Liquid Xenon Detectors for Positron Emission Tomography

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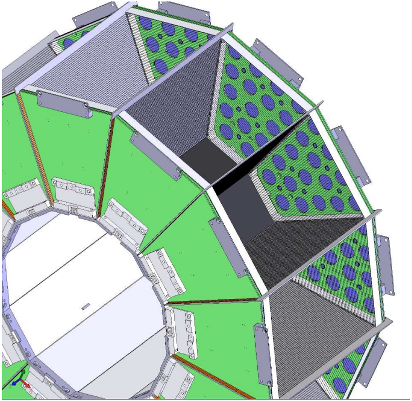
LXe micro-PET Project - Goal

Develop a PET system for preclinical applications with

- Sub-mm spatial resolution in 3D
- Uniform response throughout FOV
- Energy resolution at 511 keV < 10%(FWHM)
- Time resolution < 1ns
- High sensitivity ($>$ 15%)
- High count rate capability ($> 10^5 s^{-1} cm^{-2}$)
- Compton camera functionality

LXe micro-PET Project - Overview

- Scanner geometry: Ring
- Detector type: Liquid Xenon
- Detector: Liquid xenon TPC viewed by two arrays of APDs
- Ionization charge and scintillation light measured simultaneously
- Small scale prototype: proof of principle
  - Measured energy resolution at 511 keV = 10% (FWHM)
- LXe micro-PET sector
  - Currently under test
- Two micro-LXe PET sectors for coincidence PET measurements
- Full PET scanner



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Why Liquid Xenon?

- High detection efficiency (Z =54 and density =3g/cm^3)
- Excellent scintillator
  - High light yield (70 photons/keV at E field = 0)
    $\longrightarrow$ Large scintillation signals
  - Short scintillation decay time (2.2ns)
    $\longrightarrow$ Sub-ns time resolution
- High ionization yield (60 e-/keV at high E field) $\longrightarrow$ Large ionization signals
- Low diffusion rate (20μm for 1μs drift) $\longrightarrow$ Sub-mm position resolution
- Ionization/Scintillation anti-correlated $\longrightarrow$ Improved energy resolution

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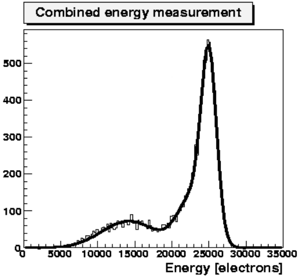
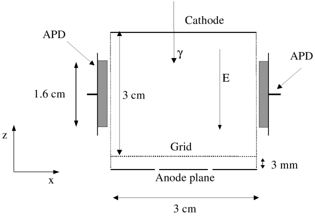
- LXeTPC 3x3x3cm^3
- 2APDs, total solid angle 10%
- 2 Anodes: central disc dia. 10 mm, Grid: 3 mm spacing, gap 3 mm
- Tests with Na22
- **Energy resolution** $= 10\% FWHM$



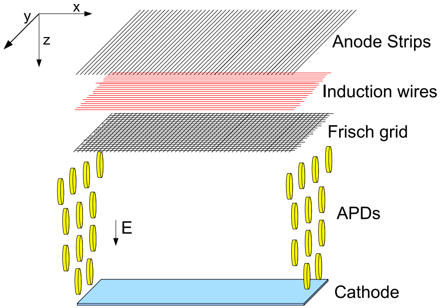


P. Amaudruz, Nucl. Instrum. Meth. A 607 (2009)

LXe micro-PET Sector - Principle of Operation

LXeTPC viewed by APDs

- Gamma rays interact with LXe
  - Prompt scintillation ligth (178nm) detected by APDs
  - Ionization charge collected by anode strips
- 3D position measurement
  - XY: anode strips and induction wires
  - Z: electron drift time and drift velocity
- Energy measurement
  - Combined charge and scintillation light signals



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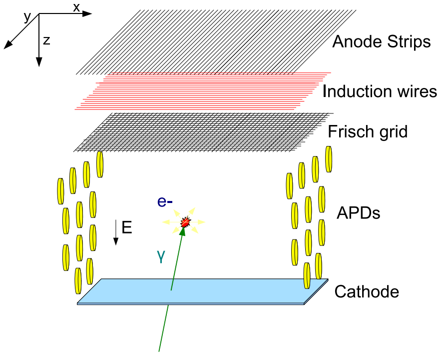

