Development of Liquid Xenon Detectors for PET

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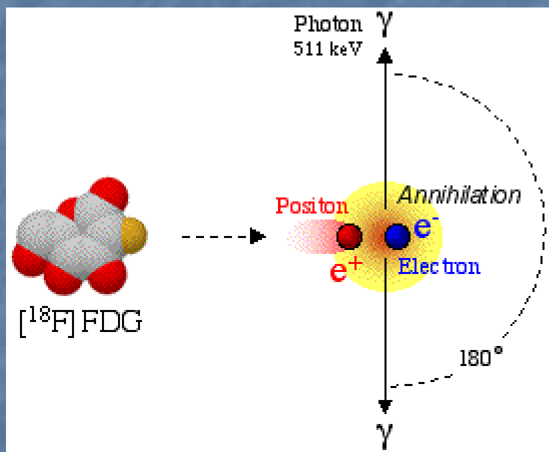
Detecting 511 keV Photons: Scintillation and Ionization Techniques



Desirable properties of scintillation detectors:

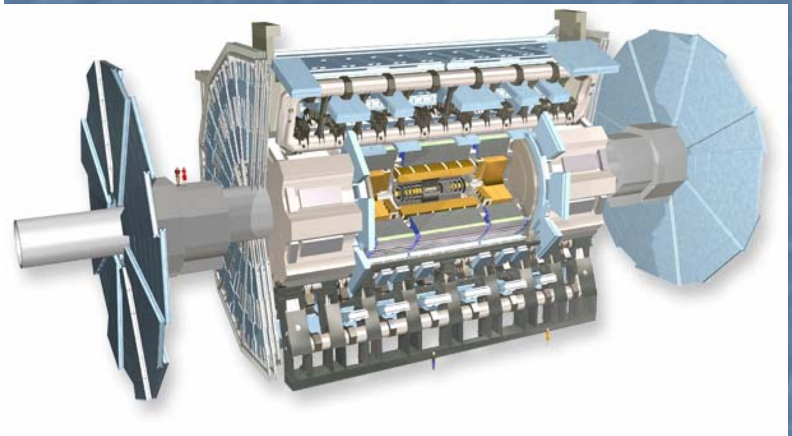
- High light yield (small Fano factor)
- Fast response
- Linearity of response with dE/dx
- Long attenuation length
- Radiation hardness
- High density

Desirable properties of ionization detectors:

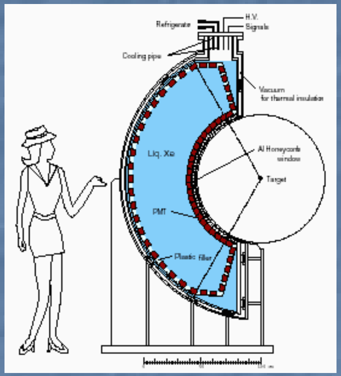
- High ionization yield (small Fano factor)
- Fast drift speed at reasonable HV
- Low diffusion rate
- Linearity of response with dE/dx
- Long drift attenuation length – high purity
- Radiation hardness
- High density

Noble liquid detectors, particularly Xenon , have much of the best of both scintillation and ionization characteristics.

Noble Liquid Detectors

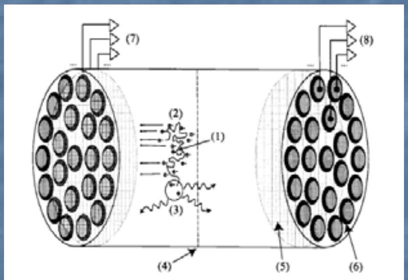


ATLAS at CERN LHC

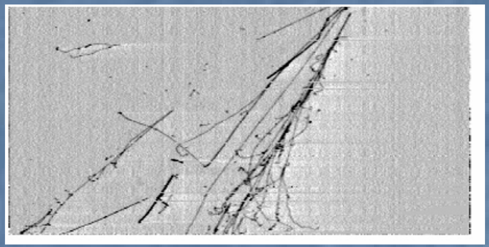


MEG $\mu \rightarrow e\gamma$ at PSI

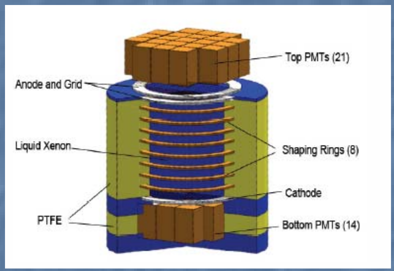
Gamma ray astronomy
LXegrit (Columbia)



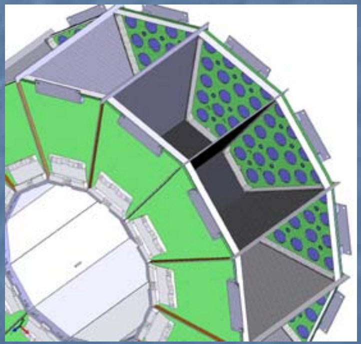
EXO: Neutrinoless
Double Beta Decay



ICARUS Neutrino Detector



XENON dark matter search



XEPET at TRIUMF
for medical imaging

Xe Properties

- Z=54 → High conversion efficiency
- Boiling point 165.1 K → "Easy" cool down
- Density of liquid ~3.0 g/cc, radiation length for γ 511 keV ~3 cm
  → compact detector
- High Voltage Working point ~2 kV/cm → Reasonable HV

