First Prototype of a Solid-State Imaging Probe for Radio-Guided Surgery

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15th Topical Seminar on Innovative Particle and Radiation Detectors

Siena October 14-17, 2019

Outline

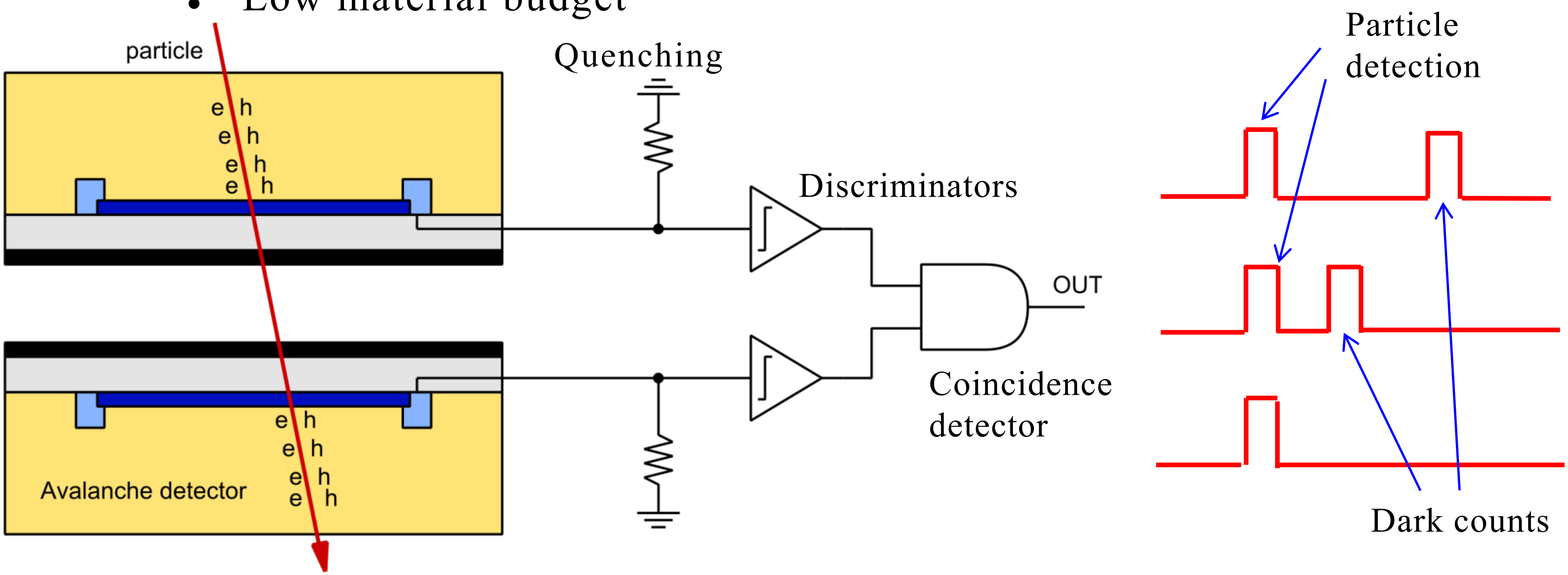
- Sensor concept and architecture
- 1st prototype characterization
- Beam Test of 1st prototype at CERN-SPS
- Imaging Probe for Radio-Guided Surgery
- 2nd prototype layout
- Summary and perspectives

APIX particle detector concept

Concept:

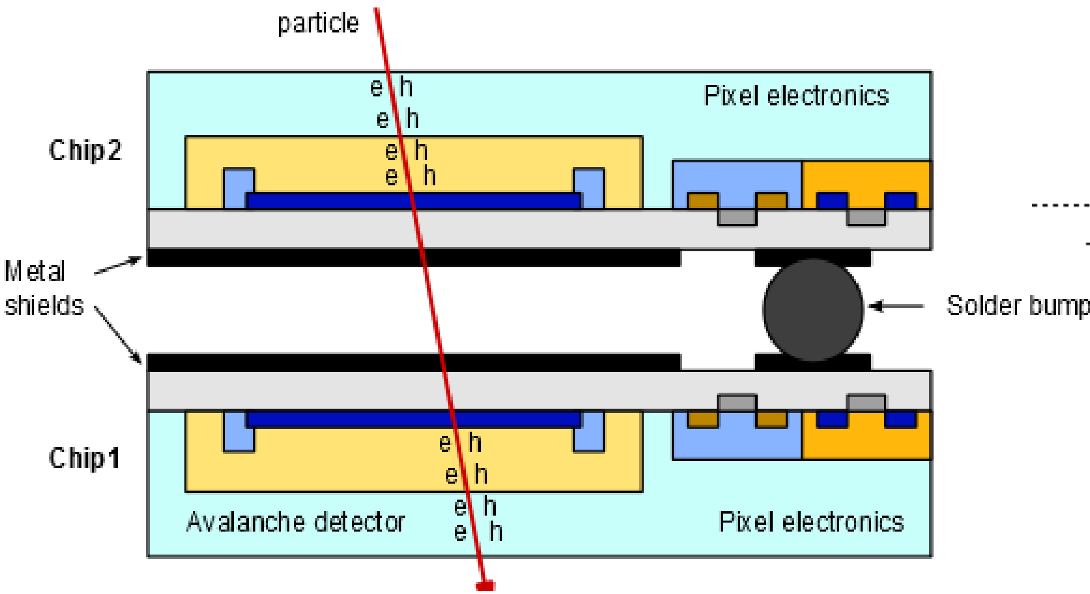
Use of two Geiger-mode avalanche detectors (SPADs) in coincidence to detect charged particles

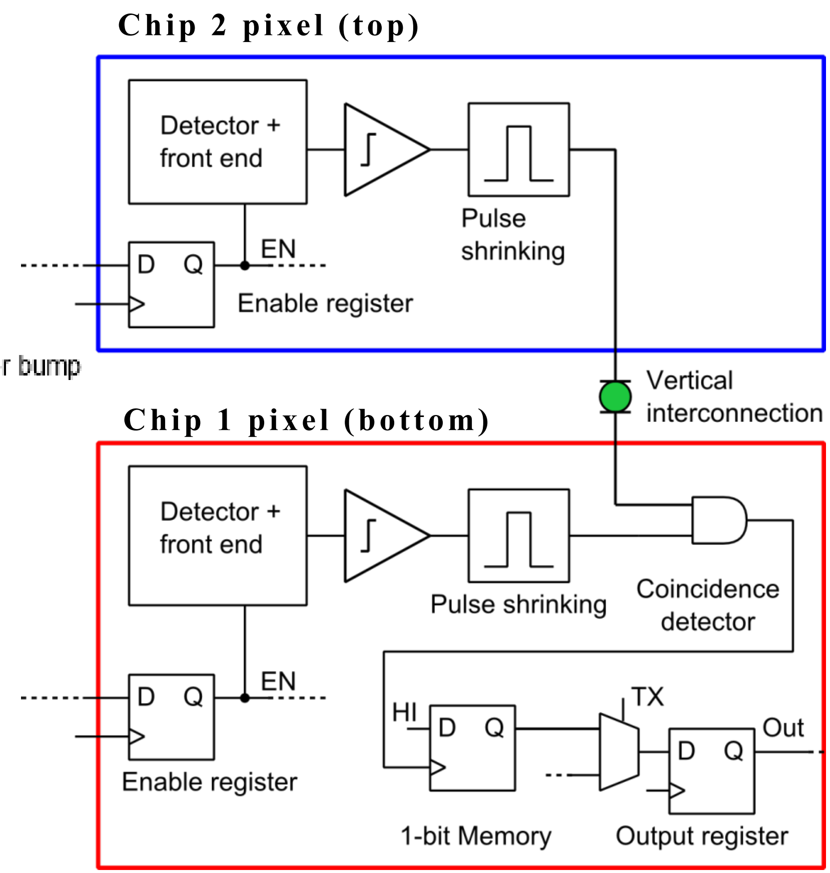
- Digital read-out
- Reduced Dark Count Rate: $DCR = DCR_1 * DCR_2 * 2\Delta T$
- Timing performances
- Low power consumption
- Low material budget



