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Photon and minimum ionizing particle detection with ultra-fast Geiger-mode APDs

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High Energy Physics - Integrated Circuits Workshop 2022

20/05/2022

École Polytechnique Fédérale de Lausanne

Outline

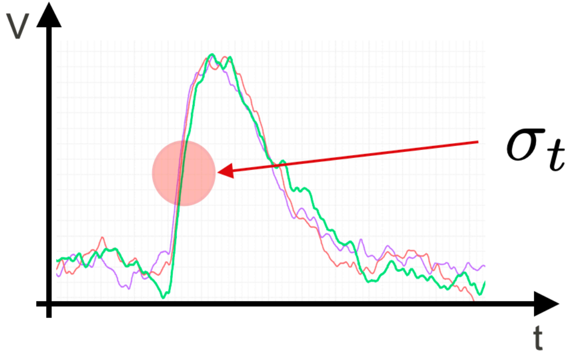
- Introduction
- Measurements
- Conclusions and future work

Introduction

Emanuele Ripiccini

Timing with Geiger-mode APDs (SPADs)

If we read-out the signal of the sensor on an ideal transimpedence amplifier of gain 1



$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \rightarrow \frac{G}{d}$$

G: Internal sensor gain[1]

d: Depletion region thickness

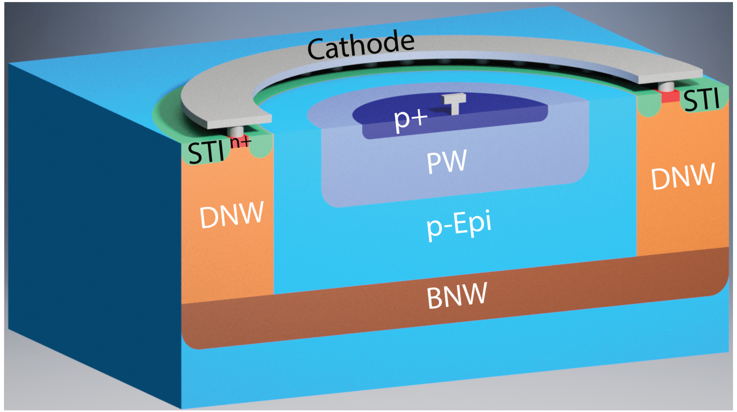
→ **SPADs are good candidates**

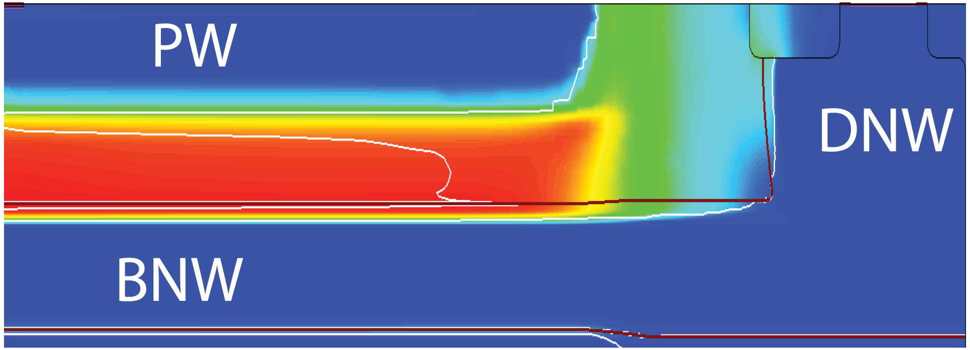
The avalanche growth dynamic represents the main contribution to the intrinsic SPAD timing resolution and this is at the picosecond scale[2]

[1] N. Cartiglia, M. Baselga, G. Dellacasa, S. Ely, V. Fadeyev, Z. Galloway, S. Garbolino, F. Marchetto, S. Martoiu, G. Mazza, et al., Performance of ultra-fast silicon detectors, Journal of instrumentation 9, C02001 (2014).

[2] W. Riegler, P. Windischhofer, P. Time Resolution and Efficiency of SPADs and SiPMs for Photons and Charged Particles. *Nucl Instr Methods Phys Res Section A: Acc Spectrometers, Detectors Associated Equipment* (2021)

