

High Energy Resolution in High-Pressure Xe Gas TPCs

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Goal:

Develop a novel detector that combines high energy resolution with measurements of event topologies to separate the desired signals from backgrounds.

The design should be scalable to match a wide range of applications, including searches for ultra-rare events.

Potential Applications

1. Search for neutrinoless double-beta decay
 - a) Verify that the neutrino is its own anti-particle
 - b) Helps determine absolute neutrino mass
 - c) If observed, lepton number not conserved
2. Large-area gamma detectors that require background suppression

Current Emphasis: Verify Energy Resolution

This device addresses only a subset of final requirements.

These applications require separation of the desired signals from a wide range of backgrounds.

This requires

- High energy resolution for electrons and gamma rays into the MeV regime
- Reconstruction of energy deposition sequence to separate full from partial energy deposition
- Discrimination between neutron and gamma signals

High-pressure Xe gas can provide energy resolution much superior to liquid Xe.

$E = 2.5 \text{ MeV}$ ($= Q$ ^{136}Xe):

- High-Pressure Xe: $\Delta E / E \approx 3 \cdot 10^{-3}$ (Fano factor ≈ 0.15)
- Liquid Xe (EXO prediction): $\Delta E / E \approx 35 \cdot 10^{-3}$ (Fano factor ≈ 20)

Implementation as a TPC yields position resolution adequate to reconstruct beta decays and the tracks of Compton recoils.

The ratio of ionization to scintillation signals provides neutron-gamma discrimination.

Neutrinoless double-beta decay is a rare nuclear transition between same mass nuclei:

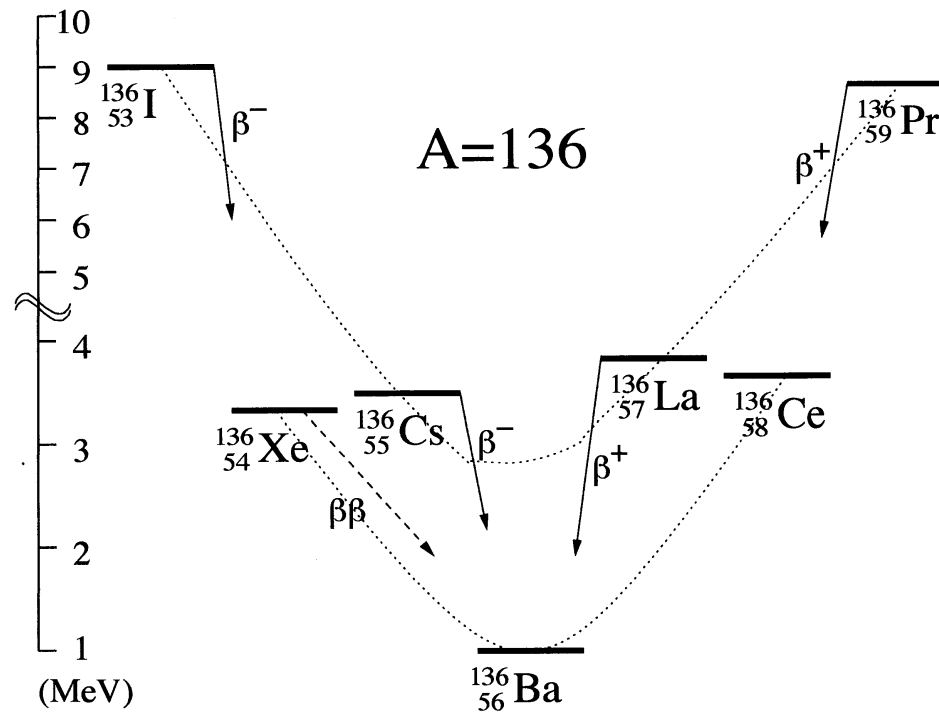


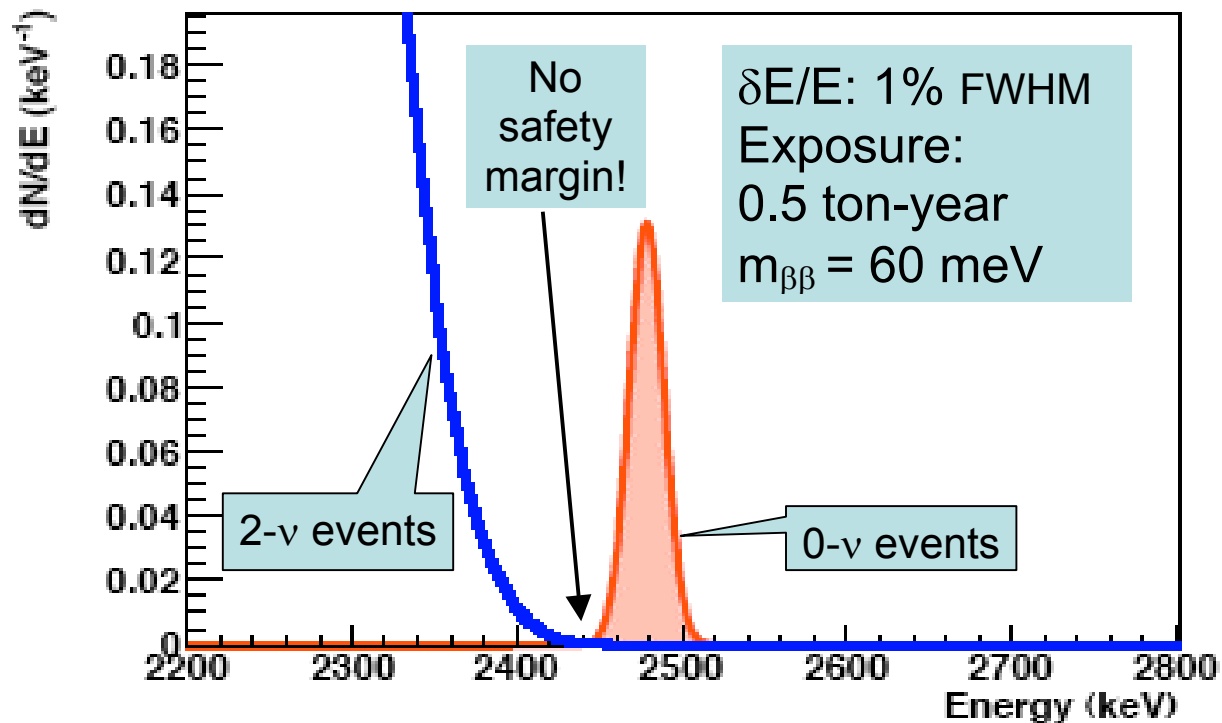
Figure 2.1: Simplified atomic mass scheme for nuclei with $A=136$. The parabolae connecting the odd-odd and even-even nuclei are shown. While ^{136}Xe is stable to ordinary beta decay, it can decay into ^{136}Ba by double-beta decay.

Energy level for daughter of ^{136}Xe standard beta decay is too high
 – very rare events! $T_{1/2}^{0\nu} > 10^{21} - 10^{25} \text{ y}$

Neutrinoless Double-Beta Decay

In the $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$ decay the entire Q value is transferred to an electron pair with a total energy of 2480 keV.

An energy resolution $<1\%$ is required to separate contamination from the tail of the $2\text{-}\nu\ \beta\beta$ spectrum.



The $\beta\beta$ topology is unique: “spaghetti with two meatballs”

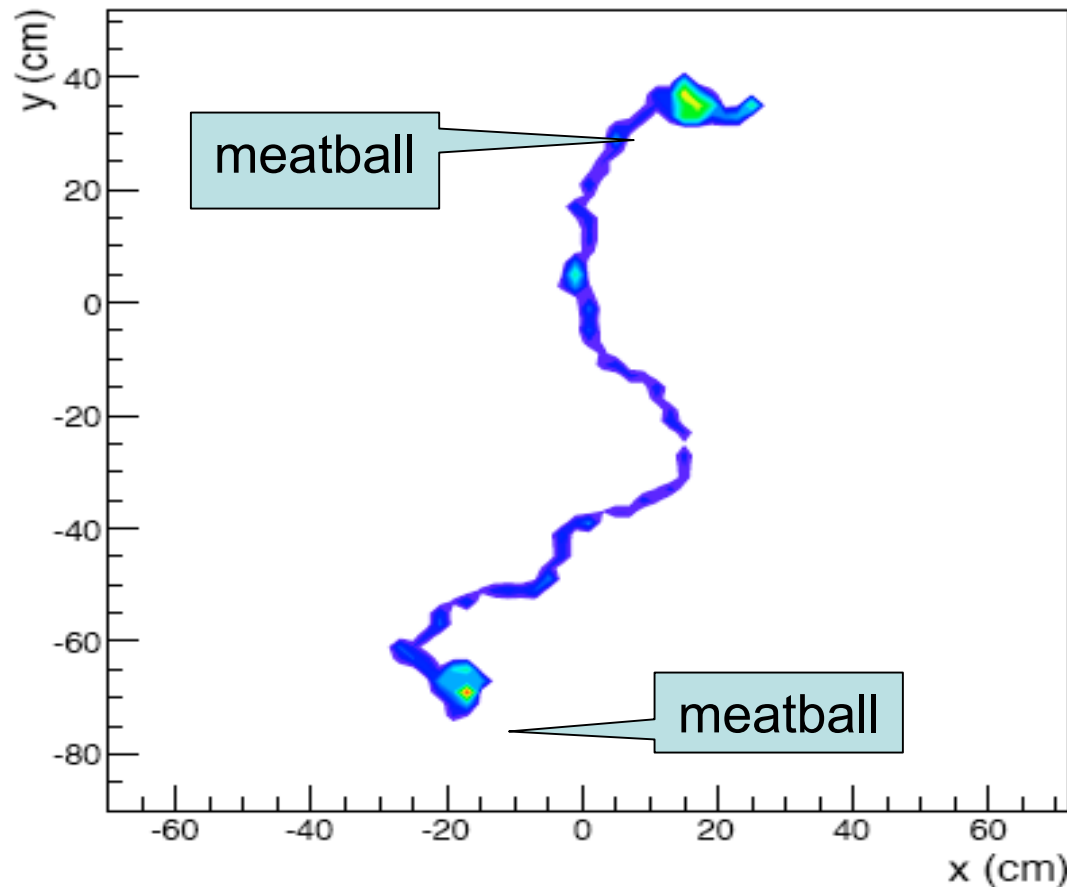


Figure: J.J. Gomez, NEXT

Energy “blobs” at
end of track:

$\beta\beta$ events: 2

γ events: 1

Data from
Gotthard TPC:

~ x30 rejection

Figure shows track
length at 10 atm,

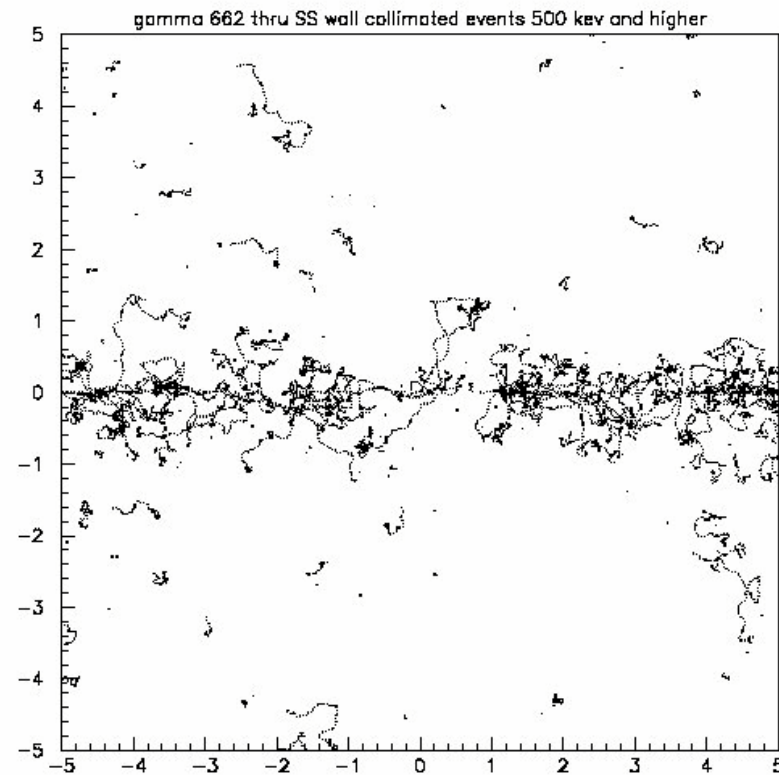
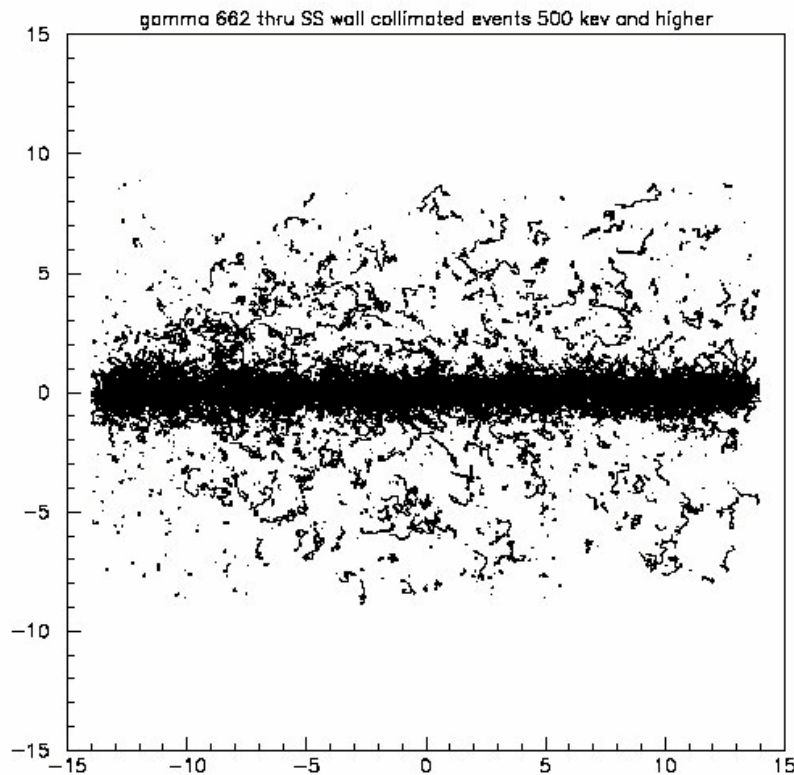
At 20 atm 2.5 MeV
track length ~16 cm

Gamma Backgrounds

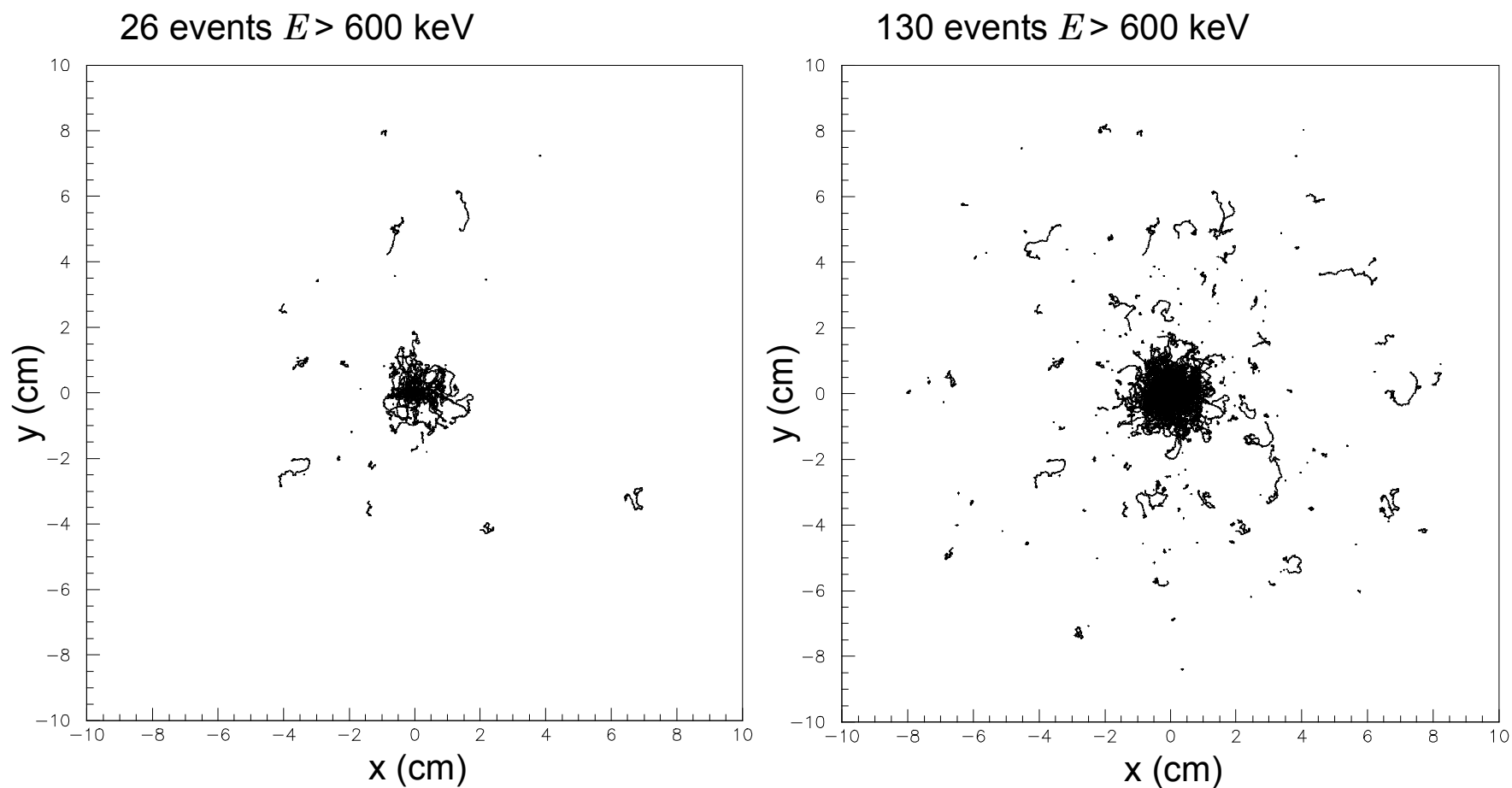
Typical: multiple Compton scatters with final photoelectric interaction

Collimated 662 keV gammas incident through 15 cm thick steel left wall

Events in central region >500 keV



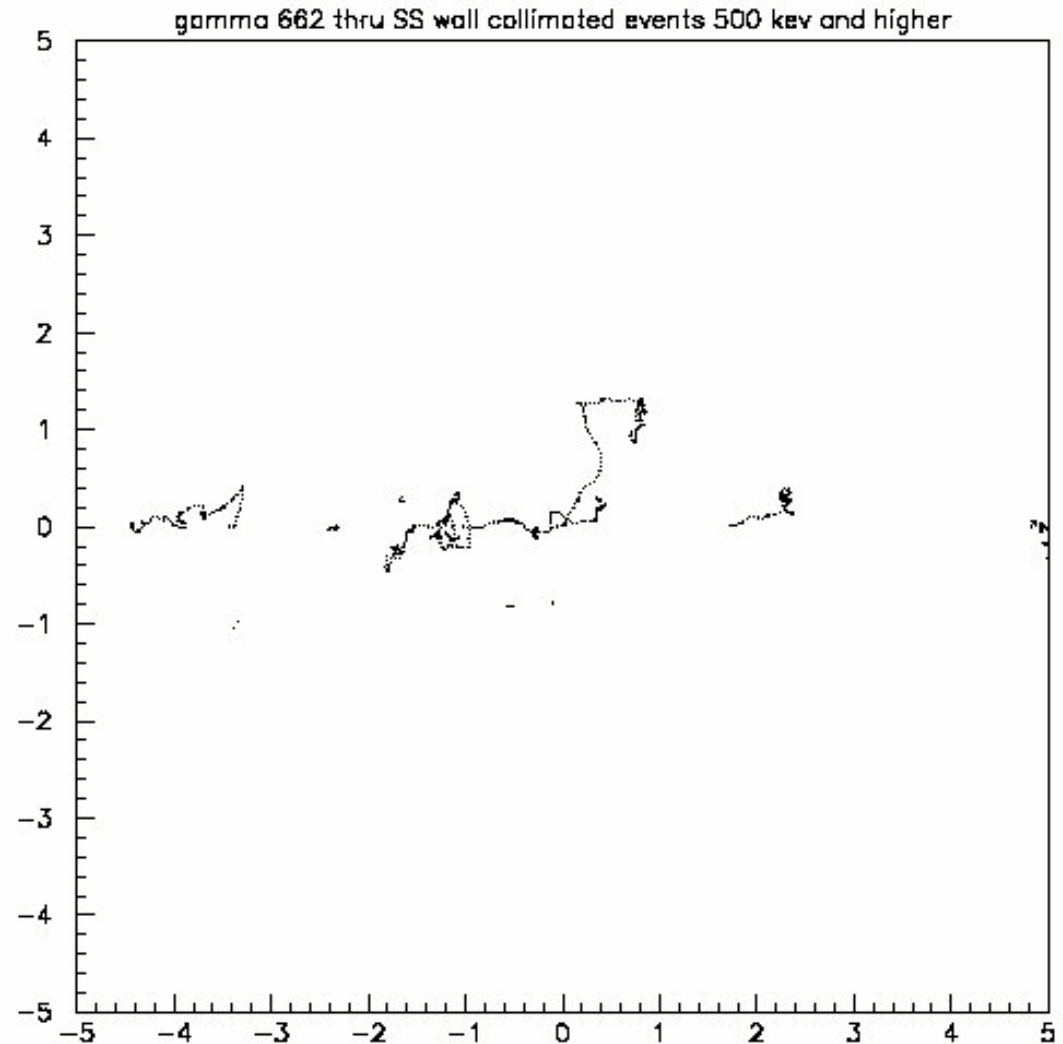
Axial view of fraction of events



Significant fraction of interactions associated with one gamma distributed in space