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

APIX top and bottom pixels connectivity

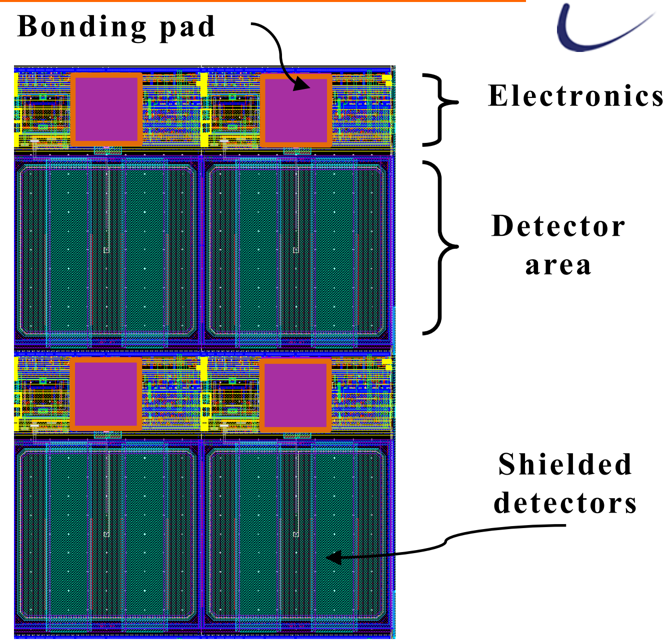




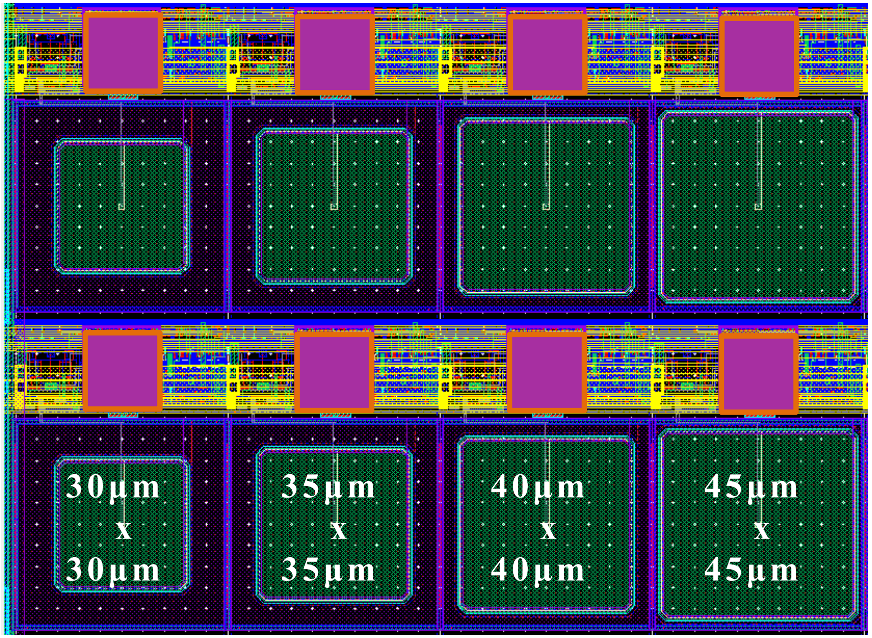
- Vertical integration via Bump-bonding
- CMOS process allows for integrated electronics (not feasible in SiPM integrated process)

APIX pixel array (1st prototype 2016)

- Sensor array of 16 rows x 48 SPADs
- Pixel size: 50 μm x 75 μm
- Total sensor dimensions: **1.2 x 2.4 mm²**



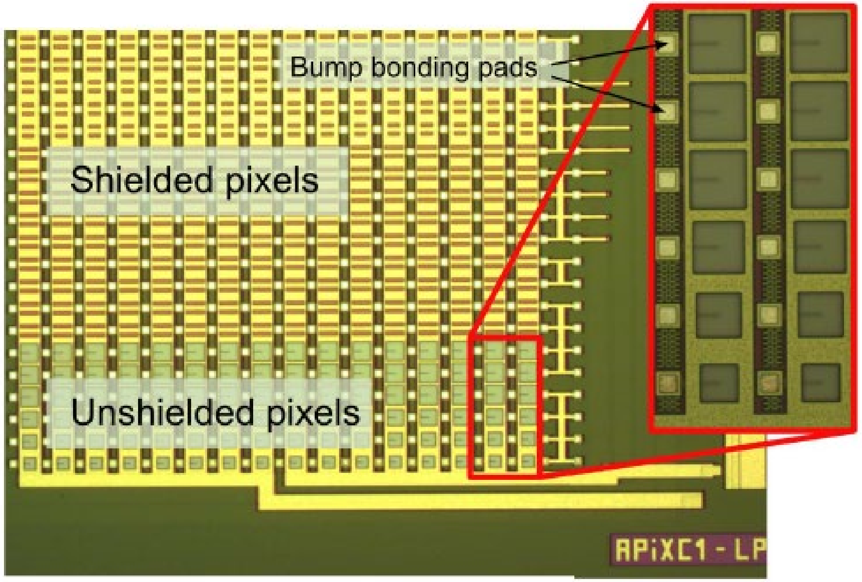
Unshielded pixels with different active area

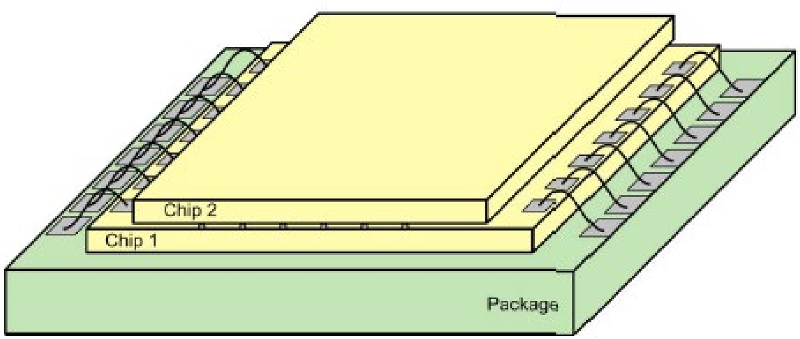


Array partitioning:

- 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

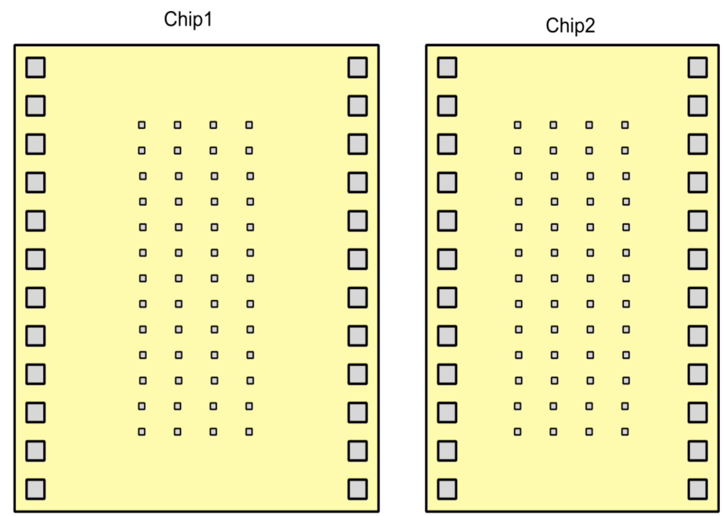
APIX chip assembly and packaging

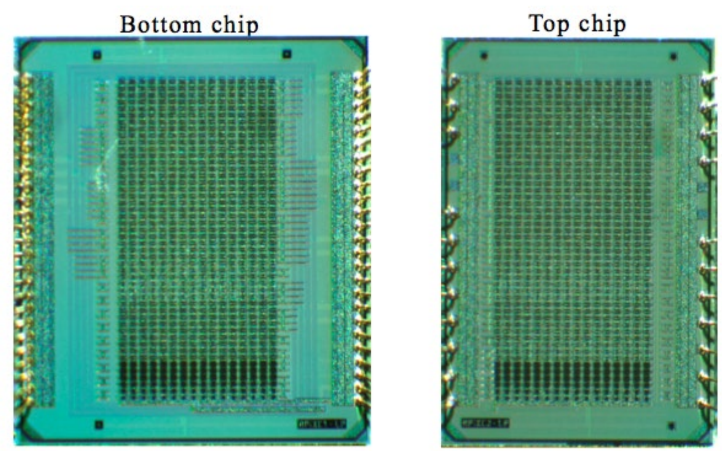




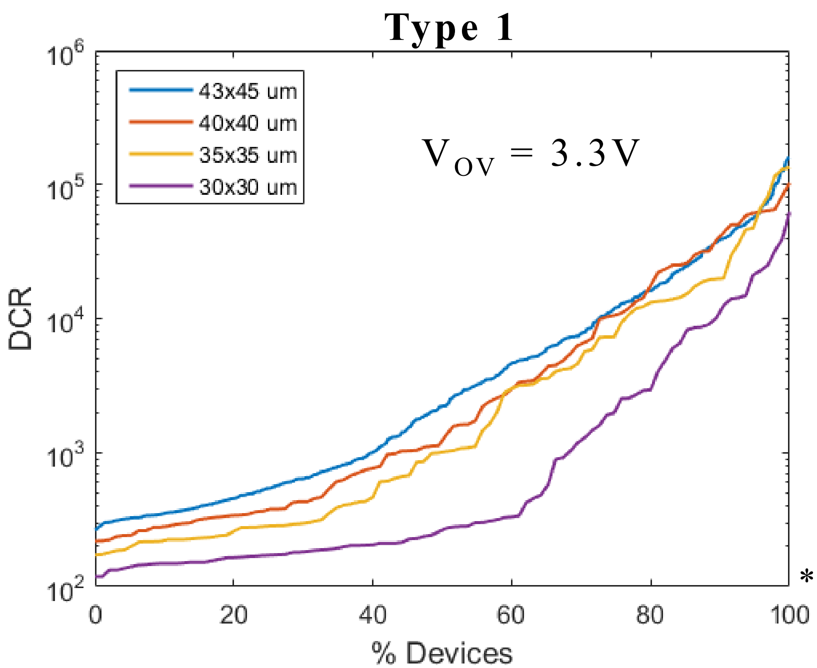
Final assembly of Tier1 and Tier2 and packaging

