MONOLITH - picosecond capability in a high granularity monolithic silicon pixel detector

Lorenzo Paolozzi — Université de Genève and CERN

UNIVERSITÉ DE GENÈVE

European Research Council
Established by the European Commission

The MONOLITH Project

Funded by the H2020 ERC Advanced grant 884447,
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European Research Council
Established by the European Commission

Our recipe for picosecond timing with silicon:

MONOLITHIC
avoid complexity and cost of hybrids
minimize material

SiGe BiCMOS

PicoAD©:
Picosecond Avalanche Detector

The UniGe Silicon Team


Giuseppe Iacobucci
- Project PI


Thanushan Kugathasan
- Lead ASIC design
- Analog electronics

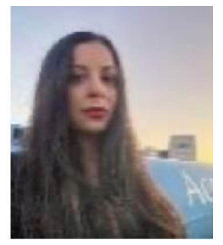

Leonardo Cecconi
- ASIC design
- Digital electronics


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


Viros Sriskaran
- Analog 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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- Analog electronics
- ASIC test


Andrea Pizarro Medina
- Data analysis
- Laboratory tests


Didier Ferrere
- System integration
- Laboratory tests


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- System integration
- Laboratory tests


Yannick Favre
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- RO system


Stéphane Débieux
- Board design
- RO system

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Swiss National Science Foundation

European Research Council
Established by the European Commission

Sinergia

ATTRACT

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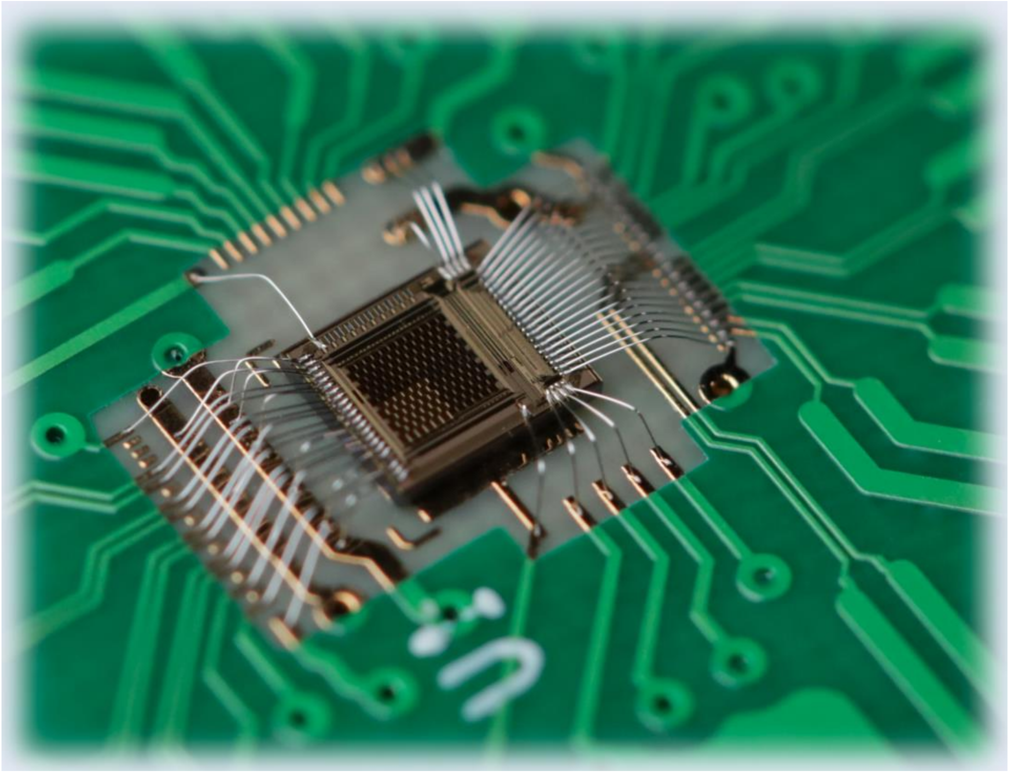
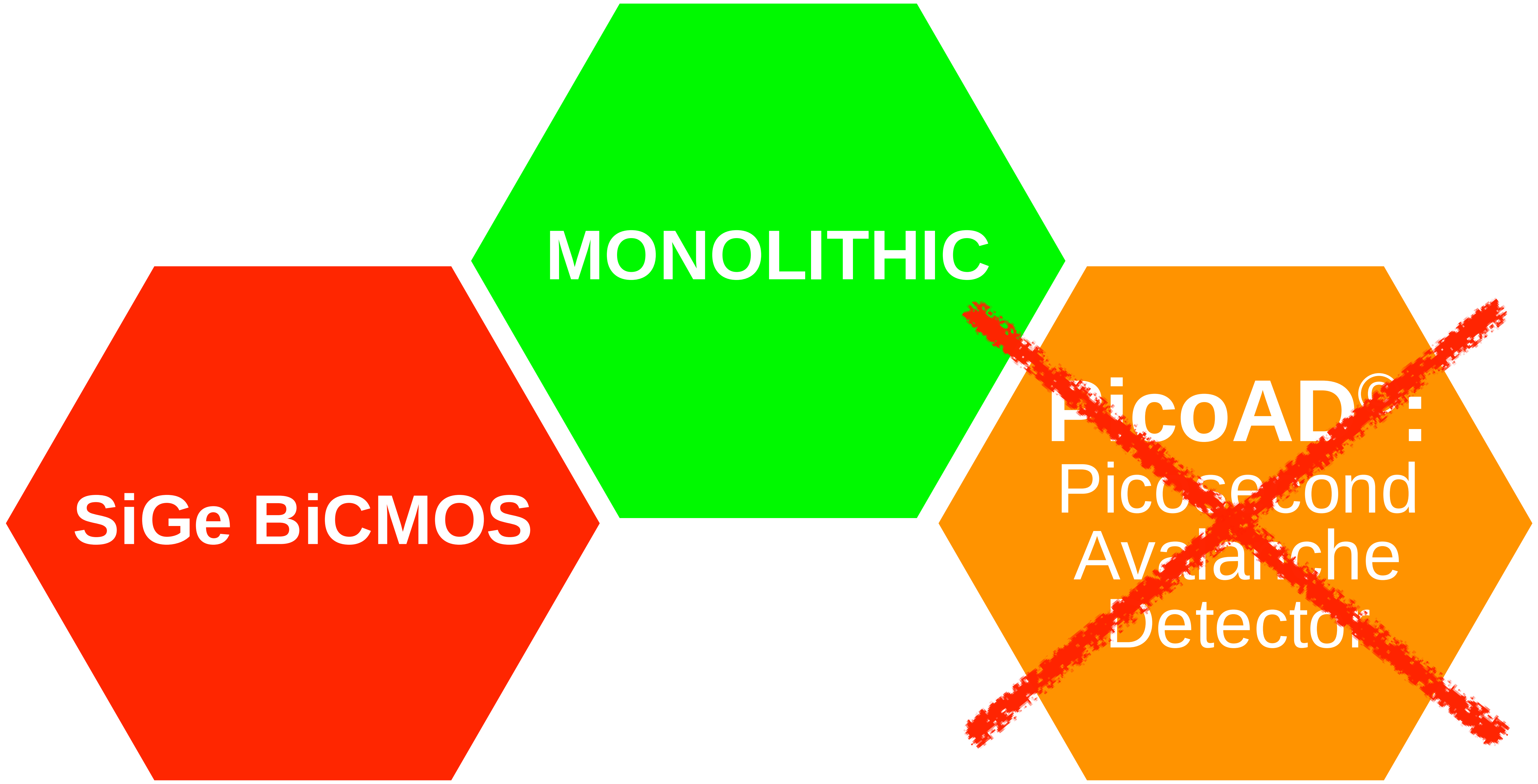
UNITEC

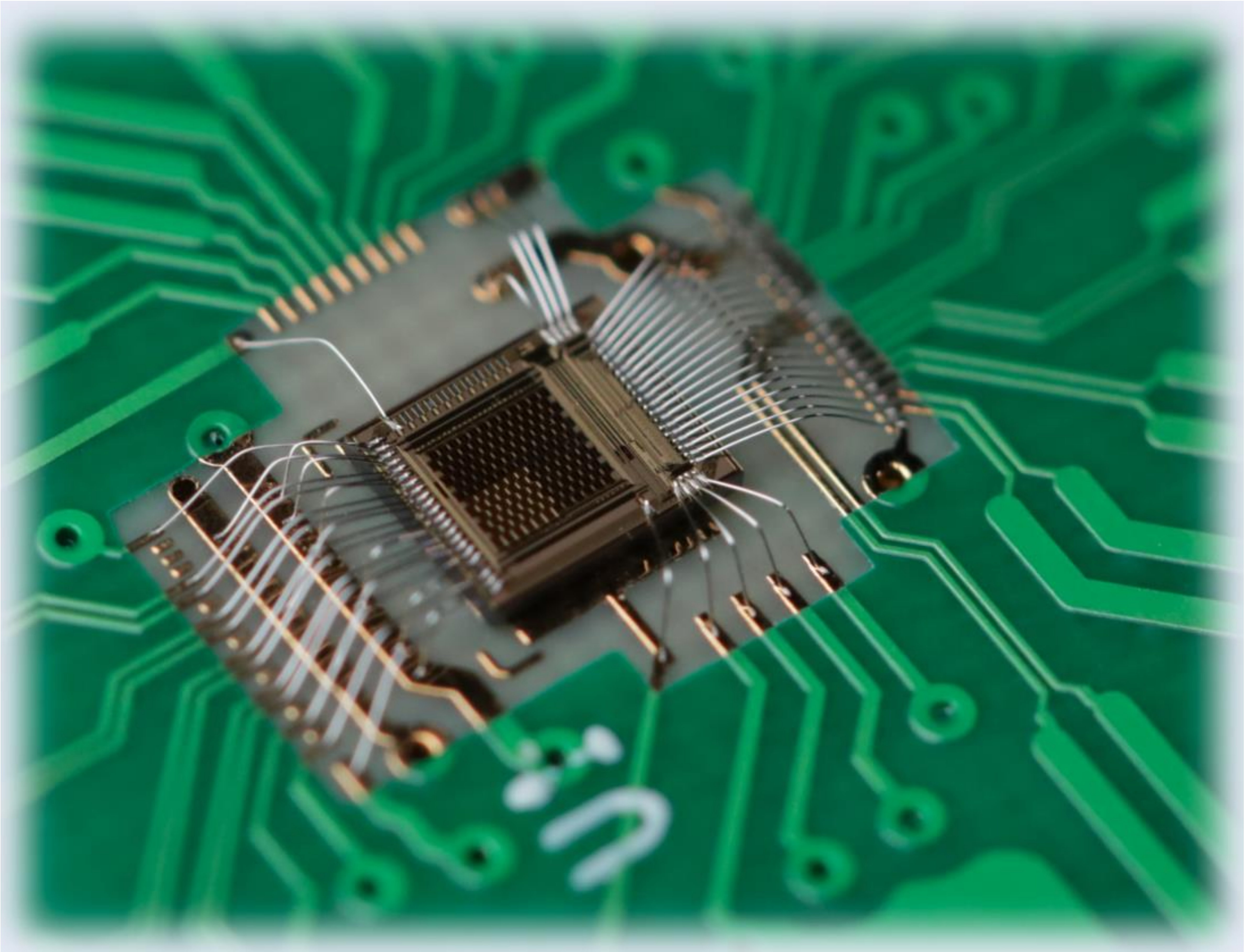
MONOLITH



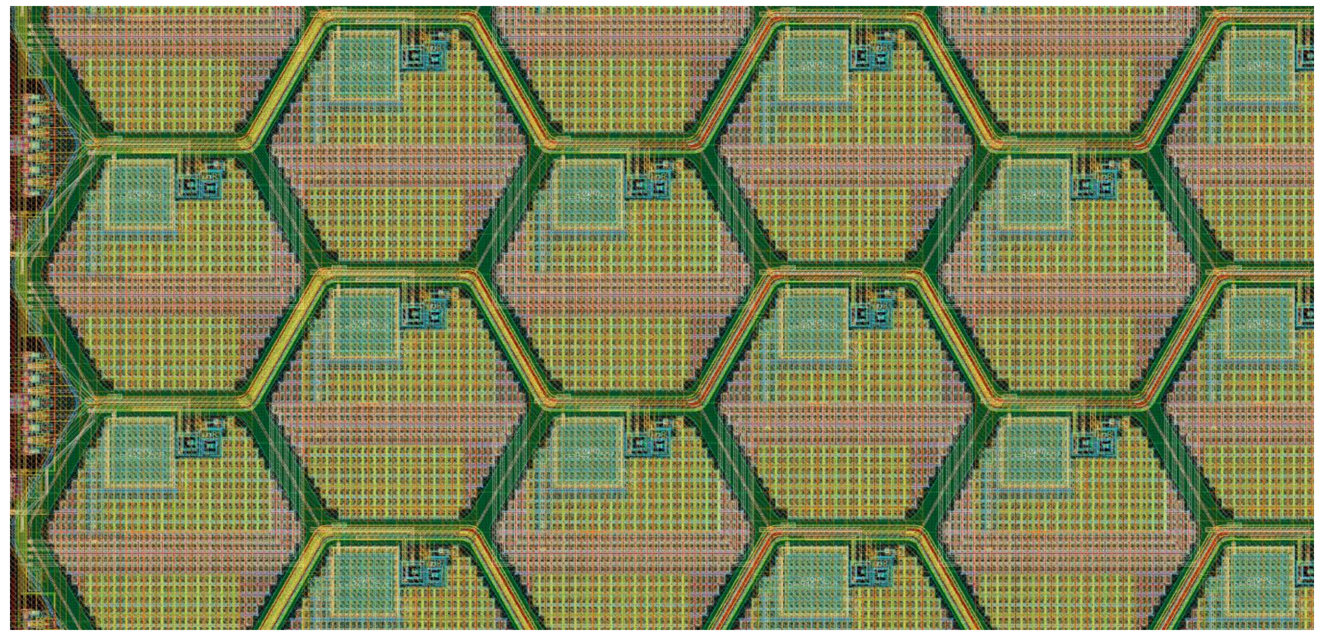
2022 prototype <u>without</u> gain layer



UniGe monolithic prototype



- **Sensor**: epilayer 350Ωcm, 50µm thick
  → simple pn junction, no gain layer
- **Electronics**: SiGe HBT frontend



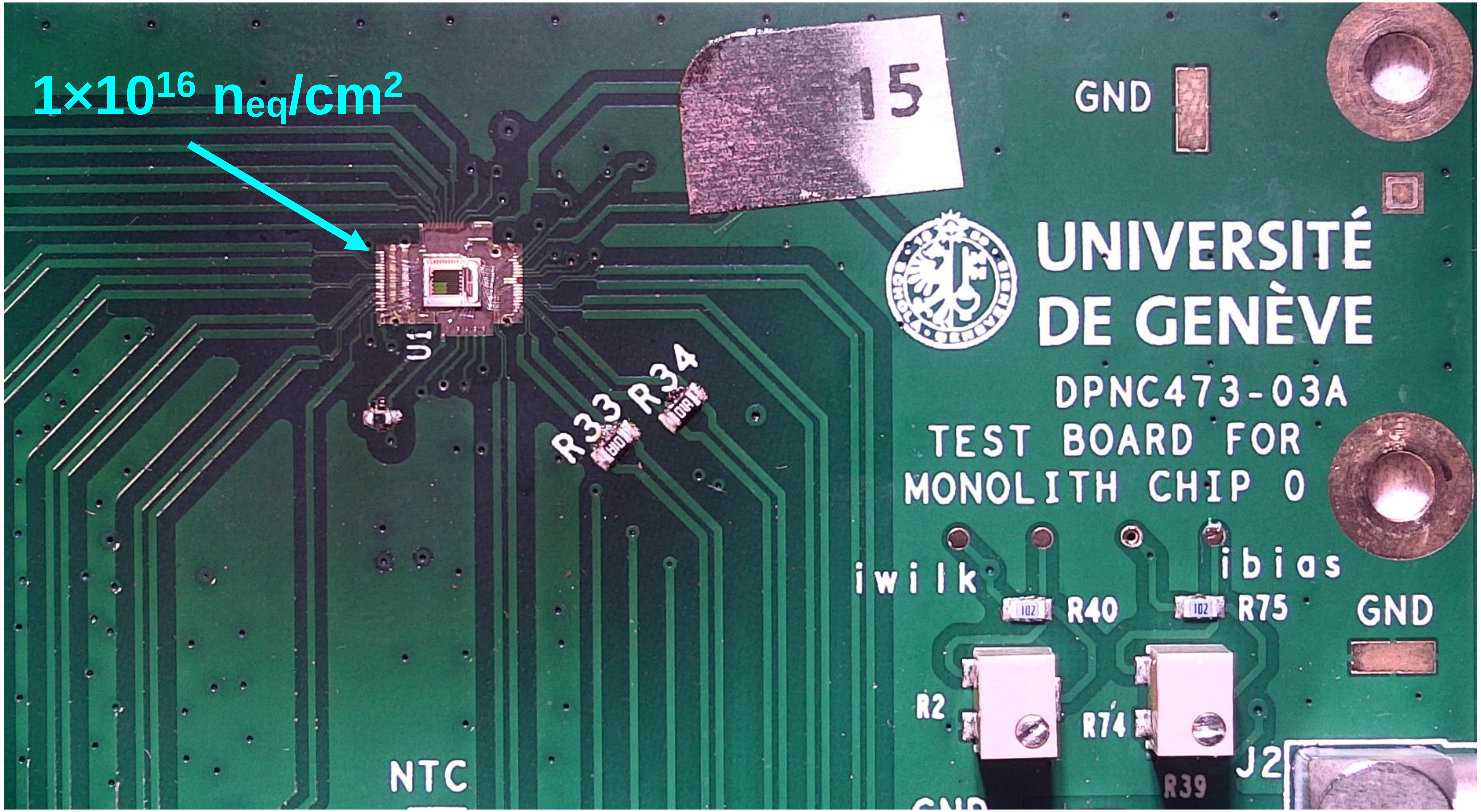
- matrix of: 12x12 hexagonal pixels
  100µm pitch
- results from 4 analog channels

