A Novel Total-Body PET Scanner Using Xenon-Doped Liquid Argon Scintillator for Outstanding Detection

An application in medical physics of the DarkSide collaboration

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

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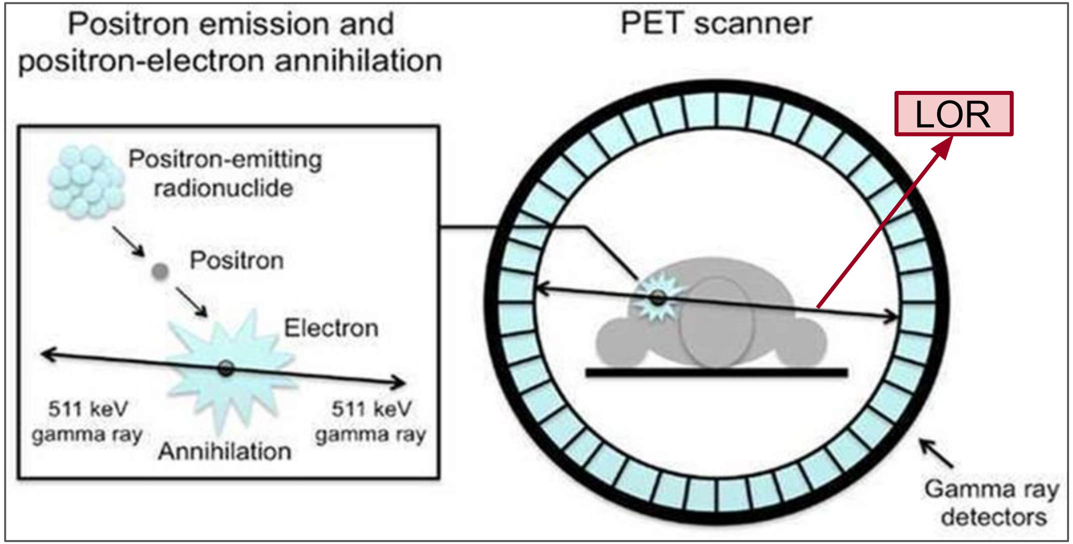
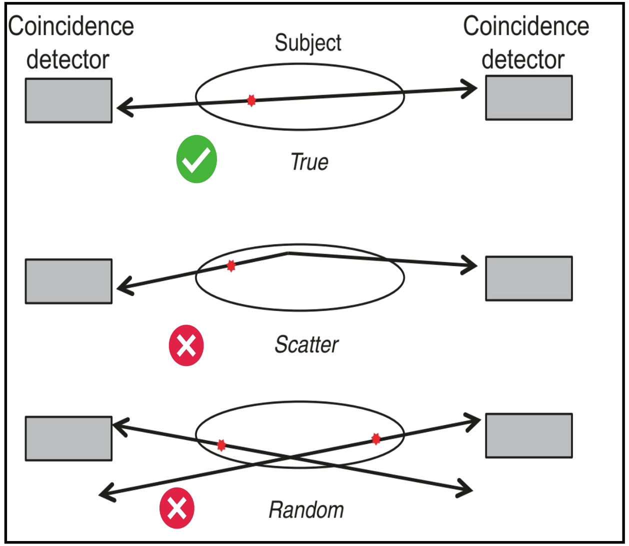
TIPP 2023 - Cape Town

