The MONOLITH ERC Advanced project: towards **picosecond timing** with monolithic silicon

Giuseppe Iacobucci — Université de Genève

UNIVERSITÉ DE GENÈVE

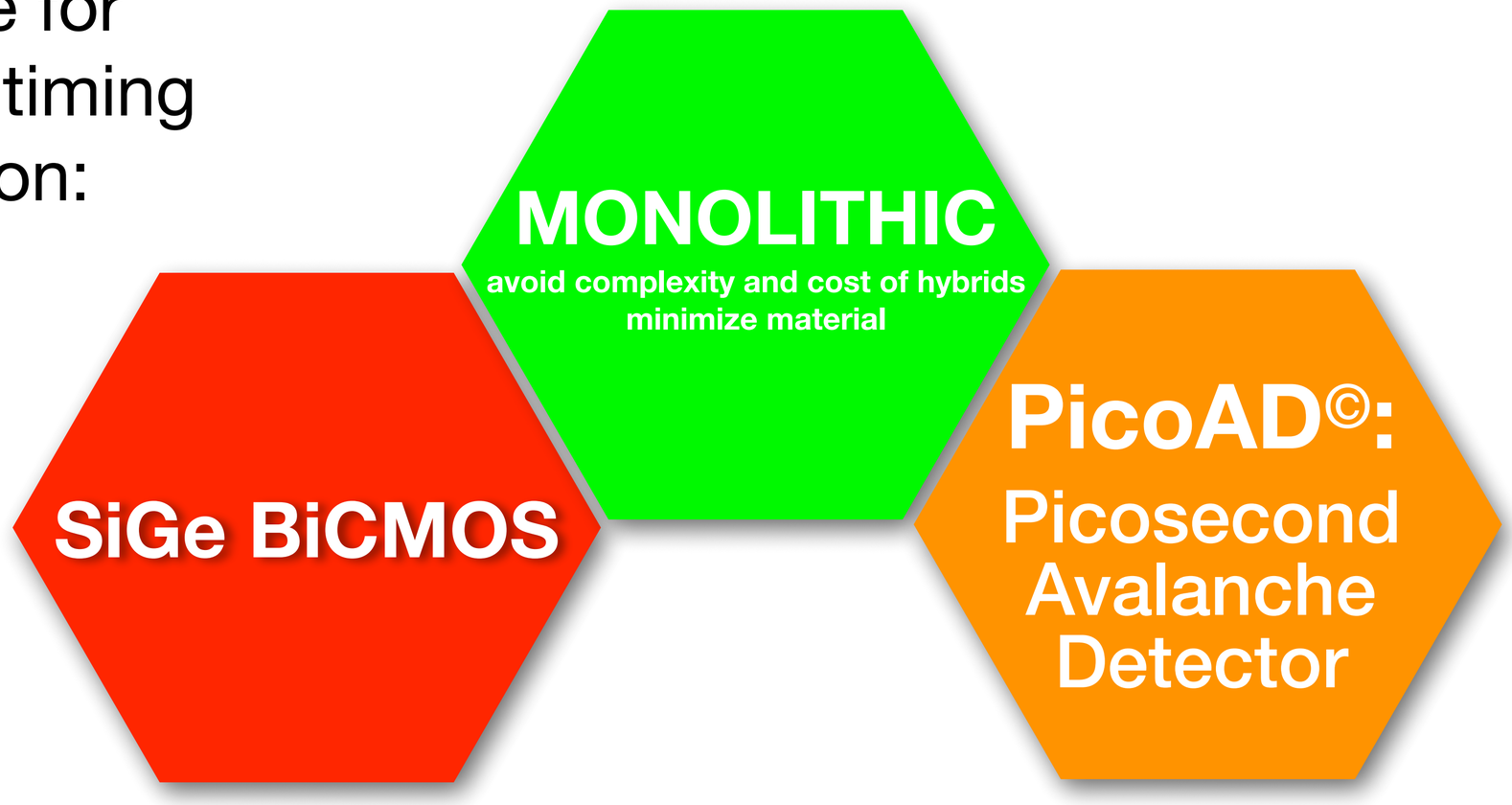
Swiss National Science Foundation

erc
European Research Council
Established by the European Commission

The MONOLITH Project

Funded by the H2020 ERC Advanced grant 884447,
July 2020 - June 2025

Our recipe for picosecond timing with silicon:



The UniGe Silicon Team

Giuseppe Iacobucci
- project P.I.

Thanushan Kugathasan
- Lead ASIC design
- Analog electronics

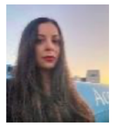
Leonardo Cecconi
- ASIC design
- Digital electronics

Stefano Zambito
- Laboratory tests
- Data analysis

Jordi Sabater Iglesias
- Detector simulation
- Laboratory tests

Matteo Milanesio
- Laboratory tests
- Data analysis

Antonio Picardi
- ASIC design
- Analog electronics

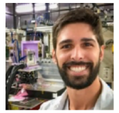


Rafaella Kotitsa
- Sensor simulation
- Data analysis

Carlo Alberto Fenoglio
- Digital electronics
- ASIC test

Lorenzo Paolozzi
- Sensor design
- Analog electronics

Roberto Cardella
- Sensor design
- Analog/Dig electronics



Mateus Vicente
- System integration
- Laboratory tests

Chiara Magliocca
- Laboratory tests
- Data analysis

Théo Moretti
- Laboratory tests
- Data analysis

Jihad Saidi
- Laboratory tests
- Data analysis

Luca Iodice
- Analog electronics
- ASIC test

Andrea Pizarro Medina
- Data analysis
- Laboratory tests

Ivan Semendyaev
- Data analysis
- Laboratory tests

Didier Ferrere
- System integration
- Laboratory tests

Yannick Favre
- Board design
- RO system

Sergio Gonzalez-Sevilla
- System integration
- Laboratory tests

Stéphane Débieux
- Board design
- RO system

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Marzio Nessi
CERN & UNIGE

Matteo Elviretti
IHP Mikroelektronik

Funded by:

Swiss National Science Foundation

European Research Council
Established by the European Commission

Sinergia

ATTRACT

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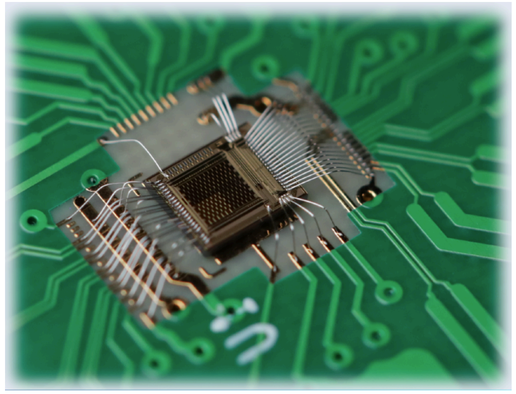
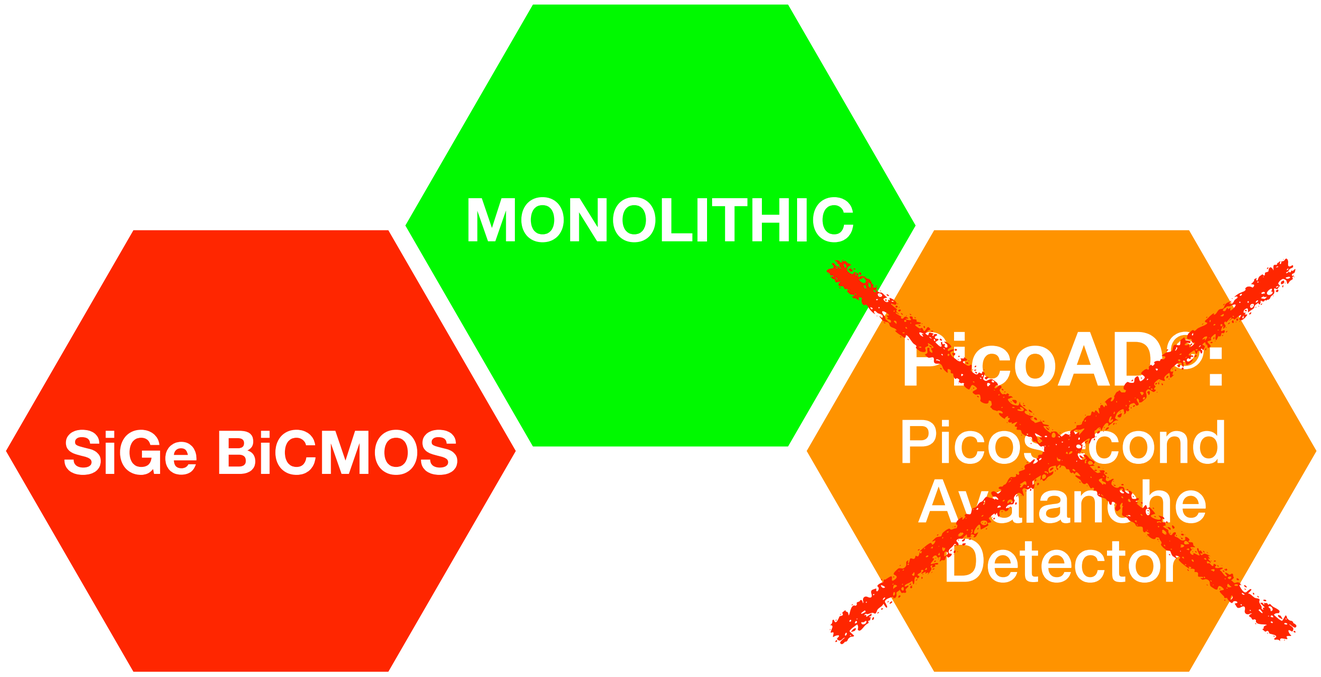
UNITEC

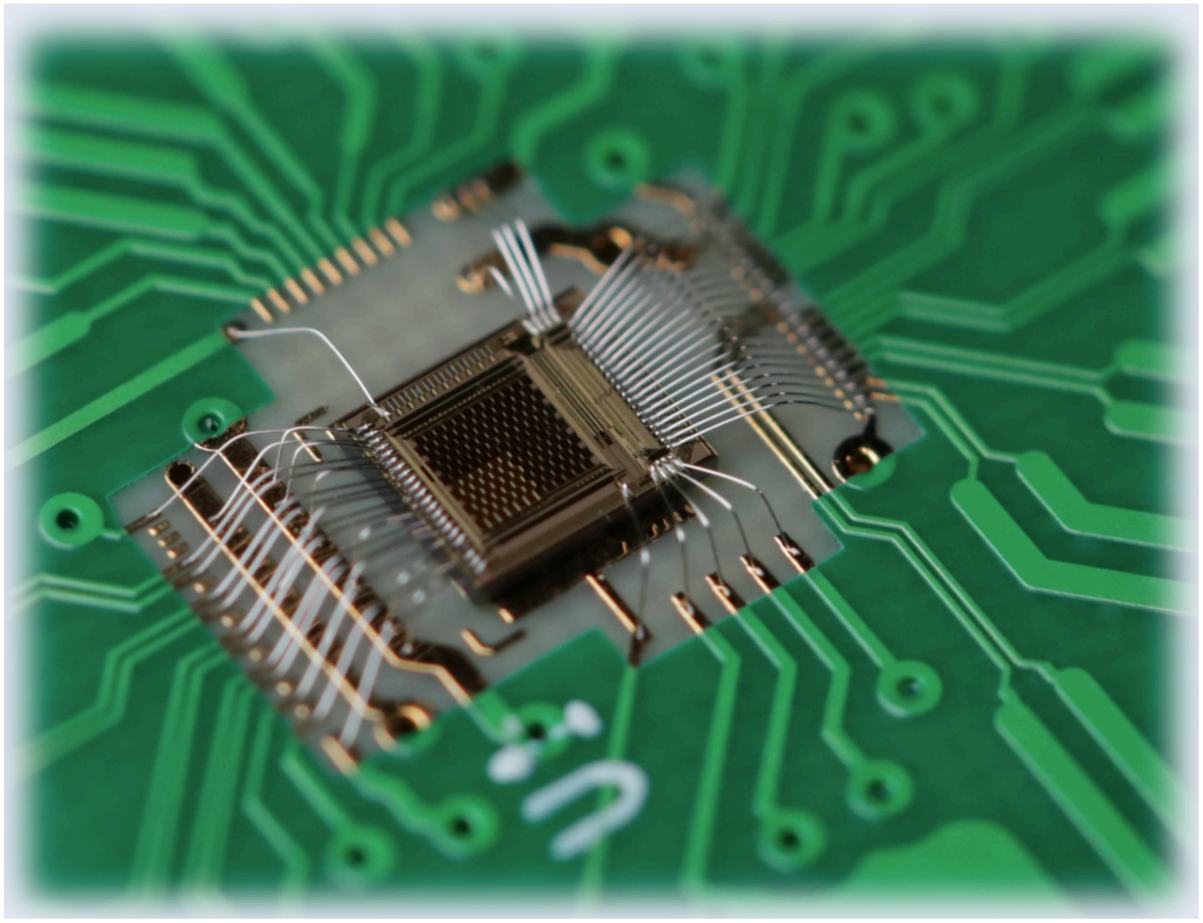
MONOLITH



2022 prototype without gain layer



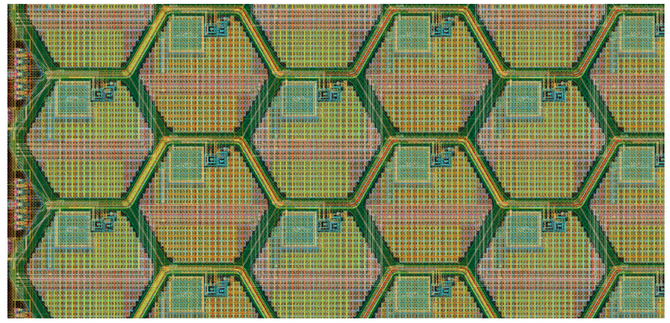
UniGe monolithic prototype



- **Sensor**: epilayer 350Ωcm, 50μm thick

  ➡ simple pn junction, no gain layer

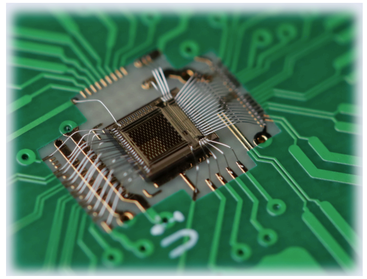
- **Electronics**: SiGe HBT frontend



- matrix of: 12x12 hexagonal pixels
  100μm pitch
- results from 4 analog channels

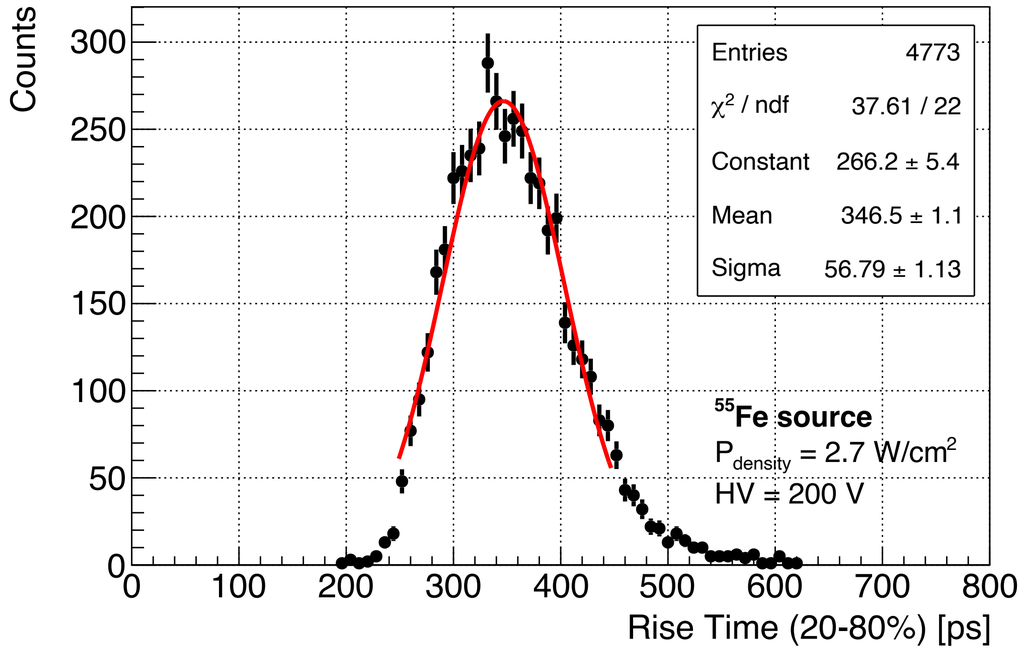
Leading-edge **IHP SG13G2** technology, **130 nm** process featuring **SiGe HBT**

