# 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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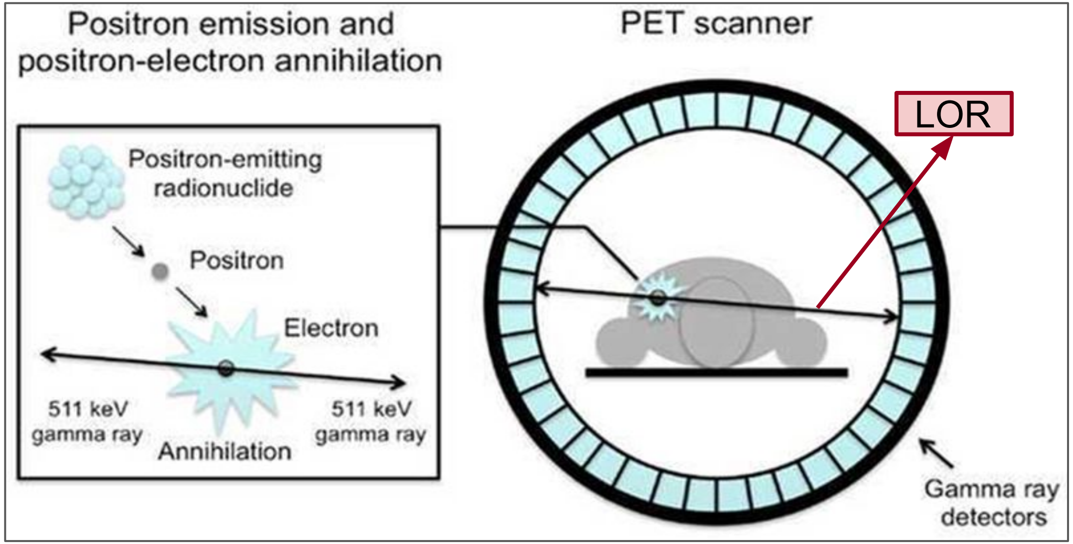
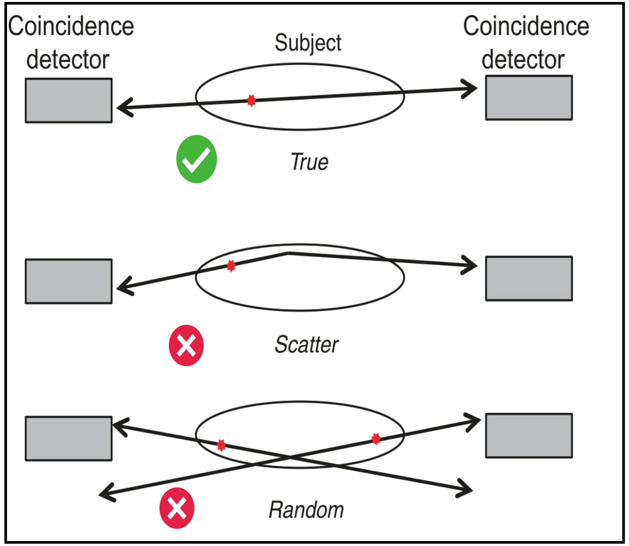
# PET Principle




