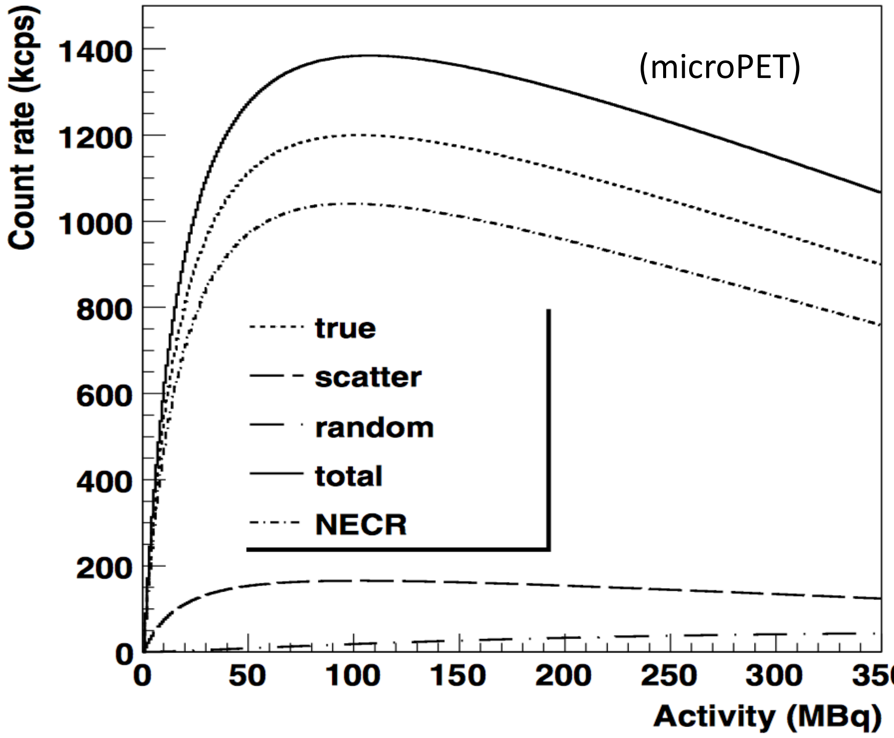
- Scanner sensitivity (coincidences per disintegration):5 %

Typical small animal PET sensitivity: from 1% to 10%

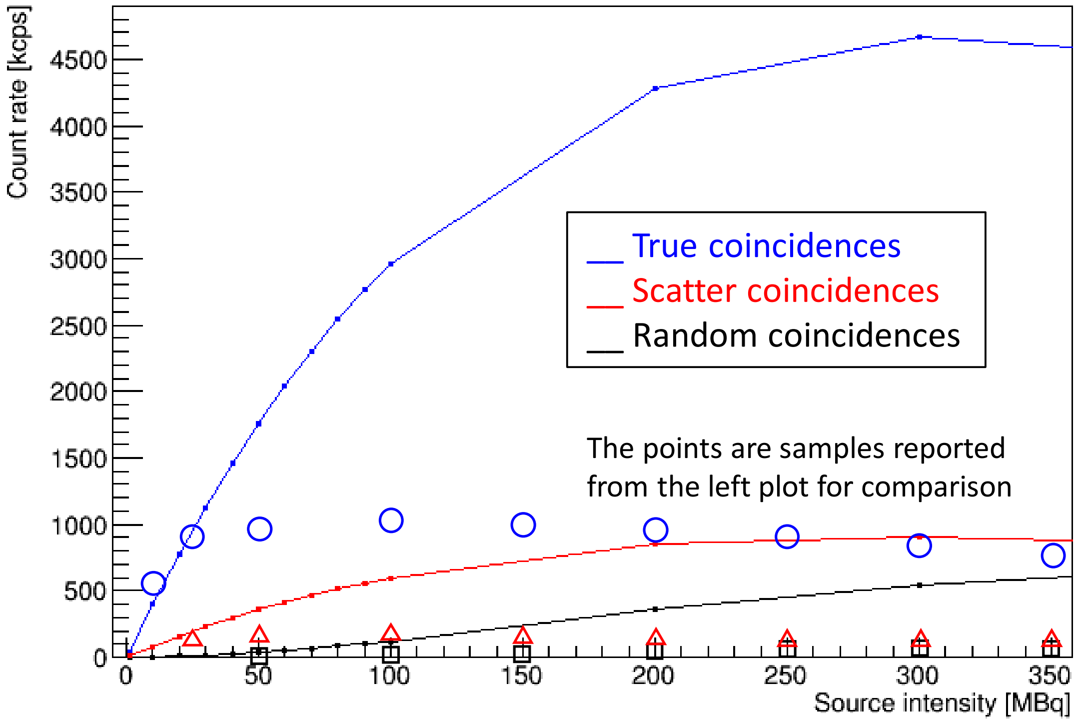
The TT-PET scanner

The high segmentation of the scanner and fast response of the silicon pixel detector allow for a very high counting rate.

Typical performance of a small animal TOF-PET



TT-PET scanner counting rates – Geant4 simulation

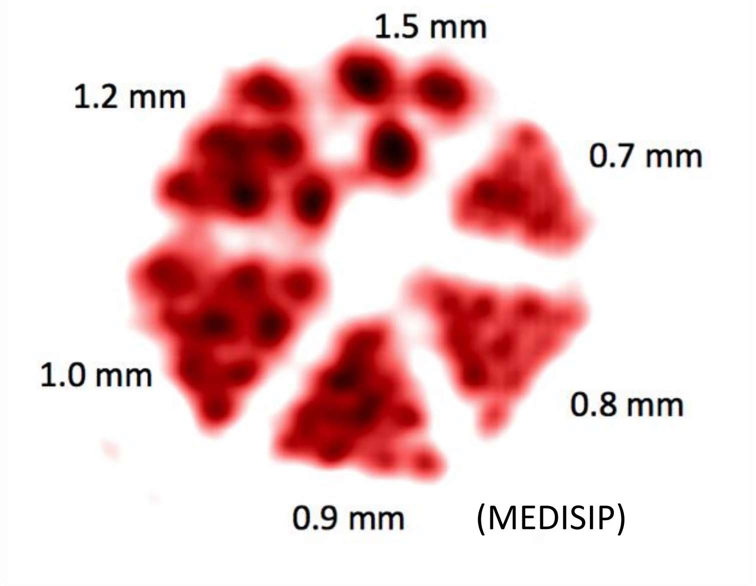


The TT-PET scanner

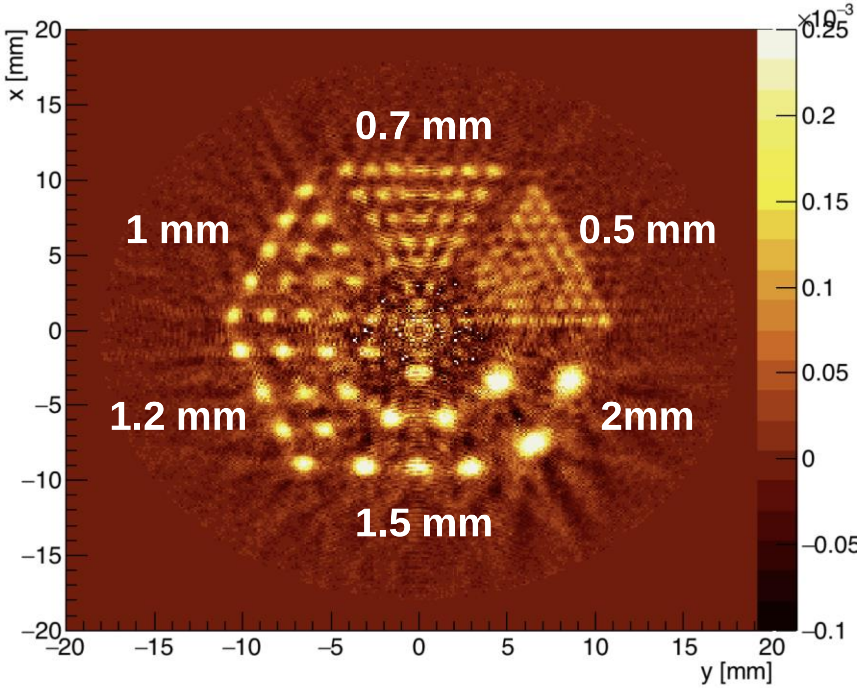
Scanner space resolution **in the whole field of view**: $< 0.8\, mm\, FWHM$

Derenzo phantom Geant4 simulation

Typical performance of a TOF PET scanner for small animals



TT-PET simulation



New image reconstruction algorithms are under development to fully exploit the time resolution and DOI measurement capability of the TT-PET scanner.

The fast, monolithic pixel sensor

What do we need to develop

1. Make a 30 ps time resolution detector for 511 keV photons…

Two orders of magnitude better than the existing monolithic silicon pixel sensors.

- Detector design.
- Electronics technology and design.
- Understanding of sensor physics.

What do we need to develop

1. Make a 30 ps time resolution detector for 511 keV photons…

2. … and make it monolithic.

Both sensor and electronics **integrated in the same chip**, in a commercial microelectronics process.

Advantages:

- Simplified interconnections.
- Integrated front end, TDC, logic, serializer.
- Cost reduction

BUT

- Requires to adapt to a process that is not optimized for sensor design.
- Experience in ATLAS group at DPNC with other technologies

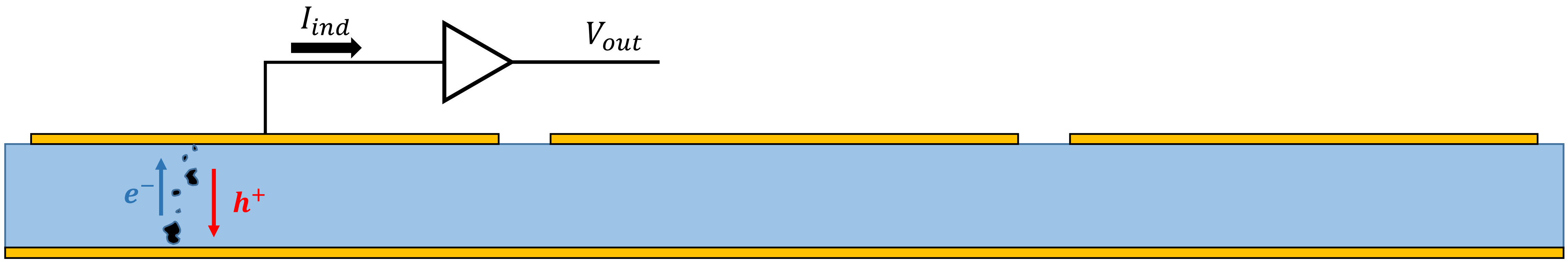
How do we do it?

Time resolution of silicon pixel detectors

What are the main parameters to improve for the time resolution of semiconductor detectors?