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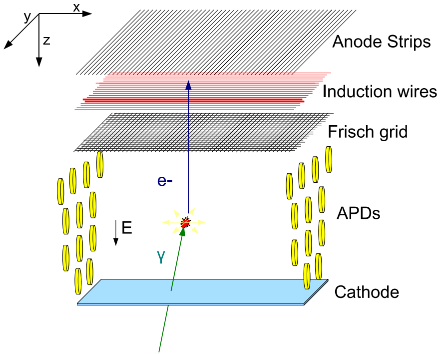

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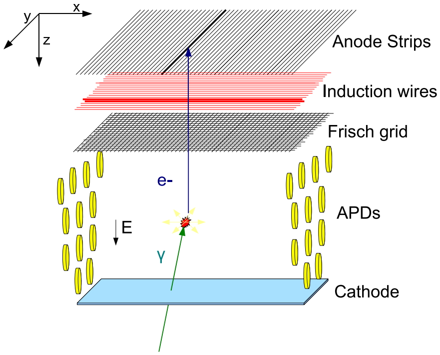

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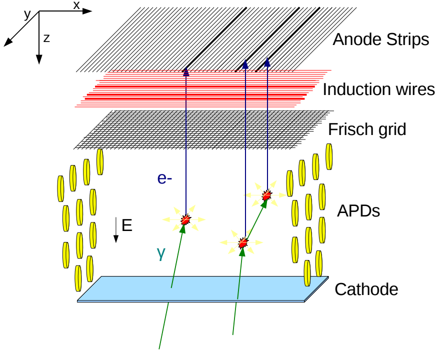
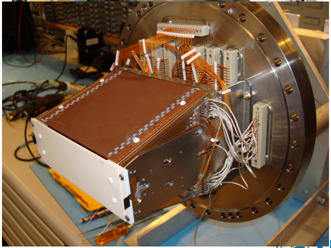


LXe micro-PET Sector

- TPC 1l active volume
- 32 16mm dia. APDs
- Anode module: 96 induction wires and 96 perpendicular anode strips (spacing 1.1mm)
- Drift length 12 cm
- Drift field 0.9kV/cm
- Xenon purification in gas (5cc/min) and liquid phase (0.35L/min)
- Pressure 17 psia. temperature 169K
- Currently under test



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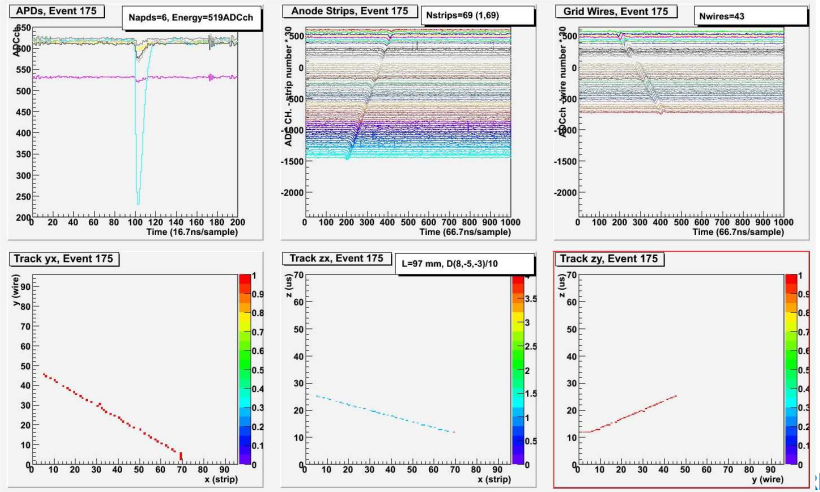
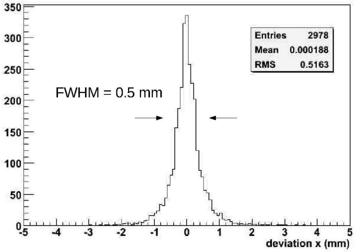
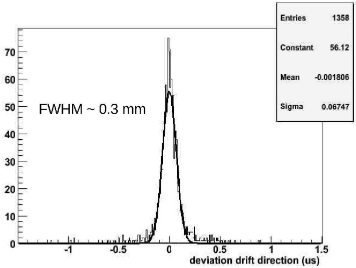
LXe micro-PET Sector - Cosmic ray muon track



LXe micro-PET Sector - Residual

- X coordinate = 0.5 mm (FWHM)
- Z coordinate (along drift direction) = 0.3 mm (FWHM)





