Design and Performance of Liquid Xenon Detectors for PET

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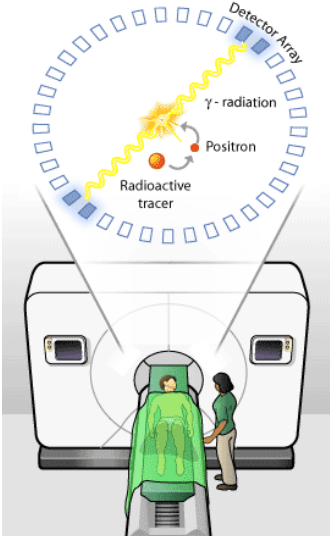
Outline

Outline

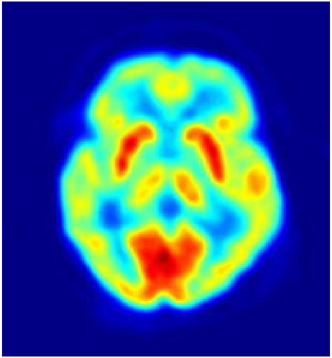
Working principle of PET



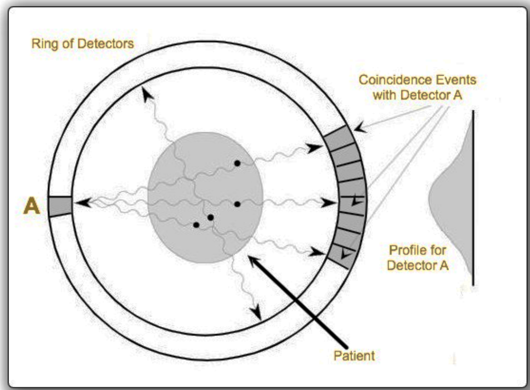
- Short lived isotopes decays emitting e^+
- e^+ drift range about 1mm (FWHM)
- e^+ annihilates into pair of 511 keV γs
- Angle between γs $\approx 180^\circ$ (small non-collinearity effect)
- Reconstruct line of response (LOR)

Medical use of PET

- PET is a functional scan, does not show anatomic features
- Non-invasive method to screen for tumors
- Traces biological processes to study pathology
- Targeted radio-pharmaceuticals with positron emitters are used
- Widely used tracer: FDG (fluorodeoxyglucose), mostly for cancer studies

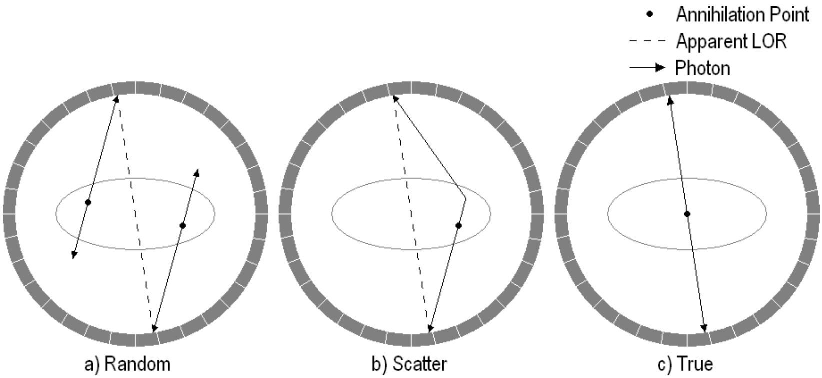


Conventional PET Detector



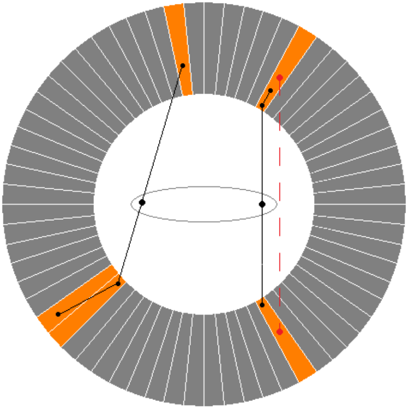
- Scintillating crystals in ring geometry
- γs deposit energy in crystals
- Crystal provides discrete location
- No information about depth of interaction
- Intersection region of LORs define tumor

Event Types



- Scatter Fraction (SF) = Background/Total (at low activity → Randoms negligible)
- Scatter = True*SF/(1-SF)
- Random = Total-True/(1-SF)

