New developments in high-pressure Xe ionization chambers, new surprises of fluid Xe

Aleksey Bolotnikov
Nonproliferation and National Security Department

Thanks to

Graham Smith
Peter Vanier
Leon Forman

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Outline

Introduction (application areas of HPXe ionization chambers)

I. Spectroscopic properties of HPXe as detecting medium

II. Technological problems

III. HPXe detector designs and examples

IV. Results from neutron measurements

Conclusion

The main goal of is to show that:

- high-pressure Xe technology is developed and ready to use
- high-pressure Xe is very interesting and surprising object for general studies

Why is Xe?

Xe has been recognize as excellent detection medium since introduction of first ionization detectors

- noble gas
- chemically stable
- not radioactive, withstand high radiation
- has high atomic number, 54
- has small Fano factor, 0.1 compare 0.06-0.13 for Ge
- doesn't trap electrons, uniform => large volume
- relatively small W-value, ~20 eV, 3.6 eV Si, 3 eV Ge, 5 eV CZT
- can be compressed or liquefied to achieve high density up to 3 g/cc, but smaller than Ge,CZT
- Low cost => large volume

What limited the development of technology for long time?

Despite many advantages of Xe, only low pressure Xe gas was used in different kinds of radiation detectors: Ionization, scintillation and proportional chambers.

The purification of Xe remained the major problem for many years.

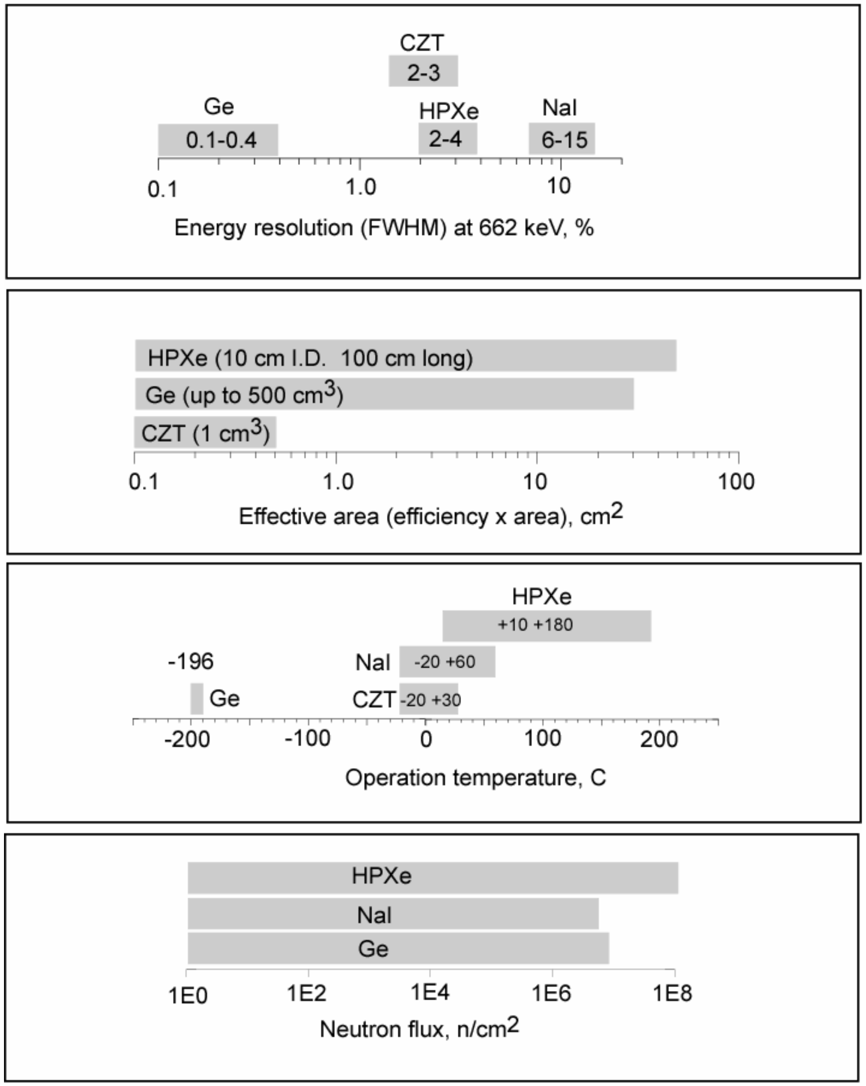
Eventually this problem was solved and reliable technologies for gas handling were developed. But still practical applications of HPXe or LXe were very limited because HPXe could not compete with other available detection techniques.

This situation has changed recently. New applied tasks for HPXe: detectors for portal security and environmental monitoring. New scientific tasks for LXe: high-energy physics, dark matter experiments which require huge LXe detectors.

General characteristics of HPXe detectors

Advantages:

- large effective area, m2
- good energy resolution, <3% FWHM at 662 keV,
- high stopping power due large Z,
- long-term stability (years) without maintenance,
- capable of operating in harsh radiation environment, at high temperatures up to 200 C,
- comparably low cost



Limitations of HPXe ionization chambers:

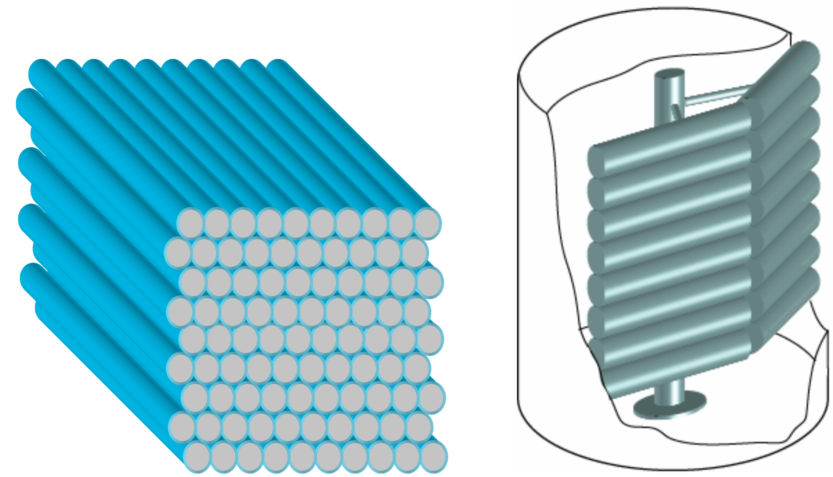
- detectors are balky and heavy,
- low-density of detection medium, ~0.5 g/cm^3
- design constrains, associated with
  high-pressure,
  high-voltage,
  high-purity requirements.

Application arias

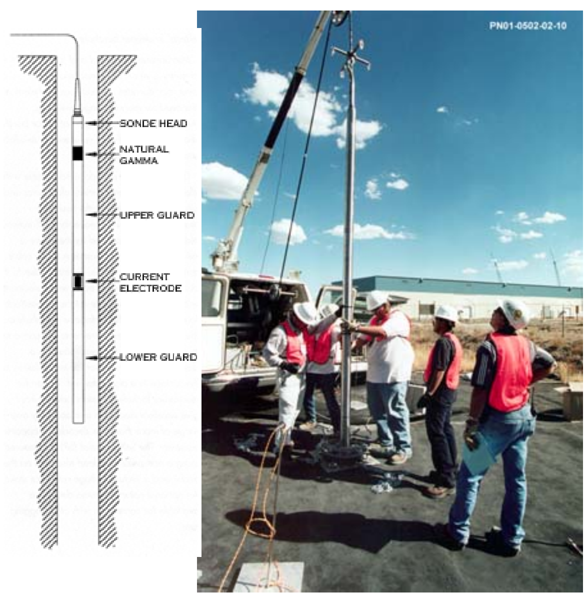
Practical devices:

(1) Large-volume, up to 1000 cm^3, high-sensitive spectrometers (single or arrays) for portal applications and environmental monitoring.

(2) Small-volume, < 200 cm^3, robust spectrometers for application in harsh environments (high-radiation, high-temperature, high-vibrations, etc.), e.g., active zone of nuclear reactors, radioactive waste, well-logging.



Portal security and environmental monitoring



Nuclear Well Logging

Outside these areas, HPXe detectors will not be able to compete with other available techniques: HPGe, CdZnTe, NaI, etc.

Electron mobility

Data from V. Dmitrenko et al., MEPhI

Adding H_2

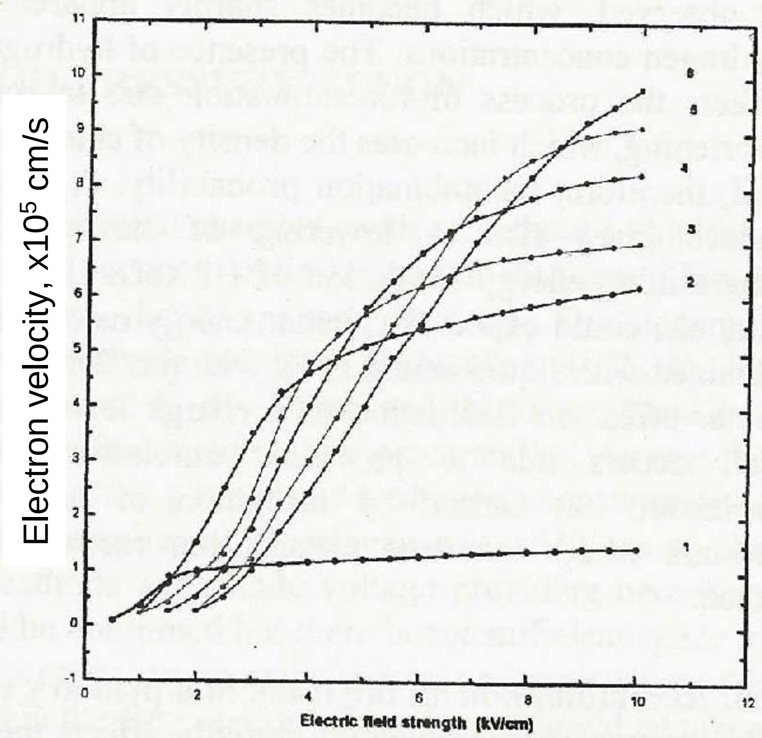
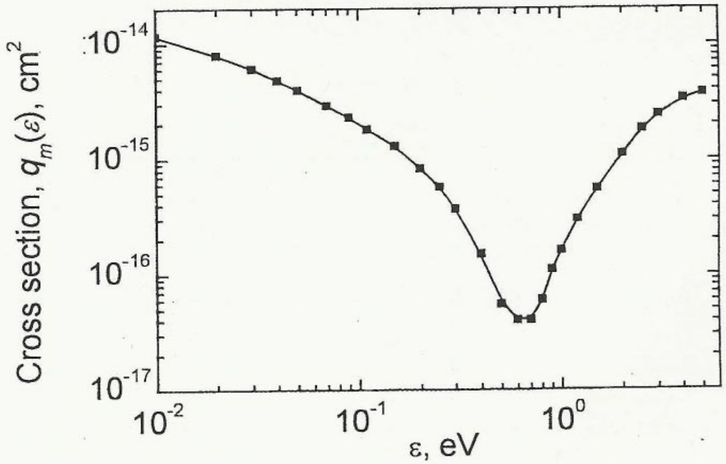


Fig. 2. Electron drift velocity in xenon with density 0.6 g/cm^3 at various hydrogen concentrations as function of electric field.
1-pure xenon, 2-Xe+0.2%H_2, 3- Xe+0.3%H_2, 4- Xe+0.5%H_2, 5- Xe+0.7%H_2, 6- Xe+1.0%H_2.

Electron scattering momentum transfer cross section.