Longitudinal structure of
some individual events

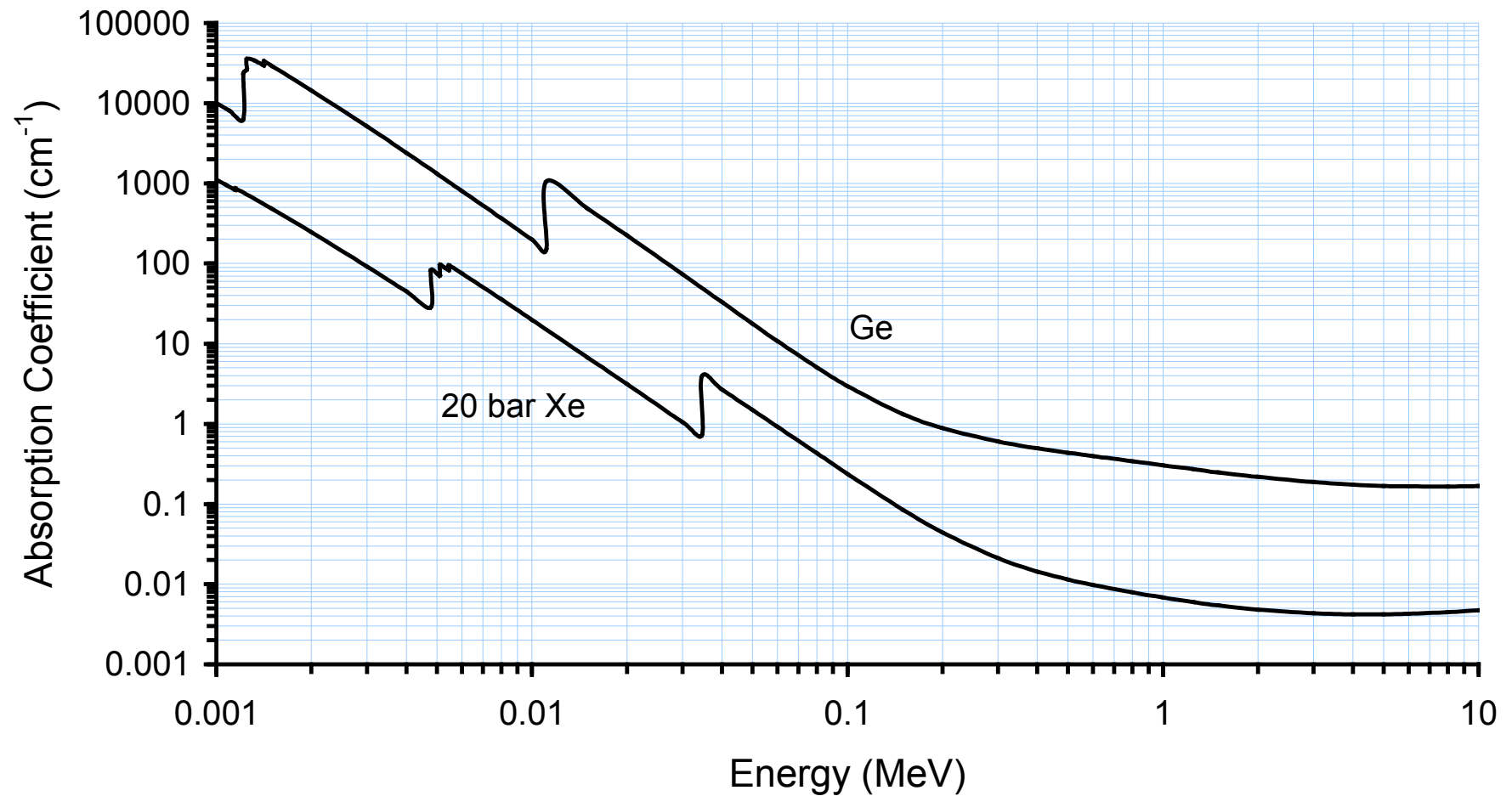
Energy threshold
 $E > 500\text{keV}$



Track reconstruction must distinguish multiple squiggly tracks.

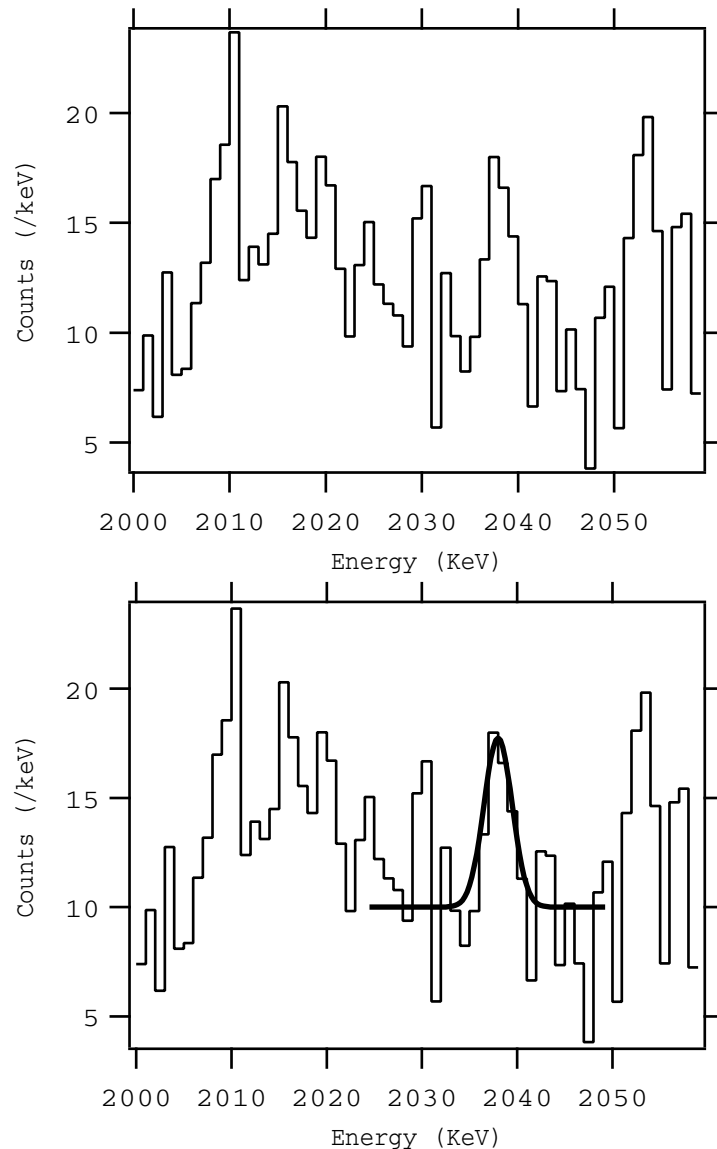
Photon Absorption Coefficients

Photon Absorption Coefficient in Ge and Xe (20 bar, 300K)



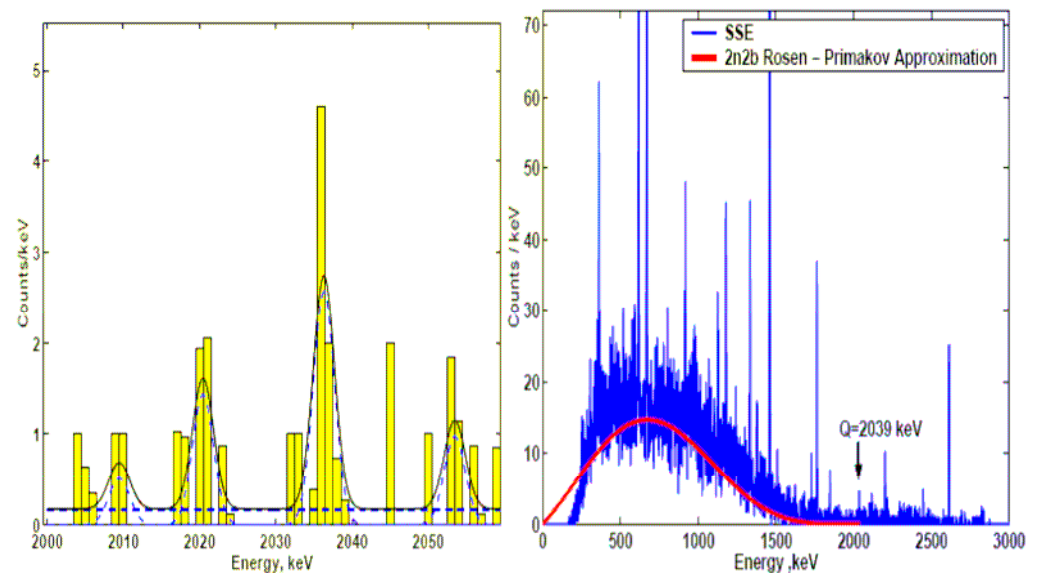
Gamma Background Example: ^{76}Ge Data

Klapdor et al. NIM **A522** (2004) 371



High Energy Resolution in High-Pressure Xe Gas TPCs
2010 Vienna Conference on Instrumentation

Utilizing pulse shape discrimination
to recognize spatially distributed
energy depositions:



$$T_{1/2} \approx 1.2 \cdot 10^{25} \text{ y}, \langle m \rangle \approx 0.44 \text{ eV}$$

Klapdor et al. Phys. Lett. **B586** (2004) 198

Helmuth Spieler
LBNL

Two important measurement properties:

- Energy Resolution
- Event Topology

TPCs are well recognized as tracking devices, but high-pressure Xe gas may add

- High Energy Resolution
- Acceptable Detection Efficiency

Xenon: Strong dependence of energy resolution on gas density

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

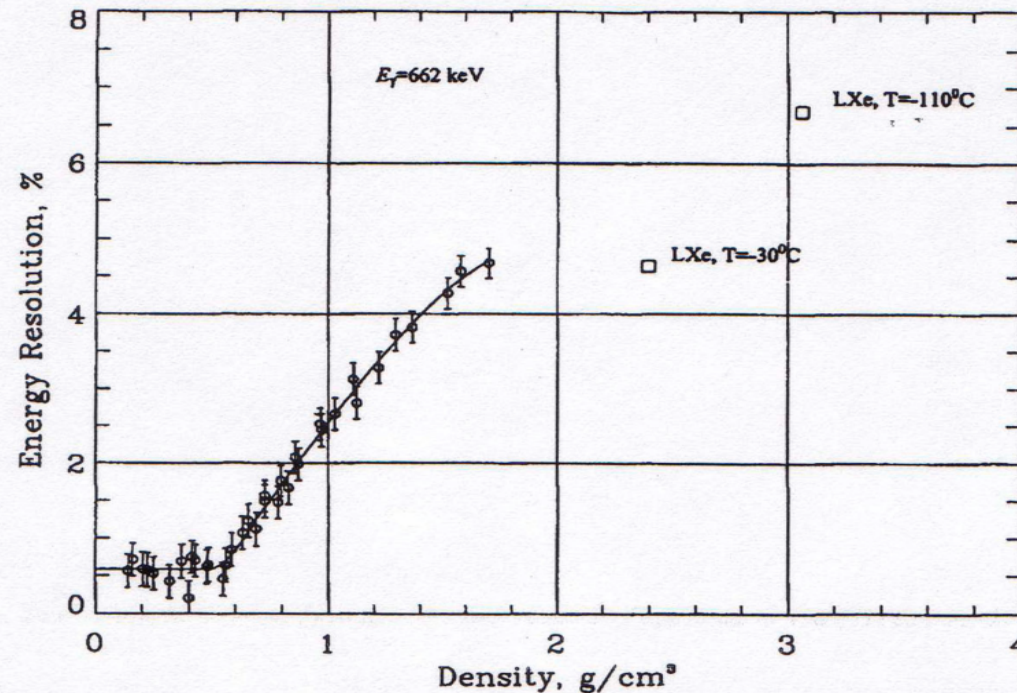


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

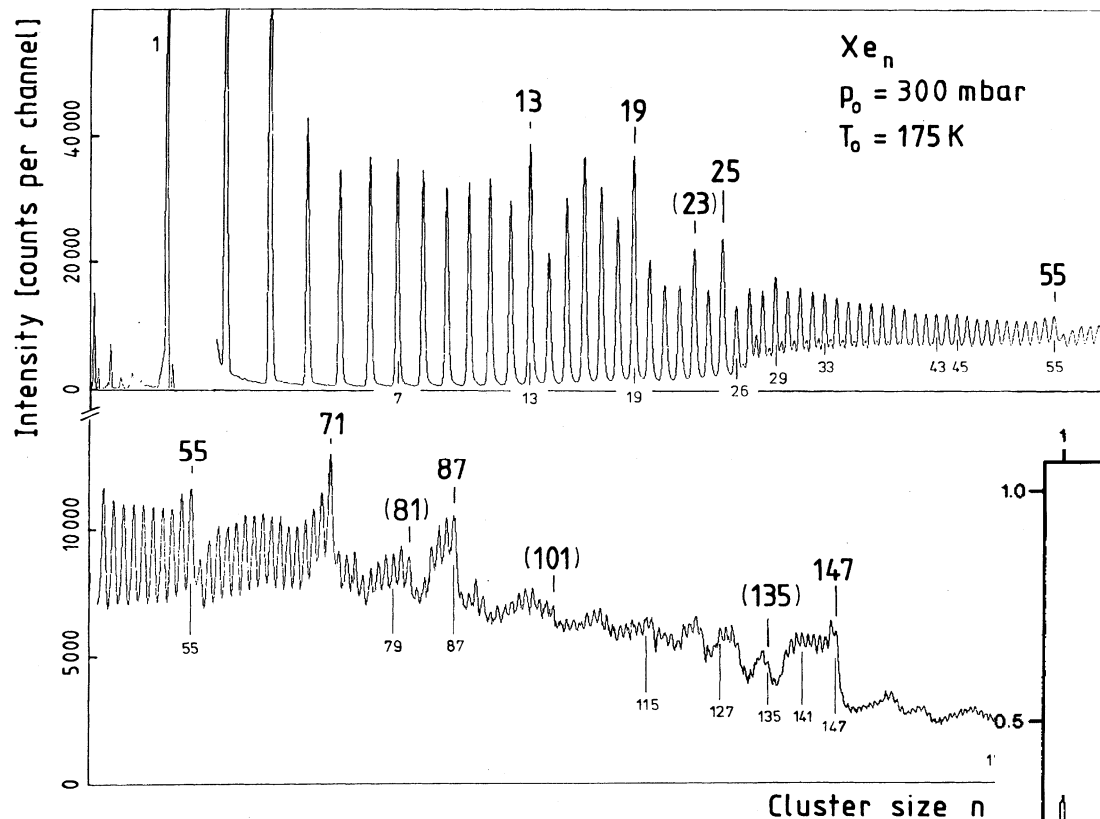
Measurement of ionization component only.

For $\rho < 0.55 \text{ g/cm}^3$ ionization resolution is “intrinsic”.

Degraded resolution in liquid Xe due to additional energy states at high density (quasi conduction band) + large fluctuations in ionization-scintillation partitioning.

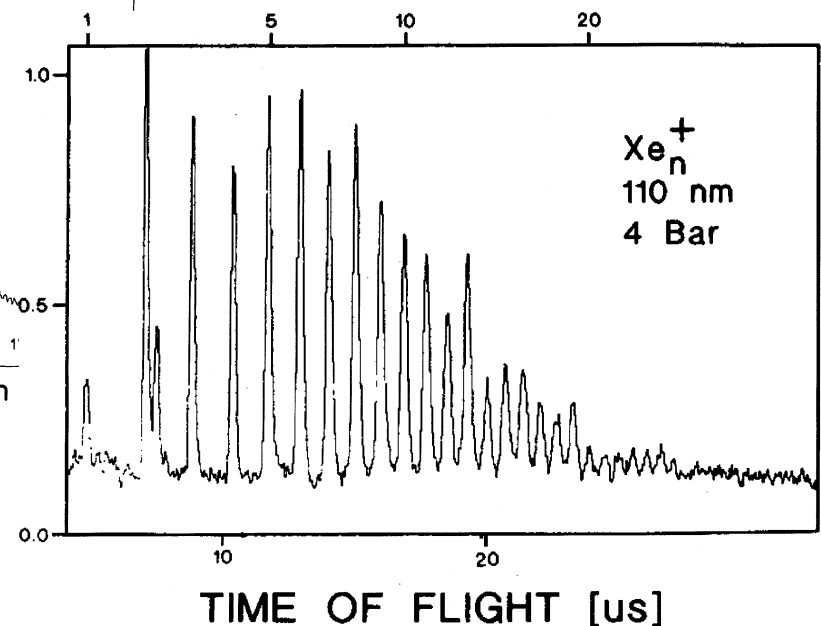
Noble gases aren't as simple as many think: Atom Clusters in Noble Gases

An excited noble gas atom can attach to another, but even larger clusters have been predicted and detected (ionization potential decreases with cluster size):



Echt et al., Phys. Rev. Lett.
47 (1981) 1121

CLUSTER SIZE



Ganteför et al., J. Chem. Phys. **91** (1989) 7972

“Intrinsic” Energy Resolution for Ionization at ^{136}Xe Q-Value

Q -value ($^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$) = 2480 keV

W = energy per ion/electron pair in xenon gas = 21.9 eV,
but W depends on electric field strength, might be ~24.8 eV

N = number of ion pairs = Q/W

F = Fano factor. Measured in Xe gas: $F = 0.13 - 0.17$ (assume 0.15)

$$\frac{\Delta E}{Q} = 2.35 \cdot \frac{\sqrt{FN}}{Q} = \sqrt{\frac{FW}{Q}} \approx 2.8 \cdot 10^{-3} \text{ FWHM}$$

Comparison:

Germanium diodes @ 2.5 MeV $\Delta E / E \approx 1 - 2 \cdot 10^{-3} \text{ FWHM}$

Fano Factor of Liquid Xe ~20 $\Rightarrow \Delta E / E \approx 3.5 \cdot 10^{-2} \text{ FWHM}$
(mixed ionization + scintillation)

Absolute Signal Charge Fluctuations

$$Q = 2480 \text{ keV}$$

$$W = 24.8 \text{ eV}$$

$$N = \text{number of ion pairs} = Q / W$$

$$N = 2480 \times 10^3 \text{ eV} / 24.8 \text{ eV} = \sim \mathbf{100,000} \text{ electron/ion pairs}$$

$$\sigma_N = \sqrt{FN}$$

$$F = 0.15$$

$$\Rightarrow \sigma_N = \sqrt{FN} \approx 120 \text{ electrons rms @ 2480 keV}$$

120 electrons: Electronic noise will dominate in practical configurations

Need internal gain without introducing significant fluctuations.

Energy Resolution Including Gain Fluctuations

If fluctuations are uncorrelated, then

$$\sigma_N = \sqrt{(F + L + G)N}$$

where F = Fano factor = 0.15
 L = Loss of primary ionization (set to 0)
 G = Fluctuations in gain process

To maintain resolution G must be smaller than F .

Avalanche charge gain introduces excessive noise because early fluctuations are amplified exponentially.

Example: for a wire $G = 0.6 - 0.9 \Rightarrow$ benefit of small F is lost!

In general, avalanche devices can't deliver $G < F$.

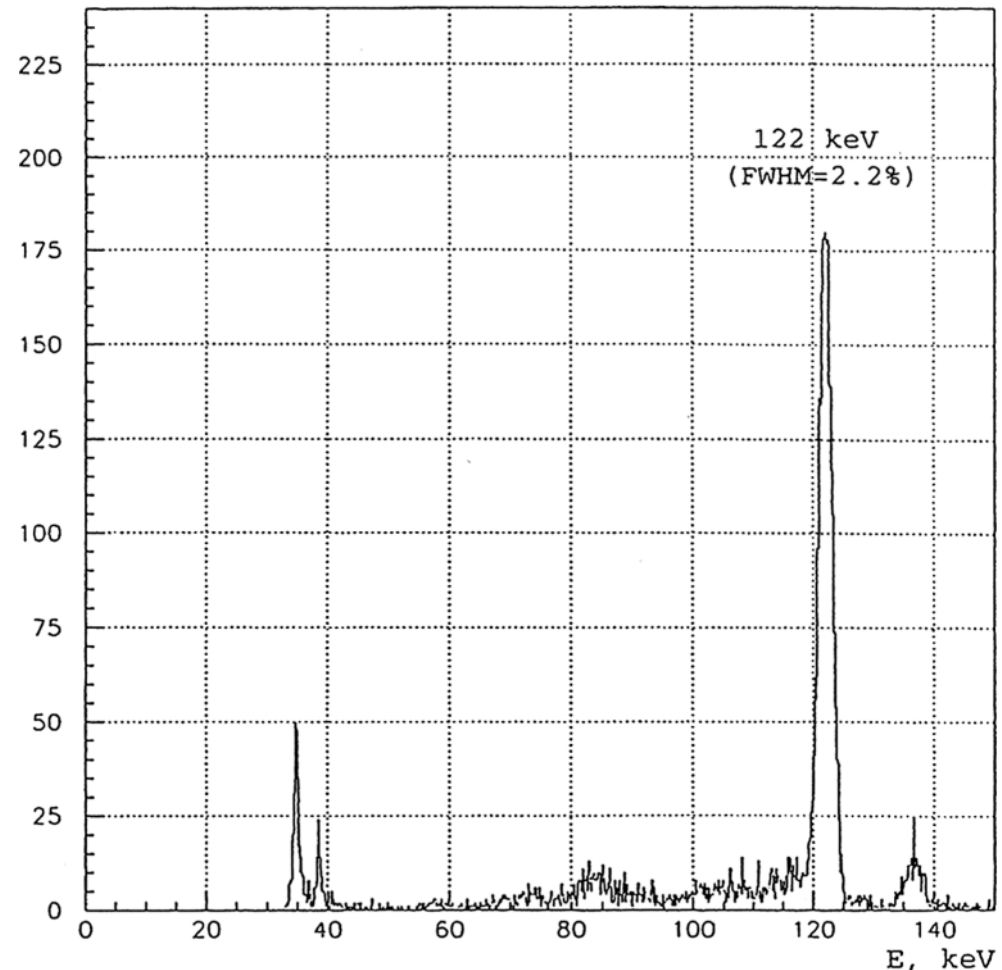
Alternative: Electroluminescence

Accelerate electrons to an energy only sufficient to excite optical states

– NOT avalanching

- Amplification is **linear** with voltage
- Sequential gain process (photons don't excite additional emissions)
- Fluctuations are very small:

$G \approx 0.1$ achievable



A. Bolozdynya et al. / Nucl. Instr. and Meth. in Phys. Res. A 385 (1997) 225–238

High-Pressure Xe Gas TPC

Energy deposition yields both ionization and scintillation.

