Liquid Xenon Detector for Medical Imaging

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- ❑ Scintillations
- ❑ Scintillators comparison
- ❑ Ionization in Xe
- ❑ Energy resolution
- ❑ Xe detectors in physics

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Xe Properties

- Z=54, A=131.3. Isotopes: 8 stable and 2 unstable. Main: 129, 131, 132
- Boiling point 165.1 K, melting point 161.4 K. Density of liquid ~3.1 g/cc
- Ratio liquid/gas 518

- Dielectric constant (f=0) 1.96. Refractive index (VUV) 1.57-1.75
- Breakdown voltage ~1000 kV/cm (???)

- Ionization potential 9.2 eV, Ionization yield Wi = 15.6 eV (next slides)
- Radiation length 2.9 cm
- Scintillation energy 7 eV (178 nm), yield Ws=14.6 eV (next slides)

Cost ~ 3$/cc (liquid equivalent)

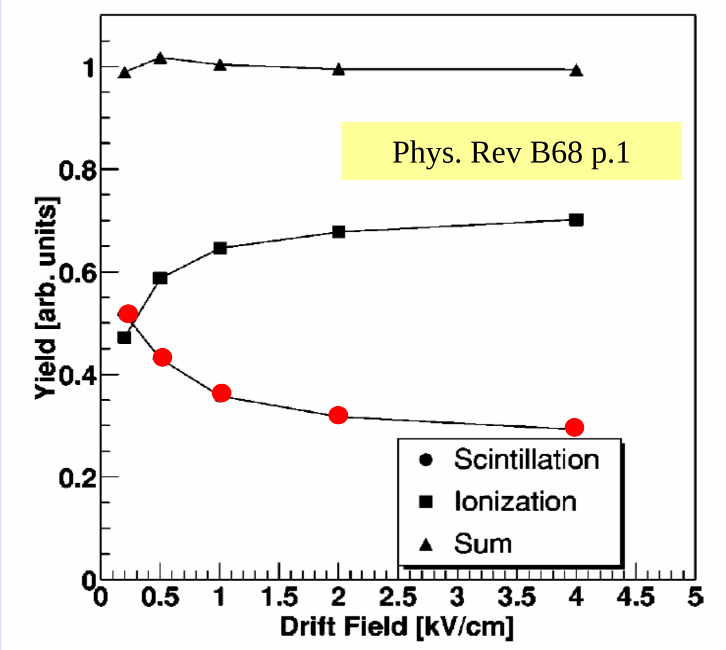
Scintillations

- Two mechanisms: primary excitation and recombination

$$R^* + R \to R_2^* \to 2R + h\nu$$

or

$$R^+ + R \to R_2^+,$$
$$R_2^+ + e^- \to R^{**} + R,$$
$$R^{**} \to R^* + \text{heat},$$
$$R^* + R \to R_2^* \to 2R + h\nu$$



- Scintillation yield depends on HV

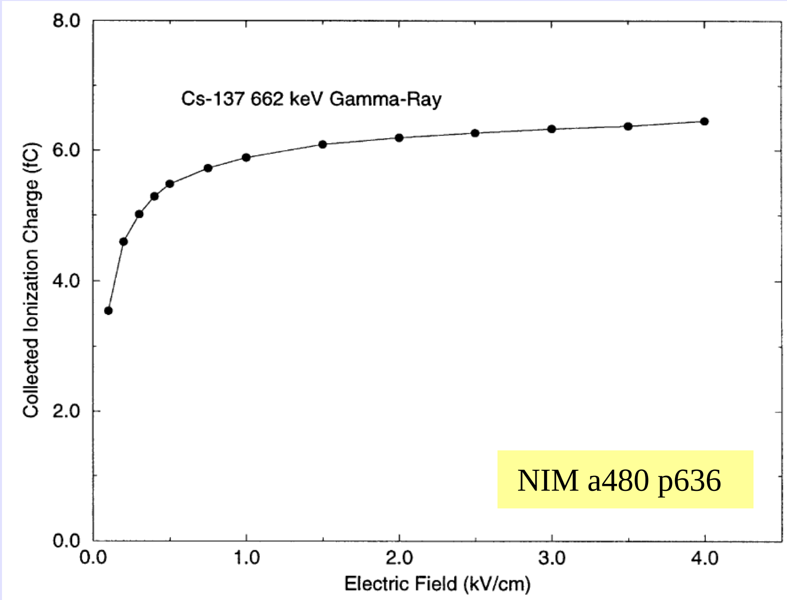
- VUV: λ = 175-178 nm; W=14.6 eV/ph
- Timing of excitation: τ1=2.2ns; τ1=27ns, τ3=45ns
- Attenuation length = 26-36 cm (absorption or Rayleigh?)
- IR: λ = 1000-1600 nm. W=~48 eV/ph

