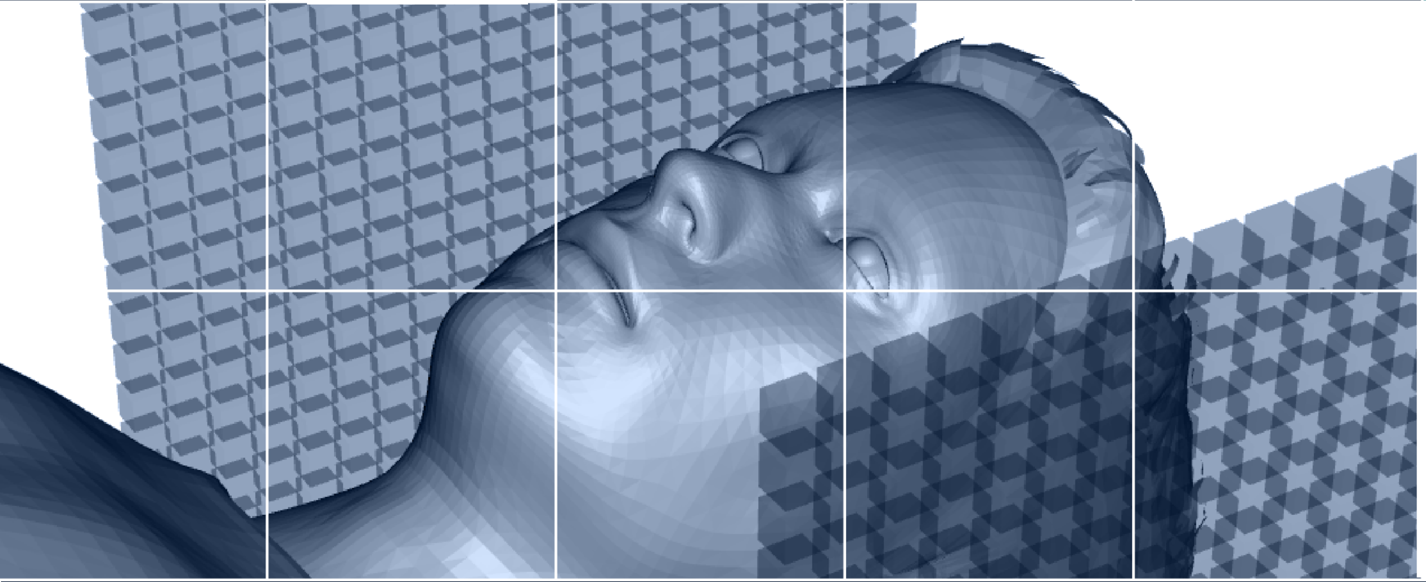
Follow **PetVision** project on LinkedIn



High-Performance modular TOF-PET imager

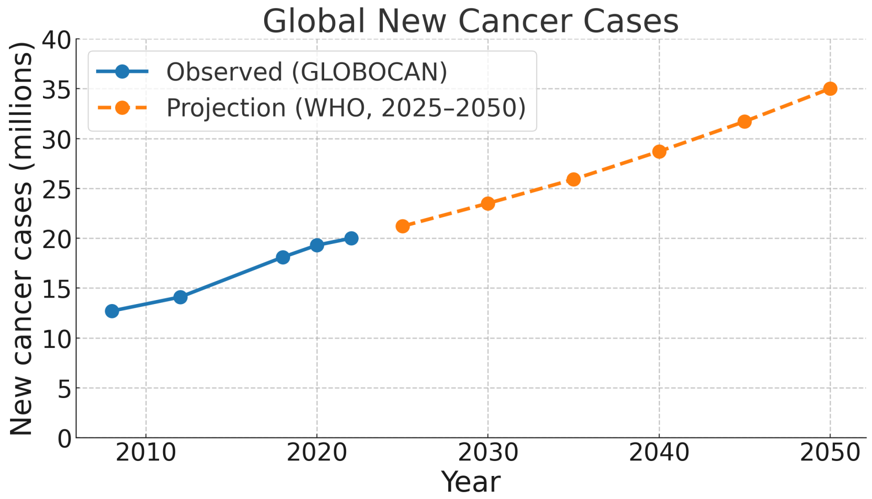
Rok Pestotnik, Jožef Stefan Institute, Ljubljana, Slovenia

Jožef Stefan Institute, Ljubljana, Slovenia

PET VISION

FAst Timing Applications for Nuclear Physics and Medical Imaging Catania - Italy, 8 - 10 October 2025

Motivation



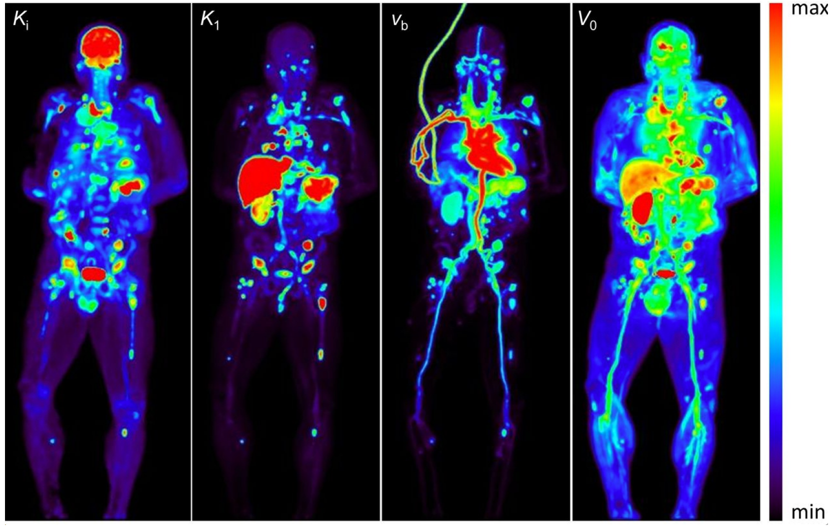
Need for **early diagnosis** and **treatment**

Strengthening medical imaging capacity resolution was adopted by the WHO in May 2025

Expected to reduce the rising burden of cancer and other diseases, especially in low- and middle-income countries.

MRI, X-ray, CT : anatomic imaging
Need for **functional imaging**

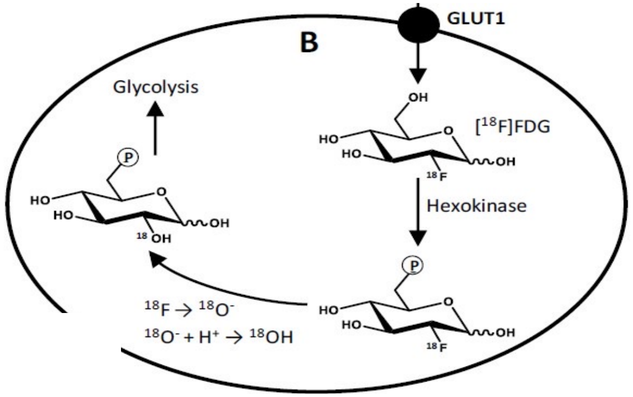
PET (Positron Emission Tomography)
- Leading method
- Also needed in other medical fields
- 🙁 **costly** (min. 2 MEUR/ device)



Funded by the European Union
This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101099896

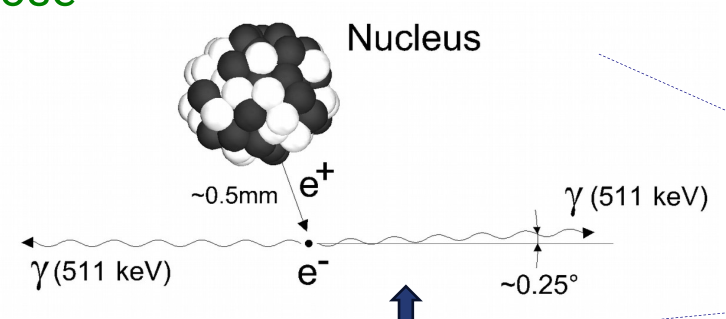
Positron emission tomography (PET)

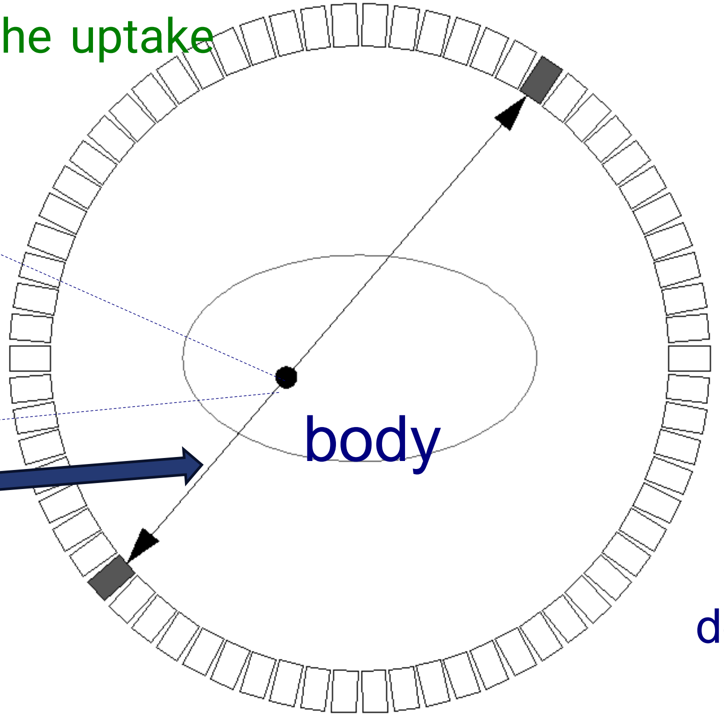
In-vivo imaging of biological processes via detection of 511 keV annihilation γ rays



By using bio-markers containing a beta+ emitter

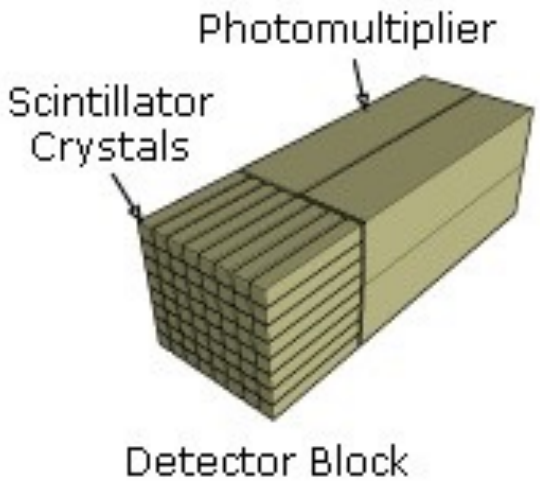
Fluorodeoxyglucose (FDG) is the most commonly used marker – indicates the uptake of glucose





line of response (LOR)