PET Annihilation Illustration




Three Types of Coincident Events

# Liquid Xenon vs. Liquid Argon

## And Benefit of Cryogenic

0.5%

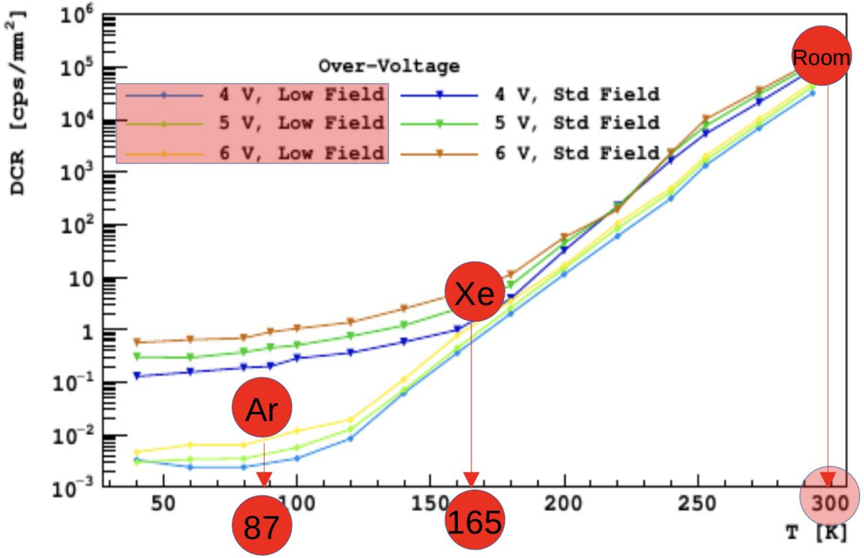
| Scintillator: | LAr | LXe | LAr + Xe | LYSO |
|---|---|---|---|---|
| Decay F/S (ns): | 7/1600 | 4.3/22 | ~6/100* | 41 |
| Wavelength (nm): | 128 | 175 | ~175 ** | 420 |
| Density (g/cm$^3$): | 1.40 | 2.94 | ~1.40 | 7.1 |
| Temperature (K): | 87 | 162 | 87*** | 298 |
| Photons/keV: | 40 | 42 | ~41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

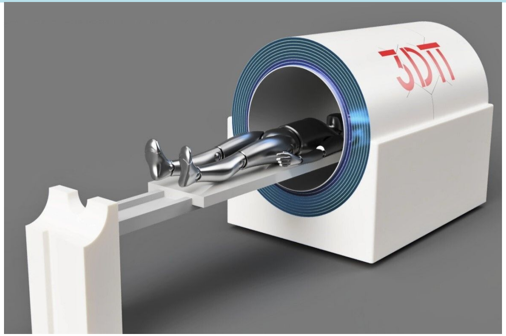
**Two configurations:**

❖ **LAr+Xe, as the main focus**

❖ LAr+TPB (TetraPhenylButadiene: an organic WLS), for comparison

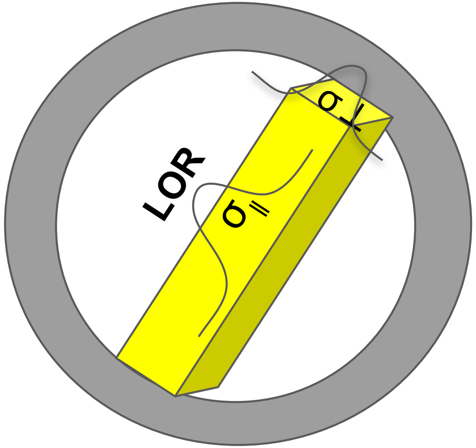
**Geant4 Geometry Parameters**

| 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.

**Desirable timing resolution: $\sigma_{SiPM}$ < 60 ps.**
**Improved PDE (>40%) ensures acceptable resolution, independent of PDE.**

In this work, we assume a **$\sigma_{SiPM}$ 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

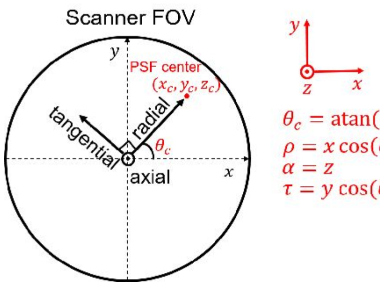
# National Electrical Manufacturers Association

NU 2-2018

**A guide to characterize PET performance**

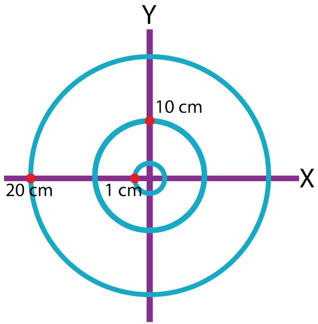
# Spatial Resolution of Single Point Sources

**The spatial resolution of a system represents its ability to distinguish between two points after image reconstruction.**