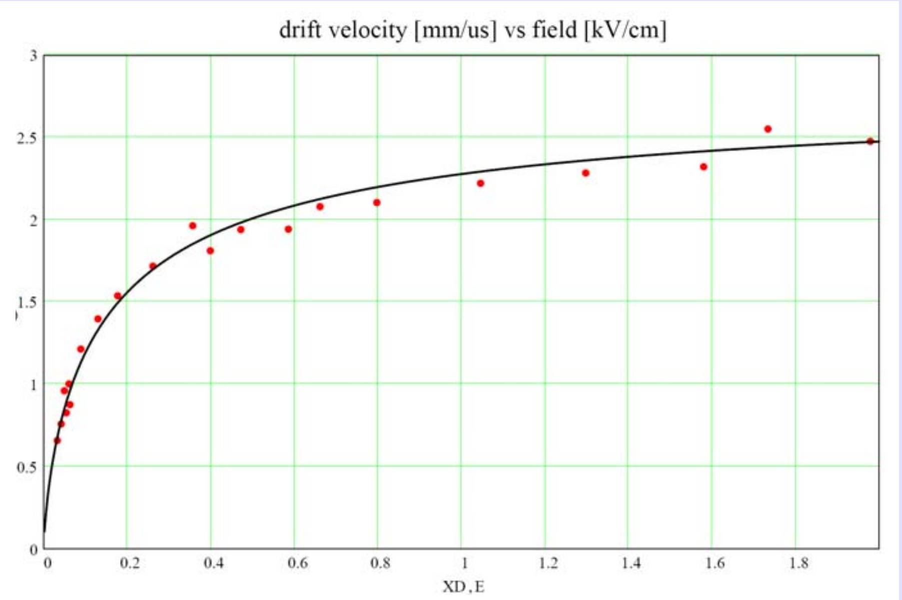
Comparison with Other Scintillations

Scintillator	BGO	LSO	LXe
Density, g/cc	7.1	7.4	3.1
Yield, photons/keV	6.4	32	68 (20)
Decay time, ns	300	40	2.2/27
Wavelength, nm	480	420	178
Photo-fraction	42%	33%	22%

Ionization in Xe

- Asymptotic high-E yield: 15.6 eV/pair → 32.8 kel for 511 keV
- Primary recombination at 2 kV/cm: ~5%
- Drift at 2 kV/cm: 2.5 mm/μs or 4μs/cm. Diffusion ~2 cm^2/s → 1μs drift gives diffusion of ~14 μm
- Purity: with 1ppb → e lifetime ~1 ms

