



Update on 3Dpi: PET Scanner with Xenon-doped Liquid Argon and SiPM



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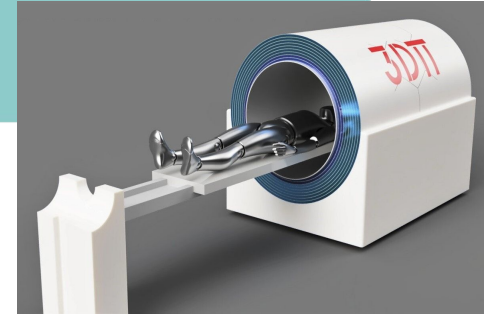
On behalf of the 3Dπ TB-TOF-PET Collaboration



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LIDINE 2025, Hong Kong

What is PET and Why?

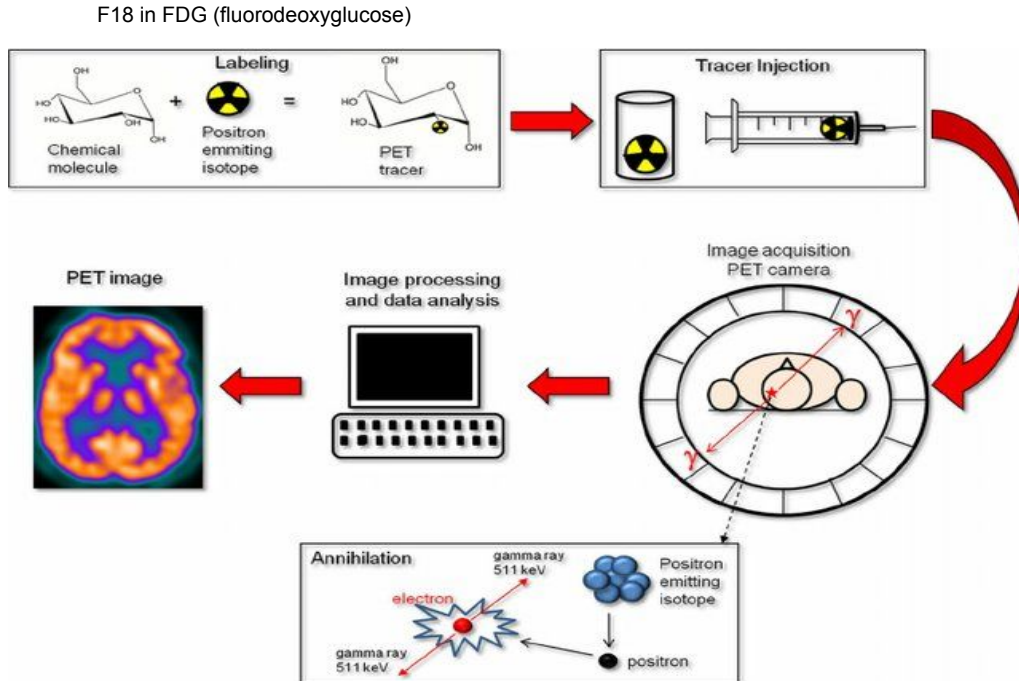


Positron Emission Tomography (PET)

- A non-invasive imaging technique.
- Visualizes **how organs and tissues function biochemically**, rather than just their structure (unlike CT or MRI).
- By using radiotracers that mimic natural molecules, PET can visualize **metabolic activity**, **blood flow**, and **cellular receptor expression**—processes that change long before structural symptoms appear.
- Useful for **early cancer detection**, **neurological disorders**, and **cardiac imaging**, where functional information guides diagnosis and treatment planning.
- Developed in the mid to late 20th century.

However, despite its remarkable sensitivity, **today's PET scanners still face limitations** in **resolution, speed, radiation dose**, and **cost**.

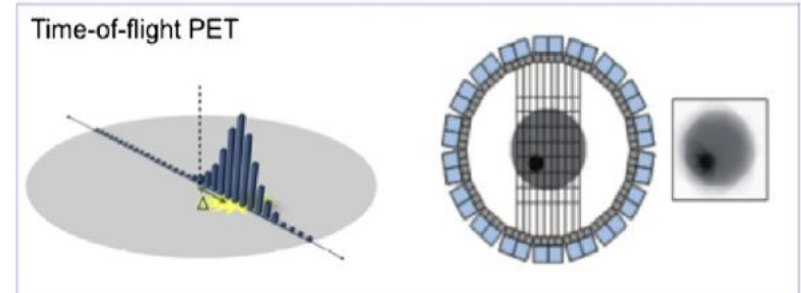
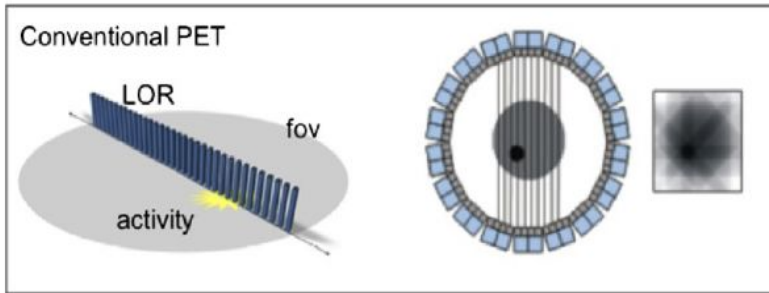
How PET Works?



1. A radioactive tracer, often **^{18}F -FDG**, is injected into the patient.
2. The tracer accumulates in active tissues—such as tumors—where it emits positrons.
3. Each positron quickly annihilates with an electron, producing **two gamma photons** traveling in opposite directions.
4. These photons are detected by a ring of sensors, and by measuring their **Time of Flight (TOF)**, the system reconstructs where the event occurred.
5. Repeating this process millions of times produces a detailed **3D image of the body's metabolic activity**.