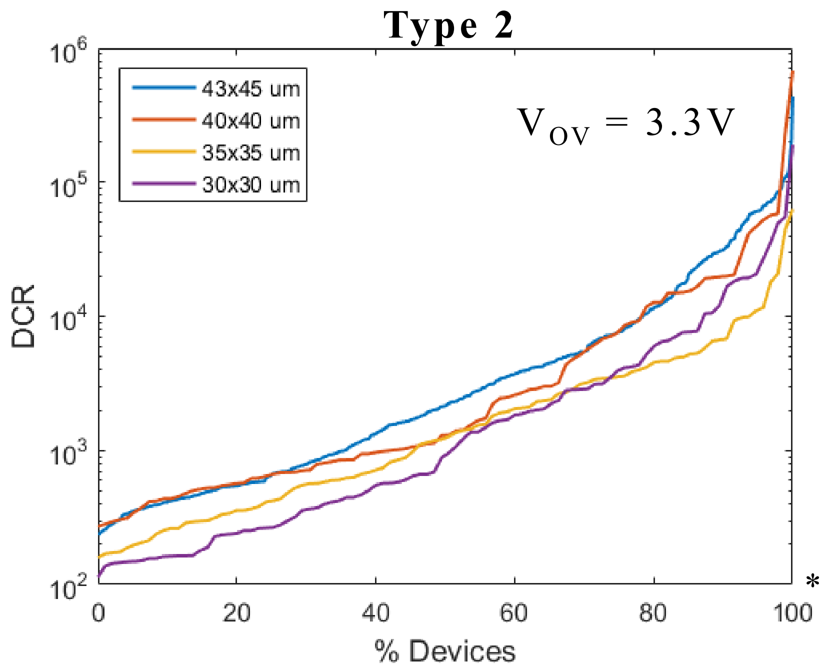
Chips layout with bonding pads





Single chip Dark Count Rate



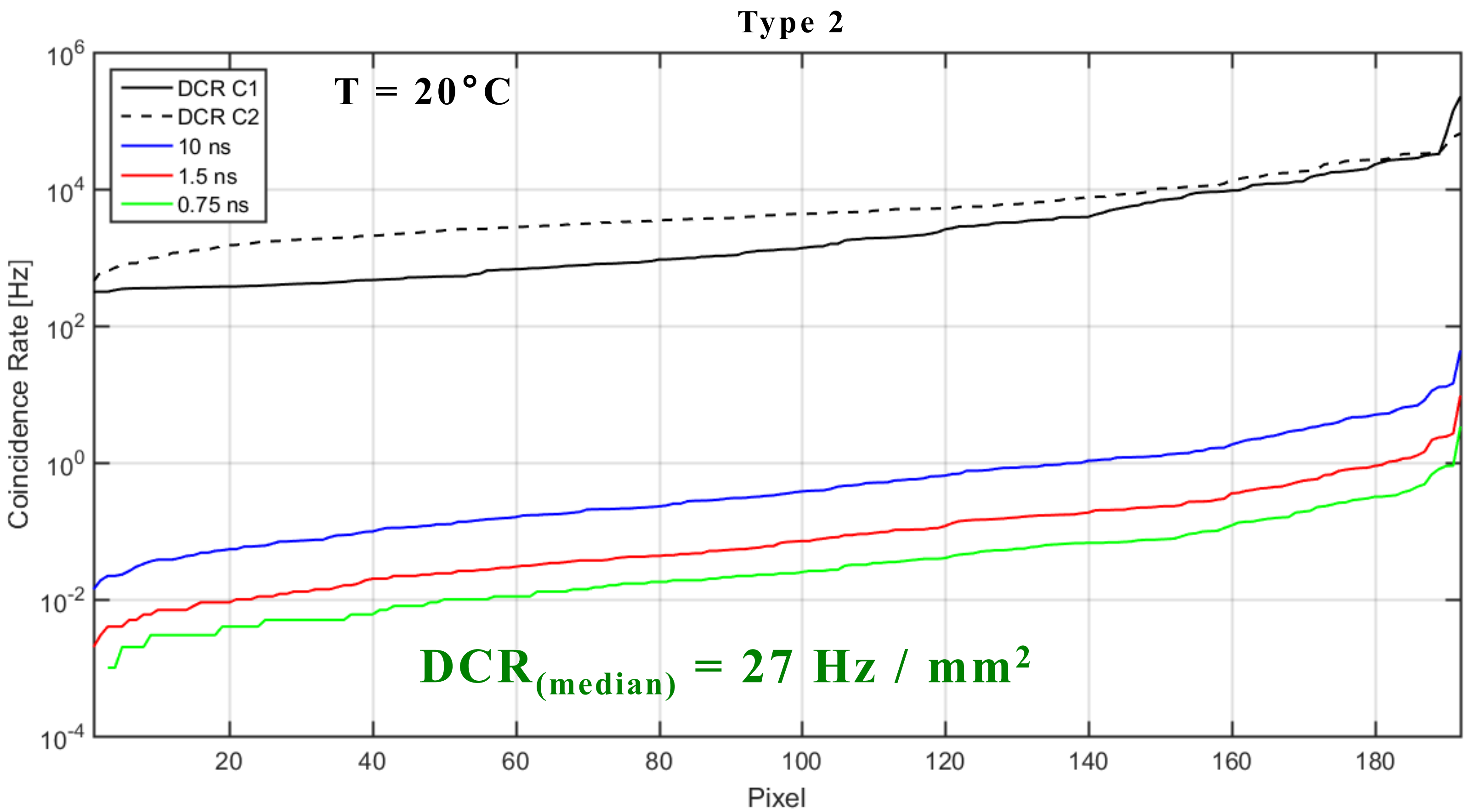


- Cumulative distributions, combined measurements on 3 chips
- 600 devices for largest size, 72 for smaller ones
- **Median DCR = 2.2 kHz** (for largest cell size of both types)

**courtesy of L. Pancheri*

APIX final assembly Dark Count Rate

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

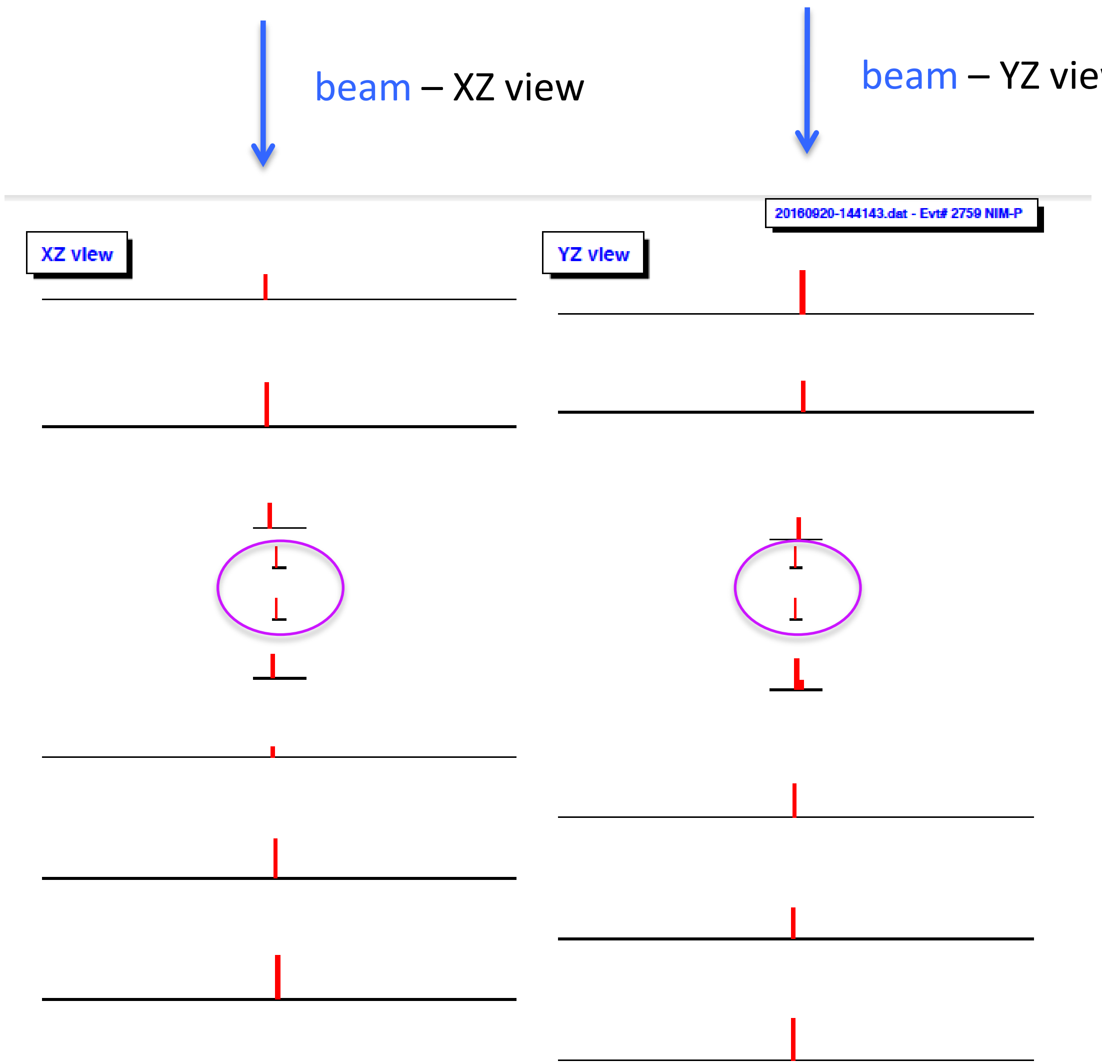


$$DCR_{COINC} = DCR_1 \times DCR_2 \times 2\Delta T$$

courtesy of L. Pancheri

2016 Beam test at CERN SPS North Area (H4 beam line)

Two APIX2 sensors under test + silicon Beam Tracker
Charged particle beams with energy 50, 100, 150, 200 and 300 GeV



