L. Kurchaninov

Liquid Xenon Detector for Medical Imaging

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- Full-scale prototype

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- Summary

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

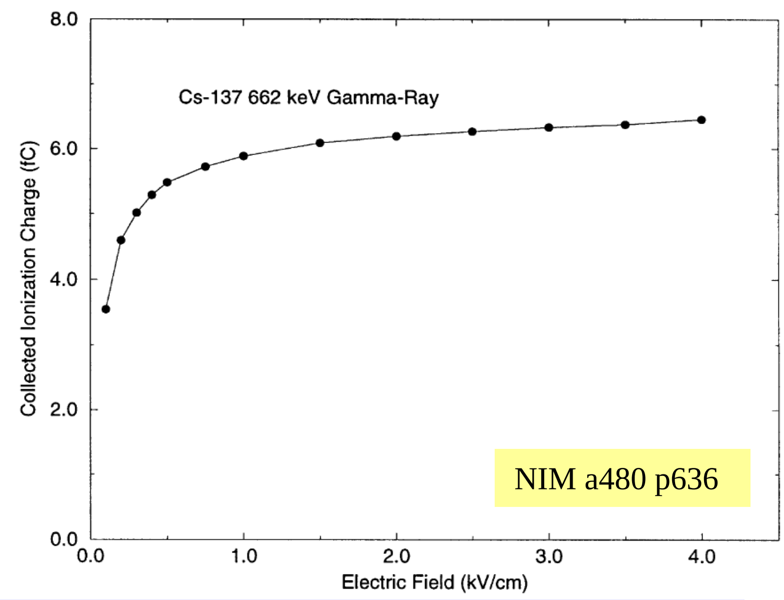
- ☐ Dielectric constant (f=0) 1.96. Refractive index (VUV) 1.57-1.75
- ☐ Breakdown voltage ~1000 kV/cm (???)

- ☐ 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)

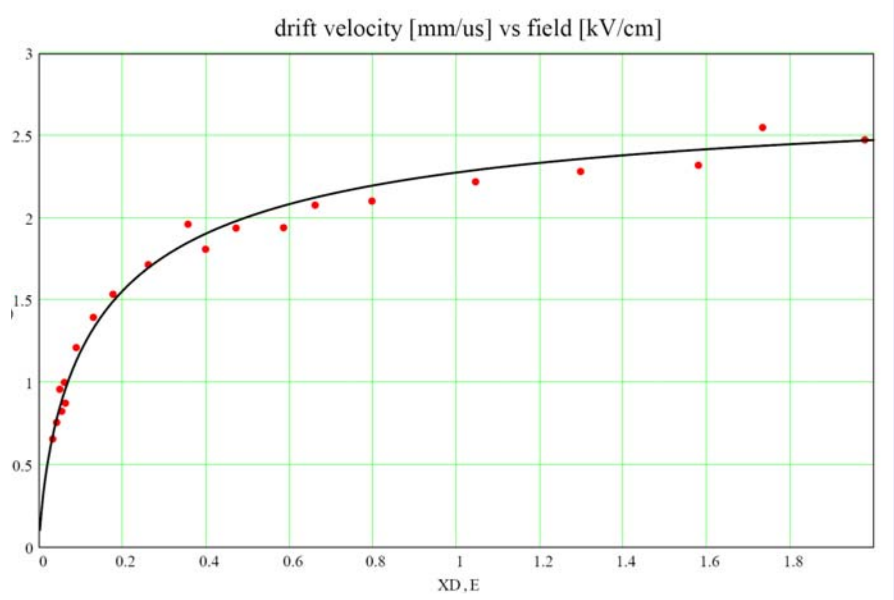
Cost ~ 3$/cc (liquid equivalent)