Conventional PET vs. TOF PET

Taken from Beyer, Thomas, et al. "The future of hybrid imaging —part 2: PET/CT." Insights into imaging 2.3 (2011): 225-234.



TOF PET

- Reduces localization uncertainty along the line of response (LOR).
- **Improves signal-to-noise ratio (SNR)**, especially in larger patients.
- **Increases effective sensitivity**, even if the physical sensitivity is the same.
- **Enhances image quality** and boosts lesion detectability

Limitations with Current PET Scanners

Current PET scanners using crystals as scintillating volume face three main challenges:

1. **Limited timing precision** — typically **200–300 picoseconds**, which blurs the exact position of events.
2. **Low sensitivity** — only a fraction of emitted photons are detected.
3. **High radiation dose and long scan times**, especially for children and repeated scans.

These limitations mean **slower imaging, higher radiodose, and reduced ability to detect small or early-stage lesions.**

Additional limitation is **high cost** of those scanners.

How to Overcome Those Limitations?

To overcome these limitations, we need detectors with **faster timing**, **higher light yield**, and **better photon collection efficiency**.

To achieve those, the detector should be

Scintillator: fine granularity of crystal volumes (costly) or **monolithic** volume.

Photo detectors: small in size (capacitance) for both faster response and better position reconstruction.

Electronics: large number of channels means necessity of local digitization, by ASICs (Application Specific IC). Disadvantage – need cooling.

Our approach: **Liquid argon (LAr) doped with xenon (Xe)** as the monolithic scintillation medium — a combination that produces **fast, bright light** and shifts it to wavelengths that are efficiently detected by **cryogenic SiPMs** + electronics and remove crystal boundaries.

3D π PET Scanner

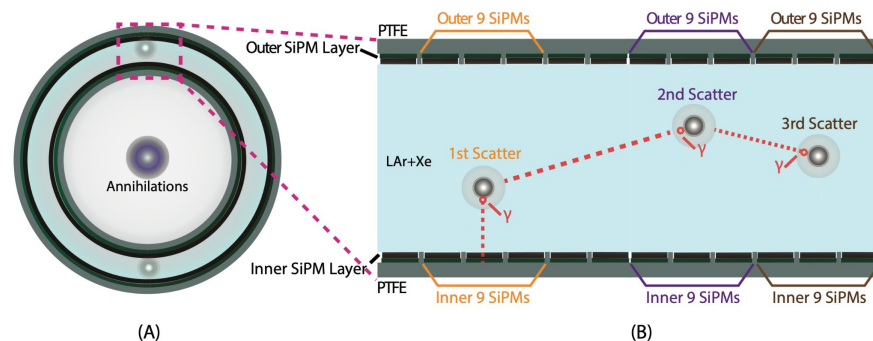
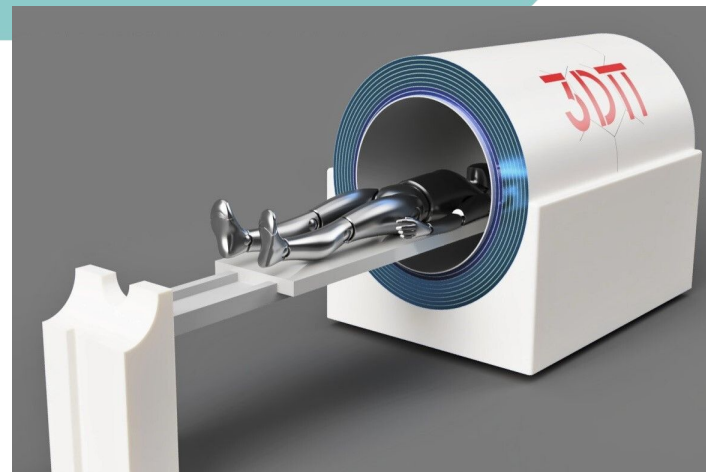
3D π Total-body TOF PET scanner

- Xe-doped LAr instead of crystal scintillators
- Multiple detection layers
- Using Silicon Photomultipliers (SiPM)
- Double sided SiPM on scintillation

Geometry:

- 9 annulus detection layers
- Each layer has the scintillator sandwiched between two layers of SiPMs
- Each detection layer has ~ 18 mm LAr thickness
- PTFE supporting structure
- 2 m in length

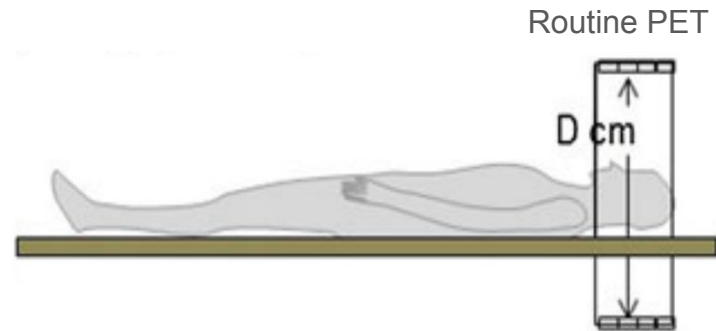
Two configurations: **LAr+Xe** and LAr+TPB
(TetraPhenylButadiene: an organic WLS)



Routine PET vs. Total-Body PET (TB-PET)

Routine PET

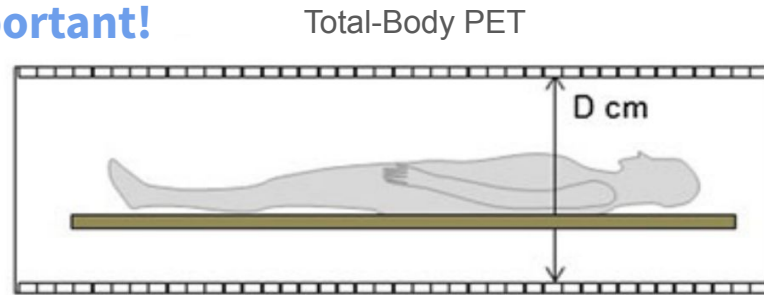
- Axial Field of View (AFOV): 10–30 cm
- About 85–90% of the body is outside the AFOV
- Only 3–5% of the available signal is collected
- Imaging duration: ~10–20 minutes (requires multiple bed positions)



Total-Body PET (TB-PET)

- AFOV: 200 cm (covers the whole body in one shot)
- Nearly 100% of the signals can be collected
- Massively reduced imaging time
- Scan time can be as short as 20–60 seconds
- Allows for lower radiation dose to the patient

Scalability is important!