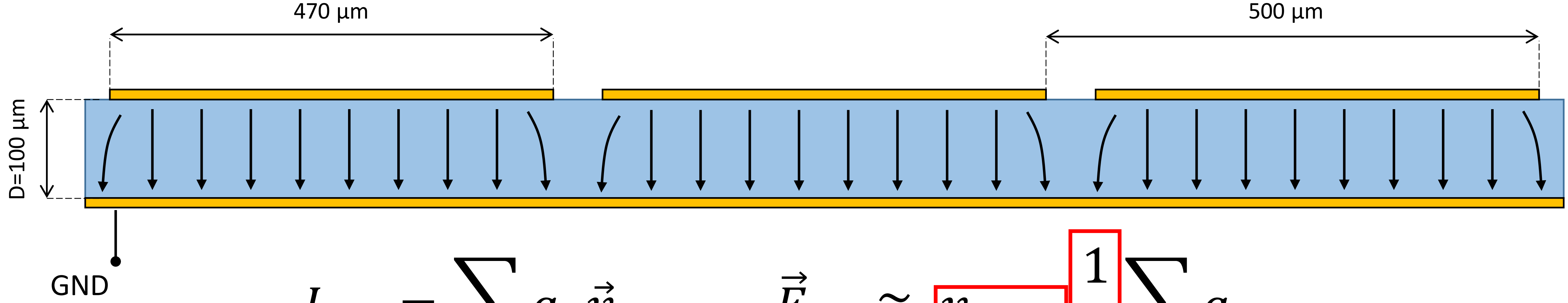
- Read out geometry (constraint)
- Electronics noise (optimization)
- Charge collection noise (limit)

$$I_{ind} = \sum_i q_i \, \vec{v}_{drift,i} \cdot \vec{E}_{w,i}$$



Read out geometry

The condition of "parallel plate" read out is fundamental to guarantee the uniformity of the weighting and the electric field.



$$I_{ind} = \sum_i q_i \, \vec{v}_{drift,i} \cdot \vec{E}_{w,i} \cong \boxed{v_{drift}} \boxed{\frac{1}{D}} \sum_i q_i$$

Scalar, saturated

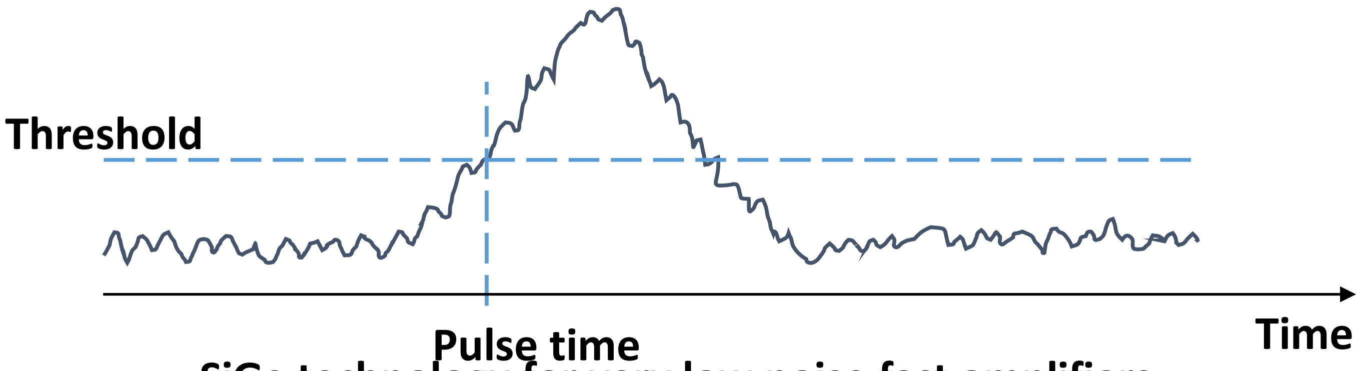
Scalar, uniform

Drawback!

Increase of the pixel capacitance → Larger equivalent noise from the amplifier.

Electronic noise

Detector time resolution depends mostly on the amplifier performance!



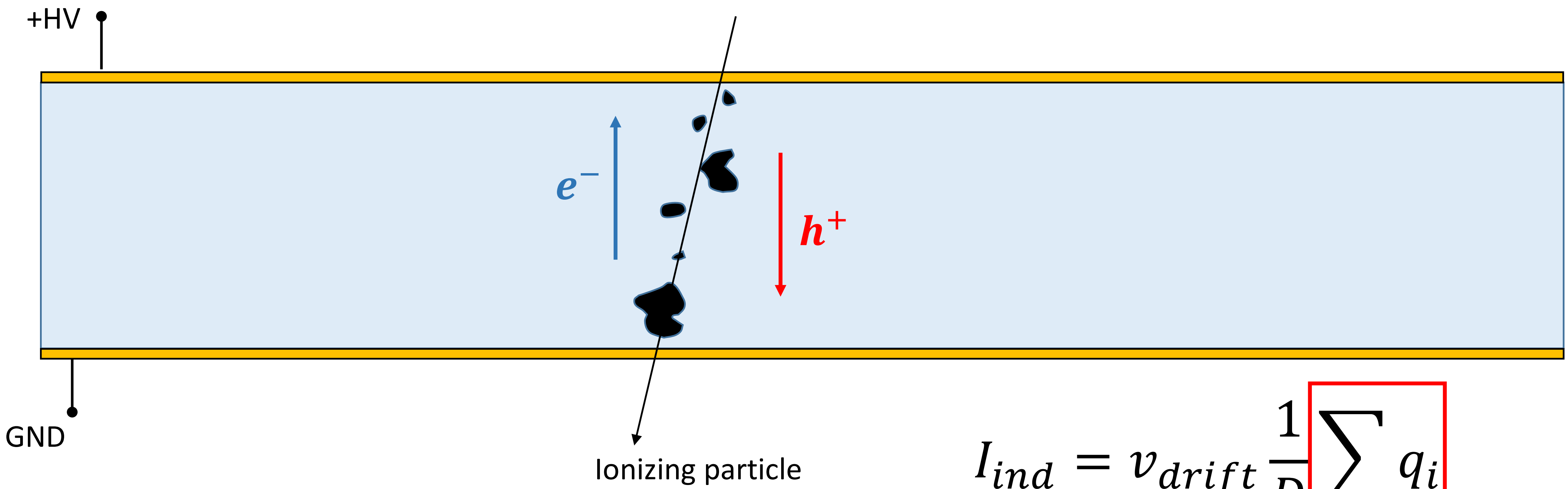
SiGe technology for very low noise fast amplifiers

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \cong \frac{Rise\ Time}{Q/_{ENC}} \qquad I_{ind} = v_{drift}\frac{1}{D}\sum_i q_i$$

Need a **fast, low-noise, low power consumption** electronics:

➡ $1\ ns$ rise time, $< 1000\ e^{-}\ ENC$ on $\sim 1\ pF$ capacitance.

Charge collection noise



$$I_{ind} = v_{drift}\frac{1}{D}\sum_i q_i$$

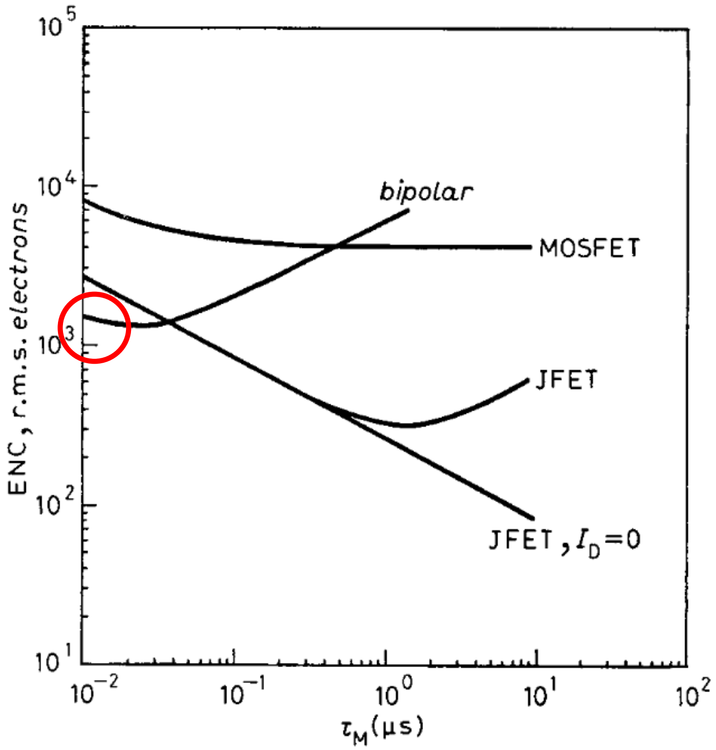
- Produced by the Landau fluctuations on the charge deposition in the sensor.
- **Intrinsic limit to the time resolution for a semiconductor detector!**

Technology choice

The fast, low noise amplifier

$$ENC^2 \propto \left(2q_e I_C + \frac{4kT}{R_P} + i_{na}^2\right)\cdot\tau + \boxed{(4kTR_S + e_{na}^2)\cdot\frac{C_{in}^2}{\tau}} + 4A_f C_{in}^2$$

Dominating term: series noise (for TT-PET $\tau < 10\ ns$)



E. Gatti, P. F. Manfredi, *Processing the Signals from Solid-State Detectors in Elementary-Particle Physics*, rivista del Nuovo Cimento Vol. 9, No. 1 (1986).

Fast integrator

➡ Minimization of series noise

➡ Low input impedance of the transistor

➡ **BJT technology**

The fast, low noise amplifier

For a fast charge integrator in BJT technology the term is expressed as:

$$ENC_{series\ noise} \propto \sqrt{2kT\langle SNI\rangle\left[(C_{in})^2\frac{h_{ie}}{\beta}+R_{bb}C_{in}^2\right]}$$

Maximize the current gain (at high frequencies!) while keeping a low base resistance

The fast, low noise amplifier

Amplifier current gain can be expressed as (NPN BJT)

$$\beta = \frac{i_C}{i_B} = \frac{\tau_p}{\tau_t}$$

τ_p = hole recombination time in base

$\boldsymbol{\tau_t}$ **= electron transit time (E to C)**

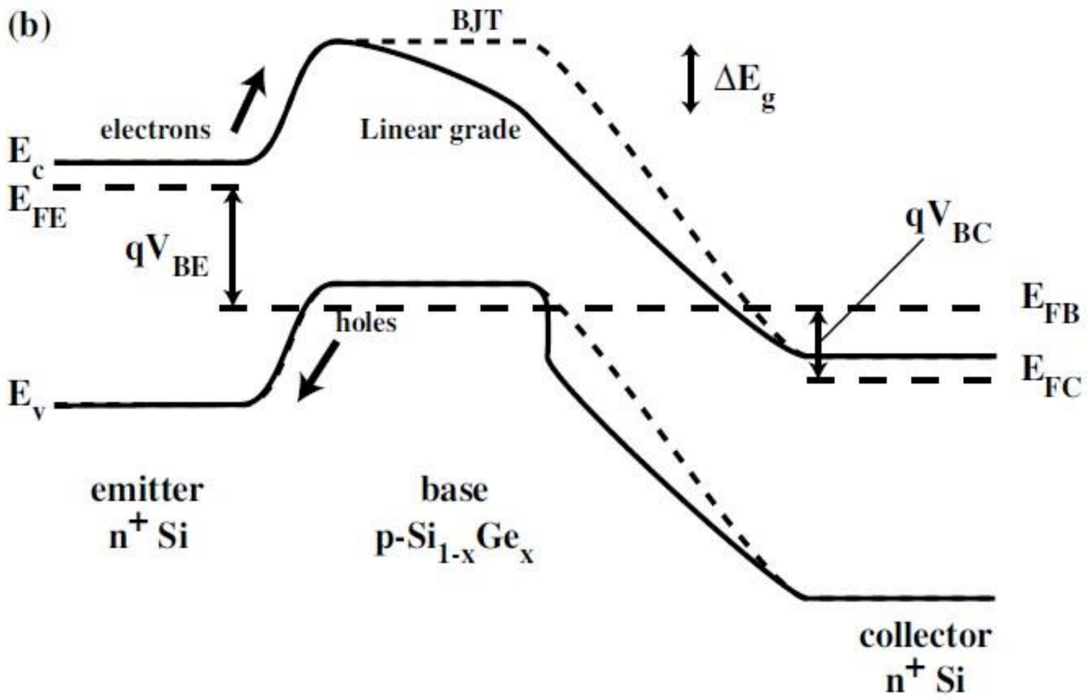
Need to minimize electron transit time in the base

Increase gain ⟹ Reduce base width ⟹ Reducing base doping

Spreading resistance increases!

SiGe technology for low noise, fast amplifiers

A possible approach: **changing the charge transport mechanisms** in the base from diffusion to drift.



SiGe heterojunction bipolar transistor technology.