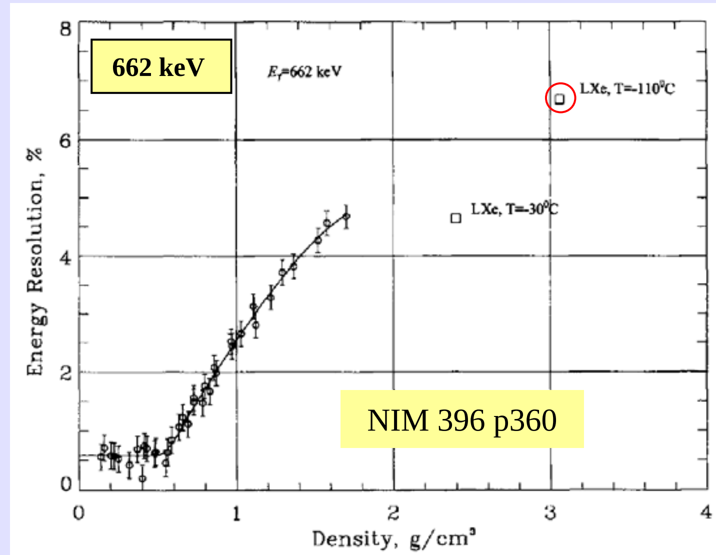


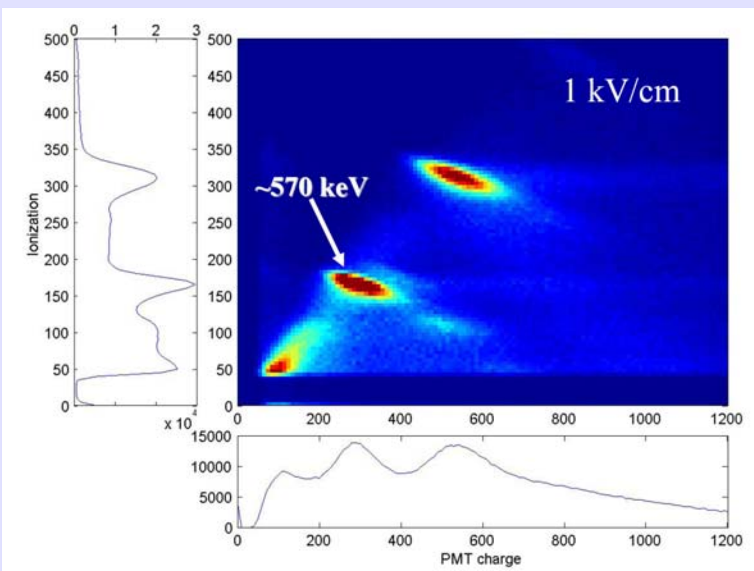


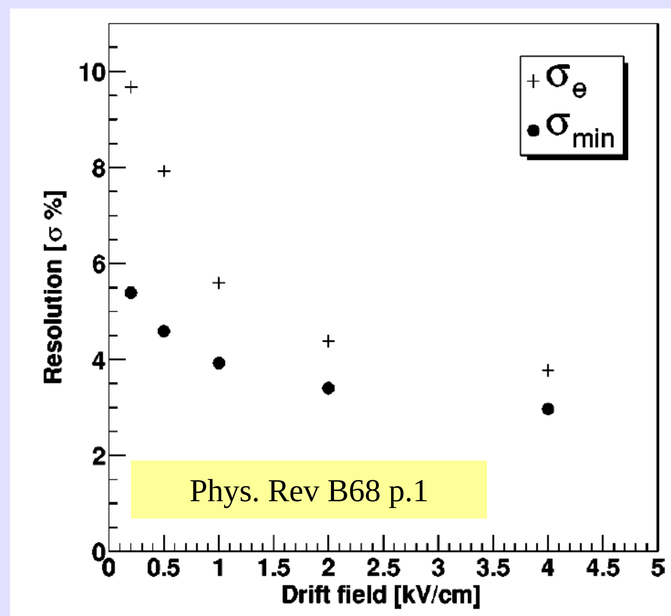
➢ Working bias ~ 2 kV/cm

Energy Resolution

- Ionization: much worse than Fano limit.
  F = 0.2 → fwhm = 0.51% for 662 keV
- No simple theory. Density fluctuations?
- Light: PE statistics. For 511 keV and QE·SA=5%, ΔE = 4.4%
- Correlations improve E-resolution







Xe Detectors in Experimental Physics

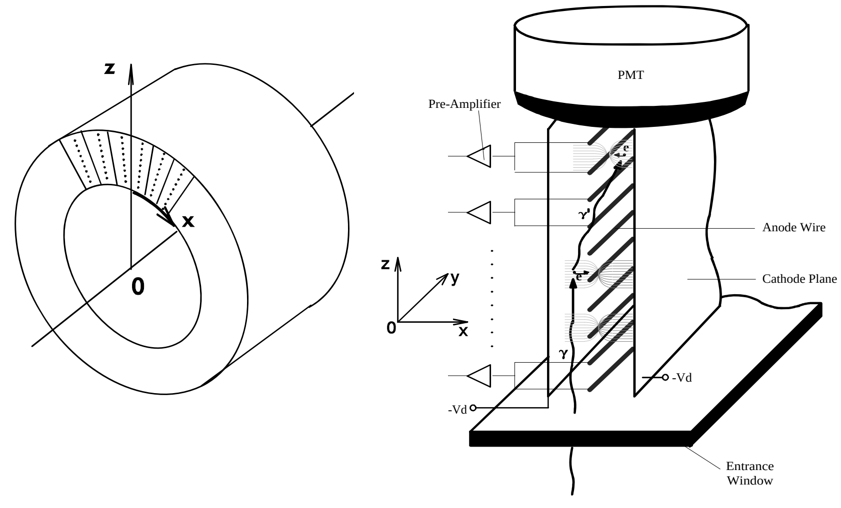
- Dark matter:
  - DAMA (Italy), XENON (Nevis), ZEPLIN
- Double-β decay:
  - EXO (Stanford)
- Astronomy:
  - GRIT, XENA (Nevis-Lab)
- Nuclear physics:
  - RD14 (CERN), MEG (PSI), RAPID (Italy)
- Medical imaging:
  - LPSC (Grenoble), LIP (Portugal)

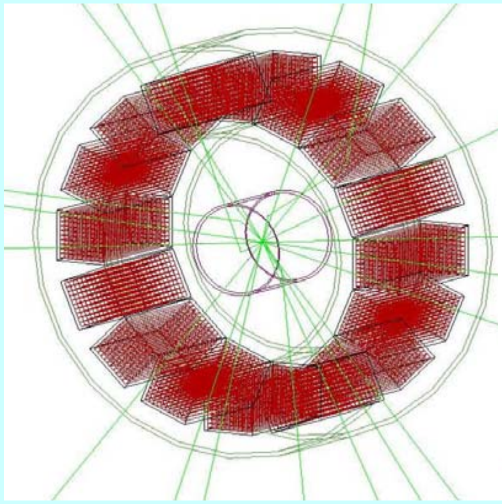
LXe Detectors for PET

Requirements (NIM A353 p189)

