Modern Status of High Pressure Xenon Gamma-ray Spectrometers and their Applications.

Valery Dmitrenko[1], Nobuyuki Hasebe[1,2,3]

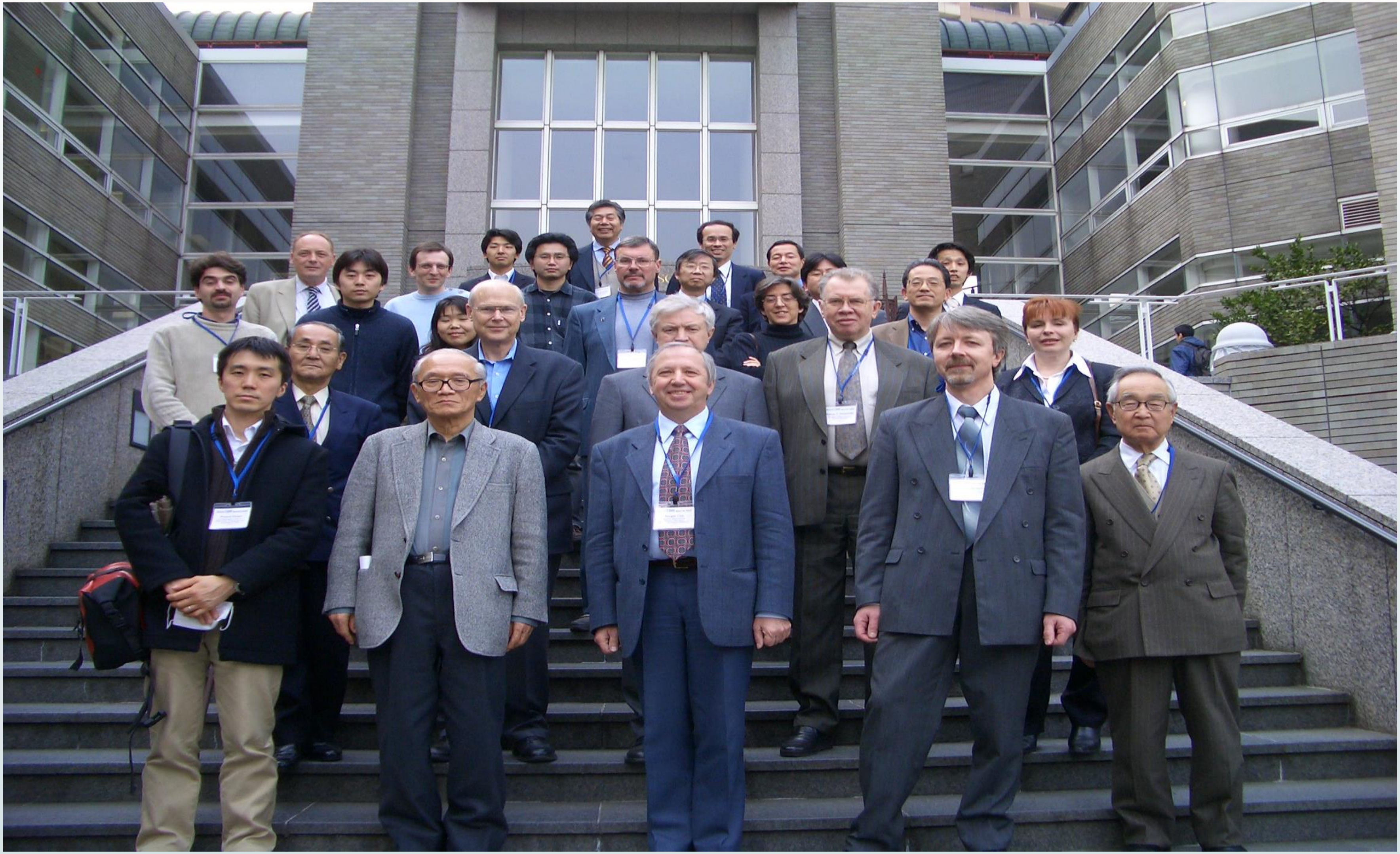
[1]National Research Nuclear University
Moscow Engineering Physics Institute (MEPhI)
Moscow, Russia
[2]Department of Physics, School of Advanced Science and Engineering,
Waseda University, Tokyo, Japan
[3]Research Institute for Science and Engineering,
Waseda University, Tokyo, Japan

Aprile 04, 2017
Khon Kaen, Thailand

HPXe2003

High Pressure Xenon: science, detectors and applications

XeSAT2005
Applications of Rare Gas Xenon to Science and Technology



smcXe

Contents

Main disadvantages of High Purity Germanium (HPGe) and NaI gamma-ray spectrometers.

- **HPGe gamma-ray spectrometers:**
  - **Operation only at low temperature (require liquid nitrogen or mechanical cooler);**
  - **Difficulties for application in field conditions, space experiments and so on;**
  - **Limited sensitive volume;**
  - **High cost.**
- **Gamma-ray spectrometers on base of NaI:**
  - **Low energy resolution.**

Xenon gas general characteristics

Element	Xe
Valence electron configuration	$5s^2 5p^6$
Atomic number	54
Atomic weight (g/mol)	131.3
Atomic radius (nm)	0.218
Ionizing potential (eV)	12.13
Standard density (kg/m^3)	5.851
Condensing temperature at normal pressure (°C)	-108.10
Congelation temperature (°C)	-111.85
Critical temperature (°C)	16.59
Heat capacity at 0° C (J/(kg·mol·degree))	20808.4
Abundance in the air (%)	10^{-5}

$$\delta = 2.36 \cdot \left(F \cdot W / E_\gamma \right)^{\frac{1}{2}}$$

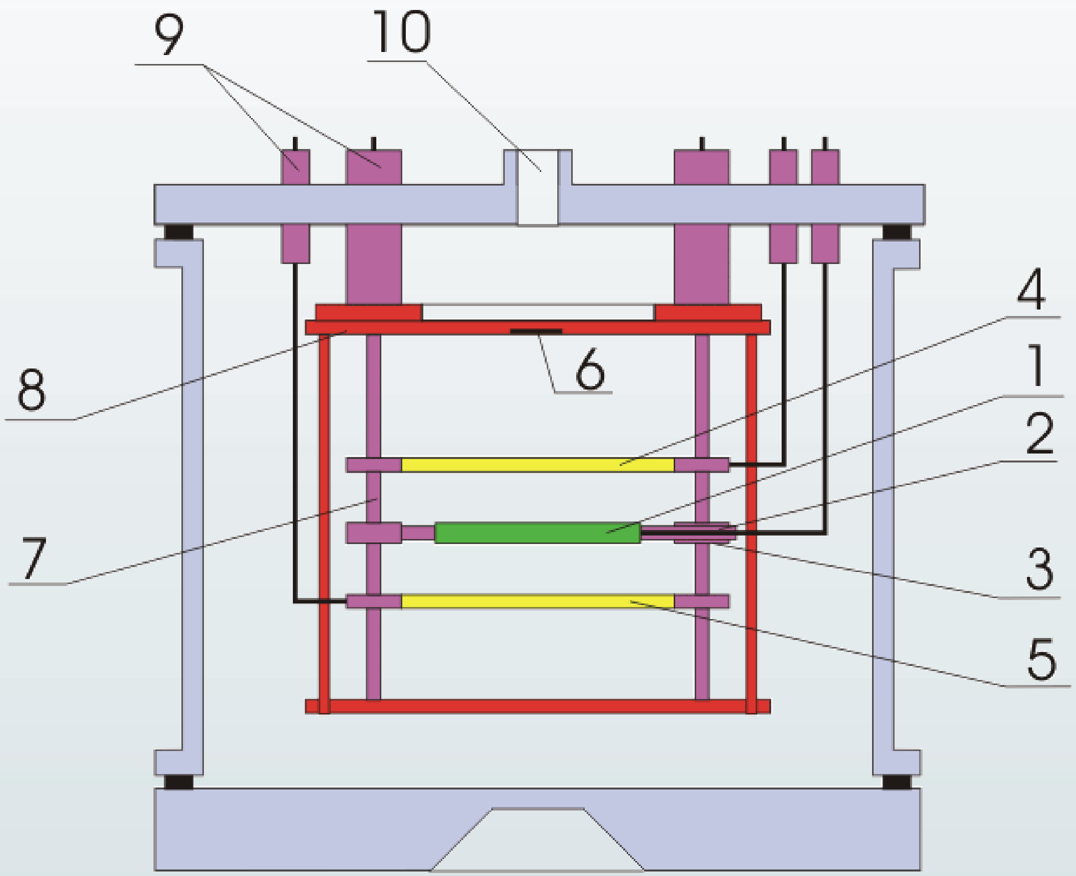
F - Fano Factor

W - mean energy for ion-electron pair production

Eγ - energy of gamma-ray

For Gas:	For Liquid:
F = 0.2 at density 0.6 g/cm³ (60 bar)	**F = 0.04**
W = 20 eV at density 0.6 g/cm³ (60 bar)	**W = 15.6 eV**
E_γ = 1 MeV	**E_γ = 1 MeV**
δ_{GXe} = 0.5 %	**δ_{LXe} = 0.2 %**

Ionization chamber for laboratory research



1 - signal electrode;

2 - ceramic insulators;

3 - guard ring;

4, 5 - shielding grids;

6 - ^{207}Bi gamma-ray source;

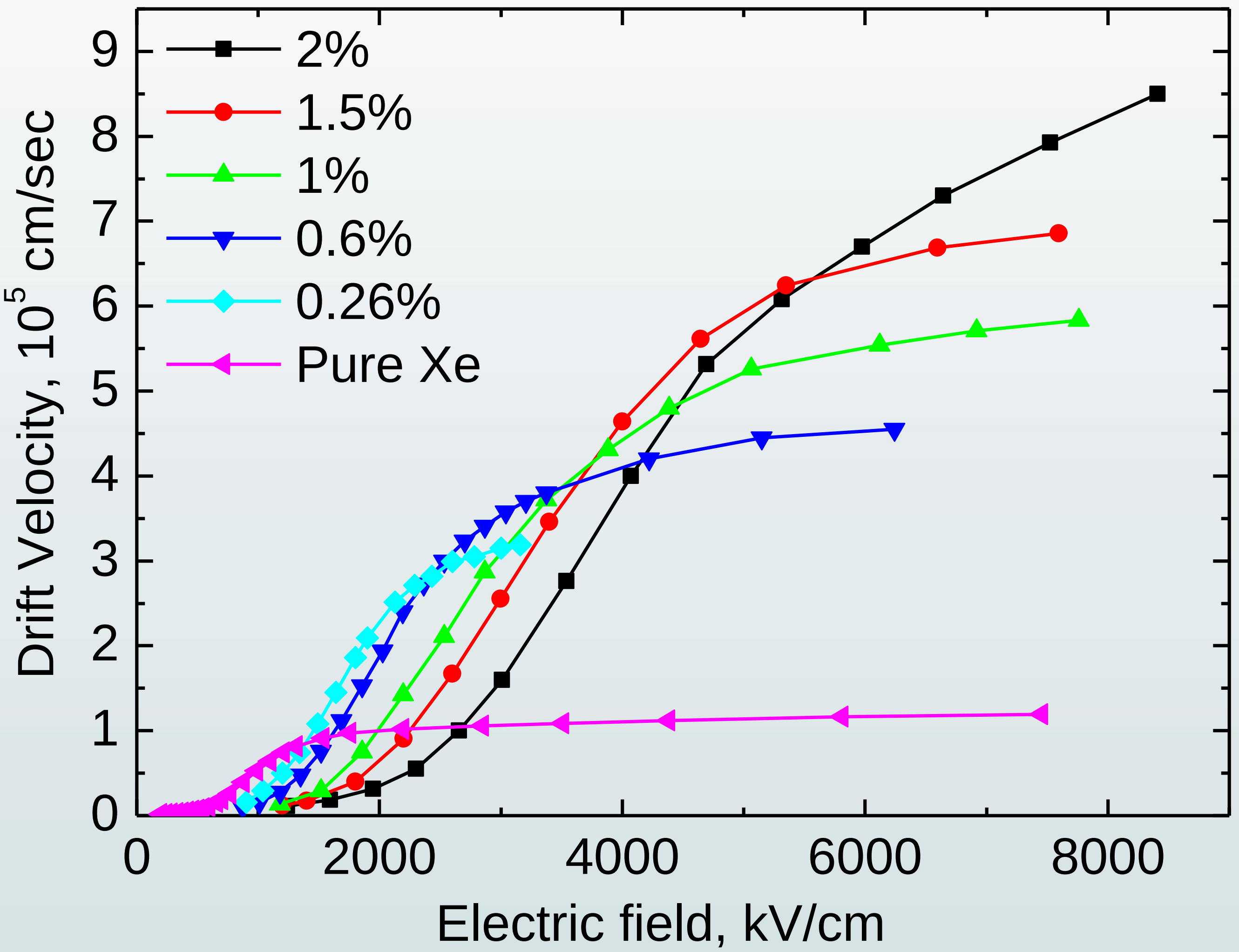
7 - ceramic rods;

8 - negative electrode;

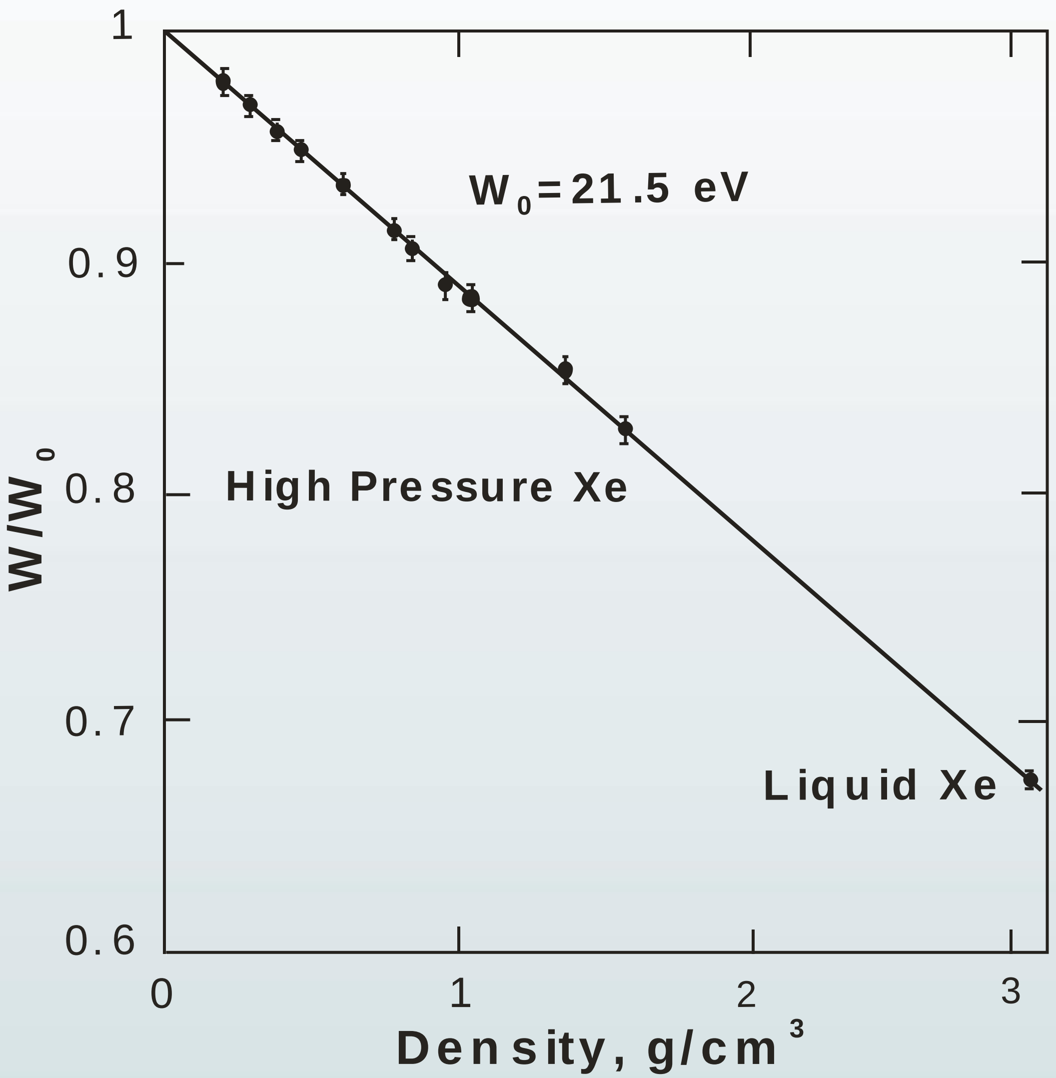
9 - feedthroughs;

10 - gas input.