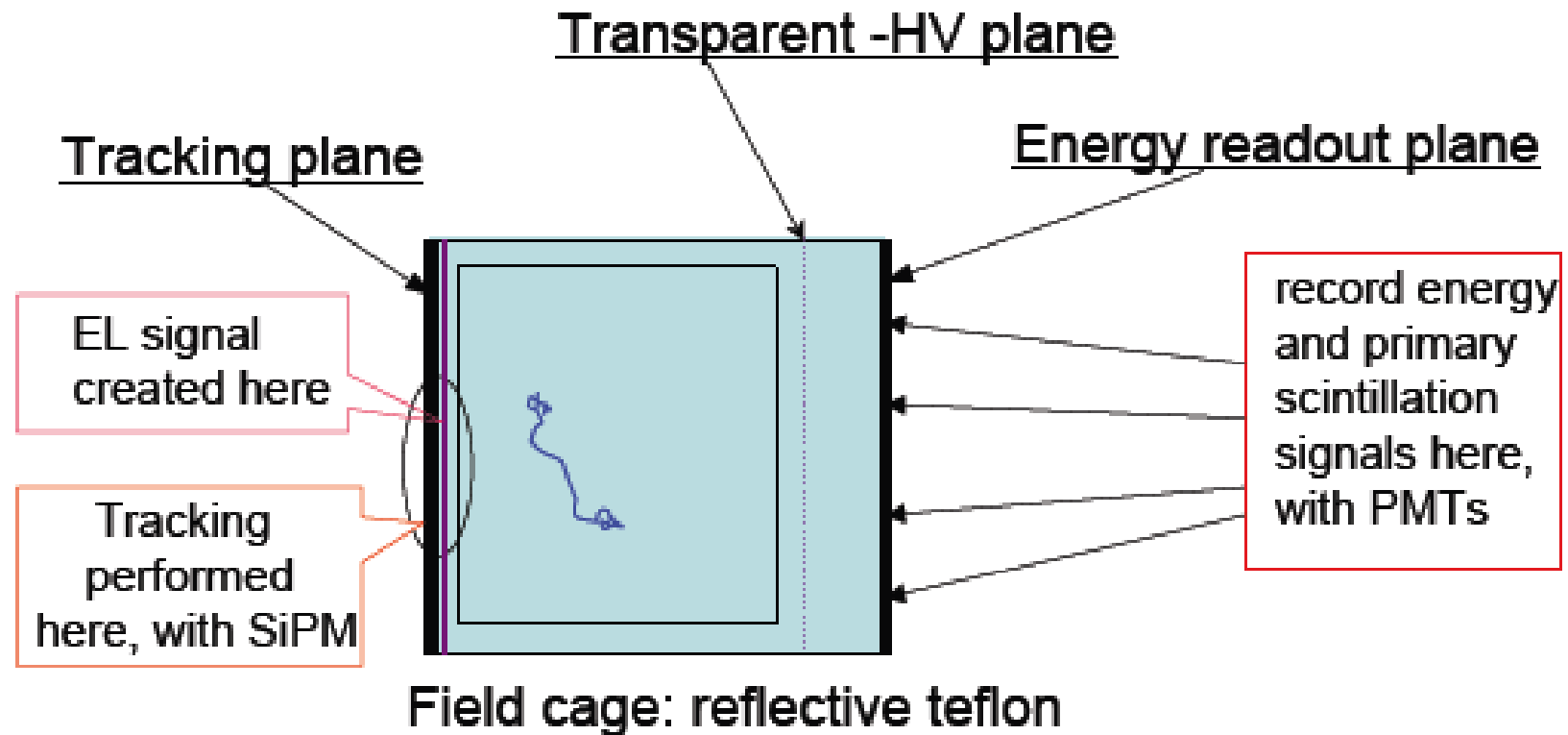
Scintillation light yields prompt start signal to measure drift time of ionization electrons

- Fiducial volume surface:
 - Single, continuous, fully active, variable,...
 - 100.000% rejection of charged particles (surfaces)
- Excellent tracking capability:
 - Available in gas phase only!
 - Topological discrimination against single electrons (meatballs)
 - X-ray fluorescence can tag γ photo-conversion events

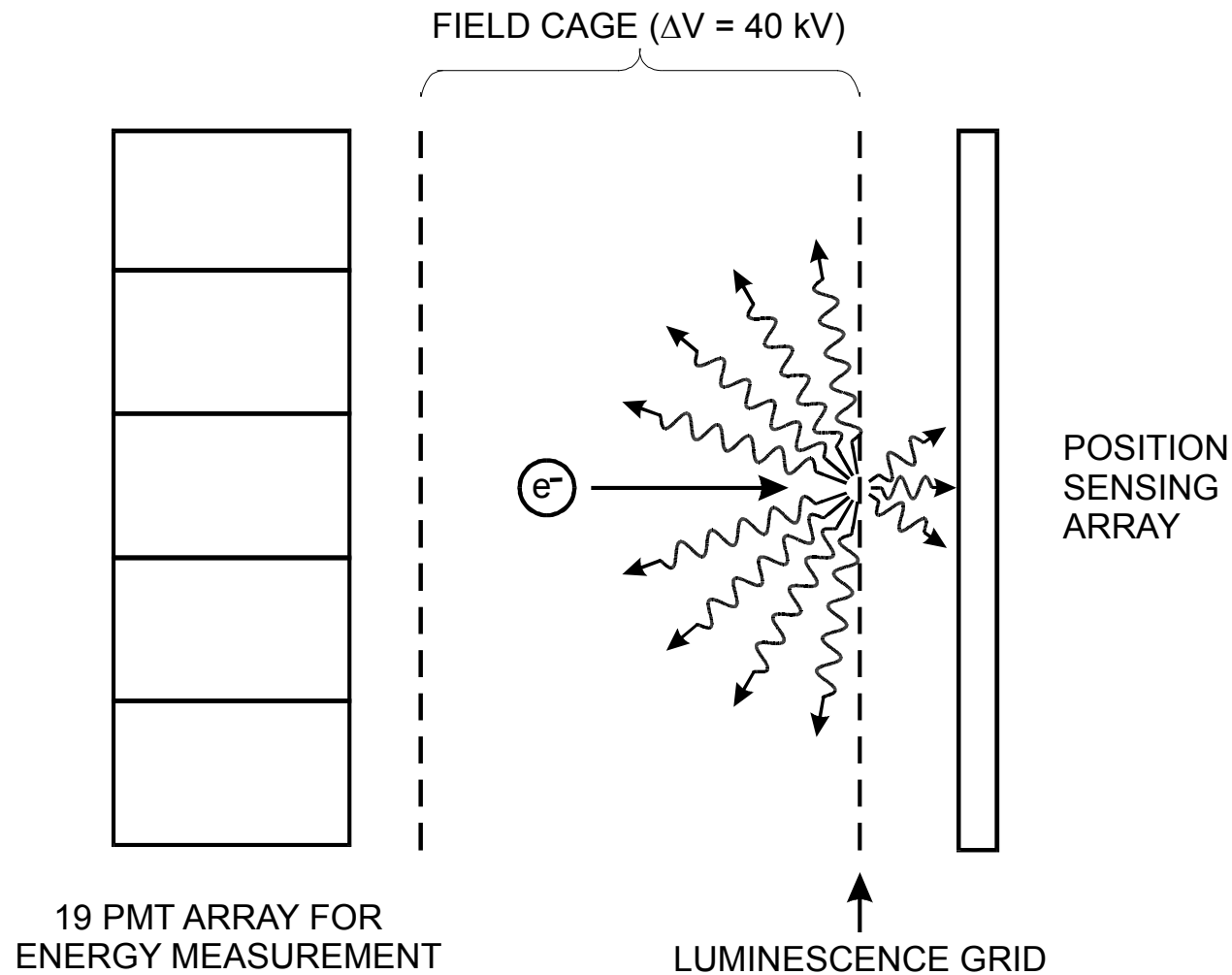
Combination of high-pressure gas and electroluminescent internal gain has not been demonstrated!

Should be scalable to 1000 kg with no degradation in resolution.

TPC Readout

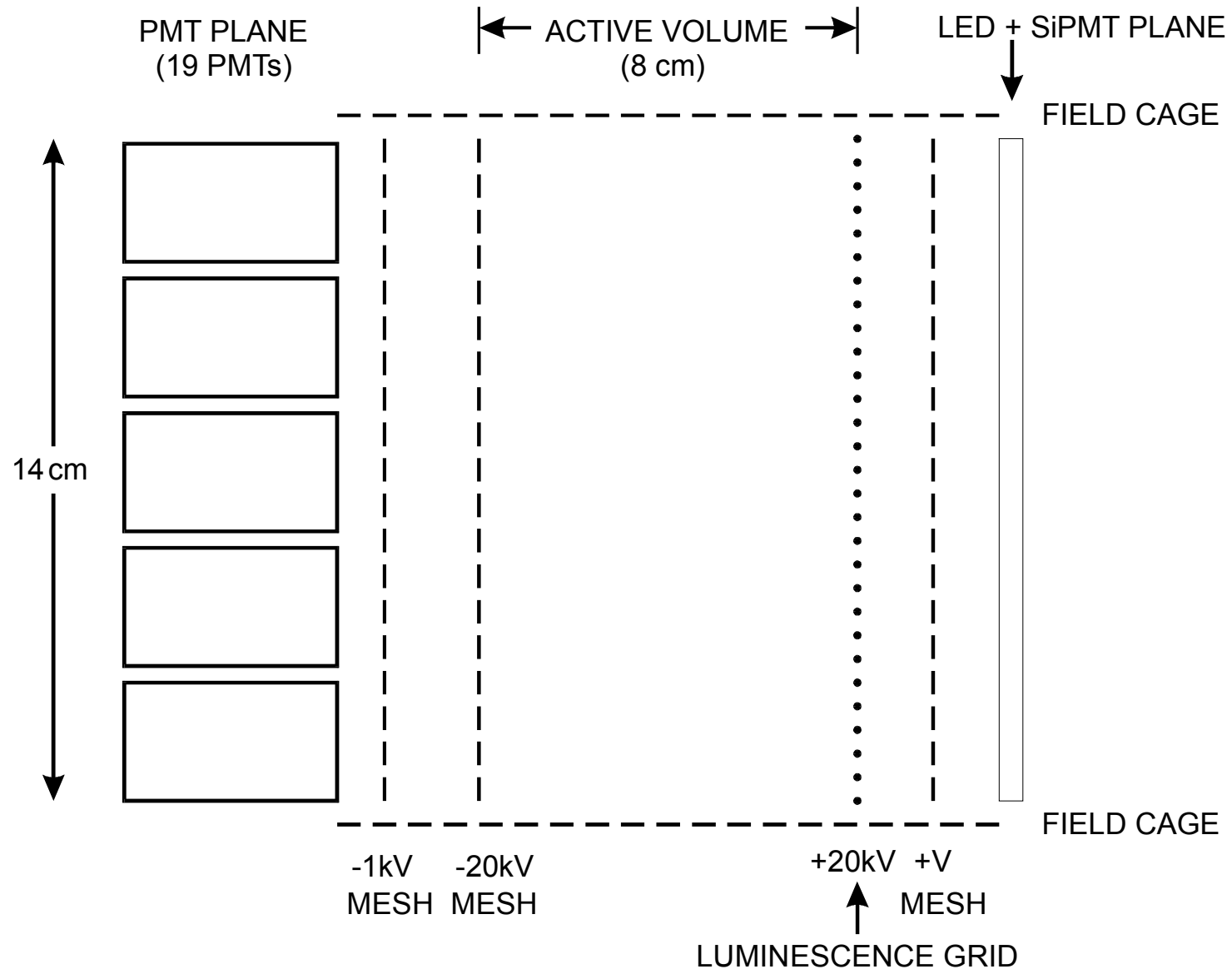


Principle of Current LBL Chamber



Field cage enclosed in reflective Teflon to increase light collection efficiency and distribute light uniformly over the PMT array.

