Design and Performance of Liquid Xenon Detectors for PET

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Outline

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Comparison of LXe and other Scintillators

Scintillator	BGO	LSO	LXe
Density [g/cc]	7.1	7.4	3.1
Yield [γs/keV]	6.4	32	68
Decay Time [ns]	300	40	2.2(98%), 27(2%)
Wavelength [nm]	480	420	178
Photo-fraction	42%	33%	22%

LXe provides:

- Faster decay and higher light yield.
- Simultaneous operation for scintillation and ionization detection when an electric field is applied $\rightarrow$ high spatial resolution and energy resolution

Advantages of LXe for PET

- Good energy resolution $<$ 10 (FWHM)%
- Compton reconstruction
  $\rightarrow$ 3D localization of first interaction (no parallax error, suppression of random and scatter backgrounds)
- Uniform 3D spatial resolution throughout the field of view: $<$ 1 mm in 3D
- Timing resolution: $<$ 1 ns
- High count rate: $> 10^5/(\text{s cm}^2)$
- Cover large volumes with just one electrode array
  $\rightarrow$ high sensitivity: $>$ 70%
- Inexpensive ($<$ \$ 3/cc)

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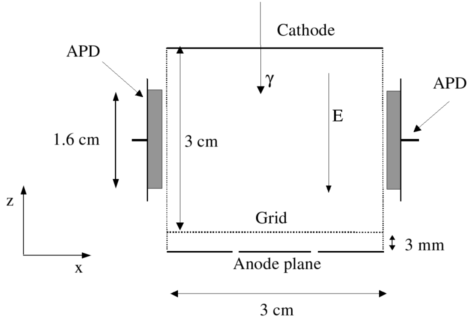
Small Prototype: Time Projection Chamber (TPC)

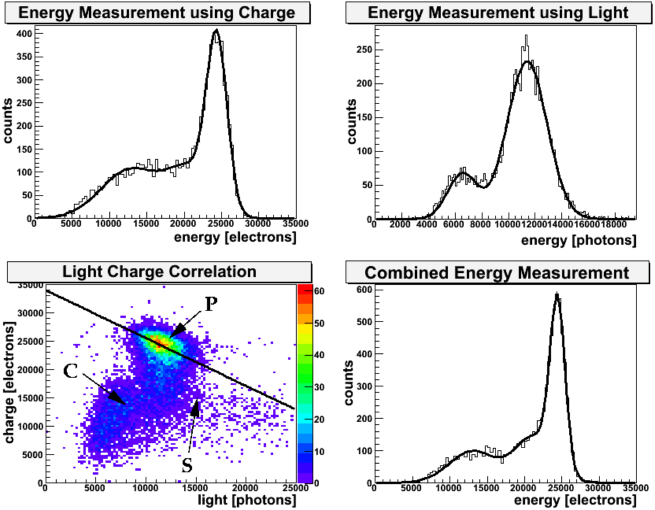
- TPC volume 3x3x3 cm^3
- typical: E=1 kV/cm, v_d =2 mm/μs
- 2 APDS; solid angle $\approx$ 12%



Results for 511 keV photons from ^{22}Na:

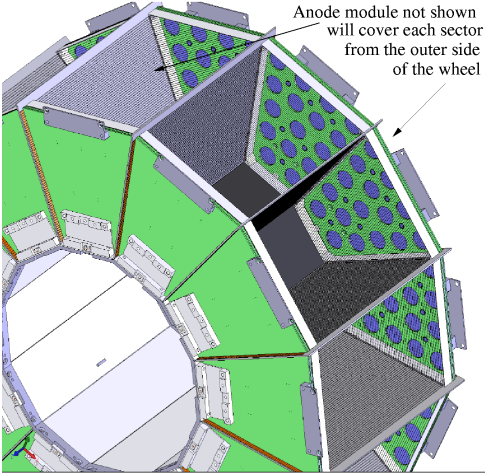
- Light resolution: 11.4% (rms)
- Charge resolution: 5.6% (rms)
- Combined energy resolution: 3.9% (rms)

Combining Light and Charge Measurement with 511 keV Photons



P: Photoelectric, C: Compton, S: Scattered outside

Micro-PET Design



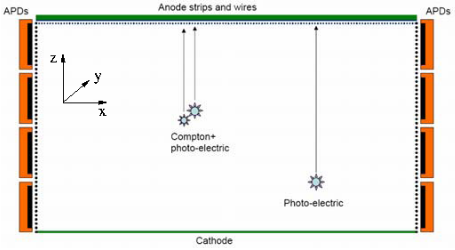
- 12 sectors, 32 APDs per sector, 96 anode wires, 96 anode induction wires
- Radial depth 12 cm
- Minimal dead space between sectors to increase active volume

Principle of LXe TPC

TPC Design based on LXeGRIT (E. Aprile et al. 2008):