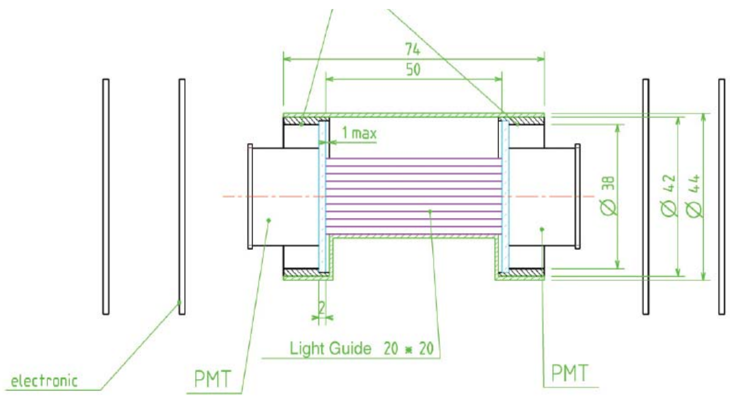
- High spatial resolution along axial and trans-axial directions (~1 mm)
- Depth of interaction ~5 mm
- Good time resolution (~1 ns)
- Energy resolution (<20%)
- High detection efficiency (>70%)
- High counting rate ($>10^5$ /s·cm^2)
- Low cost