PET Principle



PET Annihilation Illustration



Three Types of Coincident Events

Liquid Xenon vs. Liquid Argon

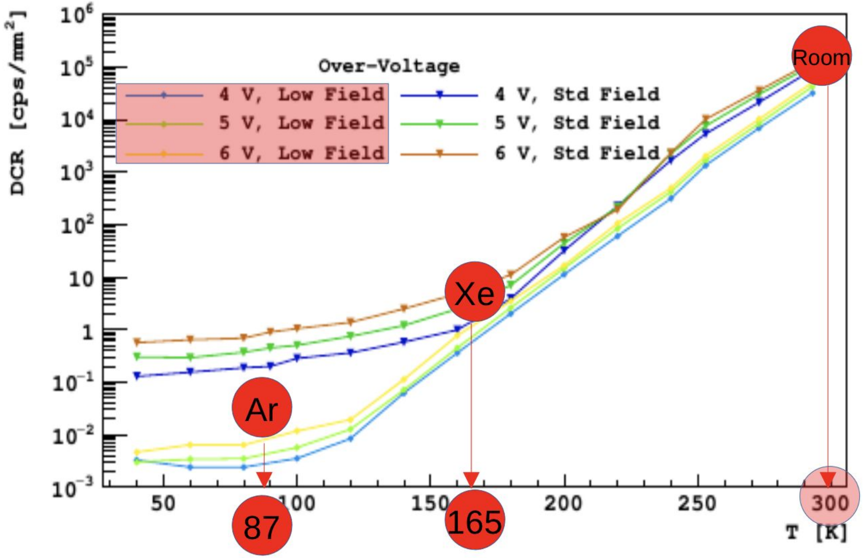
And Benefit of Cryogenic

0.5%

Scintillator:	LAr	LXe	LAr + Xe	LYSO
Decay F/S (ns):	7/1600	4.3/22	~6/100	41
Wavelength (nm):	128	175	~175	420
Density (g/cm^3):	1.40	2.94	~1.40	7.1
Temperature (K):	87	162	87	298
Photons/keV:	40	42	~41	28.5
Cost (US$/kg):	~2	~2000	~2	~4

*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)

SiPM Dark Count Rate (DCR) vs. Temperature



https://oar.princeton.edu/rt4ds/file/1663/1610.01915v1.pdf

Reduction in the dark count rate (DCR), improves the timing capability of the devices and Signal-to-Noise Ratio (SNR)

3Dπ Overview

A Total-body (TB), Time of Flight (TOF) PET scanner

- Xenon-doped Liquid Argon 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
- Geant4 simulations

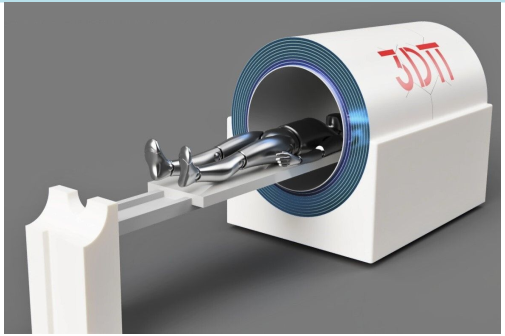
Two configurations:

*LAr+Xe

*LAr+TPB (TetraPhenylButadiene: an organic WLS)

Geant4 Geometry Parameters

Parameter	Value
Inner radius (cm)	45
Outer radius (cm)	64
Length/AFOV (cm)	200
LAr thickness (cm)	16.2
Number of LAr layers	9
SiPM size (mm x mm)	10 x 10
Number of SiPMs	~1 x 10^6
Cryostat Thickness (mm)	6



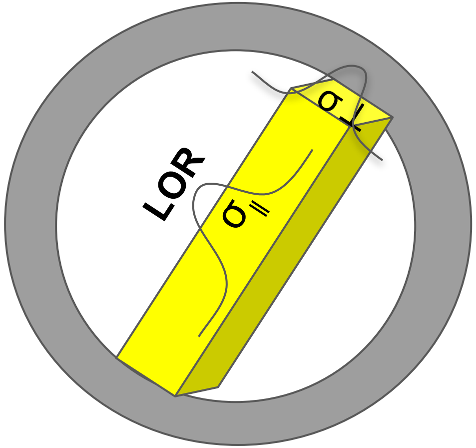
3DΠ Geometry rendered in Fusion 360

Fluctuation Sources in Parallel and Perpendicular to LOR

Sources of fluctuation for construction of events parallel to the LOR:
1- Timing fluctuations:

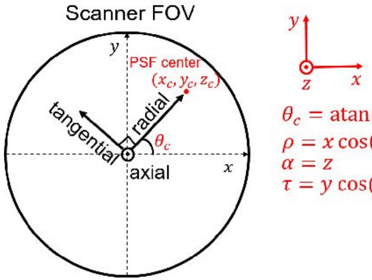
- The statistical nature of scintillation photon detection,
- The time resolution of the SiPMs and their associated electronics.

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



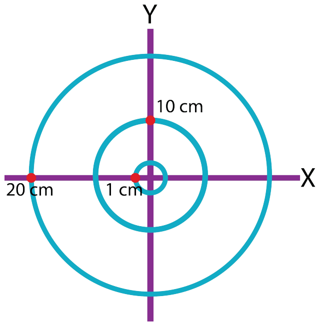
Sources of fluctuation for construction of events perpendicular to the LOR:
The lattice size of the SiPM layout imposes a limitation on the resolution in each of the two directions perpendicular to the LOR.

