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

Emanuele Ripiccini, Ming-Lo Wu, Francesco Gramuglia, Ekin Kizilkan, Jad Benserhir, Claudio Bruschini and Edoardo Charbon

UliTiMA

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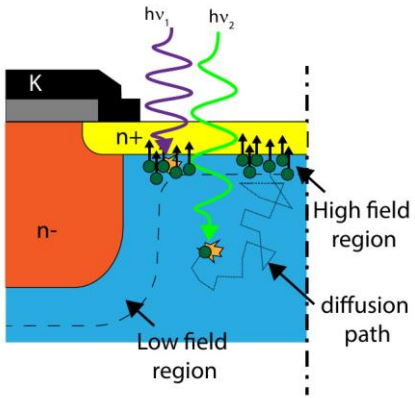
École Polytechnique Fédérale de Lausanne

Aim

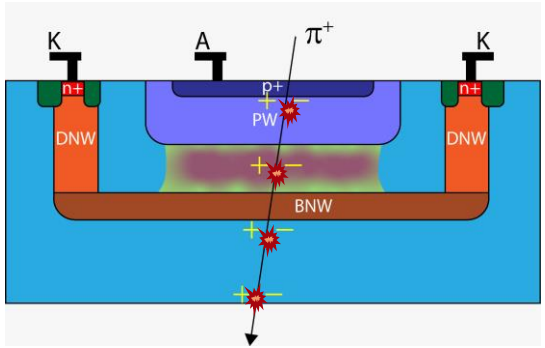
- Geiger-mode APDs or SPADs are usually used for photodetection.
- The direct detection of MIPs with SPADs (and SiPMs) has been demonstrated
- A pixel detector based on SPADs can provide high spatial resolution together with high timing resolution

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

Outline

- Timing with Geiger mode APDs (SPADs)
- Device under test
- Optical measurements
- Beam test measurements
- Conclusion and future work

Timing with SPADs

Timing with planar silicon detectors

In silicon sensors the leading edge of the current pulse is instantaneous (Schockley-Ramo's theorem)

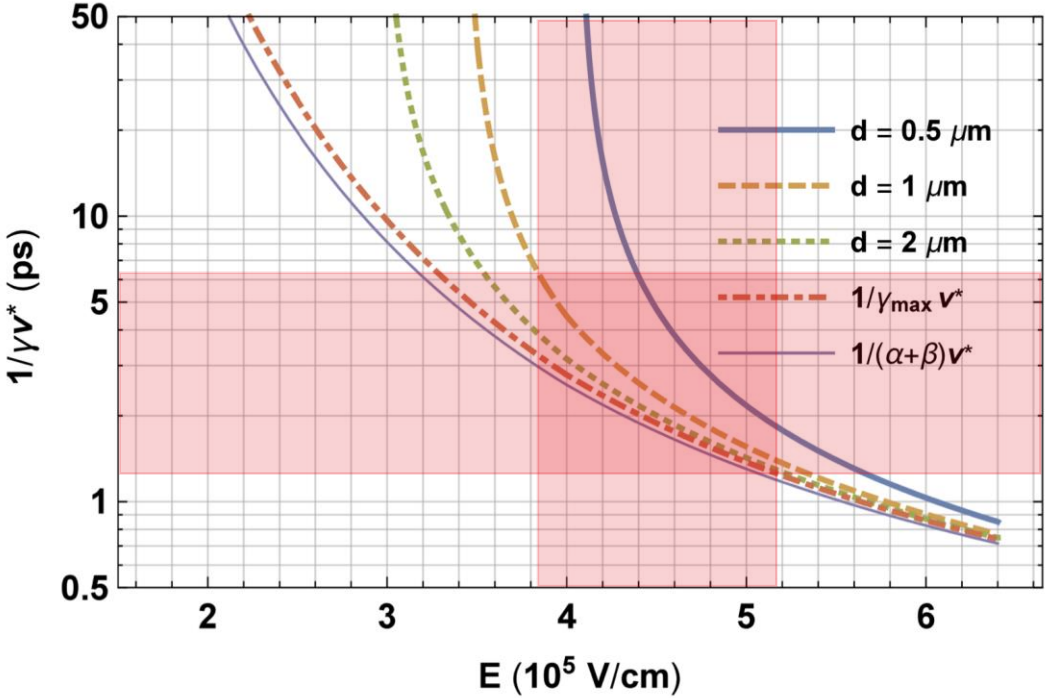
$$i = qvE_w$$

Main contributions to intrinsic timing resolution:

- Electric field non-uniformity (charge carriers velocity)
- Weighting field non-uniformity (significant when the thickness of the pixel is similar to the pixel size)
- Landau fluctuation (if MIP are detected)
- Avalanche growth dynamics (if internal gain, this is the dominant contribution for Geiger mode sensors like **SPADs**)

Timing with Geiger-mode APDs (SPADs)

Timing resolution as a function of the electric filed and high field region thickness d

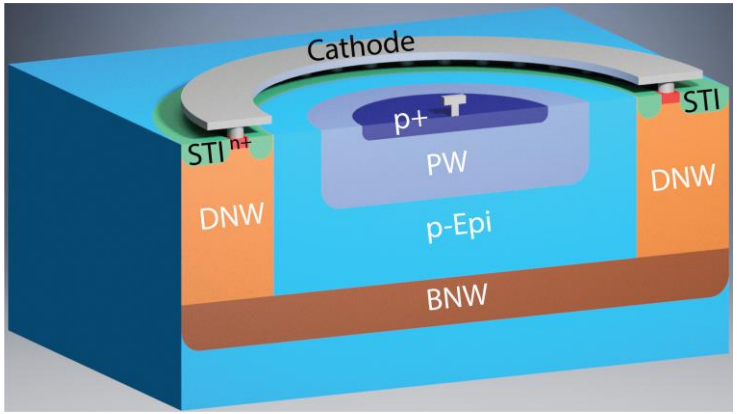


Intrinsic timing resolution is expected to be less than 10 ps for SPADs

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)

