100 ps time resolution for silicon pixel detectors

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Development of a silicon time of flight detector for Positron Emission Tomography

A silicon thin Time-Of-Flight detector.

- Space resolution of 1.0 x 1.0 mm^2
- **Target TOF** measurement of for PET $\boldsymbol{30ps\ RMS}$ (equivalent $\sim 80\ ps\ RMS$ for MIPs).
- **Silicon technology** for particle detection.
- **Monolithic** integration. Development in collaboration with a microelectronics foundry.

This talk will focus on sensor design and amplifier technology choice.

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The TT-PET Collaboration

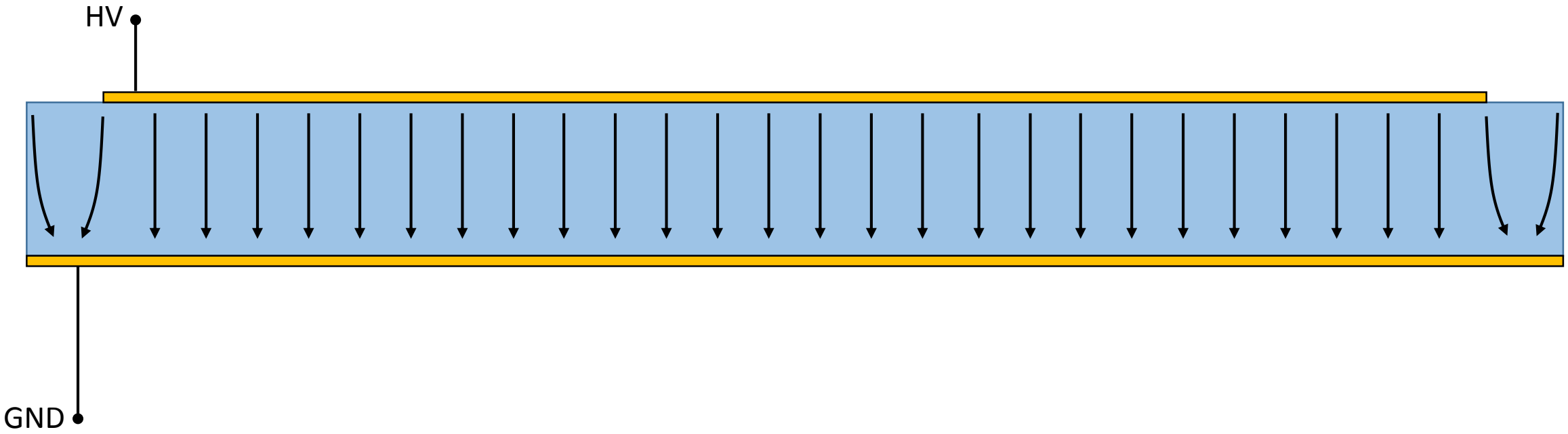
A 3-year project financed by SNSF to produce a PET Scanner for small animals **based on silicon detector technology,** insertable in an MRI machine and with 30ps RMS time resolution.

The TT-PET collaboration:

- University of Geneva → Front End Electronics and detector design.
- University of Bern
- Hôpital cantonale de Genève
- INFN of Roma Tor Vergata → Front End Electronics and detector design.
- CERN
- Stanford University

Sensor optimization for time measurement

Pad readout layout

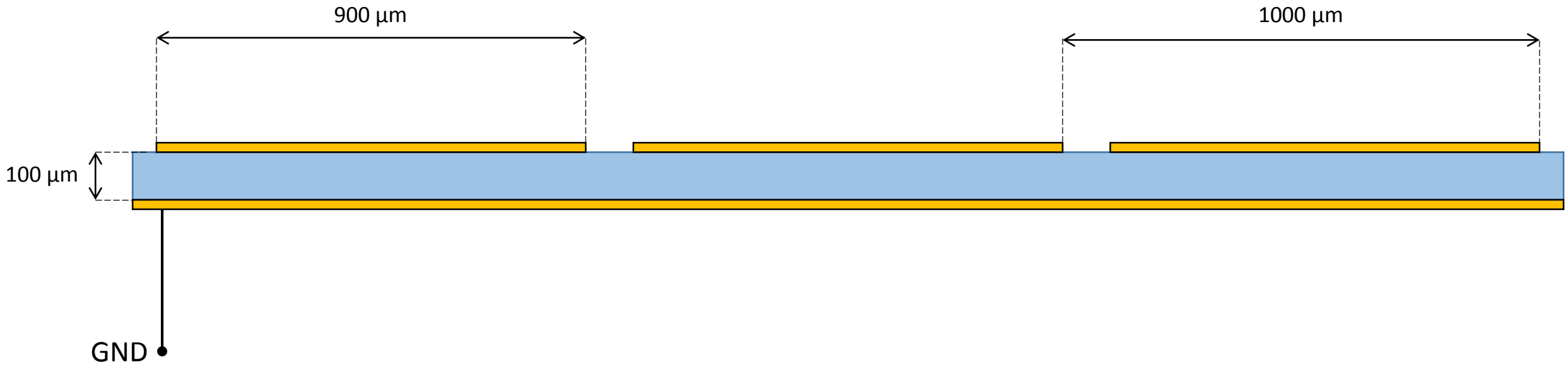


Fundamental parameters:

- Uniform electric field (charge transport).
- Uniform Ramo Field (signal induction).
- Charge drift velocity saturation.

→ Intrinsic time fluctuations independent from the particle trajectory.

Pad readout layout

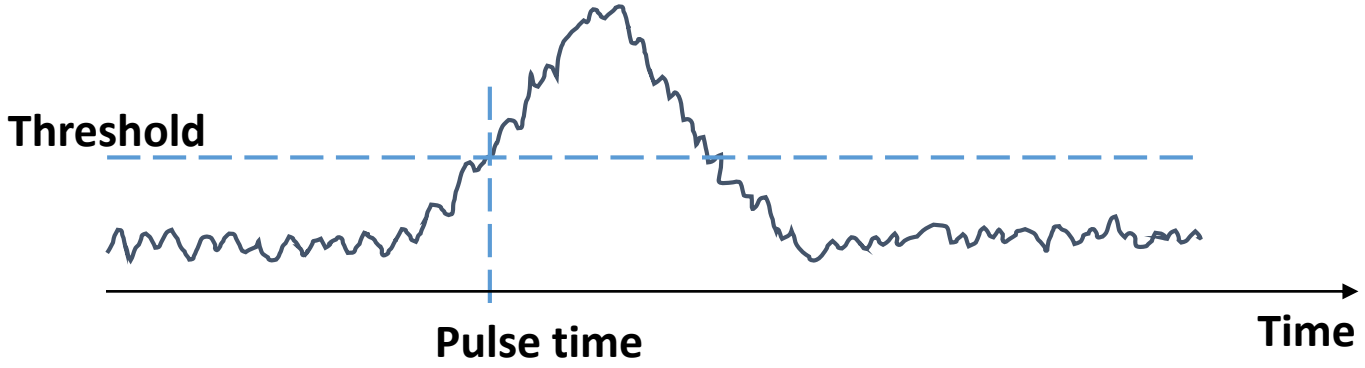


- Sensor backplane metallization.
- Pad capacitance $\gtrsim$ 1pF.
- Electric field $\cong$ 2 V/µm
- Optimization possible via TCAD.

Amplifier contribution to time resolution

Detector time resolution depends mostly on the amplifier performance.

