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


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a Università di Siena, Dipartimento di Scienze Fisiche della Terra e dell’Ambiente (DSFTA), I-53100 Siena, Italy
b INFN Pisa, I-56127 Pisa, Italy
c INFN Padova, I-35131 Padova, Italy
d Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
e Università di Trento, Dipartimento di Ingegneria Industriale, and TIFPA INFN, I-38123 Trento, Italy
f Università di Pavia, Dipartimento di Ingegneria Industriale e dell’informazione, and INFN Pavia, I-27100 Pavia, Italy

15th Topical Seminar on Innovative Particle and Radiation Detectors
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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: \( \text{DCR} = \text{DCR}_1 \times \text{DCR}_2 \times 2\Delta T \)
- 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

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*
Dark Count Rate for different coincidence time $\Delta T$: 10 ns, 1.5 ns, 0.75 ns

\[
\text{DCR}_{\text{COINC}} = \text{DCR}_1 \times \text{DCR}_2 \times 2\Delta T
\]

$\text{DCR}_{\text{median}} = 27 \text{ Hz} / \text{mm}^2$

*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

Efficiency was measured in 6 different fiducial regions.

- Measured efficiency $56.2 \pm 5\%$ (stat+sys)
- Expected (purely geometrical) fill-factor $\text{FF} = 52\%$

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

Example of two Regions-Of-Interest separated by $\sim 100\text{ um}$
**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

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GEANT4 simulations:

- two-tiers
- $\beta$-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

Not absorbed in Healthy tissue & Inside Geom. Acc.
Coincidence efficiency vs Tier1 thickness

# Coincident hits (>1keV) / Geometrical Acceptance vs. E_{kin,e} of incident particle

(no pixel structure is simulated here i.e.: GF = 100%)

Efficiency

<table>
<thead>
<tr>
<th>Thickness of Tier1</th>
<th>280um</th>
<th>250um</th>
<th>200um</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^2 / \text{ndf} )</td>
<td>0.1098 / 6</td>
<td>0.1772 / 6</td>
<td>0.196 / 6</td>
</tr>
<tr>
<td>Prob</td>
<td>1</td>
<td>1</td>
<td>0.9999</td>
</tr>
<tr>
<td>yoffset</td>
<td>0.9983 ± 0.01733</td>
<td>0.9975 ± 0.01697</td>
<td>0.9955 ± 0.01686</td>
</tr>
<tr>
<td>const</td>
<td>4.871 ± 0.4711</td>
<td>5.678 ± 0.808</td>
<td>6.684 ± 1.773</td>
</tr>
<tr>
<td>xoffset</td>
<td>0.2495 ± 0.01378</td>
<td>0.2484 ± 0.02513</td>
<td>0.2108 ± 0.05481</td>
</tr>
</tbody>
</table>

| 150um | 100um | 50um |
|\( \chi^2 / \text{ndf} \) | 0.1257 / 6 | 0.1529 / 6 | 0.01653 / 6 |
| Prob | 1 | 1 | 1 |
| yoffset | 0.9972 ± 0.01497 | 0.9973 ± 0.01448 | 0.9987 ± 0.01453 |
| const | 8.86 ± 1.53 | 10.78 ± 4.075 | 11.25 ± 20.15 |
| xoffset | 0.1877 ± 0.01618 | 0.137 ± 0.04507 | 0.008048 ± 0.4361 |
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)

- 16 strips: total width 16x75μm = 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

768 pixels

- chip size: 1.2 x 2.4 mm²
- active area ~ 1 mm²
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
APIX strengths:

- low material budget
- low power
- no cooling
- good timing properties (e.g.: time of flight with \( \sim 100 \) ps resolution)
- insensitivity to gamma radiation background
- narrow band acceptance (directionality)
- portability
- easy to configure to the specific application
- operation in real time: \( \beta \)-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 (\( \beta \) - markers) for radio-guided surgery, prostate cancer screening... etc
  - beam profile monitoring in charge particle therapy
Bibliography:


Thanks for your attention!