- LIP: scintillations and ionizations





- Grenoble: only scintillations

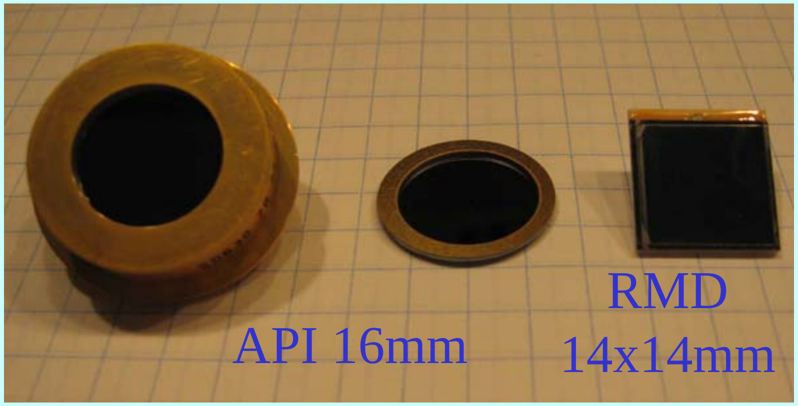


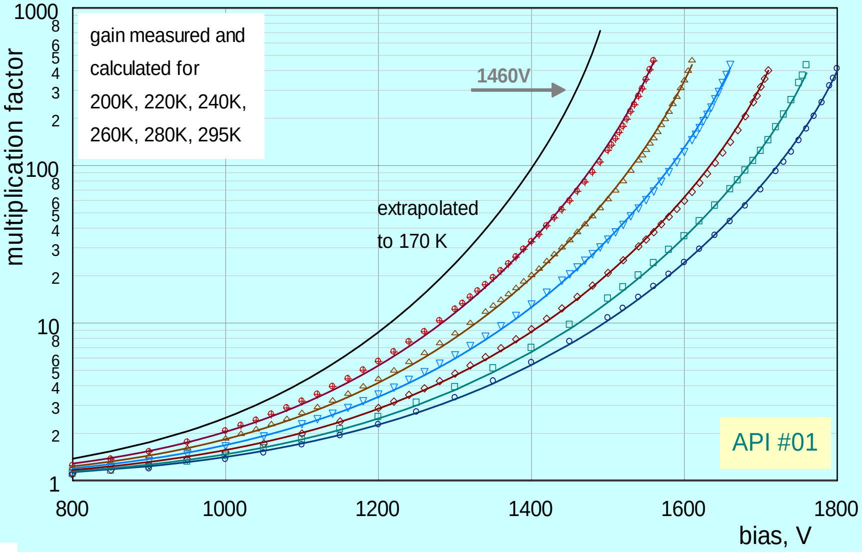
LXe Detector for PET: Our Solution

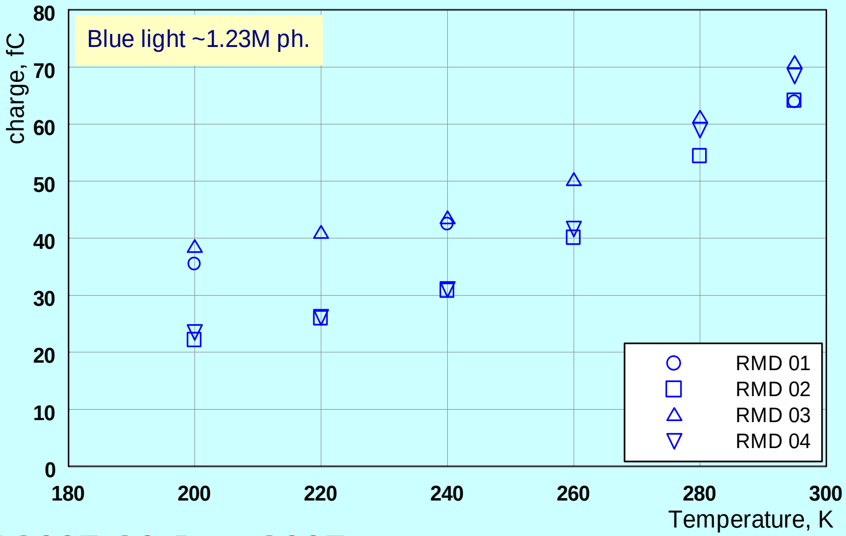
- Use both scintillation light and ionization signals for energy reconstruction
- Trigger from scintillations
- Predict region of interaction from light (to minimize pileup and readout channels)
- Reconstruct one of coordinates from drift time (less channels)
- Other two coordinates with anode electrodes (strips with perpendicular orientation or strip and wires)
- Minimize induction gap (fast induced signals)
- Digitize shapes to get better timing and reject pileup

Light Detection: APDs

- PMT: low QE, not compact. Alternative: APD
- Si works at low T and has QE~1 for UV light. Intrinsically it is fast (few ns)
- Large area high-gain APDs are available. API and RMD
- RMD diodes have worse QE at low T. Window-less option is under tests

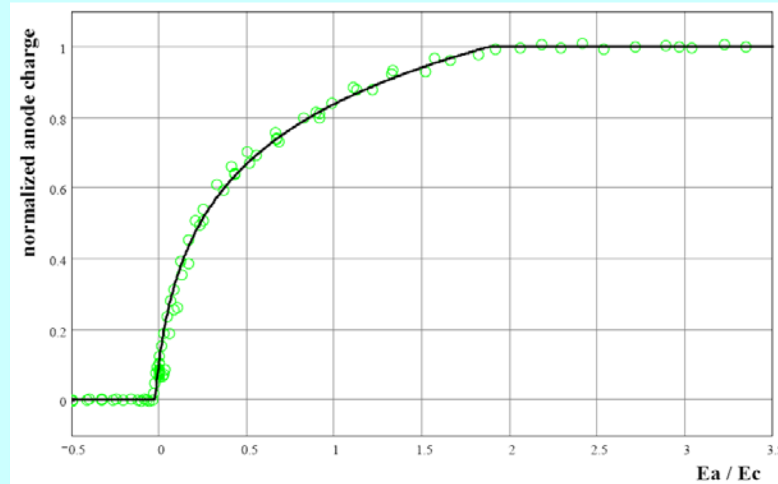




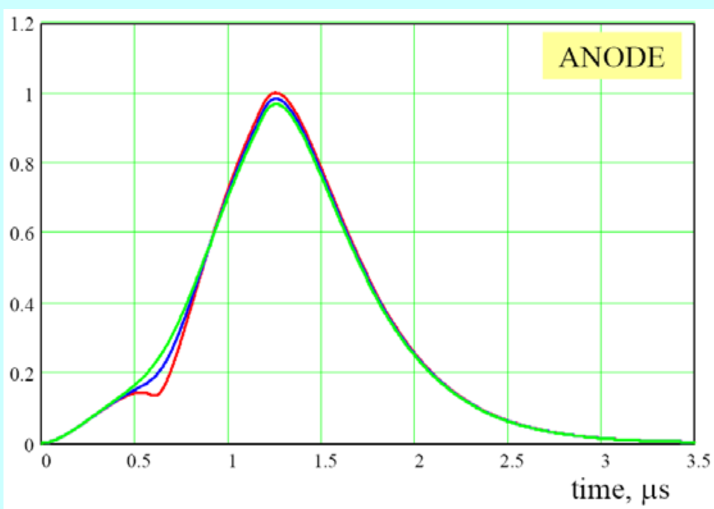


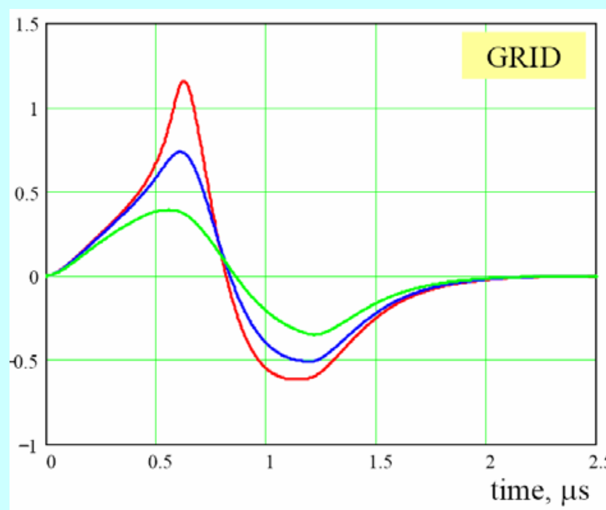
Charge Measurements

- Configuration: anode strips (pitch ~1.2 mm), wires (spacing ~1.4mm), mesh for shielding from drift region. Gaps ~1mm
- Mesh (SS, cell 500µm, wire 30µm). Transparency measured with gas ionization chamber. 100% transparent with field ratio > 1.9



