Hadron identification in the TeV momentum region and Development of Innovative Detectors for Particle Identification

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TRDs for hadron ID in the TeV range

- Motivation
  - Studies in many areas of particle and astroparticle physics require a good knowledge of hadron spectra produced at small angles to the primary particle direction
    - Large uncertainties in the modeling of high-energy cosmic-ray showers
  - Proposal of a small angle spectrometer at LHC to extend measurements at $\sqrt{s} = 13\ TeV$
    - Most recent measurements performed in the 60s at the ISR up to $\sqrt{s} = 63\ GeV$
- Experimental challenge:
  - identify charged hadrons (p,K,π) with high efficiency in the TeV energy range

State of the art

- TRDs have been widely used for electron–hadron separation in both accelerator and cosmic-ray experiments
  - The threshold Lorentz factor for TR emission is exploited
  - Gaseous detectors usually adopted
  - e/π separation up to ~100 GeV/c, e/p separation up to ~1 TeV/c
- Hadron identification is a more complex task
  - The masses of the particles are close
  - In the past TRDs based on gaseous detectors able to separate π, K, p up to 200 GeV/c were developed
- New approach: simultaneous measurement of TR photon energies and emission angles
  - Need high-granularity detectors
  - TR X-rays must be separated from the ionization energy deposit of the radiating particle

Physics goals and activities

Goal:

Development of a novel TRD based on highly segmented pixel semiconductor detectors, for measuring both the energies and the emission angles of TR X-rays

Applications:

Hadron ID in the TeV range

Activities:

Analysis of existing data

Development of MC simulations

Development and optimization of new radiators

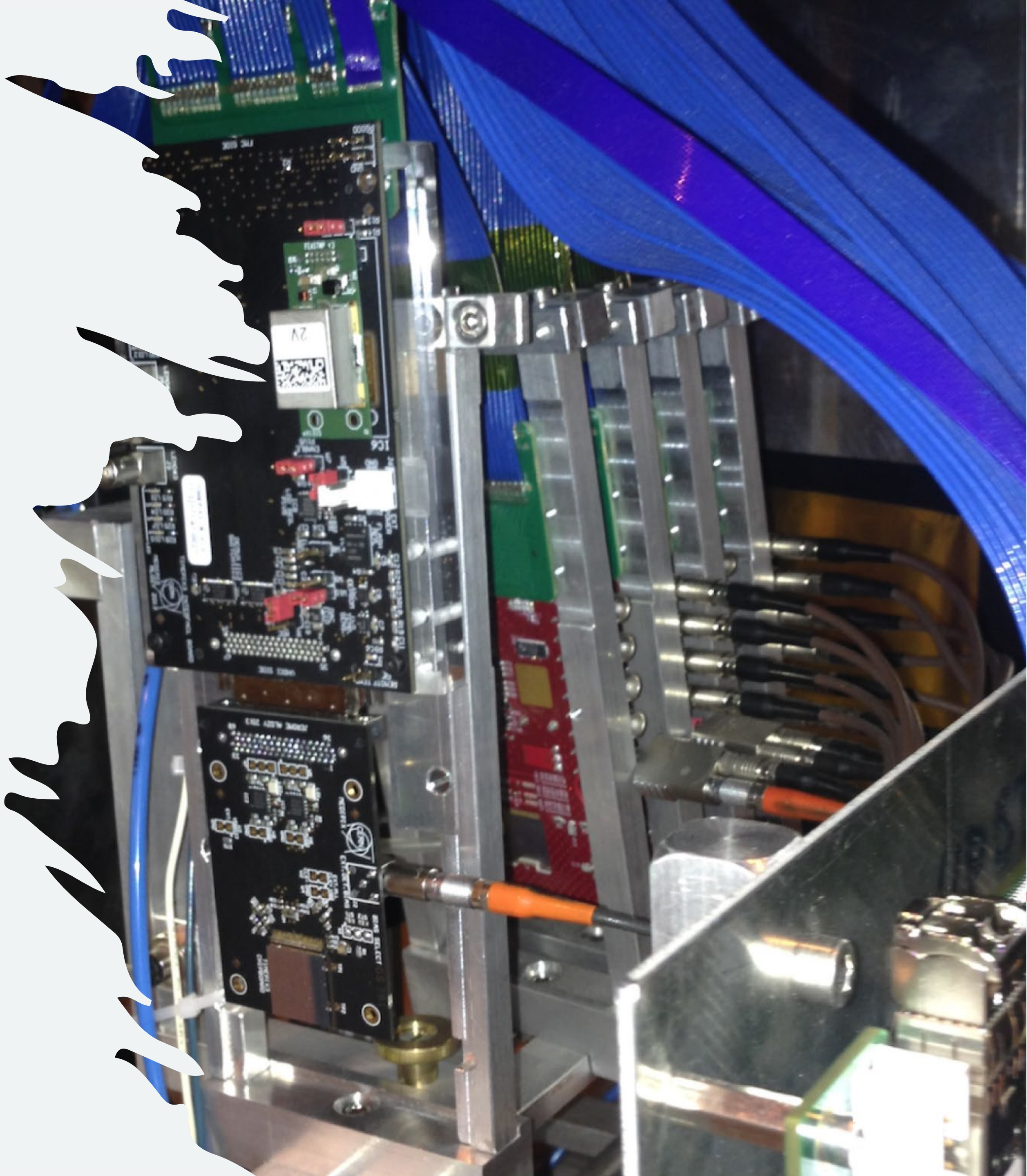
Development of highly pixelated detectors based on Si, GaAs and CdTe