Drift velocity of electrical charge in Xenon gas as function of electric field for different concentration of H_2 and Xenon density 0.6 g/cm^3



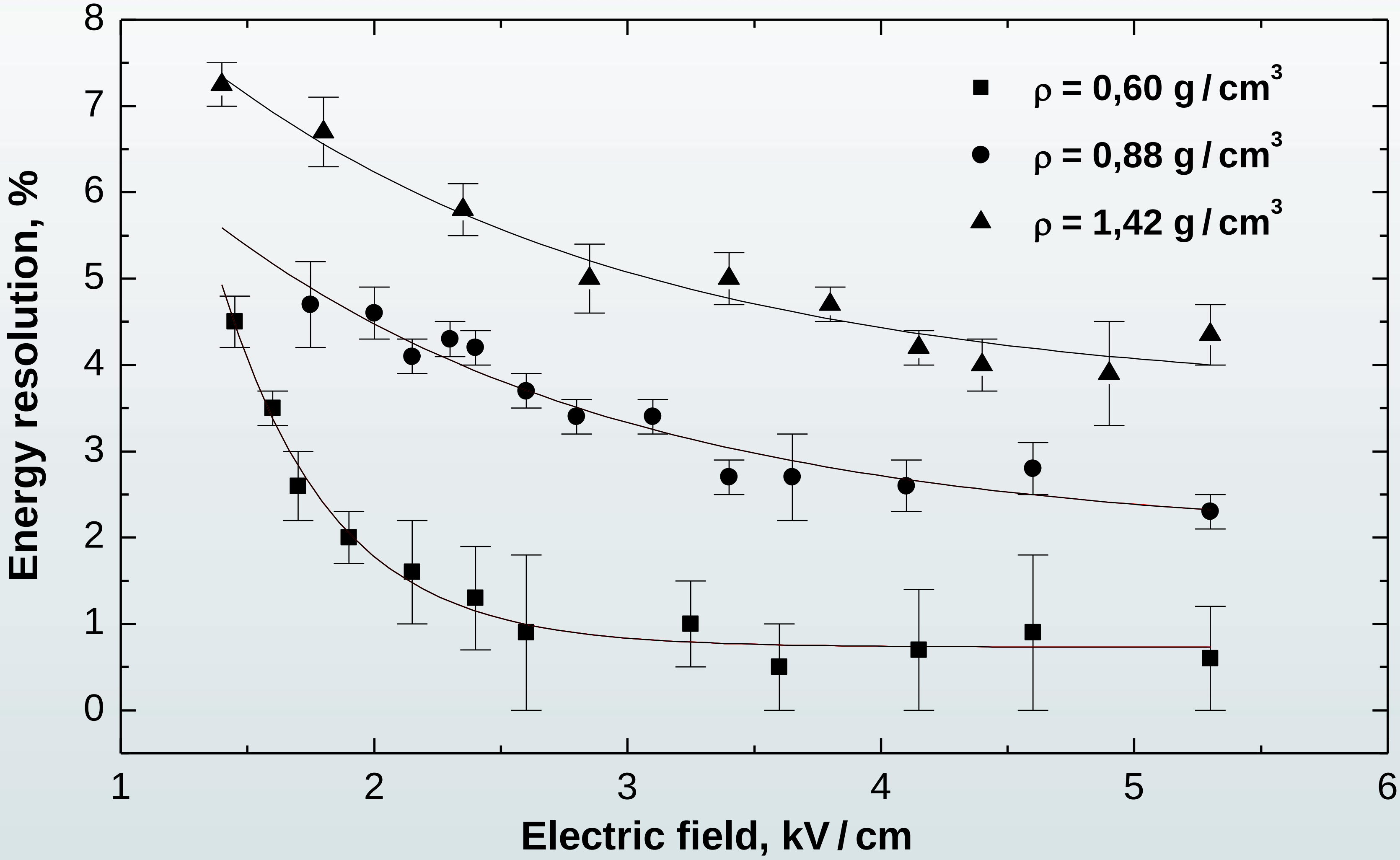
The W/W_0 ratio as function of Xenon gas density



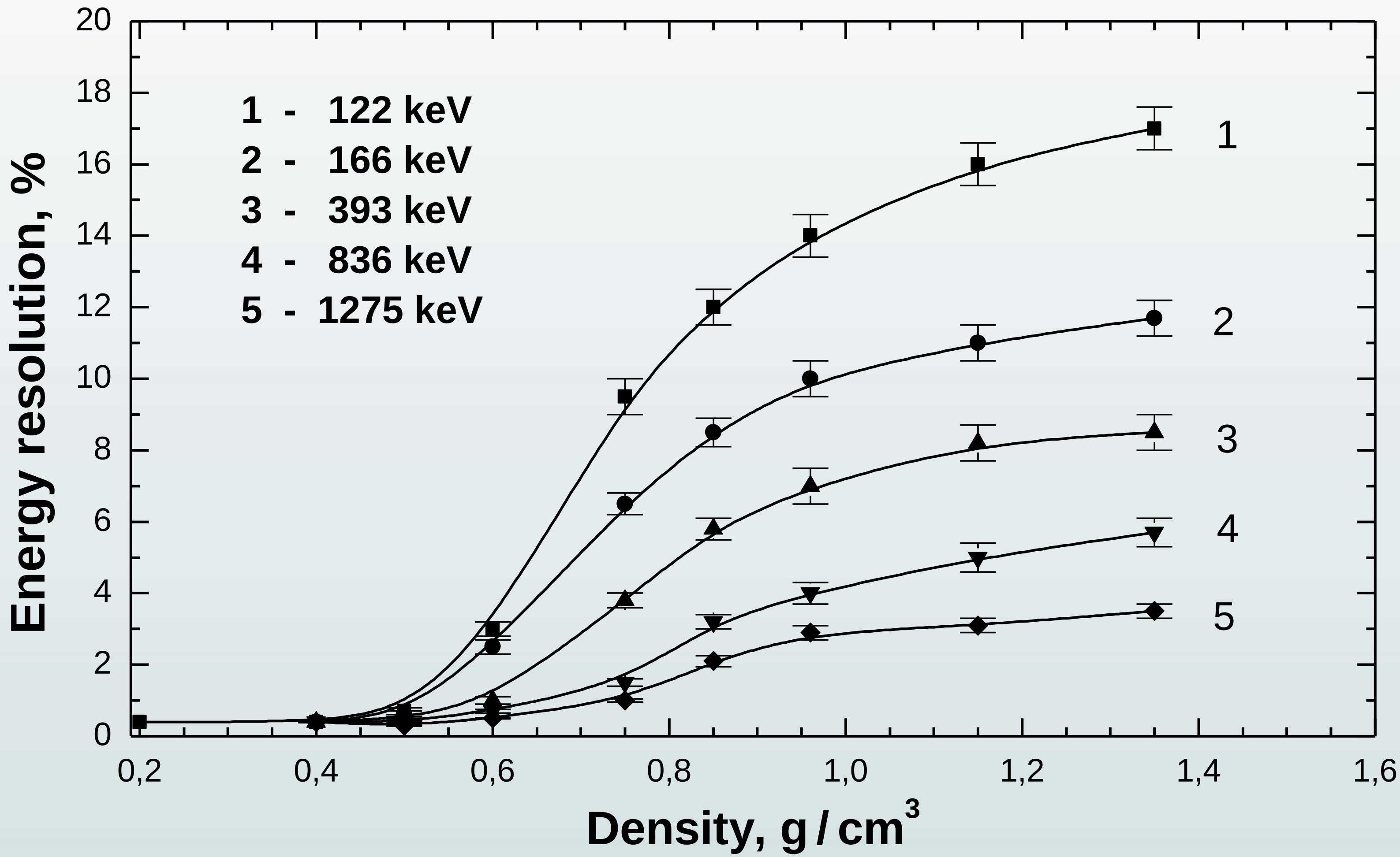
W - mean energy for ion-electron pair production;

W_0 - mean energy for ion-electron pair production in Xe gas at the normal pressure.

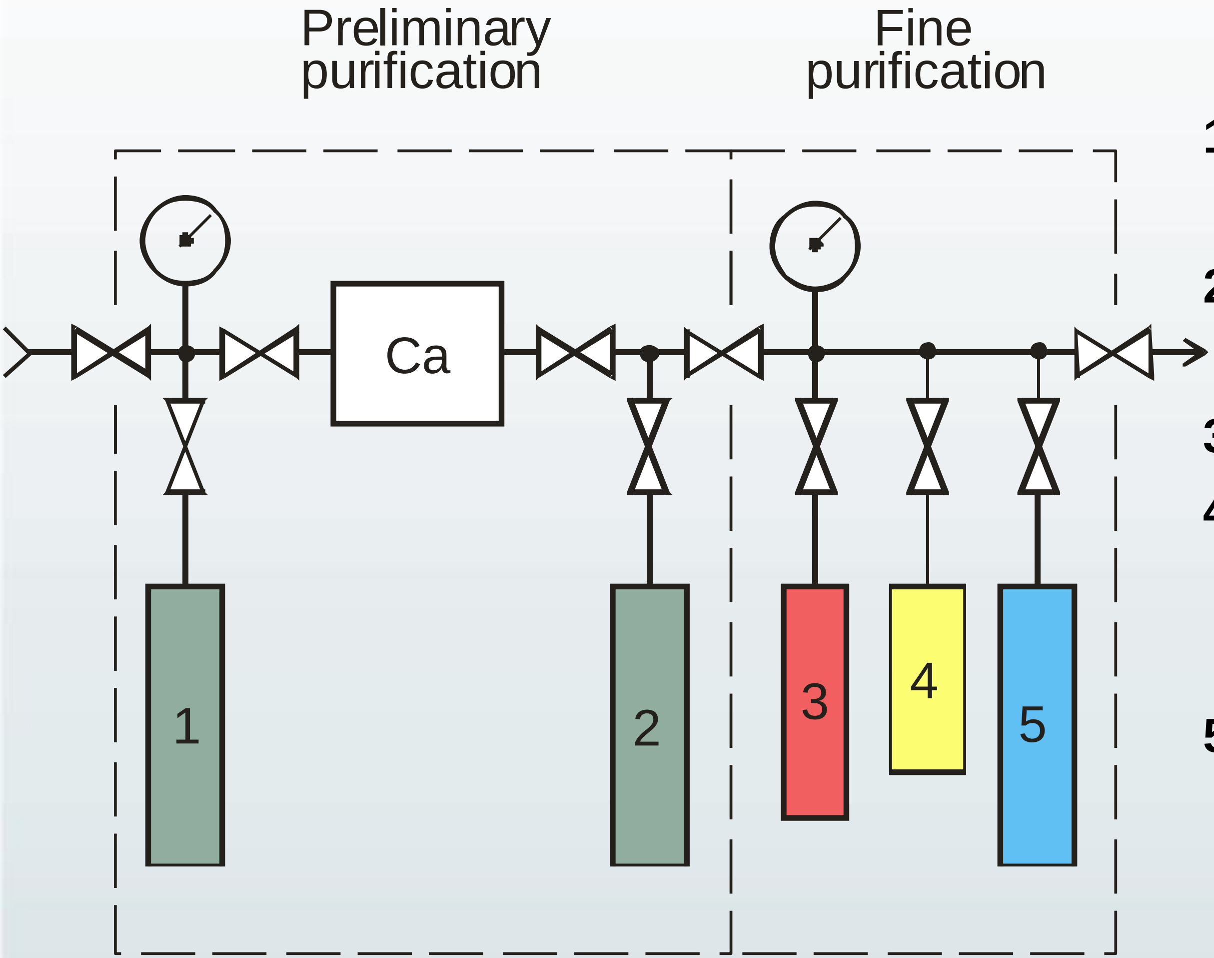
Energy resolution of ionization chamber for laboratory research as function of electric field for different densities of Xenon gas



The intrinsic energy resolution as function of Xenon gas density for different gamma-ray energies



Xenon purification system



1- vessel for unrefined Xenon;

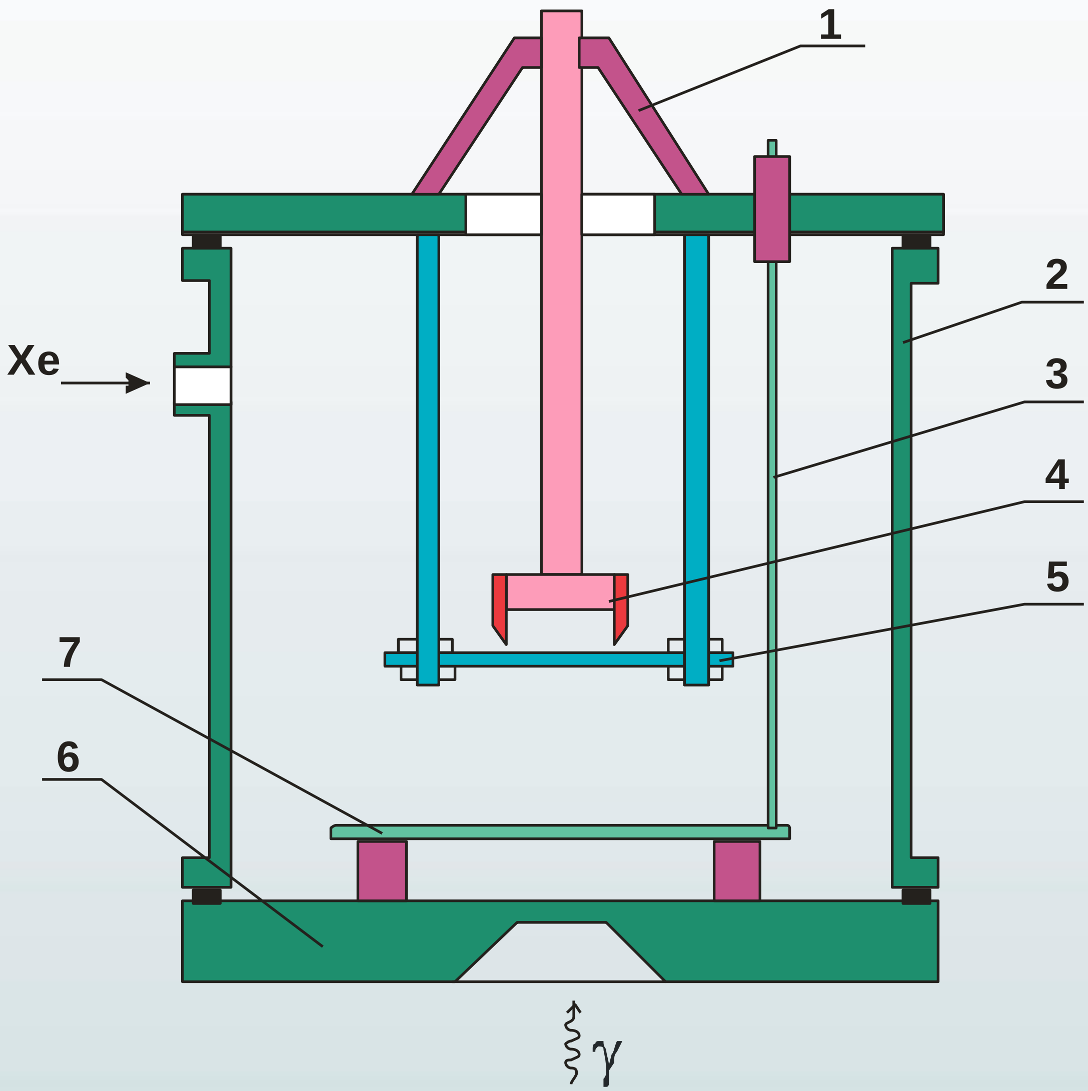
2 - vessel for preliminary purified Xenon;

3 - vessel for H_2 storage;

4 - vessel for purification and storage of finally purified Xe;

5 - vessel for storage of finally prepared mixture of Xe + H_2.

Electro-spark titanium purifier of Xenon gas



1- ceramic feedthrough;

2 - vessel;

3 - signal electrode output;

4 - titanic high-voltage electrode;

5 - titanic electrode;

6 - flange;

7 - signal electrode.

Requirements to Xenon gas and intensity of electric field to reach high spectrometric characteristics of Xenon gamma-ray spectrometers.