Spatial Resolution of Single Point Sources

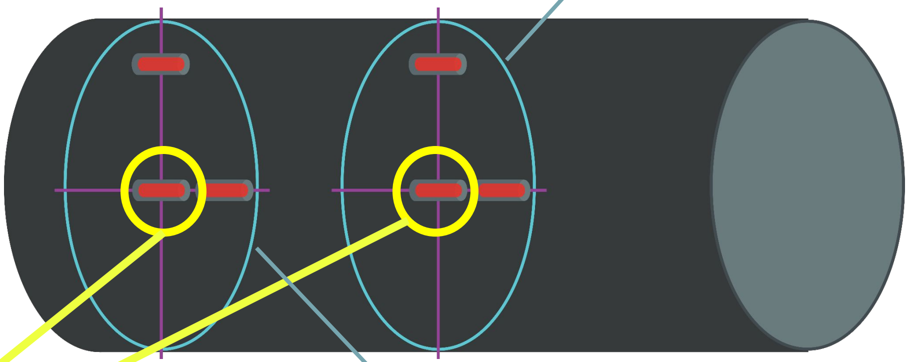


$$\theta_c = \text{atan}(y_c/x_c)$$
$$\rho = x\cos(\theta_c) + y\sin(\theta_c)$$
$$\alpha = z$$
$$\tau = y\cos(\theta_c) - x\sin(\theta_c)$$

Definition of radial, tangential, axial



Radial offsets



Center: center of the AFOV

Offset: one-eighth of the AFOV from the end of the tomography device

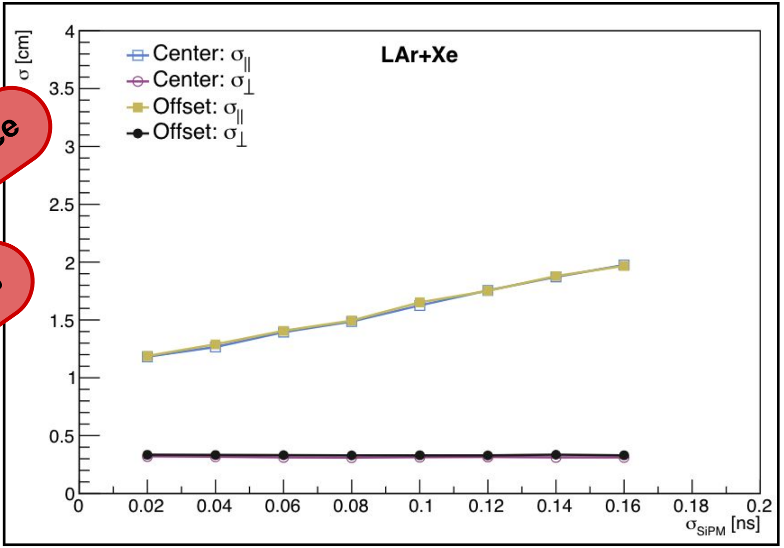
Two point sources

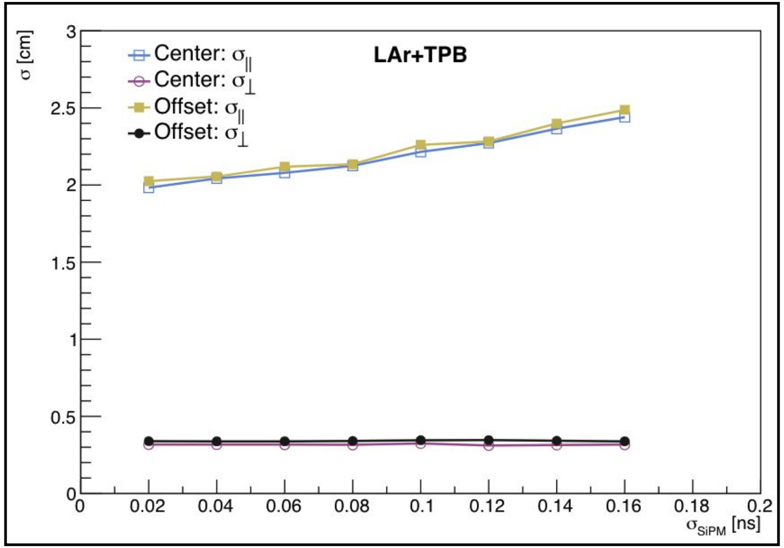
Dependence of Spatial Resolution on SiPM Parameters

