Fast sensor and front-end electronics development for TT-PET

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The TT-PET Collaboration

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

The TT-PET collaboration:

- University of Geneva
- CERN
- INFN of Roma Tor Vergata
- University of Bern
- Hôpital cantonale de Genève
- Stanford University

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

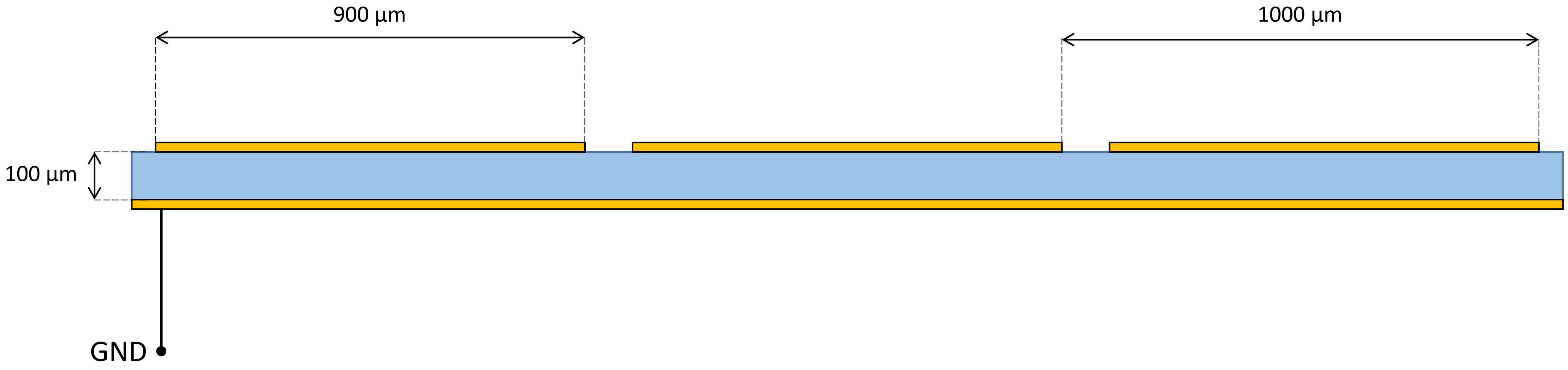
A silicon thin Time-Of-Flight detector.

- Space resolution of **1.0 x 1.0 mm^2**
- **Target TOF** measurement of for PET $\boldsymbol{30ps\ RMS}$.
- **Silicon technology** for particle detection.
- **First monolithic integration of BiCMOS technology**. Development in collaboration with IHP microelectronics foundry.

I will focus on sensor design and amplifier technology choice.

Sensor optimization for time measurement

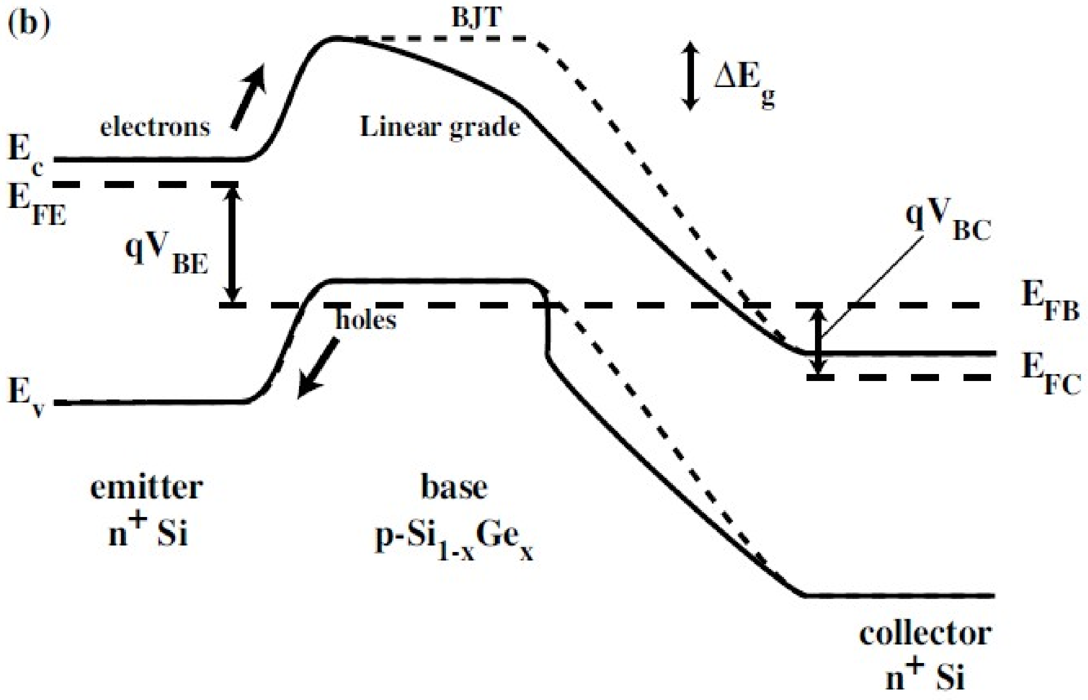
Pad readout layout



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

SiGe technology for very low noise fast amplifiers

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



SiGe heterojunction bipolar transistor technology.