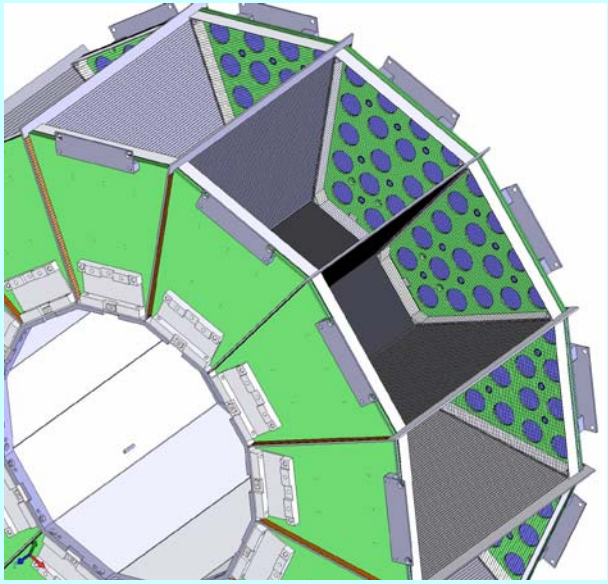
- Induced currents calculated with FEM. Electronics is optimized for S/N

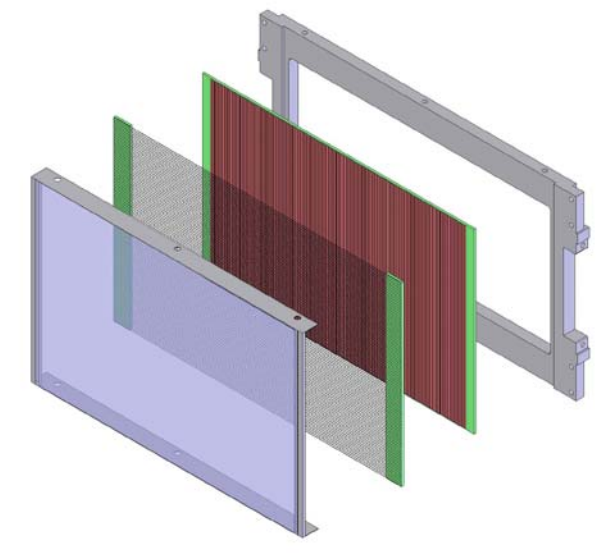




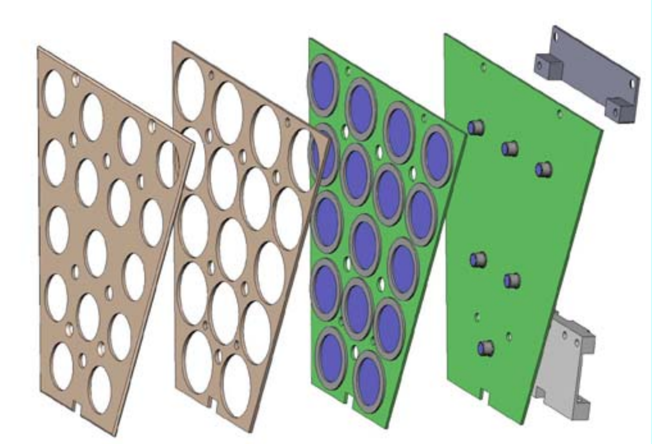
Full-Scale Prototype

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



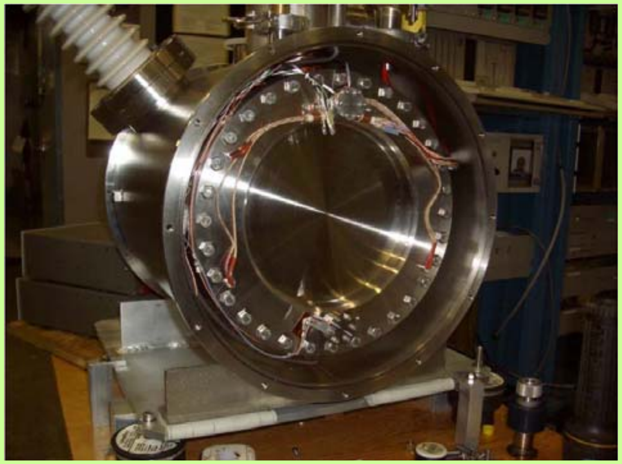


- Anode module
  - 96 wires, 96 strips
  - SS and kapton PCBs
  - AC decoupling with kapton?