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

Point Source

PDE = 70%



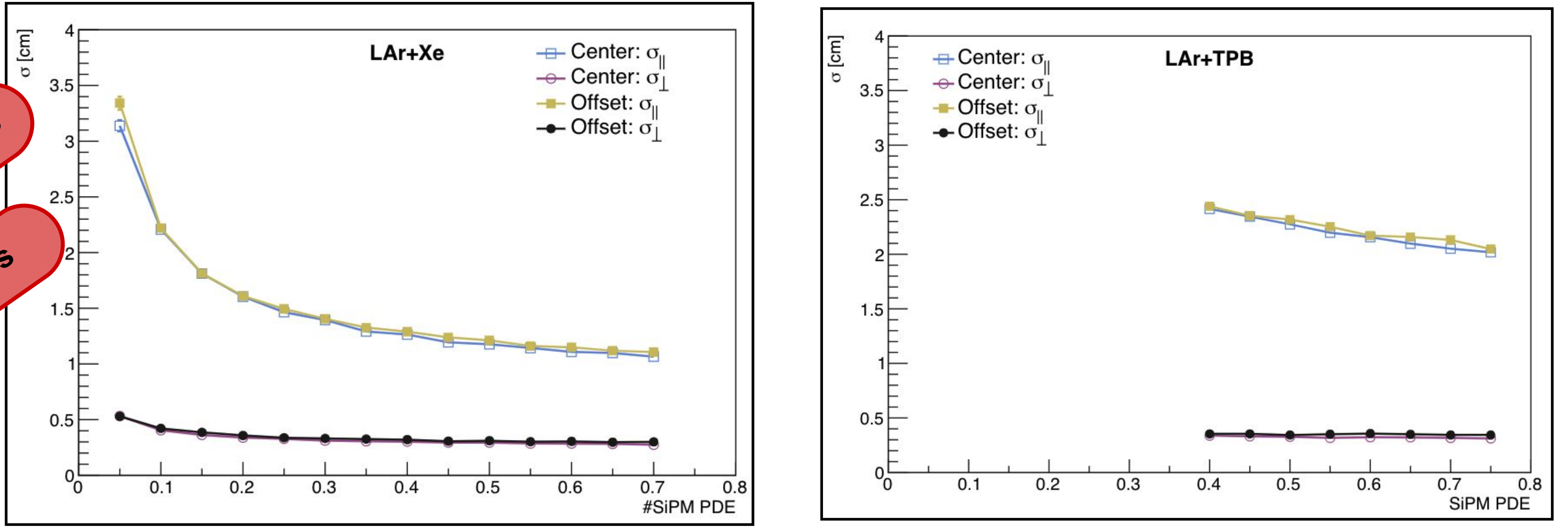


Desirable timing resolution:σ_{SiPM} < 60 ps)

Dependence of Spatial Resolution on SiPM Parameters

Point Source

σ SiPM =60 ps



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

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

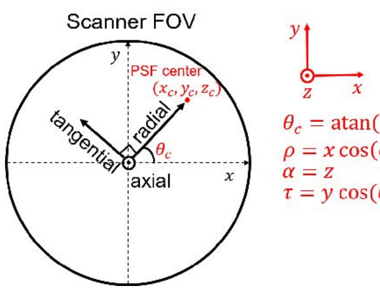
[1] FBK VUV-sensitive Silicon Photomultipliers for cryogenic temperatures, NIMB, Volume 982, 1 December 2020

National Electrical Manufacturers Association

NU 2-2018

A guide to characterize PET performance

Spatial Resolution of Single Point Sources



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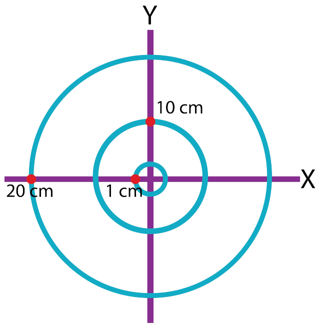
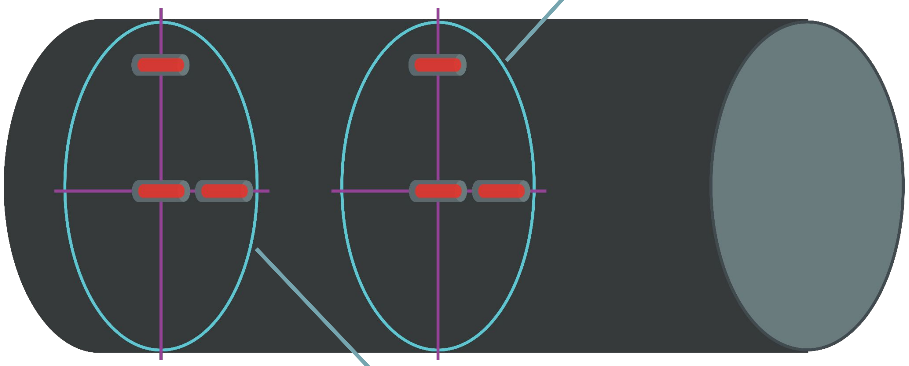
Definition of radial, tangential, axial