detector ring



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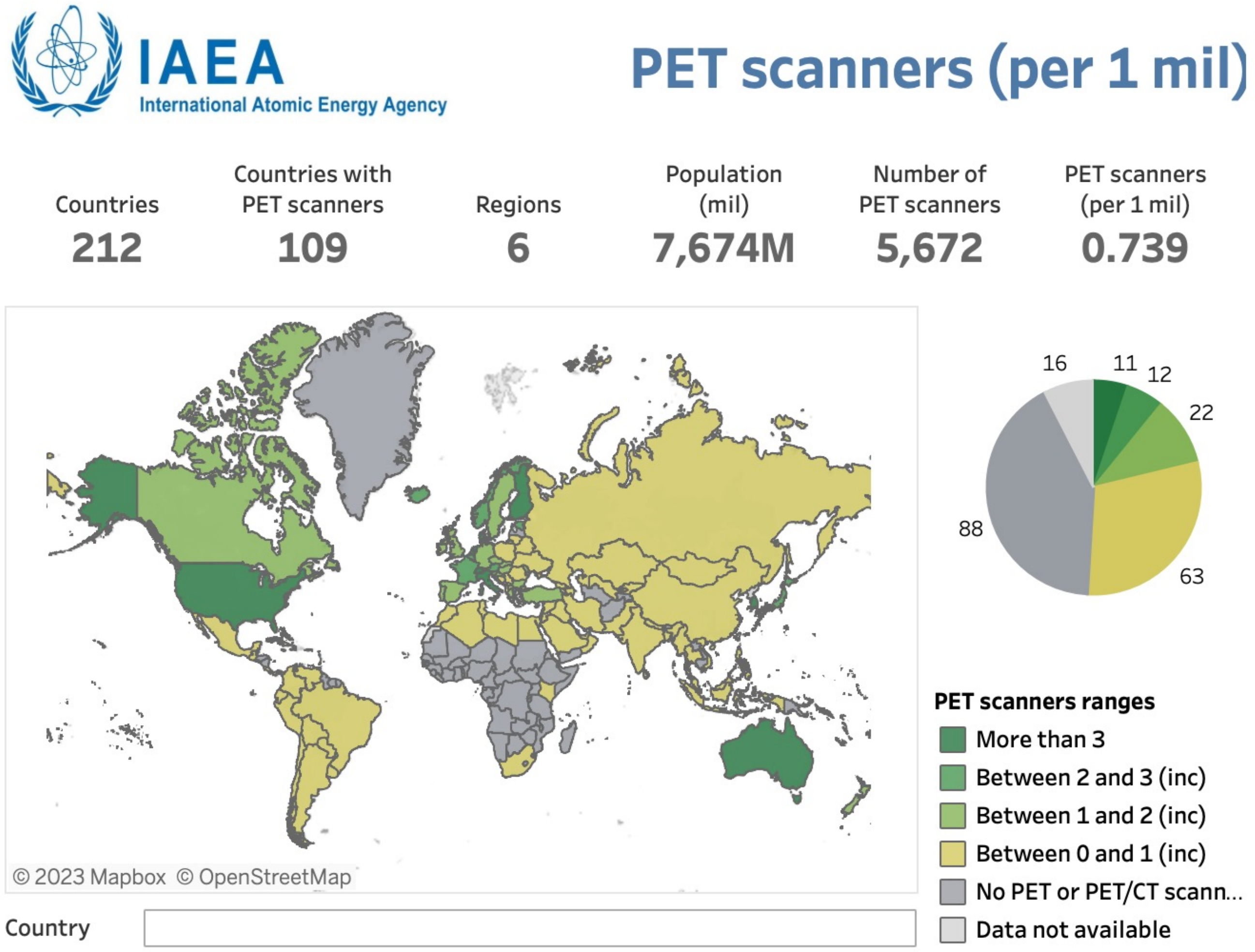
Global Imaging Access and Impact



Access gaps in low- and middle-income countries

- Severe shortages of infrastructure and workforce
- Poorer disease outcomes
- Imaging is vital for managing non-communicable and infectious diseases

Economic and health benefits:

- Better imaging could prevent **9.5 million deaths** in 10 years
- Estimated return of **€12–43 for every €1 invested**

Funded by the European Union

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Motivation for Fast TOF PET

- Paradigm shift in medicine from:
  - From the Treatment of obvious disease
  - To early diagnosis/prevention

- This leads to more stringent requirements on PET
  - Sensitivity
  - Specificity

- Targeted Radionuclide Therapy (TRT) & Theranostics
  - introduced an urgent need for more widespread and accurate PET

Funded by the European Union

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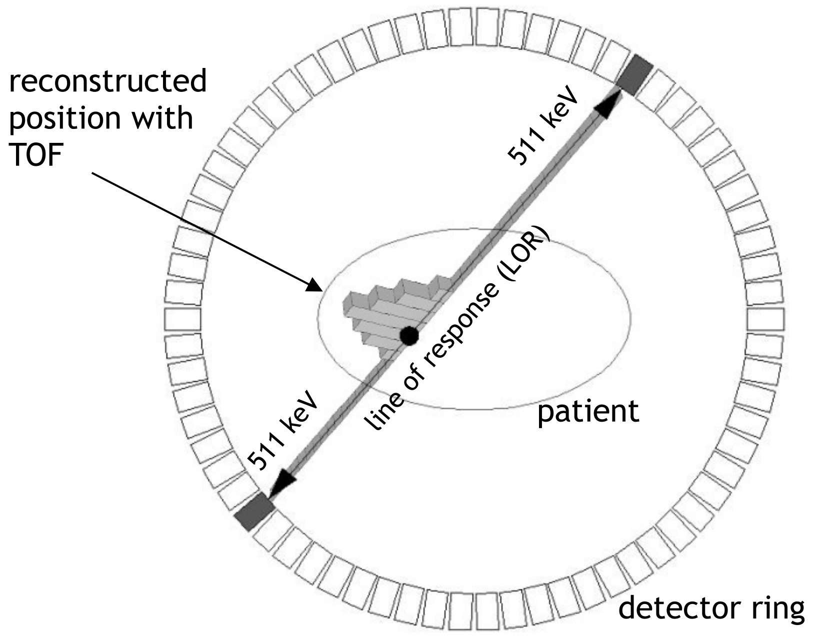
Time-of-flight Positron emission tomography (TOF-PET)

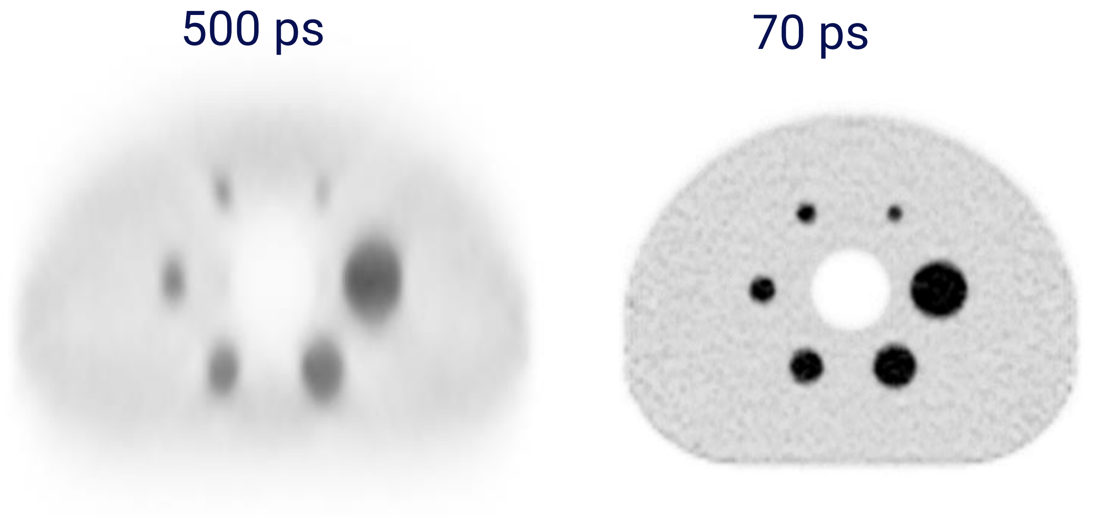
Limits the reconstructed position of annihilation by localizing source position along the LOR

Improves the quality (contrast-to-noise ratio) of reconstructed images

$\Delta t \sim 66\text{ps} \rightarrow \Delta x = c_0\Delta t/2 \sim 1\text{cm}$

Δt = coincidence resolving time, CRT





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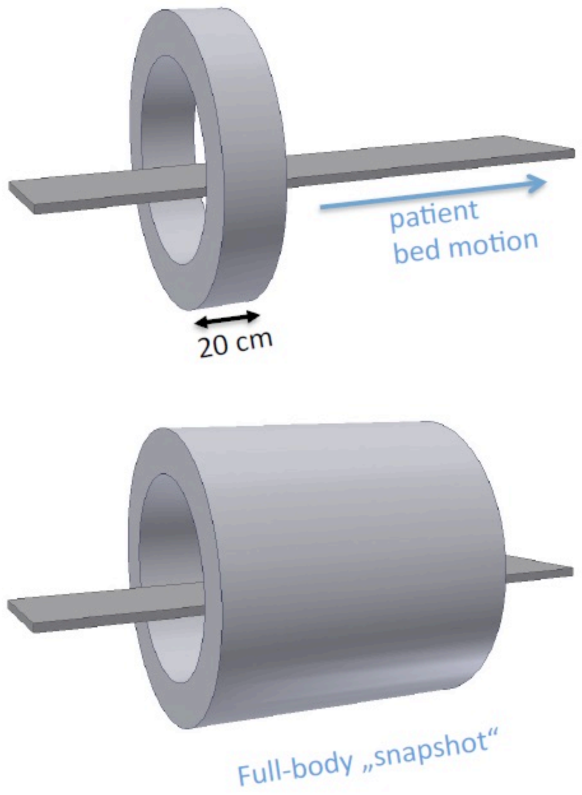
Current situation

- Standard clinical scanners are sub-optimal:
  - Cost of equipment and siting costs, limited access, and performance.
- Novel long axial PET scanners offer a very attractive solution in terms of
  - Increased sensitivity and
  - Enabling fast pharmacokinetics/pharmacodynamics.
- They pose significant challenges both.
  - Financially: Cost of equipment and operation
  - Logistically, integration with conventional PET scanners.



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State-of-the-art in TOF

- Clinical scanner:
  - Siemens Biograph Vision PET/CT → **214 ps**

https://www.siemens-healthineers.com/molecular-imaging/pet-ct/biograph-vision

- Laboratory measurement:
  - Gundacker *et al, Phys. Med. Biol.* 65 (2020) 025001 (20pp)

  2 x 2 x 3 mm LSO → **58 ps***

  2 x 2 x 20 mm LSO → 98 ps*

* measured with high power readout electronics not scalable to large devices

Funded by the European Union

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Gamma detectors for PET

Scintillating crystal:
- converts gamma energy into optical photons

Photodetector
- converts optical photons into electrical pulses

Time resolution in TOF PET limited by
- scintillation light emission
  - rise and decay time
- **optical photon travel time spread in the crystal**
- **photodetector response**
- **readout electronics**

Addressed by 10 ps challenge

https://the10ps-challenge.org/

Paul Lecoq *et al* 2020 *Phys. Med. Biol.* **65** 21RM01

Effective sensitivity $$S_{\mathrm{eff},D} \propto \eta_{\mathrm{det}}^2 \; \eta_{\mathrm{geom}} \; \frac{D}{\Delta t}$$

- detection efficiency η_{det} of the detector
- η_{geom} the geometrical efficiency (angular coverage)
- D the diameter of the object imaged

