FOTORIVELATORI A STATO SOLIDO PER APPLICAZIONI MEDICHE

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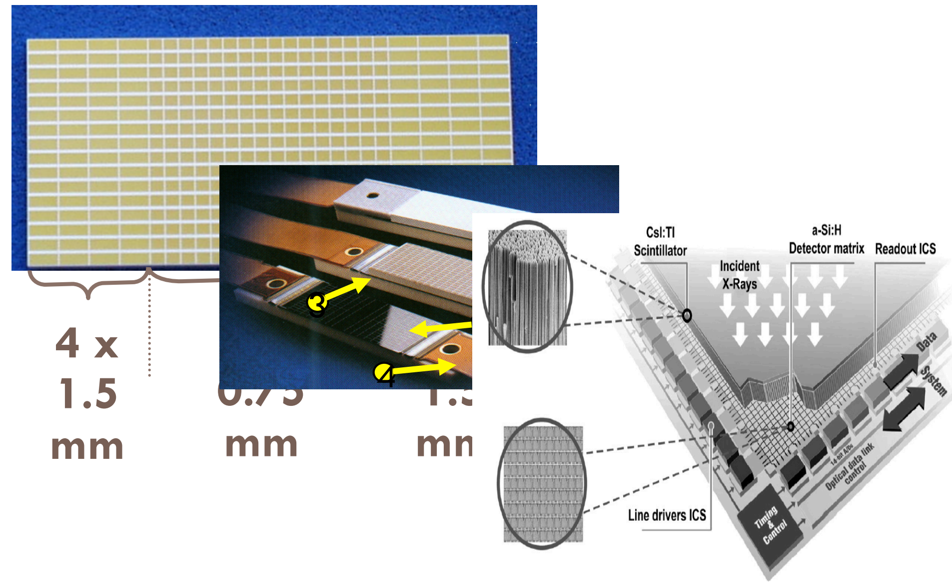
UNIVERSITA' E INFN PISA

Roma,
22 Settembre 2015

Solid state photodetectors used as light sensors in several imaging and diagnostic tools

- optical imaging
- computed tomography
- digital radiography
- Intra-operative probes
- nuclear medicine



Latest developments of solid state photodetectors for emission nuclear imaging

- Positron Emission Tomography (PET) scanners, SPECT

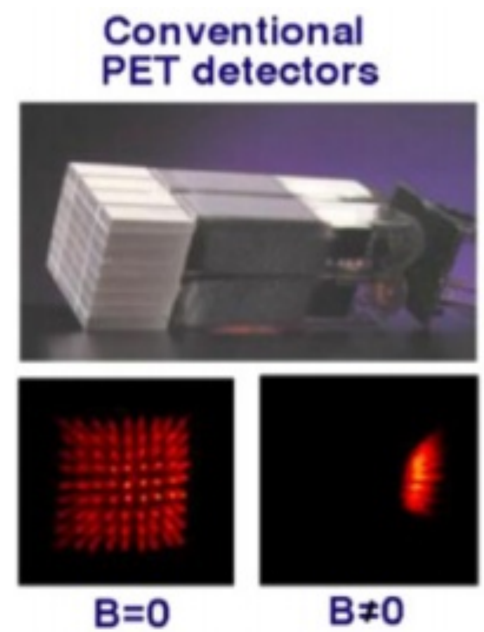
Photodetectors optically coupled to inorganic scintillating crystals still dominate in nuclear emission imaging

PMT

Today, the most used sensor for low level light detection

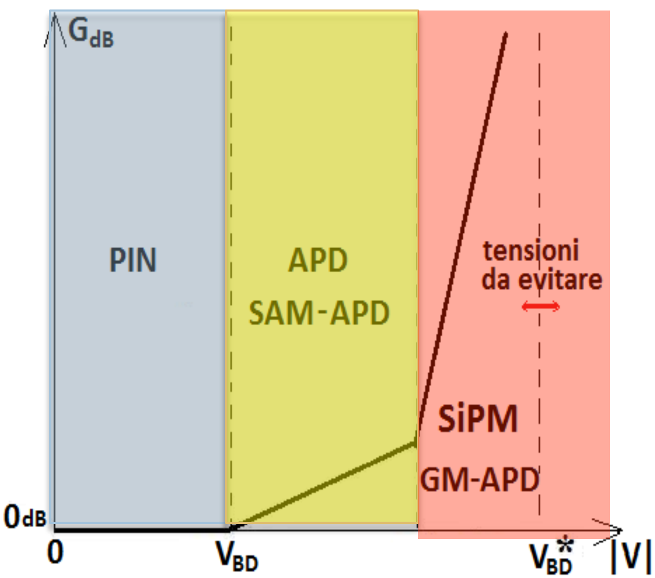
- Features
  - High gain
  - Single photon sensitivity
  - Low noise
  - High frequency response
  - Good QE from UV to nearIR
  - Low cost

- Issues:
  - Bulky and fragile
  - Influenced by magnetic field



Analog solid-state technology

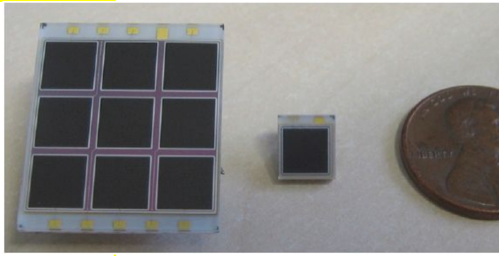
Devices with internal gain based on carrier multiplication via impact ionization



Insensitive to magnetic fields
Compactness
Scalability

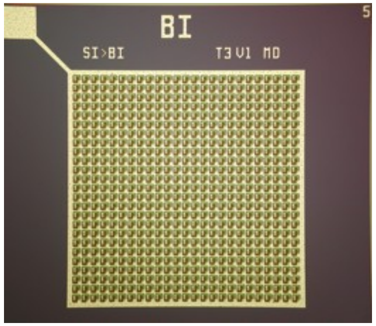
AVALANCHE PHOTODIODES

- Gain ~100
- Timing ~ ns/10 ph.e
- Bias ~ 500 V
- QE ~ high in the whole spectrum



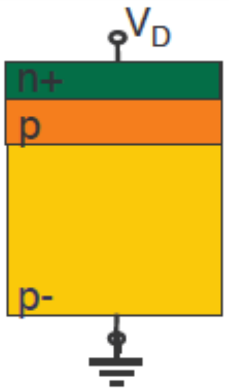
SPAD / Geiger-mode APDs

- Gain ~10^6
- Timing ~ 10 ps/10 ph.e
- Bias < 100 V
- QE ~ medium

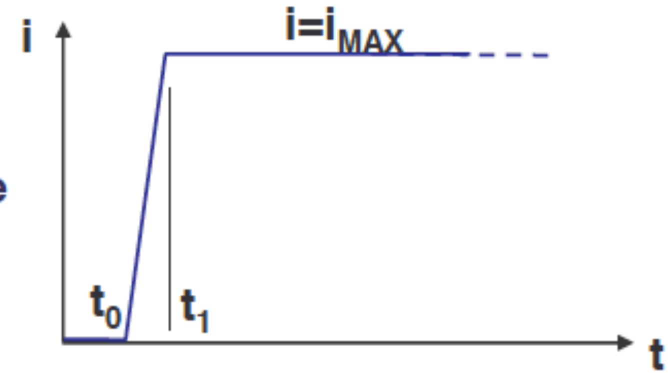


Single Photon Avalanche Diodes - SPAD

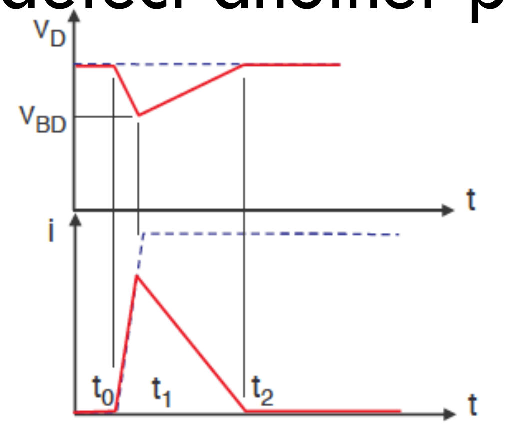
SPAD or Geiger –mode APD (G-APD) operating in reverse mode and with a high field region for carrier multiplication

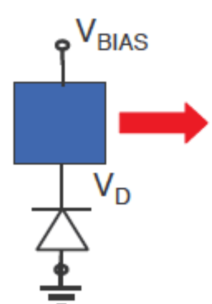


$t < t_0$	i=0 (if no free carriers in the depletion region)
$t = t_0$	carrier initiates the avalanche
$t_0 < t < t_1$	avalanche spreading
$t > t_1$	self-sustaining current



To detect another photon, quenching mechanism needed:





Two solutions:

- **large resistance:** **passive quenching**
- **analog circuit:** **active quenching**

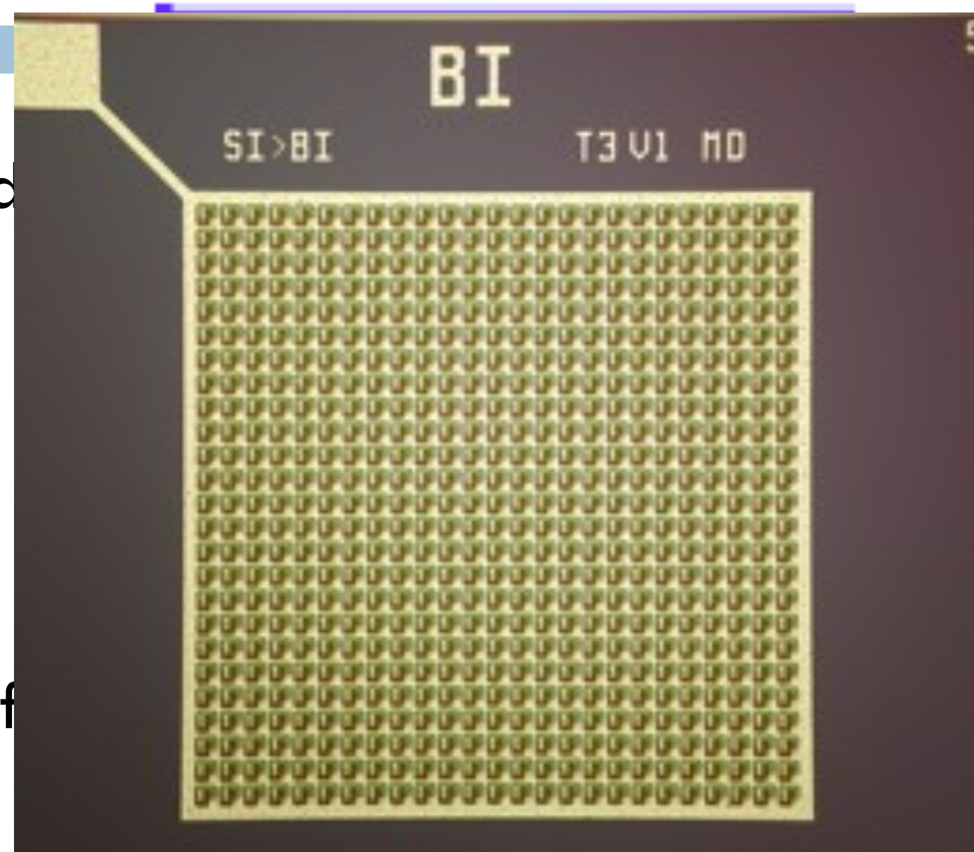
[extended literature from politecnico di Milano (Cova et al.)]

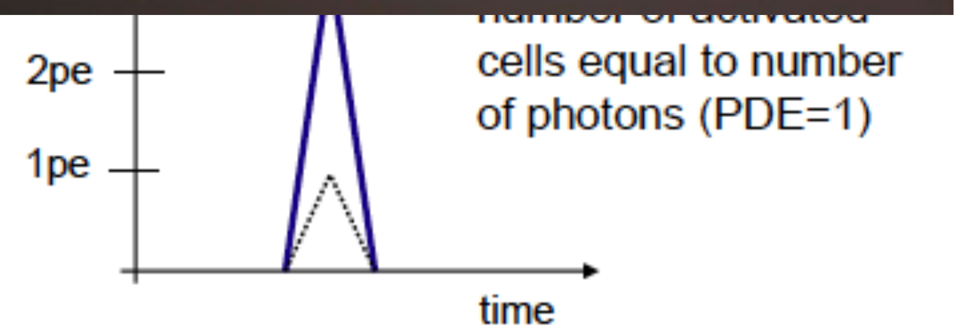
Silicon Photo Multipliers - SiPM

- Array of SPAD tightly packed and connected in parallel each equipped with a quenching resistance

(First proposed by Golovin and Sadygov in mid '90s)

- The output signal is proportional to the number of triggered cells
- Several producers: Hamamatsu, FBK-irst (AdvanSiD), SensL, ketek, Excelita





Performance comparison

Producer	Microcell size (umxum)	Fill factor (%)	Vbd (V)	PeakPDE (%), (wavelength)	Dark noise (kHz)
AdvanSiD	40x40	60	26	35 (400nm)	100
Excelitas	50x50	51	95	35 (520nm)	300
HPK	50x50	62	65	35 (450nm)	100
Ketek	50x50	70	25	50 (420nm)	400
SenSL	45x45	72	25	47 (420nm)	100

The INFN DASiPM2 Project

Progetto SiPM

- Sviluppo di rivelatori SiPM

INFN-group V - 2005

Progetto DASiPM (Development and Application of SiPM) INFN-group V - 2006

- Produzione e caratterizzazione di SiPM ottimizzati nella regione 400-500 nm
- Produzione di matrici di SiPM

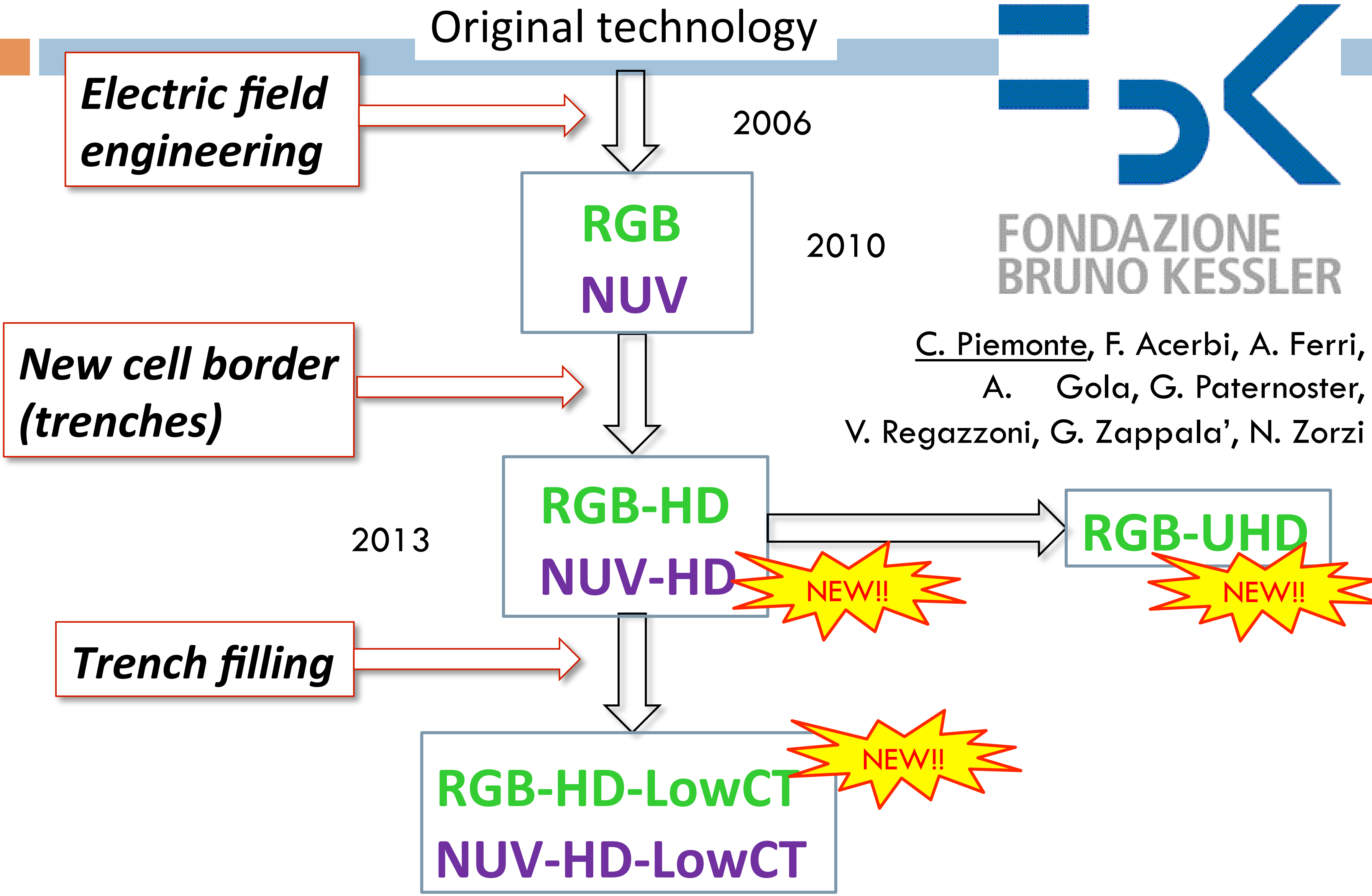
Progetto DASiPM2 (Development and Application of SiPM) INFN-group V - 2007