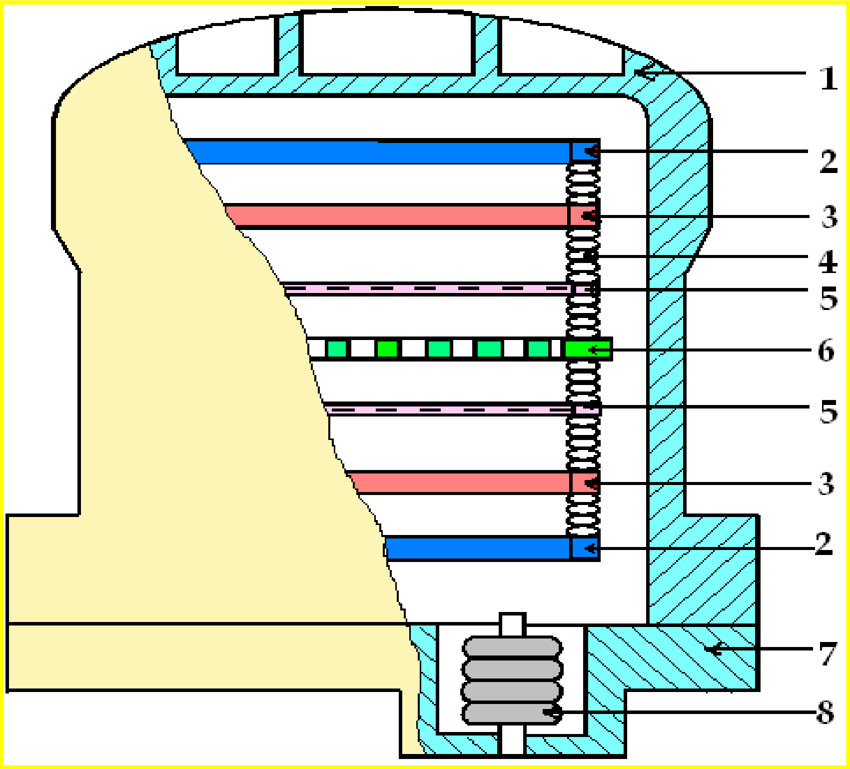
1. Xenon gas density has not to exceed 0.5 g/cc.

2. It is necessary to use Xenon + Hydrogen mixture (or another) to increase the drift velocity of electrons. Percentage of Hydrogen has not exceed 0.5%.

3. Life time of electrons in gas has to be not less than 1 - 2 msec.

4. Intensity of electric field in the drift volume has to be higher than 2 kV/cm.

PARALLEL-PLATE IONIZATION CHAMBER “KSENIA”



MAIN PARAMETERS

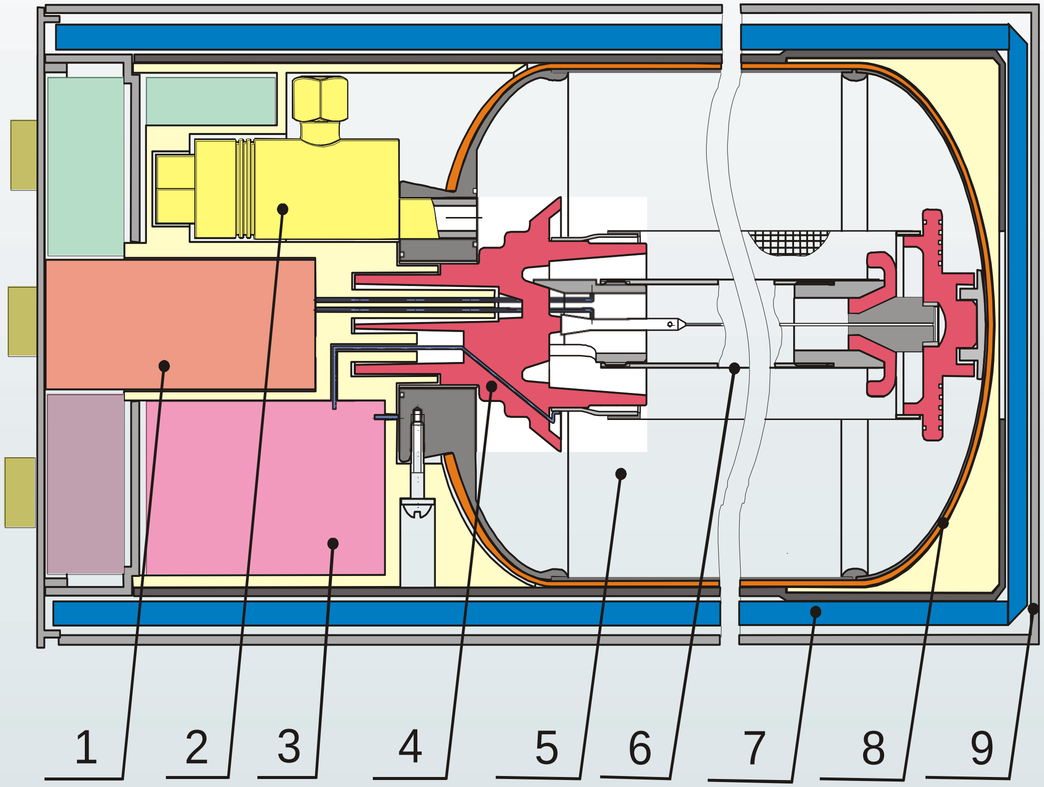
Energy range	0.1÷5 MeV
FWHM at 662 keV	23 keV
Xenon density	0.6 g/cm³
Sensitive volume	1000 cm³
Diameter	250 mm
Length	300 mm
Weight	5 kg
Voltage	± 24 V
Power	5 W

1 – vessel, 2 – cathodes, 3 – drift electrodes, 4 – ceramic insulator, 5 – shielding grid, 6 – anode, 7 – flange, 8 – metal-ceramic feed-through.

Gamma-ray telescope “KSENIA”
(Orbital station “MIR”, 1991 - 2000)

MAIN PARAMETRS	
Xenon density	0.6 g/cm³
Concentration of hydrogen	0.26 %
Pressure of a Xenon at 23° C	55 atm
Drift electric field	2.6 кV/cm
Maximum electron drift time	15 μs
Energy range	0.1÷5 MeV
Sensitive volume	1000 cm³
Sensitive area	100 cm²
Energy resolution (662 кeV)	3.5±0.25%
Energy resolution (1 MeV)	(2.0±0.2)%
Photopeak efficiency (662кeV)	(4.5±0.2)%
Photopeak efficiency (1.33MeV)	(1.5±0.1)%
Power consumption	15 W
Weight	80 kg

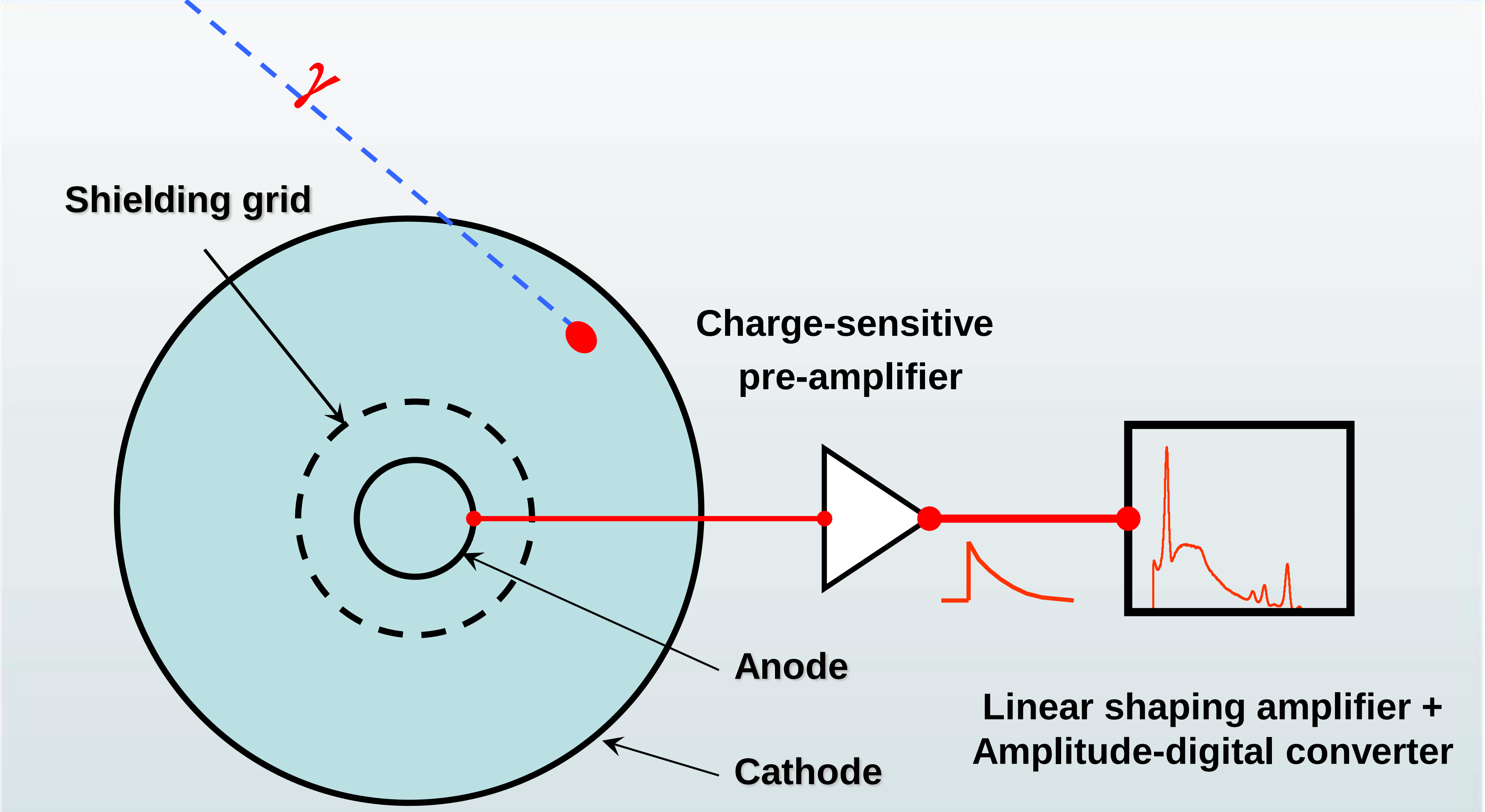
Schematic diagram of HPXe detector with shielding grid



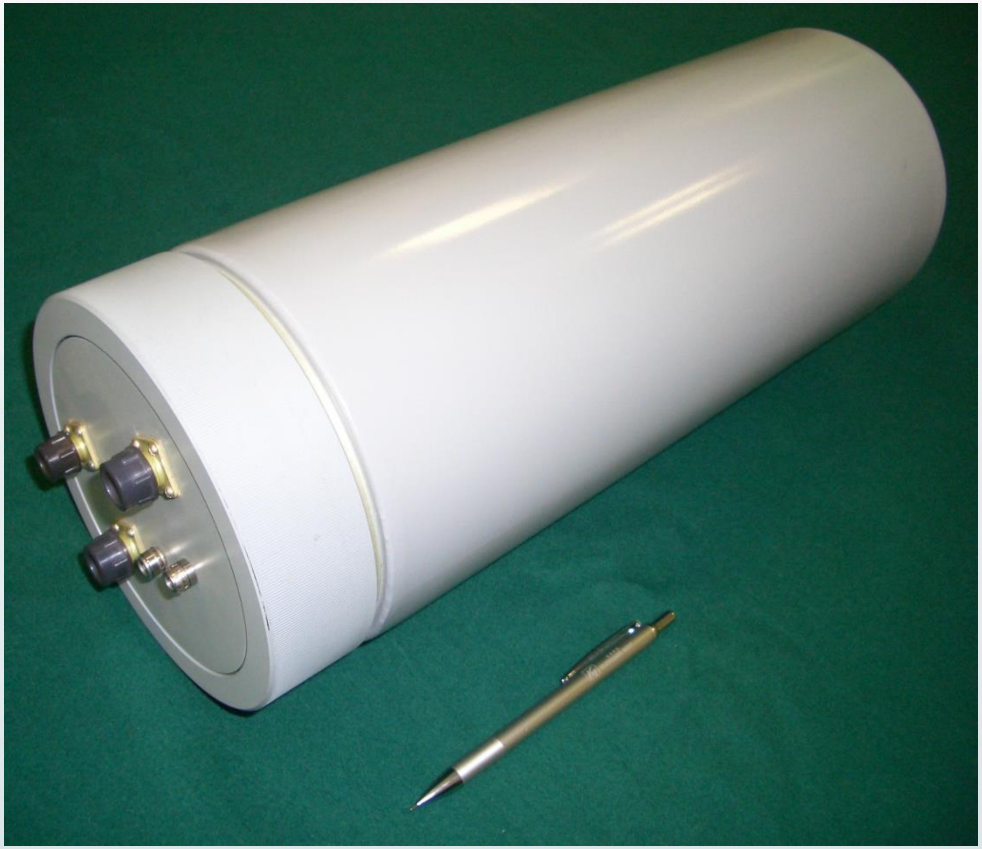
1. Charge sensitive amplifier.
2. Valve.
3. High voltage power supply.
4. Metal-ceramic feedthrough.
5. Cylindrical ionization chamber.
6. Anode.
7. Thermal insulation.
8. Vessel.
9. aluminum housing.

smcXe

Principle of gamma-ray spectrometer operation based on ionization chamber filled with High Pressure Xenon



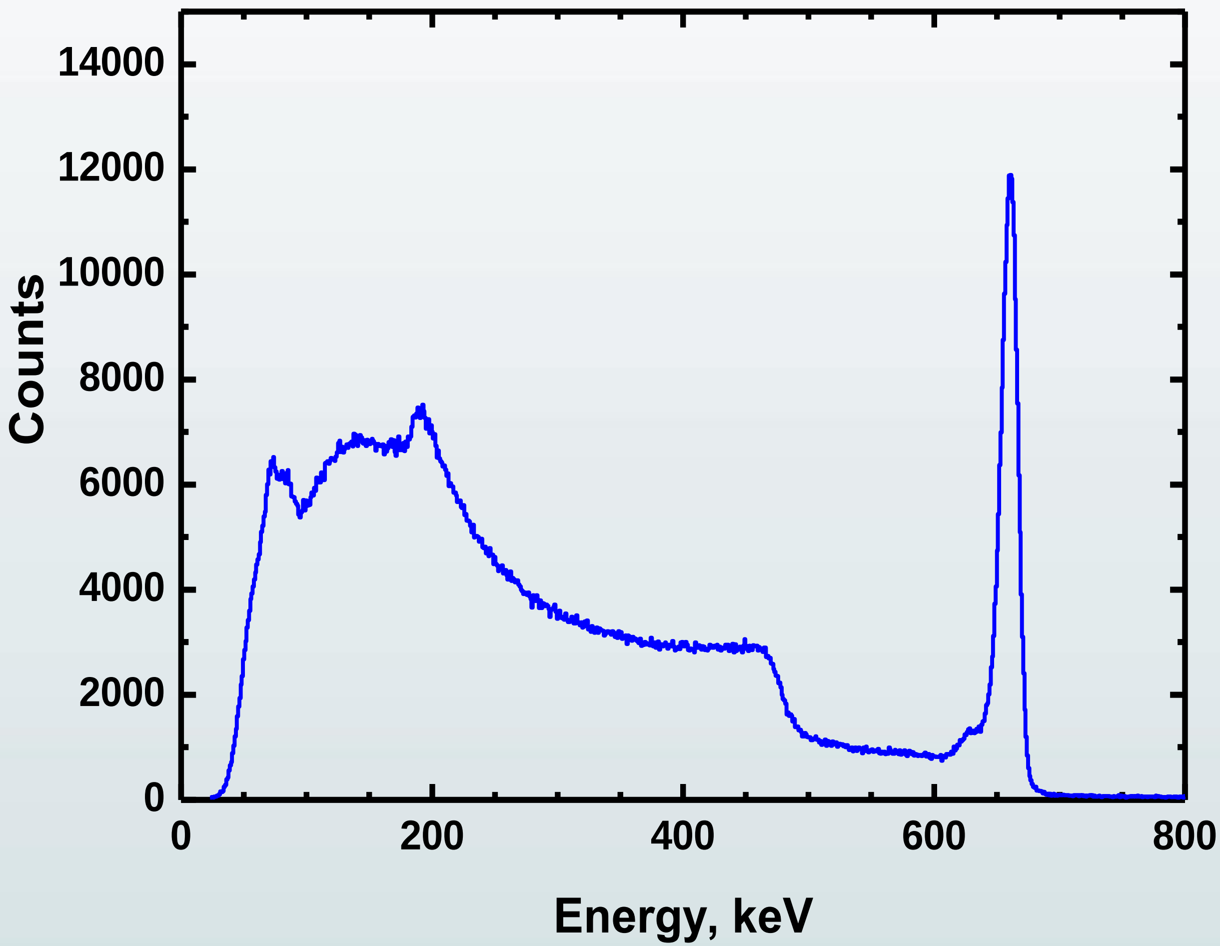
High Pressure Xenon Detector – 2 (HPXeD-2)