Limitations of Conventional PET



- Limited energy resolution (18% FWHM at 511 keV)
- Position resolution limited by crystal size ($\sim$ 6 mm, degrading away from center)
- No position information within crystal $\rightarrow$ parallax error
- Multiple hits cannot be treated, apart from taking an average
- No angular information from Compton events to supress random and scatter events

Outline

Properties of LXe

- Z=54, A=131 $\rightarrow$ Attenuation length: 36 mm
- Density: 3 g/cc at 165 K $\rightarrow$ compact detector
- Boiling/Melting point temperature: 165 K / 161 K
  $\rightarrow$ needs cryogenic system
- Produces ionization and scintillation light
  $\rightarrow$ combining both improves energy resolution
- Purity important: 1 ppb allows an e^- lifetime of 1 ms

Ionization

- Yield: 15.6 eV $\rightarrow$ 32800 e^- at 511 keV and $E_d = \infty$
- E_{drift}: 1-2 kV/cm
- v_{drift}: 2 mm/µs

Scintillation

- Yield: 13.8 eV $\rightarrow$ 37000 γs at 511 keV and $E_d = 0$
- γs with $\lambda = 178 \pm 14$ nm (special photo-detectors)

Comparison of LXe and other Scintillators

Scintillator	BGO	LSO	LXe
Attenuation length (at 511 keV)[mm]	11	12	36
Yield [γs/keV]	6.4	32	68
Decay Time [ns]	300	40	2.2, 27
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)%
- Uniform 3D spatial resolution throughout the field of view: < 1 mm in 3D
- Compton reconstruction
  $\rightarrow$ 3D localization of first interaction (no parallax error, suppression of random and scatter backgrounds)
- Expected timing resolution: < 1 ns
- High count rate: $> 10^5/(\text{s cm}^2)$
- Cover large volumes with just one electrode array
  $\rightarrow$ high sensitivity
  $\rightarrow$ high efficiency: $> 70\%$
- Inexpensive ($<$ \$ 3/cc)

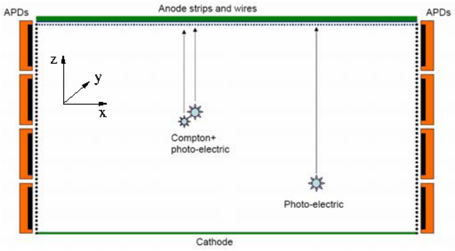
Outline

Principle of LXe TPC

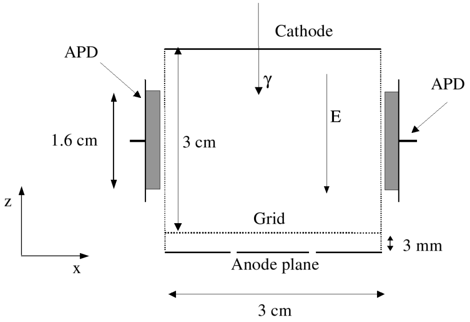
TPC Design based on LXeGRIT (E. Aprile et al. 2008):

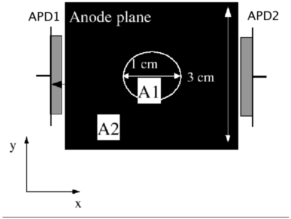
- 2D coordinates from anode wires and induction wires with resolution limited by wire spacing ($\sim$ 1mm).
- 3rd coordinate from the drift time between the prompt scintillation light trigger and the anode signal

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

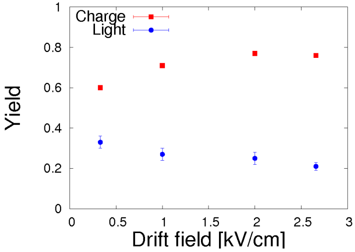


Small Prototype: Time Projection Chamber (TPC)