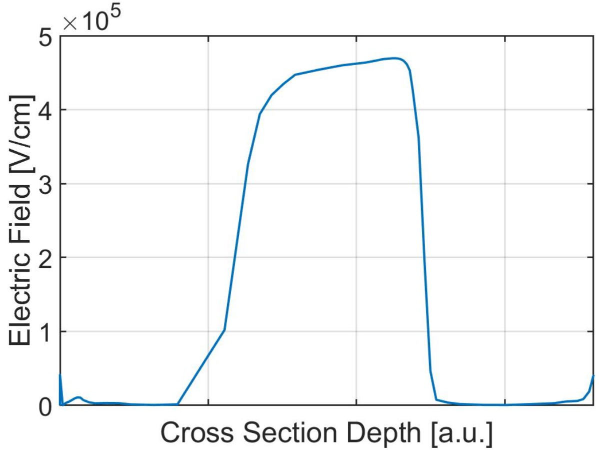
SPAD structure





SPAD

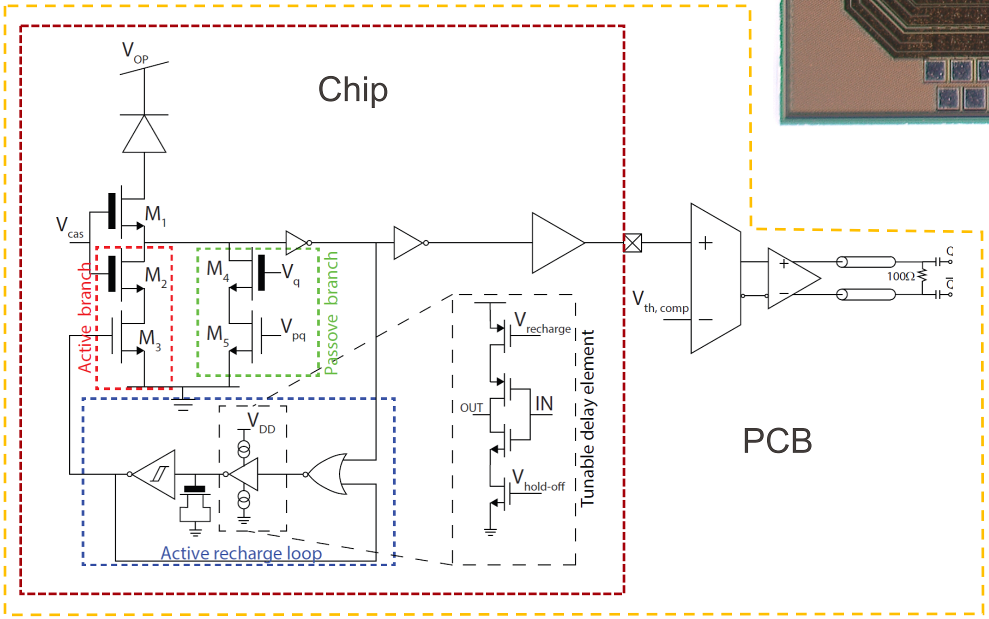
- 180 nm CMOS technology
- P-I-N structure
- Substrate-Isolated type
- P-well anode, buried N-well cathode
- HV provided through a deep N-well

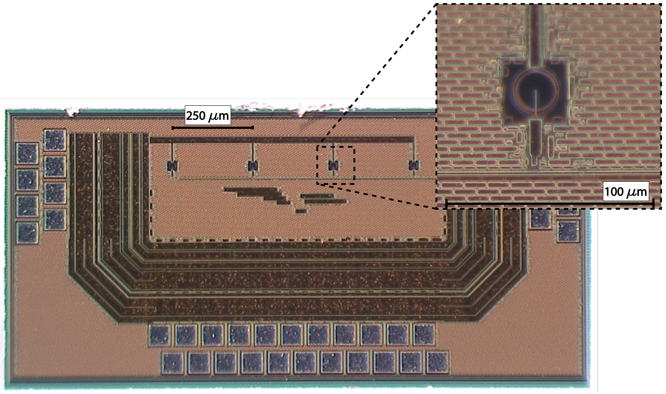


F. Gramuglia, et al., “A low-noise CMOS SPAD pixel with 12.1 ps SPTR and 3 ns dead time”, IEEE JSTQE, 2021. 2021

Chip structure and read-out PCB

No pre-amplifier





Chip

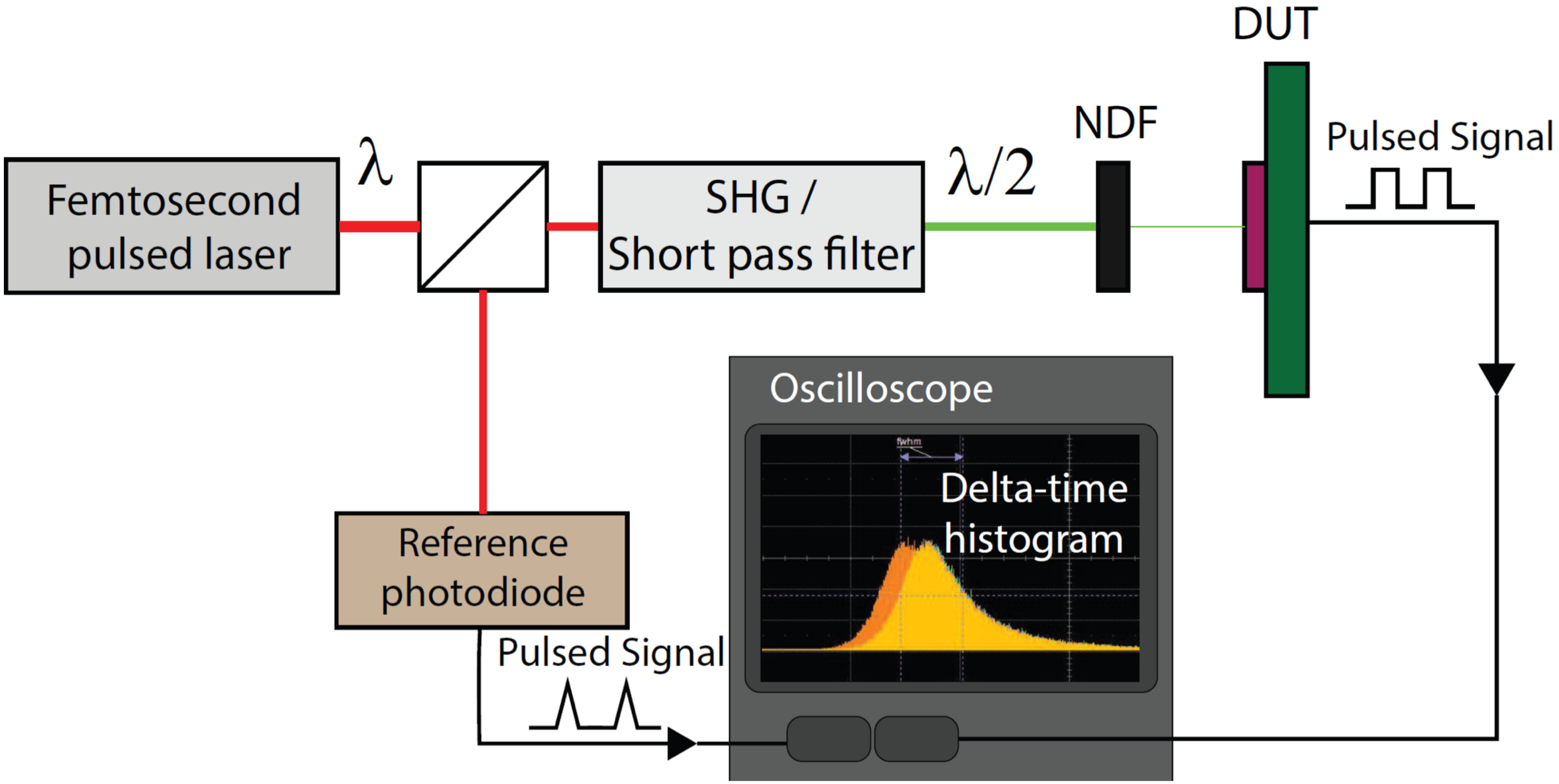
- 25 μm diameter CMOS SPAD
- Active quenching/recharge
- Tunable delay time (down to 3 ns)