Radial offsets

Center: center of the Axial FOV

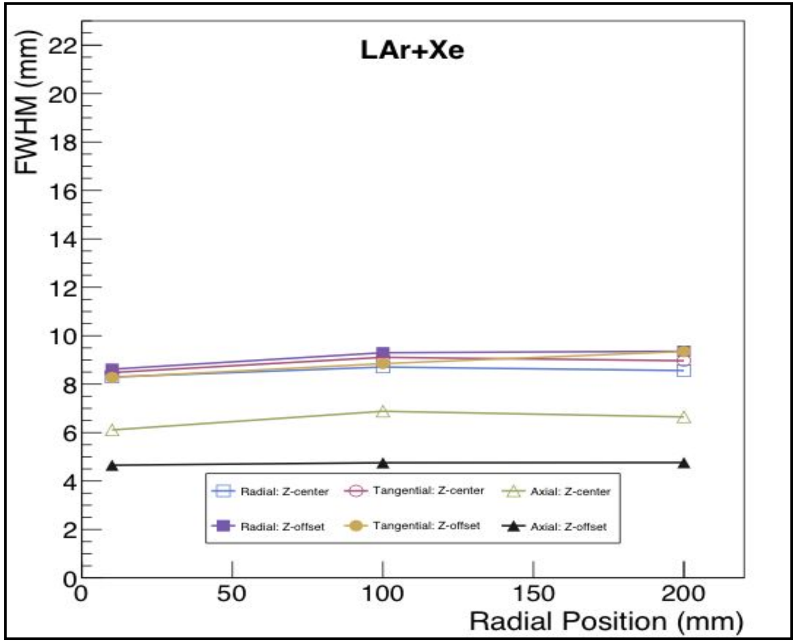


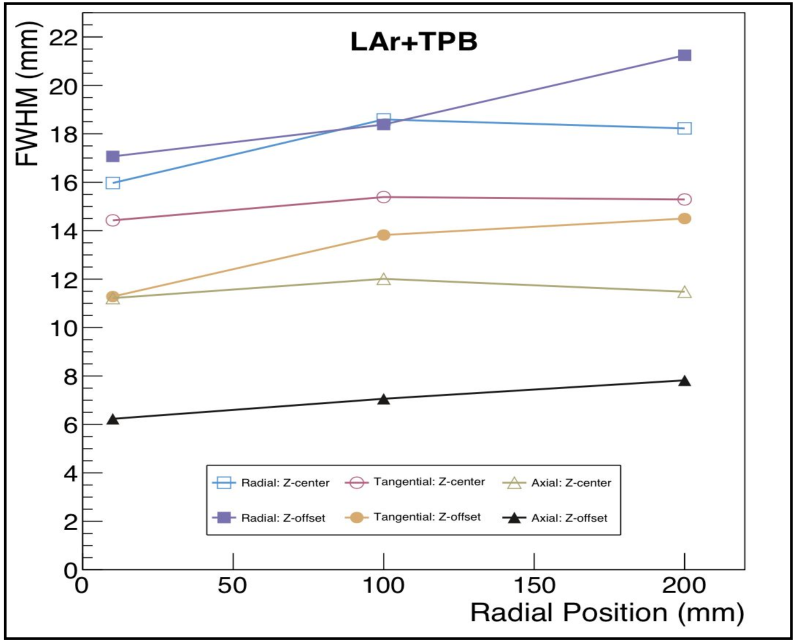
Offset: one-eighth of the AFOV from the end of the tomography device

Spatial Resolution of Single Point Sources

Preliminary Results

Raw data (before image reconstruction stage)