Development of readout chips associated to the detectors

Beam test studies

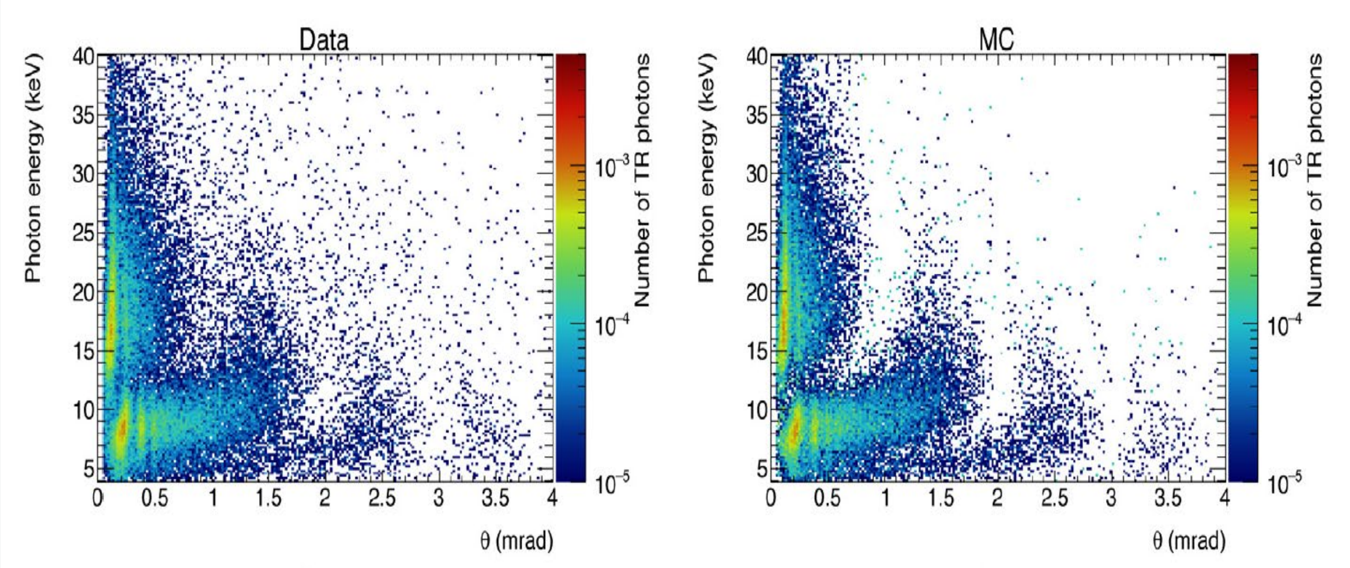
Activities with pixel sensors

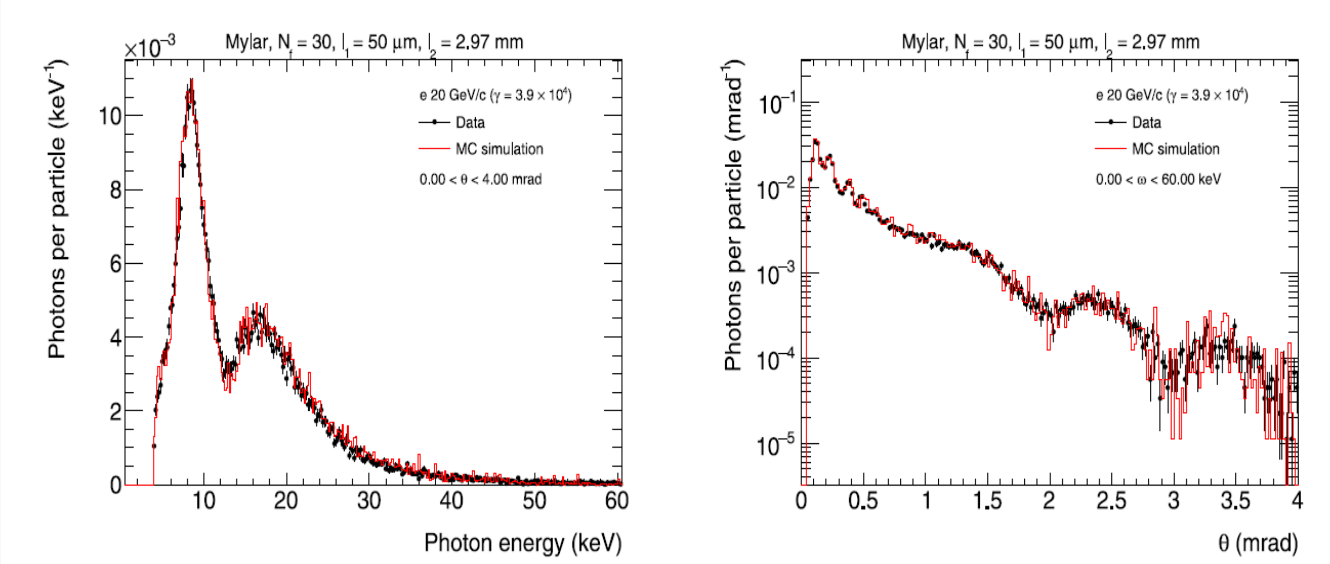
- Activities started in 2017
  - Beam test campaigns performed at the SPS H8 line and DESY
  - Different radiators tested
  - Tests with strip and pixel detectors
    - Si and GaAs detectors used
    - Pixel detectors equipped with Timepix3 chips
  - Simulation studies
- Several papers published



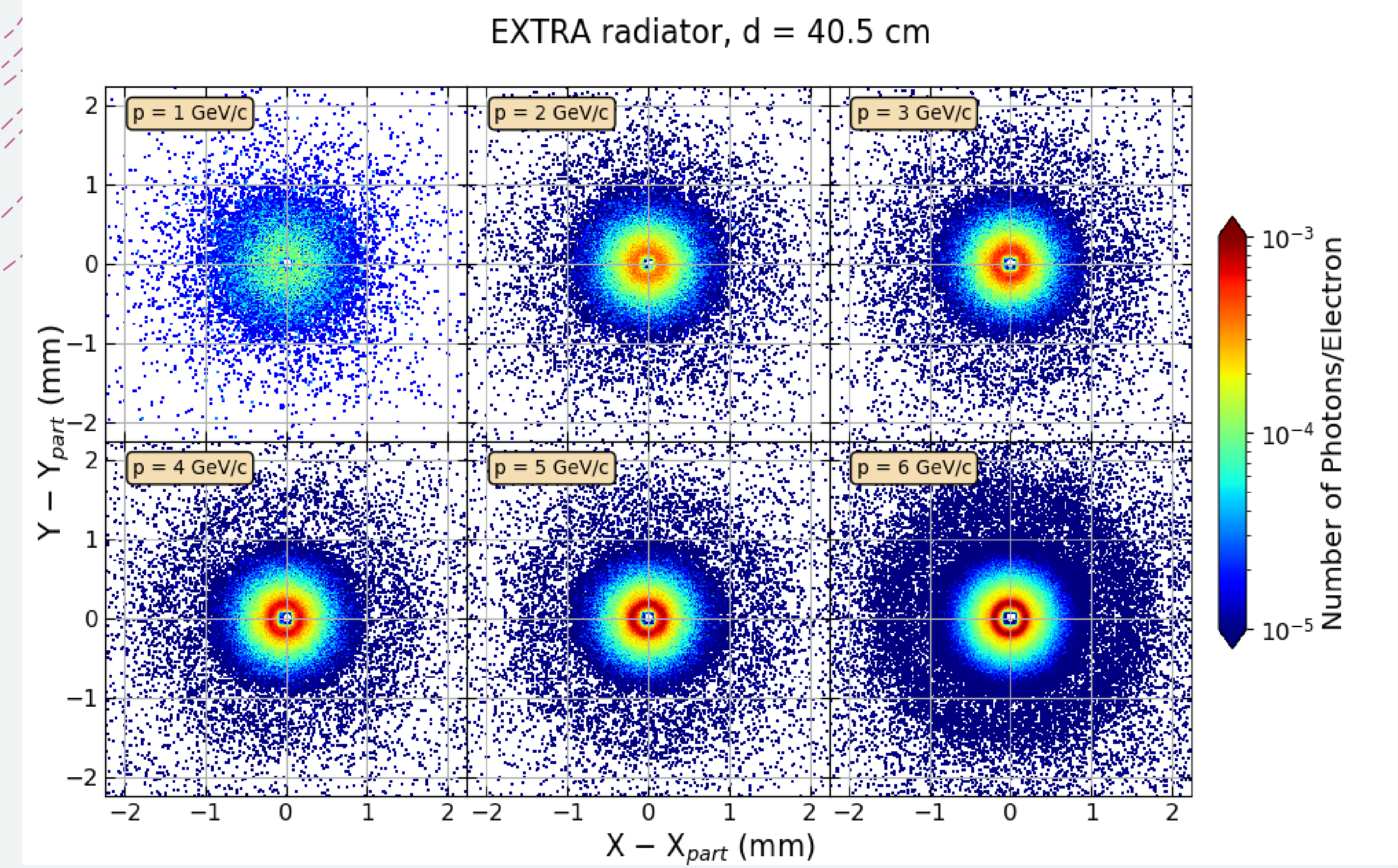
Measurements with a Si pixel detector

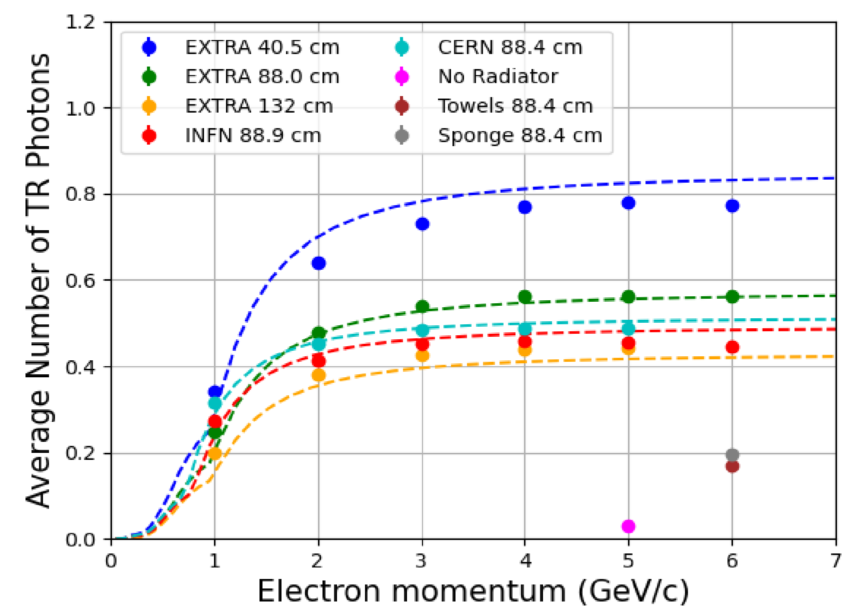
- The plots show the measured and simulated energy-angle distribution of TR X-rays produced by 20 GeV/c electrons crossing a mylar/air radiator
- Data are well reproduced by MC simulation





