SPADnet: from Concept to Realization

NSS-MIC Special Focus Workshop "Towards 10ps single soft photon detectors"

Claudio Bruschini, EPFL

On Behalf of the SPADnet Consortium

www.spadnet.eu

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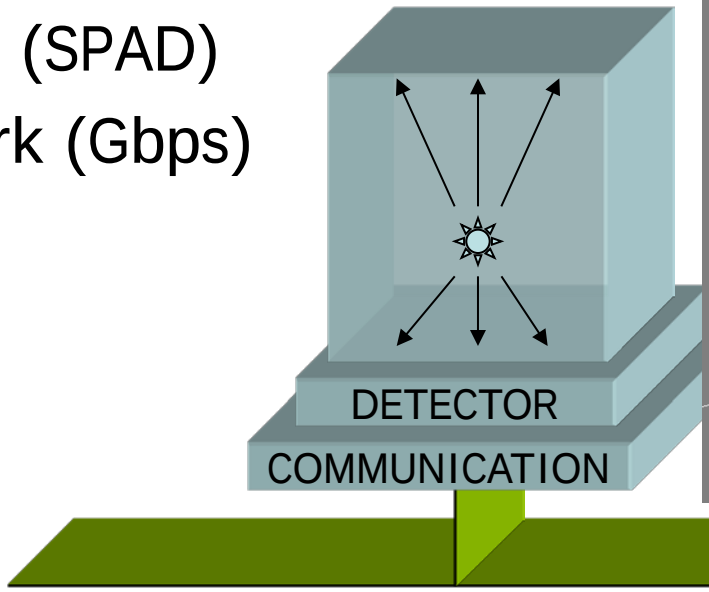
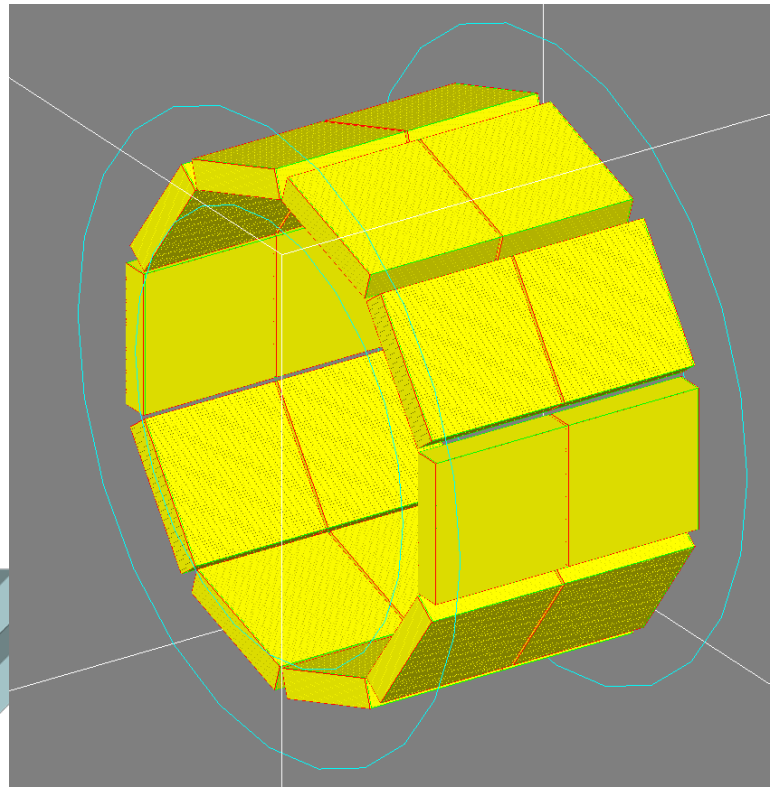
SPADnet Concept & Requirements

Photonic Component, comprising:

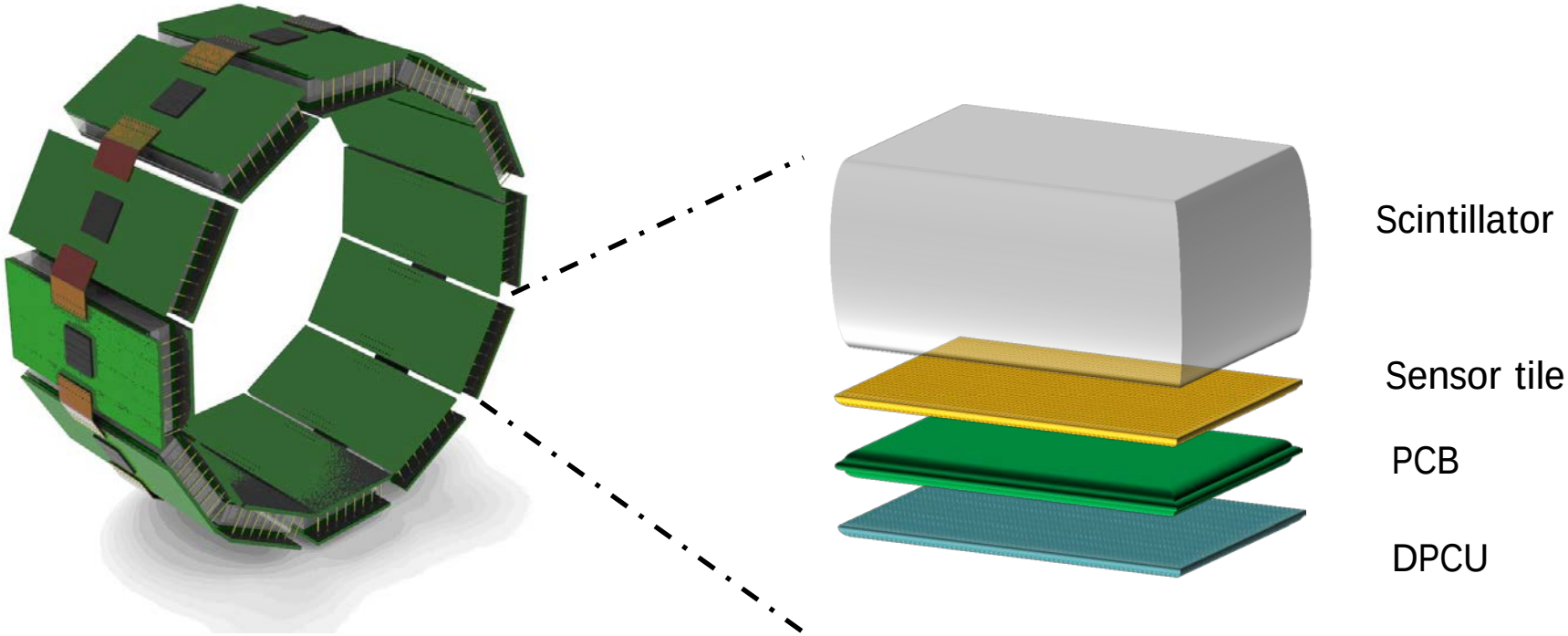
- Scintillator (LYSO)
- Sensor (SPAD)
- Network (Gbps)





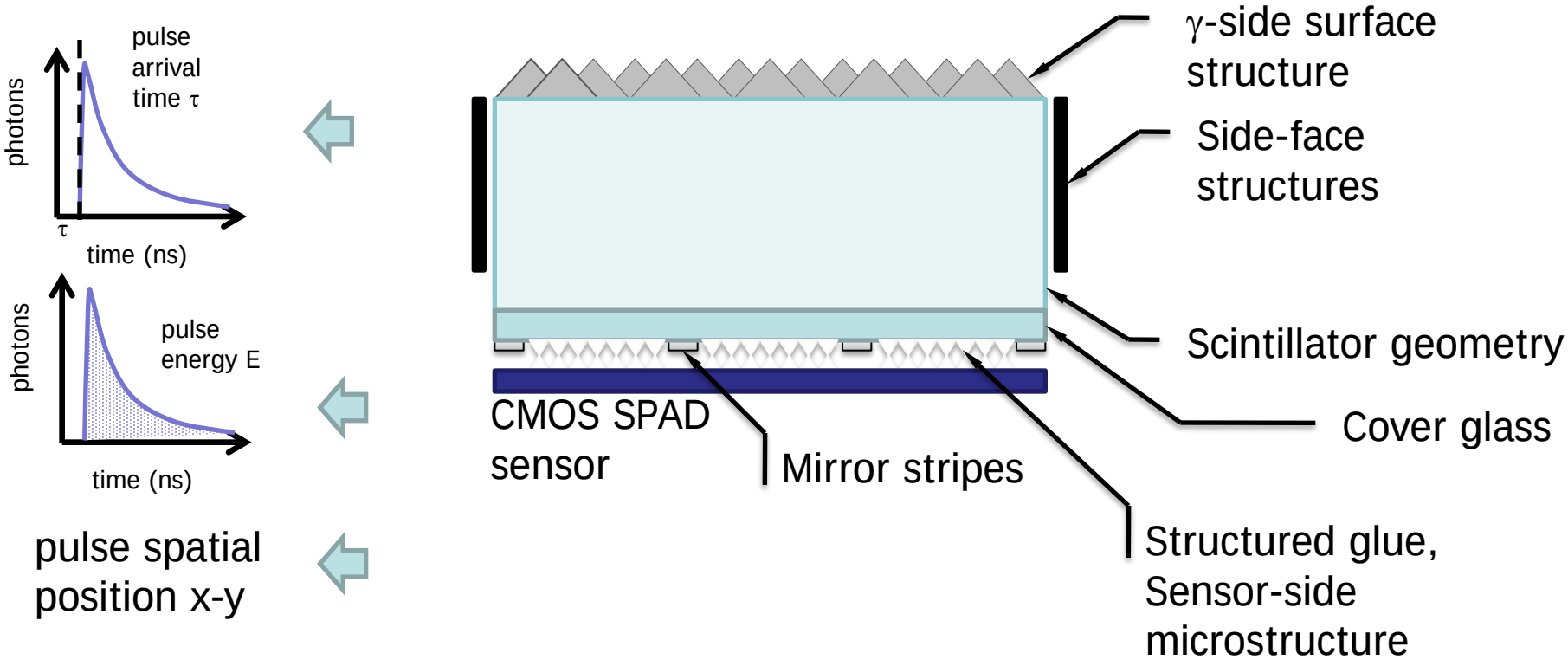
Scalable, modular System

Photonic module construction



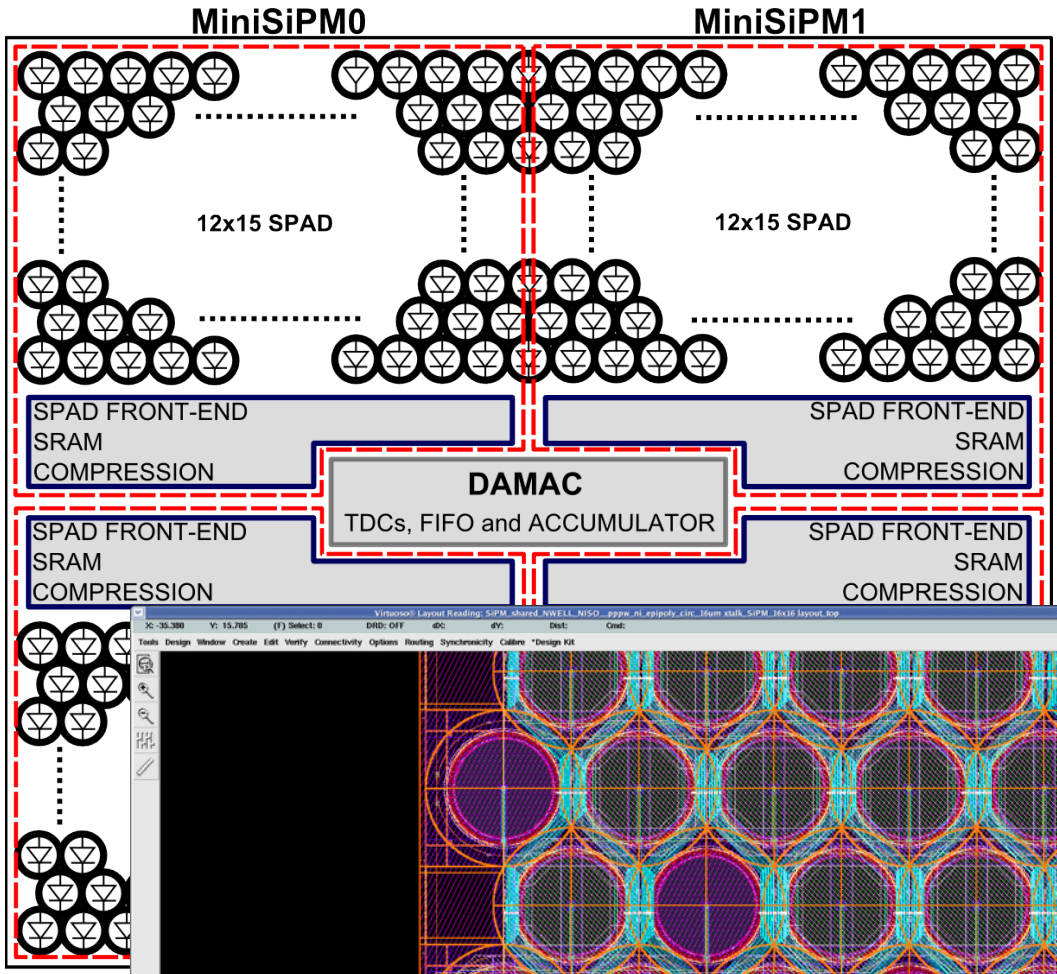
DPCU: Data Processing and Communication Unit