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



NIM a480 p636



➢ Working bias ~ 2 kV/cm

Scintillations

- ☐ Two mechanisms: primary excitation and recombination

$$R^{*} + R \rightarrow R_2^{*} \rightarrow 2R + h\nu$$

or

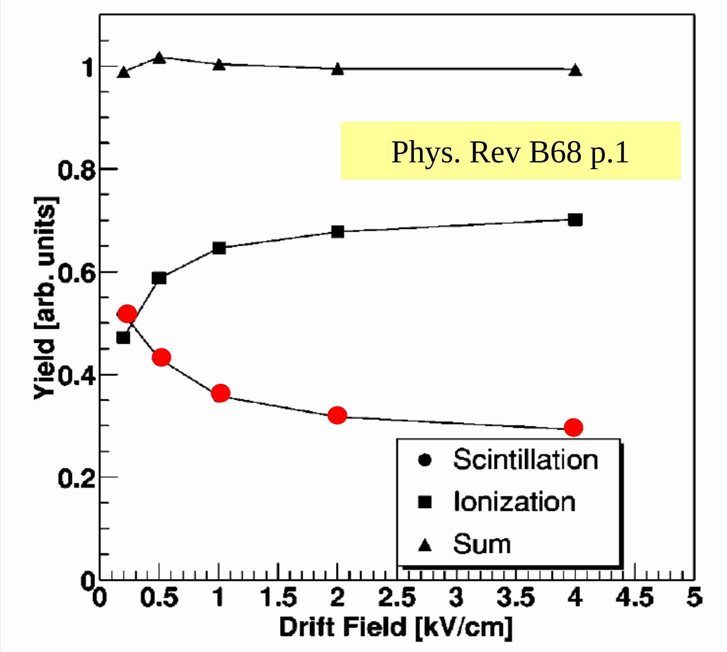
$$R^{+} + R \rightarrow R_2^{+},$$

$$R_2^{+} + e^{-} \rightarrow R^{**} + R,$$

$$R^{**} \rightarrow R^{*} + \text{heat},$$

$$R^{*} + R \rightarrow R_2^{*} \rightarrow 2R + h\nu$$

- ➢ Scintillation yield depends on HV



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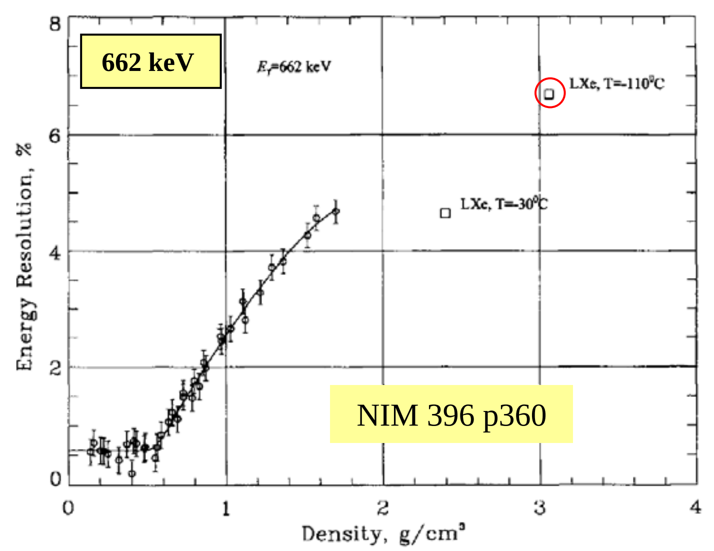
- ☐ VUV: λ = 175-178 nm; W=14.6 eV/ph
- ☐ Timing of excitation: τ1=2.2ns; τ1=27ns, τ3=45ns
- ☐ Attenuation length = 26-36 cm (absorption or Rayleigh?)
- ☐ IR: λ = 1-1.6 mm. W=~48 eV/ph

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%

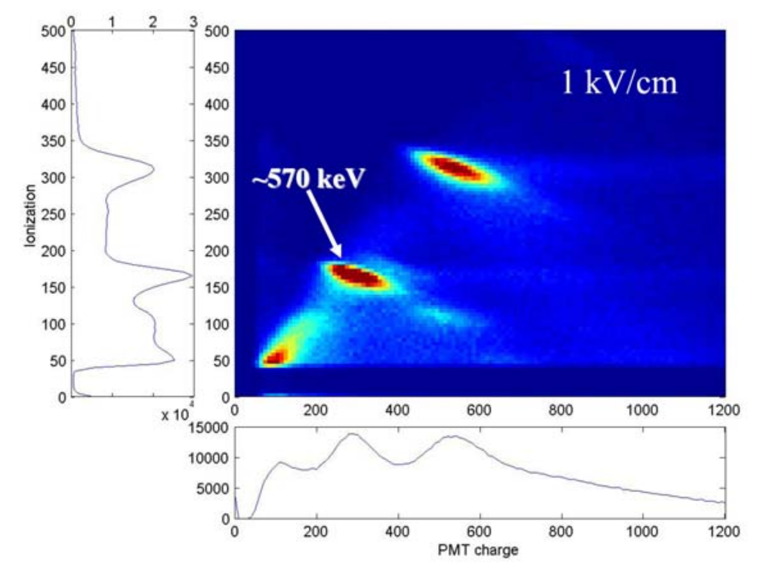
Energy Resolution

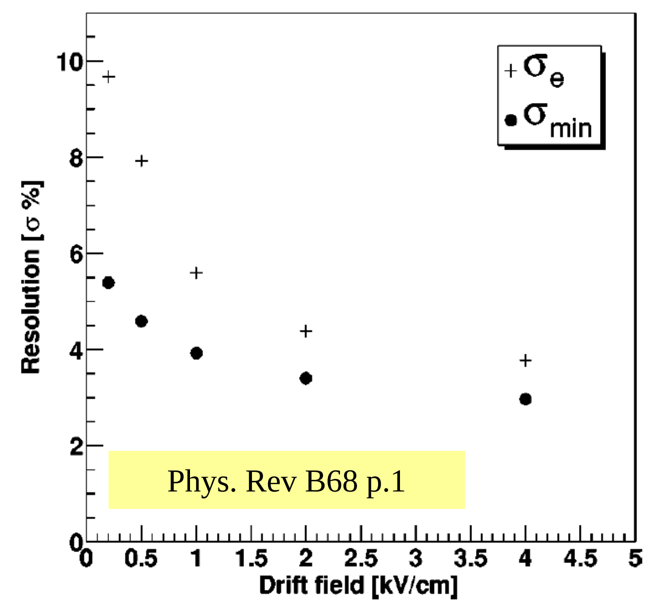
- Ionization: much worse than Fano limit.
  F = 0.2 → fwhm = 0.51% for 662 keV
- No simple theory. Density fluctuations?
- Light: PE statistics. For 511 keV and QE·SA=5%, ΔE = 4.4%
- Correlations improve E-resolution



662 keV

NIM 396 p360





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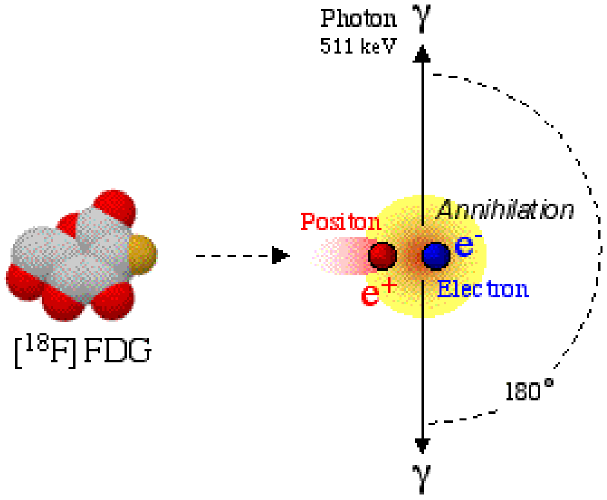
Xe Detectors in Experimental Physics

- ☐ 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)

PET Scanners

- ☐ A short lived isotope decays by emitting e+ which annihilates producing a pair of γ 511keV. The scanner uses events to map the density of the isotope in the body
- ☐ Conventional scanners are based on inorganic scintillators (LSO)
- ☐ Micro-PET – small animal camera