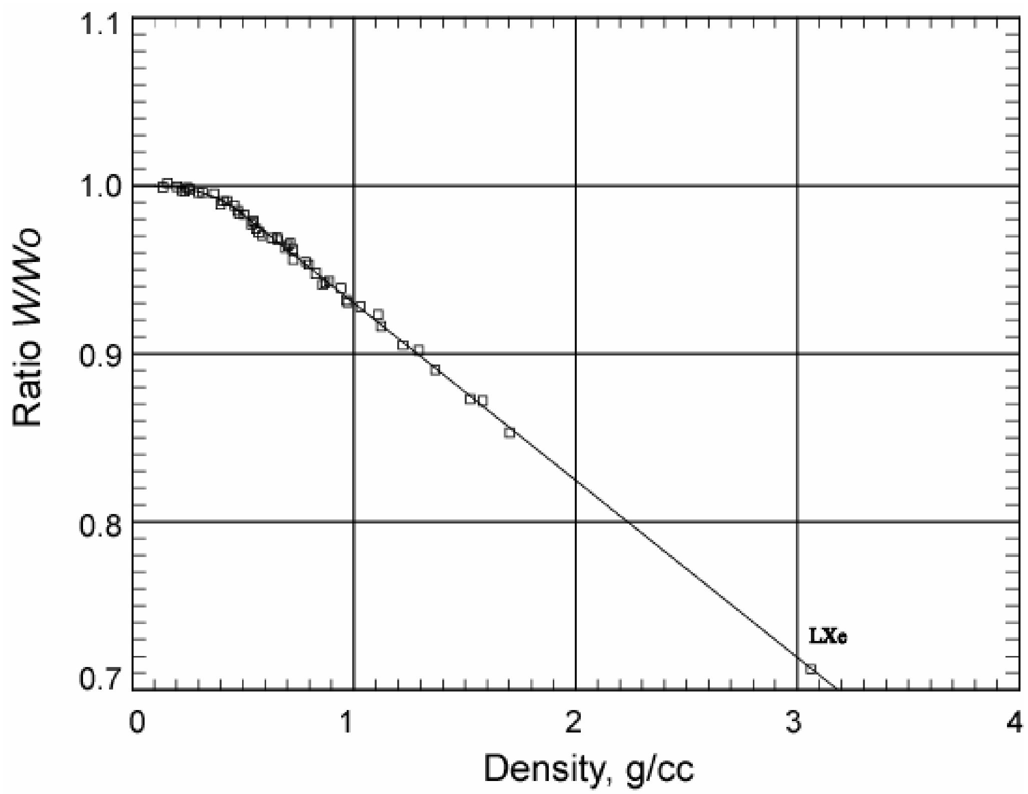


1 cm in ~10 us in pure Xe
vs.
1 cm in ~2 us in Xe+0.3%H_2

Similar effect with He

W-value (old surprises)

A. Bolotnikov and B. Ramsey, Nucl. Inst. and Meth. A396, pp. 360-370, 1997



W-value at low pressure 21.5 eV

There is no explanation of the density effect on the W-value.

It can be attributed to the formation of the conduction and valence bands at high densities

Electron-ion recombination

Primary ionizing particle generates secondary hot electrons
=>
Secondary electrons get thermolized while they diffuse away from the primary track (or delta-electron tracks)
=>
After thermolization electrons can recombine with positive ions

High electric field is required to extract electrons from the electron tracks!

This is different from the semiconductor detectors where high electric field is necessary to avoid electron trapping.

In HPXe the extracted electrons are collected with 100% efficiency.

Recombination is described by

$Q=Q_0/(1+K/E)$,

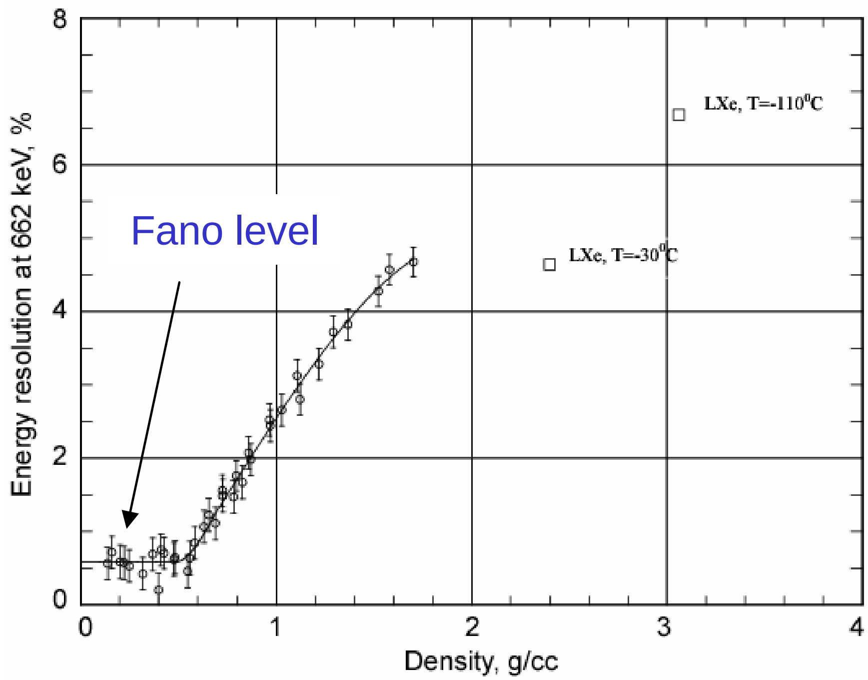
where Q_0 is the total produced charge.

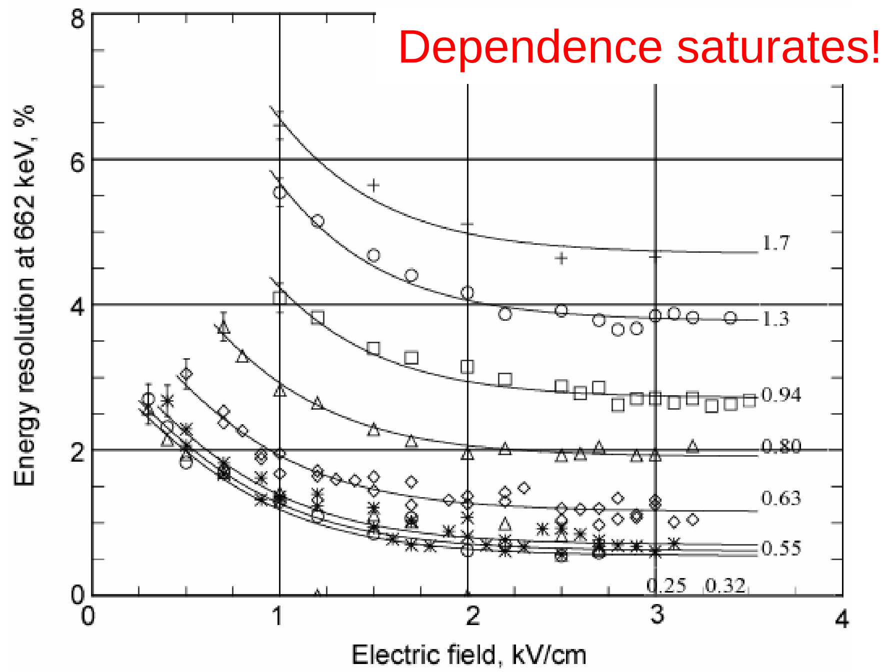
This dependence is equivalent to the depth dependence of the collected charge in semiconductor detectors.

At high densities recombination becomes very strong. As a results less charge is extracted from the tracks. Up to certain densities this charge loss is not important for device performance.

Intrinsic energy resolution (old surprises)

A. Bolotnikov and B. Ramsey, Nucl. Inst. and Meth. A396, pp. 360-370, 1997





There is no clear understanding of the density effect on energy resolution.

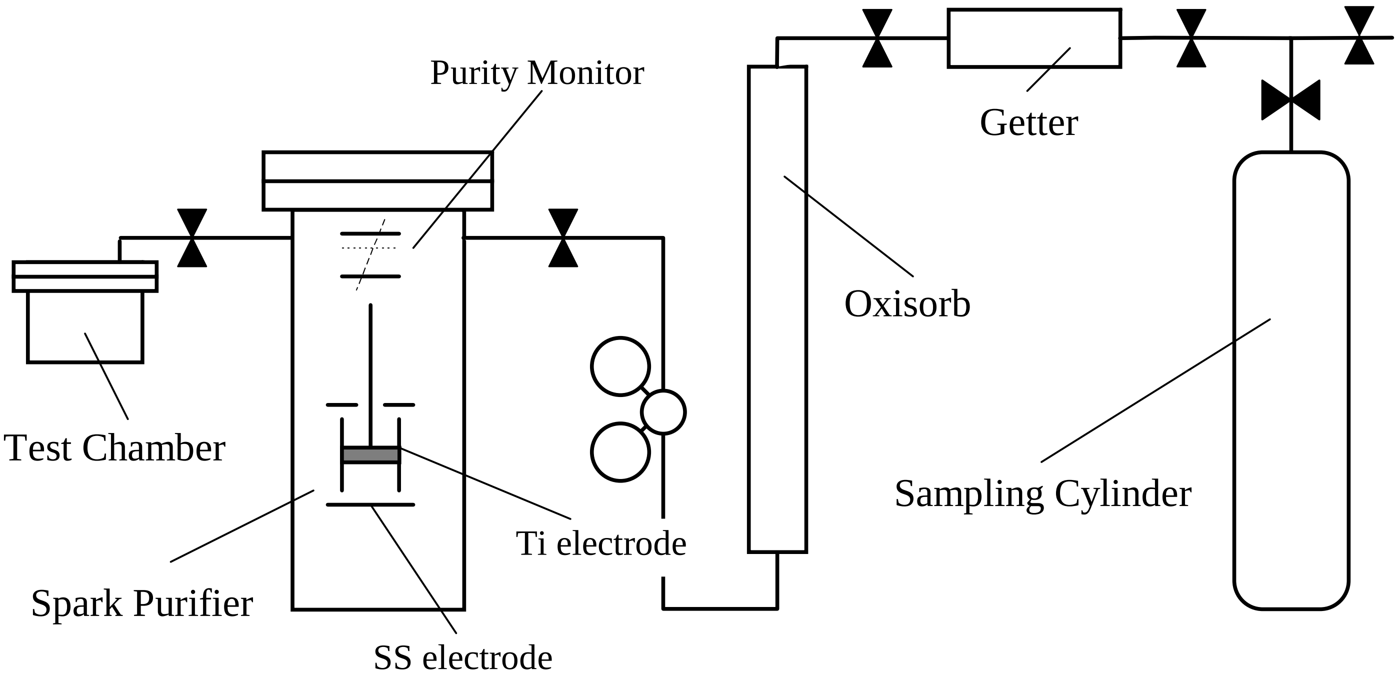
Caused by fluctuation of recombination process. There are tracks where electrons recombine with 100% regardless applied field. Fluctuations in number of such tracks degrades energy resolution. Such tracks could be formed by delta-electrons or density fluctuations (Xe clusters)?

Xe density should less than 0.55 g/cc!

Xe purification

A. Bolotnikov and B. Ramsey, Nucl. Inst. and Meth. A 383 (1996) 619 .

Removal of electronegative impurities: O_2, CO, CO_2, organic, etc.
Electron lifetime, > 1 ms
Chemical vs. spark purifier, Ti dust
Gas system/detector cleaning and preparation