Image Sensor and Coupling to Scintillator



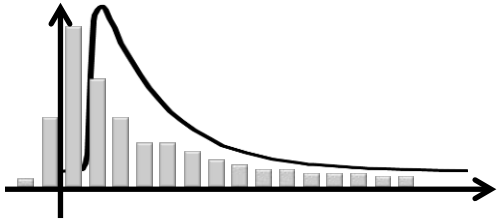
Pixel Architecture

- 2 x 2 mini-SiPMs
- 720 SPADs
- 1 active TDC
- ~0.6 x 0.6 mm²
- 42.6% FF

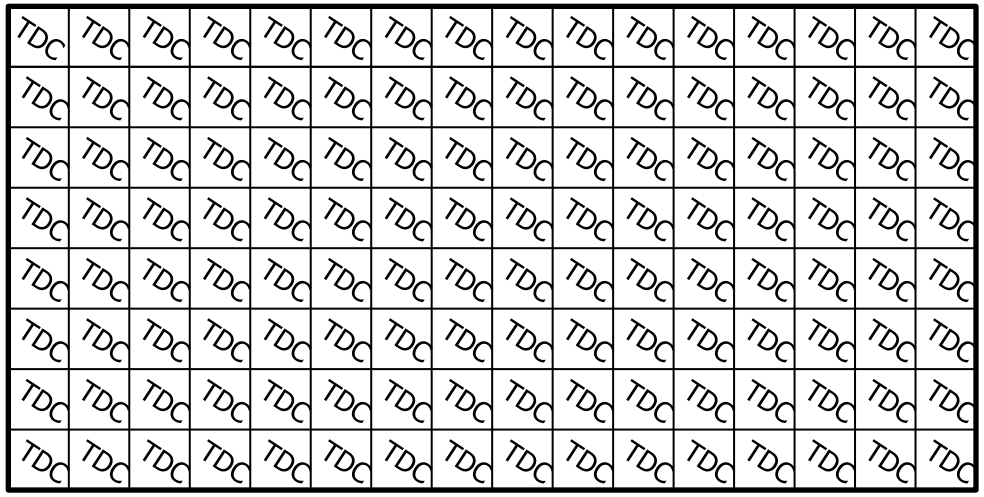


Discriminating Gamma Events

- **Photons are counted in time bins ➔ discrete derivative**



- **Time-to-digital converter (TDC) per pixel**



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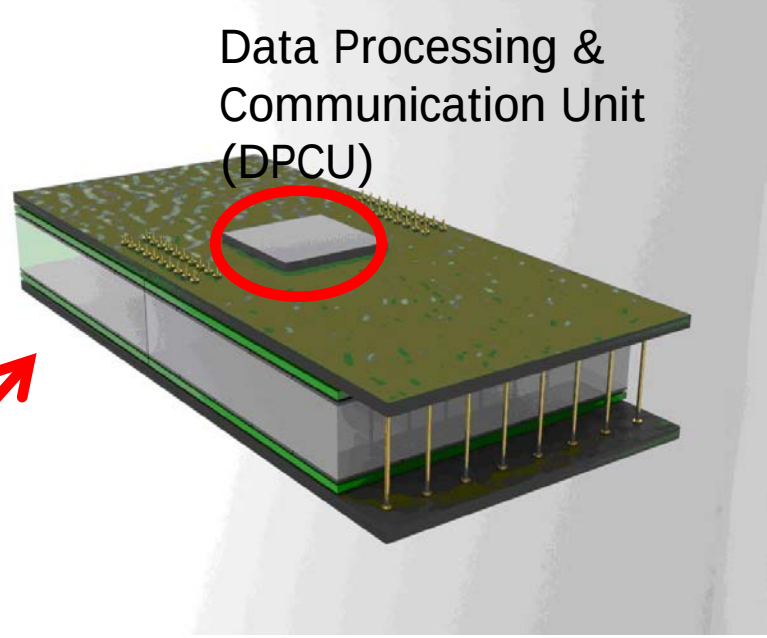
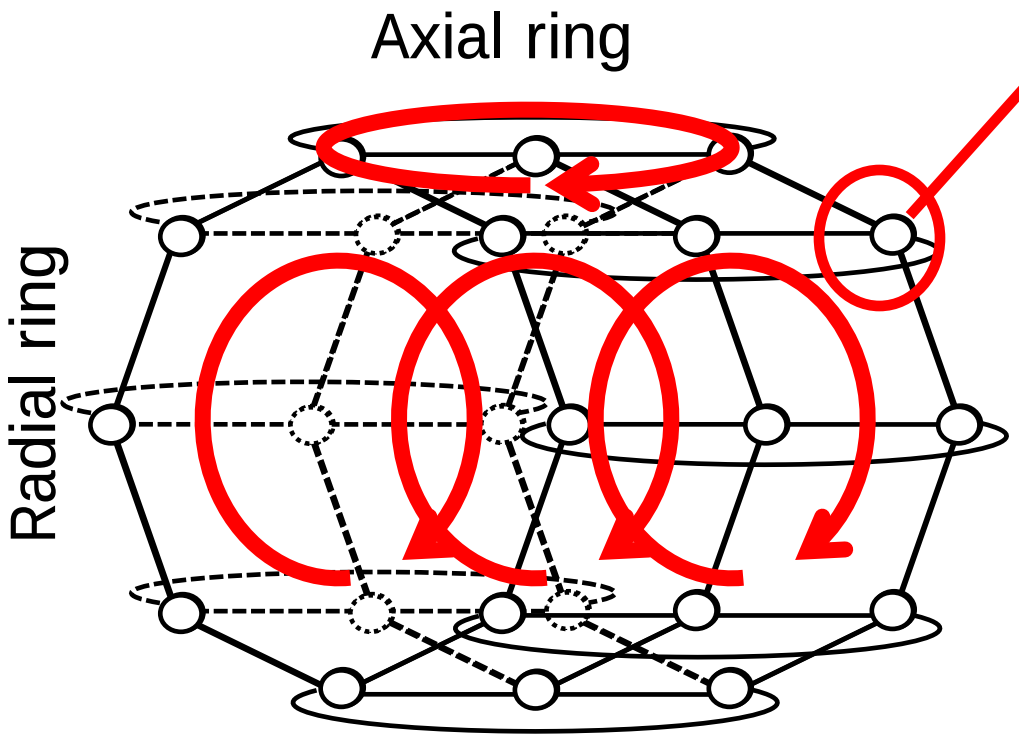
Multi-Ring Sensor Network Architecture & Coincidence Detection



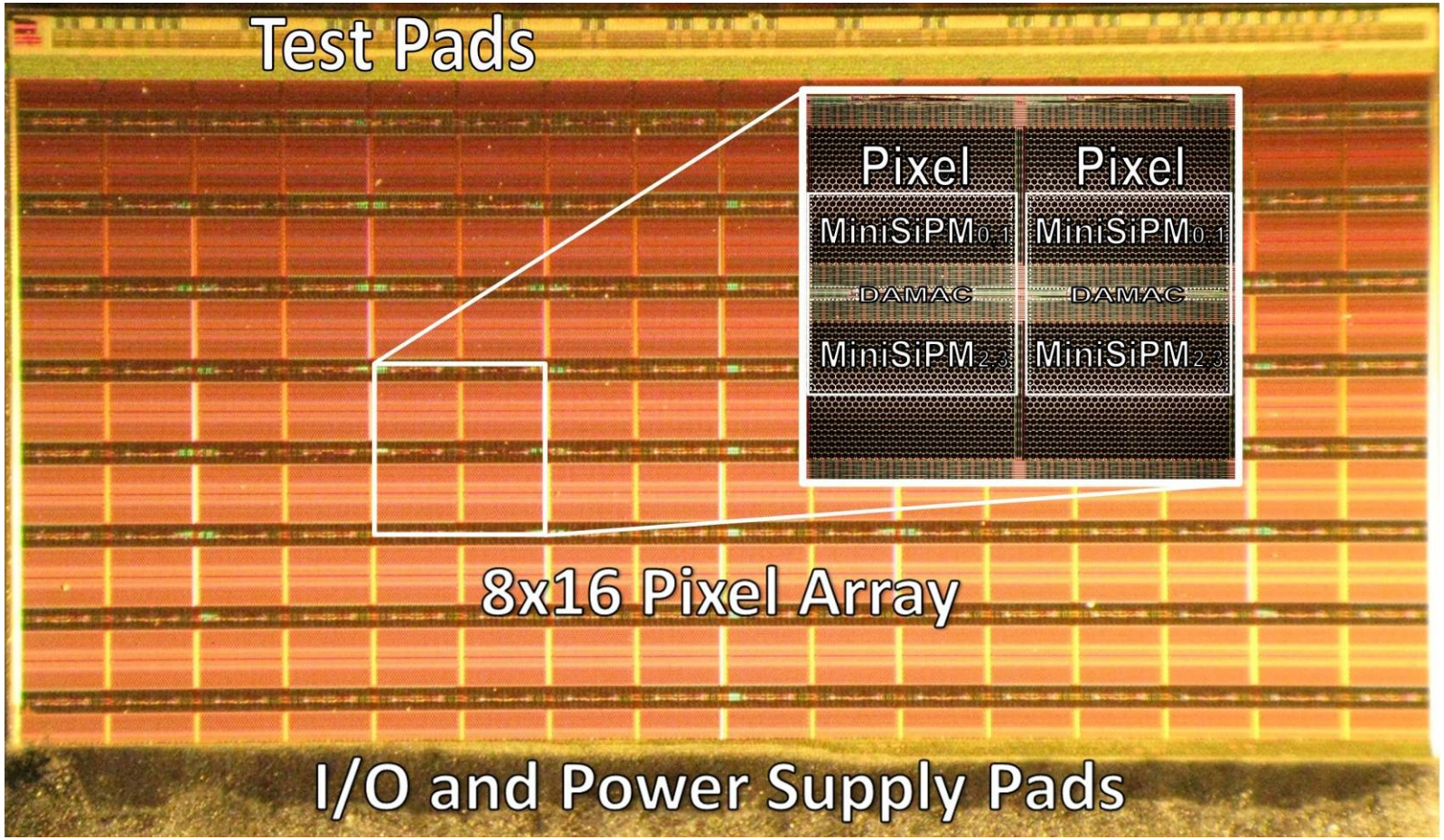


Coincidence packets are circulated first (32 bits, mainly timing information)

[If coincidence] True event Packet
64 bits
- Node information
- Scintillation τ, E, x-y