UniGe monolithic SiGe BiCMOS ASICs

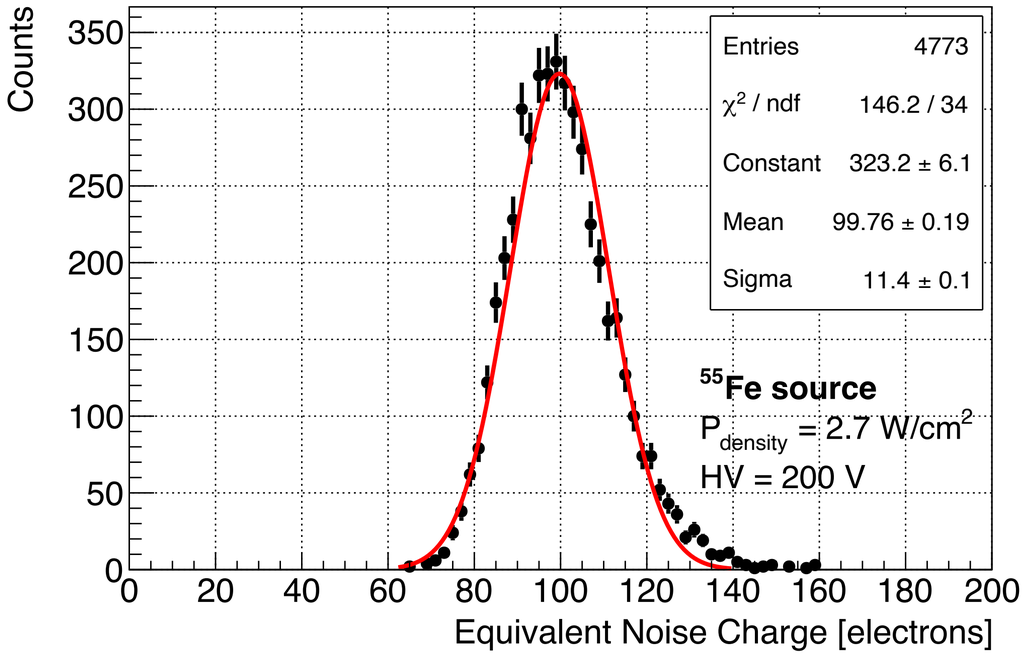


^{55}Fe measurements in cleanroom:

Risetime (20%–80%) ≈ 350 ps



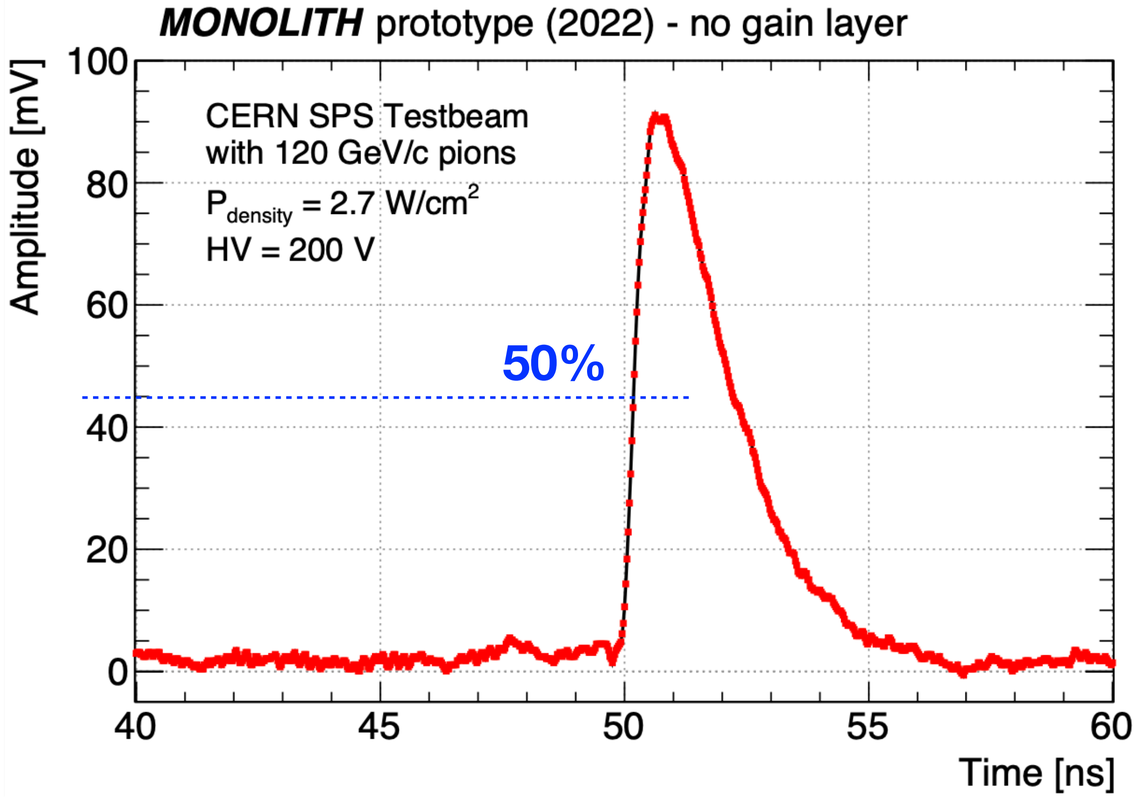
ENC ≈ 100 e⁻



Remark on the time resolution measurements

We performed a very simple analysis of the data taken with the **analog channels**:

1. **Linear interpolation** of oscilloscope samplings (25ps)
2. Time Of Arrival taken at **50% of signal height**
3. **No further time-walk correction applied**



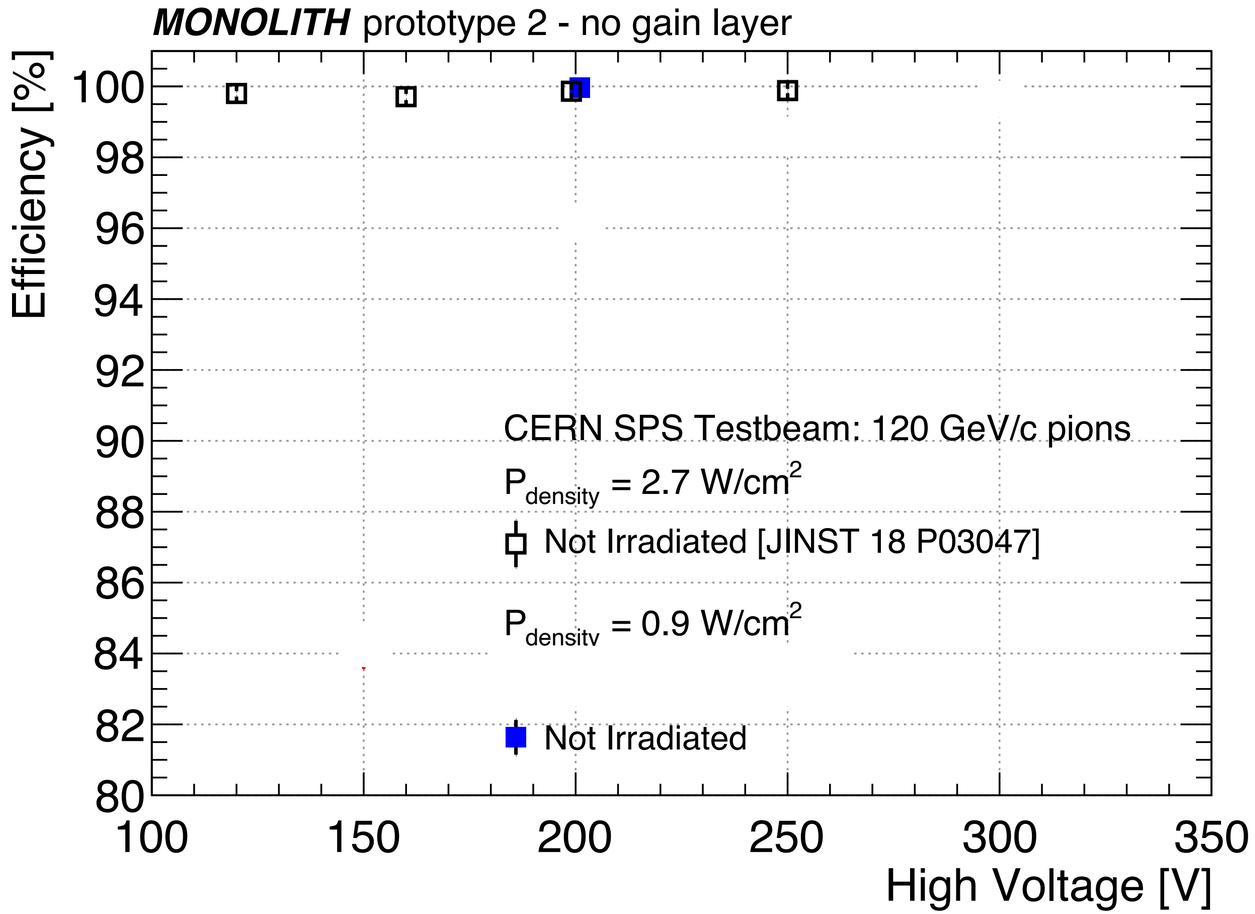
Efficiency vs. sensor bias voltage

CERN SPS testbeam results:

- Unirradiated:

  Efficiency = (99.96 ± 0.02)%

  at HV = 200 V



Time resolution vs. sensor bias voltage

CERN SPS testbeam results:

- Unirradiated:

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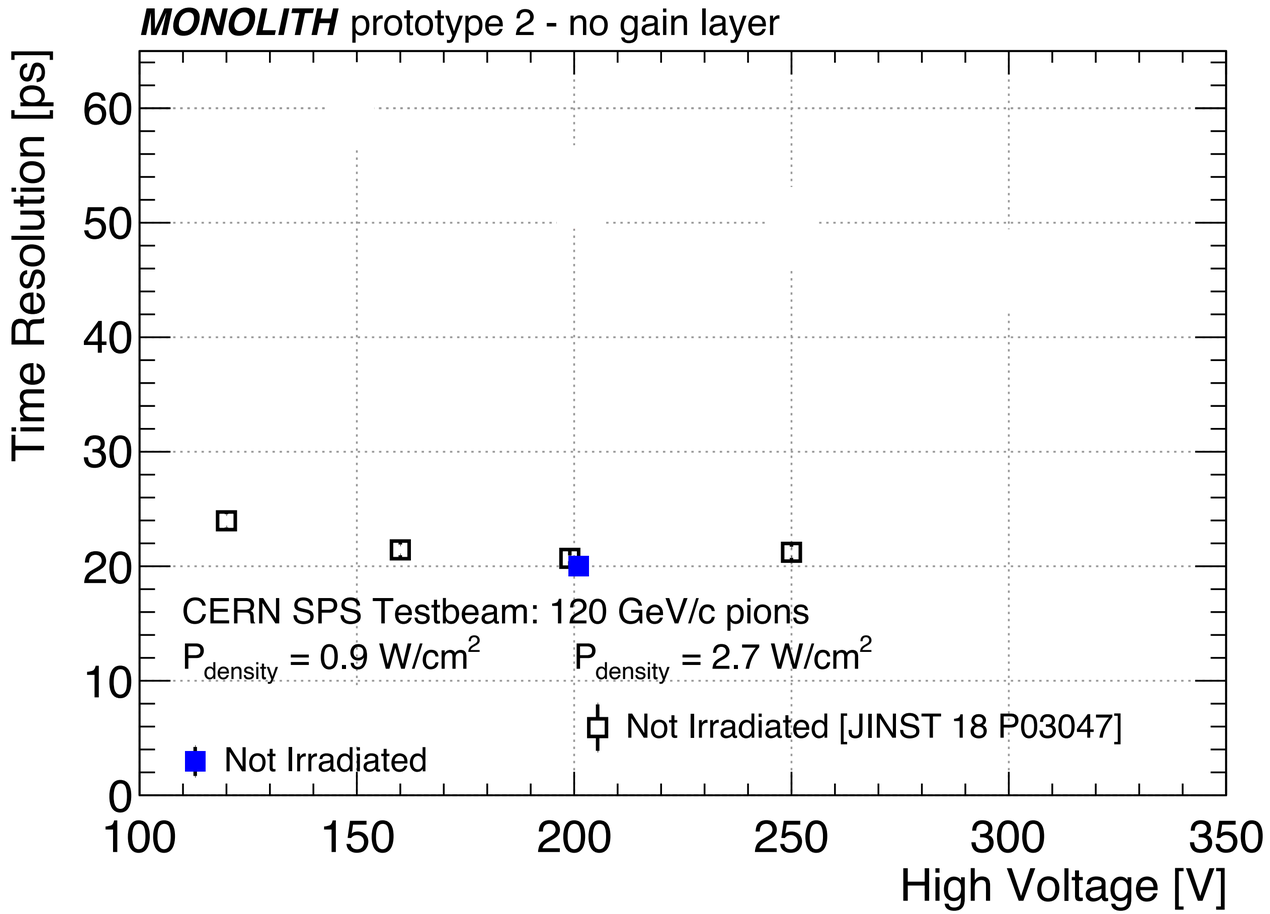


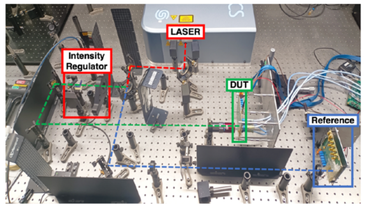
20 ps without gain layer

at 0.9 W/cm^2

Question # 1:

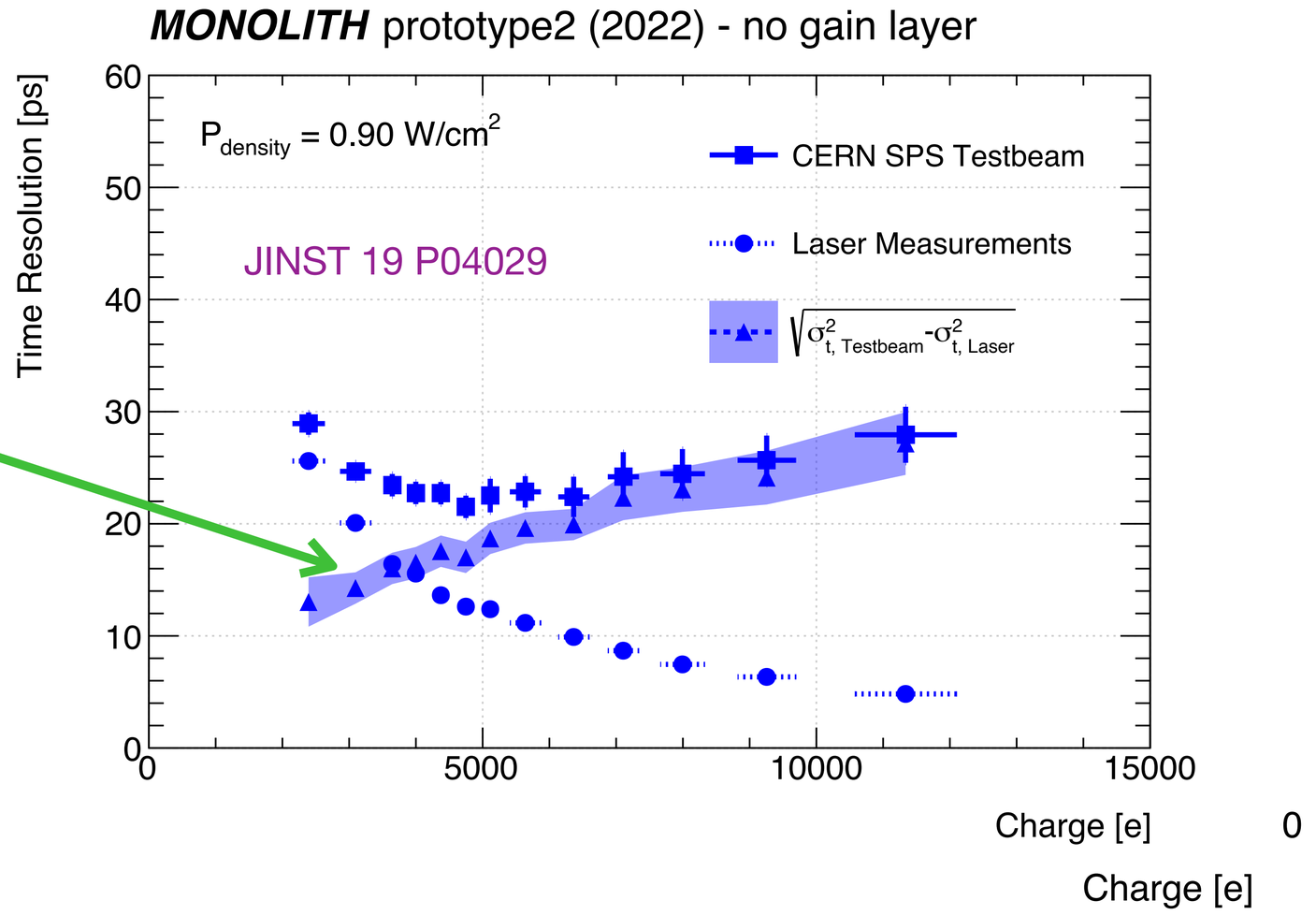
Is this the limit without gain layer ?