Our technology choice:

SiGe HBT from IHP microelectronics

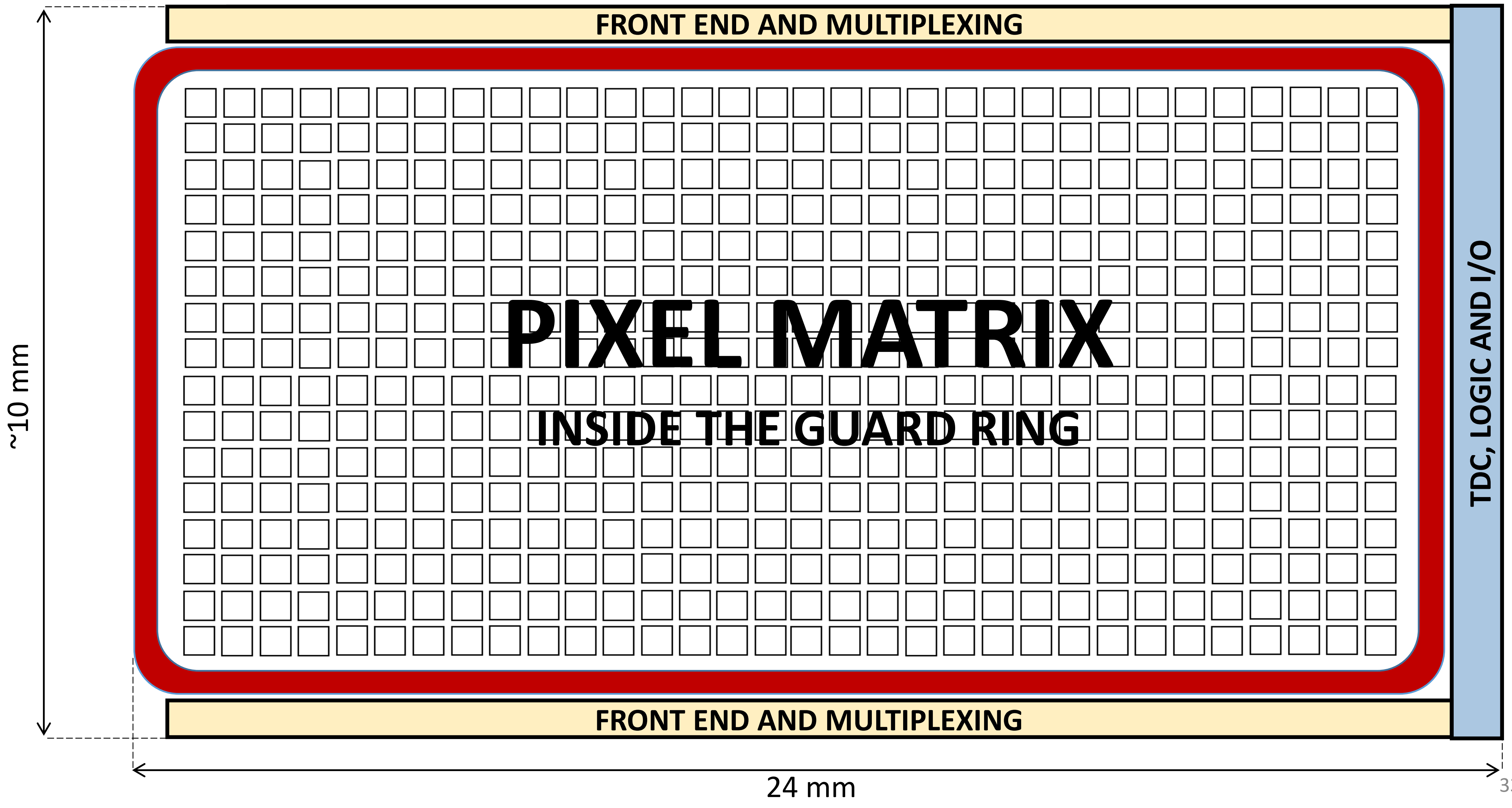
$\beta = 900$

$f_t = 250\ GHz$

Equivalent to introducing an electric field in the base.

ASIC development

TT-PET ASIC conceptual layout



The TT-PET ASIC

A monolithic silicon pixel detector:

ASIC length	$24\ mm$
ASIC width	$7, 9, 11\ mm$
Pixel Size	$500 \times 500\ \mu m^2$
Pixel Capacitance (comprised routing)	$750\ fF$
Preamplifier power consumption	$< 80\ mW/cm^2$
Preamplifier E.N.C.	$600\ e^-\ RMS$
Preamplifier Rise time (10% - 90%)	$800\ ps$
Time resolution for MIPs	$100\ ps\ RMS$
TDC time binning*	$20\ ps$
TDC power consumption	$< 1\ mW/ch$

*** NOTE: 1920 chips synchronized at $10\ ps$ precision.**

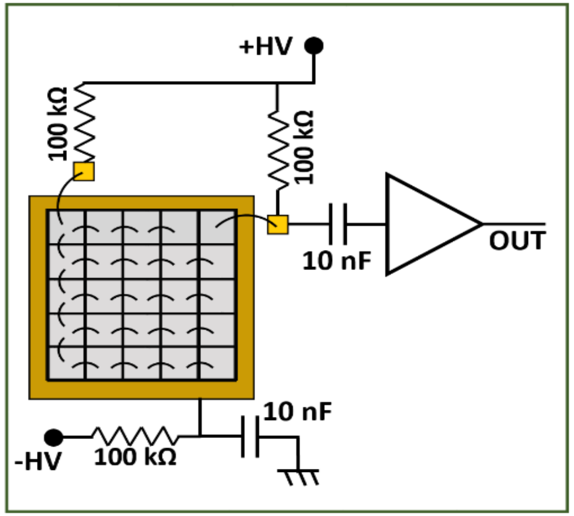
A new TDC synchronization technique developed for this project is being patented by University of Geneva / Unitec and INFN of Roma Tor Vergata.

Proof of principle

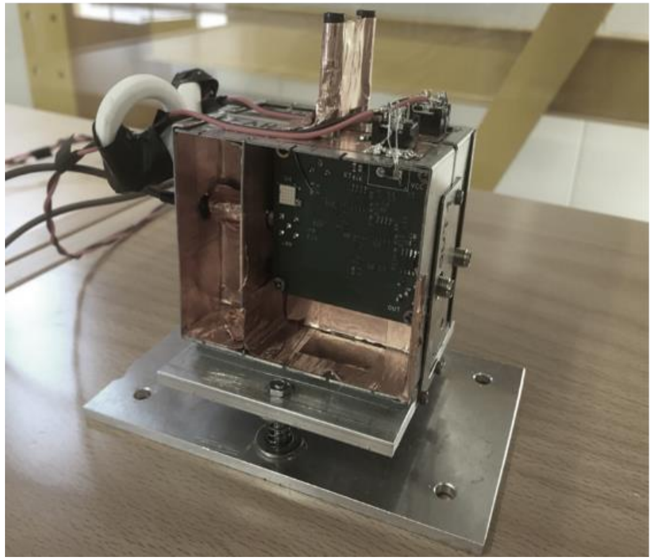
Proof of principle

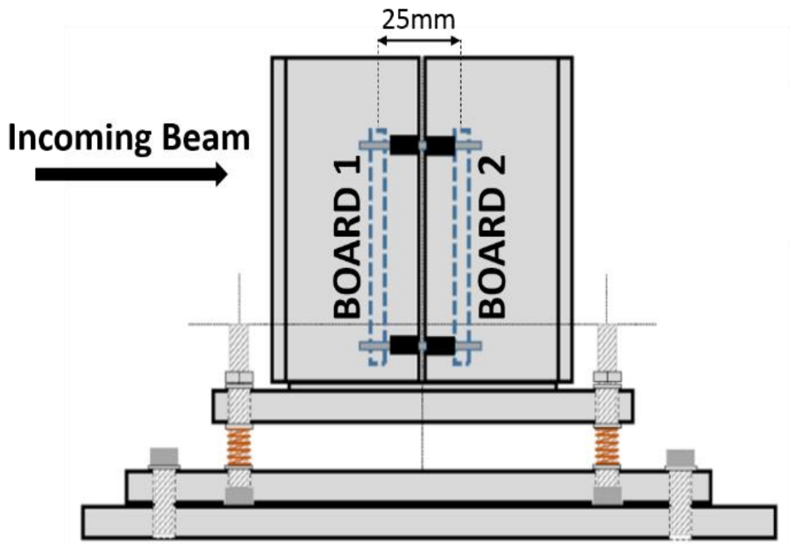
Test with discrete component SiGe amplifier and external sensor

Board schematic design:



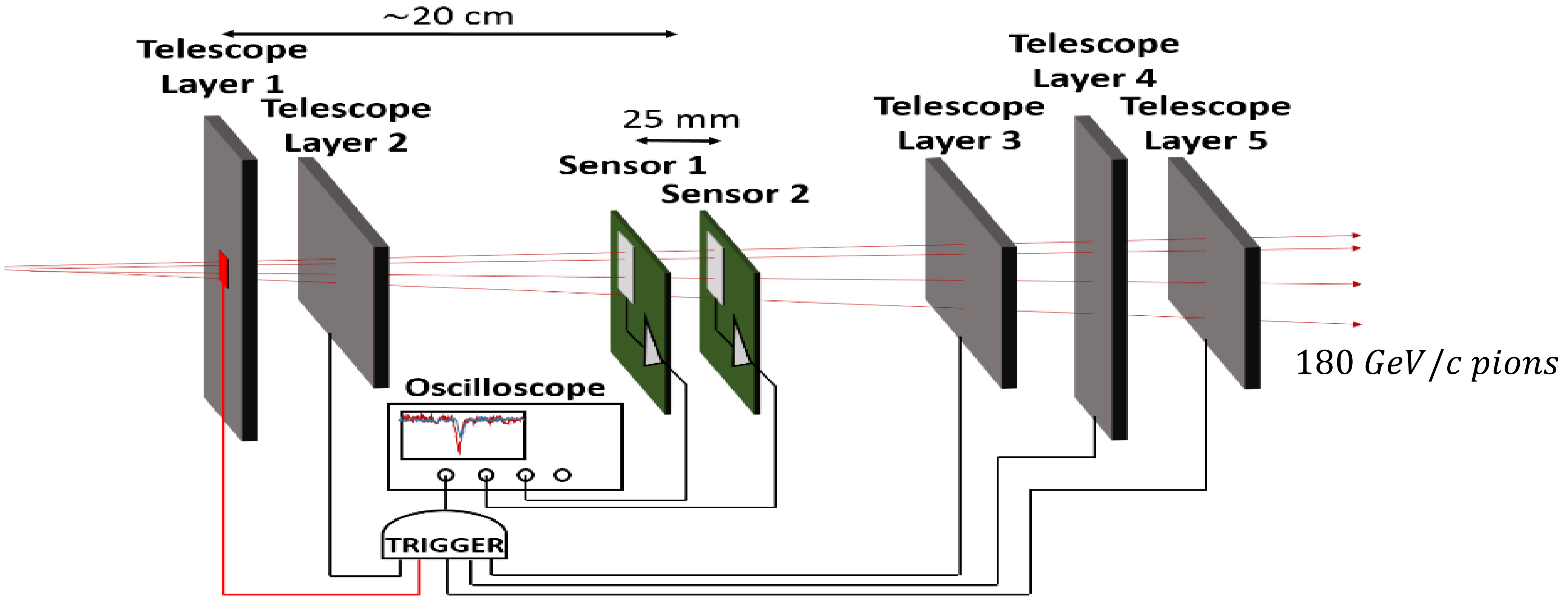
Mechanical support



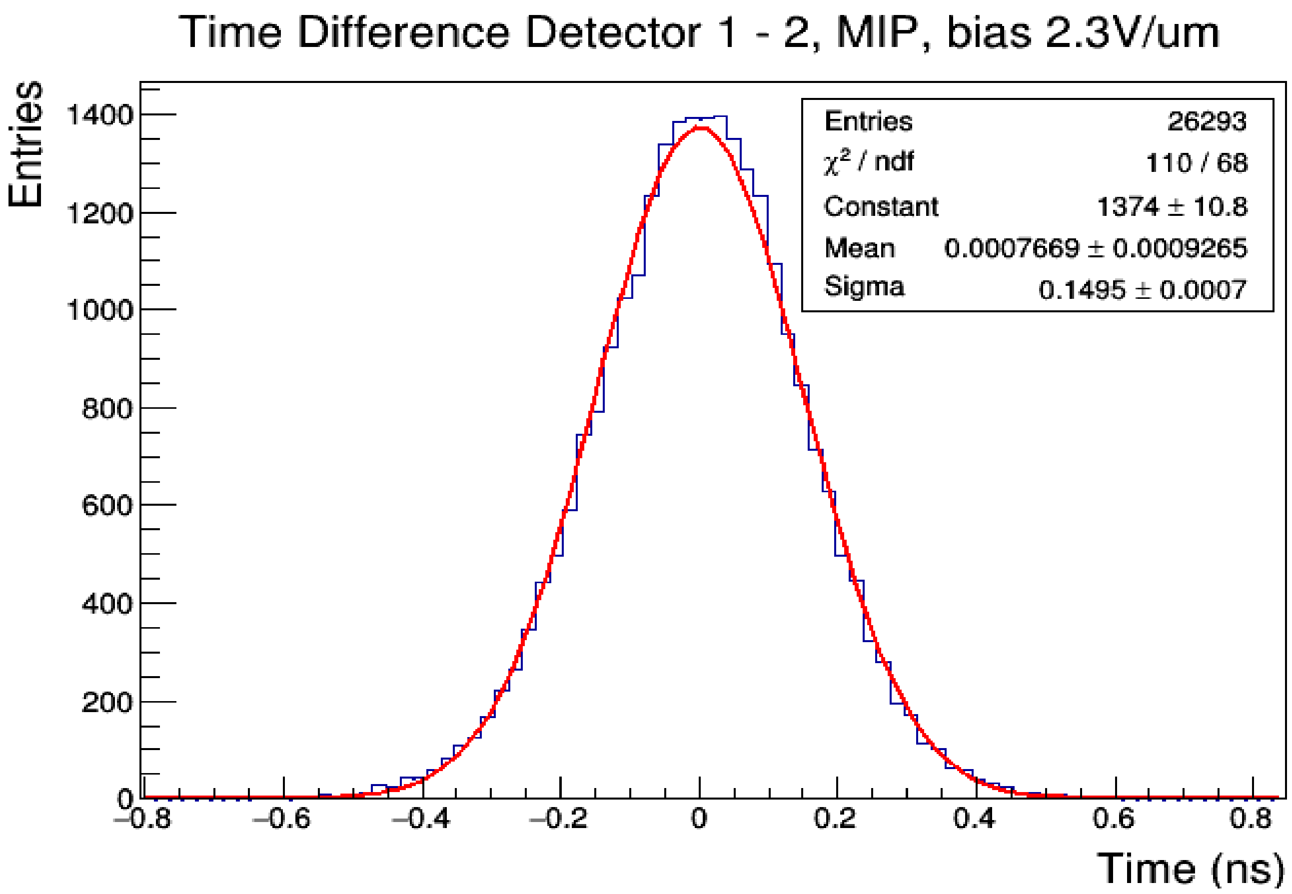


Proof of principle

Test of external sensor and custom SiGe HBT preamplifier at H8 beam line at SPS (CERN).



Proof of principle



$$\sigma_t = \frac{(150 \pm 1)ps}{\sqrt{2}} = (106 \pm 1)ps.$$

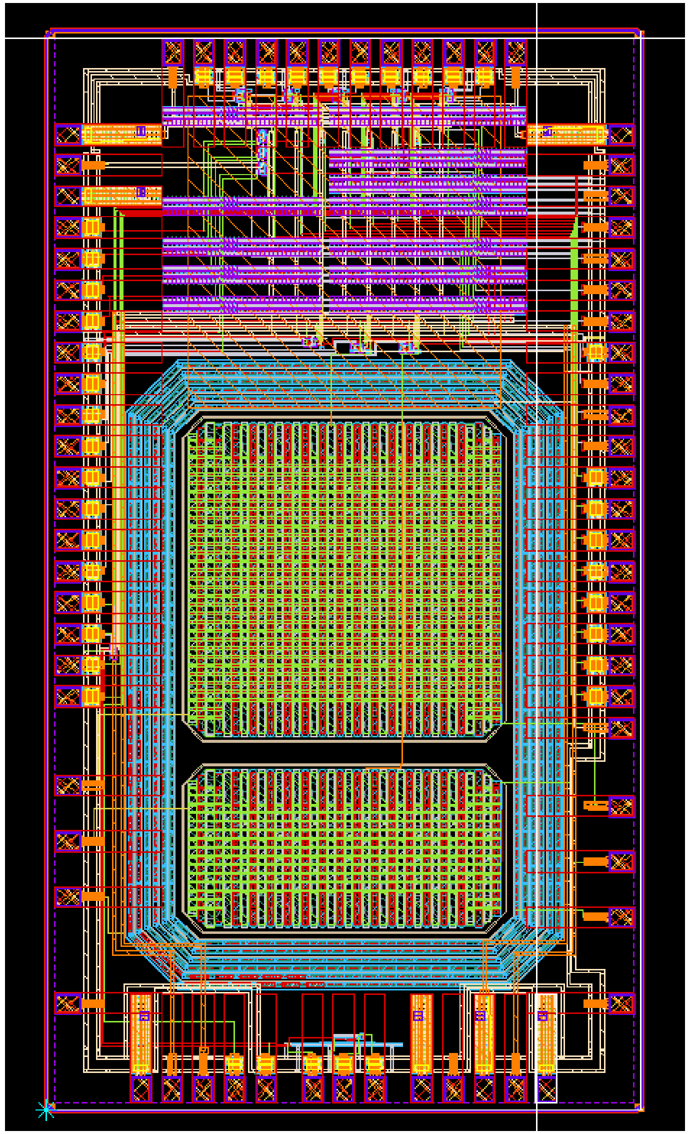
100ps time resolution measured with MIPs on 1 pF capacitance

Record for a silicon pixel detector, obtained on a large capacitance!

Published on JINST:
M. Benoit et al., *100 ps time resolution with thin silicon pixel detectors and a SiGe HBT amplifier,* JINST 11, P03011 (2016)

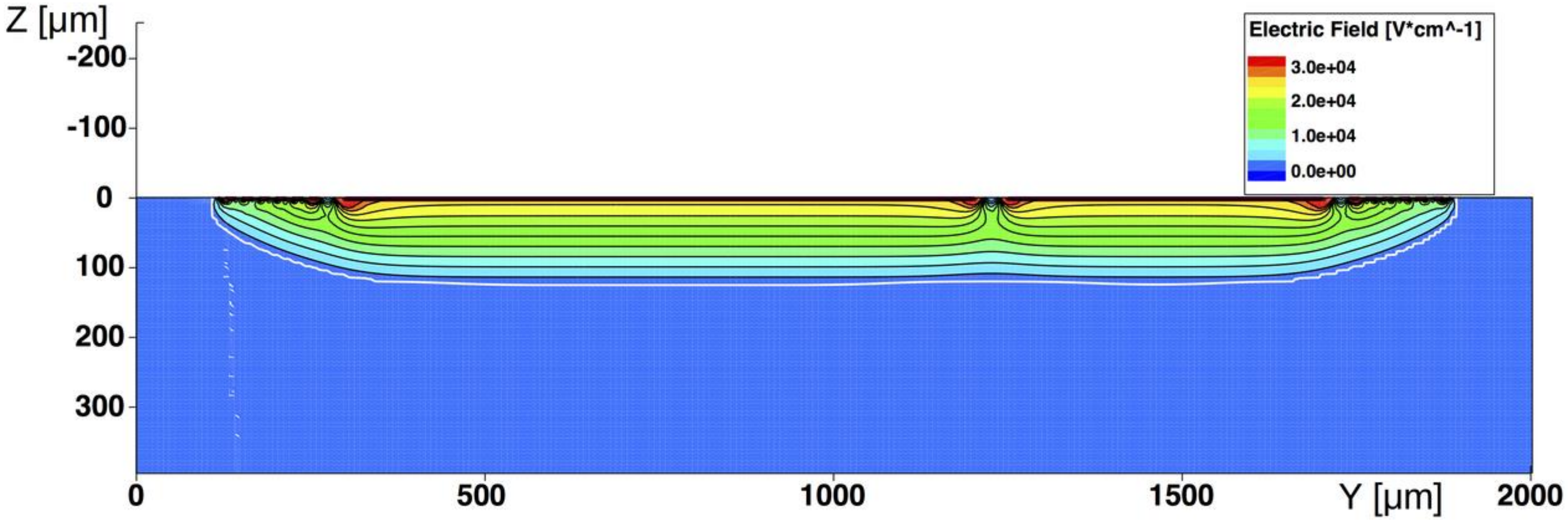
1st monolithic test chip

Chip layout



- Two pixels + amplifier + discriminator in 130 nm IHP process.
- Pixel size: $900 \times 900\ \mu m^2$ and $900 \times 450\ \mu m^2$.
- Higher wafer resistivity ($1\ k\Omega cm$)
- **No thinning, no backplane metallization.**

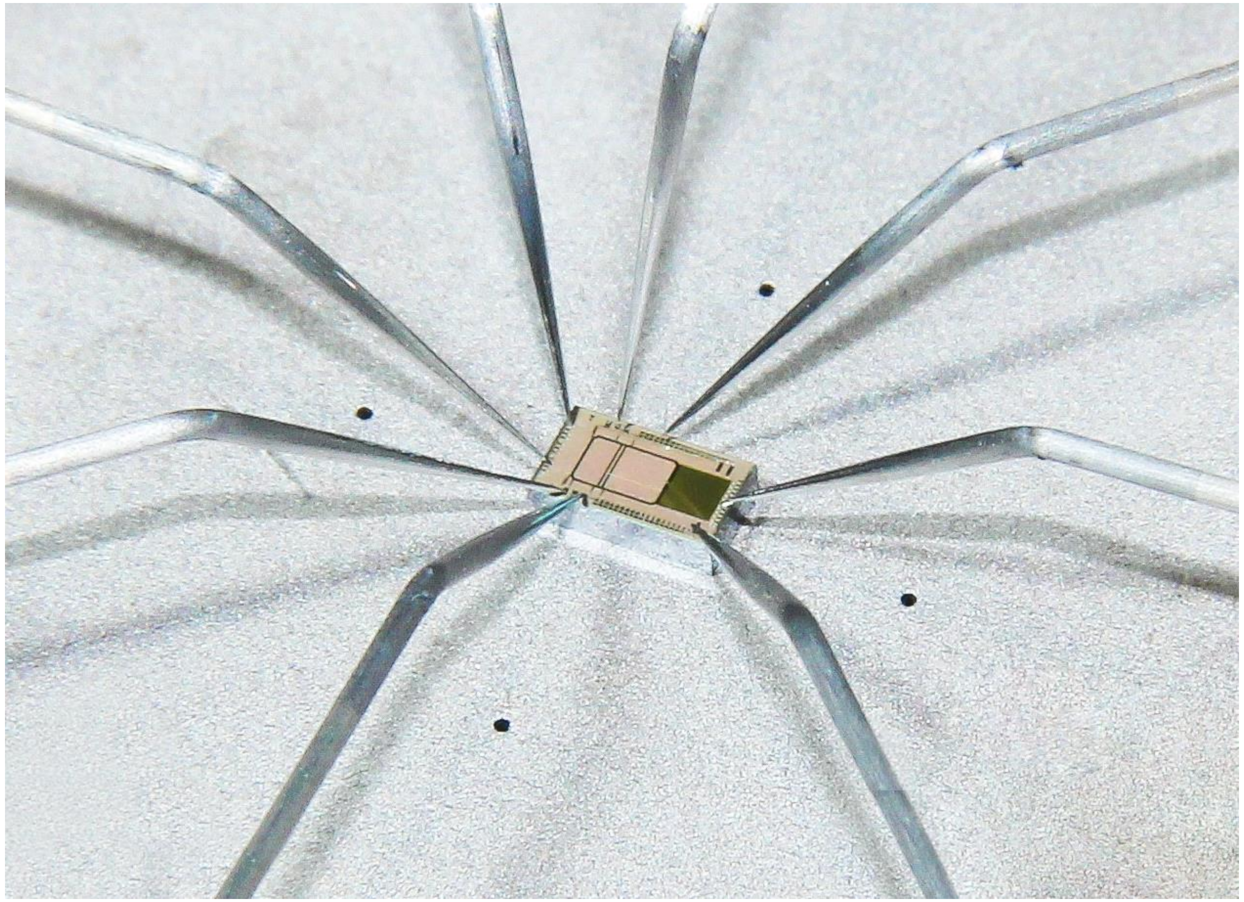
TCAD simulation of the chip



Expected depletion depth $\cong 130\ \mu m$.