System-on-board:

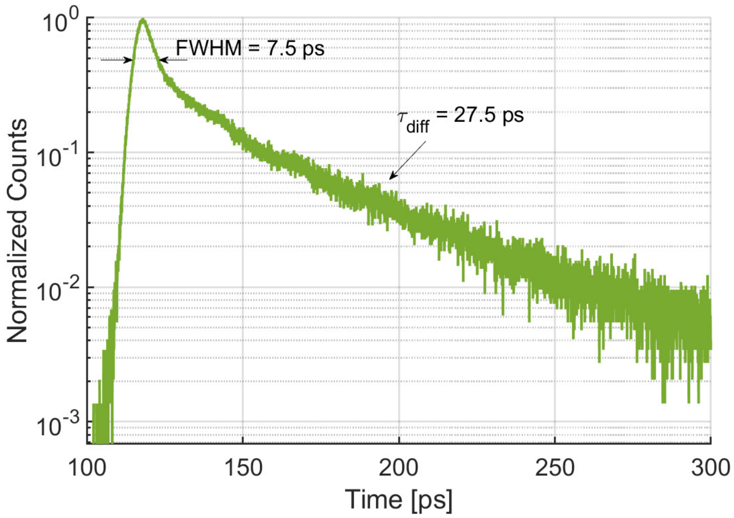
- Single external power supply source
- All voltages provided through DACs controlled with serial protocol
- Reduced cable noise
- Si-Ge comparator for 50 Ohm coupling
- High signal slew rate (≥ 1.6 V/ns)

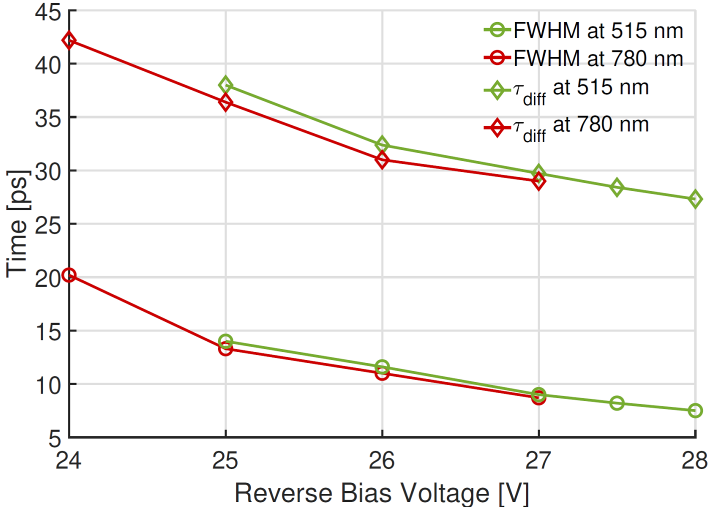
Measurements

Optical Setup



Optical measurements





- **Jitter of 7.5 ps FWHM at 6.5 Vex for green light**
- **Jitter of 8.5 ps FWHM at 5.5 Vex for red light**

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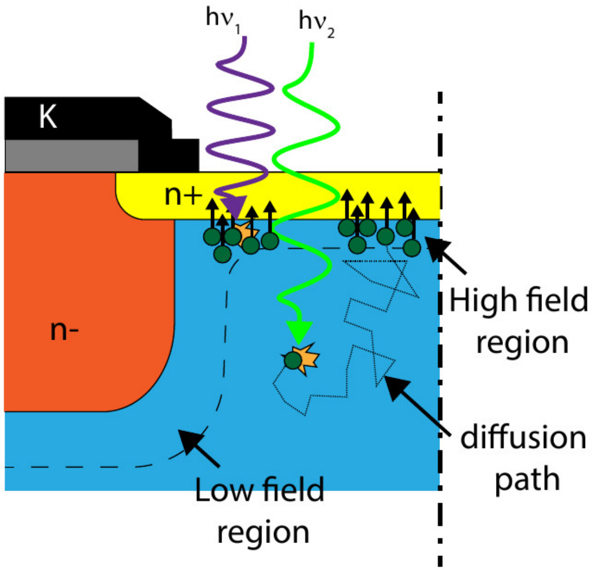
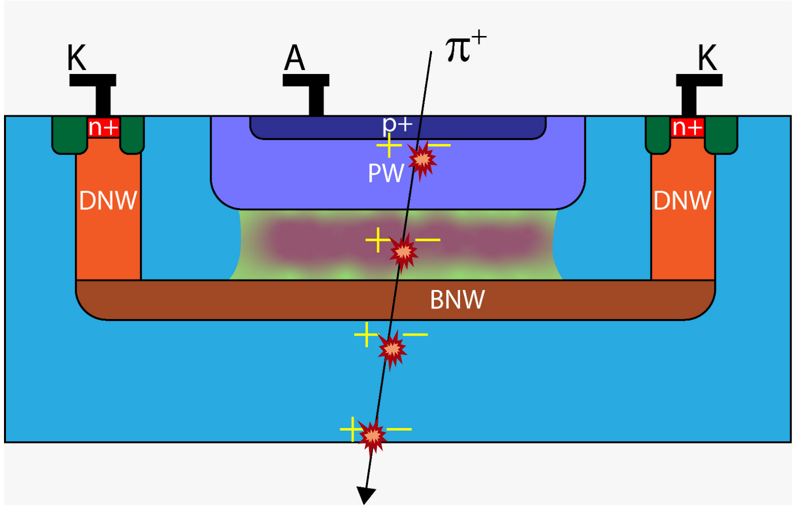
MIP vs photon detection