Realization and Results

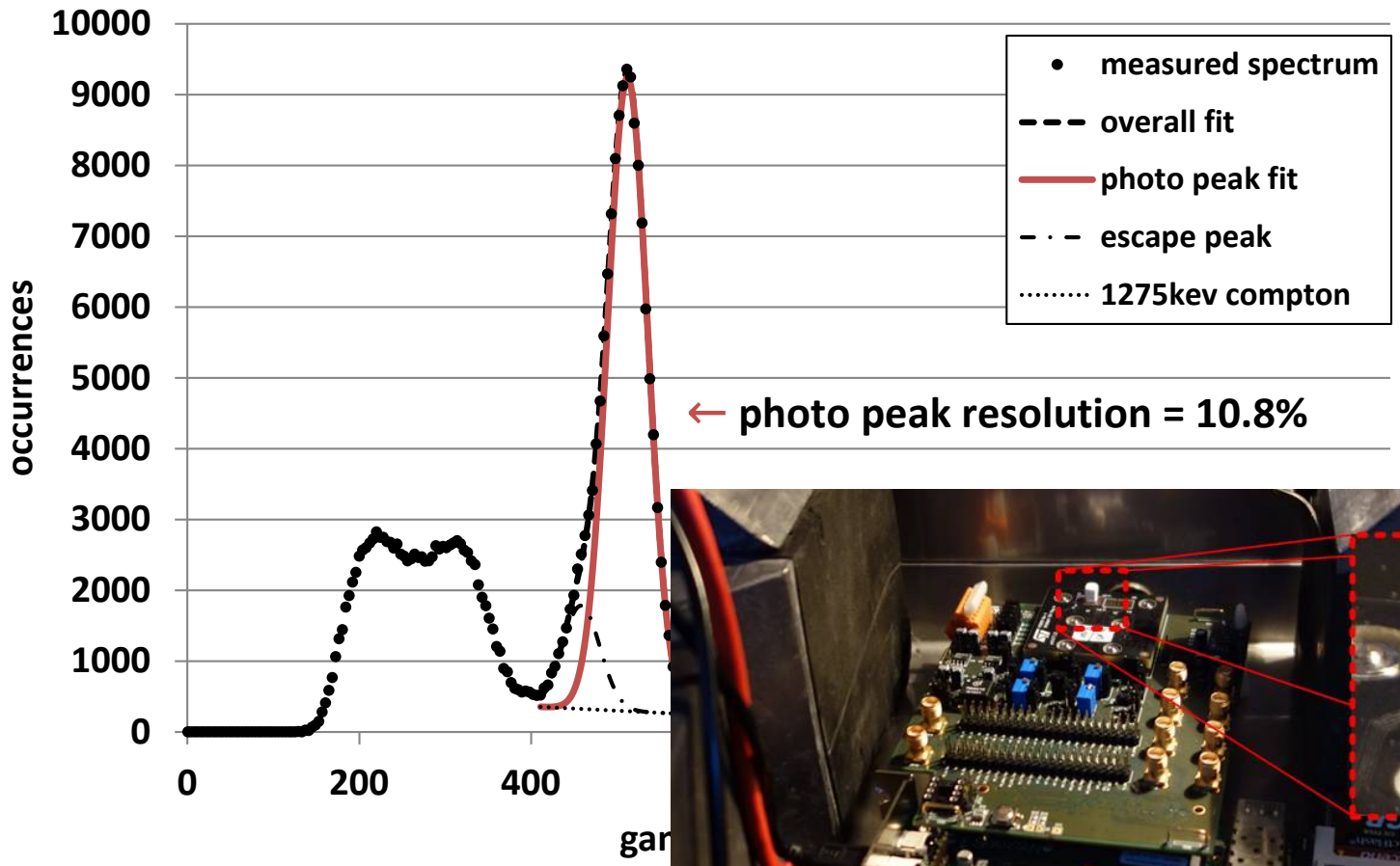
Sensor Micrograph

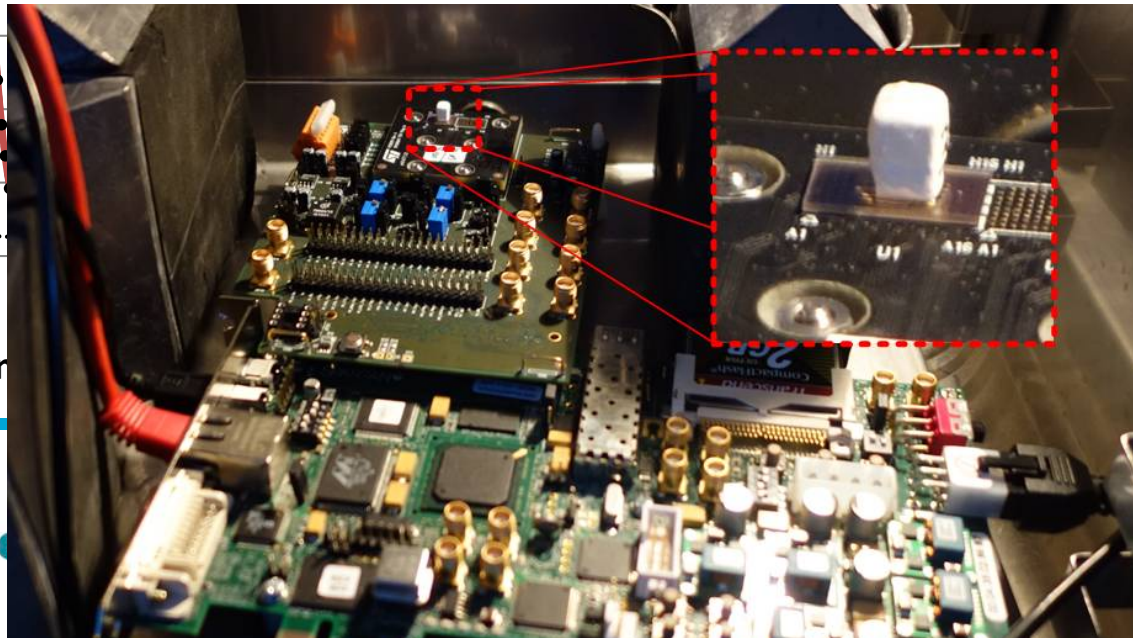


Braga *et al.*, ISSCC 2013

Characterization (^{22}Na, 370kBq): Energy Spectrum

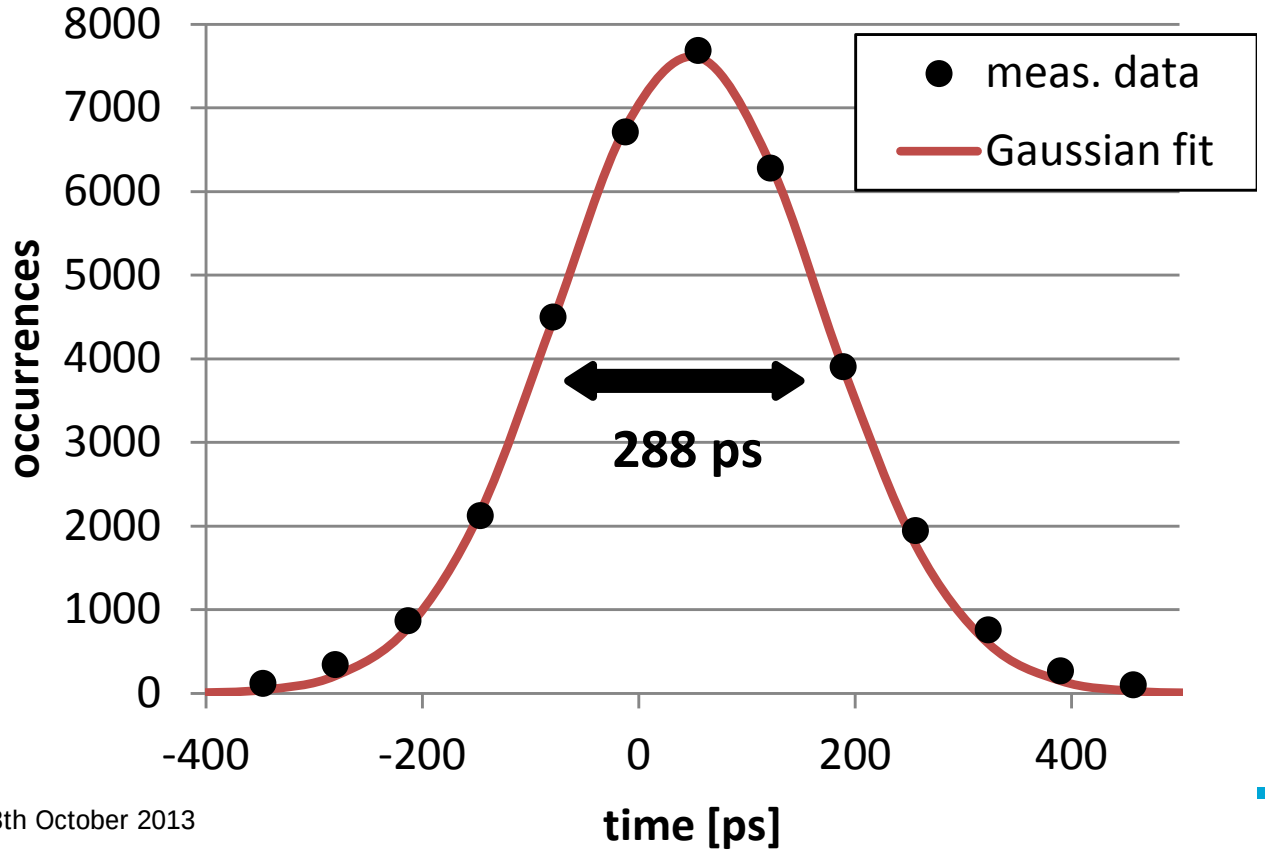
T = 20° C





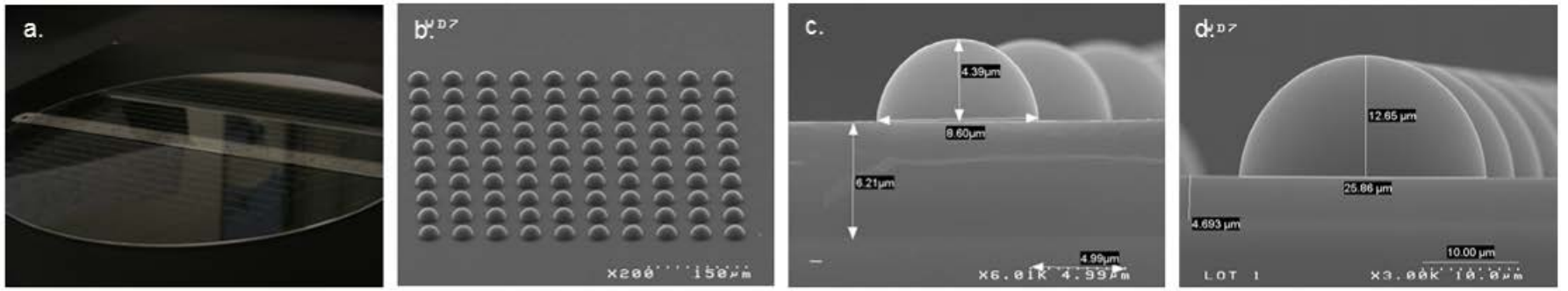
Gamma Characterization

- Coincidence timing resolution:
  - —Algorithm from [Braga, NSS 2012], with 3 timestamps.

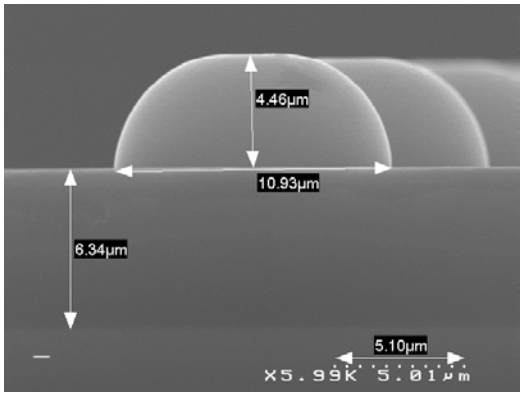


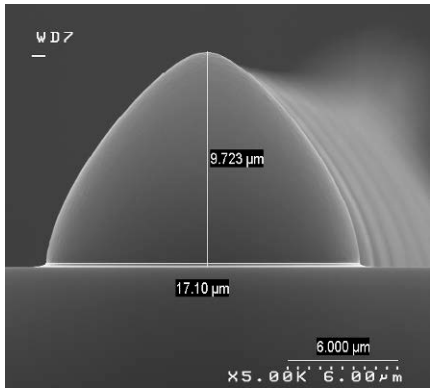
Micro-Optical Structures

- Conventional hemispherical microlenses.