Due to the absence of thinning and backplane metallization, **no charge carriers drift velocity saturation**.

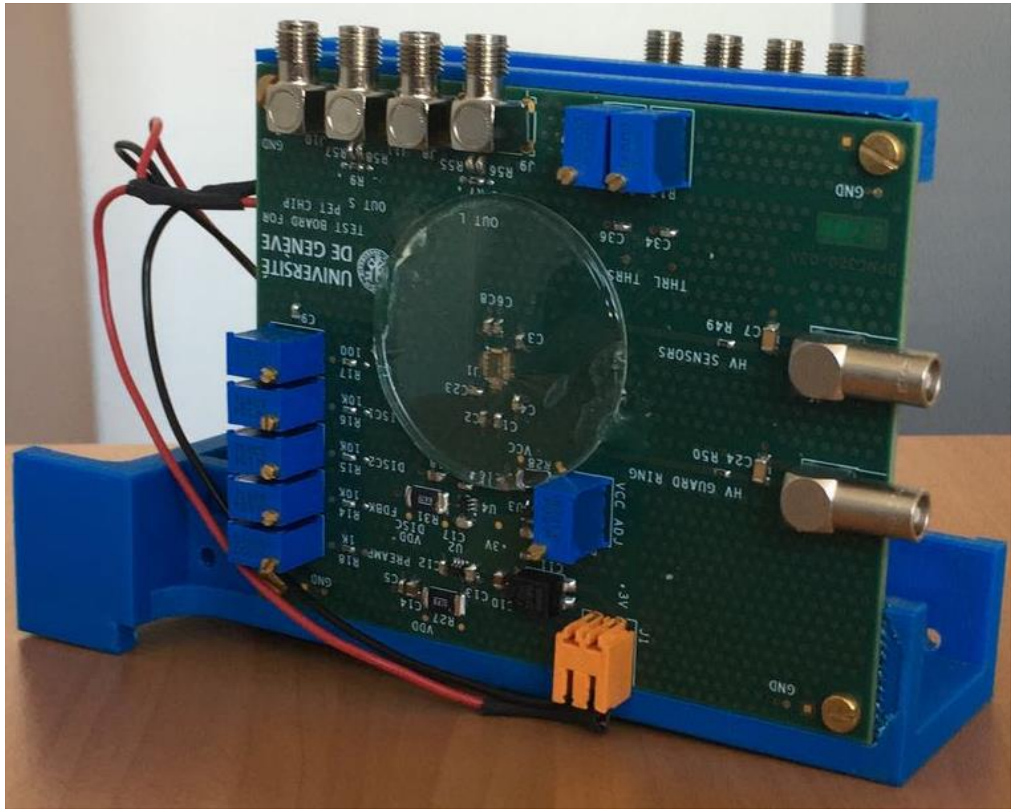
Test on DPNC probe station



Thanks to Mateus for the photo!

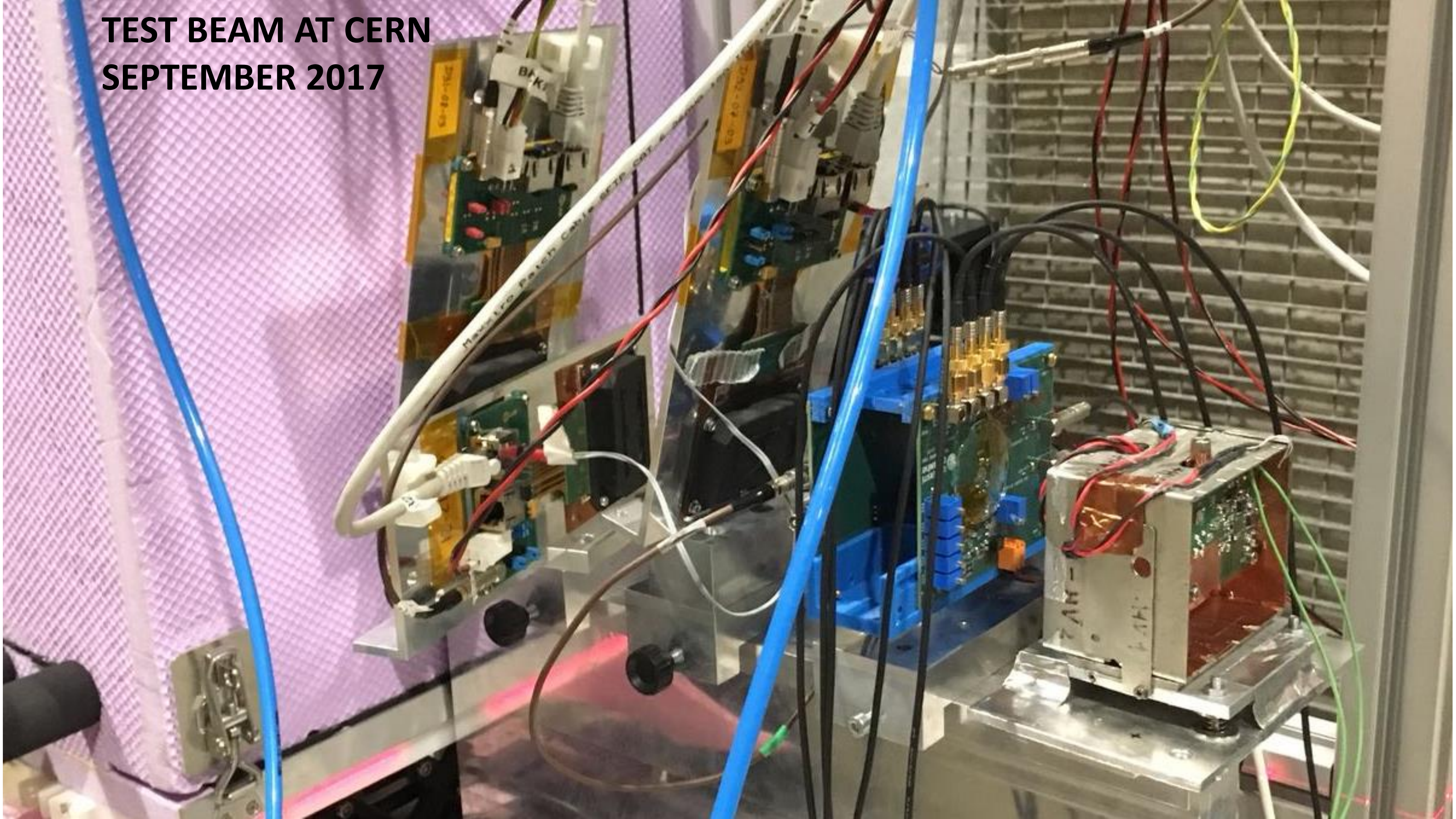
- Breakdown voltage is above $160\ V$
- Small pixel capacitance $0.8\ pF$
- Large pixel capacitance $1.2\ pF$

Test board

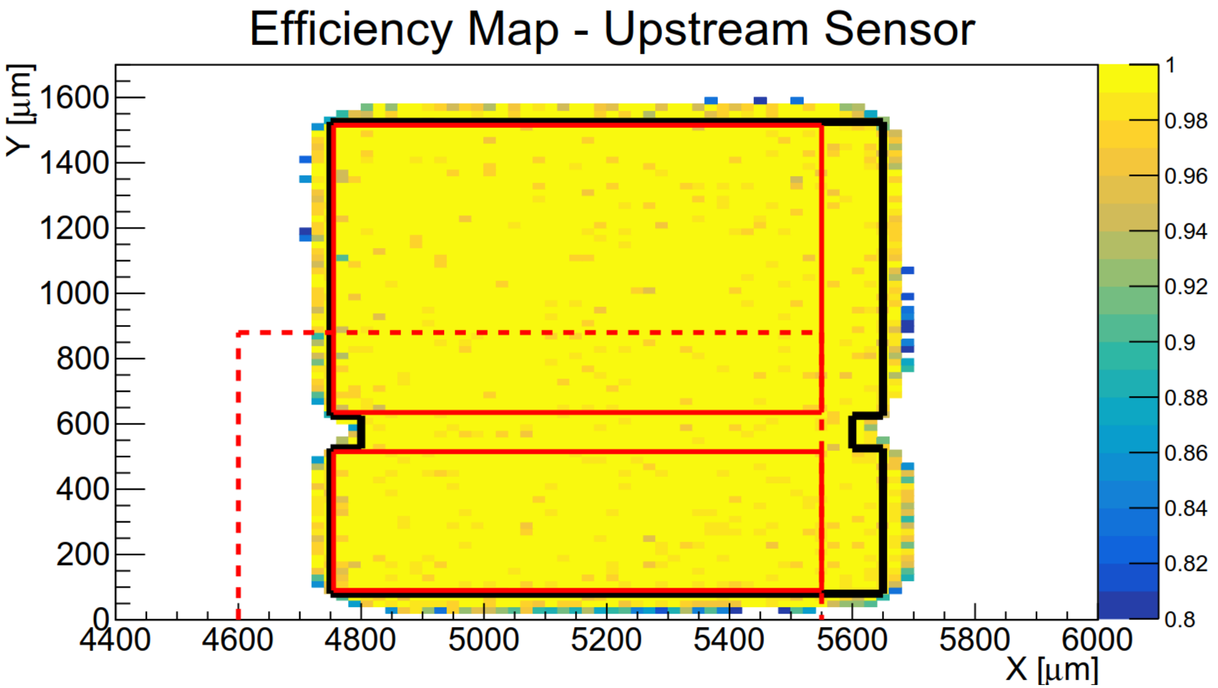


- Produced by the electronic engineering group at DPNC.
- Handles on the same board:
  - Digital pulses with 500 ps rise time.
  - Chip with $30 \frac{mV}{fC}$ gain and $0.1\ fC$ noise amplifier.