Laser measurement



Laser Measurement

The band estimates the charge-collection (“Landau”) noise



20 ps is pretty close the limit of a PN junction without gain layer, due to Landau noise

Full efficiency and 20 ps
at 0.9 W/cm^2
without gain layer

Question # 2:

what is the key to success ?

what is the key to success ?

European Research Council
Established by the European Commission

Should **SiGe BiCMOS** processes
be considered
for future 4D trackers ?

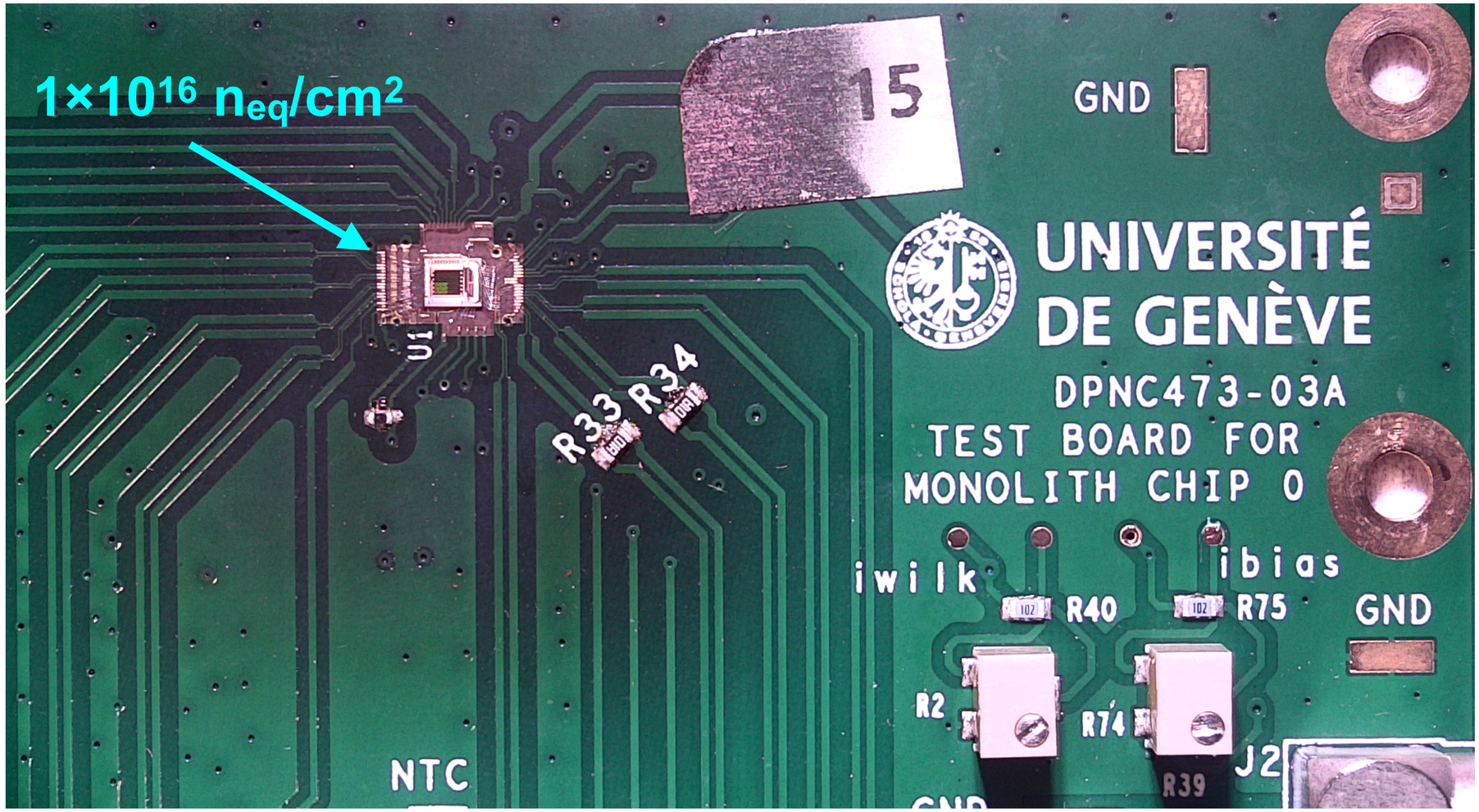
Question # 3:

Is SiGe radiation hard ?

Radiation hardness of SiGe HBTs

Radiation tolerance studies in collaboration with **KEK** and **IHP** colleagues.

8 samples of MONOLITH prototype2 were irradiated with protons in Japan **up to 1×10^{16} n_{eq}/cm^2**



Radiation hardness of SiGe HBTs

Radiation tolerance studies in collaboration with **KEK** and **IHP** colleagues.

8 samples of MONOLITH prototype2 were irradiated with protons in Japan **up to 1×10^{16} n_{eq}/cm^2**

7 out of the 8 irradiated boards had **damaged voltage regulators**:
we had to **bypass** them with wire bonds

Board Name	Fluence [1 MeV n_{eq}/cm^2]
M23	$2 \cdot 10^{13}$
M22	$9 \cdot 10^{13}$
M21	$6 \cdot 10^{14}$
M19	$6 \cdot 10^{14}$
M18	$3 \cdot 10^{15}$
M17	$3 \cdot 10^{15}$
M16	$1 \cdot 10^{16}$
M15	$1 \cdot 10^{16}$

Efficiency vs. sensor bias voltage

CERN SPS testbeam results:

- Unirradiated:

  Efficiency = (99.96 ± 0.02)%

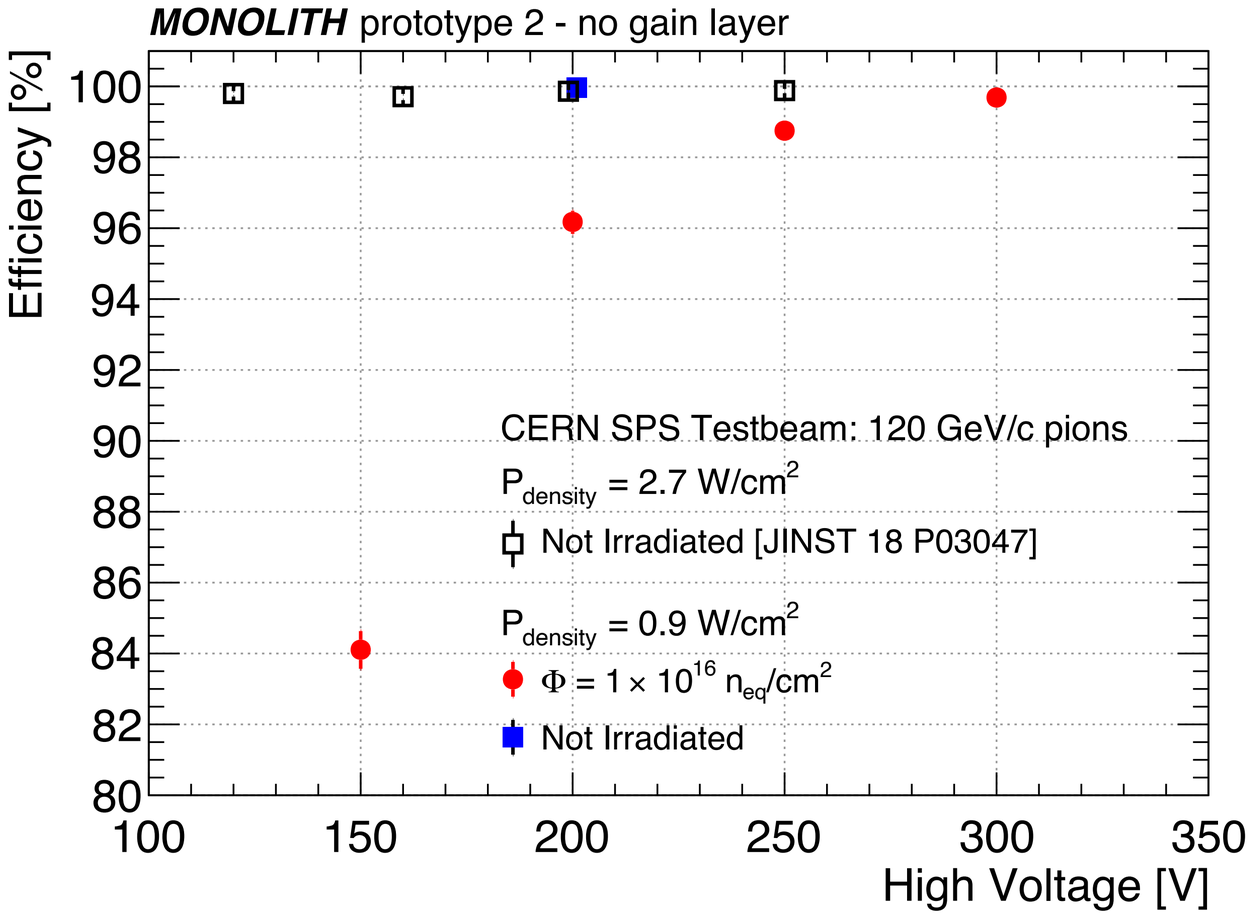
  at HV = 200 V

- 1×10^{16} n_{eq}/cm^2:

  Efficiency = (99.7 ± 0.1)%

  at HV = 300V

  (higher HV still to be exploited)



Time resolution vs. sensor bias voltage

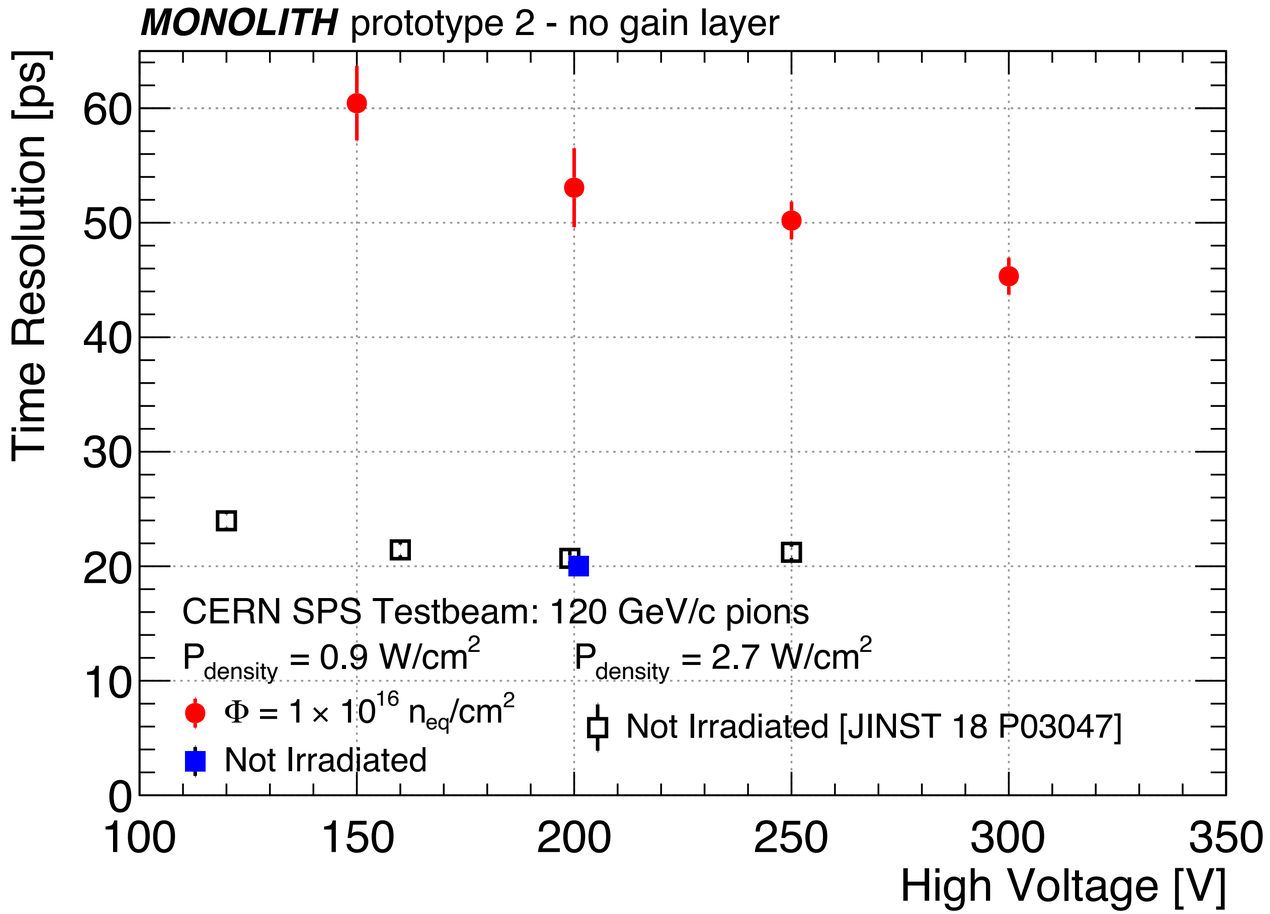
CERN SPS testbeam results:

- Unirradiated:

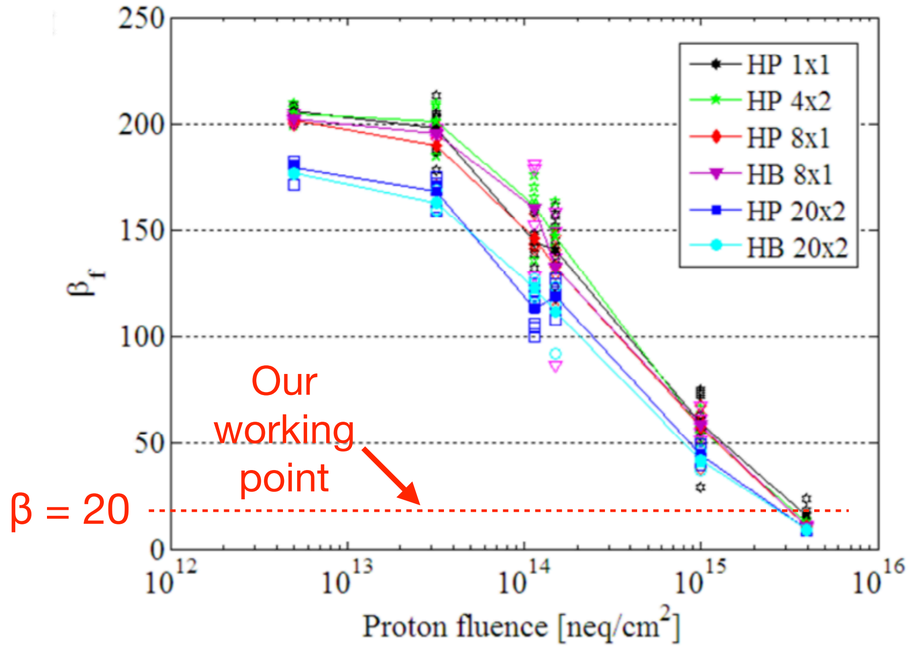
  20 ps at HV = 200 V

- 1×10^{16} n_{eq}/cm^2:

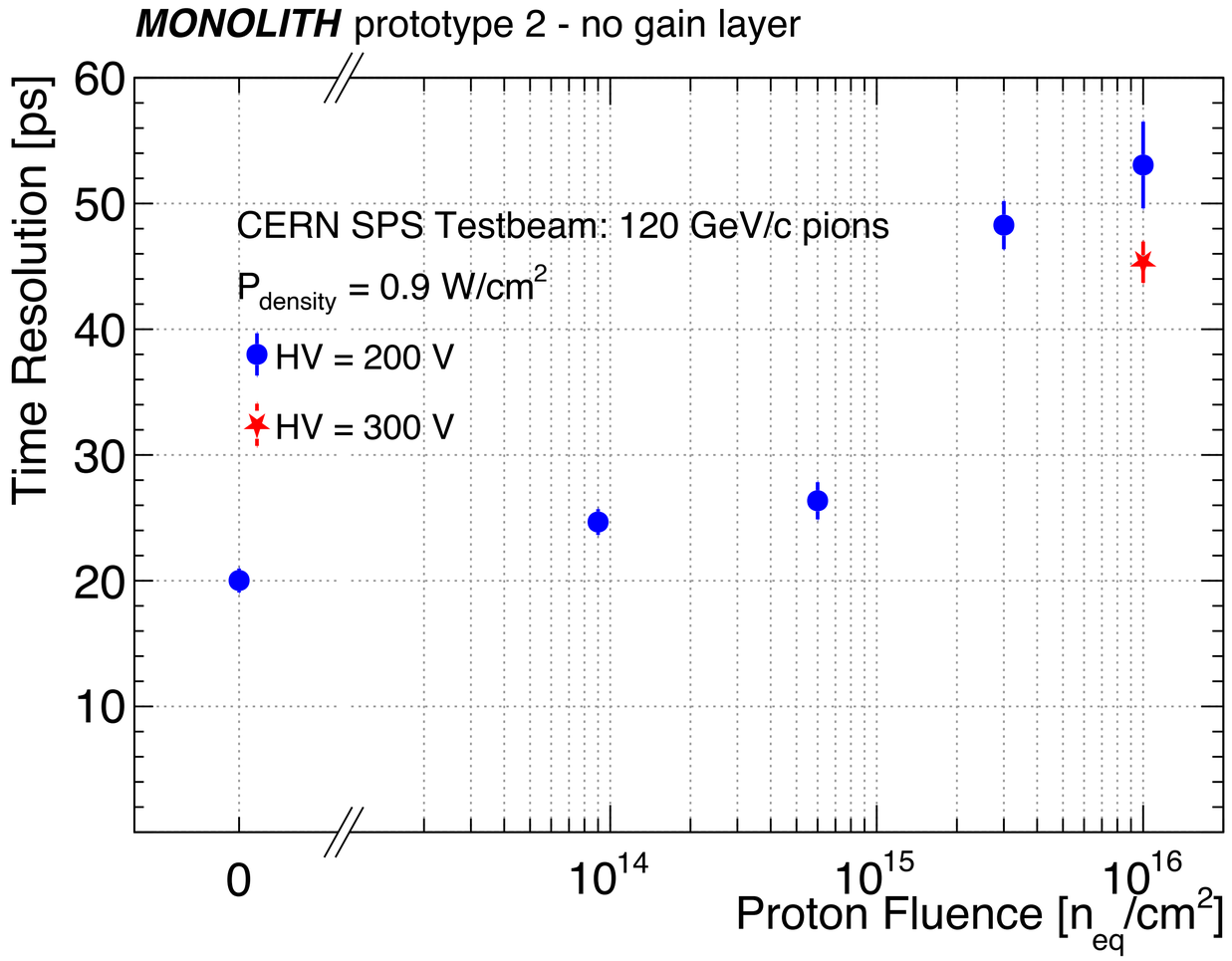
  45 ps at HV = 300V
  (higher HV still to be exploited)



Time resolution vs. proton fluence



S. Díez et al, IEEE Nuclear Science Symposium & Medical Imaging Conference, Knoxville, TN, 2010, pp. 587-593, doi: 10.1109/NSSMIC.2010.5873828.



Summary

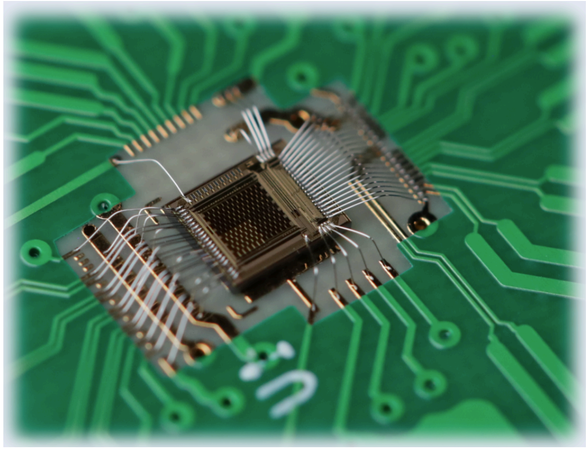
The UniGe monolithic SiGe BiCMOS prototype ASIC provided:

- Not irradiated: **Efficiency = 99.9%** and **time resolution = 20 ps** limited by Landau noise
- **1x10^{16} n_{eq}/cm^2**: **Efficiency = 99.7%** and **time resolution = 45 ps** (200→300V)

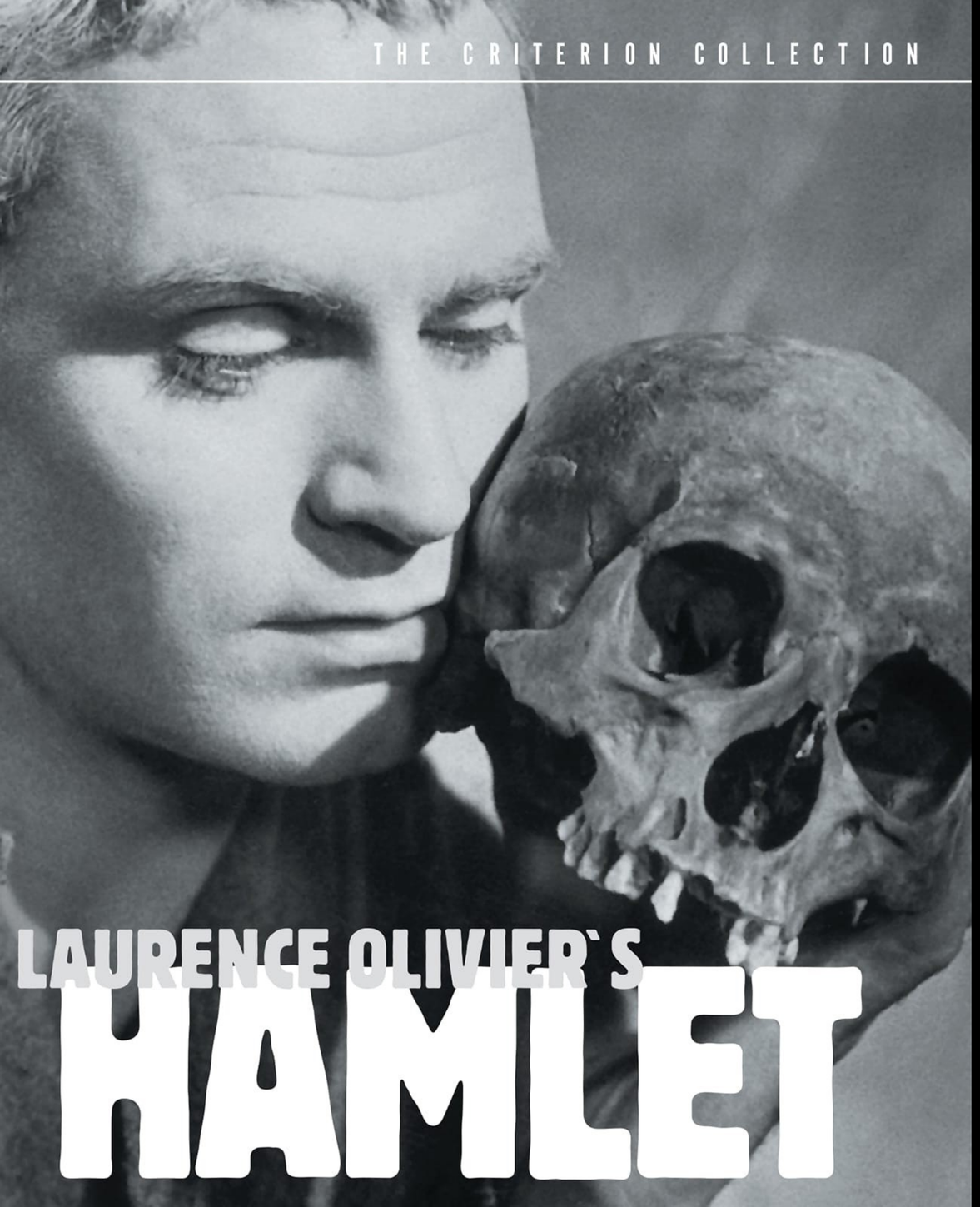
This performance was obtained with a 50 µm thick sensor

without gain layer

using SiGe HBT electronics



If the **radiation tolerance of gain layers** remains a concern, particle-physics experiments can do excellent timing **without** gain layer

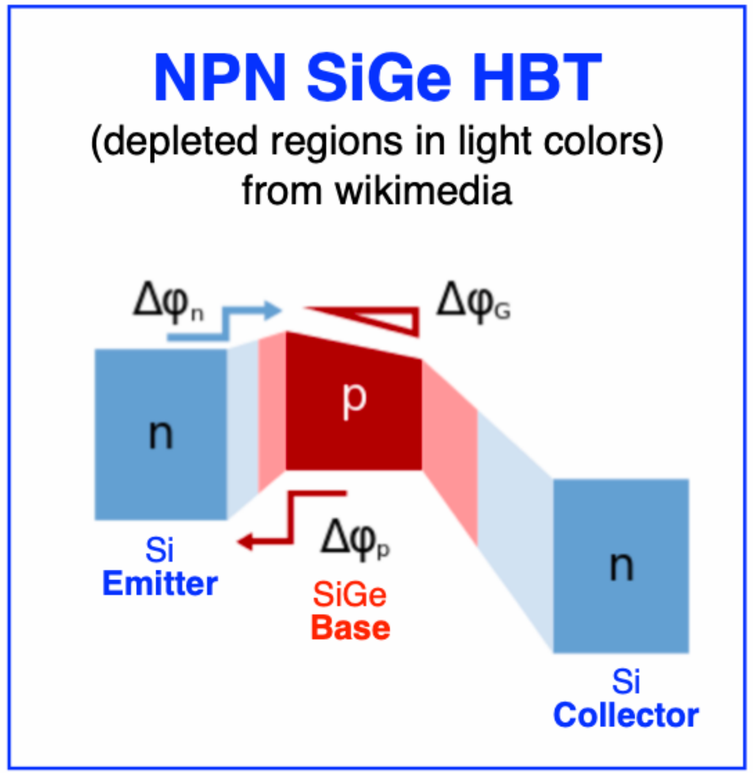


Question # 4:

28 nm CMOS
or
130 nm SiGe BiCMOS

?

SiGe BiCMOS Front-End Electronics



SiGe HBT = BJT with Germanium as base material.

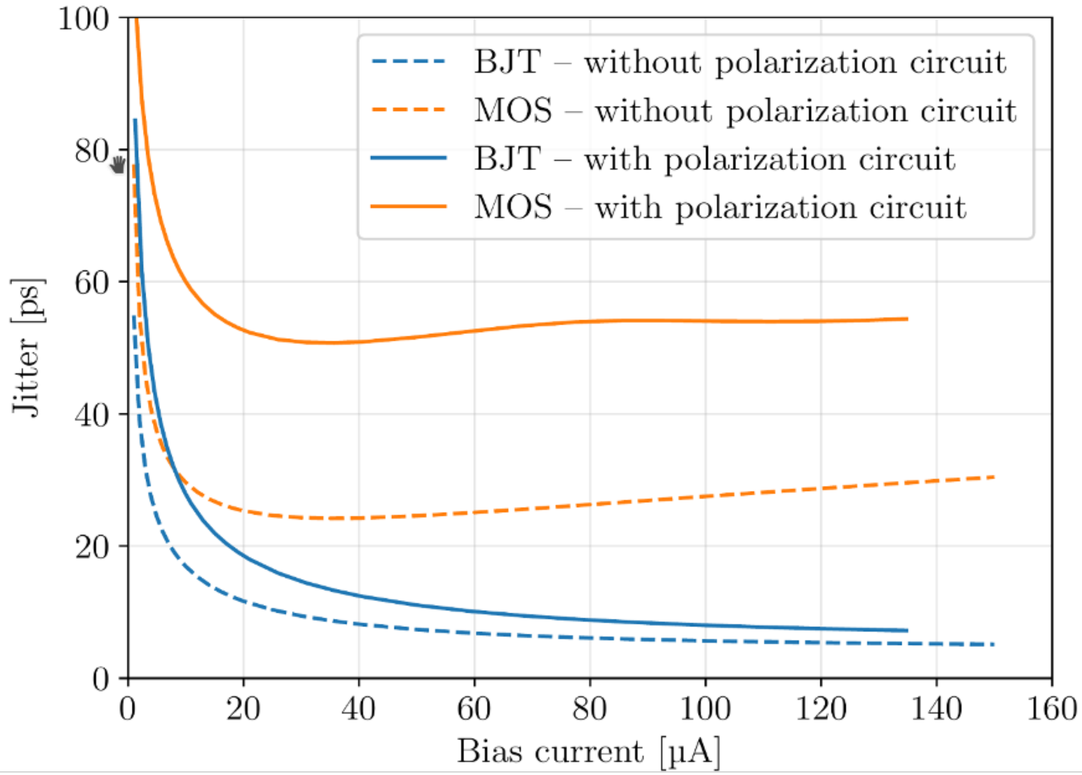
Grading of Ge doping in base:

- charge-transport in base via **drift**
  - reduced charge-transit-time in base
  - **high current gain** β
- **High doping** in base is possible:
  - thinner base
  - **reduced base resistance** R_b

$$ENC_{series\ noise} \propto \sqrt{k_1 \frac{C_{tot}^2}{\beta} + k_2 R_b C_{tot}^2}$$

SiGe HBT & CMOS: noise

Intrinsic **amplifier jitter**:
common emitter (source) configuration
in a 130nm technology