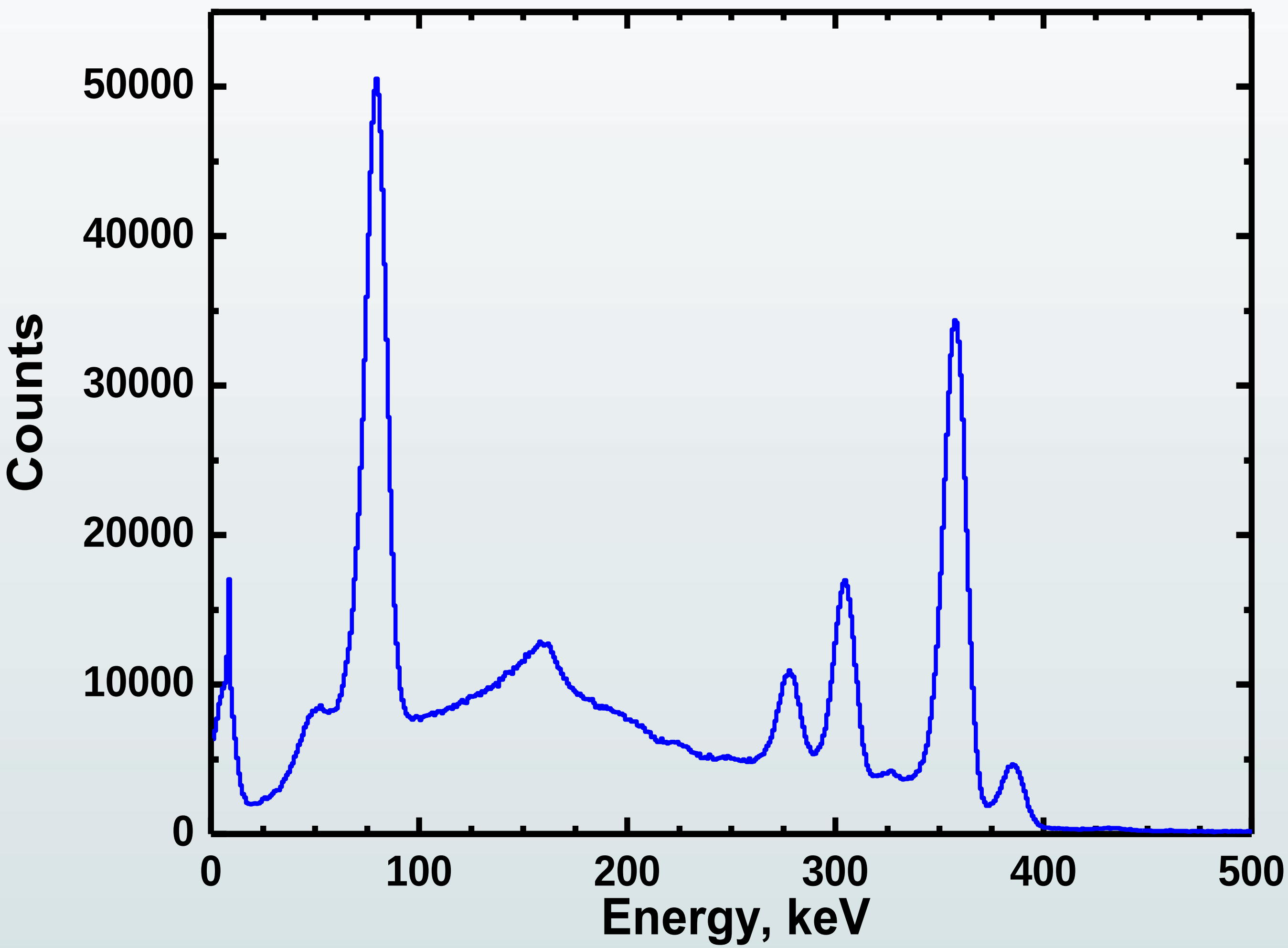
MAIN PARAMETERS

Energy range	(50-5000) keV
FWHM at 662 keV	14 keV
Density of Xe	0.4 g/cm³
Sensitive volume	2000 cm³
Diameter	120 mm
Length	300 mm
Total mass	9 kg
Voltage	=24 V or ~220 V
Power consumption	10 W

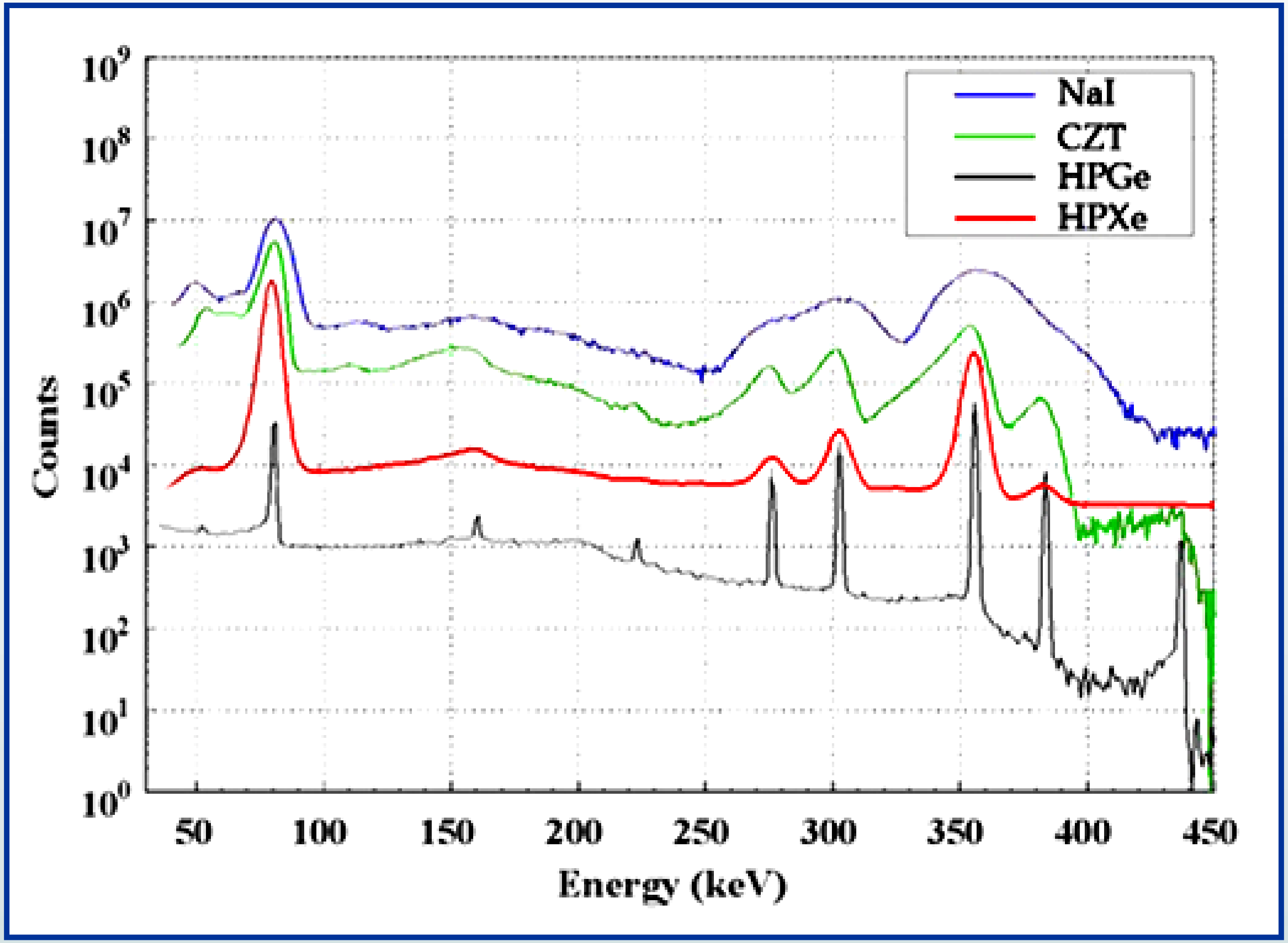
Gamma-ray source ^{137}Cs



Gamma-ray source ^{133}Ba

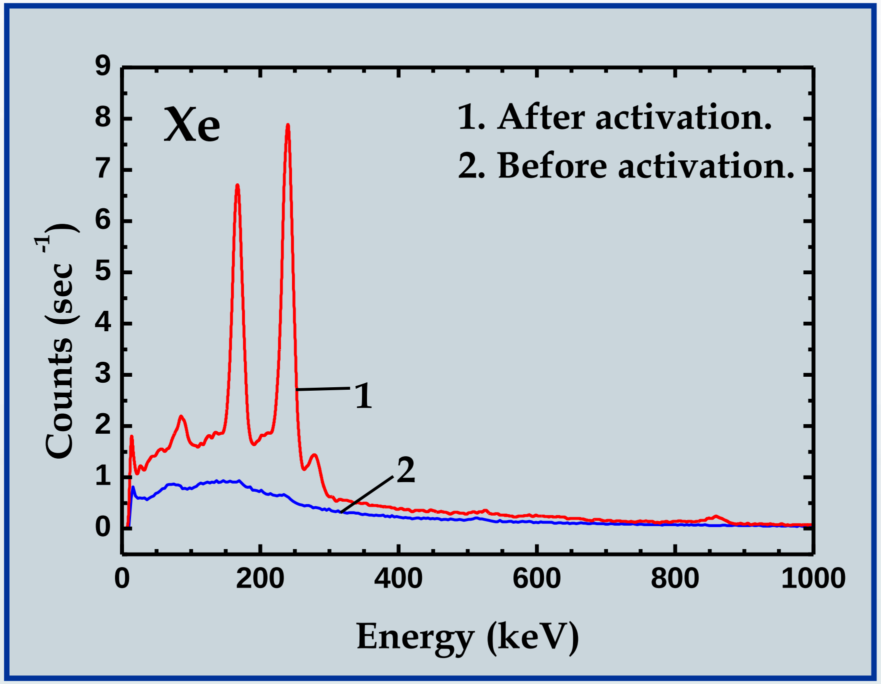


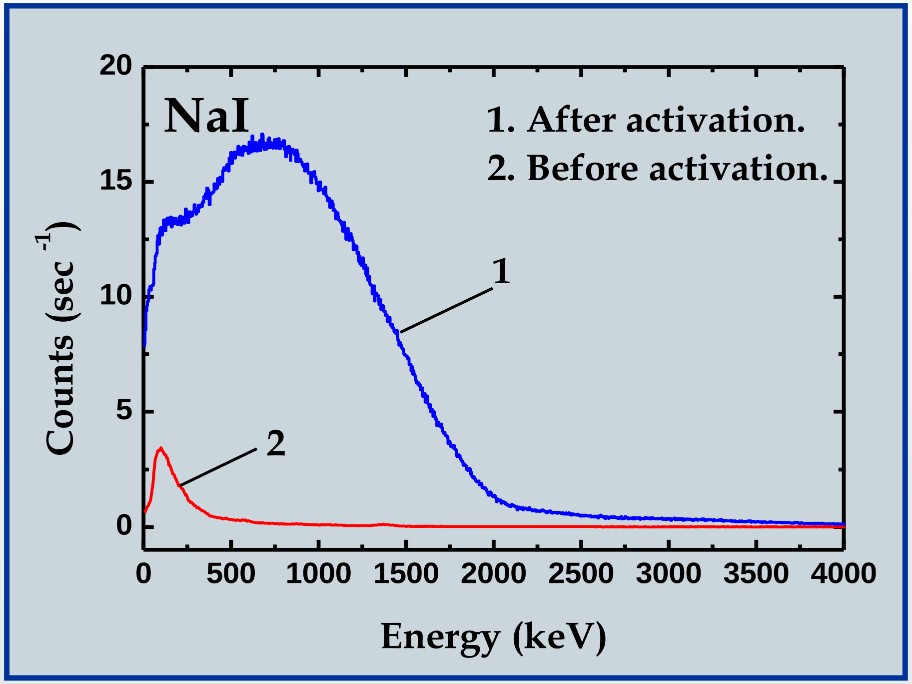
^{133}Ba spectrum comparison, measured by HPGe, CZT, NaI and HPXe gamma-ray spectrometer



ADVANTAGES OF HPXe DETECTORS

RADIATION STABILITY



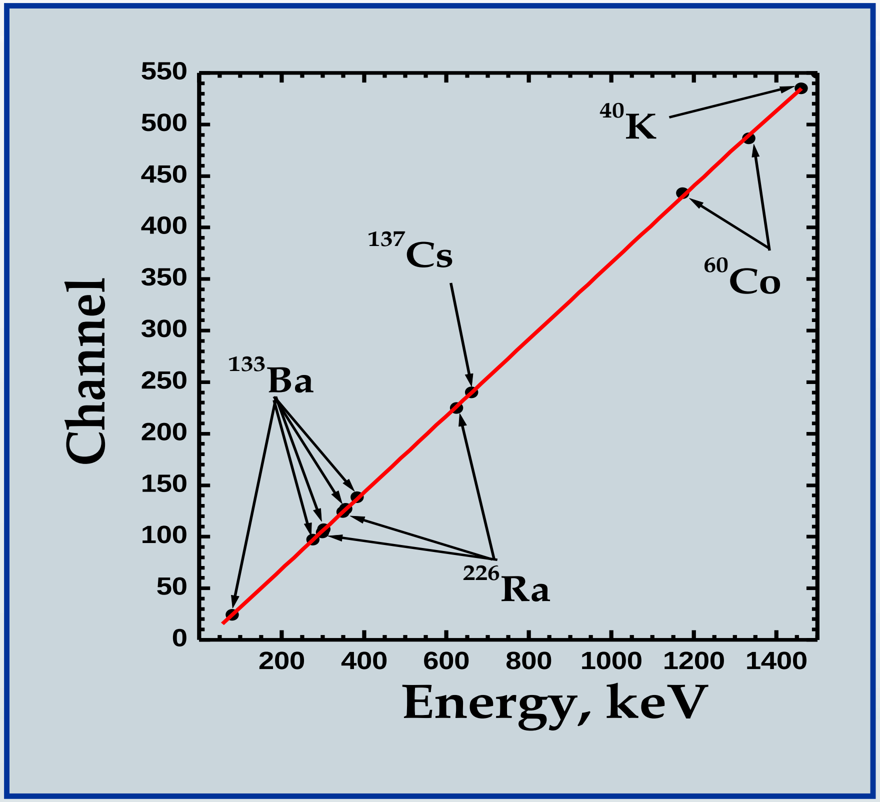


Spectra from High Pressure Xenon Detector (∅120 mm, L=500 mm, M= 1.8kg) before and after activation by Pu-Be neutron source (T=66 hours, fluence= $1.5*10^{10}$ neutrons).

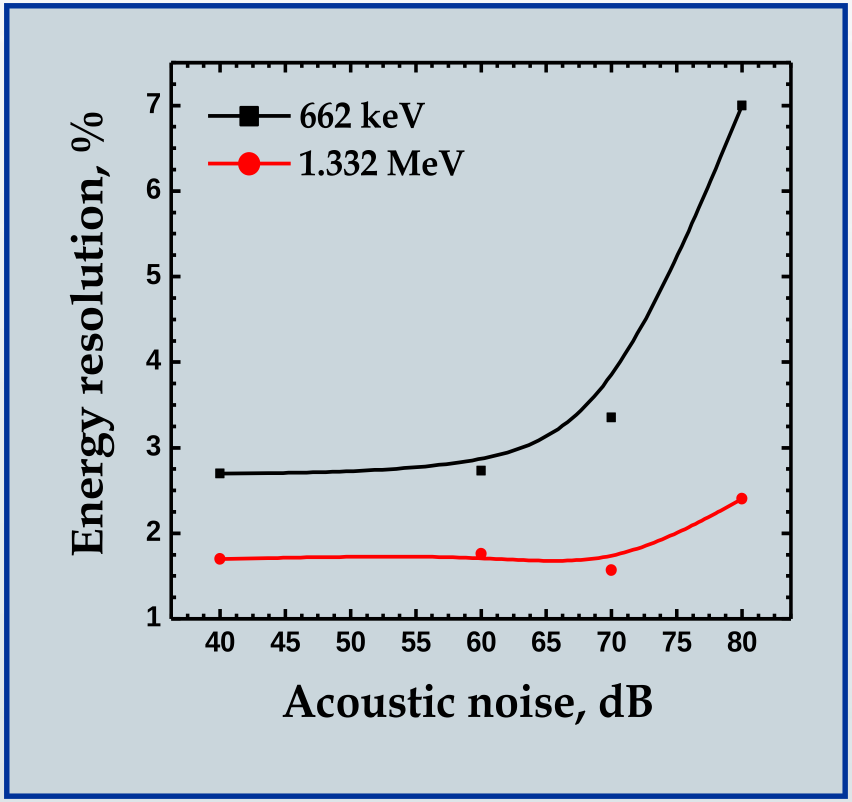
Spectra from NaI detector (∅ 80 mm, L=50 mm, M=0.9 kg) before and after activation by Pu-Be neutron source (T= 66 hours, fluence = $1.5*10^{10}$ neutrons).