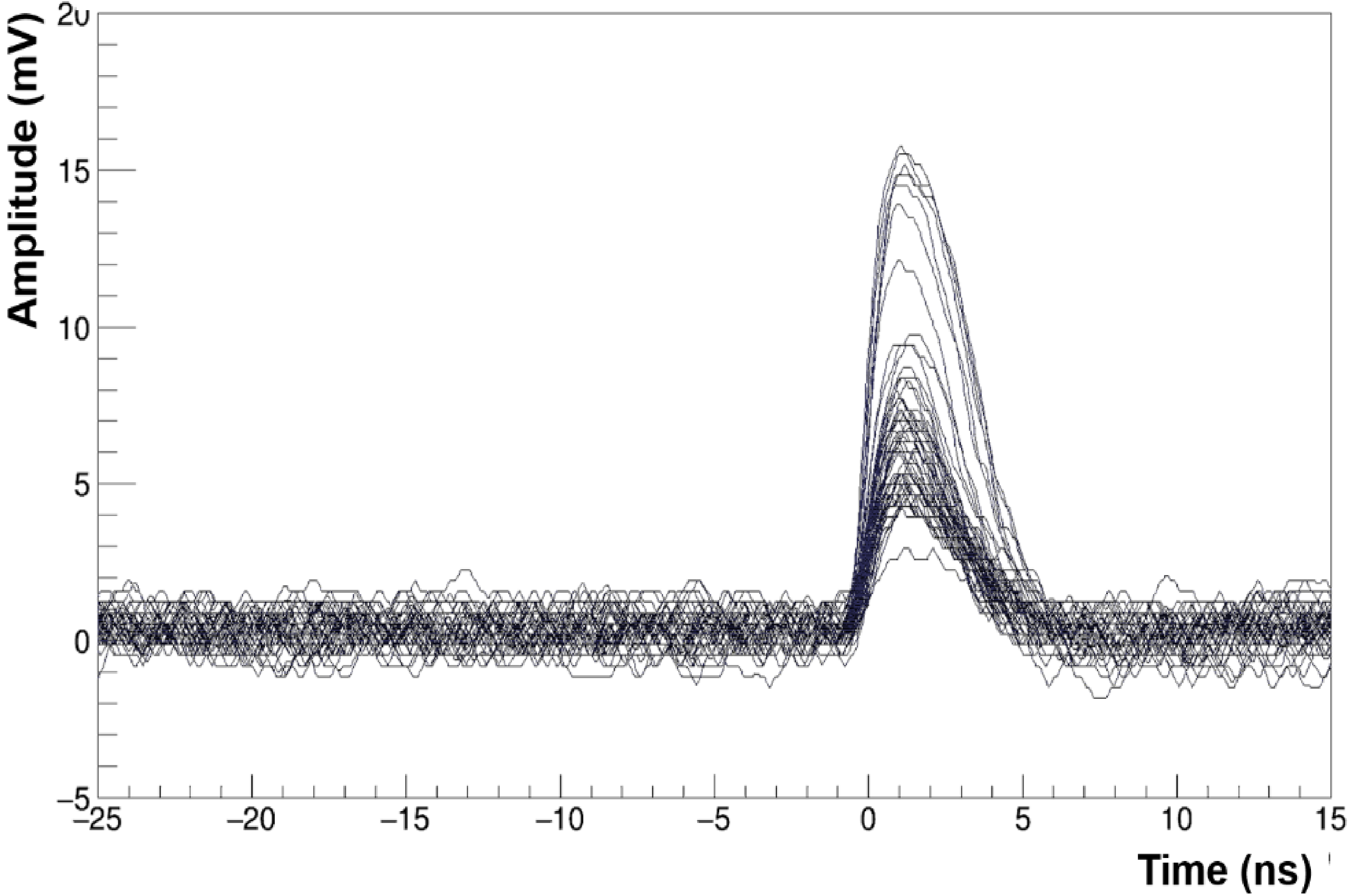
Equivalent to introducing an electric field in the base.

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

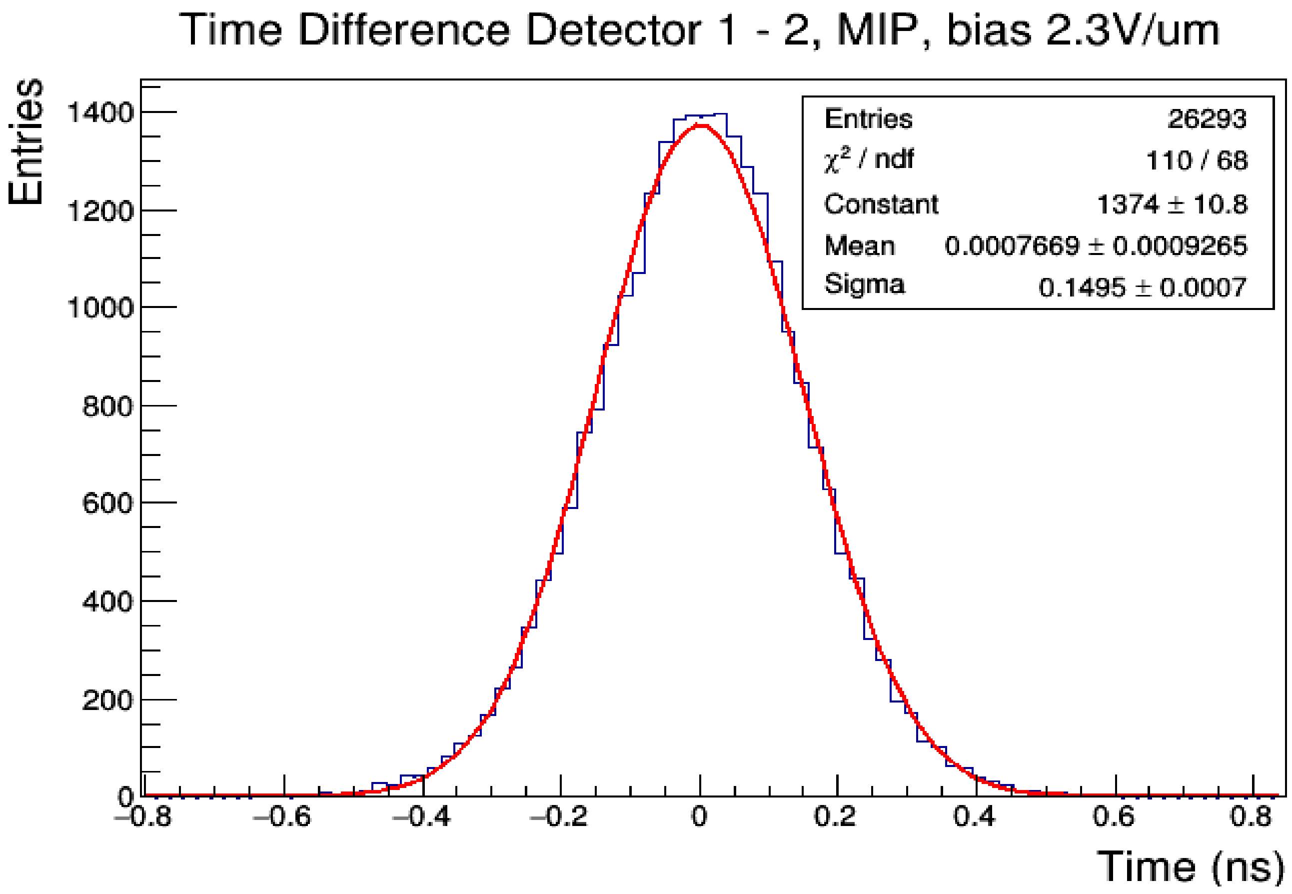
$\beta = 900$
$f_t = 250\ GHz$

Time resolution measurement with MIPs

Collection of the first 60 acquired pulses for sensor 2.
Time reference is pulse time on sensor 1