Layout of Current LBL Chamber



Luminescent Gain

$$\eta = 140 \left(\frac{E}{p} - 0.83 \right) p \cdot \Delta x \frac{\text{UV photons}}{e}$$

C.M.B. Monteiro et al. 2007 JINST 2 P05001

The luminescent field can be formed by

1. A pair of spaced grids
2. A single wire-grid

The spacing of a grid pair is critical \Rightarrow Electric force deforms grids

\Rightarrow Variation of luminescent gain vs. radius

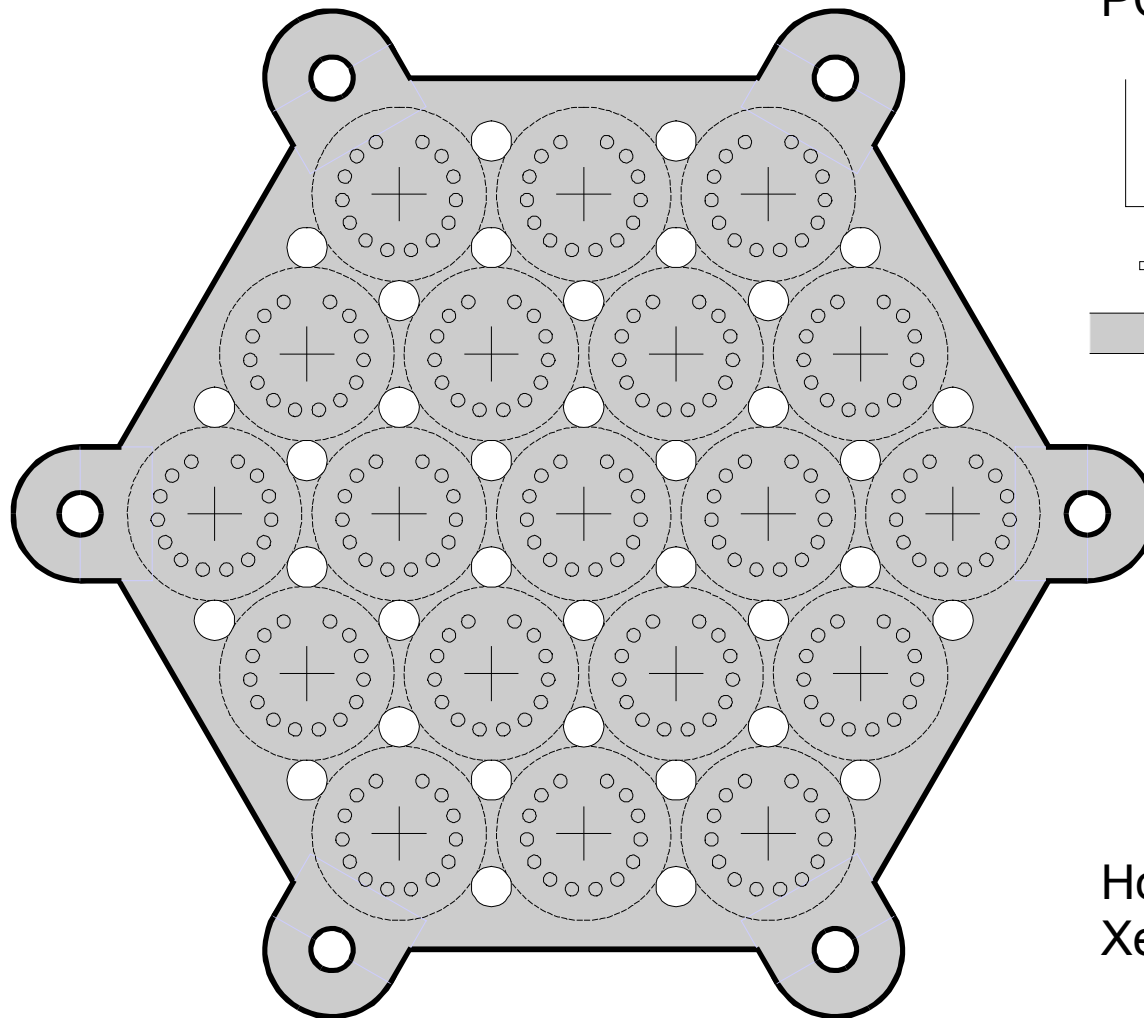
Wire Grid: Combination of applied voltage and wire radius determine the radial range where luminescent gain occurs.

Parameters must also be chosen to avoid avalanching.

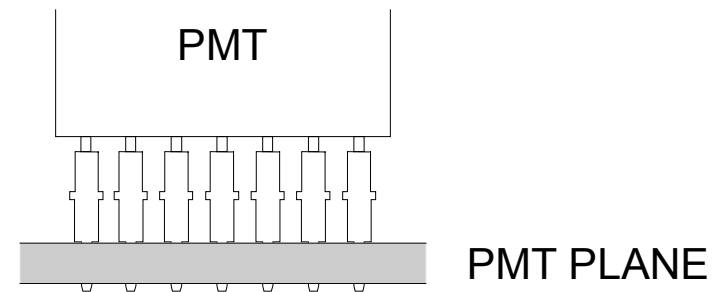
Wire diameter of 300 μm , 6mm spacing yields gain of 300.

Variations in wire diameter < 1 μm .

PMT Plane



Individual pin-contacts in
PC board form PMT socket



Local voltage dividers
with surface-mount
components

Holes in PMT plane to direct
Xe flow through active volume

Challenges

- Signal is distributed over many detectors

Relative calibrations must be accurate to $<0.1\%$

- Signal duration depends strongly on track location and shape:

Drift velocity $\sim 1 \text{ mm}/\mu\text{s}$

Track length for 2.5 MeV electrons in 20 atm Xe: $\sim 16 \text{ cm}$

Diffusion spreads out track signal: $\sim 0.3 \text{ mm}/\text{cm}^{1/2}$ longitudinal
 $\sim 0.8 \text{ mm}/\text{cm}^{1/2}$ transverse

Signals spread over time: min for tracks parallel to luminescence plane
 max for tracks normal to luminescence plane

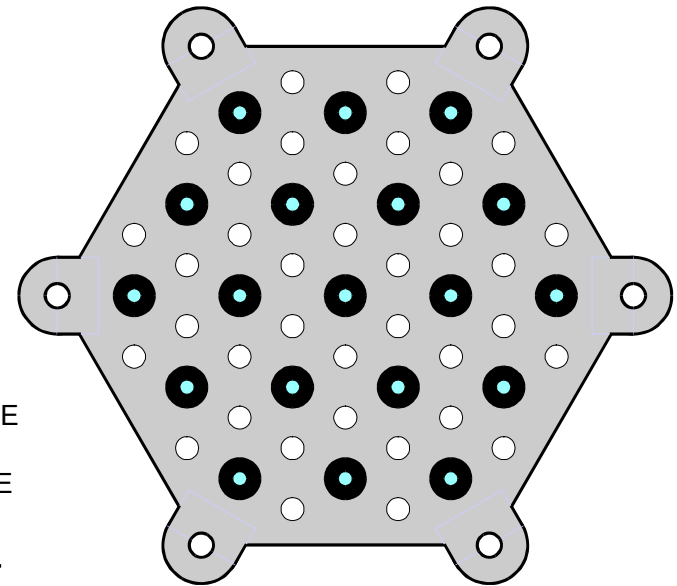
\Rightarrow requires digital integration over 1 – 200 μs

- Light collection efficiency depends on track position
- Luminescent gain must be well controlled
- Contaminants that quench signals
- Xe light emission at 170 nm, UV beyond standard photodetectors

Relative PMT Gain Calibration

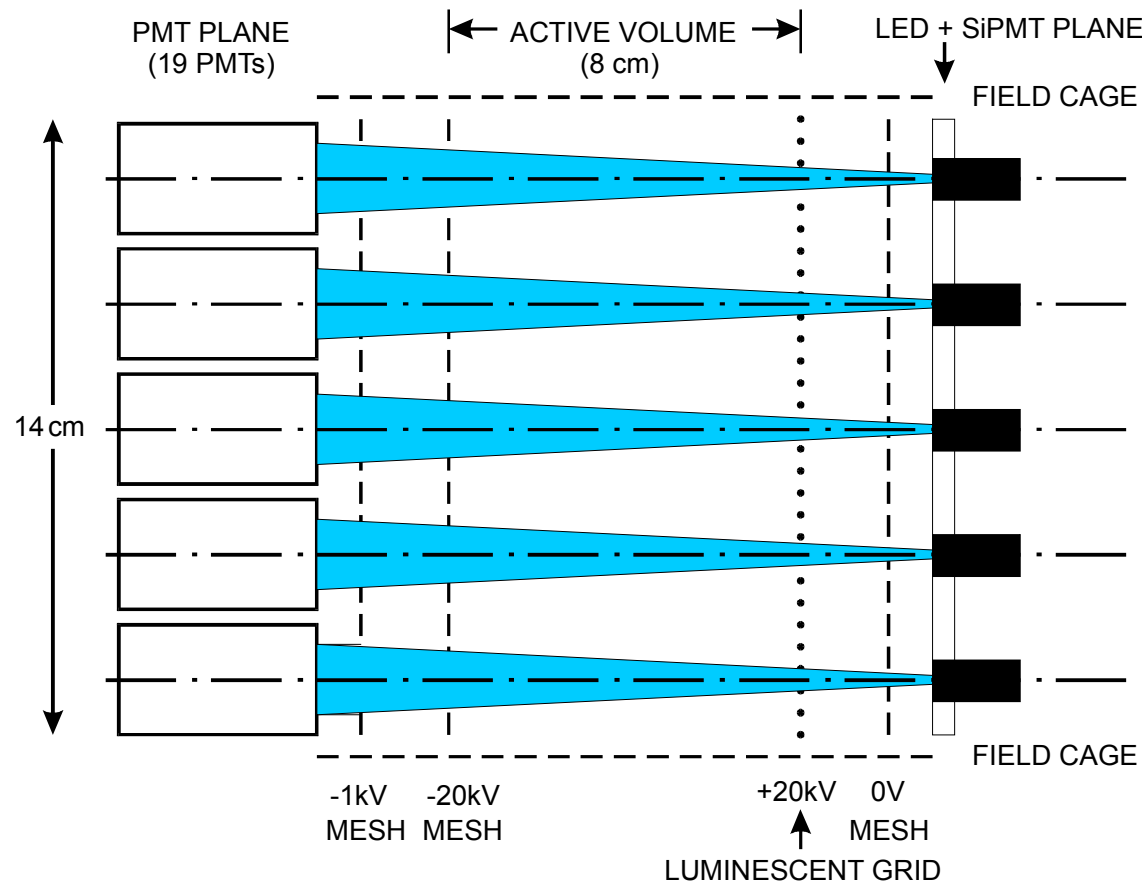
Collimated array of far-UV LEDs: one per PMT