SiPM Applications:

- Medical Imaging: small animal PET demonstrator
- Astroparticle: TOF SipM module
- High Energy Physics: tracking calorimeter w scintillating fibers

Sezioni di:
Bari, Bologna, Pisa,
Perugia,Trento

FBK SiPM technology roadmap



Commercial technologies

AdvanSiD
Advanced Silicon Detectors

cell pitch: 40μm (625 /mm^2)

Fill factor: 60%

RGB SiPM

Peak PDE: 33% @ 550nm

DCR ~ 300 kHz

Direct CT: ~25%

After-pulsing: ~15%

NUV SiPM

Peak PDE: 35%@ 400nm

DCR ~ 100kHz

Direct CT: ~30%

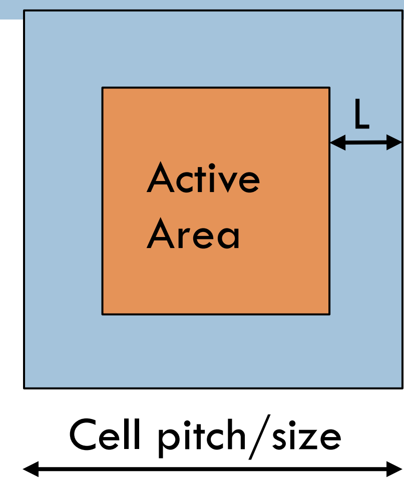
After-pulsing: <5%

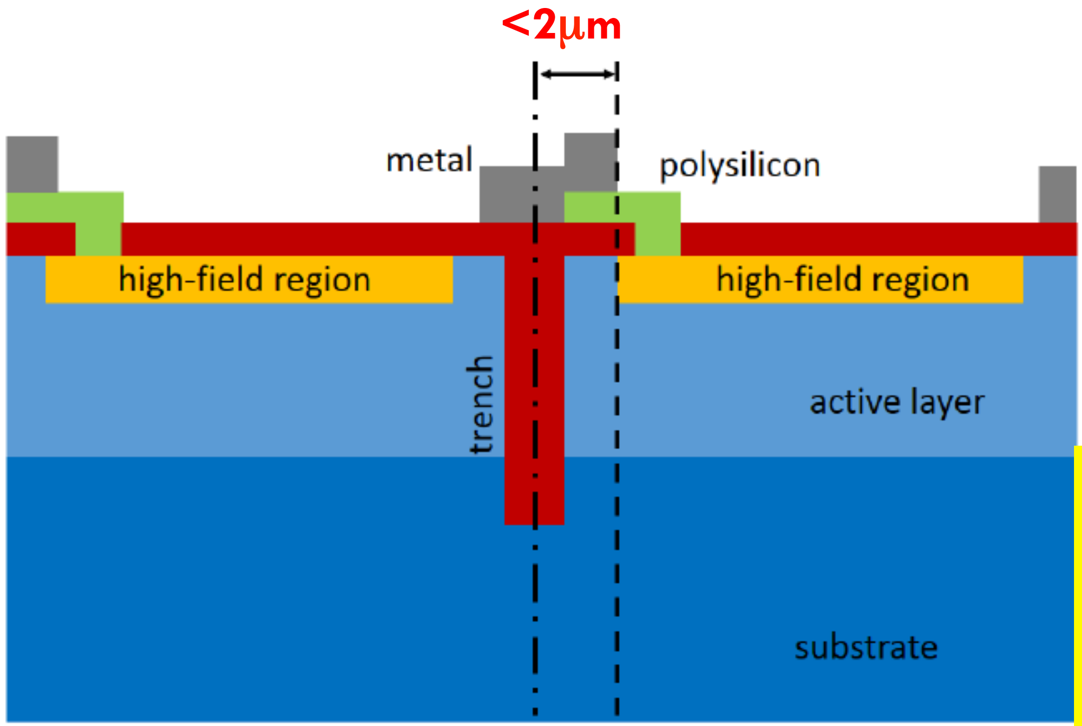
Breakdown uniformity: max variation 0.2V at wafer level.
Breakdown Temp. coefficient: 25mV/C

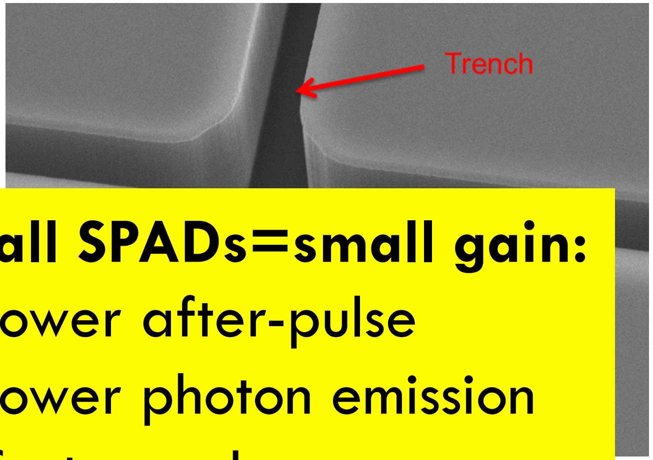
HD technology

Narrow border region around each SPAD

SiPM Cell, top view





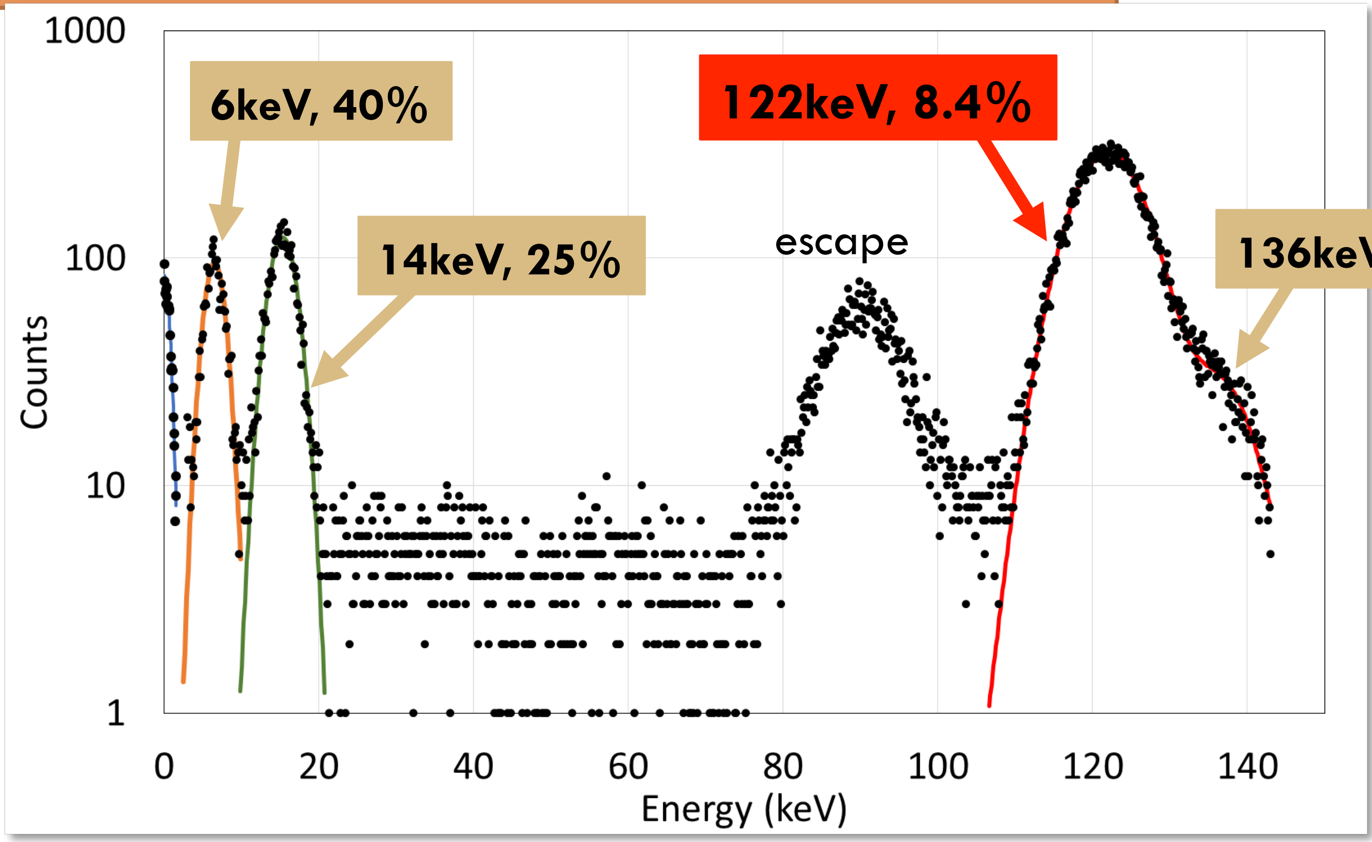


Small SPADs=small gain:

- lower after-pulse
- lower photon emission
- faster recharge
- higher dynamic range

RGB-HD with CsI(Tl) for SPECT

- **$4x4mm^2$ $25x25\mu m^2$ RGB-HD** SiPM
- $3x3x10mm^3$ **CsI (Tl)** (Hilger)

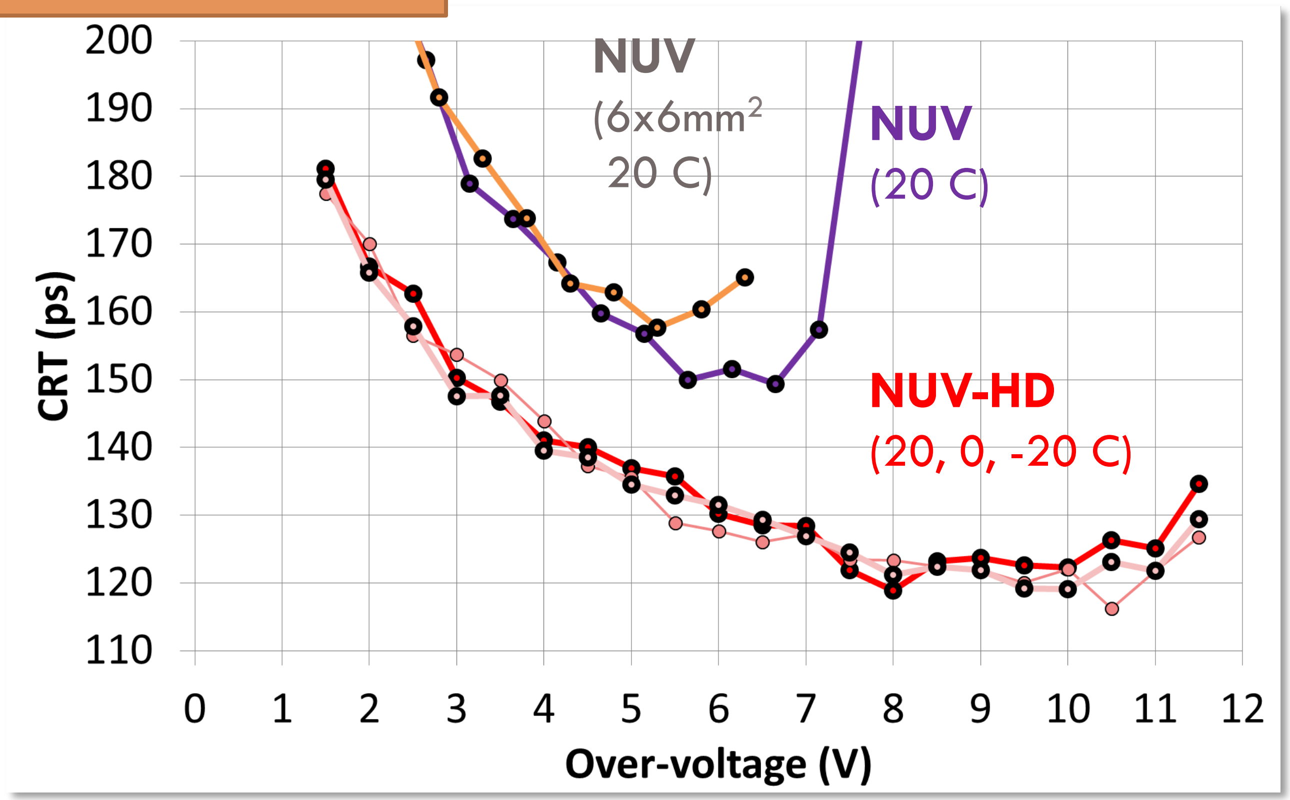


- ❖ T = 20 C
- ❖ T_{int} = 12μs
- ❖ V_{OV} = 4V

FONDAZIONE BRUNO KESSLER

Timing performance of NUV-HD for TOF-PET

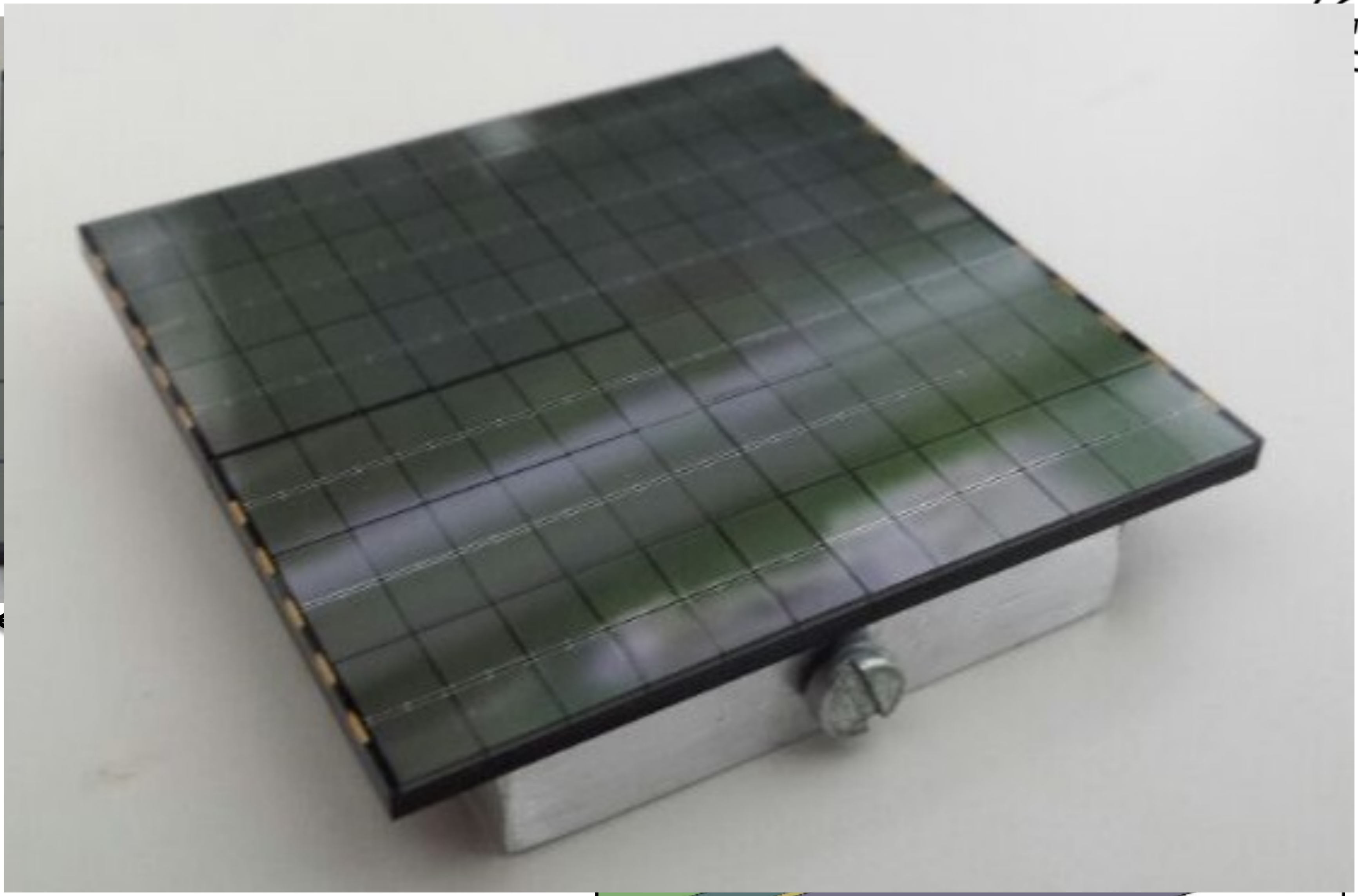
- 4x4mm2 SiPM
- 25µm cell pitch
- LYSO 3x3x10mm^3