More measurements with Si pixels

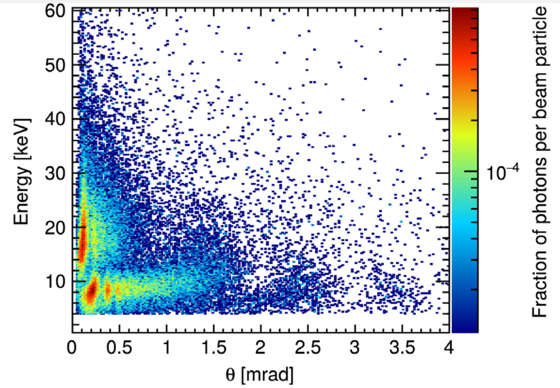




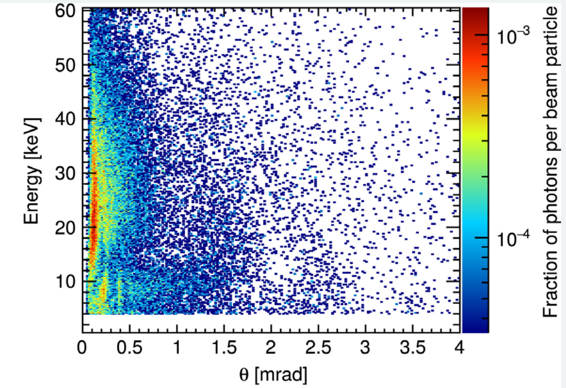
- Measurements performed at the DESY II Beam Test Facility in the framework of an experiment winning the BL4S competition
- Silicon pixel detector, 100 µm thickness, 55 µm pitch readout with a Timepix3 chip

Si vs GaAs pixel detectors

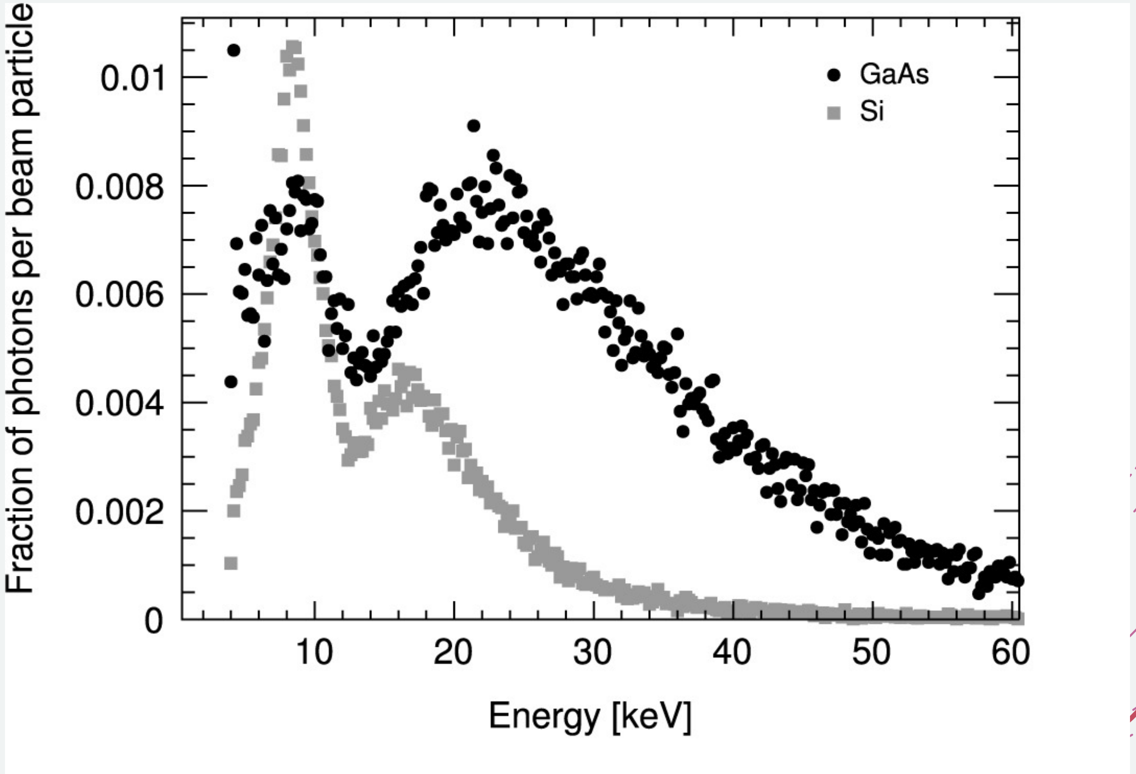
- Radiator: 30 mylar foils, 50µm thickness, 2.97mm air gaps
- Detectors separated from the radiator by a 2m He pipe
- GaAs is more effective than Si for high-energy X-rays (>20 keV)



(a) Energy over angle of TR measured with a Si sensor.



(b) Energy over angle of TR measured with a GaAs sensor.



Ongoing activities

Modern technology of semiconductor detectors offers new opportunities of combining precise tracking and particle identification devices in one detector

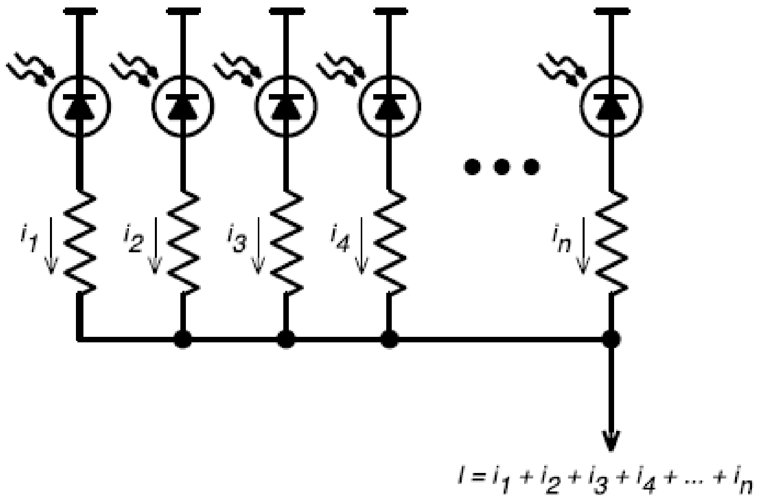
Preliminary studies show that separation of TR and particle dE/dX together with a simultaneous measurement of TR production energy and emission angles significantly enhances particle identification power