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \cong \frac{t_{rise}}{Signal/Noise}$$



For an ideal charge amplifier
(rise time equal to charge drift time):

$$\sigma_t \cong \frac{ENC}{v_d \frac{dQ}{dx}}$$

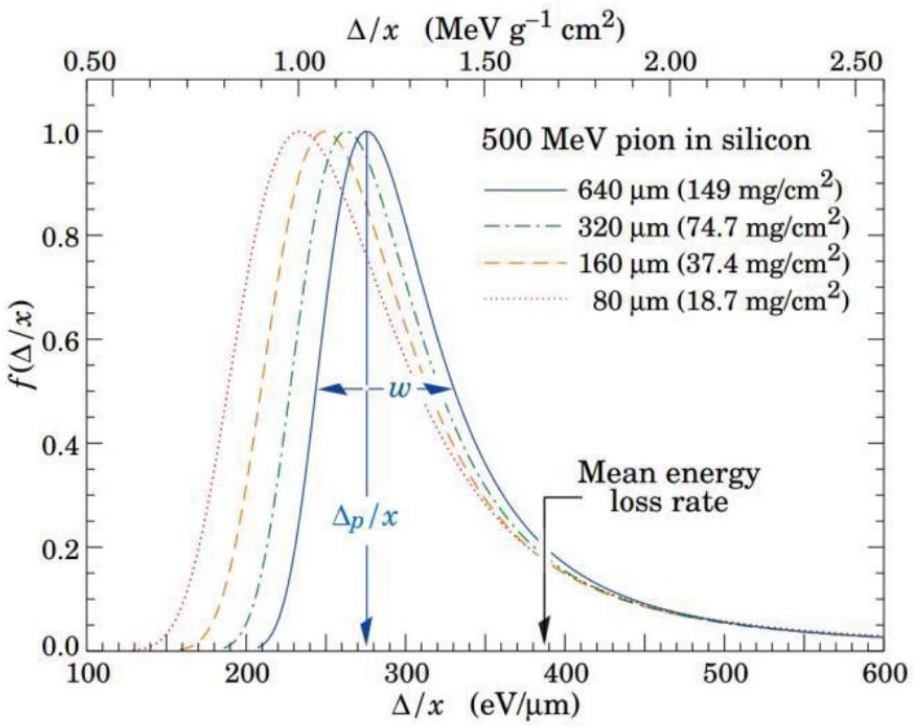
1. Minimization of Equivalent Noise Charge
2. Apparently no dependence on sensor thickness.

Charge collection noise

- Time resolution for semiconductor detectors with planar readout depends on signal to noise ratio.
- The noise introduced by the source is typically negligible with respect to the one from the amplifier itself.

For a time resolution **below $100\ ps$**, another source of noise should be introduced, that will can call **charge collection noise**.

When the ionizing particle traverses the detector, ionization occurs following Landau statistics.



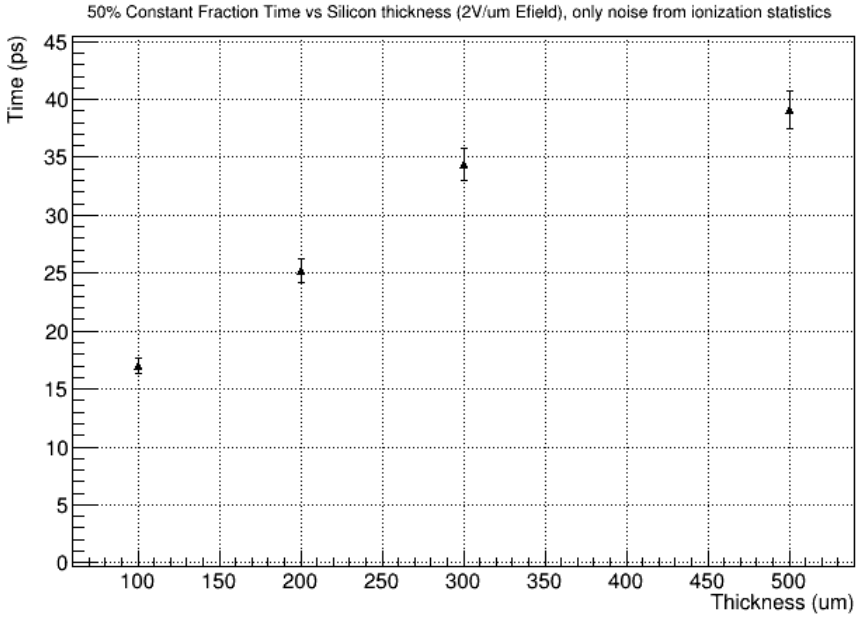
Most of the produced clusters have a small charge.
Few events with very large transferred energy are possible.

Charge collection noise

The induced current for a parallel plate readout, from Shockley-Ramo's theorem is:

$$i_{ind} = -\frac{qv}{D}$$

When the large clusters are absorbed at the electrodes, their contribution is removed from the induced current.
The statistical origin of the variability of the induced current makes this effect irreducible, so that it can be considered as an equivalent noise current.



Simulation: Time jitter introduced by the charge collection noise for a silicon detector traversed by a Minimum Ionizing Particle (MIP).

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Minimization of ENC for a fast integrator

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

Dominating term

Excellent performance in terms of series noise for fast shaping are achievable with the BJT technology

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

Transistor ENC contribution depends on current gain and base spreading resistance

SiGe technology for very low noise fast amplifiers

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)**

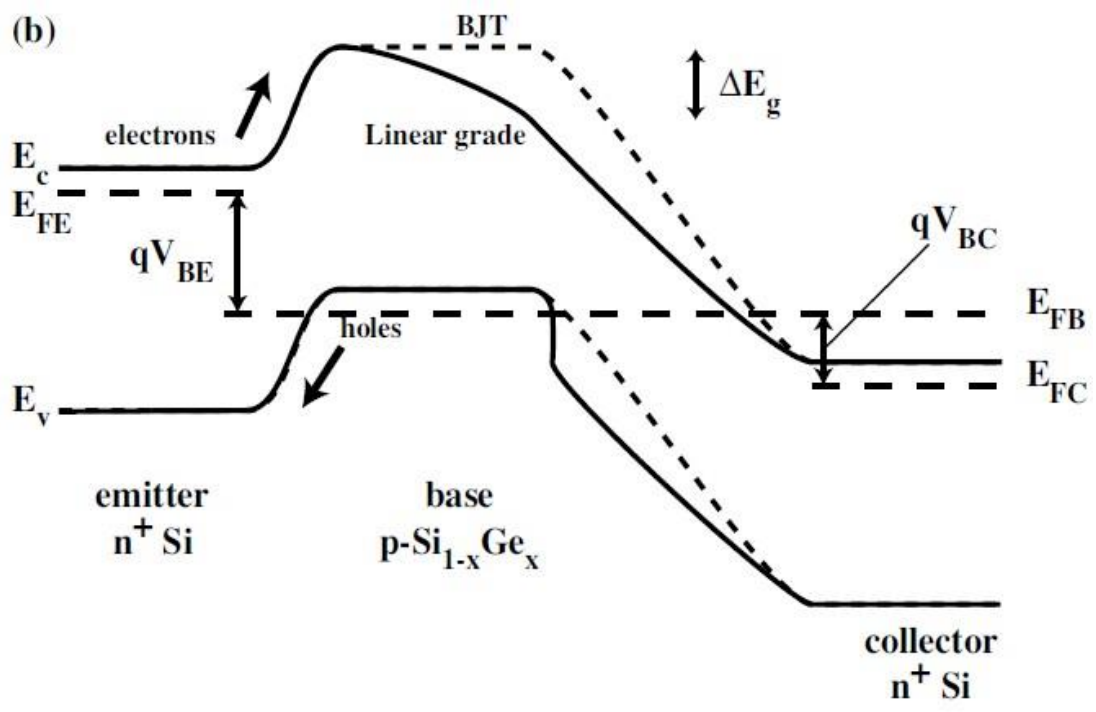
Need to minimize electron transit time in the base

Increase gain ⇒ Reduce base width ⇒ Reducing base doping

Spreading resistance increases!

SiGe technology for very low noise fast amplifiers

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



Equivalent to introducing an electric field in the base.

SiGe heterojunction bipolar transistor technology.

The technology we chose is **SG13S from IHP:**

$\beta = 900$
$f_t = 250\ GHz$

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Target performance for the preamplifier

- $ENC \cong 300\ electrons\ RMS\ on\ 1mm^2$ pads
- $Trise\ \lesssim 1\ ns.$
- $W\ \cong 200\ \mu W/channel$

Simulated with IHP SG13S technology.
First MPW run in progress.