Important: Optimize detector CTR to maximize sensitivity

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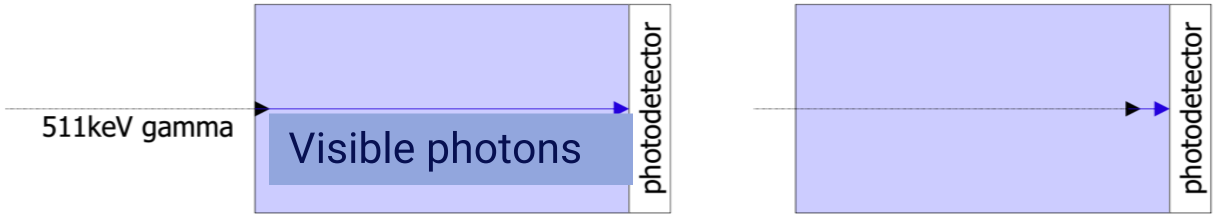
Limitations on timing due to optical travel time

- Optical photons, produced in the crystal, need to reach the photodetector
- Inside the crystal, optical photons travel more slowly than gamma rays
- **Intrinsic travel time spread** due to different gamma interaction depths
- **At the entrance** or **Exit of the crystal**



Different optical photon arrival time!

d = 15 mm, n = 1.8: $t = d \cdot n/c_0 = 90$ ps $t = d/c_0 = 50$ ps $\rightarrow \Delta t = 40$ ps

- **Can, in principle, be corrected for by:**
  - Measuring the depth of interaction (DOI) -> 20 mm crystals DOI 2,7 mm, CTR improves from 132 to 85 ps
  - Using Cherenkov radiation DOI: 10.1109/TRPMS.2022.3202138 **Potential of a Cherenkov TOF PET scanner**
  - Using shorter crystals → multi-layer configuration

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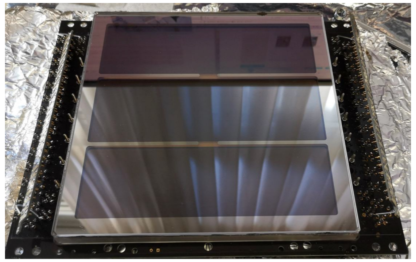
Choice of photodetector

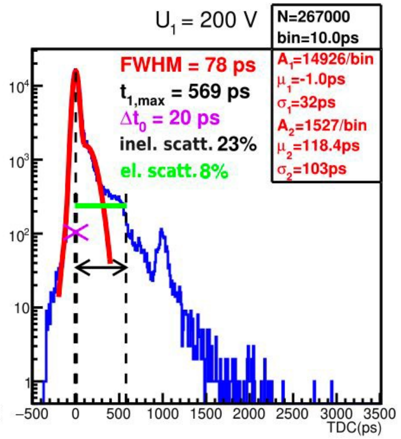
$$S_{\mathrm{eff},D} \propto \boxed{\eta_{\mathrm{det}}^2} \eta_{\mathrm{geom}} \frac{D}{\Delta t}$$

Microchannel plate PMT - Incom LAPPD GenII 20x20cm2

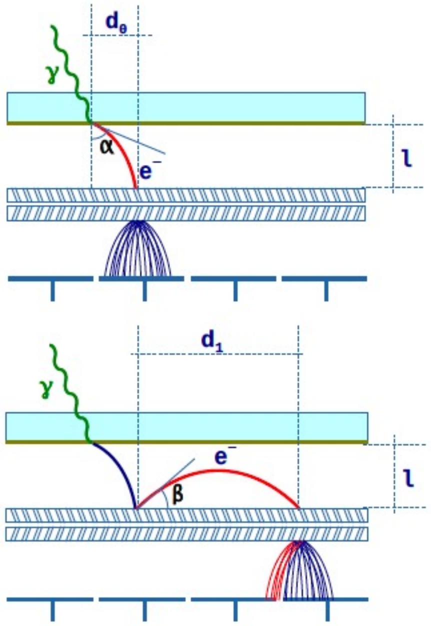
PDE ~30%, SPTR FWHM 80 ps

Monolithic ground plane anode, capacitively coupled to the readout electronics on the external side





R. Dolenec, RICH 2025

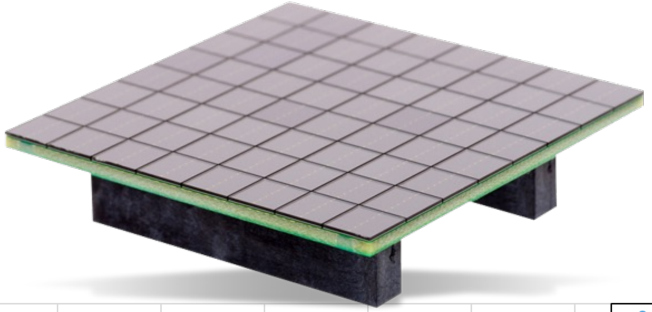


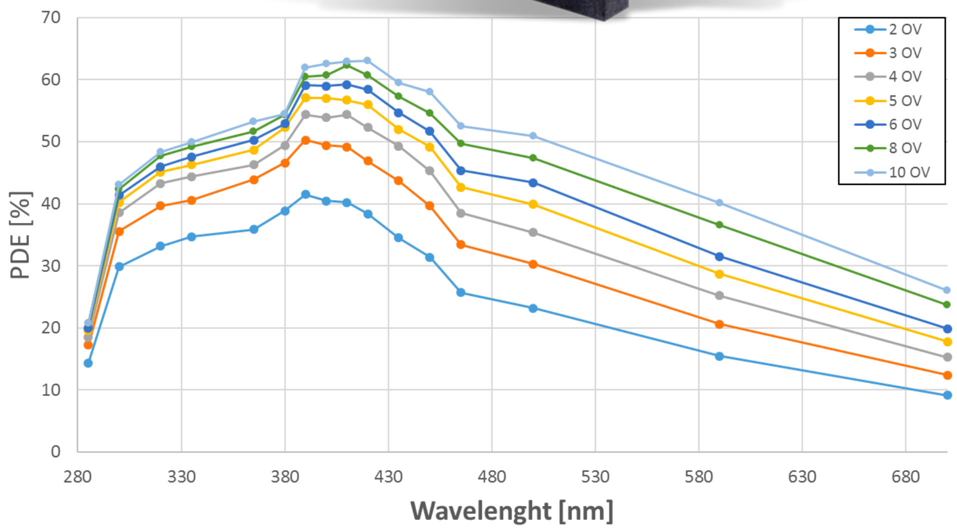
S. Korpar, PD07

Silicon photomultipliers – 3x3 mm

PDE ~65%

SPTR FWHM ~ 100 ps





Pestotnik, FATA 2025

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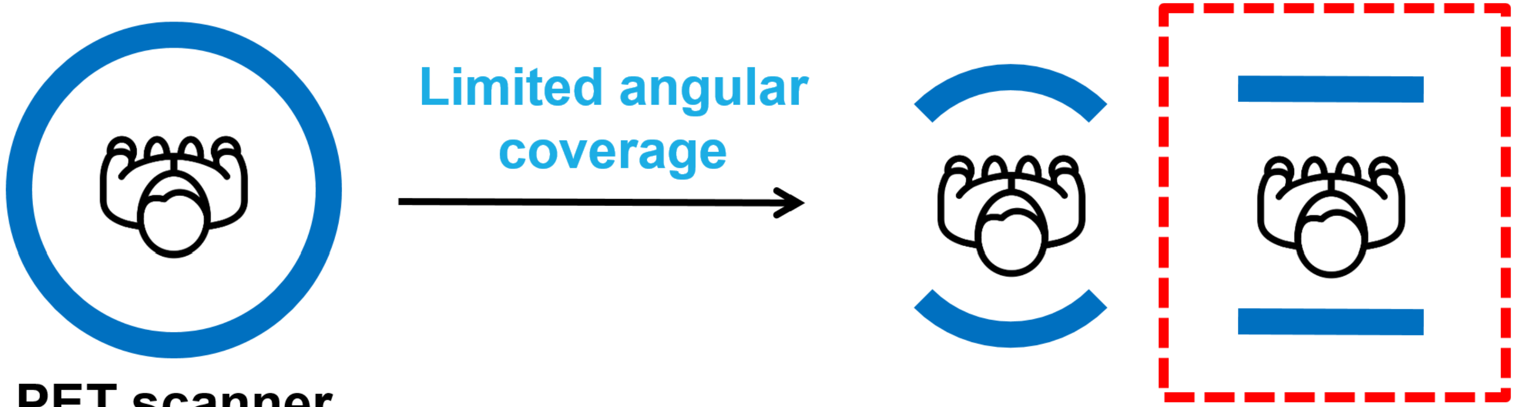
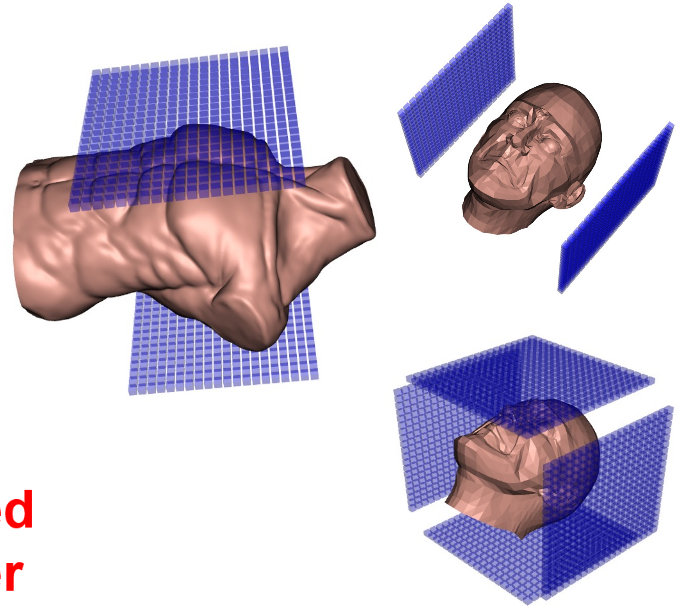
Next generation scalable time-of-flight PET

Superb time resolution enables simplifications in the scanner



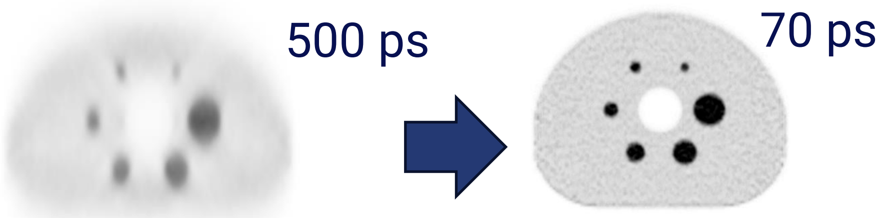
PET scanner

Panel-based limited angle PET scanner



Limited-angle PET scanners generally produce distorted images with artefacts unless they have good **time-of-flight** information

The angular sampling requirement to obtain distortion-free images decreases
S. Surti, J. S. Karp, Physica Medica 32 (2016) 12–22



G. Razdevšek *et al.*, "Multi-panel limited angle PET system with 50 ps FWHM coincidence time resolution: a simulation study," in *IEEE TRPMS*, doi: 10.1109/TRPMS.2021.3115704.

