A Novel Total-Body PET Scanner Using Xenon-Doped Liquid Argon Scintillator with SiPM-based Photosensors

An application in medical physics of the DarkSide collaboration

Azam Zabihi and Masayuki Wada on behalf of 3Dπ collaboration

I.Introduction

A novel PET imaging methodology using a monolithic xenon-doped liquid argon (LAr+Xe) scintillator, read out by silicon photomultipliers (SiPMs) at cryogenic temperatures.

3Dπ leverages total-body coverage, time-of-flight (TOF) technology, ultra-low dose imaging, and ultra-fast readout electronics to enhance sensitivity and reduce scan times. Inspired by dark matter detection, it integrates advancements from the DarkSide collaboration in cryogenic photosensors and low-radioactivity argon technology.

Key Features

Monolithic Liquid Argon Scintillator:

I. Scalable & Cost-Effective: LAr is cheaper than traditional segmented crystal PET systems.
II. Cryogenic Operation (87K): Ensures stable SiPM performance.
III. Fast Scintillation: Reduces noise and improves timing resolution.

Xenon Doping (LAr+Xe)

I. Suppresses long-lifetime component, improving signal quality.
II. Improved detection efficiency at 172 nm emission.
III. Enhances energy resolution and photon statistics.
IV. Cost-effective alternative to pure xenon.

Table 1: Liquid Xenon vs. Liquid Argon

Scintillator:	LAr	LXe	LAr+Xe	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

Fast Cryogenic SiPMs

I. Timing resolution below 100 ps enhances image precision.
II. Photon Detection Efficiency (PDE) up to 30% in key wavelength ranges.
III. Reduced Dark Count Rate (DCR) at cryogenic temperatures.

II.Materials and methods

Monte Carlo Simulations based on NEMA NU 2-2018 standard, For direct comparison with commercially available PET scanners.

Table2: 3Dπ detector (Geant4 geometry) parameters

Parameters	Value
Bore diameter	90 cm
Transaxial Field of view (FOV)	64 cm
Axial FOV	200 cm
LAr thickness per layer	18 mm
Number of LAr layers	9
SiPM size	10×10 mm^2
Number of SiPMs	1×10^6

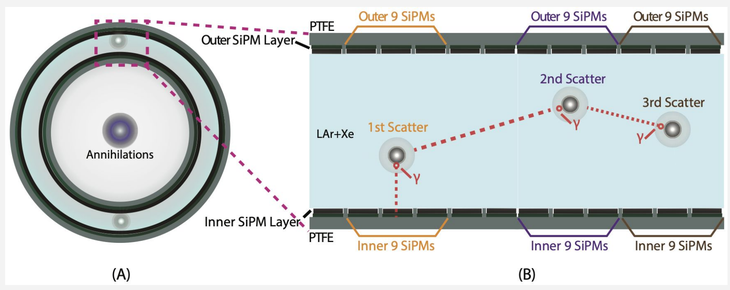


Fig 1: A: An illustration of a single detection layer of the 3Dπ detector with the LAr+Xe scintillation configuration. B: Each detection layer contains both outer and inner layers of PTFE supporting material with an array of SiPMs.

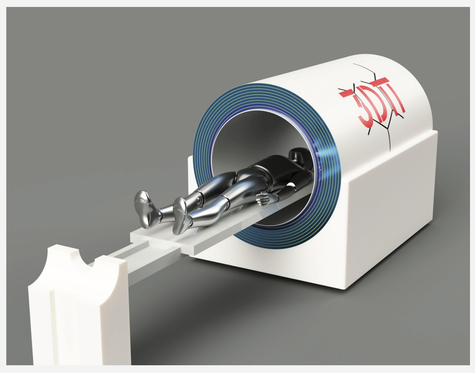


Fig2: CAD model of the 3Dπ detector

III.Results

1-Spatial Resolution of Single Point Sources

Mean spatial resolution	
At center:	2.7 mm
At offset	2.7 mm

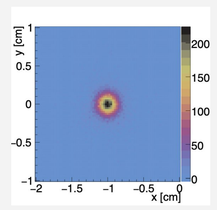


Fig 3: 2D image at 1 cm radial offset and at center of FOV

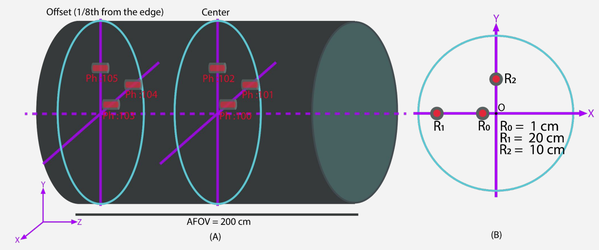
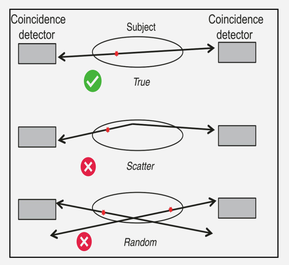


Fig 4: Phantom and point sources positions

2-Count Rate Performance

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

Fig 5: Three Types of Coincident Events.