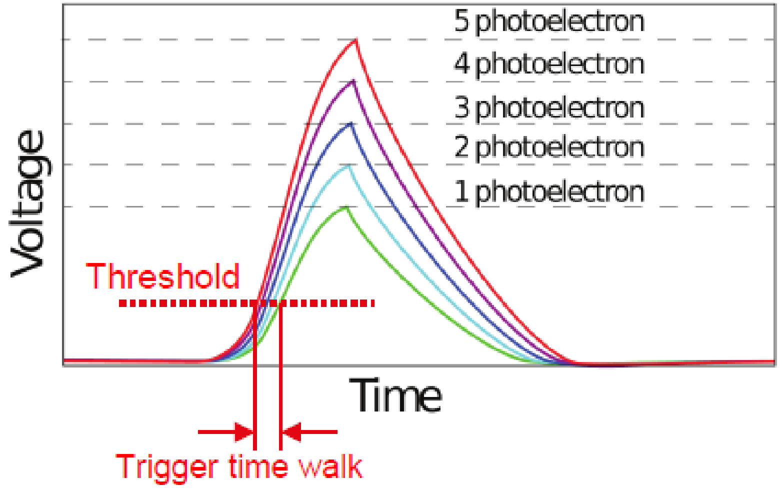
A R&D activity on TRDs based on pixel detectors is ongoing in the framework of the WG 5 of the DRD4 Collaboration

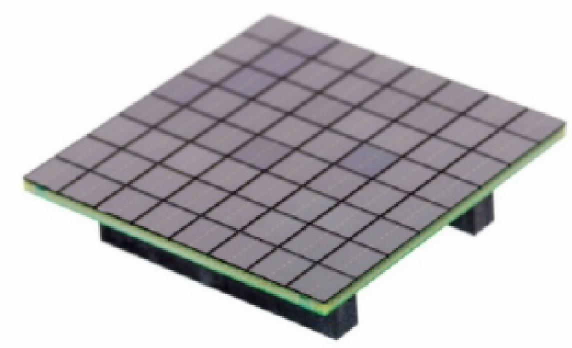
R&D of CMOS SPADs

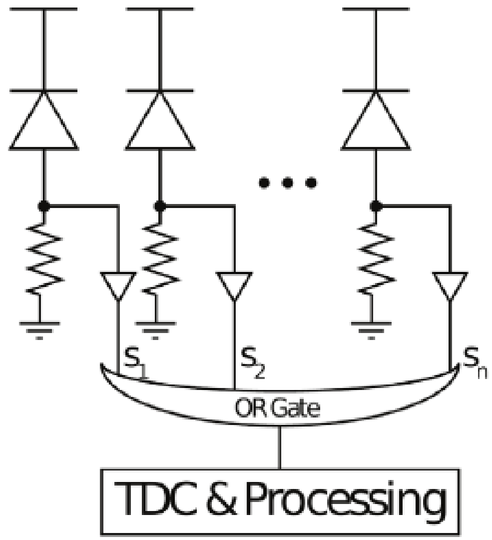
- **Goal:** development of sub-mm single photon sensors with low time jitter
- Standard CMOS processes provide a mature and reliable technology, which allows the co-integration of SPADs and electronics at low costs
- Advantages of CMOS SPADs:
  - Light detection and readout on a single chip
    - simple mechanics, low cost ➔ suitable for mass production
  - Active pixel quenching
  - Each SPAD can read out individual cells and bad SPADs can be turned off to reduce overall noise (trade-off between active area and noise)
  - Back-side illumination possible
  - Timing resolution < 100 ps
  - Fast tracker devices
- CMOS SPAD developments for high-energy physics could find applications for large instrumented surfaces highly segmented (e.g., RICH)

Analog vs Digital SiPMs

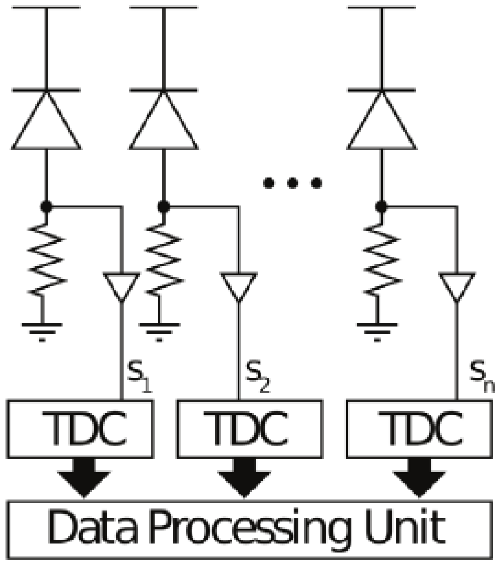








Standard dSiPM



Ideal (multi-channel) dSiPM

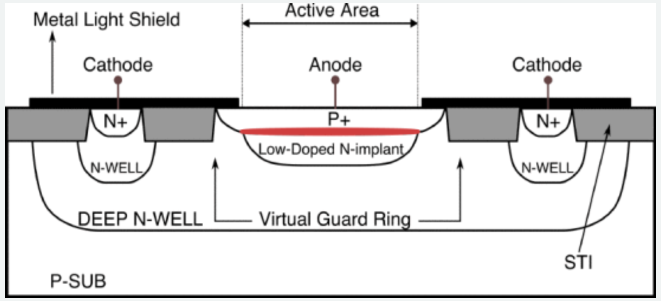
[S. Mandai & E. Charbon, NSS-MIC 2012; E. Venialgo, NSS-MIC 2016]

ASPiDeS: A CMOS SPAD and Digital SiPM Platform for High Energy Physics

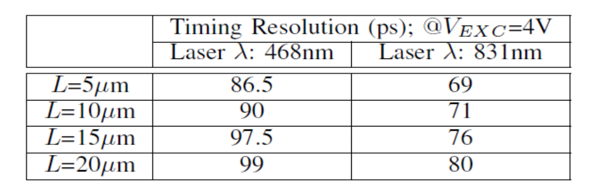
- **ASPiDes goal**: development of a technology platform for the design, production and commissioning of digital silicon photomultipliers (dSiPMs), detectors with single-photon sensitivity and embedded functionalities
  - Applications to scintillation and Cherenkov light detection in calorimetry, RICH and neutrino physics
  - Activities in the framework of WP1 of the DRD4 Collaboration
    - Task 1.1 - SSPD with new configurations and modes
    - Objective 4: Implementation and characterization of CMOS-SPAD sensors for light detection in HEP, mainly for RICH and calorimetry application
- Experimental activity approved by INFN CSN V
  - Leader: L. Ratti (Pavia)
  - INFN Units involved: Bari, Bologna, Milano, Napoli, Padova, Pavia, Torino, Trento
  - Researchers of the INFN Bari Unit: F. Licciulli, N. Mazziotta et al.
  - Tasks:
    - Simulation, design and verification of the prototype chip and the demonstrator in the LFoundry 110 nm CMOS technology
    - Characterization in the lab and in a test beam

FBK CMOS-SPAD in 110 nm process node

- CMOS Image Sensor (CIS) technologies used to design Single Photon Avalanche Diodes (SPADs)
  - SPAD integrated in the LFoundry CMOS process design kits (PDK) in 150/110 nm nodes
- Active area defined by the side length (L) of the high electric field region
  - L is few tens of microns
- Breakdown voltage of about 20 Volt
- Photon Detection Efficiency (PDE) peak around 450 nm
- Timing resolution of about 86-99 ps FWHM @ 468 nm