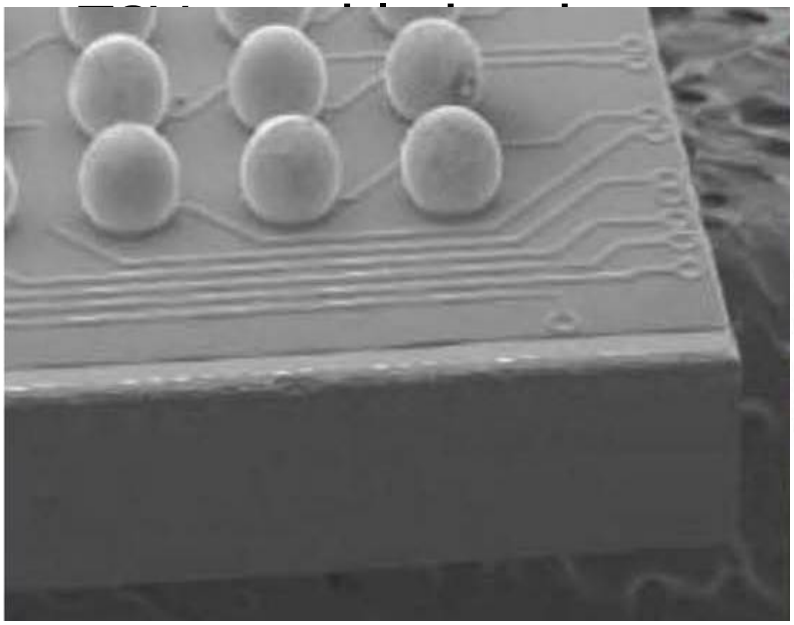


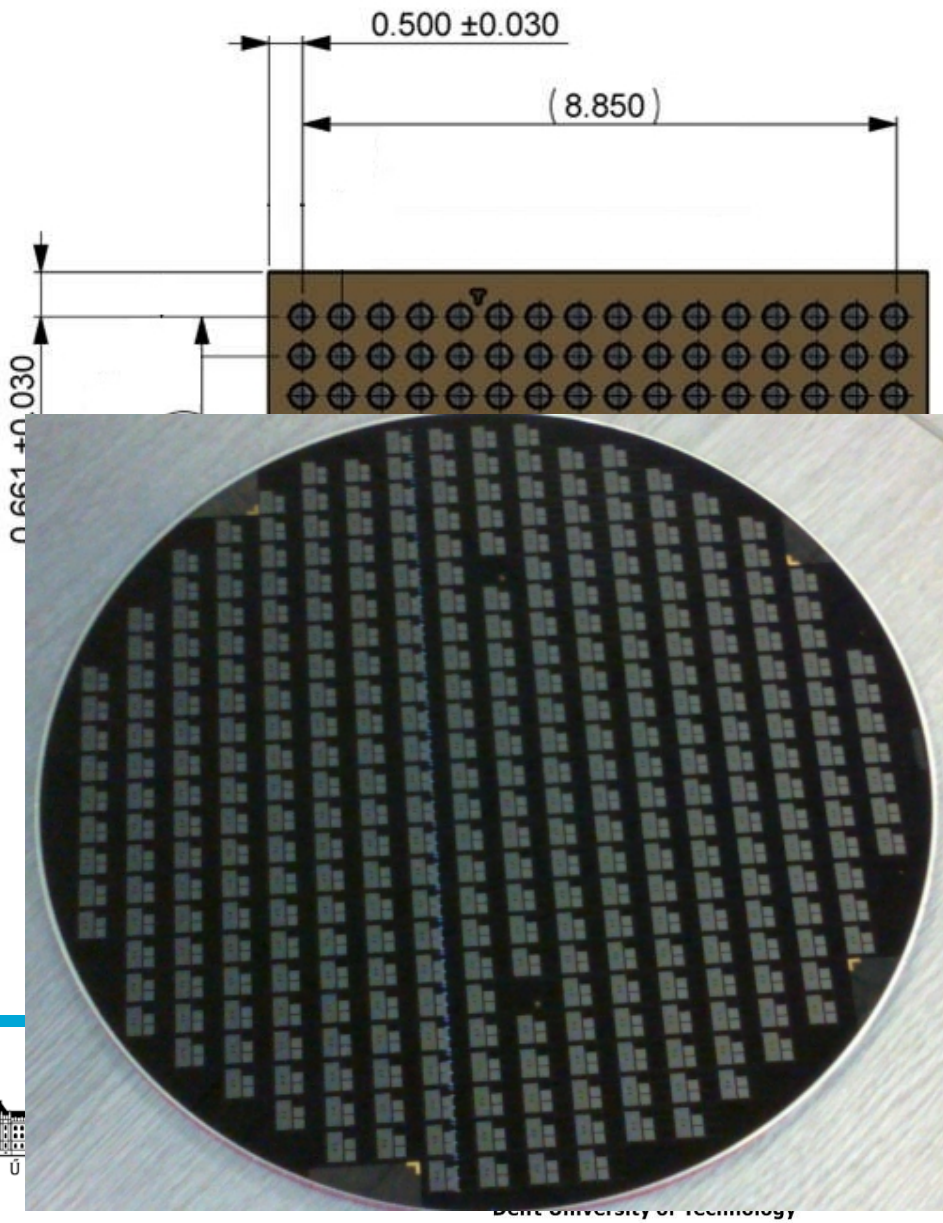
- The etching technique for the realization of the master leads to various shapes: Flat microlens (→ for parabolic structures) and sharp edge



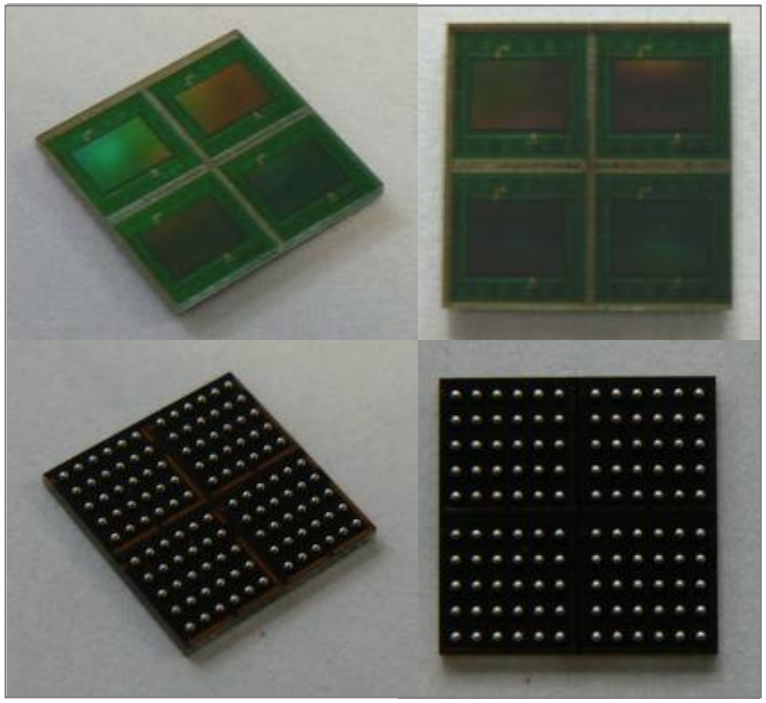


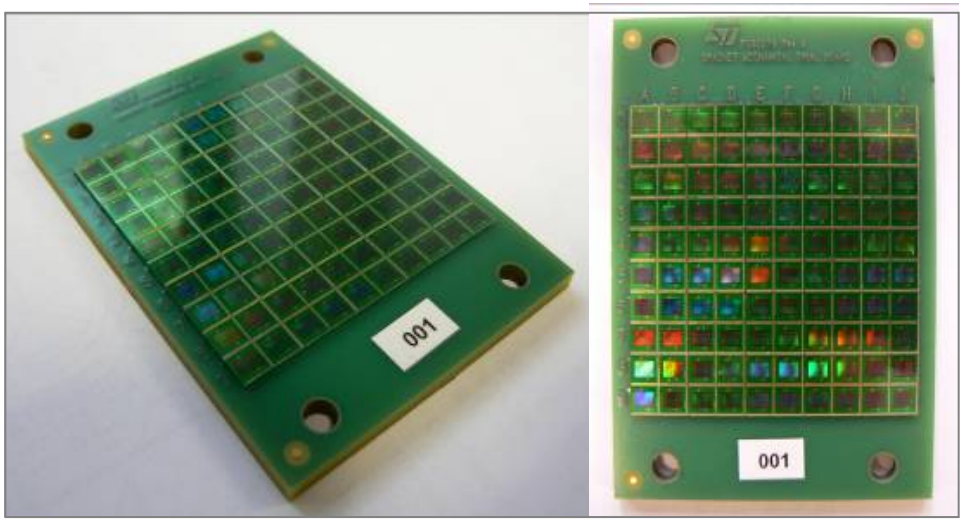
Compact Packaging: Through-Silicon Vias (TSVs)





Frontside: Smooth Abutment





Assembly with similar TSV chips

- Flat and level for scintillator mounting
- Easy X,Y scalability
- Standard reflow assembly

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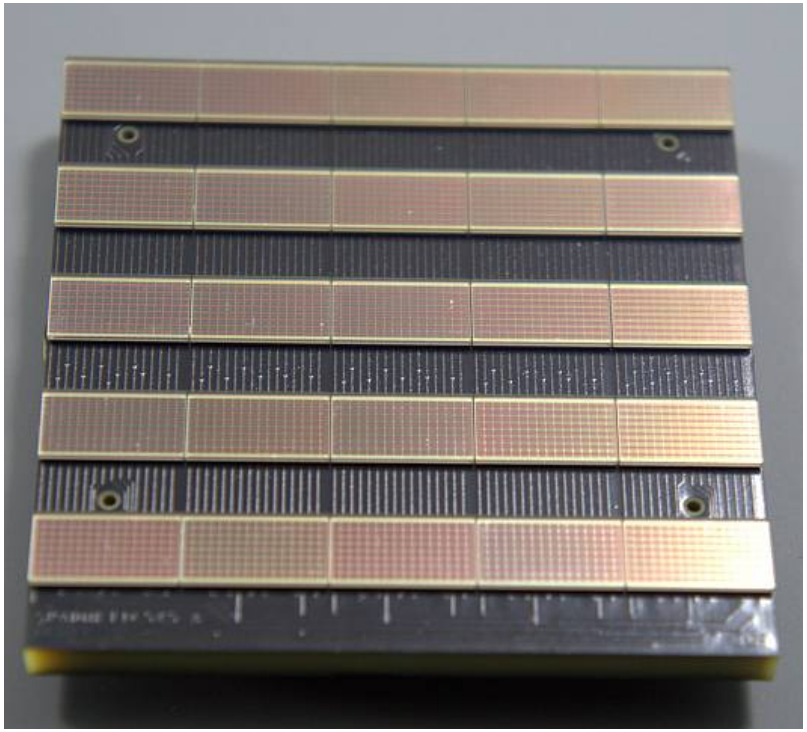
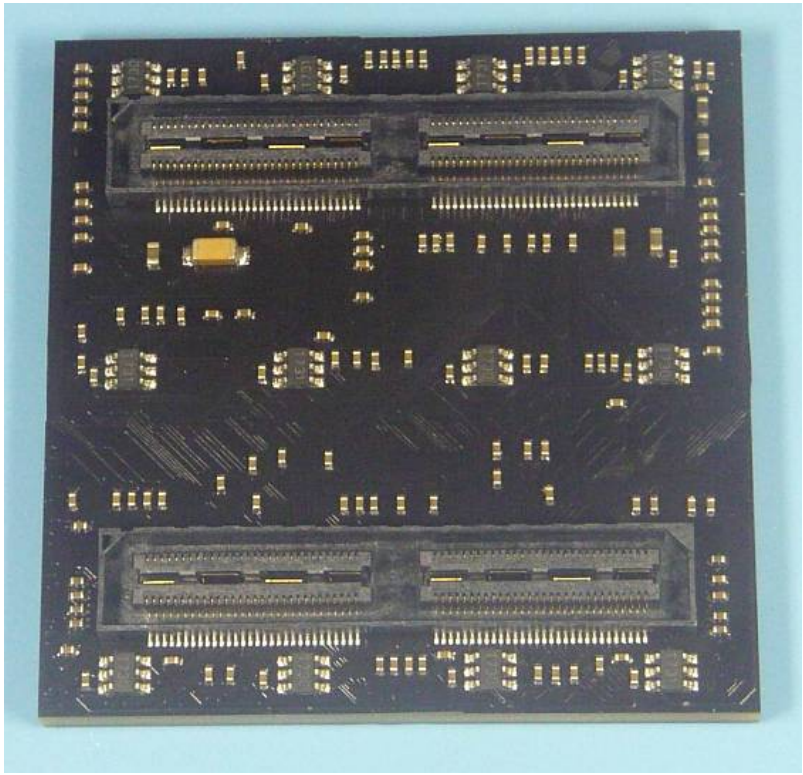
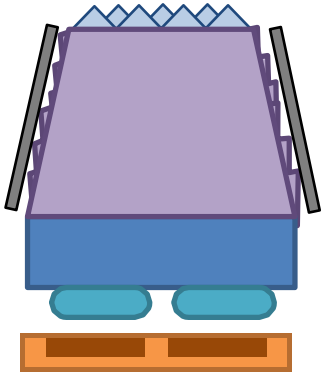
SPADnet tile





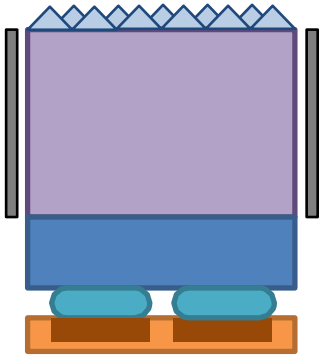
PET detector module optimisation

Primary choice



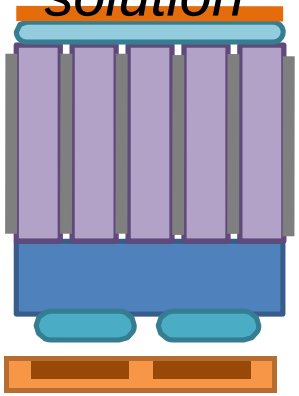
- 2x better total count
- works with modified COG