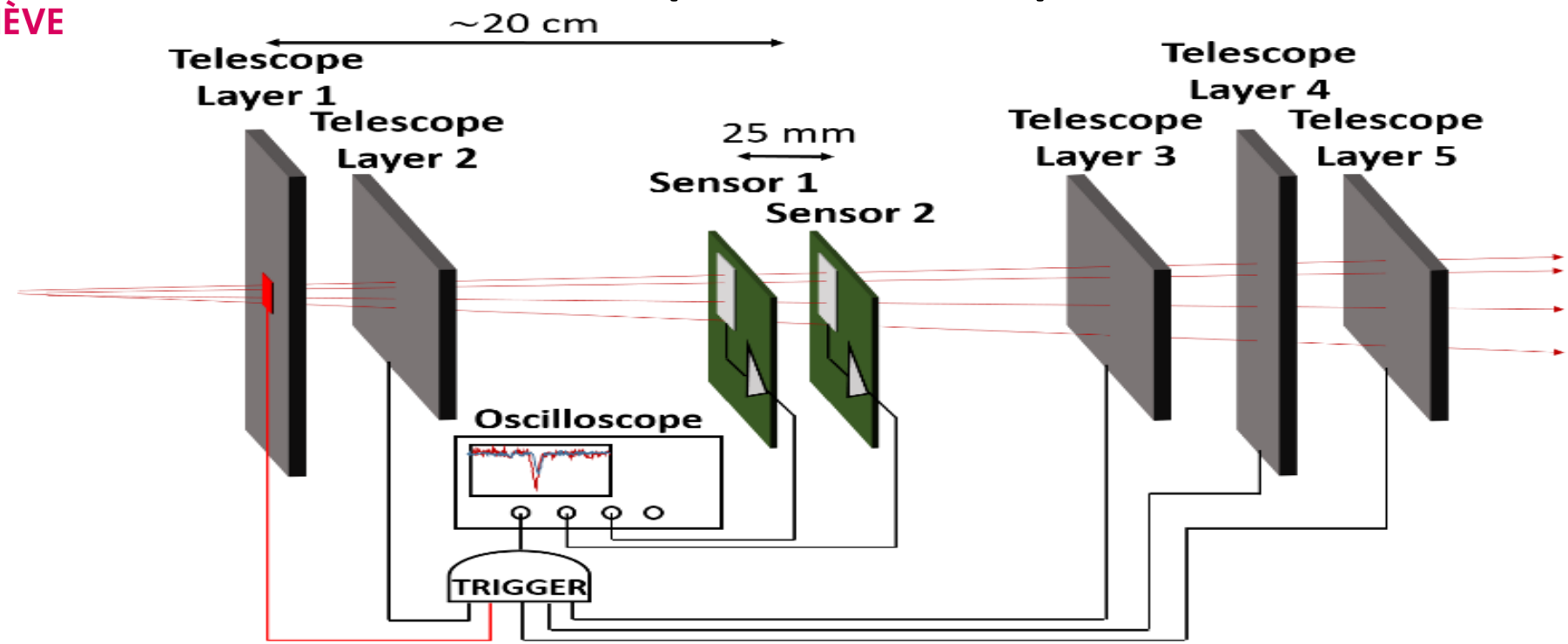
Present measured performance with SiGe discrete component amplifier

- $ENC \cong 550\ electrons\ RMS\ on\ 1\ pF$
- $Trise\ \cong 1.0\ ns.$

100 ps time resolution measured in this working condition.

First time resolution measurement with MIPs

Experimental setup



Detectors under test:

- 100 um thick p-on-n silicon sensors with 1mm^2 area readout pad ($> 1\ pF$ capacitance).
- Signal amplified by means of custom amplifier with commercial SiGe HBT transistors.
- Amplifier is used with inverse dynamics due to constraints on sensor polarization.

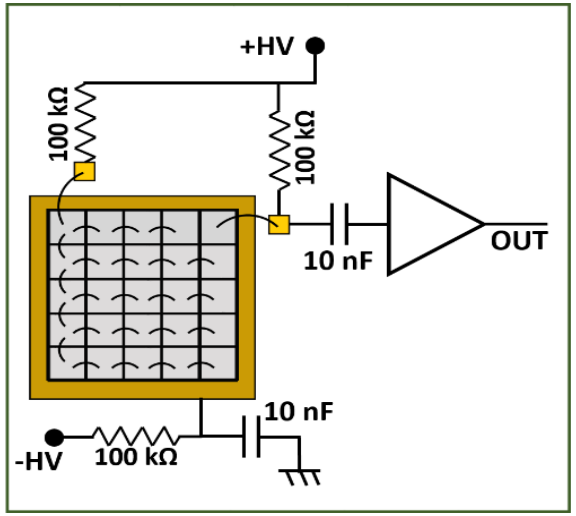
Signal digitized with Lecroy WaveMaster 820zi oscilloscope.

Trigger produced by the external telescope.

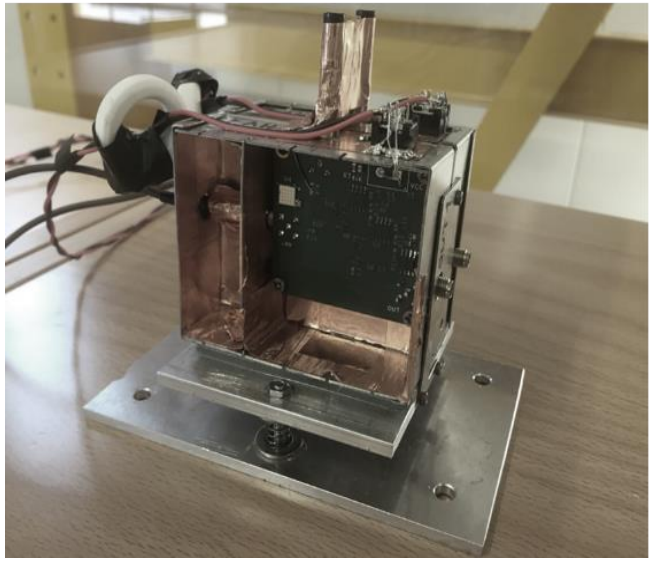
Trigger area limited to 500 um x 500 um (centered on test detectors) by the first telescope layer, to evaluate efficiency.