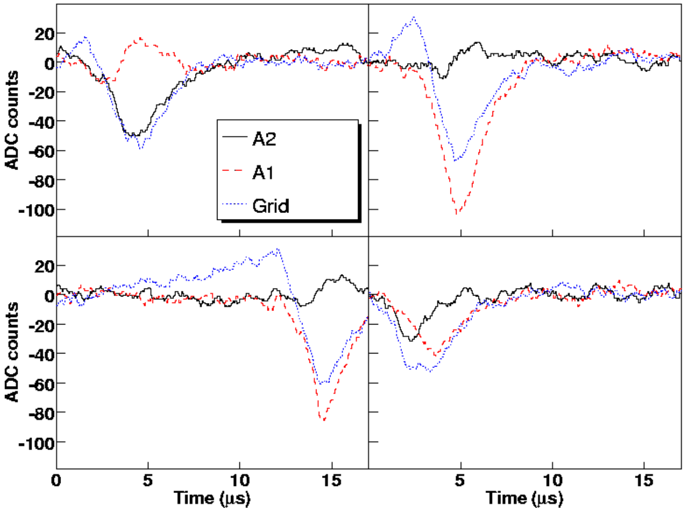




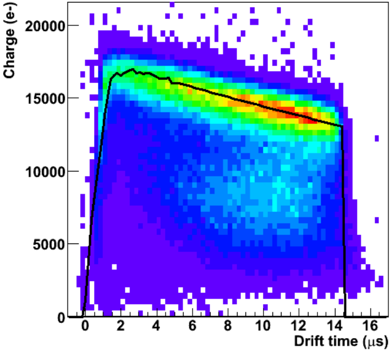
- TPC volume 3x3x3 cm^3
- typical: E=1 kV/cm, v_d =2 mm/μs
- 2 APDS; solid angle $\approx$ 12%
- Data from 511 keV γs from ^{22}Na



Waveform Signals



Ionization Signal



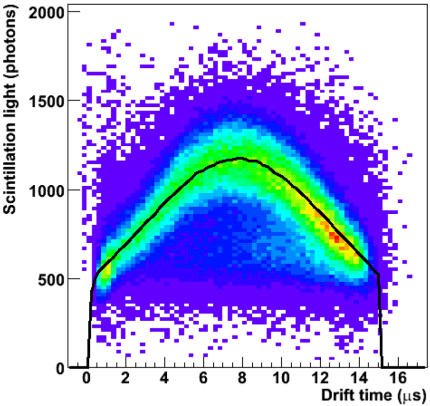
Dropping charge is caused by attachment *A* and needs correction:

$$Q_f = Q_m / A$$

From the Fit:

- total number of electrons created: Q_f=19700
- drift velocity: v_d=0.20 cm/μs
- electron lifetime: τ=60 μs
- charge yield: Q_f/Q_0=0.6

Scintillation Signal



Shape caused by solid angle variation that needs to be corrected in addition to the total solid angle F_Ω and quantum efficiency ϵ:

$$S_f = S_m/(\epsilon F_\Omega)$$

From the Fit:

- drift velocity: v_d=0.21 cm/μs
- total number of photons created: S_f=10100
- light yield: S_f/S_i=0.27

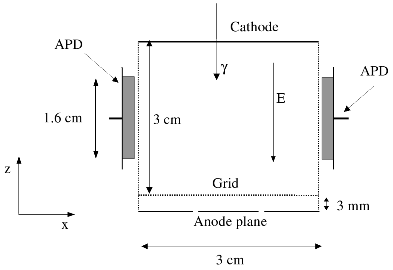
Event Selection

Charge:

Consider only central events with complete charge deposited on central anode A1.

Light:

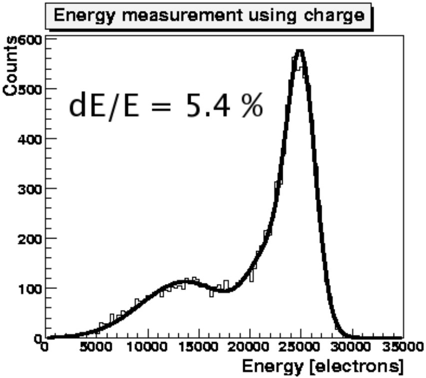
APDs show different efficiency. They have to be scaled to one another because quantum efficiency is unknown.



Time:

2 mm window around the middle of the chamber where the measured light is maximal.