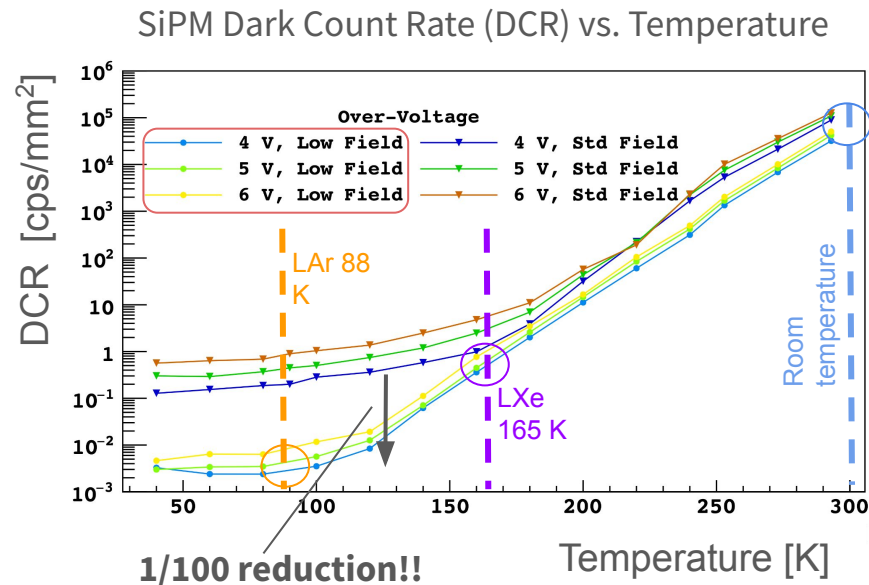


Taken from I. Ismet, et al. "Simulation of sensitivity and NECR of entire-body PET scanners for different FOV diameters." 2013 NSS/MIC. IEEE, 2013, 1.

Xe-doped LAr as scintillator

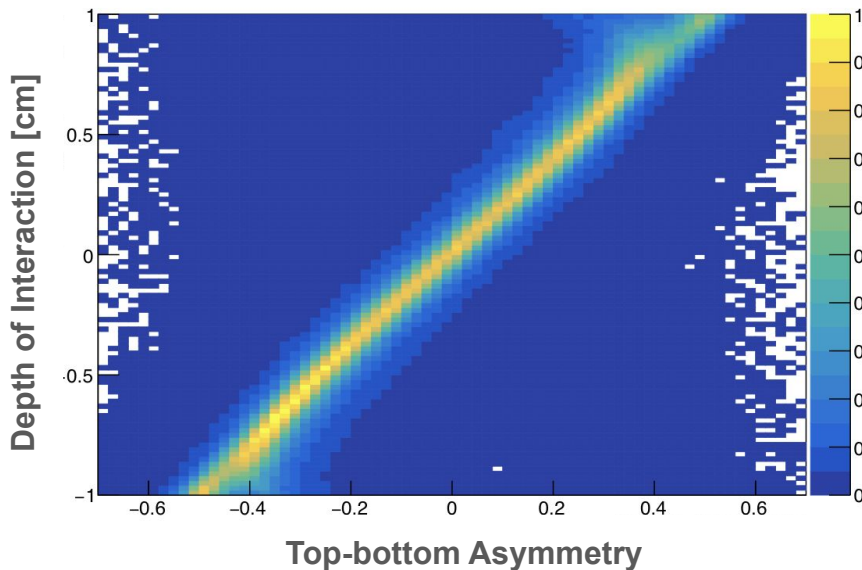
Scintillator:	LAr	LXe	LAr+Xe (0.5%)	LYSO
Decay F/S (ns)	7/1600	4.3/22	~6/100	42
Photon/keV	40	42	~41	41
Temperature (K)	87	162	87	298
Wavelength (nm)	128	175	~175	420
Density (g/cm ³)	1.40	2.94	~1.40	7.1
Cost (US\$/kg)	~2	2k	~2	~7k

*Shorter slow decay time than the pure liquid argon
 *Scintillation light at a wavelength of 175 nm; Xe operates as a wavelength shifter (WLS)
 *Operating at temperatures near the boiling point of argon eliminates the need for cooling and results in lower Dark Count Rate (DCR)

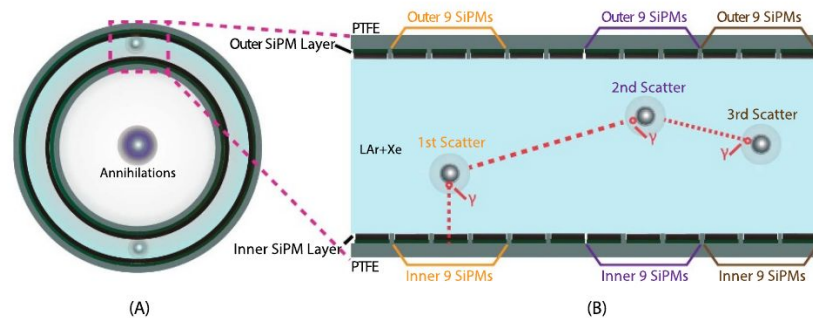


Reduction in DCR at LAr temperature.
 Improve the timing resolution and SNR.