Time resolution studies



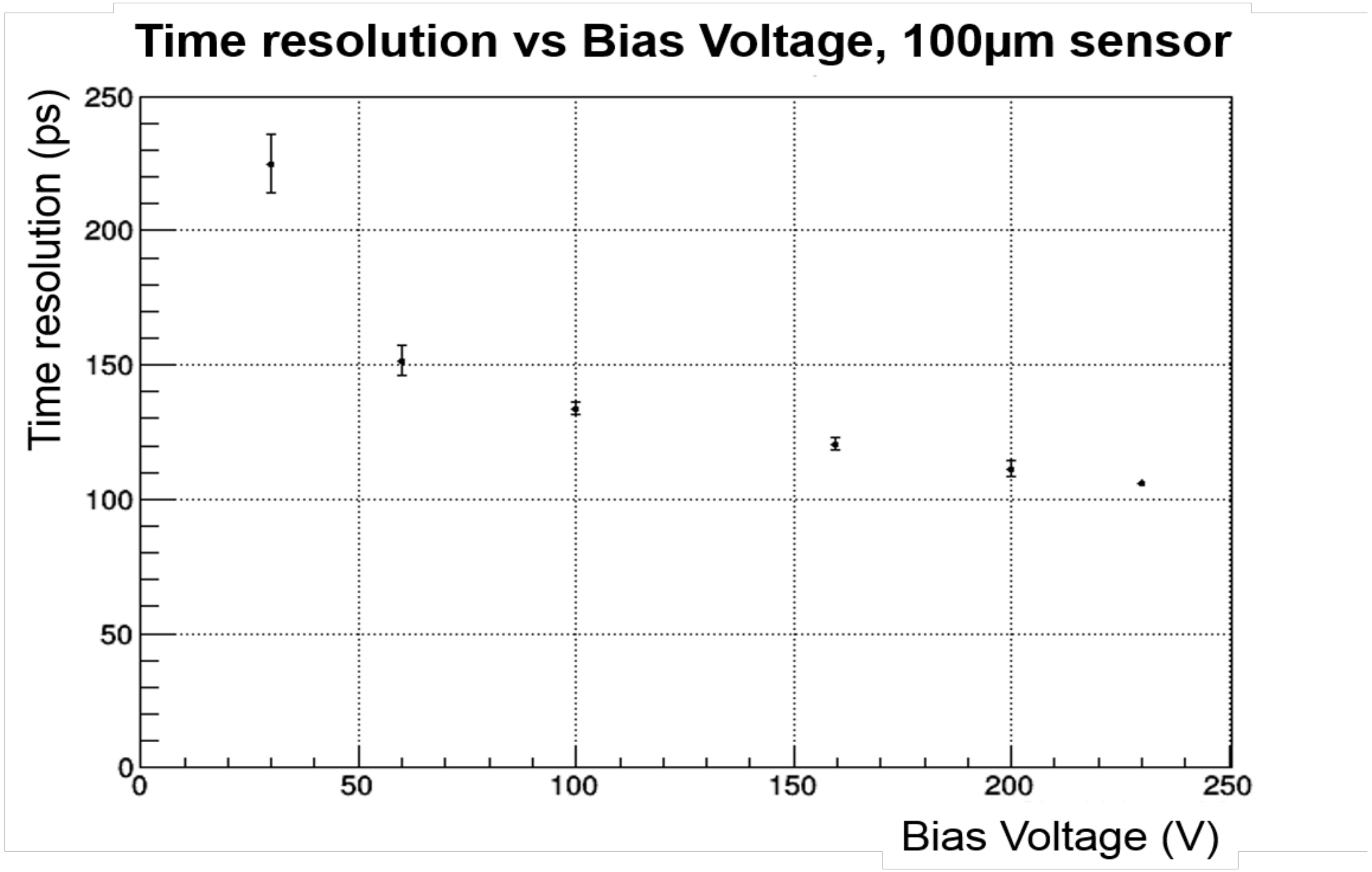
100ps time resolution with thin silicon pixel detectors and a SiGe HBT amplifier

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



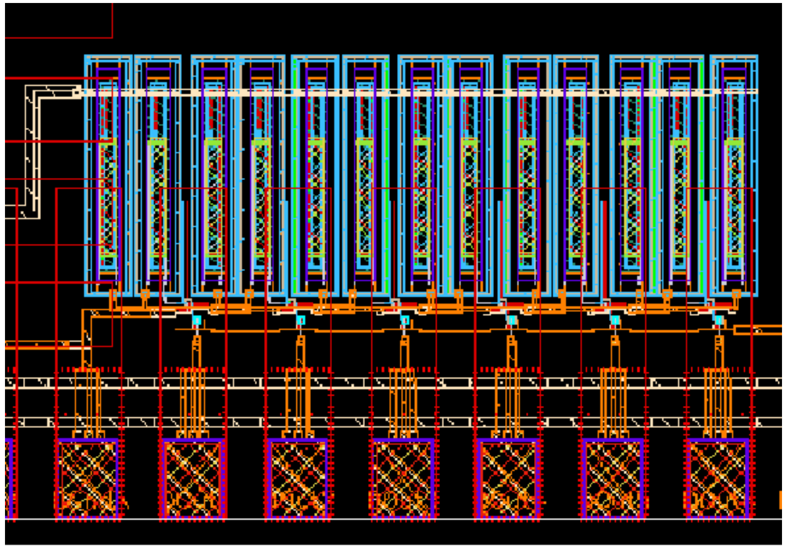
All measurements are done in the same experimental conditions.

Monolithic integration in a SiGe process

Monolithic integration studies

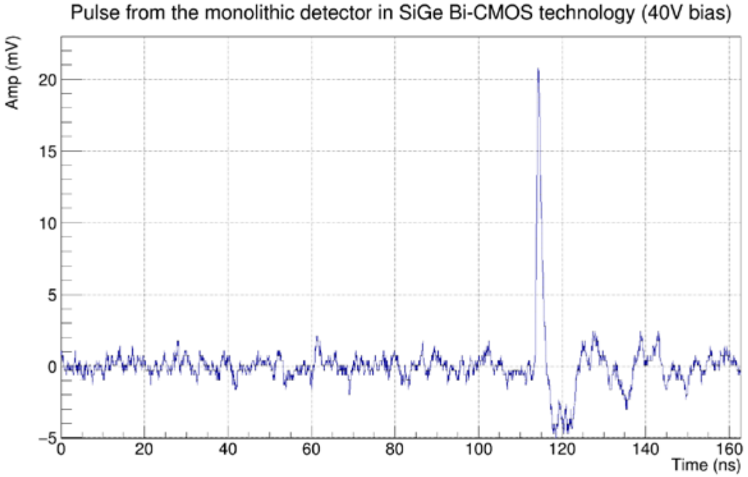
Part I: singe side sensors.

- A first test was done in April 2016, with simple structures that did not require backside processing and very high voltage.
- Sensor design done in collaboration with professor Peric (Karlsruhe Institute of Technology)

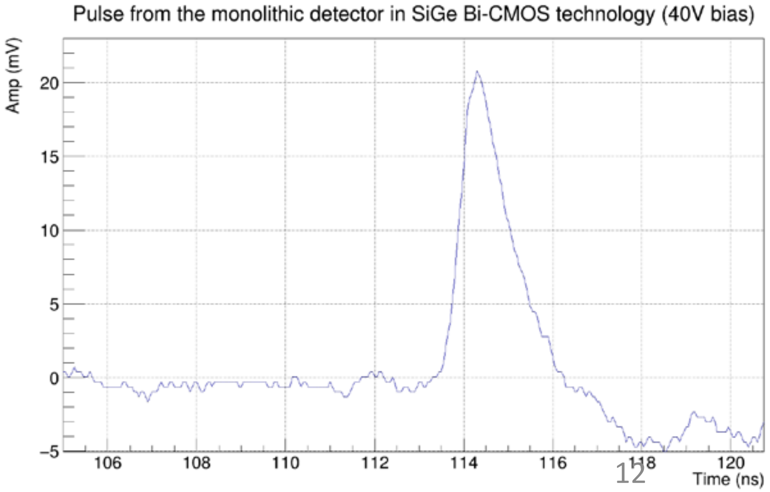


The sensors are working and the amplifier performs a very fast integration with very low power consumption.