Photons



One photon absorption:
one e/h pair generated

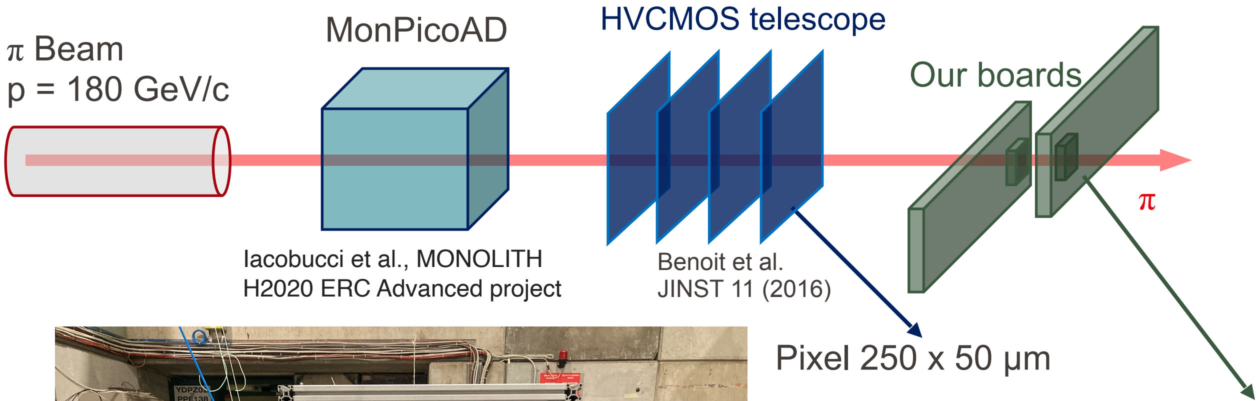
MIP

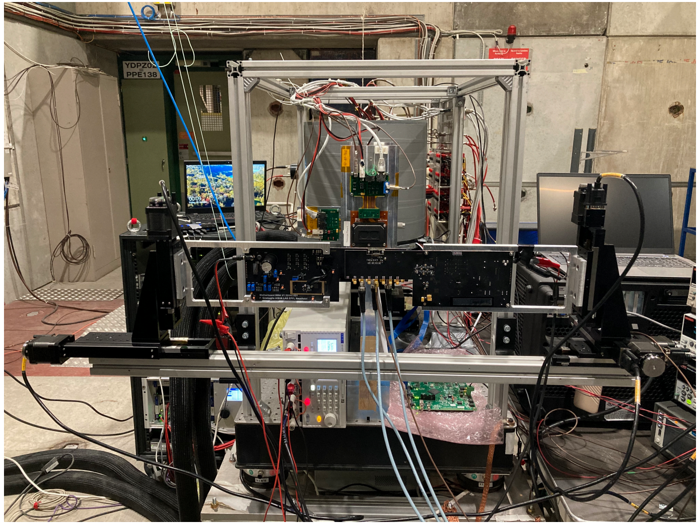


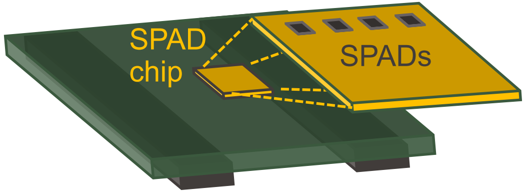
MIP is **not** absorbed: several interactions can occur, more pairs are generated

MIP mean free path in Si: 200 nm

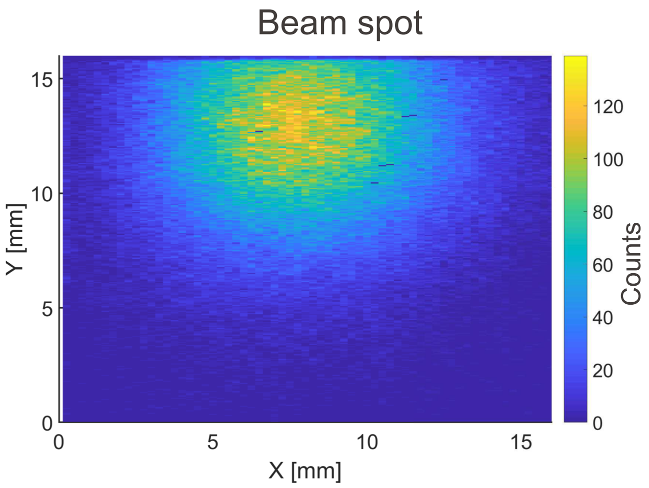
Detection System



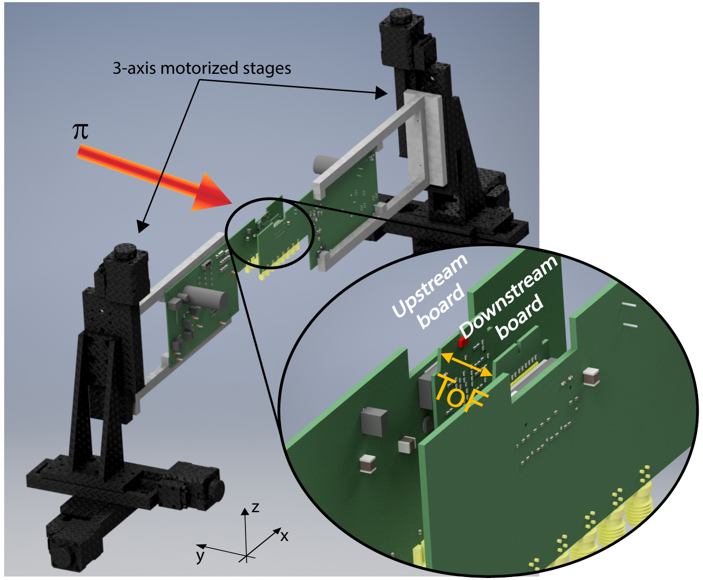




Device alignment



Alignment with motorized stages (2.5 μm steps)