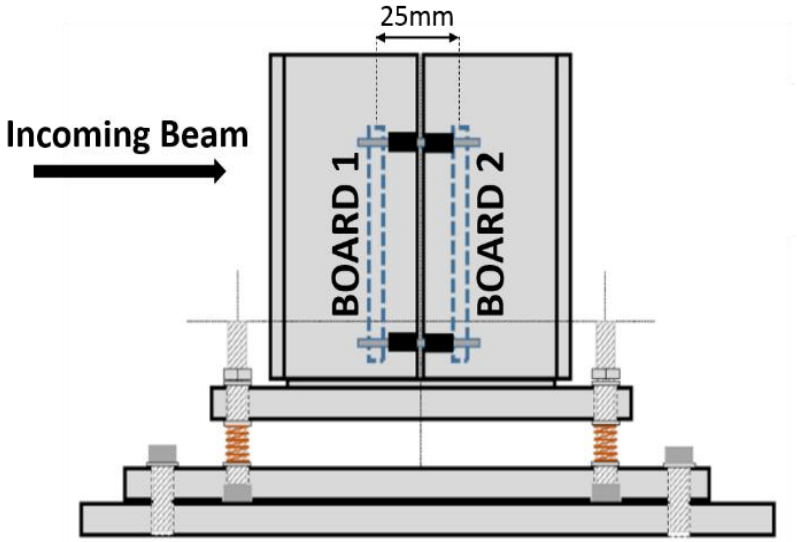
Experimental setup

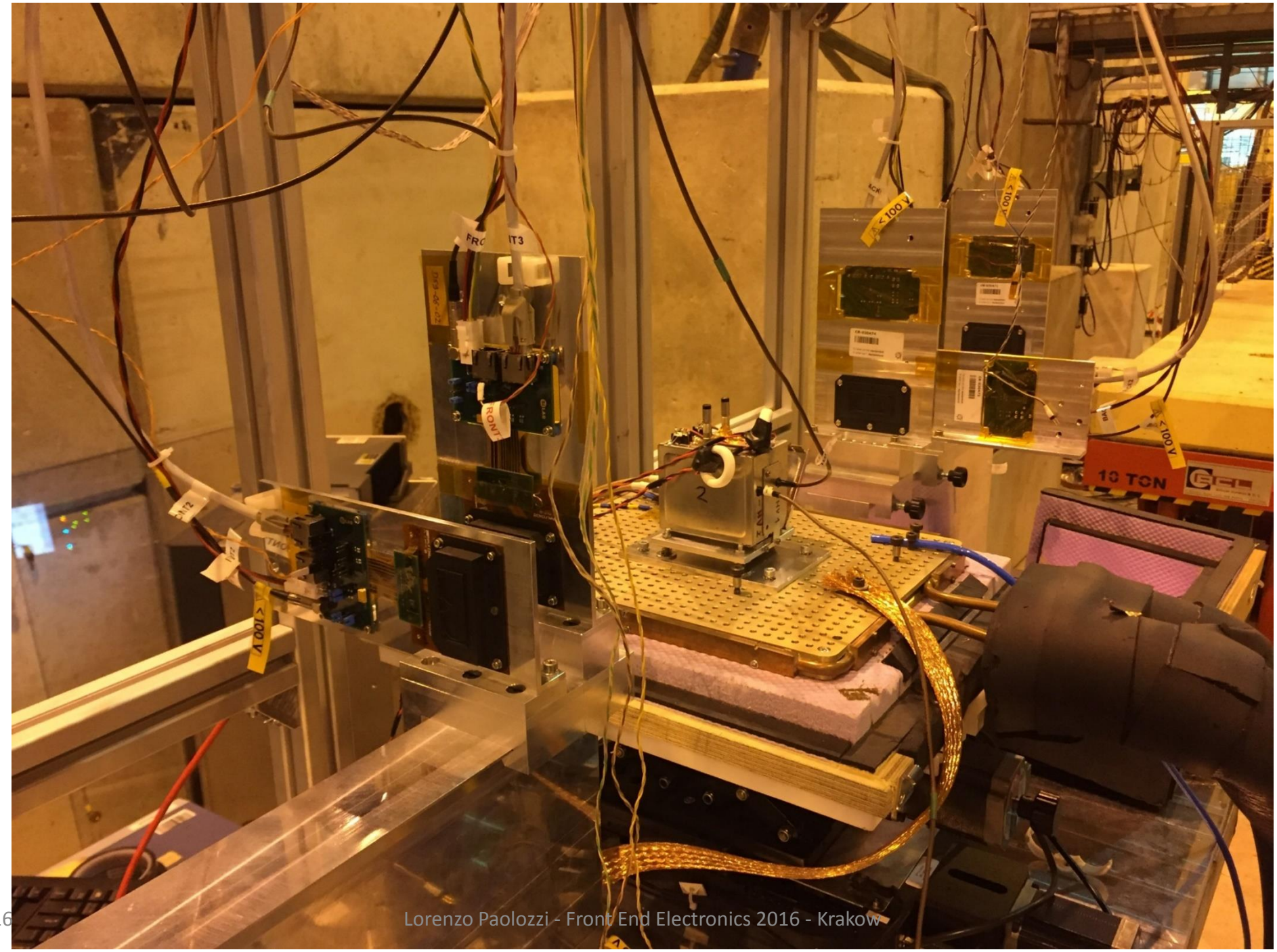
Board schematic design:



Mechanical support



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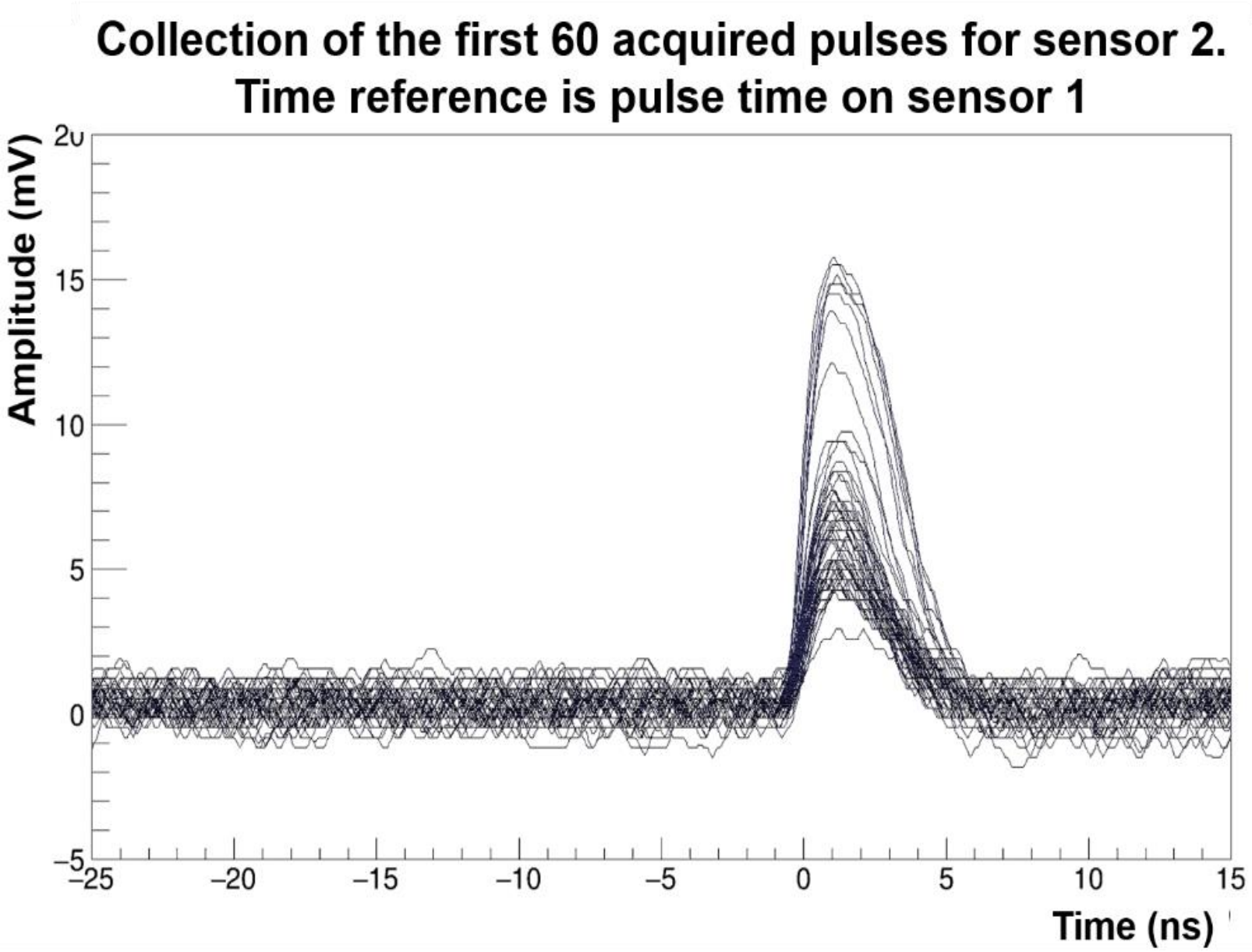
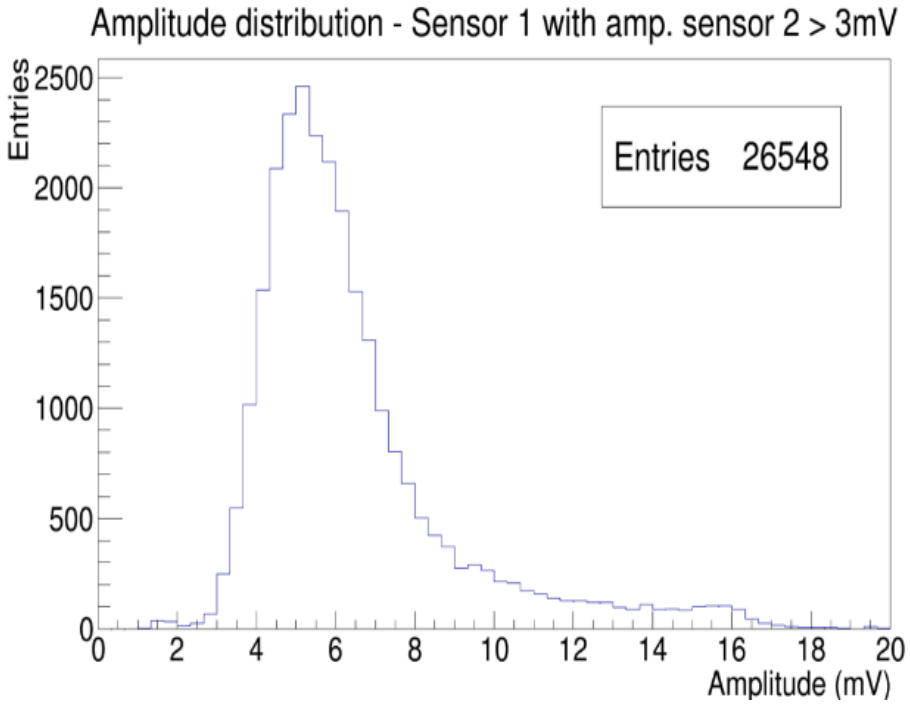
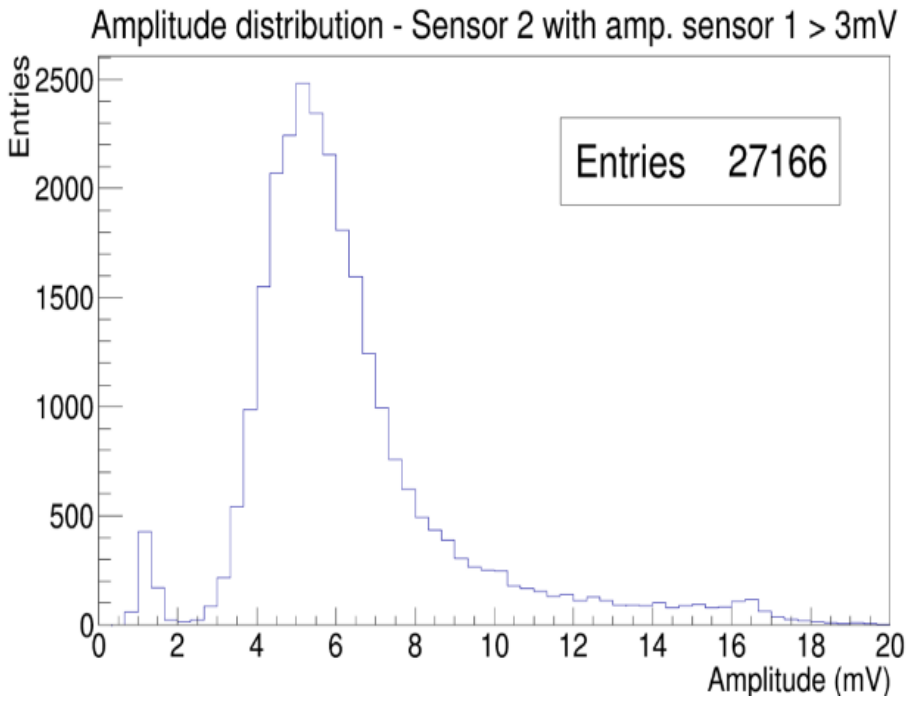