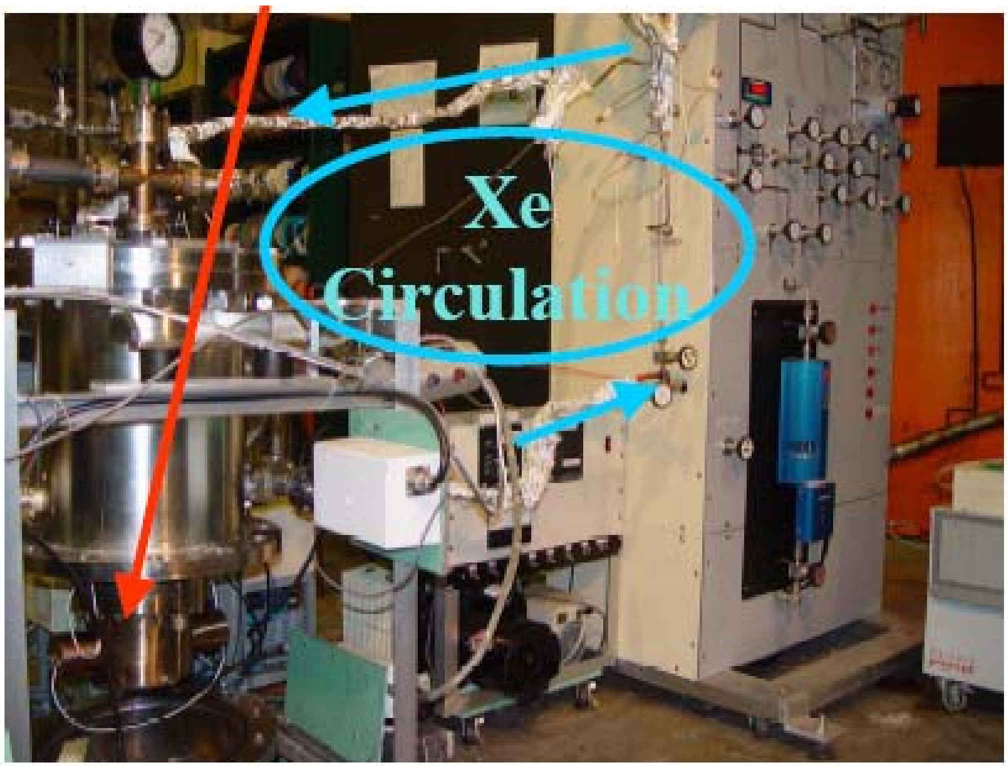


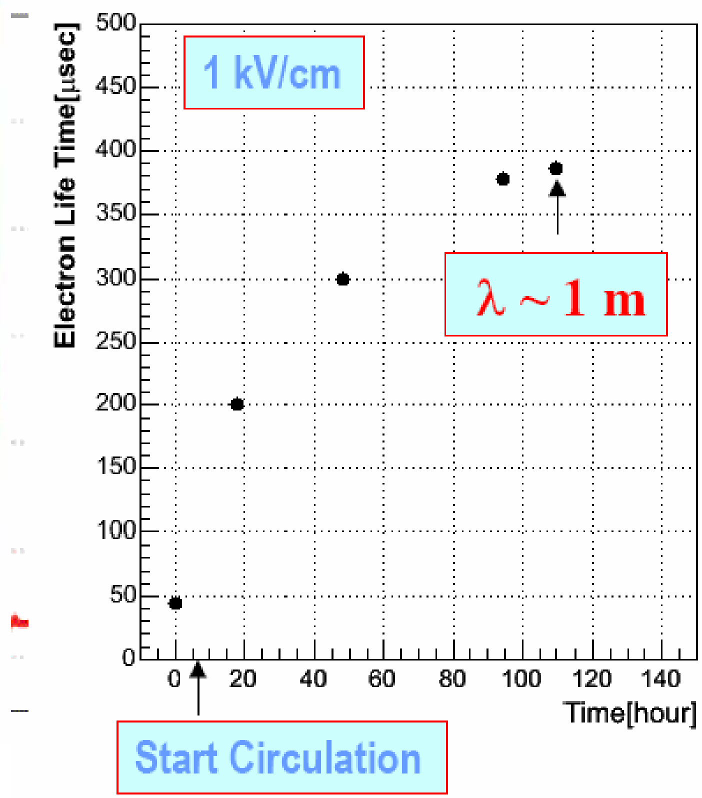
G. Smith el al., BNL

Xe purification system developed at Columbia University

E. Aprile, et al. (Astrophysics Laboratory website)

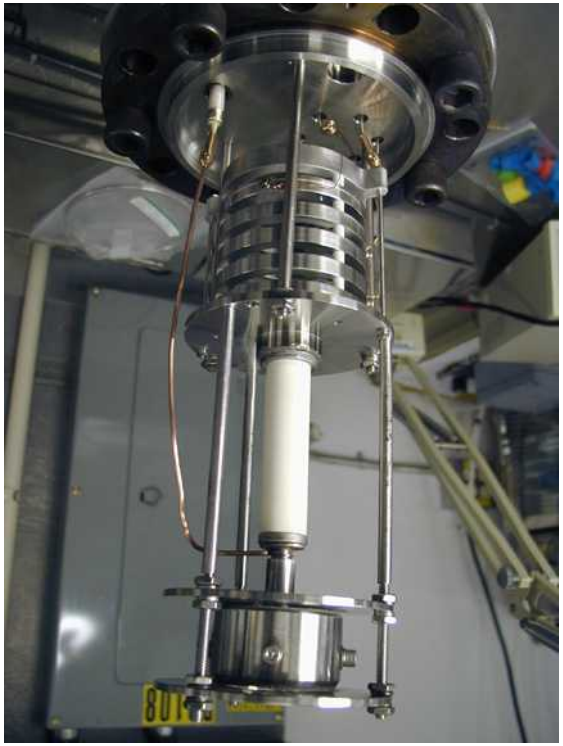
Similar approach was used by G. Smith in BNL





Spark purification system/storage

The device is being used by CTC, Michigan University, Virginia Commonwealth University, Mirmar Sensors, MEPhI



Xe purity monitoring

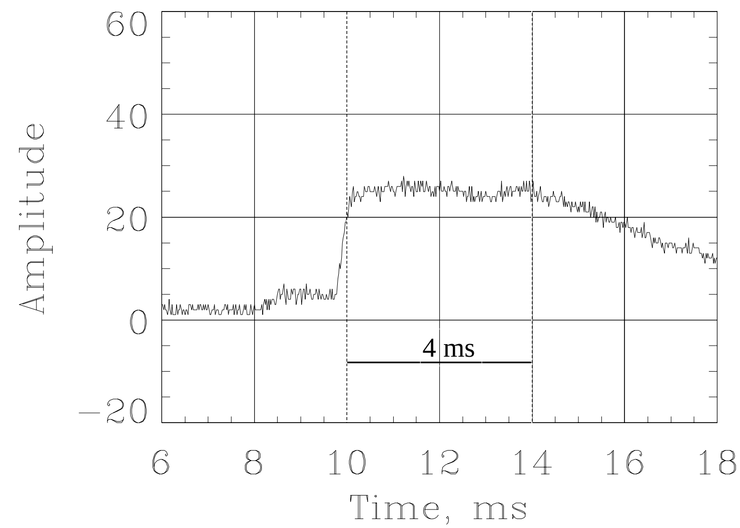
A. Bolotnikov and B. Ramsey, Nucl. Inst. and Meth. A 383 (1996) 619 .

Purity monitor

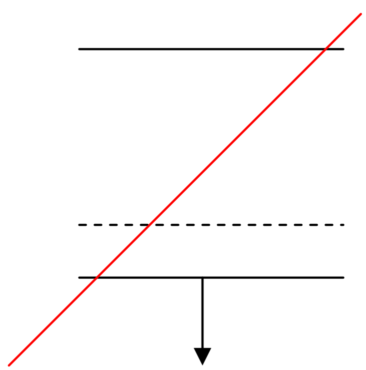
Good detector response is the best purity indicator, but …

Simple and robust method

Take measurements inside Xe storage and detector



Ionization chamber

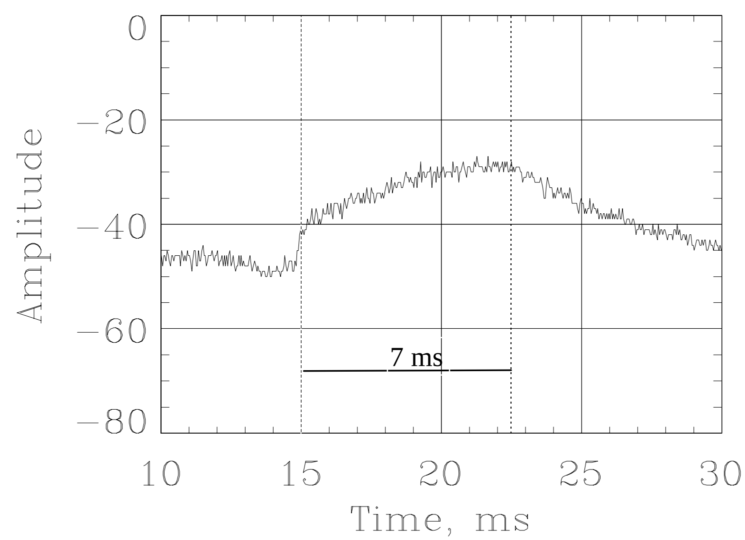


Cosmic muons

Low field

High field

Charge-sensitive preamplifier



Density monitor (dielectric constant measurements)

A. Bolotnikov and B. Ramsey, Nucl. Inst. and Meth. A 383 (1996) 619 .

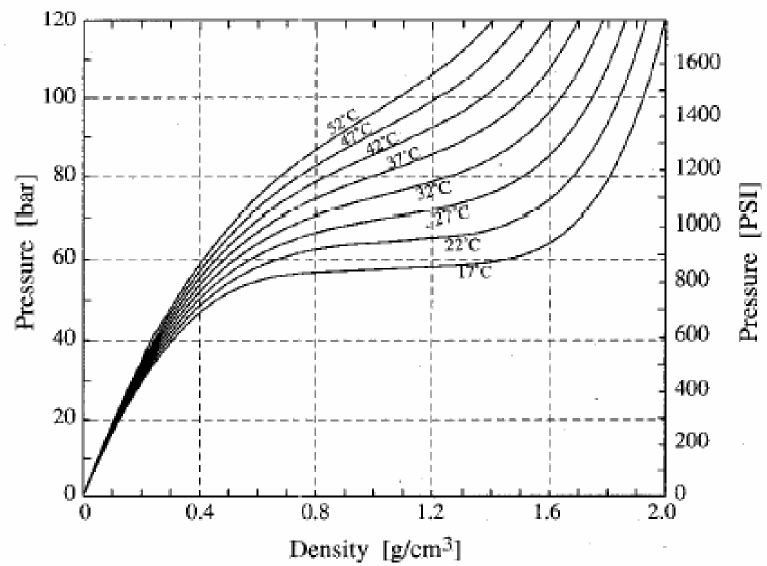
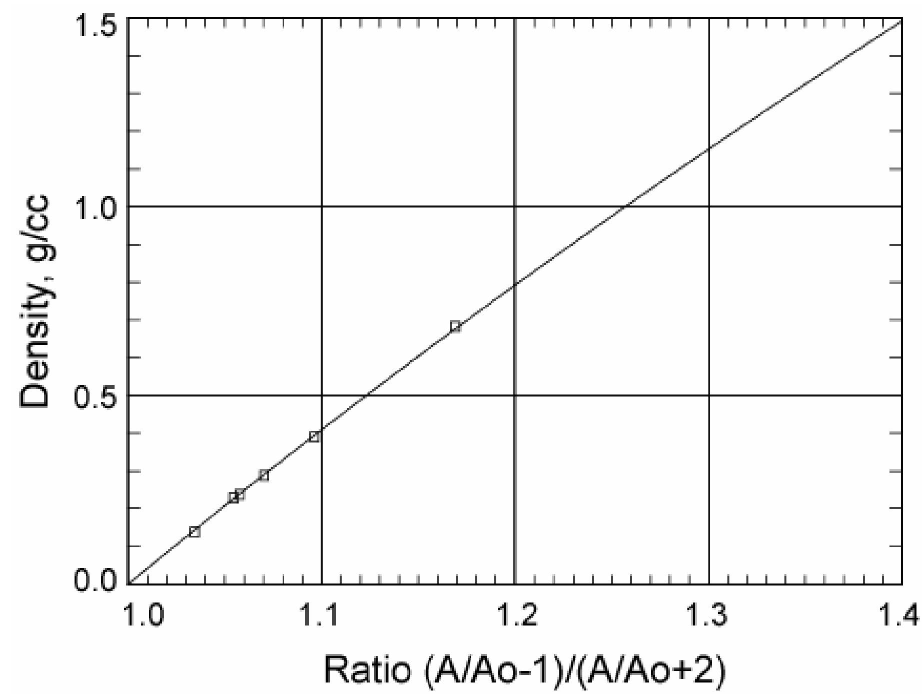


Figure 1. Isotherms of xenon. The detector vessel used in the portable system contained xenon with $\rho = 0.55$ g/cm^3.



$A \sim CV/(C+Cp+(1+g)C_f) \sim \varepsilon$ (dielectric constant)

$\varepsilon = A/Ao$

$R_0 = (\varepsilon-1)/(\varepsilon+2)$. Using the Clausius-Mossoti function:

$R_0 = A\rho + B\rho^2$,

where *A* and *B* are the first and the second dielectric virial coefficients. *A*=10.9 cm^3/mole

With calibrations an accuracy is ~2-3%

Conclusion 1

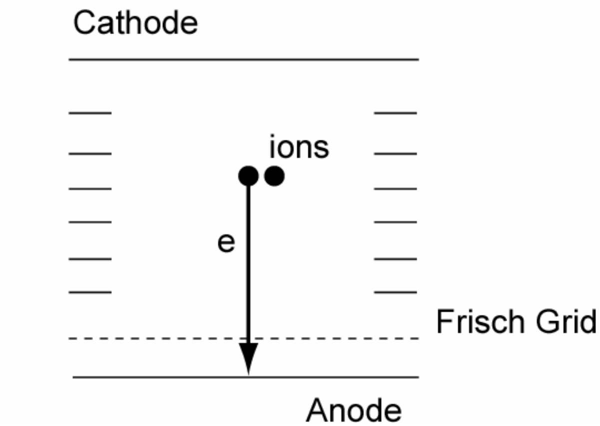
Technology of high-pressure Xe gas is developed and ready to use. It includes:

- Purification of Xe
- Gas handling gas detector filling procedures
- Suitable material and technologies for device fabrication

III. HPXe ionization chamber designs

Classic gas ionization chamber-parallel plate ionization chamber

Drift region



A~Q(1-δ(L-Z)/L)

δ - shielding inefficiency of the grid.