Individually pulsed and intensity controlled



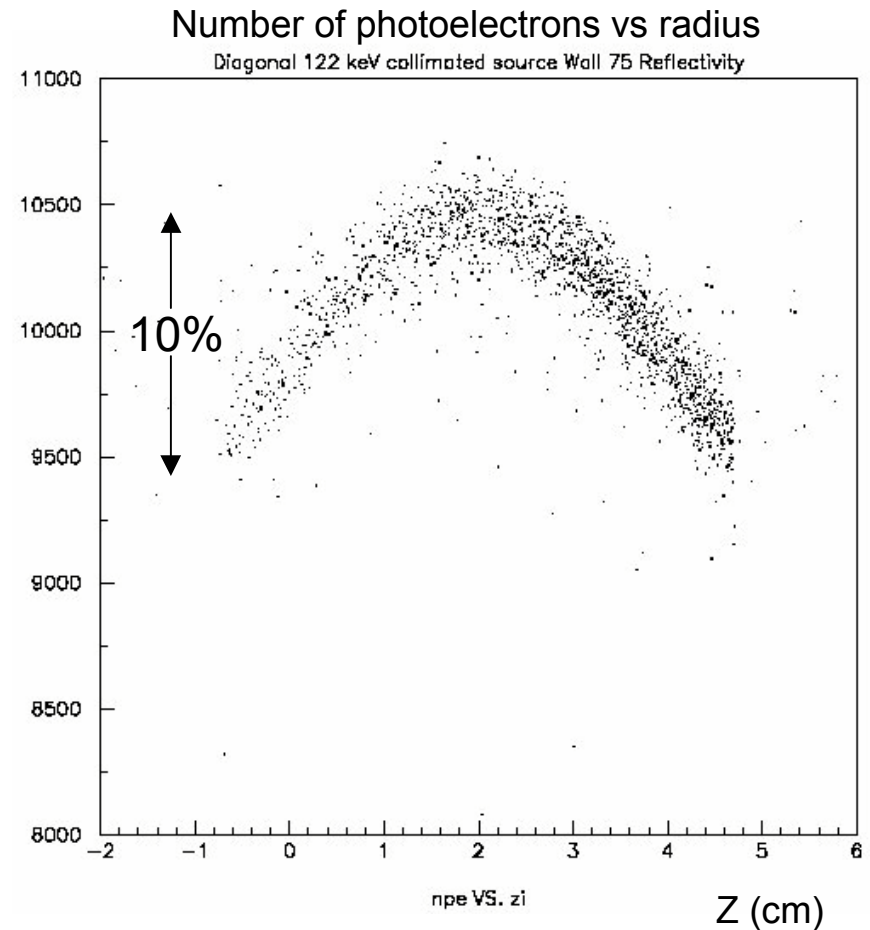
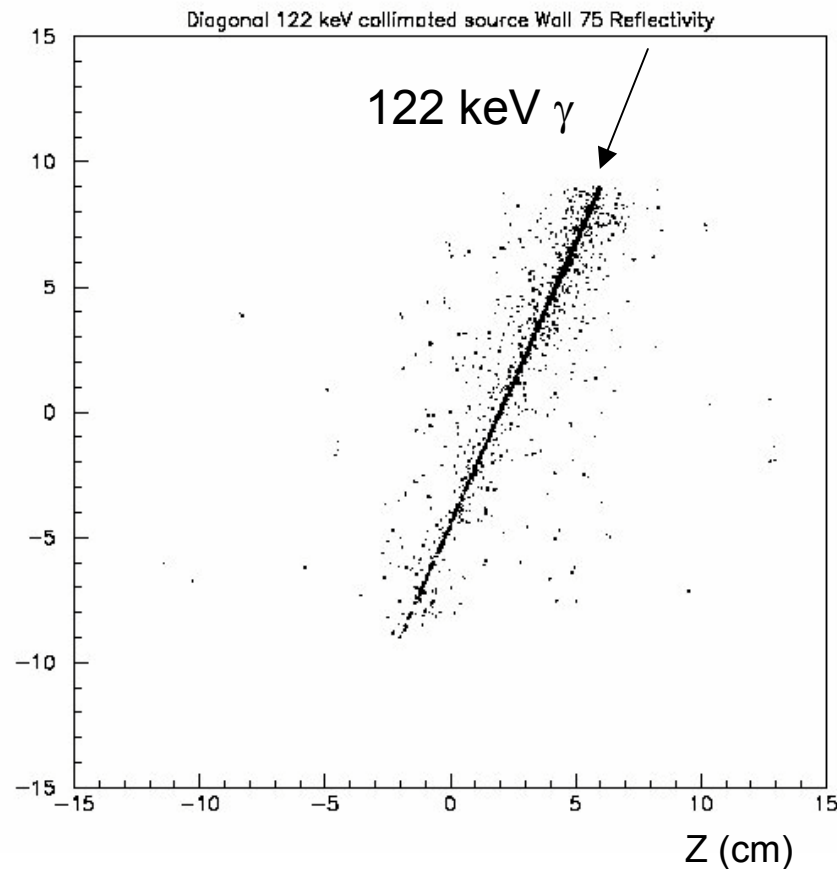
LED Plane

Open holes for Xe flow



Simulated Light Collection Efficiency vs. Position

- Simulation with 75% reflectivity on walls
- Collimated source inside the pressure vessel
- Use drift time to determine Z and thus radius



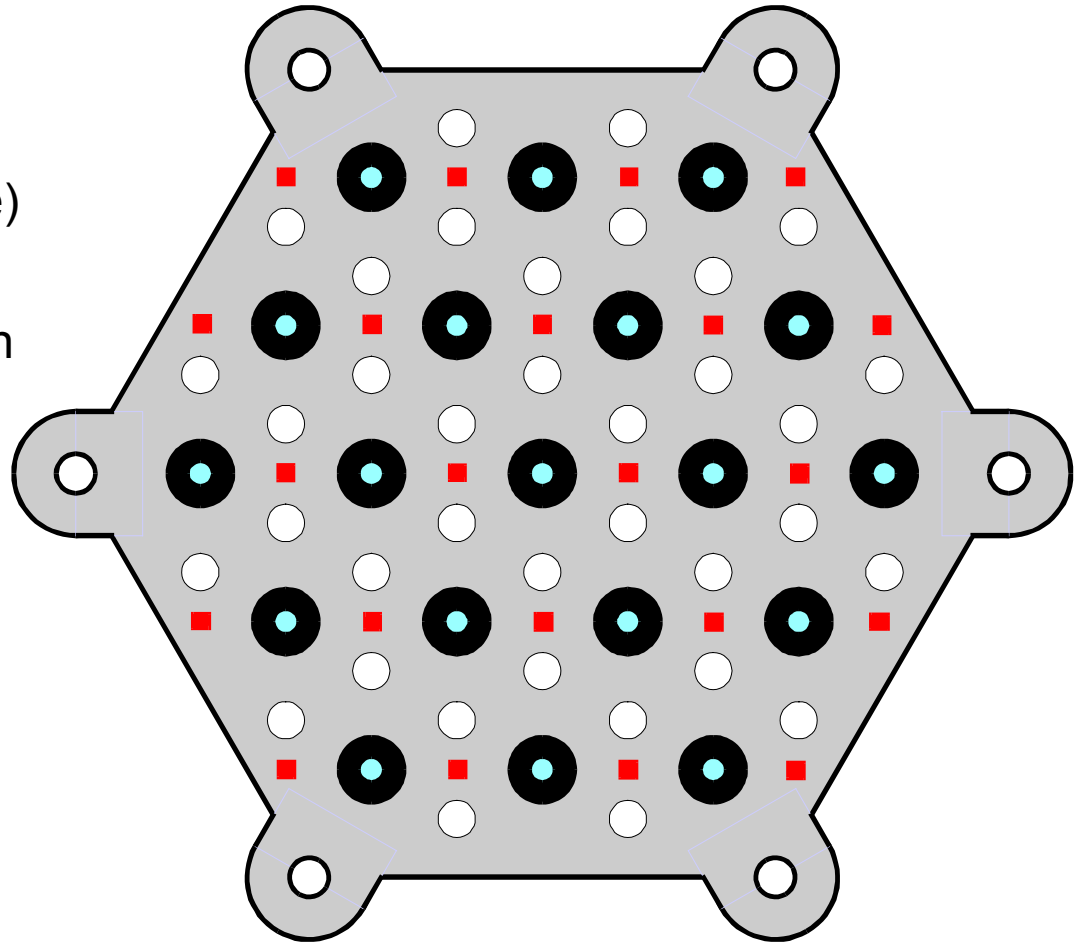
Measured signal also includes variation of luminescent gain vs. radius.

Light collection efficiency vs. position requires coarse position sensing

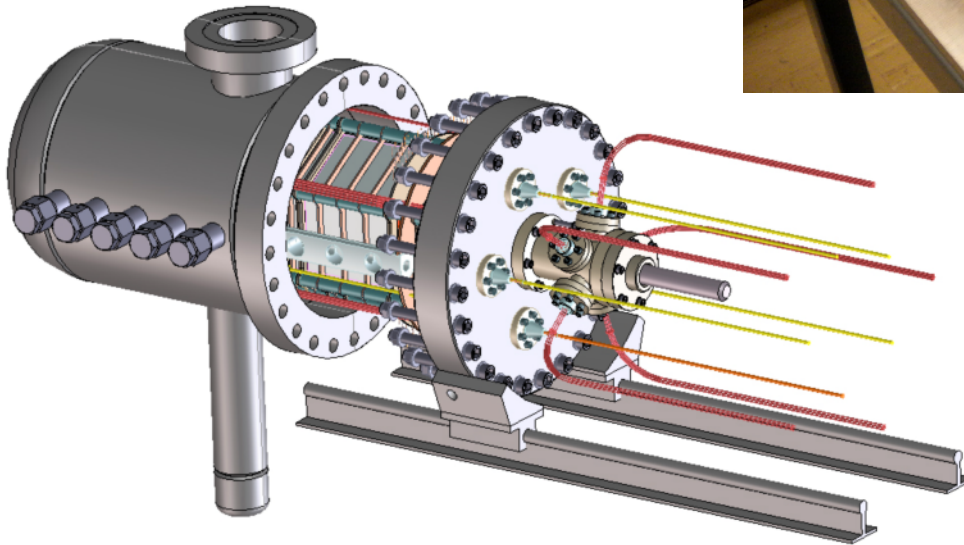
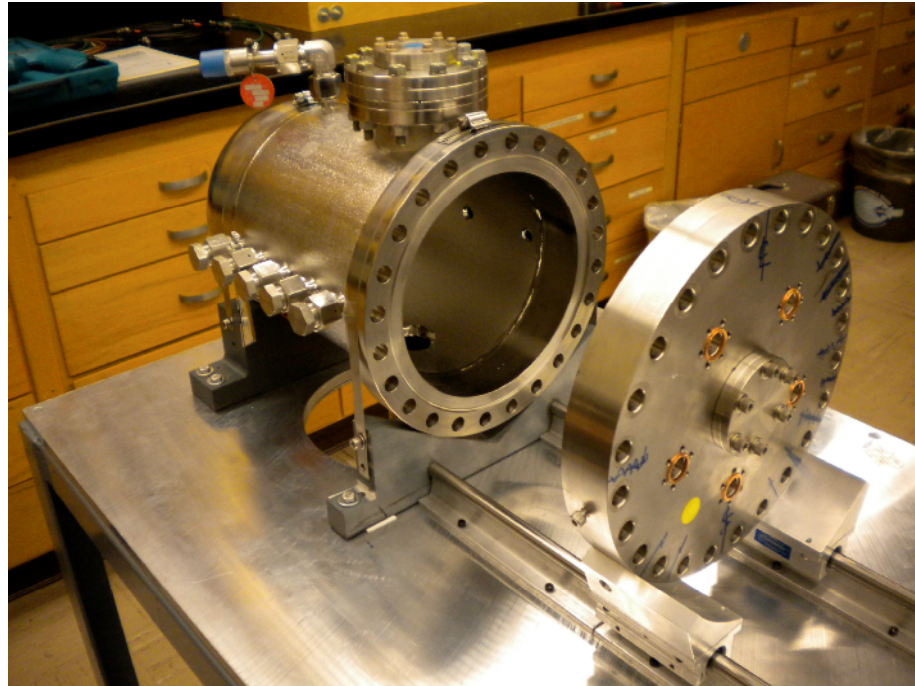
⇒ Array of SiPMTs (■) mounted on LED-SiPMT plane

SiPMT surface-mount chips will be coated with TPB (Tetra-Phenyl-Butadiene) wavelength shifter.