ADVANTAGES OF HPXe DETECTORS

Linearity

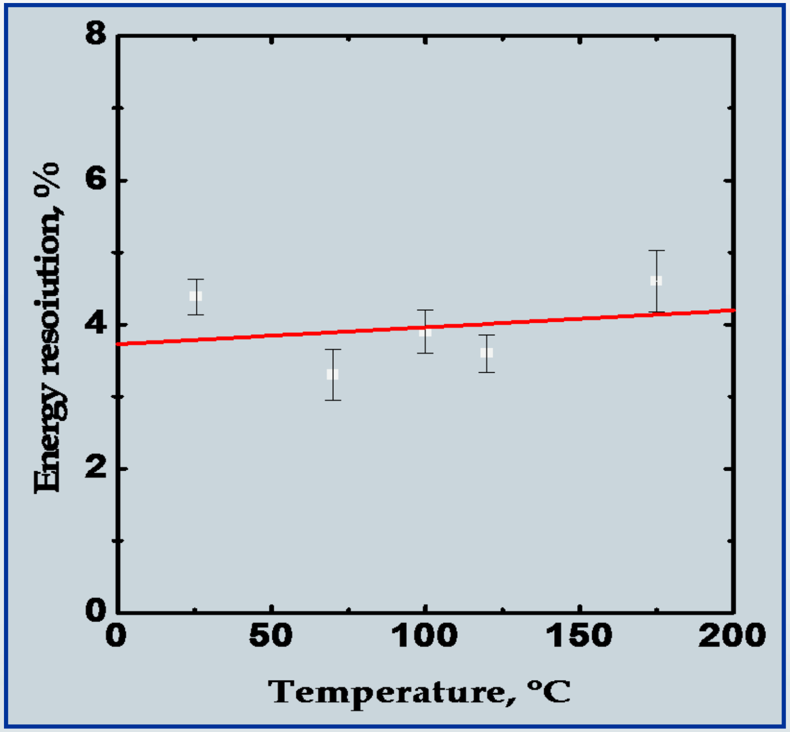


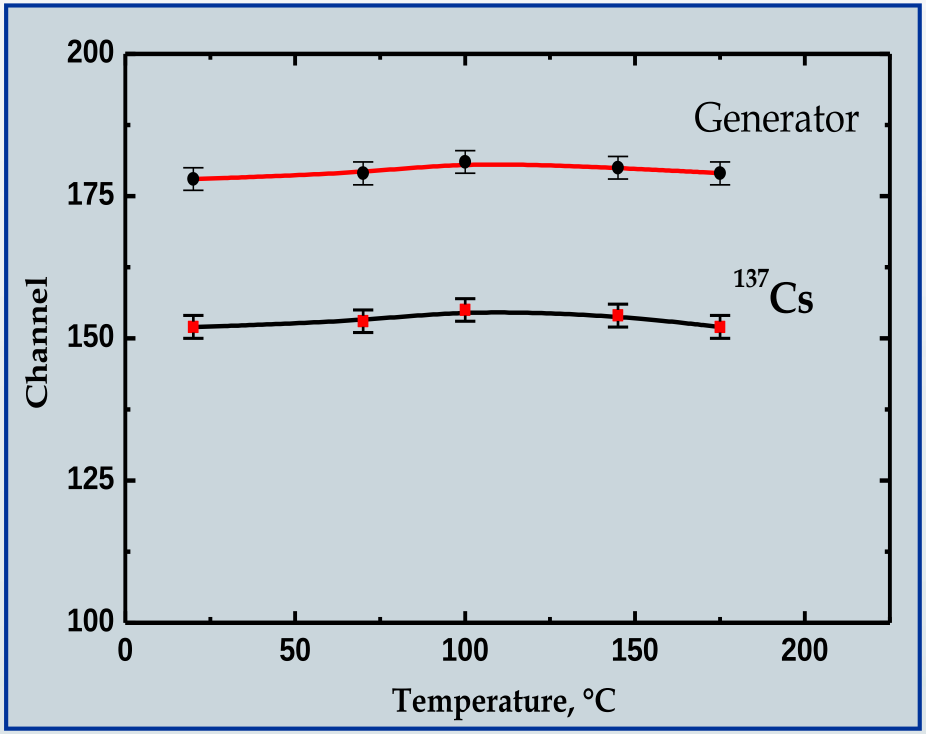
Vibrostabitity



ADVANTAGES OF HPXe DETECTORS

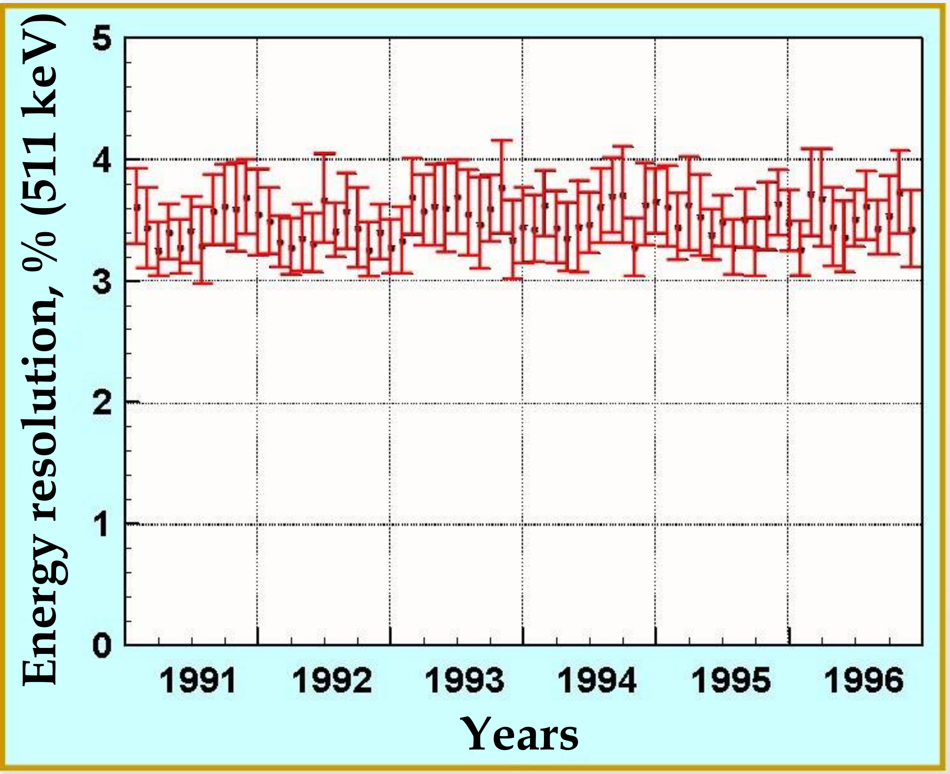
THERMOSTABILITY

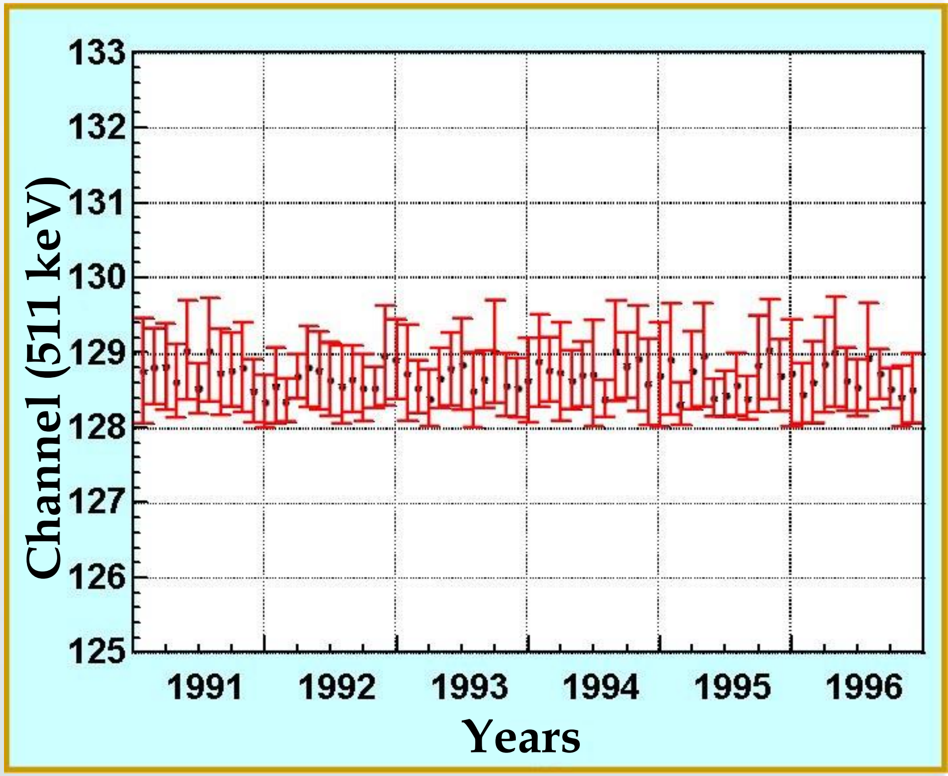




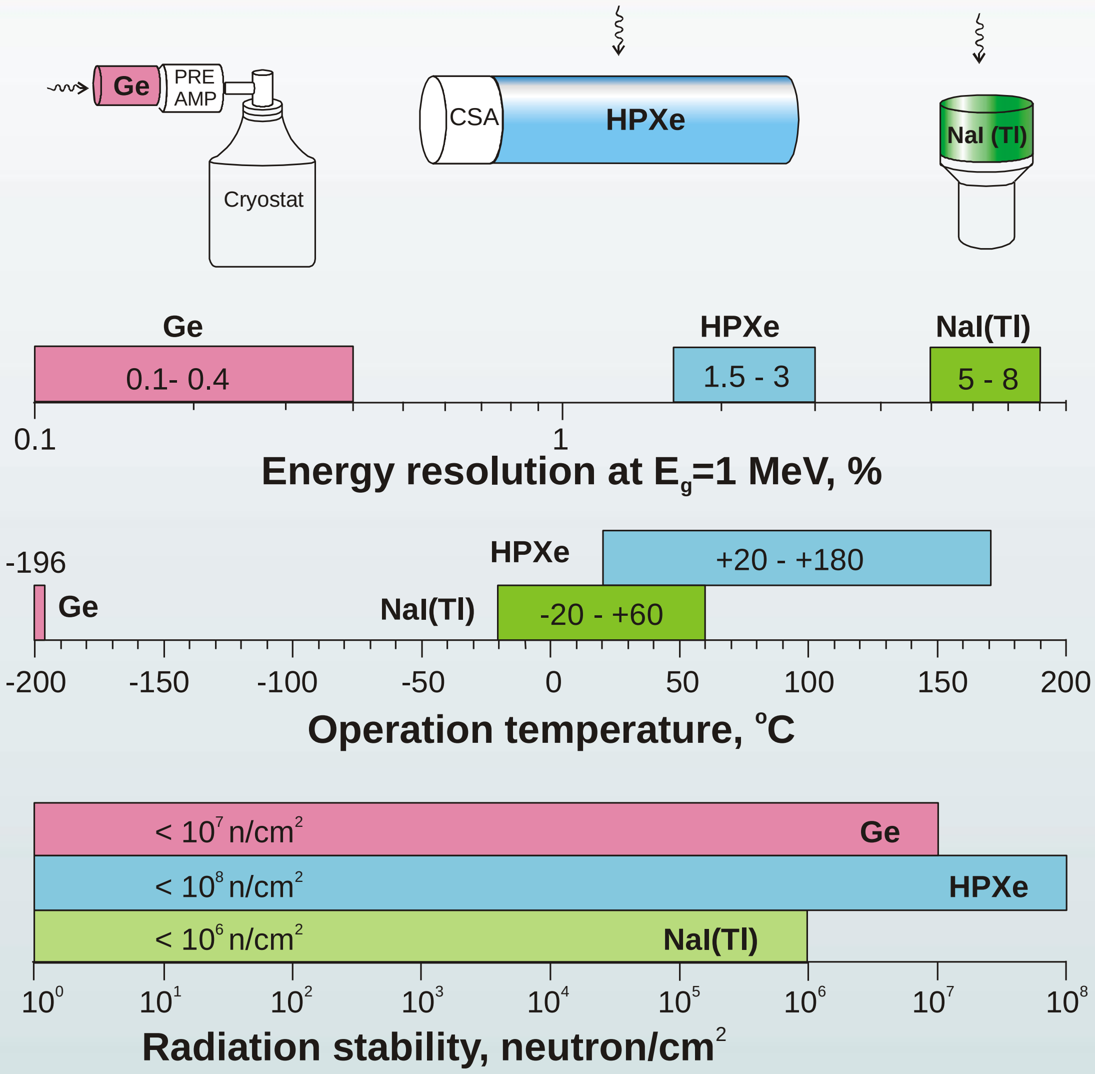
ADVANTAGES OF HPXe DETECTORS

LONG PERIOD OF OPERATION





ADVANTAGES OF HPXe DETECTORS



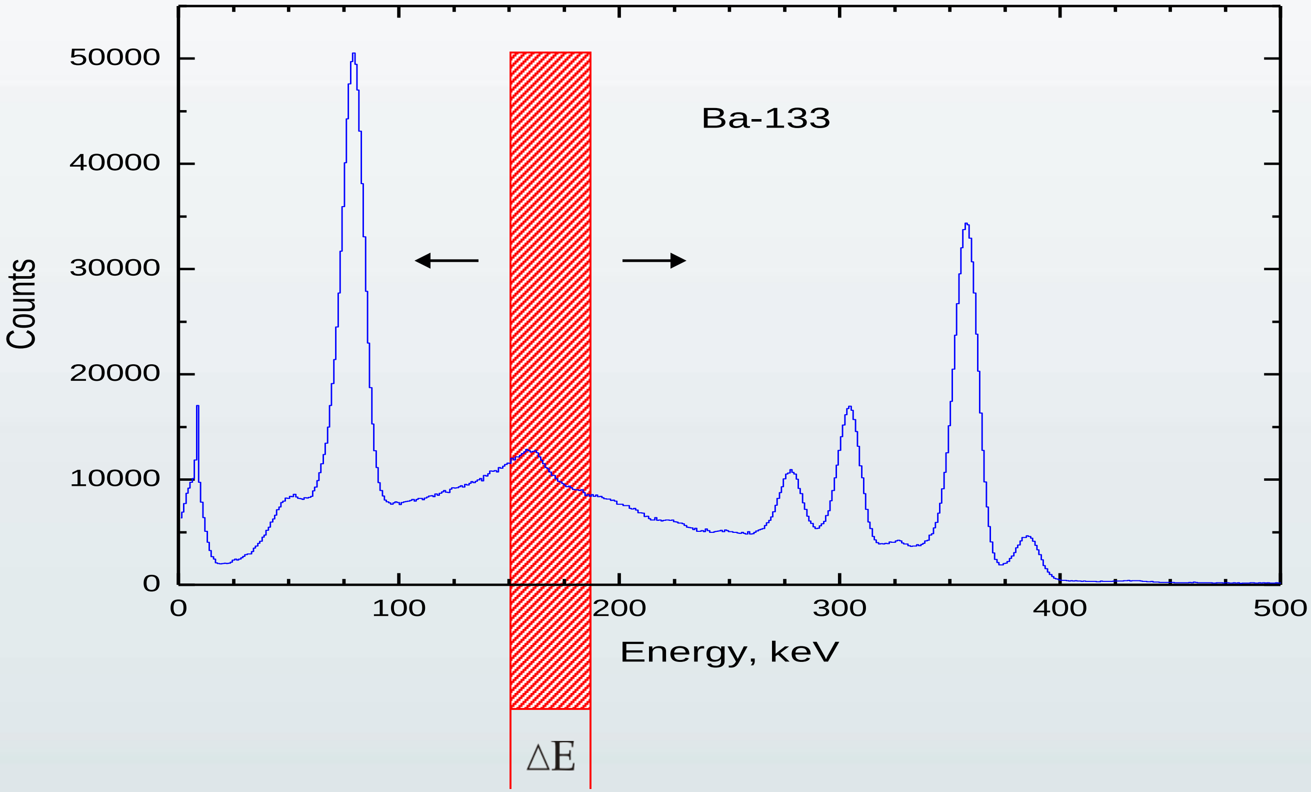
RADIATION CUSTOMS CONTROL OF PASSENGERS

Portal monitor ВНИИЭМ-ПМ
(equipped with 2 liters HPXe detector)

Detection time of radionuclide
(662 keV, 50 kBq)……………….. 1 sec.