- **Ionization** yield W_i = 15.6 eV (High E field) → Large detectable signal!
- Drift velocity: v = 2.5 mm/ms or 4μs/cm. → Fast drift
- Diffusion for 1μs drift 20 μm → Sub-mm position resolution!
- *Purity required* <1ppb (O_2) → Purification is critical

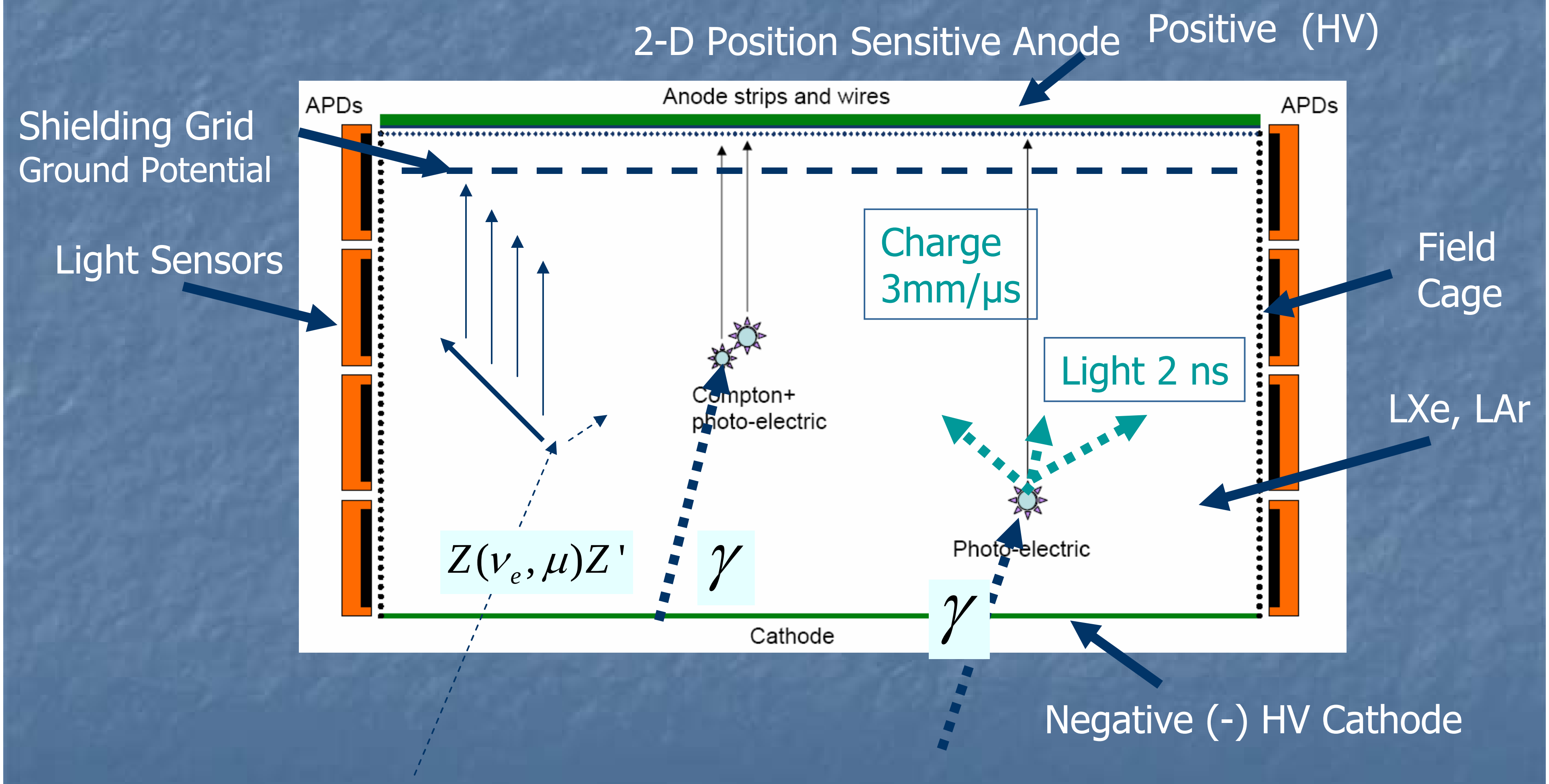
- **Scintillation** at 178 nm → Special photo-detectors
- Photon yield W_s = 14.6 eV (zero E field) → Bright scintillator!
- Timing of excitation: τs=2.2ns; τt=27ns → Sub-ns time resolution!
- Attenuation length >1m → OK

- Available in industrial quantities → reasonable price (~$3/cc)

Comparison with Other Scintillations

Scintillator	BGO	LSO	LXe	NaI(Tl)
Density, g/cc	7.1	7.4	3.1	3.67
Yield, photons/keV	6.4	32	68	40
Decay time, ns	300	40	2.2/27	230
Wavelength, nm	480	420	178	420
Photo-fraction	42%	33%	22%	