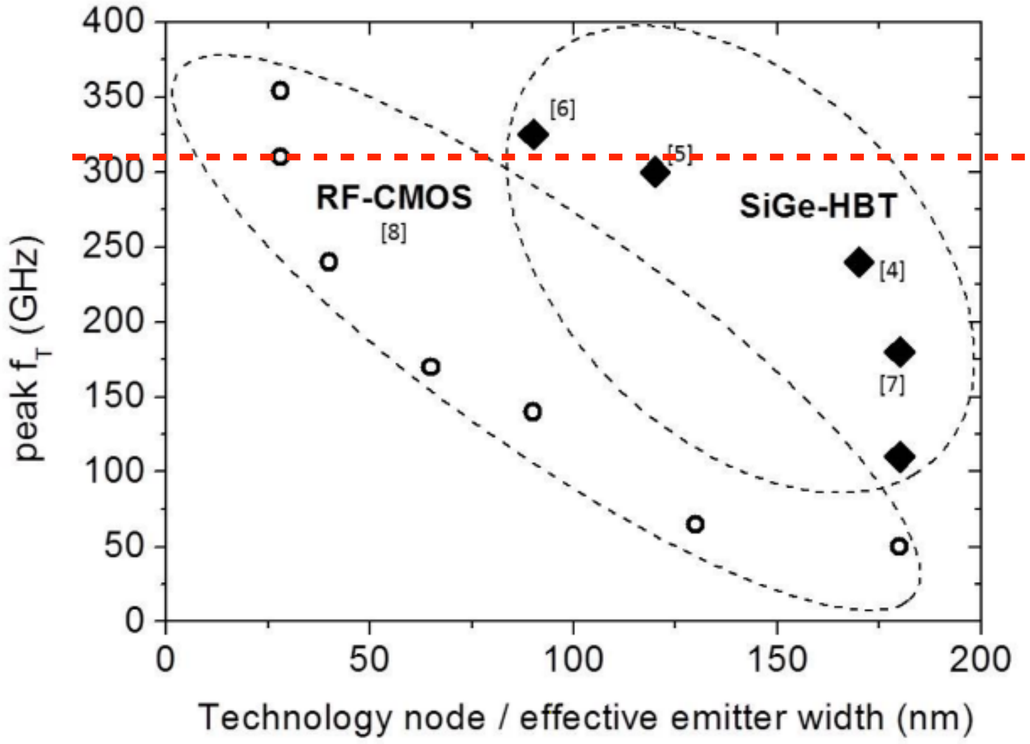
At equal node size,
SiGe HBT
has much smaller jitter than
CMOS

L. Paolozzi et al.,
Time resolution and power consumption of a monolithic silicon pixel prototype in SiGe BiCMOS technology,
JINST 15 (2020) P11025, https://doi.org/10.1088/1748-0221/15/11/P11025

SiGe HBT & CMOS: f_T

Peak transition frequency vs. technology node

signal speed



A. Mai and M. Kaynak,
SiGe-BiCMOS based technology platforms for mm-wave and radar applications.
DOI: 10.1109/MIKON.2016.7492062

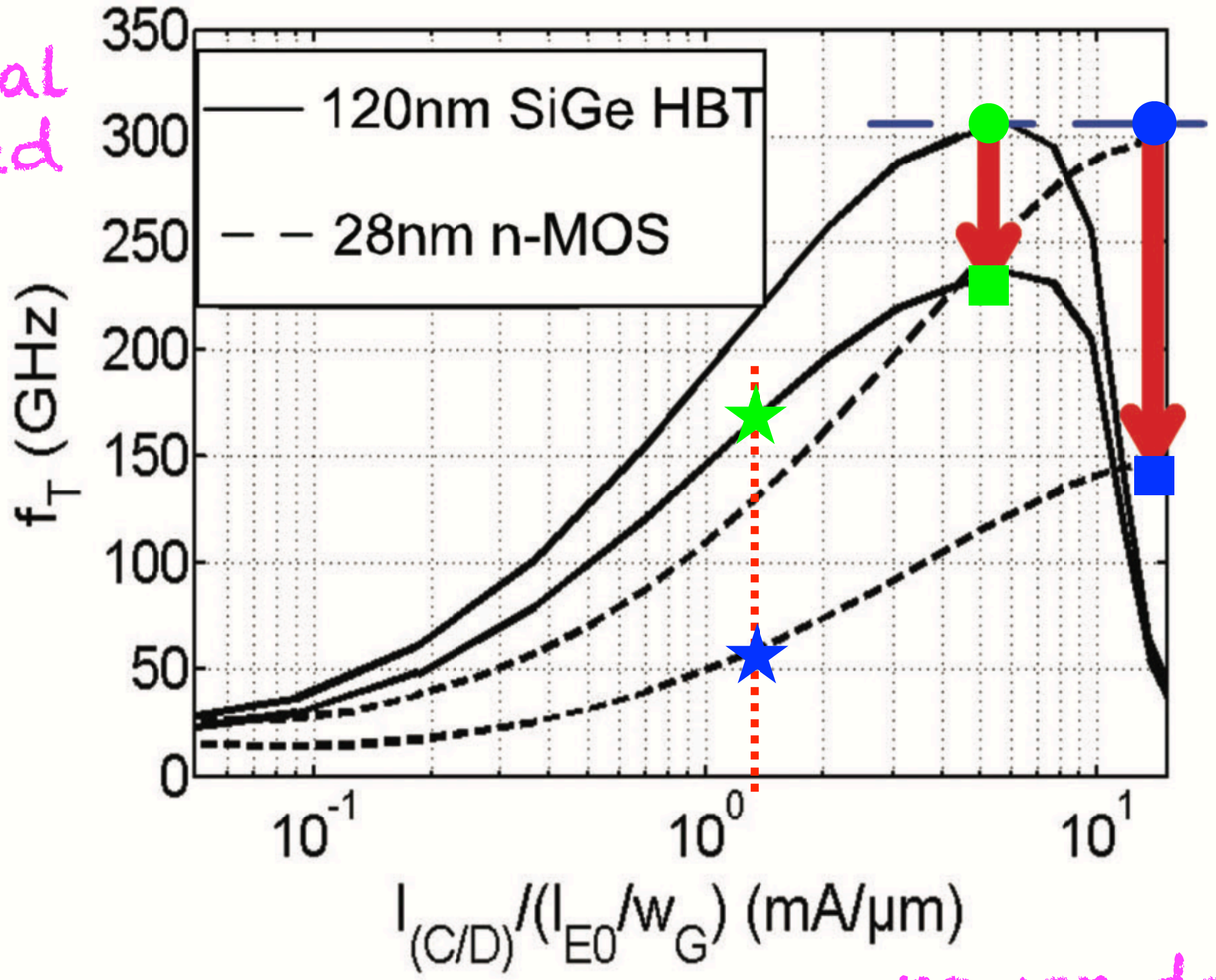
28 nm CMOS
and
130 nm SiGe HBT

have

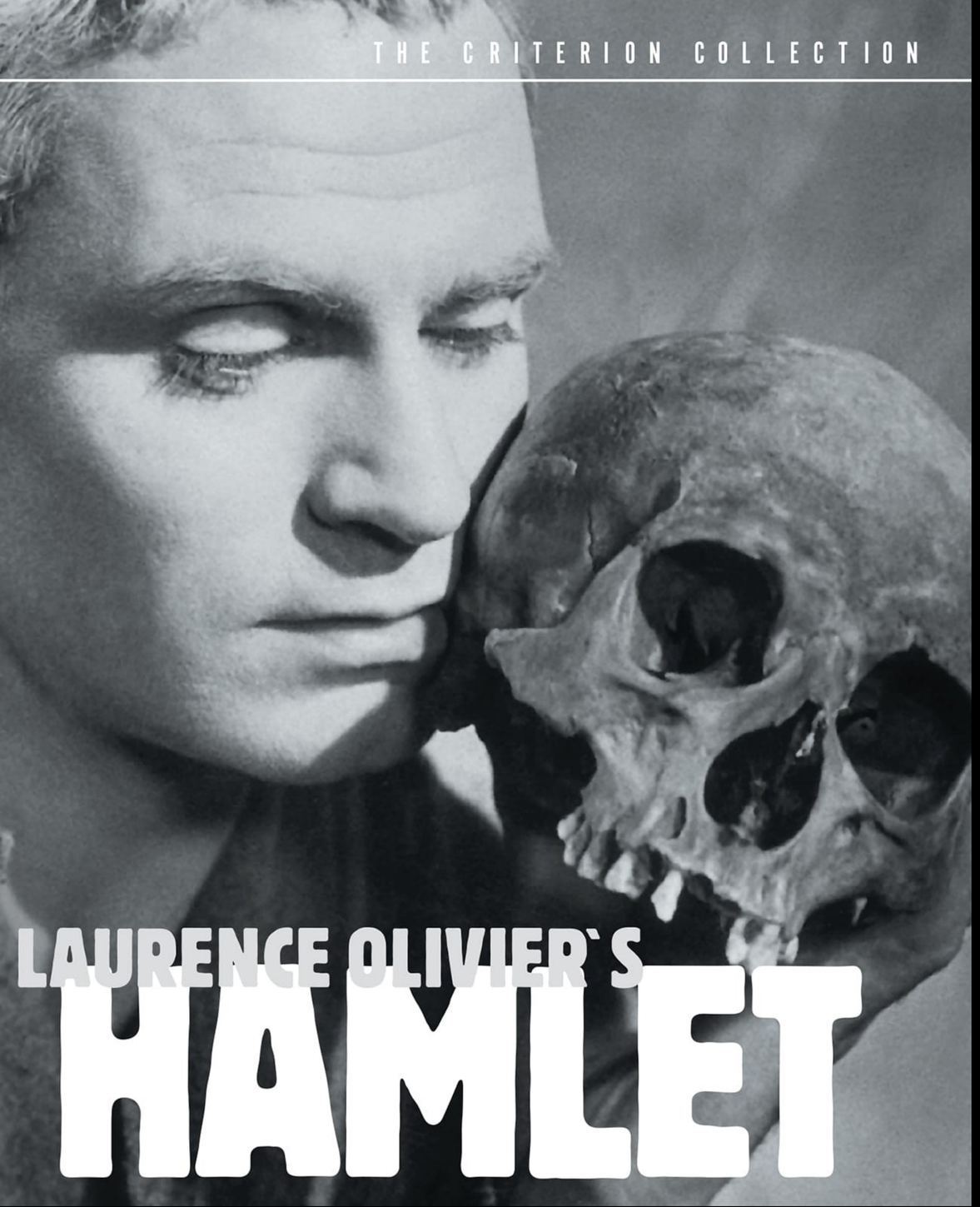
same peak f_T

SiGe HBT & CMOS: speed vs. power

https://doi.org/10.13052/rp-9788793519602, March 2018, page 311



- at peak ft (without a load): three times less power for same timing
- at peak ft, if you put a load: three times less power for twice better timing
- at equal (lower) power: SiGe HBT ≈ 3 times faster (**but** size of CMOS transistors would become prohibitively large)



Hamlet,

for best timing,
you better chose SiGe.

At UniGe, we have no doubt.

SiGe BiCMOS availability & growth

Markets served by SiGe BiCMOS:


Optical fiber networks


Smartphones


IoT Devices


Microwave Communication


Automotive: LiDAR, Radar and Ethernet


HDD preamplifiers, line drivers, Ultra-high speed DAC/ADCS

source: https://towerjazz.com/technology/rf-and-hpa/sige-bicmos-platform/

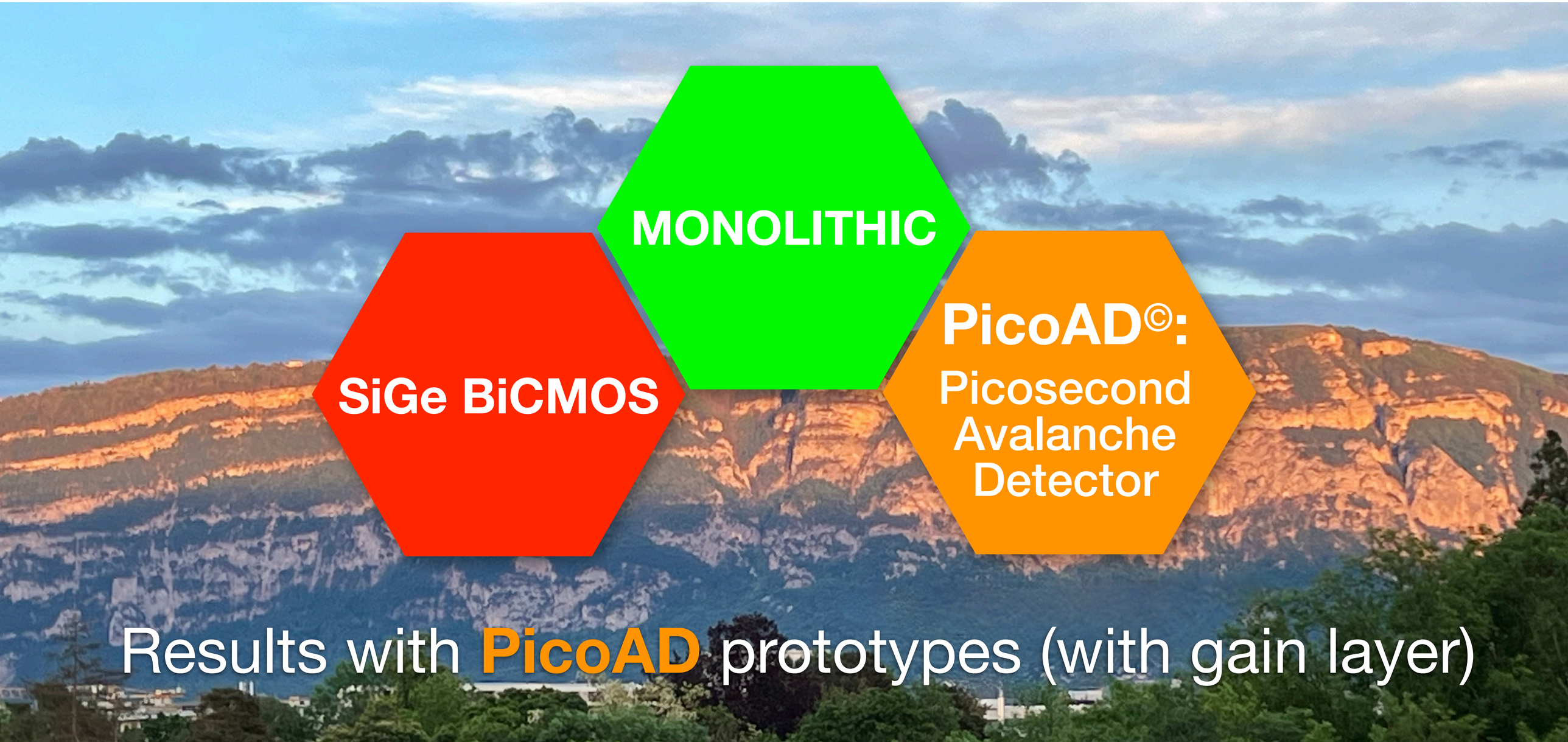
Several large-volume foundries offer SiGe processes: Tower Semiconductor, tsmc, ST, amn, …

Fast growing technology:

1. new IHP process SG13G3Cu, **now available through EUROPRACTICE,** includes transistor with **f_T/f_{max} = 500/700 GHz** (f_T/f_{max} = 350/450 GHz for SG13G2 process)
2. **ST Microelectronics** offers a **55nm** process, with HBT with f_T/f_{Tmax} = 320/370 GHz

The MONOLITH Project

European Research Council
Established by the European Commission



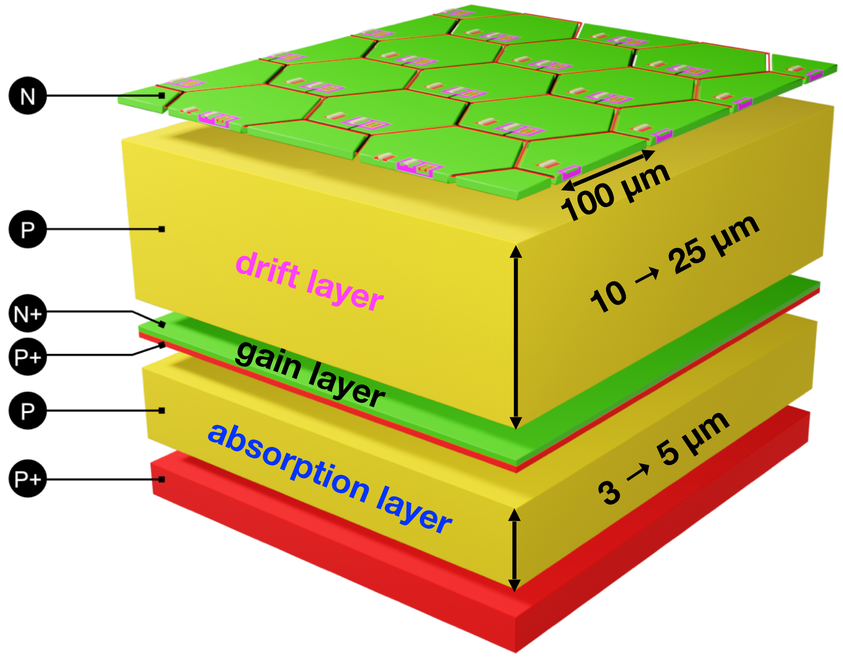
Results with PicoAD prototypes (with gain layer)