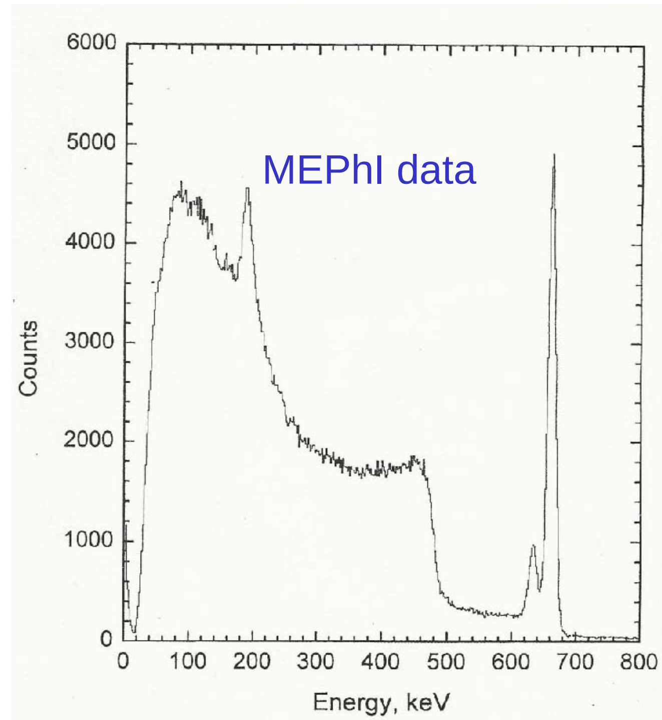
Electron transmission across the grid

The FWHM of the energy peak can be broken down in three terms

$$\Delta E_{tot}=(\Delta E_0^{\,2}+\Delta E_{el}^{\,2}+\Delta E_{in}^{\,2})^{1/2},$$

ΔE_{in} is the contribution due to shielding inefficiency of the mesh (or geometrical width), which in turn can be expressed as $\Delta E_{in}=\delta E_\gamma$, ~2-3% at 662 keV.

Good energy resolution is easy to achieve with a small chambers (small drift region).



Examples: “Xenia” spectrometer onboard “MIR” (3.5% at 662 keV), BNL detector (2.5% at 662 keV).

Cylindrical ionization chamber with Frisch-grid

Drawbacks of parallel plate chamber:

- resolution is limited by shielding inefficiency
- chamber's vessel is not suitable for high pressure

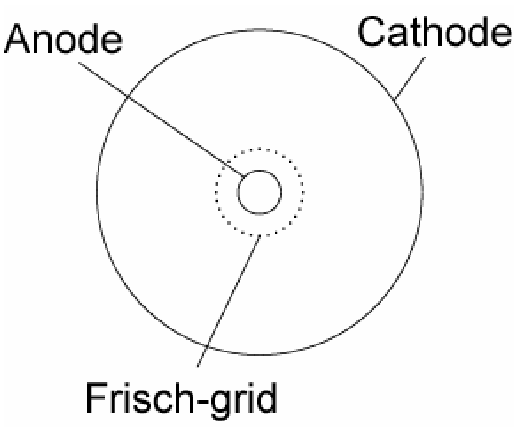
Cylindrical ionization chamber is the most optimal detector geometry for high-pressure Xe:

- more suitable for HPXe (minimize dead areas)
- allows one to compensate shielding inefficiency
- easy to fabricate grid (large spacing)

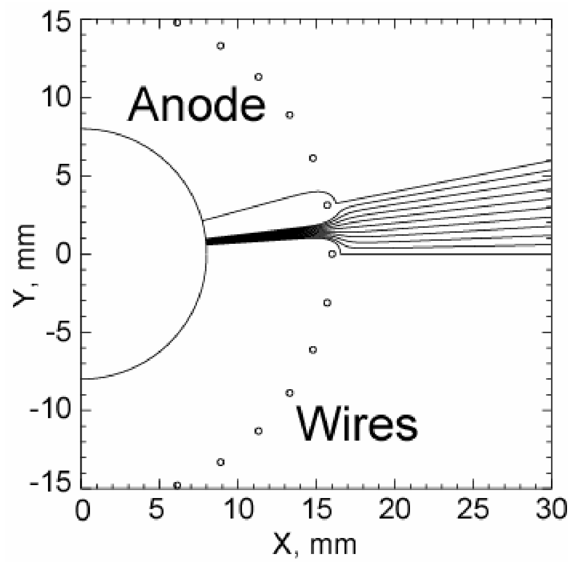
First cylindrical ionization chambers have a Frisch-grid comprised of discrete wires, which made the detector very fragile and sensitive to acoustic noise.

Use of such devices for industrial and field applications was very impractical.

Schematic of cylindrical ionization chamber



Electric field line distribution near the anode



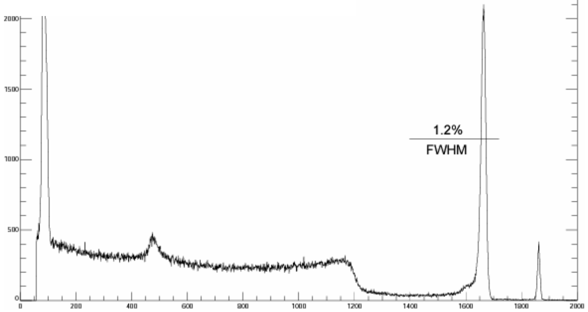
Grid has 100% transparence for electrons and < 1% shielding inefficiency

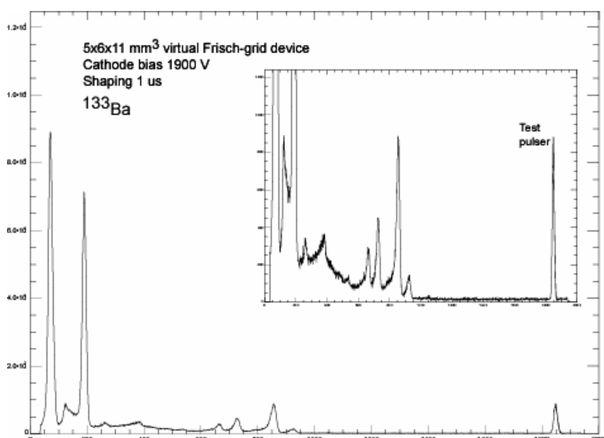
Cylindrical ionization chamber with self-supporting mesh

A. Bolotnikov, B. Ramsey, IEEE NS-44, p. 1005, 1997

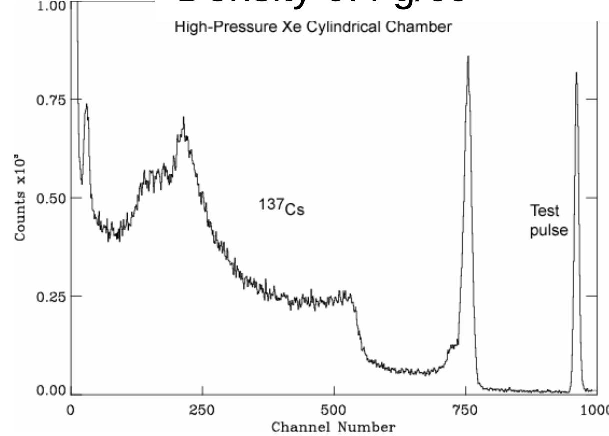
A significant improvement in the design was achieved by implementing a self-supporting cylindrical mesh, which makes the detector more stable and less sensitive to acoustic noise. NASA/MSFC chamber.

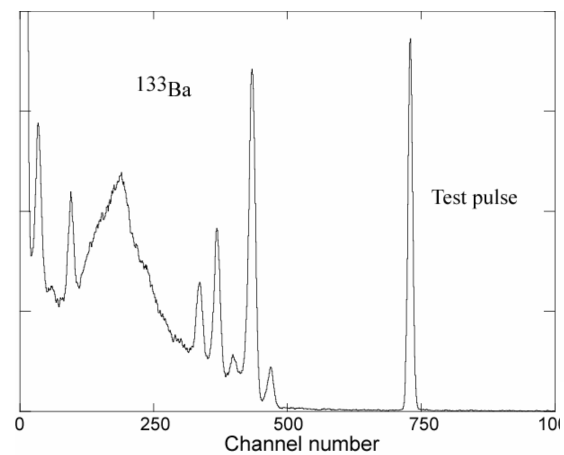
5x6x11 mm^3 "Yinnel Tech"
Resolution: 1.2%
at 662 keV
Temperature ~5 C





50 mm diameter 20 cm long
Density 0.4 g/cc





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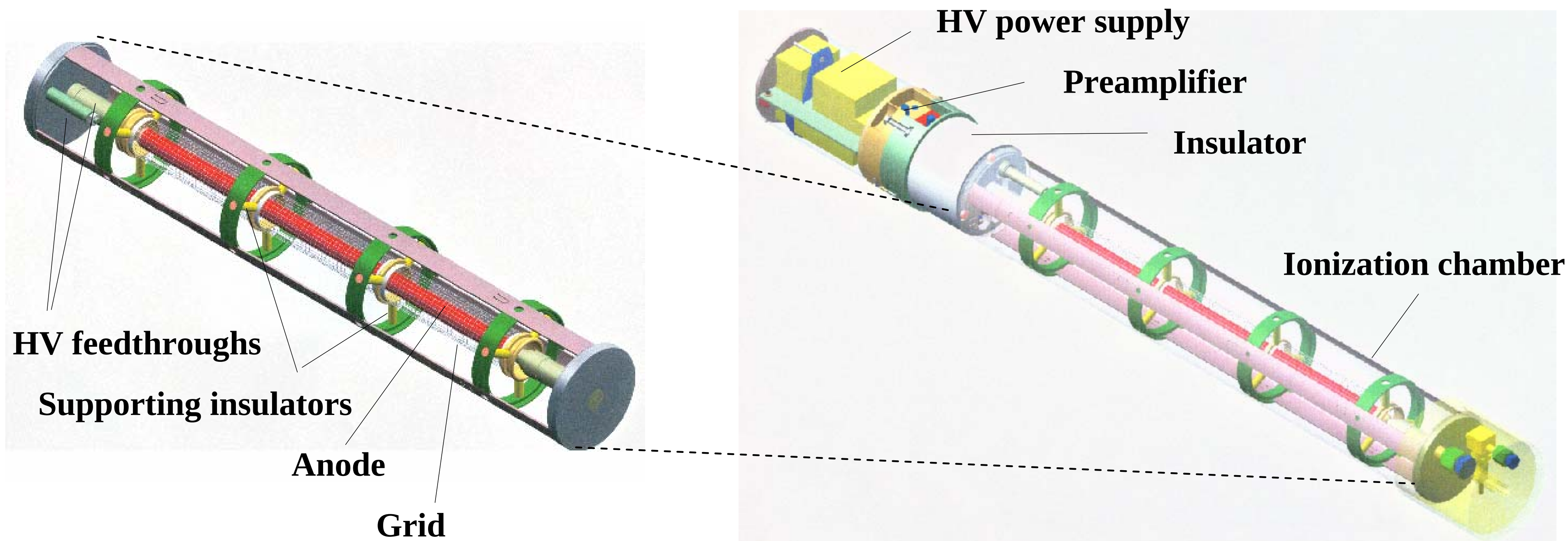
Examples of cylindrical ionization chambers with self-supporting mesh

Chamber developed for CTC (prototype)