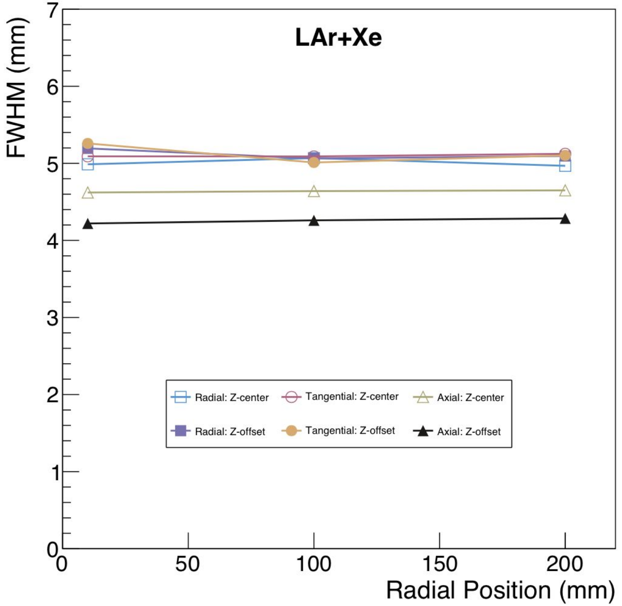


LAr+Xe improves spatial resolution by more than a factor of 2.

Spatial Resolution of Single Point Sources

after image reconstruction

The spatial resolution of a system represents its ability to distinguish between two points *after image reconstruction (Filtered backprojection)*



3Dπ is able to produce consistent and accurate images regardless of the location of the source.

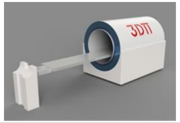
Central Phantoms:	1 cm radial position			10 cm radial position			20 cm radial position		
Scanner	Radial [mm]	Tangent [mm]	Axial [mm]	Radial [mm]	Tangent [mm]	Axial [mm]	Radial [mm]	Tangent [mm]	Axial [mm]
3Dπ (LAr+Xe)	4.8	4.9	4.5	4.9	4.9	4.5	4.8	5.0	4.6
uExplorer (LYSO)	3.0	3.0	2.8	3.4	3.1	3.2	4.7	4.0	3.2

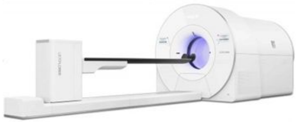
Sensitivity

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

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

S$_{tot}$:System Sensitivity
R$_{Corr0}$:The true coincidences count rate with no attenuation
A$_{cal}$:Line source radioactivity



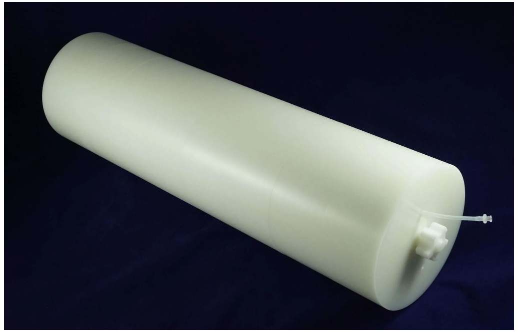
Line source radial position in transaxial field of view	3Dπ LAr+Xe (200 cm AFOV) [kcps/MBq]	GE SIGNA PET/MR (25 cm AFOV) [kcps/MBq]	uExplorer PET/CT (192 cm AFOV) [kcps/MBq]
Center	564.0	21.8	174.0
10 cm radial offset	501.1	21.2	177.0

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.

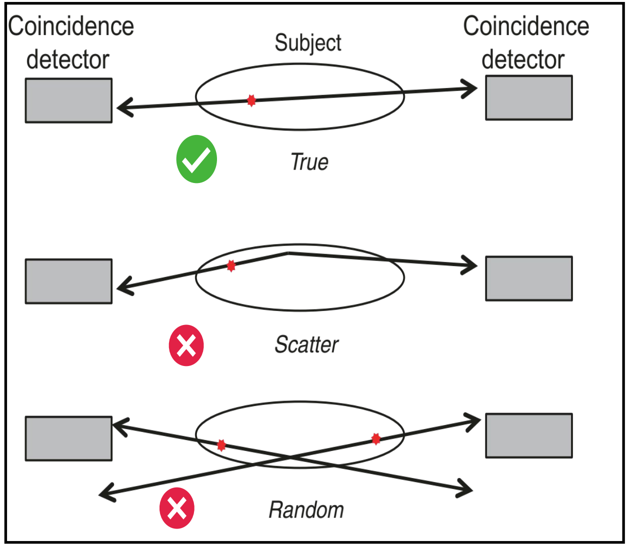
Noise Equivalent Count Rate (NECR)