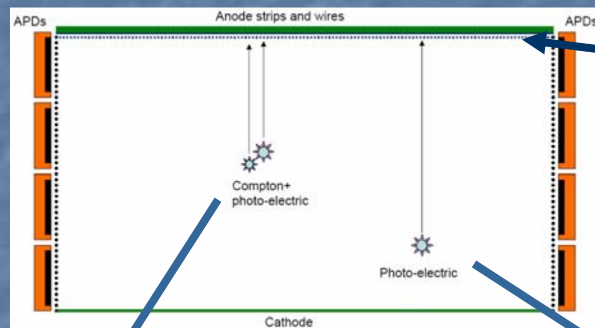
Time Projection Chamber (TPC): 3-D Imaging

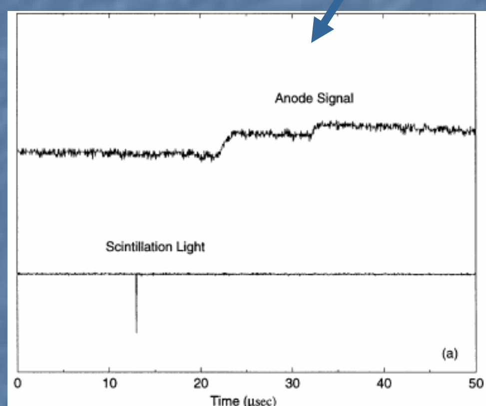


Charge Signal in a Gridded Ionization Chamber: TPC Geometry

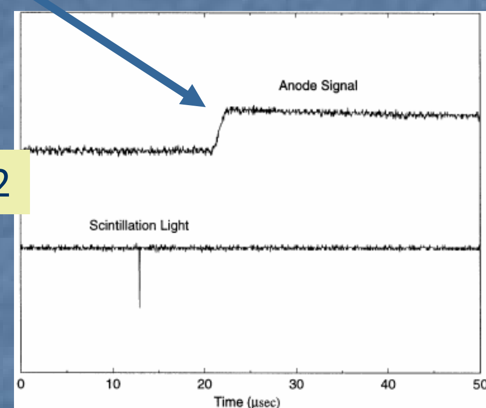
- Grid shields anode from induced charge during drift
- Signal Shape independent of drift length.

GRID





Aprile et al. 2002



Compton Scattering

Photo-absorption

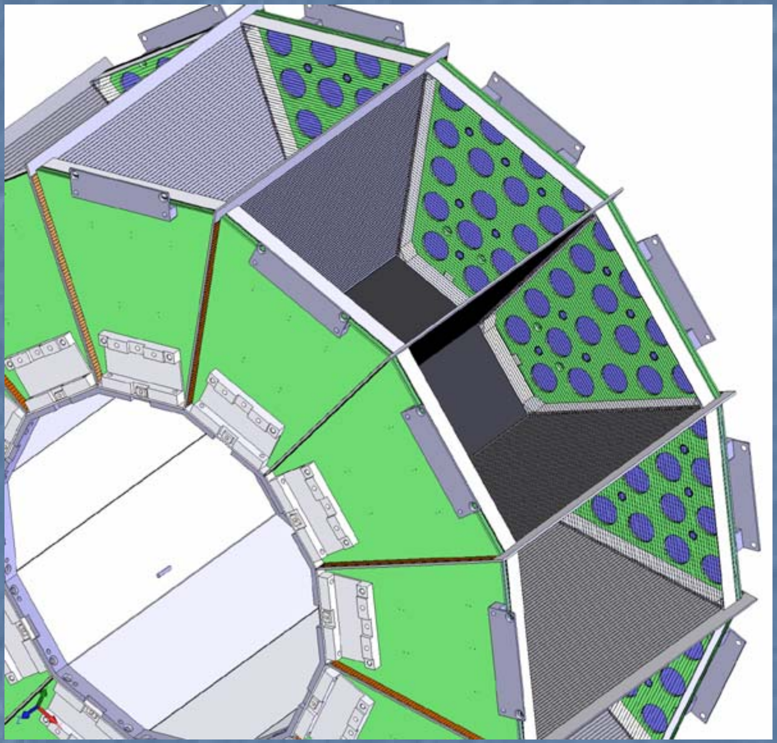
TRIUMF LXe PET

Goal: ***Remove detector performance as a limitation for PET.***

(i.e only physics effects of positron range, non-colinearity.