On-line event display

Beam Tracker

4 Si-strip detectors

2 HD Si-strip detectors

2 APIX2 pixel detectors

2 HD Si-strip detectors

6 Si-strip detectors

Efficiency of charged particle detection

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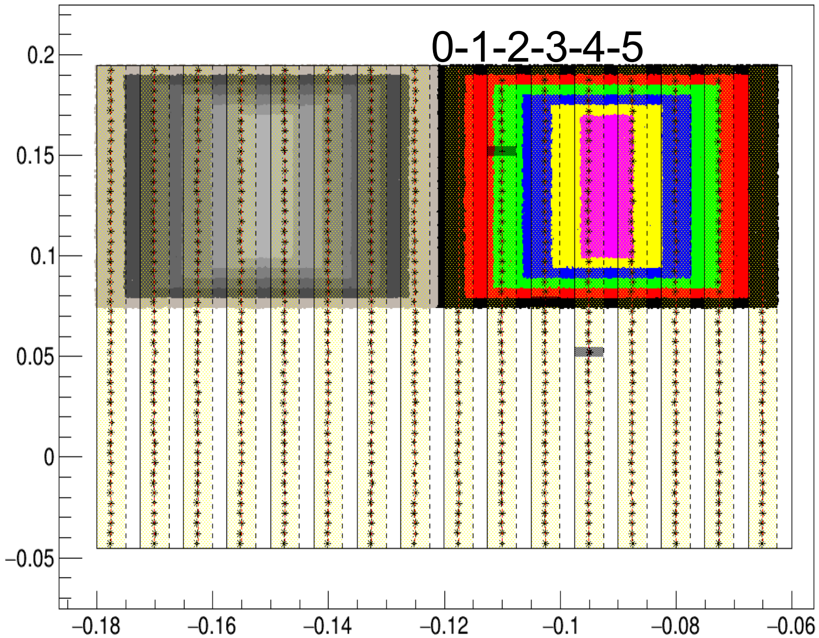
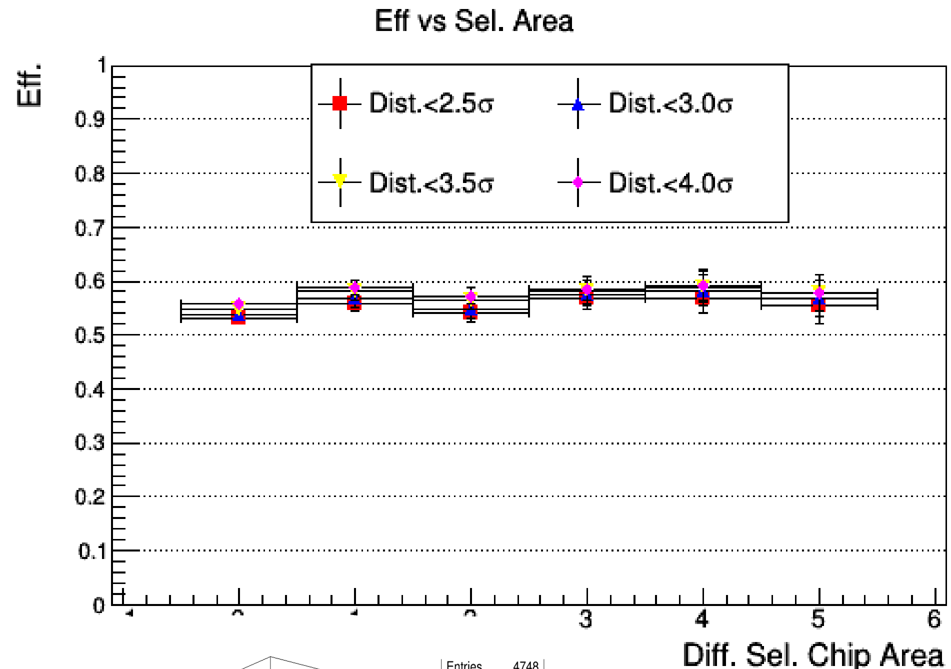
Efficiency was measured in 6 different fiducial regions.

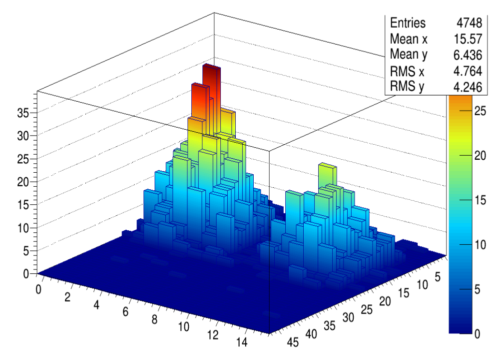
Definition of 6 areas covered by the reconstructed track impact point (IP)





- Measured efficiency 56.2 **± 5 %** (stat+sys)
- Expected (purely geometrical) fill-factor

  FF = 52%



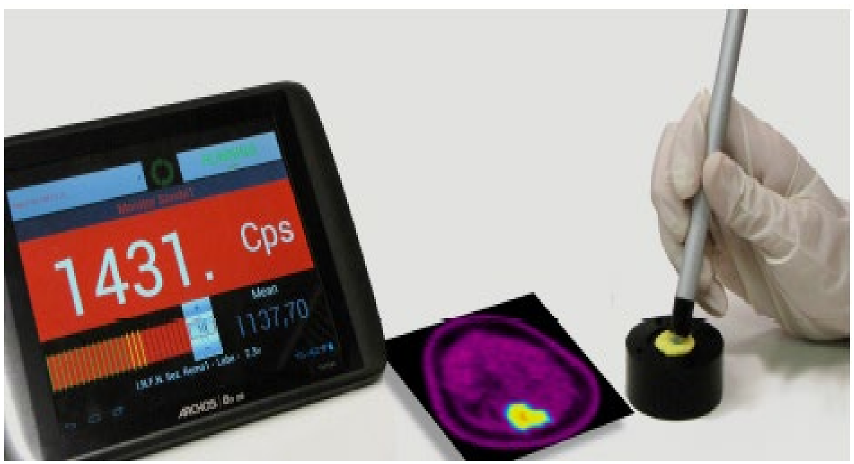
Example of two Regions-Of-Interest separated by ~ 100 um

Intra-operative β- Probe for Radio-Guided Surgery

Rationale: use **electrons** rather than positrons (like in PET) to reduce the background from annihilations in the healthy tissue. APIX probe is insensitive to gamma-radiation.