Ionization Chamber

Integrated Detector Unit

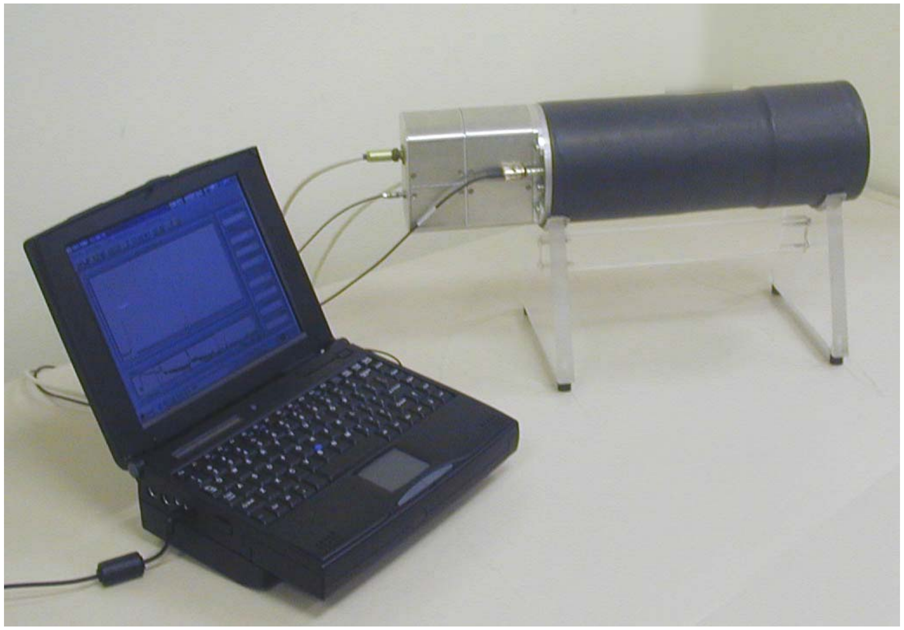


CTC chamber

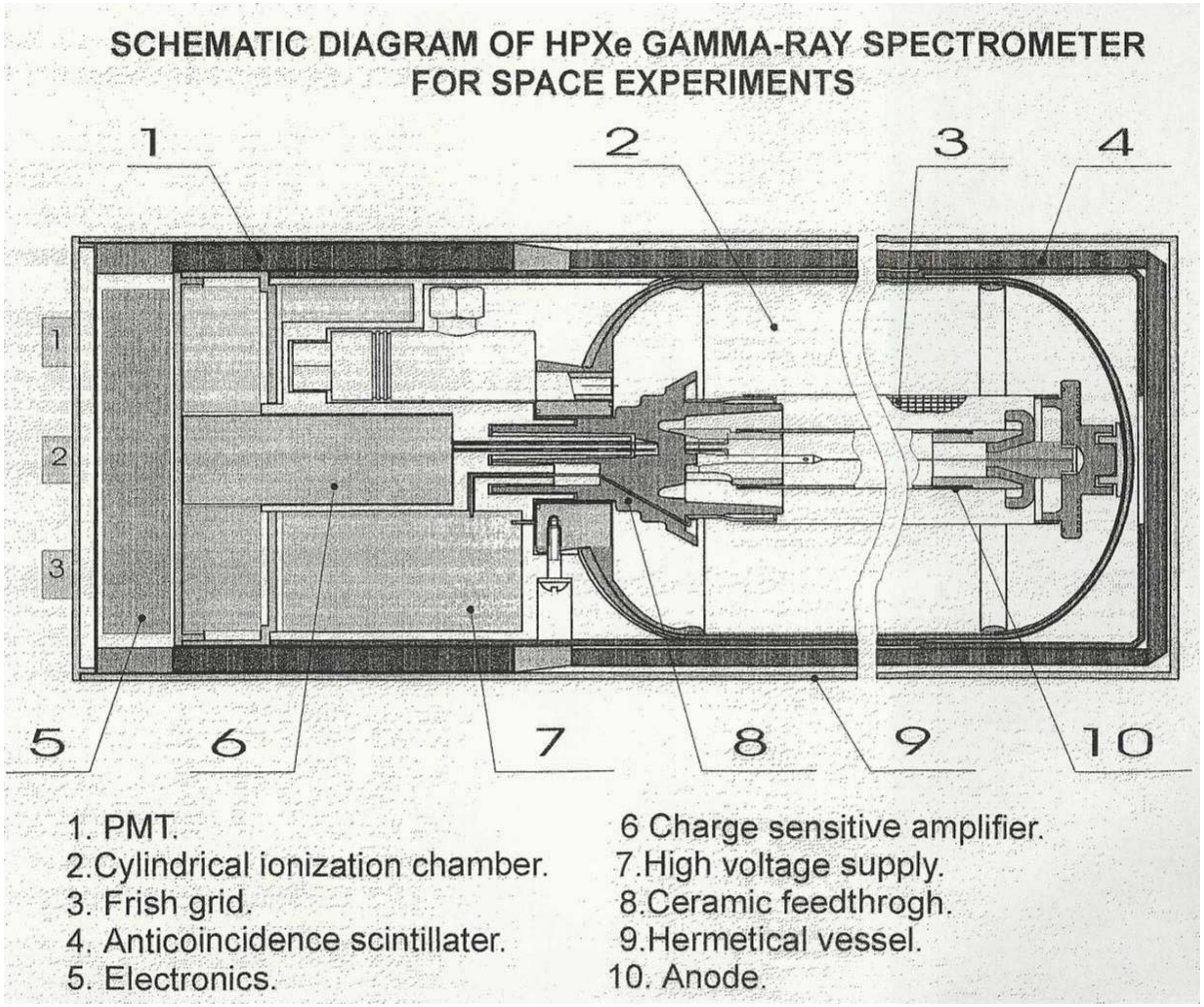
Specifications

Detector Medium	Xenon, 3 kg
Energy Range, MeV	0.1 - 5.0 MeV
Energy Resolution, % FWHM	4.0% @ 662 keV; 1.7% @ 1.33 MeV
Energy Resolution Drift	<0.1% per year
Total Detection Efficiency at 511 keV	18% in direction perpendicular to the axis
Maximum Count Rate	10^4 s^{-1}
Sensitive Volume, cm	∅12 cm x 56 cm
Total Detector Mass	18 kg
Power	7 W (+/-12 V, +24 V)
Read-out system	Canberra InSpector 2000
Packaging	SKB Rail-Pack case; Dimensions: 50” x 20” x 13.5”

Chambers developed in MEPhI



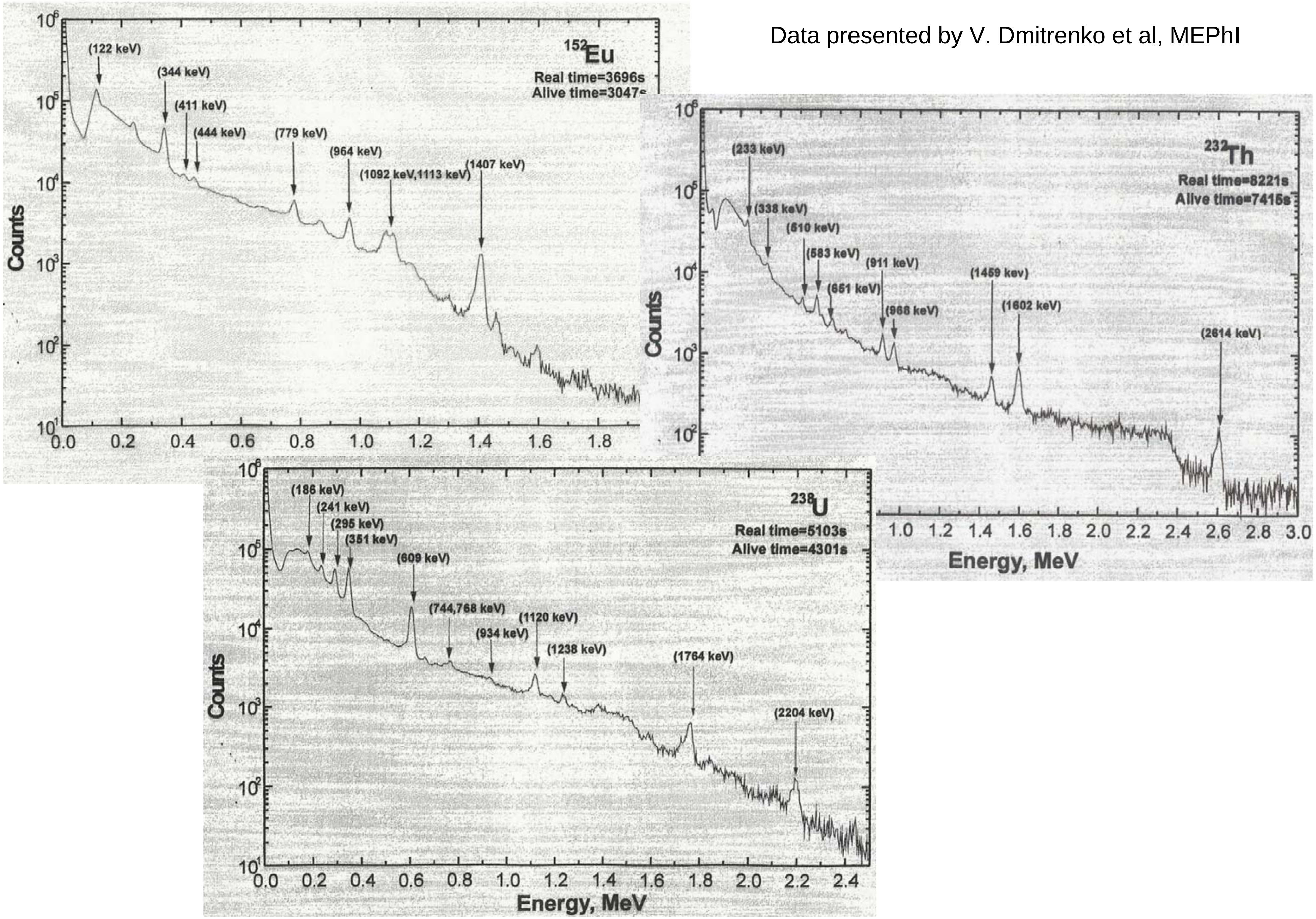
Chambers developed in MEPhI



Chambers developed in MEPhI

Examples of spectra measured with a chamber developed in MEPhI

Data presented by V. Dmitrenko et al, MEPhI



New approaches to HPXe ionization chamber designs

In the past two approaches have been considered to eliminate the use of the shielding grid in HPXe ionization detectors:

Coplanar-grid and Rise-time correction.

A coplanar-grid works well for the small solid-state detectors, but it faced many problems when applied to the bulky gas ionization chambers:

coplanar electrodes result in high detector's capacitance and microphonic noise magnified by differential bias applied to the grids;

if coplanar grids are deposited on a ceramic substrate, it causes charging of the ceramic surface and this affects field distribution inside the chamber.

Rise-time (or biparametric) correction can potentially provide resolution < 2% and 662 keV; however, it requires precise timing to indicate the beginning of the charge signal.

Primary scintillation can be potentially used as a trigger. However, the light signal is weak, and not easy to detect, especially in the case of large volume high-pressure chamber.

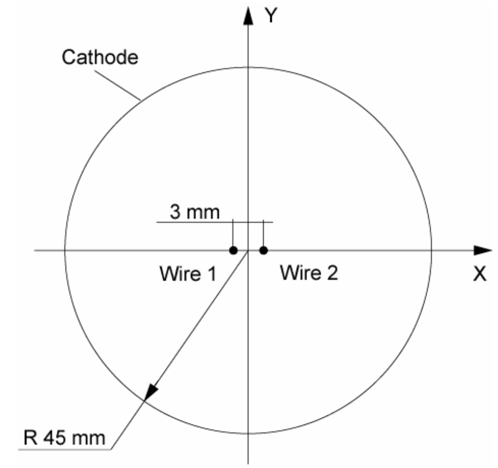
As a result these good ideas have never materialized in any practical designs for gas ionization chambers.

Dual-anode cylindrical ionization chamber (DACIC)

This design takes advantage of cylindrical geometry and coplanar-grid readout approach.

It is suitable for large-volume spectrometers, ~1000 cm^3, which can be used for portal applications and environmental monitoring.

Detect both gamma-rays and thermal neutrons (if a small percentage of ^3He is added to Xe).



Two wires replace a single anode and the shielding grid in conventional chamber. Both wires are at the ground potential (important feature that makes it different from coplanar-grid device).

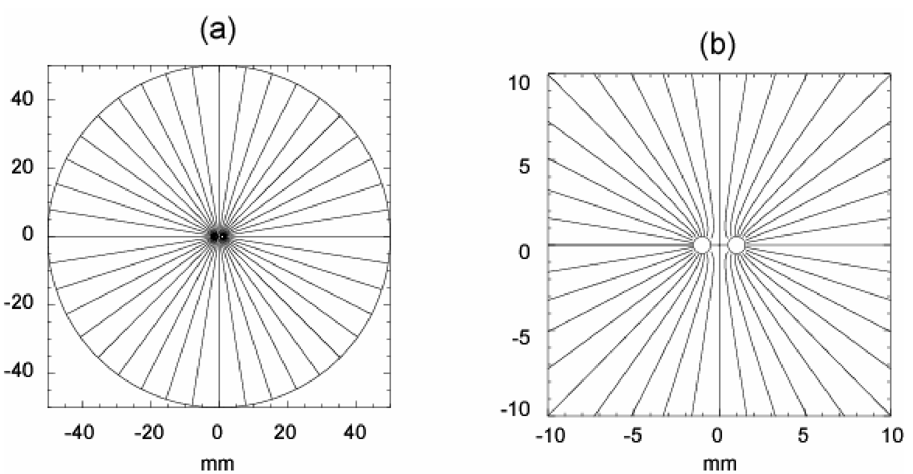
Only one wire (it can be either one) collects electrons but both wires sense uncollected ions. So, the difference between the signals read out from the wires gives collected charge only.