Reserve solution



- good spatial resolution w. COG
- acceptable total counts

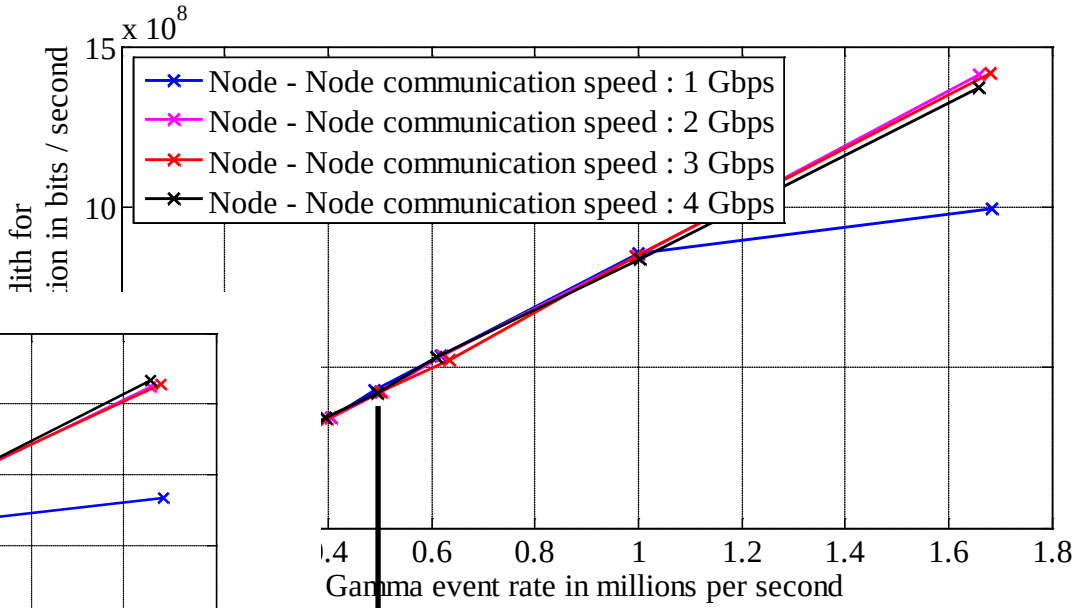
Conventional solution



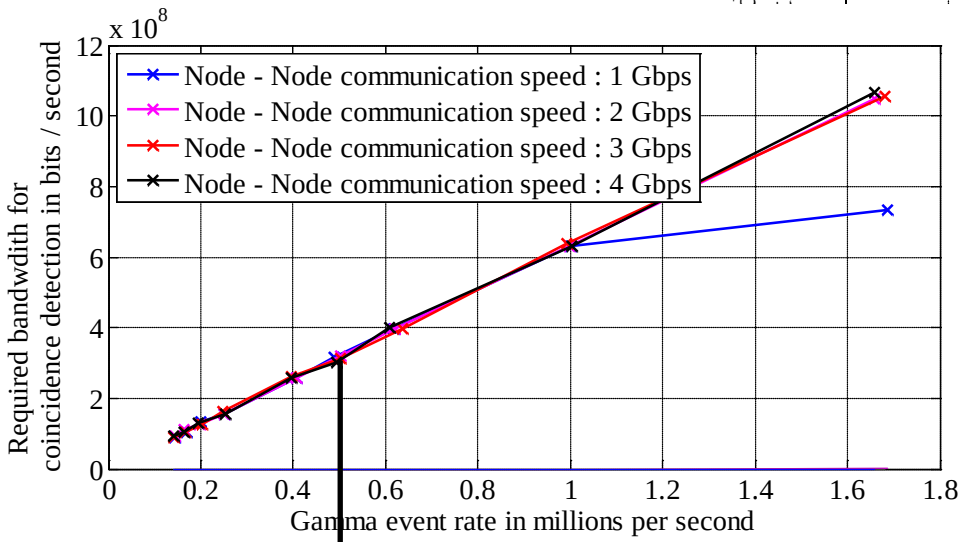
- non-DOI capable
- safe, prooven solution

Clinical PET Network Simulations

Axial ring



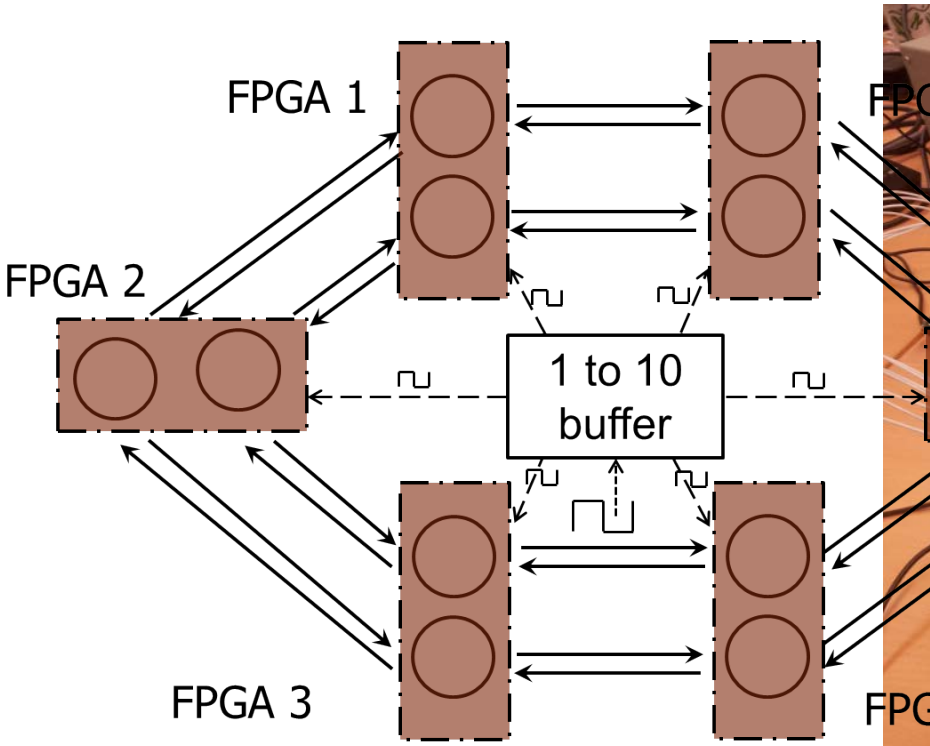
Radial ring

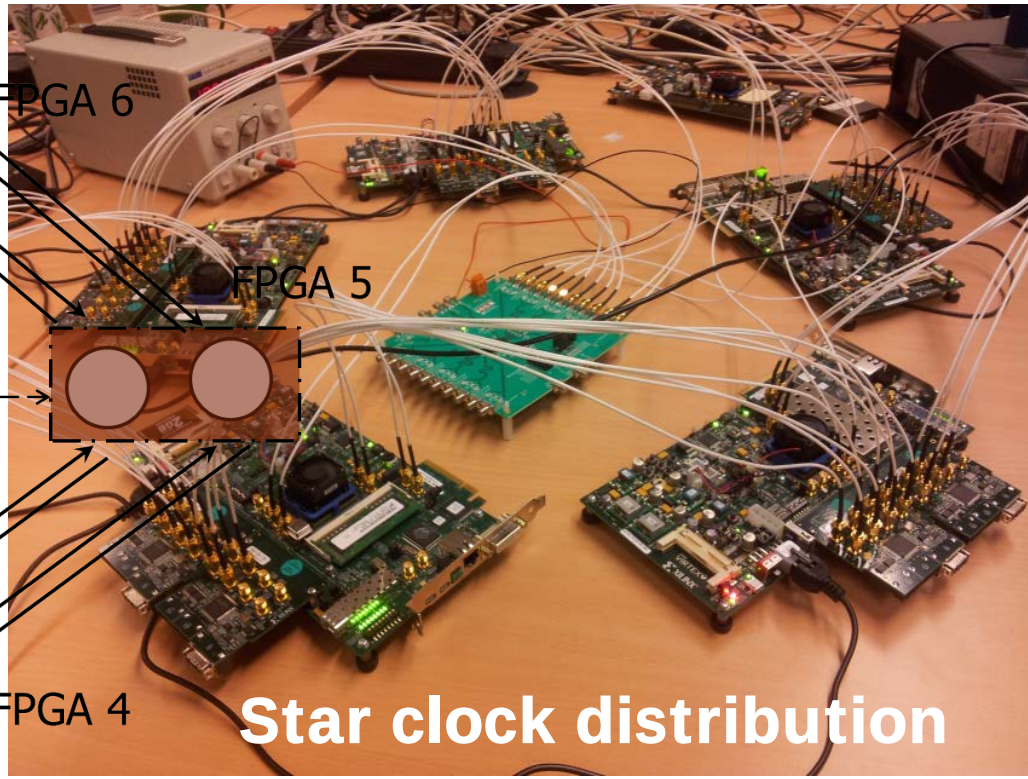


Worst case expected gamma event rate per module

Network Implementation

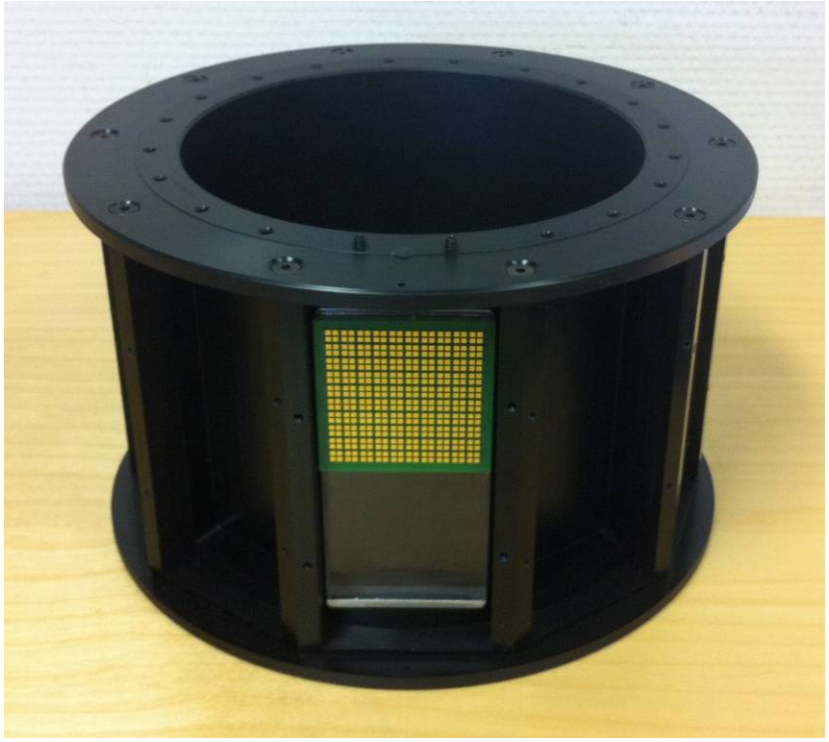
- Migration to multi-ring for three applications (H, B, P)
- Clock synchronization completed

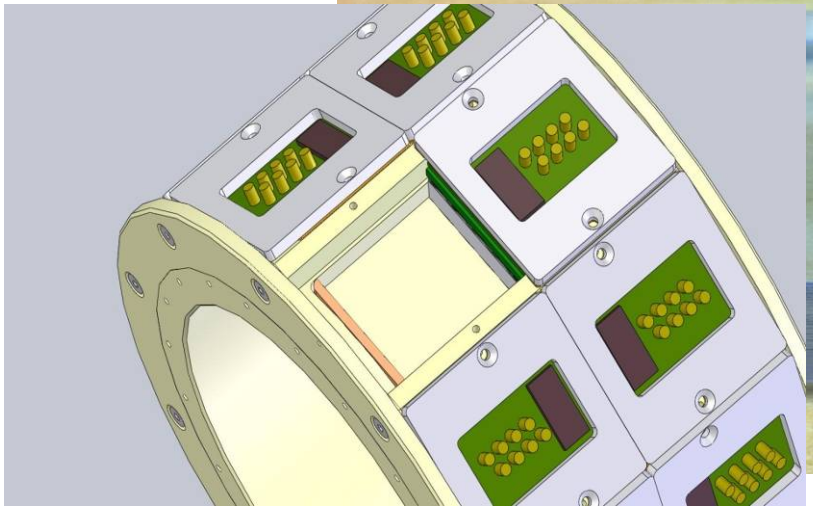


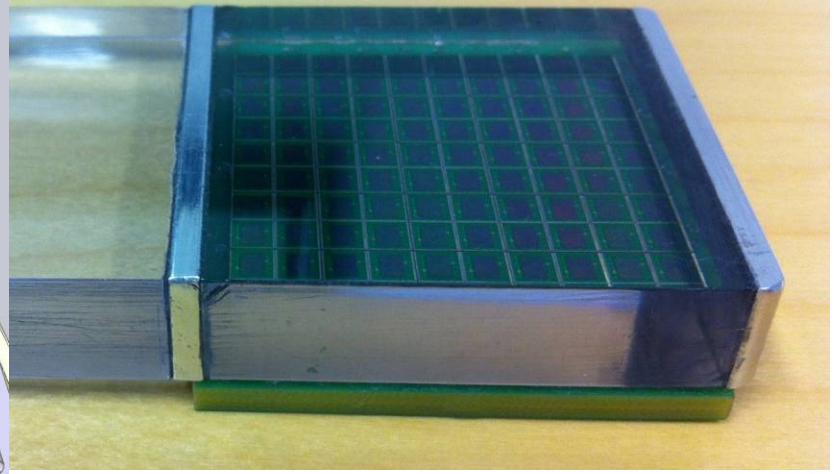


Preliminary System

- Non-magnetic material
- Mechanical stability (~3.5 kg crystal)
- Mechanical precision
- Flexibility
- Easy to mount on Mediso's existing gantry