LXe Pet Properties

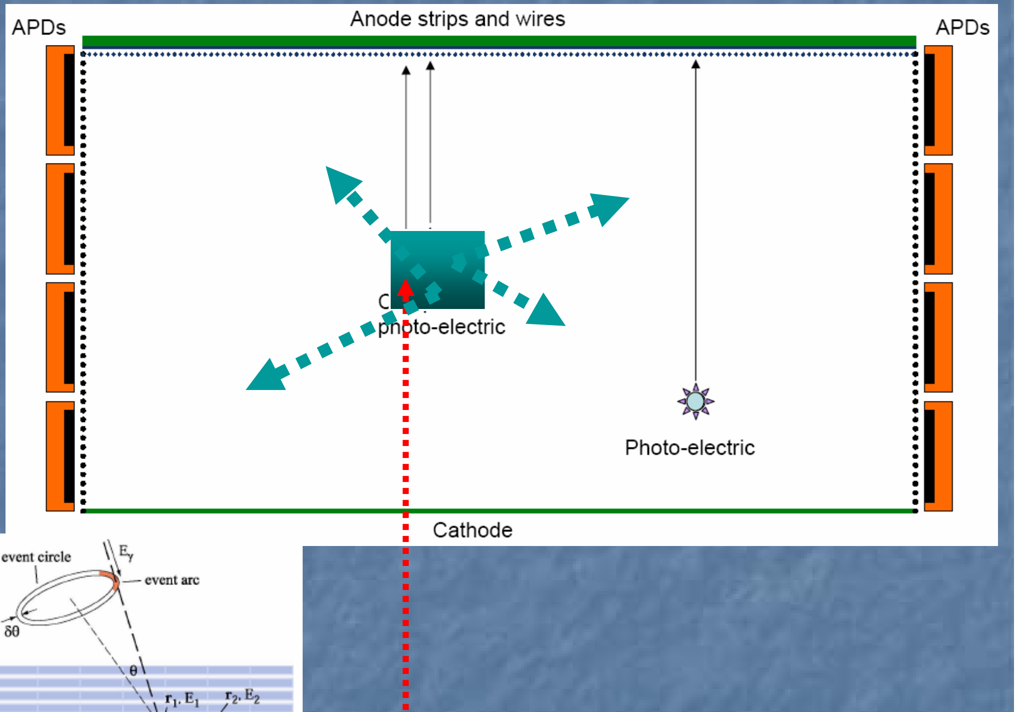
- High spatial resolution along axial and transaxial directions (1 mm)
- Depth of interaction resolution (<1 mm)
- Good time resolution (<1 ns)
- High detection efficiency (>75%)
- Good energy resolution (<10% FWHM)
- High count rate capability (>10^5 /s/cm^2)
- Low cost
- Reduced random and scatter noise using Compton scattering reconstruction

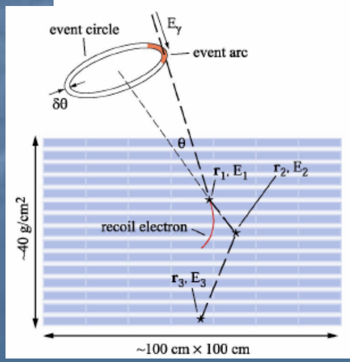


TRIUMF XEPET

Liquid xenon TPC with distributed light collection

- Scintillation and ionization signals both used for position and for energy reconstruction
- Fast light signal gives region of interaction from distribution (minimizes pileup)
- Reconstruct drift coordinate from drift time; other two coordinates from anode electrodes (induction wires perpendicular to anode strips)
- **3-D Spatial resolution: <1 mm** (FWHM) ; **uniform over FOV**
- **Energy resolution: 9% (FWHM)**; suppresses scatter/random image noise
- **Compton reconstruction** further suppresses scatter and random backgrounds.





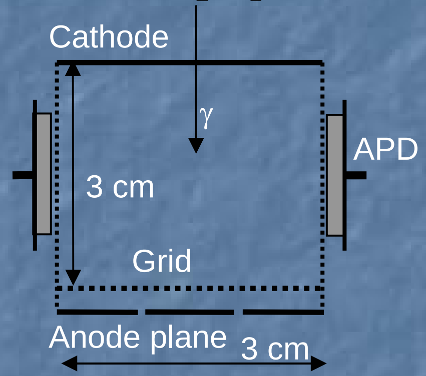
Simulations of Compton Reconstruction (Next Talk by Fabrice Retiere)

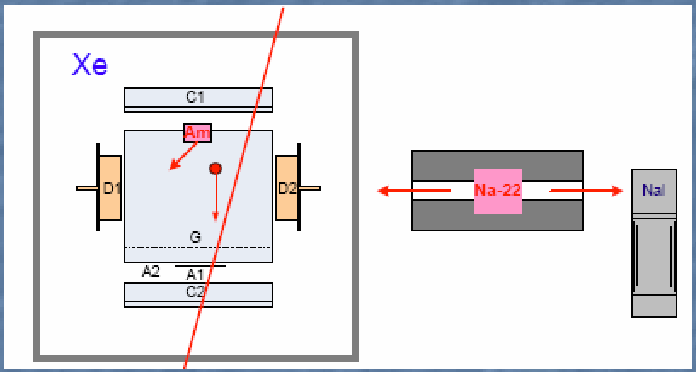
- Simulations of LXe micro-PET with ID = 15cm, OD = 39cm, 12cm LXe
- Positron range included. Non-colinearity not included
- Dead material: SS 1mm
- Assumitions: ΔE = 9% and ΔX = 1mm (FWHM), dead time 500ns
- Compton events: first interaction point determined by using E-Θ correlations