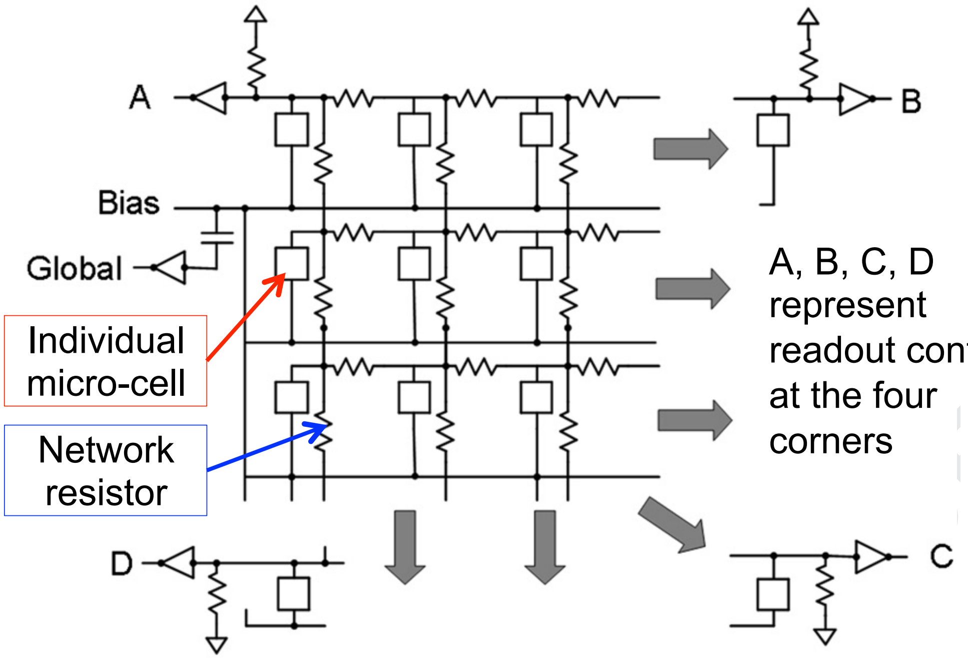
FONDAZIONE BRUNO KESSLER

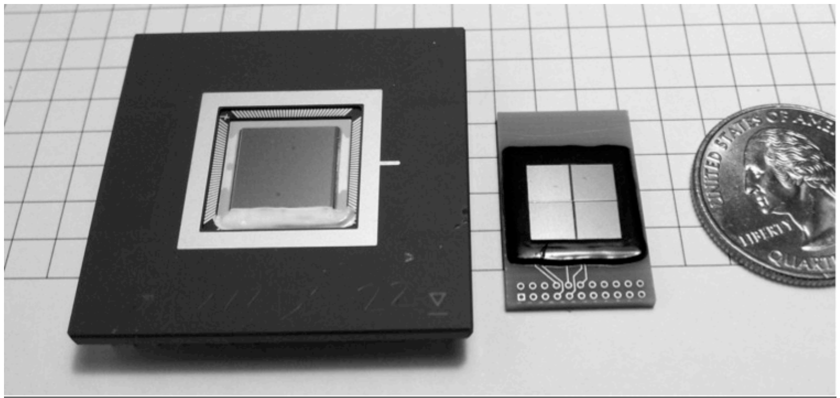
Large SiPM tiles

Tile developed within FP7 project INSERT



Position-Sensitive Solid-State Photomultiplier (PS-SSPM)





Continuous 10 mm PS-SSPM	2 x 2 array of 5 mm PS-SSPMs

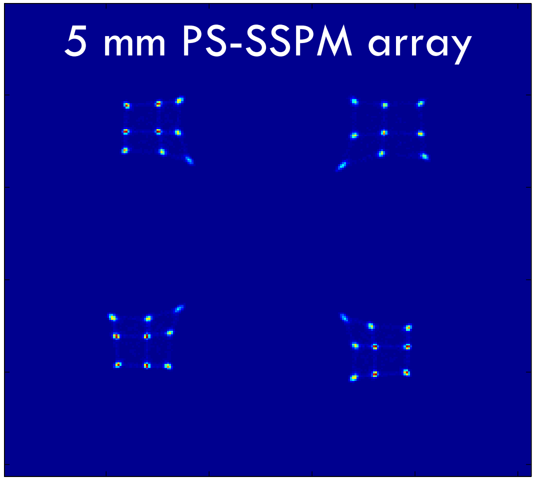
Parameters	10 mm PS-SSPM	5 mm PS-SSPM
PDE @ 420 nm	~10%	~10%
Micro-pixel area	30µm×30µm	30µm×30µm
Micro-pixel pitch	44.3µm×44.3µm	44.3µm×44.3µm
Geometrical Fill Factor	0.46	0.46
Total number of Micro-pixels	40000 (200×200)	11664 (108×108)

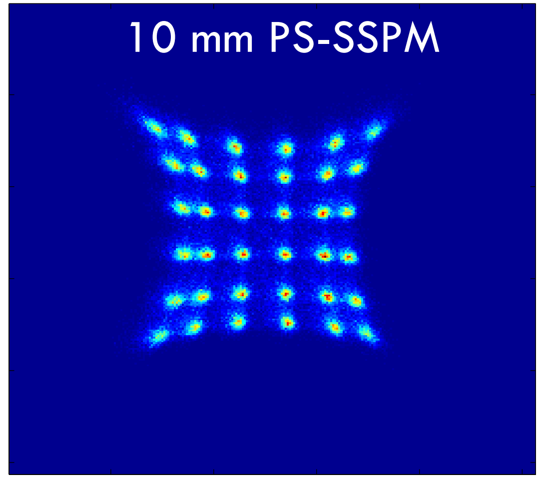
UC DAVIS UNIVERSITY OF CALIFORNIA

Jeffrey Schmall, Junwei Du, Purushottam Dokhale, Kanai Shah, and Simon R Cherry

RMD A Dynasil Company

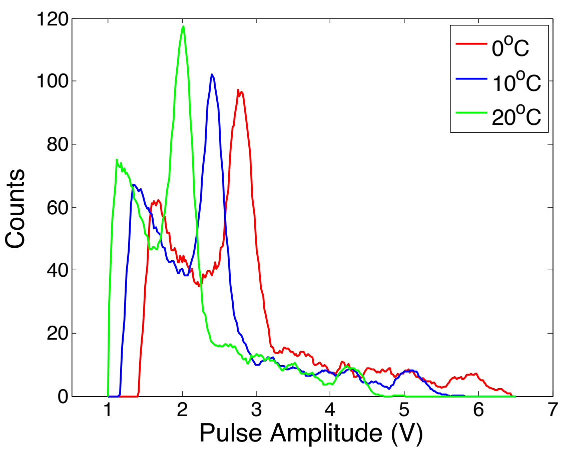
Flood Histograms

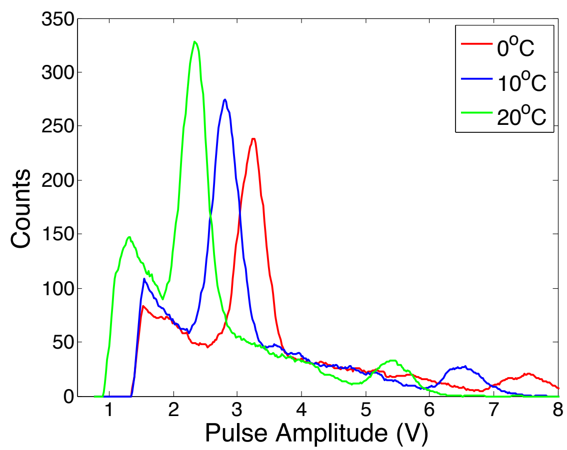




6x6 LSO array with 1.3 mm crystal pitch

Energy Resolution





Block results	10 mm PS-SSPM	5 mm PS-SSPM
Energy Res.	18.4%	16.2%
Timing Res.	8.6 ns	8.0 ns

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Jeffrey Schmall, Junwei Du, Purushottam Dokhale, Kanai Shah, and Simon R Cherry

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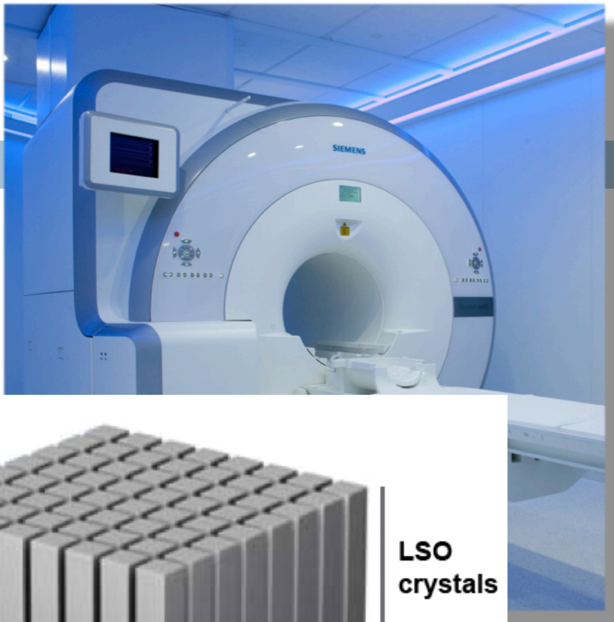
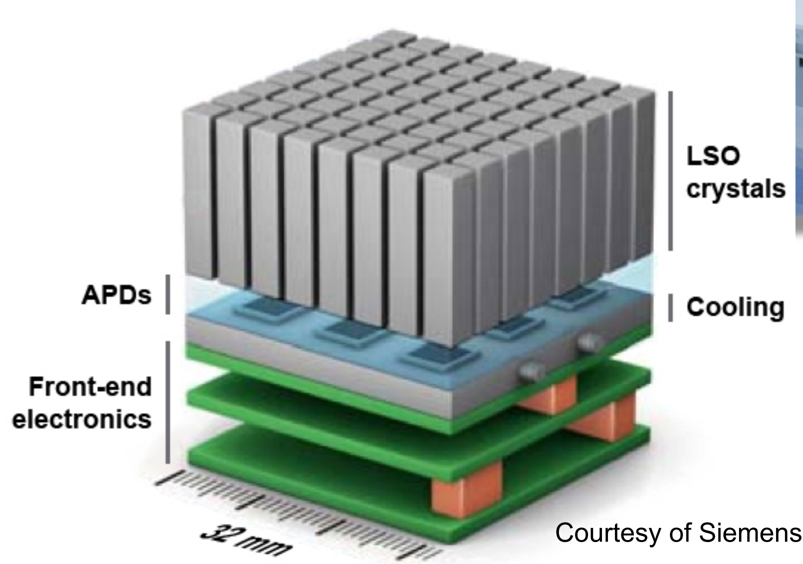
First APD based PET/MR scanner

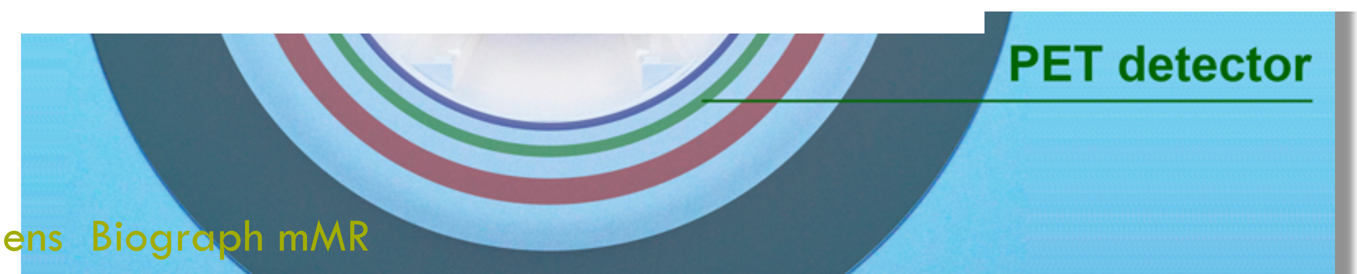
- PET:
  - 448 detector blocks with
  - 8 x 8 LSO crystals and
  - 3 x 3 APDs each
  - Axial FOV: 25.8 cm
  - Spat. resolution: 4.3 mm

/MR
ner





Courtesy of Siemens



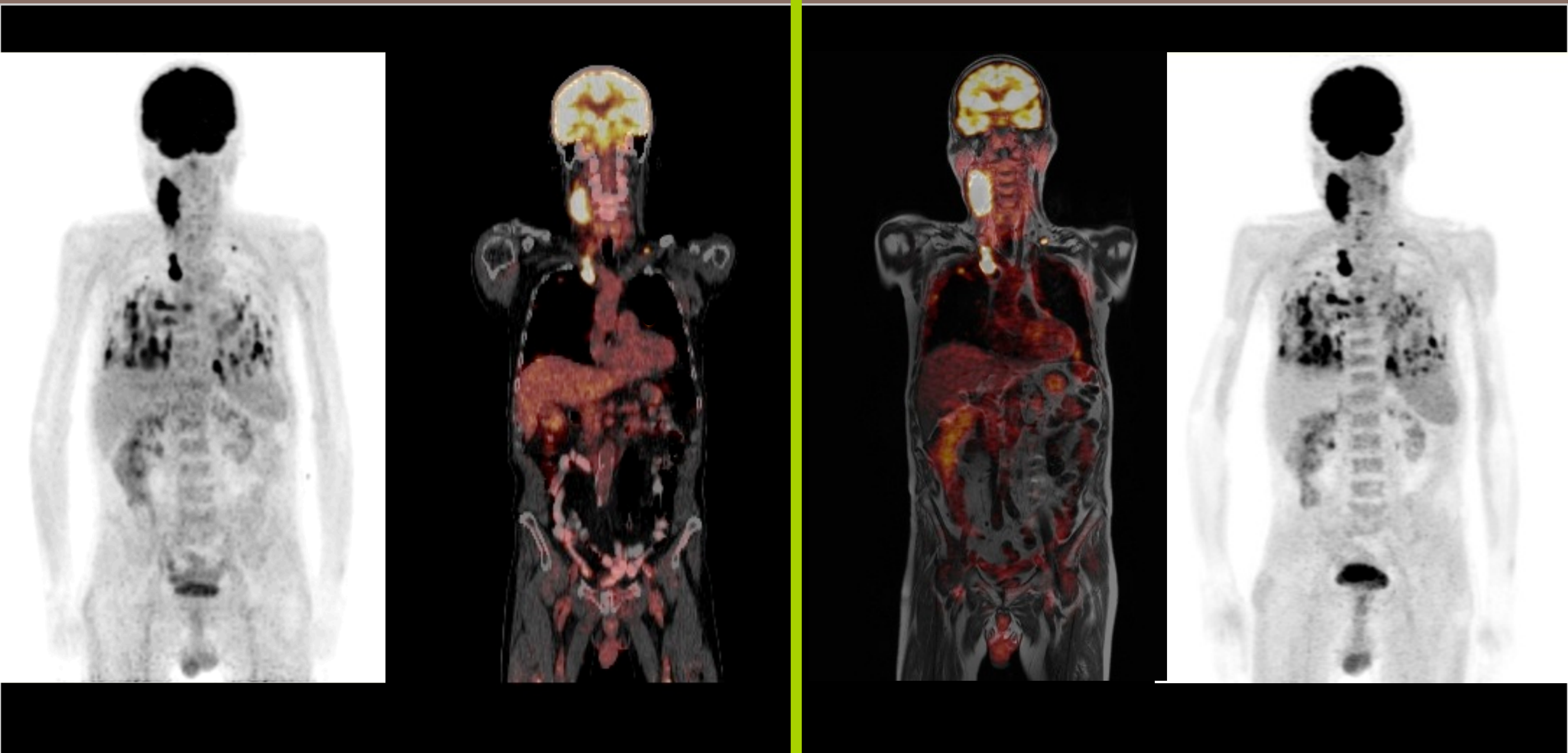
Siemens Biograph mMR

Detection of lesions

[18]FDG-PET in thyroid cancer

PET/CT
(Siemens Biograph, 90 min p.i.)