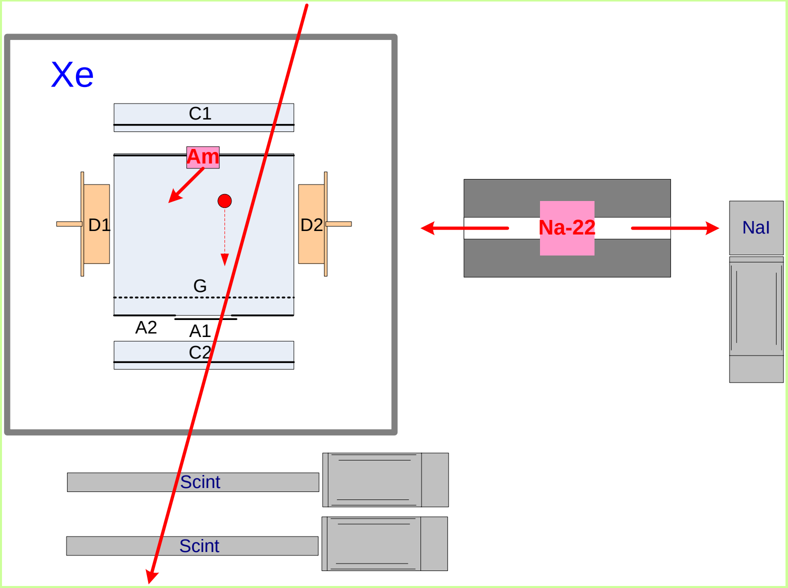


- APD module
  - 16 APDs and 6 LEDs for monitoring
  - 1 HV line and 16 LV lines (HV tuning)

Small TPC Tests



- Run May-August 2006
  - 8.5-l cryostat, small TPC 3x3x3 cm
  - 2 anodes, grid 3 mm gap and 3 mm wire spacing. 2 16mm APDs
  - Both QDC and digitizers
- Measured
  - Na-22 γ 511keV coincidence with external NaI and 1275 keV
  - Cosmic muons
  - Alpha signals
  - Anode and cathode HV curves,
  - APD bias
  - Stability, …



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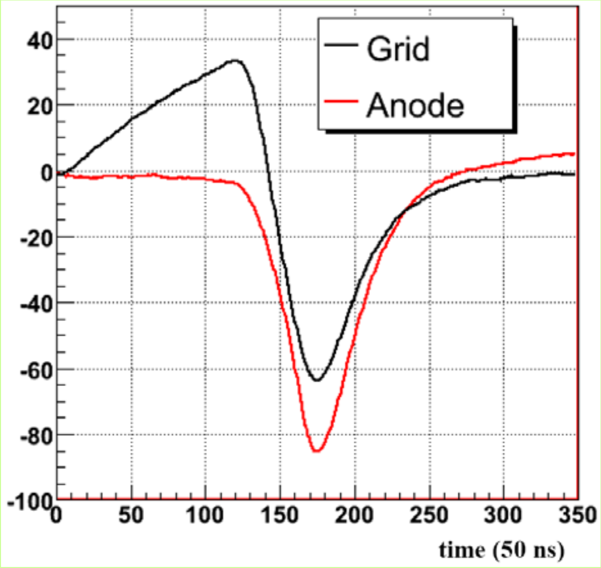
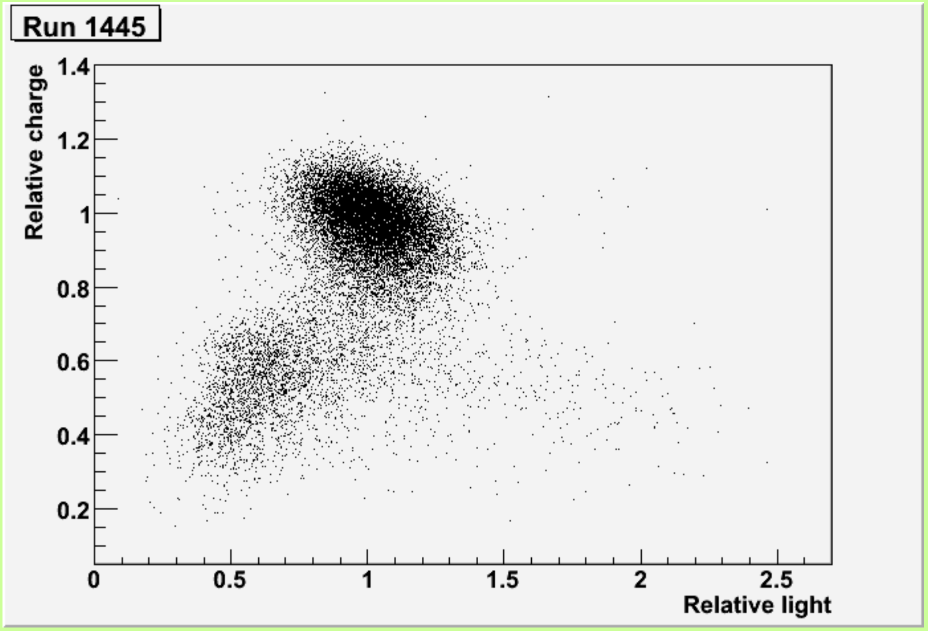
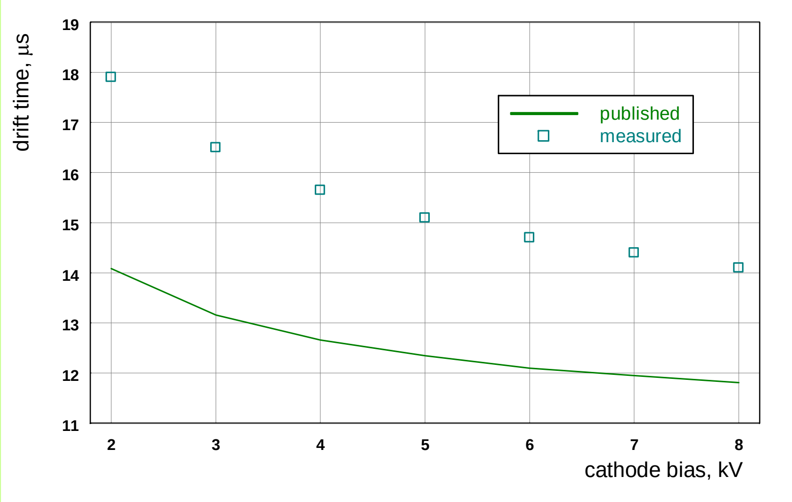
Results from Small TPC