First implementation of a monolithic sensor in SiGe Bi-CMOS technology.



Zoomed view

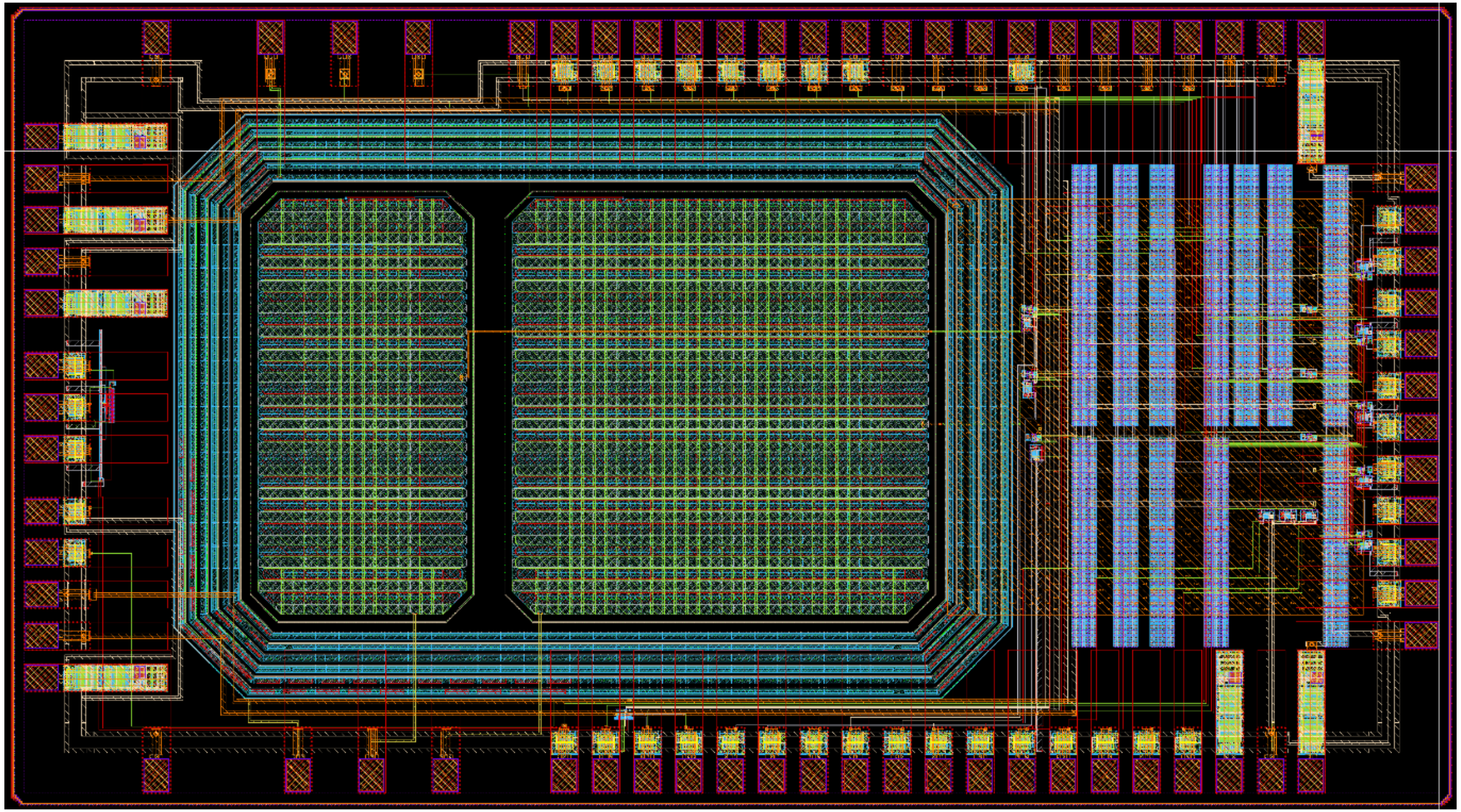


$$t_{rise,20-80\%} = 325\ ps$$

Monolithic integration studies

Part II: double side sensors.

- New layout on high resistivity wafer and backside processing: September 2016. In production.



Study the charge collection, high voltage biasing on chip and sensor coupling to front end.

Sensor design done in collaboration with Dr Rücker (IHP microelectronics).

Time digitization

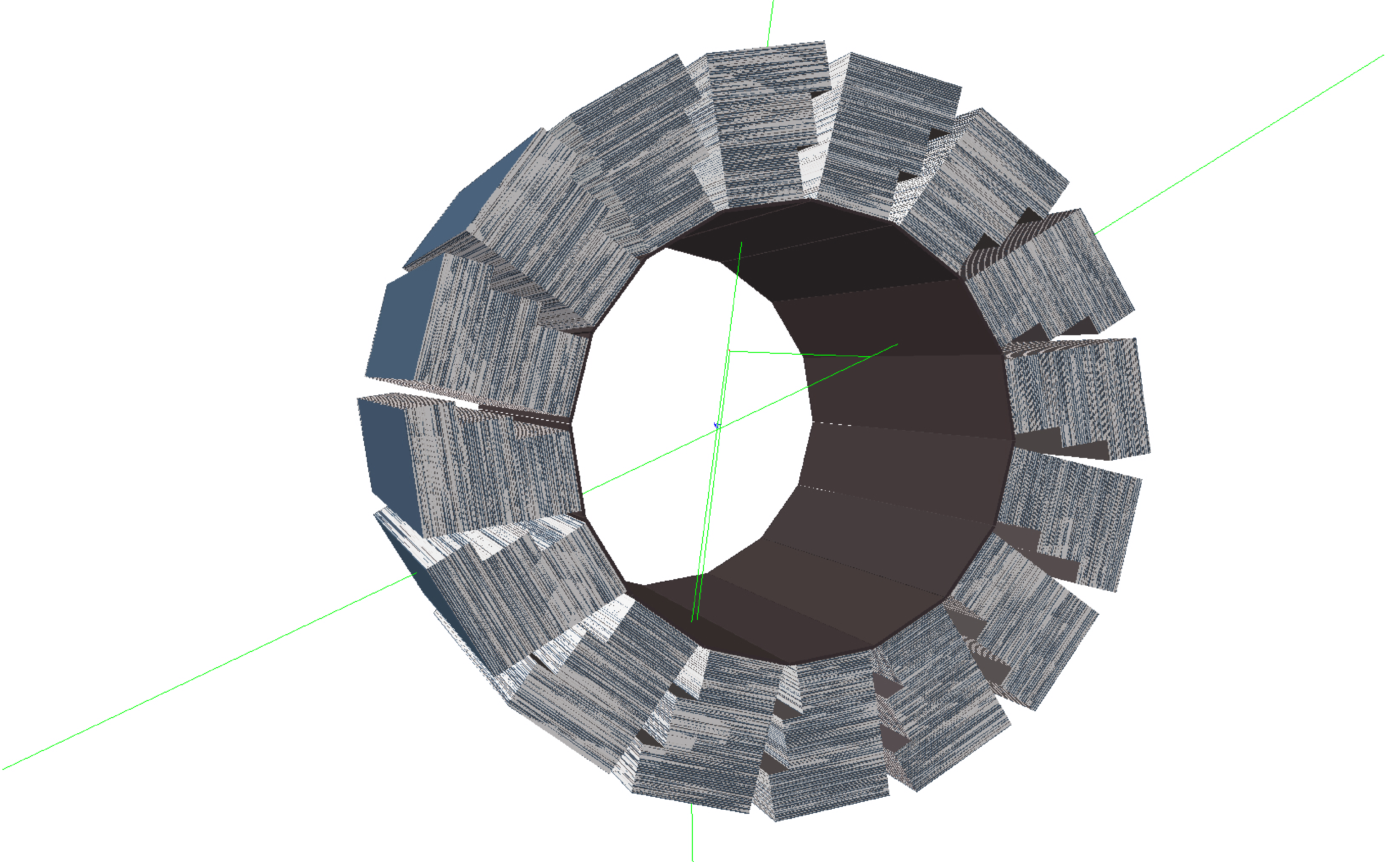
Exploit the properties of state of the art SiGe transistors to produce a 10 ps **TDC**.