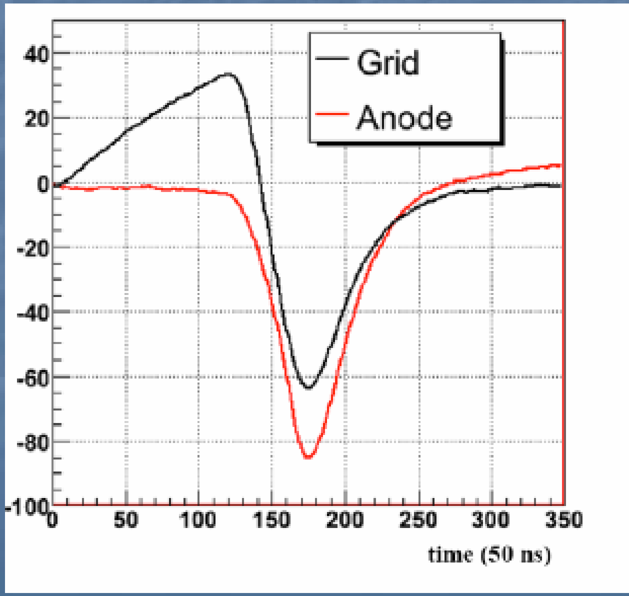
  - Absolute sensitivity 12%
  - Background suppression
  - Excellent Image quality

Small Scale Prototype

- TPC 3x3x3 cm,
- Grid: 3 mm spacing, gap 3 mm
- 2 APDs, Total solid angle ~ 10%
- 2 Anodes: Central disc dia. 10 mm
- Tests with Na22