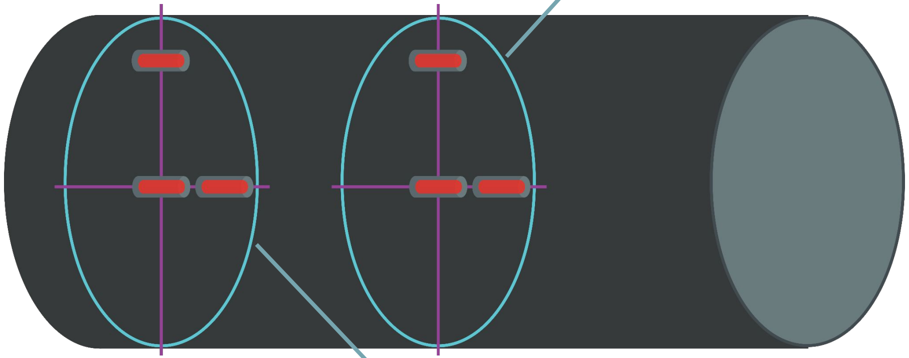

$$\theta_c = \mathrm{atan}(y_c/x_c)$$
$$\rho = x\cos(\theta_c) + y\sin(\theta_c)$$
$$\alpha = z$$
$$\tau = y\cos(\theta_c) - x\sin(\theta_c)$$

Definition of radial, tangential, axial




Radial offsets

**Center**: center of the Axial FOV

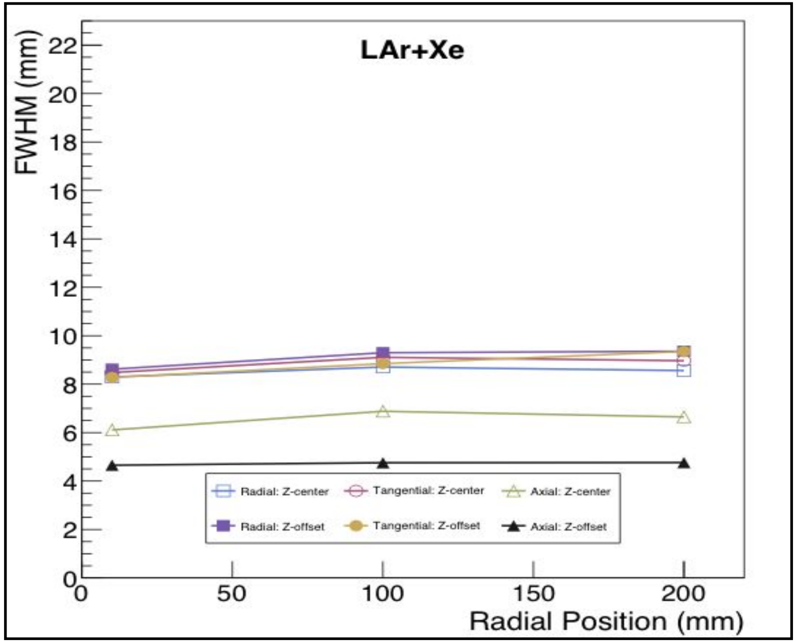


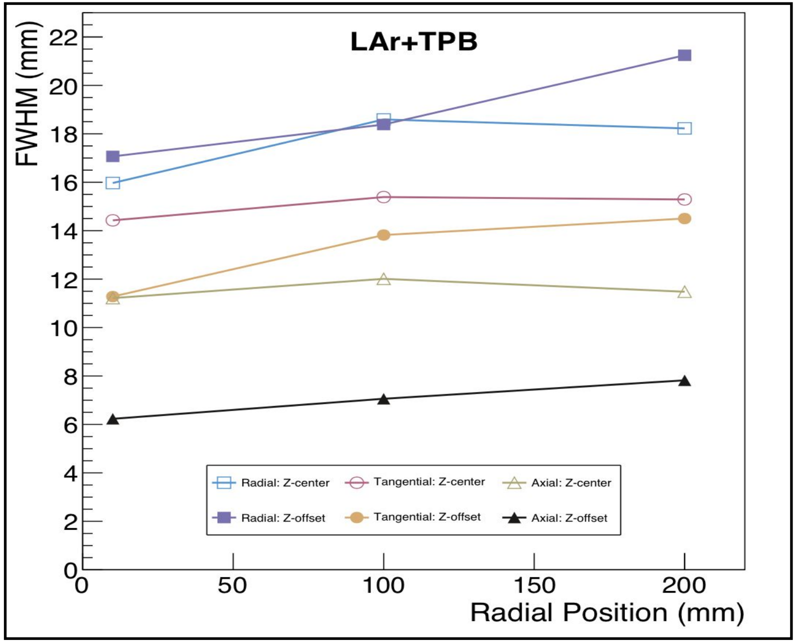
**Offset**: one-eighth of the AFOV from the end of the tomography device