- Analysis in progress
- Purity looks OK
- Ionization signal shapes are reasonable
- Charge-light anti-correlations are seen
- Energy resolution (RMS):

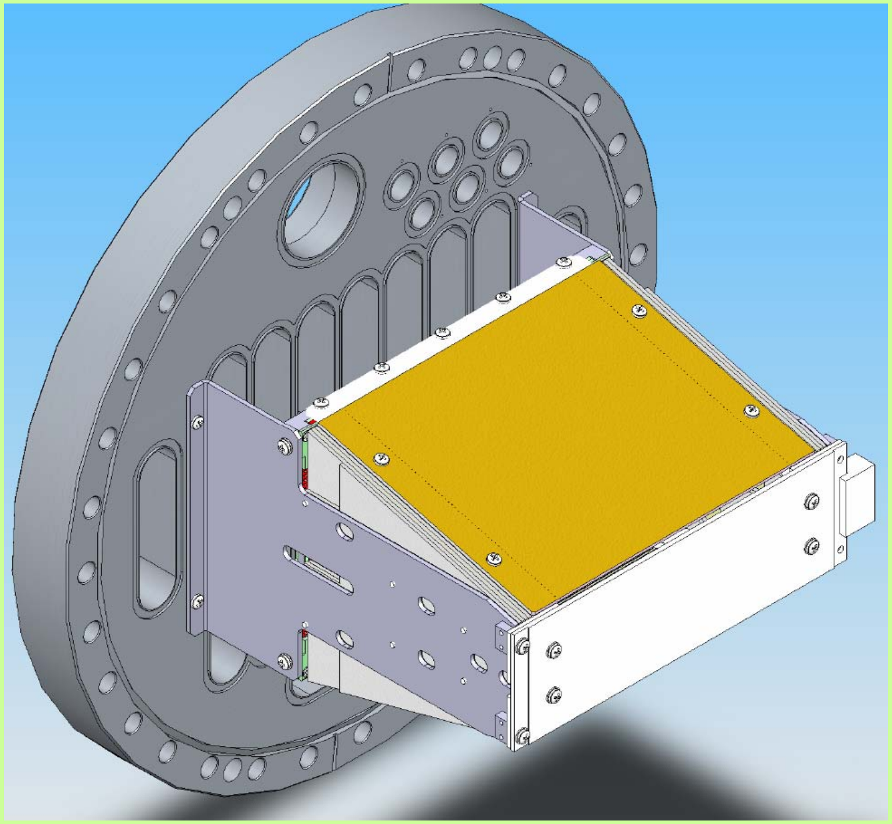
  S-12.6%, Q-6.3%, Sum-4.7%







R&D Program



- 2007: Sector prototype
  - Fits to existing cryostat
  - 96 anode strips, 96 grid wires
  - 32 APDs in ends (plus 32 APDs at sides in second prototype)
- 2008: Two sectors
  - mPET cryostat
  - Final design of sectors
  - Final electronics and readout
- 2009: PET prototype
  - Fully (half) populated
  - Computing: data farm
  - Develop off-line and image reconstruction SW

Summary

- LXe is a very promising technology for PET and other applications
- Still requires extended R&D to design and build detector

- Supported by CFI-UBC-BCKDF and TRIUMF Tech Transfer Division and Science Division

- Group:

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