Identification time of radionuclide
(662 keV, 50 kBq) .... 5 sec.

Software

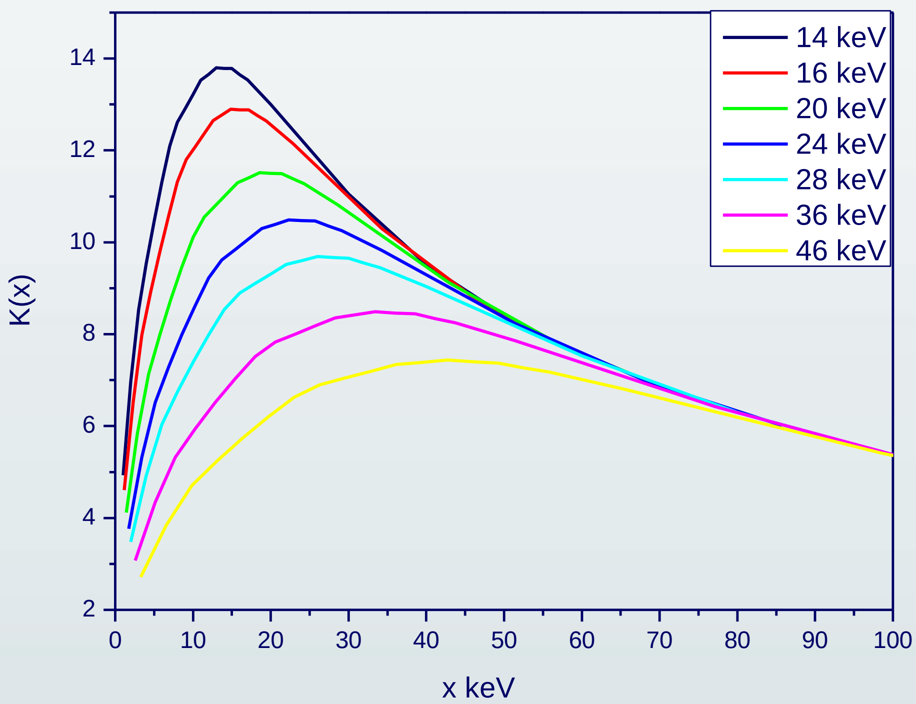


Scanning spectrum of variable energy interval.

Software

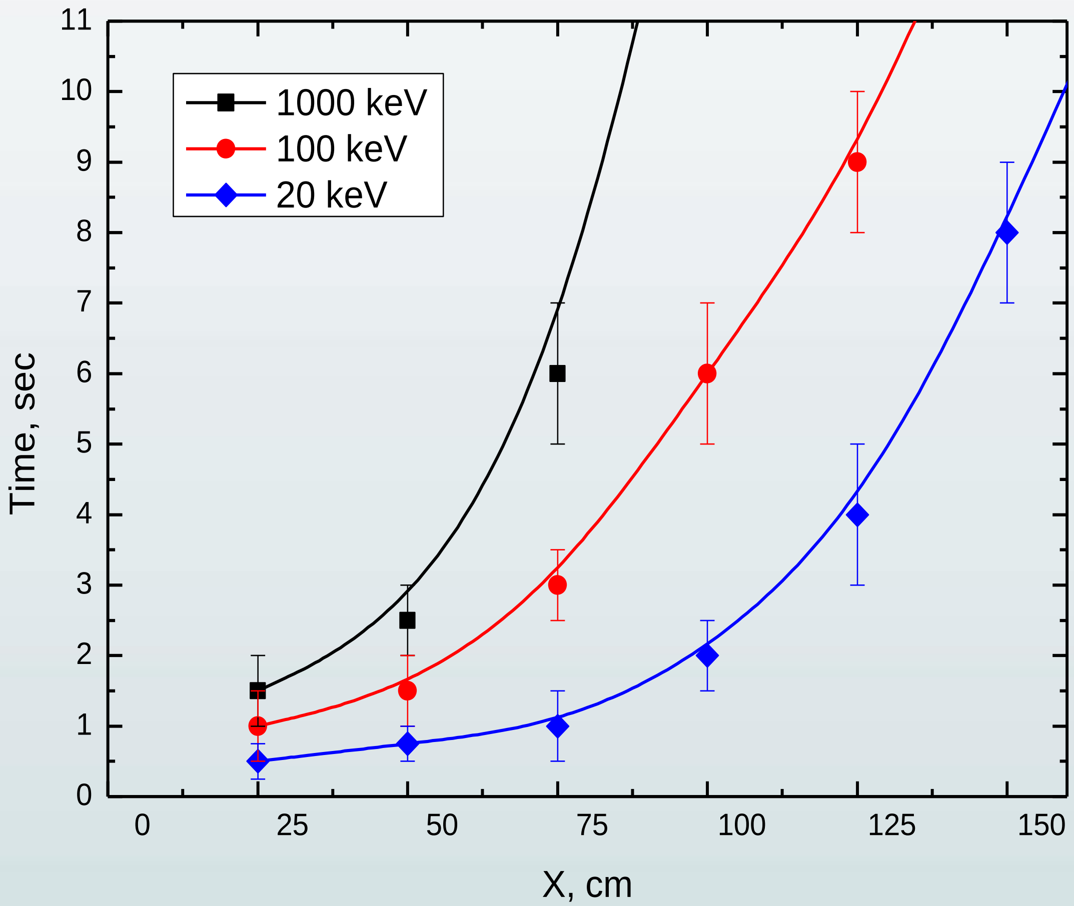
Sensitivity of the gamma-detector as function of a scanning interval

$$K(x)=\frac{\displaystyle\int_{E_0-x/2}^{E_0+x/2}\frac{N_0}{\sqrt{2\pi\Delta E^2}}\times e^{-\frac{(E-E_0)^2}{2\Delta E^2}}\,dE}{\left[\displaystyle\int_{E_0-x/2}^{E_0+x/2}\alpha\times e^{-\beta E}\,dE\right]^{\frac{1}{2}}}$$



Software

Minimum detecting time of the source 137Cs (75 kBq) as function of distance from Xenon Gamma-ray Detector.

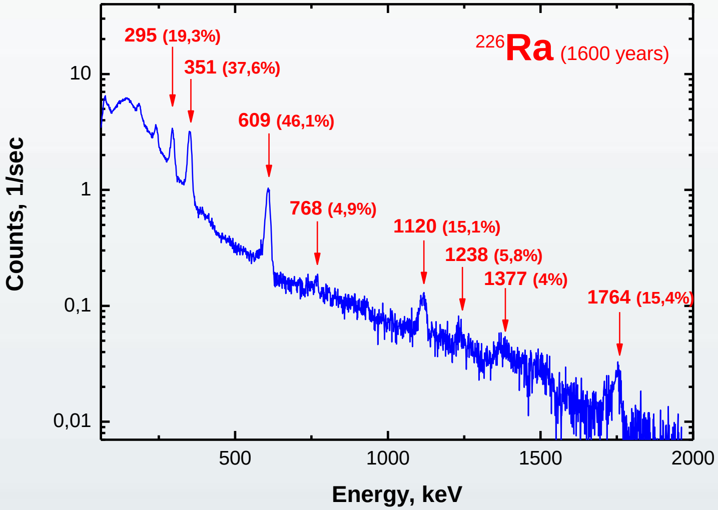


Movable security checkpoint for river and sea ports

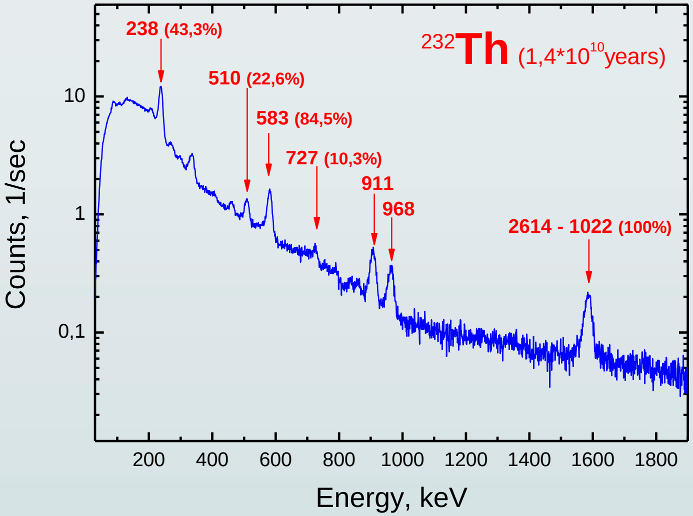
Movable security checkpoint for river and sea ports

RADIATION CUSTOMS CONTROL OF LUGGAGE

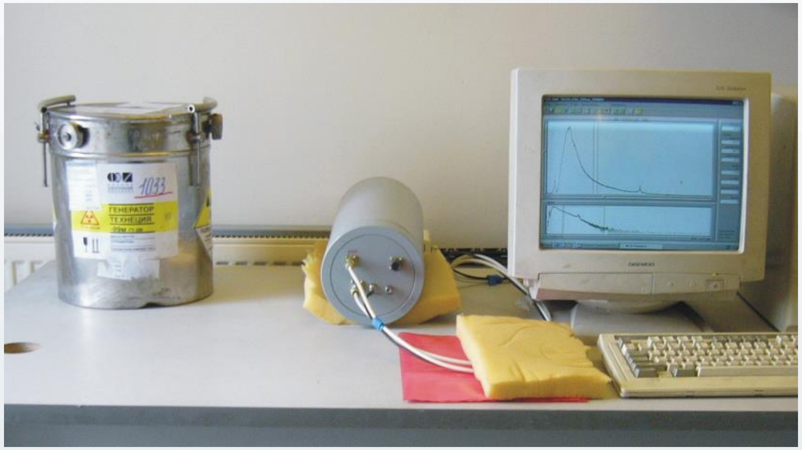
A clock

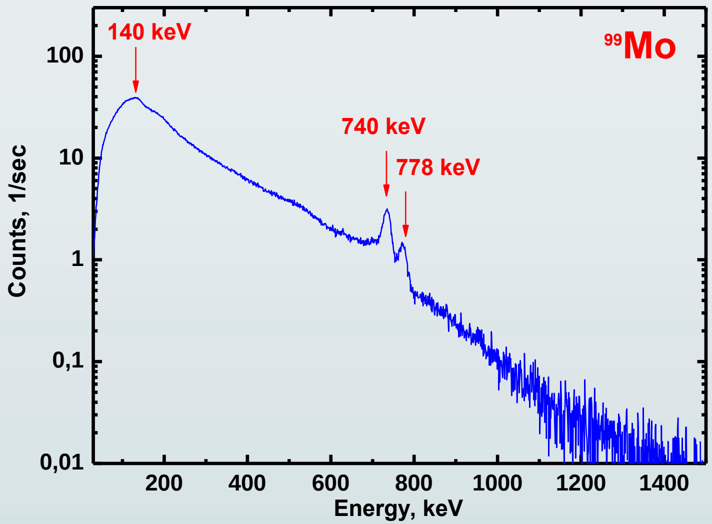


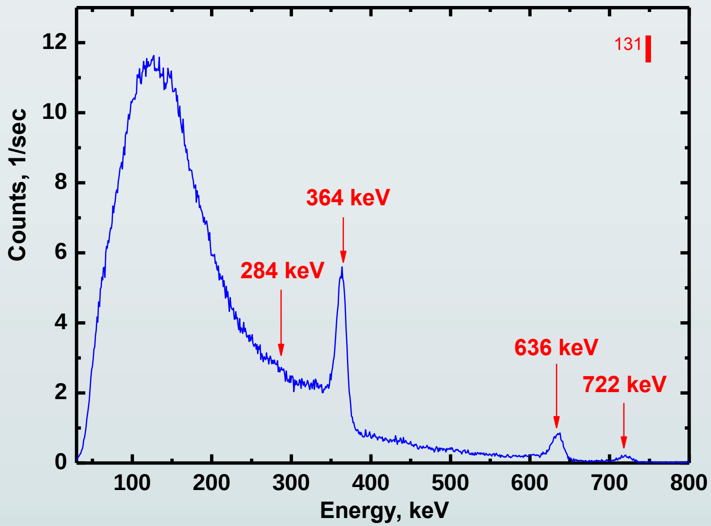
Camera lens



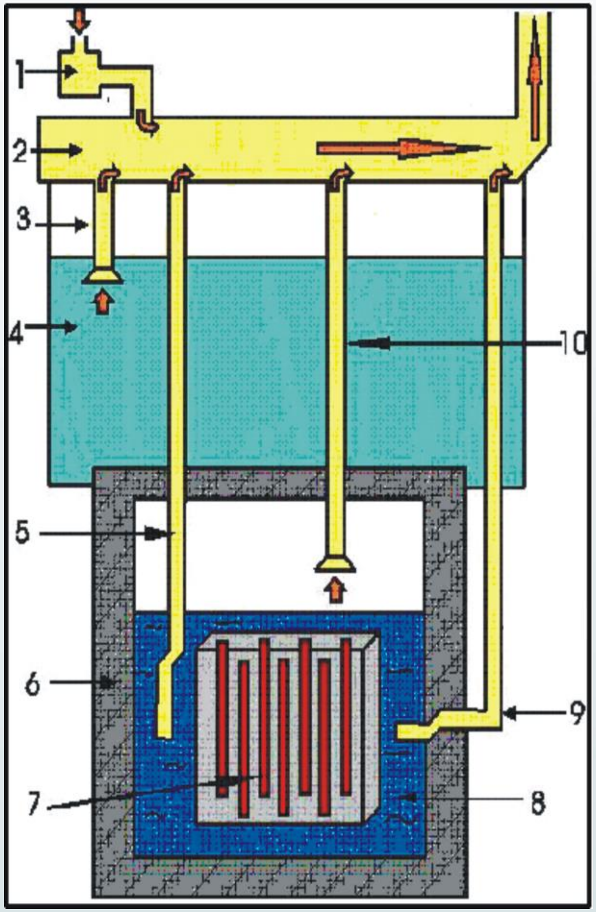
RADIATION CUSTOM CONTROL OF TRANSPORT CONTEINERS WITH DECLARED RADIONUCLIDES



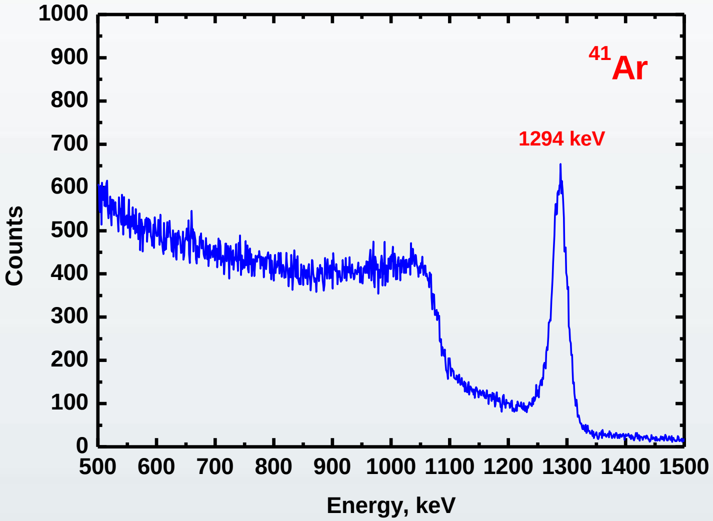


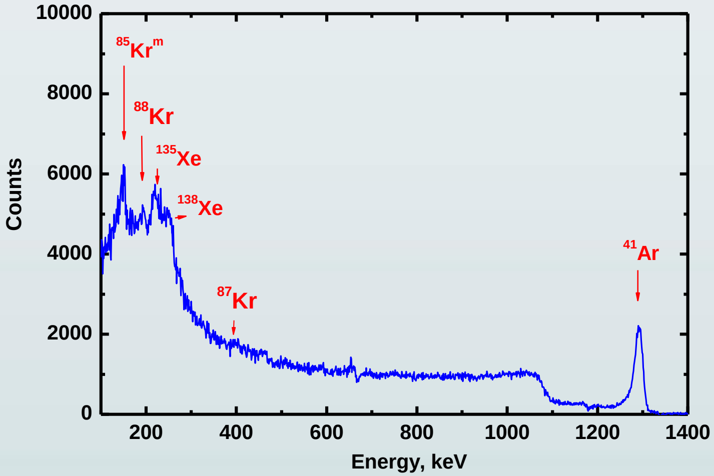


Control for gaseous radionuclide pollution from nuclear reactors

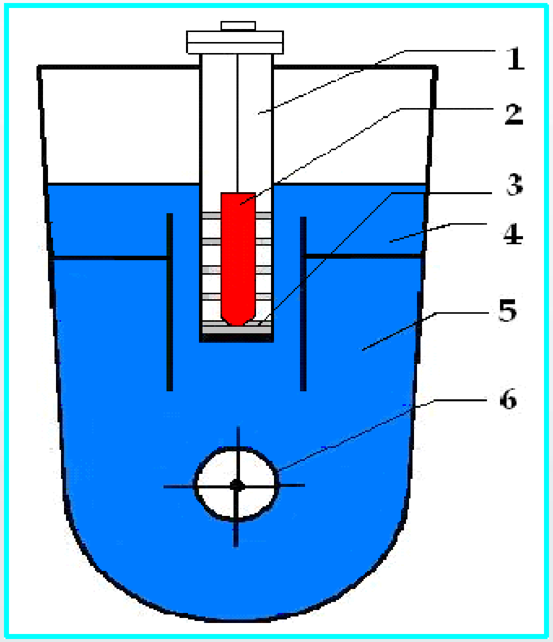


1. Atmosphere manifold
2. Main airway of special ventilation.
3. Air-ejector ventilation from operation research hall.
4. Operation research hall.
5. Vertical ventilation experimental channel.
6. Concrete protection.
7. Reactor.
8. Moderator – water.
9. Horizontal ventilation experimental channel.
10. Air-ejector ventilation above reactor space.