Charge Spectrum



Measured charge after recombination F_r:

$$Q_m = AQ_i(1 - F_r)$$

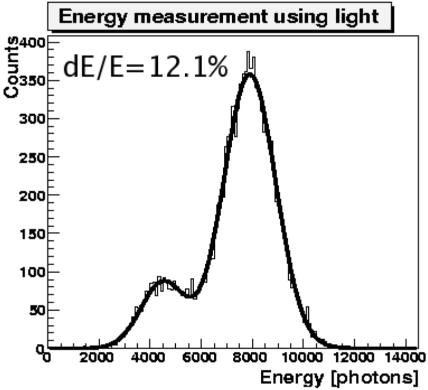
Error contributions:

$$\left(\frac{\Delta Q_m}{Q_m}\right)^2 = \left(\frac{ENC_q}{Q_m}\right)^2 \quad (3.5\%)$$
$$+ \left(\frac{\Delta F_r}{1 - F_r}\right)^2$$

$\rightarrow$ intrinsic charge resolution: 4.2%

$\rightarrow$ charge-light-fluctuation ΔF_r = (3.2 $\pm$ 0.3) %

Light Spectrum



Measured light:

$$S_m = F_\Omega \epsilon (S_i + Q_i F_r P_{e\rightarrow h\nu})$$

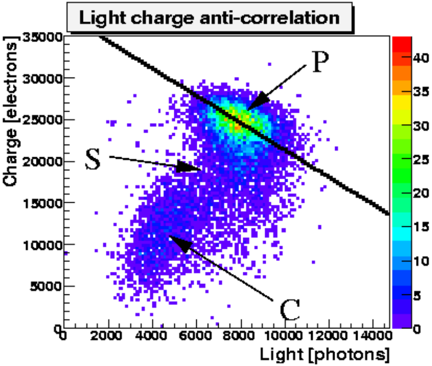
Error contributions:

$$\left(\frac{\Delta S_m}{S_m}\right)^2 = \left(\frac{ENC_s}{MS_m}\right)^2 \quad (4.7\%)$$
$$+ \frac{F(M)}{S_m} \quad (0.6\%)$$
$$+ \left(\frac{\Delta F_\Omega}{F_\Omega}\right)^2 \quad (5.6\%)$$
$$+ \left(\frac{P_{e\rightarrow h\nu} Q_i \Delta F_r}{S_f}\right)^2$$

→ intrinsic light resolution: 5.5%

→ charge-light-fluctuation ΔF_r = (2.5 ± 0.8) %

Light Charge Anti-Correlation



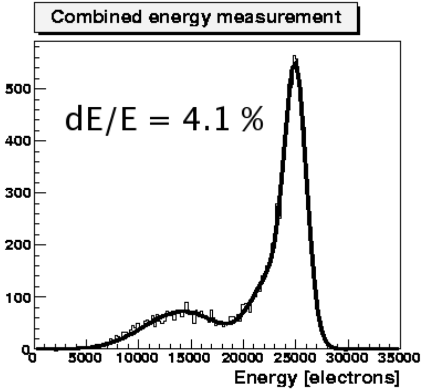
P: photo-electric, C: Compton,
S: scattered outside

Using the anti-correlation to rotate coordinate system so that charge axis is perpendicular to the axis of the ellipse:

$$E_c = \bar{y}\frac{\sin(\theta)x + \cos(\theta)y}{\sin(\theta)\bar{x} + \cos(\theta)\bar{y}}$$

Correlation coefficient: $\rho = -0.26$
Correlation angle: $\theta = 58^\circ$

Combined Energy Spectrum



Combine light and charge to eliminate F_r:

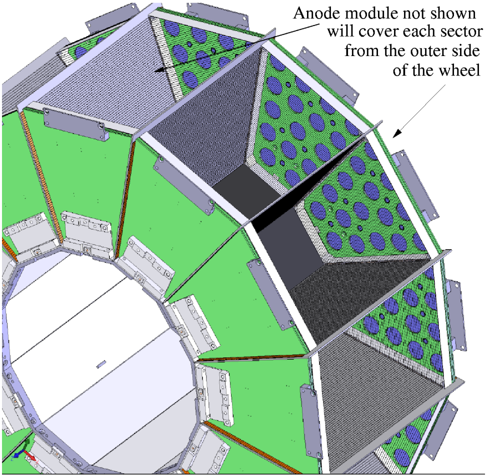
$$E_c = \frac{Q_m}{A} + \frac{S_m}{F_{\Omega\epsilon}} = Q_i + \frac{S_i}{P_{e\to h\nu}}$$