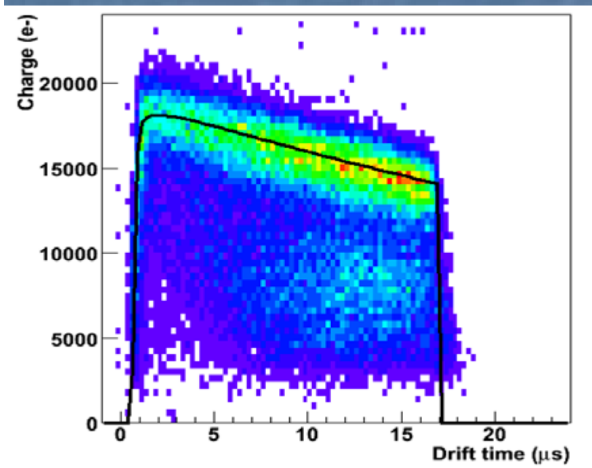




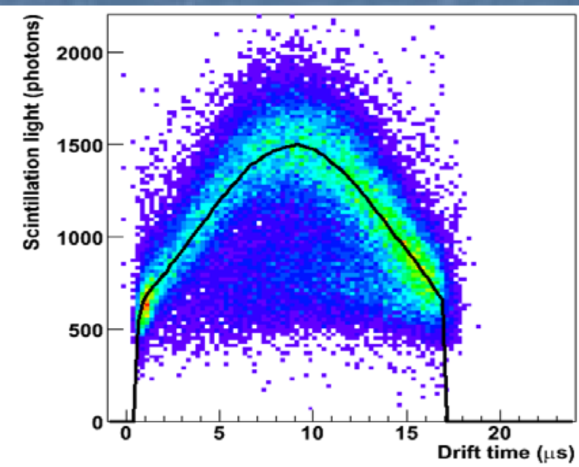


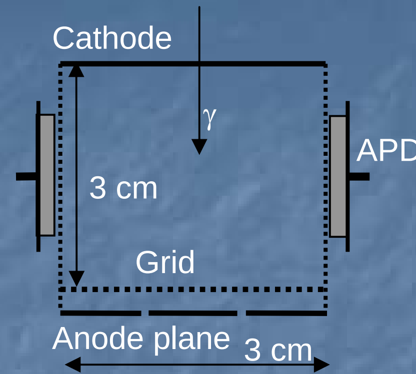
TPC Prototype Tests

Charge *vs.* Drift Time

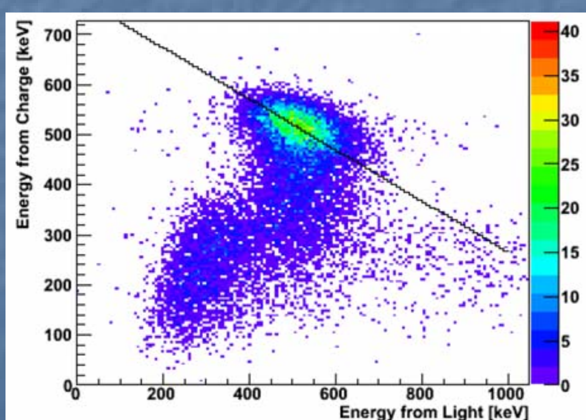


Light *vs.* Drift Time

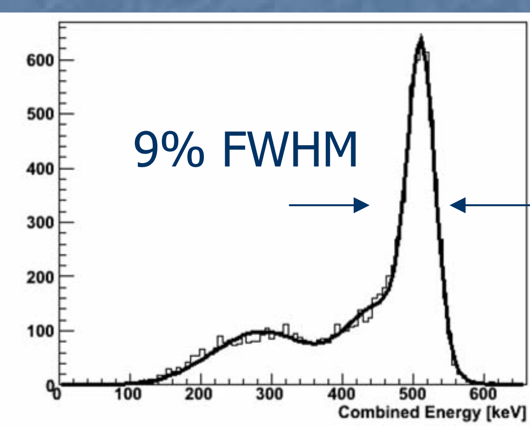




Charge *vs.* Light



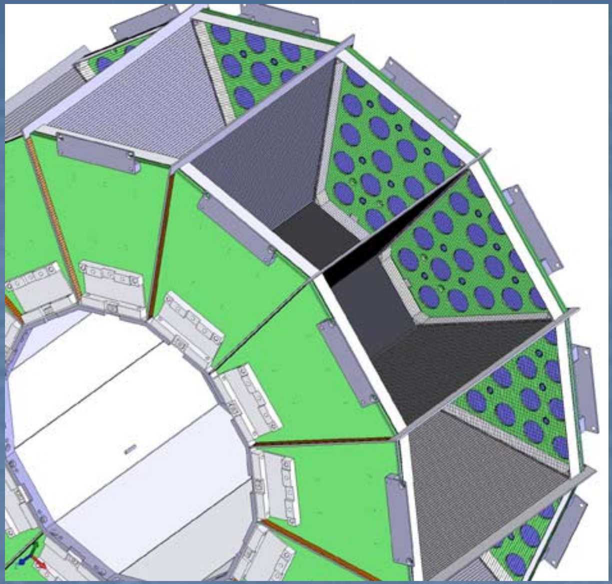
511 keV Energy

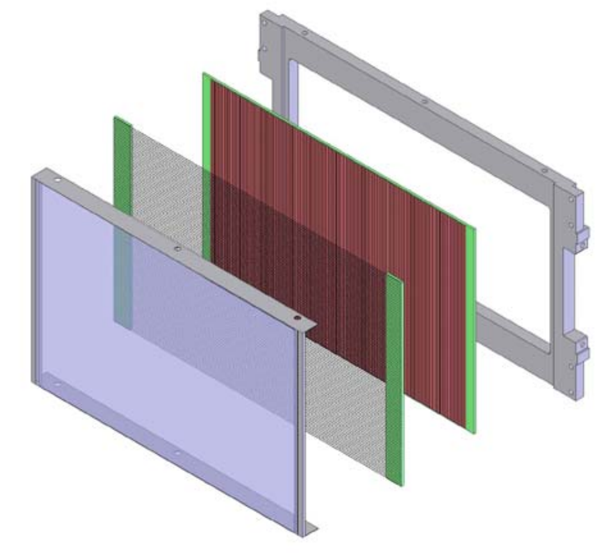


- Electrons lifetime > 100 μs, purity < 10 ppb
- Light resolution (rms) 12.7%
- Charge resolution (rms) 5.5%
- Light and charge (rms) 3.8%

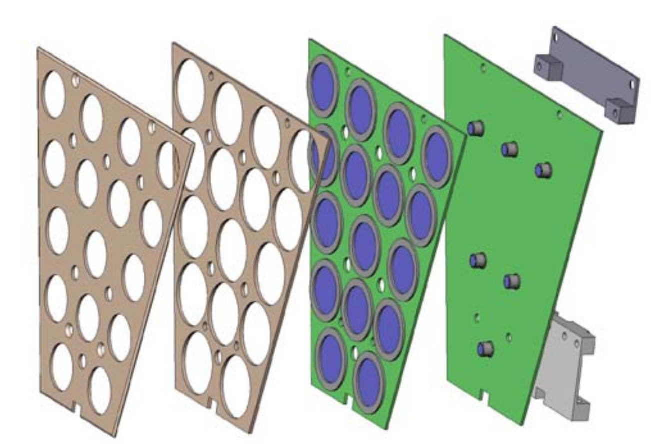
LXPET Design

- 12 sectors.
  - Field cage formed with strips (between sectors) and wires (ends)
  - Cathode: resistive kapton on ceramic plates





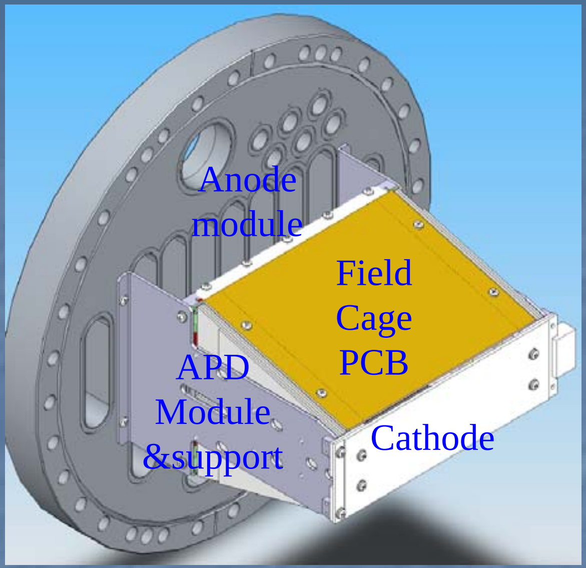
- Anode module
  - 96 wires, 96 strips
  - SS and kapton PCBs
  - AC decoupling with kapton?