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

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)%

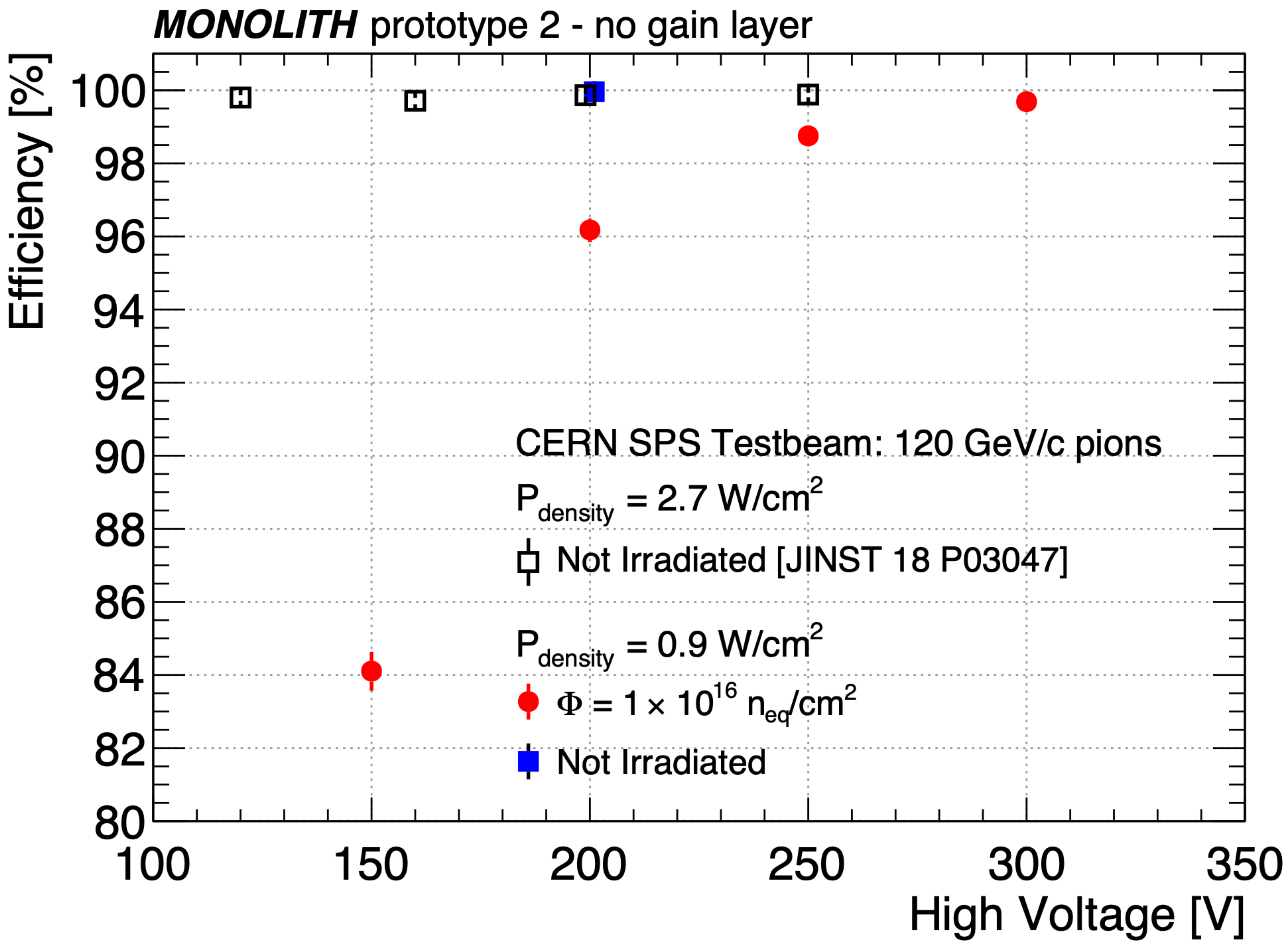
at HV = 200 V

● $1x10^{16}$ n_{eq}/cm^2:

Efficiency = (99.7 ± 0.1)%

at HV = 300V

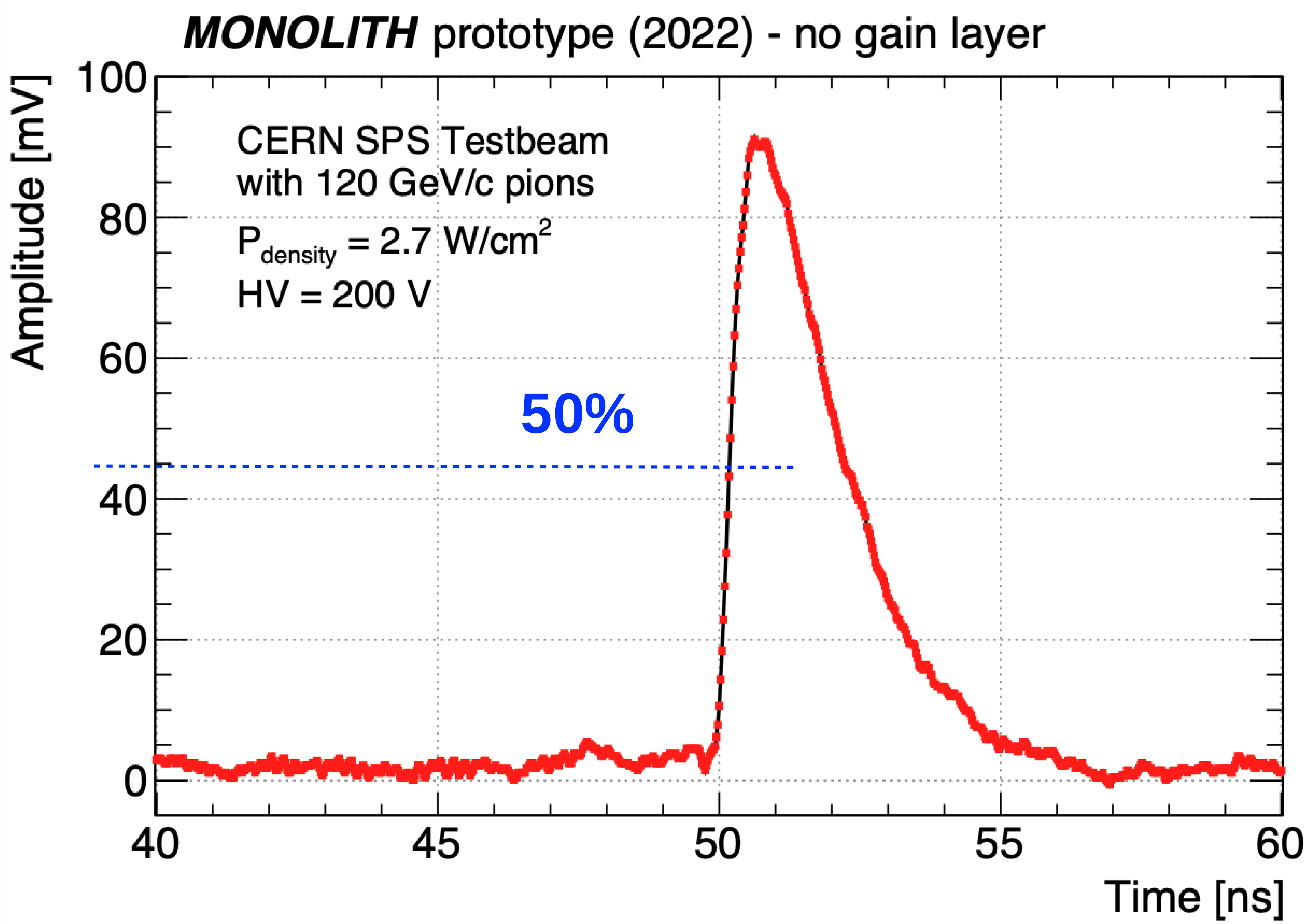
(higher HV still to be exploited)



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**



Time resolution vs. sensor bias voltage

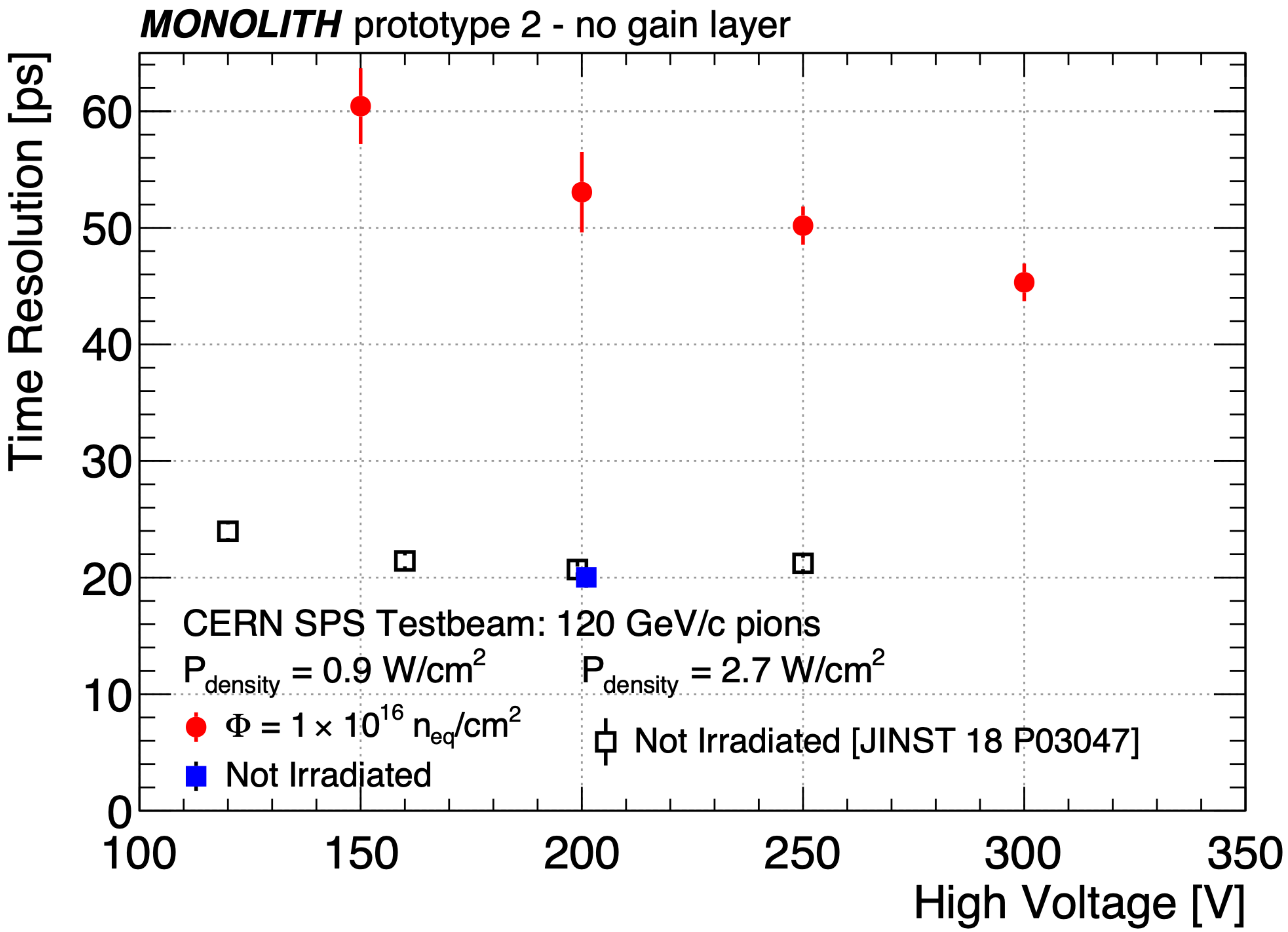
CERN SPS testbeam results:

□ Unirradiated:

20 ps at HV = 200 V

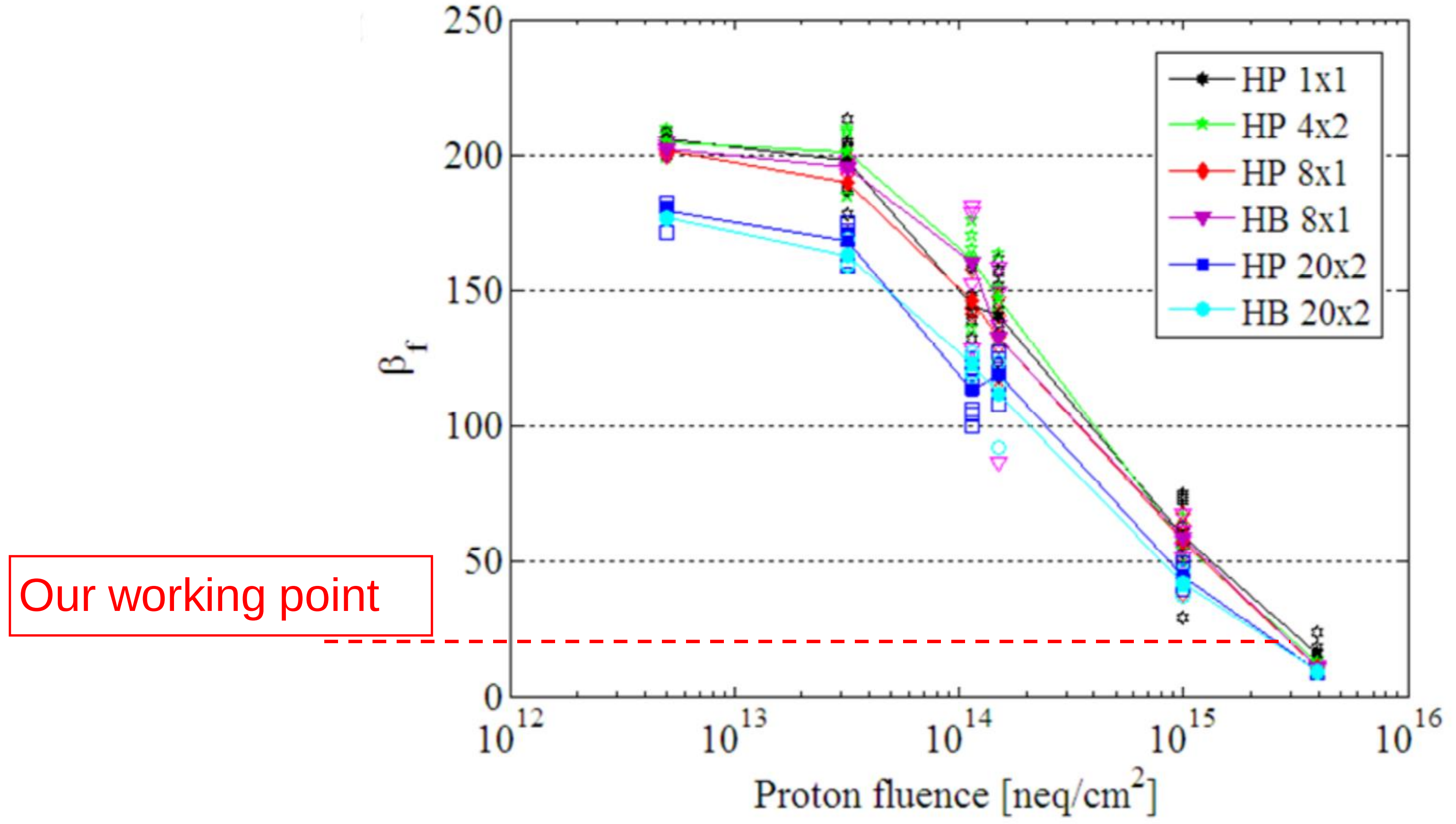
● $1x10^{16}$ n_{eq}/cm^2:

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

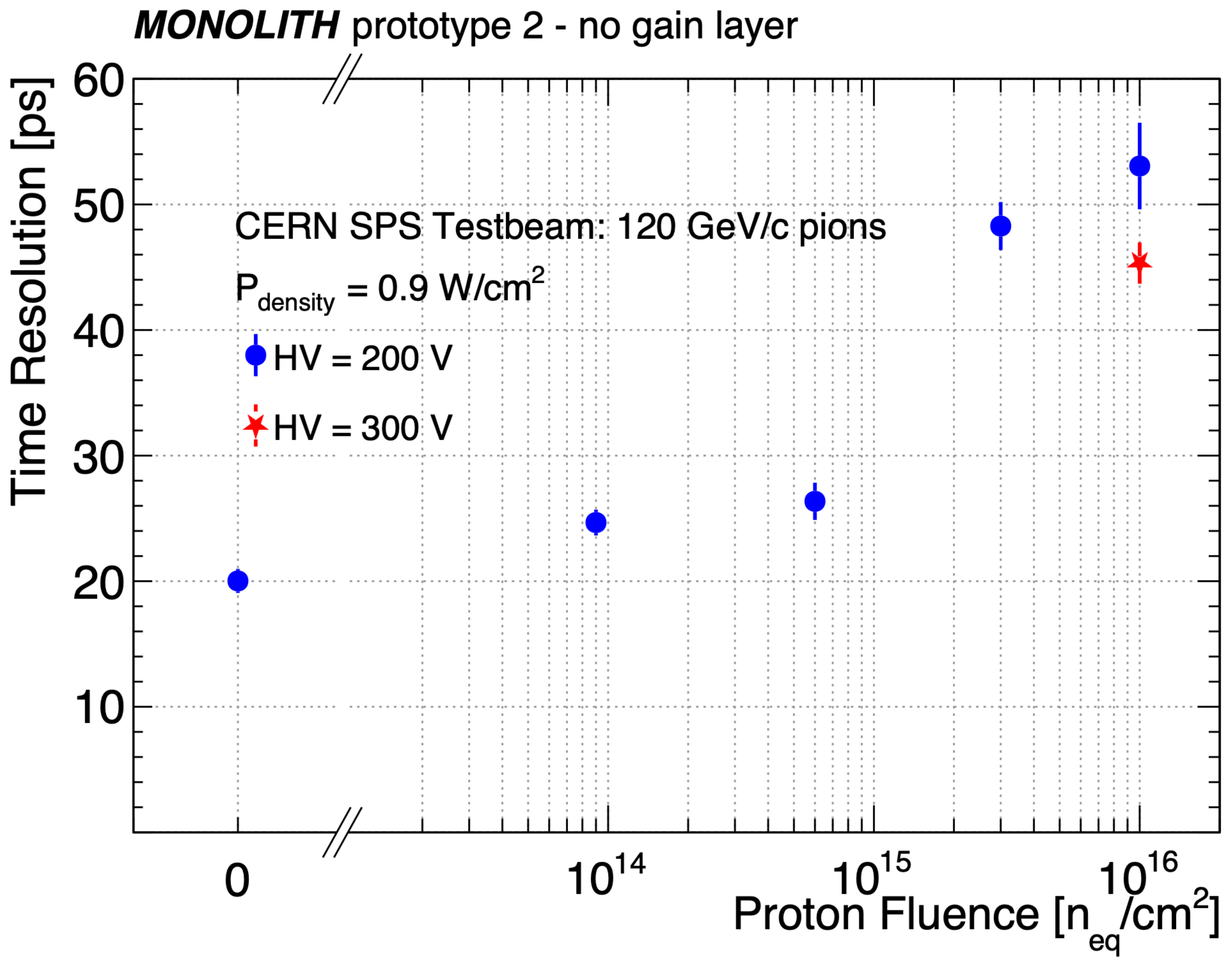


Time resolution vs. proton fluence

DC characteristics



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



Summary

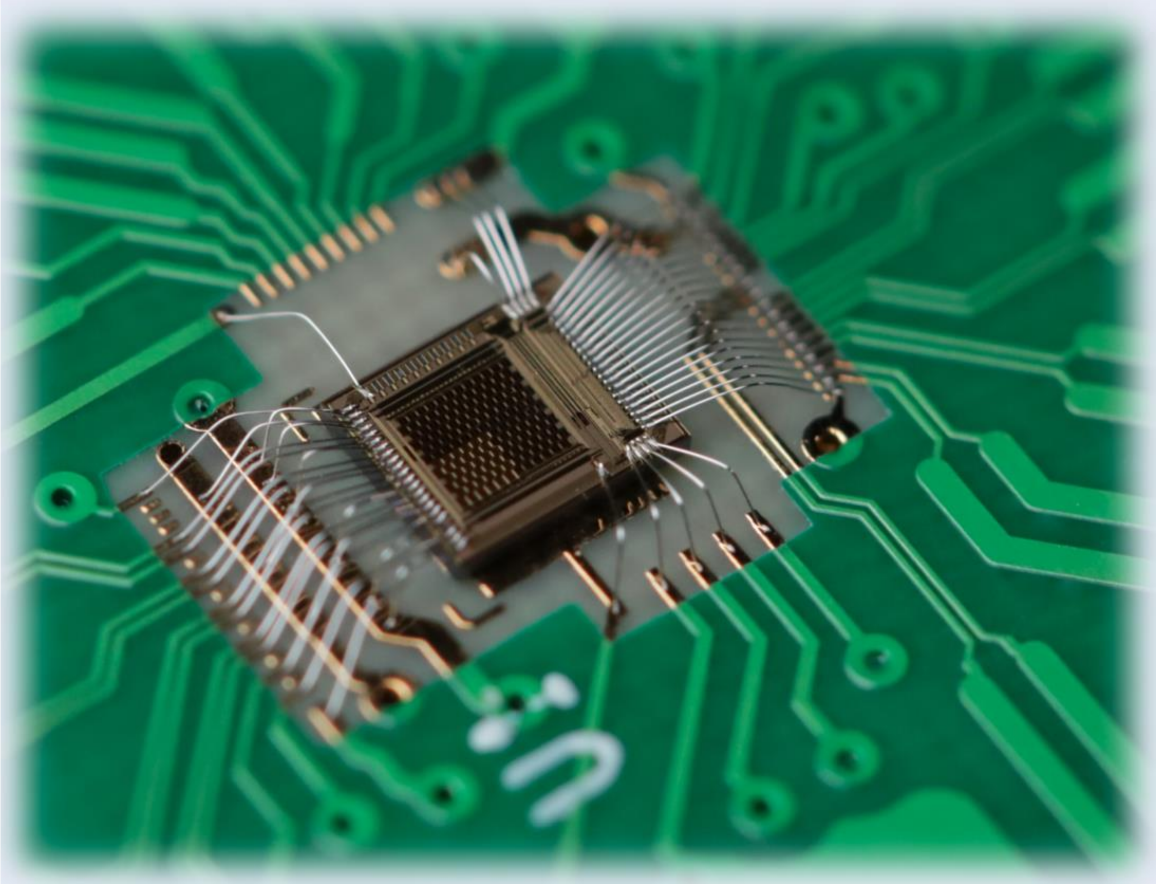
The UniGe monolithic SiGe BiCMOS prototype ASIC provided:

- 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

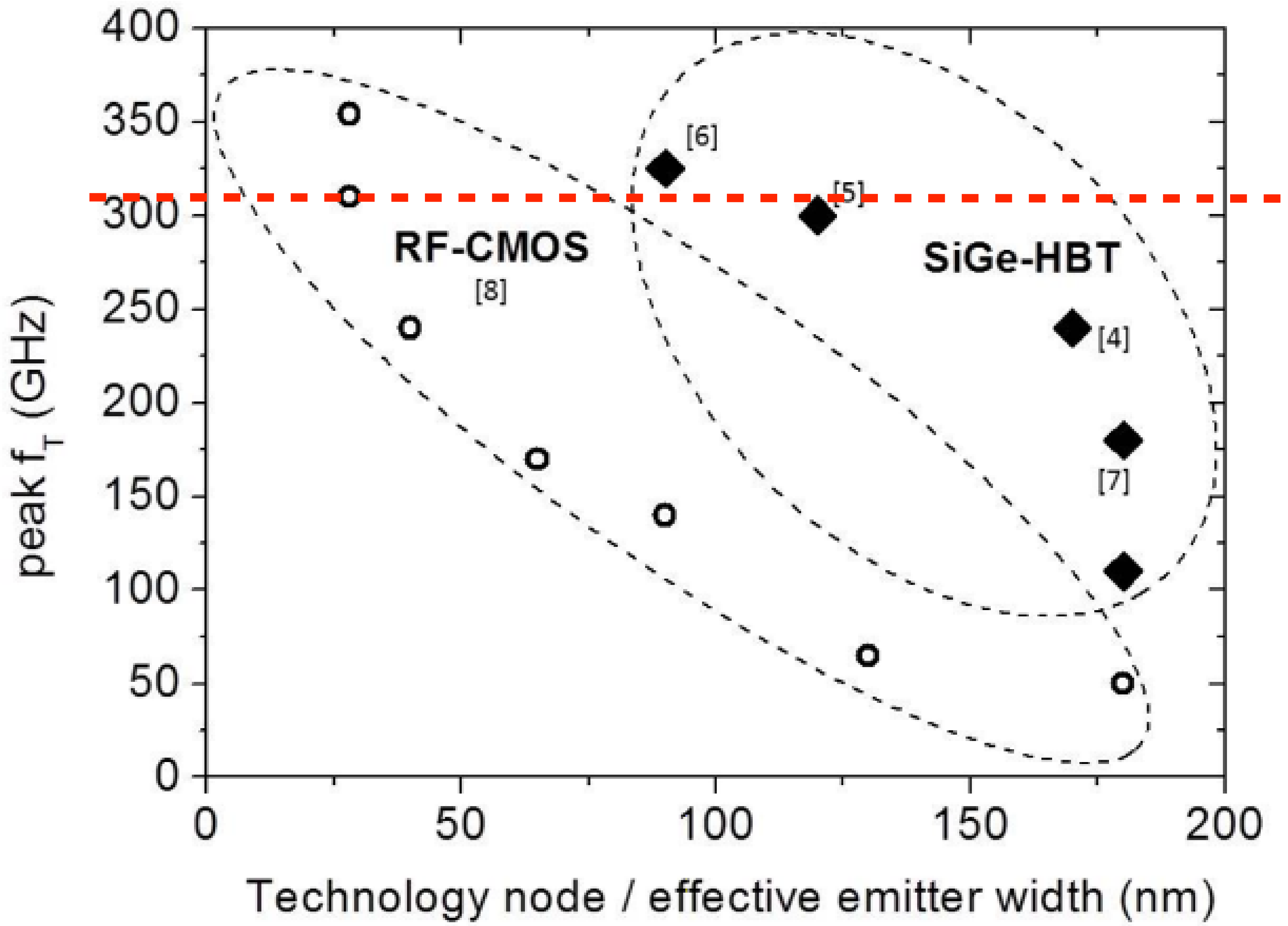


If the **radiation tolerance of gain layers** remains a concern, particle-physics experiments can do excellent timing **without** gain layer

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

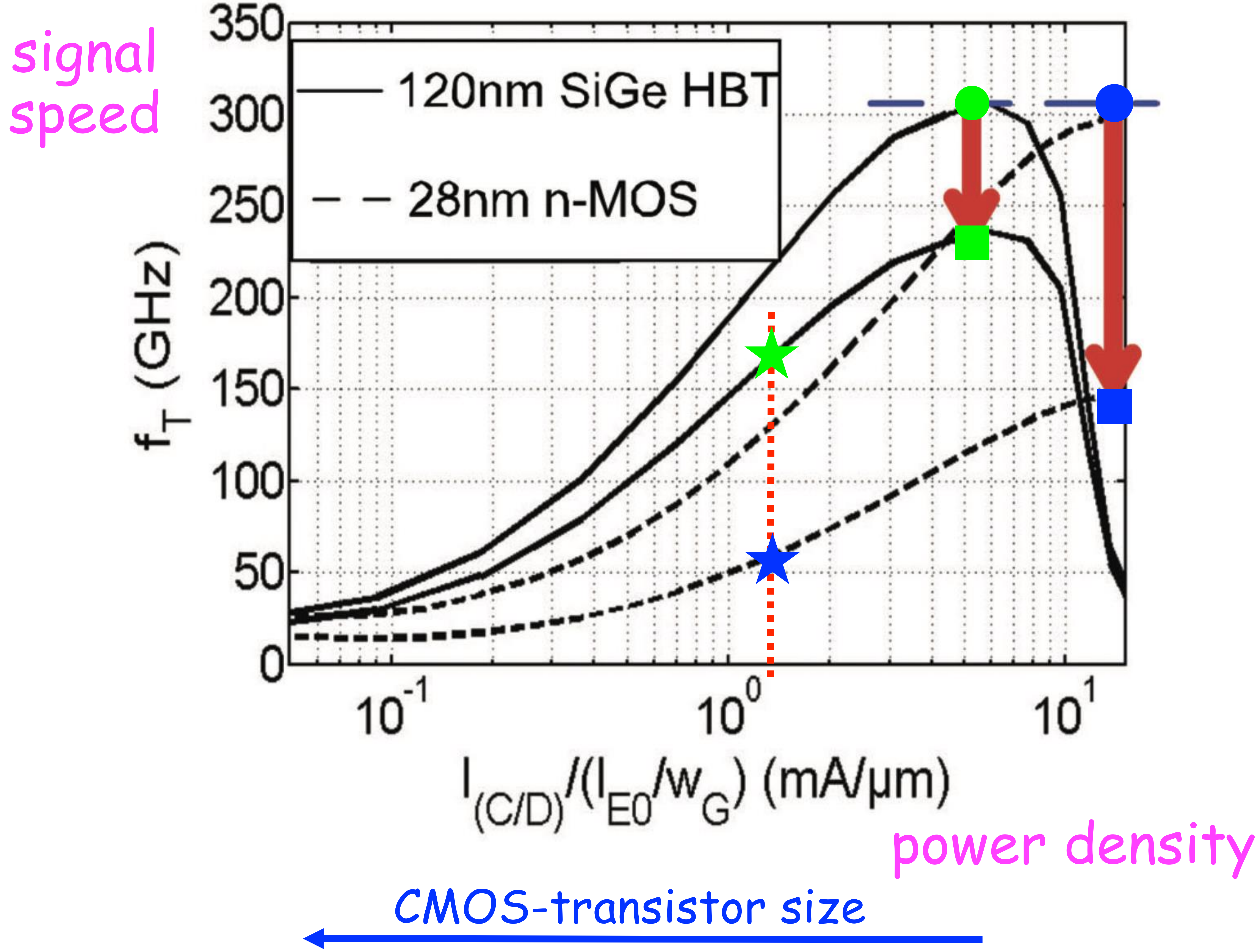
28 nm CMOS
and
130 nm SiGe HBT

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)

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, ams, …

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

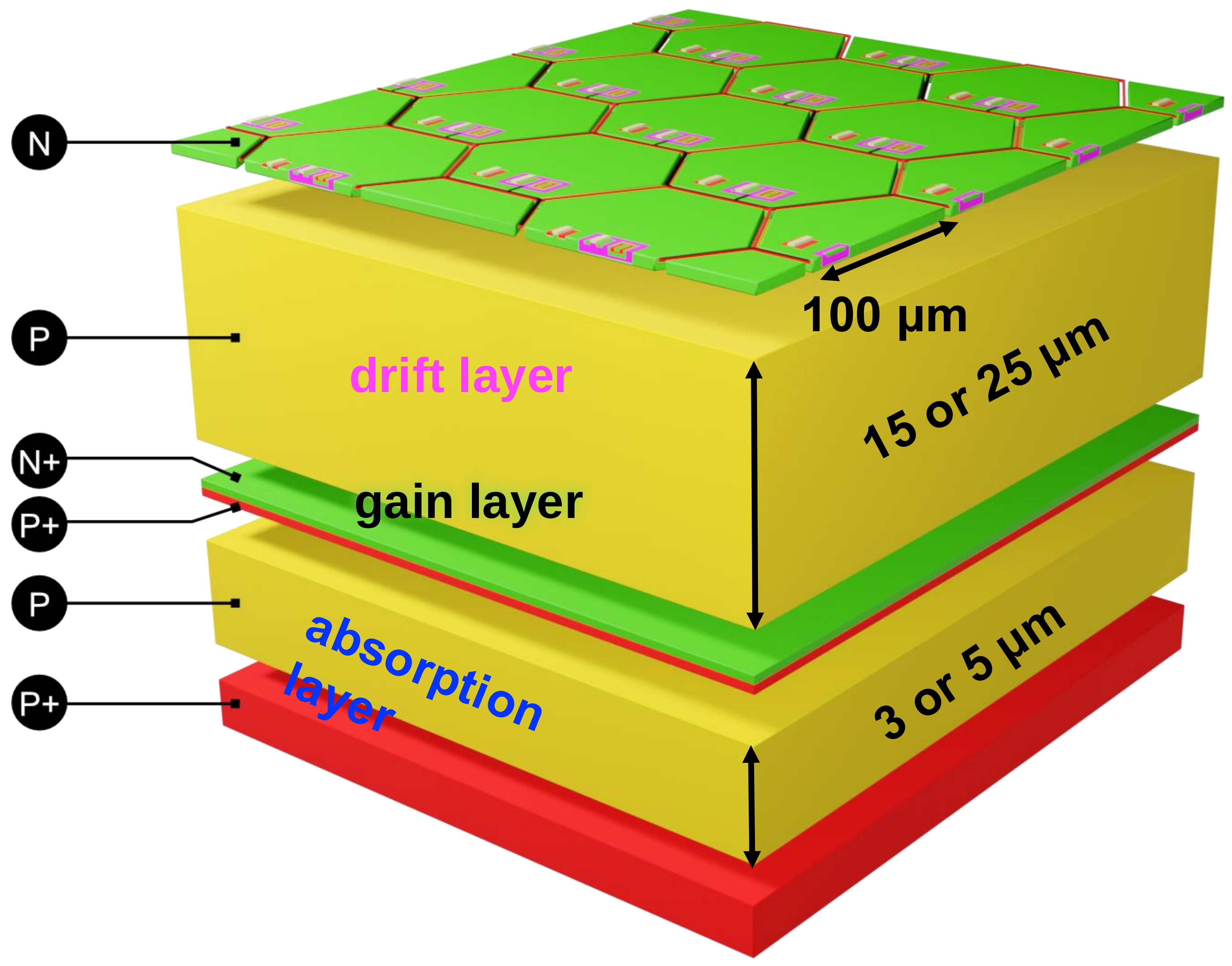
© G. Iacobucci, L. Paolozzi and P. Valerio. Multi-junction pico-avalanche detector; **European Patent** EP3654376A1, **US Patent** US2021280734A1, Nov 2018

PicoAD:

Multi-Junction Picosecond-Avalanche Detector©

with continuous and deep gain layer:

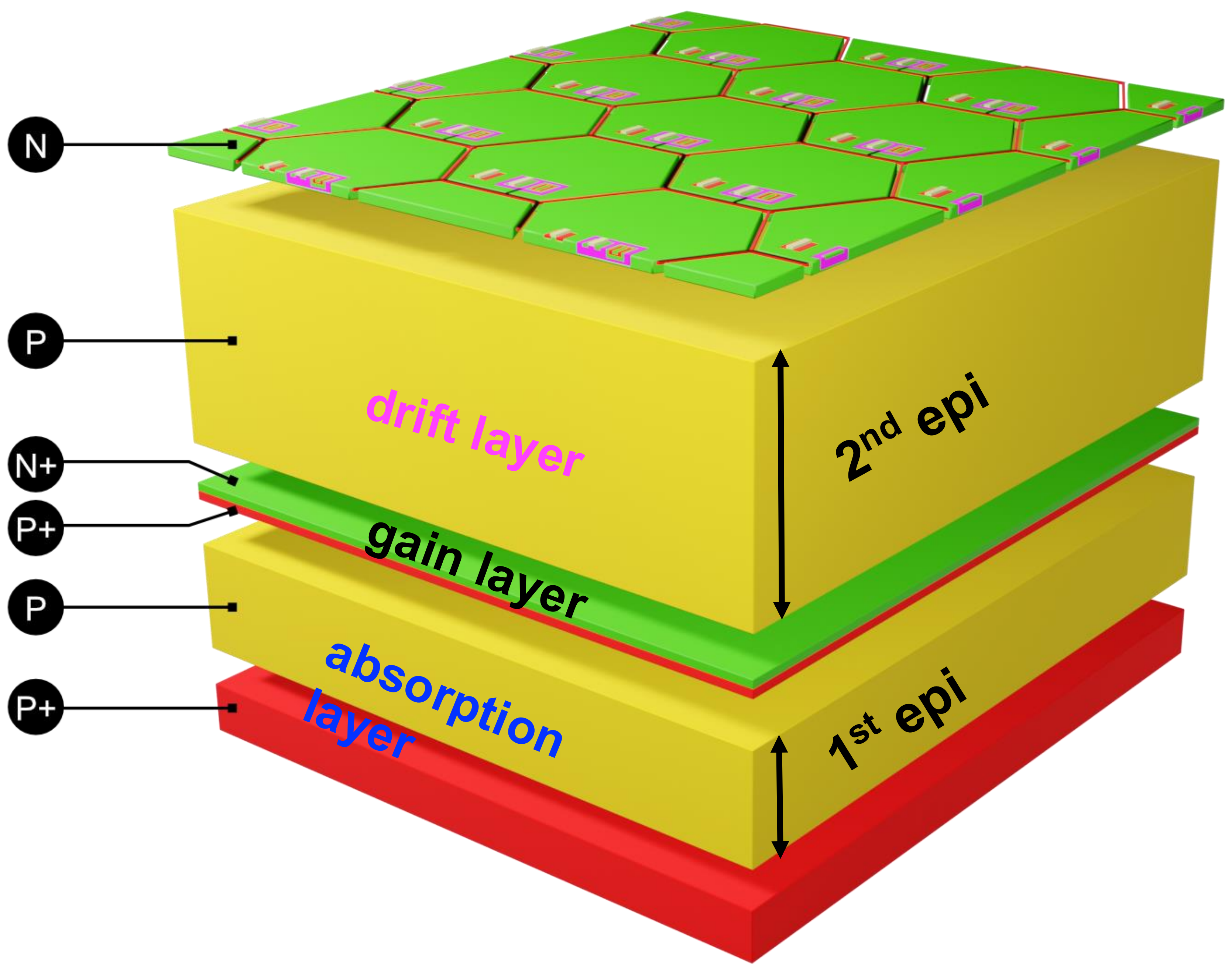
- De-correlation from implant size & geometry
  → **high pixel granularity and full fill factor**
  (to get homogeneous efficiency and timing)
- Only the small fraction of charge produced in the thin **"absorption layer"** gets amplified
  → **reduced charge-collection (Landau) noise**
  (to enhance 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 →