PicoAD Sensor Concept

PicoAD:

Multi-Junction Picosecond-Avalanche Detector©
with continuous and deep gain layer:

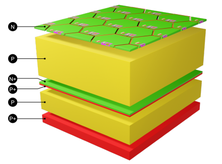
- De-correlation from implant size & geometry
  ➙ **high pixel granularity and full fill factor**
  (to get homogeneous efficiency and timing)
- Only the small fraction of charge produced in the thin **"absorption layer"** gets amplified
  ➙ **reduced charge-collection (Landau) noise**
  (to enhance timing resolution, like a very thin LGAD)
- Landau noise of initial part of the signal is minimal
  ➙ **keep threshold low** (to enhance timing resolution)



Monolithic PicoAD **proof-of-concept** ASIC produced in 2022 ⟶

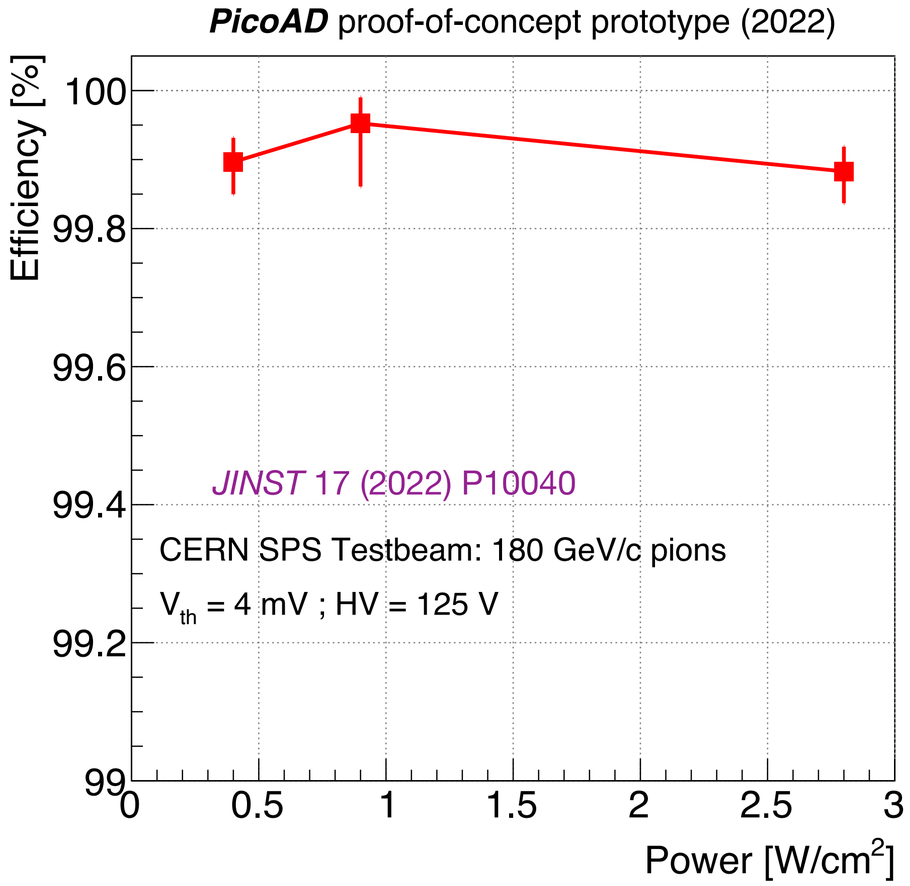
Testbeam PicoAD proof-of-concept (2022)

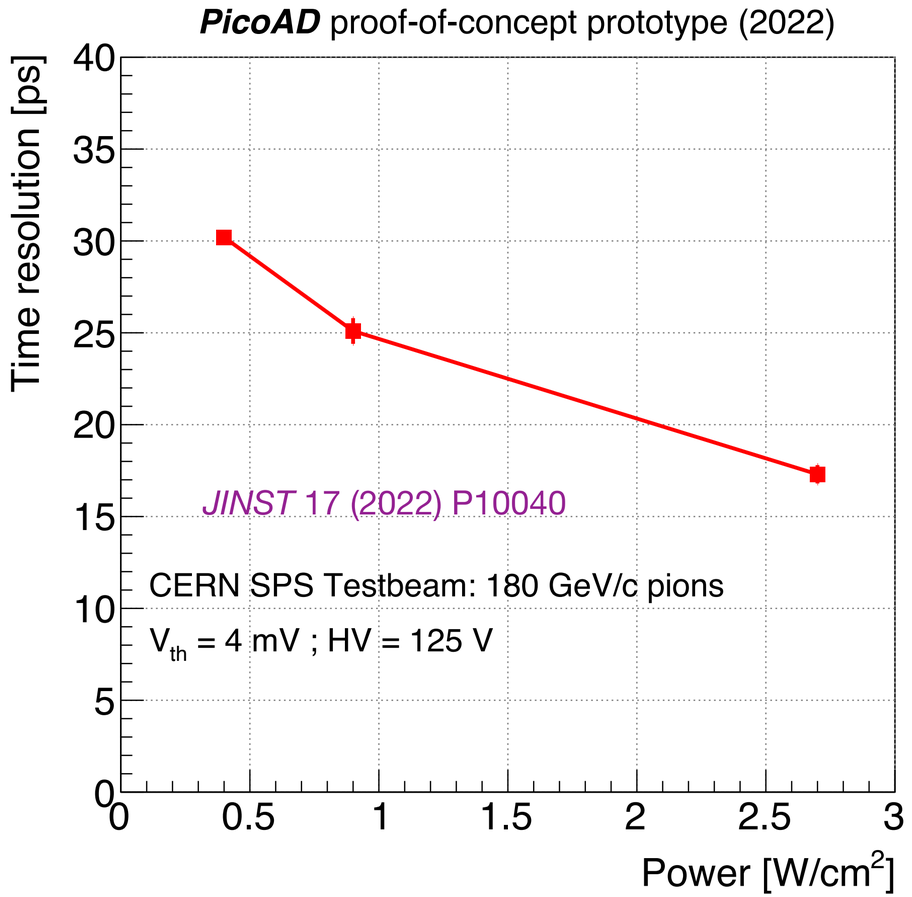
PicoAD



99.9% for all power consumptions

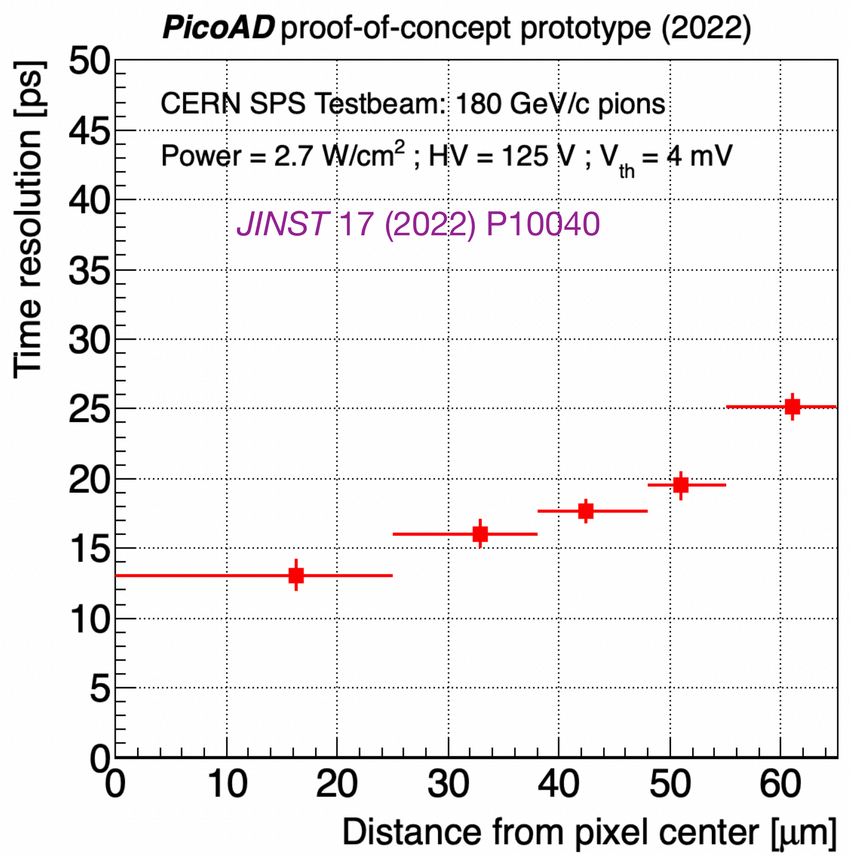
30 ps at **0.4 W/cm²**
17 ps at **2.7 W/cm²**



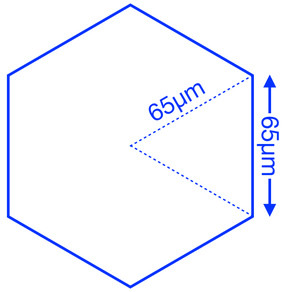


Testbeam PicoAD proof-of-concept (2022)

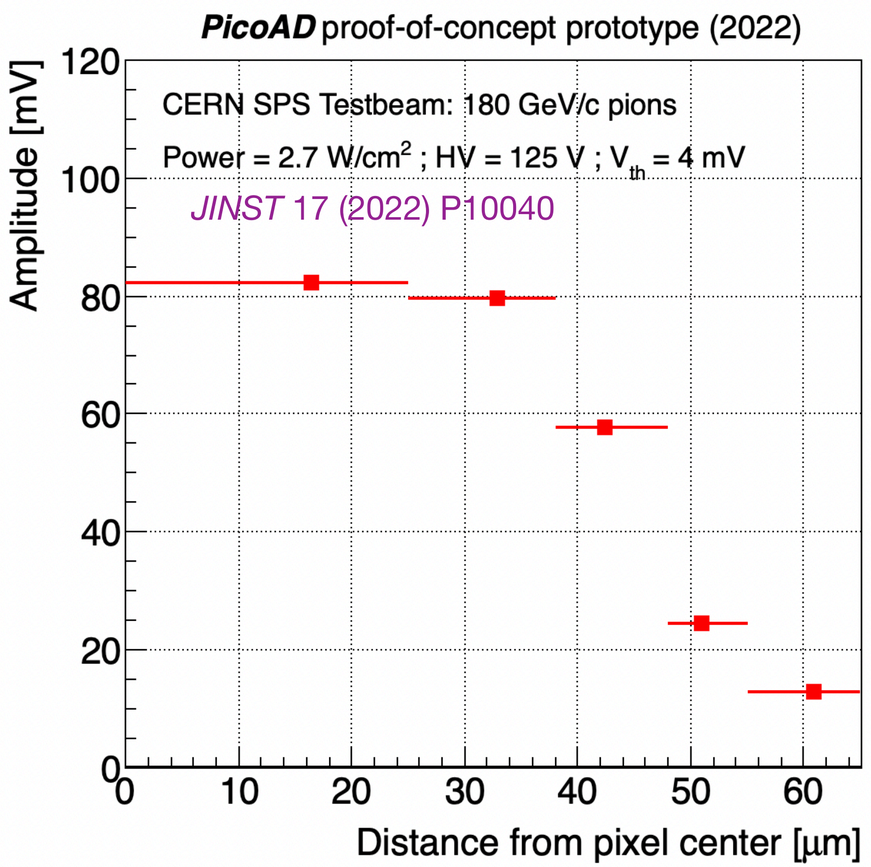
Time resolution



13 ps at the pixel center
25 ps at the pixel edge



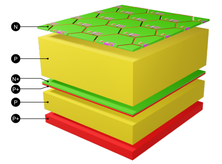
Signal MPV amplitude



strong decrease of signal amplitudes
at the edge of the pixel. **Problem to solve.**

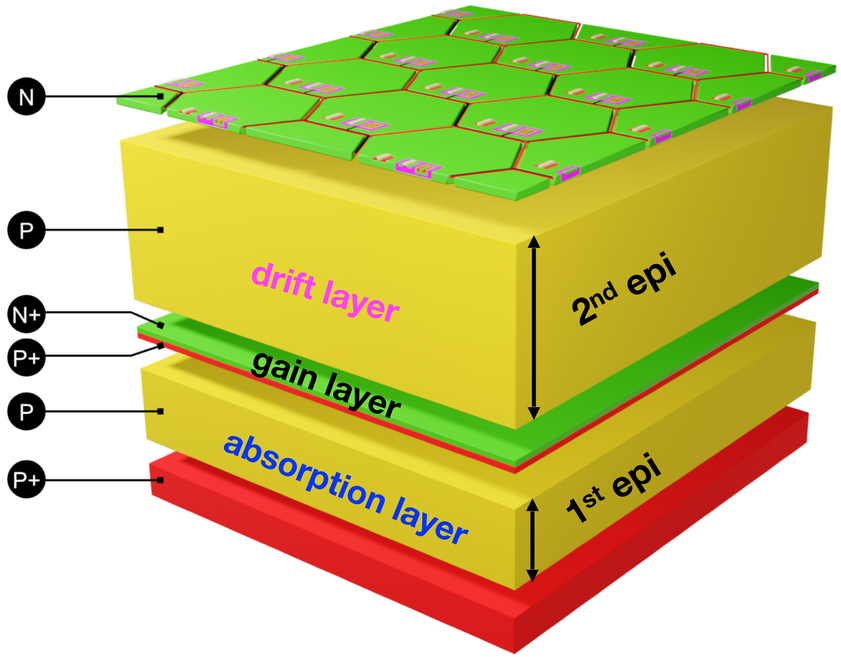
New prototypes devised to improve this dependence

PicoAD



2024 PicoAD production

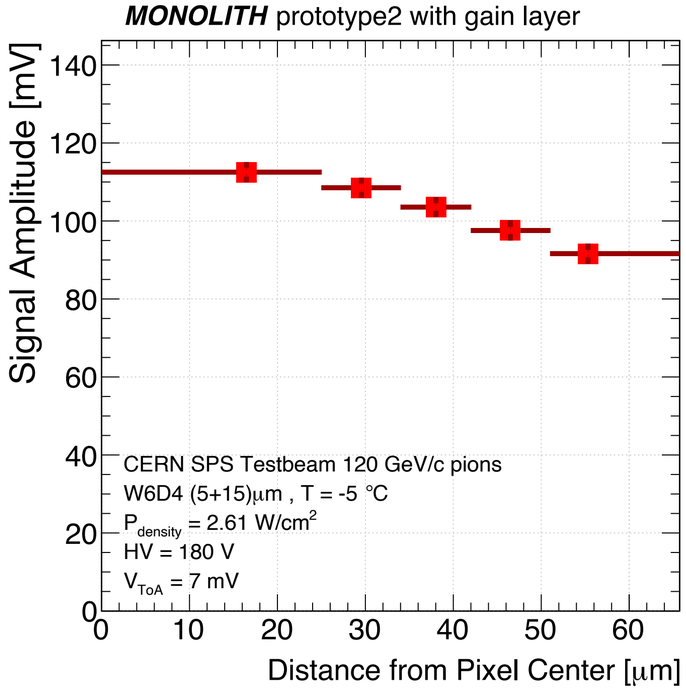
Wafer	1st epi thickness [µm]	2nd epi thickness [µm]	Gain-layer implant dose
3	3	15	3
			3.5
			4
4	3	25	3.5a
			3.5b
			4.75
5	3	25	4
			4.5
			5
6	5	15	3
			3.5
			4
7	5	25	4
			4.5
			5