- Few picosecond buffer delay.
- Delay precision of the order of $\sim 100\ \mathrm{fs}$.
- Original design with very low power consumption (<1 mW/channel).
- Dynamic range optimized for a PET scanner.

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

Conclusions

- **A challenging project** in medical physics field, that will require **a great R&D effort on sensor and electronics.**
- A contact between the community of **fast timing** and silicon **pixel** detector**.**
- A time resolution of approximately **100 ps for the detection of minimum ionizing particles** has been measured.
- The **sensor layout and the electronics technology** were carefully selected in order to achieve this result.
- Great improvement is possible thanks to the **fast developing** SiGe technology.



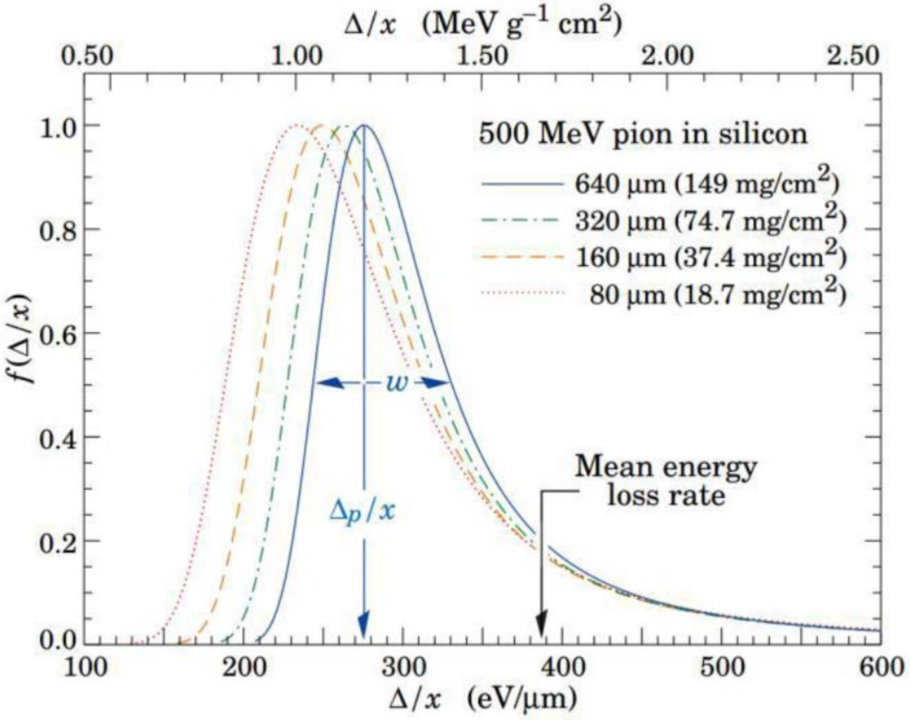
Backup

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.



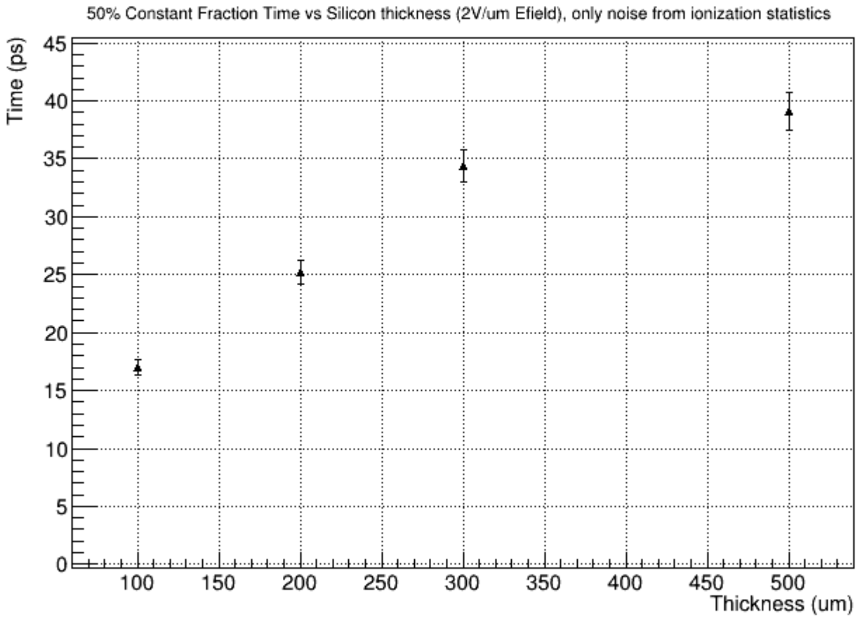
Most of the produced clusters have a small charge.
Few events with very large transferred energy are possible.