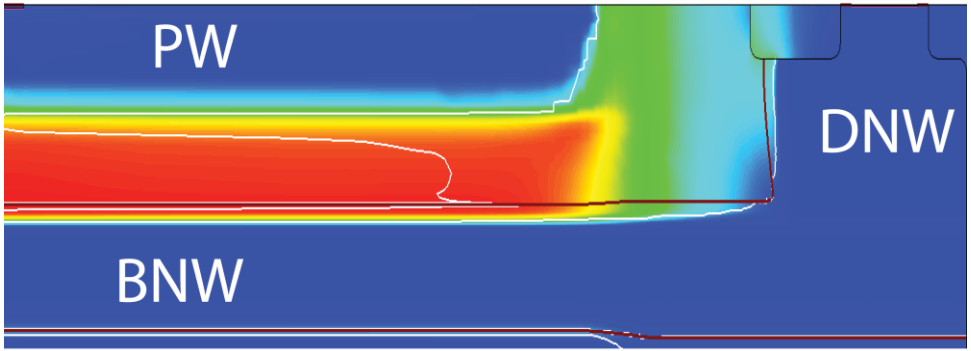
Device under test

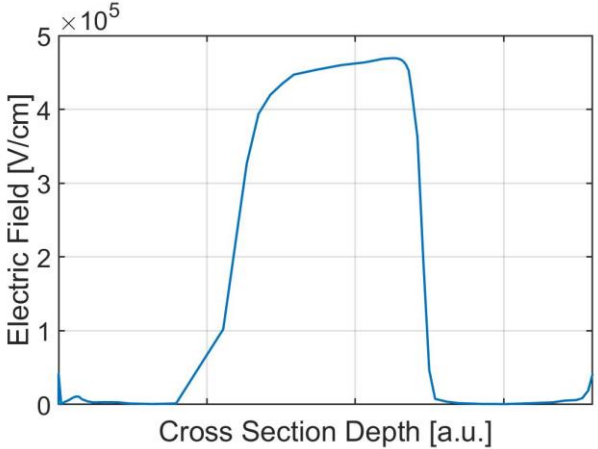
SPAD structure



SPAD

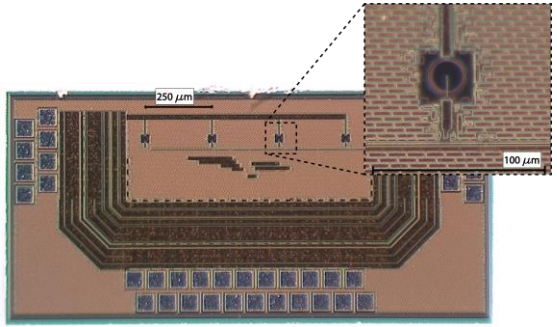
- 25 µm diameter 180 nm CMOS technology
- P-I-N structure
- Substrate-Isolated type
- P-well anode, buried N-well cathode
- HV provided through a deep N-well

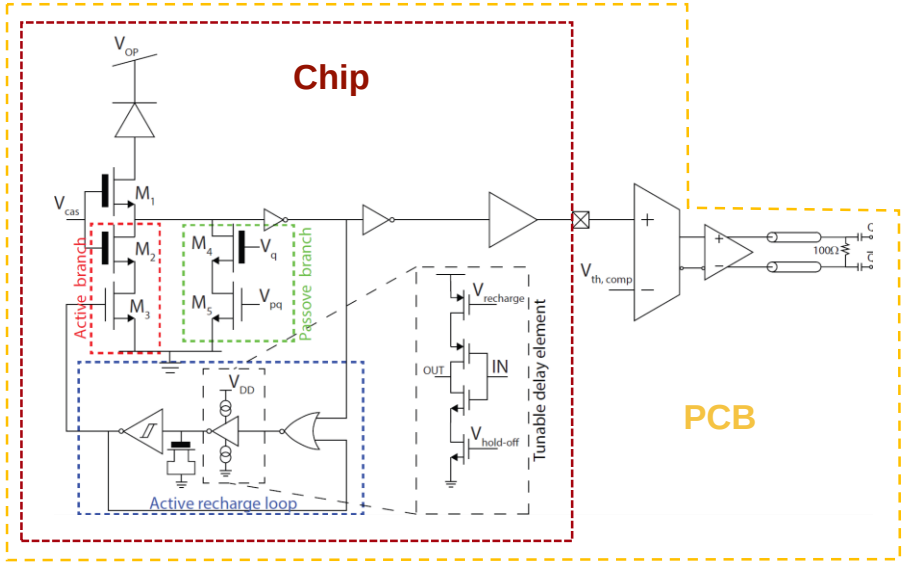




F. Gramuglia, et al., “A low-noise CMOS SPAD pixel with 12.1 ps SPTR and 3 ns dead time”, IEEE JSTQE, 2021. 2021

Chip structure and read-out PCB





Chip

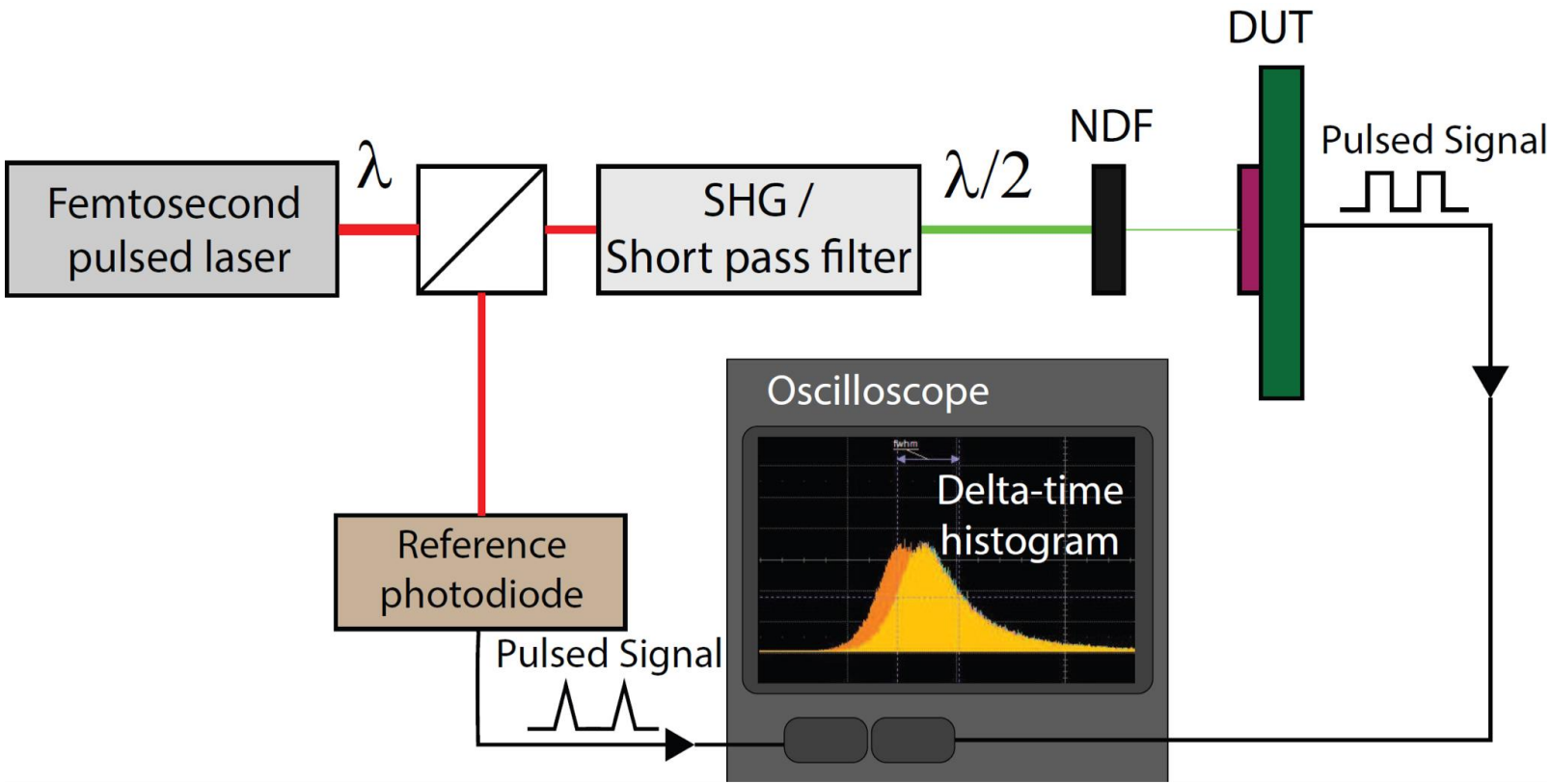
- Fully digital
- Passive quenching / Active recharge
- Tunable delay time (down to 3 ns)