Depth of Interaction Determination



- **Disadvantage** of LAr is **light density** compared to LXe or crystals.
- **Compton scatters** are dominant (less full energy absorption).
- Difficulty in **position reconstruction** and energy cut.



Depth of Interaction (DOI) in one layer can be reconstructed from the asymmetry between light in top and bottom SiPMs.

National Electrical Manufacturers Association

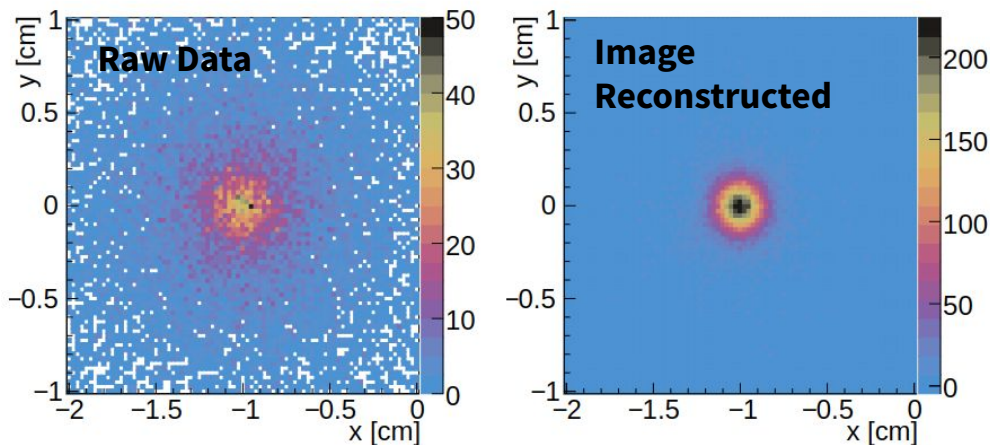


NU 2-2018

A guide to characterize PET performance

This is an industrial standard that most of scanners are evaluated by following this.

Spatial Resolution of Single Point Sources



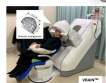
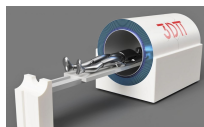
3D π is able to produce **consistent** and **accurate** images regardless of the location of the source.

Configuration: LAr+Xe and for a point sources at 1 cm radial offset and at the center of the AFOV

<u>Central Phantoms:</u>	<u>1 cm radial position</u>			<u>10 cm radial position</u>			<u>20 cm radial position</u>		
<u>Scanner</u>	Radial [mm]	Tangent [mm]	Axial [mm]	Radial [mm]	Tangent [mm]	Axial [mm]	Radial [mm]	Tangent [mm]	Axial [mm]
3D π (LAr+Xe)	2.8	2.7	2.5	2.8	2.8	2.6	2.6	2.9	2.5
uExplorer (LYSO)*	3.0	3.0	2.8	3.4	3.1	3.2	4.7	4.0	3.2

*6x6 mm² silicon photomultipliers (SensL J-series) and 53,760 silicon photomultiplier channels.

Comparison of NEMA Test Results



Scanner	Peak NECR [Mcps]	Activity concentration at peak [kBq/mL]	Sensitivity [kcps/MBq]	TOF resolution [ps]
3Dπ (MC)	~3.2	17.3*	Two times higher! 373	151
	~4.3	30**		
uEXPLORER TB-PET/CT	~1.5	17.3	174	412
J-PET-TB (MC)	0.63	30	38	500
GE SIGNA PET/CT	0.22	20.8	21.8	386
VRAIN PET	0.14	9.8	25	229

Our scanner system performance is better performance than commercial scanners.

*Activity concentration at peak NECR, uEXPLORER

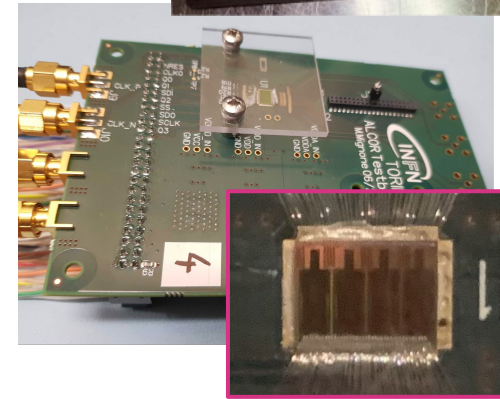
**Activity concentration at peak NECR, J-PET

Cryogenic Readout Electronics, ASIC

Large number of SiPM channels leads to necessity of local digitization, by ASICs (Application Specific IC).

- ALCOR chip is developed by INFN Torino group and testing with FBK VUV SiPMs are on going.
- We piggyback on DENEb, an ASIC developed for the GRAIN detector in DUNE experiment.
- The suitability check for PET application with MC is on going. Key specifications are time resolution and communication speed.
- The first production of DENEb will be in the beginning of 2026 and we will test it at LAr temperature.

Check <https://doi.org/10.1088/1748-0221/20/05/C05008> for more details for GRAIN detector.