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

* *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*

Simulate APIX detection of hidden source

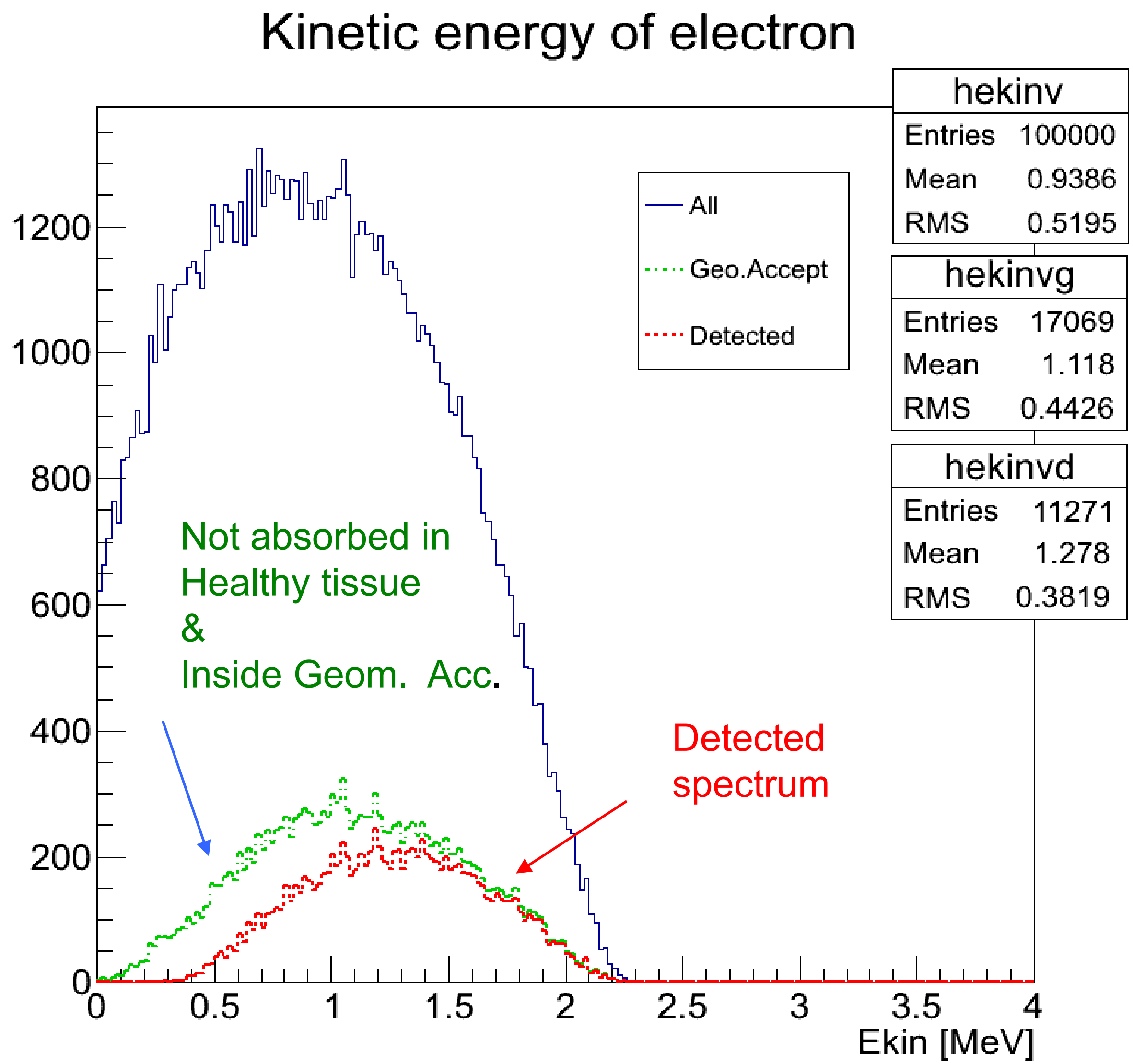
GEANT4 simulations:
- two-tiers
- β-source: 90Y

Example of simulation run:

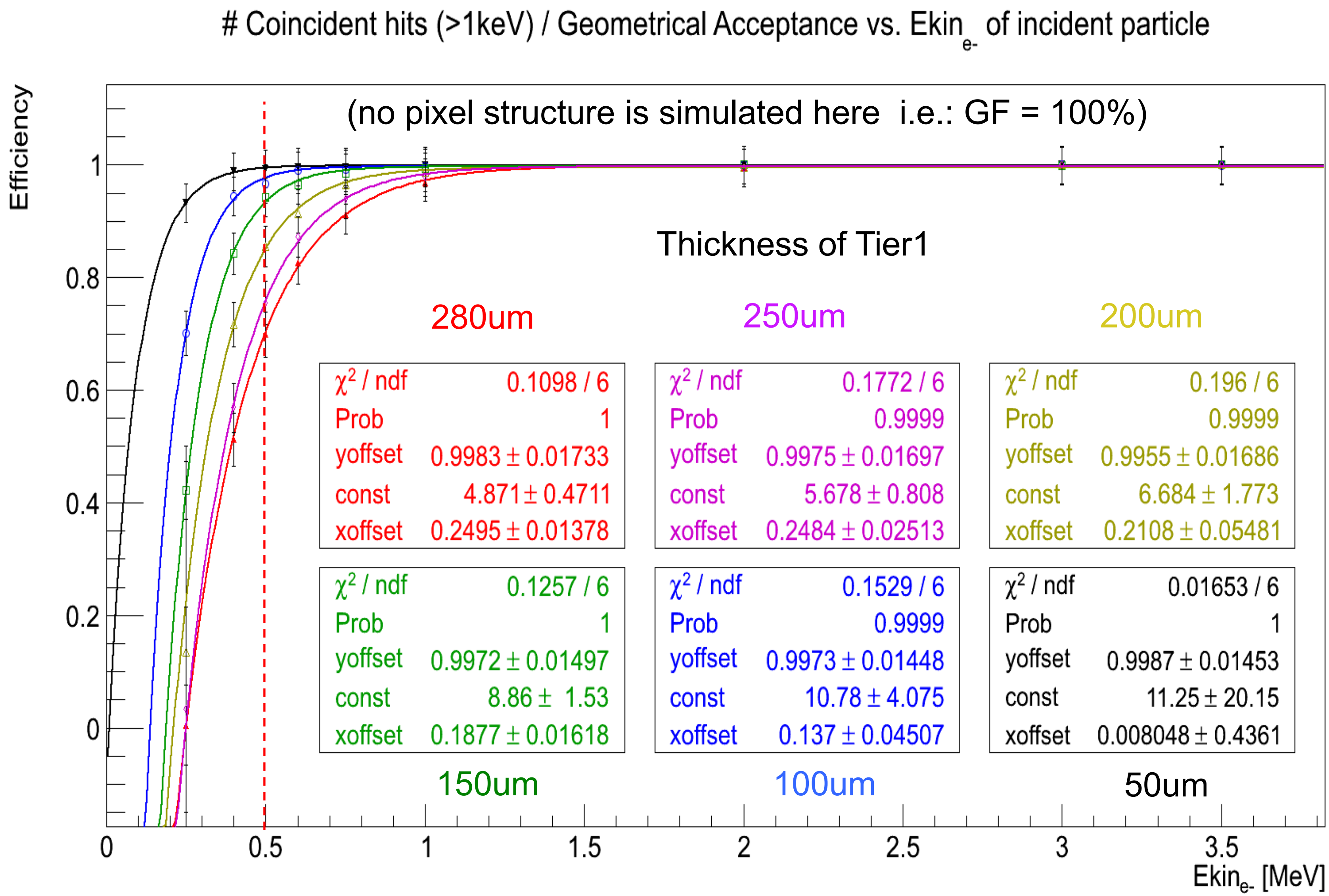
Source emission: isotropic
Activity: 1 kBq
Volume source: cylindrical
in water (5mm diameter & 0.05ml)