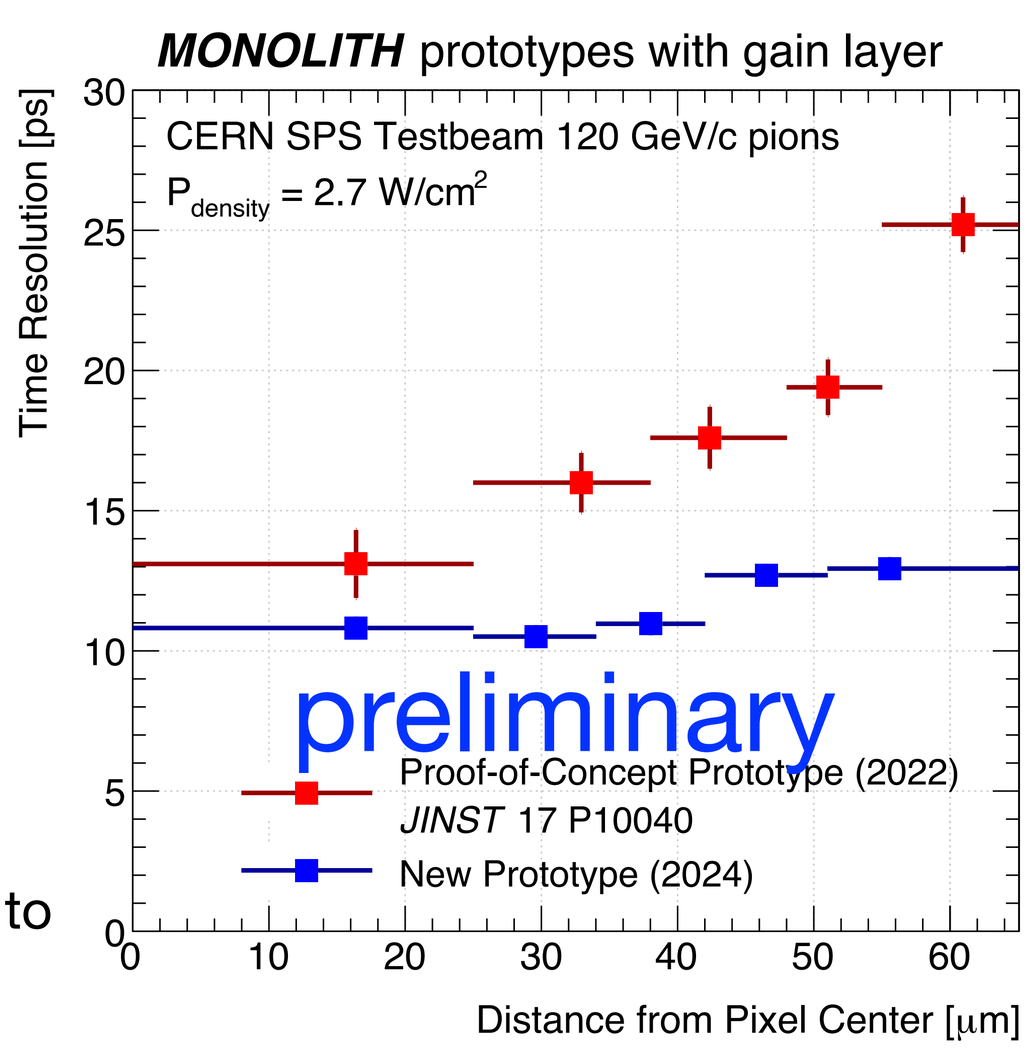


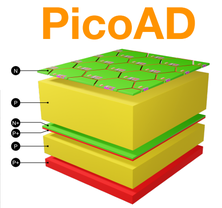
15 different flavours produced;
in 4 geometries.

Some of them presently at CERN testbeam.

Testbeam of 2024 PicoAD prototype





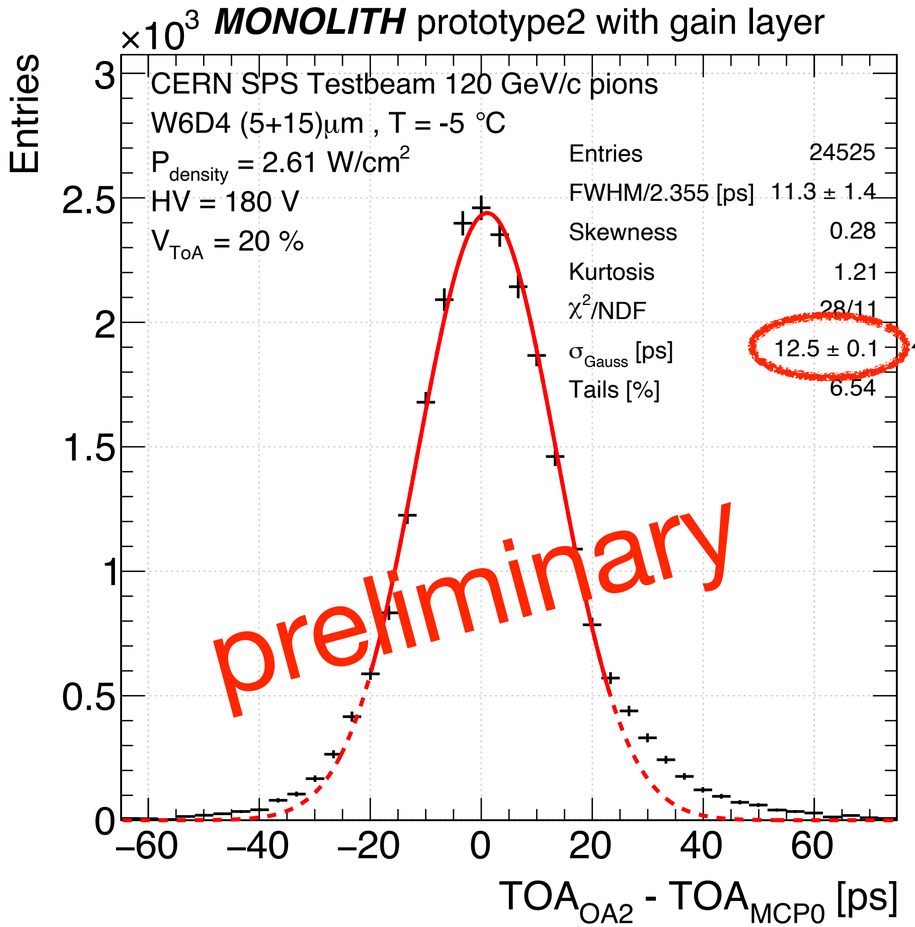


Much improved uniformity of the electric field due to

1. larger “drift” epilayer (10 → 15 μm)
2. larger resistivity (50 → 350 Ωcm).

produced an avalanche detector that gains everywhere.

Testbeam of 2024 PicoAD prototype



Preliminary full offline analysis for one working point gives :

$ToA_{PicoAD} - ToA_{MCP} =$ **12.5 ps**

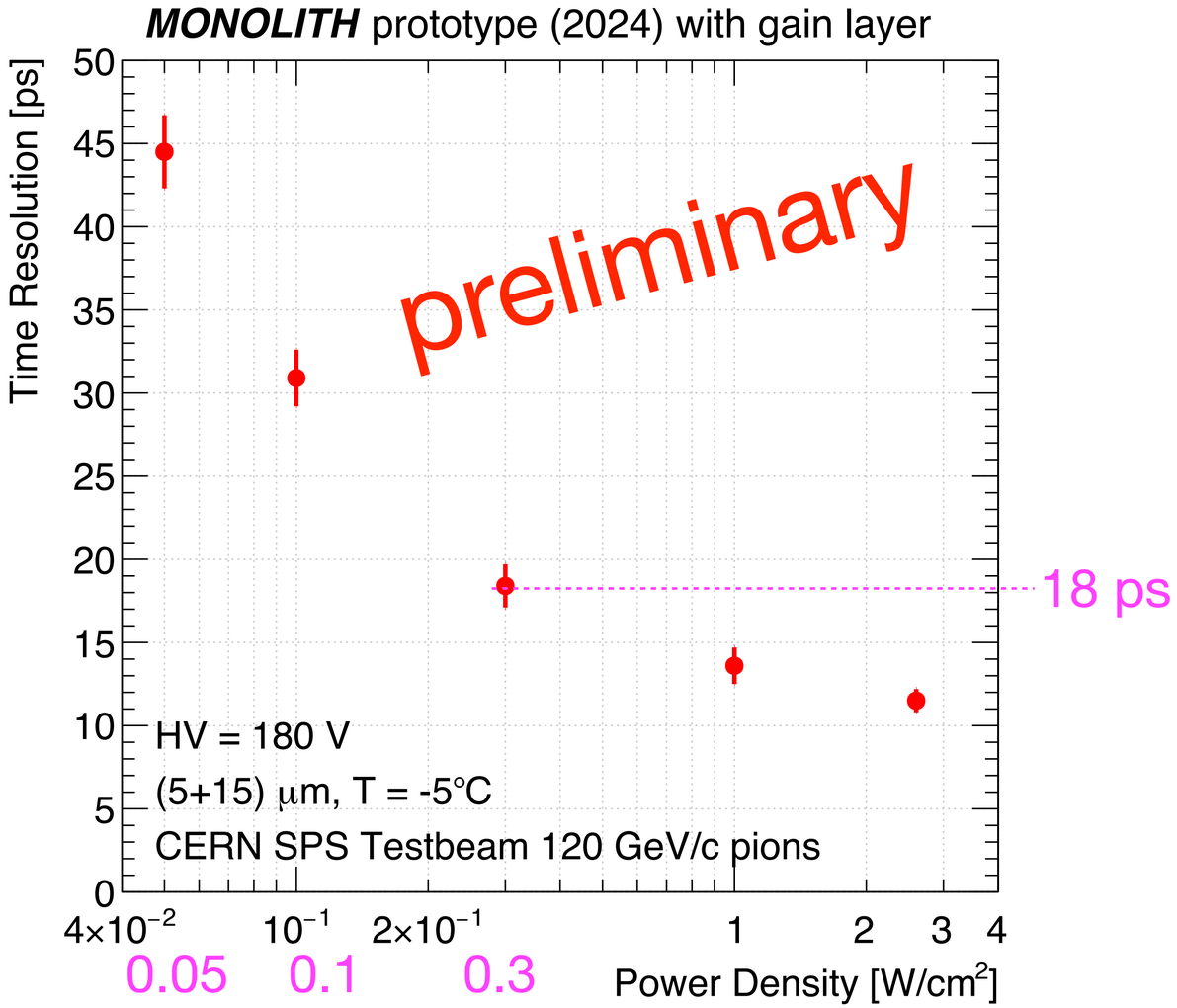
Subtraction in quadrature of MCP contribution

$$\sigma_t = \sqrt{12.5^2 - 4.9^2} = 11.5 \text{ ps}$$

MCP resolution

(it was 17 ps with the proof-of-concept prototype)

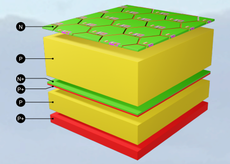
Testbeam of 2024 PicoAD prototype



18 ps achieved at 0.3 W/cm^2

PicoAD — Summary & Outlook

PicoAD



The PicoAD© sensor works (*JINST* 17 (2022) 10 P10032 ; *JINST* 17 (2022) 17 P10040)

Testbeam of the monolithic ASIC provided:

- **Efficiency = 99.9 %** including inter-pixel regions
- **Time resolution σ_t = 11.5 ps**

Measurements still going on.

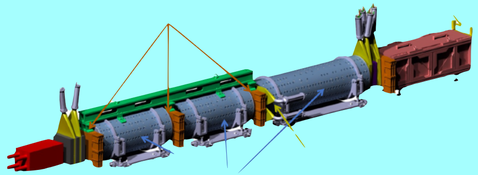
We produced a **fully efficient** avalanche detector with **homogeneous gain everywhere**

Although the UNIGE research programme concentrated so far on monolithic detectors, **standalone PicoAD sensors** can be produced to be hybridised on a readout ASIC (discussions started with a manufacturer leader in the field of silicon sensors)

UniGe monolithic SiGe BiCMOS ASICs

European Research Council
Established by the European Commission

FASER experiment: W-Si high-resolution pre-shower



2022

JINST **16** P12038

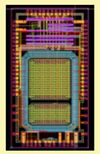
2023

pre-production ASIC (full column)

2024

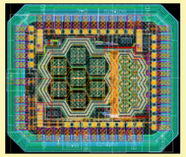
Timing prototypes (no gain layer):

2016



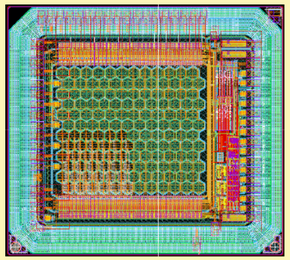
200ps
JINST **13** P02015

2018



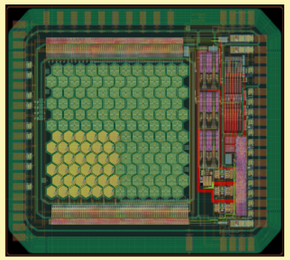
50ps
JINST **14** P11008
JINST **15** P11025

2020



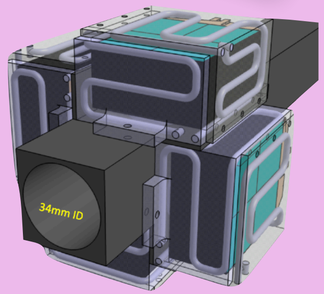
36 ps
JINST **17** P02019

2022

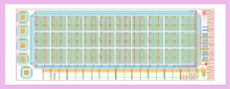


20 ps
JINST **18** P03047 *JINST* **19** P04029
JINST **19** P01014 arXiV:2404.12885

Medical: TT-PET and 100µPET projects



2017



110ps
JINST **14** P02009
JINST **14** P07013

2024

100µPET production ASIC full reticle

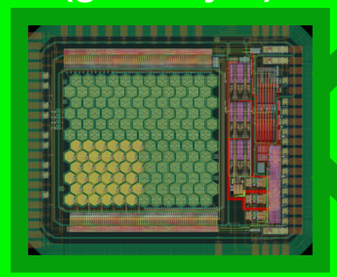
future possibilities

without gain layer

MONOLITH prototypes production is now complete

high-radiation tolerance
high granularity
timing layers
for **particle physics**

PicoAD©
(gain layer)



12 ps
JINST **17** P10032
JINST **17** P10040
+ paper in preparation

moderate radiation level
extremely thin
timing layers,
e.g. **mu3e experiment**
(Lorenzo Paolozzi)

photonics
(Thanushan Kugathasan)
(Roberto Cardella)

Extra Material

C. Enz, et al., "Nanoscale MOSFET Modeling",
IEEE Solid-State Circuits Magazine, vol. 9, no. 4, pp. 73-81, 2017,
doi: 10.1109/MSSC.2017.2745838

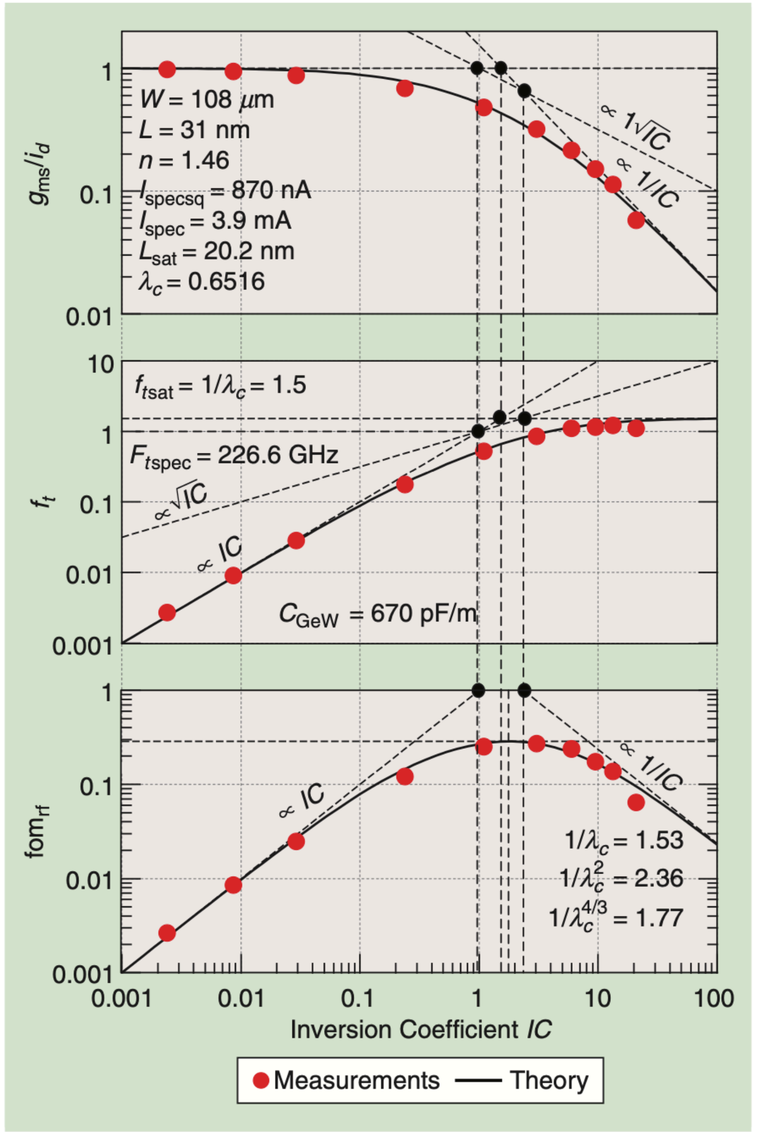


FIGURE 12: g_{ms}/i_d, f_t and fom_{rf} versus IC for a 30-nm device [12].