A test board with ALCOR for SiPM (credit INFN Torino)

Summary

- PET scanner is a powerful imaging device useful for **early cancer detection**, **neurological disorders**, and **cardiac imaging**
- To improve image quality further, **larger number** and **faster** photosensors are necessary.
- Xe-doped LAr is a monolithic scintillator with good light yield acting as coolant for electronics.
- Development of cryogenic ASIC for GRAIN is ongoing and it might be applicable for our PET scanner.
- Based on MC study of the NEMA test, our **sensitivity is twice higher** and **TOF is less than half** compare to the state of art TB TOF PET scanner, uEXPLORER

Backups

Recent Publication

IOP Publishing

Phys. Med. Biol. **70** (2025) 065015

<https://doi.org/10.1088/1361-6560/adbaac>

Physics in Medicine & Biology



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PAPER

$3D\pi$: three-dimensional positron imaging, a novel total-body PET scanner using xenon-doped liquid argon scintillator

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Keywords: TOF-PET, $3D\pi$, liquid argon, total-body imaging, performance evaluation

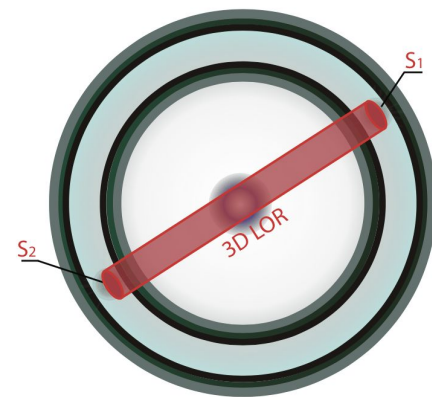
Fluctuation Sources in Parallel and Perpendicular to LOR

Sources of fluctuation for construction of events parallel to the LOR:

1- Timing fluctuations:

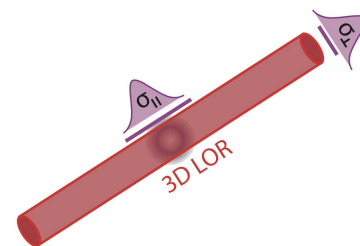
- The statistical nature of scintillation photon detection,
- The time resolution of the SiPMs and their associated electronics.

2-Uncertainty resulting from imperfect scatter depth correction within the annular cylinder.



Sources of fluctuation for construction of events perpendicular to the LOR:

The lattice size of the SiPM layout imposes a limitation on the resolution in each of the two directions perpendicular to the LOR.



Dependence of Spatial Resolution on SiPM Parameters

Raw data (before image reconstruction)

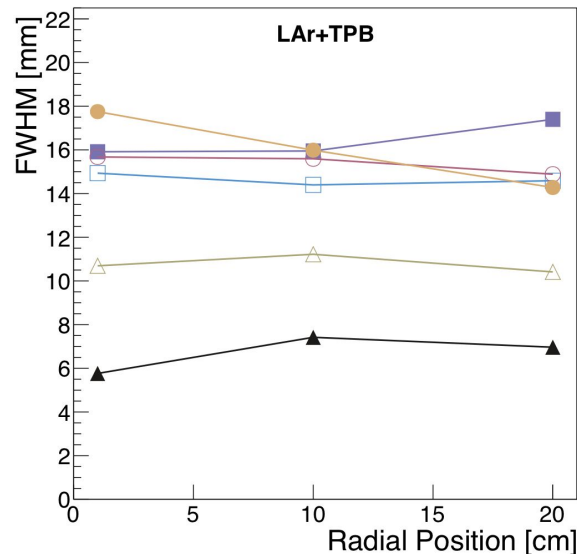
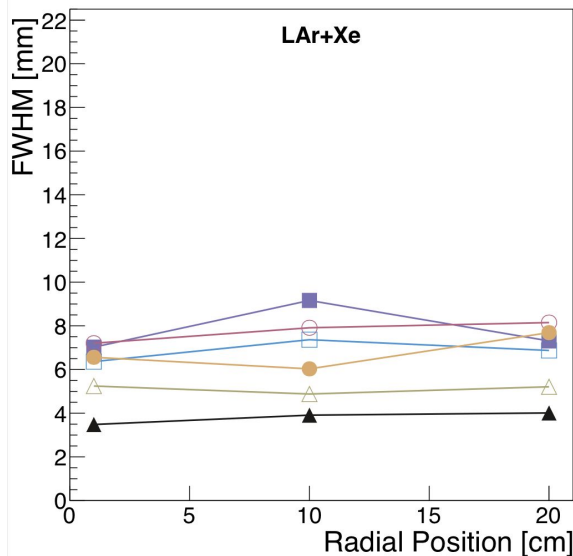
Summary of spatial resolution parallel and perpendicular to LOR and SiPM parameters without optical photon cut and image reconstruction

	PDE	σ_{SiPM}	$\sigma_{\parallel}$	$\sigma_{\perp}$
LAr+TPB	40%	60 ps	27.2 mm	1 mm
LAr+Xe	25%	60 ps	15.1 mm	1 mm

LAr+Xe demonstrates a factor of 1.8 improvement in resolution compared to LAr+TPB.

Spatial Resolution of Single Point Sources

Raw data (before image reconstruction)



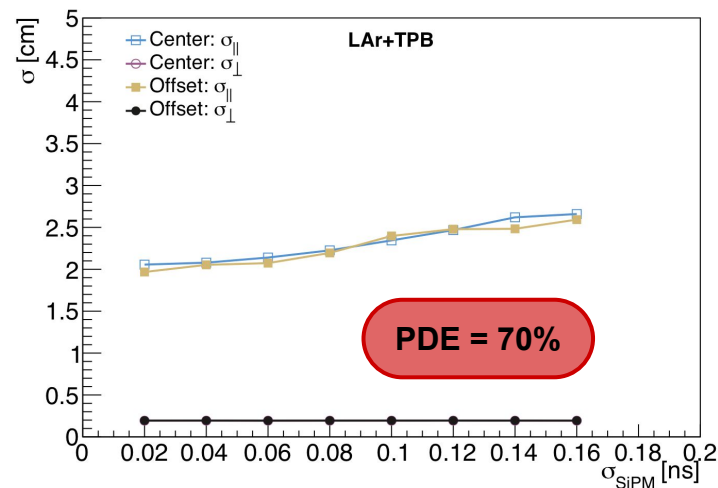
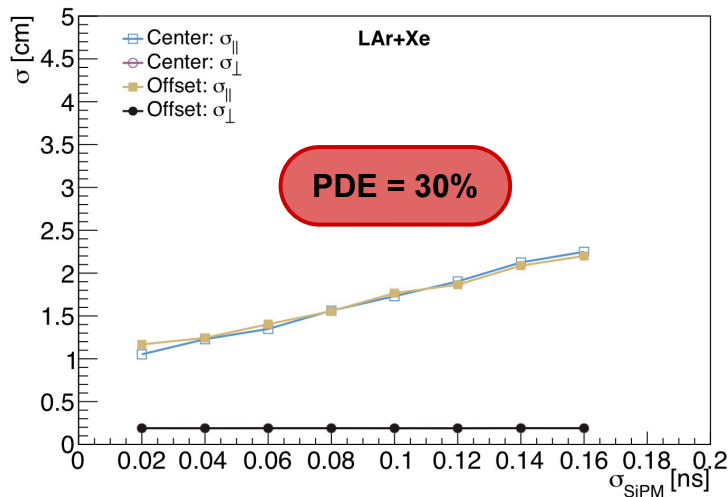
LAr+Xe improves spatial resolution by more than a factor of 2.