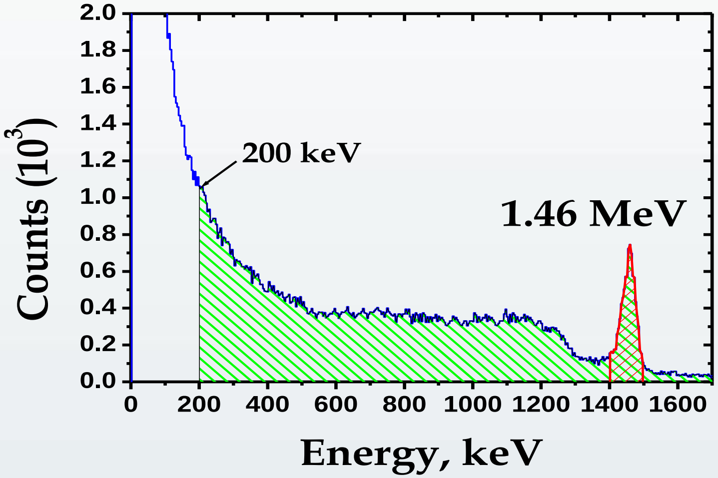


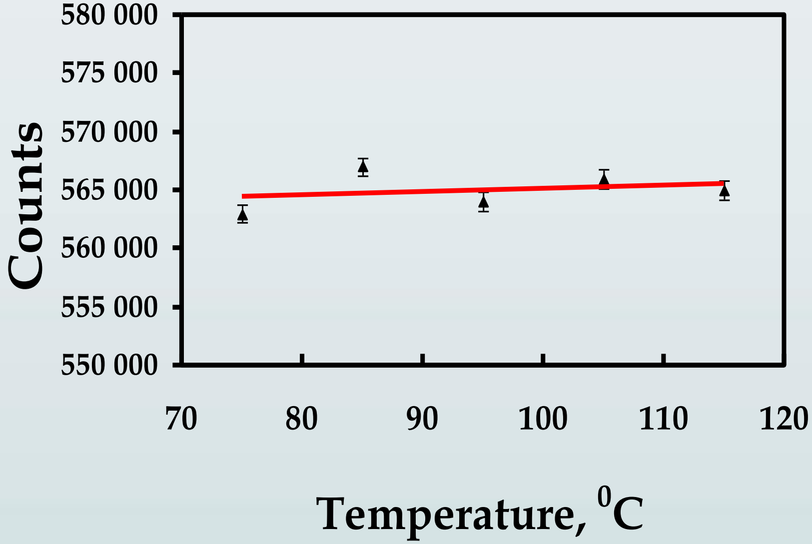


Control of KCl concentration in process of potassium chloride fertilizer manufacturing

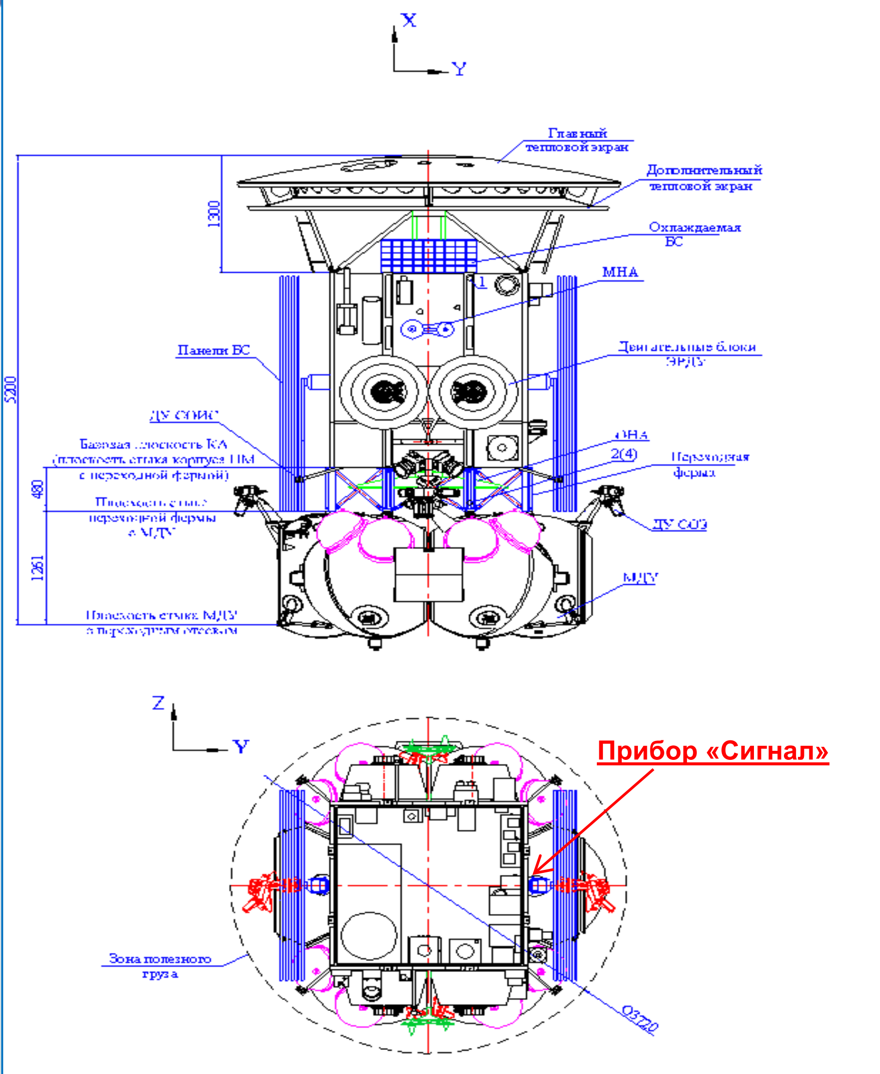


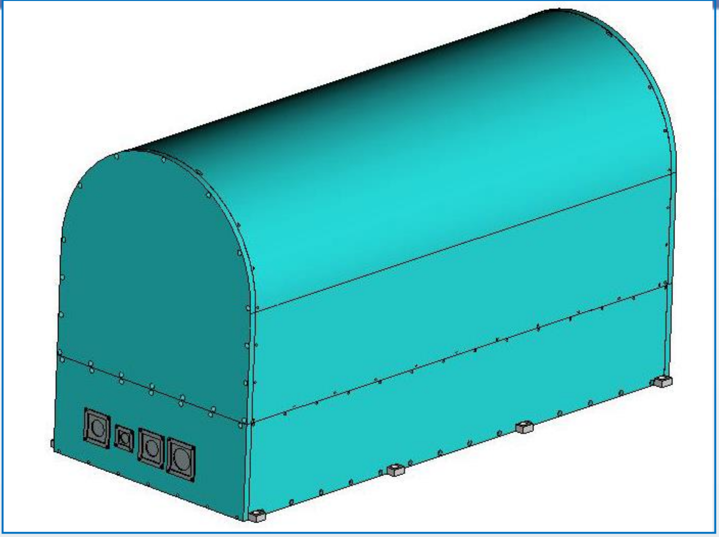
1. Waterproof container
2. HPXe detector
3. Lead collimator
4. Drain
5. KCl and NaCl solution
6. Rotor

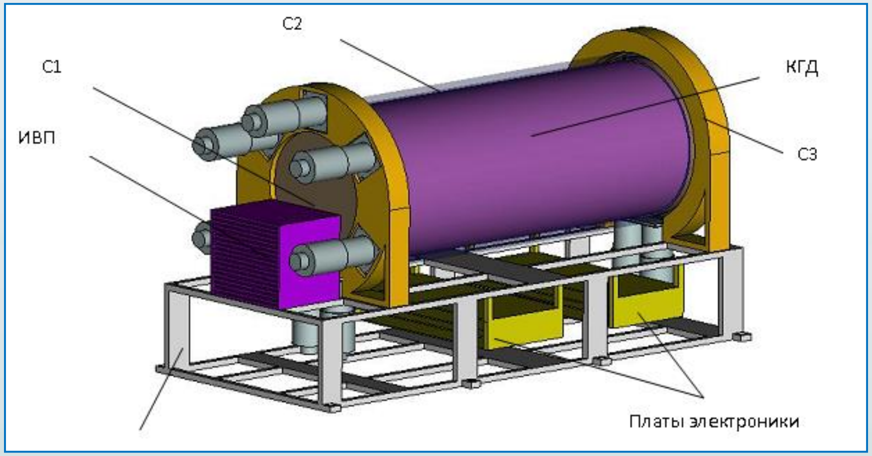




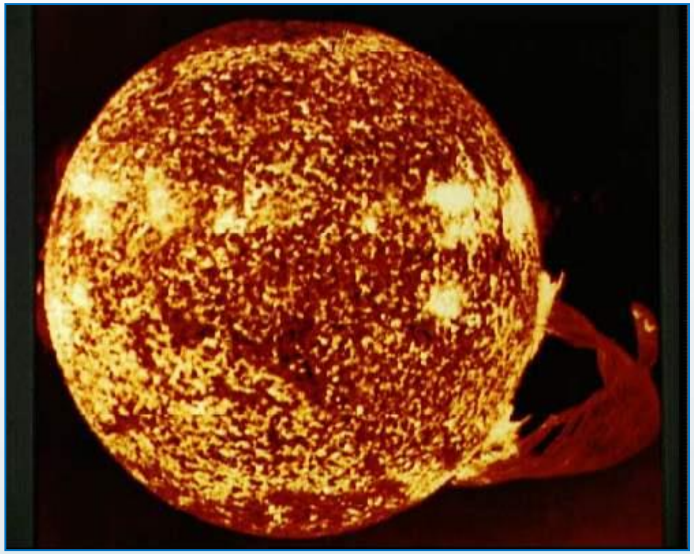
EXPERIMENT "SIGNAL" ON SOLAR MISSION "INTERGELIOPROBE"

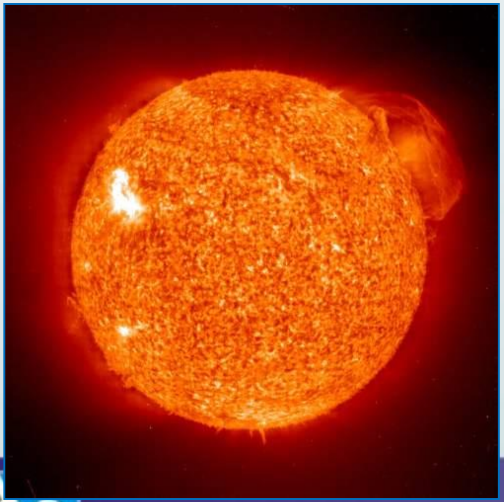


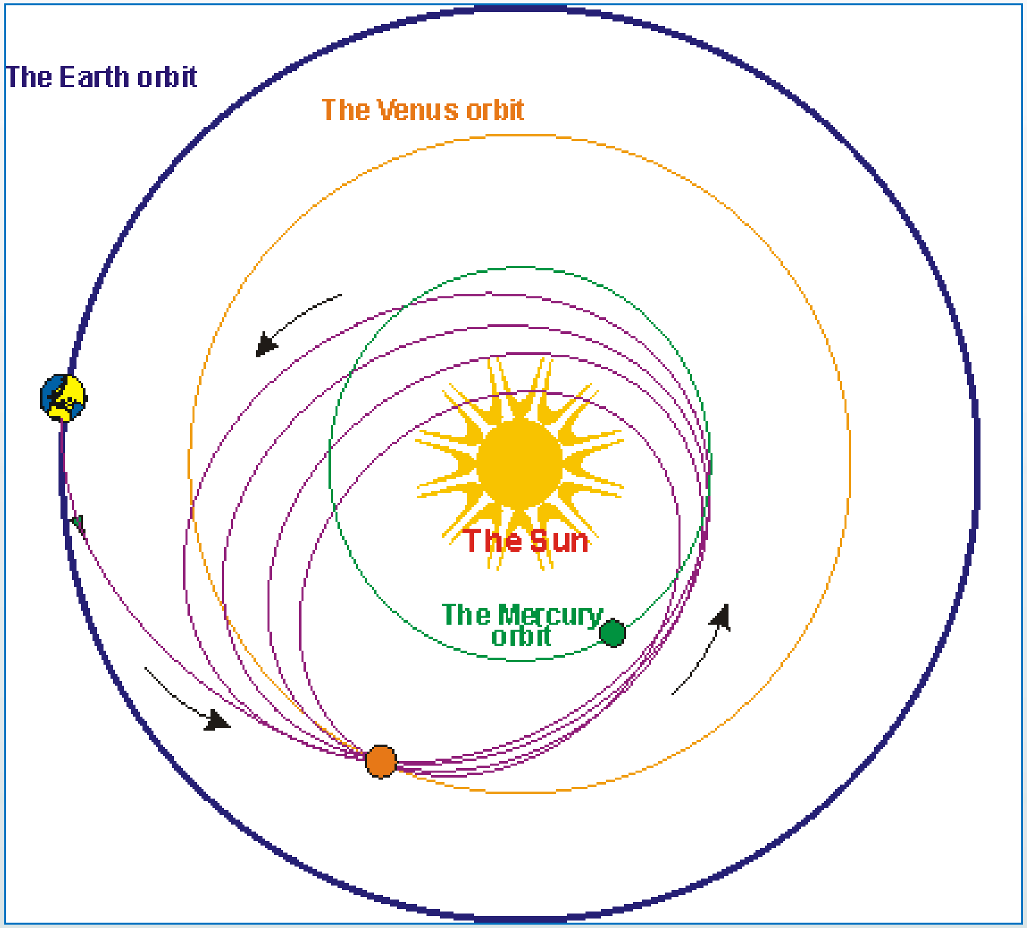




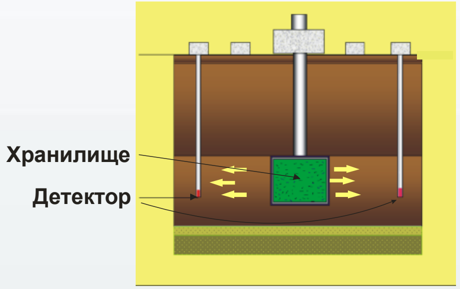
SOLAR MISSION "INTERGELIOPROBE" TRAJECTORY