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Potential benefits

Mobility

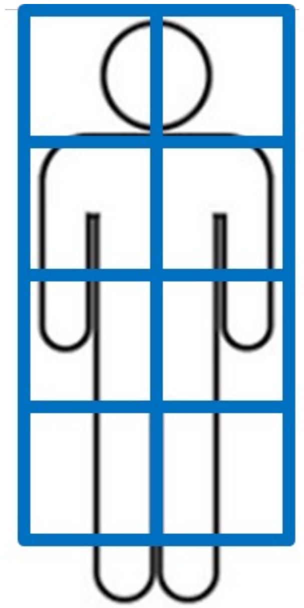
- Portable or bedside PET imaging

Flexibility

- Adjustable FOV and sensitivity

Modularity

- Combining multiple panels → multi-organ/total-body PET scanner



Accessibility

- Reduced manufacturing cost (4-5x lower) and complexity
- More devices, Higher throughput of patients, decreased waiting times, improve cancer survival rates

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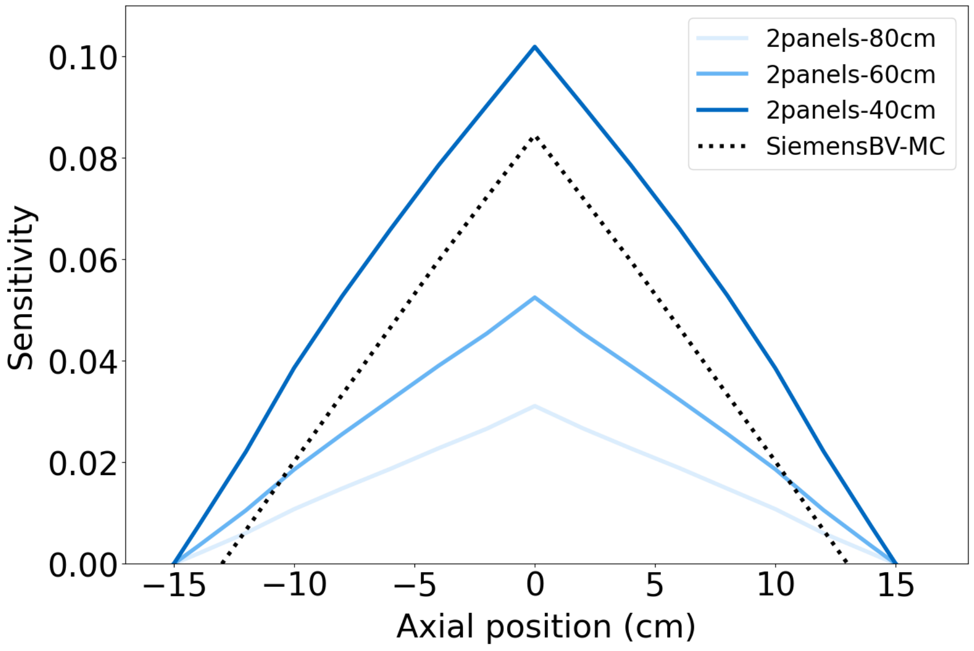
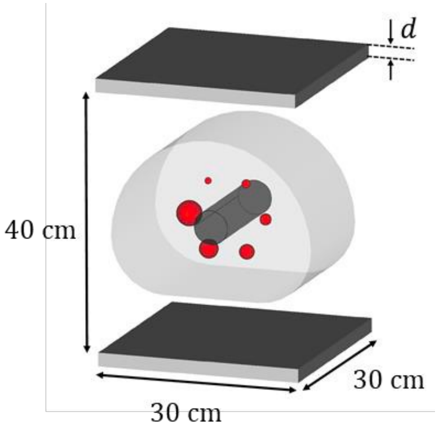
Simulations of a limited angle system - Sensitivity and NECR

2 panels 30x30 cm^2

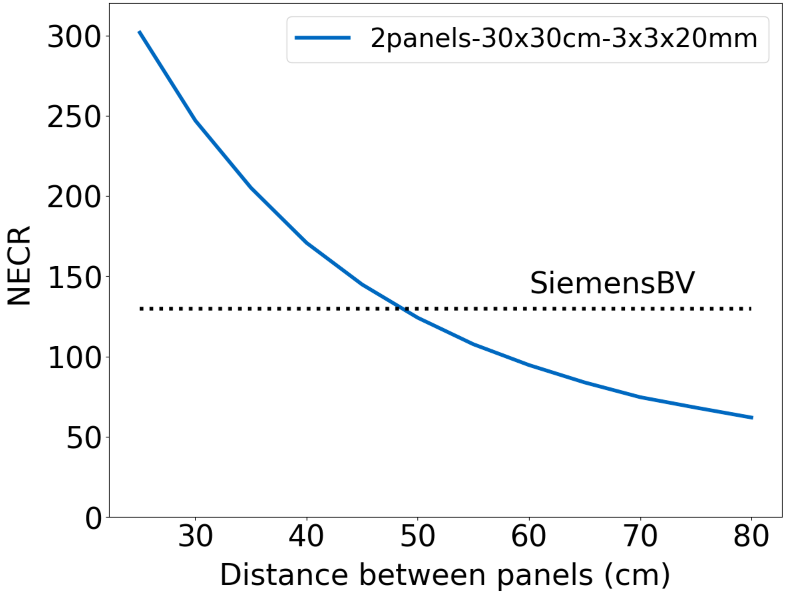
Sensitivity for different panel-panel distances





Geant4/GATE → Monte Carlo simulations of digital phantoms and different scanner designs

CASToR → image reconstruction with Maximum Likelihood Expectation Maximization (**MLEM**) algorithm



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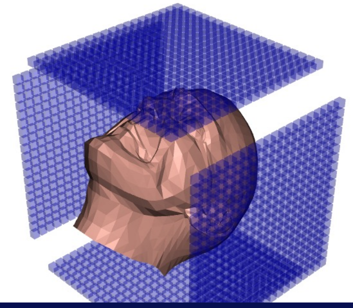
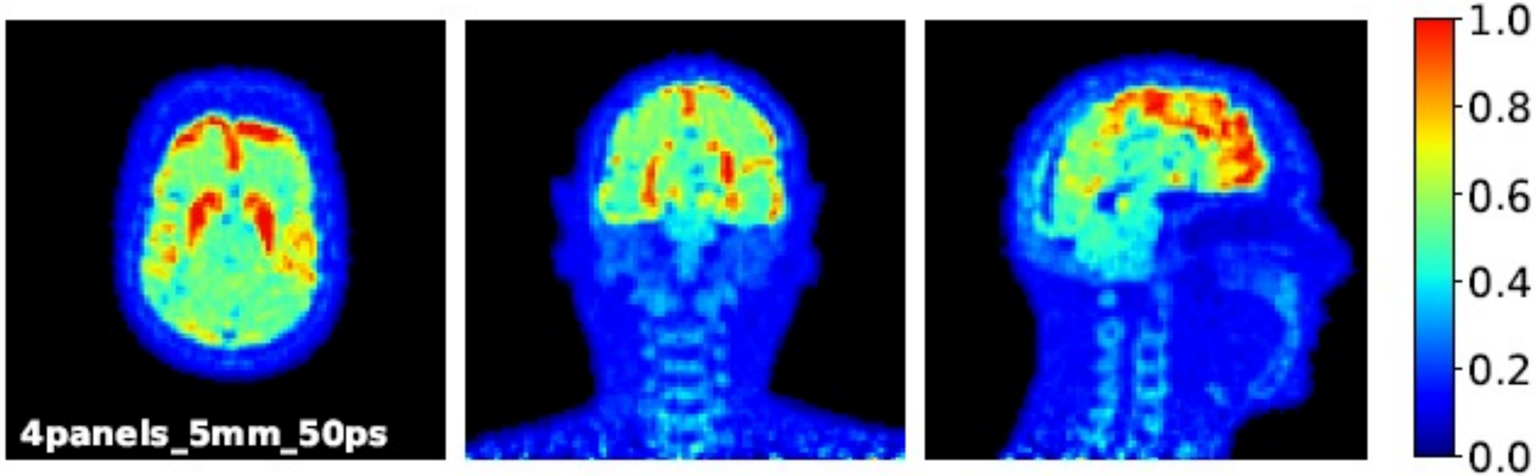
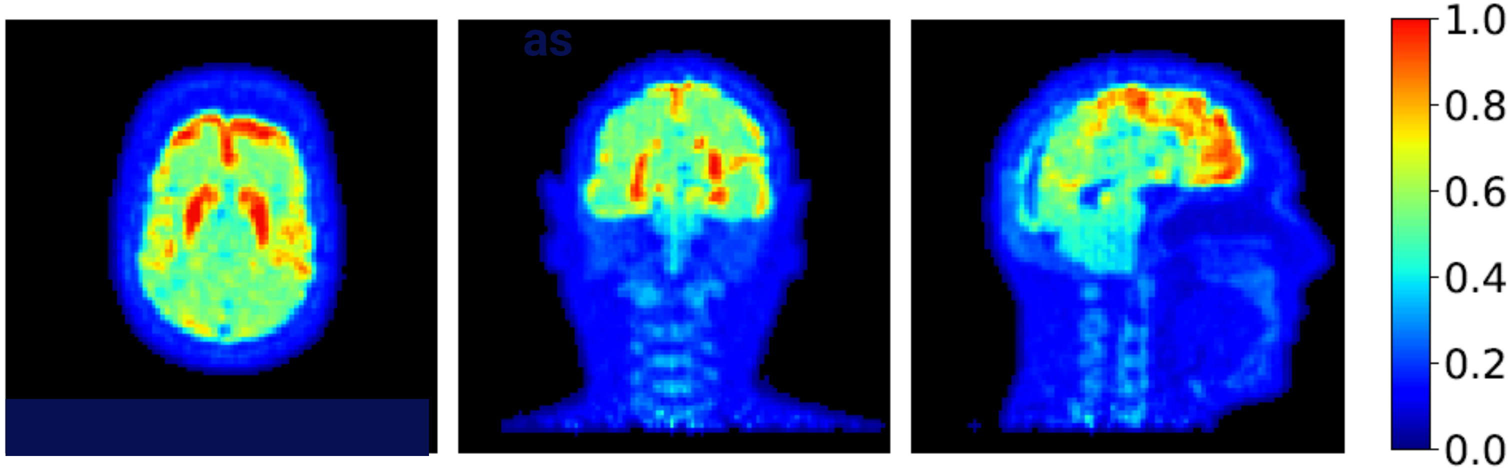
Simulation - Enabling Open Geometry systems