2024 PicoAD production

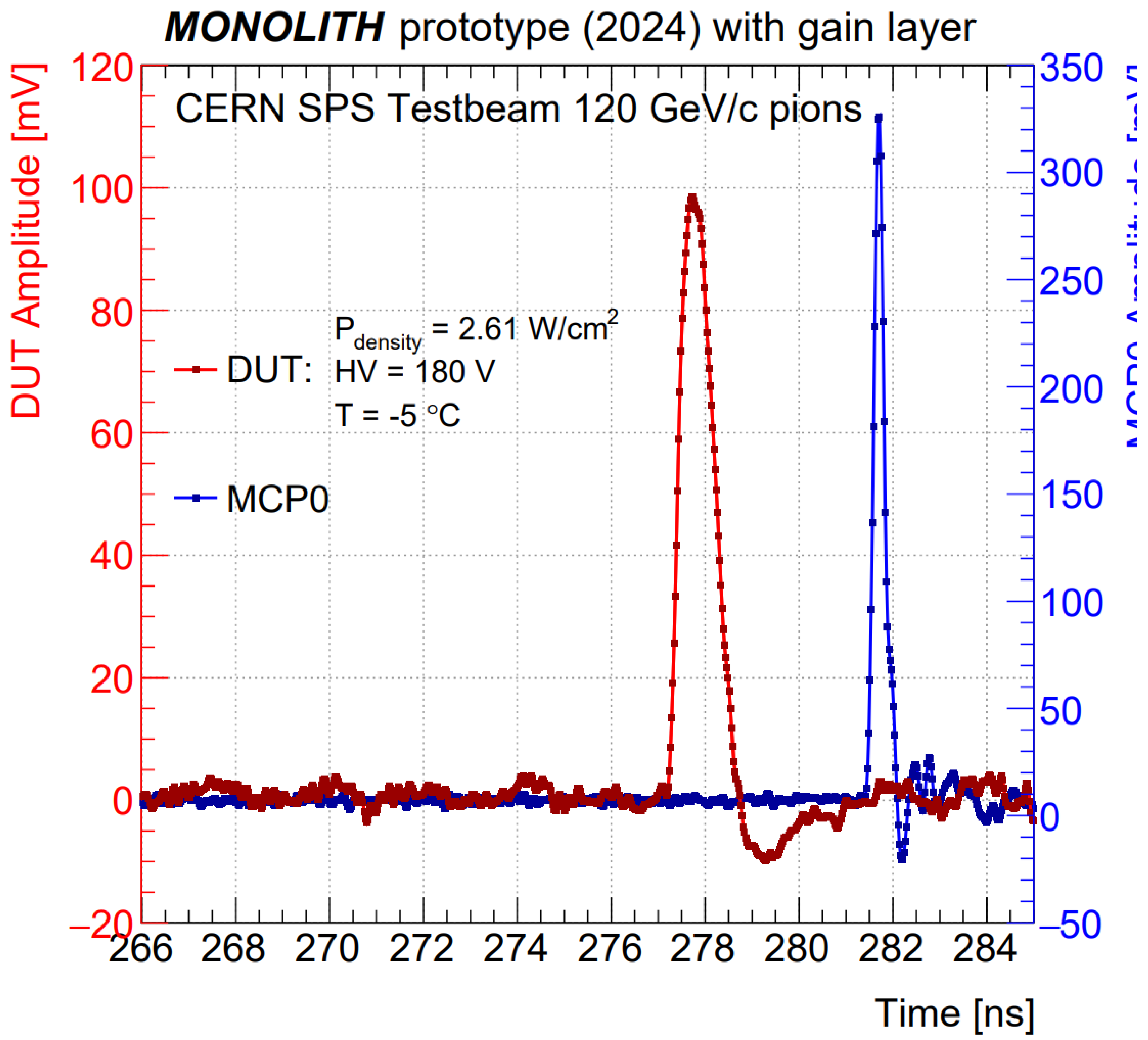
Wafer	1st epi thickness [μm]	2nd epi thickness [μm]	Gain-layer implant dose
3	3	15	3
			3.5
			4
4	3	25	3.5a
			3.5b
			4.75
5	3	25	4
			4.5
			5
6	5	15	3
			3.5
			4
7	5	25	4
			4.5
			5



15 different flavours produced;
in 4 geometries.

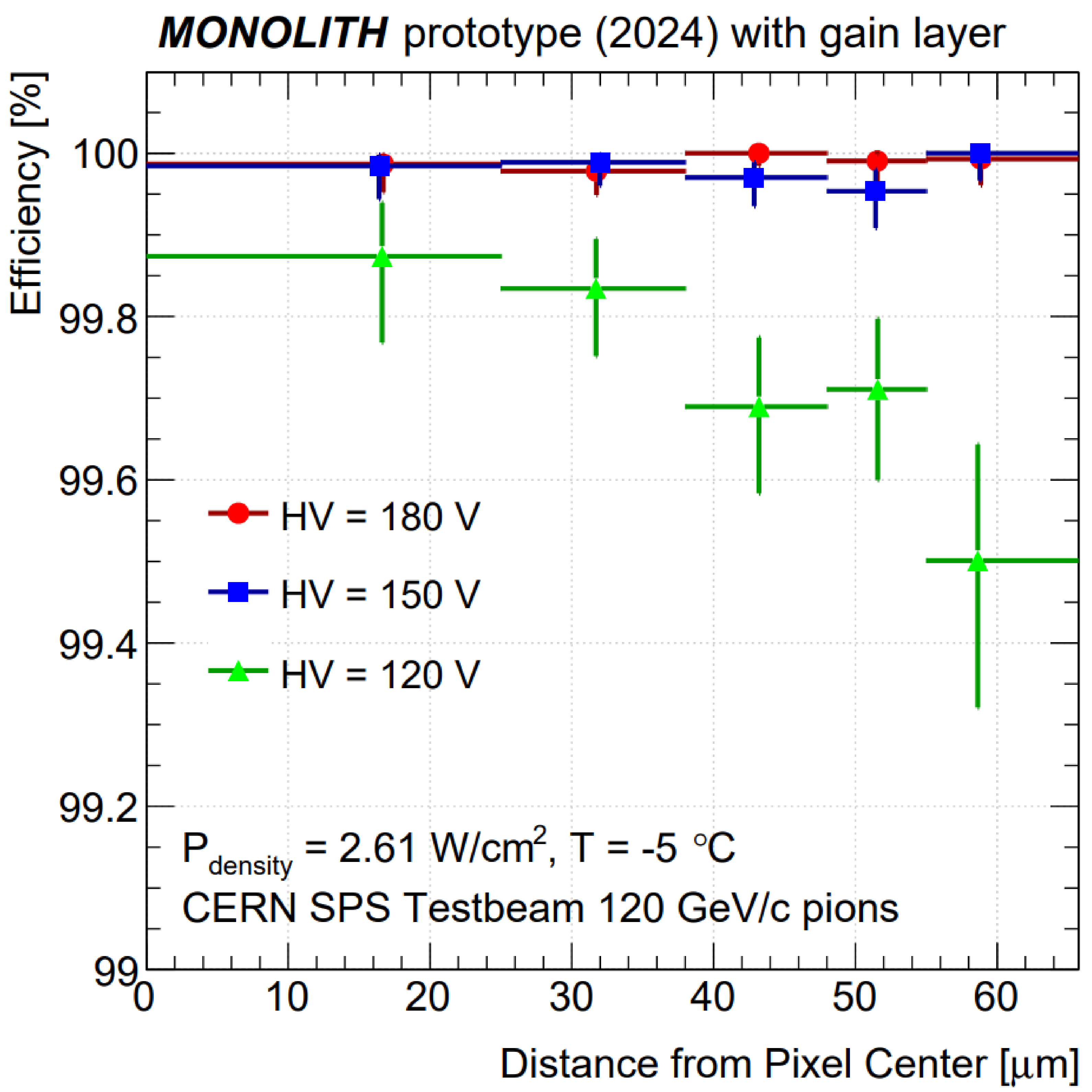
Tested at CERN SPS beamline

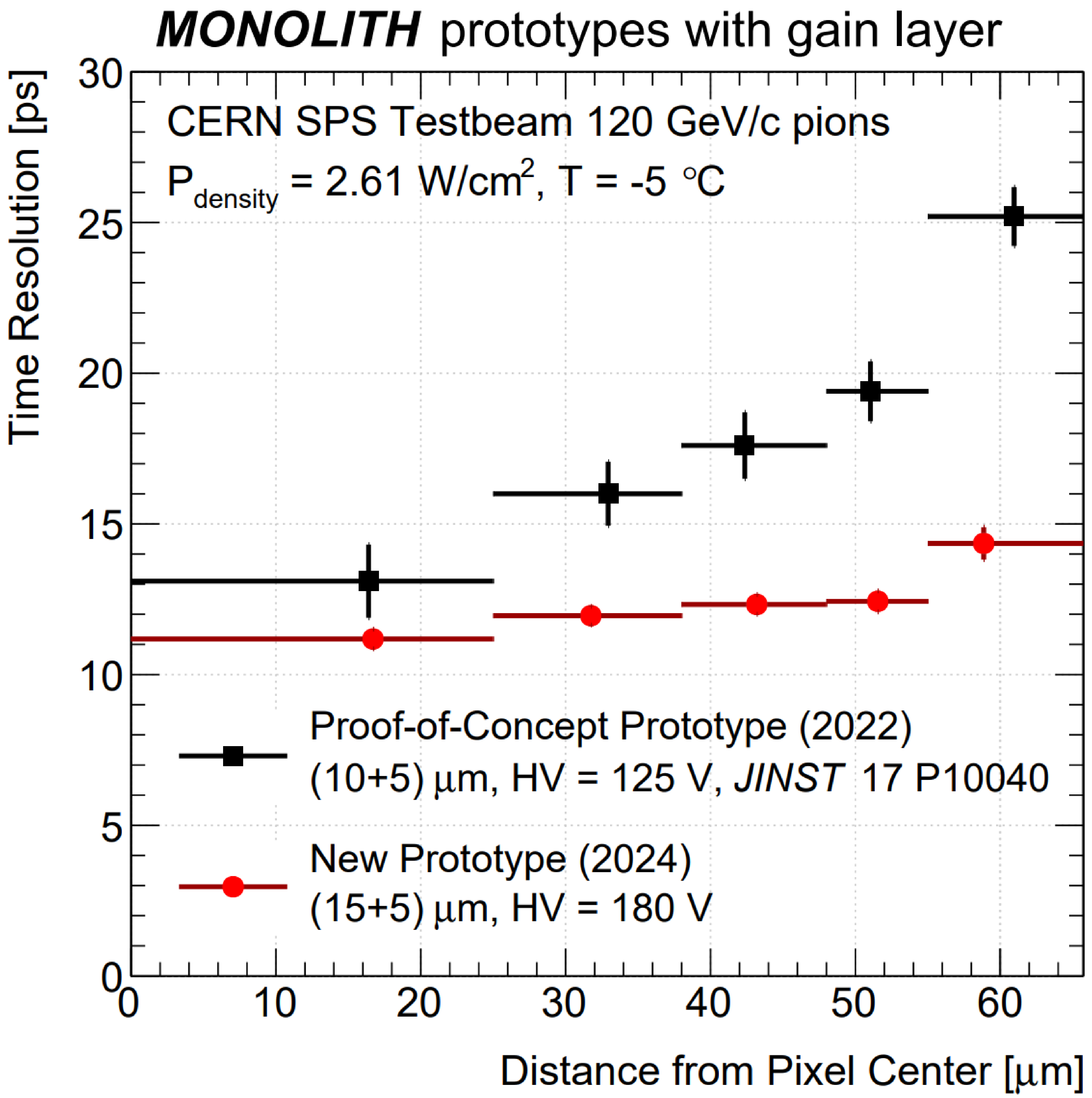
Testbeam of 2024 PicoAD prototype

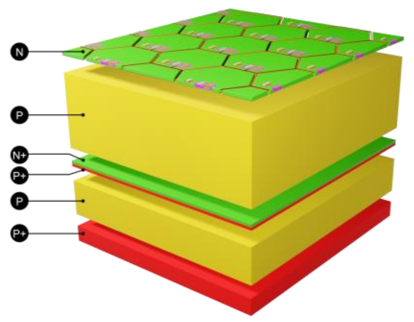


Typical signal pulse

Testbeam of 2024 PicoAD prototype





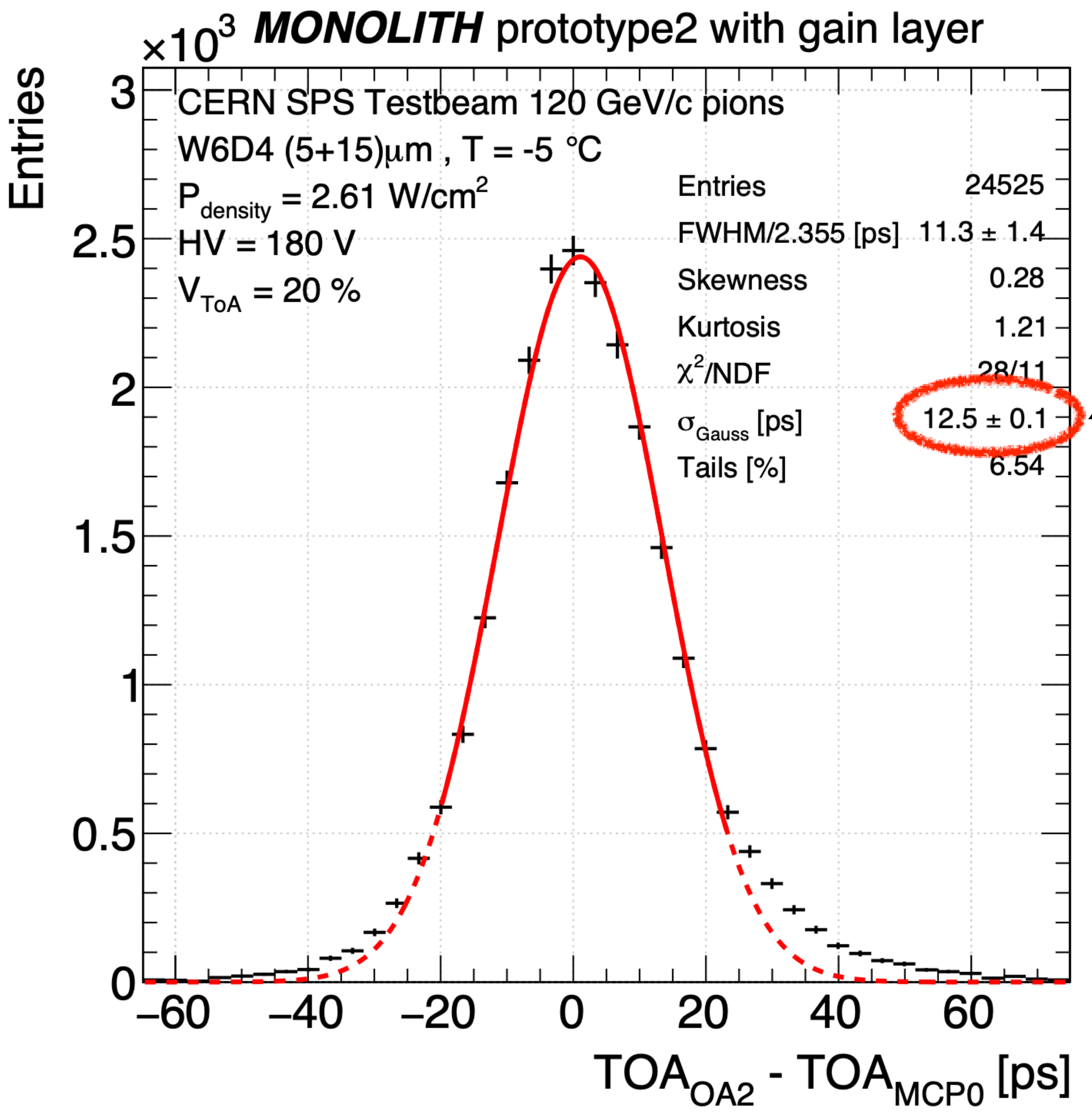


Much improved uniformity of the electric field due to

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 :

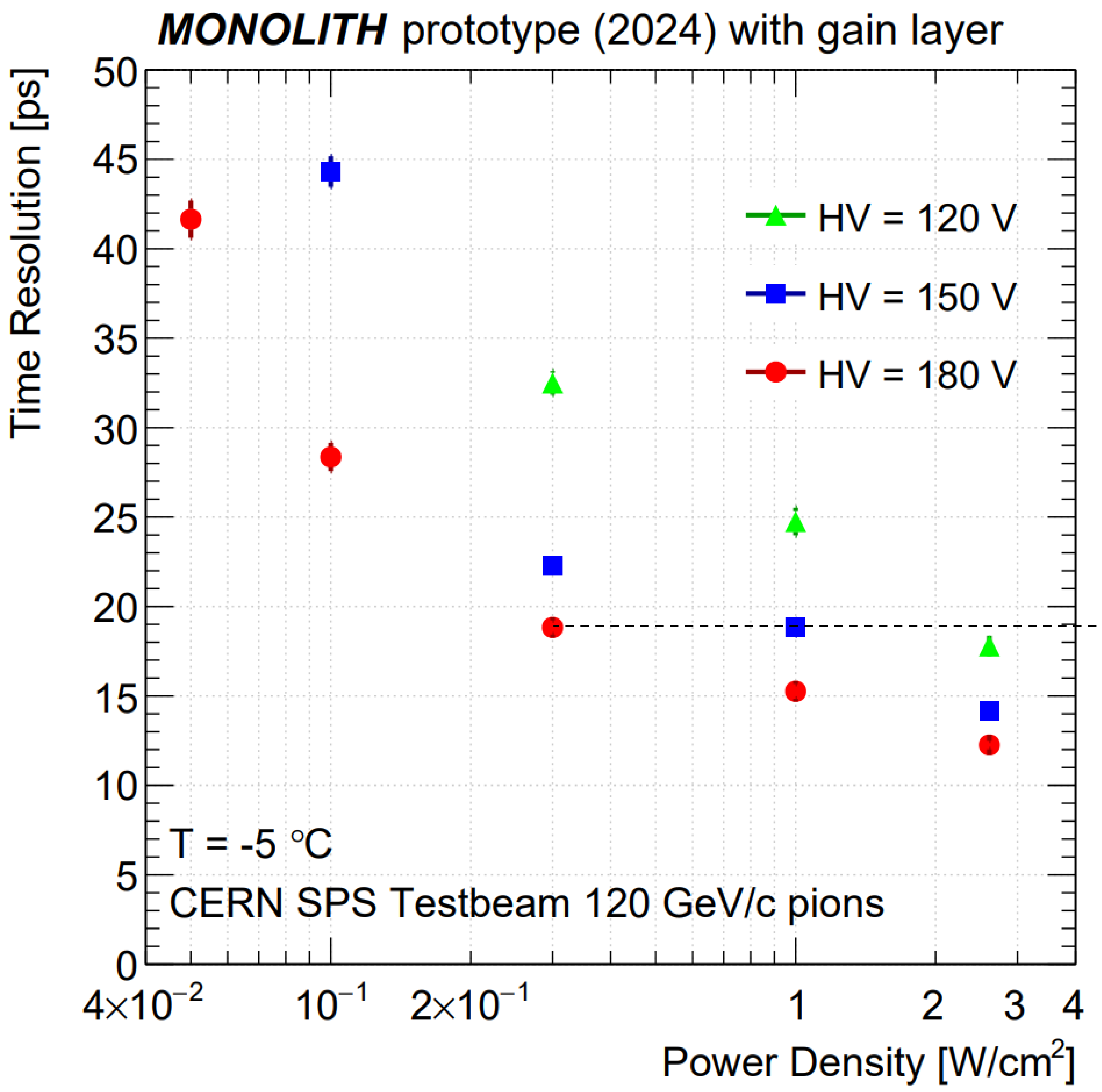
$ToA_{PicoAD} - ToA_{MCP} =$ **12.5 ps**

Subtraction in quadrature of MCP contribution

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

MCP resolution

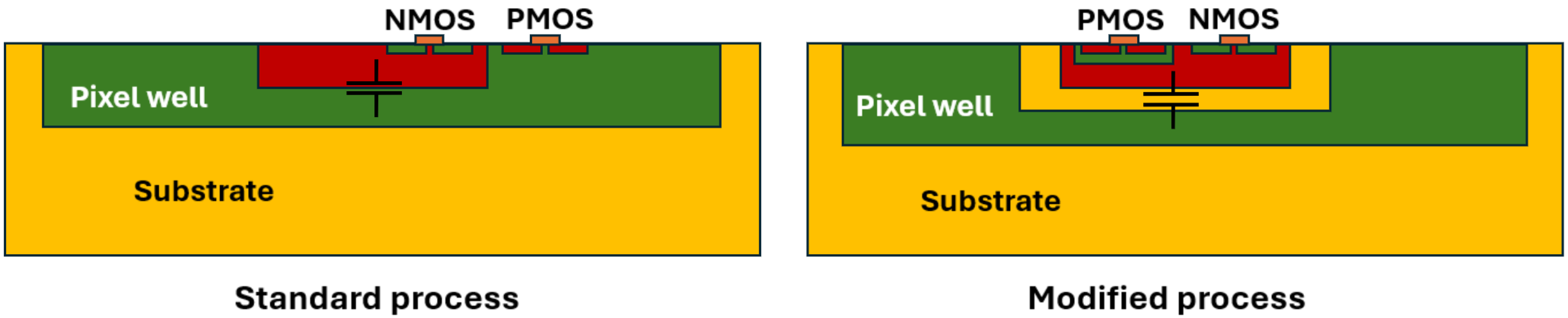
Testbeam of 2024 PicoAD prototype



18 ps achieved at 0.3 W/cm^2

18 ps

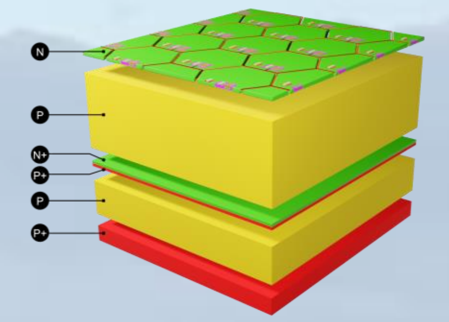
Next steps



- Improving transistor isolation in pixel and reducing parasitic capacitance
- First prototype submitted for production in August 2024

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.