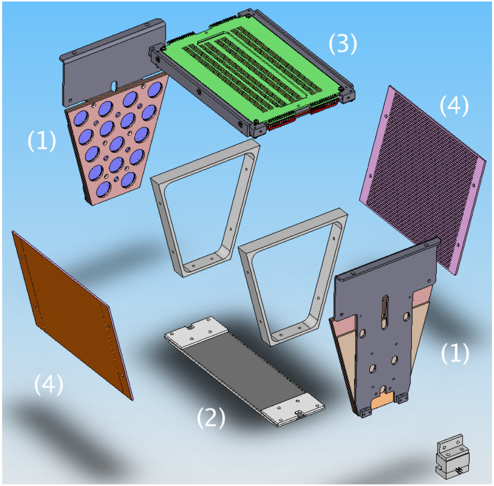
- 2D coordinates from anode wires and induction wires with resolution limited by wire spacing ($\sim$ 1mm).
- 3rd coordinate from the drift time between the prompt scintillation light trigger and the anode signal

Both light and charge are used for spatial location of interactions and for energy measurements.



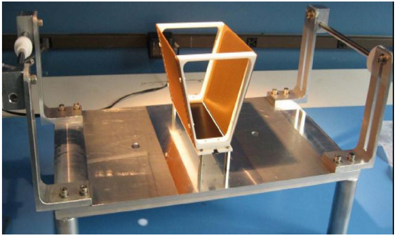
Prototype Sector

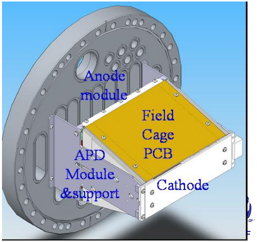
1. APD Module with 16 APDs
2. Cathode Plate: resistive kapton on ceramic plates
3. Anode Module: 96 wires, 96 strips
4. Field Cage: strips between sectors, wires on APD sides



Prototype Status

- Design finished
- Assembly almost complete
- First tests with APDs (no field cage) in LXe in progress





Simulation Framework

- Used GEANT4 package
- Simulated a micro-PET, 14 cm inner diameter, 38 cm outer diameter, 8 cm length.
- Dimension chosen to match commercially available Focus 120 detector.
- Used Compton reconstruction for LXePET to get the first point of interaction of each 511 keV photon and to suppress backgrounds
- Positron range included, non-collinearity not included
- Assumptions: ΔE=9 %, ΔX=ΔY=ΔZ=1 mm (FWHM); dead time of 500 ns

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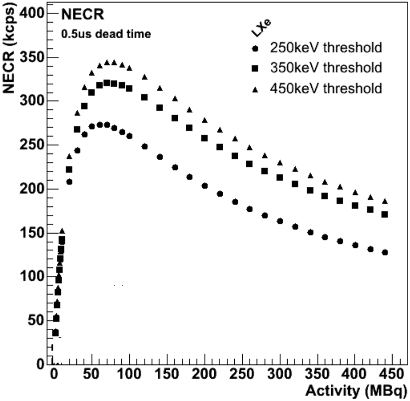
Sensitivity

Sensitivity = Attenuation-less True coincidence count rate divided by the source activity, for a point source at the center of the field of view.
A 6 ns coincidence window used.

Energy Window	LXe Sensitivity [%]
250	10.2
350	9.3
450	8.7

For the same solid angle profile, the LXePET simulation gives improved sensititvity. Reasons for that are more active detection volume (less escapes) and less inactive material that can absorb/scatter photons.

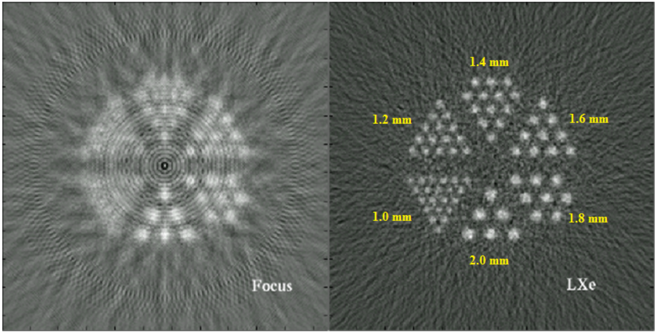
Noise Equivalent Count Rates



- Most widely used indicator for image quality.
- NEMA-like rat sized phantom
- Coincidence window: 6ns
- LXe system gives very high NECR.

Image Reconstruction from Simulations

Same simple reconstruction method (Filter-Back Projection) used for both (emphasis on resolution not image quality):



In the simulation, the limitations of the LXe system are primarily due to physics effects such as the positron range.

Conclusion and Outlook

- A small liquid xenon TPC has been shown to give excellent energy resolution ($<$10% FWHM) by combining ionization charge and scintillation light signals observed with avalanche photodiodes.
- We are presently designing and building a prototype of one sector for a Micro-PET scanner
- Design of full Micro-PET system in progress

Next steps:

- Operate and test the first sector prototype
- Build a second sector and operate in coincidence for PET measurments within a cryostat designed for a full PET ring

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