Preliminary Results

# Spatial Resolution of Single Point Sources

**Raw data (before image reconstruction stage)**



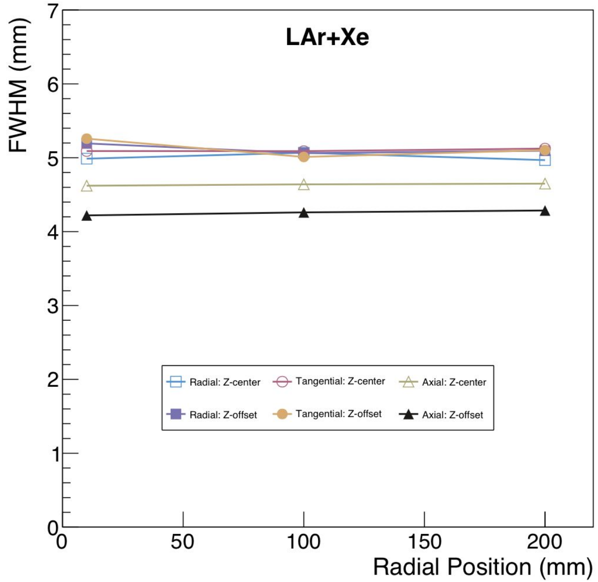

LAr+Xe improves spatial resolution by more than a factor of 2.

Preliminary Results

# Spatial Resolution of Single Point Sources

**after image reconstruction: Filtered backprojection**

| **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 |



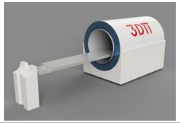

**3Dπ is able to produce consistent and accurate images regardless of the location of the source.**

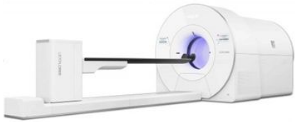
# Sensitivity

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



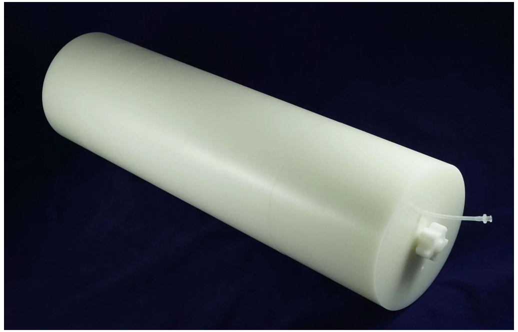
| Line source radial position in transaxial field of view | 3Dπ LAr+Xe (200 cm AFOV) [kcps/MBq] | GE SIGNA PET/MR (25 cm AFOV) [kcps/MBq] | uExplorer PET/CT (192 cm AFOV) [kcps/MBq] |
|---|---|---|---|
| **Center** | 564.0 | 21.8 | 174.0 |
| **10 cm radial offset** | 501.1 | 21.2 | 177.0 |

**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.**

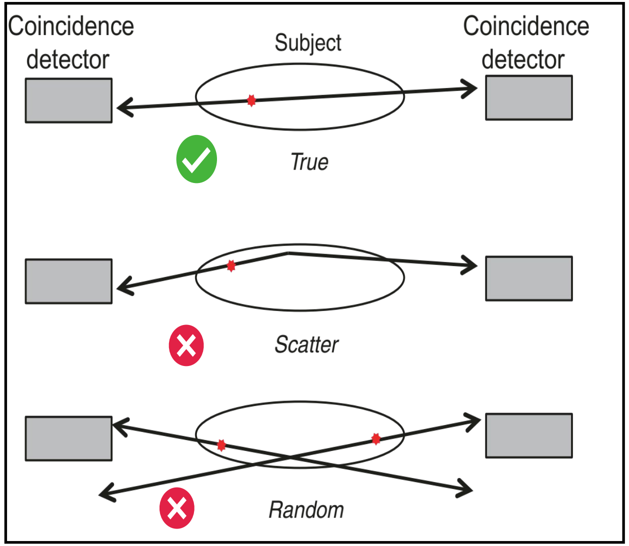
# Noise Equivalent Count Rate (NECR)