Dependence of Spatial Resolution on SiPM Parameters

Raw data (before image reconstruction)

Spatial resolution, in directions parallel and perpendicular to Line Of Response (LOR)

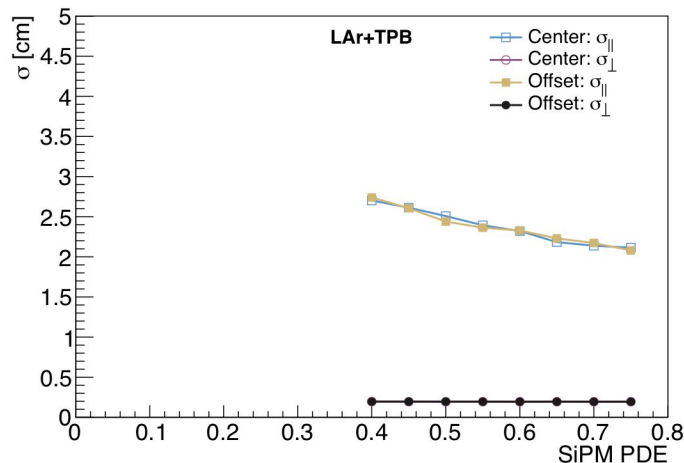
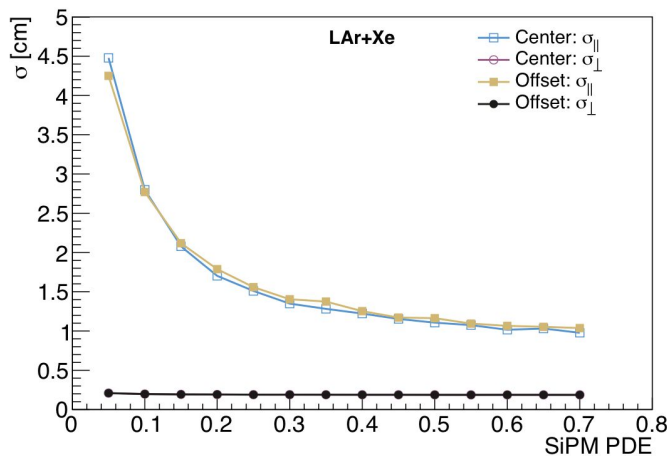
Point Source



Desirable timing resolution: $\sigma_{\text{SiPM}} < 60 \text{ ps}$

Dependence of Spatial Resolution on SiPM Parameters

Raw data (before image reconstruction)



Improved PDE (>40%) ensures acceptable resolution, independent of PDE.

In this work, we assume a $\sigma_{\text{SiPM}} = 60 \text{ ps}$ and the PDE is based on ref [1] at an over-voltage of 4 V.

System Sensitivity

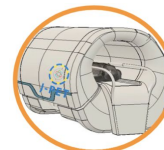
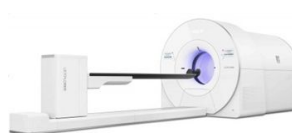
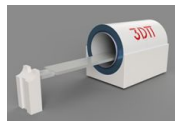
The sensitivity test measures the counts per second that the scanner measures for every unit of activity present in a source.

$$S_{\text{tot}} = \frac{R_{\text{CORR},0}}{A_{\text{cal}}}$$

S_{tot} : System Sensitivity

$R_{\text{CORR},0}$: The true coincidences count rate with no attenuation

A_{cal} : Line source radioactivity



Sensitivity (kcps/MBq)	3Dπ	uExplorer	J-PET	DMI Gen26R PET/CT
AFOV (cm)	200	194	200	30
0 cm offset	373	174	38	32.64
10 cm offset	347	177	-	32.88

A higher system sensitivity indicates that the scanner can detect a larger fraction of the emitted photons, which allows for shorter scan times or lower radiotracer doses.

Noise Equivalent Count Rate (NECR)

$$NECR = \frac{T^2}{T + R + S}$$

T = True counts
S = Scatter counts
R = Random counts

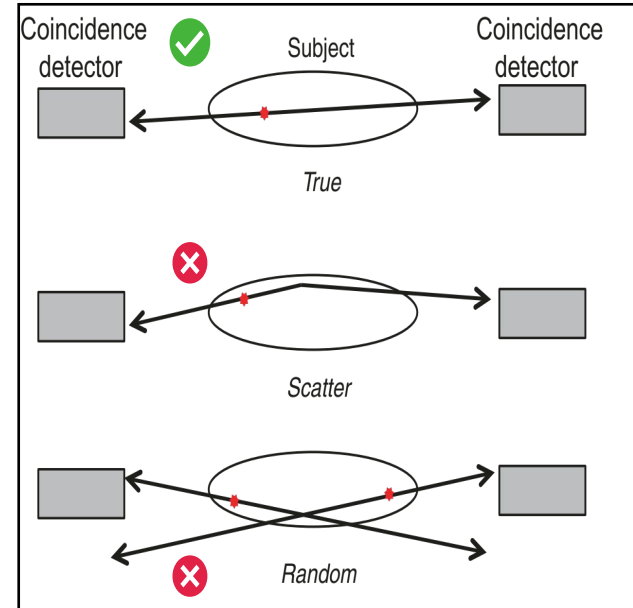
Noise Equivalent Count Rate: ability to detect and accurately quantify true coincident counts while minimizing the impact of noise, (random, and scatter events.)