System-on-board:

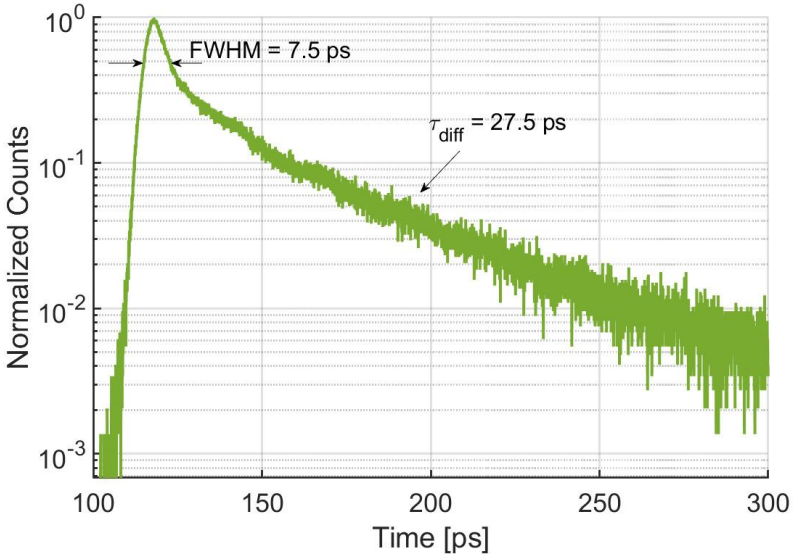
- Single external power supply source
- All voltages provided through DACs controlled with SPI protocol
- Si-Ge comparator drives 50 Ohm output
- High signal slew rate (≥ 1.6 V/ns)

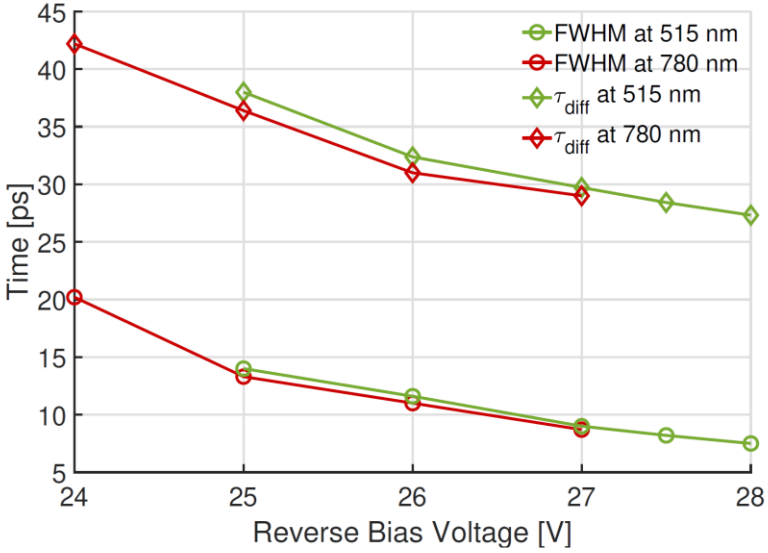
Optical measurements

Optical measurements



Optical measurements

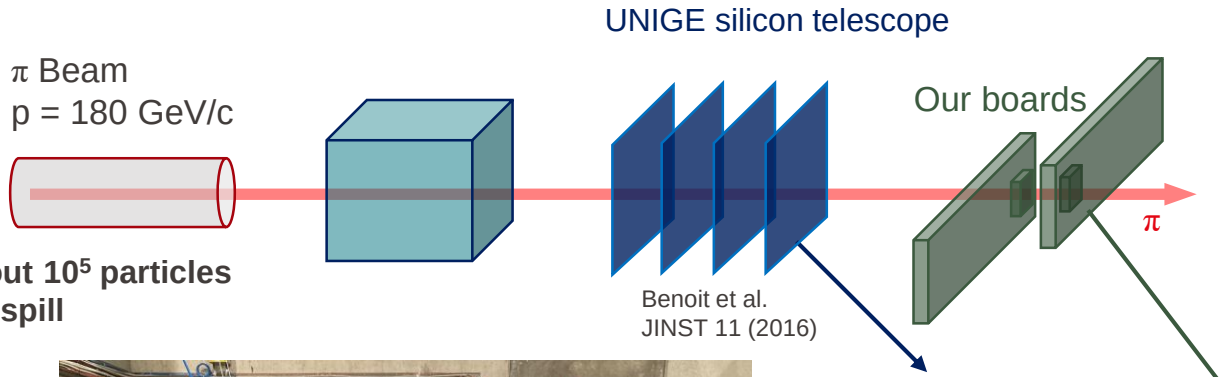




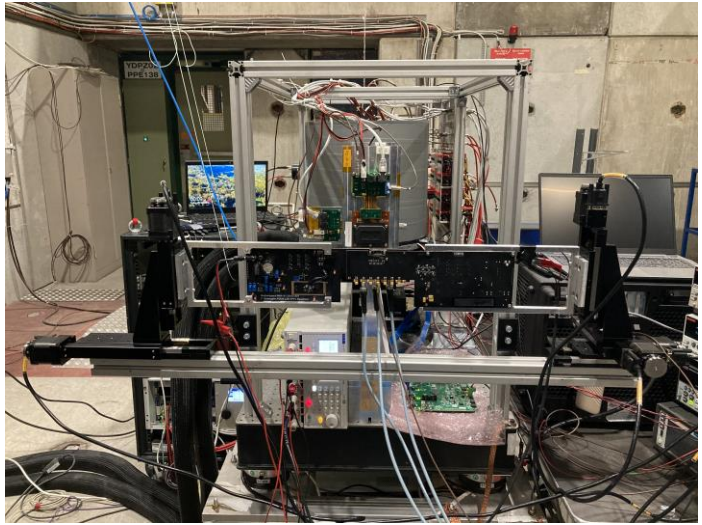
Jitter of 7.5 ps FWHM at 6.5 V excess bias for green light (PDP 45%)

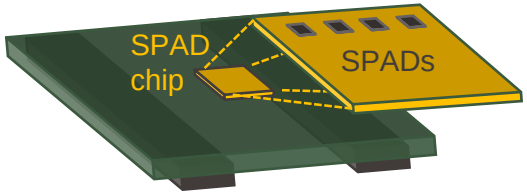
Beam test measurements

Detection System (October 2021)