TEST BEAM AT CERN
SEPTEMBER 2017

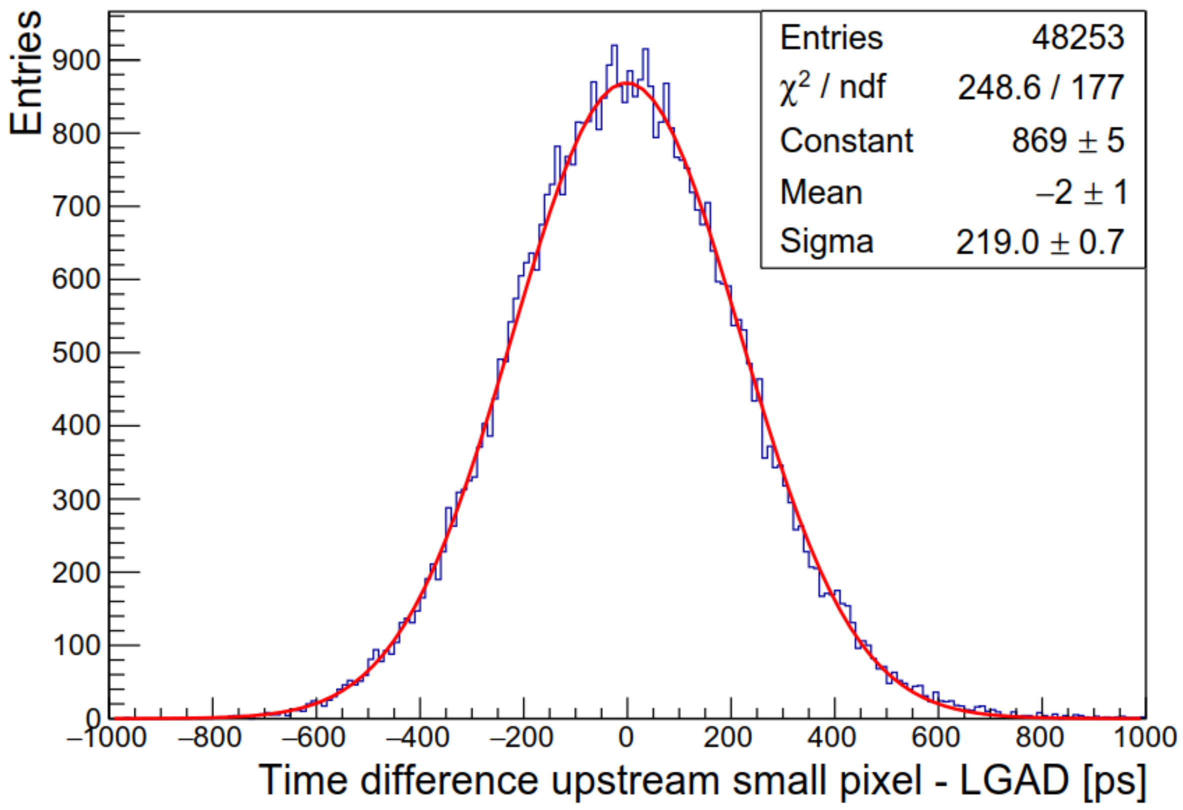


Test beam results: efficiency



- Efficiency 99.8%.
- Amplifier $ENC < 600\ electrons\ RMS$.
- Amplifier power consumption: $< 350 \frac{\mu W}{channel}$, corresponding to $70 \frac{mW}{cm^2}$

Test beam results: time resolution



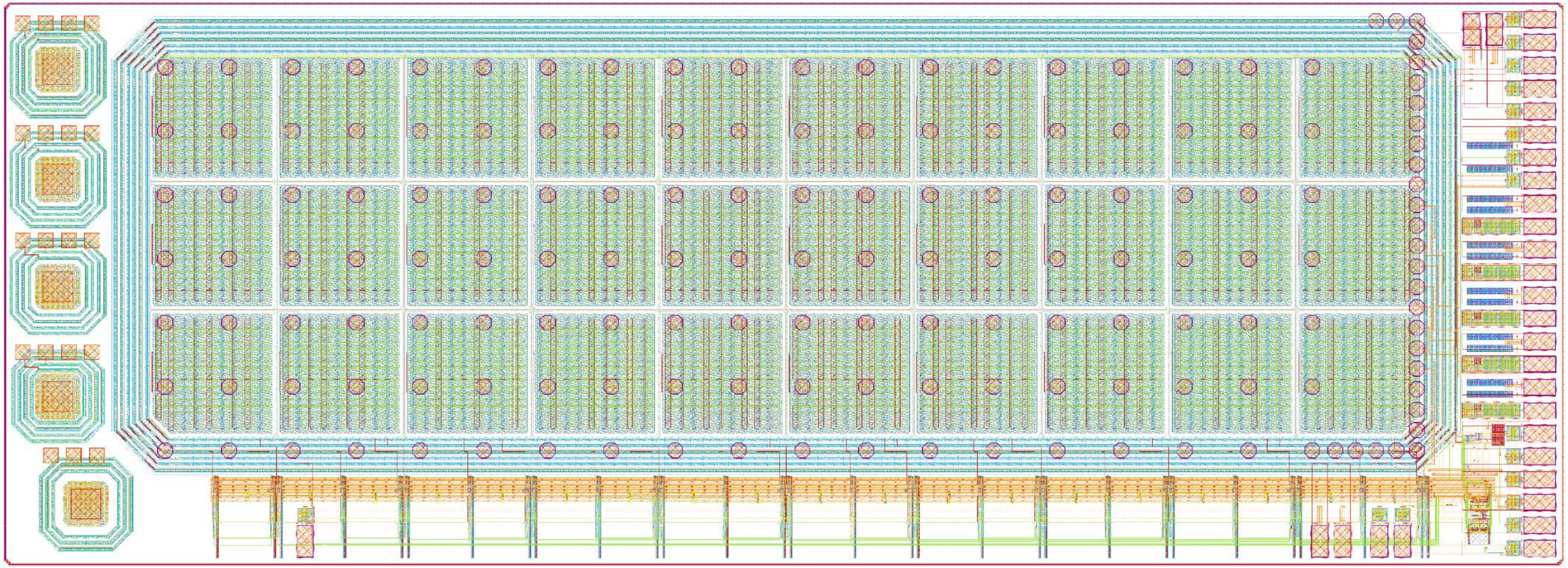
Time resolution $\sim 220\ ps\ RMS$

Record for a monolithic pixel detector!

Submitted for publication.
Avaiable on: http://arxiv.org/abs/1802.01319

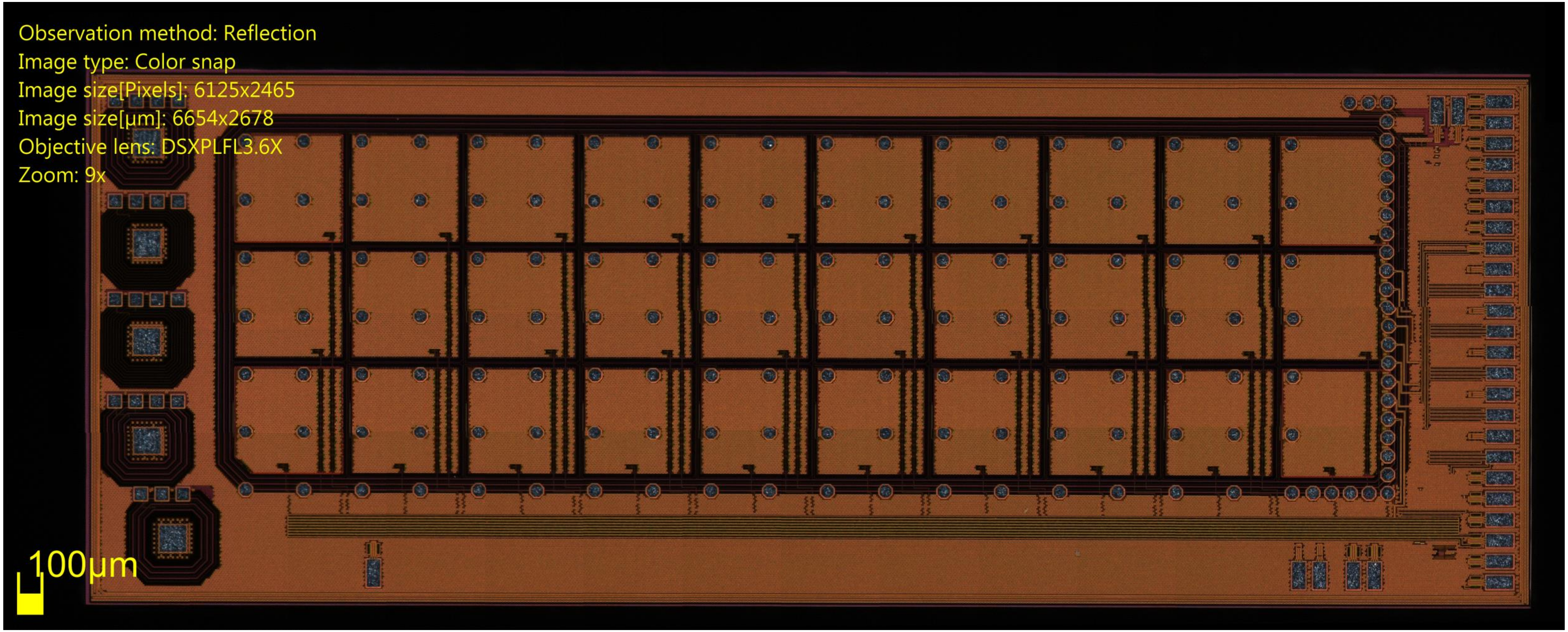
2^{nd} monolithic test chip "prototype 0"

Prototype 0 layout



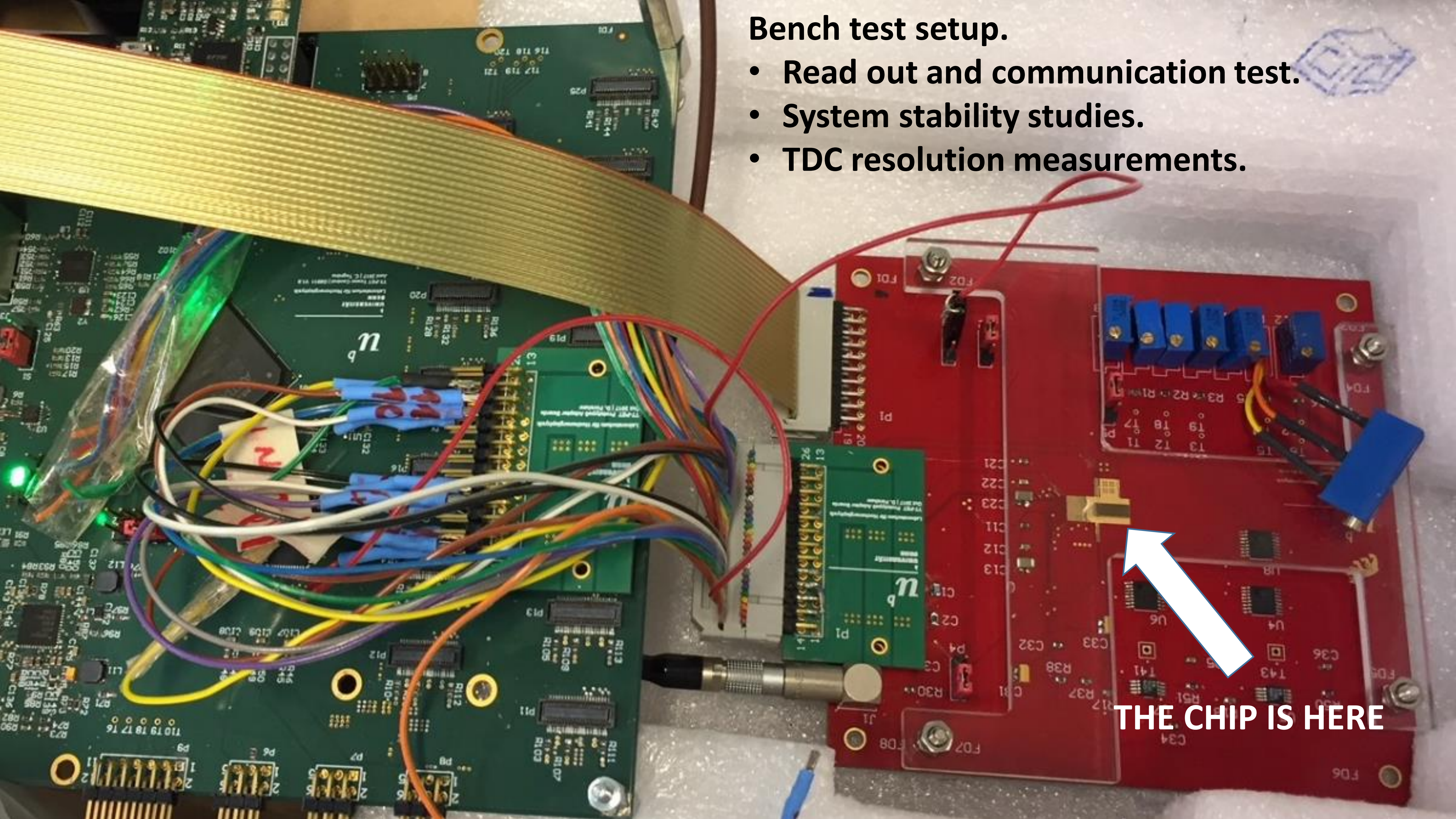
- 3×10 matrix, $500 \times 500\ \mu m^2$ pixels.
- Preamplifier, discriminator, $20\ ps$ binning TDC, logic, serializer integrated in chip.
- Thinned to $100\ \mu m$.
- Full backside processing.
- **High resistivity version will be back from foundry next week. Low resistivity version under test.**