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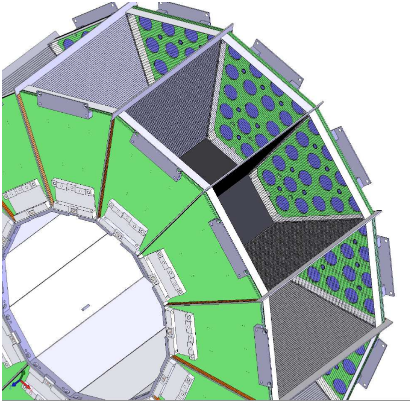
LXe micro-PET Design

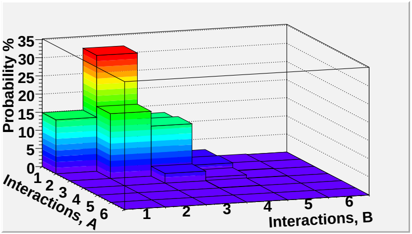
- 12 LXe micro-PET sectors
- Anode module: 96 induction wires, 96 strips (spacing 1.1mm)
- 32 16 mm dia. APDs
- Axial FOV 10 cm
- Transaxial FOV 12 cm
- Drift length 12cm



Dealing with Multi-interaction Events

- 85% Multi-interaction events
- Compton reconstruction algorithm
  - Find 1st interaction point
  - Suppress scatter and random backgrounds

Event topology

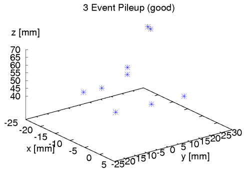


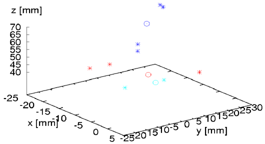
Compton reconstruction algorithm

- For each possible sequence calculate scattering angles from energy and geometry
- Sequence with the lowest χ^2 = Correct interaction sequence

Dealing with High Rates

- 3D position extracted from light pattern on APDs (Neural network)
- Match fast light with slow charge signals
- Method efficiency = 99% (*)
  (*) 2 pile-up events
  activity 1mCu





A. Muennich

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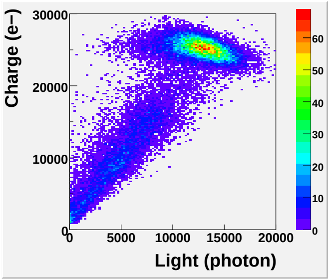
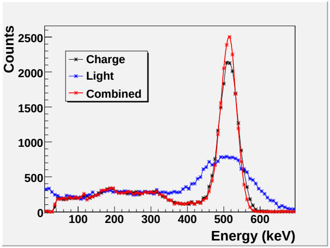
LXe micro-PET - Simulated Performance

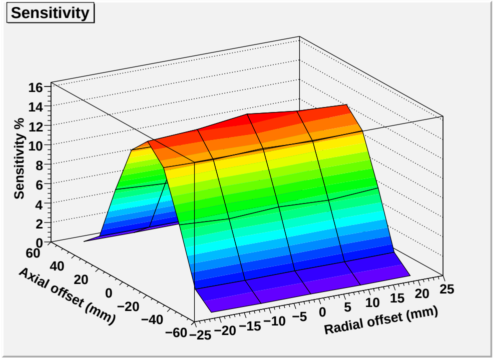
- Geant4 simulation, parametrization of detector response
  Compton reconstruction algorithm for multi-site events, positron range and photon non collinearity included, dead materials
- Energy resolution at 511 keV = 10 % (FWHM)





LXe micro-PET - Simulated Performance

- Absolute Sensitivity (CFOV point source) = 15 %



Summary and Conclusions

- Measured energy resolution at 511 keV 10%*FWHM* (small scale prototype)
- Measured position resolution with cosmic rays $< 1mm$ (LXe micro-PET sector)
- LXe micro-PET (MC studies)
  - Energy resolution 10%*FWHM*
  - Absolute sensitivity CFOV 15%
- LXe micro-PET sector under test
- Coincidence PET measurements with 2 LXePET sectors starting in 2011

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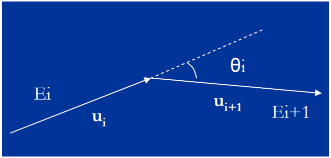
Compton Reconstruction algorithm



$$cos\theta_G = \frac{u_i \cdot u_{i+1}}{\parallel u_i \parallel \parallel u_{i+1} \parallel} \quad (1)$$

$$cos\theta_E = \frac{1}{mc^2} + \frac{1}{E_i} - \frac{1}{E_{i+1}} \quad (2)$$

$$\chi_2 = \frac{1}{N-1} \sum_{i=1}^{N} \frac{(cos\theta_G^i - cos\theta_E^i)^2}{\sigma_G^2 + \sigma_E^2} \quad (3)$$