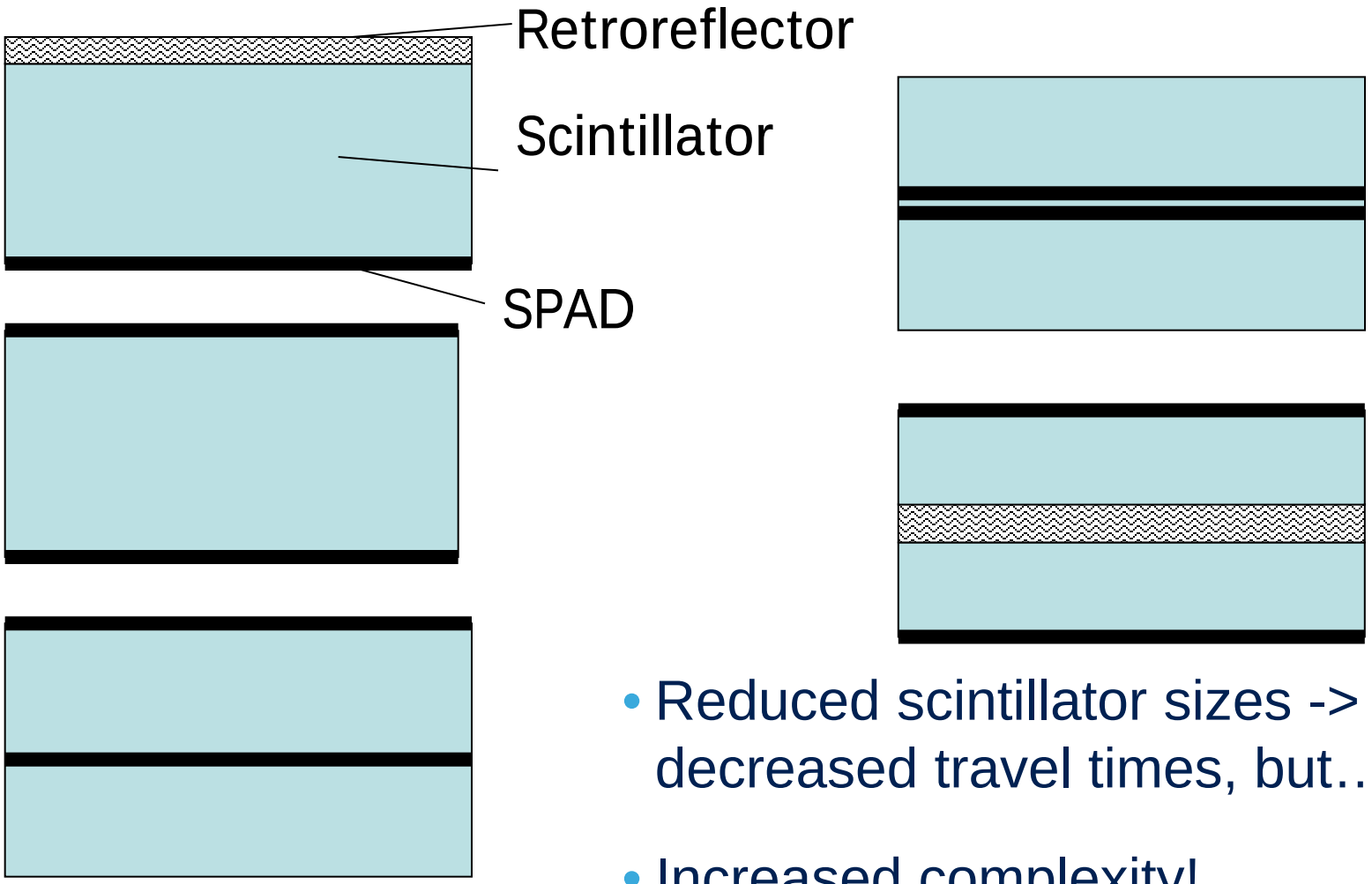






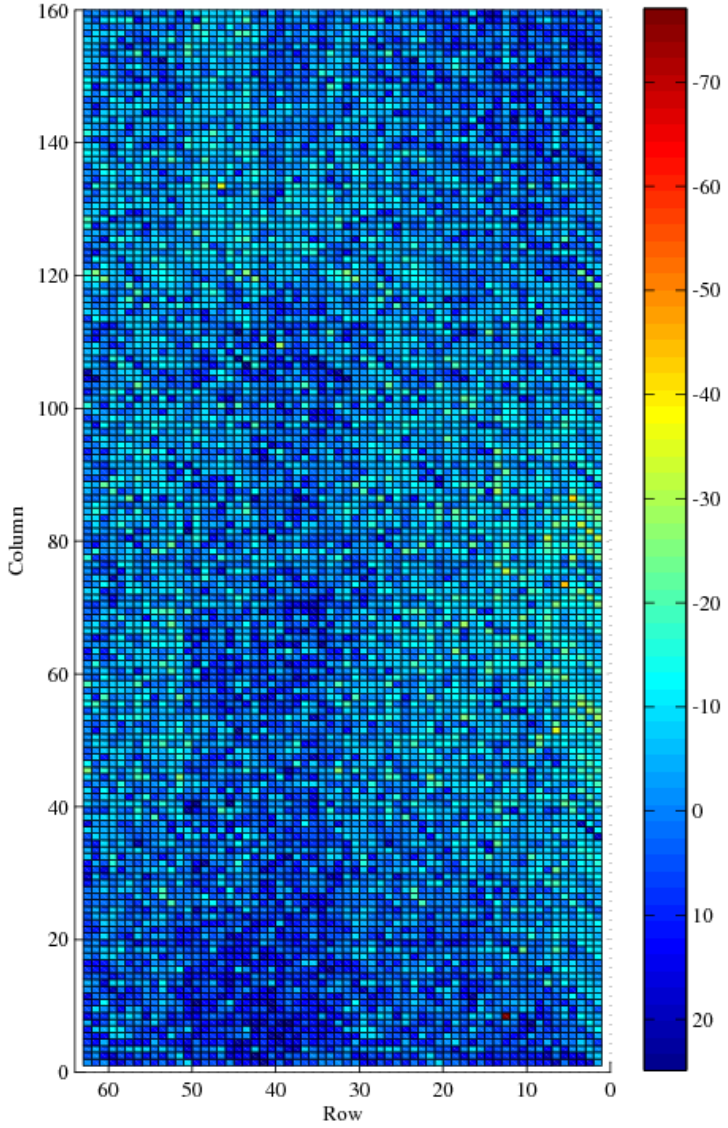
Beyond SPADnet – Possible Enhancements of the underlying Concepts

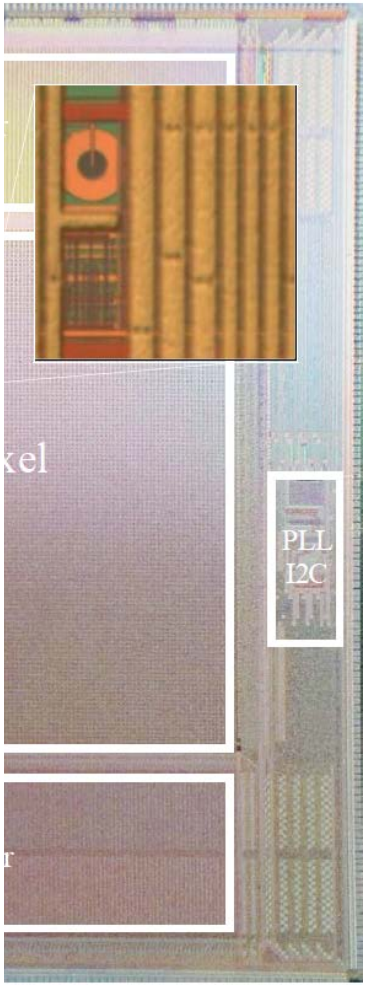
Alternative detector modules



- Reduced scintillator sizes -> decreased travel times, but…
- Increased complexity!

TDCs: use of more advanced processes





- MEGAFRAME128: an array of 160x128 TDCs
- Pixel size: 50μm, Timing res: 55ps, 0.13μm process
- Move towards more advanced processes -> even better time resolution?

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TDCs: ASIC vs FPGA

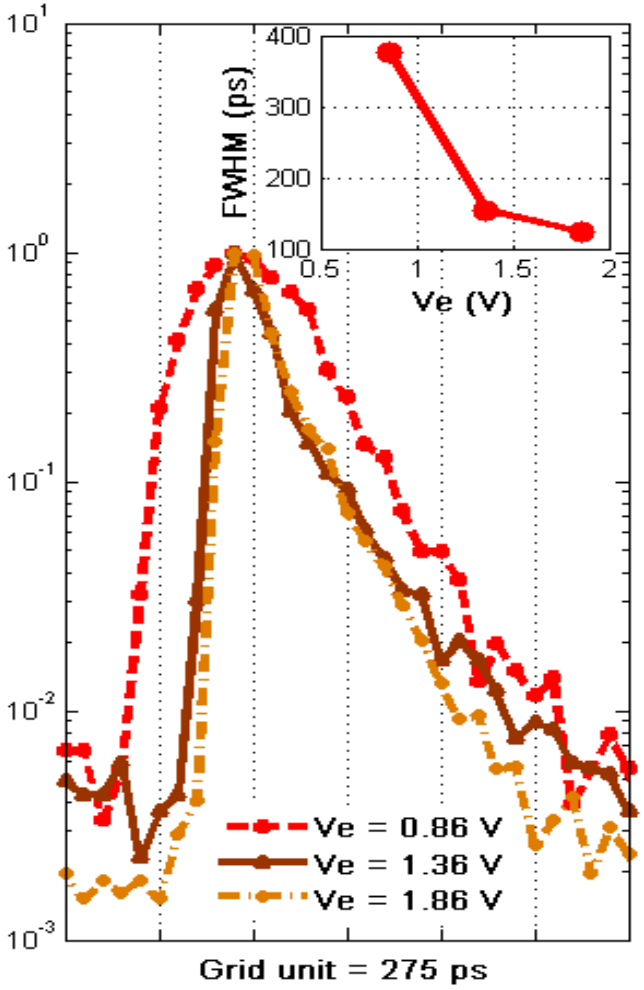
FPGA

- Best time uncertainty: 20ps
- Usage examples
  - —High-energy physics
  - —OpenPET

ASIC

- Best time uncertainty: <1ps
- Examples
  - —Time-correlated imaging
  - —Frequency synthesizers for RF

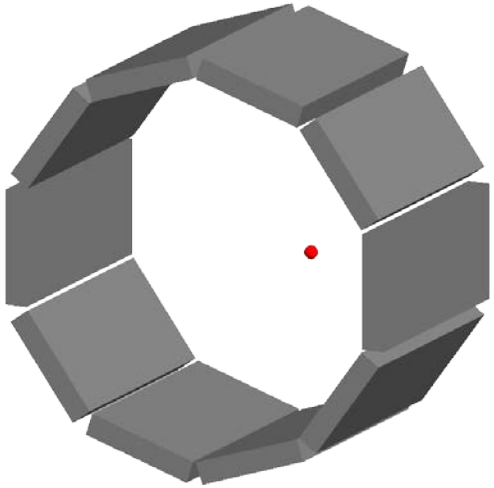
SPADs: increase bias voltage

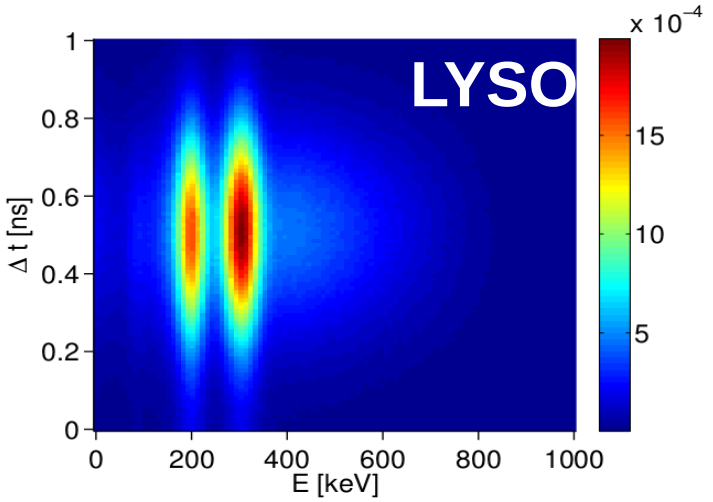


Red laser (637 nm)