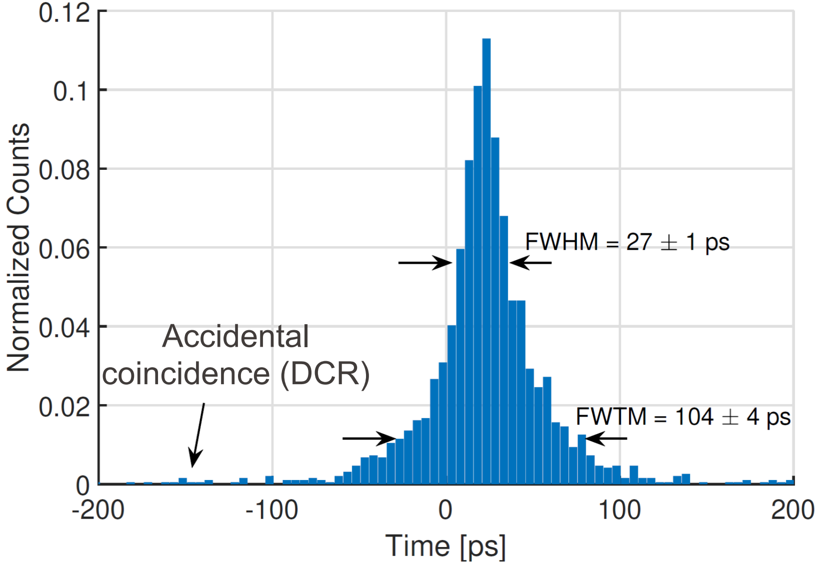


Alignment procedure:

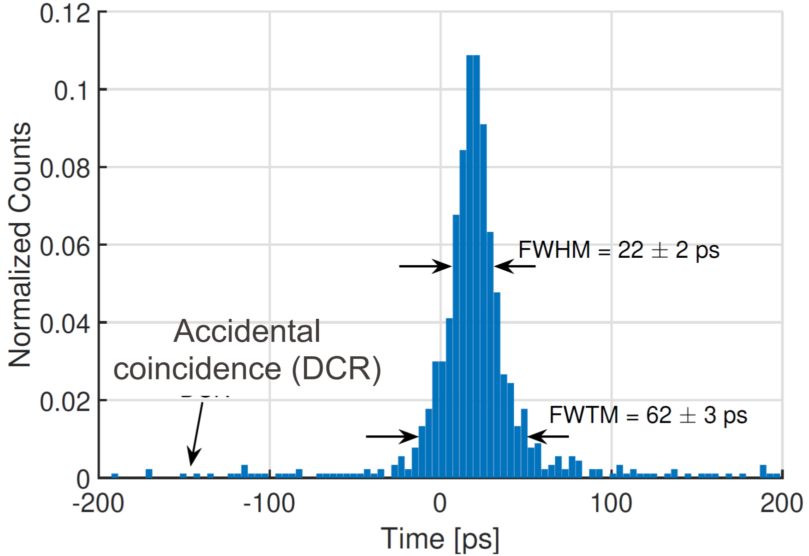
- Upstream SPAD is aligned with the most illuminated pixel of one of the central telescope planes by using the SPAD itself as trigger
- Downstream SPAD is aligned with the most illuminated pixel of one of the central telescope planes by using the SPAD itself as trigger
- The downstream SPAD is moved at steps of 5 μm until the position that maximizes the coincidence rate is reached

ToF Results

24 V (Vex = 2.5 V)



27 V (Vex = 5,5 V)



Bias (V)	FWHM (ps)	FWTM (ps)	σ (ps)	σ_{single} (ps)
24	27 ± 1	104 ± 4	11.5 ± 0.4	8.1 ± 0.3
27	22 ± 2	62 ± 3	9.4 ± 0.7	6.4 ± 0.5

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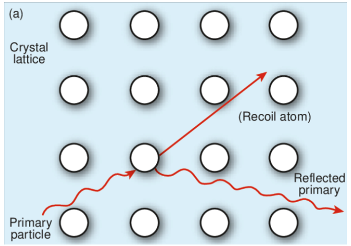
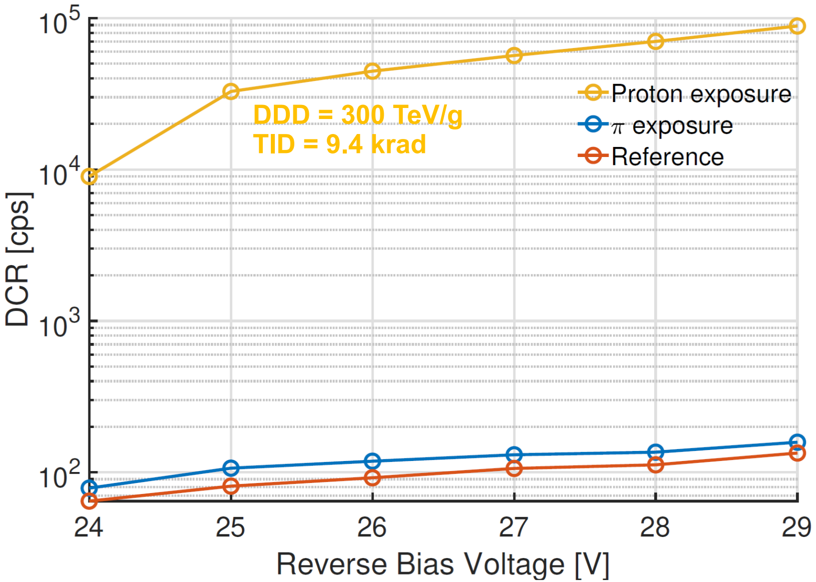
Radiation hardness

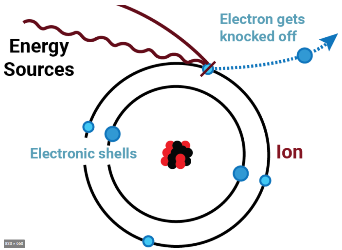


Maurer, Richard et al. (2008).