Prototype 0 layout

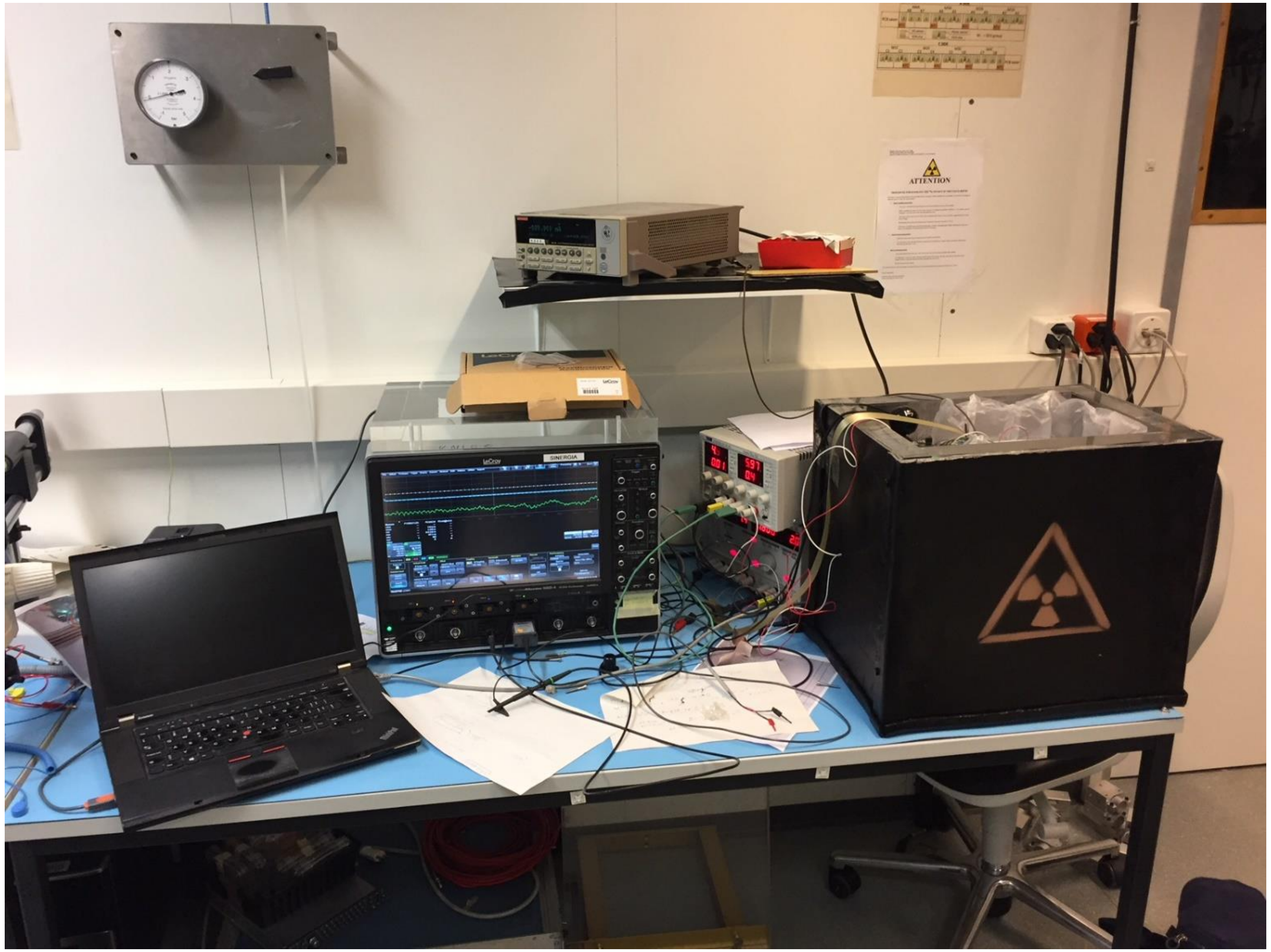


Bench test setup.

- Read out and communication test.
- System stability studies.
- TDC resolution measurements.



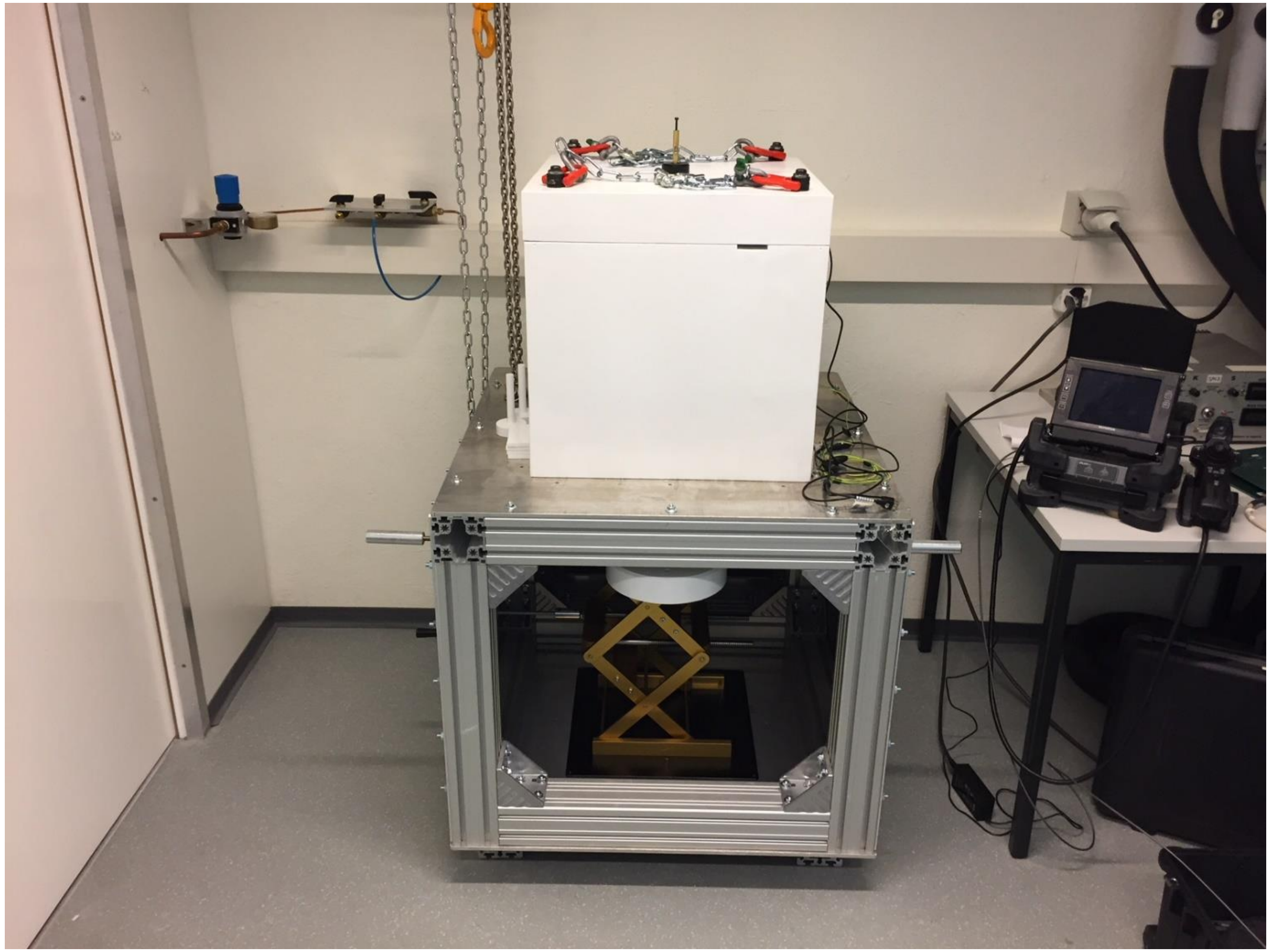
Test setup at DPNC



^{241}Am and ^{90}Sr sources.

- Front end / sensor noise and gain measurement with ^{241}Am and ^{90}Sr sources.
- Performance validation in preparation of the test beam with Minimum Ionizing Particles.

Test setup at DPNC



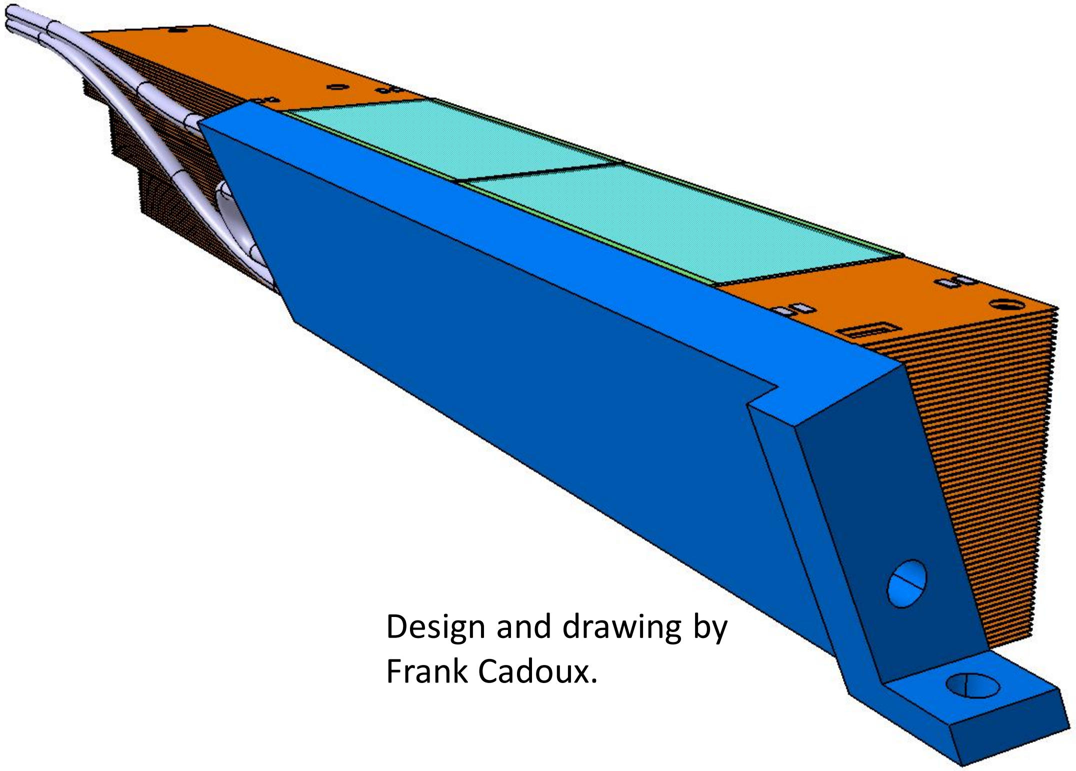
^{22}**Na source setup.**

- ~1 ton of lead.
- Crabbing system for source pick up.
- Sensitivity for 511 keV photons measurement.
- Time of flight to 511 keV photons measurement.