About 10^5 particles per spill

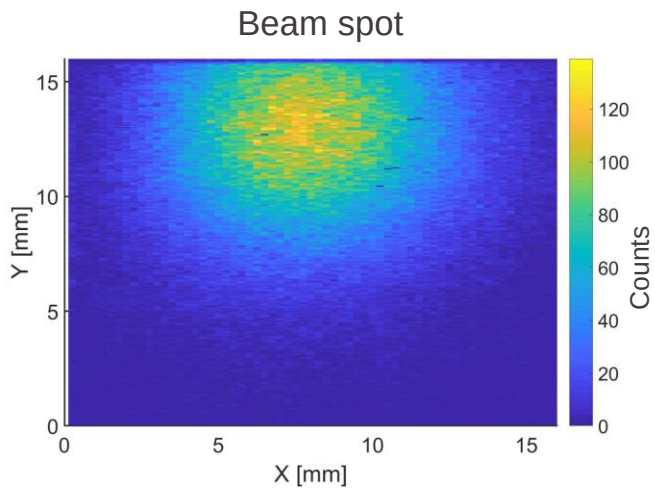




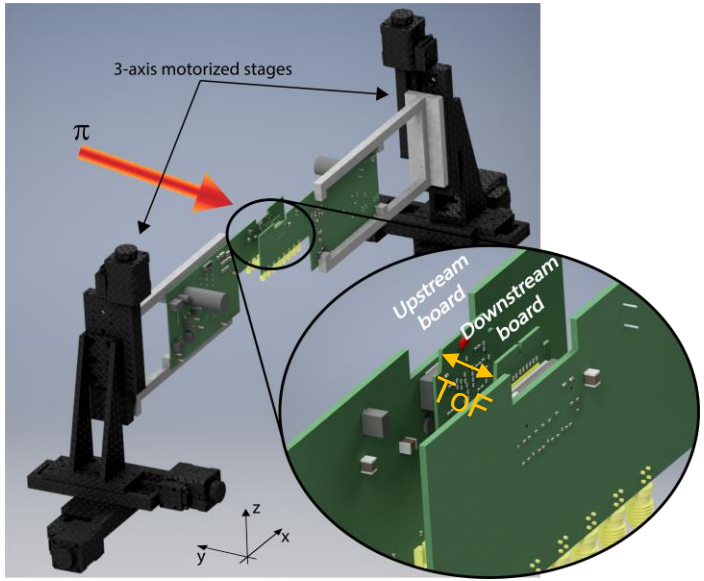
Facing SPADs are in coincidence to suppress DCR

Many thanks to Prof. Iacobucci and its group for the support!

Device alignment



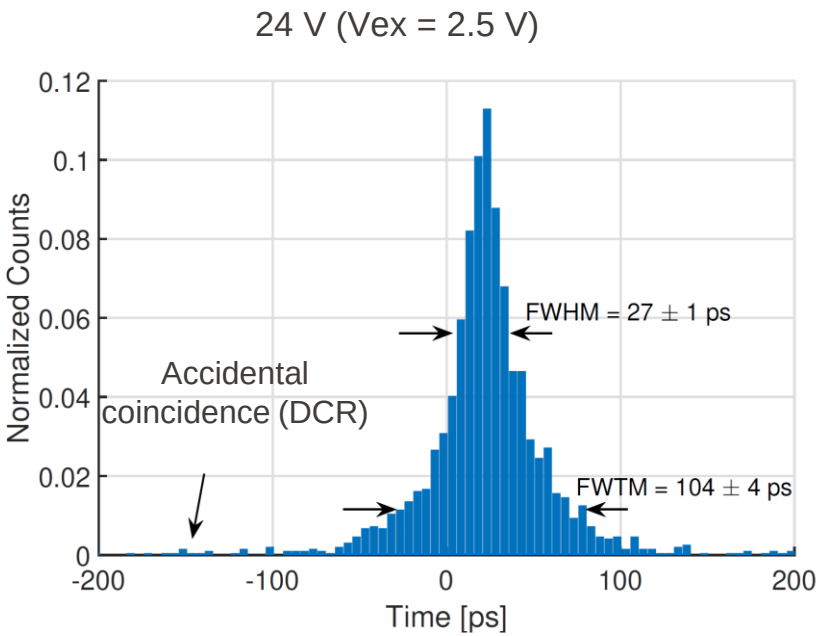
Alignment with motorized linear stages (2.5 µm steps)

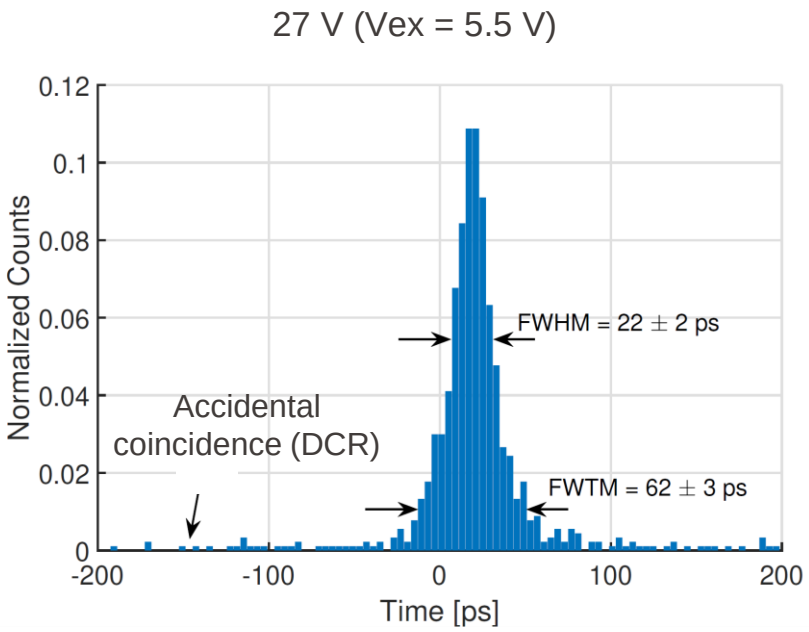


Alignment procedure:

- 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

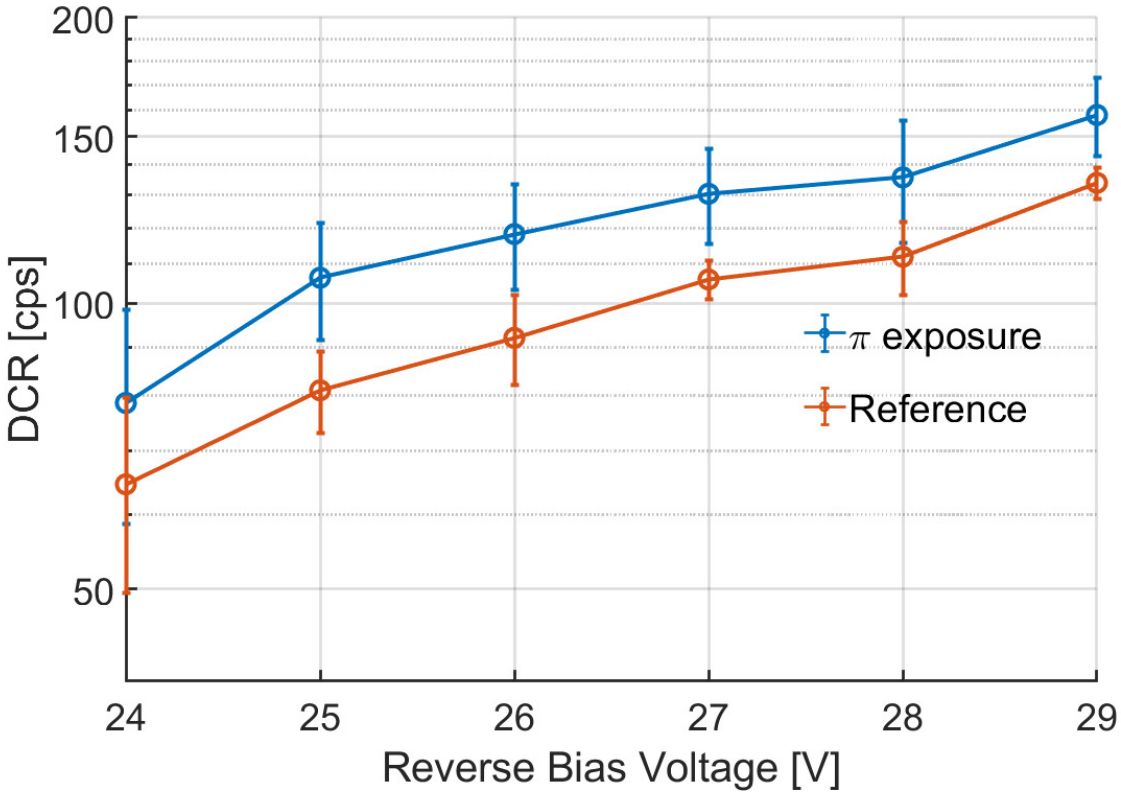
Timing resolution





Bias (V)	FWHM (ps)	FWTM (ps)	FWHM single (ps)	FWTM single (ps)
24	27 ± 1	104 ± 4	19.1 ± 0.7	73± 3
27	22 ± 2	62 ± 3	15 ± 1	43 ± 2

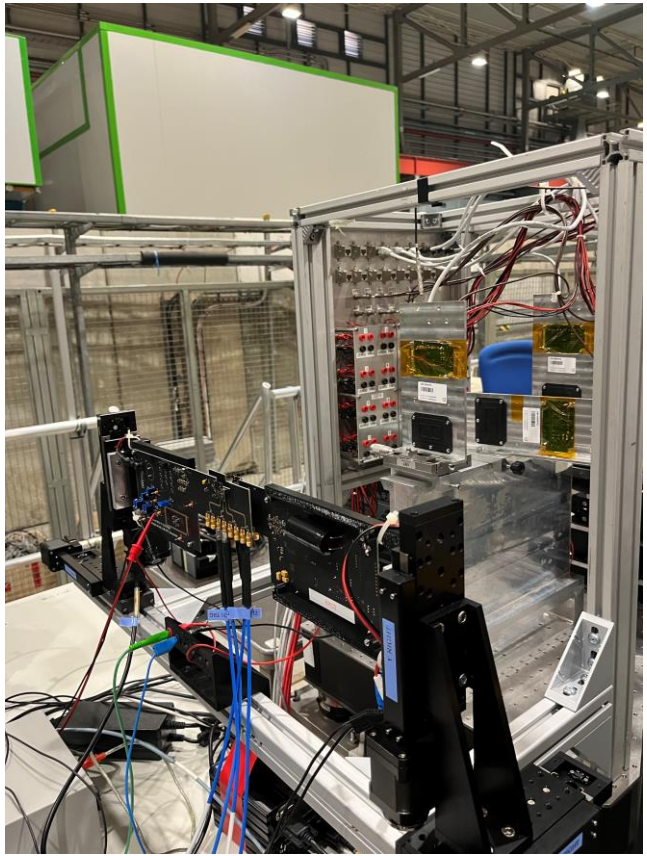
Radiation hardness



Beam test October 2022

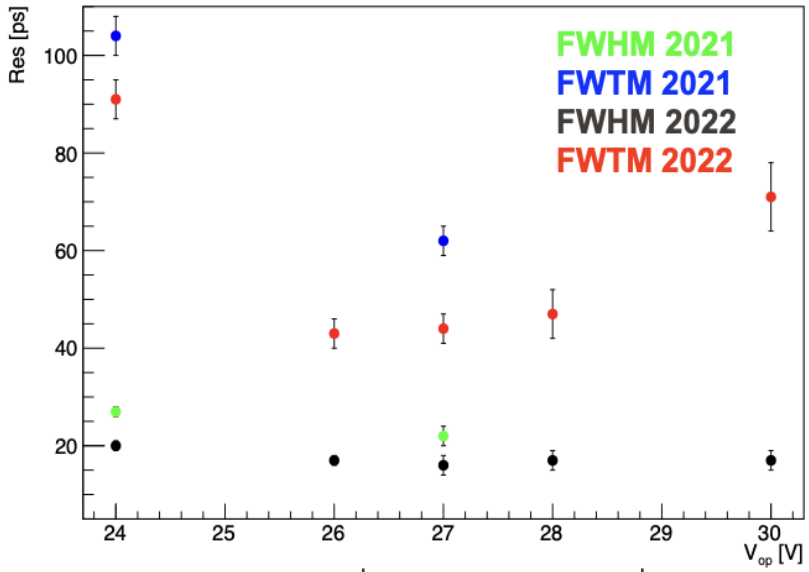
What's new with respect to 2021?

- Lighter and more precise mechanical PCB supports
- Improved light tightening with acrylic black painting
- More stable Vop provided
- A scan in Vop has been performed

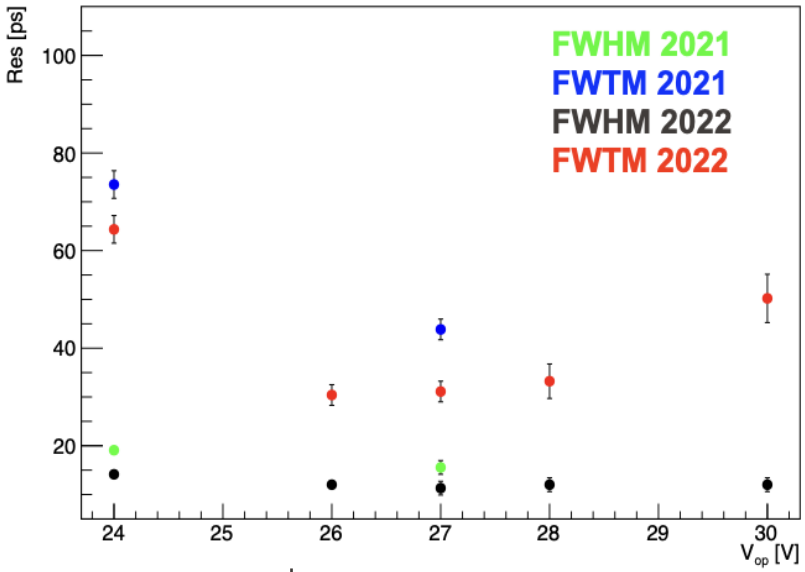


Timing resolution

TOF resolution



Single detector resolution



Bias (V)	FWHM single 2022 (ps)	FWTM single 2022 (ps)	FWHM single 2021 (ps)	FWTM single 2021 (ps)
24	14.1 ± 0.7	64 ± 3	19.1 ± 0.7	73± 3
27	11.3 ± 0.7	31 ± 2	15 ± 1	43 ± 2