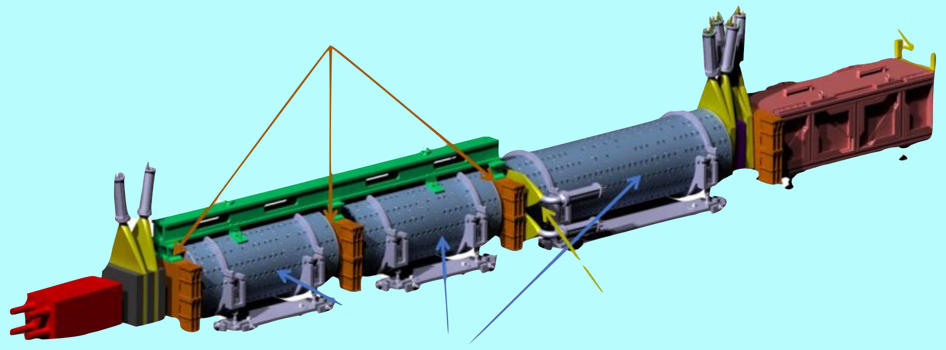
We produced a **fully efficient** avalanche detector with **homogeneous gain everywhere**

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)

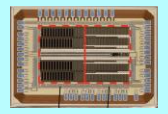
UniGe monolithic SiGe BiCMOS ASICs

European Research Council
Established by the European Commission

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

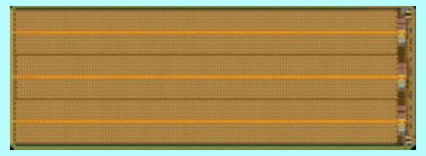


2022



JINST **16** P12038

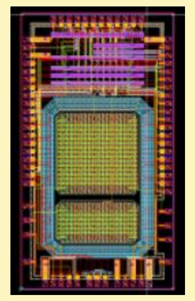
2023



pre-production ASIC (full column)

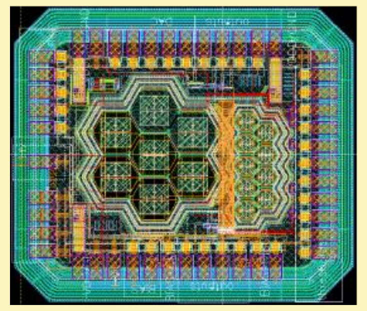
Timing prototypes (no gain layer):

2016



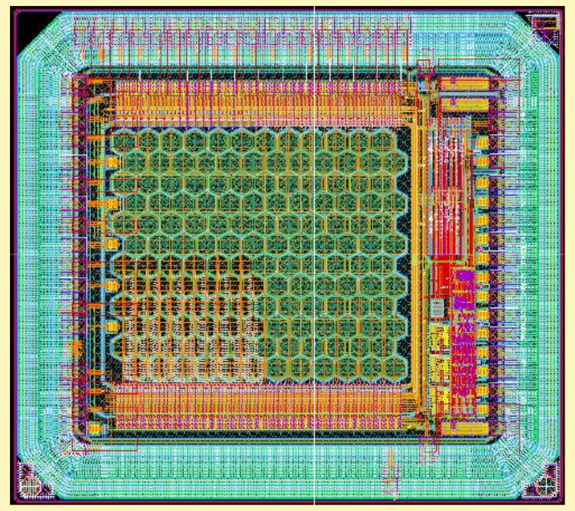
200ps
JINST **13** P02015

2018



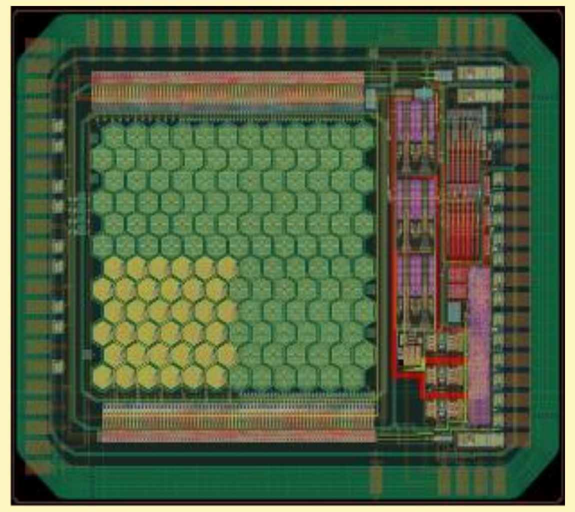
50ps
JINST **14** P11008
JINST **15** P11025

2020



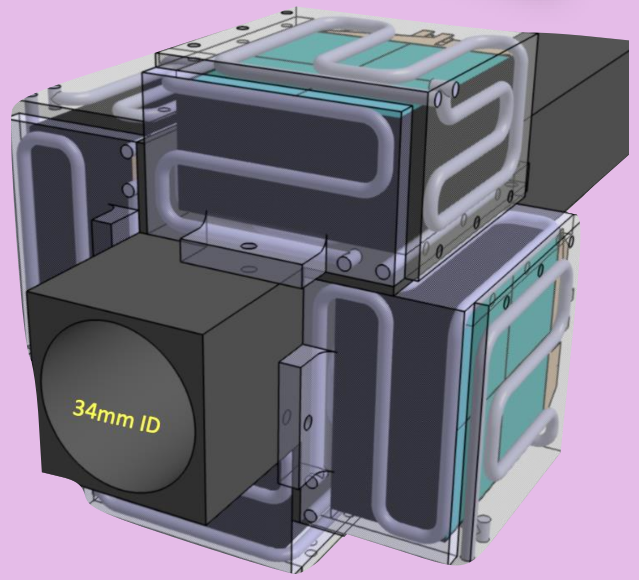
36 ps
JINST **17** P02019

2022

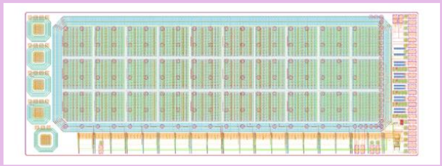


20 ps
JINST **18** P03047 *JINST* **19** P04029
JINST **19** P01014 arXiv:2404.12885

Medical: TT-PET and 100µPET projects



2017



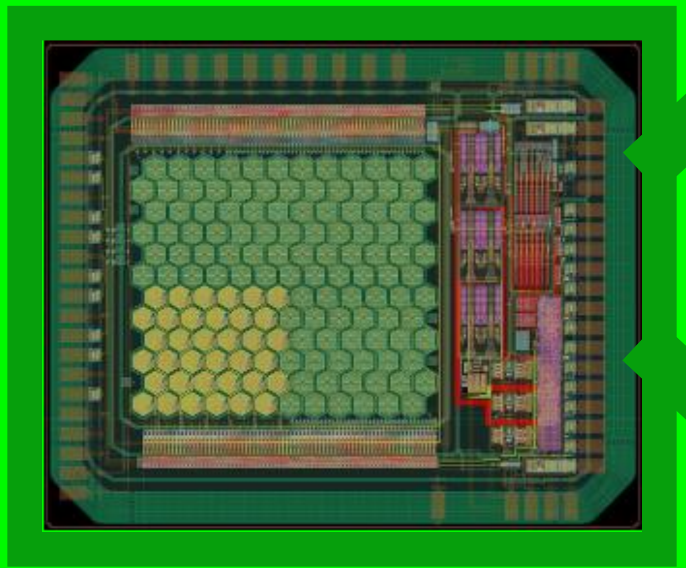
110ps
JINST **14** P02009
JINST **14** P07013

2024

MONOLITH prototypes production is now complete

without gain layer

PicoAD©
(gain layer)



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

future possibilities

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

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

photonics
(Thanushan Kugathasan)
(Roberto Cardella)

Extra Material

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

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

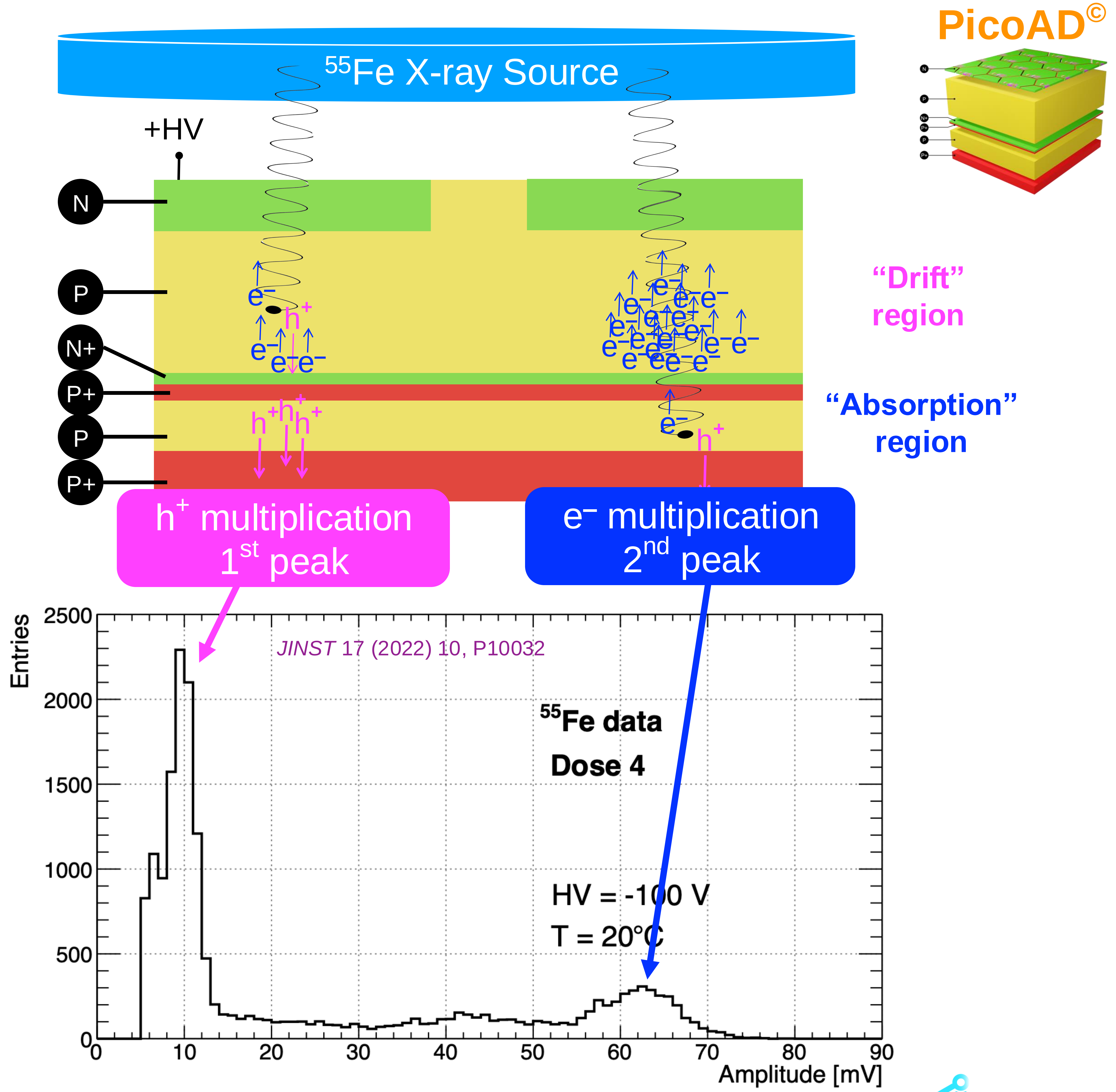
- mainly ~5.9 keV photons
- point-like charge deposition

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

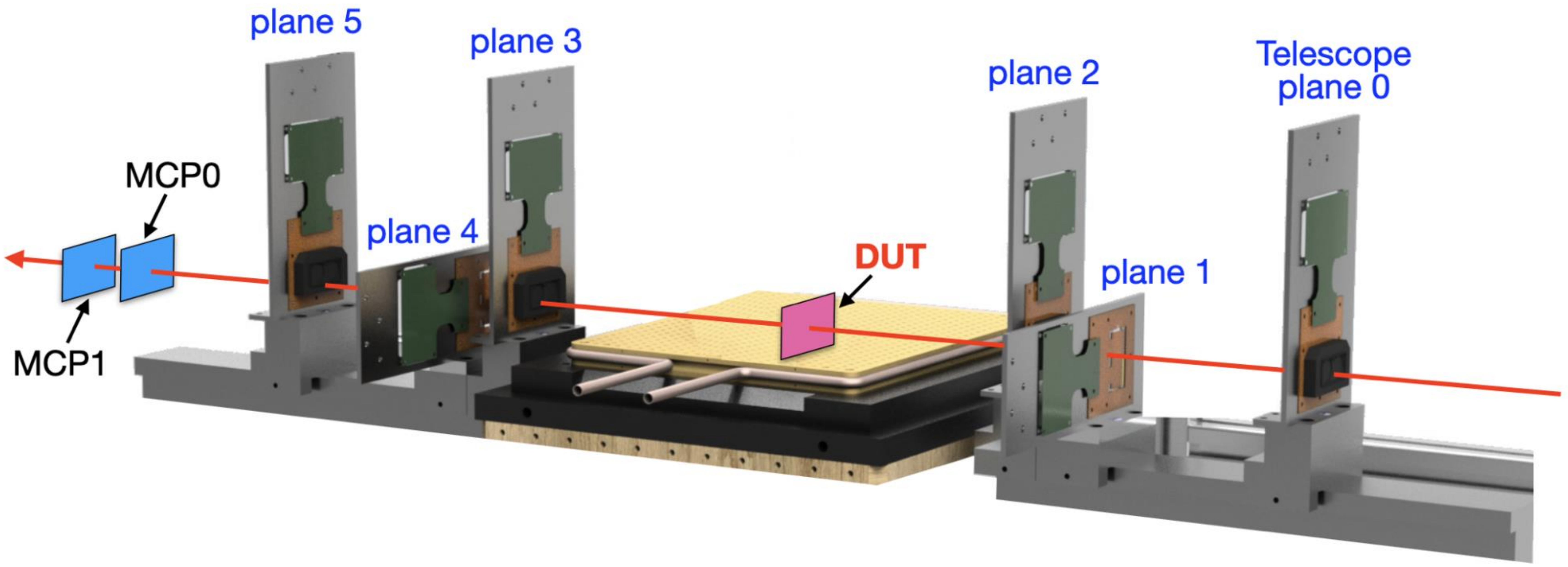
Gain measured: ~20 for ^{55}Fe

(corresponding to ~60 for a m.i.p.)