PET/MR
(Siemens mMR, 140 min p.i.)



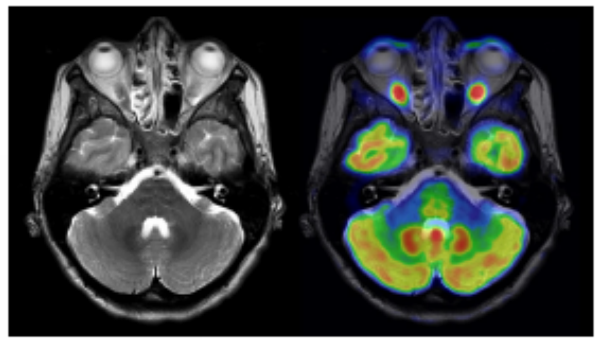
PET (PET/CT) | **PET/CT-Fusion** | **PET/MR-Fusion** | **PET (PET/MR)**

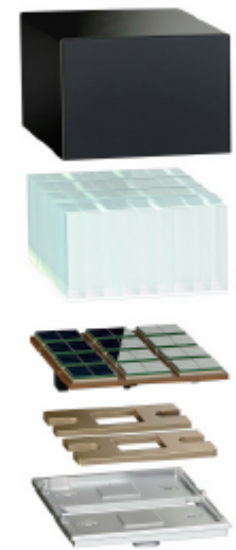
S.Ziegler, TUM, 2015

First SiPM based clinical scanner

GE Signa SiPM-based PET/MRI system

Based on Hamamatsu silicon photomultipliers (SiPMs)





System Performance	
CRT	< 400 ps FWHM
Sensitivity	21 kcps/MBq
FOV	60 x 25 cm
Spatial res	4.1 mm
Energy res	< 12%

D. Schaart, Delft University of technology, 2015

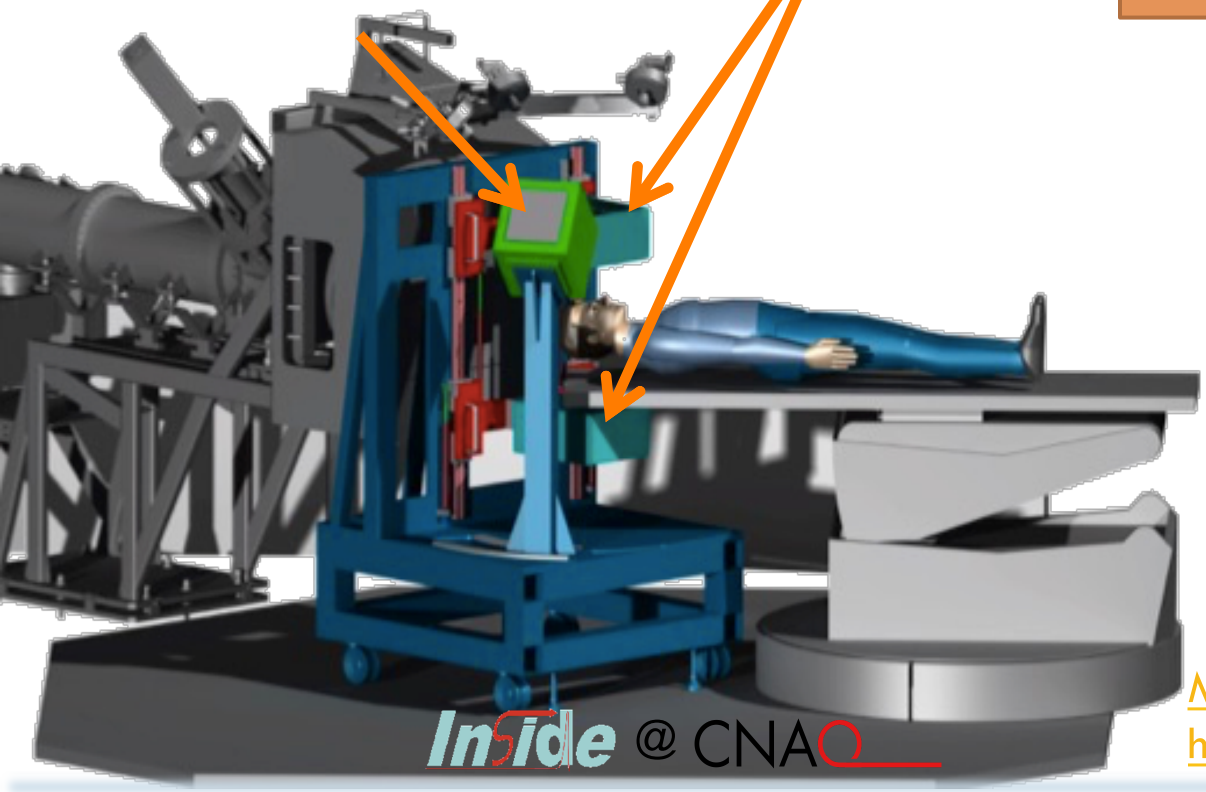
Particle Range monitoring in HT

Prompt secondary particles emission

β⁺ activity distribution

DOSE PROFILER Tracker + Calorimeter = + IN-BEAM PET HEADS → BI-MODAL MONITORING SYSTEM

Detectors based on SiPM technology



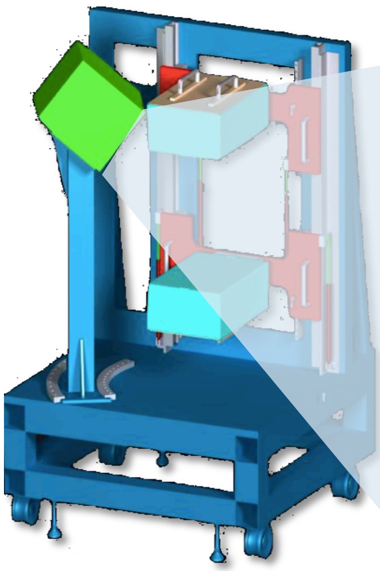
Goals:

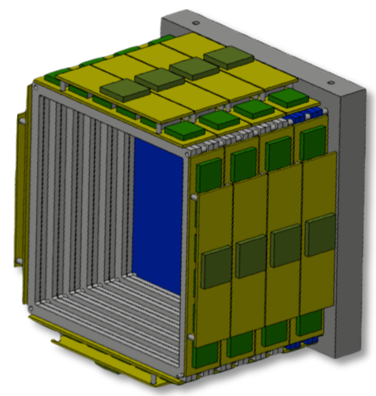
- To be integrated in the gantry
- To be operated in-beam
- **To provide an IMMEDIATE feedback on the particle range**

More on INSIDE
http://131.114.131.146/insidewiki/

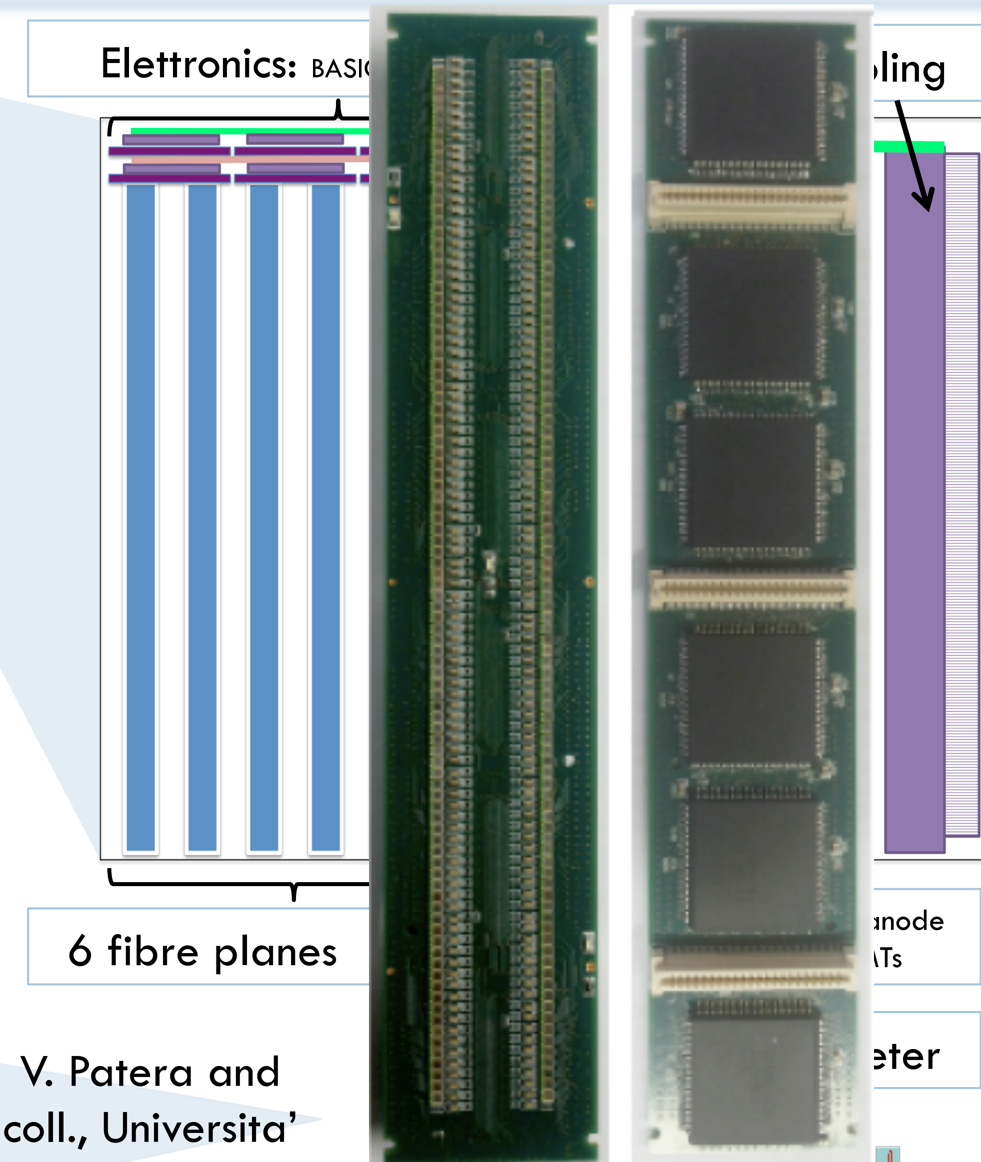
InSide

Dose Profiler (DP)

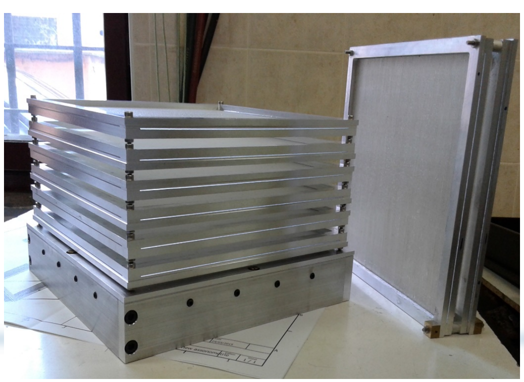




28 x 28 x 35 cm^3

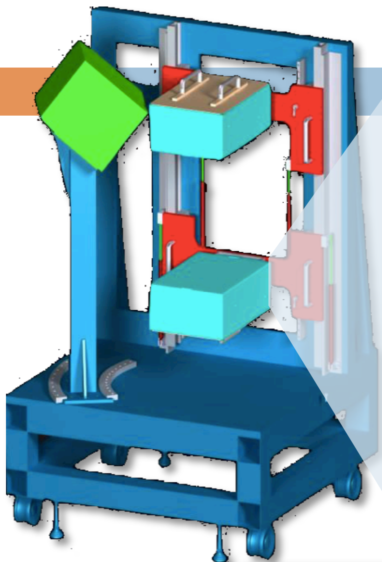


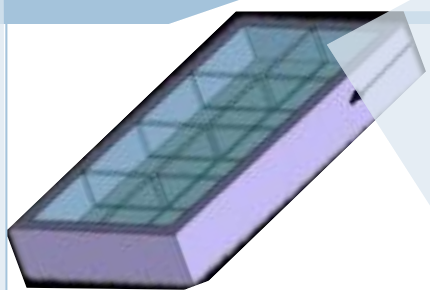
- 6 planes of orthogonal squared scintillating fibers coupled to SiPMs
- an electromagnetic calorimeter coupled to Position Sensitive PMTs.



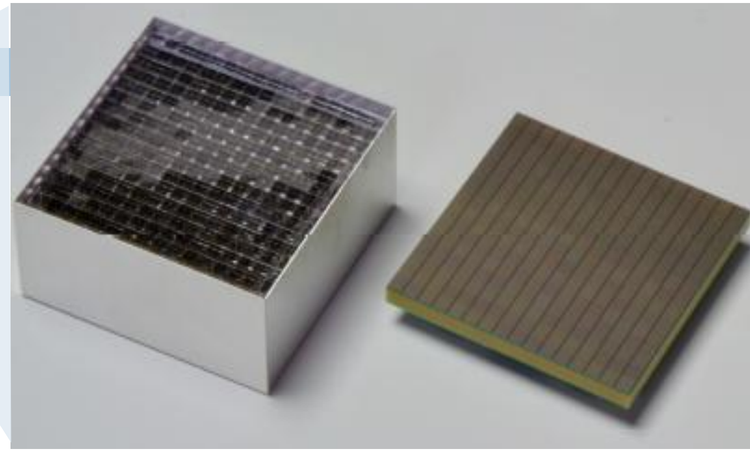
V. Patera and coll., Universita' di Roma e INFN

In-beam PET (ibPET)



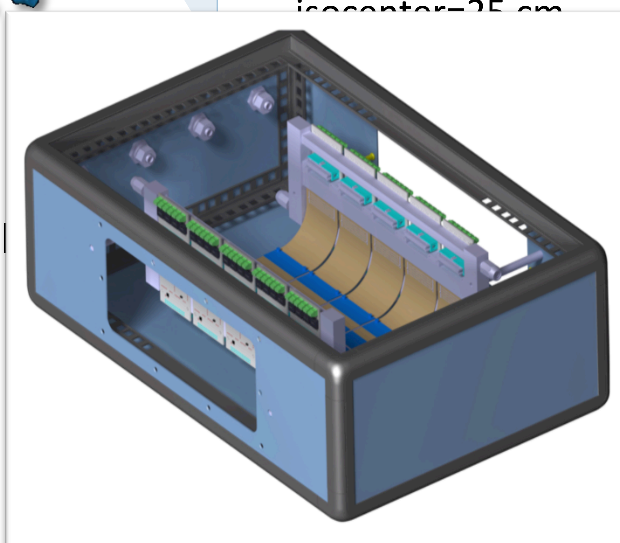


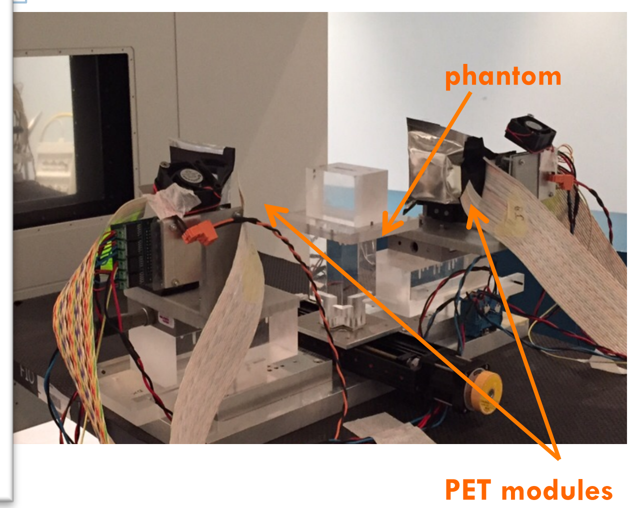
10x 20 x 5 cm^3
Distance from the isocenter=25 cm