Typical performance

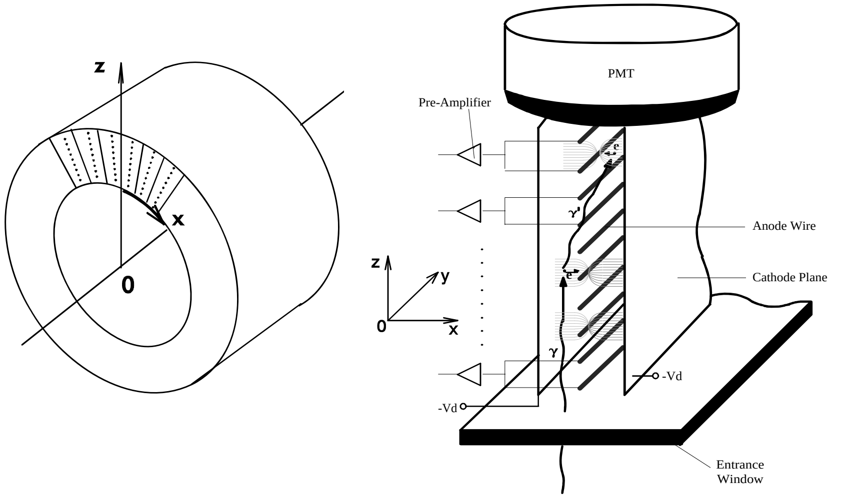
- ✓ Detection efficiency 85%
- ✓ Time resolution 3 ns (fwhm)
- ✓ Spatial resolution 6 mm
- ✓ Energy resolution 22% (@511 keV)
- ✓ No DOI information

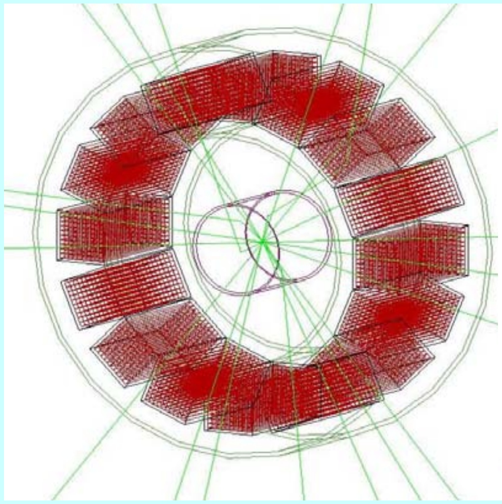
LXe Detector for PET

Requirements (NIM A353 p189)

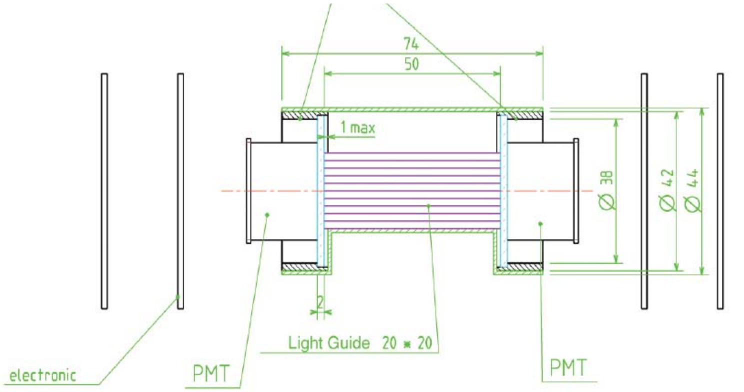
- ❑ High spatial resolution along axial and trans-axial directions (~1 mm)
- ❑ Depth of interaction ~5 mm
- ❑ Good time resolution (~1 ns)
- ❑ Energy resolution (<20%)
- ❑ High detection efficiency (>70%)
- ❑ High counting rate (>10^5 /s·cm^2)
- ❑ Low cost