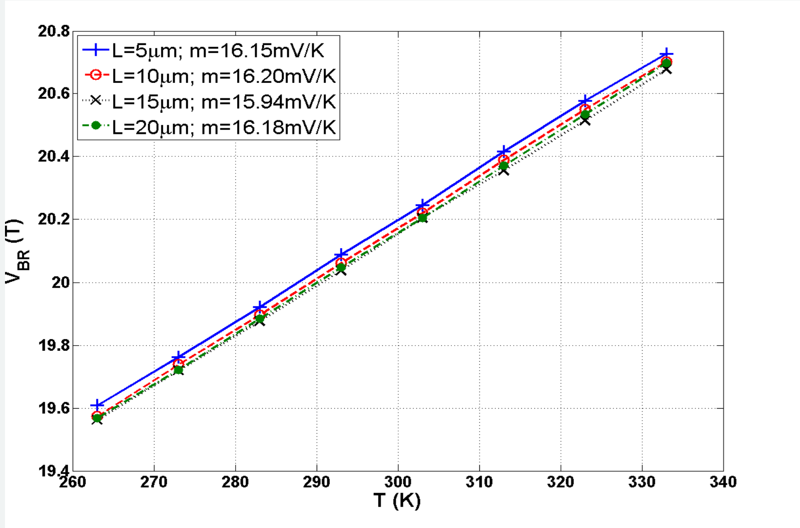


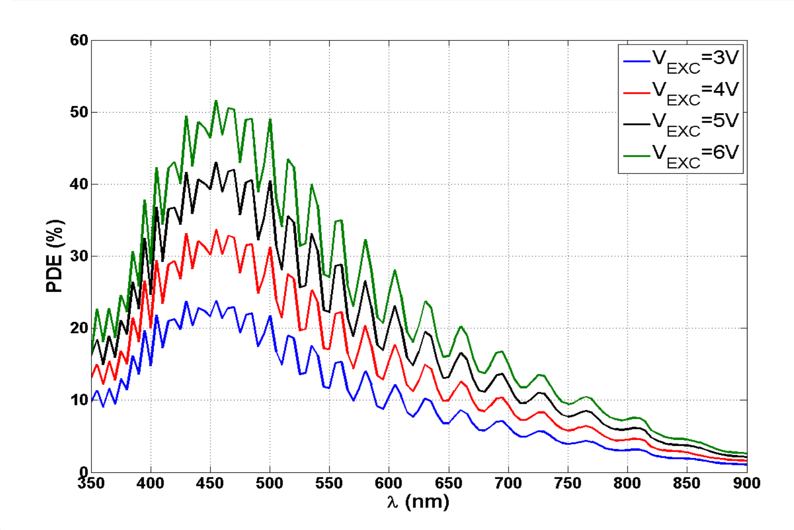
Cross-section of a p+/n-implant SPAD implemented in a 110 nm CIS technology with virtual deep n-well guard ring. The avalanche region is highlighted in red.

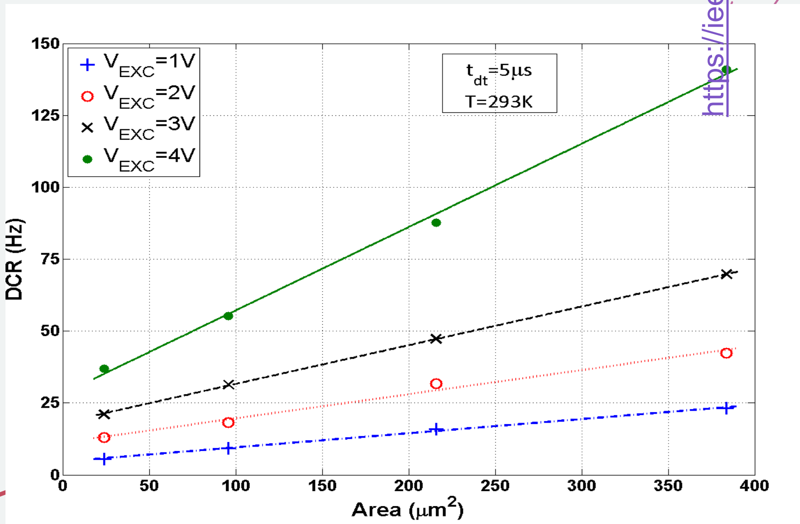


	Timing Resolution (ps); @V_{EXC}=4V	
	Laser λ: 468nm	Laser λ: 831nm
L=5μm	86.5	69
L=10μm	90	71
L=15μm	97.5	76
L=20μm	99	80

https://ieeexplore.ieee.org/document/8486883







Activity plan

2025:

Development of small-scale prototypes of CMOS SiPMs

Specific structures included to test the chip functionalities

Submission 3Q 2025

2026:

First prototype characterization from 1-2Q 2026

Development of a demonstrator chip including o(10) SiPMs, pitch of o(mm), cell size o(10um)

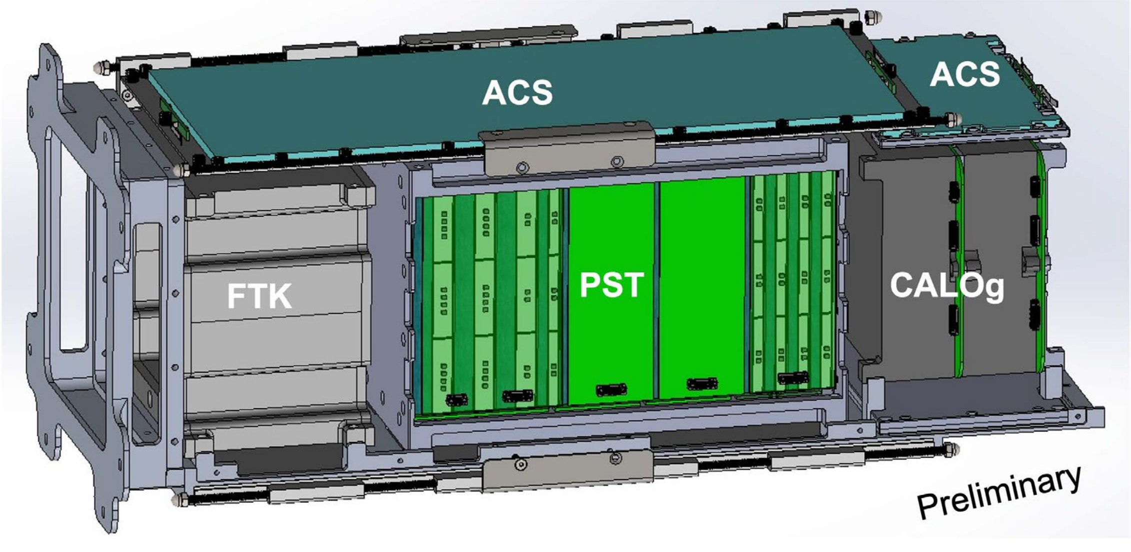
Submission 4Q 2026

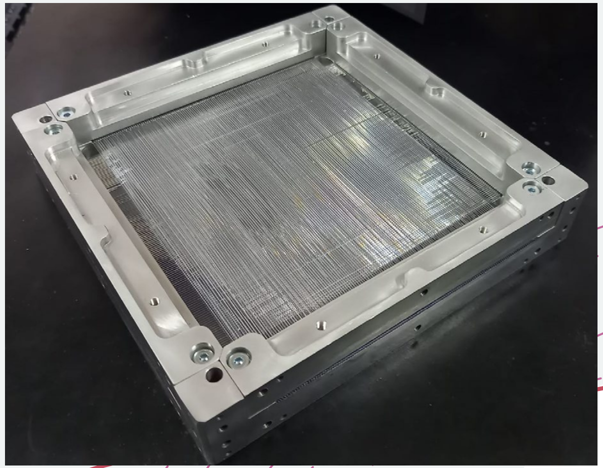
2027:

Characterization to be performed in the lab and possibly in a beam test

Development of a scintillating fiber tracker with SiPM readout

- Activities performed in the framework of the NUSES experiment
  - R&D on the Zirè detector
    - Measure the flux (E<300 MeV) of cosmic-ray e^+/e^-, p and light nuclei of solar/galactic origin
    - Detection of 0.1 - 30 MeV photons for study of transient and stable gamma sources
- The Zirè FTK (Fiber TracKer)
  - Fast trigger
  - Particle tracking
  - PID/energy loss measurement
- Several FTK prototypes assembled and tested in our laboratories with radioactive sources and at the CERN PS and SPS beam lines