Since either wire can be collecting, the differential signal can be of two polarities: negative or positive. But this can easily be sorted electronically.

Electric field inside inside the chamber

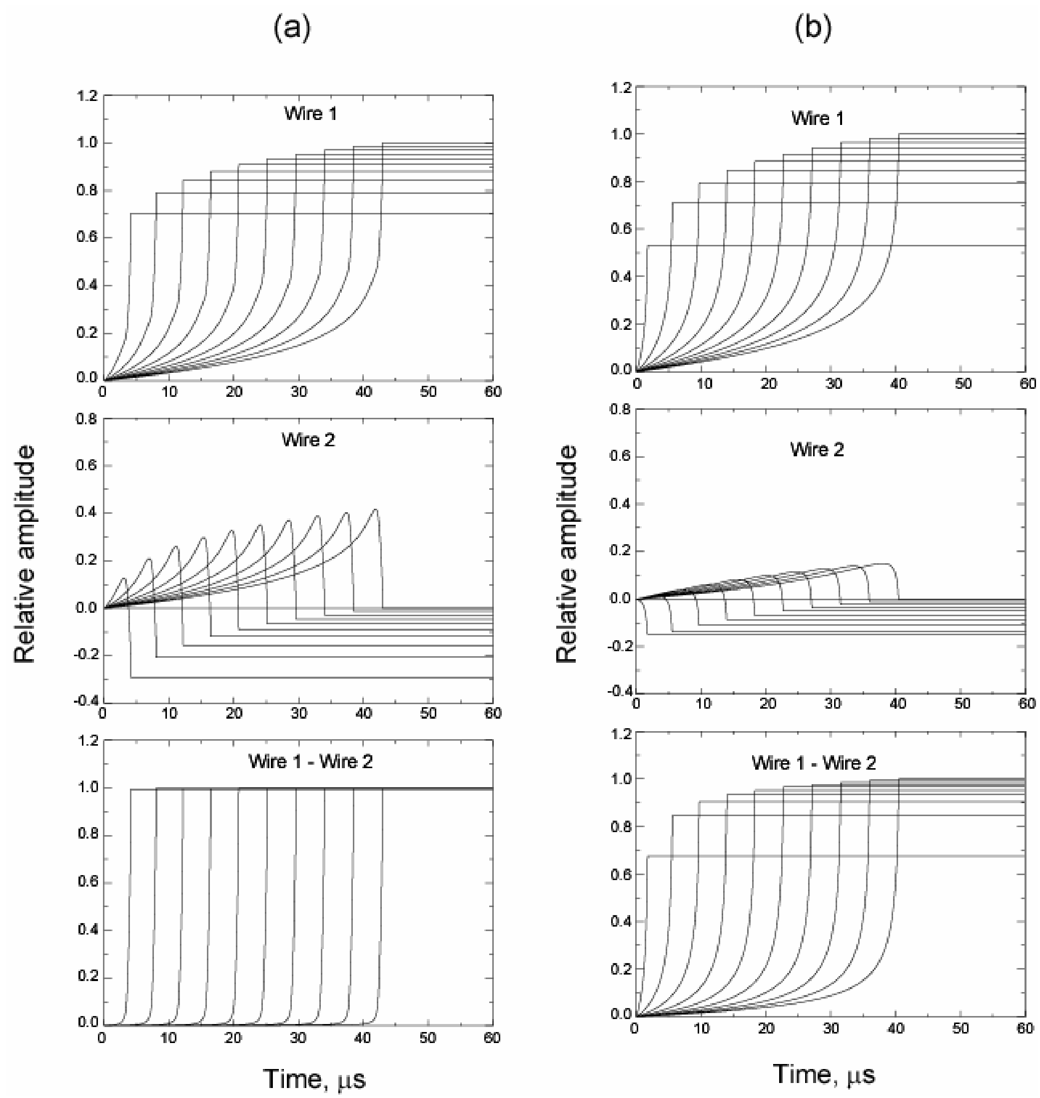
Large scale

Small scale

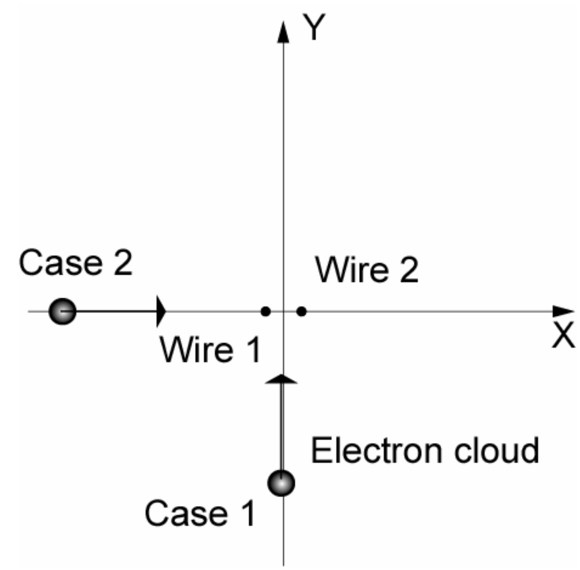


Pulse-shapes calculated for different locations of interaction point

Case 1 Case 2



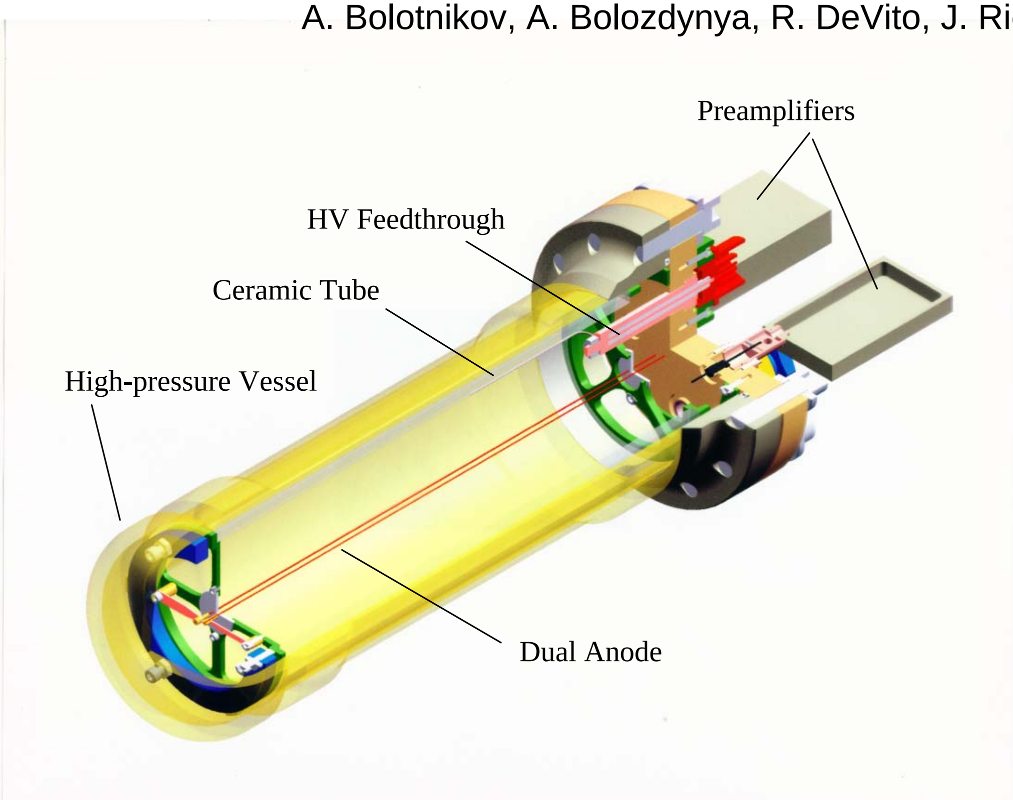
Asymmetrical response due to mutual shielding



This effect degrades energy resolution, but it can be minimized by (1) using small spacing and small diameters of wires or (2) starching wires crisscross, (3) making double helix.

Dual-anode cylindrical ionization chamber prototype tested at CTC

A. Bolotnikov, A. Bolozdynya, R. DeVito, J. Richards, IEEE, NS-51, p. 1262, 2004



Dual-anode chamber was tested by using simple prototype consisting of two parallel anode wires stretched inside the ceramic tube.

The inner surface of tube was coated with an aluminum layer and used as a cathode.

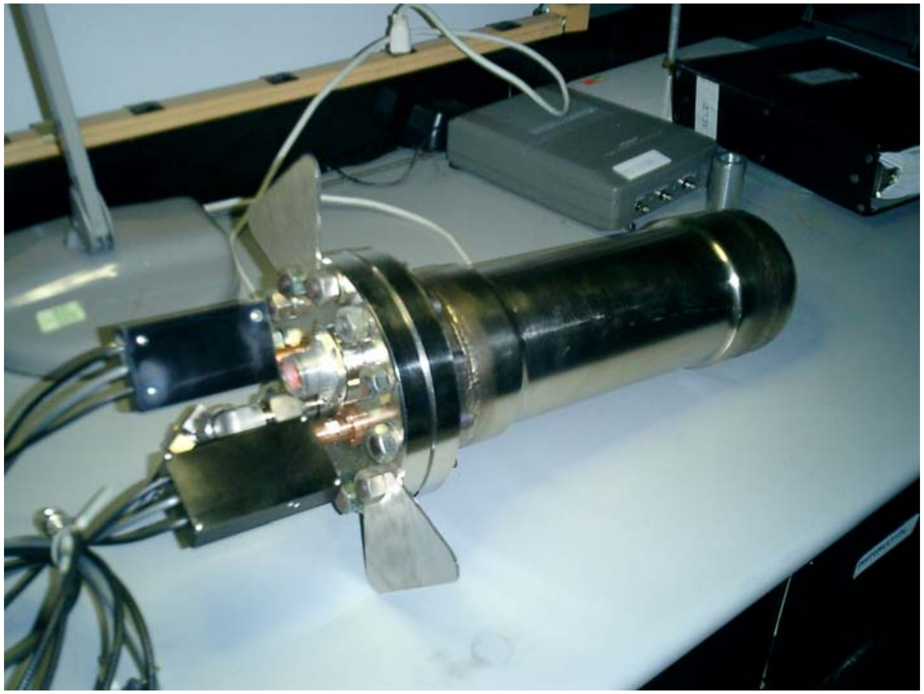
Detail of experimental setup can be found in our previous publications.

The expected energy resolution for this is ~4% at 662 keV for 15 keV electronic noise per channel. If reduce the wire spacing below 2 mm we would expect ~2%. However, for this test we chosen a conservative approach which was motivated by concern about the diffusion.