❑ LIP: scintillations and ionizations





❑ Grenoble: only scintillations

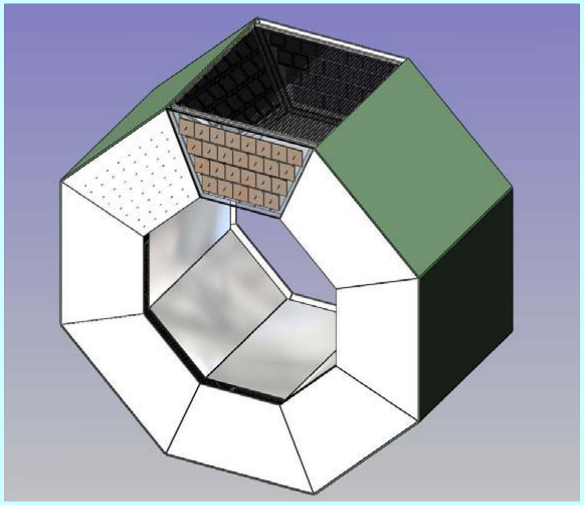


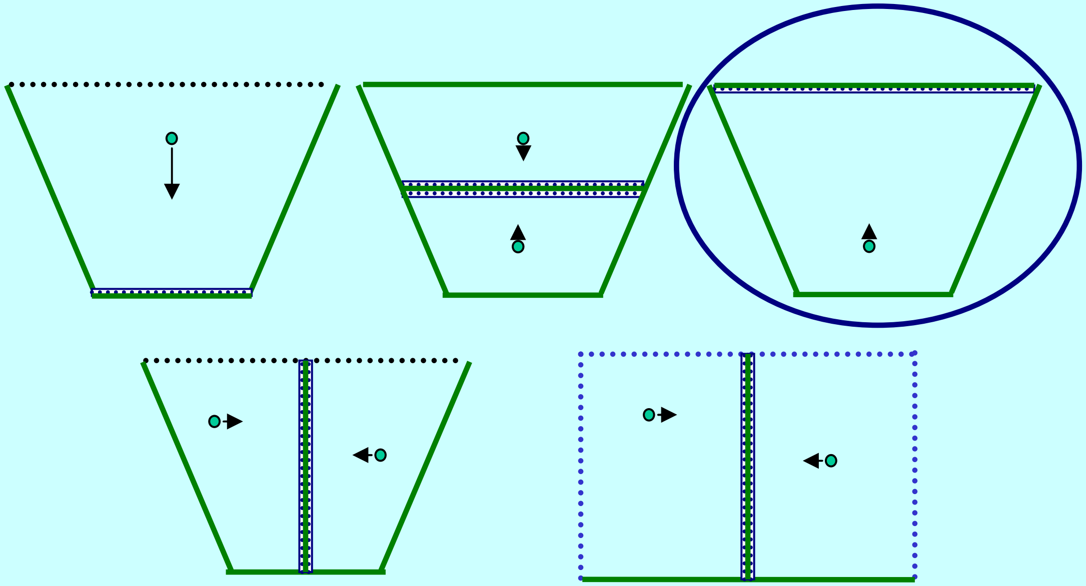
LXe Detector for PET: Our Solution

- ☐ 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

Detector Geometry

- Sectors (8, 12, 16). Calculations of pileup conditions show that 12 sectors is an optimum.
- Sector geometries:
  - Radial drift
  - Axial drift
  - Azimuthal drift

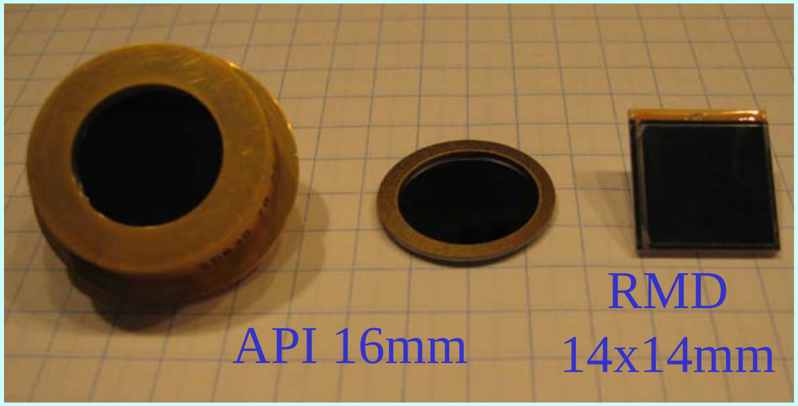


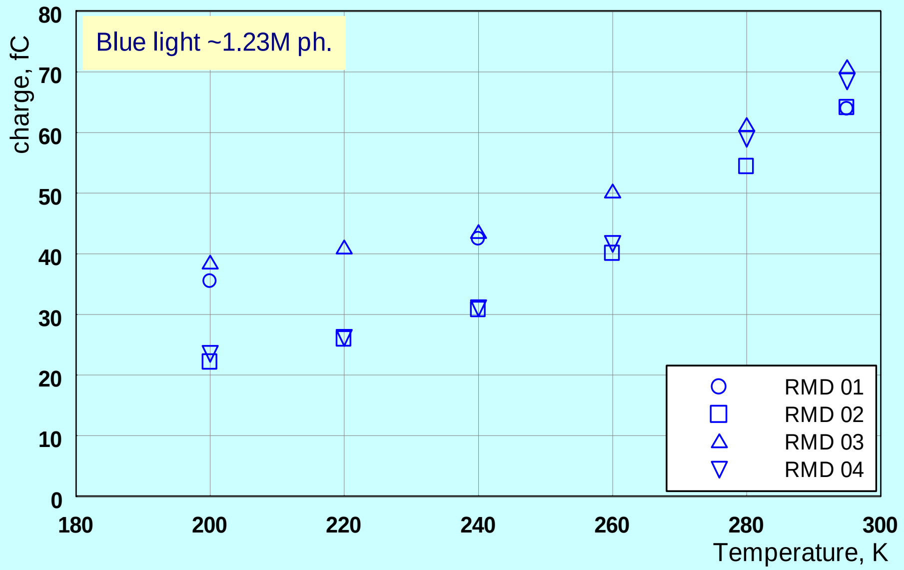


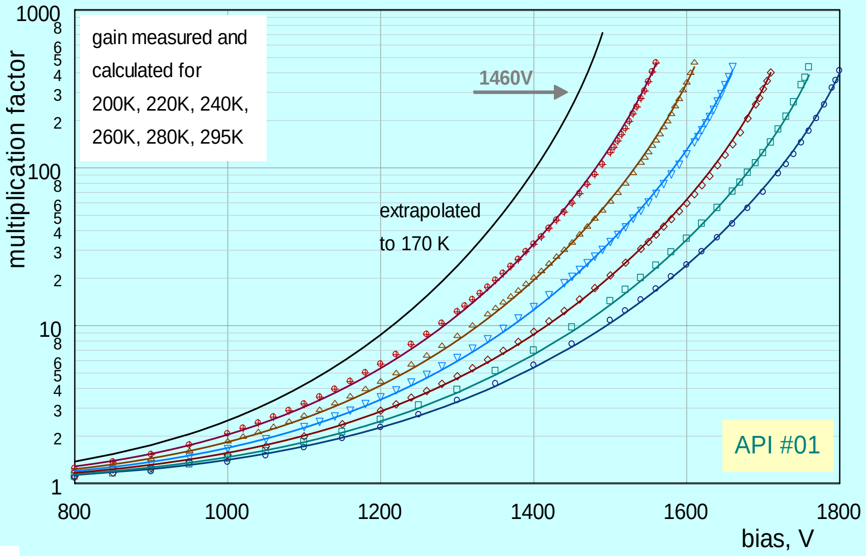
Drift to outer radius has a number of advantages. Chosen for prototyping