Test Beam: Experimental Setup

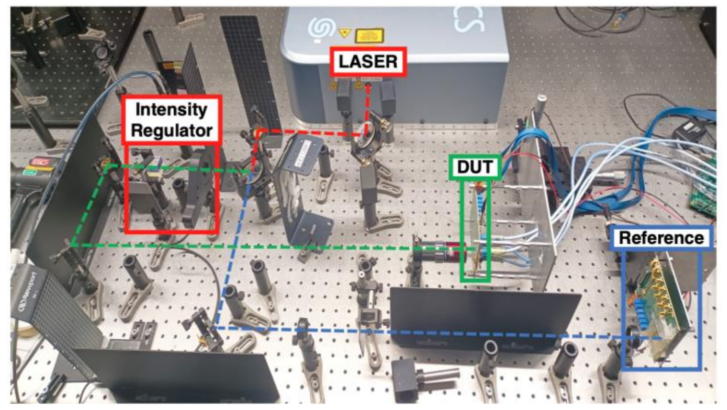
SPS testbeam in 2023 with 120 GeV/c pions to measure **efficiency** and **time resolution**



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

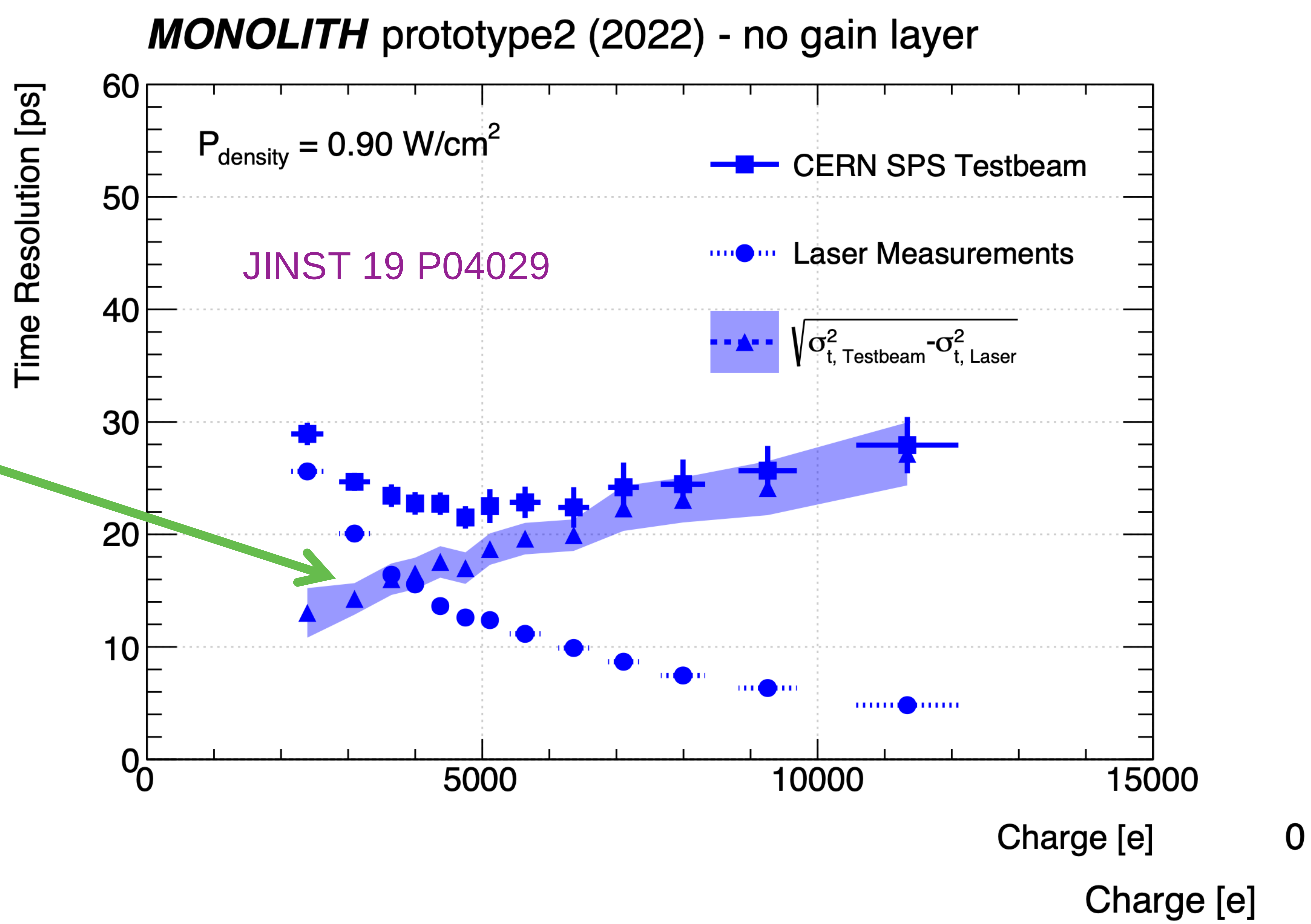
Two MCPs (σ_t ≈ 5 ps) to provide the timing reference

Laser measurement



Laser Measurement

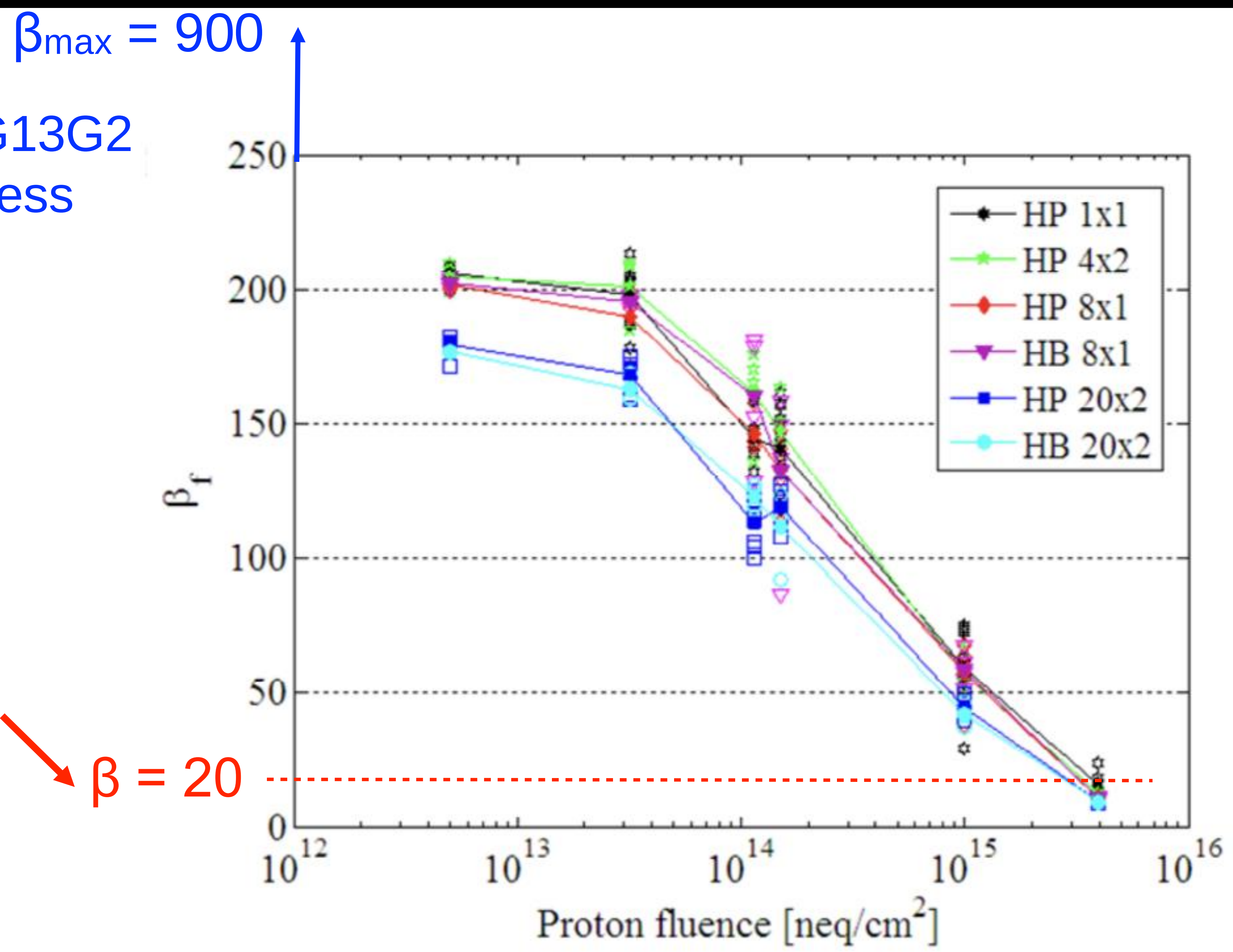
The band estimates the charge-collection (“Landau”) noise



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

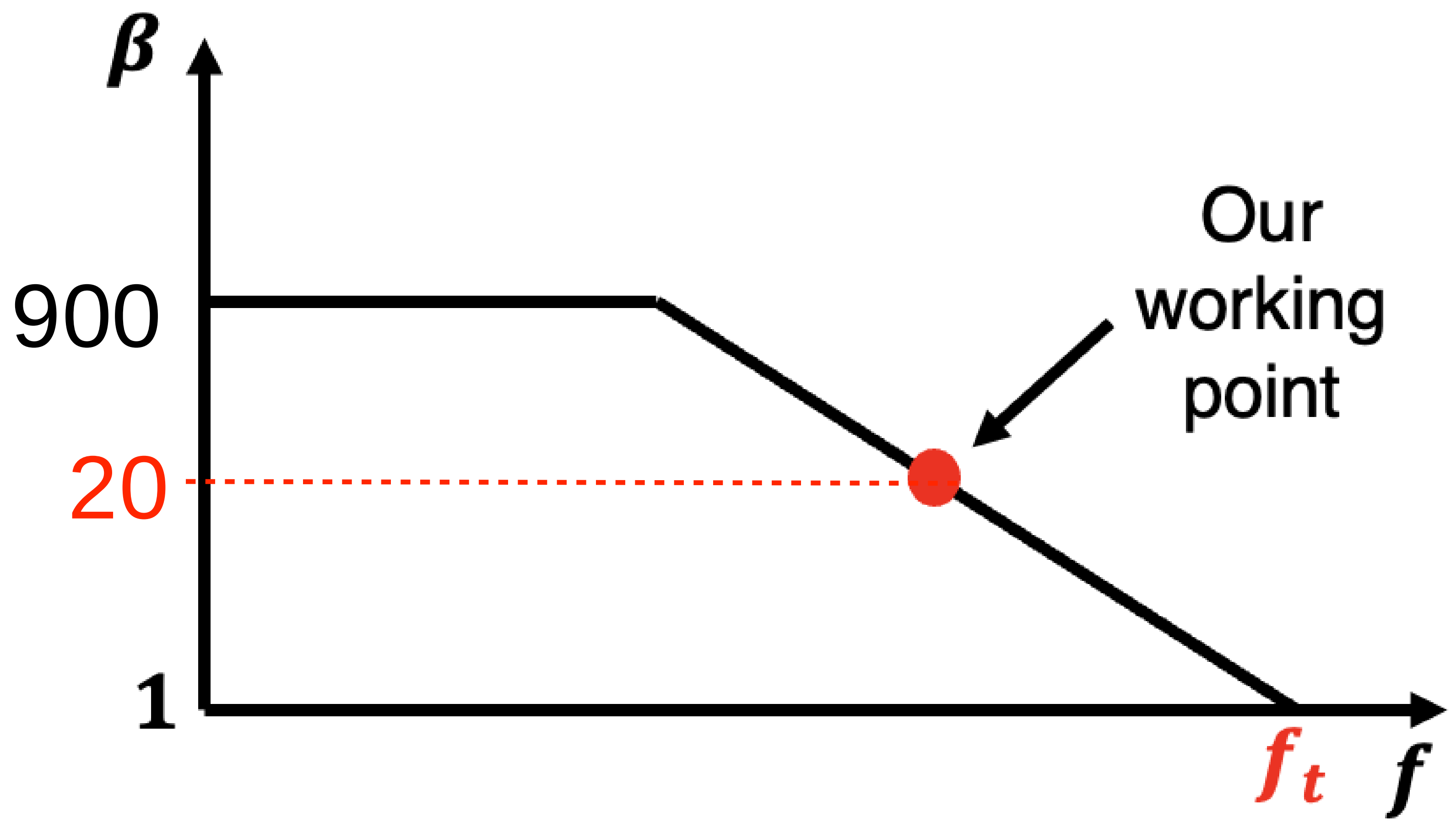
Radiation hardness of SiGe HBTs

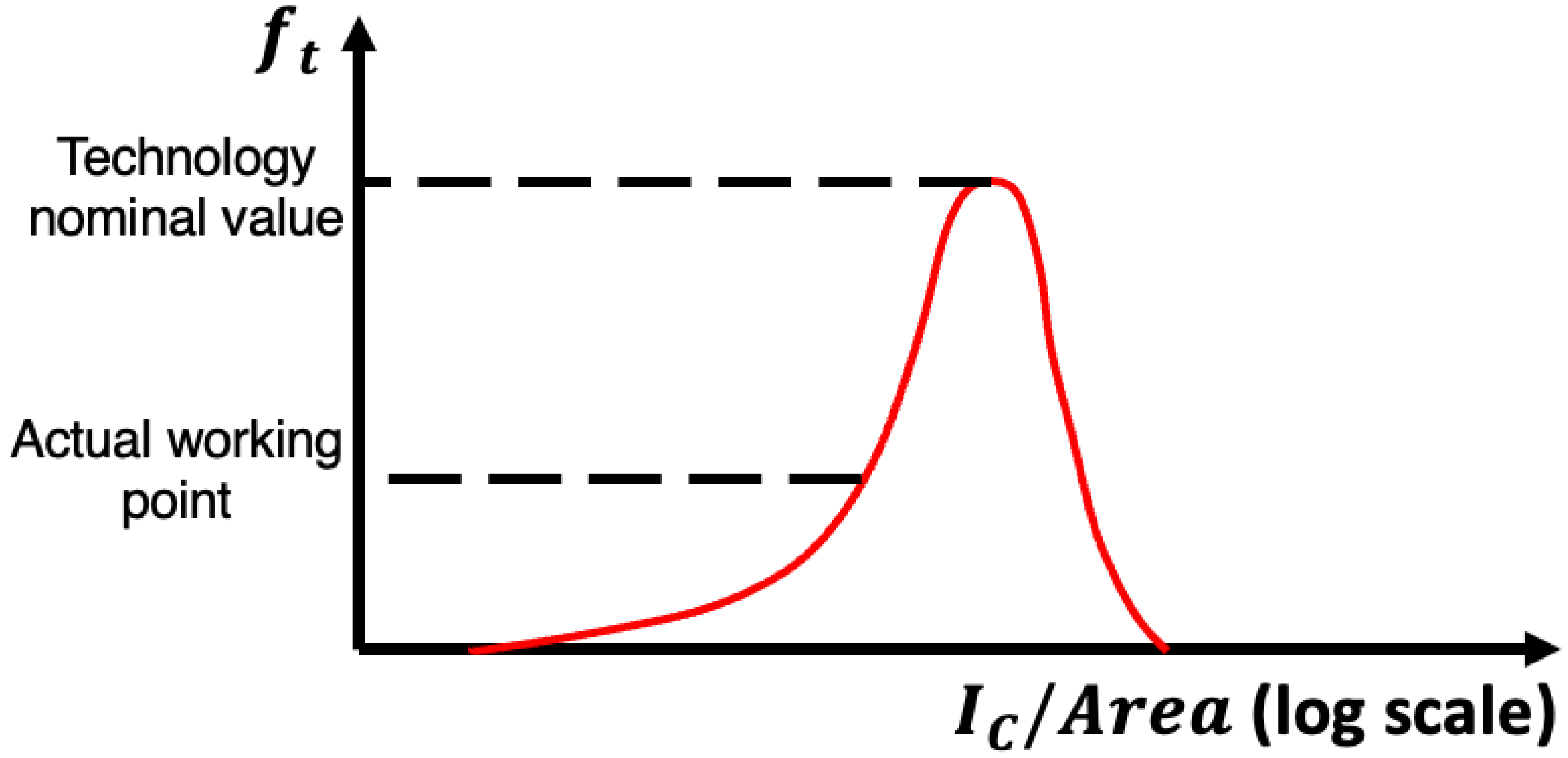
Our SG13G2 process



Our working point

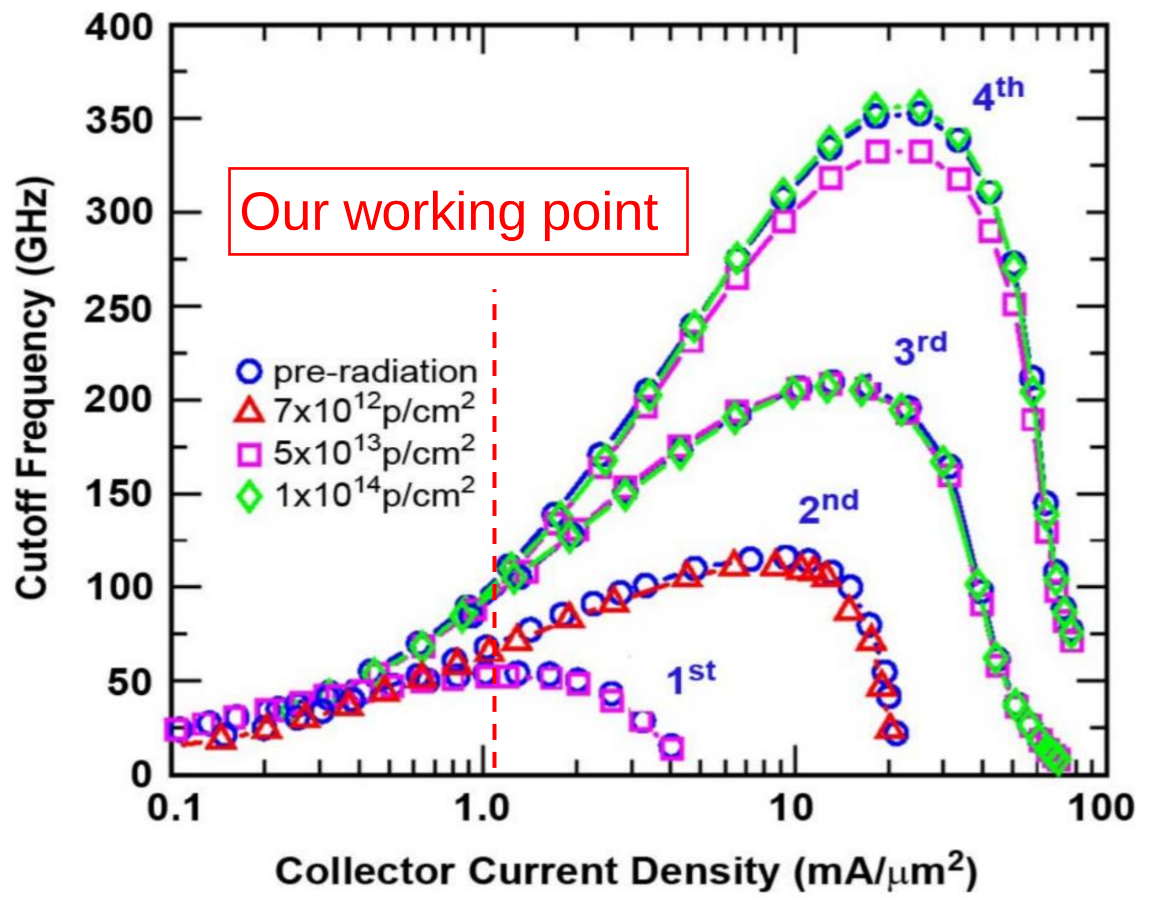
S. Díez et al, IEEE Nuclear Science Symposium & Medical Imaging Conference, Knoxville, TN, 2010, pp. 587-593, doi: 10.1109/NSSMIC.2010.5873828.