Detected / Geom. Acceptance
~ 66%

GF = 1 in this simulation

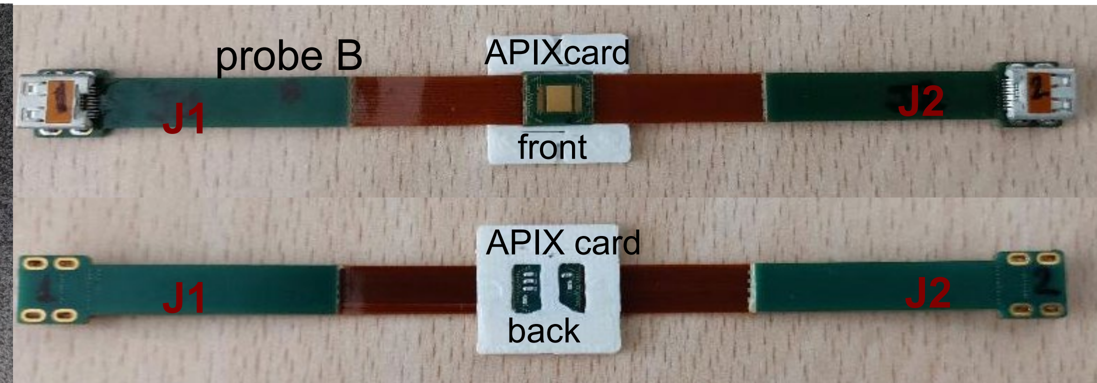


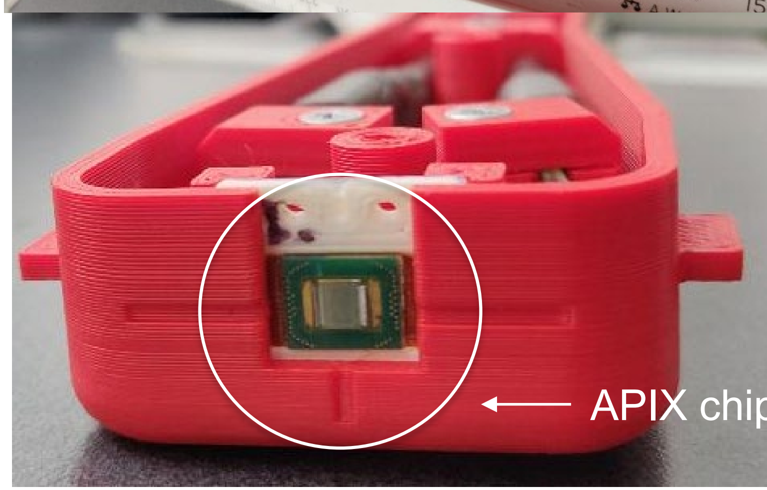
Coincidence efficiency vs Tier1 thickness