Charge collection noise

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

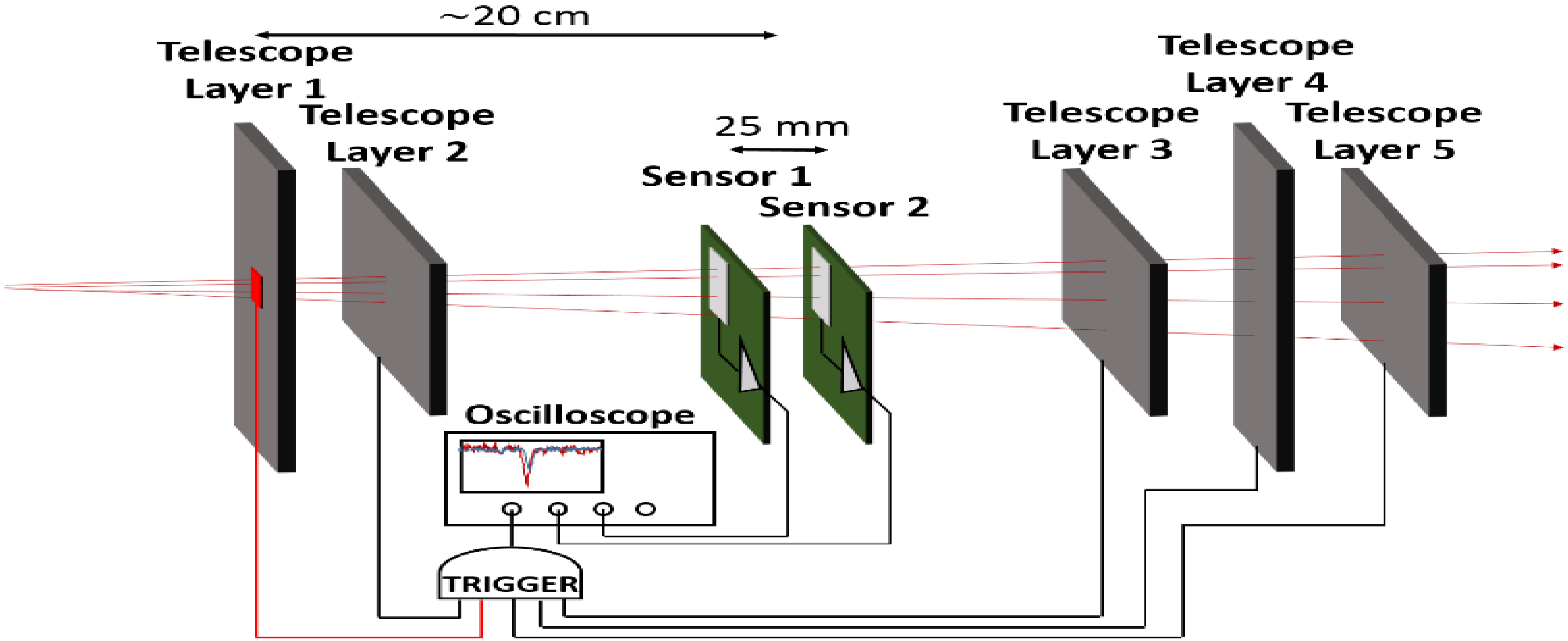
$$i_{ind} = -\frac{qv}{D}$$

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).

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.

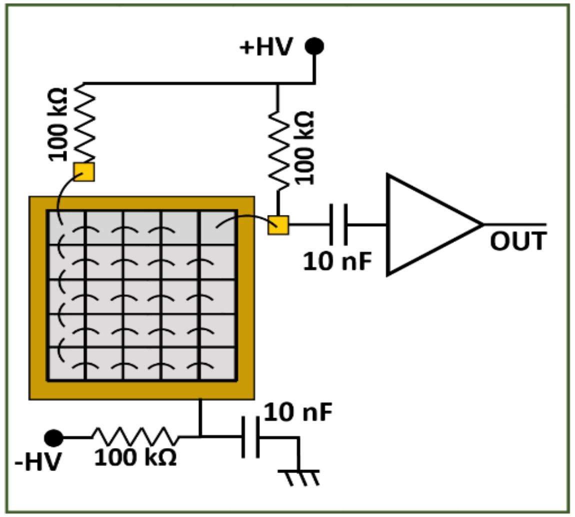
Signal digitized with Lecroy WaveMaster 820zi oscilloscope.

Trigger produced by the external telescope.

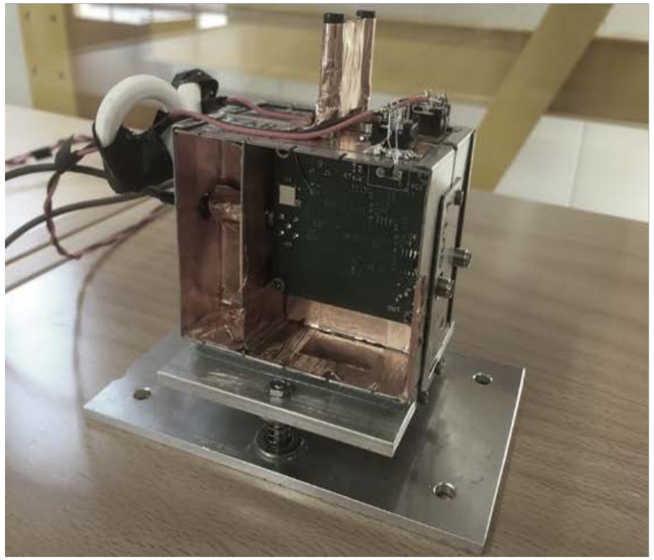
Trigger area limited to 500 um x 500 um (centered on test detectors) by the first telescope layer, to evaluate efficiency.