Source Distribution:

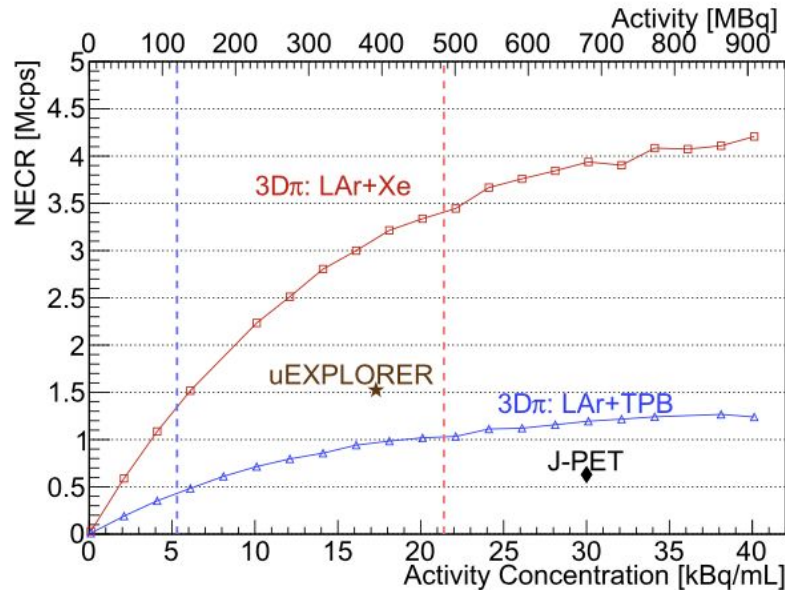
A solid circular high density polyethylene cylinder with a line source.

Taken from <https://radiologykey.com/pet-physics-and-instrumentation/>

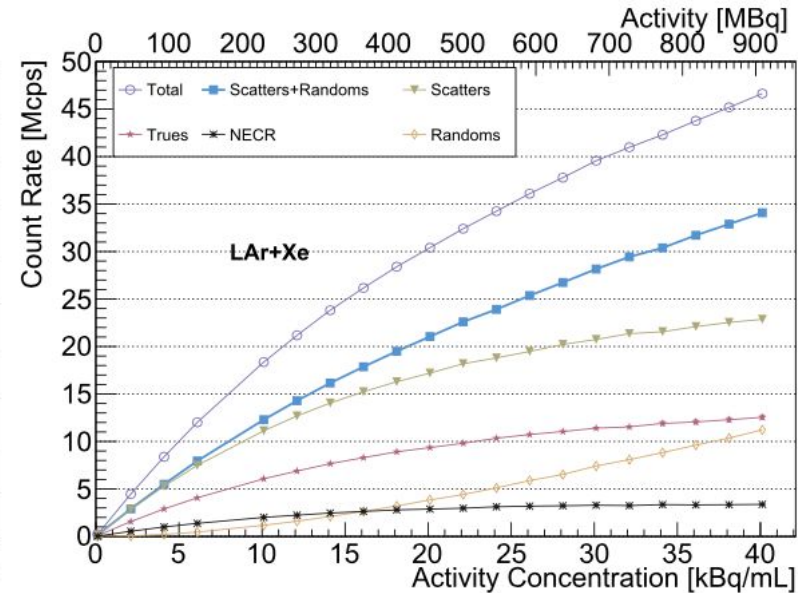


Three types of coincident events

Noise Equivalent Count Rate (NECR)

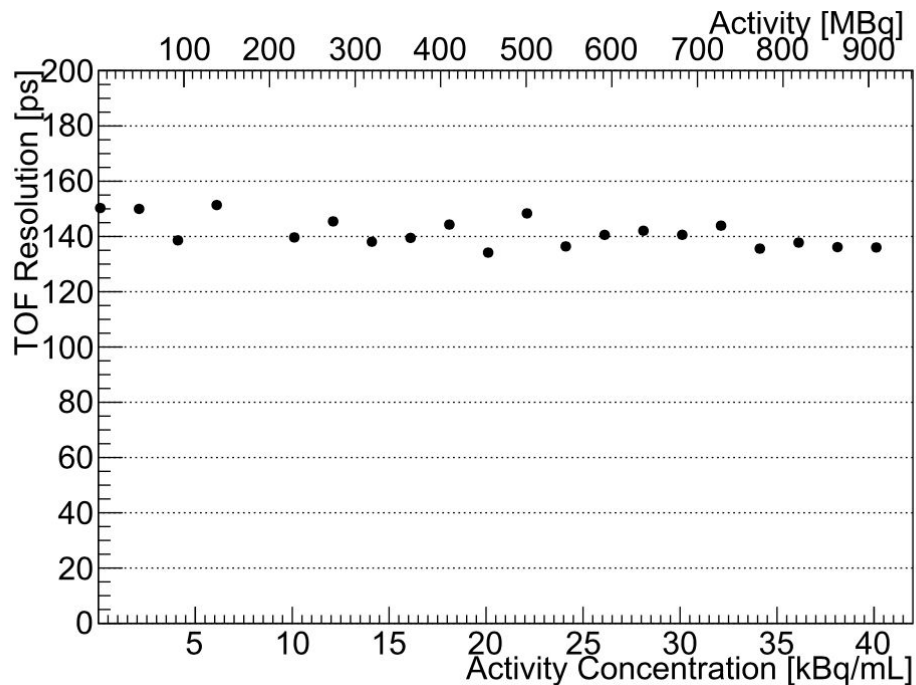


- Background: Activity concentration used as the background in the Image Quality test
- Signal: Activity concentration used as the signal in the Image Quality test