Efficiency



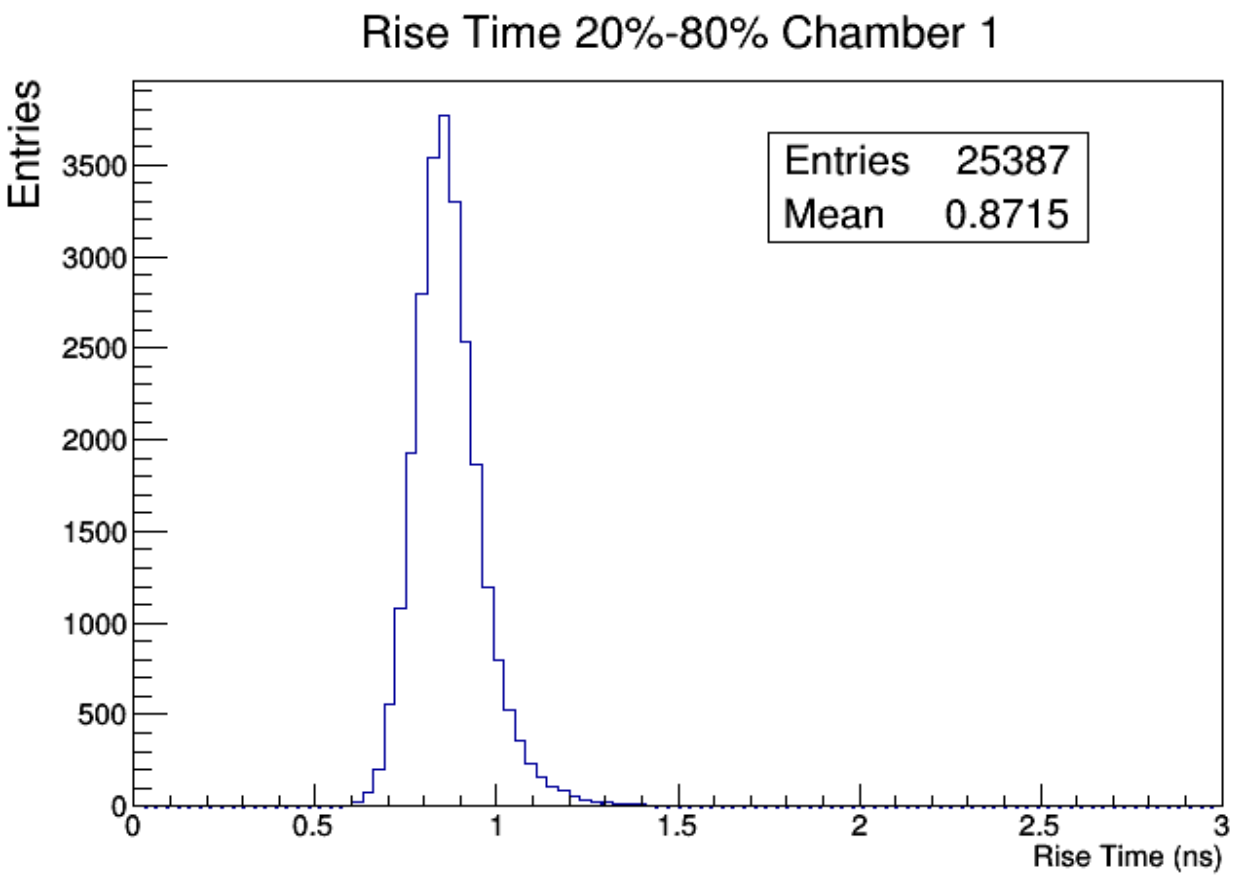


(Left) Pulse amplitude distribution for sensor 1, with event selection on sensor 2. (Right) Pulse amplitude distribution for sensor 2, with event selection on sensor 1

The result is a lower limit for efficiency of 99.7% for sensor 1 and 97.5% for sensor 2, being the latter limited by the beam divergence.