Error contribution: 3.3 %
$\rightarrow$ intrinsic energy resolution: 2.5%

With position information available from charge, expect:

$\rightarrow$ light resolution: 10.4%
$\rightarrow$ combined energy resolution: 3.6% ($<$ 8% FWHM)

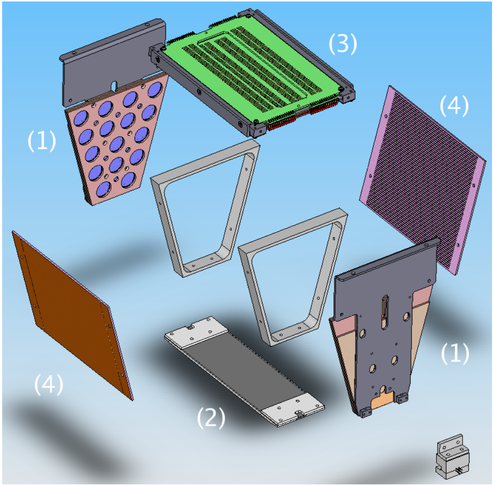
Micro-PET Design



- 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

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



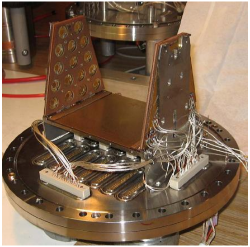
Prototype Status

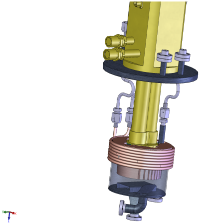
Recent Progress

- Finished test with 16 APDs
- 1st use of liquid purification
- 1st test of pulse tube refrigerator

Problems Solved

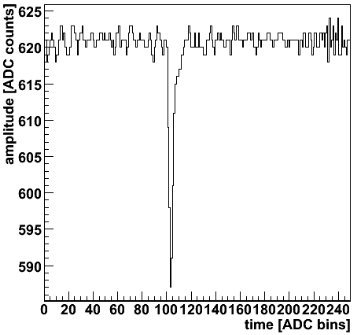
- High voltage issues with APDs in LXe
- APD spring contacts faulty $\longrightarrow$ replaced
- Devised procedure of evacuating, baking and cool down





APD Sector Test (just completed)

APD signals were observed from 511 keV photons from ^{22}Na



Test ended prematurely due to vacuum problem

But:

Signal amplitude lower than expected

Probable Causes

Impurities in LXe like H_2O
$\rightarrow$ Attenuation too high
But: Currently no equipment to measure LXe purity

Possible Solution

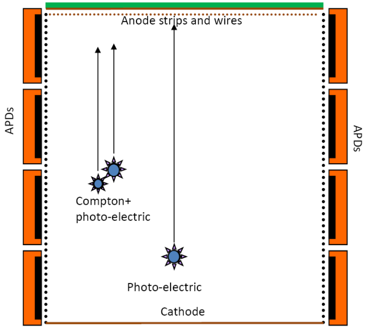
Use gas purifier in addition to liquid phase purifier + longer high temperature bake-out

Outline

High Rate Capability

Limit event pile up at high rates:

- Use fast light signal to pinpoint location of energy deposit to define region of interest (goal within 1 ml).
- Match light with corresponding slow charge signal.
- Benefit: Only region of interest is blind to next event occuring while charge from first event is still drifting.



Neural Networks (NN)

Challenge

- input: 32 APD signals
- looking for 3D position
- multiple interactions producing light

Solution

- Neural Network
- 32 inputs, 3 outputs, one hidden layer with 160 neurons
- implemented in ROOT/C++

Idea:

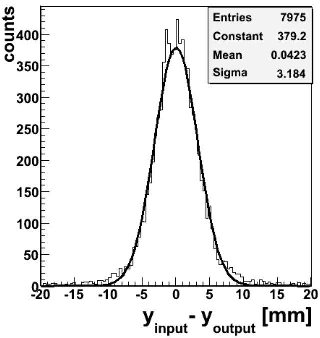
Train NN on solid angle calculation as opposed to realistic Geant4 simulated data