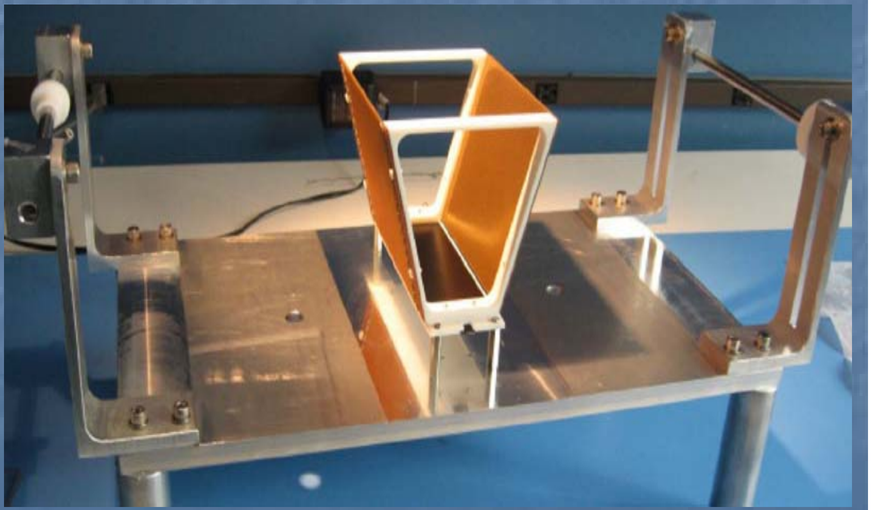
- APD modules (5% solid angle)
  - 16 APDs and 6 LEDs for monitoring
  - 1 HV line and 16 LV lines (HV tuning)

Single Sector Test Status

- Full-scale sector
  - ✓ Fits into existing cryostat
  - ✓ Designed, parts built
  - ✓ Assembly is going on
- Cryogenics and controls
  - ✓ More cooling power
  - ✓ Better purification

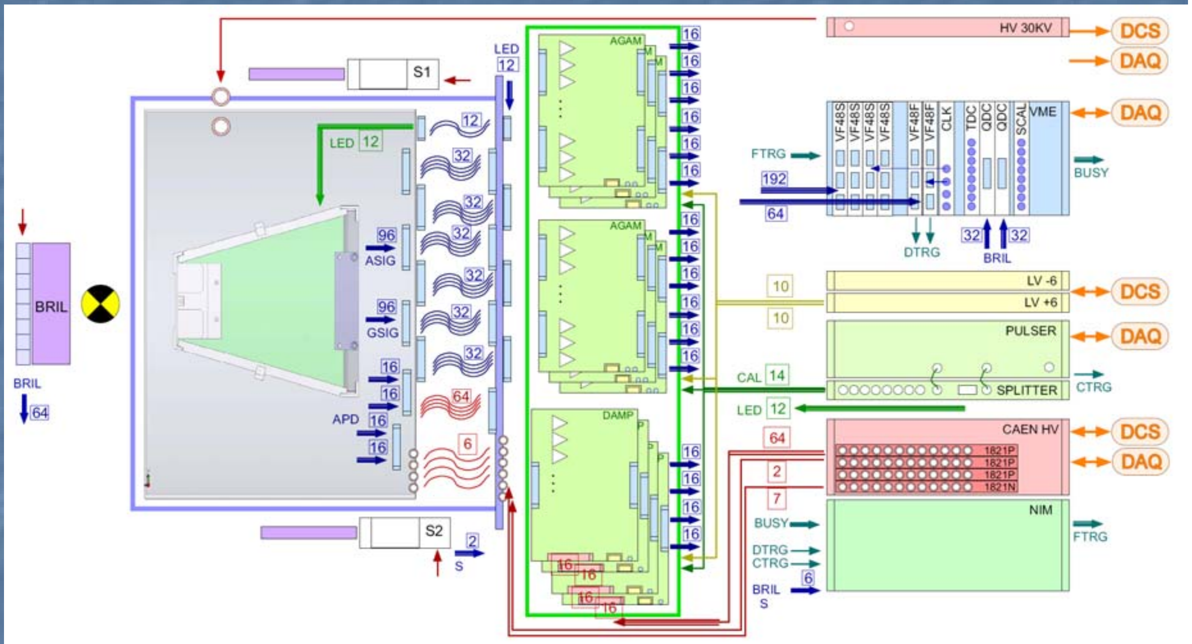


- FE and RO electronics prepared
- Assembly is nearly complete
- DAQ and monitoring are nearly complete
- First cool-down in progress (with APDs and cables, no field cage)
- Final Assembly in May
- Tests in June-December (could continue in 2009)