Two pairs of 30x30 cm2
panels with 50ps CRT
3x3 mm2 LYSO crystals



works almost as well
as



Siemens Biograph

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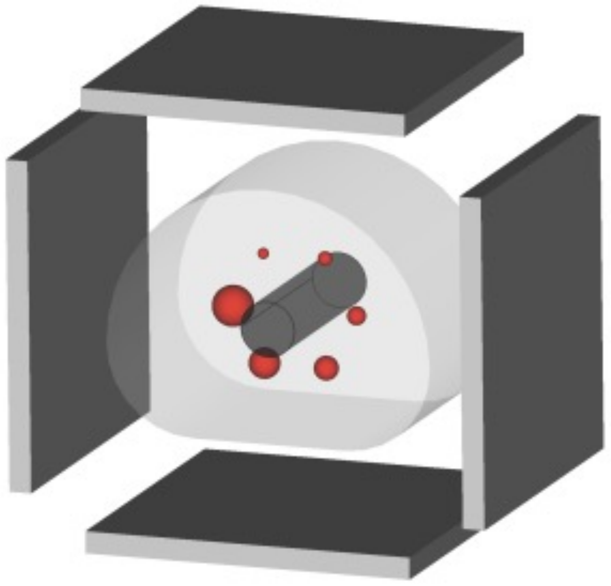
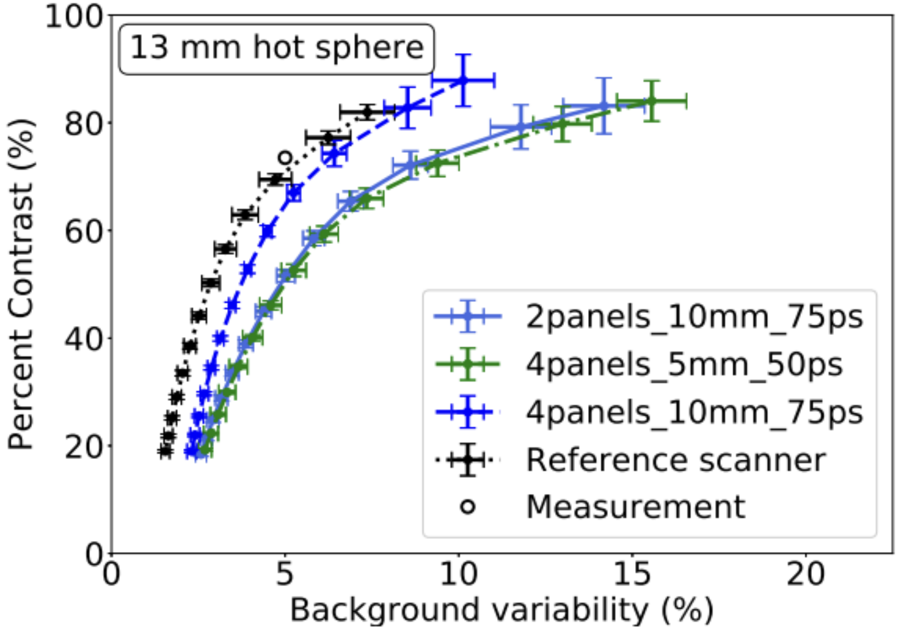
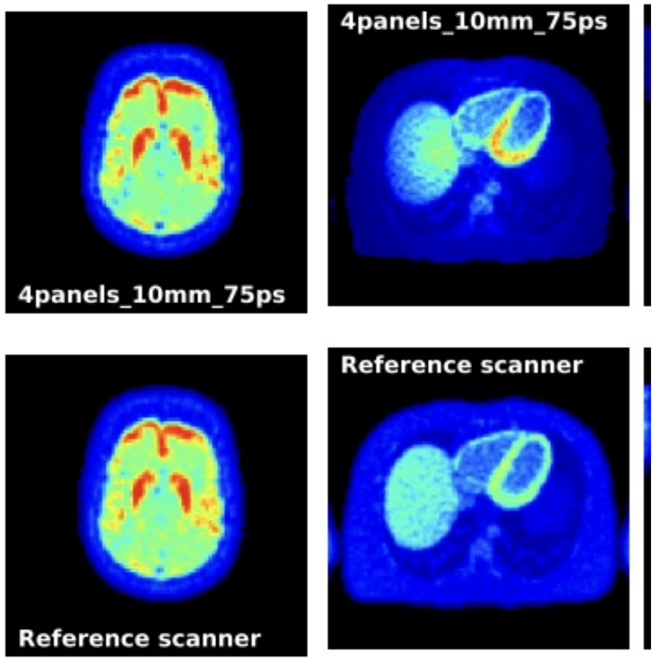
Simulation study – qualitative analysis



Simulated arrangement of 30x30 cm2 flat panel detectors



Percent contrast versus background variability



Reconstructed images of a torso and head for the flat panel detectors and the reference scanner Siemens BV

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This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101099896

Next generation scalable time-of-flight PET

European Innovation Council

Funded by the European Union

Address PET challenges by decreasing different contributions using fast CTR

PetVision Project https://petvision.org/

European Innovation Council Pathfinder Open 2022 Call

Aim: Improve (SNR) without increasing the cost associated with axial coverage by resorting to very sparse angular coverage of the patient and long axial field coverage

- Front-end electronics: Develop a low-noise, high-dynamic-range ASIC with a time resolution of 20 ps & on-chip TDC
- Improve the SiPM sensor PDE and increase the geometrical efficiency
- Explore 2.5D integration with the photo-sensor to achieve sub-100 ps CTR
- Demonstrate the functionality by building a prototype

PET VISION

The European Innovation Council

Europe's flagship innovation programme to identify, develop and scale up game changing innovations

Follow **PetVision** project on LinkedIn

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Project partners

European Innovation Council

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Chip design
UNIVERSITAT DE BARCELONA

Rok Pestotnik
Coordination, Design Integration, Reconstruction
Institut "Jožef Stefan" Ljubljana, Slovenija

Alberto Gola
Photo sensors
2D integration
FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

Jose Benlloch
Readout Electronics
Data Acquisition
i3M

PET VISION

David Sanchez
SME: Mechanics & Software
ONCO VISION

Georges El Fakhri
Associated P. Hospital: Design & Validation
Yale

Rafael Ballabriga
Associated P., Chip design
CERN

Wolfgang Weber
Hospital: Validation
MRI TUM
Klinikum rechts der Isar
Technische Universität München

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Breakthrough innovations

New gamma sensor with improved coincidence timing resolution:
- 200 ps -> 75ps
- enabling new geometries

Key improvement: 10 x image sensitivity*

Images of comparable quality

with many fewer sensors

***wrt. the state-of-the-art reference scanner**

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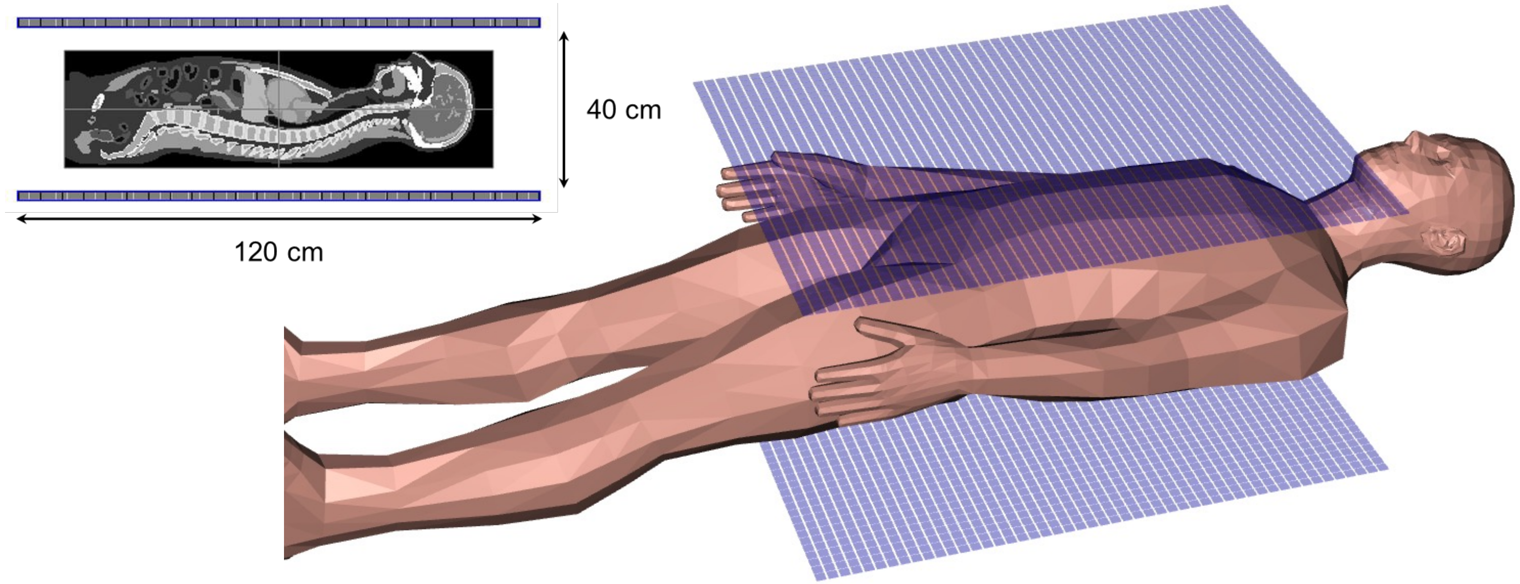
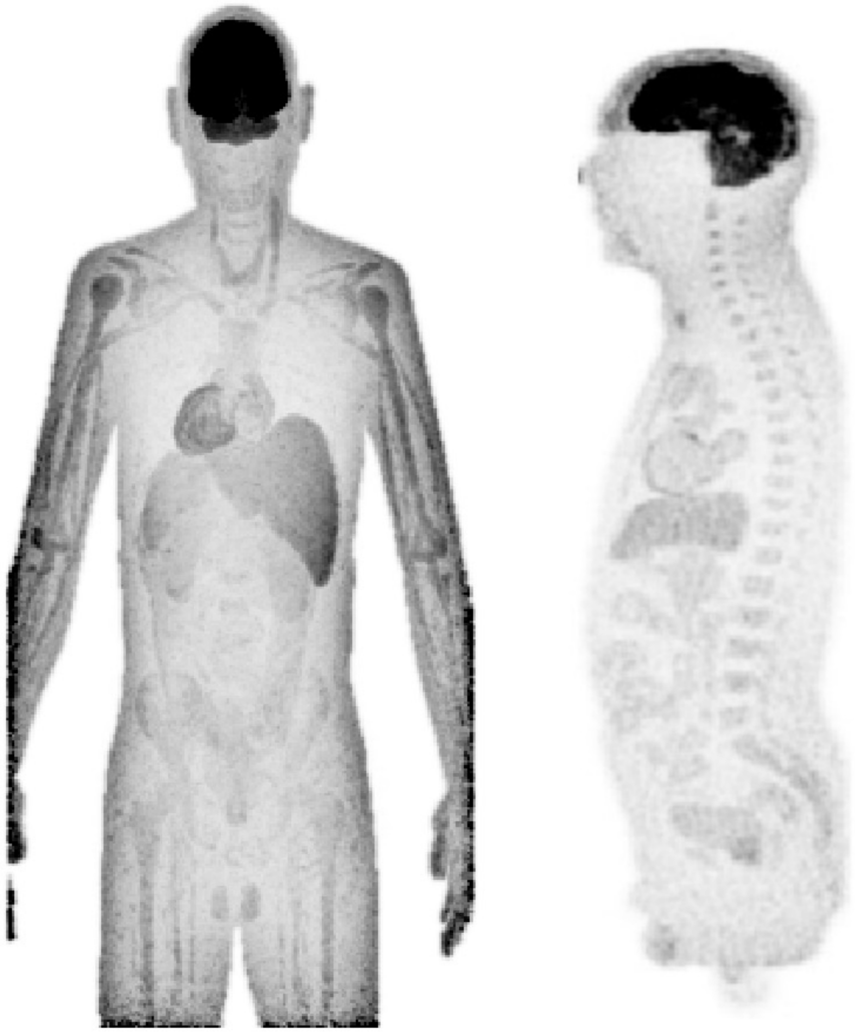
From Limited-angle panels to Total-body

Increased sensitivity by larger panels





Capability of the planar TOF PET imager:

Image of a reconstructed 3 mm slice of a digital phantom acquired by two 120x60cm2 panel detectors (above and below the patient), assuming 100 ps TOF resolution and 10 mm LYSO scintillator thickness.