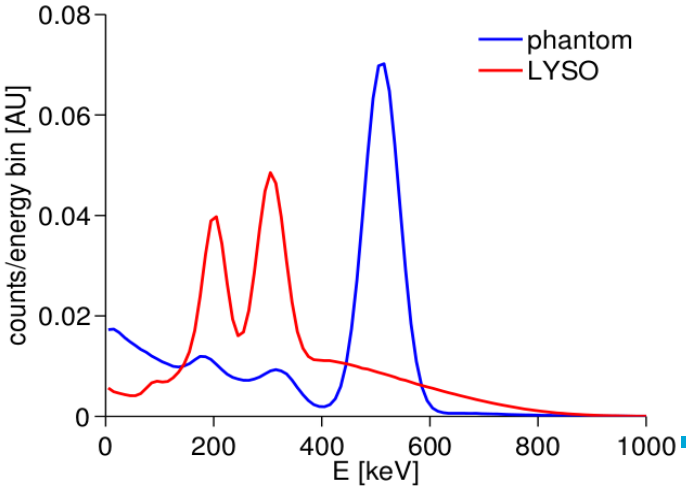
- Increased bias voltage – better timing resolution vs increased noise (DCR)
- Advantageous when using robust architectures

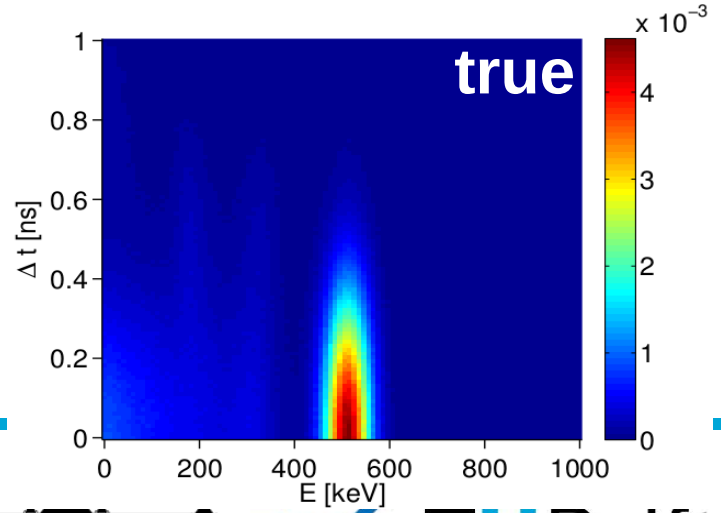
Preclinical ToF Application





Lower Minimal Detectable Activity (extend system dynamic range)





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Conclusions
- SPADnet Innovates in:

- Gamma detection via multi-pixel sensor with embedded TDCs and digital output
- Large format with through-silicon-via based packaging and CMOS compatibility, Advanced optical coupling
- Scalable, multi-ring network with coincidence detection at gigabit data rates
- Image reconstruction exploiting spatial information

Overall considerations

- Let's not forget practical aspects: Scalability, room temperature operation, mass production, and... cost!

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Live sensor demo & Presentations

- **Come see a live sensor demo at:**
  - ➔ Booth #16 (**MEDISO**);
  - ➔ Tuesday 19:00-20:00 and Wednesday 16:00-17:00.

- **SPADnet presentations:**
  - L. H. C. Braga et al, **N08-6**
  - E. Charbon *et al*, **M02-3**
  - L. Gasparini *et al*, **N34-8**
  - B. Jatekos *et al*, **M11-31**
  - G. Patay *et al*, **M13-6**
  - L. H. C. Braga *et al*, **M14-3**

Back-up Slides

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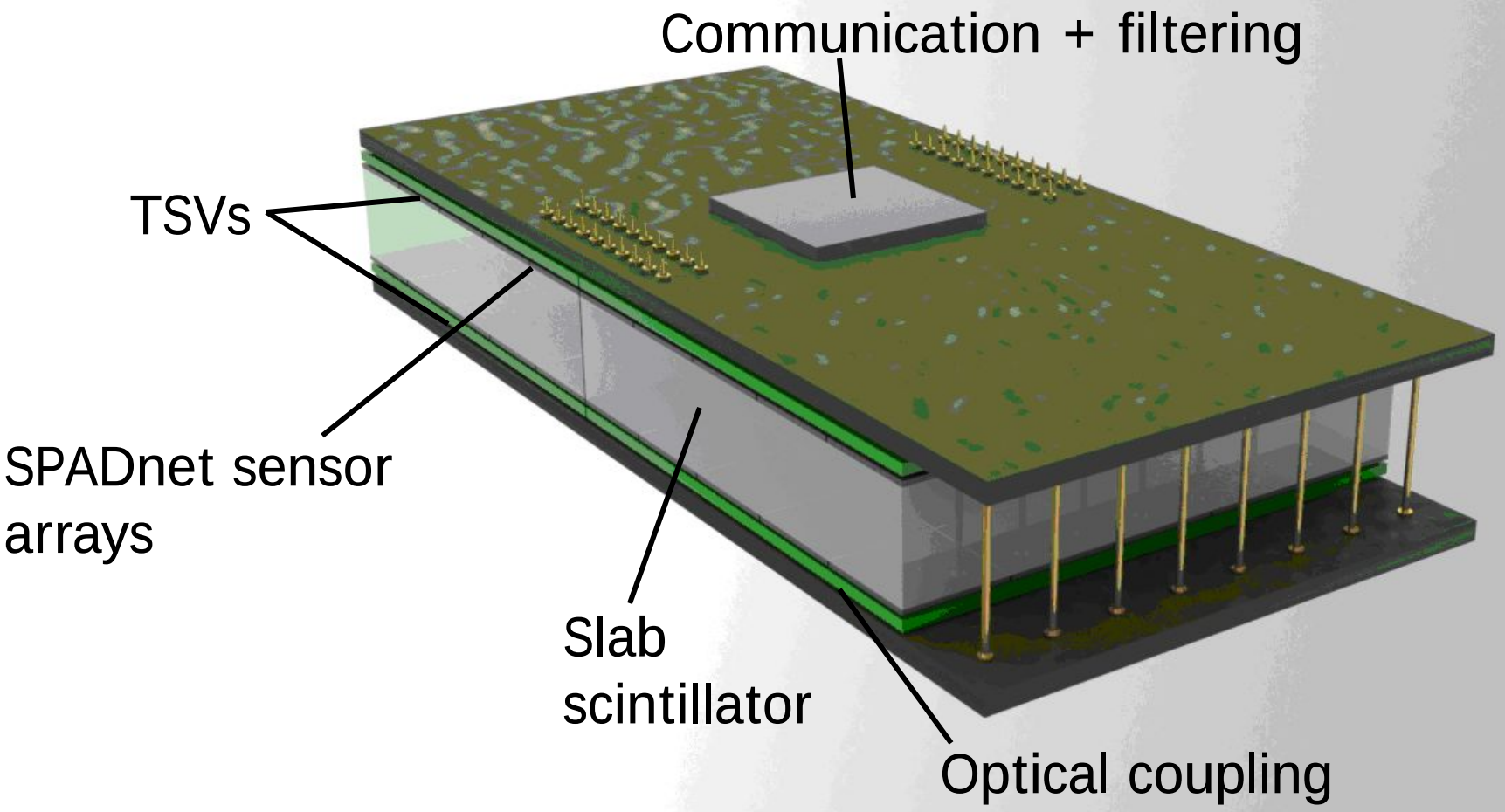
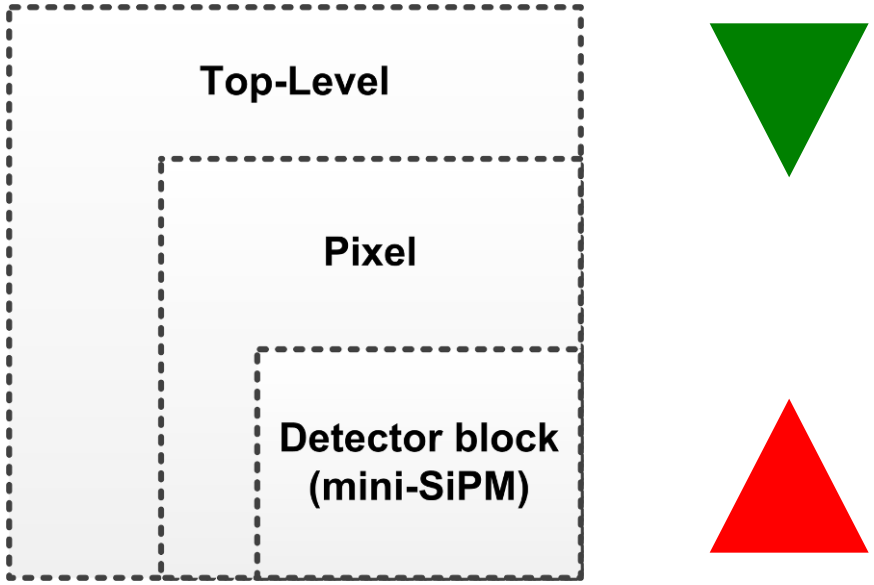
Next: Complete Photonic Component

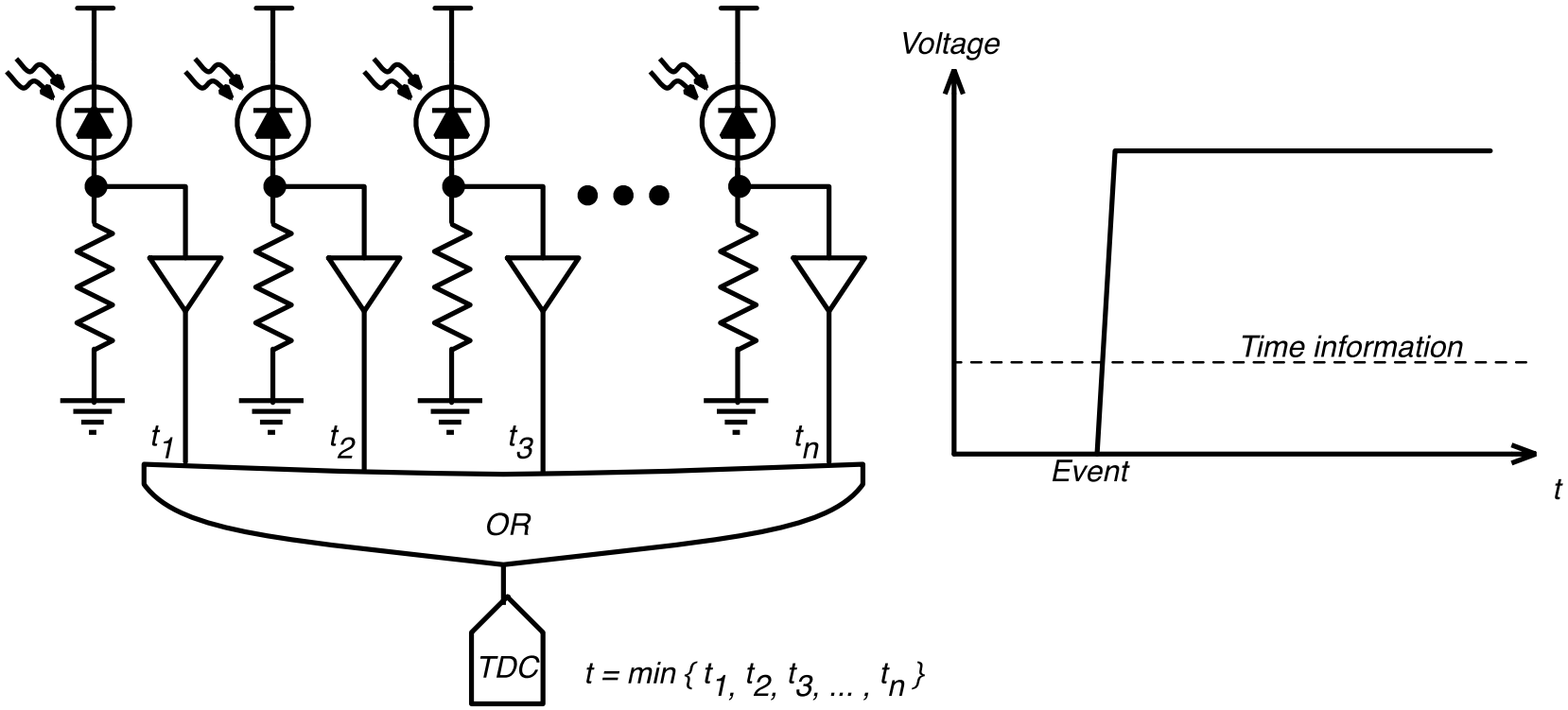


Sensor Requirements

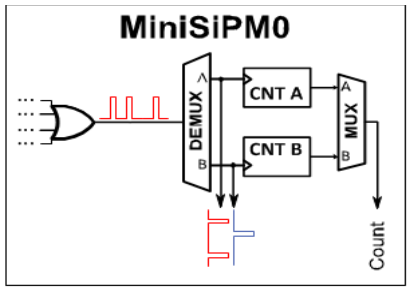
- Single- and multi-photon detectability
- Multi-pixel
- Time-of-arrival
- Digital output
- CMOS