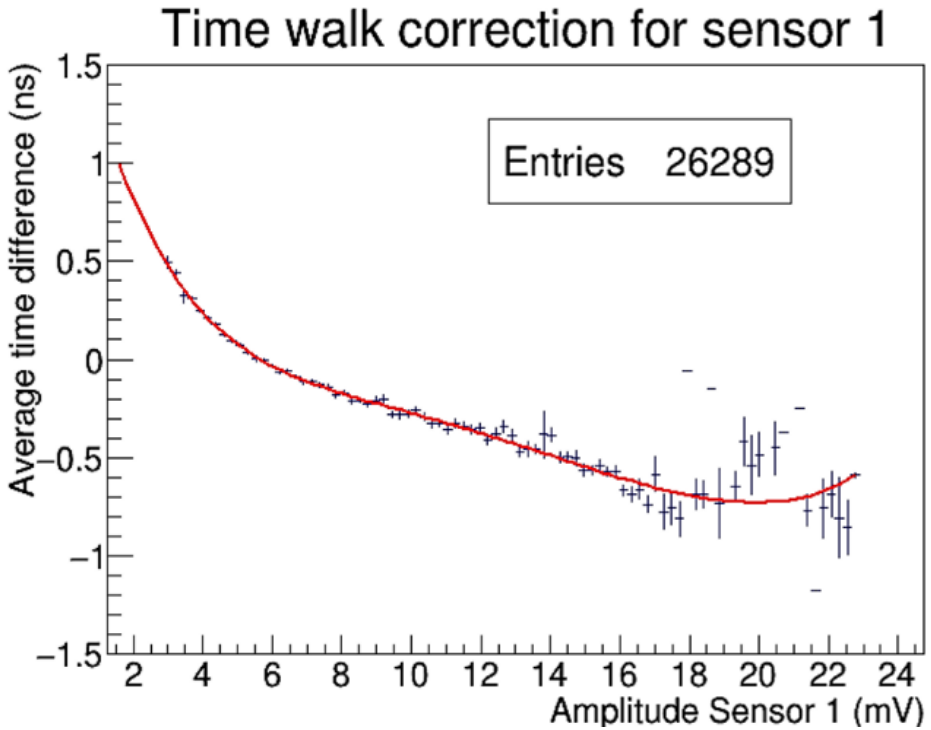
The measured amplifier ENC is 540 electrons RMS in the present working condition

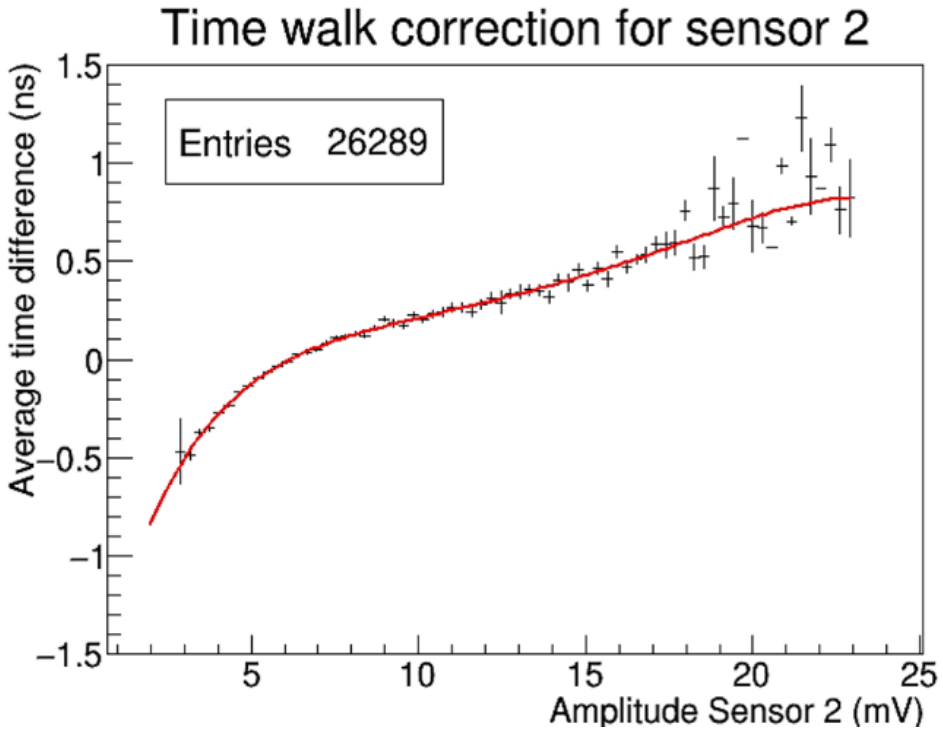
Time resolution studies



Rise time is compatible with the charge collection time for 100 um sensor with planar readout.

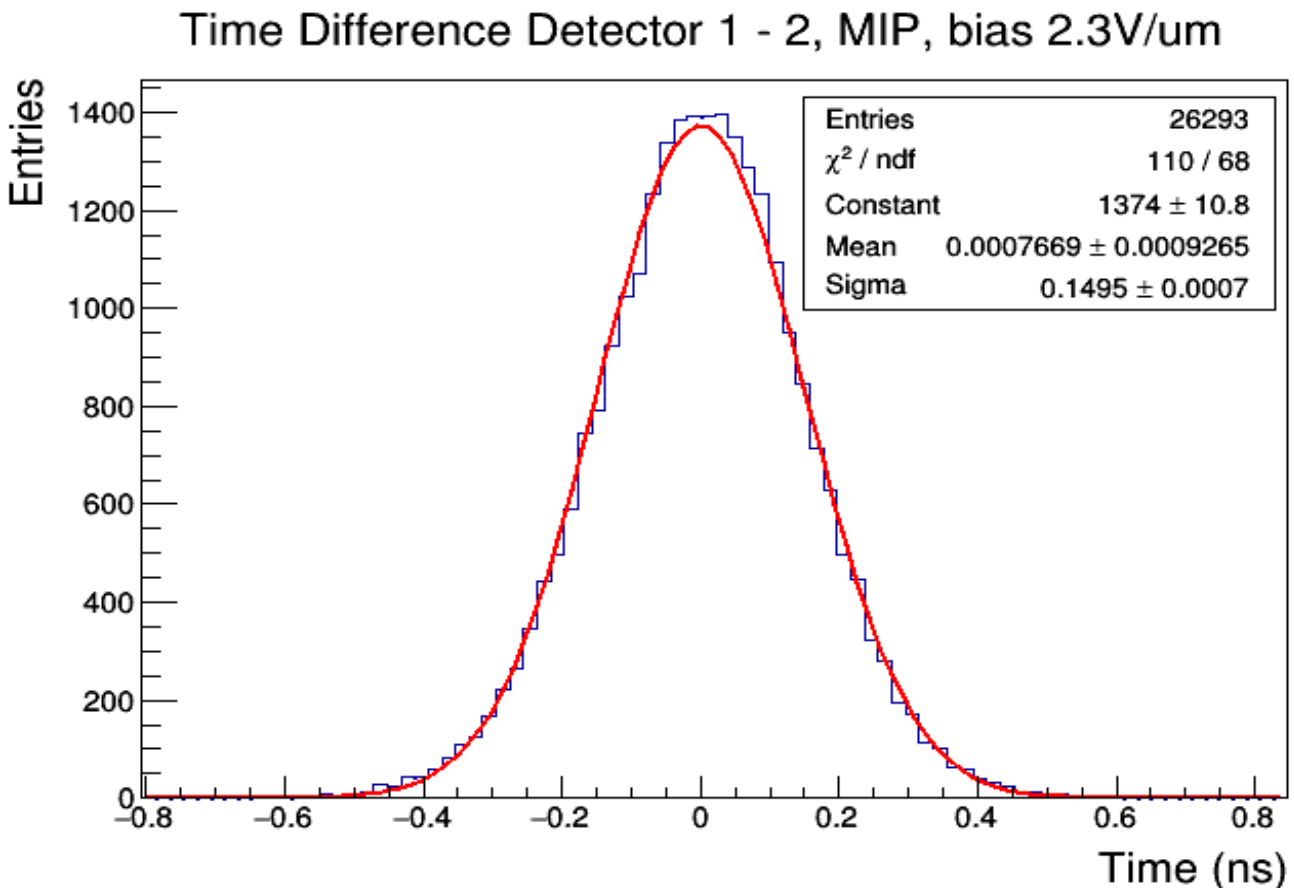
Time resolution studies





- The average pulse time difference as a function of the amplitude of sensor 1 (left) and sensor 2 (right).
- The pulse arrival time is evaluated at a fixed threshold of 2.3 mV in each sensor.
- The polynomial functions used for the correction are also shown.