Funded by the European Union

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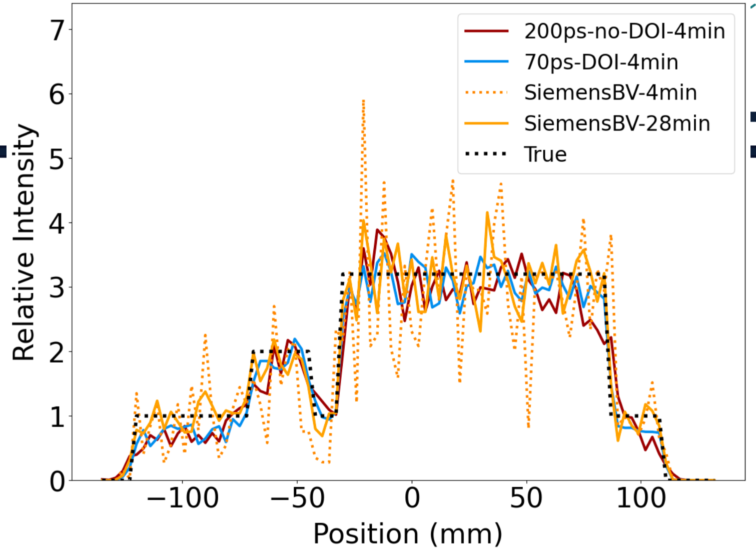
Increasing sensitivity by DOI

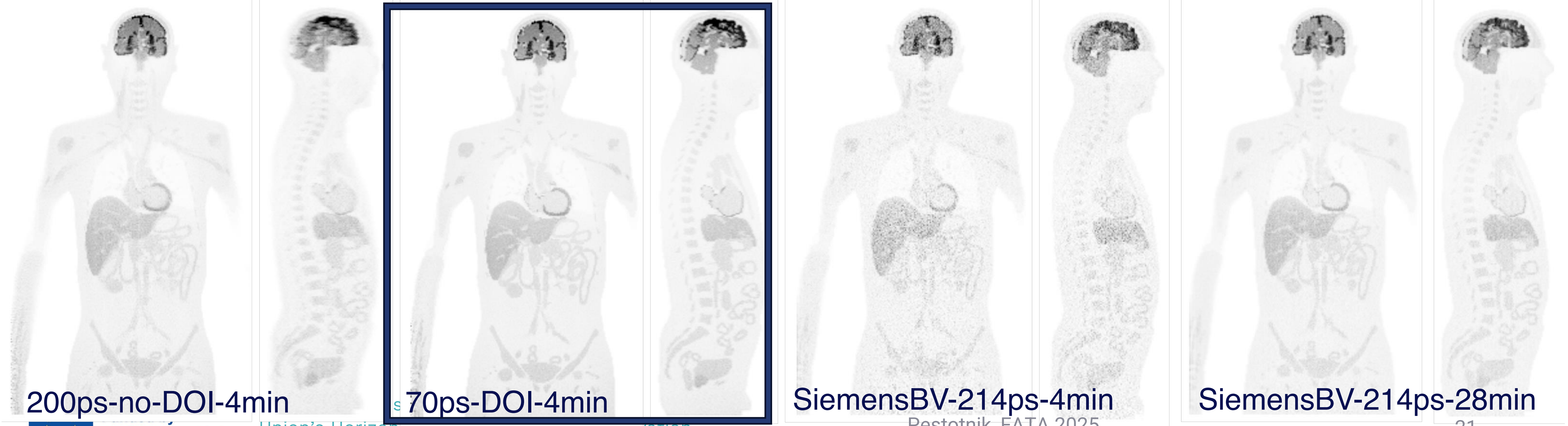
- **TOF** crucial to compensate for limited angular sampling,
- **DOI** improves image quality by mitigating the parallax error.

Simulation of a Highly anatomically detailed phantom (XCAT)

- 2x 120x60 cm2 panels
- Scan time: 4 min
- **No filter applied**



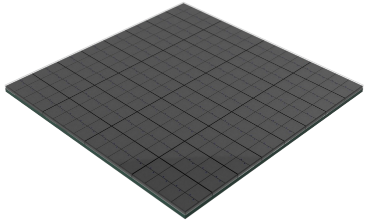
2-panel PET system can achieve image quality comparable to clinical scanners while utilizing 4x less material.

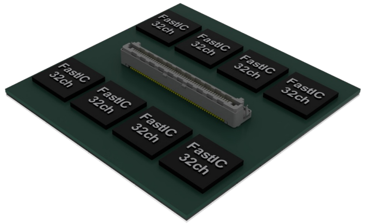


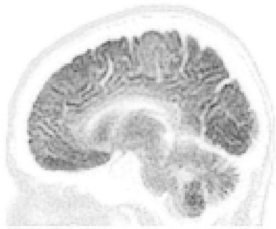
the European Union
Union's Horizon Europe research and innovation
programme under grant agreement No 101099896

Timeline

Year 2	Year 3	Year 4	Year 5	Year 6-7
Photo Sensor with improved performance	**ASIC chip and integration into a digital module**	**Integration of the prototype**	**Validation in two hospitals**	**Further developments & exploitation**







Further funding

Funded by the European Union

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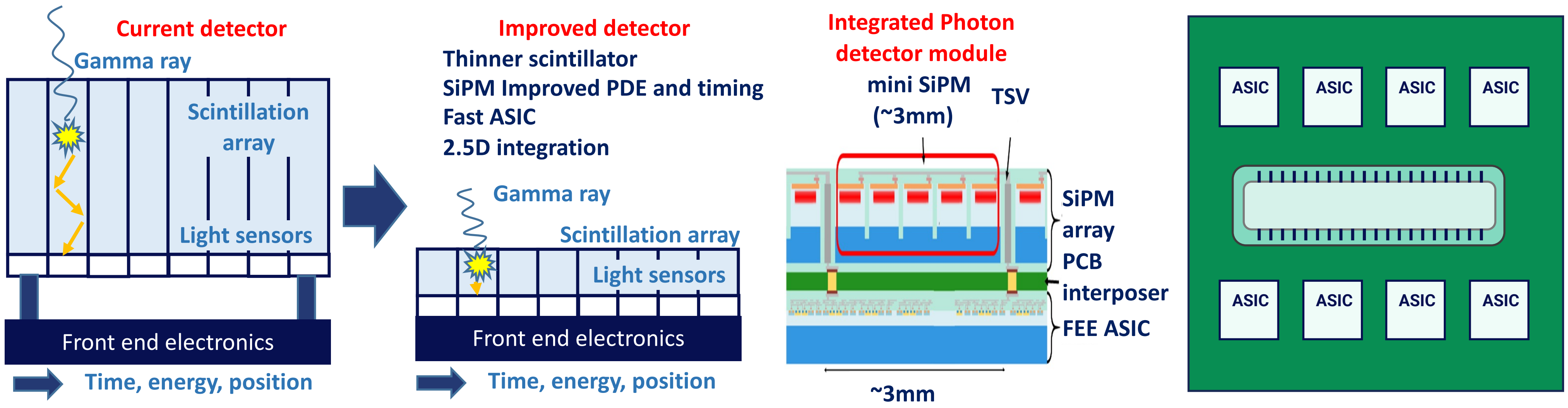
Fast CTR PET module

How do we achieve such a good CTR



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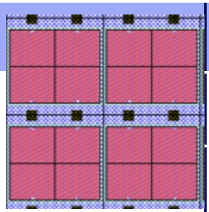
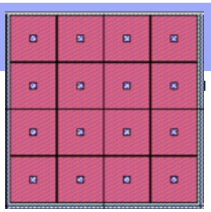
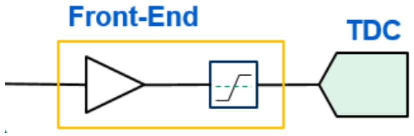
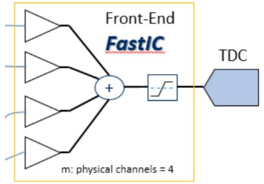
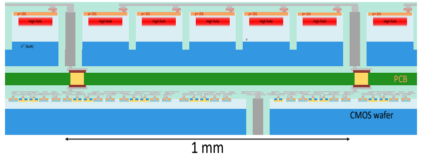
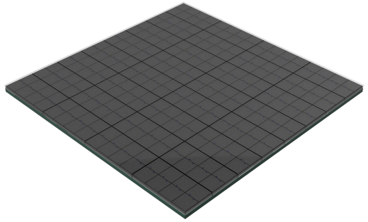
Technology Choices	Current PET	PetVision
Photosensor: Latest SiPM cell NUV-HD	Traditional technology 	Through silicon via (TSV) 
PDE up to 70% , SPAD SPTR 20 ps FWHM		
Better sensitivity: Increase active area	71%	92%
Better timing: decrease C_{det}	3mm pad - SPTR 150 ps	1.5mm pad – SPTR <50 ps
Front-end: fast timing low noise ASIC	e.g. PETsys	PetVision chip
Current mode: Linear Time over Thresh. with high dynamic range	180 nm CMOS 	65 nm CMOS 
		Summation in clusters of 4 ch.
CTR with 10mm LYSO (FWHM)	120 ps	75 ps
Integration of photosensor and ASIC	Wire bonding	2.5D integration (SiPM + interposer + CMOS)
		Medium-density interconnection SoC and Flip-Chip 
Scintillator:	Co-doped L(Y)SO:Ca:Ce	
Pixel Size	3 x 3 x **20 - 25**mm^3	3 x 3 x **10**mm^3 -
	Reduced parallax error	Compromise between sensitivity and CTR/ parallax error
Detector design	Full ring	Panels

Funded by the European Union
This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101099896