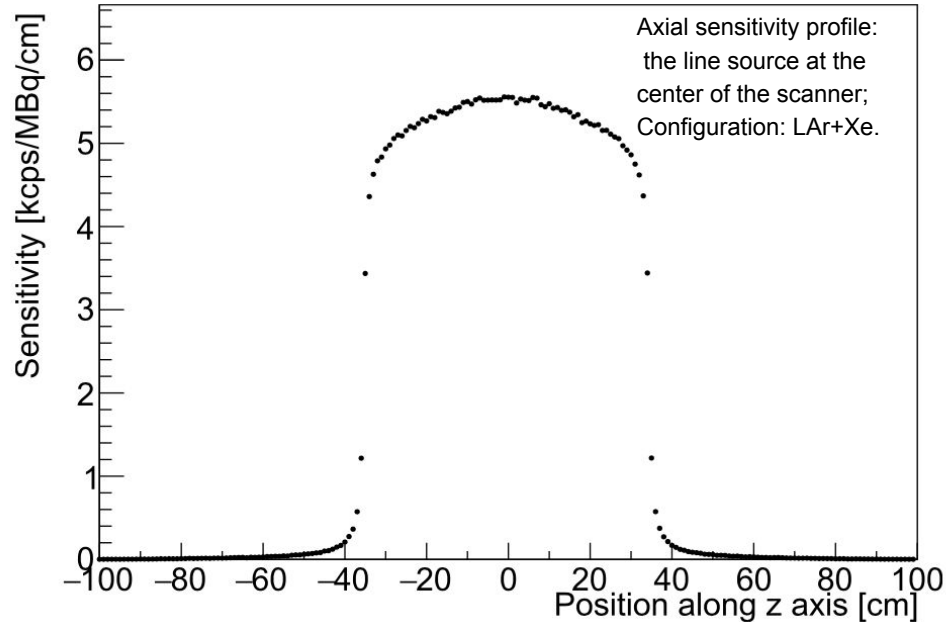
Higher NECR with low activity indicates the possibility to reduce radioactive dose significantly

TOF Resolution



TOF resolution is constant against the activity concentration change.

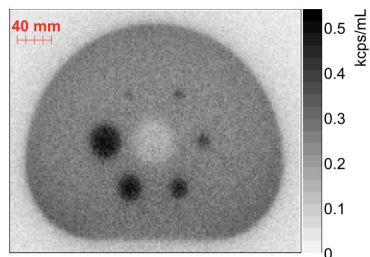
System Sensitivity



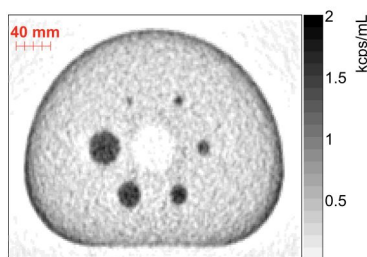
The sensitivity profile remains high and constant (<10% variation) across the axial direction.

Image Quality

3D π
scanned for 60 s.

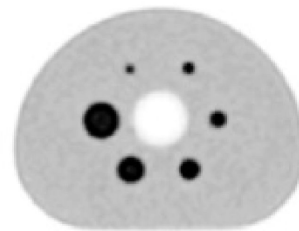


Raw Coincidence Data



Filtered Deconvolution Reconstruction (FDR) Images

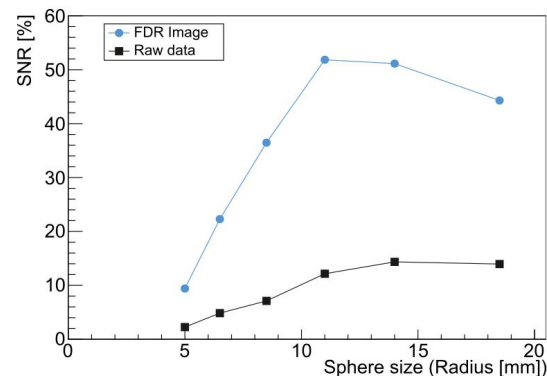
uEXPLORER
scanned for 30 min.



scale: 0–20 kBq/mL

Sphere diameter	PC (Image*)	PC (raw**)	BV (Image*)	BV (raw**)
10 mm	68%	4%	22%	5%
13 mm	90%	8%	12%	5%
17 mm	101%	12%	8%	5%
22 mm	126%	20%	7%	5%
28 mm	124%	23%	7%	5%
37 mm	110%	23%	7%	5%

Percent contrast (PC) and background variability (BV); configuration: LAr+Xe,
*Image reconstruction,** Raw coincidence data.



Energy Cut: Optical photons cut for Scatter Reduction

Concept

- Like energy windows in conventional PET, we apply an **optical photon cut** to filter out scattered gamma events.
- Threshold set on **number of detected optical photons** per event, targeting true coincidences.

Threshold Determination

- Monte Carlo simulations showed:
 - True events generate **> 6000 detected photons** per event (both Compton scatters in active region)
 - Events with **< 6000 photons** typically scattered in non-active regions → excluded

Optimization & Results

- Post-vertex reconstruction, threshold refined to maximize **Noise Equivalent Count Rate (NECR)**
- At **3000 photon cut**, NECR peaks at **3.2 Mcps** (vs. 2.8 Mcps without cut)
- Optical photon cut reduces scatter & random events **without losing true coincidences**
- This method replaces traditional energy filtering, enhancing image clarity