256 LFS pixel crystals (3x3x20mm^3) coupled one to one to MPPCs (Multi Pixel Photon Counters, SiPMs).

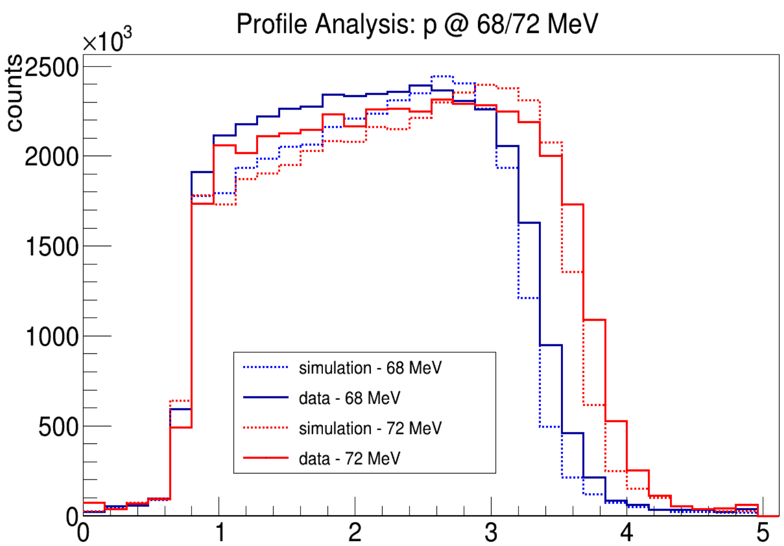
Solid model
Of the PET
head

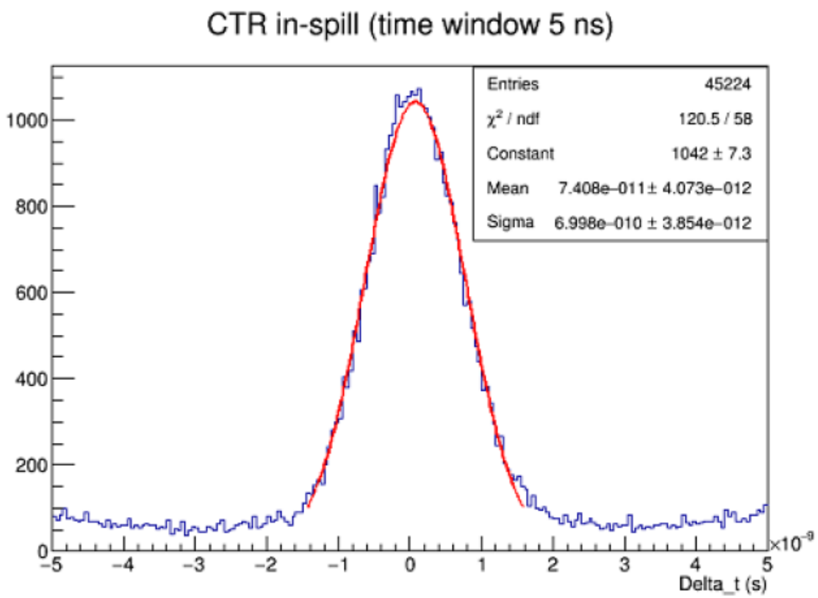




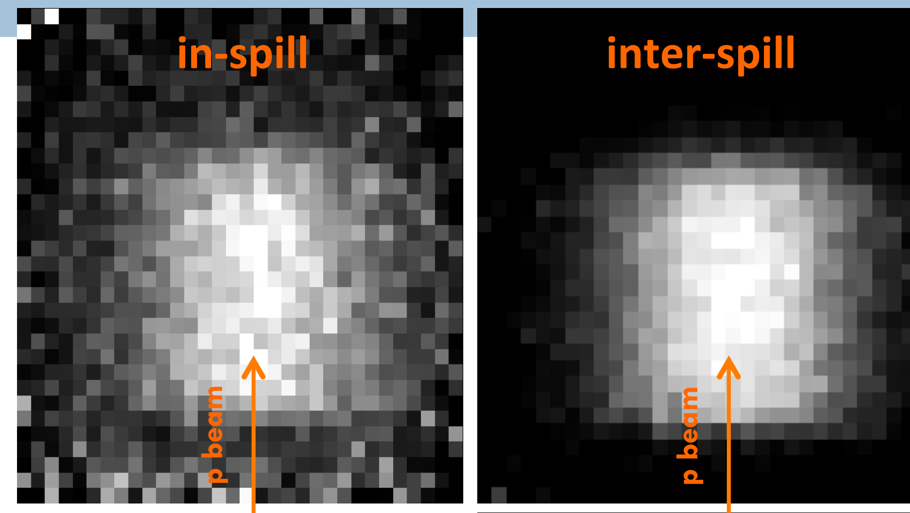
Demonstrator
1 vs 1 module
Tested at CNAO
On may 5 2015

IbPET activity maps and profiles

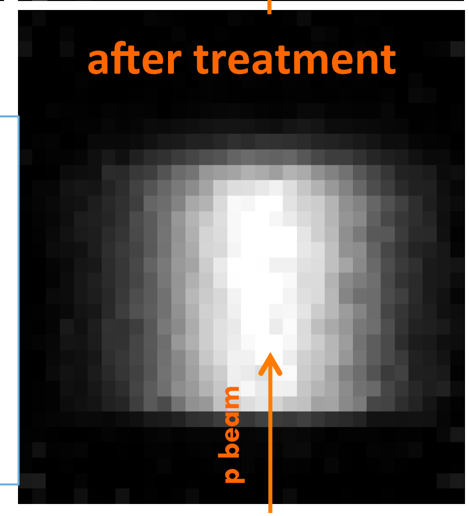




PET reconstructed activity

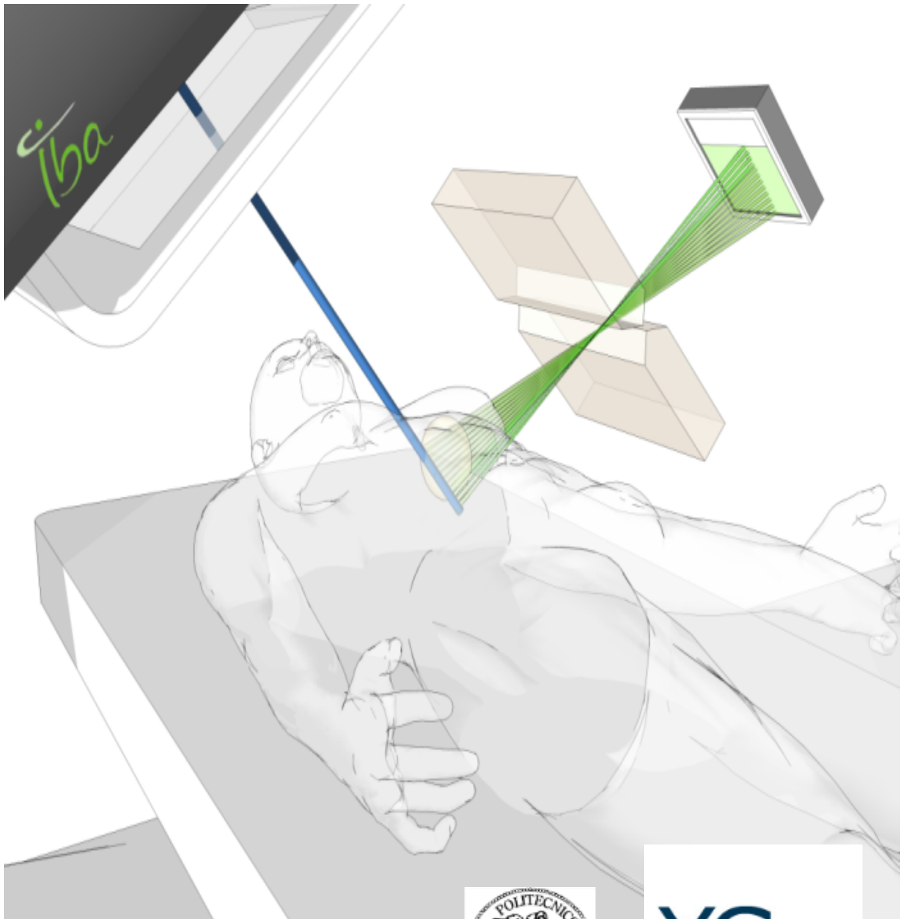


β^+ **activity** distribution can be determined both in-spill,
Inter-spill after few minutes of Irradiation



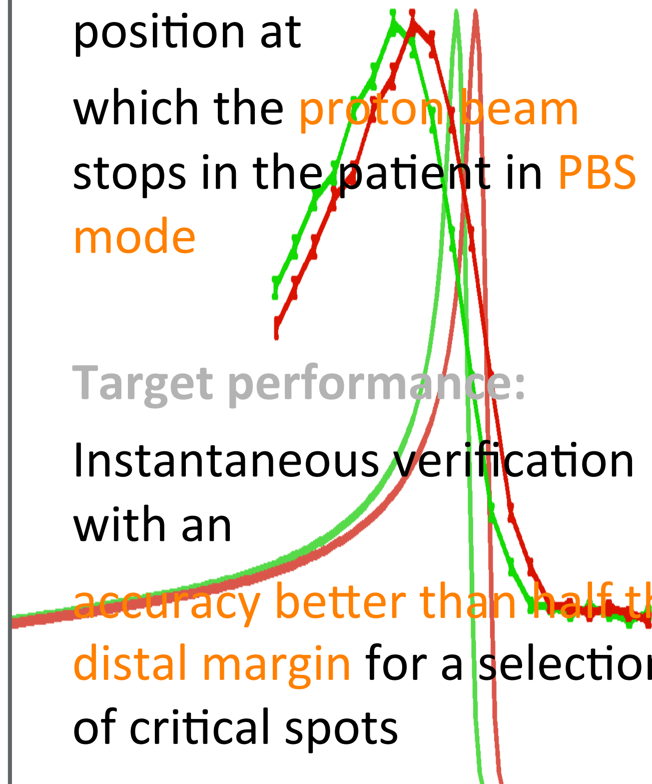
Comunicazione M.A. Piliero, sif, 21/9/2015

Knife-edge slit camera concept



Intended application:

Measurement of the position at which the proton beam stops in the patient in PBS mode



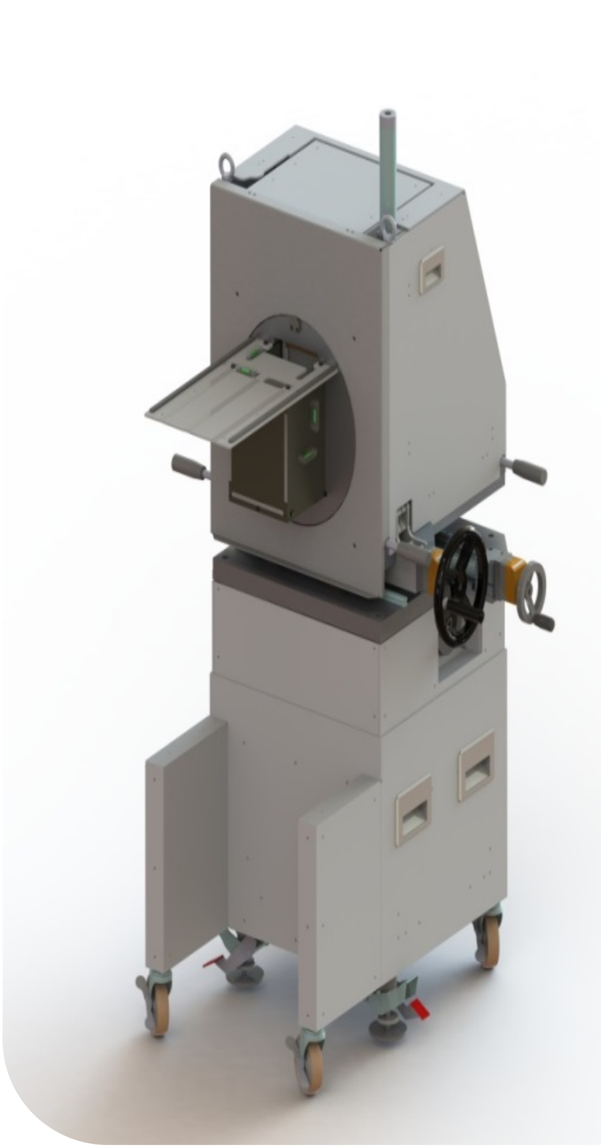
Target performance:

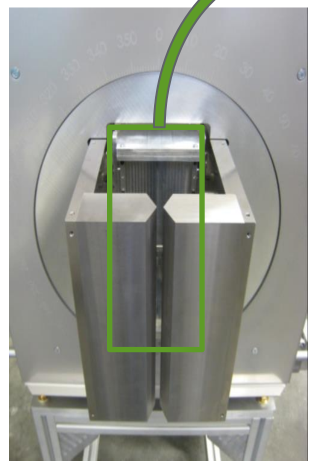
Instantaneous verification with an accuracy better than half the distal margin for a selection of critical spots

Points of attention:

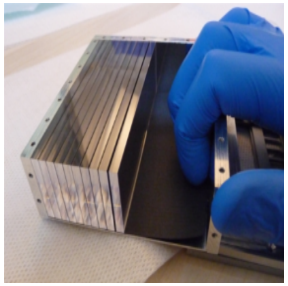
Simplicity, cost effectiveness

Two full-size prototypes built for clinical evaluation

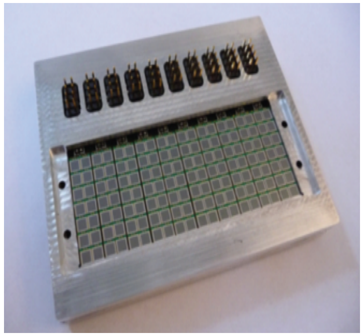




53 kg W collimator in 5:4 magnification



500 cm³ LYSO distributed in 2 rows of 20 slabs



Light readout of one extremity of each LYSO slab by a row of 7 SiPM

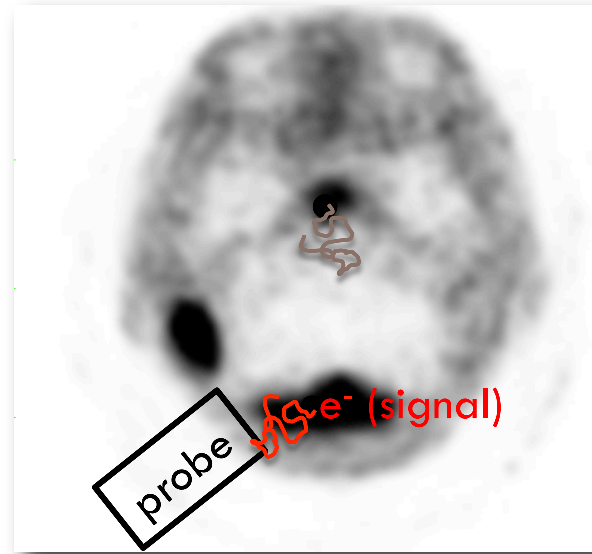
(3 × 3 mm² & 3600 microcells each)

40 independent acquisition channels operating in two modes

A novel radio-guided surgery technique with β- radiation

E. Solfaroli Camillocci et al, Sci. Repts. 4,4401 (2014)

- Use of β^- tracers (electrons)
  - Detect electrons that travels ~100 times less than γ
  - Tracers with ^{90}Y can be used (already used for Molecular RT)
  - No background from gamma



p-terphenyl directly coupled to a
Silicon photomultiplier (SiPM sensL B-series 10035)
developed and under test
Optimization of the light collection.
Low dark current.
Compactness and small size

