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APIX2: a Pixelated avalanche Sensor for charged particle detection.

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“Trento” Workshop on Advanced Silicon Radiation Detector
Munich, Germany, February 19-22, 2018

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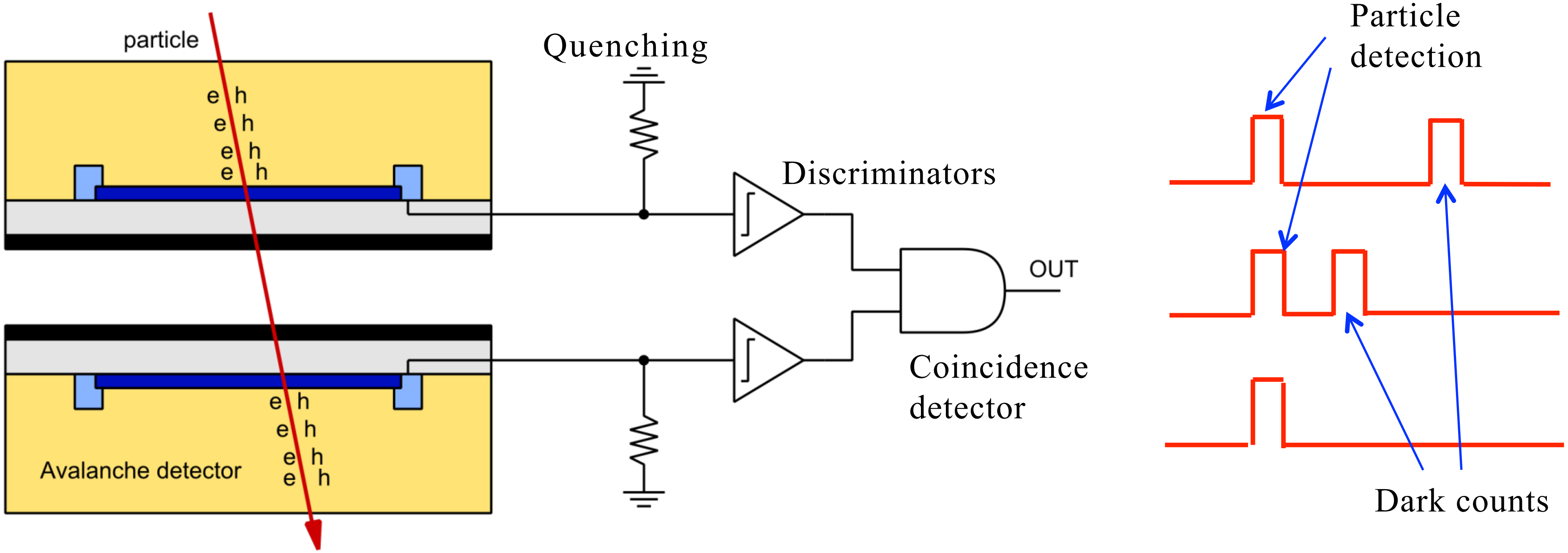
Outline

- Sensor concept and architecture
- Sensor 1st prototype characterization
- Beam Test of 1st prototype at CERN-sps
- 2nd prototype layout
- Possible applications
- Summary and perspectives

APIX particle detector concept

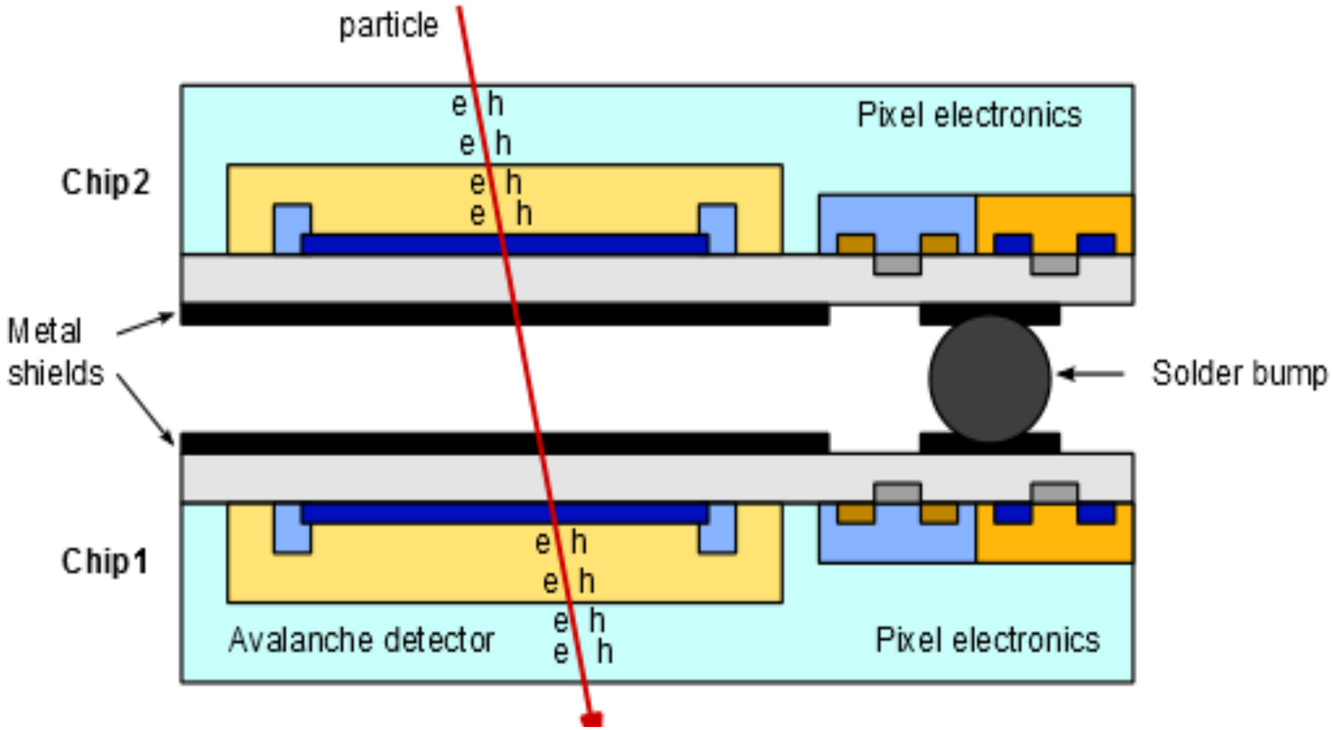
Basic idea:
Use of two Geiger-mode avalanche detectors (SPADs) in coincidence to detect particles

- Digital read-out
- Reduced Dark Count Rate: $DCR = DCR_1 * DCR_2 * 2\Delta T$
- Timing performances
- Low power consumption
- Low material budget



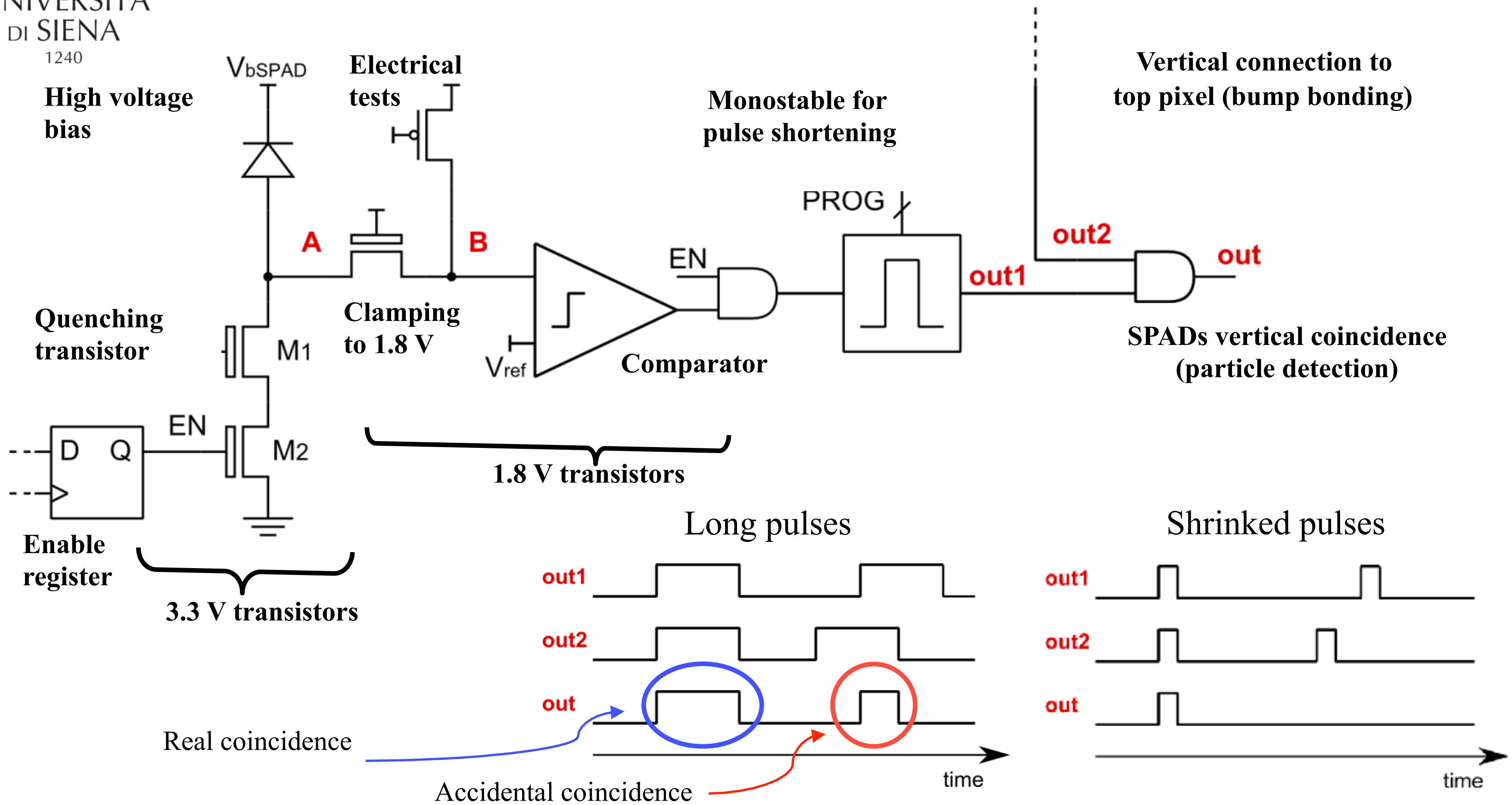
*N. D'Ascenzo et al., JINST 2014

APIX demonstrator: pixel cross-section



- ➔ CMOS process allow integrated electronics (not feasible in SiPM integrated process)
- ➔ Metal shielding to avoid optical cross-talk
- ➔ Vertical interconnection by **bump bonding**

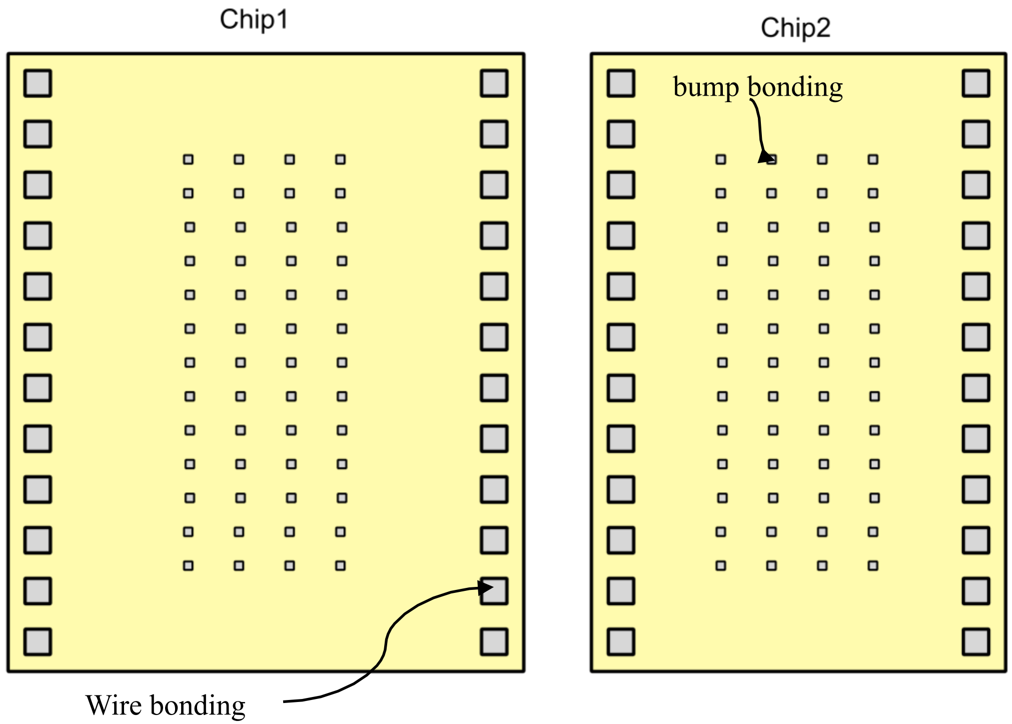
APIX pixel: pulse shortening

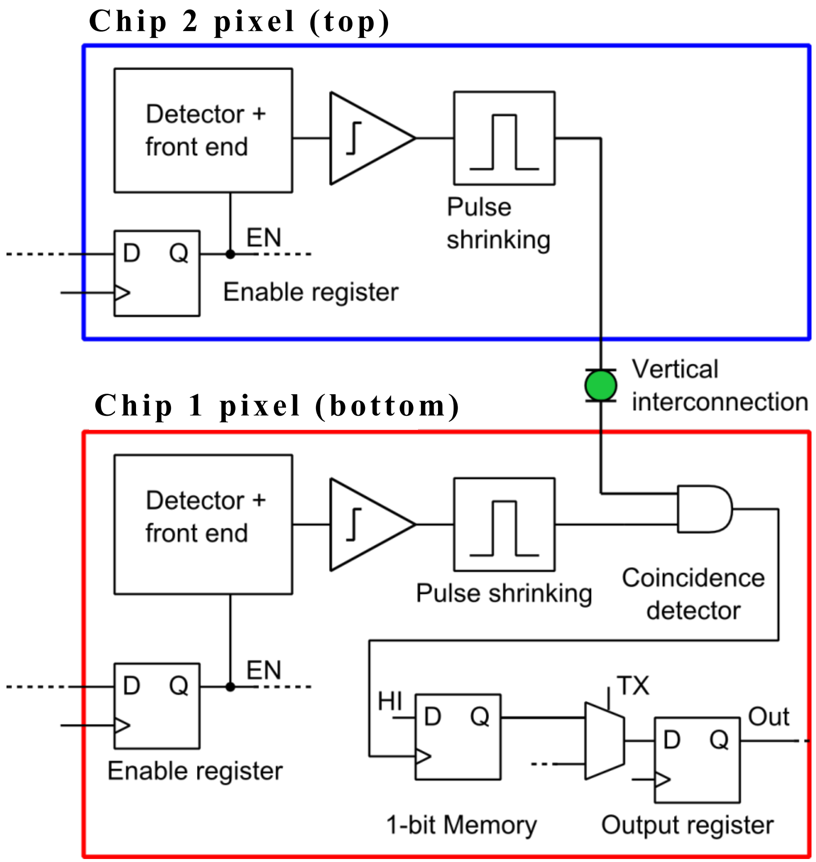


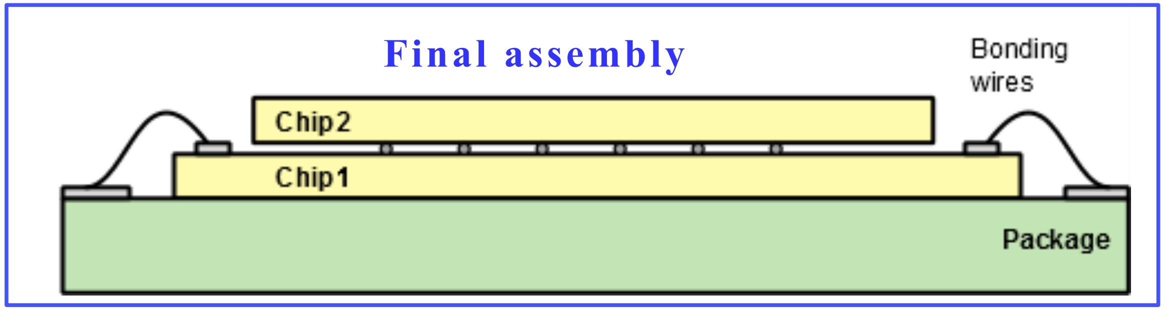
- Digital circuitry at 1.8V: compact, fast, low-power
- Individual pixel enable/disable: M2 disables recharge, AND gate disables output pulses
- Pulse shortening: reduces the rate of accidental coincidence
- Programmable pulse width: **750 ps, 1.5 ns, 10 ns**