Time resolution studies



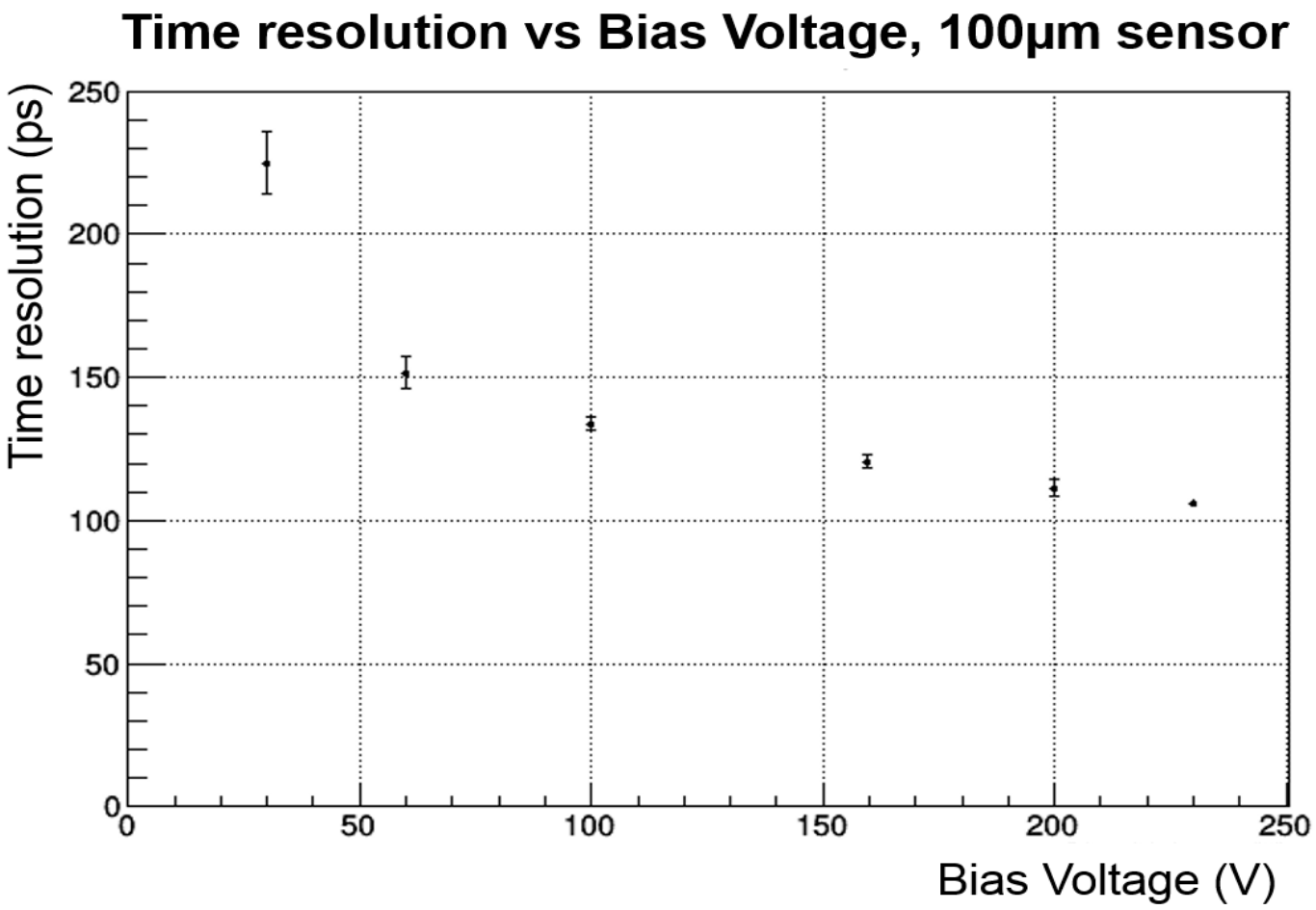
100ps time resolution with thin silicon pixel detectors and a SiGe HBT amplifier

http://dx.doi.org/10.1088/1748-0221/11/03/P03011

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

Assuming that both detectors have the same time resolution.

Time resolution studies



All measurements are done in the same experimental conditions.

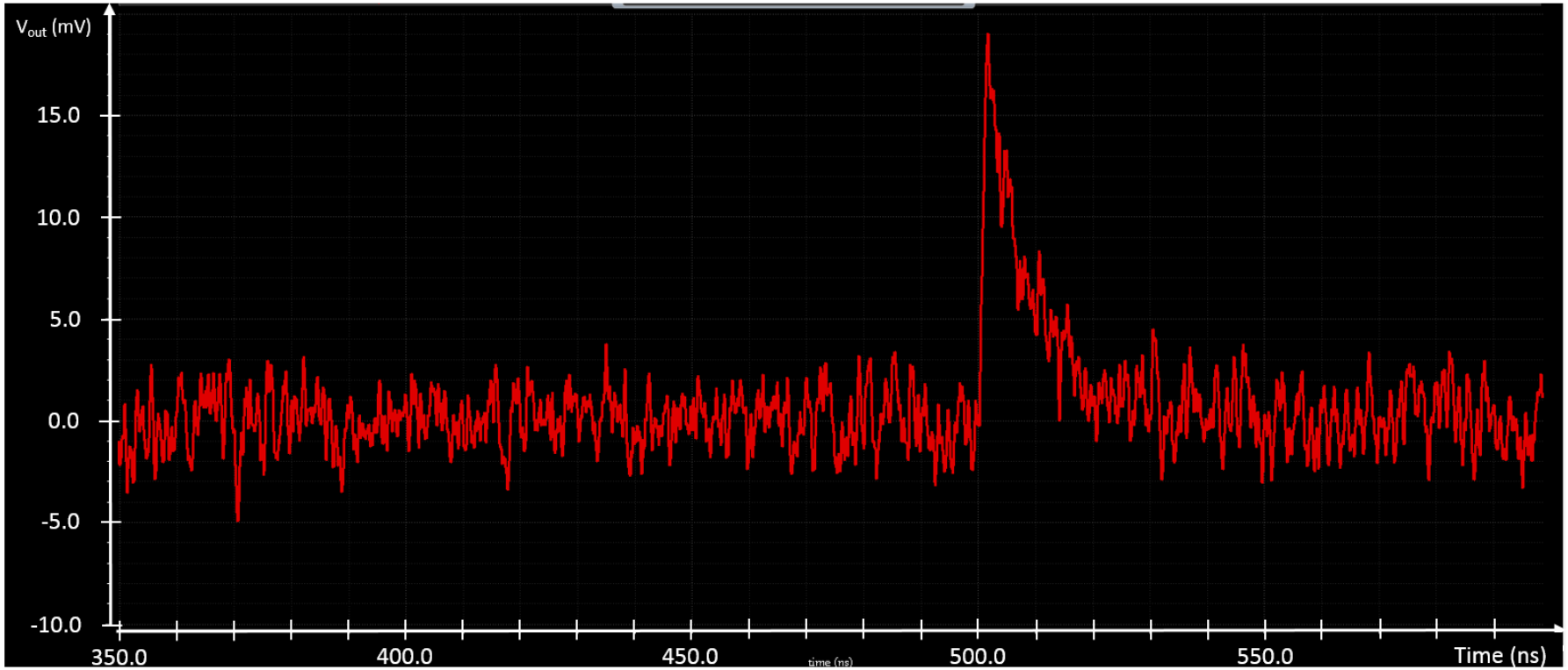
Future steps

Recent developments with new technology

The final chip will be developed in SG13S Bi-CMOS technology by IHP.

$$f_t = 0.25\ THz$$
$$\beta = 900$$

A new low-power consumption version of the amplifier has been developed and submitted on April 2016.