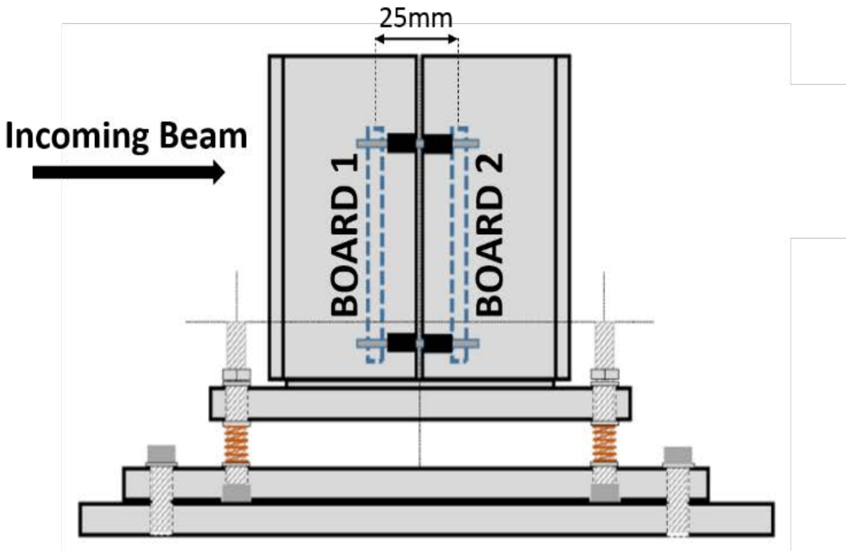
Experimental setup

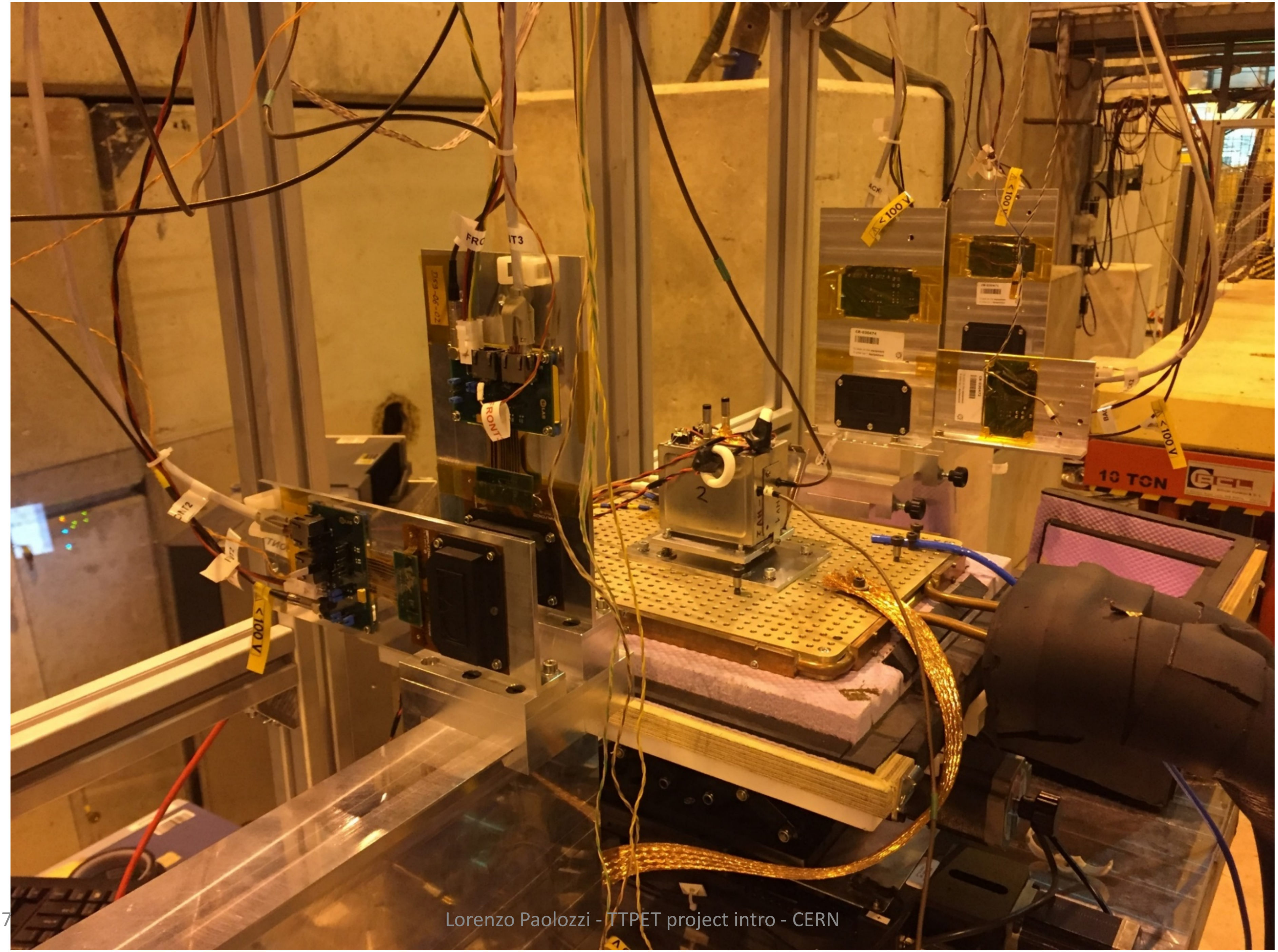
Board schematic design:



Mechanical support






< 100 V
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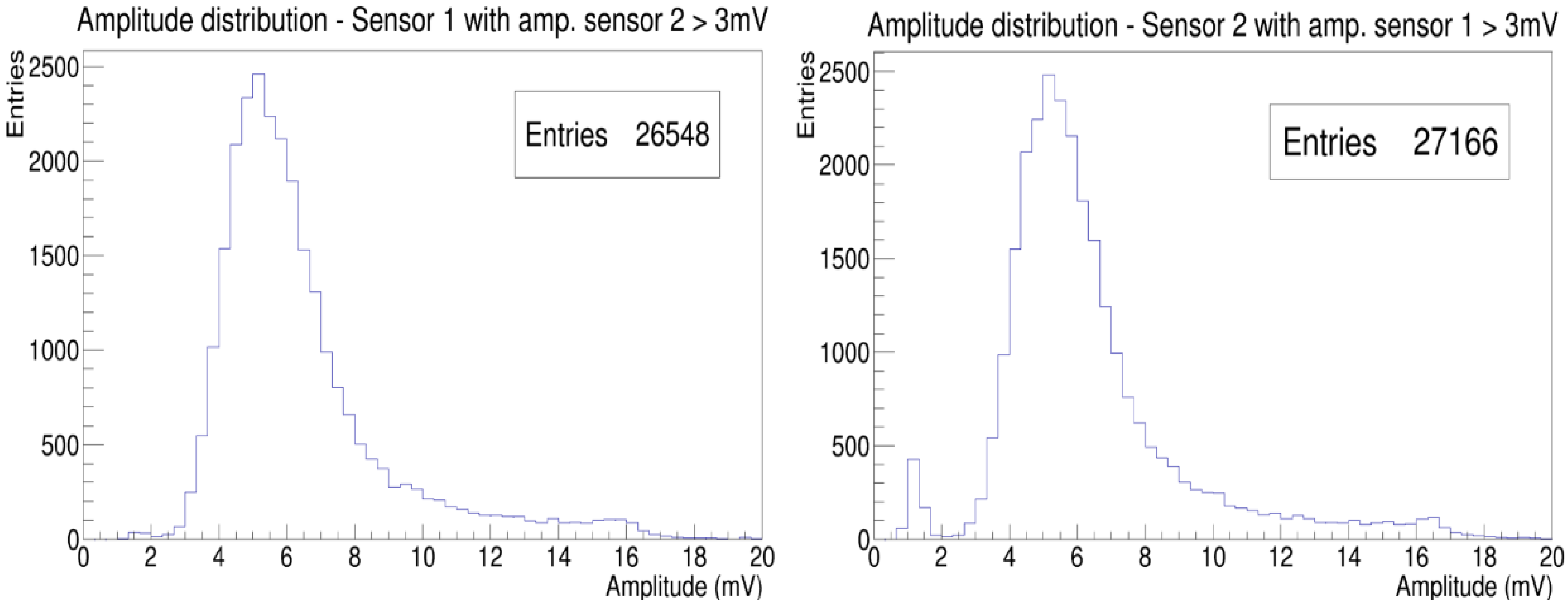
2