Displacement damage

Annealing required





Ionisation damage (necessary for detection!)

Collection of the free charges by the electric field

- 100 MeV proton exposure (heavy ionisation)
- 180 GeV/c pions exposure (MIP)

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State of the art

Device	σ_{single} (ps)	Time walk correction	Pre-amplifier	MIP Detection efficiency
SPAD AQUA	6.4	No	No	[3]~99%
TIMESPOT	[1]19	Yes	Yes	99%
UFSD (LGAD)	[2]27	Yes	Yes	99%

[1]D. Brundu et al., Accurate modelling of 3D-trench silicon sensor with enhanced timing performance and comparison with test beam measurements, JINST 16 (2021) 09, P09028

[2]N. Cartiglia et al. Beam Test Results of a 16 ps Timing System Based on Ultra-fast Silicon Detectors. Nucl Instr Methods Phys Res Section A: Acc Spectrometers, Detectors Associated Equipment (2017) 850:83–8.

[3] W. Riegler, P. Windischhofer, P. Time Resolution and Efficiency of SPADs and SiPMs for Photons and Charged Particles. *Nucl Instr Methods Phys Res Section A: Acc Spectrometers, Detectors Associated Equipment* (2021)

Conclusions and future work

Conclusions

An optimized CMOS SPAD chip has been developed, showing outstanding performance:

- Tunable dead time down to 3 ns
- High timing resolution for green light: 7.5 ps FWHM
- These SPADs can detect MIP with unprecedented **timing resolution (6.4 ps gaussian sigma)**
- Preliminary **radiation hardness** results show that the performances are not affected

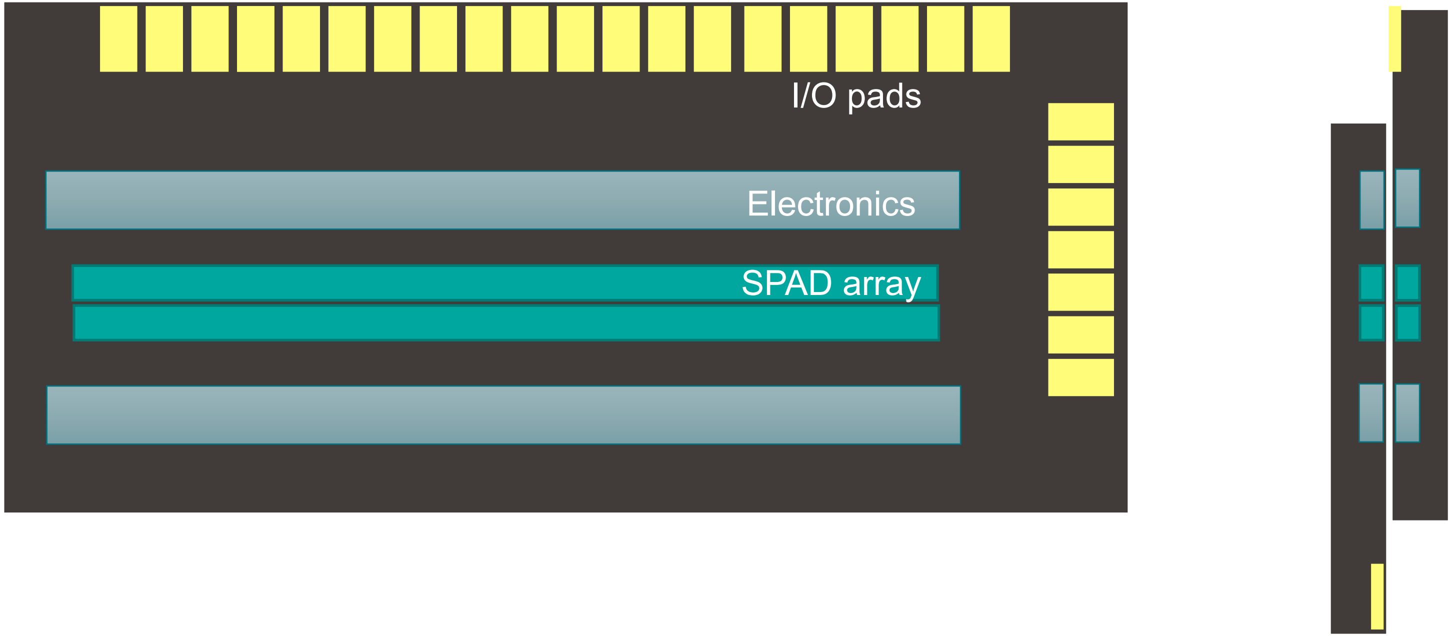
Future work

Next steps

- MIP Detection efficiency measurements (Oct 2022)
- Design of a multichannel prototype
- Feasibility study for the implementation of ***high timing resolution particle tracker for particle beam facilities:***
  - Monolithic chip with two rows of N SPADs (like the one presented, possibly in 55 nm) each
  - Electronics on the periphery
  - Facing SPADs in **coincidence to suppress the DCR**
  - Cooling system

Future work

Chips glued on the front-side with flip chip machine: 1 µm precision



Thank you!