Conclusions

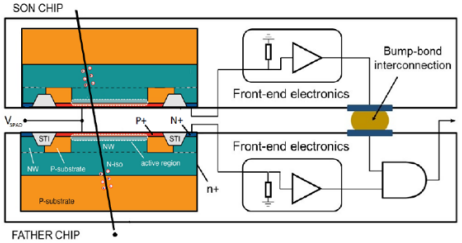
An optimized CMOS SPAD fully digital chip has been developed, showing outstanding performance:

- Tunable dead time down to 3 ns (crucial for high rate)
- High timing resolution for green light: **7.5 ps FWHM**
- Improved timing resolution for MIP detection has been achieved with an optimised experimental setup: **11 ps FWHM at 27 V**

Future work

Next steps

- Performing SPTR measurements as a function of the position
- Design of a multichannel prototype
- Feasibility study for the implementation of ***high timing resolution particle tracker***
- Two chips bonded, one with only sensor and FE electronics and the other one with FE electronics and logic



Torilla et al. DCR and crosstalk characterization of a **bi-layered** 24×72 CMOS SPAD array for charged particle detection

Thank you!

frontiers

1

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

Francesco Gramuglia [1,*], **Emanuele Ripiccini** [1,*], **Carlo Alberto Fenoglio** [1], **Ming-Lo Wu** [1], **Lorenzo Paolozzi** [2,3], **Claudio Bruschini** [1,†] **and Edoardo Charbon** [1,†]

[1] *Advanced Quantum Architecture Laboratory, Ecole polytechnique fédérale de Lausanne (EPFL), Neuchatel, Switzerland*
[2] *Departement de Physique nucléaire et corpusculaire, Université de Genève, Geneva, Switzerland*
[3] *European Organization for Nuclear Research, CERN, Meyrin, Switzerland*

Correspondence*:
Francesco Gramuglia
francesco.gramuglia@epfl.ch

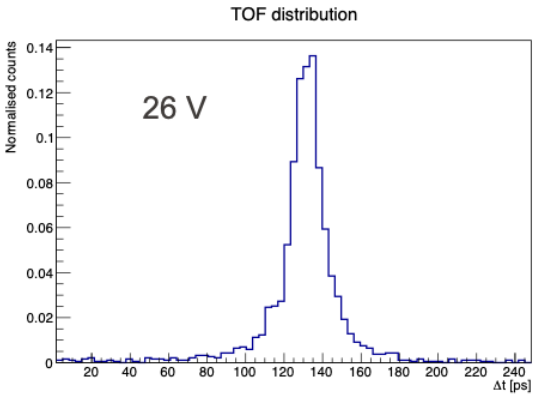
2 **ABSTRACT**

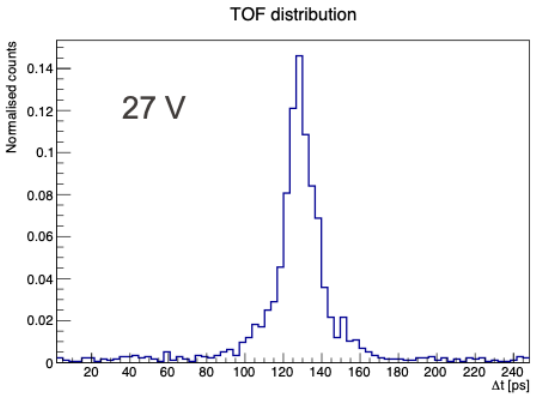
3 Major advances in silicon pixel detectors, with outstanding timing performance, have recently
4 attracted significant attention in the community. In this work we present and discuss the use of
5 state-of-the-art Geiger-mode APDs, also known as single-photon avalanche diodes (SPADs),
6 for the detection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

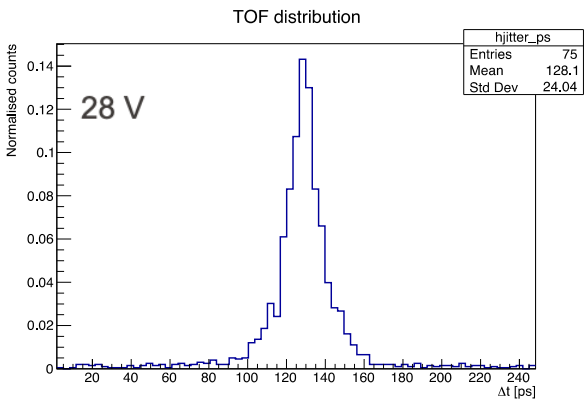
12 **Keywords: Beamline, Coincidence, Jitter, Timing resolution, MIP detection, particle physics, SPADs, Time-of-flight**