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

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



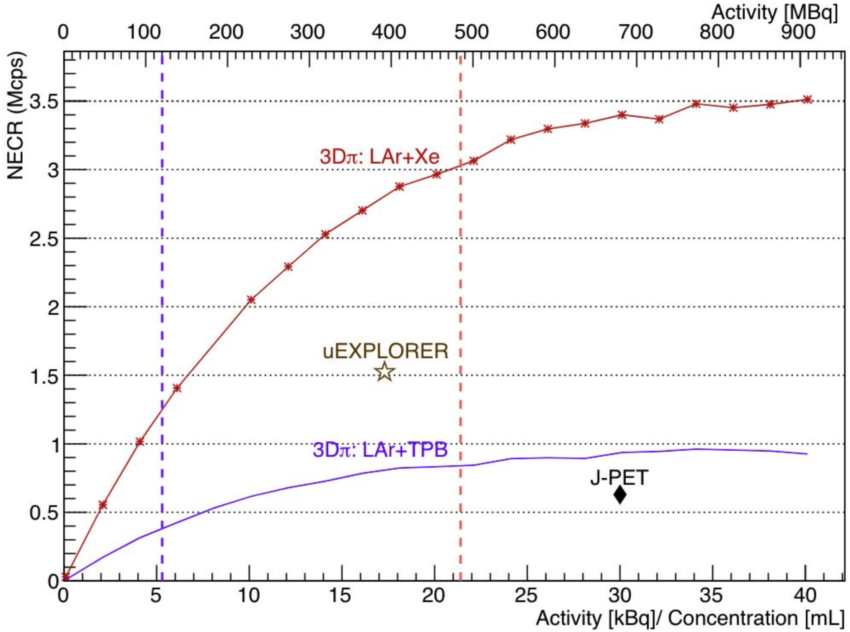
**Source Distribution:**
A solid right circular high density polyethylene cylinder with a line source.




Three types of coincident events

**Preliminary Results**

# Noise Equivalent Count Rate (NECR)



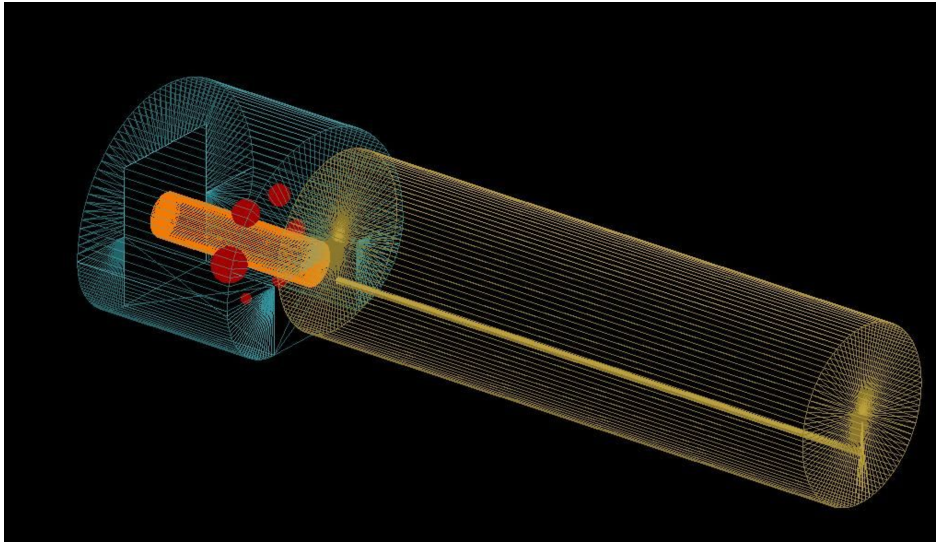

---Background: Activity concentration used as the background in the Image Quality test
---Signal: Activity concentration used as the signal in the Image Quality test