PicoAD p.o.c.: Gain with ^{55}Fe source

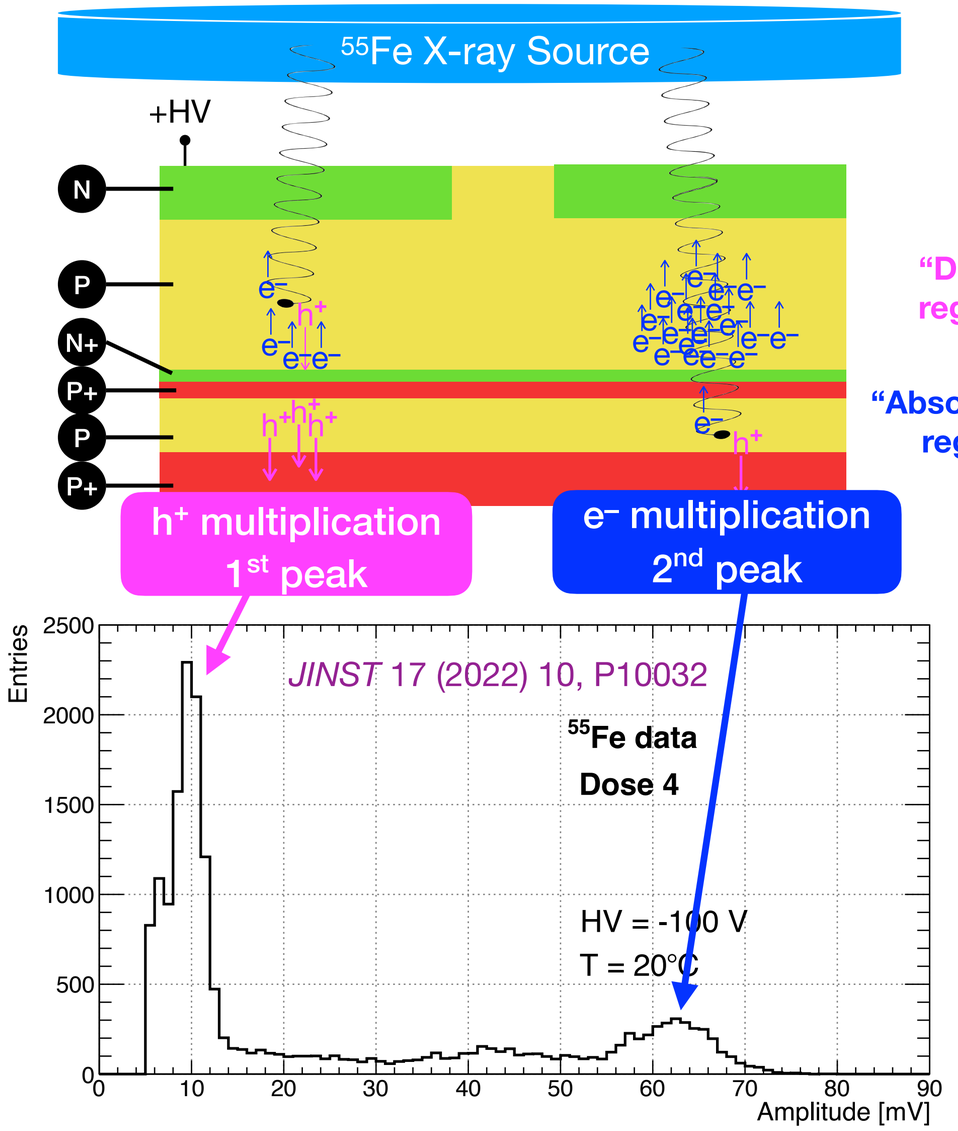
X-rays from ^{55}Fe radioactive source:

- mainly ~5.9 keV photons
- point-like charge deposition

We found a double-peak spectrum

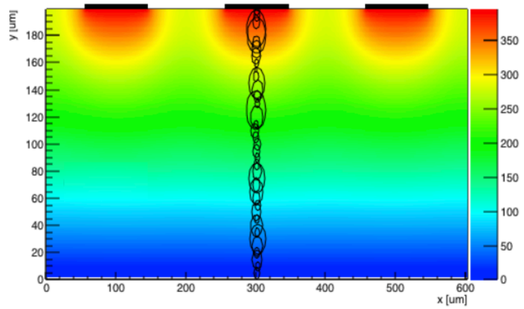
- photon absorbed in **drift region**
  - ➡ **holes** drift through gain layer & multiplied
  - ➡ **first peak** in the spectrum
- photon absorbed in **absorption region**
  - ➡ **electrons** through gain layer & multiplied
  - ➡ **second peak** in the spectrum

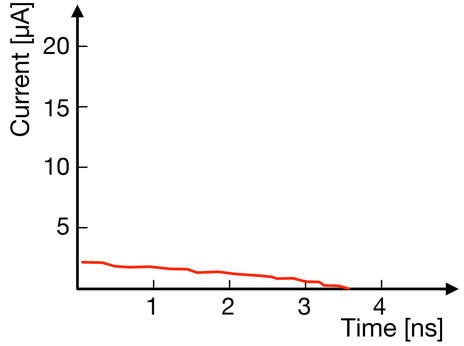
Gain measured: ~20 for ^{55}Fe
(corresponding to ~60 for a m.i.p.)



Landau noise contributions

PN junction
(no gain layer)

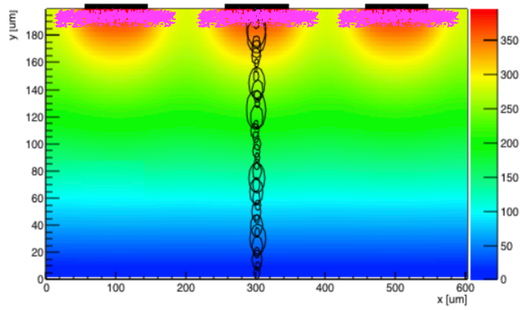


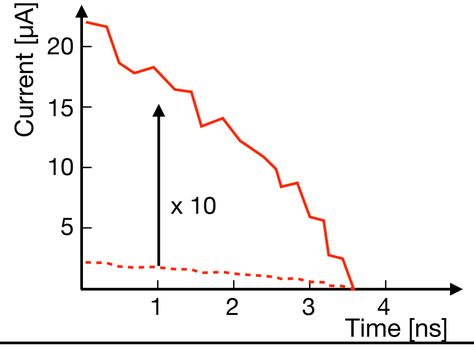


Landau noise is produced by the **charge collection** at the electrode: when a large cluster of charge is collected, the current drops suddenly producing a **jitter in the signal**

gain layer ⟶

LGAD

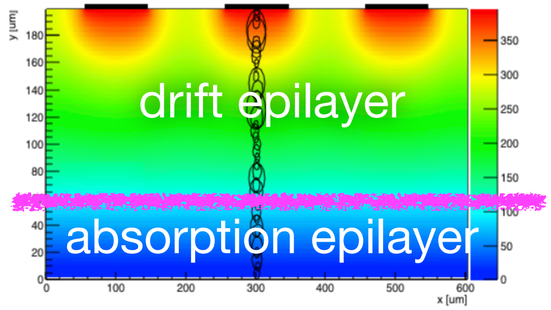


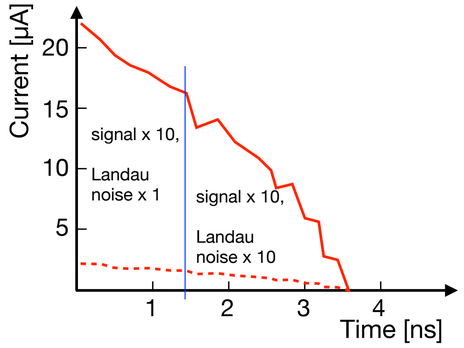


In an LGAD, **all the Landau noise is multiplied by the gain factor** (G = 10 in the figure) and becomes a limiting factor.

PicoAD

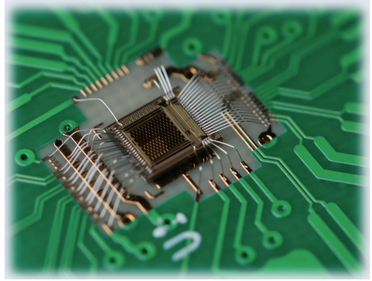
gain layer ⟶



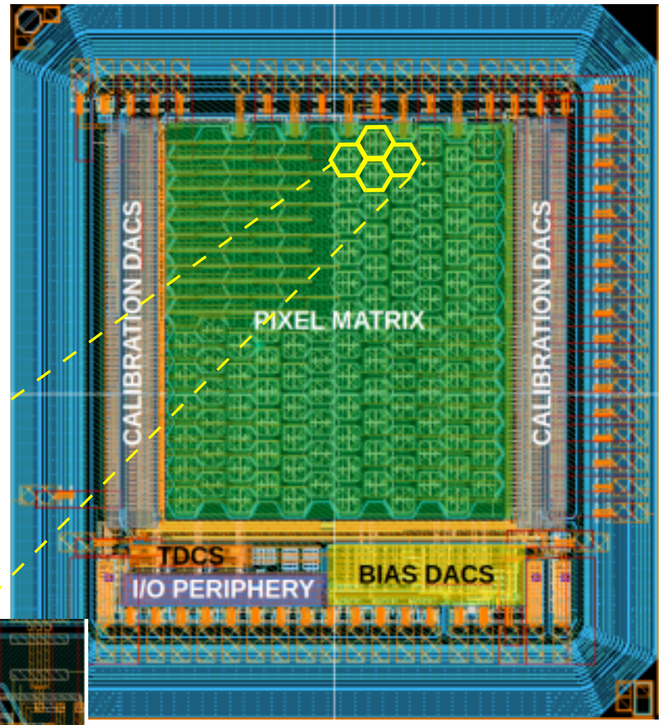


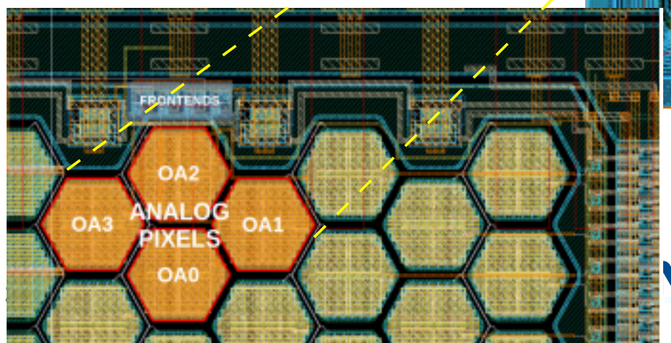
In a PicoAD, only the Landau noise produced by the absorption layer (that arrives at the electrode late) is multiplied by the gain factor. Thus the **Landau noise at the start of the signal is minimised**.

prototype2 — no gain layer



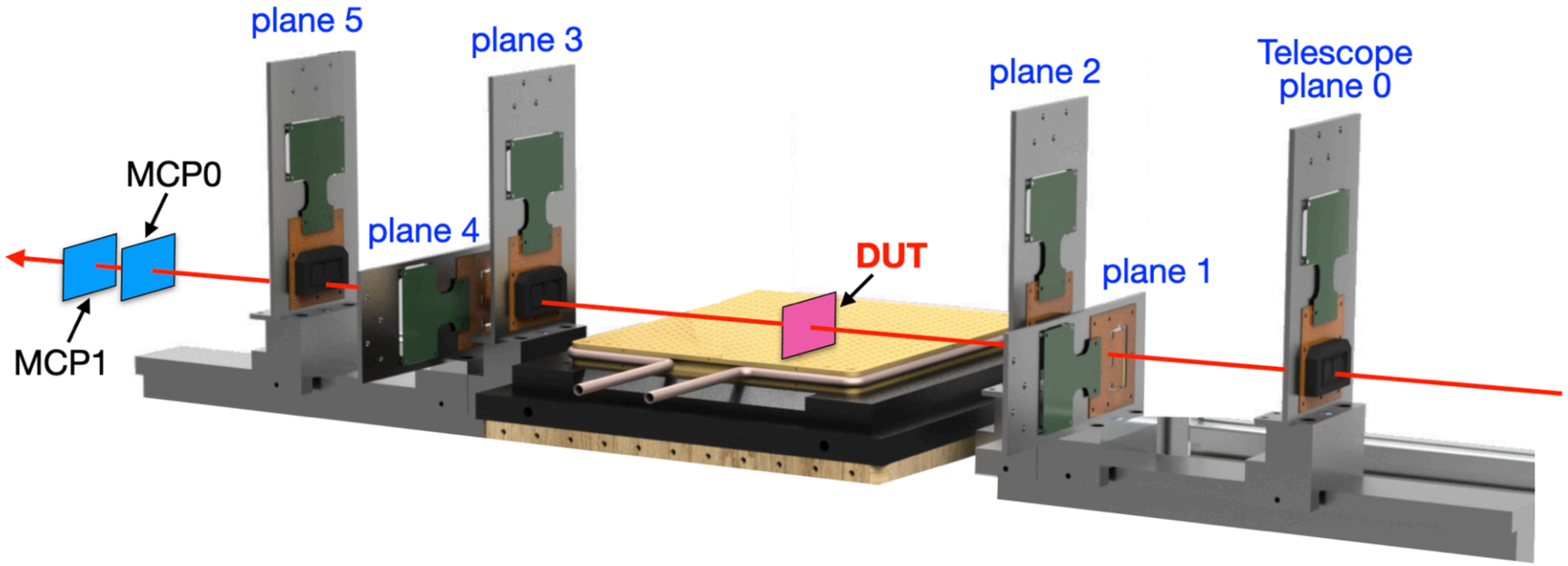
- Same matrix configuration as prototype1, but
  - **Substrate**: 50Ωcm → 350Ωcm epilayer, 50µm thick on low-res (1Ωcm)
    - ➡ smaller pixel capacitance
    - ➡ depletion 23µm → 50µm
    - ➡ larger voltage plateau
    - ➡ that allows operating sensor with v_{drift} saturated everywhere
  - **Preamp and driver voltage decoupled**
    - ➡ was limiting optimal amplifier operation
    - ➡ was creating cross-talk; removed
  - **Optimised FE layout**, **differential output**, high-frequency cables
    - ➡ better rise time (600ps → 300ps)





Test Beam: Experimental Setup

SPS testbeam in 2023 with 120 GeV/c pions to measure **efficiency** and **time resolution**



UNIGE FE-I4 telescope to provide spatial information ($\sigma_{x,y} \approx 10$ μm)

Two MCPs ($\sigma_t \approx 5$ ps) to provide the timing reference