Input pulse characteristics:

$Q_{in} = 1\ fC$

$C_{in} = 1\ pF$

$\Delta t_{in,50\%} = 500ps$

Amplifier characteristics:

$W_{amp} = 150\ \mu W$

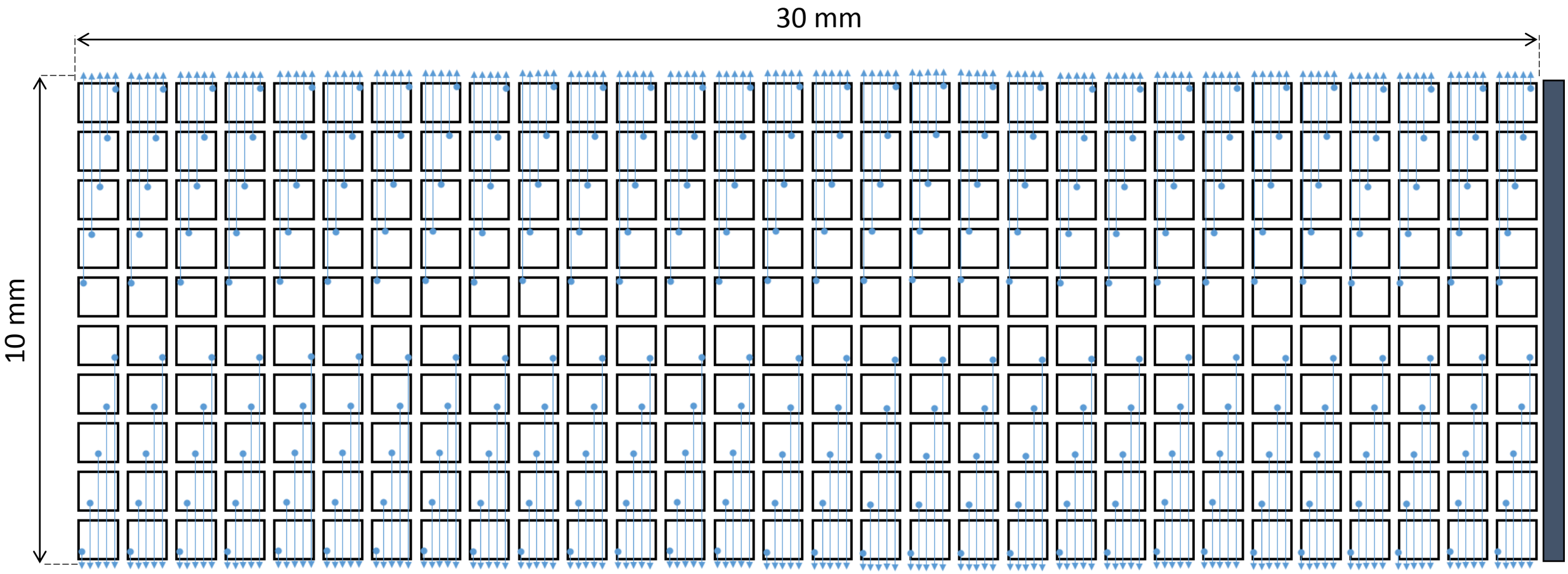
$ENC \cong 500\ e^{-}\ RMS\ on\ 1pF$

$dV_{out}/dQ_{source} = 30\ \frac{mV}{fC}$

The amplifier is followed by a single transistor driver to study the response on scope.
(Output amplitude loss $\sim 40\%$)

The new technology performance has been used only for reducing the power consumption of a factor ~ 20.

Sensor readout with monolithic chip.



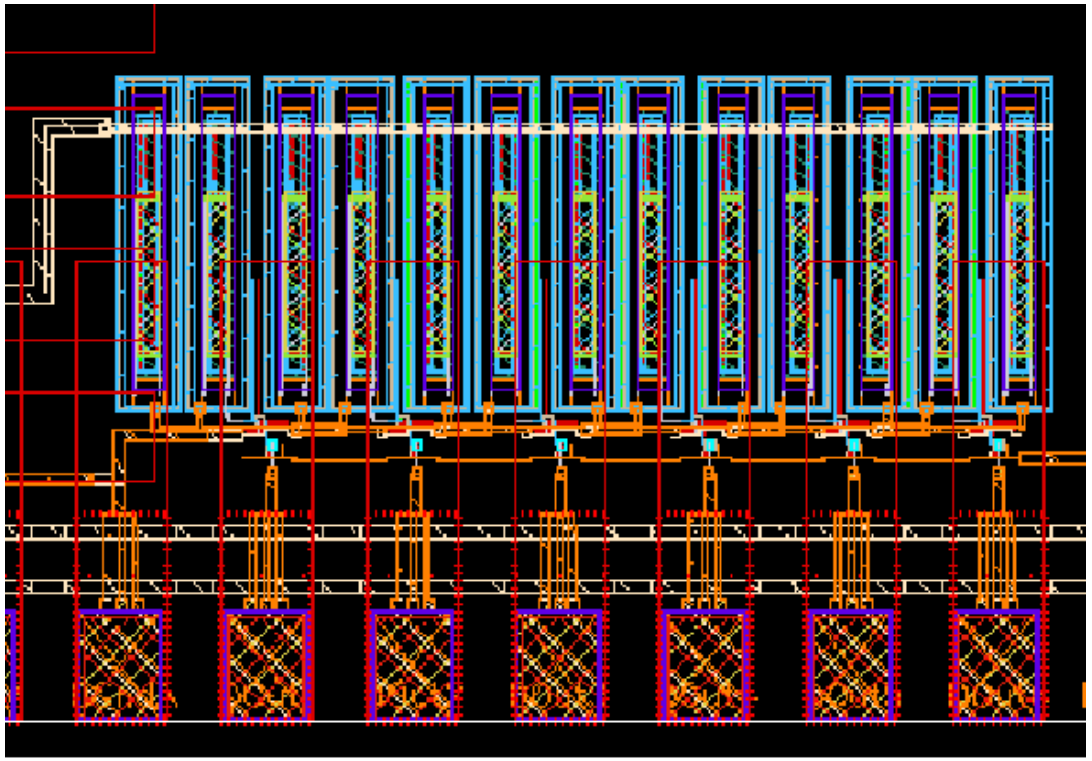
- Signal routing on sensor extremely simplified.
- Pre-amplification as close as possible to the pad (on the top and bottom sides in the example).
- Pulse discrimination and time digitization on chip.

Why monolithic integration ?

- Cost reduction.
- Simpler coupling sensor-electronics.
- Simpler implementation of the layered structure for a PET scanner.
- Easier signal extraction from the scanner.
- Scientific collaboration with the Foundry (IHP Microelectronics).

First monolithic integration studies

Test structures for the monolithic integration were submitted in the same run.



Study the charge collection, high voltage biasing on chip and sensor decoupling.

Design done in collaboration with Ivan Peric.

For the test structures we expect a collected charge of the order of $1000\ electrons$ and less than $100\ fF$ capacitance.

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Time digitization

Exploit the properties of state of the art SiGe transistors to produce 10 ps TDC.

SG13S technology from IHP: transistor performance $f_t = 0.25\,THz$ $f_{max} = 0.3\,THz$ $\beta = 900$

- Few picosecond buffer delay.
- Delay precision of the order of ~ 100 fs.
- $> 20\,GHz$ oscillation frequency can be easily achieved with a purely digital schematics.
- Small dynamic range required for PET scanners.

- 10 ps binning TDC with 4 ps statistical resolution and low power consumption can be designed with a very simple schematics.

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Conclusions

- **A strategy** to obtain excellent sub-ns time resolutions with silicon sensors has been defined and tested.
- A time resolution of approximately **100 ps for the detection of minimum ionizing particles** has been measured with a 100µm thick p-on-n silicon sensor read out by SiGe HBT discrete component electronics and with 1 mm^2 pad pitch.
- The **sensor layout and the electronics technology** were carefully selected in order to achieve this result.
- **No pulse fitting** or multi-threshold techniques have been used.
- The time resolution obtained is **compatible with our expectations**.
- Great improvement is possible thanks to the **fast developing** SiGe technology.

Thank you