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

**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.

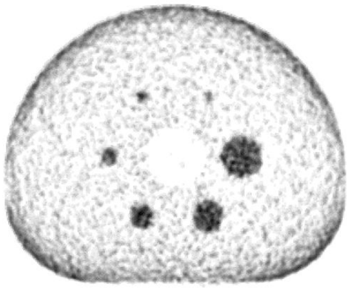


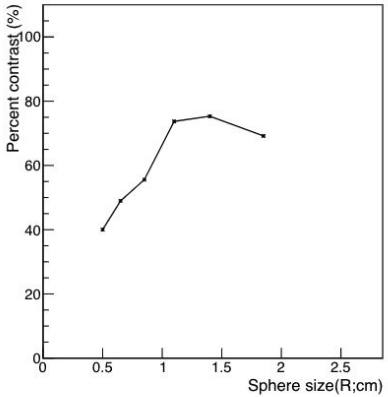
Body (Cyan) and Test (Gold) phantom geometries
Activity concentration: 5.3 kBq/mL

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

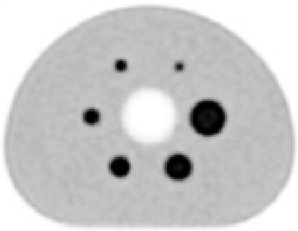
# Image Quality

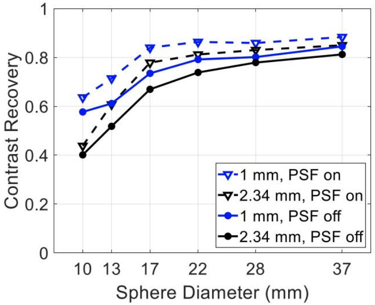
**3Dπ scanned for 35 s.**






**uEXPLORER scanned for 30 min.**



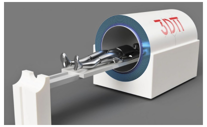


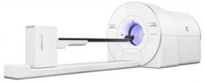

Percent contrast=

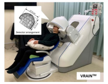
$$\frac{\left( {C_{H,j}}/{C_{B,j}} \right) - 1}{\left( {a_H}/{a_B} \right) - 1} \times 100\%$$

$C_H$: the counts in the ROI for sphere j
$C_B$: The average of the background ROI counts for sphere j
$a_B$: The activity concentration in the background
$a_H$: The activity concentration in the hot sphere

# Comparison of NEMA Test Results





| Scanner | Peak NECR [Mcps] | Activity concentration at peak [kBq/mL] | Sensitivity [kcps/MBq] | TOF 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 developing a front end ASIC board

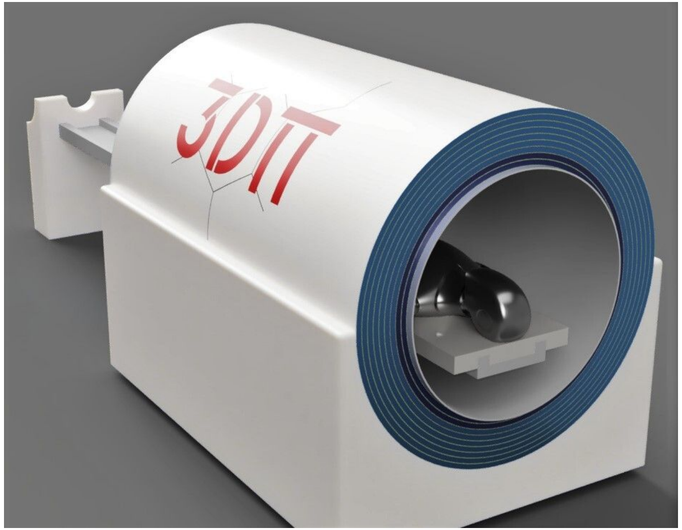
## Next steps

### 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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