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

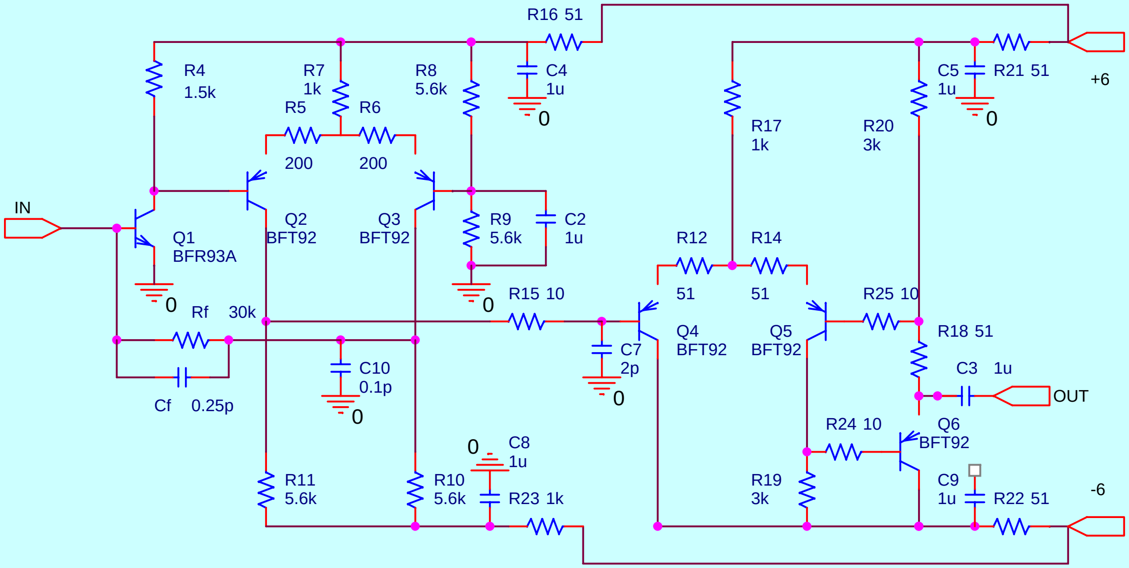


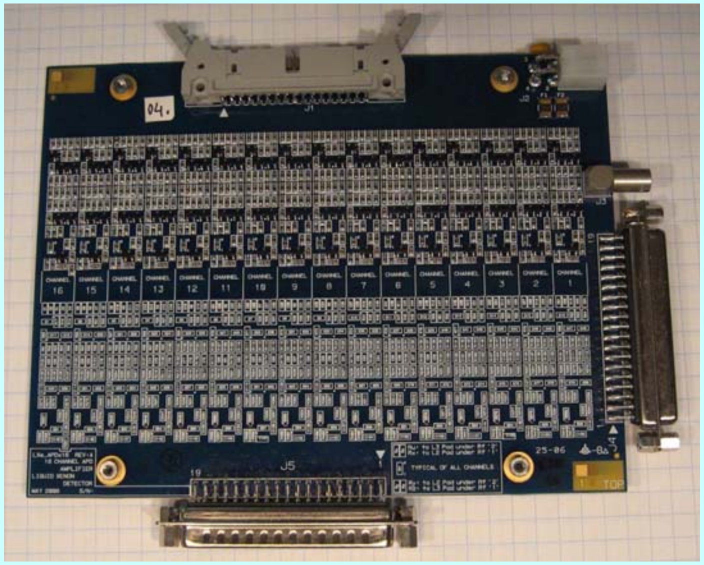




Light Detection: Electronics

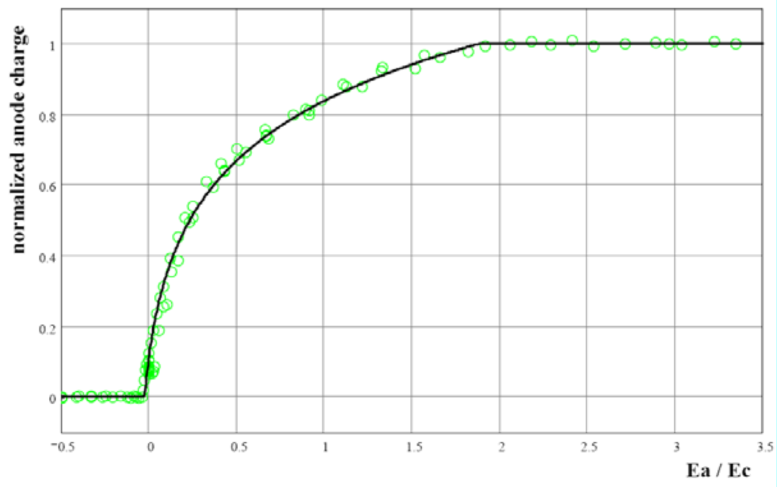
- ☐ Fast and low-noise for Cd=200pF, low input impedance
- ☐ For 2kV/cm and SA·QE=0.4% and G=500, Signal= 20,000e
- ☐ BJT provides better S/N. ENC ~4,000e for 20 ns peak time
- ☐ Choice of low-noise BJT: Philips BFR93
- ☐ 16-ch prototype done