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

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



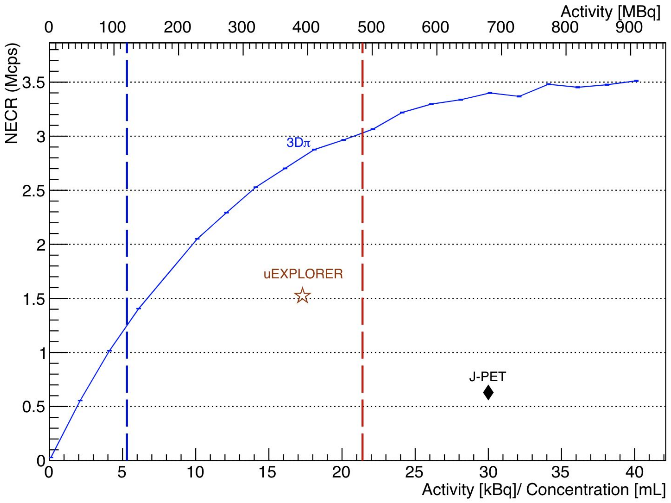
Source Distribution:
A solid right circular high density polyethylene cylinder with a line source.



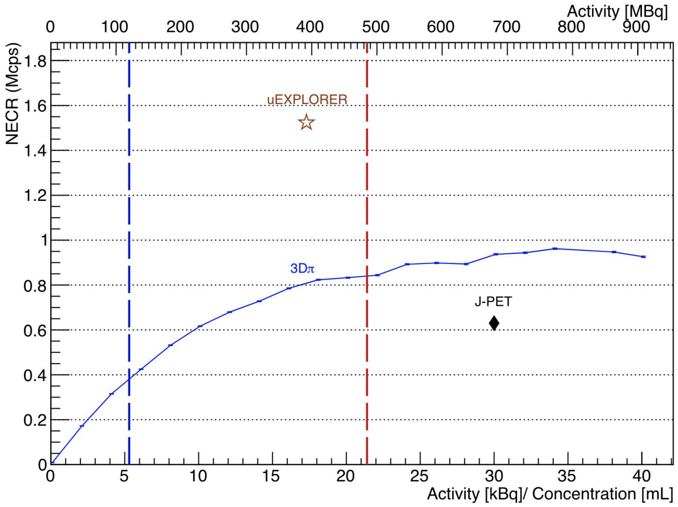
Three types of coincident events

Noise Equivalent Count Rate (NECR)

LAr+Xe



LAr+TPB



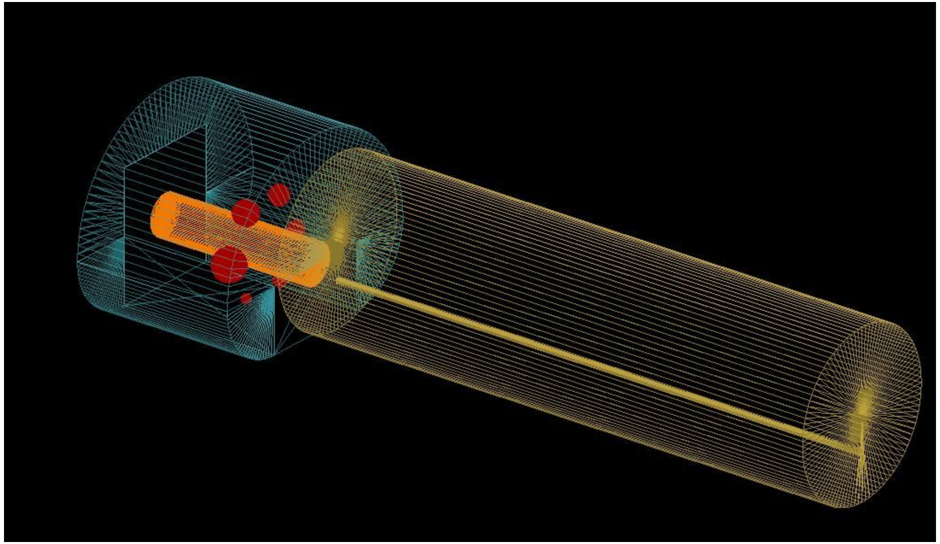
- -Background: Activity concentration used as the background in the Image Quality test
- -Signal: Activity concentration used as the signal in the Image Quality test

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

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

Image Quality

Measure **image contrast** and **background variability** using “hot” spheres in a uniform background