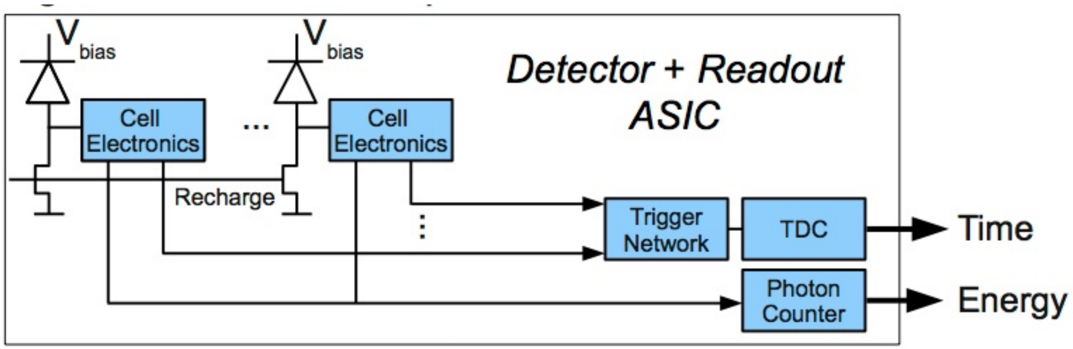
Digital SiPM - dSiPM

Local integration of SPAD with logic circuitry in CMOS technology

- Active quench and recharge techniques→faster and less sensitive to gain variation
- Functionalities to mask noisy pixels → reduced DCR impact
- Signal processing and read-out circuits→application specific devices

Digital Photon Counter

PHILIPS
sense and simplicity



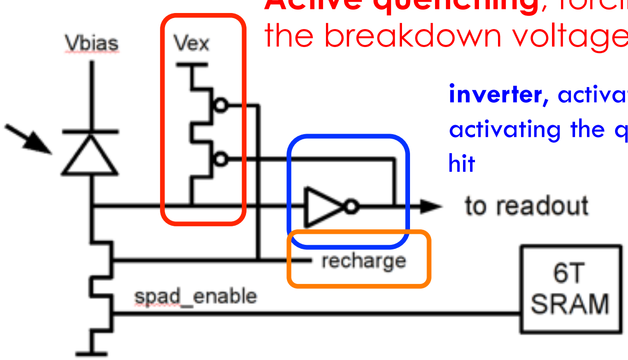
Rely on the power of today's CMOS processes to get as much as you can ON CELL or ON CHIP

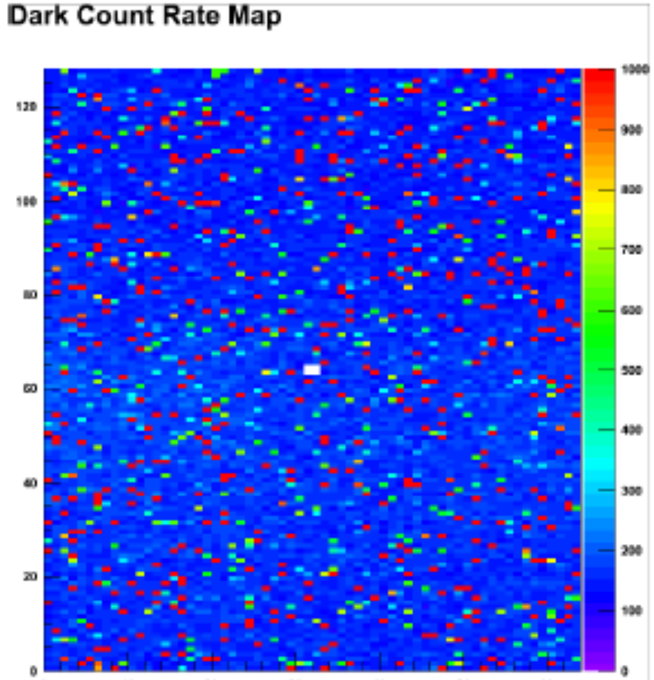
Thomas Frach et al., IEEE-NSS conf. Records 2009

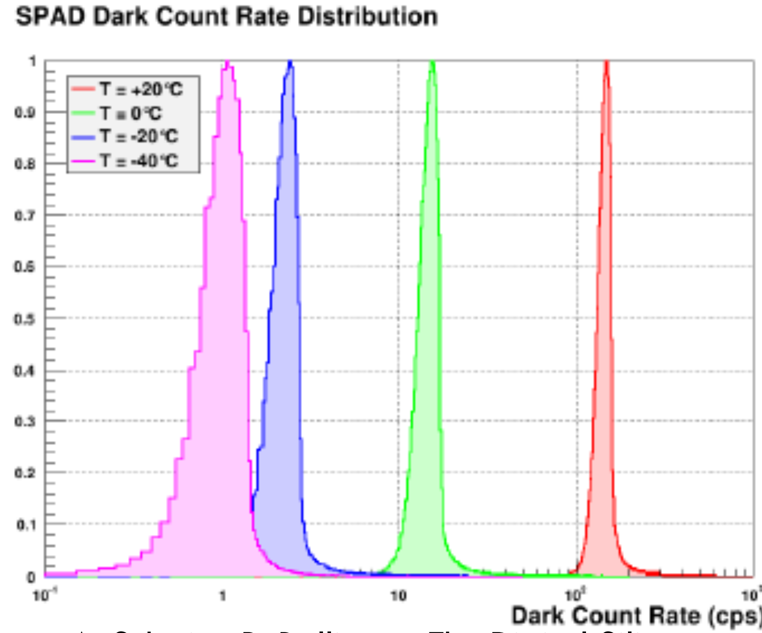
- Cell size 120 x 64 µm^2
- Fill Factor 77.7%
- PDE ~ 30% @420 nm
- Modified 0.18 µm 5M CMOS
- Foundry: NXP Nijmegen

Active quenching, forcing the anode to the breakdown voltage

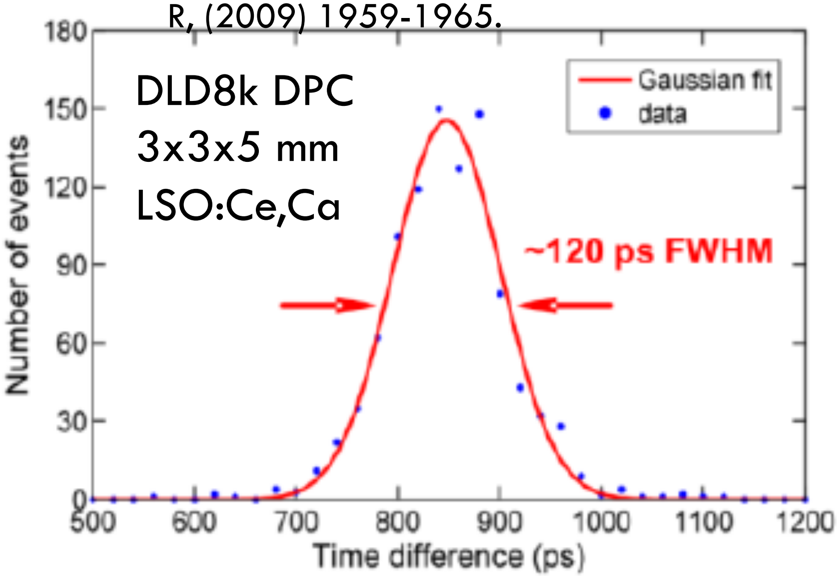
inverter, activated by the anode voltage variation, activating the quenching mech. and identifying the cell was hit

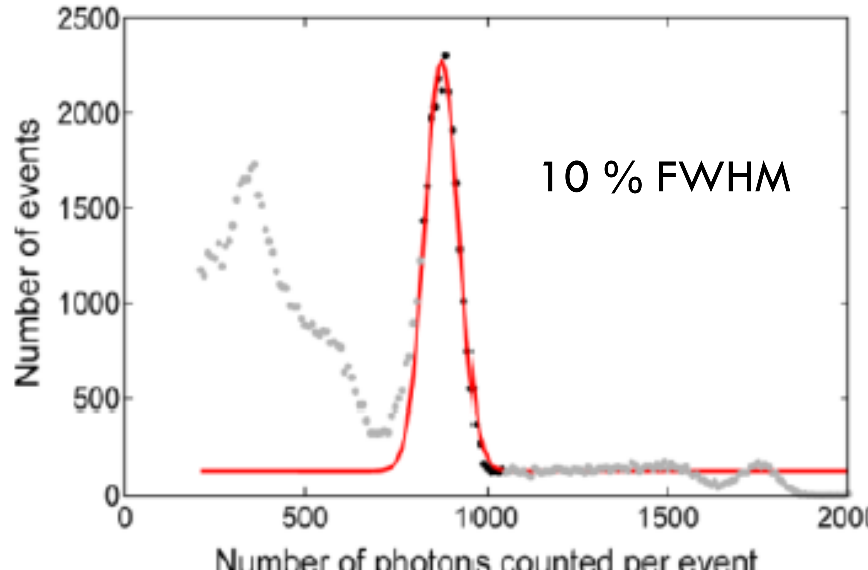






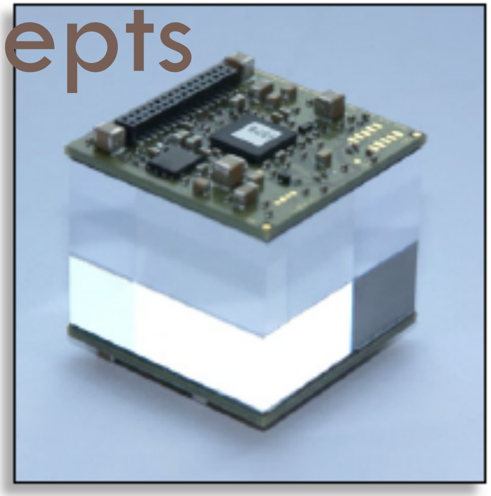
T. Frach, G. Prescher, C. Degenhardt, R. de Gruyter, A. Schmitz, R. Ballizany, The Digital Silicon Photomultiplier - Principle of 961 Operation and Intrinsic Detector Performance, Ieee Nucl Sci Conf R, (2009) 1959-1965.





D.R. Schaart, H.T. van Dam, G.J. van der Lei, S. Seifert, The Digital SiPM: Initial Evaluation of a New Photosensor for Time-of-Flight 1001 PET, 2011 IEEE NSS MIC, Valencia, Spain, 2011

PET new Block Detector concepts



A practical and cost effective detector for PET/CT and PET/MRI devices with ultrahigh spatial resolution, CRT, and detection efficiency

Performance parameter	DSR monolithic	State of the art
Energy resolution (FWHM)	**10.2%**	< 12%
Spatial resolution (FWHM)	**1.1 mm**	~4 mm
DOI resolution (FWHM)	**2.4 mm**	None
CRT (FWHM)	**148 ps**	350 - 400 ps

32 mm x 32 mm x 22 mm commercial LYSO:Ce with DSR dSiPM readout

TU Delft
Dennis R. Schaart
Delft University of Technology

SPADnet-I

Leo Huf Campos Braga[1], Leonardo Gasparini[1], Lindsay Grant[2], Robert K. Henderson[3], Nicola Massari[1], Matteo Perenzoni[1], **David Stoppa[1]** and Richard Walker[3]

- Digital SiPM fabricated in 0.13 µm CIS technology:
  - ➔ 8 x 16 pixels, 0.6 mm pitch;
  - ➔ 92k SPAD cells, 19.3 µm pitch;
  - ➔ 42.6% pixel array FF;
- Real-time output of incoming energy at up to 100 MHz;
- Integrated Gamma event discrimination:
- 10.8% energy resolution, 288 ps CRT.

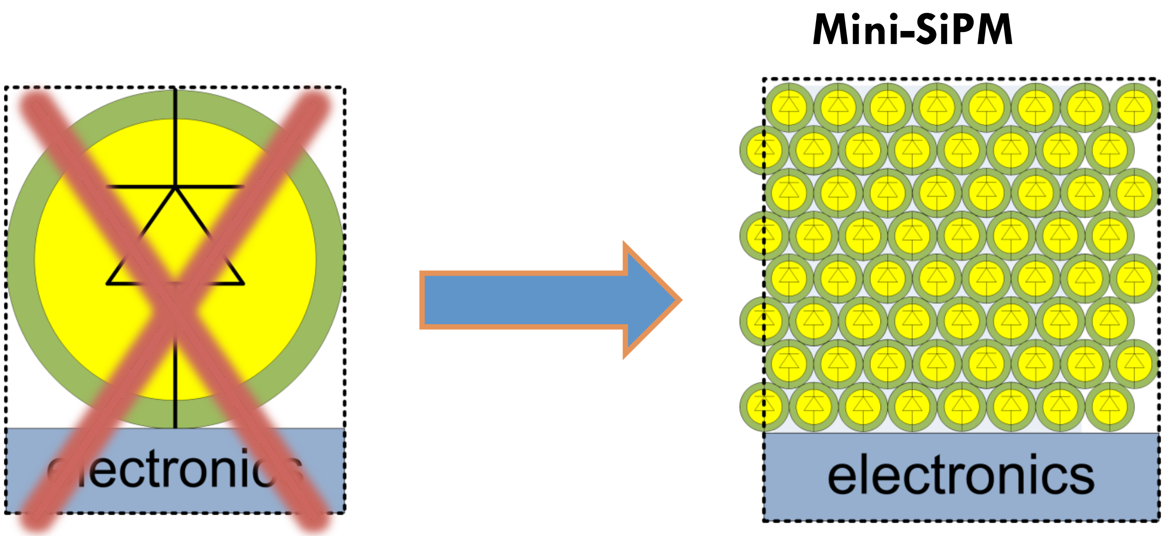
SPADnet SINGLE PHOTON AVALANCHE DIODE NETWORK

FONDAZIONE BRUNO KESSLER

Sensor architecture: mini-SiPM

- The mini-SiPM: counting pulses
  - Large SPADs desirable due to high FF;
  - DCR and X-talk worsen more-than-linearly with area;

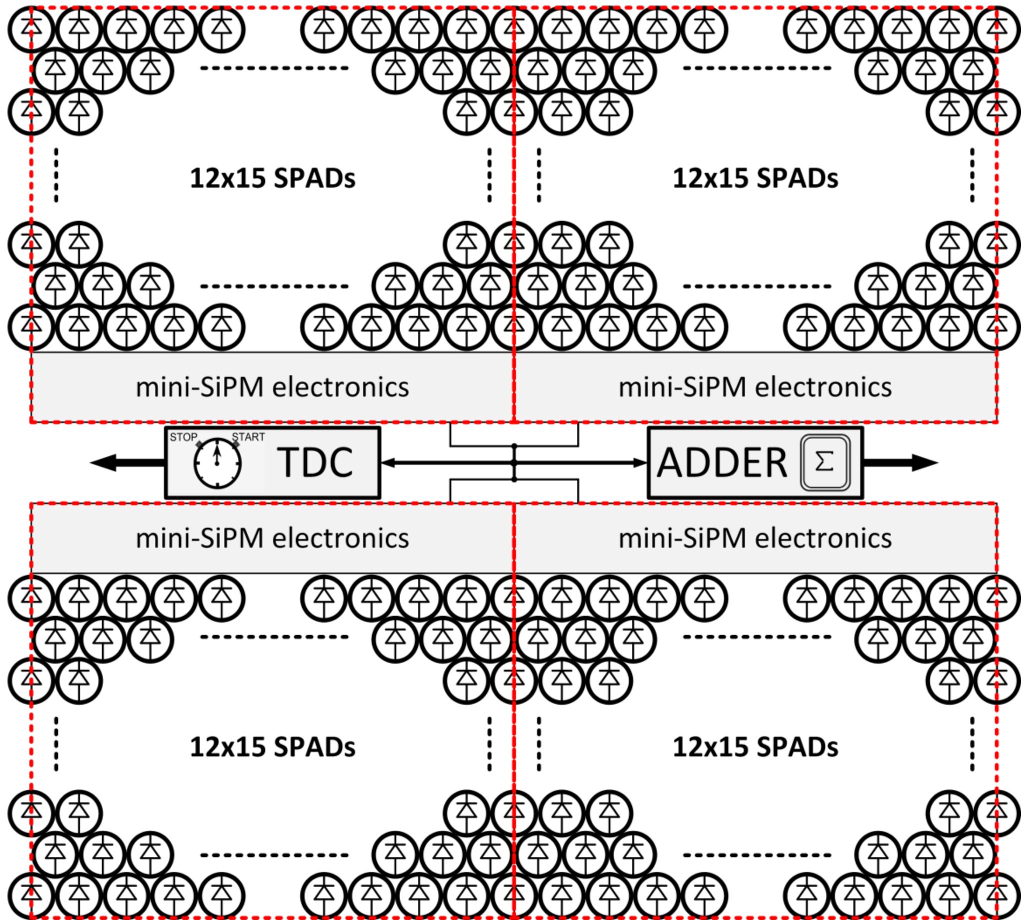
  ➔ **Limited max practical SPAD diameter**