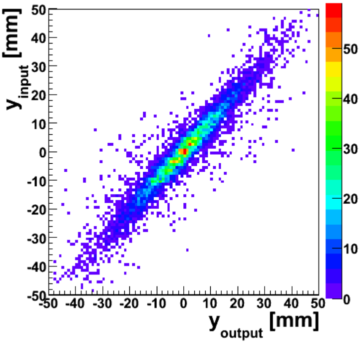
Why:

Much faster (∼min.) and better coverage of chamber possible compared to generating Geant4 data (∼weeks)

Performance of Neural Networks

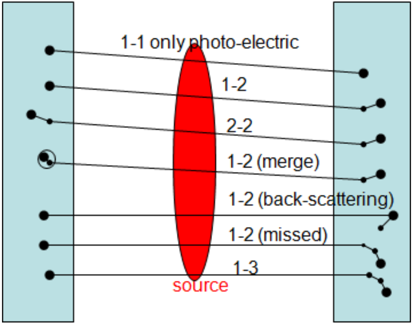
Although training data for NN does not include any fluctuations or multiple interactions the capability to reconstruct the center of gravity for the light emmission works surprisingly well:





Volume in which interaction can be found can be restricted to $\sim$ 1 ml depending on noise

Dealing with Compton Events



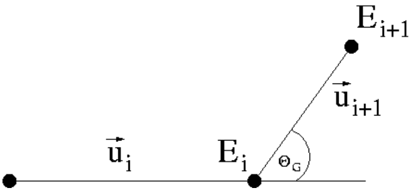
- Task: Identify first point
- Solution: Compton reconstruction algorithm
- Difficulties:
  - Merging of points not separated within resolution capabilities
  - Missing points with energy below threshold
  - Ambiguities in kinematics

Benefit:

Increase statistics of usable events
suppress background events (scatter and random)

Compton Algorithm

Two methods to calculate scattering angle for all possible combinations i:



Geometric:

$$\cos(\theta_G)_i = \frac{\vec{u}_i \cdot \vec{u}_{i+1}}{|\vec{u}_i||\vec{u}_{i+1}|}$$

Kinematic:

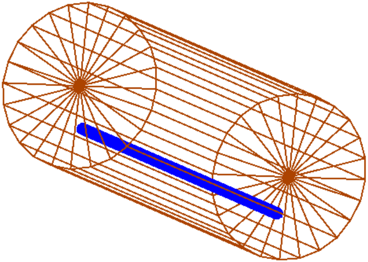
$$\cos(\theta_E)_i = 1 + \frac{m_e c^2}{E_i} - \frac{m_e c^2}{E_{i+1}}$$

Find combination with lowest χ^2:

$$\chi^2 = \sum_{i=2}^{N-1} \frac{(\cos(\theta_E)_i - \cos(\theta_G)_i)^2}{\delta\cos(\theta_E)_i^2 + \delta\cos(\theta_G)_i^2}$$

Compton Reconstruction Evaluation

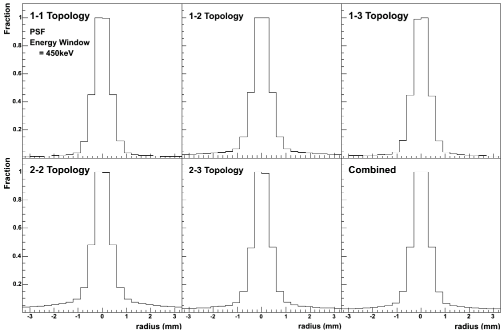
Geant4 simulation of NEMA phantom scaled for mico-PET



- 1-2 and 2-2 have the worst signal to background
  → Some irresolvable ambiguities
- Background mostly due to selecting wrong first point (Random and scatter very much suppressed due to very good energy and time resolution)

Compton Reconstruction Evaluation

Geant4 simulation of NEMA phantom scaled for mico-PET



- 1-2 and 2-2 have the worst signal to background
  → Some irresolvable ambiguities
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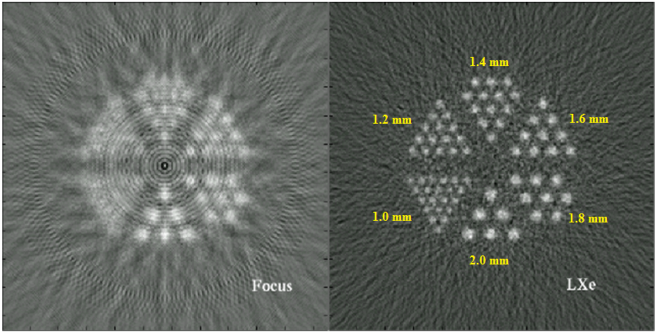
Image Reconstruction from Simulations

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.