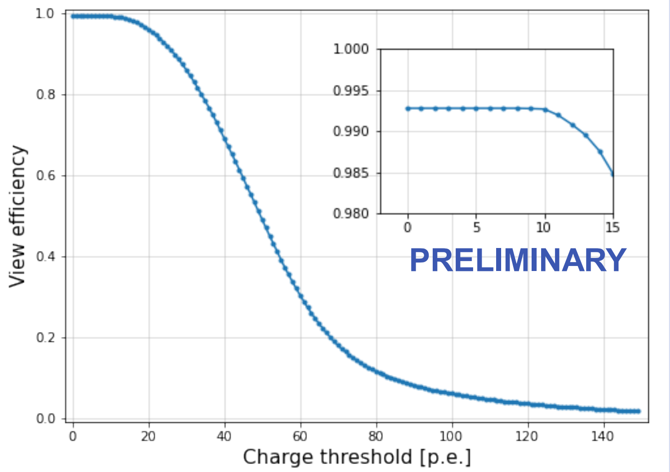




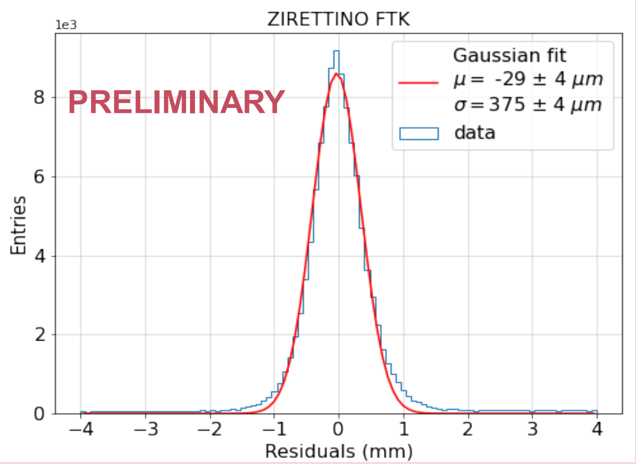
Fiber tracker performance

- Several modules assembled
- Each view: two staggered round scintillating fiber ribbons
  - Kuraray/Saint-Gobain fibers
  - 500 μm and 750 μm diameter
- SiPM array readout: Hamamatsu S13552, 128 channels
  - 250 μm strip pitch
  - “OR4 readout”
- Readout with Weeroc/Omega PETIROC2A ASICs installed on a custom Front End Board
- Measurements performed in a beam test campaign at the CERN PS and SPS

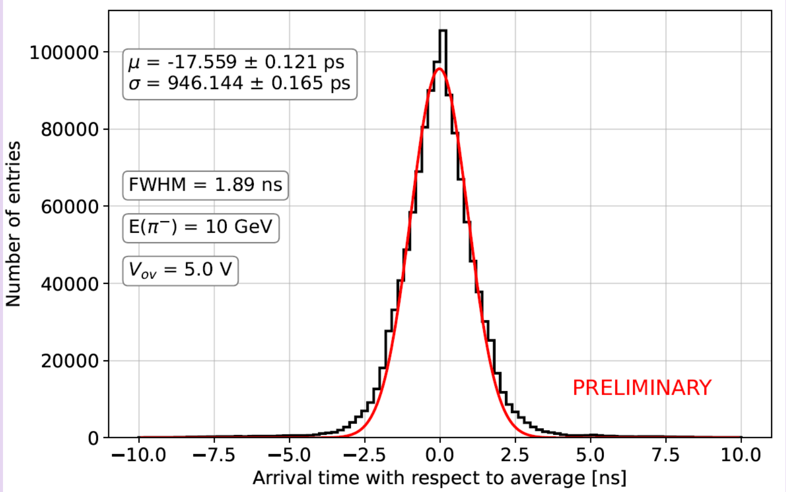
Efficiency



Space resolution



Timing



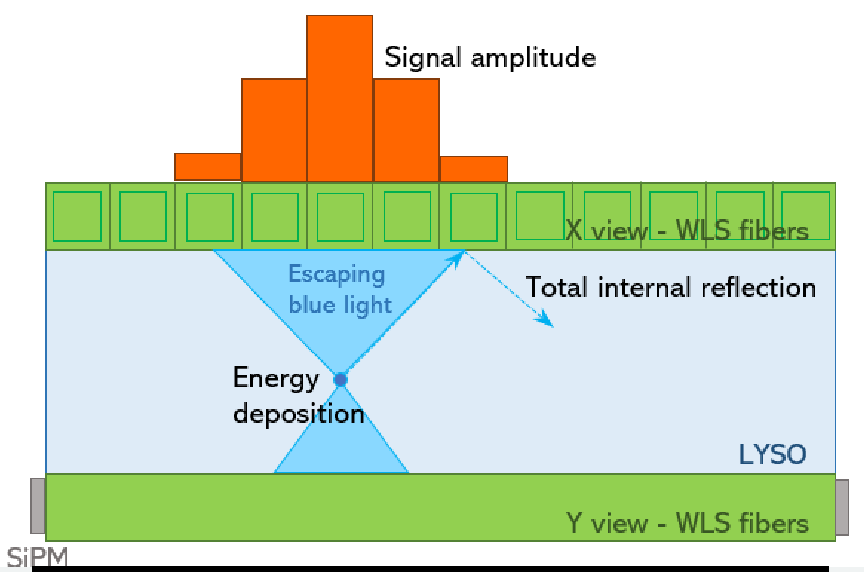
- FTK prototype with PETIROC-FEB readout
- PETIROC: single channel TDC with 40 ps time resolution
- Timing measurements with 10 GeV/c pion beam at CERN PS:
- Arrival time FWHM 1.89 ns

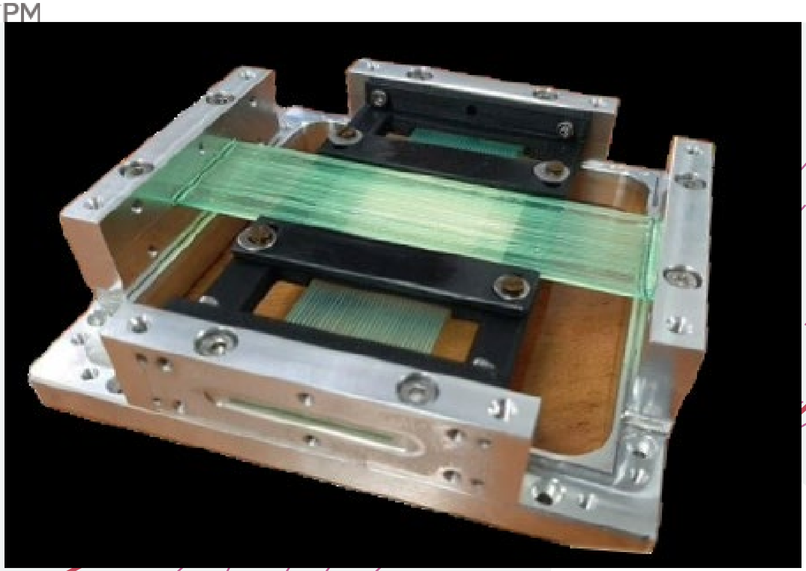
Imaging calorimeter with a scintillator crystal and WLS fibers