APIX top and bottom pixels connection

Chips layout with bonding pads



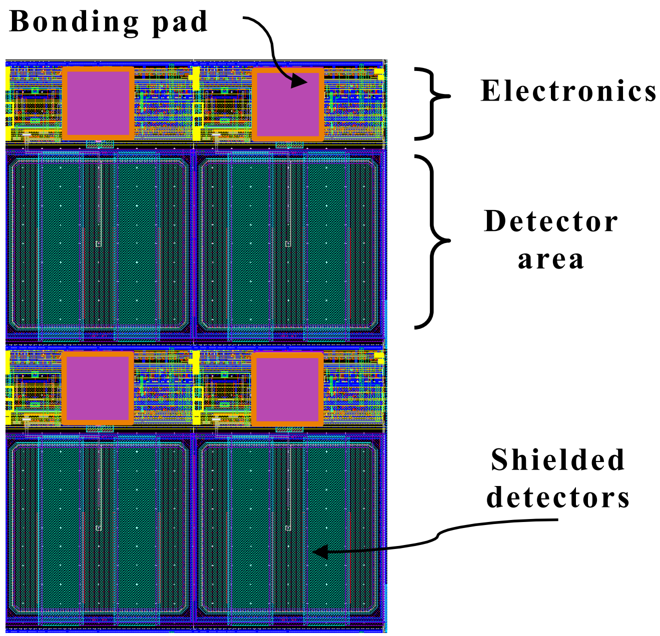




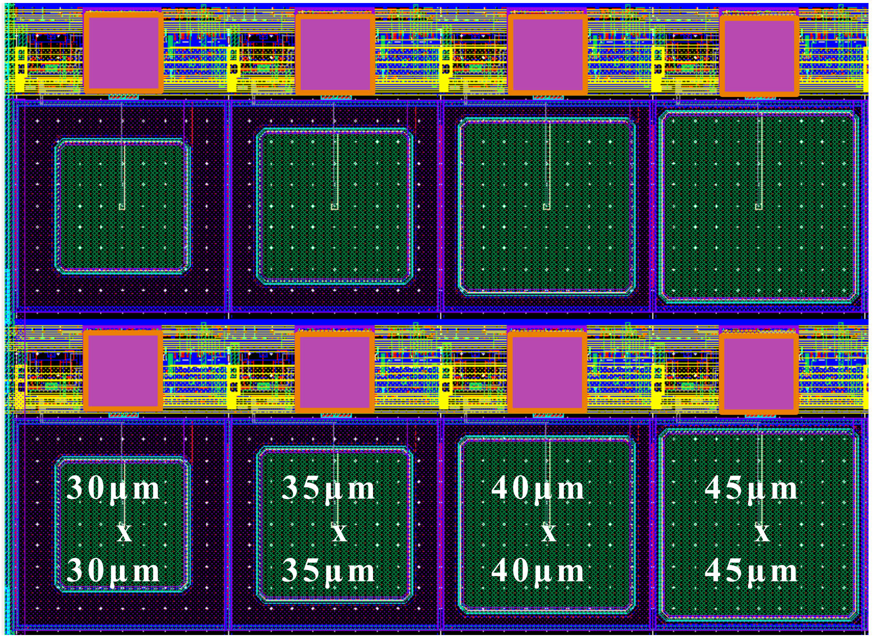
Vertical integration via Bump-bonding (IZM)

APIX pixel array

- Sensor array of 16 rows x 48 SPADs
- Pixel size: 50 μm x 75 μm
- Total sensor dimensions: 1.2 x 2.4 mm^2



Unshielded pixels with different active area



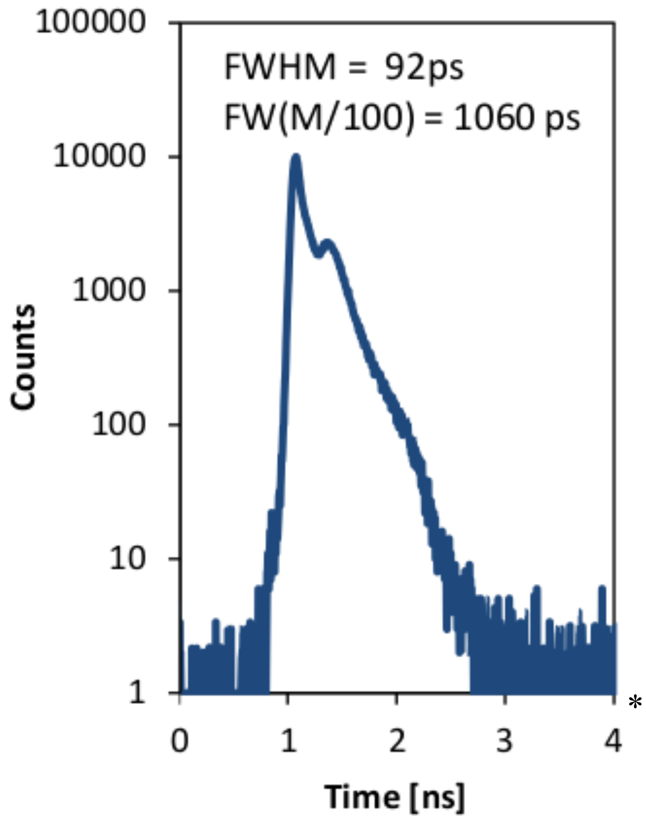
Array partitioning:

- Two SPAD types: p+/nwell and p-well/ n-iso
- Different SPAD active areas: 30 – 35 – 40 – 45 micron side
- Some unshielded structures for testing with light
- Coincidence between SPAD with the same size and with different sizes

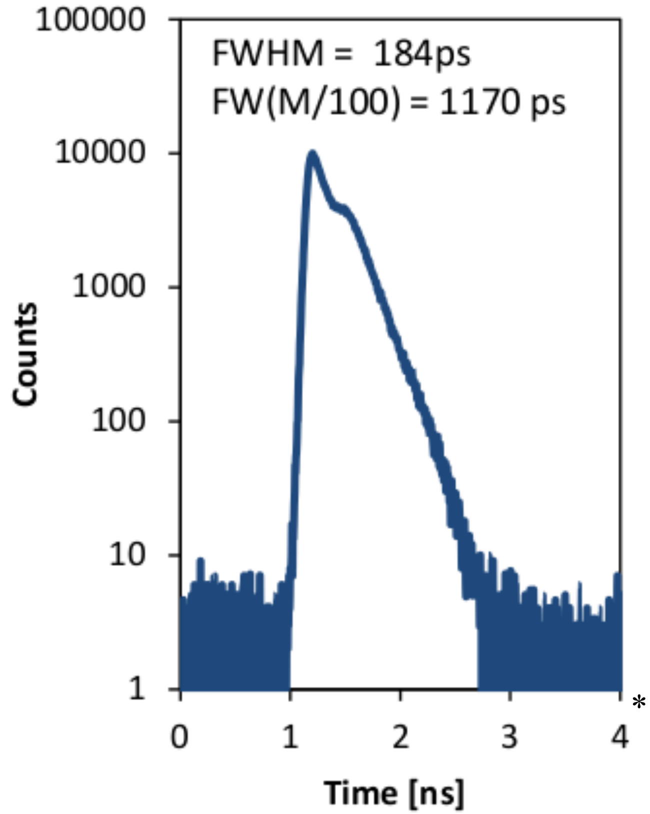
SPADs single-photon timing resolution

Measured on 10 µm devices, with blue laser (470 nm), 70 ps FWHM

Type 1: **60 ps FWHM**



Type 2: **170 ps FWHM**



Same types of SPADs used in APIX pixels

*L. Pancheri, D. Stoppa, "Low-noise Single Photon Avalanche Diodes in 0.15 µm CMOS Technology" Proceedings of IEEE ESSDERC.

Breakdown voltage characterization

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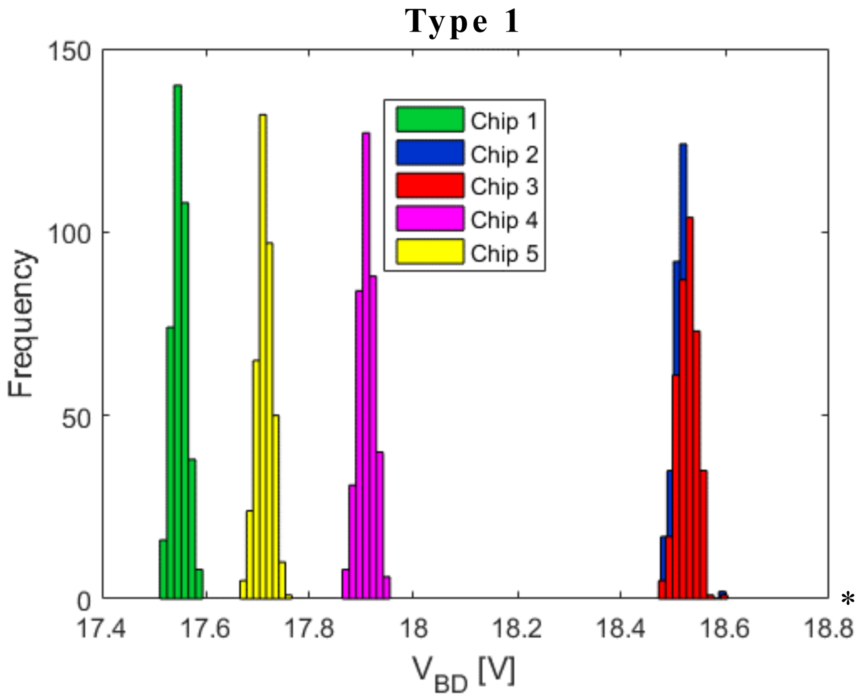
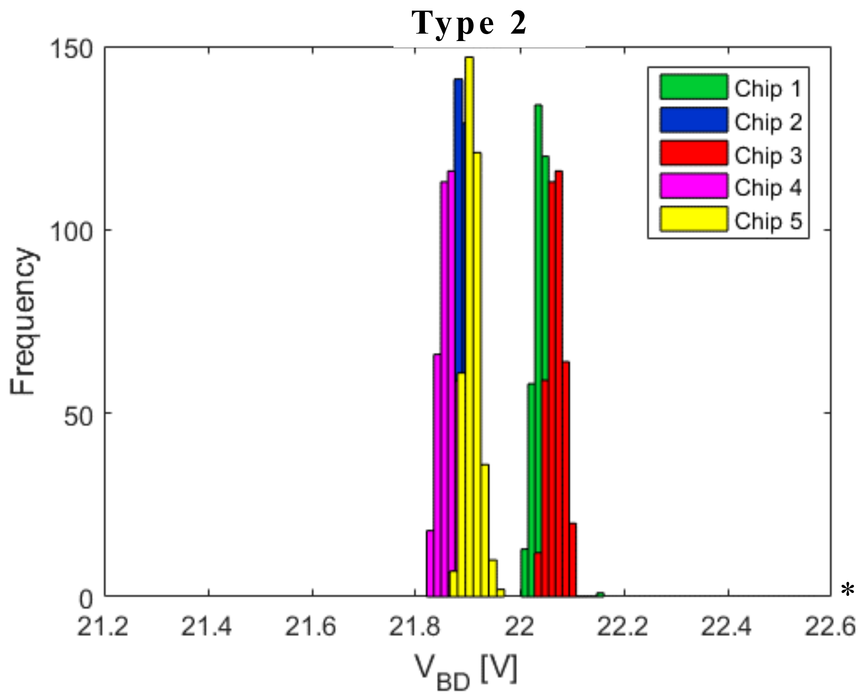
Measurements on 5 different chips
Two SPAD types and 196 pixels per chip



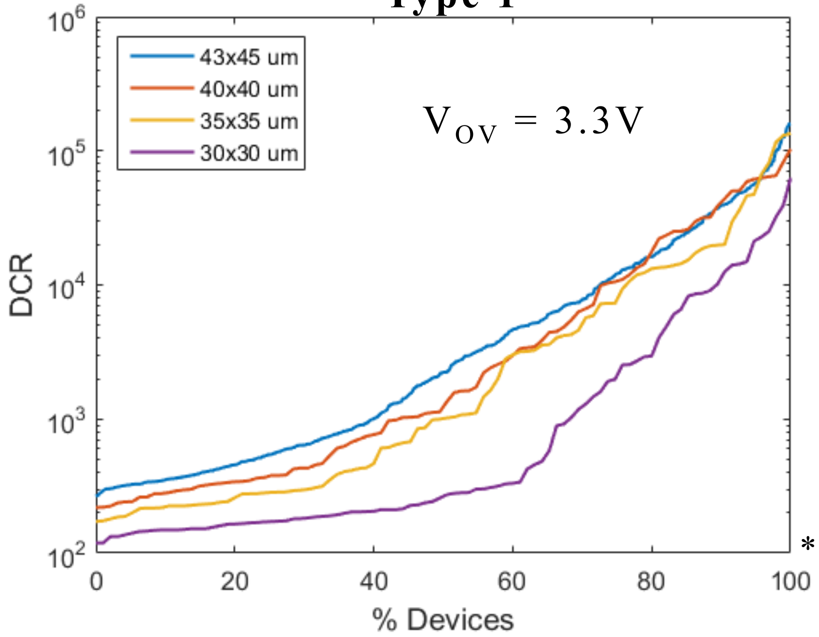


- Very good SPADs uniformity inside the same chip (**σ < 20 mV**)
- Large difference (1V) between different chips for type 1

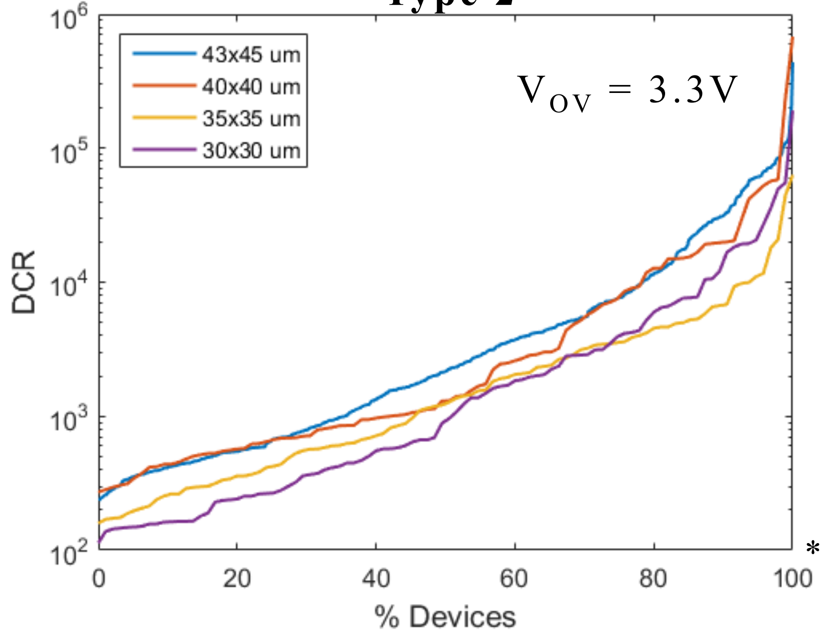
*L. Pancheri et al. "First prototypes of two-tier avalanche pixel sensors for particle detection", Nuclear Instruments & Methods in Physics Research A (2016).