Outline

Operating and Testing First Sector Prototype

Now assembling TPC and APDs together
→ operational in Summer 2009

Technical Performance

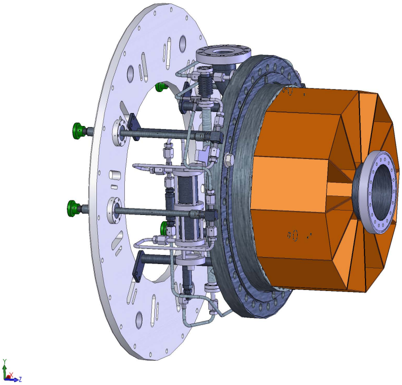
- Purity
- Stability
- Mesh and grid transparency
- APD gain and noise
- Electronics noise
- Crosstalk, etc.

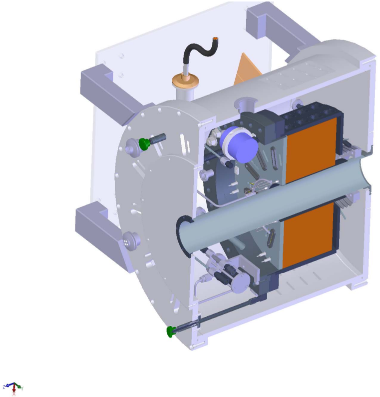
Detector Performance

- Light and charge yield
- Drift velocity
- Position resolution with light and ionization
- Time resolution and rate capability
- Energy resolution with light and ionization

Long Term Plans

CHRP Project: Design of cryostat in progress:





Build two new opposing sectors and operate in coincidence

Outline

Conclusion and Outlook

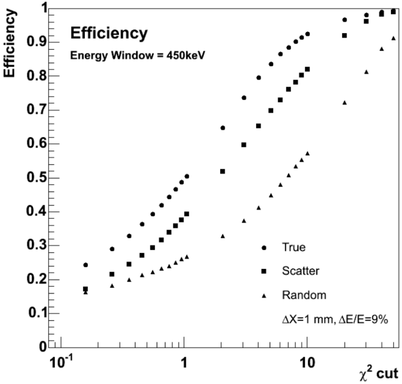
- A small liquid xenon TPC has been shown to give excellent energy resolution ($<$8% FWHM) by combining ionization charge and scintillation light signals observed with avalanche photodiodes.
- We are presently testing a prototype of one sector for a Micro-PET scanner
- Design of full Micro-PET system in progress

Next steps:

- Continue testing of the first sector prototype
- Build two new sector and operate in coincidence for PET measurements within a cryostat designed for a full PET ring

BACKUP

Reconstruction Efficiency



- χ^2 threshold can reduce Random events and improve SN ratio but at the expense of count rate
- Energy threshold on total energy suppresses Scatter events and some Randoms
- Reconstruction efficiency depends on event topology

Scatter Fraction

The intrinsic Scatter Fraction (SF) of the system is defined as the ratio of total Scatter background to total count rate, when measured at low activity where Random rates would be negligible. Numbers are given for the NEMA phantom.

Energy Window [keV]	LXe [%]	Focus[%]
250	31	35
350	23	24
450	20	22

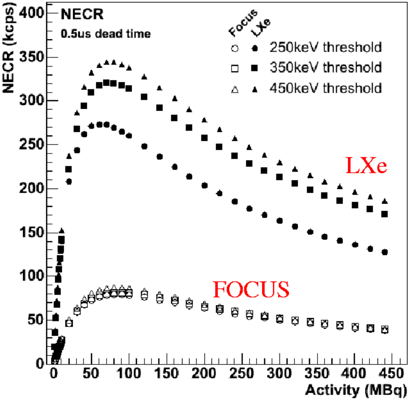
Sensitivity

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 [keV]	LXe [%]	Focus[%]
250	10.2	3.5
350	9.3	3.1
450	8.7	2.6

For the same solid angle profile, the LXePET simulation gives improved sensitivity. 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
- NECR=True^2/Total
- LXe system gives very high NECR.