frontiers

Sub-10 ps Minimum Ionizing Particle Detection with Geiger-Mode APDs

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[2] *Departement de Physique nucléaire et corpusculaire, Université de Genève, Geneva, Switzerland*
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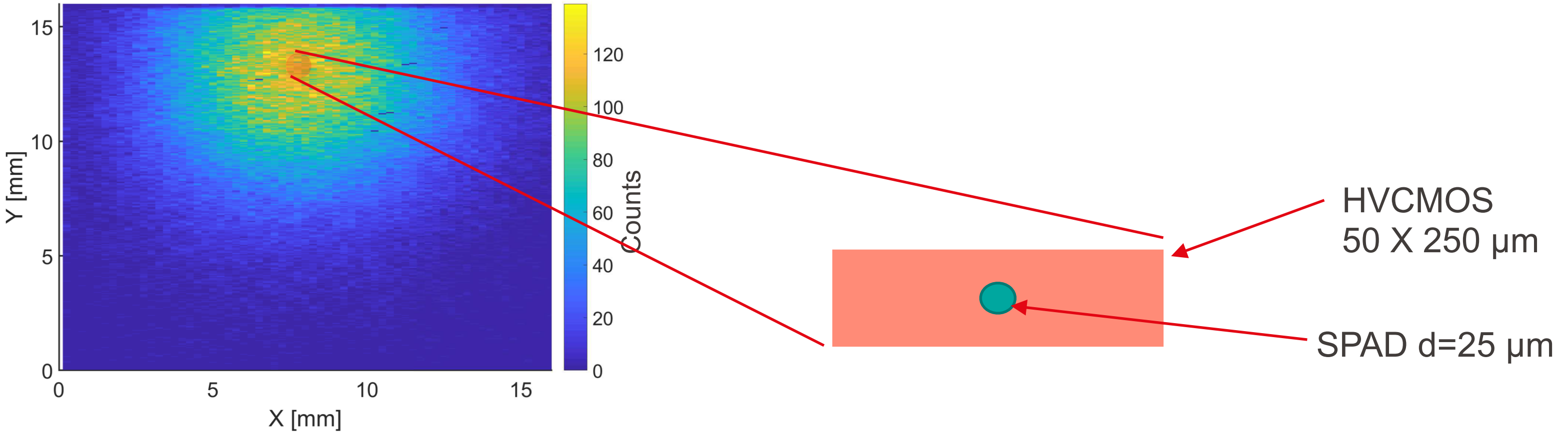
ABSTRACT

Major advances in silicon pixel detectors, with outstanding timing performance, have recently attracted significant attention in the community. In this work we present and discuss the use of state-of-the-art Geiger-mode APDs, also known as single-photon avalanche diodes (SPADs), for the detection of minimum ionizing particles (MIPs) with best-in-class timing resolution. The SPADs were implemented in standard CMOS technology and integrated with on-chip quenching and recharge circuitry. Two devices in coincidence allowed to measure the time-of-flight of 180 GeV/c momentum pions with a coincidence time resolution of 22 ps FWHM (9.4 ps Gaussian sigma). Radiation hardness measurements, also presented here, highlight the suitability of this family of devices for a wide range of high energy physics (HEP) applications.

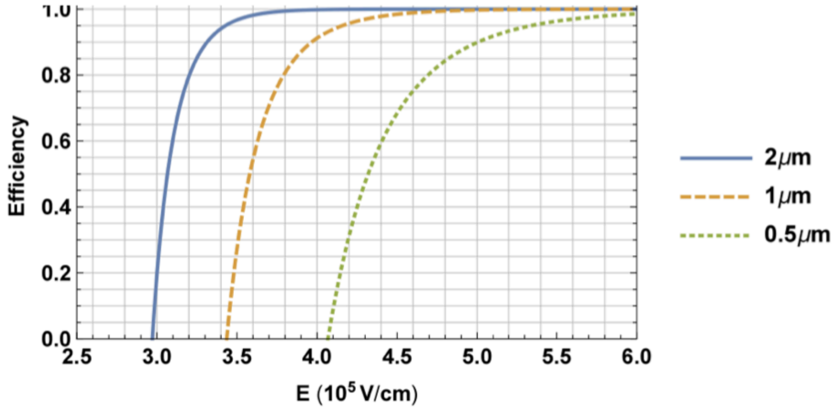
Keywords: Beamline, Coincidence, Jitter, Timing resolution, MIP detection, particle physics, SPADs, Time-of-flight