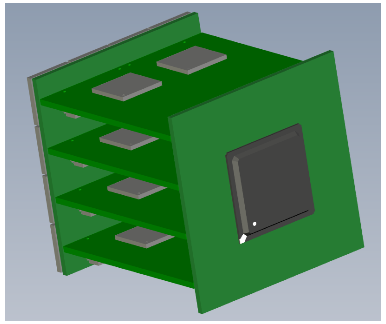
On the way and beyond PetVision

ARIS-PET

Year 1 — 3x3mm2 Photo Sensor with improved performance

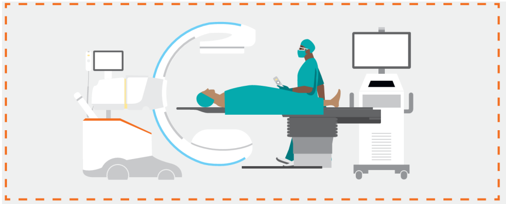


Year 2 — FastIC+ ASICs on the plugin cards



Year 3 — Integration of the smaller prototype 10 x 10 cm2

Year 4 — Validation in a hospital



aris Slovenian Research and Innovation Agency

Jožef Stefan Institute, Ljubljana, Slovenia

UNIVERZA V LJUBLJANI
University of Ljubljana

univerzitetni klinični center ljubljana
University Medical Centre Ljubljana

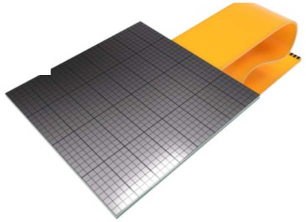
Project no. J7-50229

Year 1 | Year 2 | Year 3 | Year 4 | Year 5

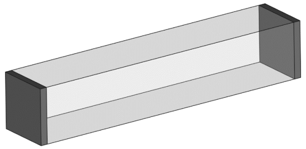
Fastsight

Year 1 — DOI from the photon yield from the first and second sensors

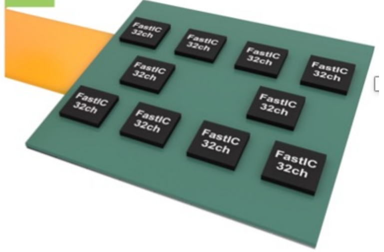
Year 2 — 1.5x1.5 mm2 Photo Sensor



Year 3 — 20-25mm crystals Dual-sided readout



Year 4 — FastSight ASICs to combine info from both sides



Year 5 — Integration and validation in a hospital

NIH National Institutes of Health
Turning Discovery Into Health

Yale

FBK, I3M, JSI, ICCUB

Funded by the European Union

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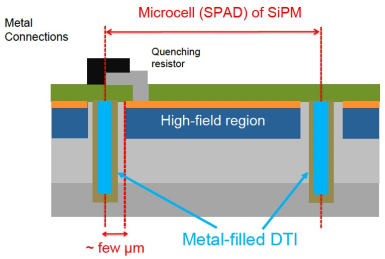
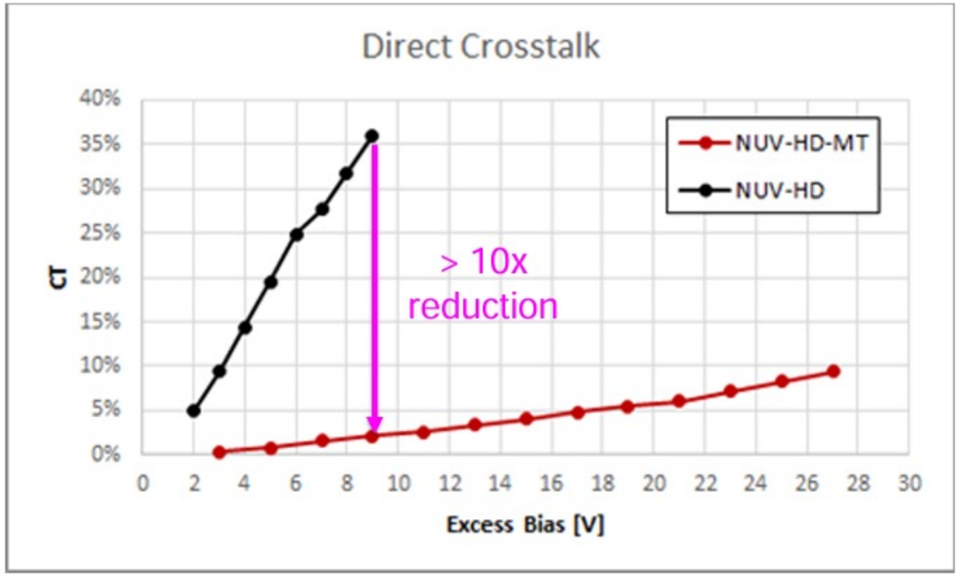
Reduction of optical crosstalk of SiPMs

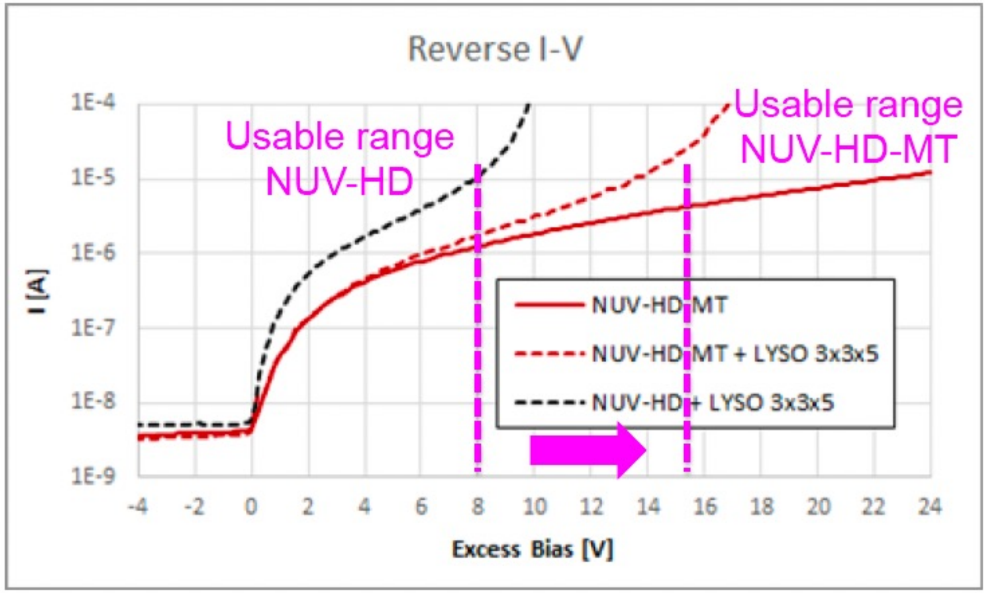
- FBK and Broadcom: new NUV-HD-MT technology with metal-filled Deep Trench Isolation
- Reduction of c-talk *increases the maximum usable excess bias of the SiPM*



Conceptual drawing of the NUV-HD-MT, with the addition of metal-filled Deep Trench Isolation.



Reduction of optical crosstalk probability in NUV-HD-MT, compared to the "standard" NUV-HD. Measurement without encapsulation resin, i.e. *only considering internal crosstalk probability*.



Reverse IV measured on a 4x4 mm^2 NUV-HD-MT SiPM with 45 um cell pitch under different conditions.

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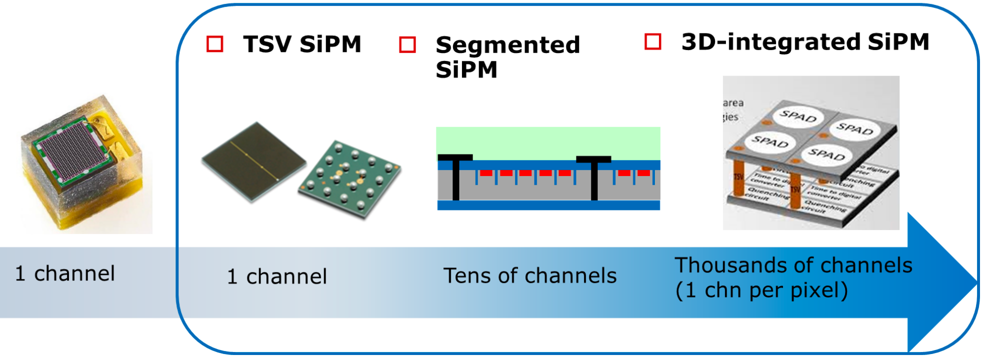
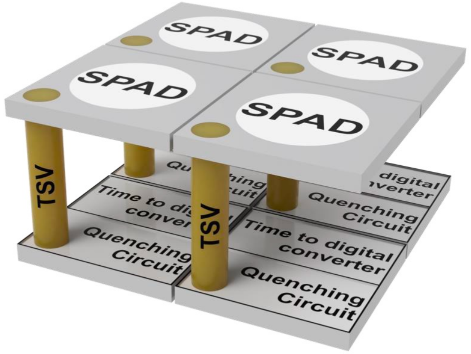
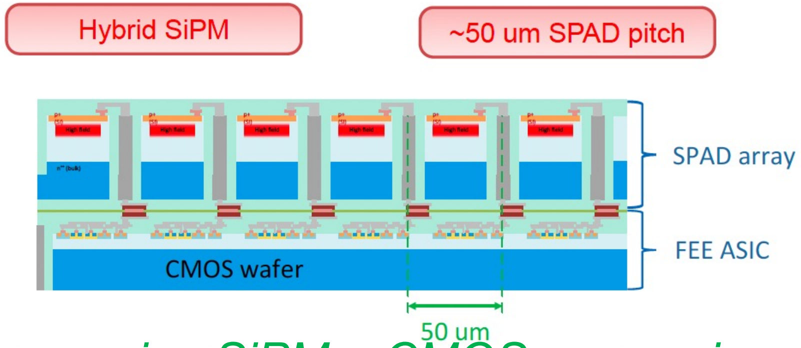
Integration: Enabling TSV technology

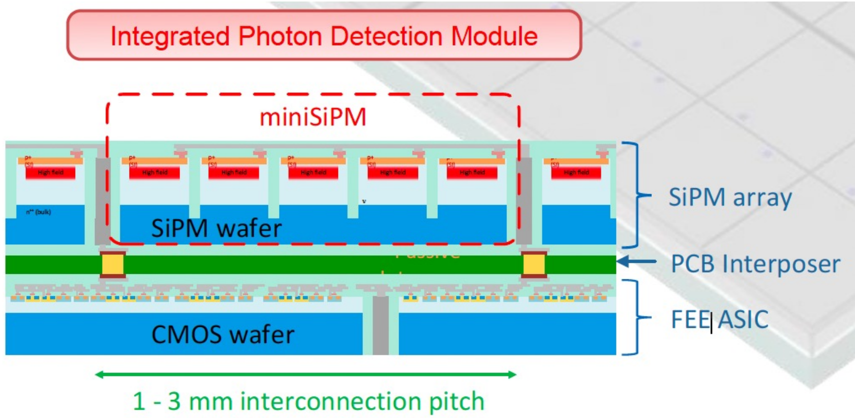
- Allows for high-density interconnections to the front-end and high-segmentation.
- Technological advancements in the SiPM production at various levels are necessary.



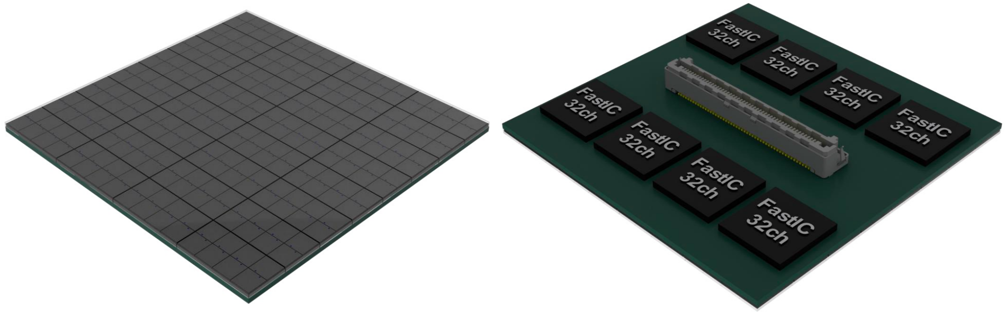


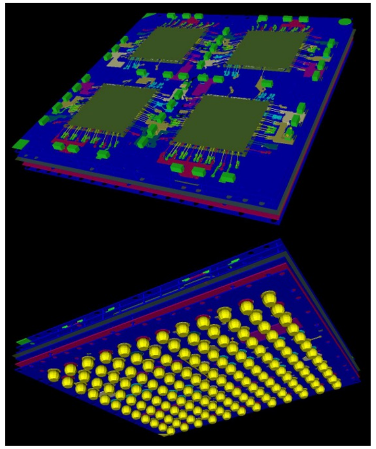


Hybrid SiPM: Custom sensing SiPM + CMOS processing layer, exploit optimal segmentation – Digilog project



The 2.5D integrated module (50x50 mm2)