- **Scientific goal:** detection of sub-GeV gamma rays
  - Activities carried out in the framework of the APT experiment
- **Principle of operation:**
  - Ionizing particles and absorbed gamma rays release an energy deposit (ΔE) into the crystal (LYSO or CsI)
  - Scintillation blue light is isotopically produced in the crystal
  - WLS fibers within the acceptance cone collect scintillation photons, shift wavelength towards green and transport them to SiPMs:

$$N_{pe} = LY \times \Delta E \times f_T \times \varepsilon \times PDE$$

  - Crossed fiber planes allow to evaluate (x,y) into the crystal
- **Detector module prototype:**
  - 3 mm thick LYSO crystal coupled with two crossed planes of 1mm side Kuraray Y-11 square WLS fibers, on its top and bottom faces
  - Fibers read-out by Hamamatsu 128-channels SiPM arrays S13552 at their ends
- **Measurements performed with radioactive sources in our lab and in a beam test campaign at the CERN-PS and SPS**

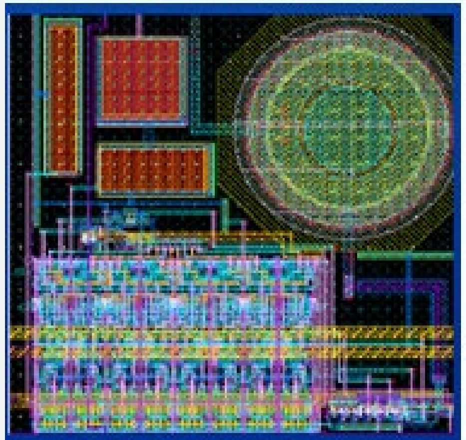


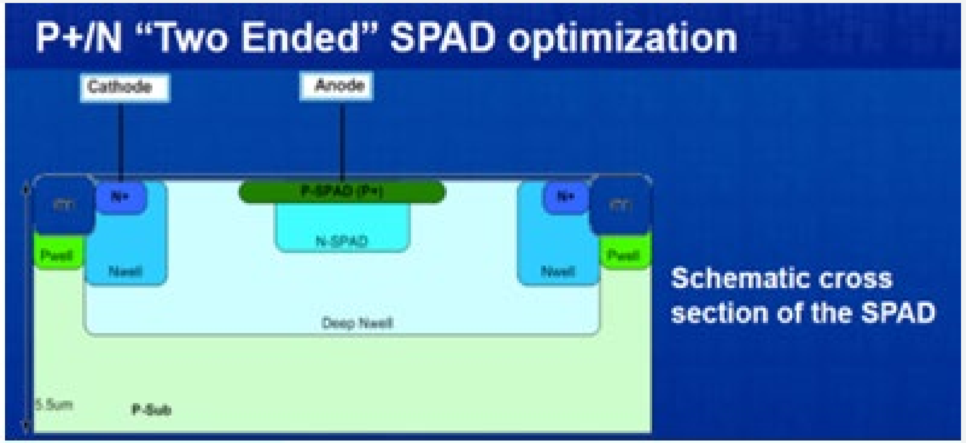


Backup

Tower Jazz (TOWER Semiconductor) SPAD technology

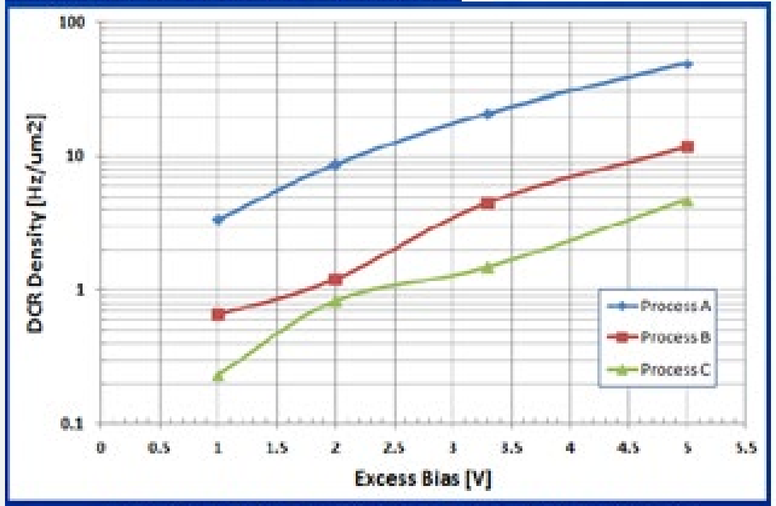
- Technology: 180 nm CMOS (1.8V/3.3V or 1.8V/ 5.0V) and CIS state of the art pixels
- Breakdown voltages: 12 V, 14 V and 20 V
- PDE peak around 450 nm



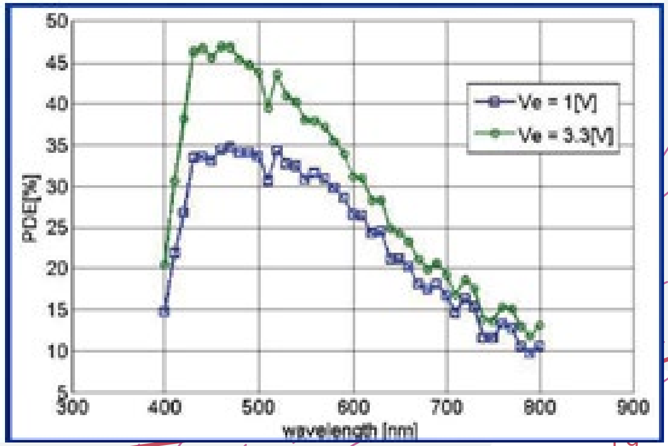


P+/N "Two Ended" SPAD optimization

Schematic cross section of the SPAD



Measured DCR density vs. Excess bias at room temperature

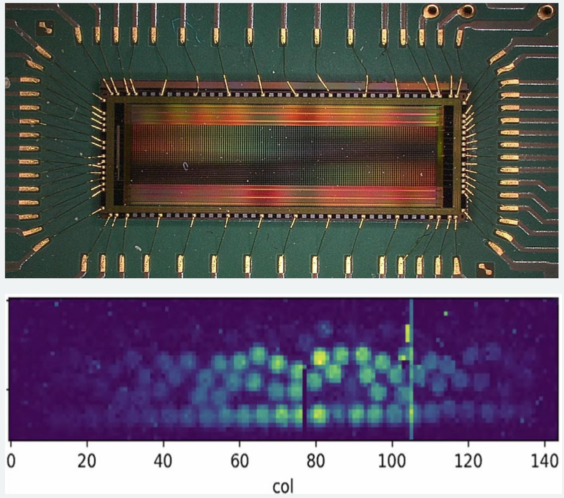


Dr. Amos Fenigstein, TowerJazz February, 2018
https://imagesensors.org/wp-content/uploads/2019/05/Amos_Fenigstein.pdf

CMOS SPAD for the readout of scintillating fibers

- Detection of light from optical fibers for particle fiber trackers
- SPAD pitches of 42/56 µm to accommodate large or small fibers
  - 350 nm CMOS technology with 4 metal layers (IMS in Duisburg, Germany)
- Each SPAD can be associated to a group by enabling a programmable switches
  - The total current is $N \times I_0$ when N (enabled) SPADs have fired and I_0 the unit current