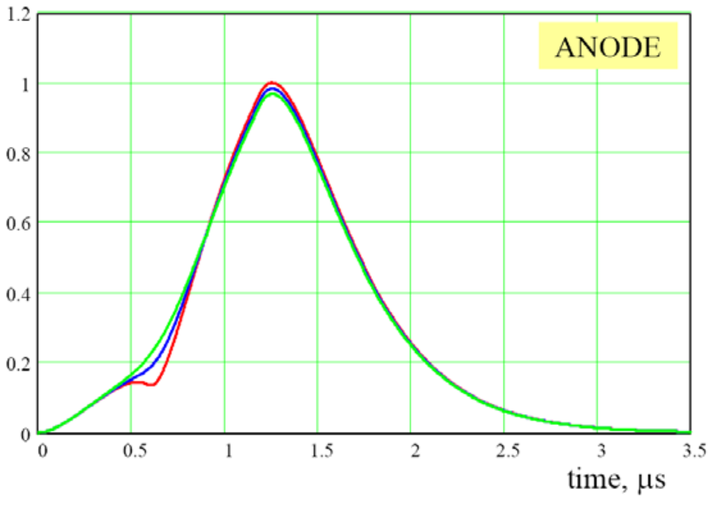


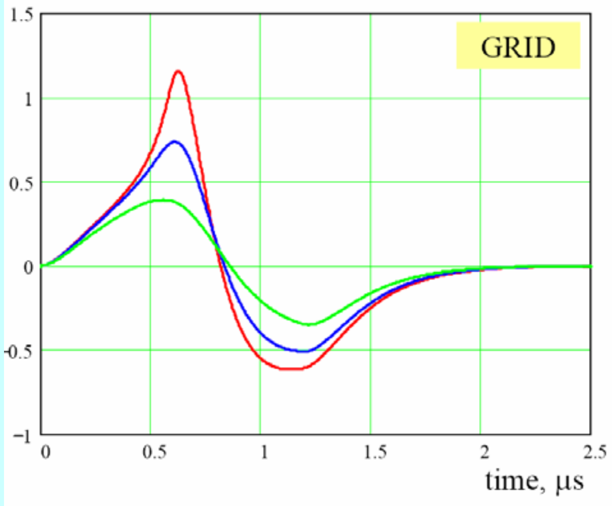
Charge Measurements

- ☐ Configuration: anode strips (pitch ~1mm), wires (spacing ~1mm), mesh for shielding from drift region. Gaps ~1mm
- ☐ Mesh (SS, cell 500µm, wire 30µm). Transparency measured with gas ionization chamber



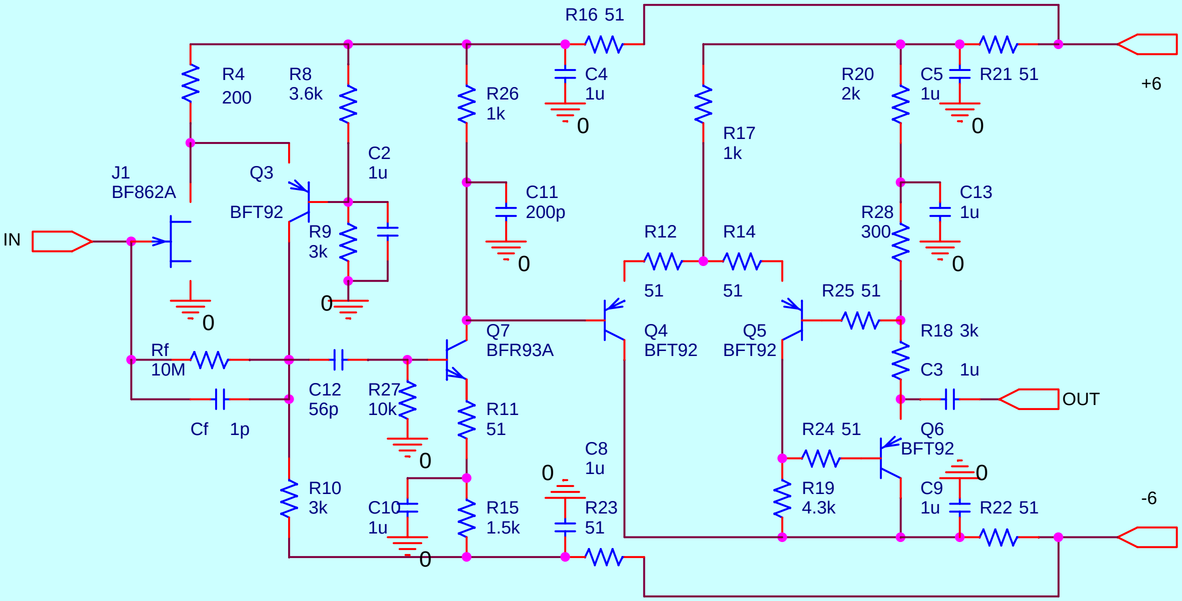
- ☐ Induced currents calculated with FEM. Shaper is optimized for S/N

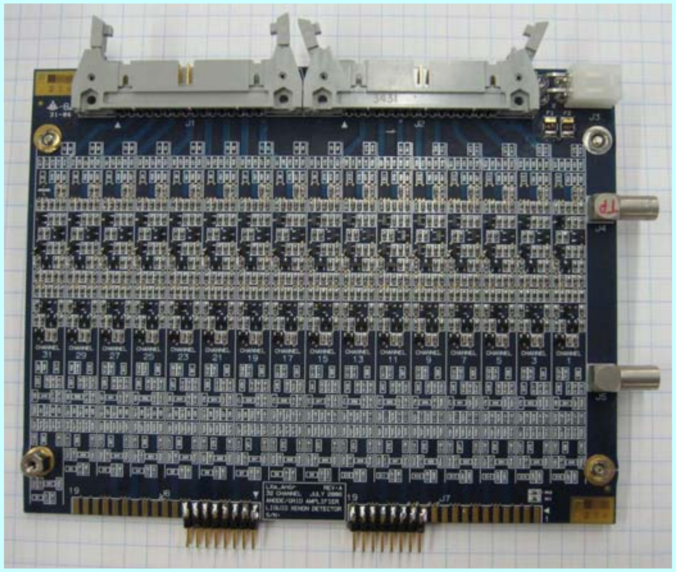




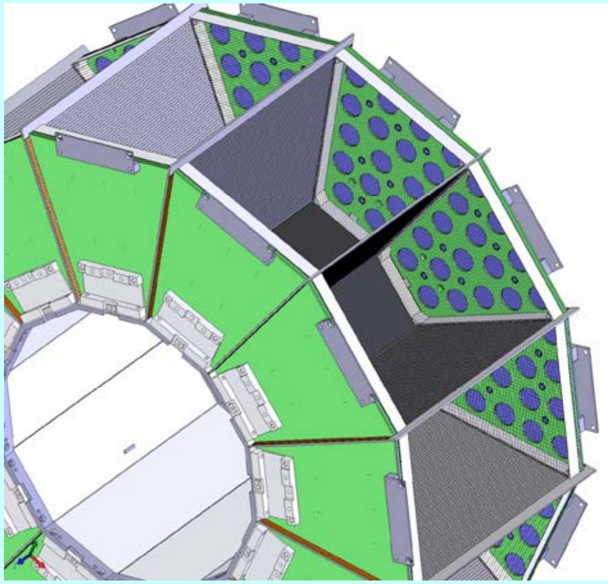
Electronics for Ionization Signals

- Expected signal ~30,000e; fluctuations 4% = 1,200e
- Low-noise for Cd=20pF, and shaping ~ 0.3 μs
- JFET provides better S/N. ENC ~600e for 270ns shaping time
- Choice of low-noise JFET: Philips BF862
- 32-ch prototype under tests