Future steps

Cell assembly test

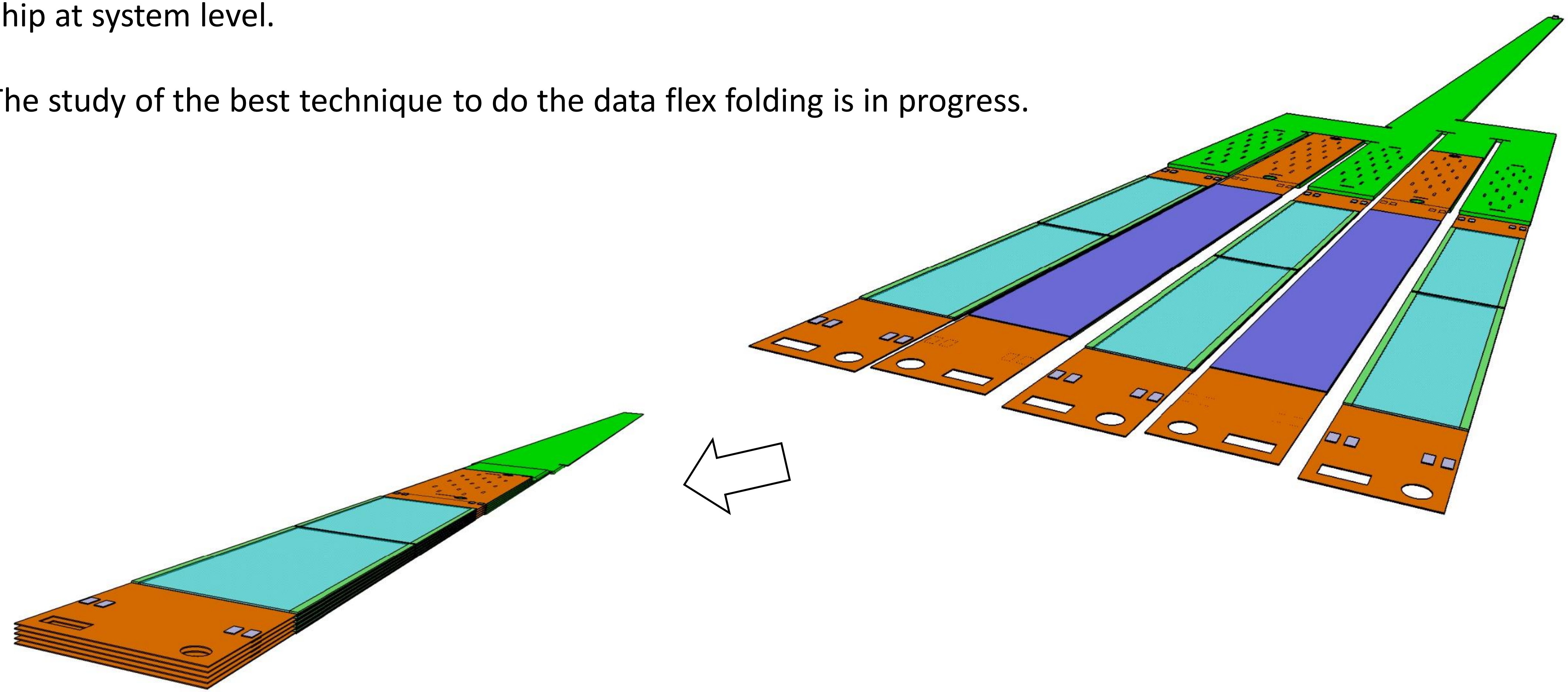
- A thermal mock-up of the sensor will be prepared to test the assembly procedure and the performance of the active cooling.



Design and drawing by
Frank Cadoux.

Cell assembly test

- A prototype of the module flex has been produced in order to study the expected electrical performance of the chip at system level.
- The study of the best technique to do the data flex folding is in progress.



Final assembly

- The final assembly will be done by using the DPNC flip-chip machine.

TT-PET

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Chip submission

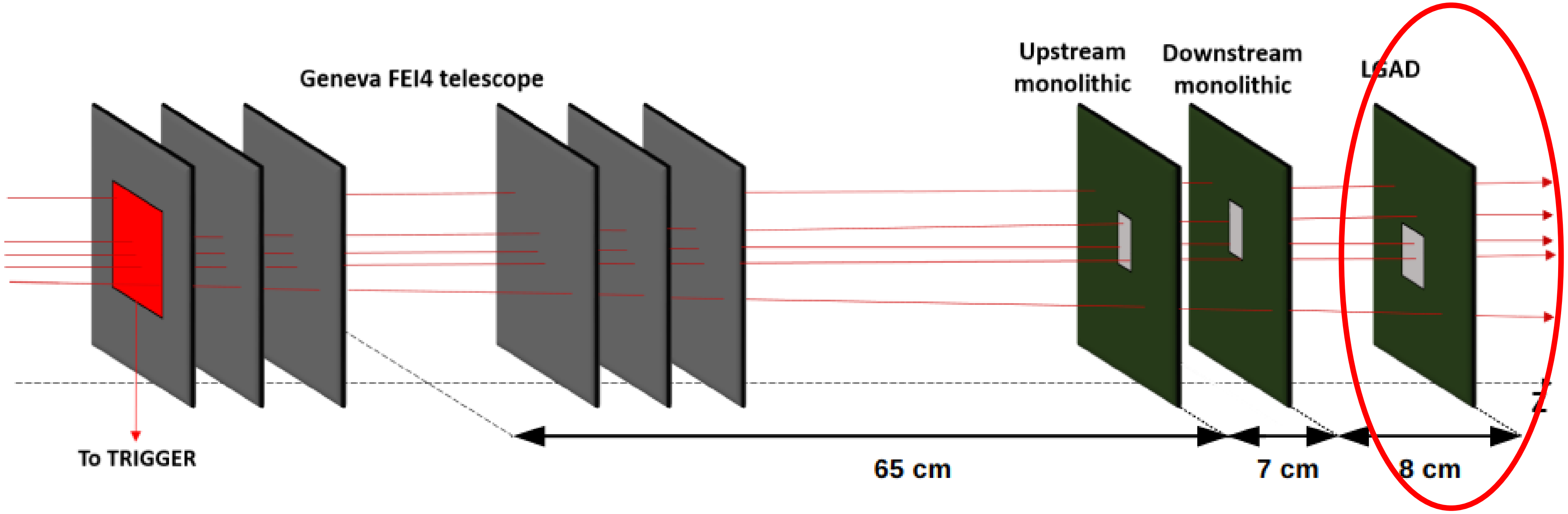
- The design of the final chip will start in May 2018.
- The engineering run is scheduled for September 2018.
- The tower assembly will start in January 2019.

Conclusions

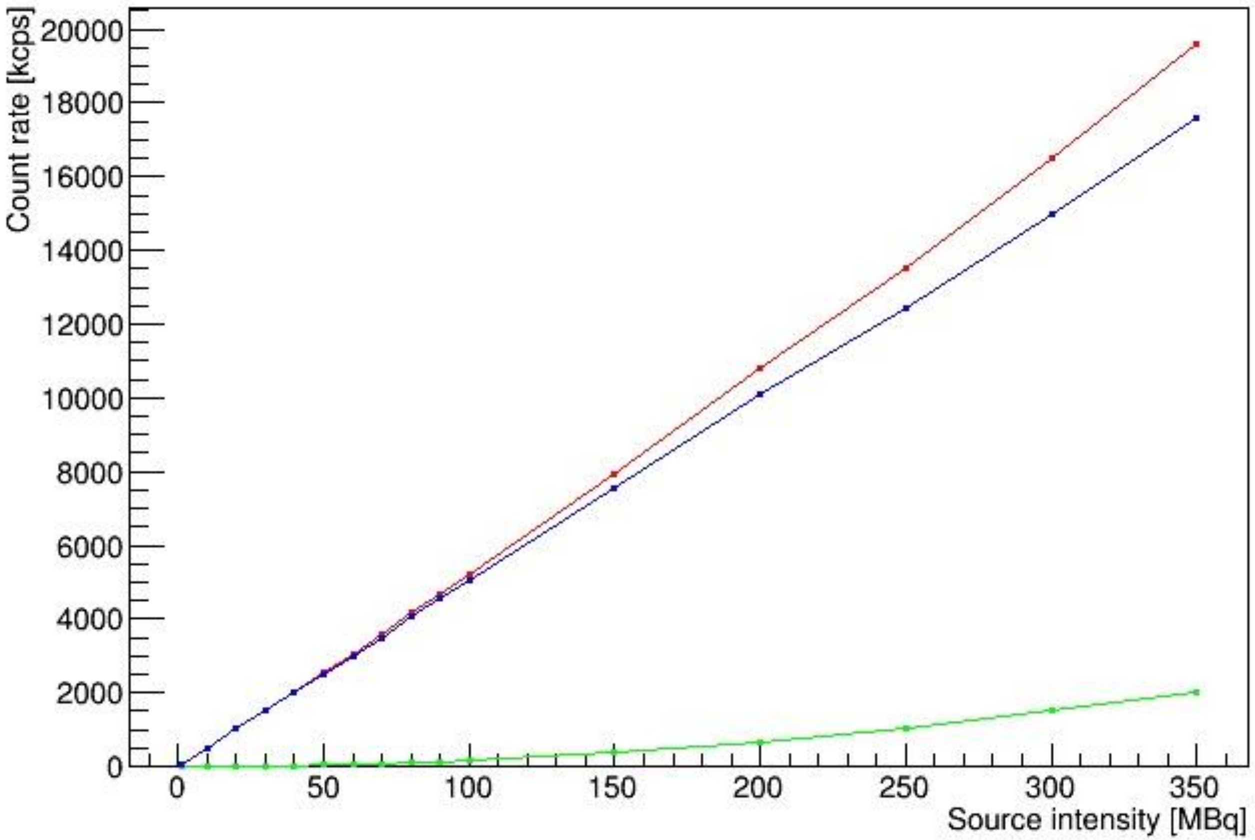
- A **new technique to exploit the timing performance** of the semiconductor sensor has been developed.
- Thanks to this technique, the TT-PET collaboration **obtained the record time resolution** of **106 ps** with silicon sensors and **220 ps** with monolithic silicon pixel detectors.
- The project is very challenging: the assembly of the scanner will **make use of the expertise present in the DPNC** of the University of Geneva.
- The TT-PET scanner will have **unprecedented Time of Flight, space resolution and counting rate capability**, allowing for better study of the metabolic processes.

Backup

Measurements at CERN SPS beam test facility



180 GeV/c
pion beam

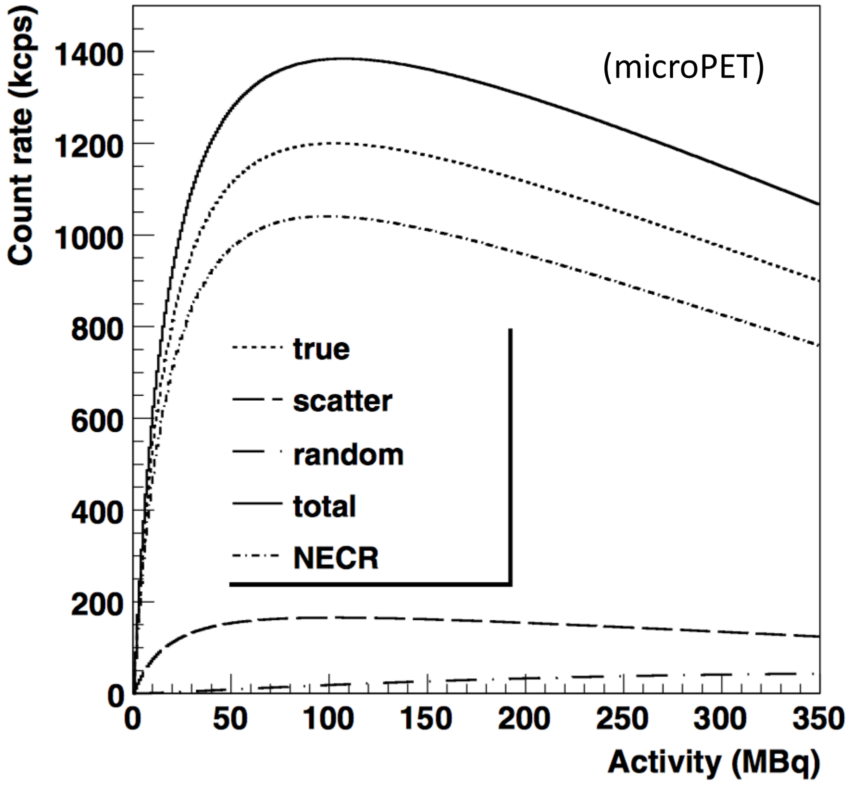


Count rate [kcps]
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Source intensity [MBq]

The TT-PET scanner

The high segmentation of the scanner and fast response of the silicon pixel detector allow for a very high counting rate.

Typical performance of a small animal TOF-PET



TT-PET scanner counting rates – Geant4 simulation