Backup

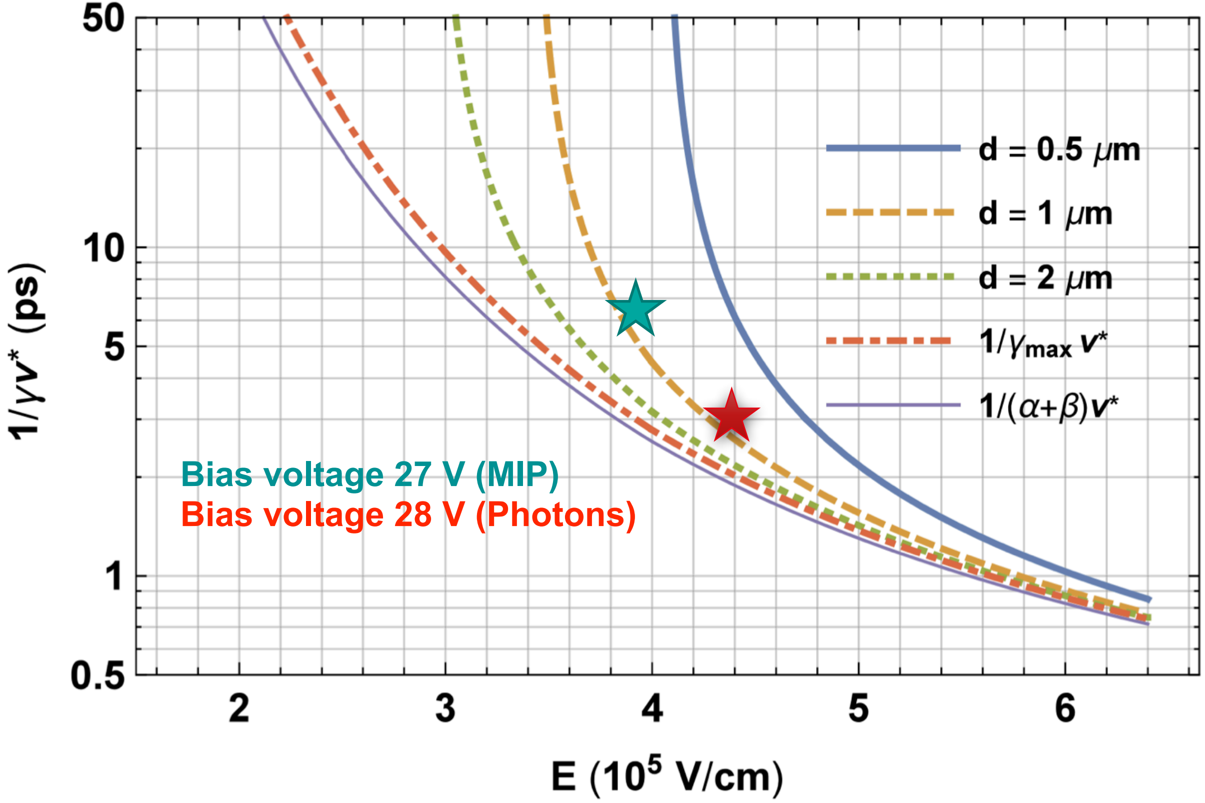
Efficiency calculation



$$eff = \frac{R_{SPAD}}{\frac{S_{SPAD}}{S_{HVCMOS}} R_{HVCMOS}} \sim 99\%$$



Time resolution with SPADs



Minimum Ionizing Particles

Bethe-Bloch equation:

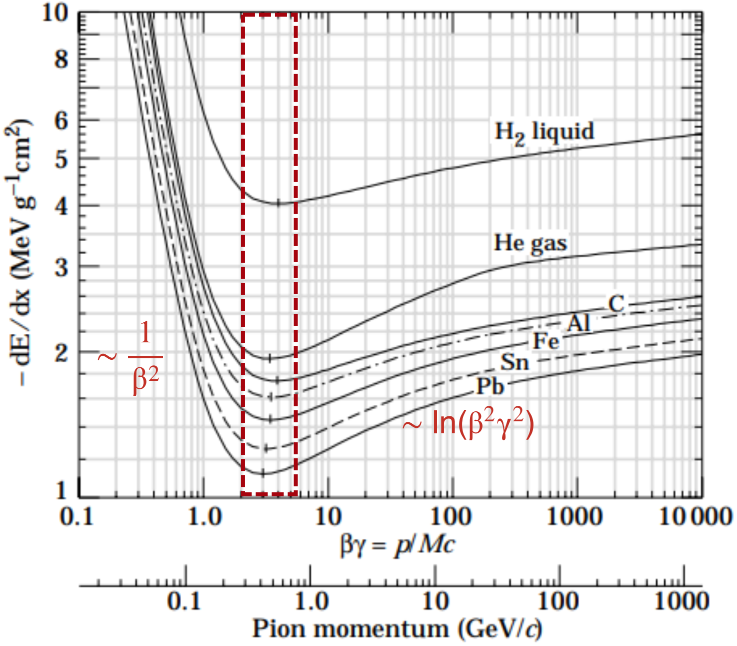
mean energy loss by relativistic charged particles (“*stopping power*”)

$$- < \frac{dE}{dx} > \; \sim \frac{1}{\beta^2} \cdot \ln(\text{const} \cdot \beta^2\gamma^2)$$

β = v/c *(velocity)*

$\gamma = (1- \beta^2)^{-1/2}$ *(Lorentz factor)*

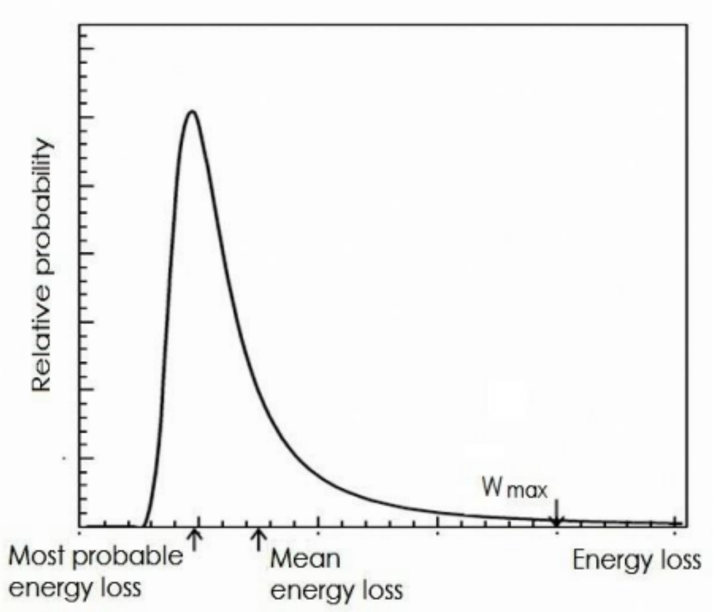
Minimum ionization: $\beta\gamma$ = 3-4



Groom, D.E., Klein, S.R. *Eur. Phys. J. C* **15,** 163–173 (2000).

Minimum Ionizing Particles

- Number of interaction fluctuates according to the Poisson law
- Energy-loss distribution of MIP in *thin absorber* (< hundreds of um) follows a **Landau distribution → Straggling function**
- Large energy losses in single interaction is less likely
- Most probable value (MPV) and the sigma of the function are the main parameters



The Landau distribution of the signal introduces a timing jitter that is not negligible at the picosecond scale for a proportional pixel detector