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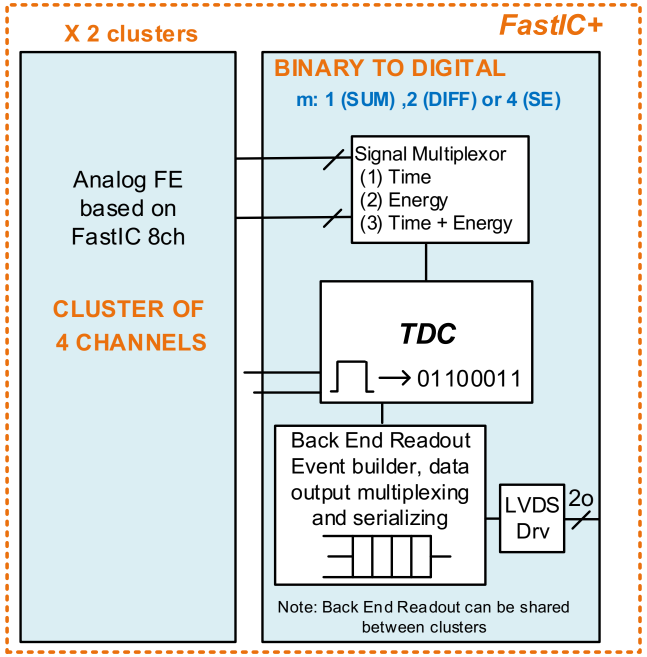
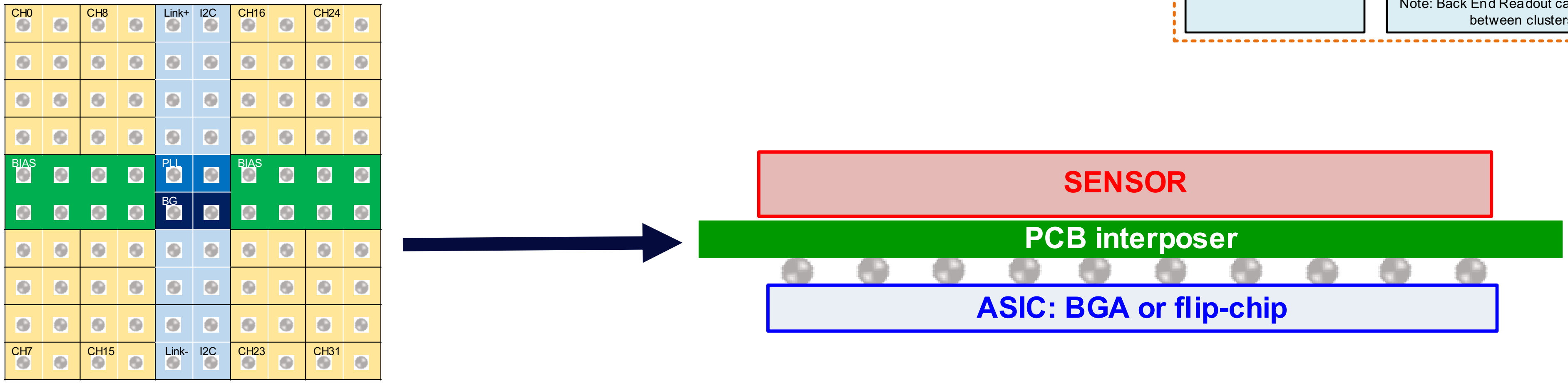
Next generation ASICs

- FastIC: Highly configurable ASIC for Fast Timing applications - collaboration between the University of Barcelona and CERN
- FastIC+: integration of 25 ps bin TDC integration on FastIC
  - First production finished, currently exploitation of functionalities
  - See the following talk by David Mazzanti
- Next step: 32-channel ASIC (PetVision) with pixelated structure
  - For 2.5D (BGA, flip-chip, etc) or 3D integration



FastIC 32



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Selection of the scintillator

Samples 2.8x2.8x10mm to fit

on the 3x3mm2 HD-NUV-MT SiPMs

- Slight differences in the samples
- 25% difference in the CTR

Sample	Rel. Light Yield [%]	Decay Time [ns]	Rise Time [ps]	FOM [%]	CTR [ps FWHM]
A	97	34.2 ± 0.8	107 ± 25	104	86
B	93	35.0 ± 0.7	109 ± 46	105	100
C	90	34.3 ± 0.4	122 ± 34	107	108
D	99	36.1 ± 0.7	111 ± 39	107	95
E	100	31.8 ± 0.7	83 ± 26	100	81
F	107	34.8 ± ?	114 ± ?	101	86
G	104	38.6 ± ?	130 ± ?	108	103

scintillation rise time

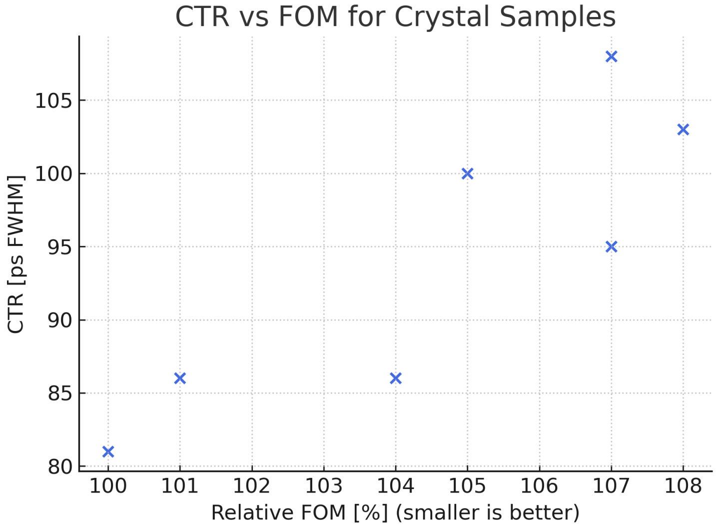
scintillation decay time

photodetector + crystal size contribution

$$\mathrm{CTR} \approx 3.33 \cdot \sqrt{\frac{\tau_{\mathrm{d,eff}} \cdot (1.57 \cdot \tau_{\mathrm{r}} + 1.13 \cdot \sigma_{\mathrm{SPTR+PTS}})}{\mathrm{LTE} \cdot \mathrm{PDE} \cdot \mathrm{ILY}}},$$

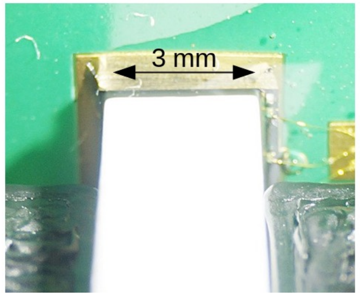
S. Gundacker *et al* 2020 *Phys. Med. Biol.* **65** 025001

Number of detected scintillation photons (detection efficiency x scintillation light yield)



FOM = SQRT(Rise * Decay / LY)

Alignment
No protection on the SiPM



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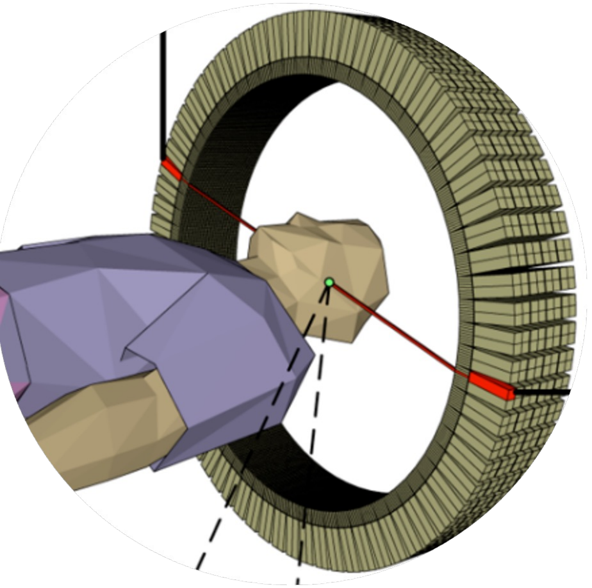
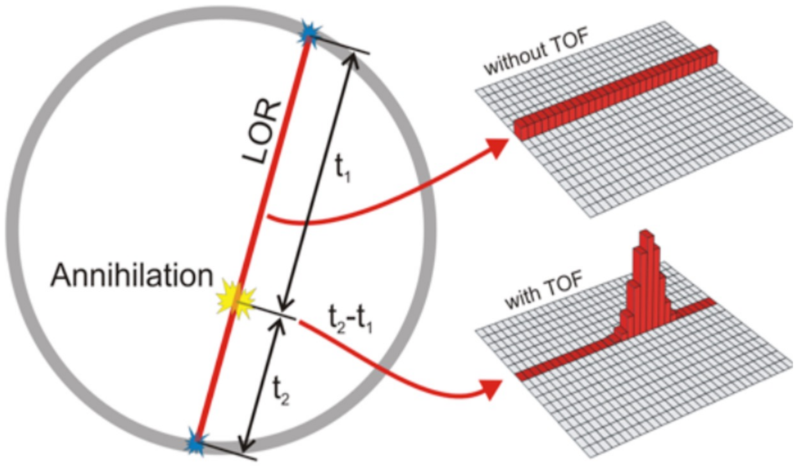
Summary

PetVision project is developing a mobile, accessible, flexible, modular PET scanner, based on two opposite detector panels with exquisite TOF resolution

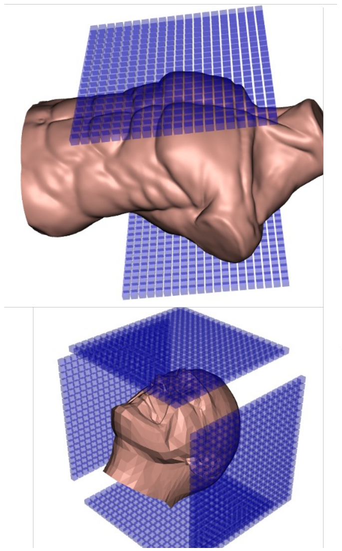
Current PET



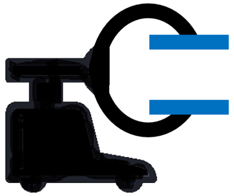
Time-of-flight PET principle

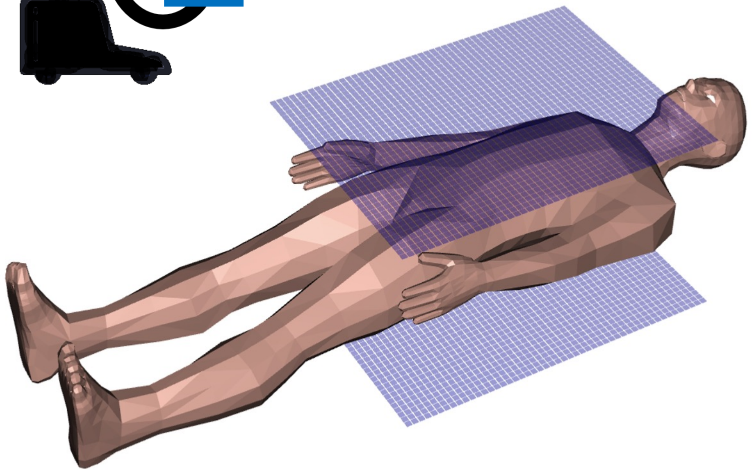


Enabling Modular scanner



Total body PET imager





Enable total body imaging:
Very early diagnosis of cancer, use of PET in operating rooms, guided surgery, proton therapy, cardiac and brain applications, and **effective personalized radionuclide cancer therapy.**

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https://youtu.be/Uksh-YXpV8k

“We are what we repeatedly do. Excellence, then, is not an act, but a habit.” - *Will Durant.*

European Innovation Council

Funded by the European Union

PET VISION

Follow **PetVision** project on LinkedIn

Pioneering the Future of Cancer Diagnostics

Jožef Stefan Institute Ljubljana, Slovenia

onco vision

Yale

MRI Klinikum rechts der Isar Technische Universität München

i3M Instituto de Instrumentación para Imagen Molecular

ICCUB Institut de Ciències del Cosmos Universitat de Barcelona

FBK Fondazione Bruno Kessler

CERN