Single chip Dark Count Rate

Type 1



Type 2



- Cumulative distributions, combined measurements on 3 chips
- 600 devices for largest size, 72 for smaller ones
- Median DCR = 2.2 kHz for largest cell size of both types

*courtesy of L. Pancheri

APIX final assembly Dark Count Rate

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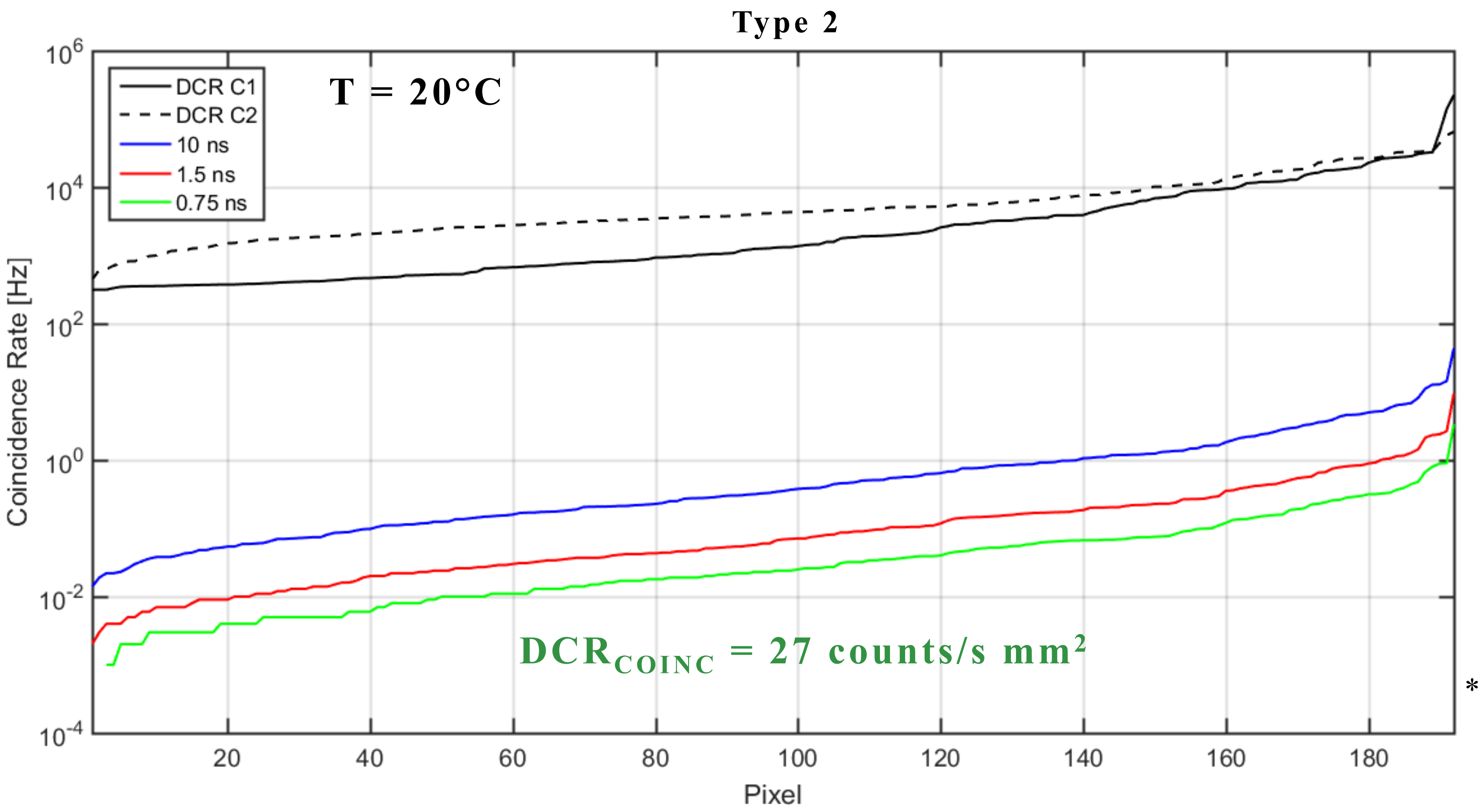
Dark Count Rate for different coincidence time ΔT: 10 ns, 1.5 ns, 0.75 ns



$$DCR_{COINC} = DCR_1 \times DCR_2 \times 2\Delta T$$

*courtesy of L. Pancheri

Preliminary Radiation Test with neutrons

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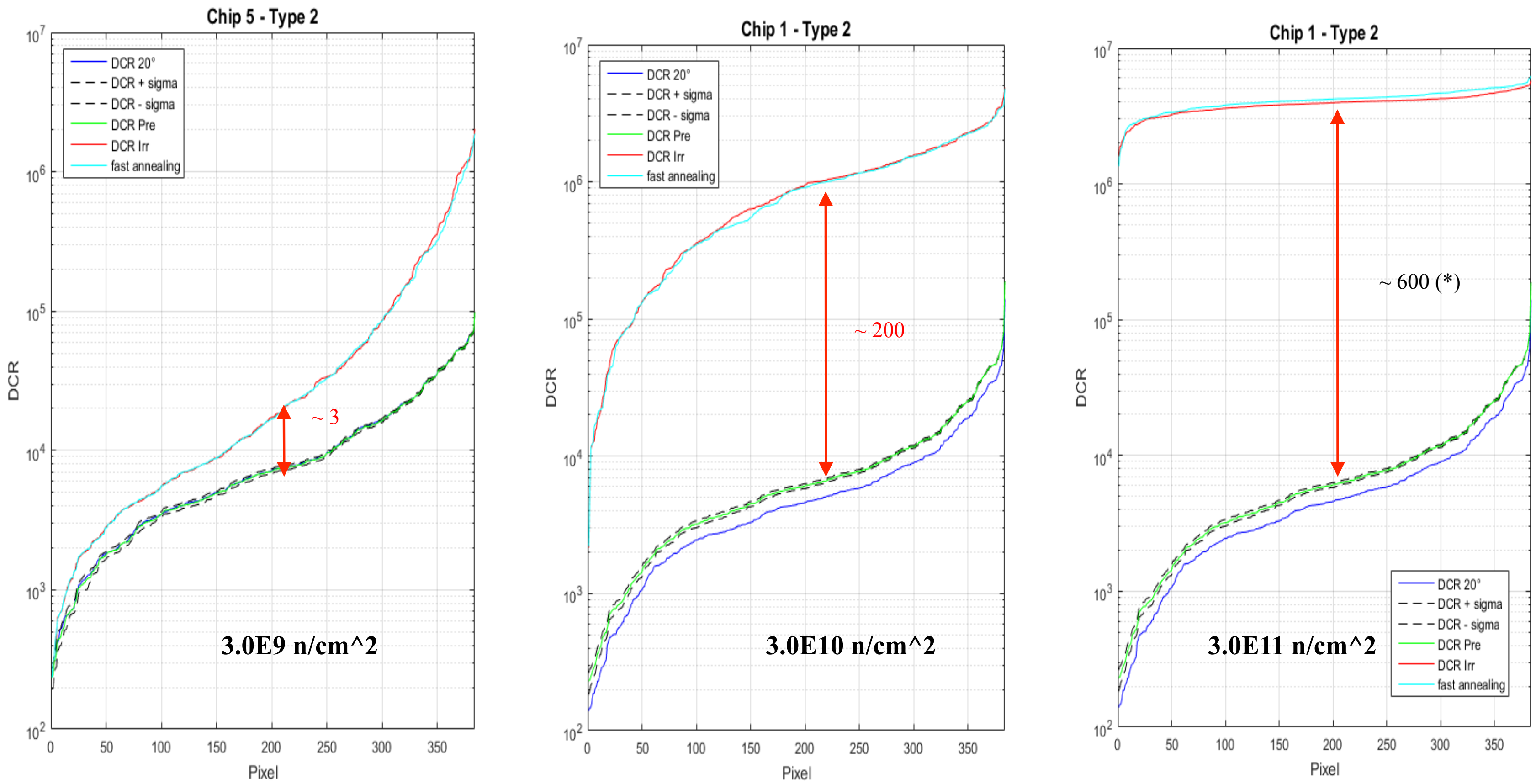
- Irradiation at Legnaro National Laboratory (5 MeV proton on Be target) in June 2017
- neutron spectrum with energy from 0.5 to 3 MeV
- max fluence: 3 x 10^{11} neq /cm^2
- annealing at room temperature

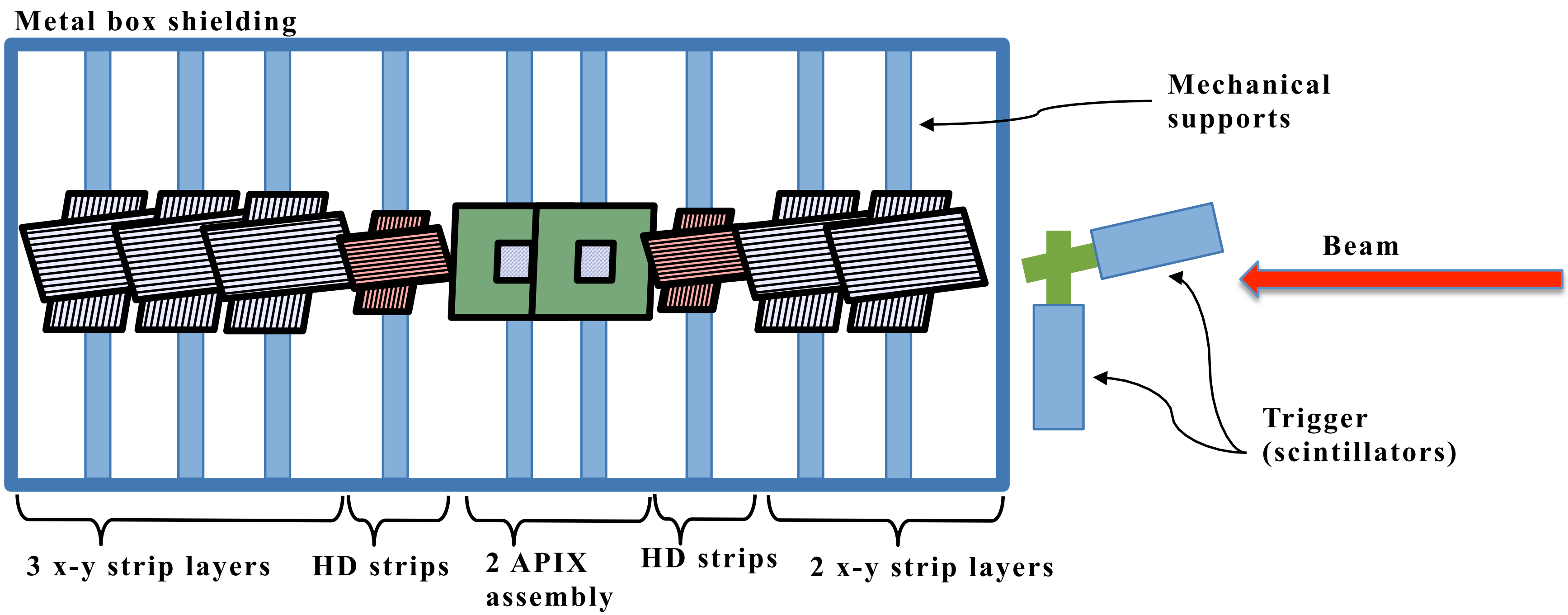
DCR distribution for different fluences before and after beam exposure



(*) Saturation for high DCR due to dead time (> 100ns during rad. test)

Beam Test layout

Scheme of Experimental apparatus on beam line:



- Test took place at CERN SPS (H4 beam line) on September 2016
- Positrons and π+ beams at 50, 100, 150, 200 and 300 GeV
- 2 APIX demonstrator and 14 silicon strip detectors (for tracking)
- 5 X-Y strip layers with 730 μm pitch + 2 X-Y HD layers with 80 μm pitch
- Asynchronous APIX reset at 1 MHz.
- Off-Spill random triggers to measure APIX DCR and strip pedestal

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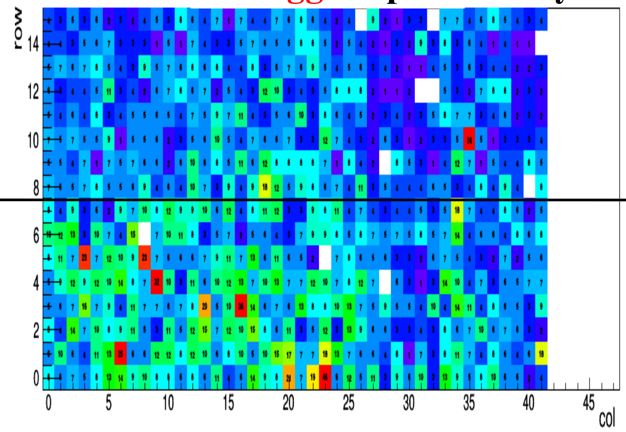
APIX detects test beam particles

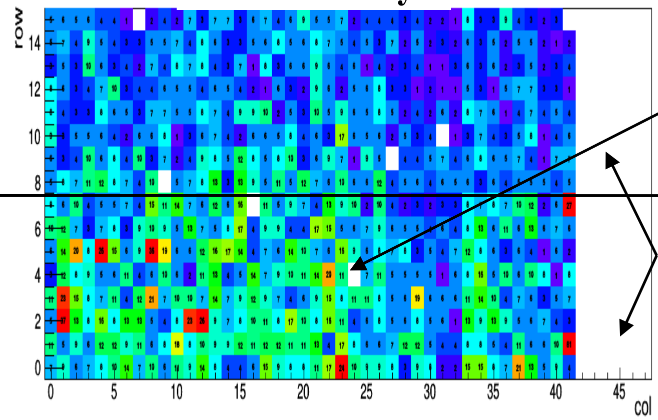
Type 2
(Vov = 1 V)

Type 1
(Vov = 2 V)

APIX **beam trigger** upstream layer



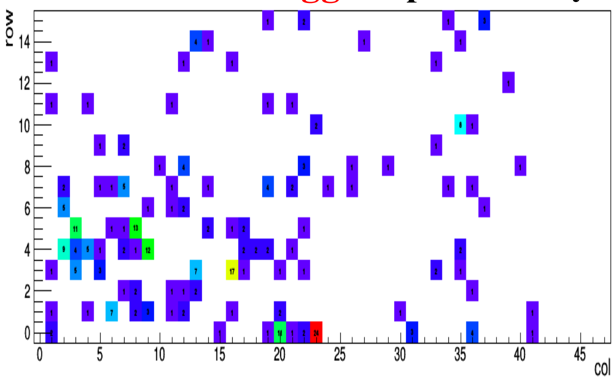
downstream layer



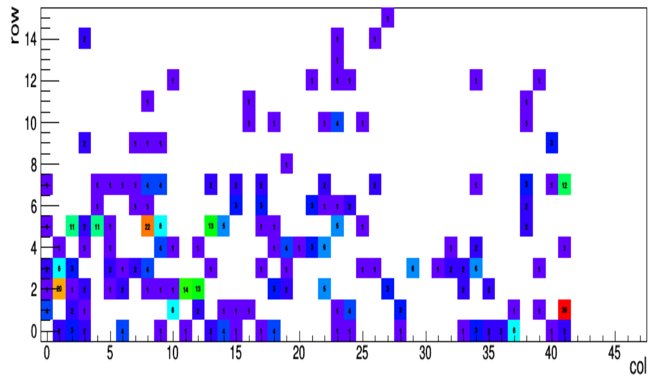
noisy pixel
disabled (white)

pixels disabled in the
light unshielded area

APIX **random trigger** upstream layer

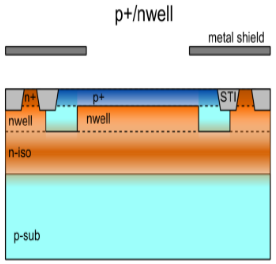


downstream layer



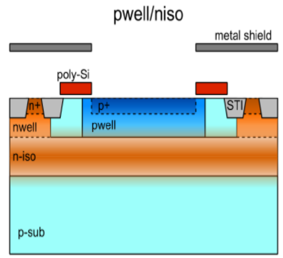
Type 1:

- Shallow step junction
- Active thickness ~ 1µm



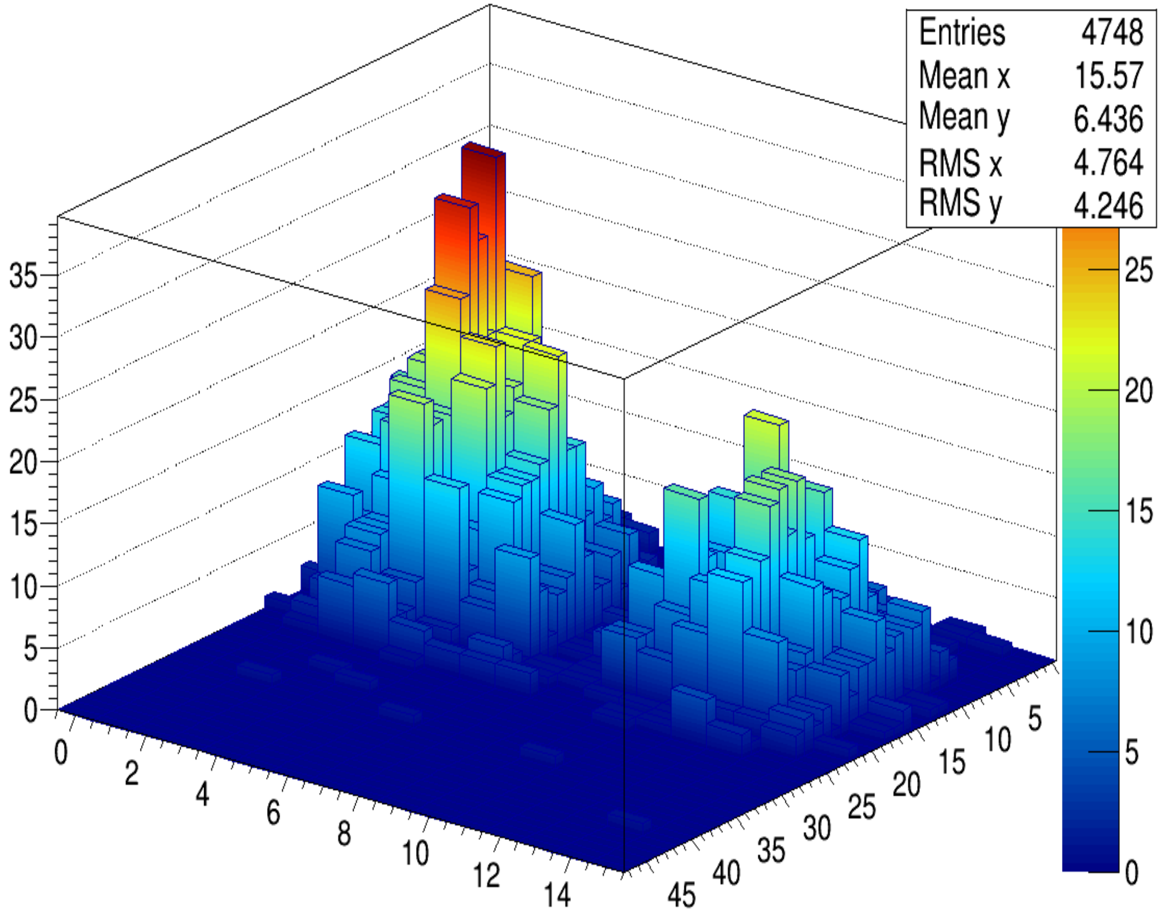
Type2:

- Deep graded junction
- Active thickness ~ 1.5µm



APIX2 imaging

Example of two Regions-Of-Interest separated by ~ 100 um

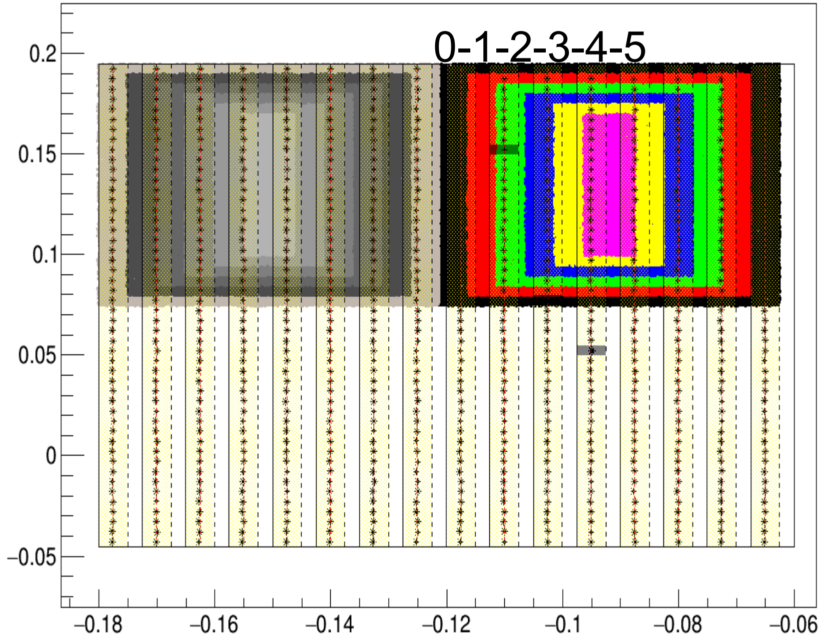


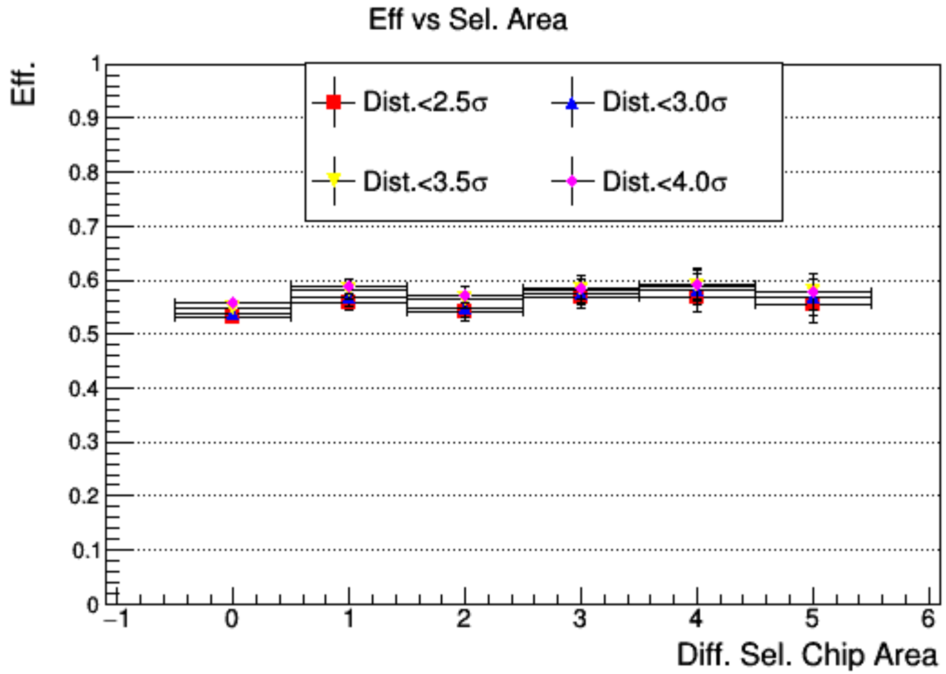
ROI selected via tracking

Efficiency for particle detection

Despite some difficulties with tracking (noisy HD strip)
efficiency has been preliminarily measured in 6 different fiducial regions

Definition of 6 areas covered by the reconstructed track impact point (IP)



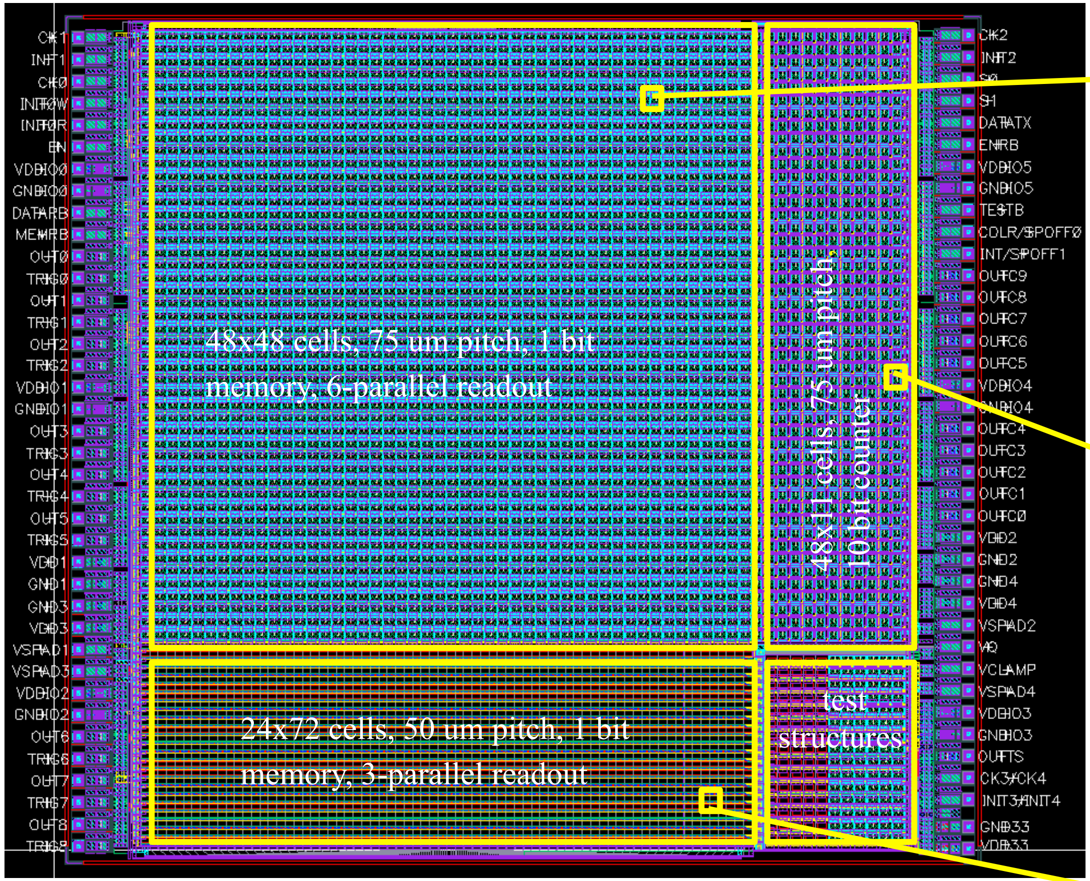


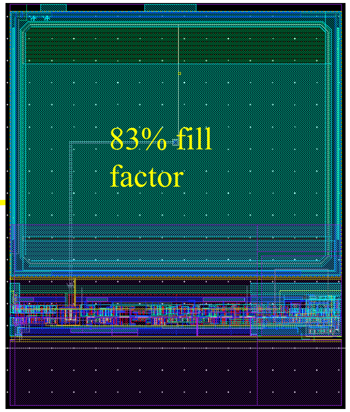
- Measured efficiency 56.2 ± 5 % (stat+sys)
- Expected (purely geometrical) FF = 52%
- => Effective detector efficiency close to 100% (only limited by FF)
- Higher statistics and improved beam tracking accuracy foreseen for next beam test

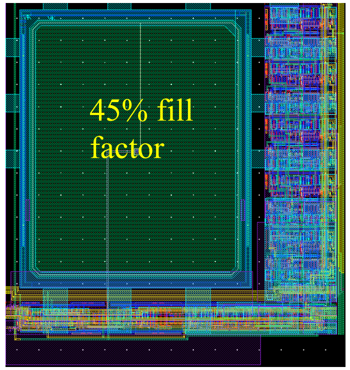
APIX pixel array (2nd prototype)

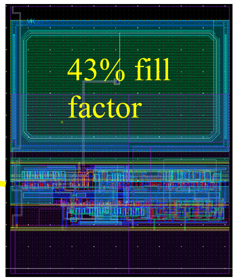
150 nm CMOS technology

- Fill Factor expected improvement: 52% → 83%









- "1st layer" chip is 5 mm x 5.4 mm
- "2nd layer" chip is 5 mm x 6 mm

Possible applications of APIX sensors

APIX strengths:

- **low material budget**
- low power
- no cooling
- **good timing properties** (e.g.: time of flight with ~**100 ps resolution)**
- insensitivity to gamma radiation background
- narrow band acceptance (directionality)
- portability
- easy to configure to the specific application
- operation in real time: ß-time resolved studies (very high frame rate)

➢ **Tracking + Minivertexing:** use timing to disentangle event pileup (4D detector)

- ❑ however: difficult to operate with fluences above ~ 10^{10} n/cm^2
- ❑ radiation tolerant **for space-borne applications** and intermediate radiation environment
  (e.g.: - wearable mini-radiation sensor for astronauts (fly-eye mosaic of APIX sensors
  - minivertexing for ILC-like colliders)

➢ **APPLICATIONS in NUCLEAR MEDECINE**:

- ❑ imaging probe (β - markers) for radio-guided surgery, prostate cancer screening... etc)
- ❑ beam profile monitoring in hadron therapy

Example of application (nuclear medicine)

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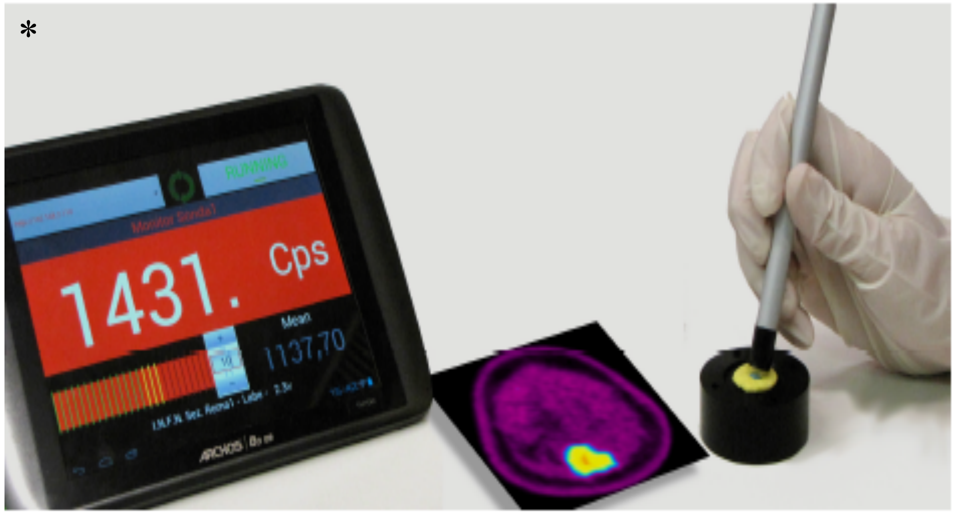
Intra-operative β- Probe for Radio-Guided Surgery

State-of-the-art:

- scintillator based + PMT (or readout by SiPM)
- counts per second
- **no imaging**

APIX β- Probe under development :

- imaging probe + counts per second
- insensitivity to gamma radiation background
- low power
- no cooling



* A. Russomando et al. “An Intraoperative β − Detecting Probe For Radio-Guided Surgery in Tumour Resection” arXiv:1511.02059v1 [physics.med-ph] 6 Nov 2015

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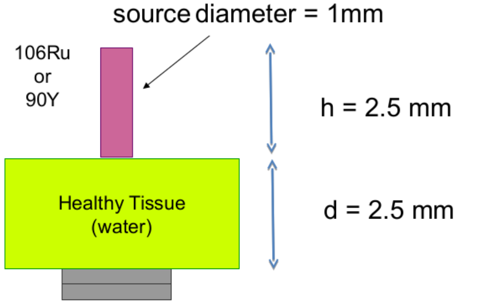
Simulate APIX detection of hidden source

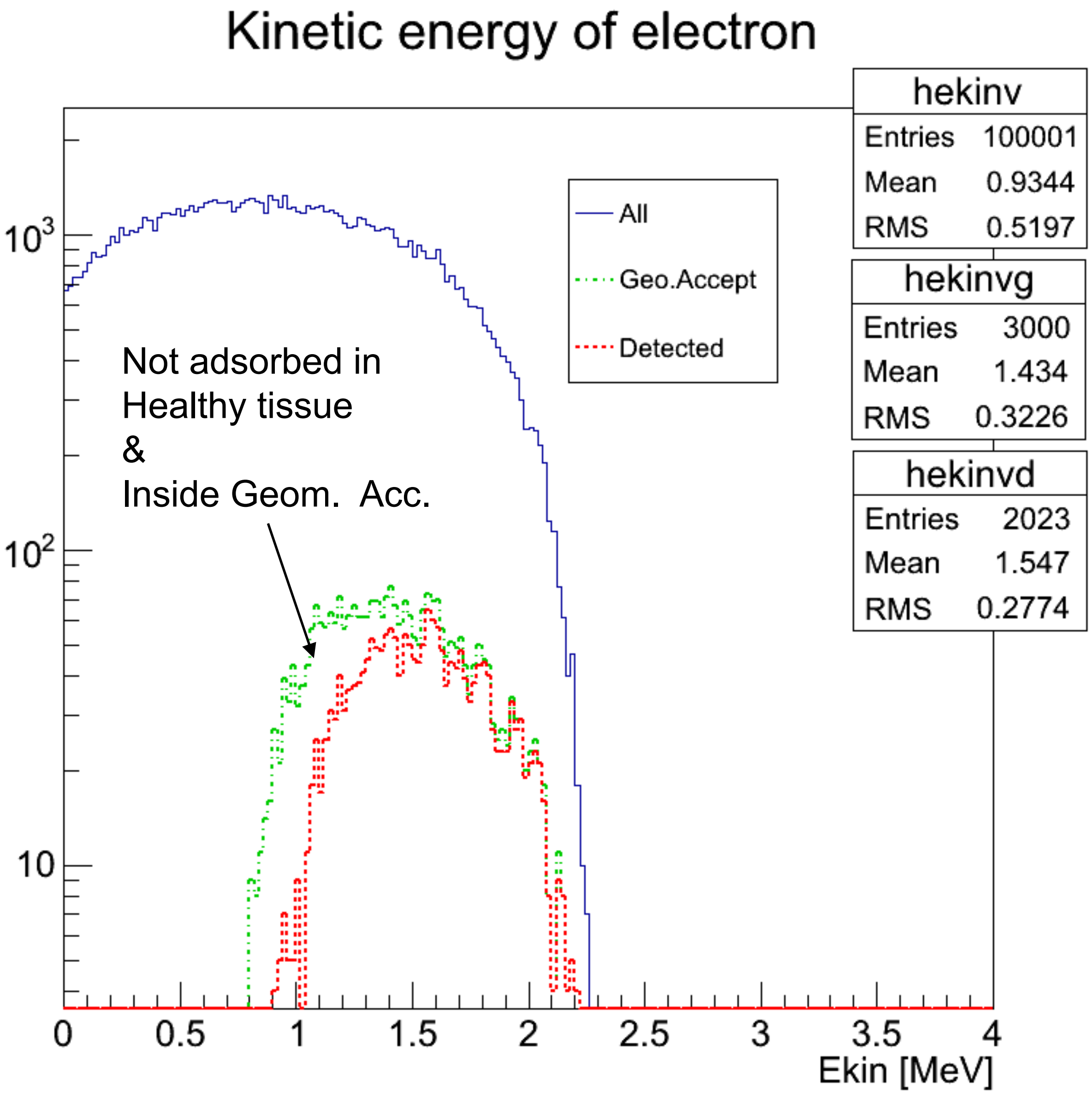
GEANT4 simulations:

- two-tiers
- β- source: 90Y



Dimension of APIX (each tier) :
5mm x 5mm x 0.28mm

Detected / Geom.Accept = 67.61%



Triple vertical pixels coincidence

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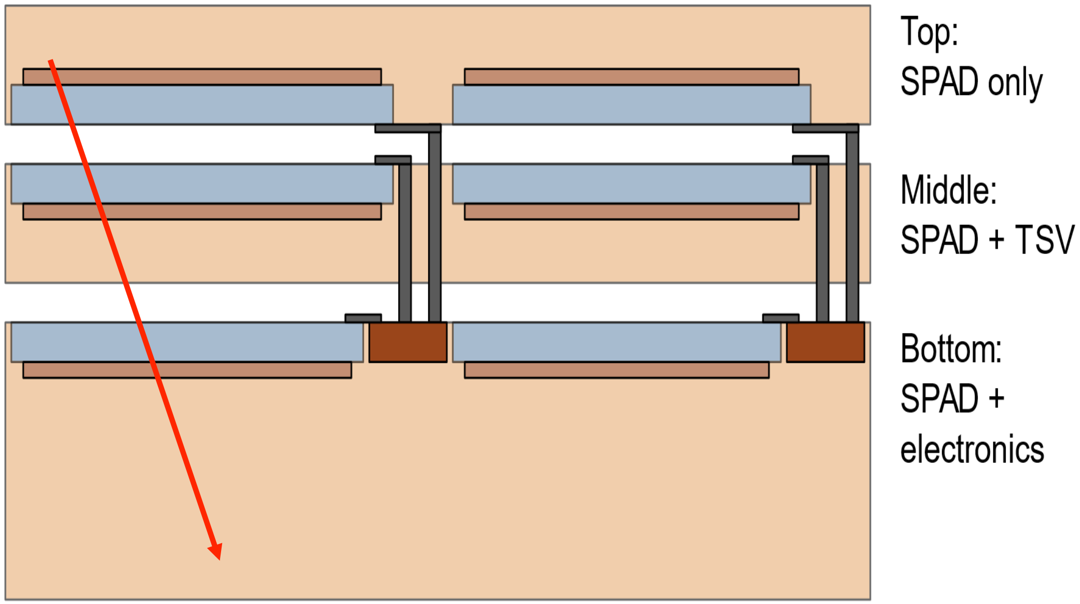
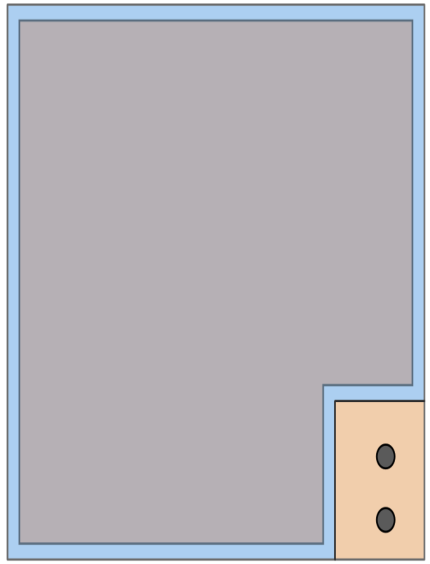
Possible advantage of triple coincidence

3-Tiers detector concept:



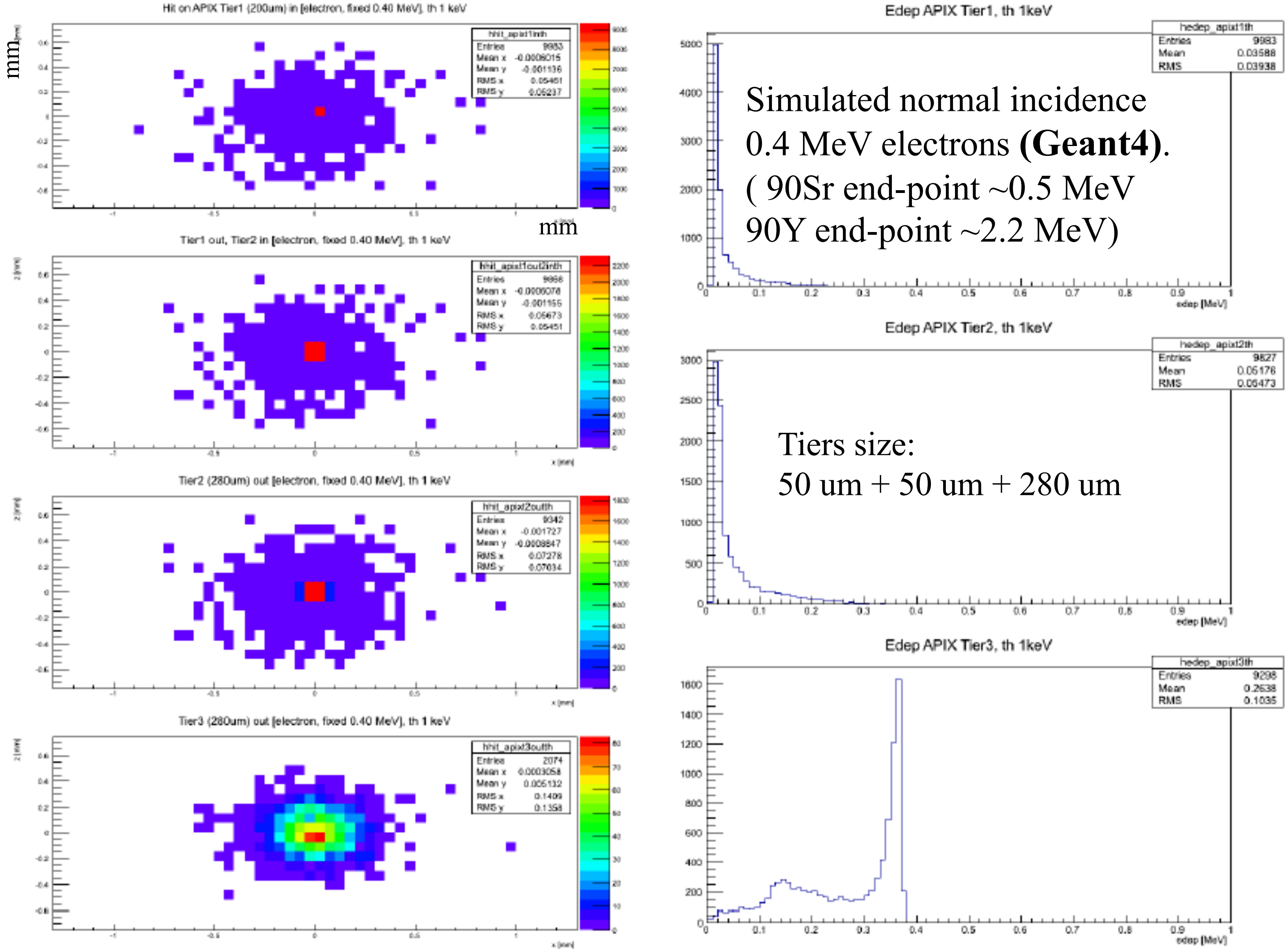


Pixel layout

TRIPLE/DOUBLE coincidence ratio **estimate** =

$$3*DCR^{3}*\Delta t^{2} / 2*DCR^{2}*\Delta t = 1.5*DCR*\Delta t \sim 10^{-5}$$

0.4 MeV electron on 3 tiers prototype



Simulated normal incidence
0.4 MeV electrons **(Geant4)**.
(90Sr end-point ~0.5 MeV
90Y end-point ~2.2 MeV)

Tiers size:
50 um + 50 um + 280 um

3 Tiers estimated efficiency (Geant4)

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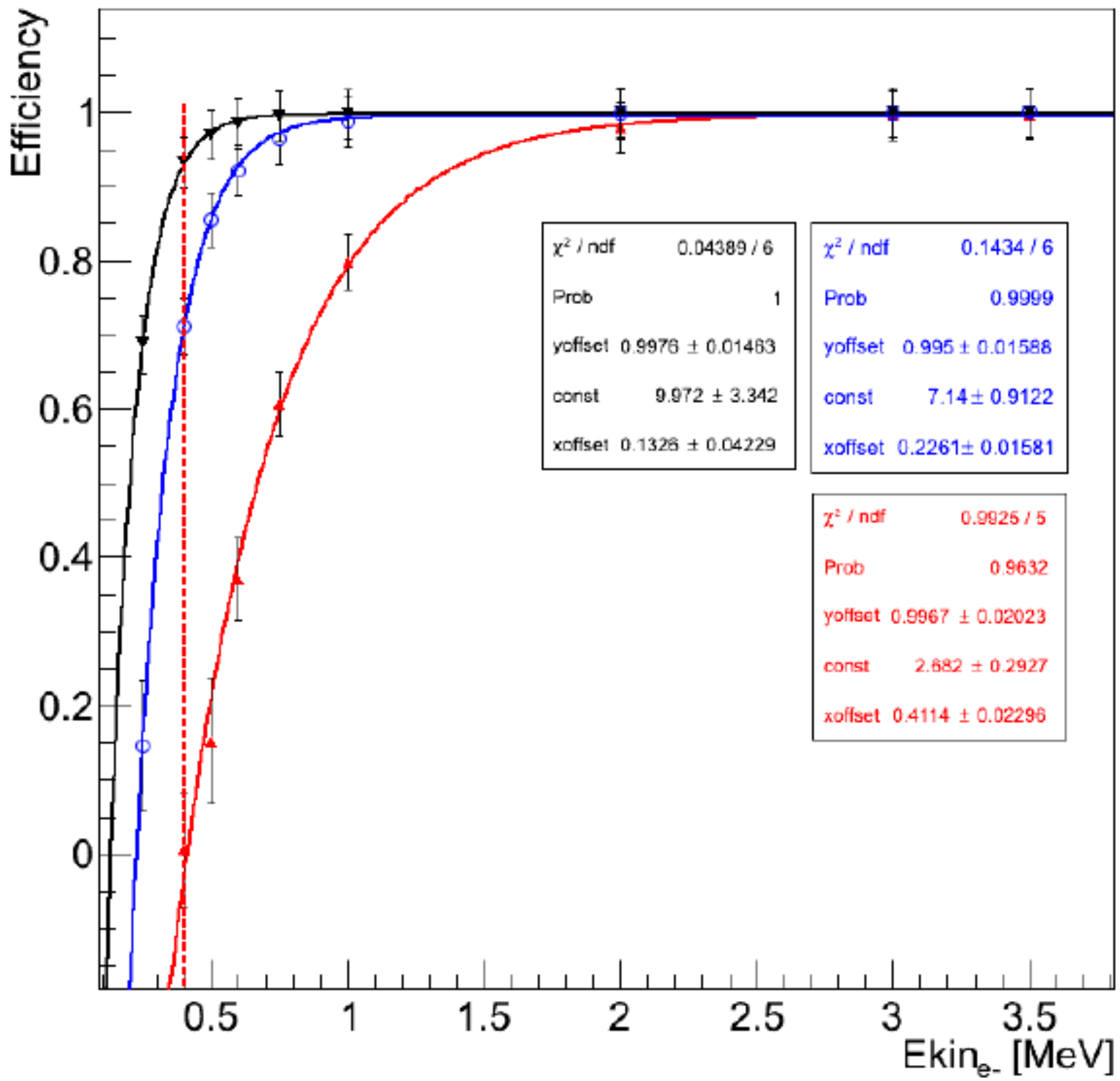
Efficiency vs total thickness of first two layers

- Total thickness (mm) of Tier1+Tier2:

50+50

100+100

280+280



Ongoing analysis and future plans

- Current prototype is fully operative
- First beam test of demonstrator successfully accomplished
- First evidence of high-efficient particle detection
- More accurate radiation hardness tests are still on-going
- A new test beam campaign has been planned to better characterize the actual prototype
- A new optimized prototype is under construction:
  - Larger array
  - Improved fill factor
  - Optimized timing
  - Optimized power consumption

Thanks for your attention!

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Bibliography:

[1] N. D'Ascenzo et al, "Silicon avalanche pixel sensor for high precision tracking", 2014 JINST 9 C03027, doi:10.1088/1748-0221/9/03/C03027.

[2] L. Pancheri et al., “First prototypes of two-tier avalanche pixel sensors for particle detection”, 14th Vienna Conference on Instrumentation, Vienna, Austria, 15 – 19 February 2016.

[3] A. Ficorella et al., "Crosstalk mapping in CMOS SPAD arrays," 2016 46th European Solid-State Devices Research Conference, ESSDERC, Lausanne, Switzerland, 12 – 15 September 2016.

[4] L. Pancheri et al., “Vertically-integrated CMOS Geiger-mode avalanche pixel sensors,” 14th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD16), Siena, Italy, 3 - 6 October 2016.

[5] L. Pancheri et al., Two-Tier Pixelated Avalanche Sensor for Particle Detection in 150nm CMOS, IEEE NSS/MIC, Strasbourg, France, 29 October – 5 November 2016.

[6] L. Pancheri et al., ”First Demonstration of a Two-Tier Pixelated Avalanche Sensor for Particle Detection”, Journal of the Electron Devices Society, Vol. 5 NO.5, September 2017.

[7] A. Ficorella et al., “Crosstalk Characterization of a Two-Tier Pixelated Avalanche Sensor for Charged Particle Detection”, IEEE Journal of Selected Topics in Quantum Electronics Vol. 24 Issue 2 (2017.09.21)

[8] A. Russomando et al., “An Intraoperative β − Detecting Probe For Radio-Guided Surgery in Tumour Resection”, arXiv:1511.02059v1 [physics.med-ph] 6 Nov 2015