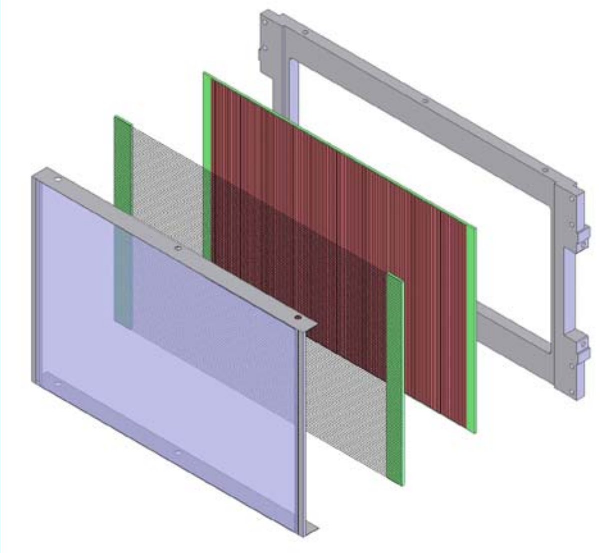




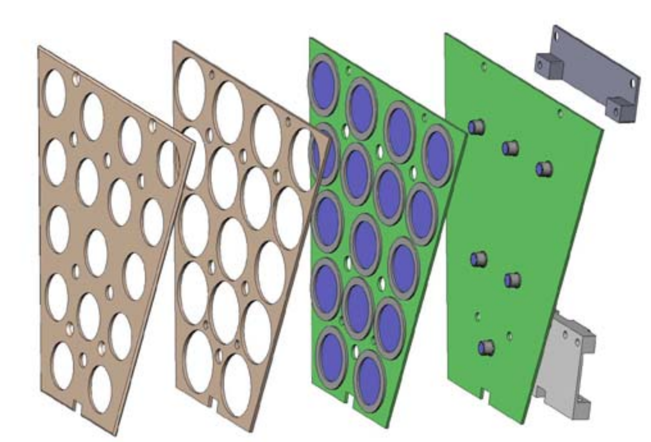
Full-Scale Prototype



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



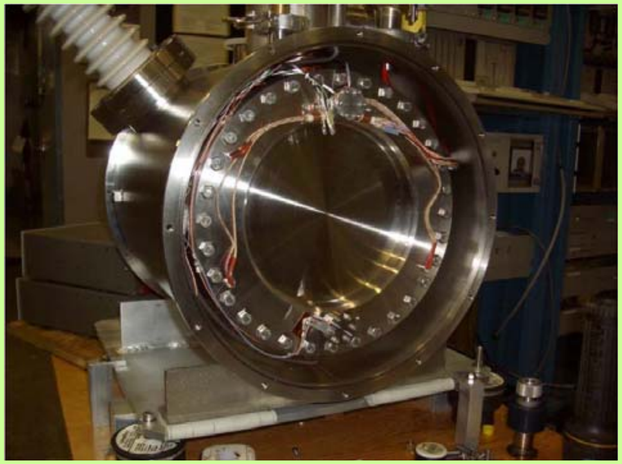
- ❑ Anode module
  - 96 wires, 96 strips
  - SS and kapton PCBs
  - AC decoupling with kapton?

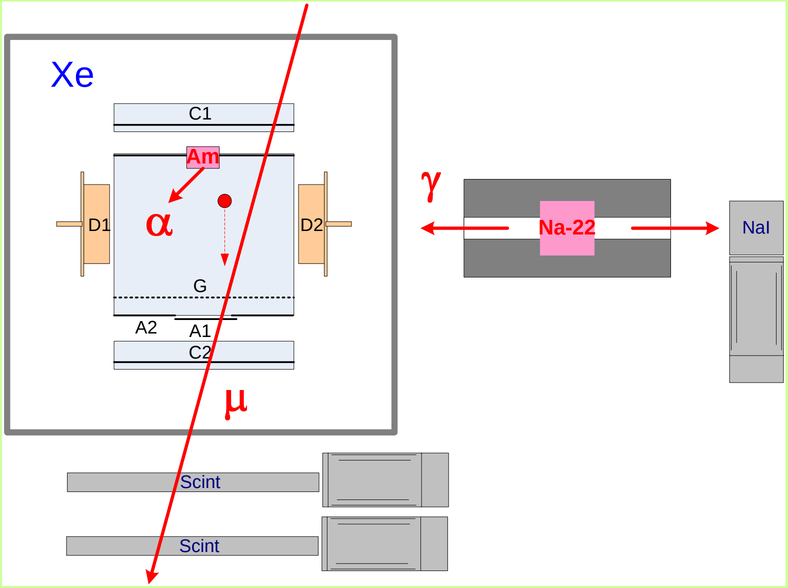


- ❑ APD module
  - 16 APDs and 6 LEDs for monitoring
  - 1 HV line and 16 LV lines (HV tuning)