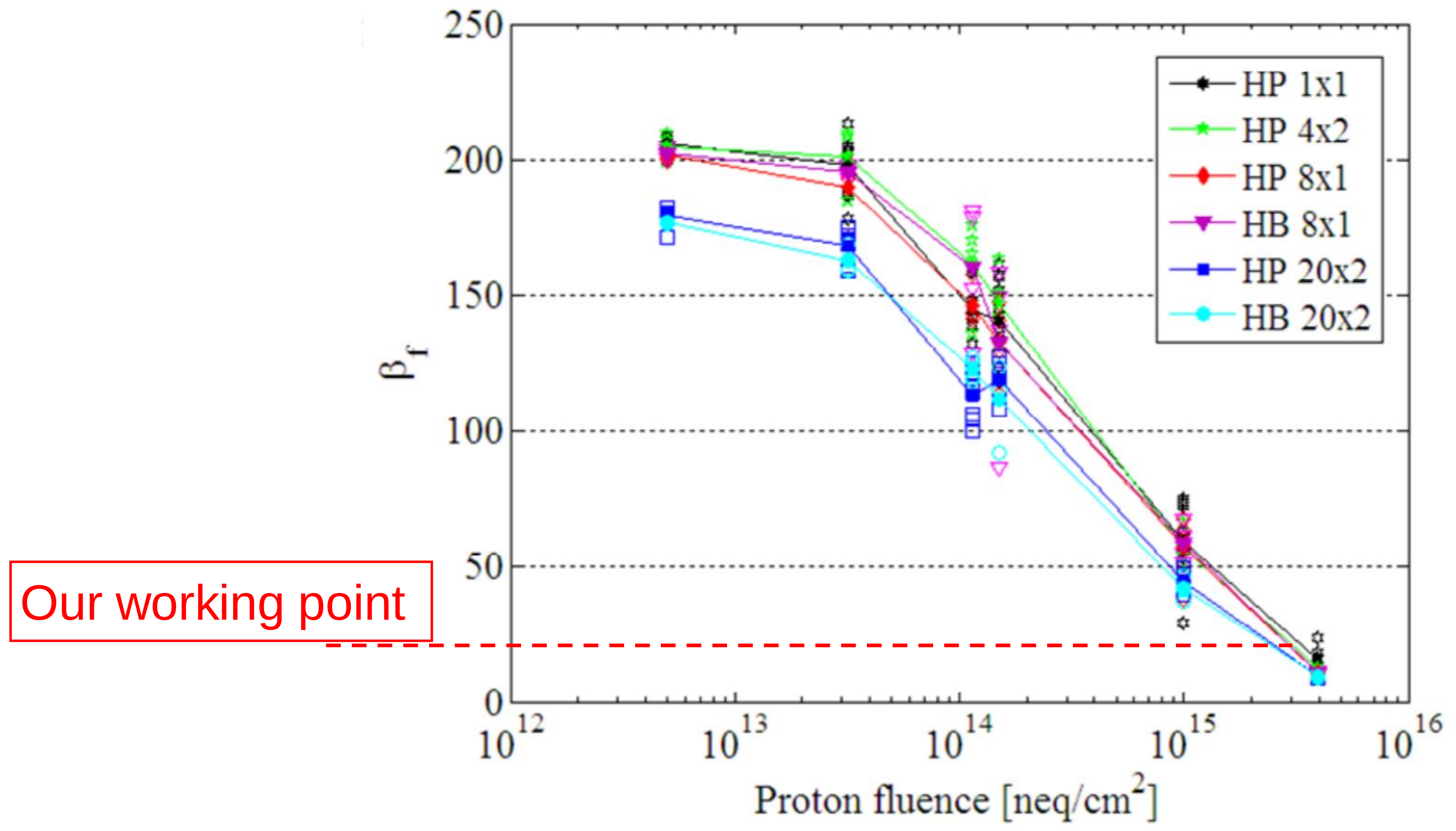
Time resolution vs. proton fluence

AC characteristics

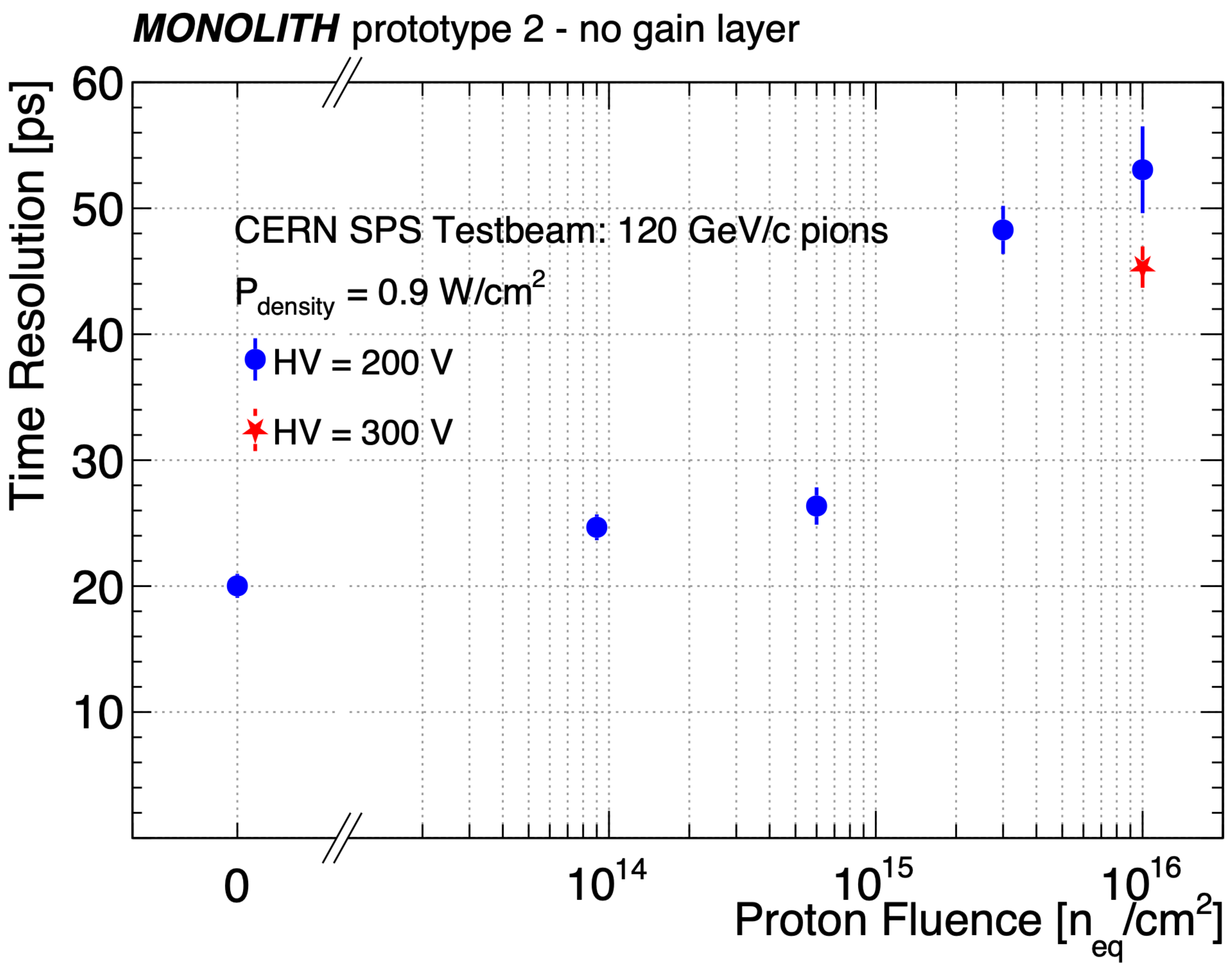


From: J.D. Cressler, IEEE transactions on nuclear science, vol. 60, n. 3 (2013)

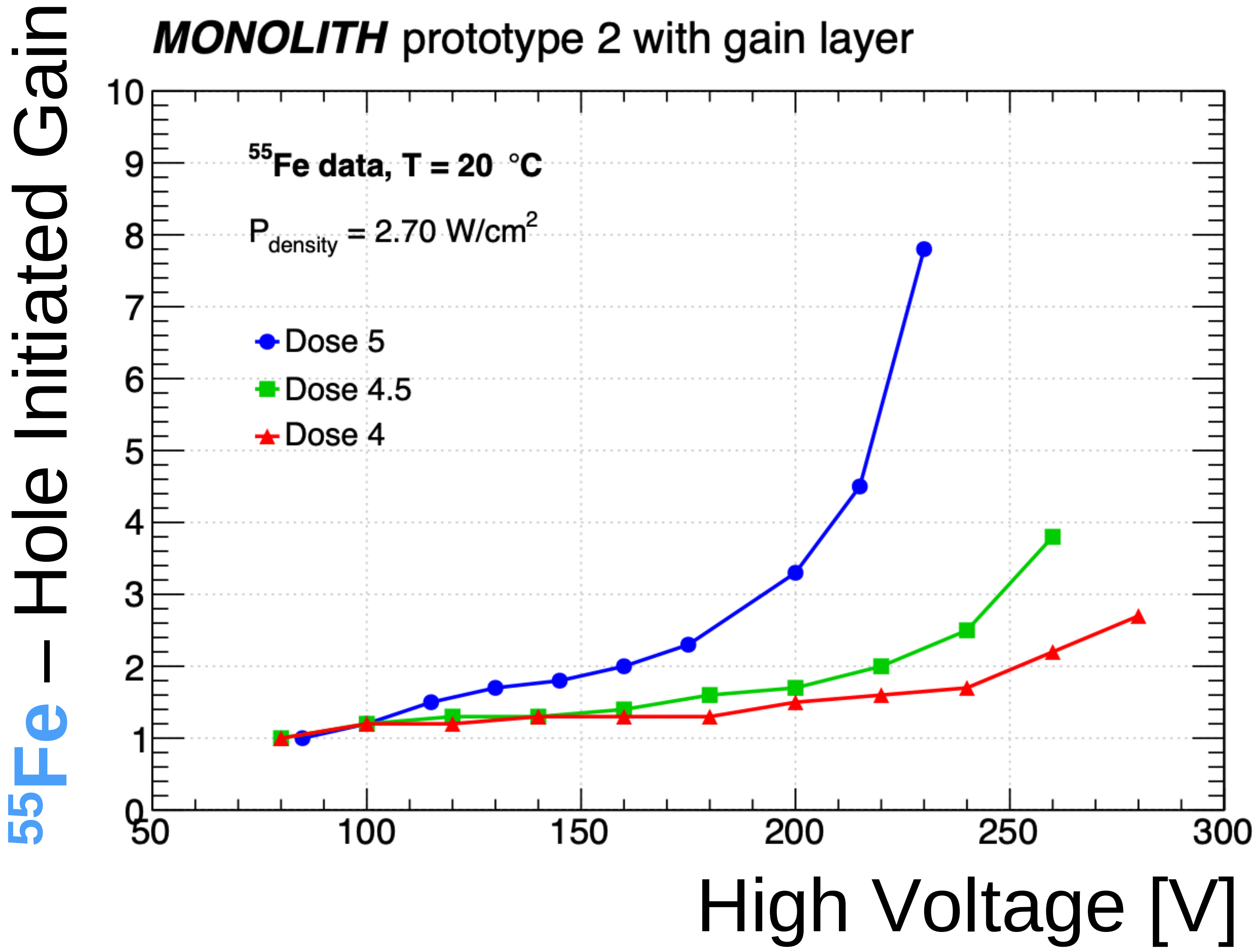
DC characteristics

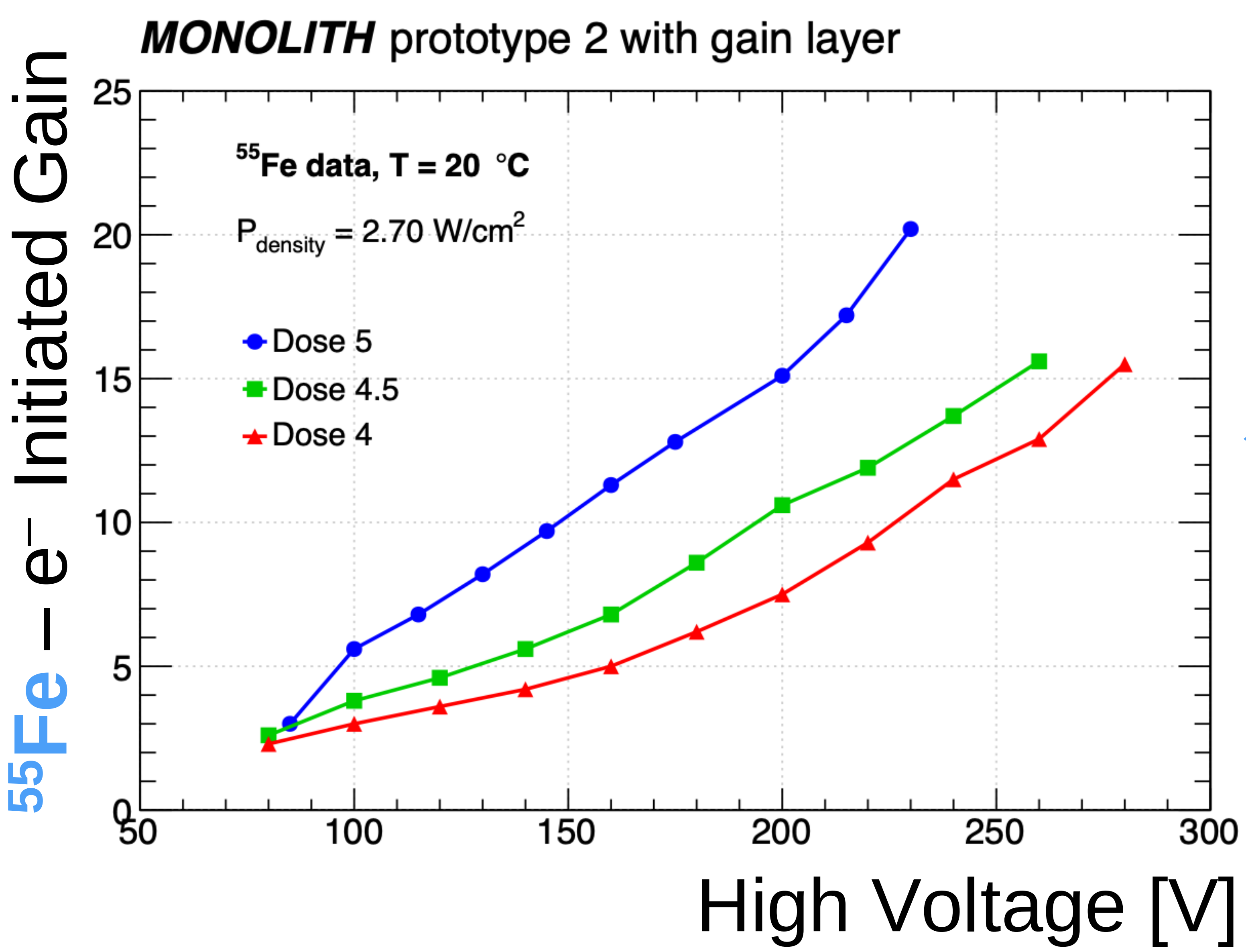


S. Díez et al, IEEE Nuclear Science Symposuim & Medical Imaging Conference, Knoxville, TN, 2010, pp. 587-593, doi: 10.1109/NSSMIC.2010.5873828.



2024 PicoAD: ^{55}Fe and ^{90}Sr Measurements

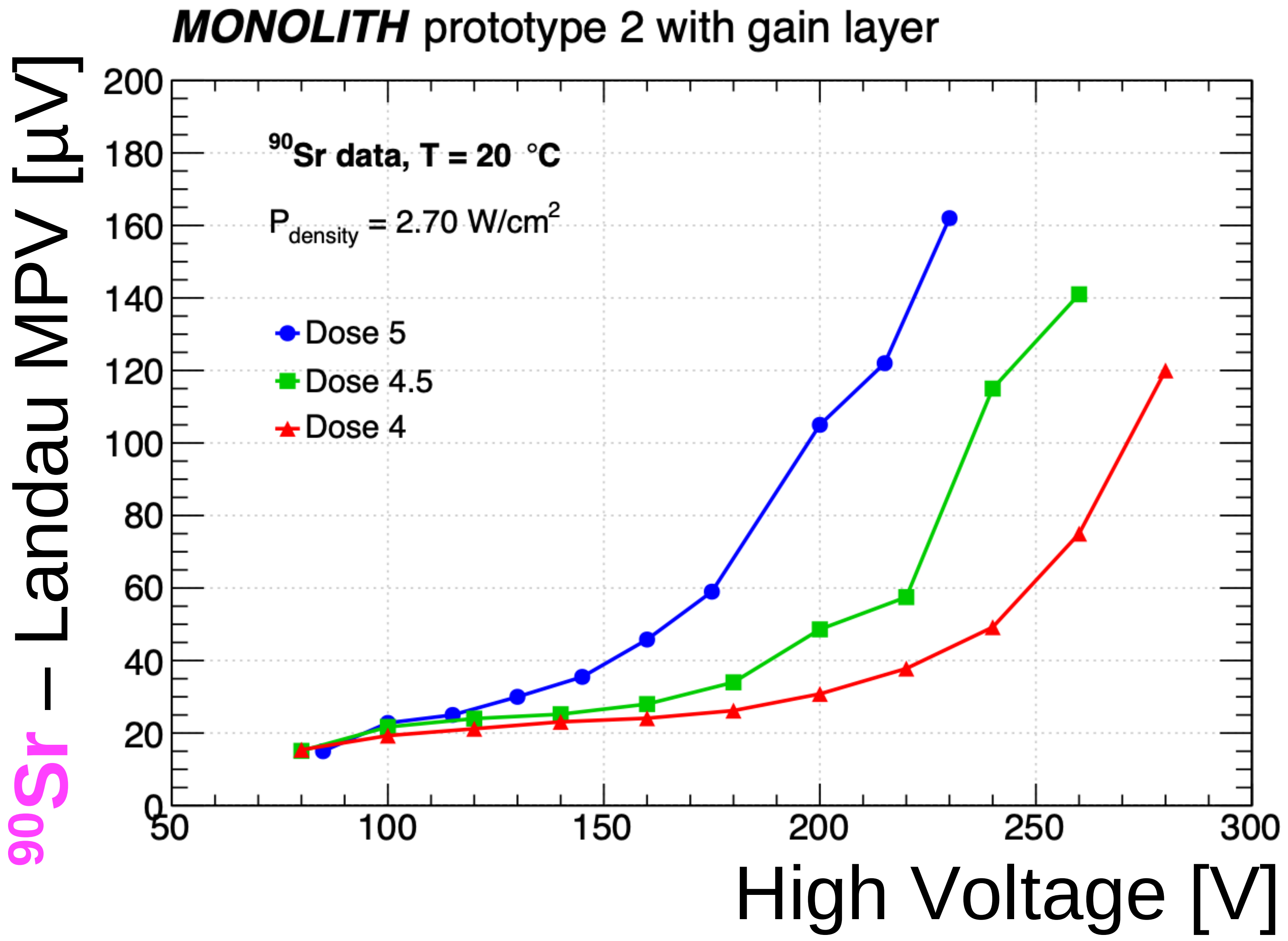


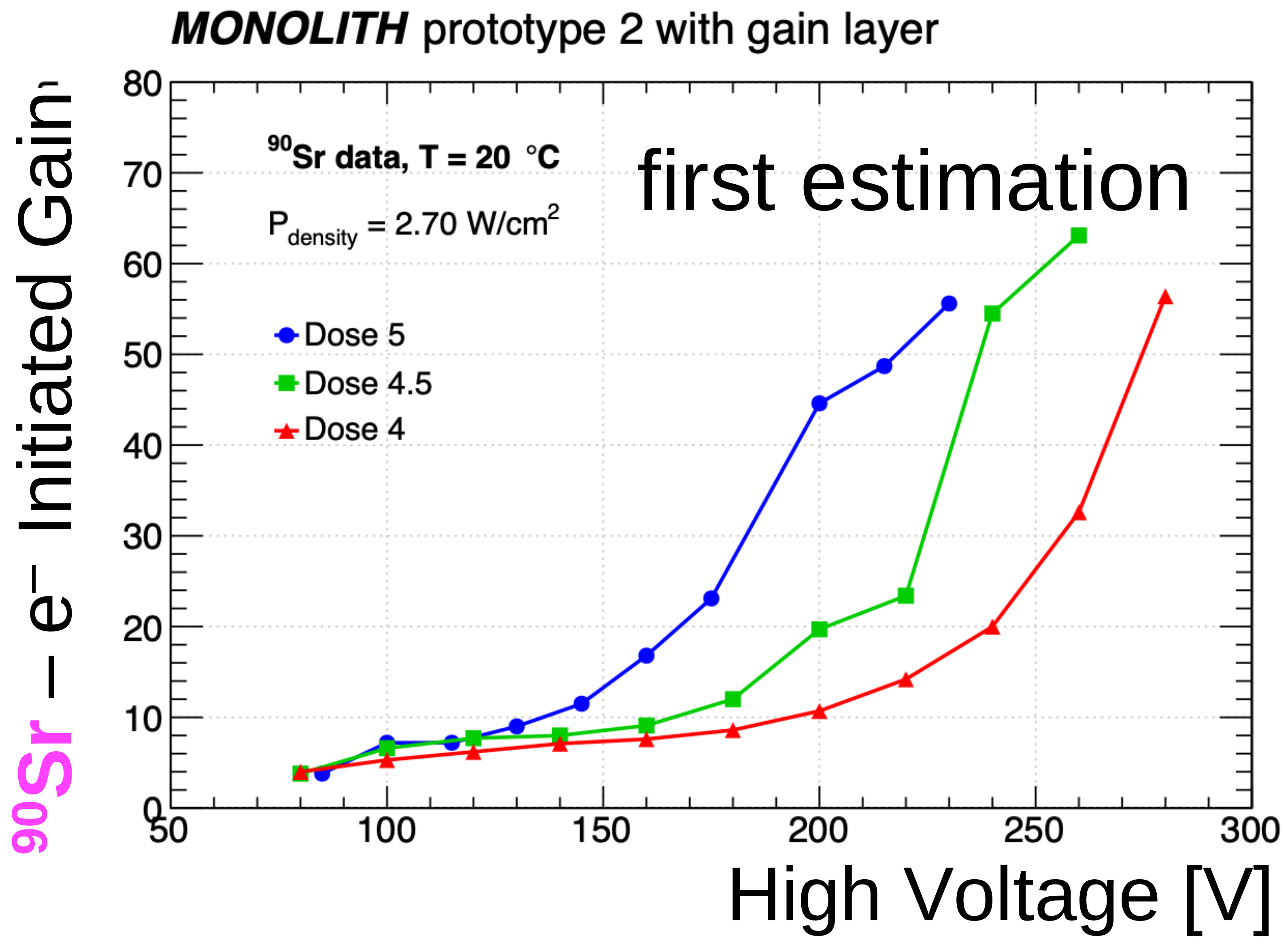


^{55}Fe measurements

Charge-space effects limit e⁻ gain, see JINST 17 P10032 (2022)