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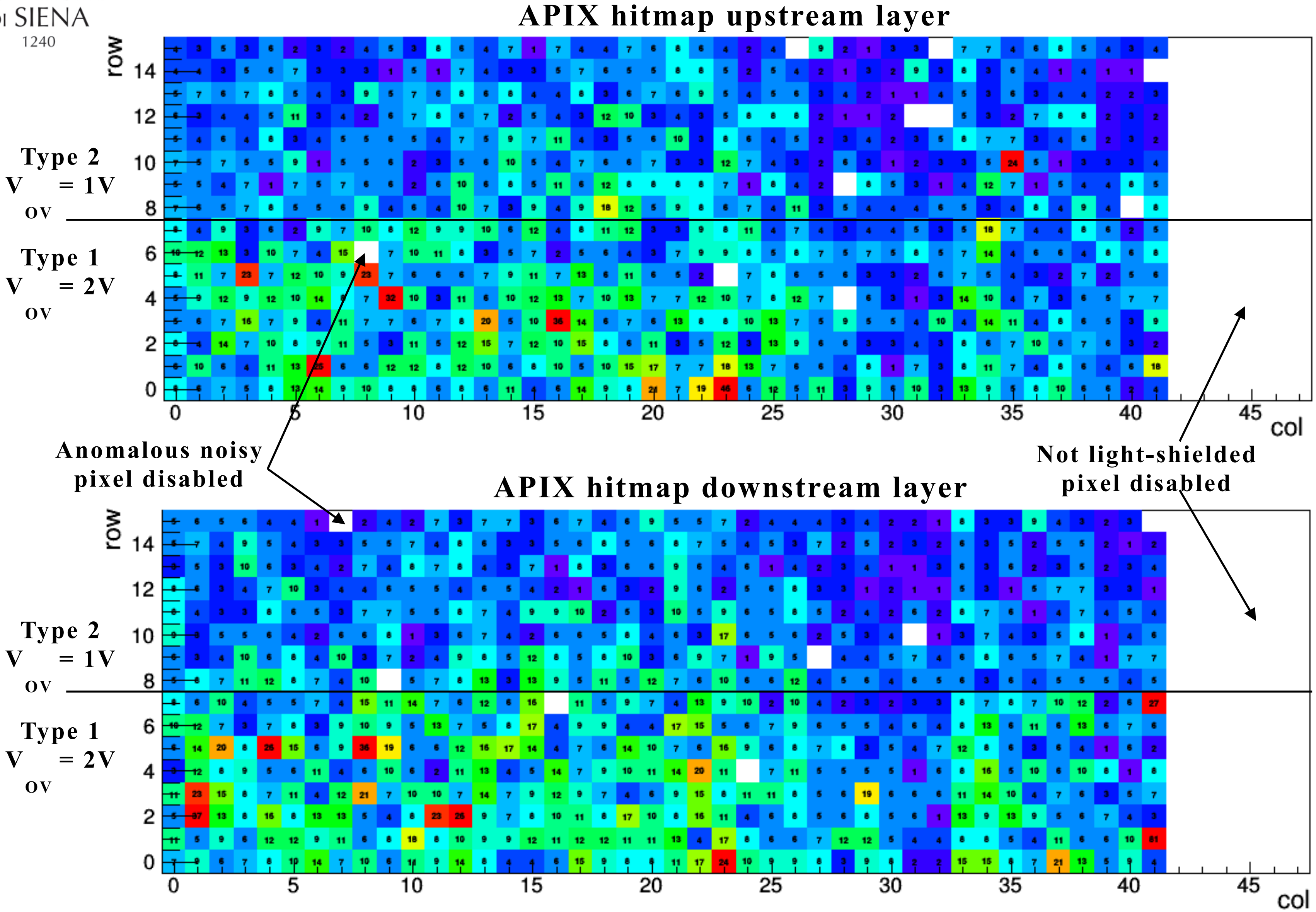
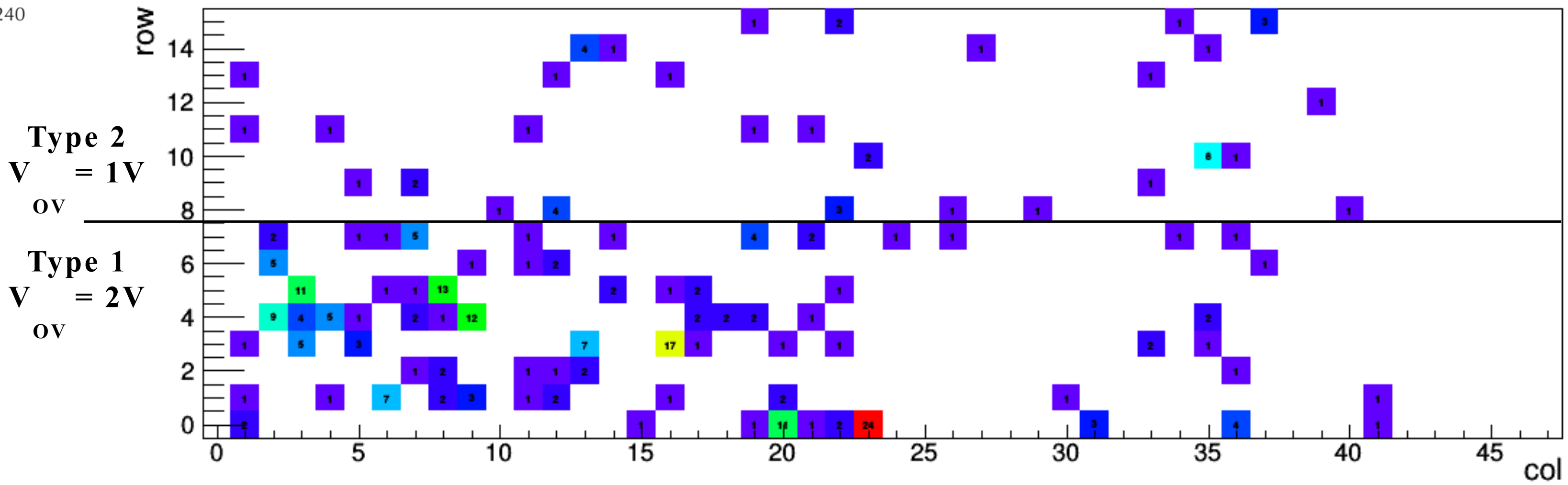
BACKUP

APIX detects test beam particles

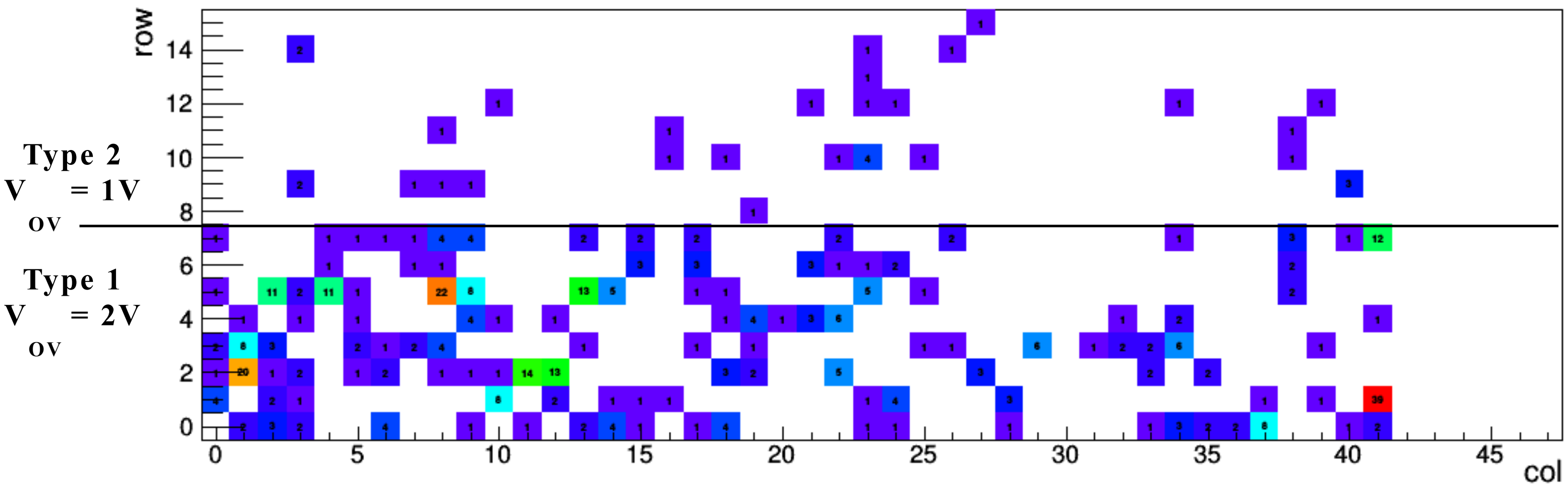


APIX detects test beam particles

APIX random trigger upstream layer



APIX random trigger downstream layer



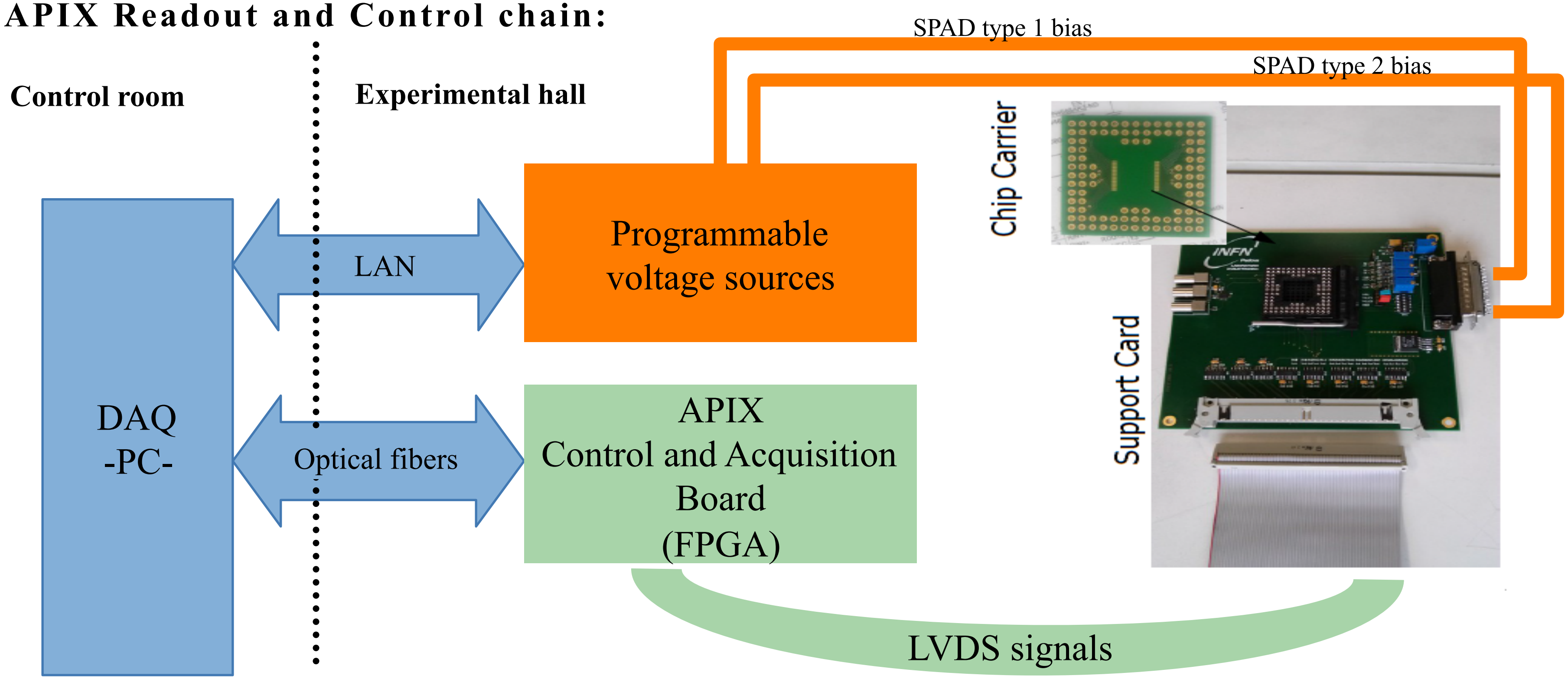
About 3 times less statistics than in the previous hitmaps

APIX Beam Test

First APIX beam test on September of this year

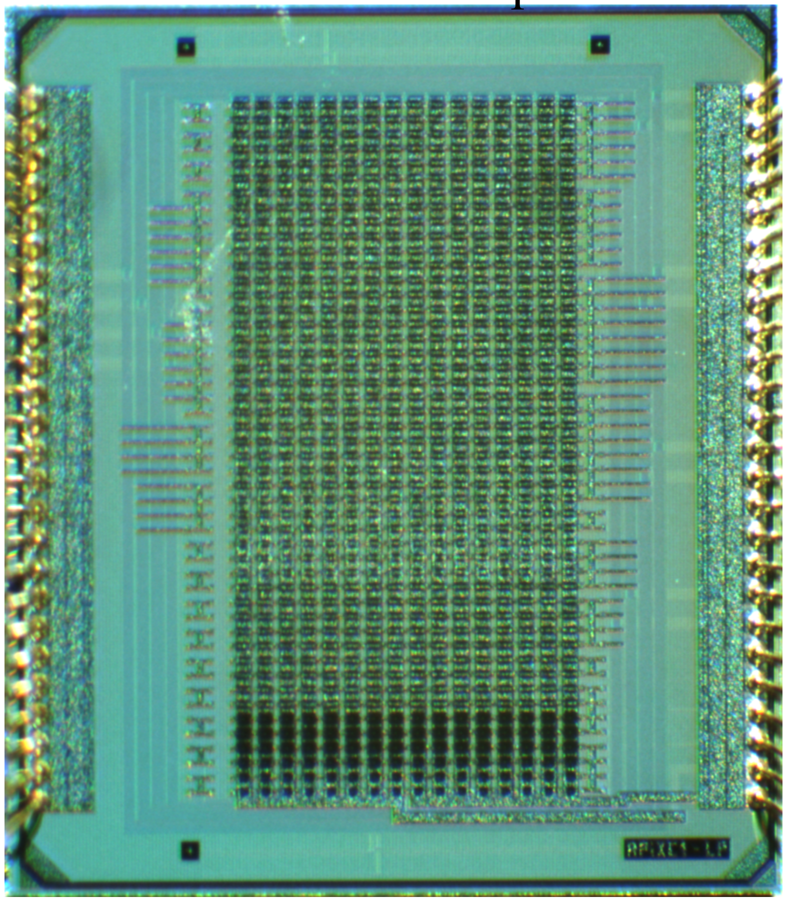
- Test took place at CERN SPS north area facility (H4 beam line)
- Two prototypes of APIX under test + auxiliary Beam Tracker detector
- Positrons and π^+ beams at 50, 100, 150, 200 and 300 GeV
- Good amount of data taken with different APIX voltage settings

APIX Readout and Control chain:

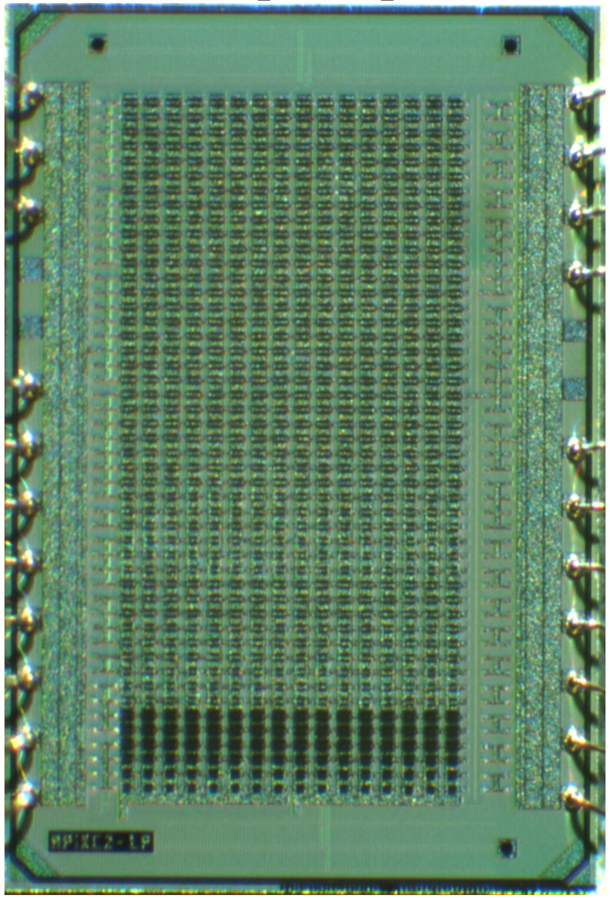


APIX sensor micrographs

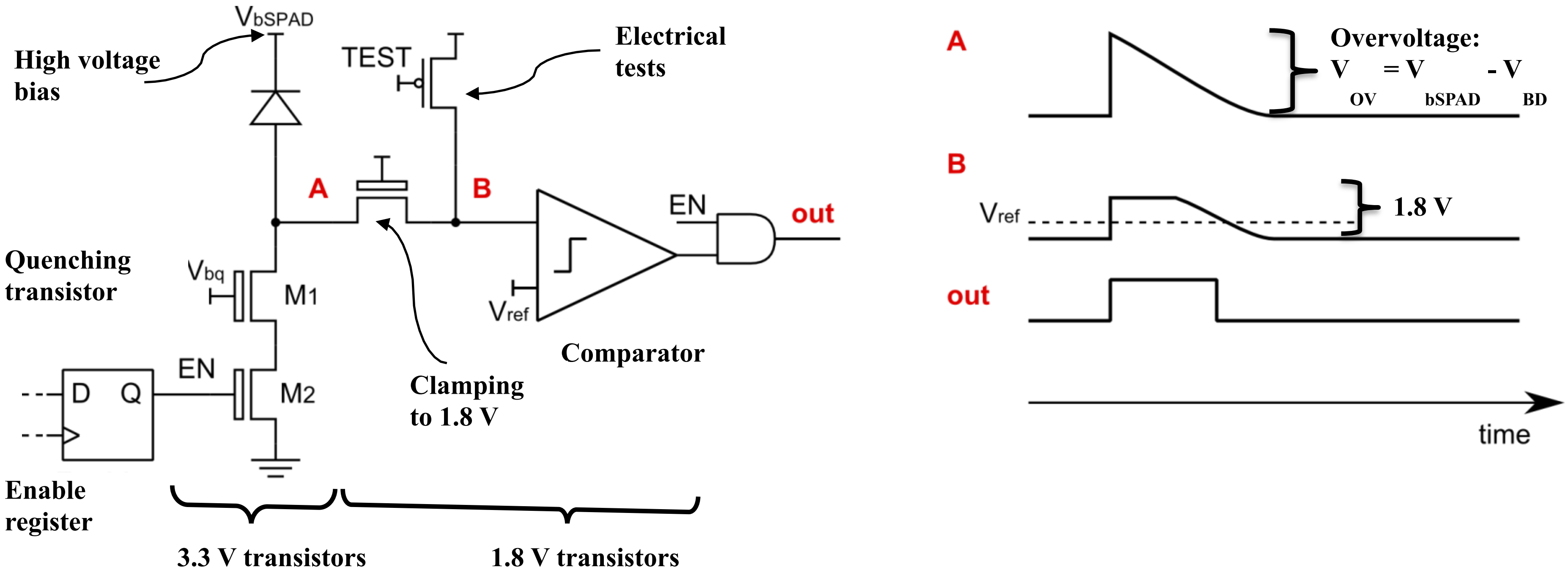
Bottom chip



Top chip

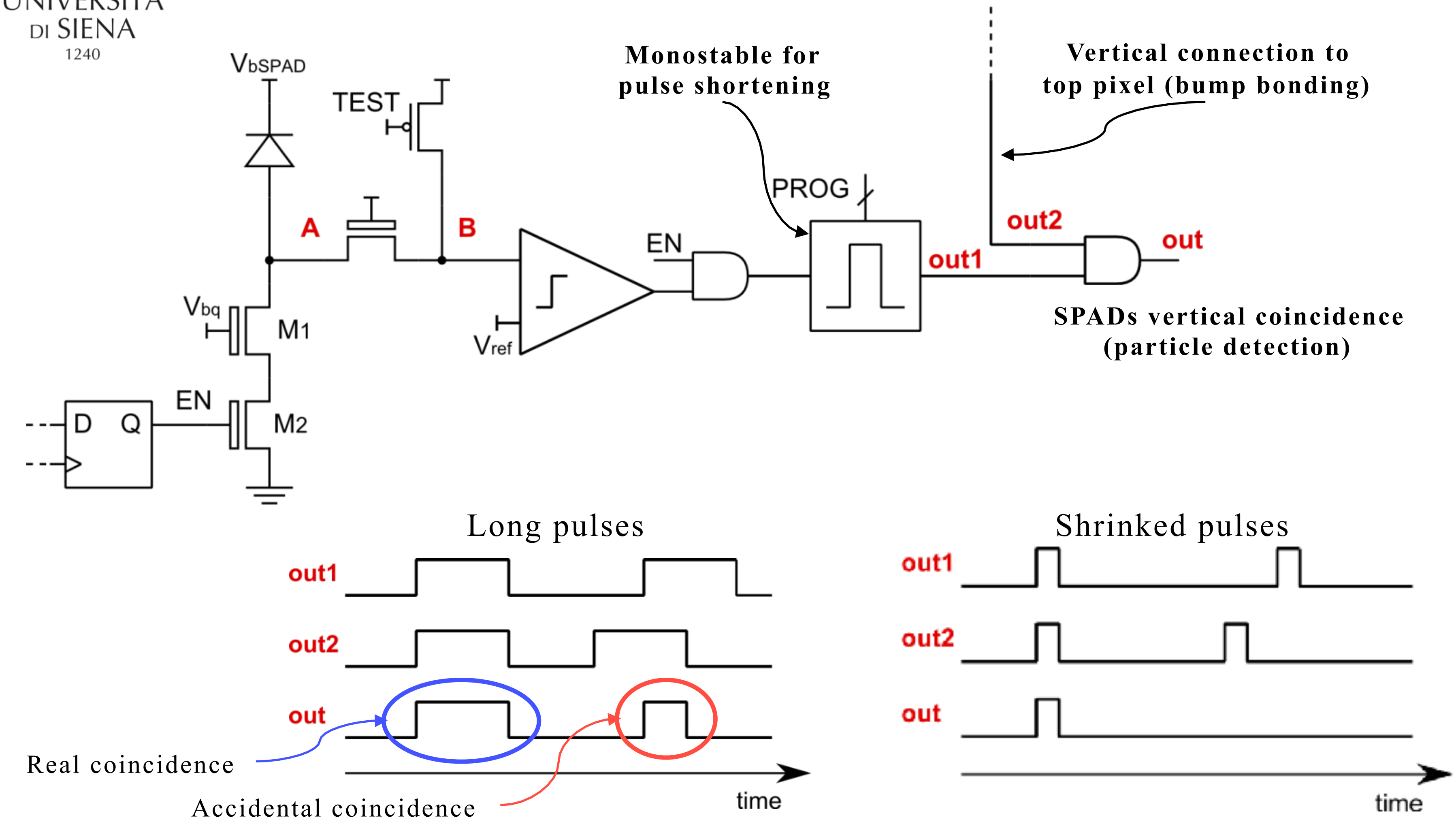


APIX pixel circuitry



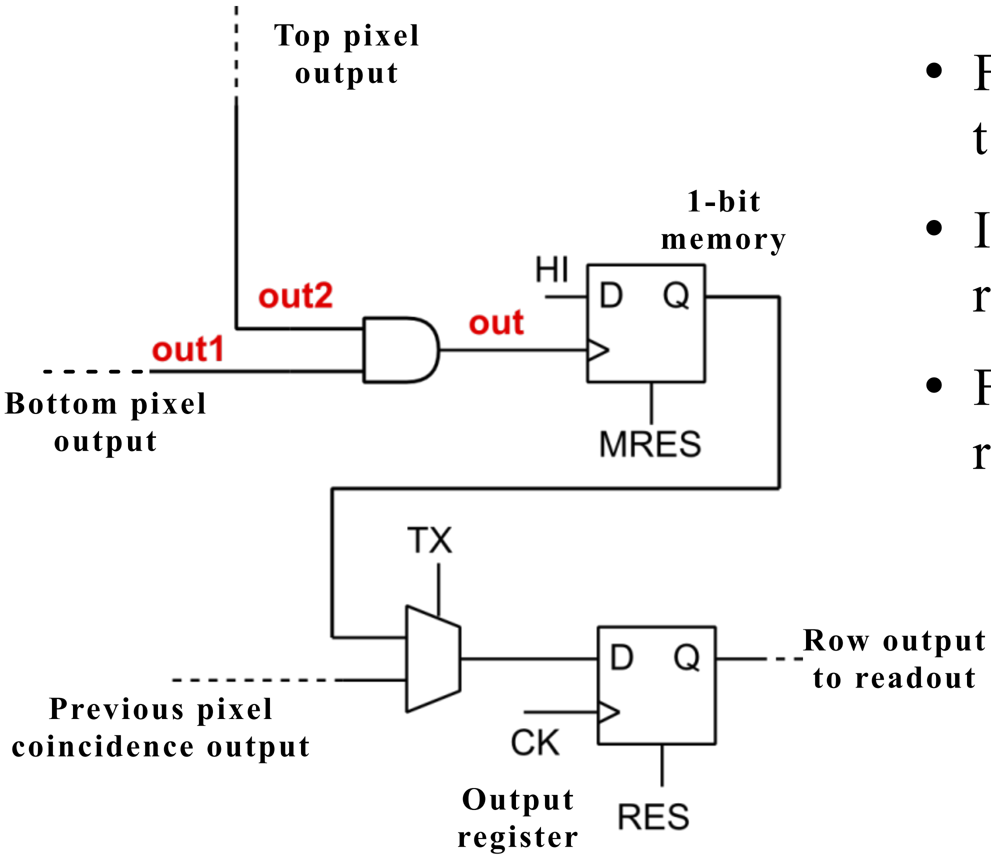
- Front-end transistors: 3.3V ⇒ Maximum overvoltage 3.3V
- Digital circuitry at 1.8V: compact, fast, low-power
- Individual pixel enable/disable: M2 disables recharge, AND gate disables output pulses

APIX pixel: pulse shortening



- Pulse shortening: reduces the rate of accidental coincidence
- Programmable pulse width: **750 ps, 1.5 ns, 10 ns**

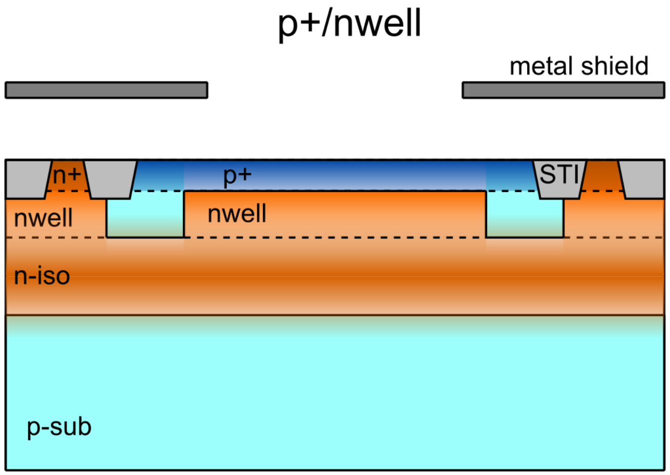
APIX pixel: Data readout architecture



- Each pixel have 1-bit memory and an output register.
- Fast transfer from memory bit to output register
- It is possible to acquire and read-out data at the same time
- Fast parallel read-out of two rows at a time

The SPADs Avalanche detectors

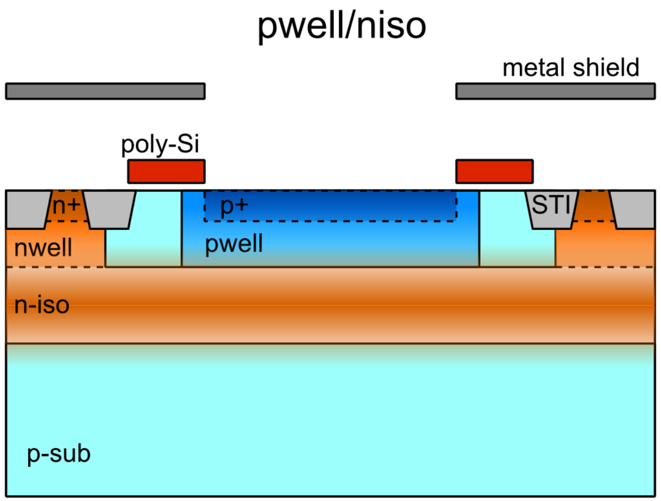
- Two different SPADs architecture in the demonstrator
- Built in standard 150 nm CMOS process
- Avalanche diodes in deep nwell: isolated from substrate



Type 1:

➔ Shallow step junction

➔ Active thickness ~ 1µm



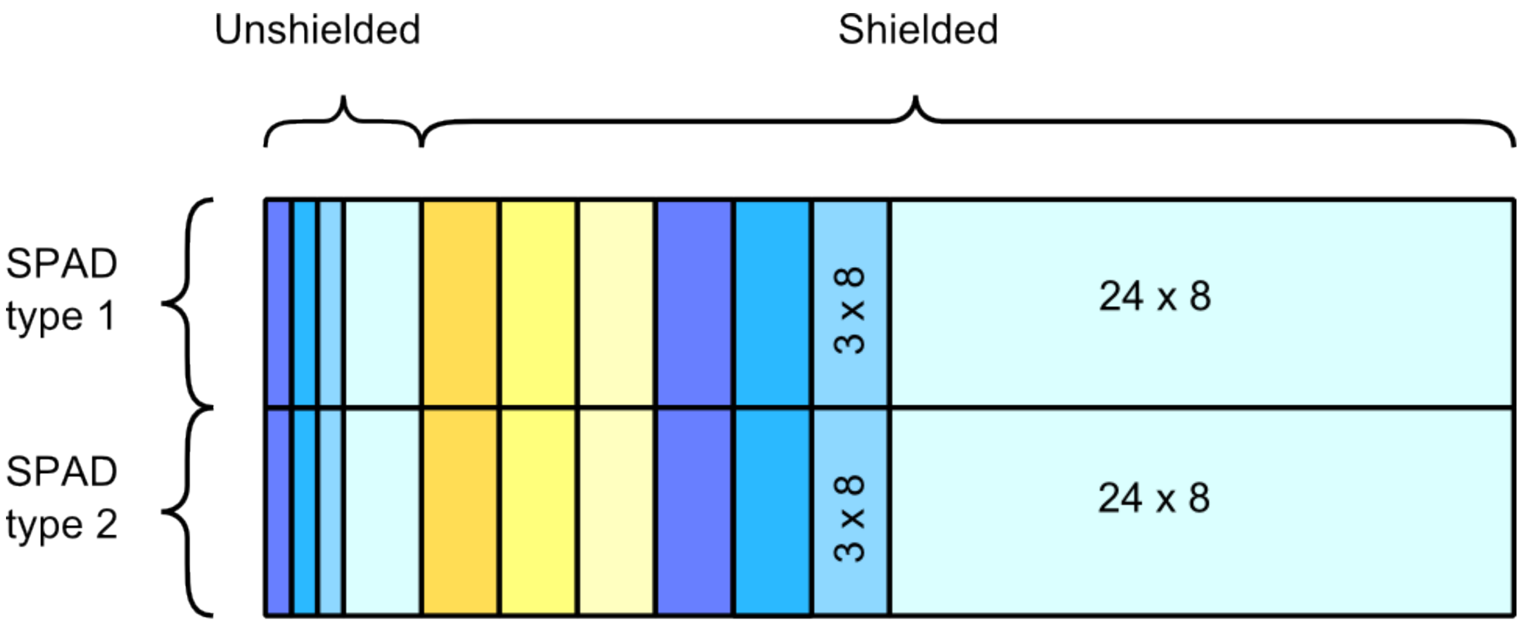
Type 2:

➔ Deep graded junction

➔ Active thickness ~ 1.5µm

*L. Pancheri et al., J. Selected Topics Quantum Electron, 2014

Sensor array partitioning



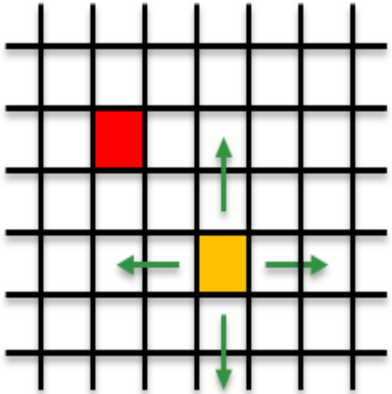
Array size: 48 x 16

SPAD active area sizes:
- A: 45um
- B: 40um
- C: 35um
- D: 30um

SPAD pairs size combinations (Chip1 - Chip2)