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, …

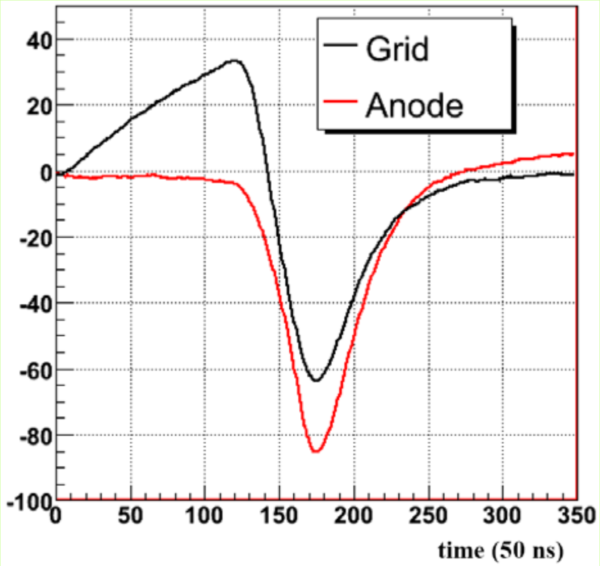


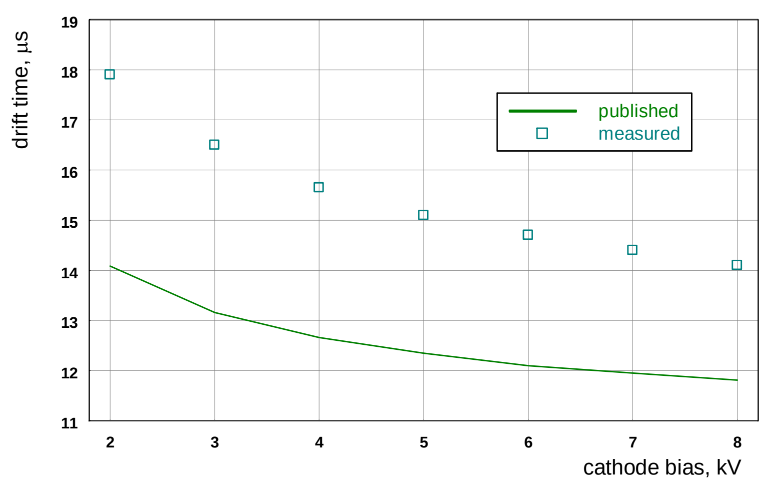


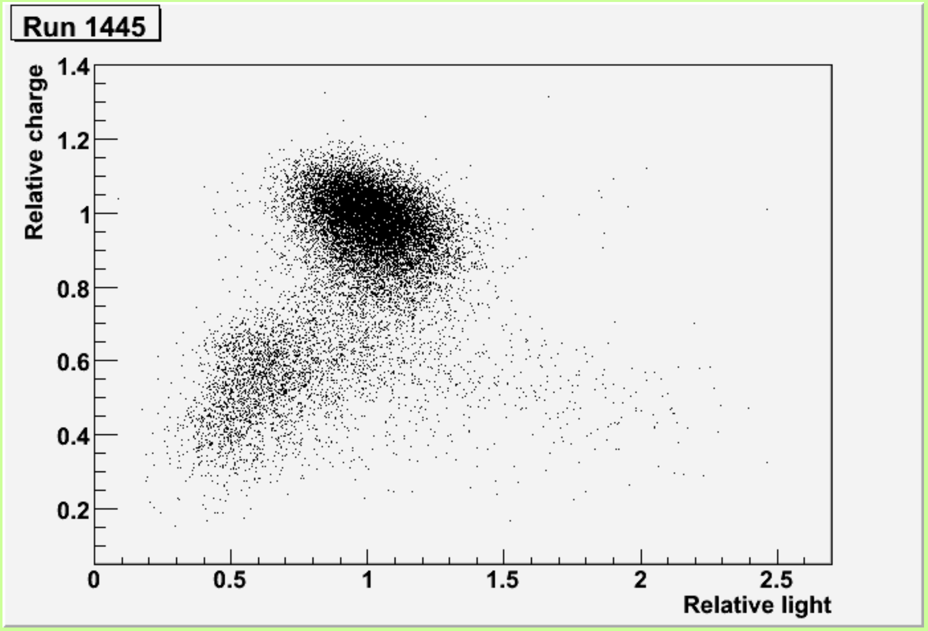
Results from Small TPC

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

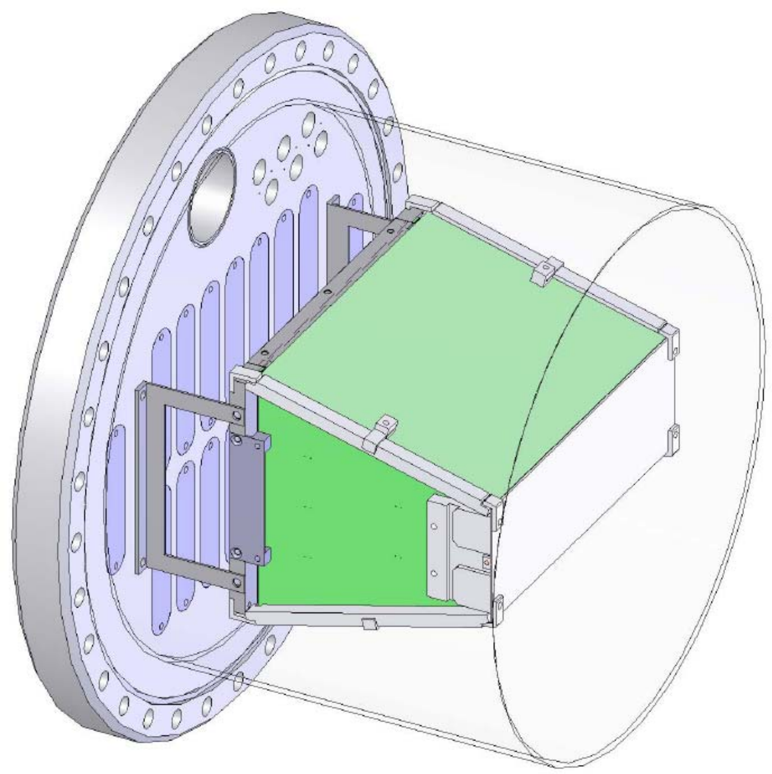
  S-12.6%, Q-6.3%, Sum-4.7%







R&D Program



- ☐ 2006-2007: Sector prototypes
  - Fits to existing cryostat
  - 96 anode strips, 96 grid wires
  - 32 APDs in ends (plus 32 APDs at sides in second prototype)
- ☐ 2007-2008: Two sectors
  - mPET cryostat
  - Final design of sectors
  - Final electronics and readout
- ☐ 2008-2009: 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:

P.Amaudruz, D.Bryman, R.Bula, M.Constable, L.Kurchaninov,
C.Lim, P.Lu, C.Marshall, J.-P.Martin, F. Retiere, T.Ruth,
V.Semenoff, V.Sossi