^{90}Sr measurements



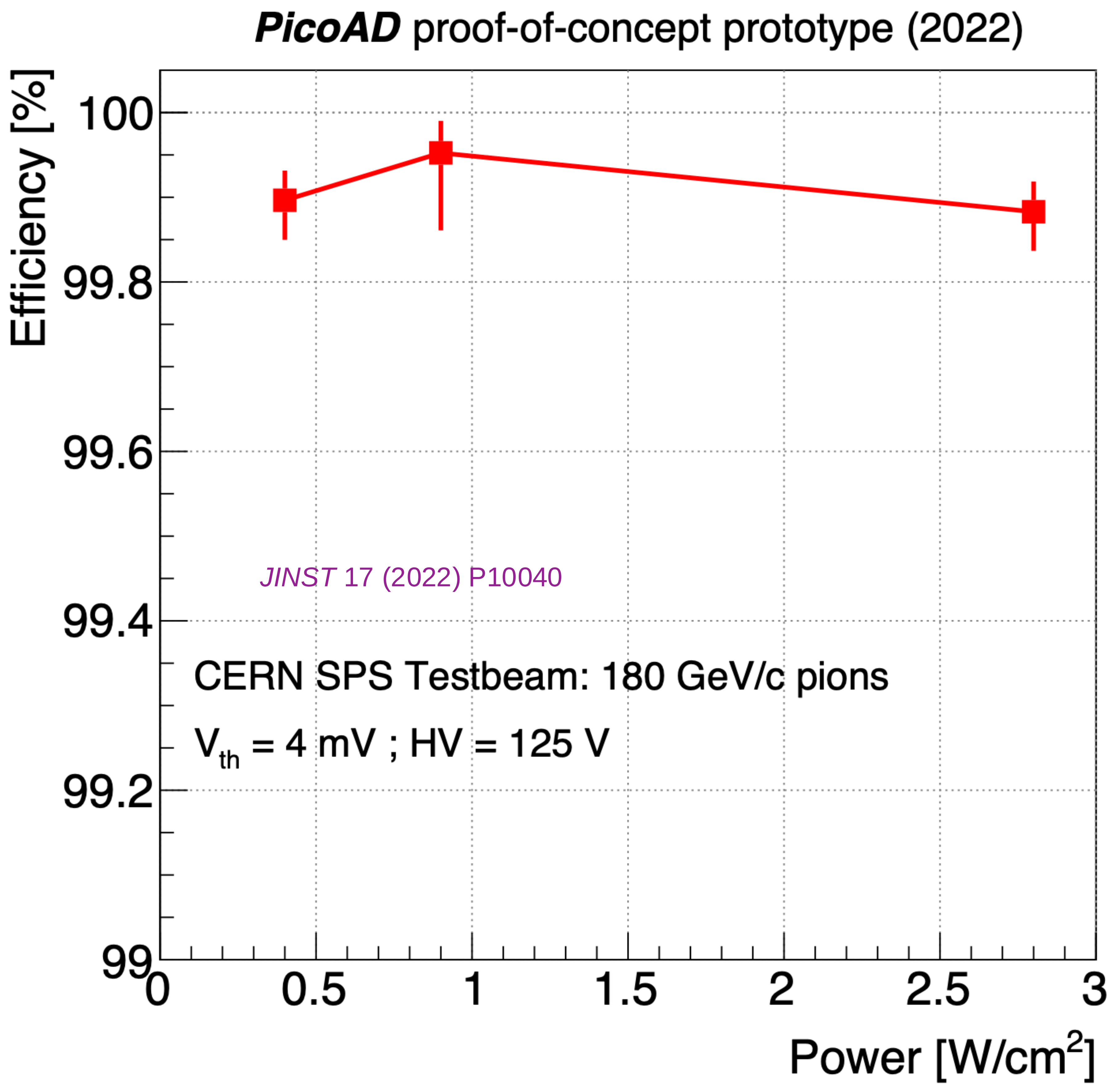


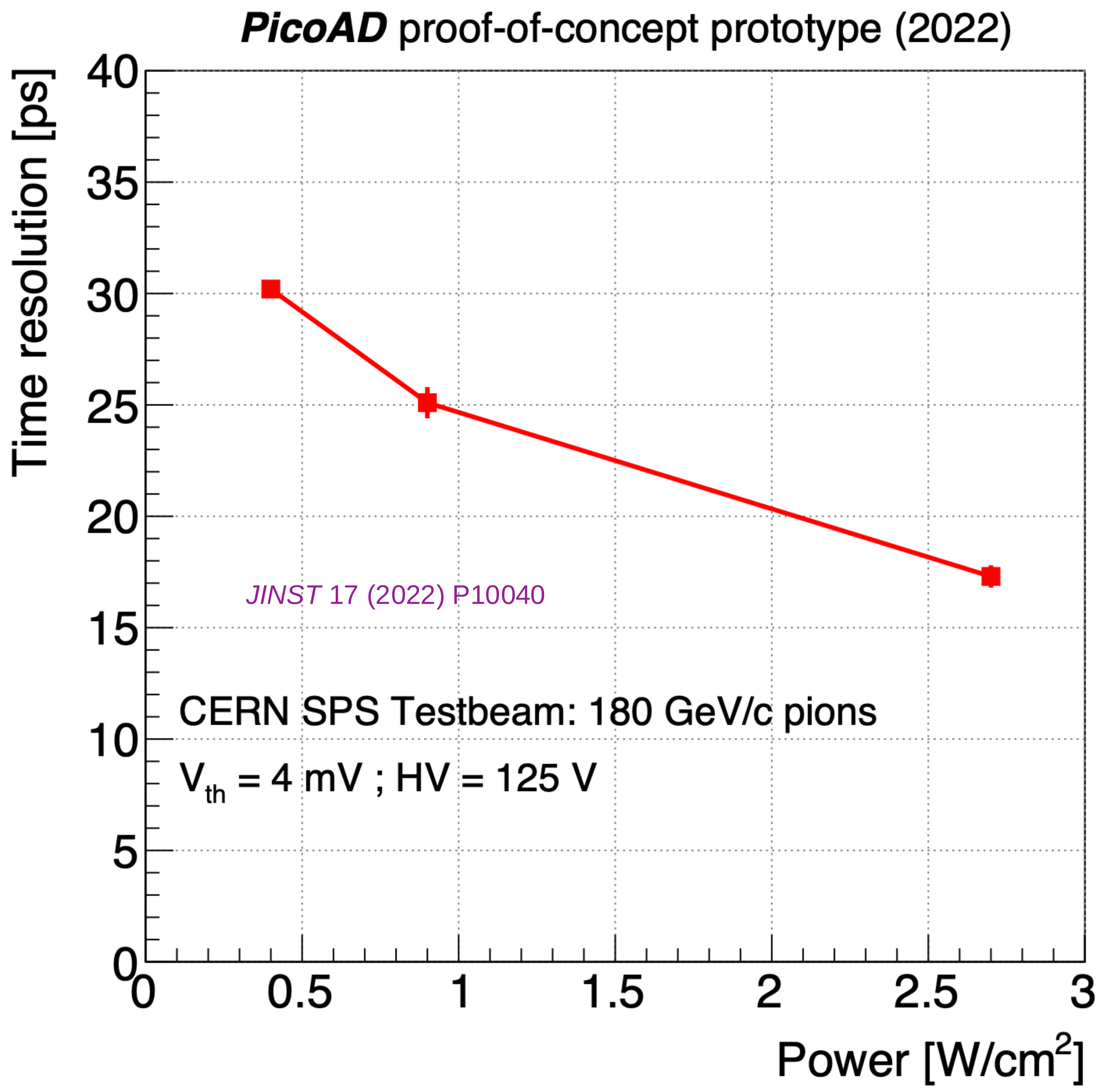
Testbeam PicoAD proof-of-concept (2022)

PicoAD

99.9% for all power consumptions

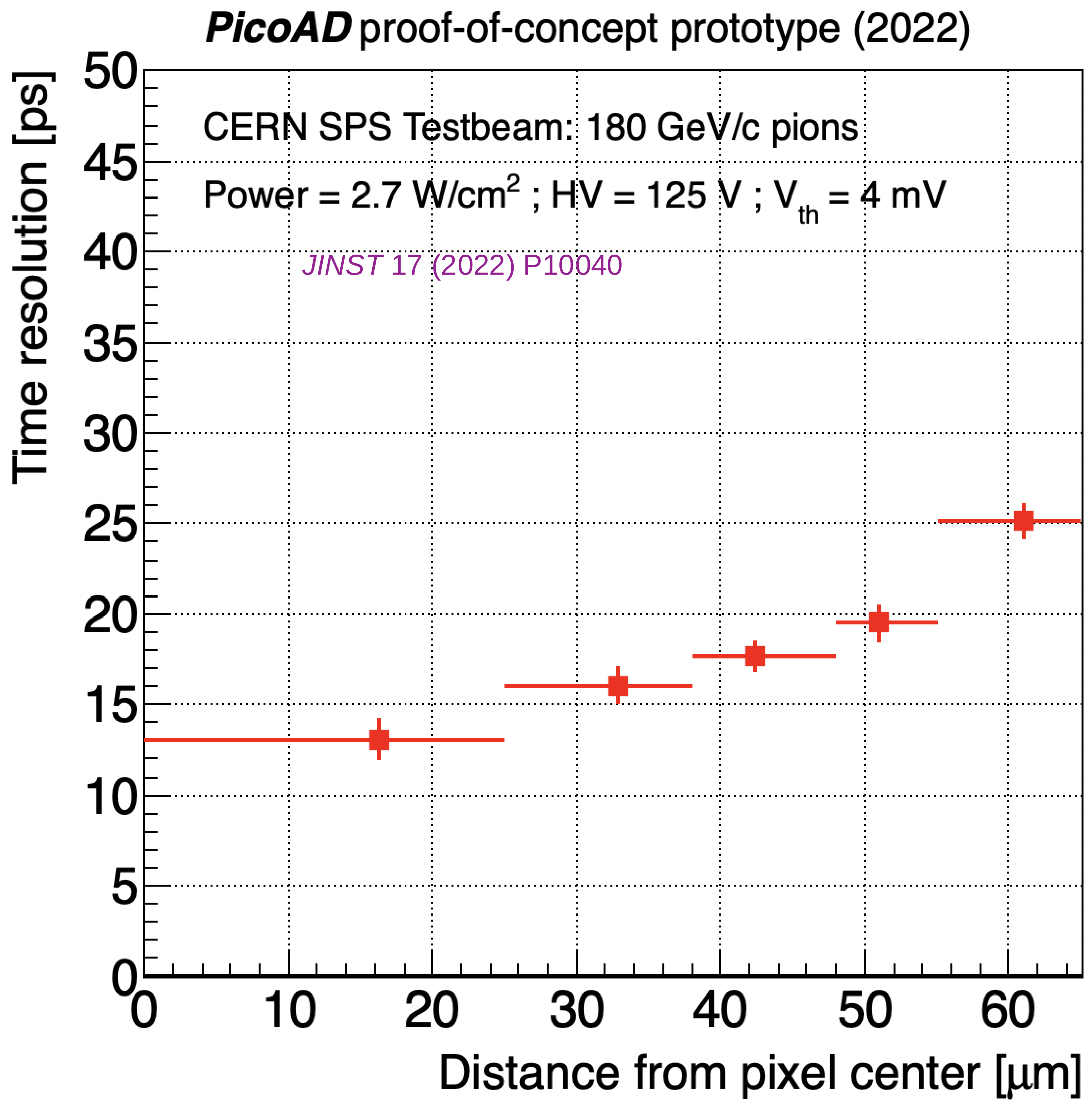
30 ps at 0.4 W/cm²
17 ps at 2.7 W/cm²



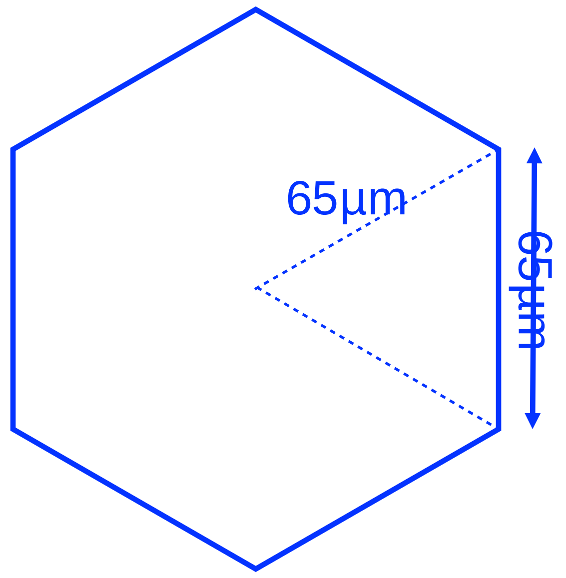


Testbeam PicoAD proof-of-concept (2022)

Time resolution

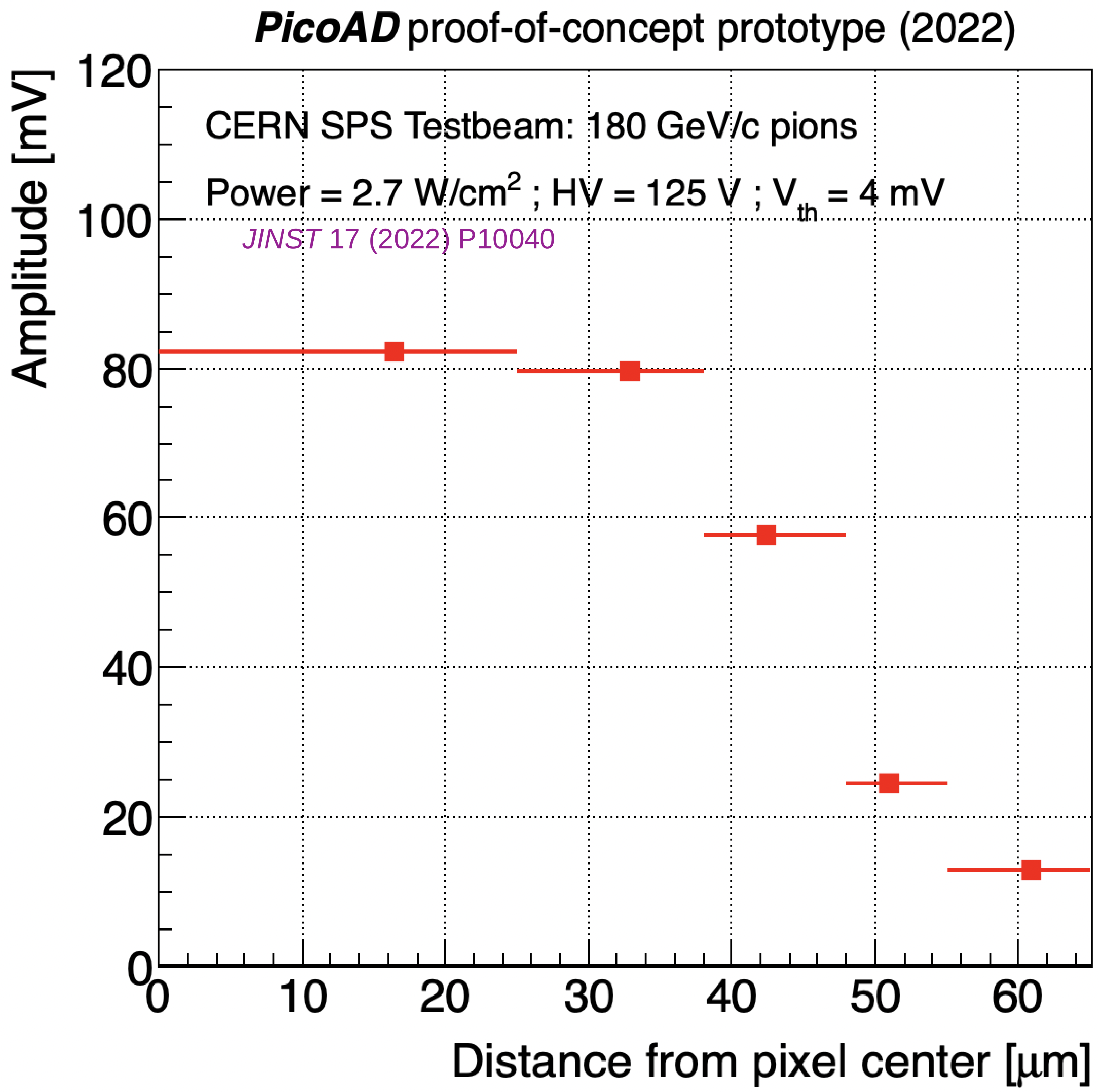


13 ps at the pixel center
25 ps at the pixel edge



Signal MPV amplitude

PicoAD



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

New prototypes devised to improve this dependence