Sensitive area: $8064 \times 1792\ \mu m^2$
Pixel size: 56 x 56 μm^2



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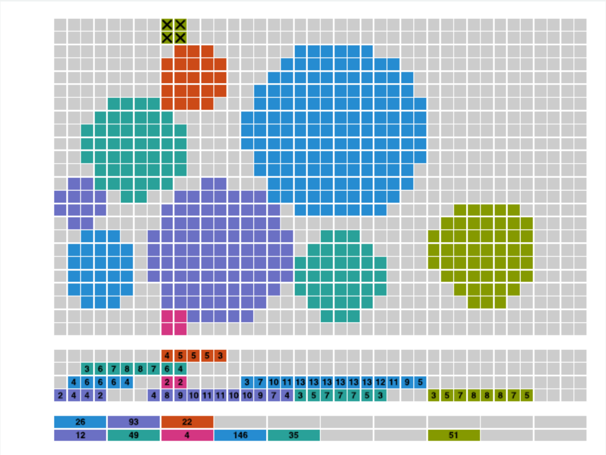
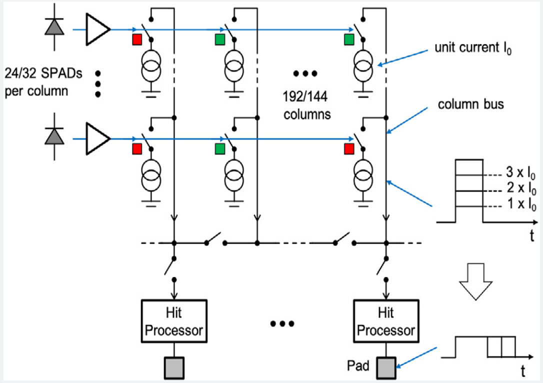
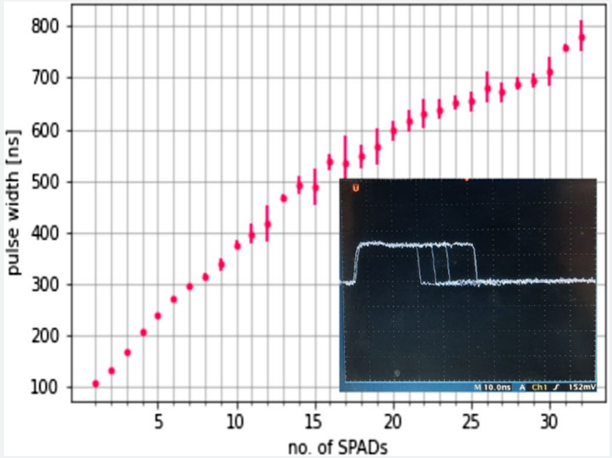
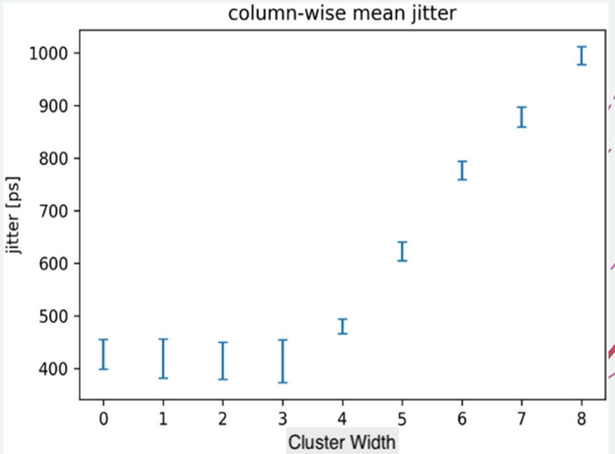


Example of SPAD groupings and limitation of the architecture



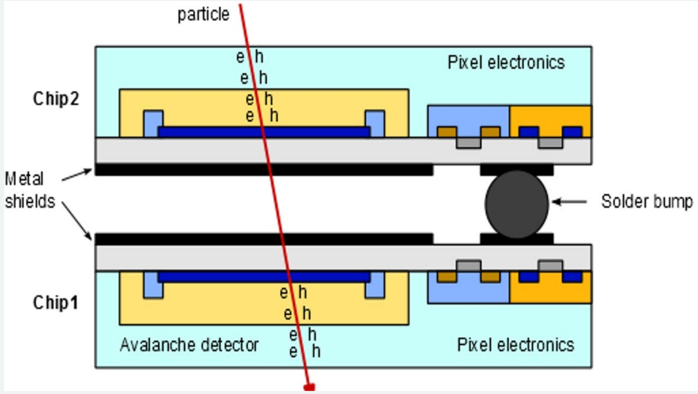
Principle of SPAD counting in a column group.

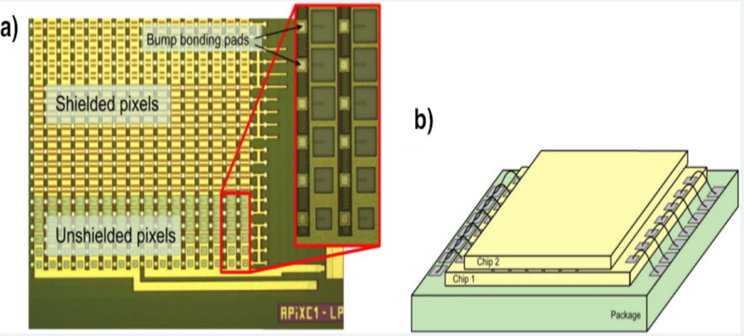


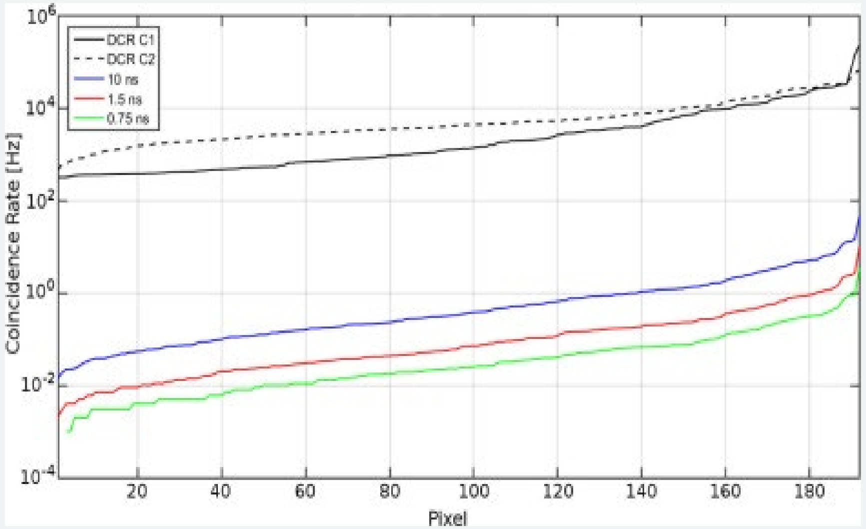


Avalanche Pixel Sensor for tracking applications

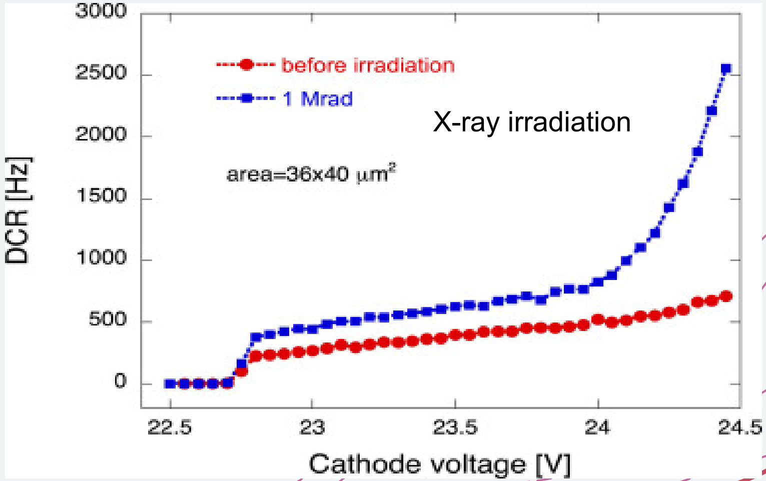
- A position-sensitive detector based on the vertical integration of pairs of aligned pixels operating in Geiger-mode regime and designed for charged particle detection
  - This device exploits the coincidence between two simultaneous avalanche events to discriminate between particle-triggered detections and dark counts
  - A proof-of-principle prototype was designed and fabricated in a 150 nm CMOS process and vertically integrated through bump bonding







Cumulative DCR is plotted as a function of the number of pixels included in the sum, as measured separately in each chip and in coincidence



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https://doi.org/10.3389/fphy.2020.607319