➔ **Requires an efficient way to count all SPAD pulses**

Sensor Architecture: Pixel

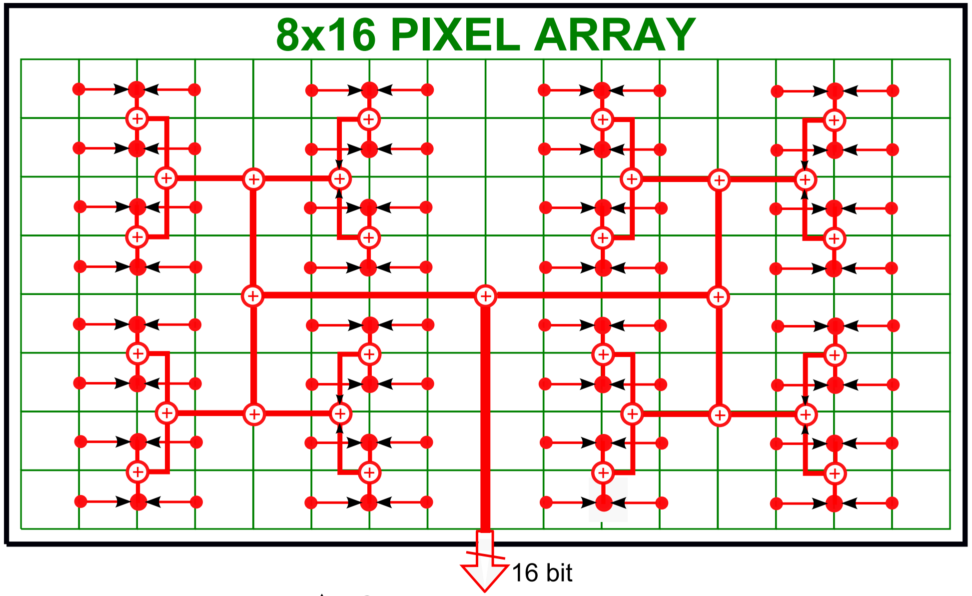
- Pixel: meeting in the middle
  - Pulse timestamping;
  - Count summing;
  - Data storage.
- Pixel features
  - 720 SPADs
  - ~0.6 x 0.6 mm^2
  - 42.6% FF

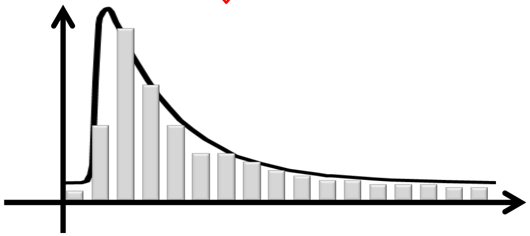


Sensor Architecture: Top Level

Discriminating events: time binning

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

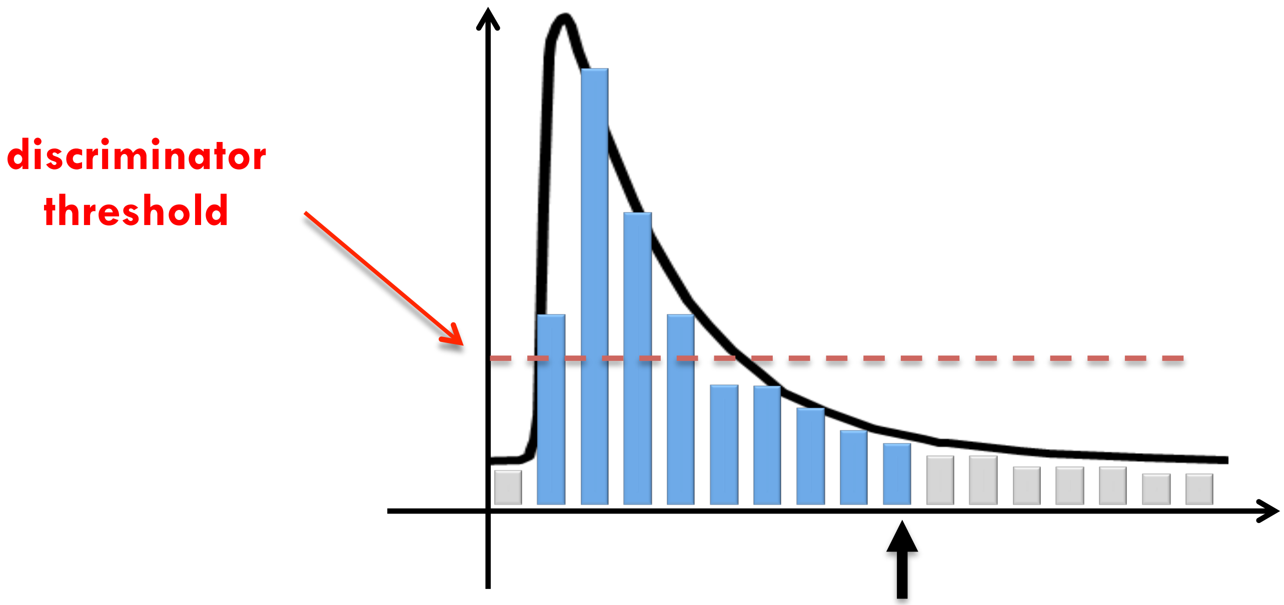




→ up to 100 Msamples/s

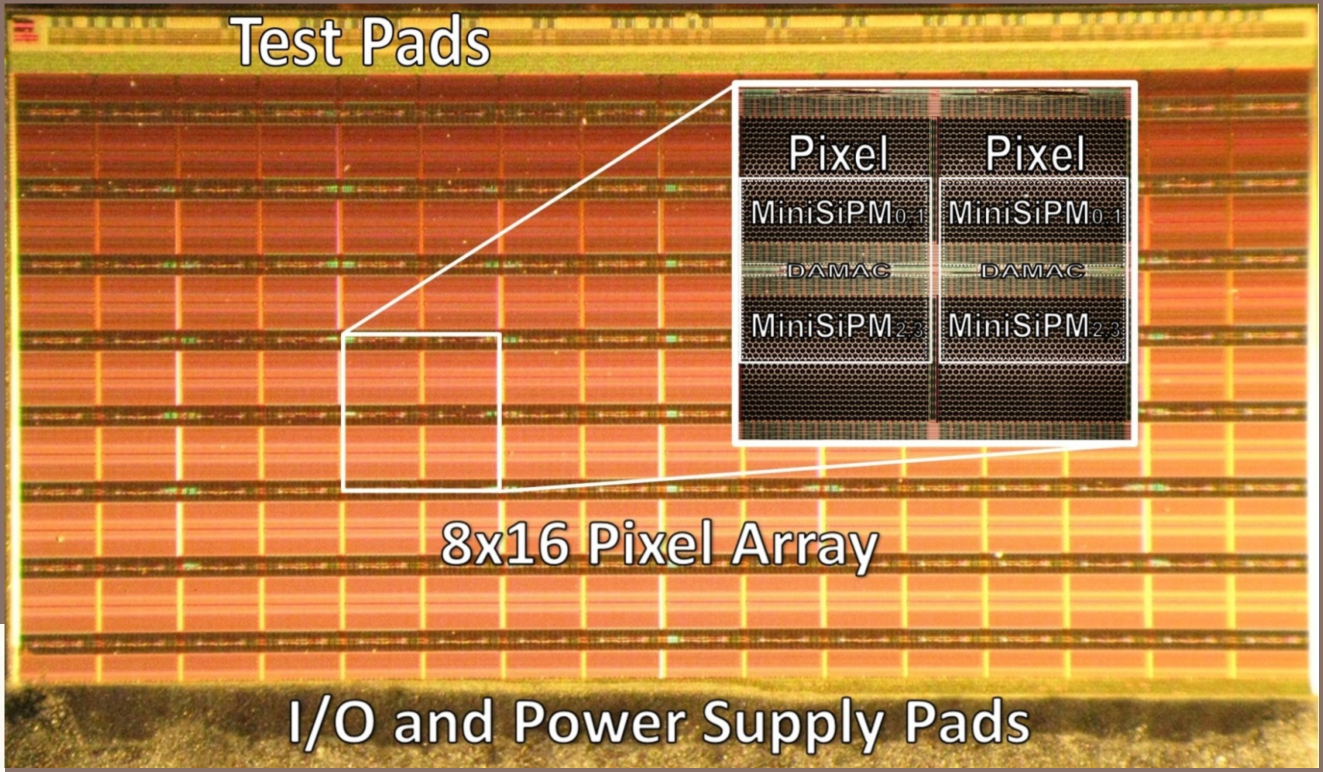
Sensor Architecture

- Discrimination and exposure control
  - **Top-level sensor time diagram**



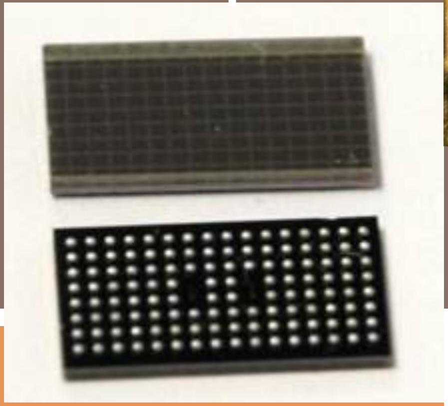
➔ **Integration time is externally configurable**

Chip implemented in 0.13 µm CIS technology:

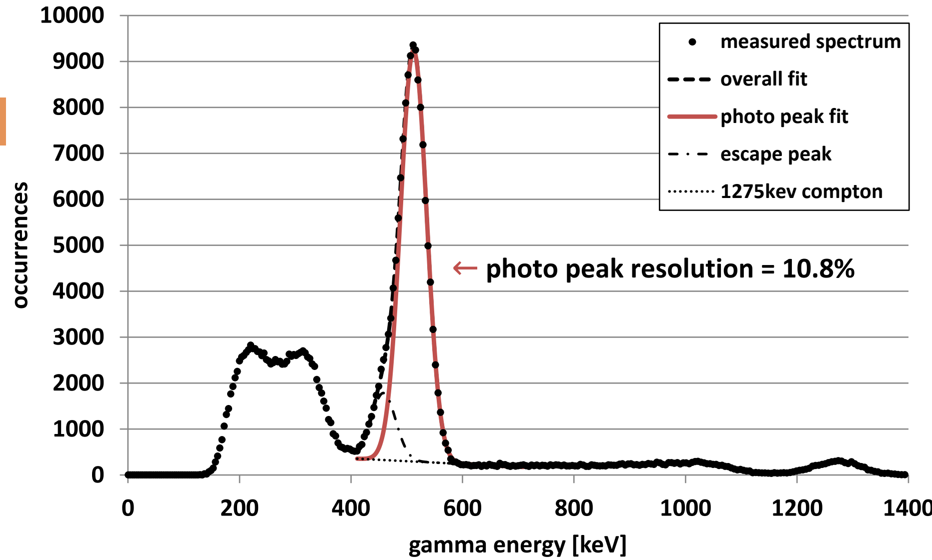


micrograph

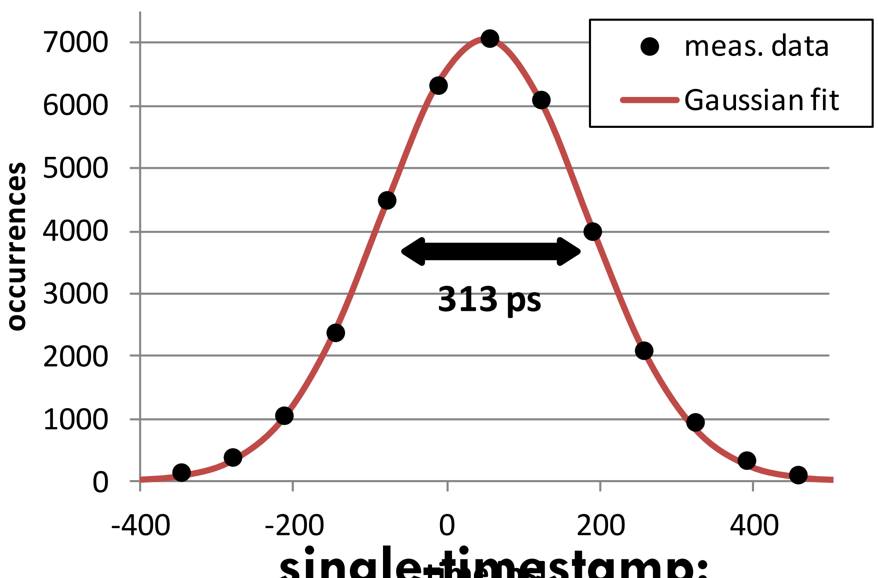
TSV chip



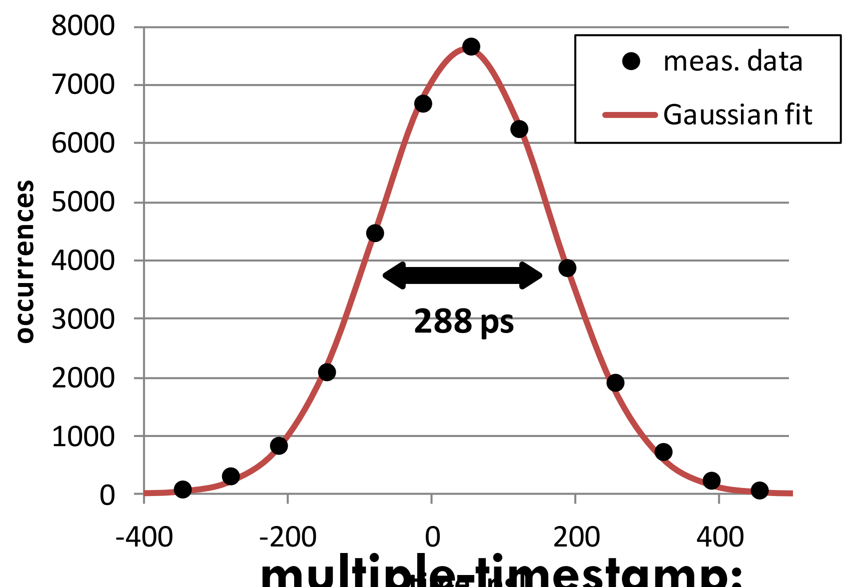
SPADnet Performances for PET



- Na^{22} source 370kBq;
- 3 x 3 x $5mm^3$ LYSO
- Temperature: 20^o C;
- SPAD excess bias: 2V;
- Integration time: 150 ns;