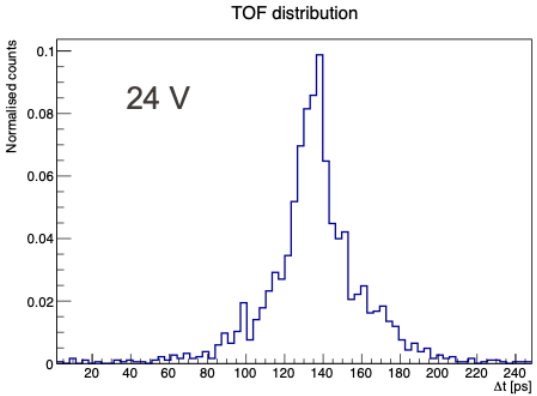
Backup

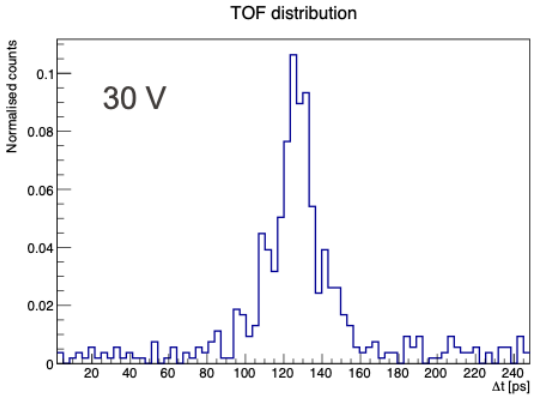
Time-of-flight distributions



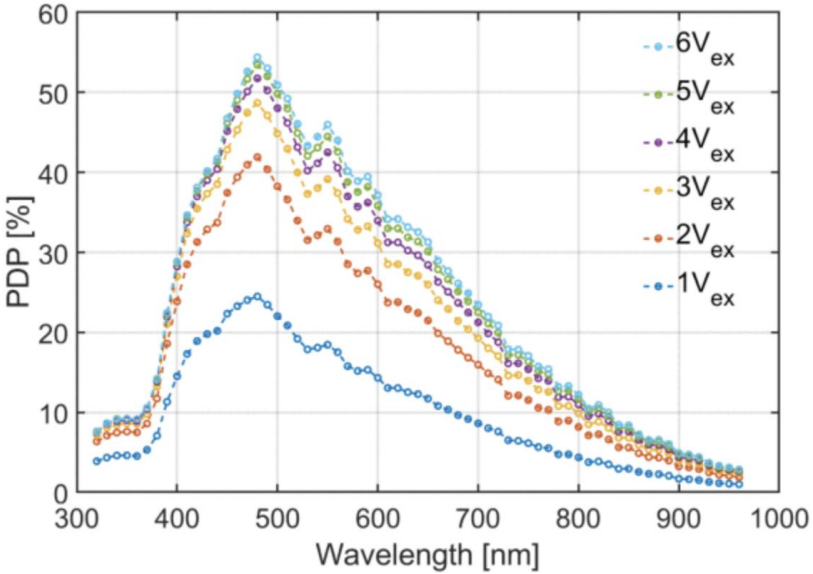


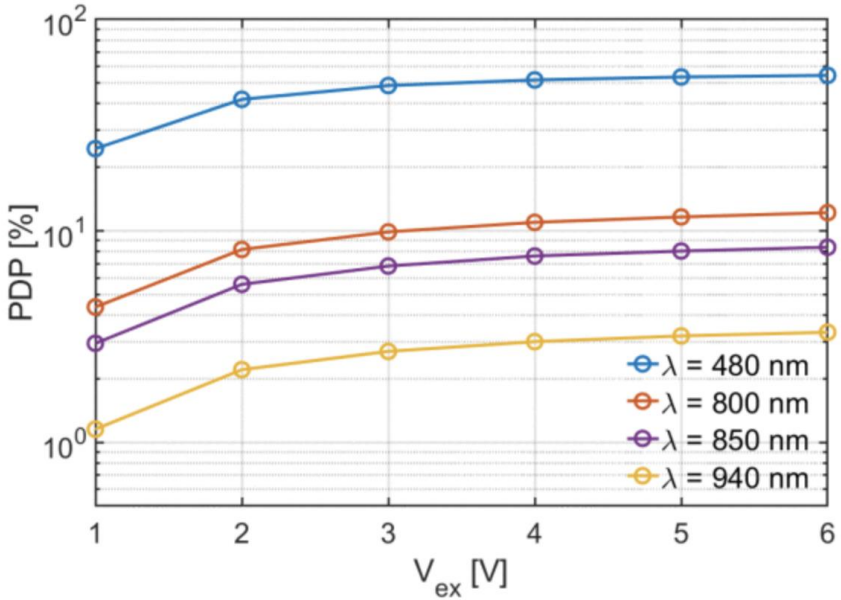






PDP measurements





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

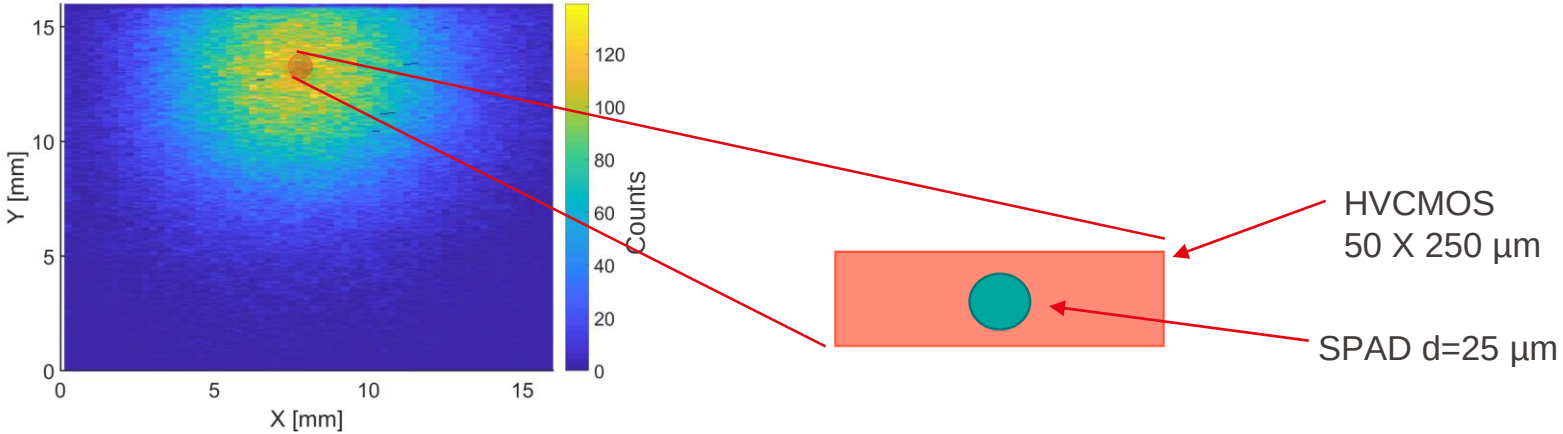
Comparison optical performance

Comparative Table

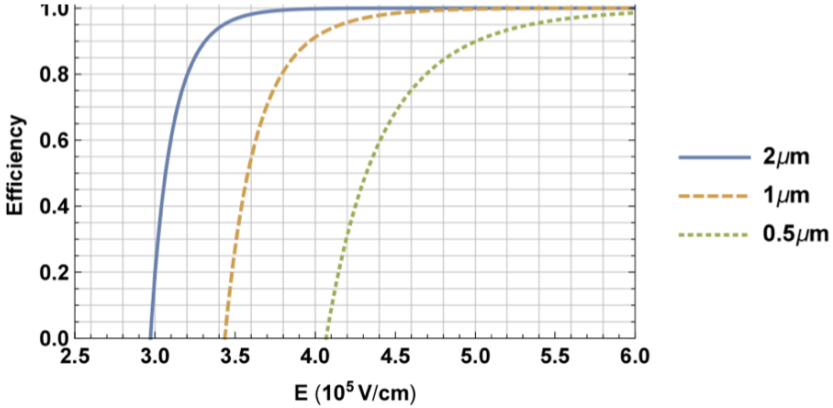
	Technology (nm)	Diameter μm	V_{EX}/V_{BD} (V)	Peak PDP (%) @λ (nm)	PDP (%) @850 nm	DCR/unit area $(cps/\mu m^2)$	AP (%)	Jitter (ps)	FoM_T [44]
Ghioni [7]	Custom Thin	50-200	5-10/30-35	52-68 @550	12-15	0.4-1.6[a]	2[b]	35[c]	1.88E+11
Gulinatti [8]	Custom RE	50	20/45-55	58 @650	28	0.3[d]	N/A	93[c]	N/A
Villa [16]	350	10-500	2-6/25	37-53 @450	2-4.5	0.05[a]	1[e]	90[f]	6.52E+11
Leitner [17]	180	10	1-3.3/21	35-47 @450	N/A[g]	0.3-1.8[a]	N/A	N/A	N/A
Veerappan [18]	180	12	2-10/23.5	24-48 @480	3-8	0.16-176[a]	0.03-0.3[h]	112-88[i]	1.37E+9
Veerappan [19]	180	12	1-4/14	23-47 @480	4-7	0.28-16[d]	0.2[j]	161-141[i]	2.78E+9
Veerappan [21]	180	12	1-12/25	18-47 @520	2-8	0.2-6[d]	7.2[k]	139-101[i]	5.88E+9
Xu [22]	150	10	2-5/19	24-32 @450	2-3.5	0.1-1	1-13[l]	42[m]	1.33E+11
Lee [20]	140(SOI)	12	0.5-3/11	12-25 @500	2.5-7	0.9-260	1.7[n]	65[o]	1.17E+9
Richardson [13]	130	8	0.6-1.4/14	18-28 @500	3-5	0.24-0.6[a]	0.02[p]	200[q]	9.04E+9
Richardson [12]	130	8	0.2-1.2/12-18	18-33 @450	2-5	0.4-0.8	0.02[r]	237-184[s]	4.01E+10
Niclass [10]	130	10	1-3.5/10	31-41 @450	3	120-1300[d]	N/A	144[i]	N/A
Niclass [43]	180	25	5/20.5	64.8 @610[ii]	24	0.6	0.49[dd]	190	1.83E+11
Gersbach [11]	130	4.3	1-2/9	18-30 @480	3.5-5	1.5-11.5	<1[t]	125[i]	3.89E+9
Charbon [15]	65	8	0.05-0.4/9	2-5.5 @420	0.2-0.4	340-15.6k[a]	<1[u]	235[i]	3.71E+5
Sanzaro(A) [24]	160(BCD)	10-80	3-9/36	31-58 @450	2.5-6.5	0.12-0.2[v]	0.43-1.59[w]	39-28[c]	9.12E+11
Sanzaro(B) [24]	160(BCD)	10-80	3-9/25	2-47 @450	2.5-6.5	0.1-0.18[v]	0.02-0.14[w]	36-28[c]	7.9E+11
Sanzaro(C) [24]	160(BCD)	10-80	3-9/26	55-71 @490	6-9	0.13-0.19[v]	0.41-1.26[w]	41-28[c]	1.15E+12
Pellegrini [25]	40	18.36	1/15.5	45 @460[+]	5	N/A[†]	0.1	170[*]	N/A
Nolet [5]	65	20	1.75/9.9	8 @470	N/A	2.8k	<10	7.8[‡]	N/A
Webster [14]	90	6.4	14.9/2.4	44 @700	22	8.1k	0.375	84	N/A
This Work	**180**	**25-100**	**1-11/22**	**25-55@480**[2]	**3-8.4**[x]	**0.06-0.23**[y]	**~0.12-3**[z]	**12.1**[1]	**2.78E+13**