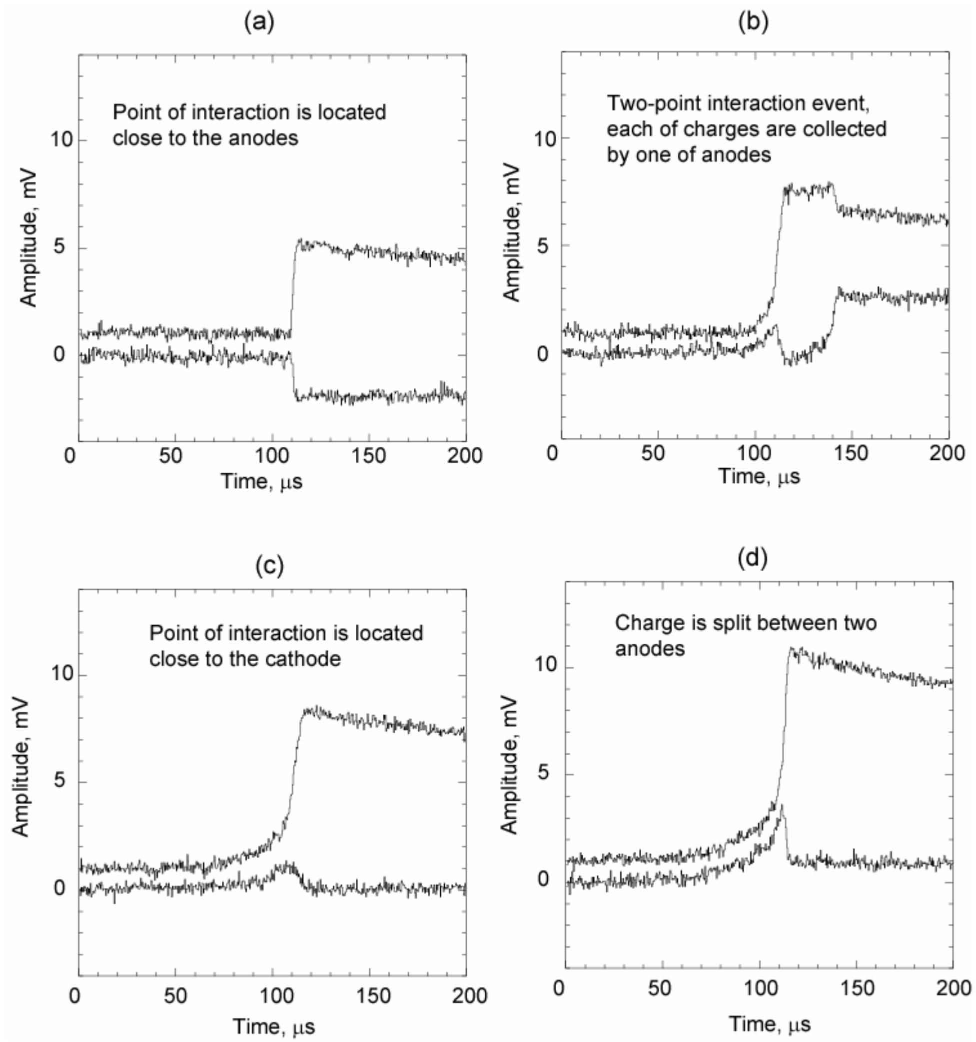
Geometrical parameters of the chamber:

Wire diameter 0.75 mm
Wire length 30 cm
Spacing 3 mm
Inner diameter of ceramic tube 90 mm

DACIC



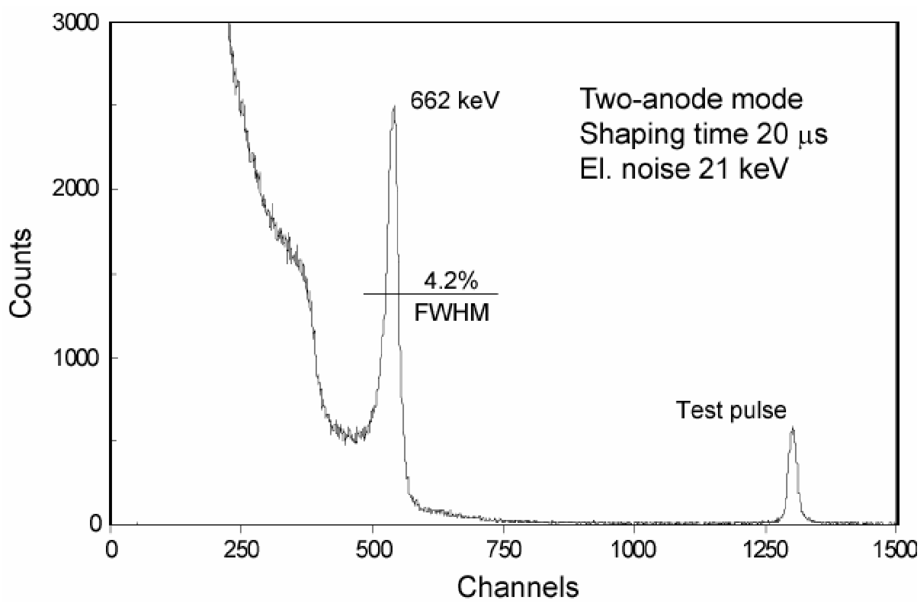
Charge signals measured from the two anodes

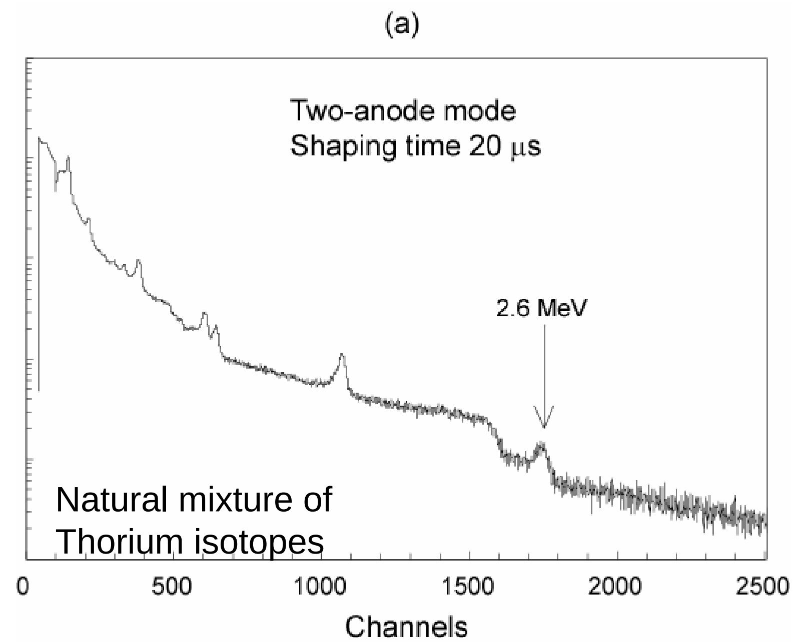


These waveform are very similar to those measured for typical coplanar-grid devices; however, in this case we didn't apply any differential bias between the wires.

Typical pulse-height spectra measured with the device prototype

Density of Xe is 0.3 g/cm³





The energy resolution is ~4% FWHM at 662 keV at electronic noise ~ 14 keV (~270 el)

This spectrum, collected for thorium isotopes, illustrates the capably of the device to detect high-energy gamma-rays.

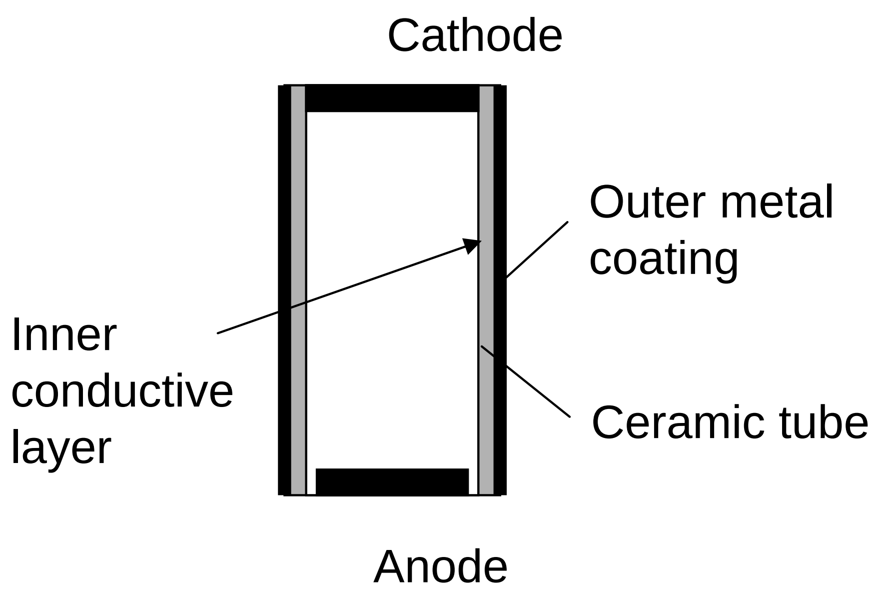
These results demonstrate the feasibility of the dual-anode chamber, however more work is required to develop a practical device with better resolution.

Virtual Frisch-grid ionization chamber

This design is proposed for small volume, ~200 cm^3, but very robust and mechanically stable spectrometers which can be used for applications in very harsh conditions: high-radiation dose, high-temperature, strong mechanical vibration.

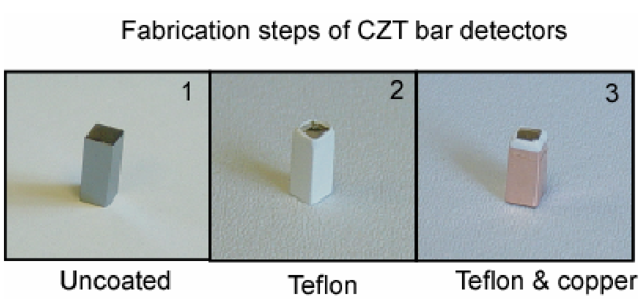
Applications include active zone of nuclear reactors, radioactive waste, and well-logging.

Schematic of the device

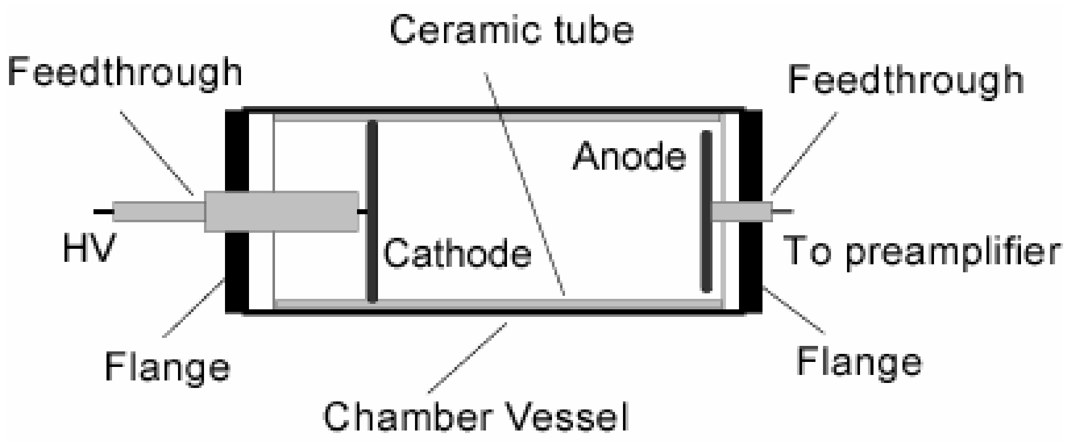


Active area is inside a ceramic tube which has high-resistivity internal and low-resistivity external coatings

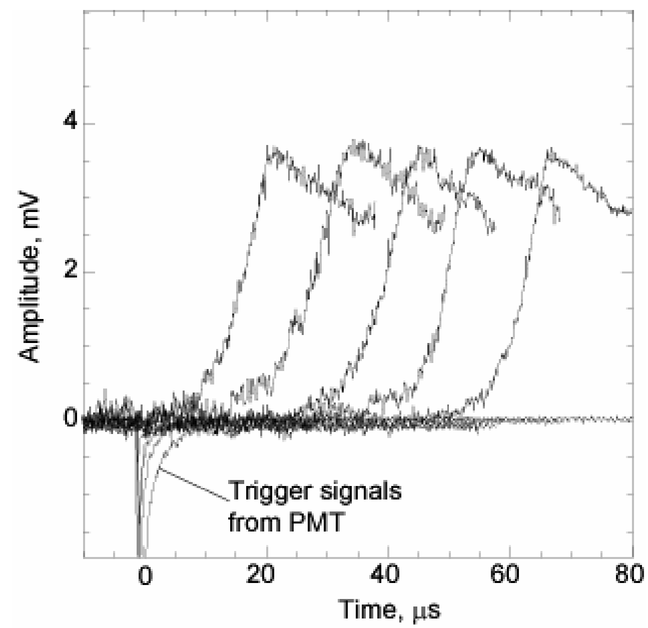
CZT Virtual-Frisch grid device analog



Preliminary results from the testing of the detector prototype



Typical waveforms measured with detector prototype



The device was assembled inside a thin ceramic tube which had a special coating.

The tube was mounted inside a high-pressure vessel with two flanges. The anode and cathode were attached directly to the feed-throughs.

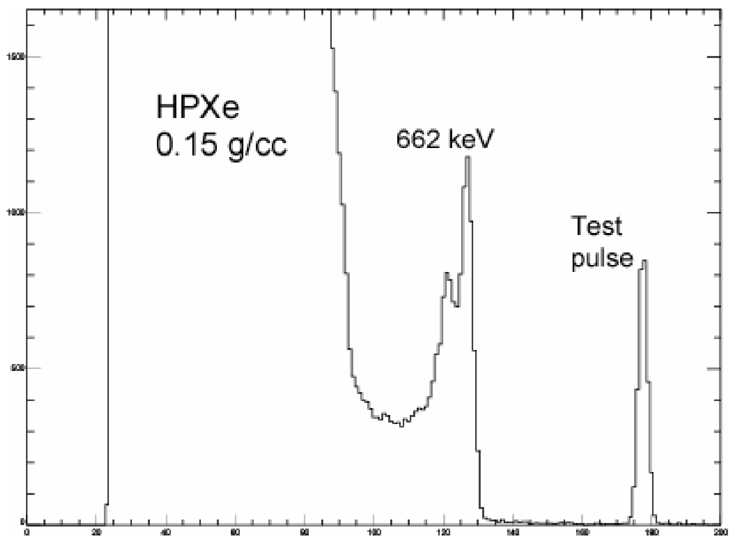
The chamber was tested at low pressure Xe.