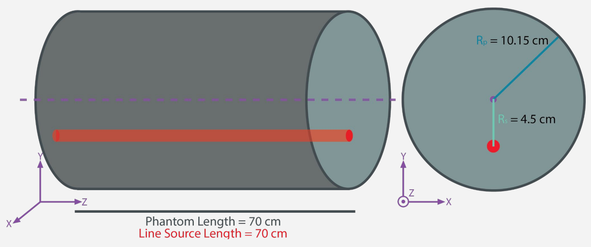


Fig 6: Phantom and line source position

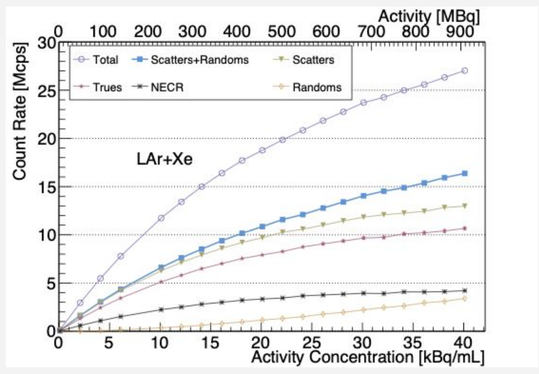


Fig 8. Count rates

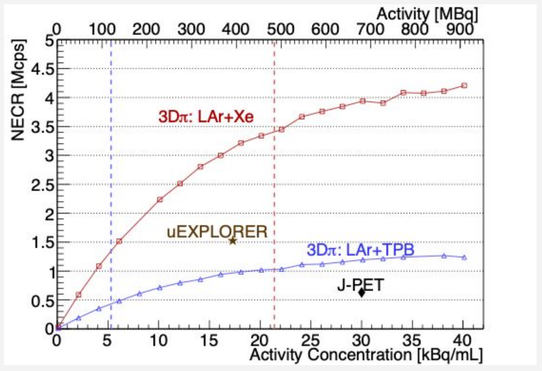


Fig 7. Relationship between NECR and activity concentration for LAr+Xe and LAr+PTB compared with the peak NECR values of uExplorer and J-PET.

3-Time Of Fight resolution

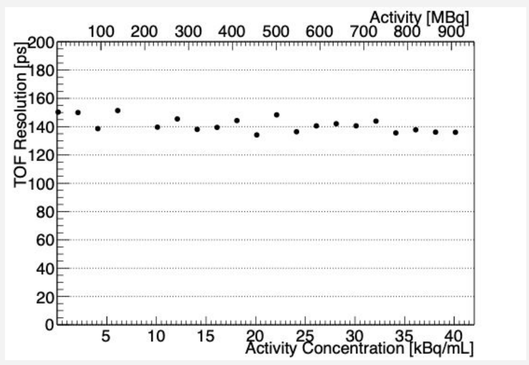


Fig 9. Time-of-flight (TOF) resolution as a function of activity concentration. The phantom and line source setup are identical to those in Fig. 6.

4-System Sensitivity

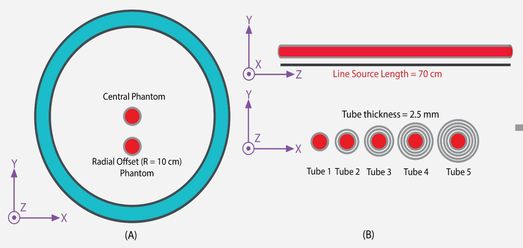


Fig 10: Phantom and line source position

Table 3: System sensitivity and TOF resolution

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
TOF resolution (ps)	151	505	240	

4-Image Quality

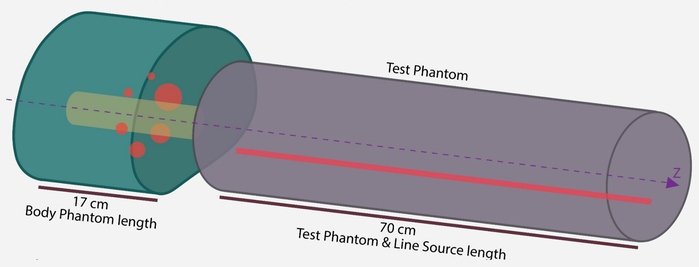


Fig 11:Body, six spheres and test phantoms and lung insert

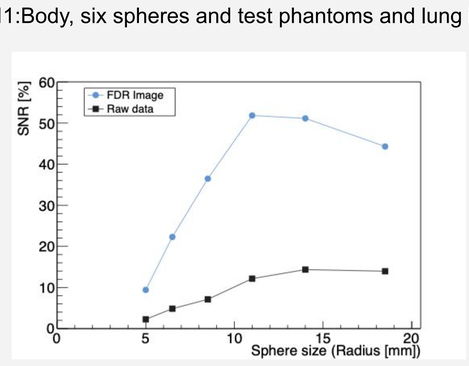


Fig 12: Comparison of SNR between image reconstruction and raw coincidence data.

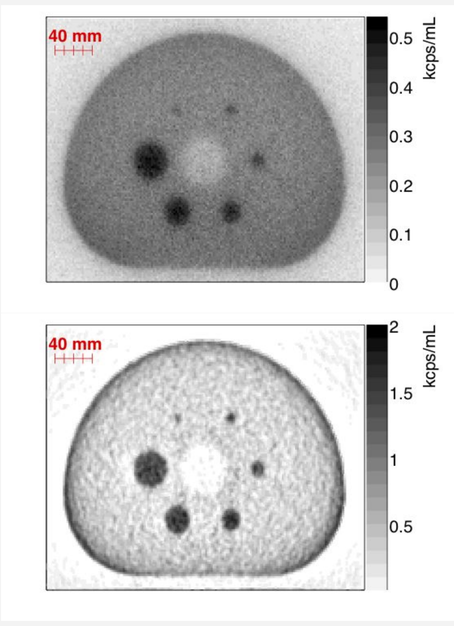


Fig 13: Central slice of the image quality phantom. top: raw coincidence data, bottom: reconstruction images.

IV.Concolotion

LAr+Xe offers fast scintillation for better TOF, higher sensitivity, and electronic cooling to decrease SiPM dark counts. Future work will focus on optimizing SiPM size, Scatter correction, layer geometry, and implement newer reconstruction algorithms.

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