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

Efficiency calculation



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



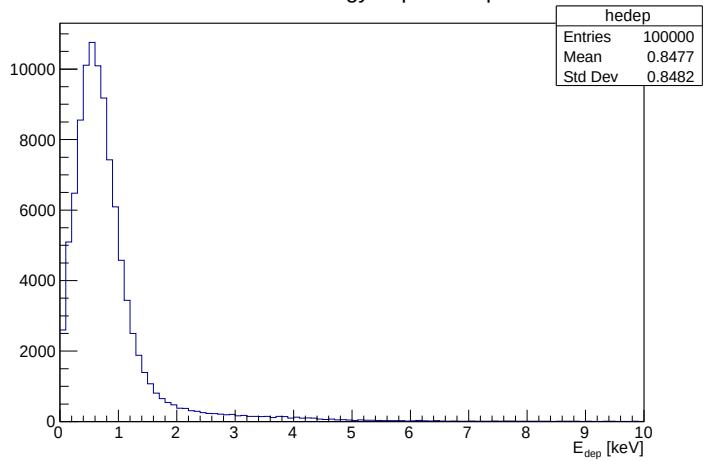
Emanuele Ripiccini

Passage of MIPs through the SPAD (MC simulation)

Emanuele Ripiccini

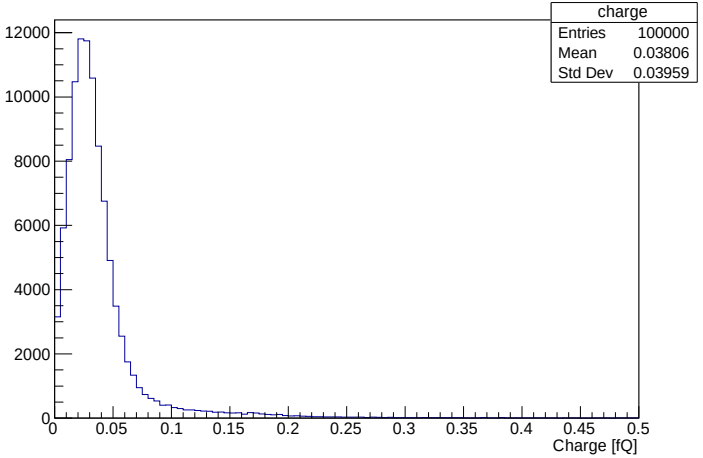
Assuming that the active region of the SPAD is 3 μm thick

Distribution of the energy deposition per event



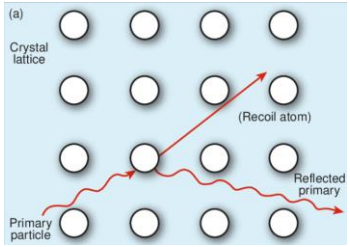
3.6 eV are needed to produce one e-h pair

totat charge generated



More than 99% of the MIPs passing through the active region release enough energy to produce at least 1 e-h pair

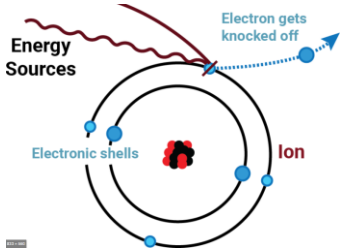
Radiation hardness



Maurer, Richard et al. (2008).

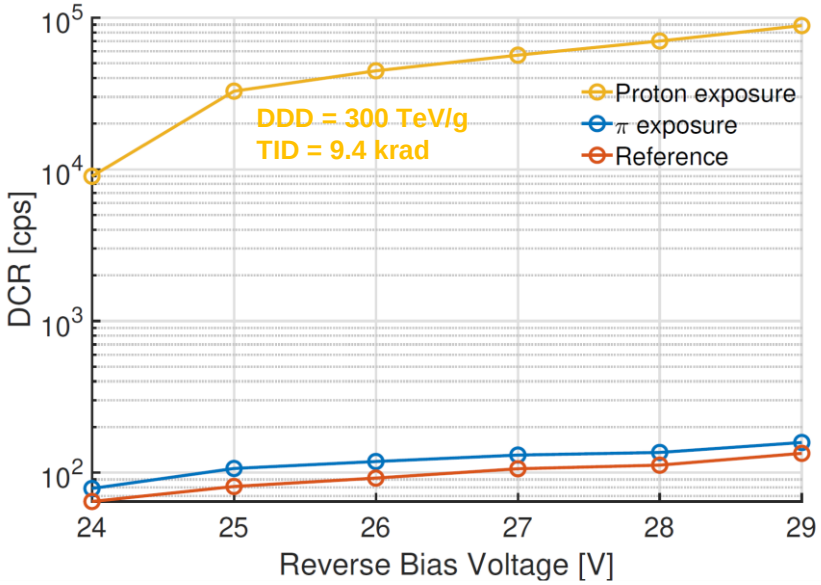
Displacement damage

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)