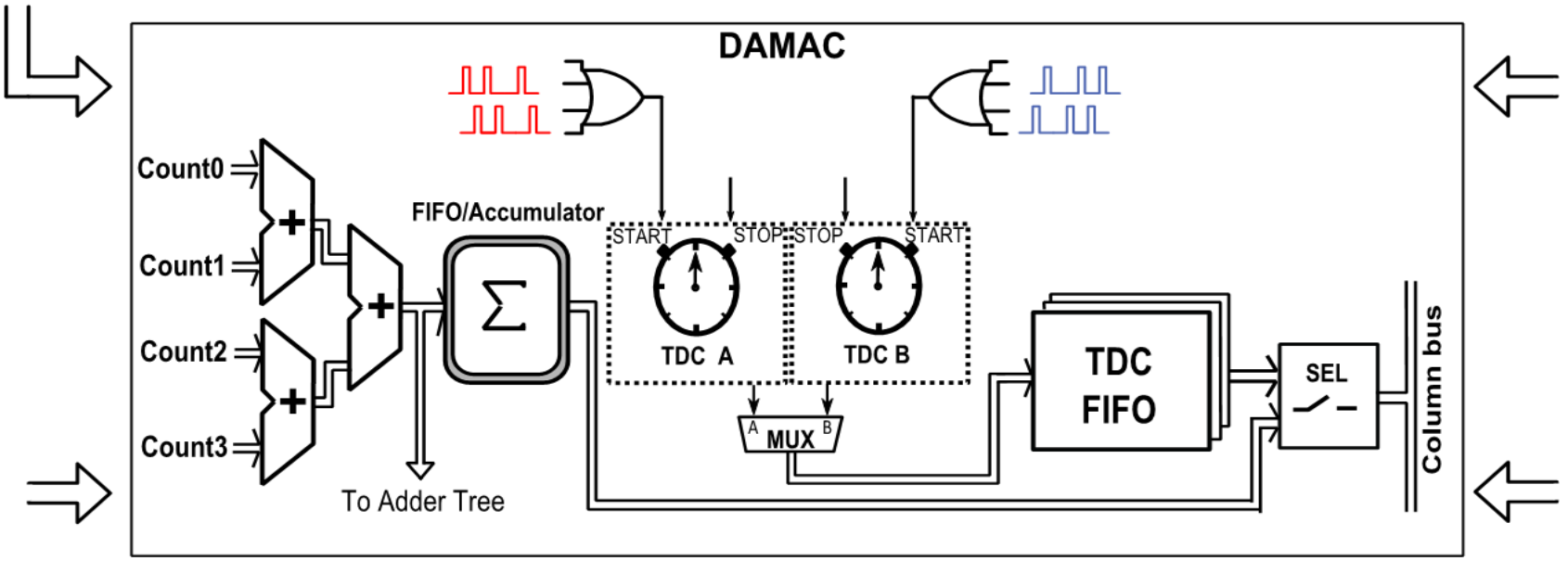


Conventional Digital SiPM



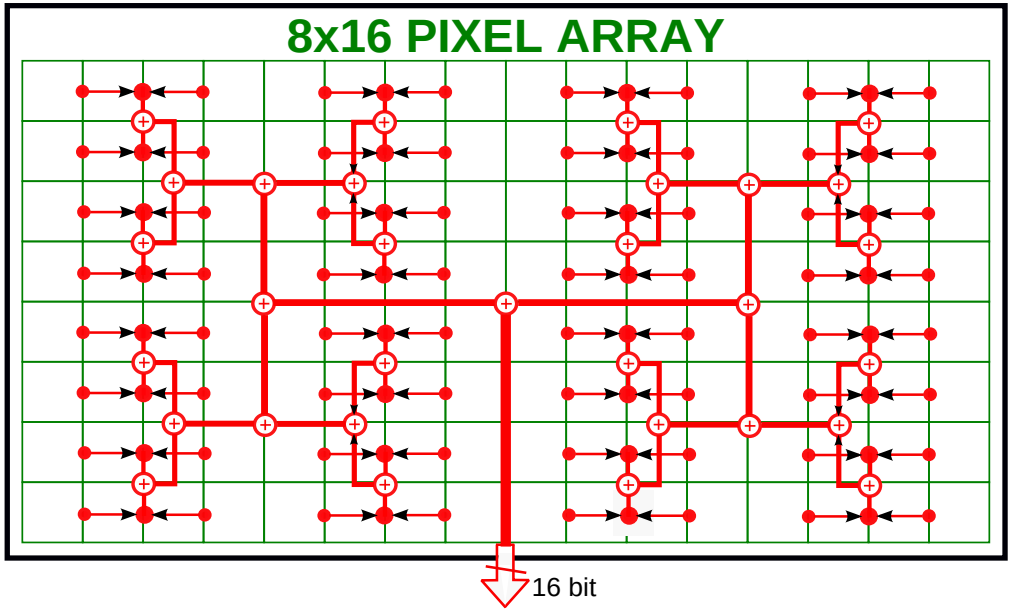
Pixel Architecture





Discriminating Energy

- Fast readout of the counted photons which are proportional to the energy of the Gamma ray
- Fast evaluation of event to reduction of noise impact



up to 100 Msamples/s

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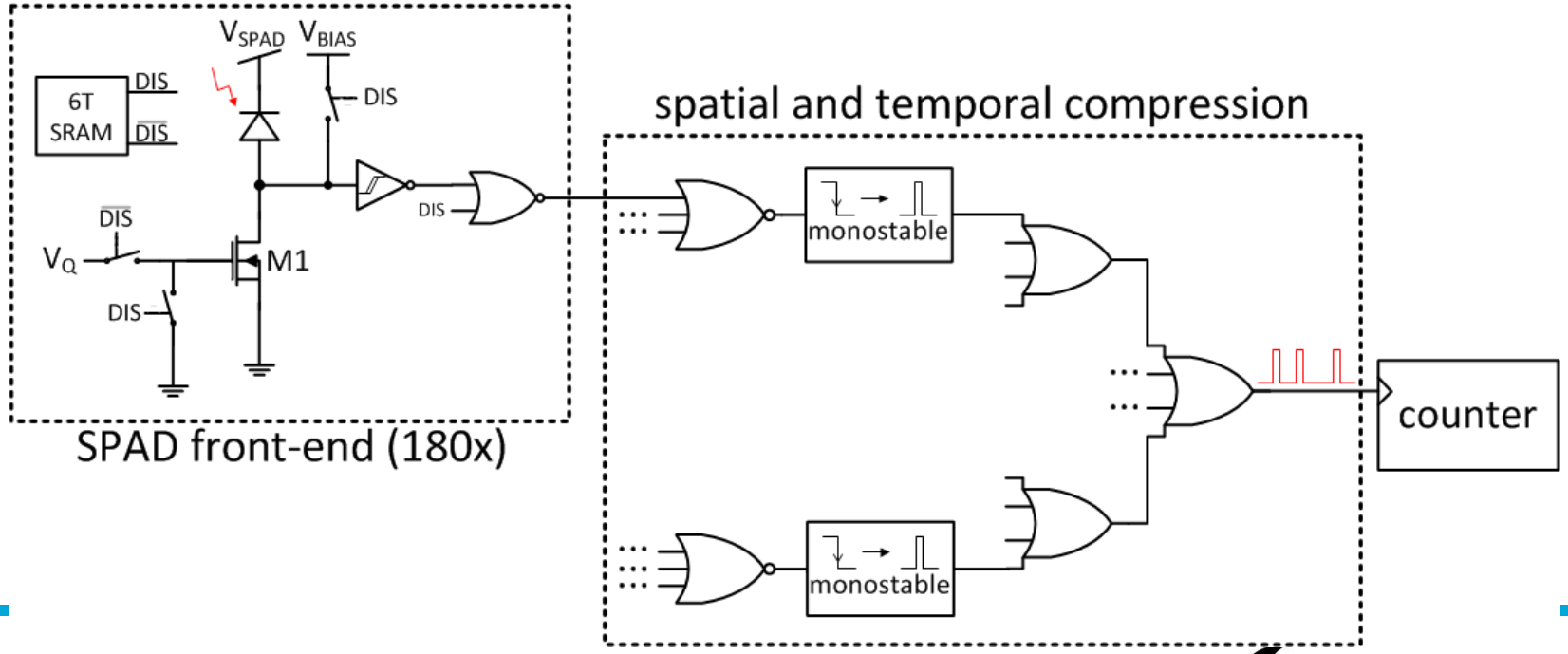
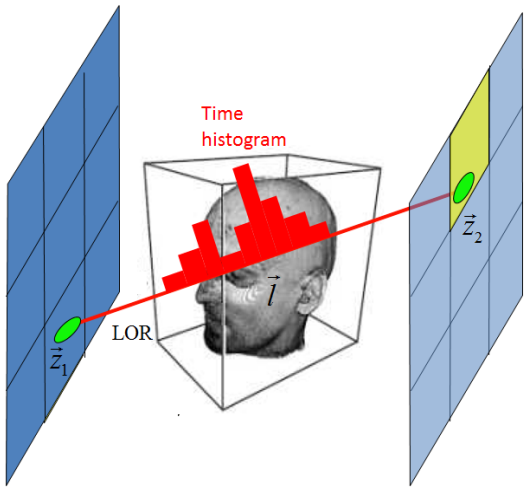
Spatial and Temporal Compression

- Detector block: the mini-SiPM
  - —Shortened SPAD pulses flow through a compression tree up to a counter.



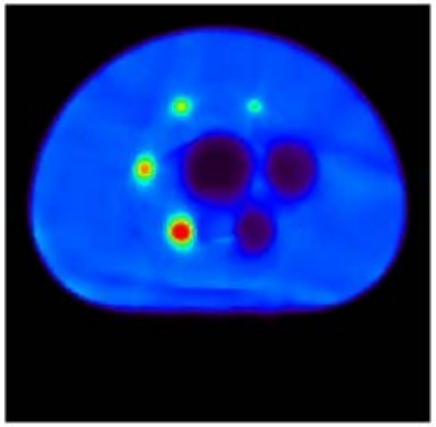
The Advantages of TOF PET



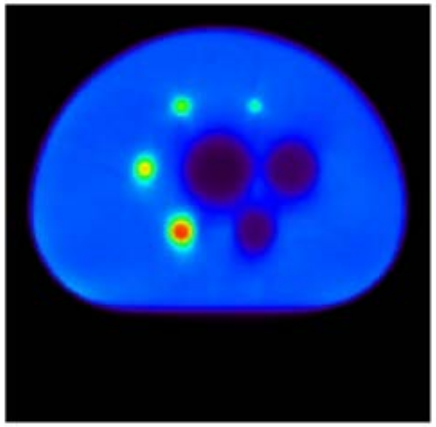
Tera-Tomo™ based, binned ToF reconstruction

Any finite support distribution can be used

Boxcar, 1 iteration

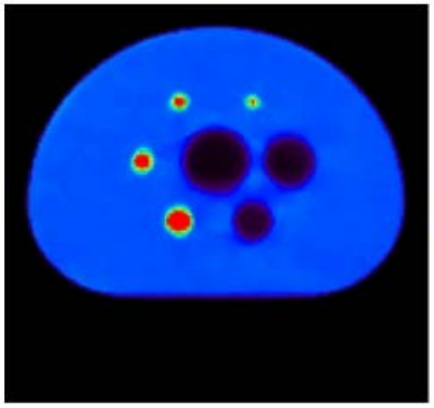


Gaussian, 1 iteration

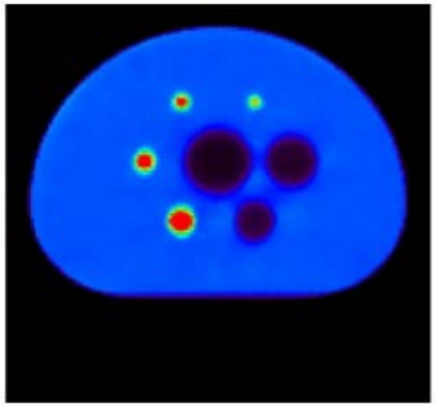


Edge artefacts in the quickest "boxcar" approximation vanish in the first iterations

Boxcar, 3 iterations



Gaussian, 3 iterations



ToF + AC + SC + TV are working and optimized simultaneously

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Expected Impact

- Cheaper, simpler, scalable, robust PETs
- MRI compatibility, radhardness
- New radiotracers with low lifetime and high specificity will be feasible