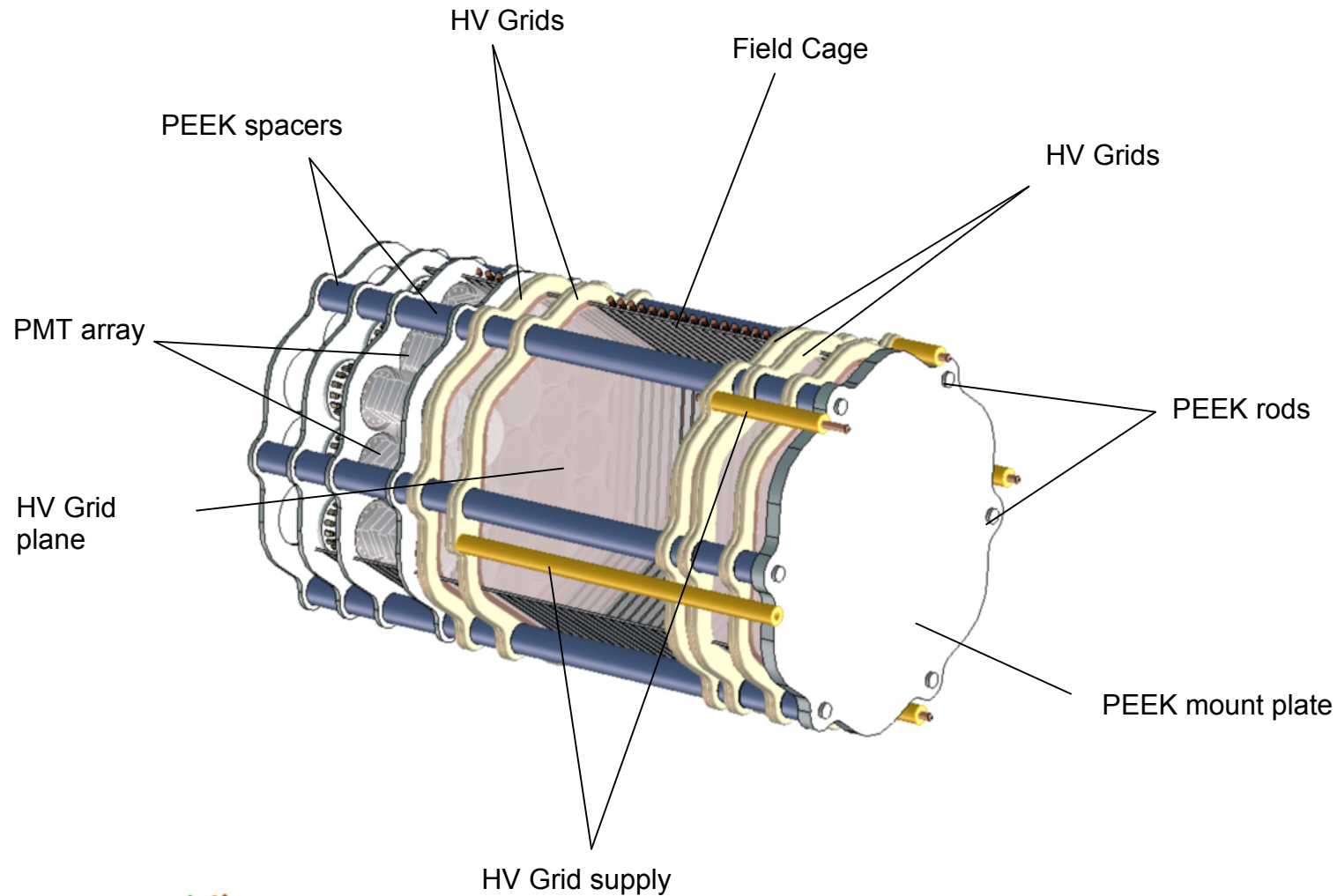
Converts 170 nm Xe emission to 440 nm.



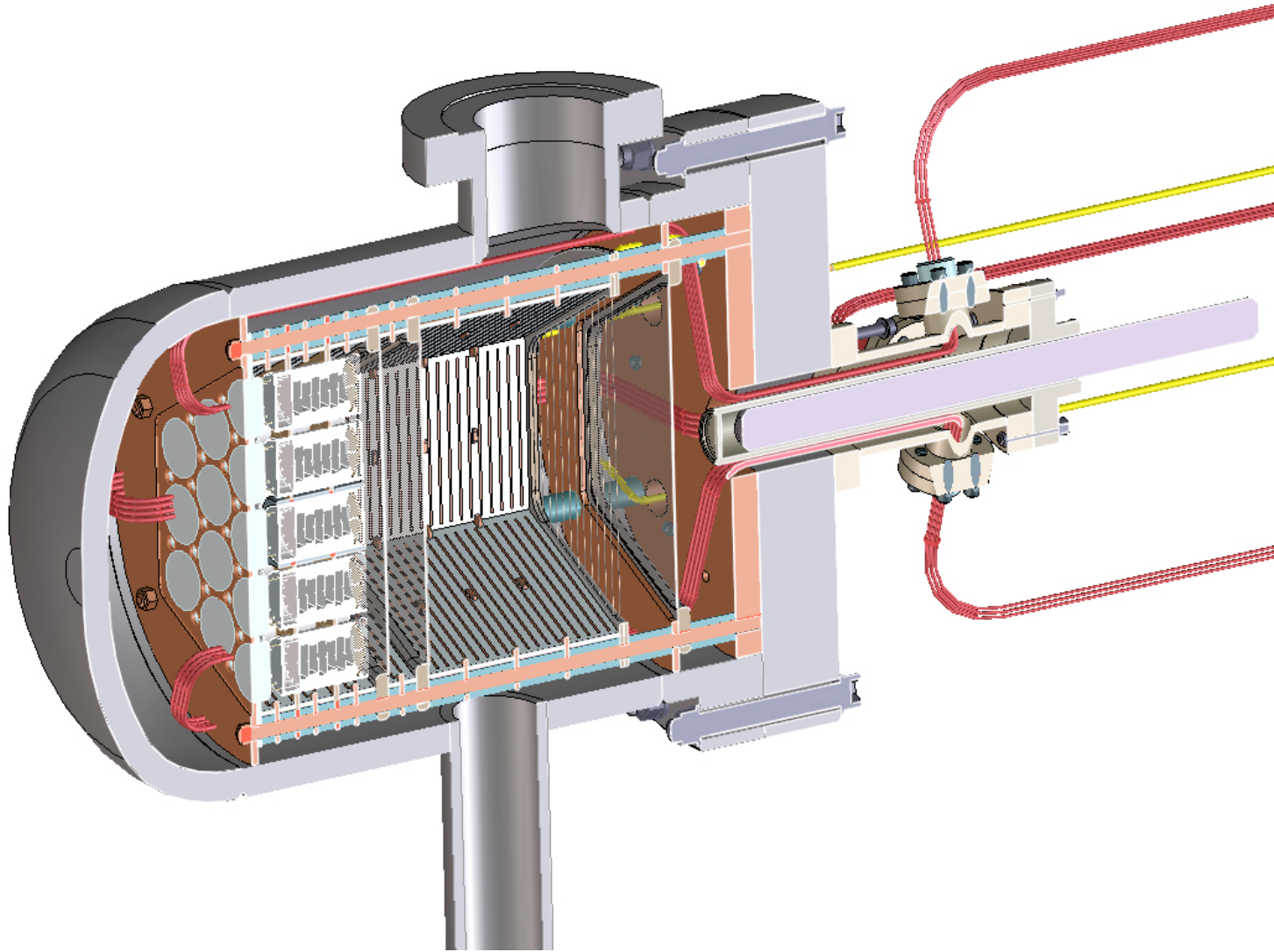
High-pressure chamber exists and inner components now under construction.



Chamber formed of individual layers supported by six rods to facilitate modifications in testing various configurations.

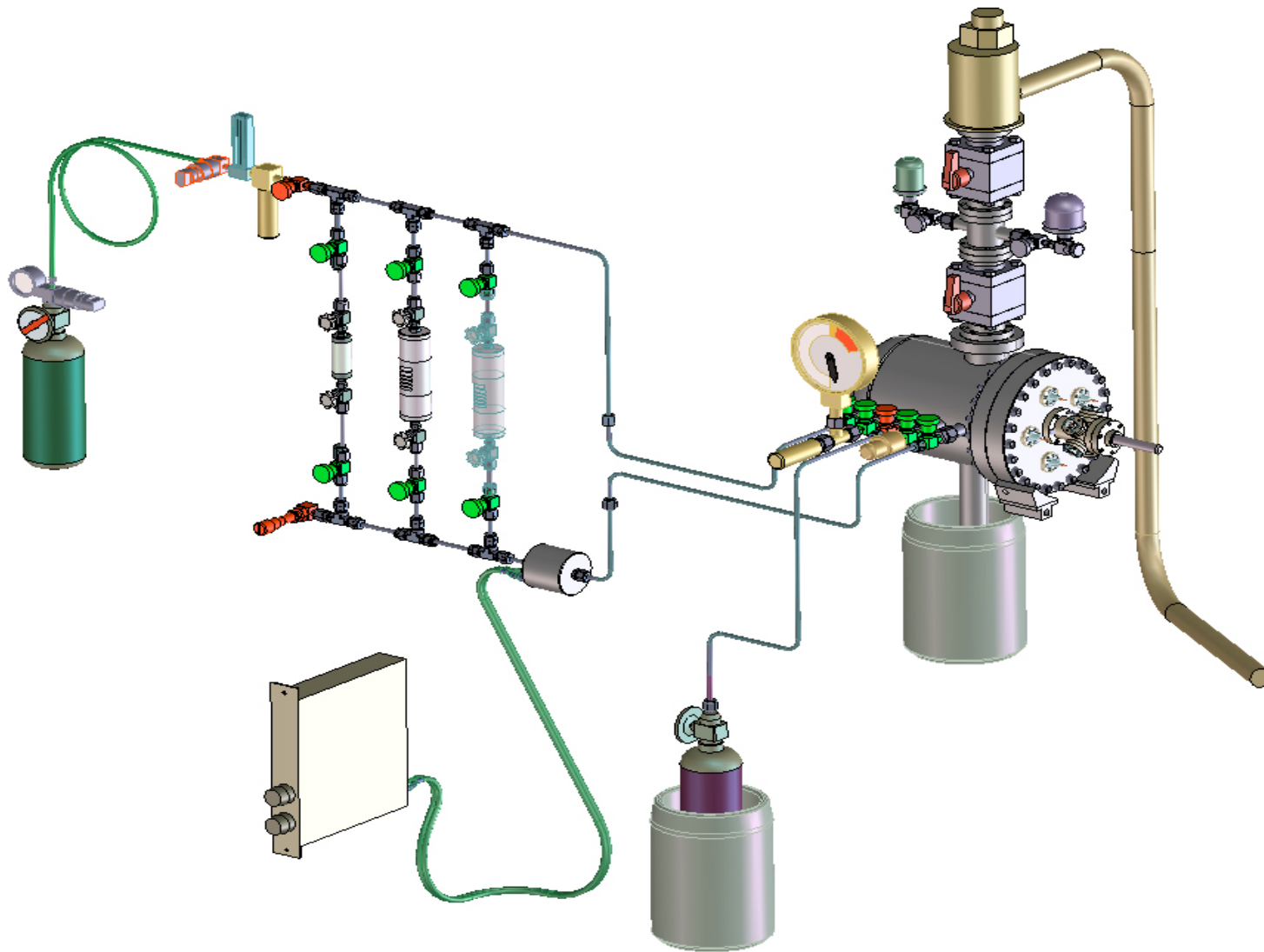


The Teflon field cage will enclose the active volume to direct the purified Xe flow.



Gas System

Utilize getters and continuous recirculation to purify Xe.



Gas Cycle

- Vacuum pump the chamber ($< 10^{-4}$ Torr)
- Flush with Argon
- Vacuum pump again
- Transfer Xe by freezing in chamber reservoir
- Let Xe warm up and reach high pressure
- Recirculate Xe continuously
- Run experiments
- Recapture Xe by freezing in reservoir

Summary

High-pressure Xe Time Projection Chambers can provide a unique combination of

- high energy resolution
- particle tracking
- mapping of event topology

to improve signal to background ratios.

Potential applications include

- Searches for rare events,
e.g. neutrinoless double-beta decay and WIMP searches
- Large-area gamma-ray detectors with background suppression

Energy resolution still to be verified – lots of work ahead!