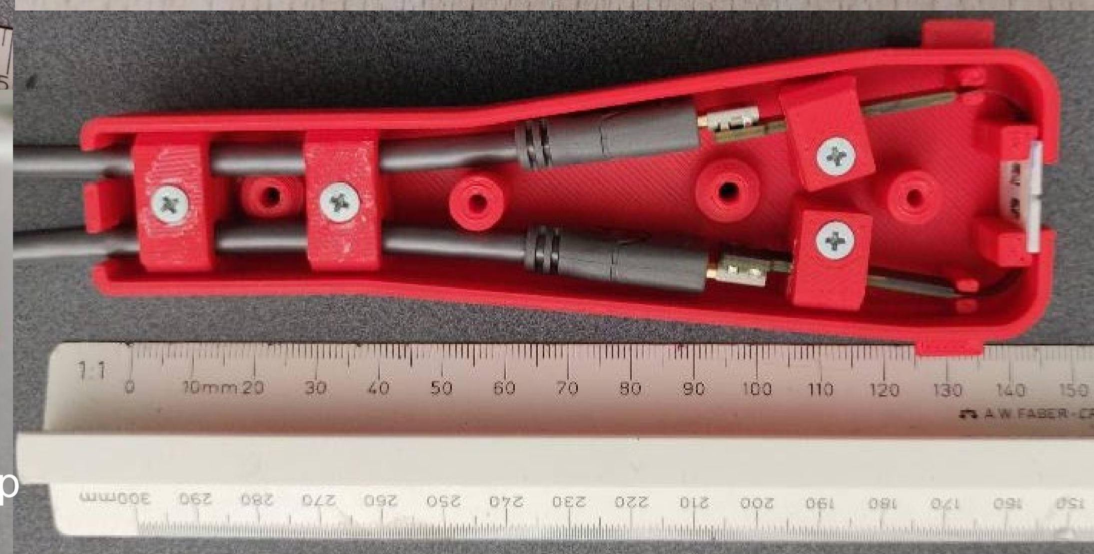


First prototype of APIX probe

- 2nd version will have one cable instead of two
- wireless version under study

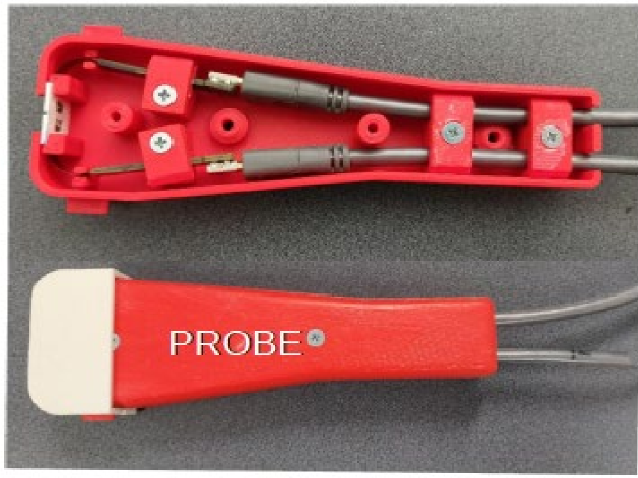


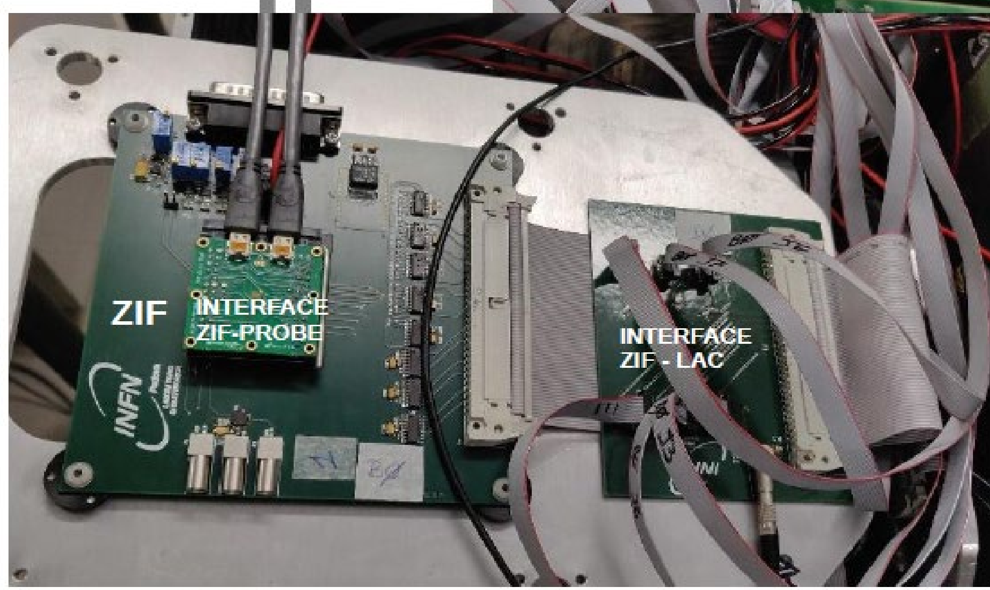




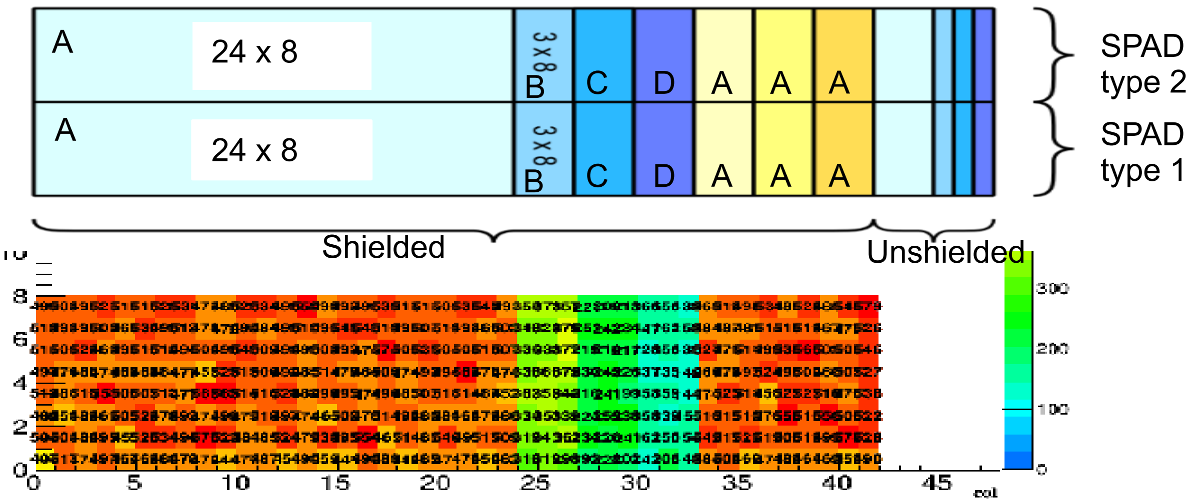
Lab test of probe prototype

Preliminary tests with test beam readout chain





First prototype of APIX probe (partitions)



A = 45 µm
B = 40 µm
C = 35 µm
D = 30 µm

768 pixels

- 16 strips: total width 16x75um = 1.2mm
- 48 SPADs per strips: total length 48x50 = 2.4mm
- **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**

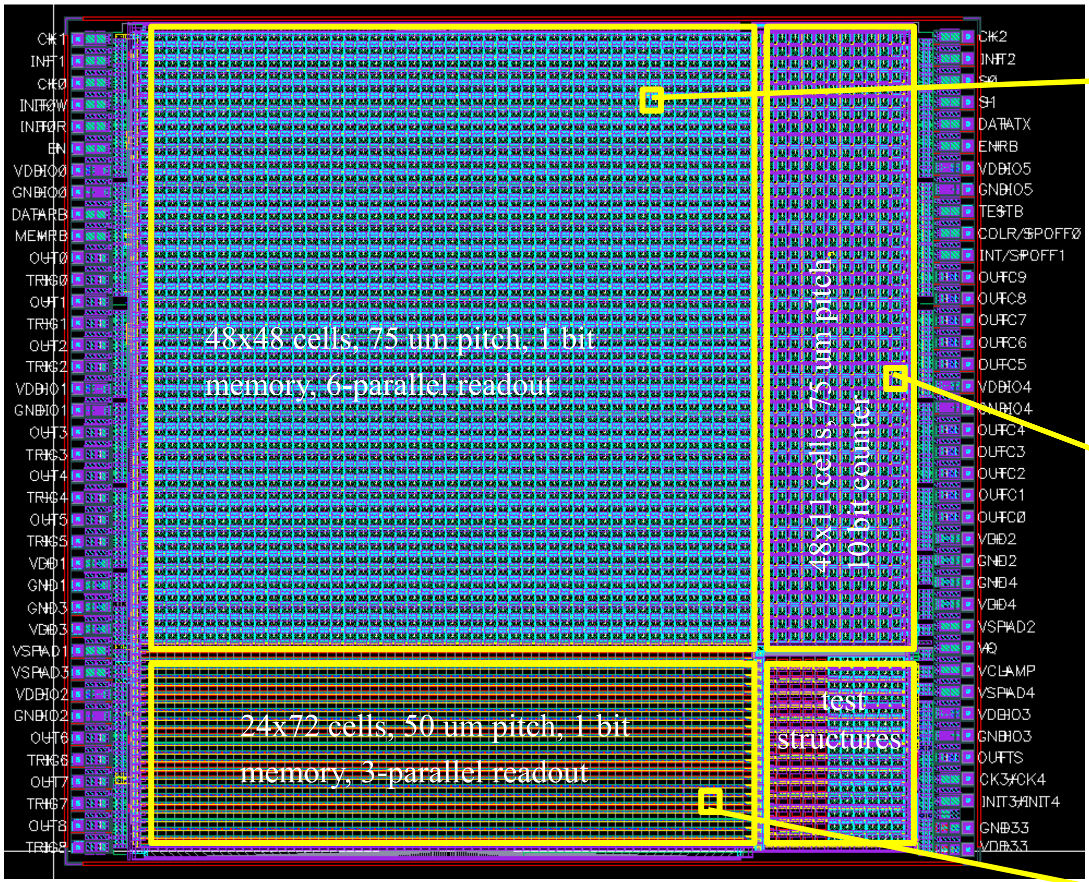
chip size: 1.2 x 2.4 mm^2

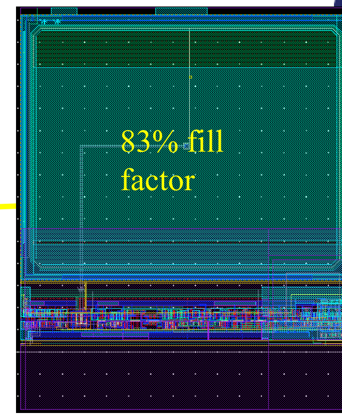
active area ~ 1 mm^2

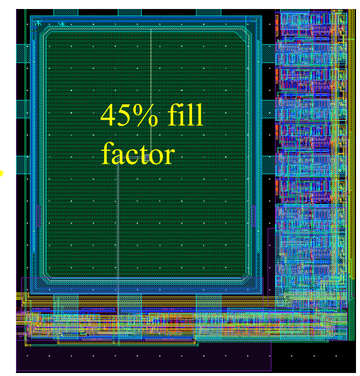
APIX pixel array 2nd prototype (5 mm x 5.4 mm)

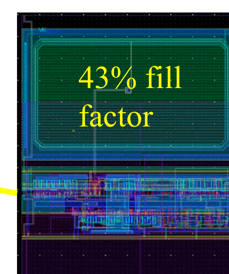
150 nm CMOS technology

- 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

2nd probe prototype: 2300 pixels of size 75 μm x 75 μm

Summary and perspectives

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 $\sim 10^{10}$ 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)

➢ **APPLICATIONS for NUCLEAR MEDICINE**:

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

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[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.

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[9] L. Ratti et al. "Dark count rate degradation in CMOS SPADs exposed to X-rays and neutrons", IEEE Transactions on Nuclear Science, DOI 10.1109/TNS.2019.2893233.

Thanks for your attention!