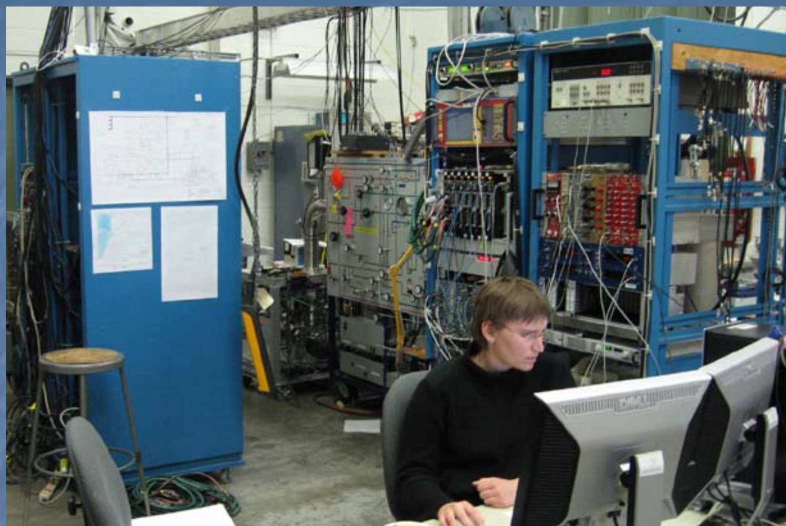
Single Sector Test Plans

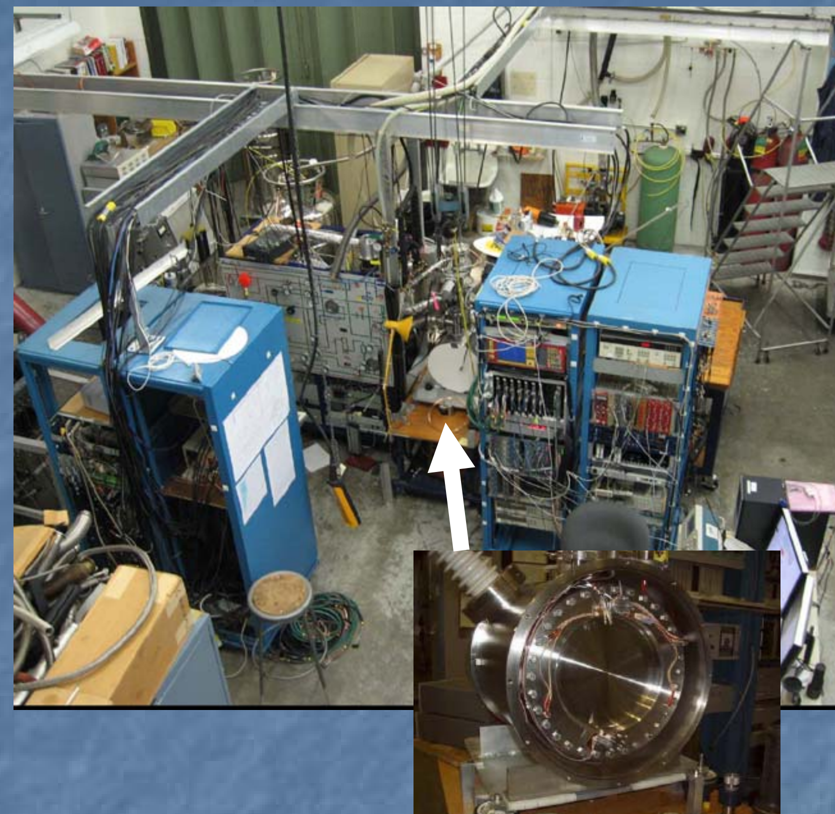
- Technical studies
  - Xe purity, stability
  - Mesh and grid transparency
  - APD gain and noise
  - Electronics noise, Xtalk, etc.
- Basic Xe characteristics
  - Light yield
  - Charge yield
  - Drift velocity
- Detector performance
  - Position resolution with APDs and with ionization signals
  - Time resolution and rate capability
  - Energy resolution with APDs and with ionization signals
  - Uniformity, dead area



- 1 month of technical studies, 1 month of HV curves and 3 month of data taking
- 20TB of raw data, to be stored: 3-4TB

Lab Setup





- Light detection
  - Fast and low noise for Cd = 200 pF
    - Signal ~ 20,000 electrons
  - BJT gives 4000 e- ENC for 20 ns peaking time
  - Working 16 channel prototype

- Ionization signal
  - Low noise, rather slow for Cd = 30 pF
  - JFET gives 600 e- ENC for 270 ns shaping time
  - 32 channel prototype being tested

Long Term Plans

Double-sector test

- Iteration of sector design (alternative photosensors, anode/grid geometry, gap width, field cage, reflections, etc.)
- Cryogenics developments: new cryostat, custom feedthroughs, purification system, cooling, controls HW and SW
- Electronics developments: FE redesign (look at new technologies like SiGe), fast (200MHz 12bit) digitizers for APDs (or PMTs) with trigger capabilities and fast data transfer, readout driver for data collection and pre-processing, fast trigger processor, calibration system

Further Simulations for PET optimization (number of sectors, dimensions)

Build a Full PET scanner

Summary

- Liquid xenon is a promising technology for PET
- Limitations may be reduced to physics effects (positron range, non-colinearity) rather than detector performance
- R&D to establish proof-of-principle is proceeding.
- Application of LXe techniques to SPECT, radiography may also be feasible.

Thanks to LXe PET Participants

- *BCCA: F. Benard*
- *TRIUMF: P.Amaudruz, R. Bula, M. Constable, F.Retiere, L. Kurchaninov, C. Lim, C. Marshall, A.Muennich, T.Ruth*
- *UBC: D.Bryman, P.Lu, V.Sossi, J.Stoessl*
- *U. Montreal: J.-P. Martin*