- A - A
- B - B
- C - C
- D - D
- A - B
- A - C
- A - D

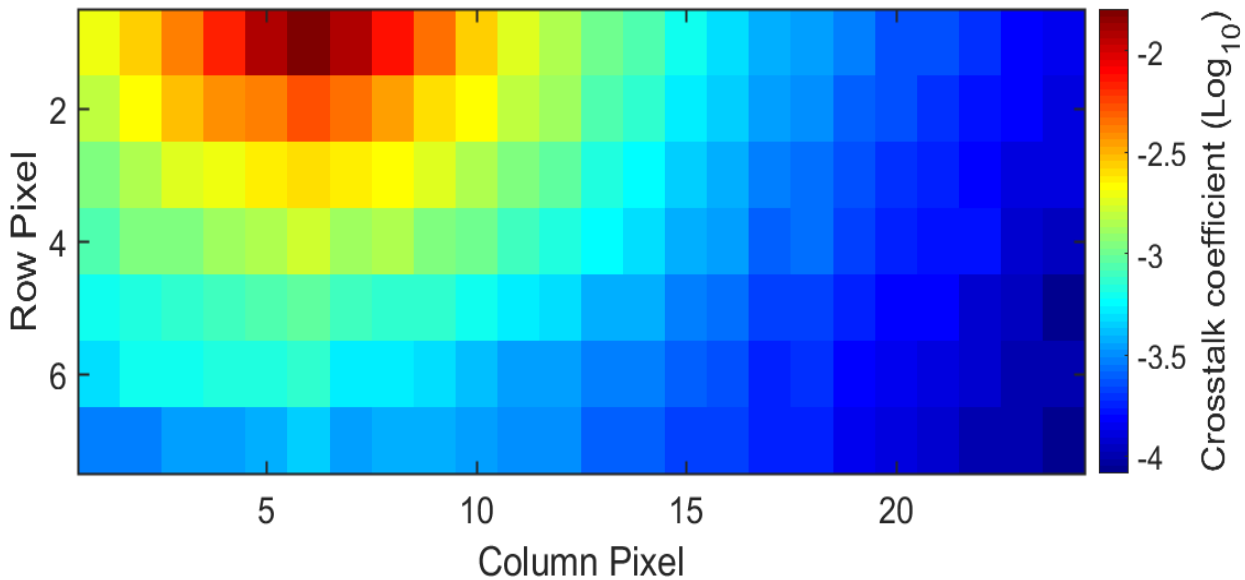
Crosstalk characterization



- Crosstalk coefficient

$$CR_m = DCR_e \cdot DCR_d \cdot 2\Delta T + \mathbf{K} \cdot (DCR_e + DCR_d)$$

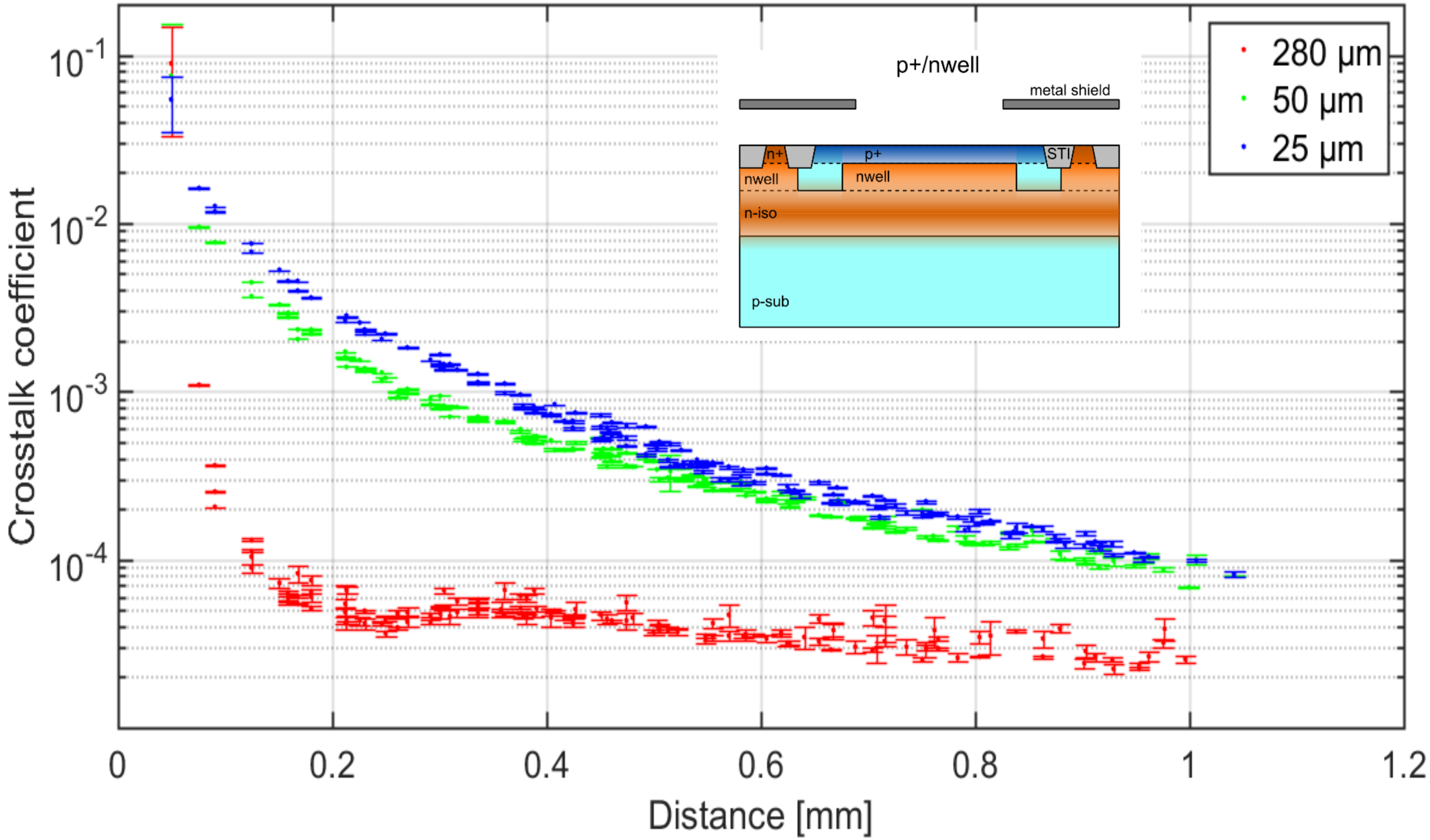
- **Emitter** (fixed)
- **Detector** (scan)



Crosstalk map – Type 1, 25µm thickness

*courtesy of L. Pancheri

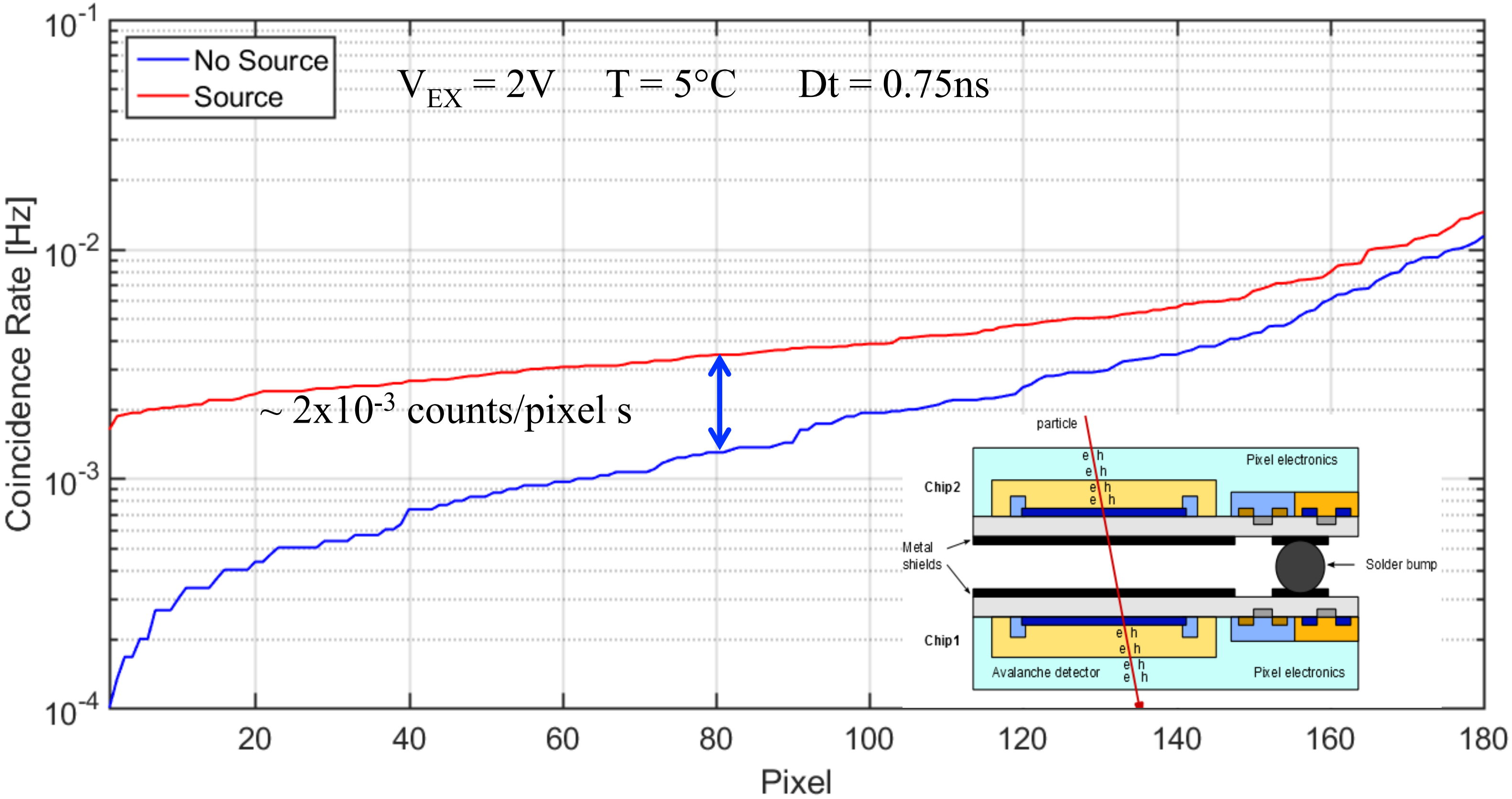
Crosstalk vs substrate thickness



*courtesy of L. Pancheri

β-source measurements

^{90}**Sr** β source – 37kBq at 2mm distance from sensor



Count rate ~**0.5 counts/s mm^2**

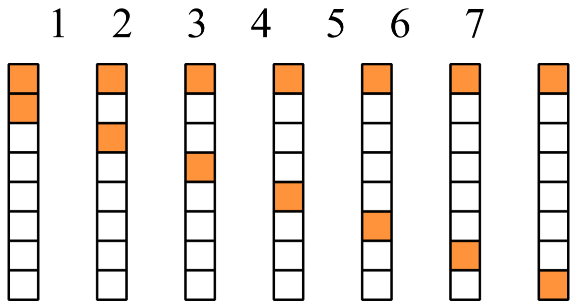
*courtesy of L. Pancheri

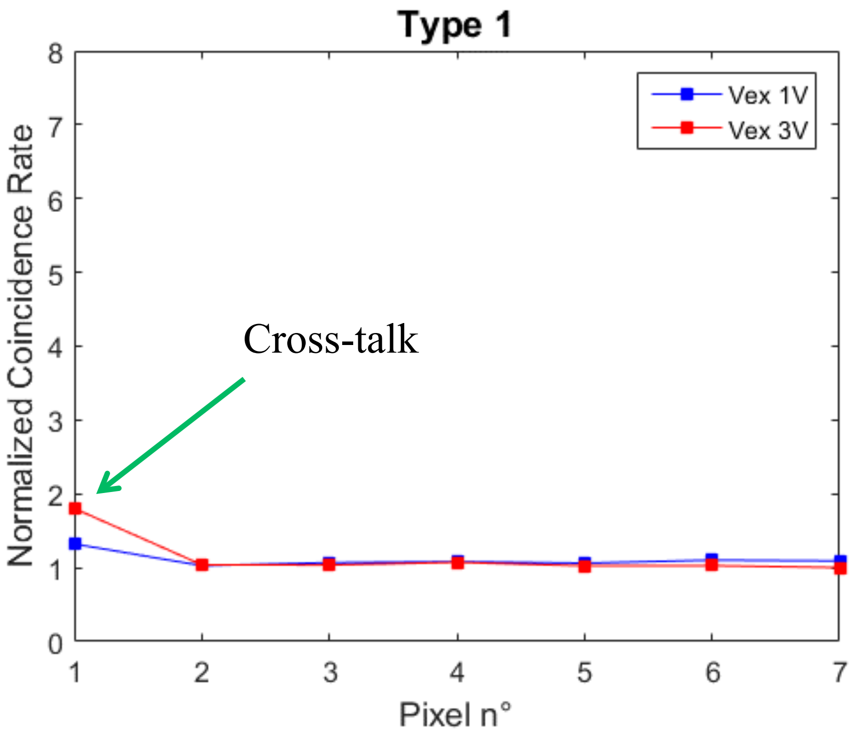
Coincidence detection

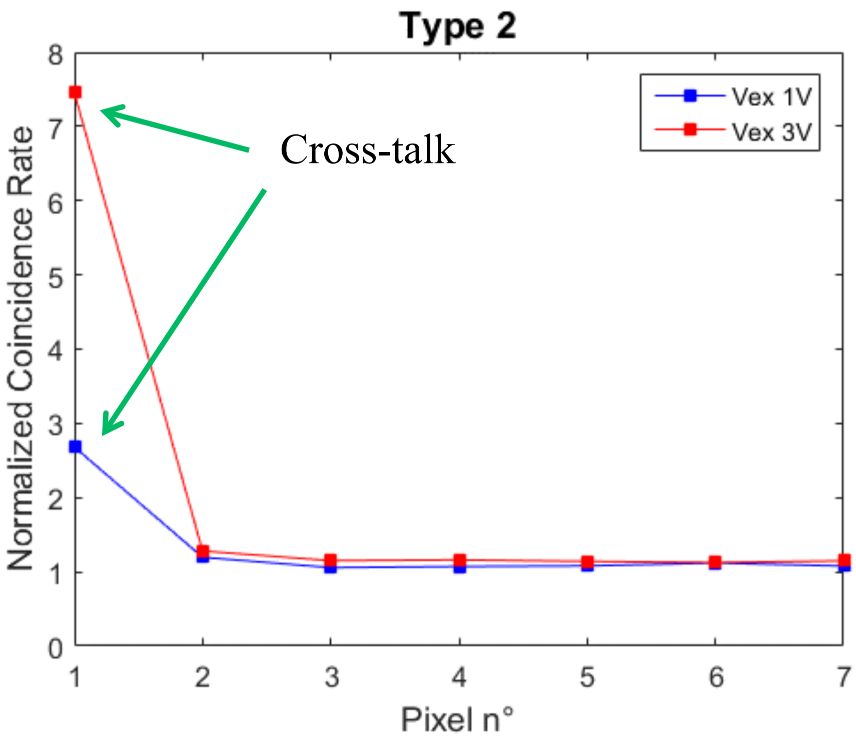
Count rate in coincidence between two pixels in the same column

Normalized rate:

$$\frac{CR_{Meas}}{2 \cdot CR_1 \cdot CR_2 \cdot \Delta T}$$

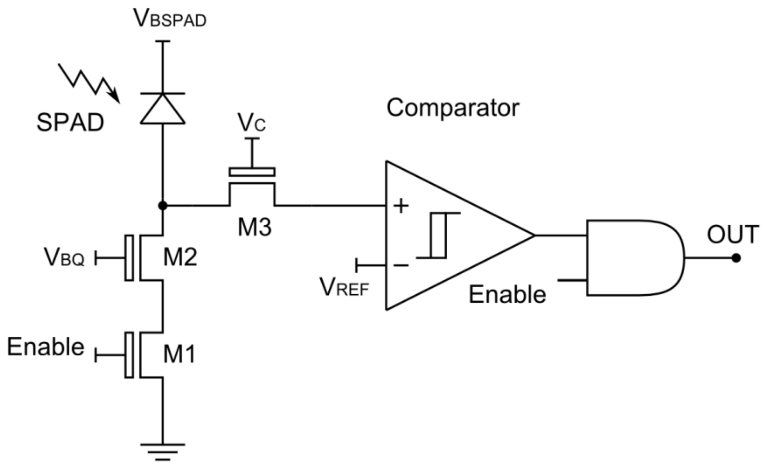






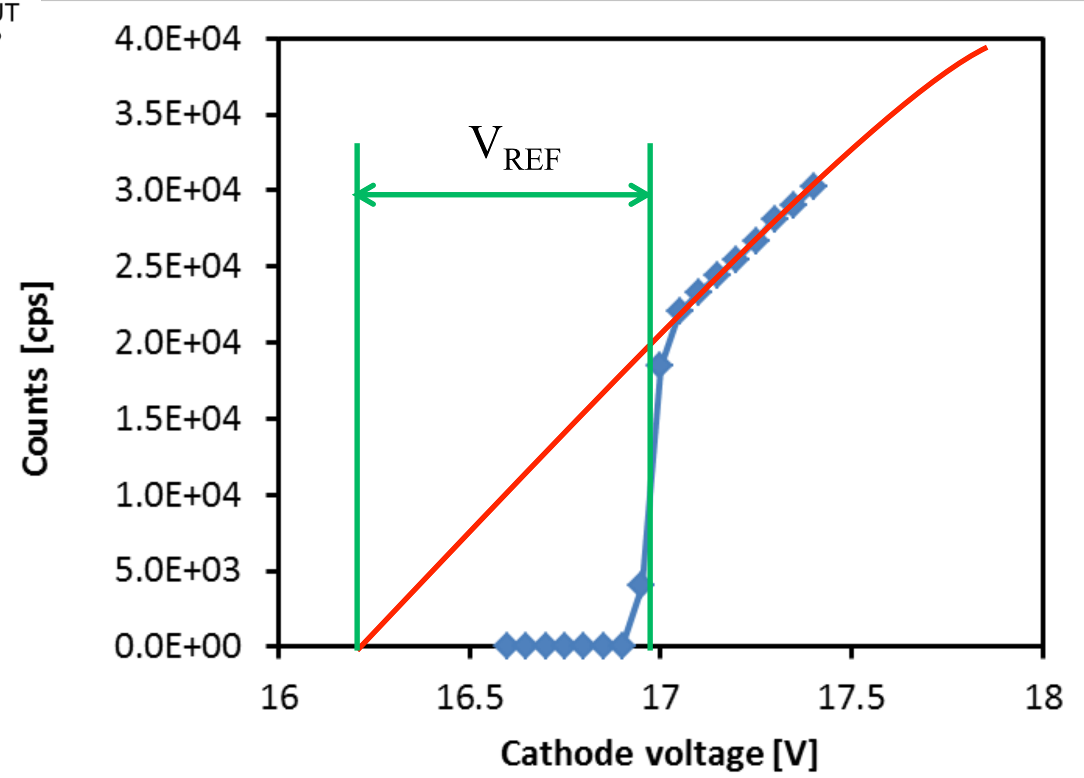
*courtesy of L. Pancheri

VBD extraction method



V_{BD} extraction from I-V curves: not possible

V_{BD} extracted from the dark count rate vs. voltage curve



*L. Pancheri et al., Proc. IEEE ICMTS, 2014

Summary

Strengths:

- Fine segmentation (tens of microns)
- Digital readout
- Low material budget (sensors can be thinned to a few microns)
- Timing resolution
- Low power consumption and low bias voltages

Weaknesses:

- Limited Radiation tolerance
- Geometric efficiency (due to surface device guard ring and electronics)
- Cost and accessibility of 3D integration processes