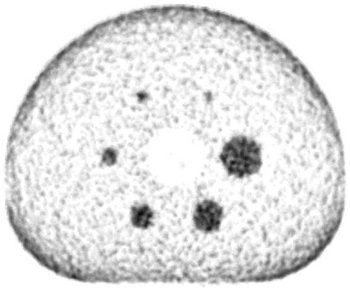
Spheres (Red) phantom geometries
Activity concentration: 4*5.3 kBq/mL=21.2 kBq/mL

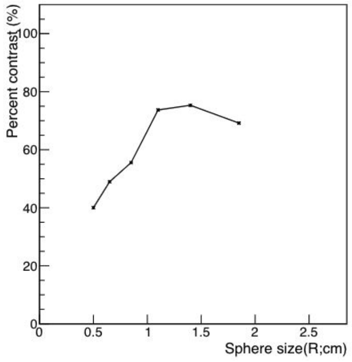
Activity concentration: 5.3 kBq/mL
Body (Cyan) and Test (Gold) phantom geometries

Preliminary Results

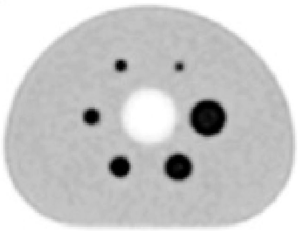
Image Quality

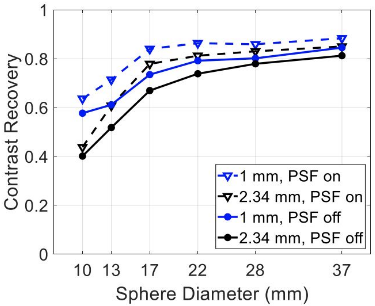
3Dπ scanned for 35 s.





uEXPLORER scanned for 30 min.





Percent contrast=

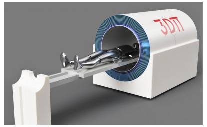
$$\frac{\left(C_{H,j} / C_{B,j} \right) - 1}{\left(a_H / a_B \right) - 1} \times 100\%$$

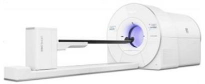
a_B: the activity concentration in the background; 5.3 kBq/mL

a_H: The activity concentration in the hot spheres; 4*5.3 kBq/mL

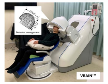
Preliminary Results

Comparison of NEMA Test Results









Scanner	Peak NECR [Mcps]	Activity concentration at peak [kBq/mL]	Sensitivity [kcps/MBq]	Timing resolution [ps]
3Dπ (MC) (Preliminary)	~3	17.3*	560	163
	~3.5	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

The preliminary results demonstrate that our scanner system performance is comparable to commercial scanners.

*Activity concentration at peak NECR, uEXPLORER

**Activity concentration at peak NECR, J-PET

Ongoing activities: Cryogenics and Hardware

- Developing a hardware prototype of a LAr+Xe PET ring at Cagliari, Sardinia
  - ❖ A dedicated laboratory is being set up in Sardinia for conducting tests and commissioning the cryostat.
- INFN Torino developed a front end ASIC board
- Testing the ALCOR board at Princeton University

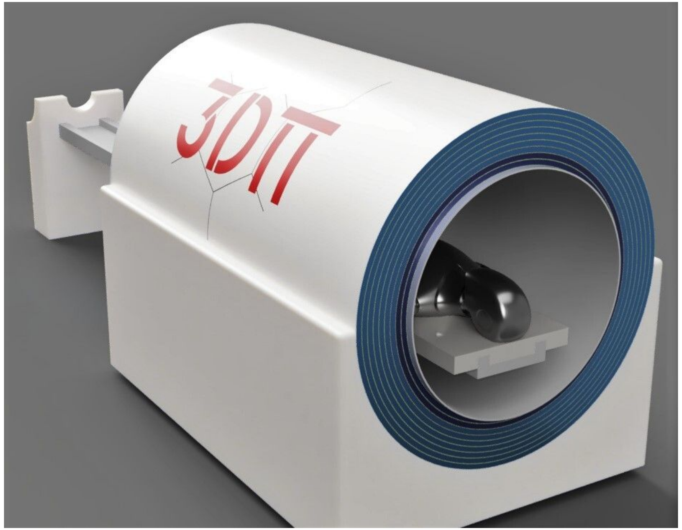
Next steps

Simulation/Software

- Experiment with newer reconstruction algorithms
- Improve Geant4 simulation
- Optimize detection layer geometry

Hardware

- Testing ALCOR board with LAr+Xe
  Ensuring stability and homogeneity of LAr+Xe
- Set up cryogenic infrastructure at Sardinia
- Develop the PET scanner prototype



Thank you

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