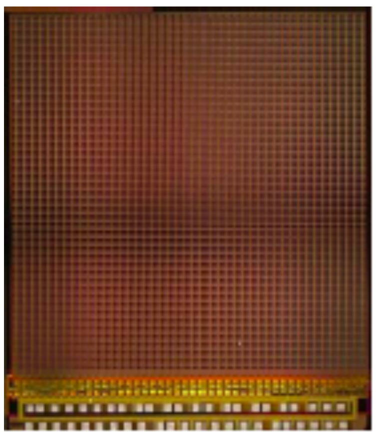
single-timestamp: 2nd photon



multiple-timestamp: 3 photons combined

IDP SPAD array chip

SPAD Array Chips with Full Frame Readout for Crystal Characterization



RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

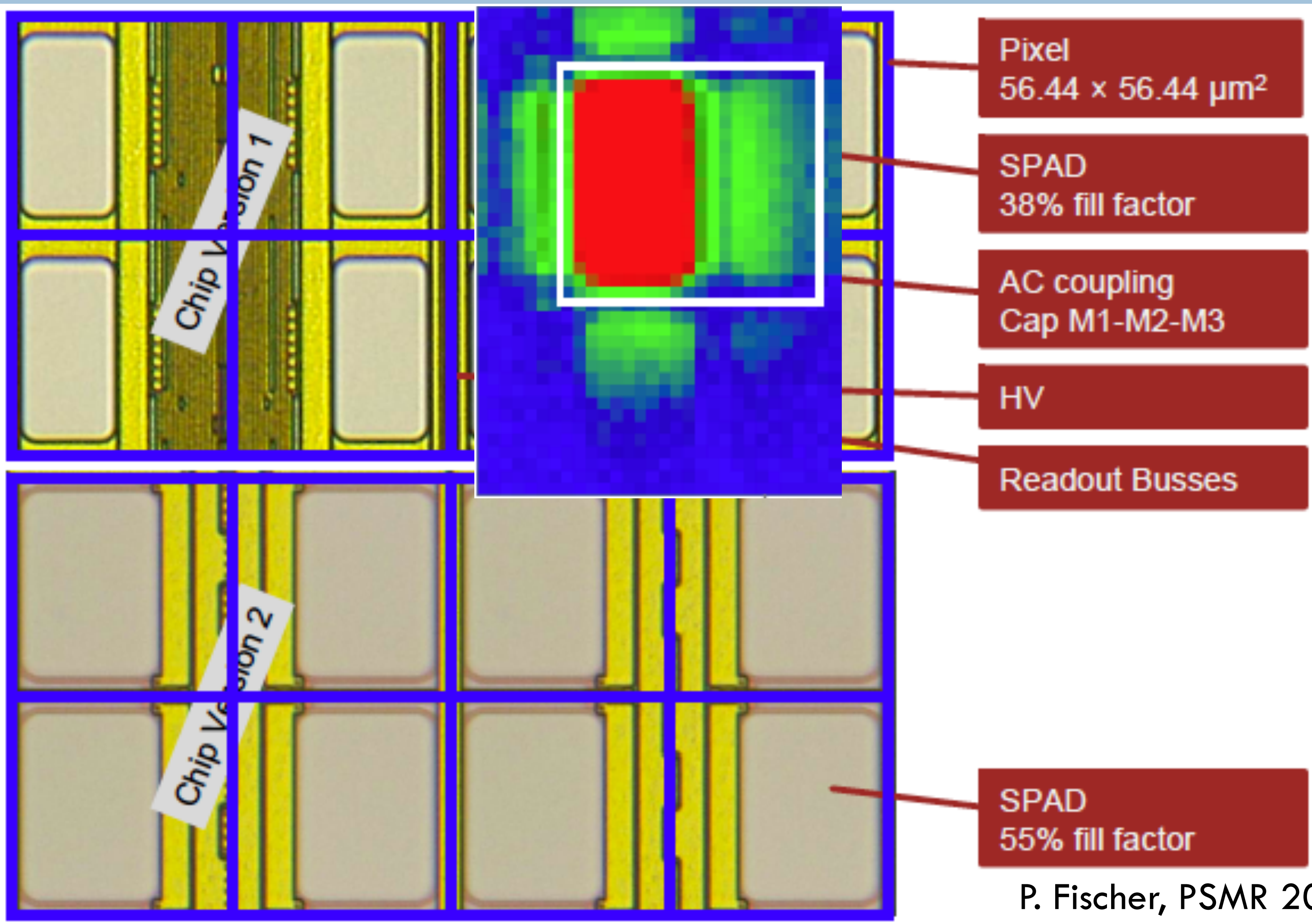
SUBLIMA
EU contract
#241711

Peter Fischer, Roberto Blanco, Michael Ritzert, Ilaria Sacco
Heidelberg University
Sascha Weyers
Fraunhofer Institute for Microelectronic Circuits and Systems, Germany

CMOS technology from the Fraunhofer Institute IMS 0.35 μ m gate length, 4 metal levels →challenge to achieve good fill factor (PDPC uses 0.18 μ m…)

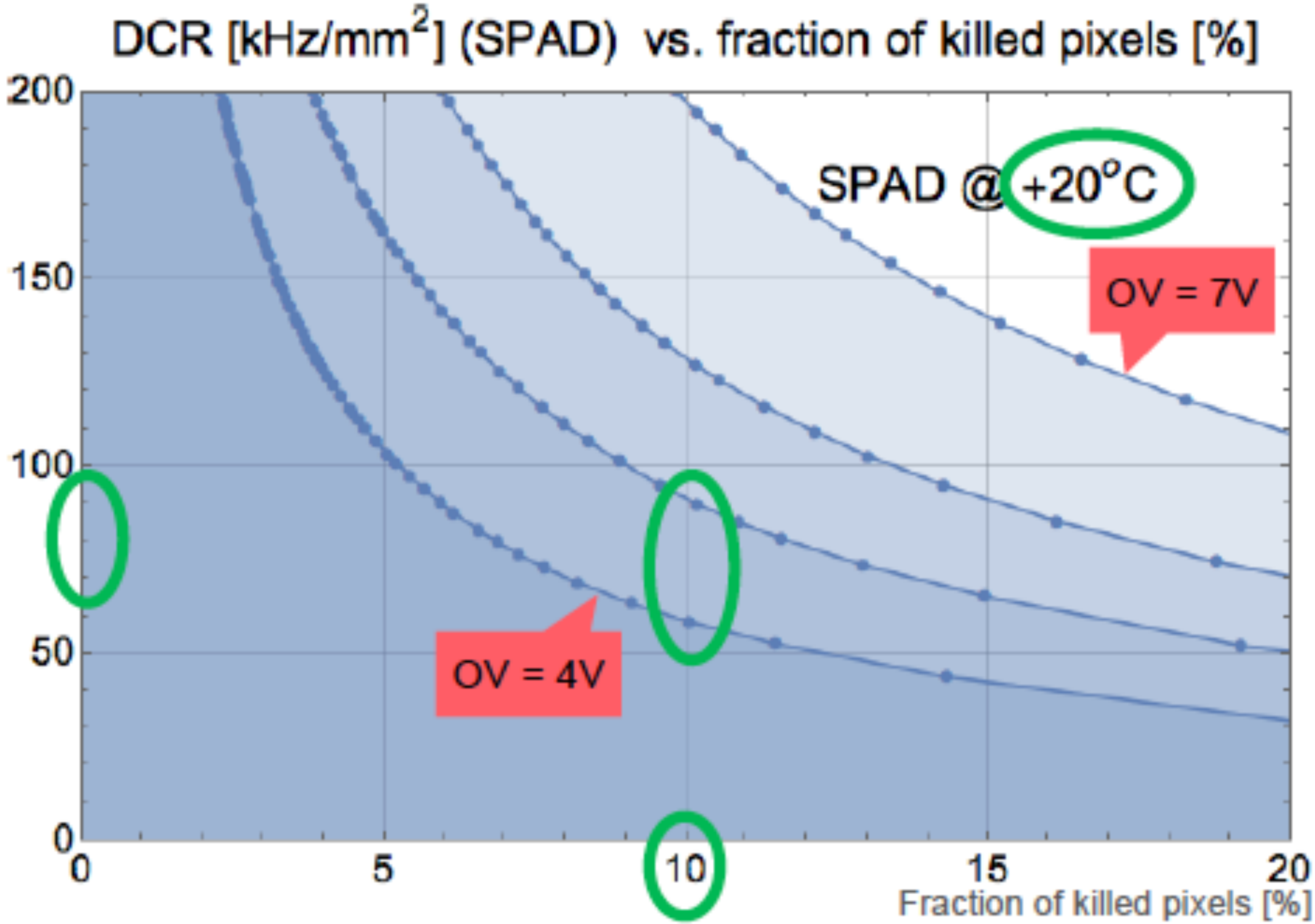
- 88 x 88 Pixel of 56.44 x 56.44 μ m2 size
- IDP1 has a self contained readout architecture & *slow* full frame readout
  Design fill factor **38%**
- IPD2 has ***fast*** full frame readout (design: 400k frames/s), no self contained RO
  Design fill factor **55%**

Two versions



P. Fischer, PSMR 2015

Dark Count Rate



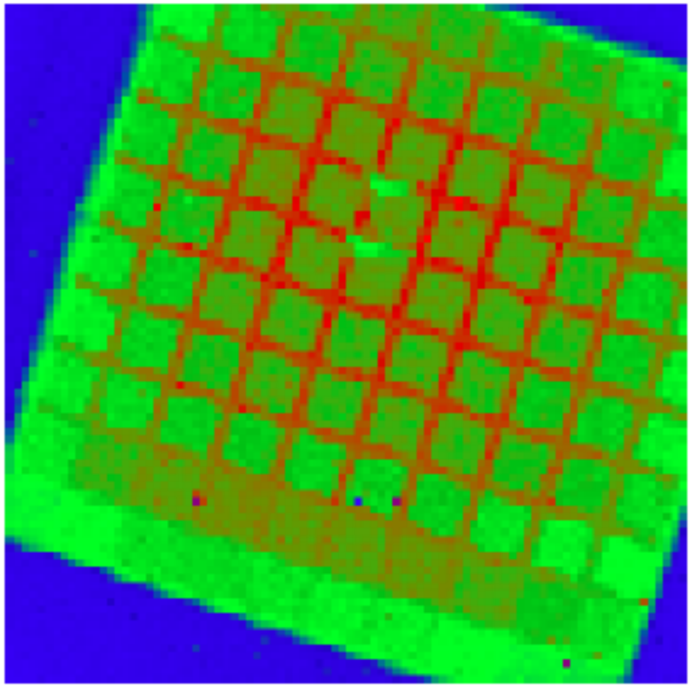
P. Fischer, PSMR 2015

IDP performances

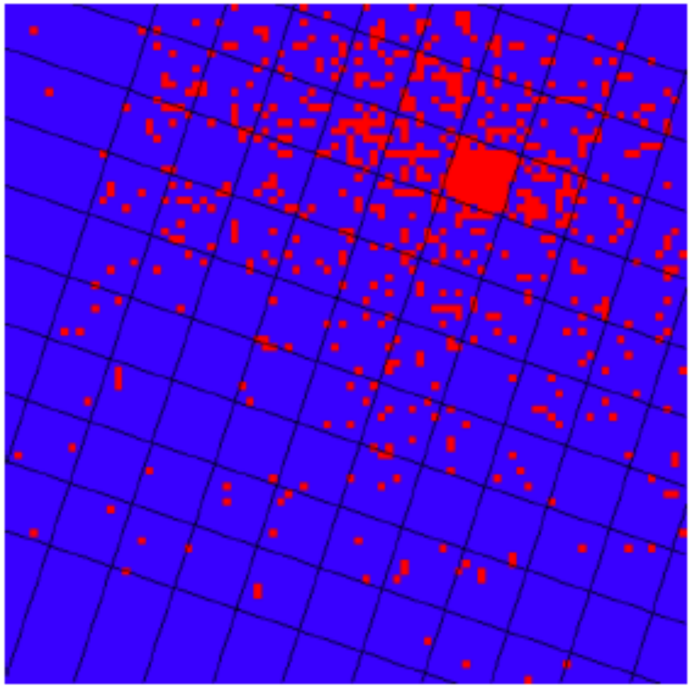
LYSO Arrays with 0.48 mm pitch (!)

UNIVERSITÄT HEIDELBERG

- Measured at ~30°C, OV = 3 V
- Trigger on Mult ≥ 4, 200 ns integration



Overlay of 20k events



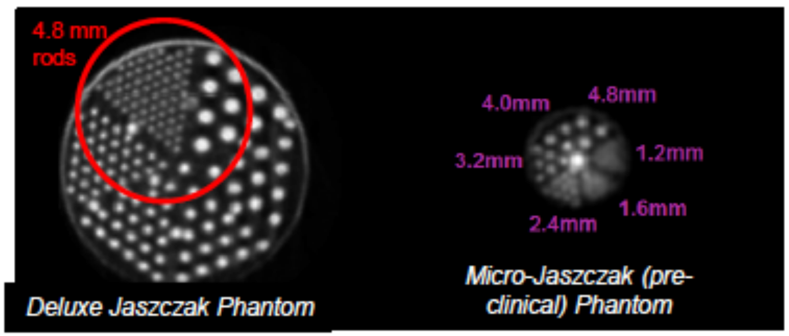
Single events

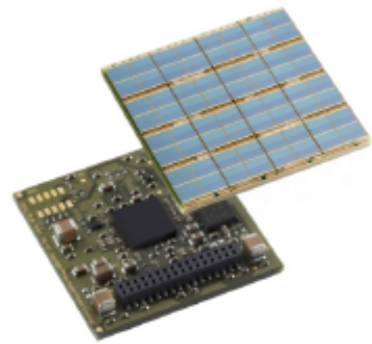
P. Fischer, PSMR 2015

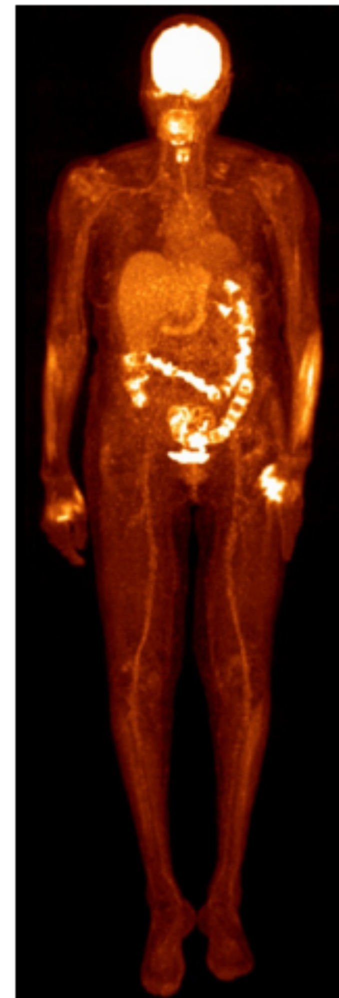
First dSiPM based clinical scanner

Philips Vereos digital PET/CT system

Based on PDPC digital silicon photomultipliers (dSiPMs)







System Performance	
CRT	~350 ps FWHM
Sensitivity	22 kcps/MBq
FOV	67.6 x 16.4 cm
Spatial res	4.1 mm
Energy res	< 12%

D. Schaart, Delft University of technology, 2015

First PET/MR dSiPM scanner

Based on DPC Hyperion detector

Preclinical device

3 rings of LYSO:Ce scintillator arrays

30x30 crystals of 1 mm • 1 mm • 12 mm each

Clinical device

1 ring of LYSO:Ce scintillator arrays

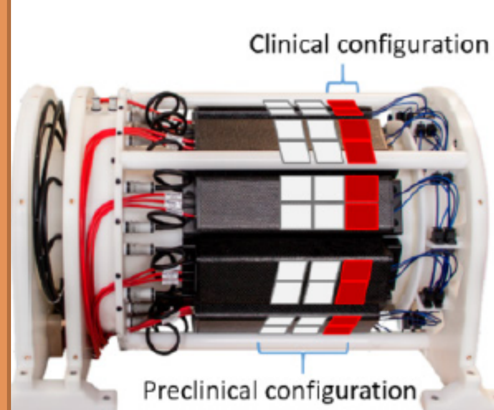
8 x 8 crystals of 4 mm • 4 mm • 10 mm each

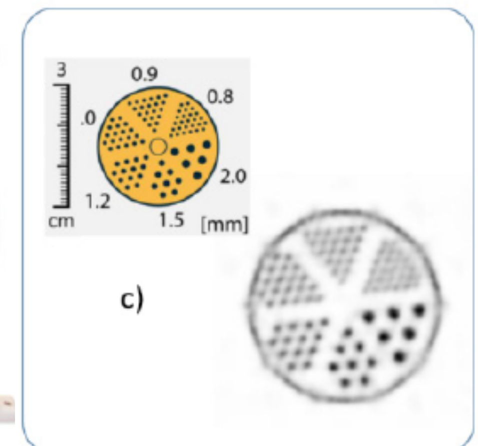
Precl. Performances

En.res. 12.6 %

Sp. Res. 0.73 mm^3

CTR 260 FHWM





B. Weissler et al., A Digital Preclinical PET/MRI Insert and Initial Results, IEEE Trans Med 1051 Imaging, (2015).

Conclusions I

- Analog SiPM technology
  - mature to meet the requirements of the most challenging applications (High Res/DOI/TOFPET/Multimodal imaging PET/MRI, custom applications)
  - Still room for improvements (DCR, Xtalk, AP reduction, new interconnections technologies)
  - Large-scale industrial production is now possible at prices competitive with PMTs

Conclusions II

- Digital SiPM technology
  - on-chip integration of the light-sensing components with (near-) real-time data processing and readout circuits
  - one type of dSiPM available commercially, large-scale availability of other types of dSiPM expected in the near future
  - Room for improvements (DCR mitigation strategies, Xtalk reduction, 3D vertical integration technology)
  - Trend towards fully digital and highly integrated detection, acquisition and processing of optical information.

Acknowledgements

- Claudio Piemonte, FKB
- David Stoppa, FBK
- Dannis Schaart, TUDelft
- Vincenzo Patera, Michela Marafini, Riccardo Faccini, Universita' La Sapienza e INFN Roma
- G. Battistoni, INFN MI
- Massimo Caccia, Uni Insubria e INFN MI
- Damien Bertrand, Julien Smeets, IBA
- Sibylle Ziegler, TUM
- Simon Cherry, UCDavis
- Peter Fischer, Heidelberg Uni
- Collaborazione INSIDE