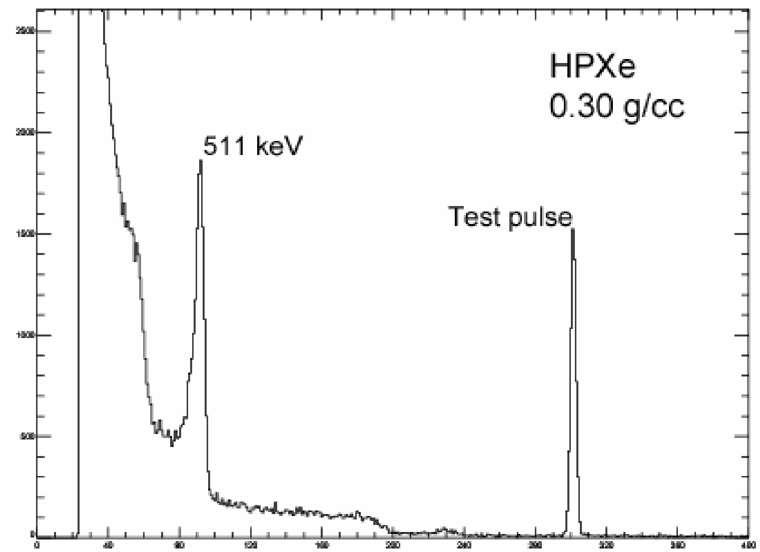
511 keV photons from ^{22}Na were used to generate pulse signals.

A signal from NaI detector was used as a trigger to indicate the moment of interaction.

The signal is induced when electron cloud is located close to the anode which indicates formation of the virtual Frisch-grid.

Pulse-height spectra measured with prototype





A spectrum measured at a density of 0.15 g/cm^3 clearly shows an escape peak which indicates that the energy resolution is ~2% FWHM at 662 keV.

Because of low density of Xe used in these measurements both spectra have a large Compton background.

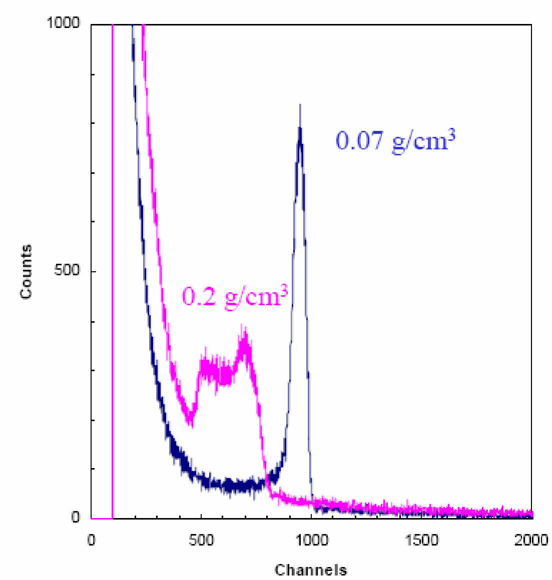
In a real device, filled with Xe at higher density, the peak-to-Compton ration will be significantly improved.

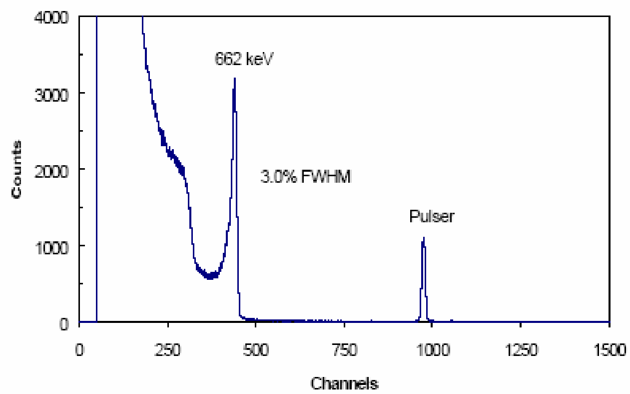
HPXe+3He chamber for detection thermal neutrons and gammas

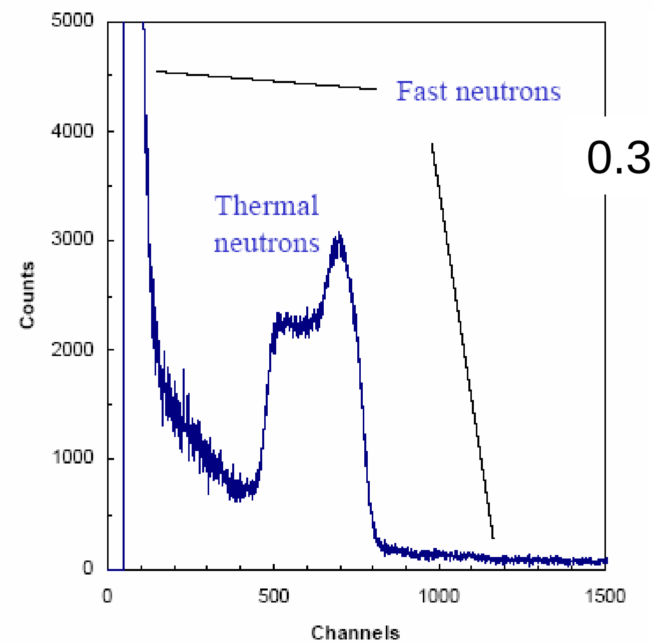
A. Bolozdynya, A. Bolotnikov, J. Richards, A. Proctor, *NIM* vol. A522, pp.595-597, 2004.

Adding a small percentage of He-3 to HPXe to detect thermal neutrons. The capture of thermal neutrons by ^{3}He yield a triton and a proton, which share the total reaction energy of 764 keV plus the kinetic energy of the incident neutron.

A 30 μCi AmBe source was immersed inside a water moderator and shielded with 5 cm thick lead bricks to eliminate escaping photons.







0.3 g/cc

“Wall effect”

Density effect on the ionization yield in xenon+ ^{3}He mixture irradiated with thermal neutrons

^{3}He+n -> triton (191 keV) + proton (573 keV) (neglecting the kinetic energy of the thermal neutron).

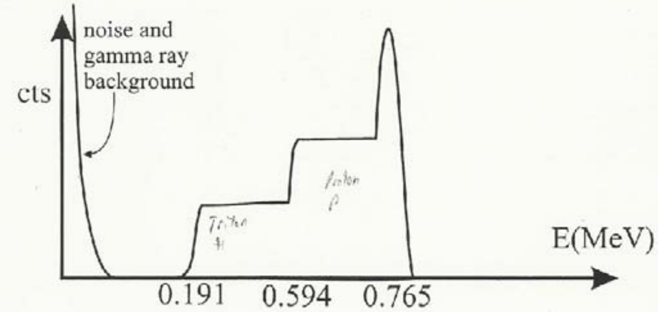
Tritons and protons have very small ranges in high-density xenon.

Assuming a uniform density of xenon gas at a density of 0.2 g/cm^{3}, proton and triton ranges are less then 200 μm.

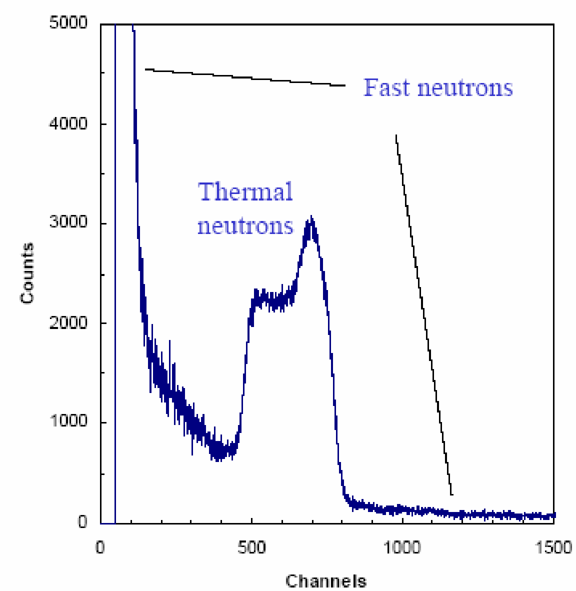
For comparison, at the same density, the range of alpha particles, is 650 μm, while a penetration depth of 0.5 MeV electrons is ~3 mm, i.e. much larger than the triton or proton ranges.

Simplest explanation is the formation of Xe clusters?

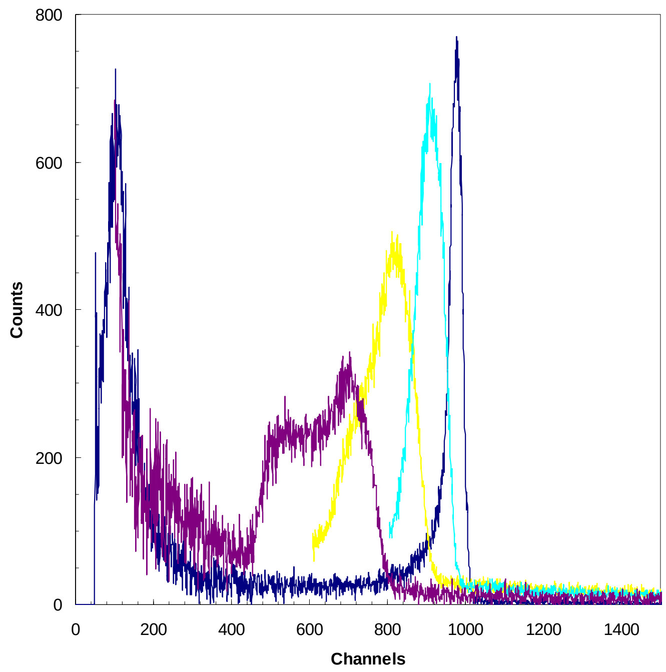
Particle ranges are shorter, hence wall effect is more prominent.

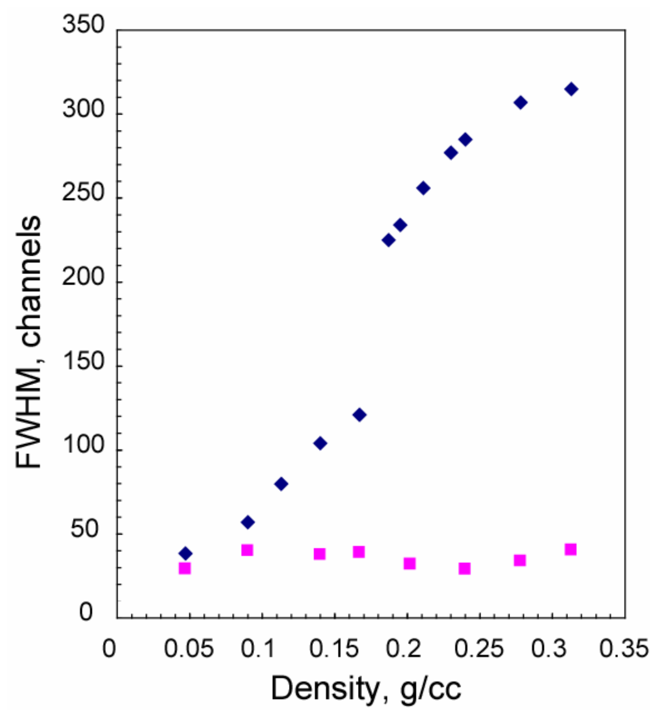


Expected spectrum from a ^{3}He detector



Evolution of FWHM with density





Indication of Xe transition from single entity medium (gas-like) to two entity medium (gas-like and liquid-like, i.e., clusters?

Conclusions

Today HPXe is a well developed and ready to use technology for nuclear radiation.
However, HPXe detectors have very limited area of applications where they can truly compete with other techniques. Some of them are portal security, environmental monitoring, and detectors operating in harsh environments where others do not work at all.

Optimized “classic” and new “gridless” designs for HPXe ionization chambers have been proposed and tested.

Fluid Xe is a very interesting object for general studies which continues to surprise researchers by its unusual properties and effects.