Efficiency

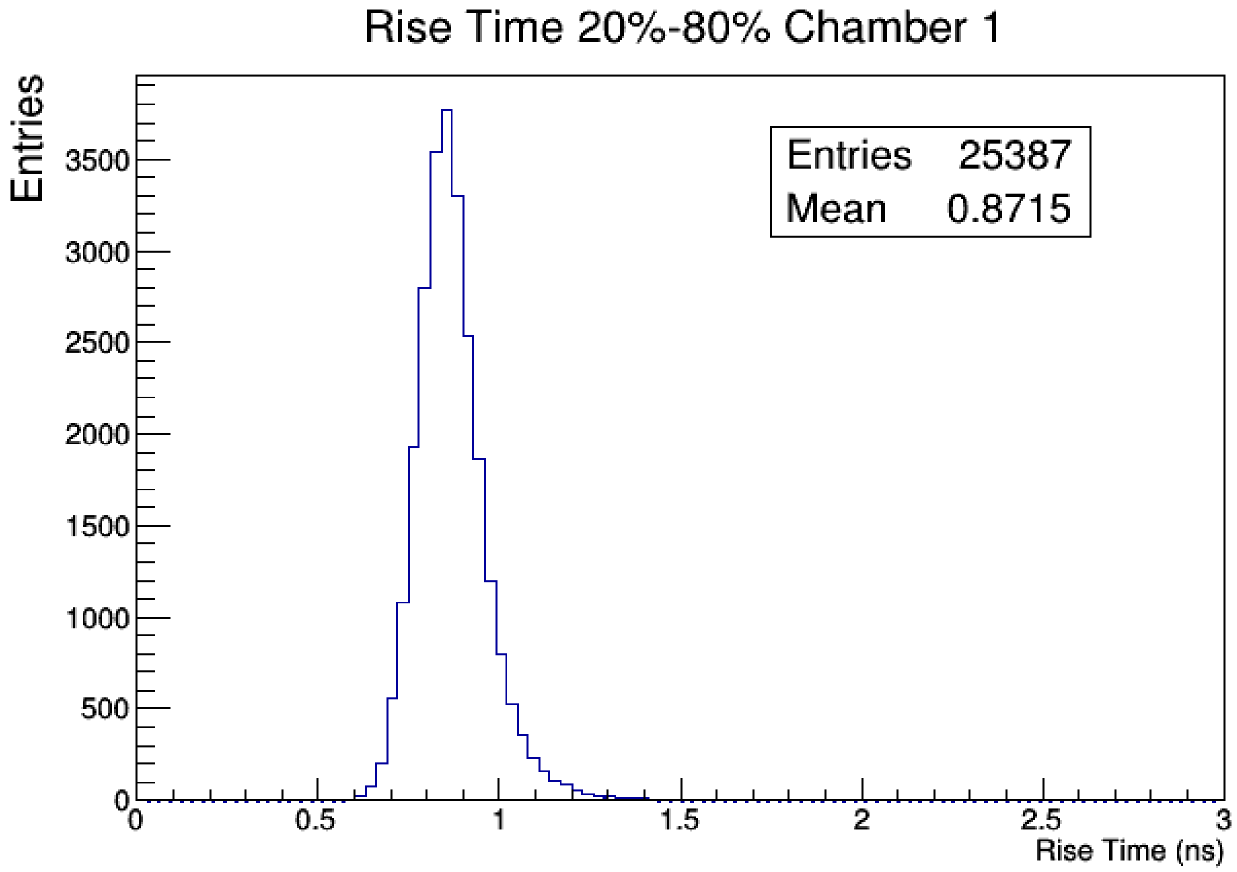


(Left) Pulse amplitude distribution for sensor 1, with event selection on sensor 2. (Right) Pulse amplitude distribution for sensor 2, with event selection on sensor 1

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.

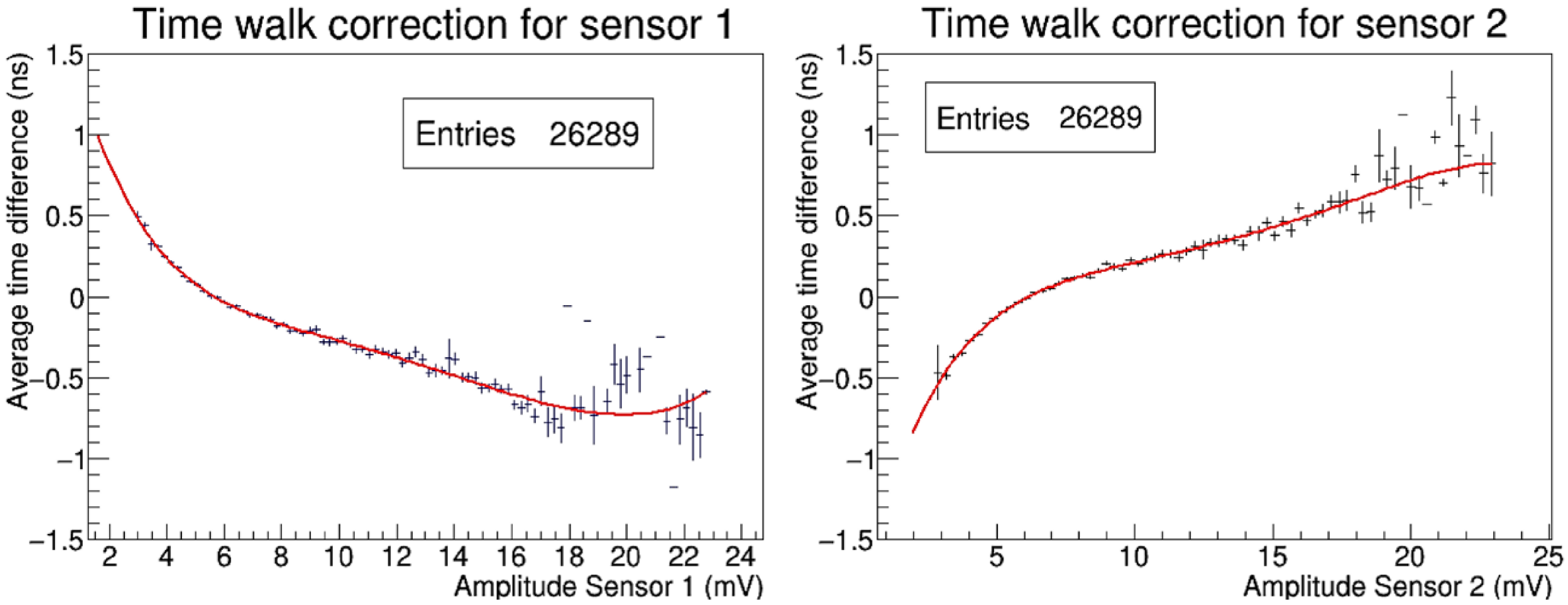
The measured amplifier ENC is 540 electrons RMS in the present working condition

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.