PERSPECTIVE FIEIDS OF APPLICATION



• **RADIOACTIVE WAIST RECICLING AND STORIGE**

• **MEDICINE**

- ***Measurement of douse radiation of a patient with taking into account of gamma-ray spectrum distribution.***

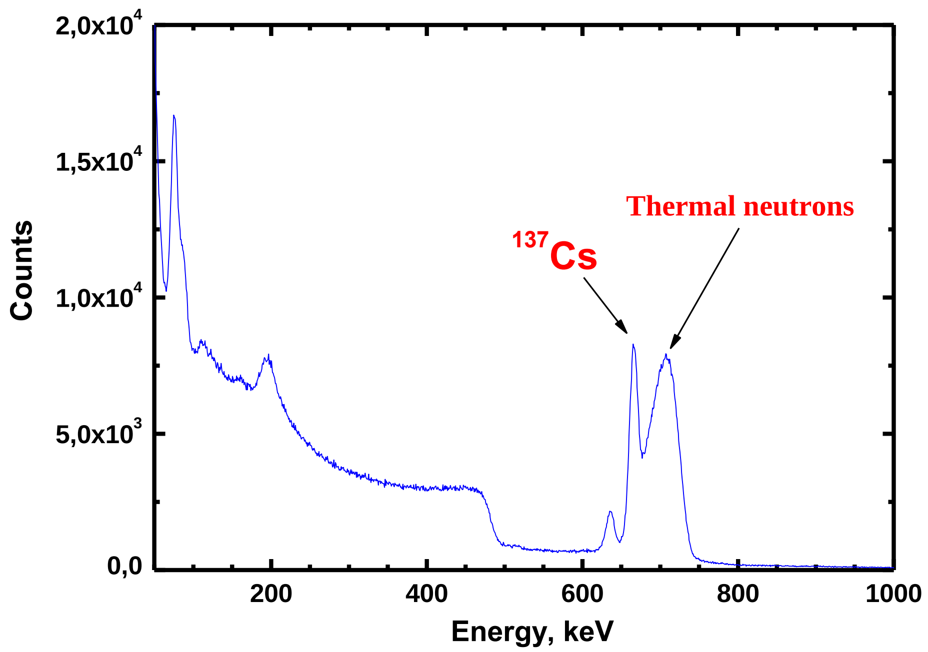
центральный кондиционер

• **PREVENTIOM OF RADIOLIGICAL TERRORISM.**

- ***Installing of gamma-ray spectrometers on ventilation systems and water supply stations.***
- ***Control for shipping of radioactive sources at the airports, tracks and cars terminals, railroad stations and so on.***

Advanced gamma-ray detectors technology

Xenon gamma-neutron detector



Gamma-ray detector filled on with Xenon+Helium-3 mixture. Interaction of neutrons with Helium-3 through reaction:

$$ {}^{3}_{2}He + {}^{1}_{0}n \rightarrow {}^{3}_{1}H + {}^{1}_{1}p $$

Energy yield of this reaction is 765 keV,
Interaction Cross-section of thermo neutrons with ^{3}He - 5327 barn.

Advanced gamma-ray detectors technology

Thin-walled vessel of xenon gamma-ray detector

The wall of the body was made of 0,8 mm stainless steel covered with 2.5 mm of synthetic fiber (Kevlar) and successfully tested under pressure more than 400 atm.

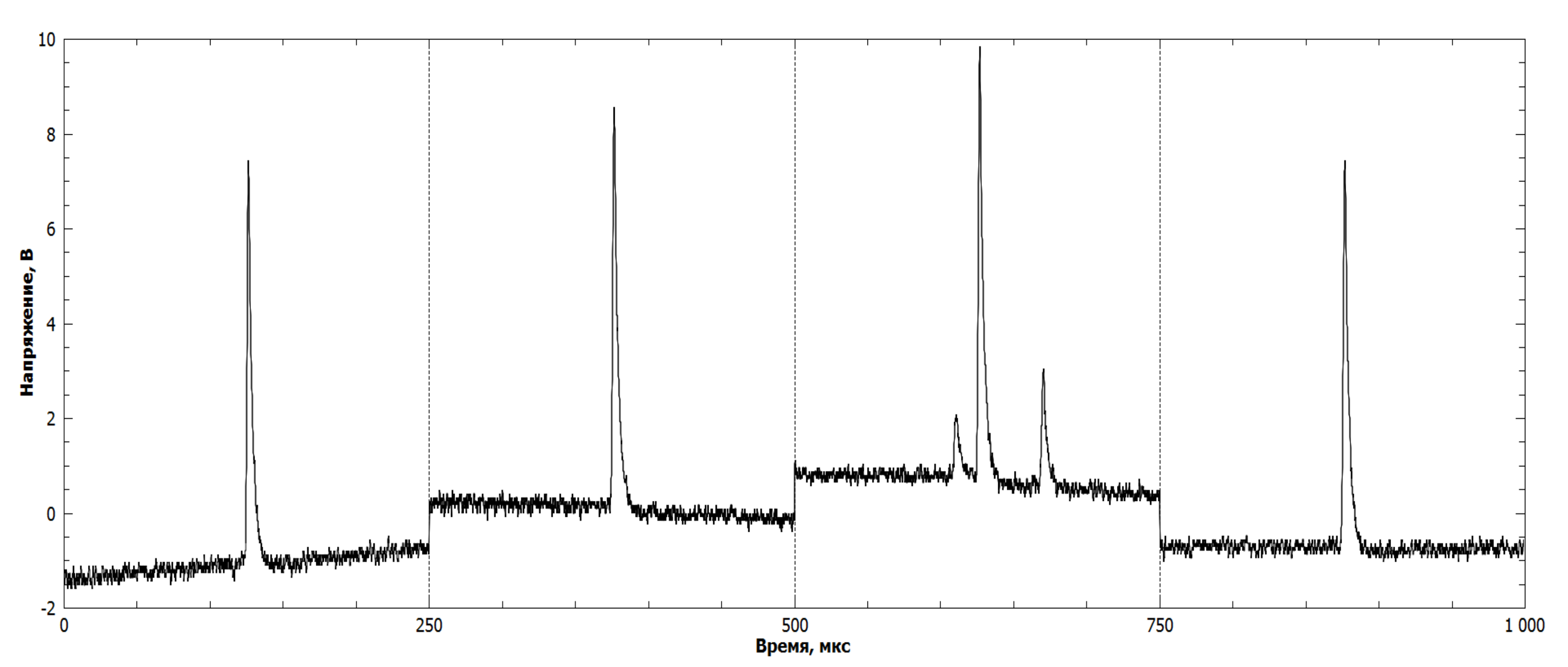
Advantage of construction:

- **Total mass three times smaller;**
- **Compton scattering in the wall decreased ;**
- **Energy range widened to low energies.**

Manufacturing technology of thin-walled housing of Xenon gamma-ray detector

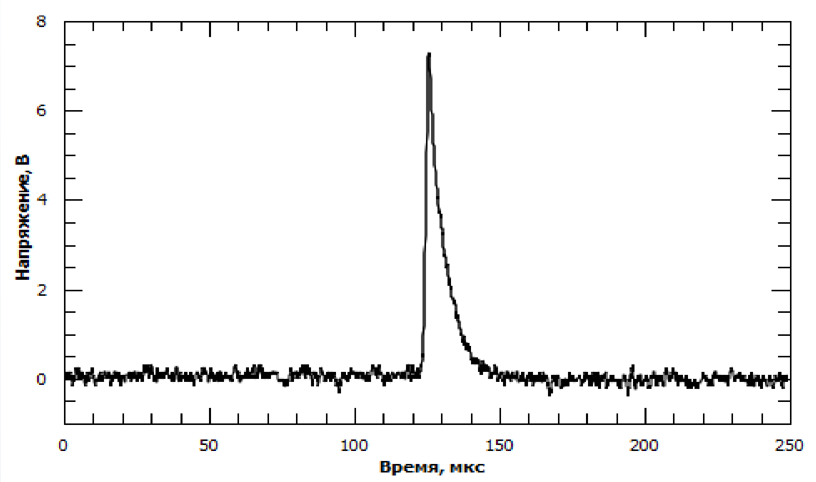
- The thickness of the steel housing 0.5 mm.
- The outer shell material: carbon fiber, Kevlar or fiberglass. Thickness 2 mm.
- This housing can withstand the pressure more than 400 atmospheres.

Electrical signals from HPXe detector under high acoustic impact



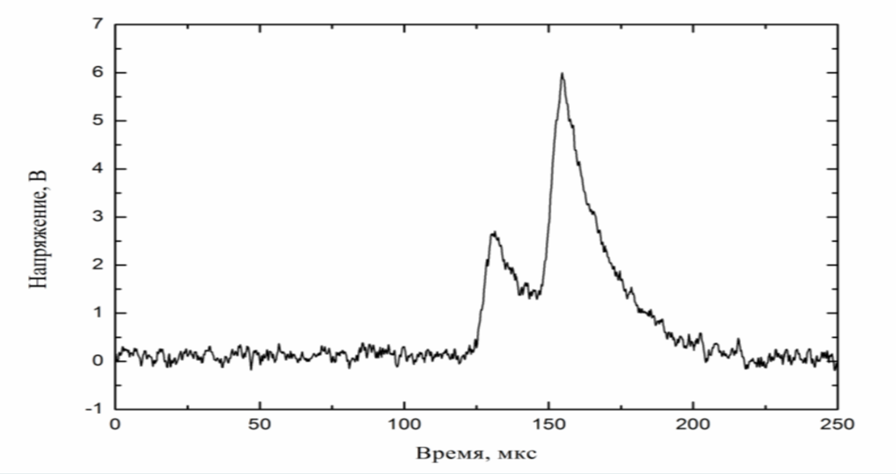
Electrical signals from the HPXe detector from 137Cs gamma-ray source at the level of the acoustic impact of ~ 90 dB

Methods of mathematical processing electrical signals from HPXe gamma-ray detector



1) Digitalization and memorizing the signal. Continuous storing digitized electrical signals. Thus in addition to the wanted signal, and stored voltage values before and after its arrival, which makes it possible to implement a number of mathematical operations.

2) Finding the beginning of the pulse. By setting the required amplitude threshold determined by the timestamp, which is attached to all further calculations



3) rejection of superimposed signals. This consists of each signal in the study for the presence therein of two or more pulses that are close in time of arrival.

Methods of mathematical processing electrical signals from HPXe gamma-ray detector

4) Compute baseline subtraction.

By approximating the linear dependence of digitized voltage values before and after the arrival of the useful pulse baseline is calculated, which is then subtracted from the corresponding value of the desired signal.

5) Analysis of pulse front time.

At this stage, the calculation and analysis of the pulse edge time, and if it does not fall in the desired range of values (time corresponding to desired signals), this impulse is excluded from further processing. If the rise time corresponds to the desired signal, this value is used to correct the amplitude of the total in the integration the pulse.

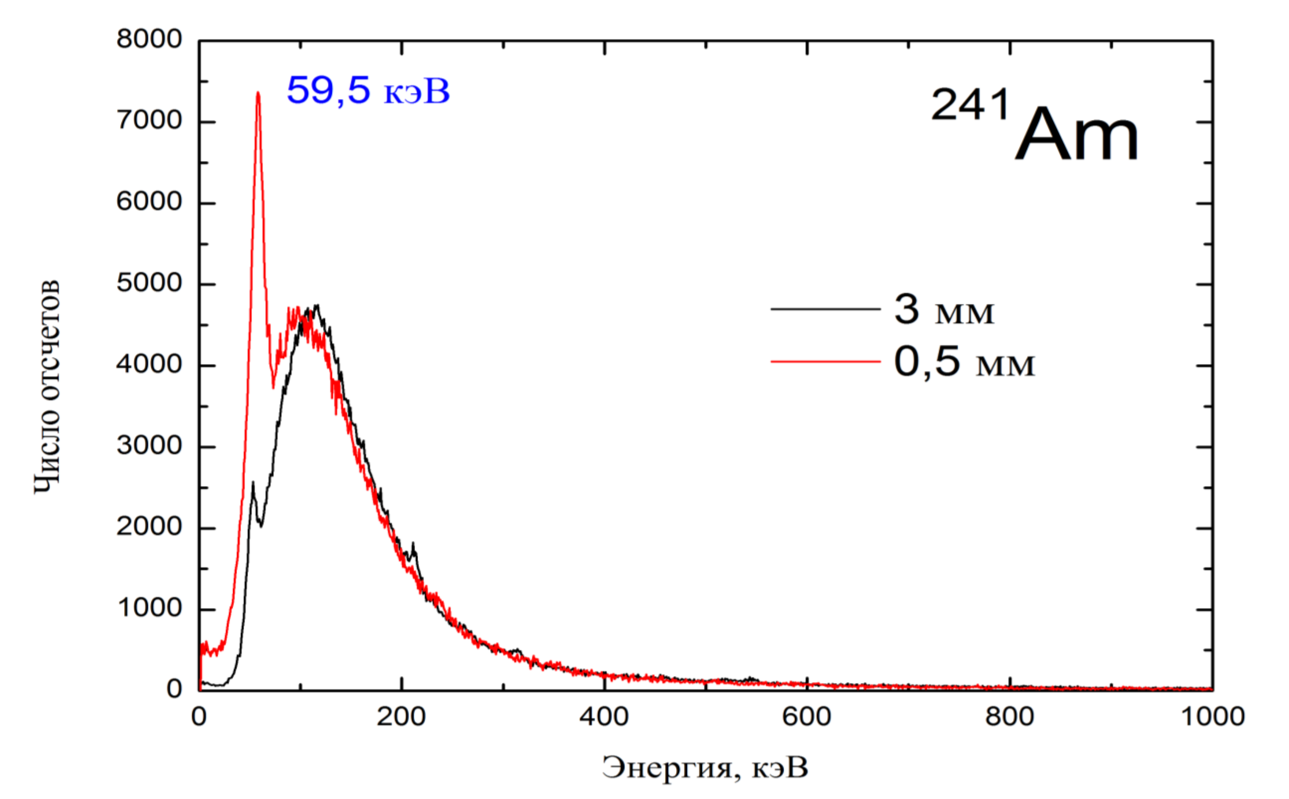
6) The integration of the pulse and the spectrum set.

After subtracting the baseline occurs useful signal integration within the established time limits. Then, the amplitude distribution (spectrum) is formed on the basis of the obtained integral values.

7) Calculation of the dead time of the spectrometer.

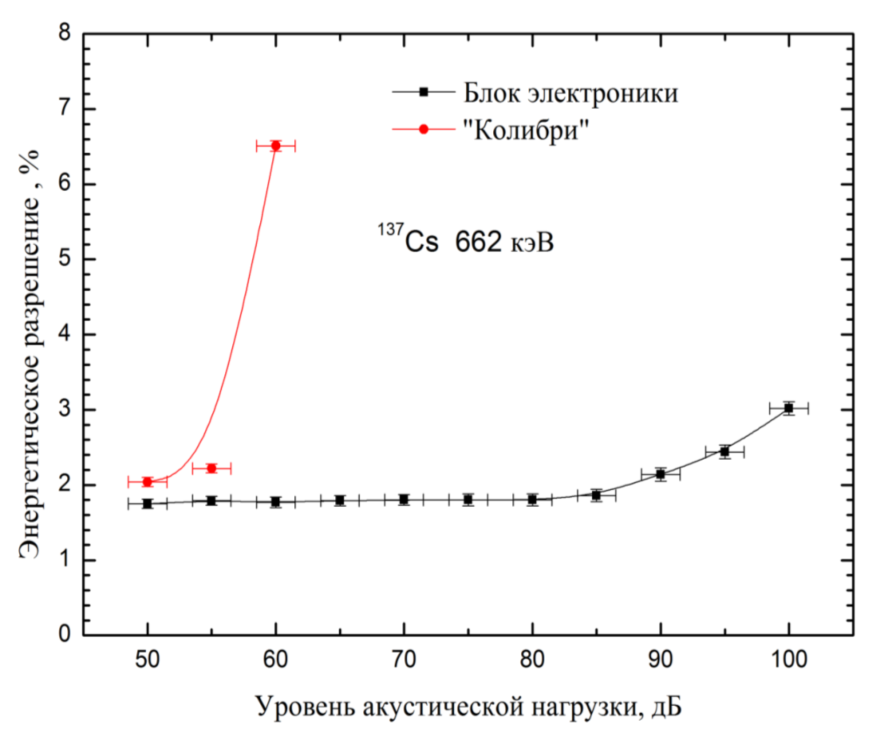
The time during which each pulse is processed, and the spectrometer does not register the following event, is summed, and the value of "dead time“ is taken into account in the processing of the spectra.

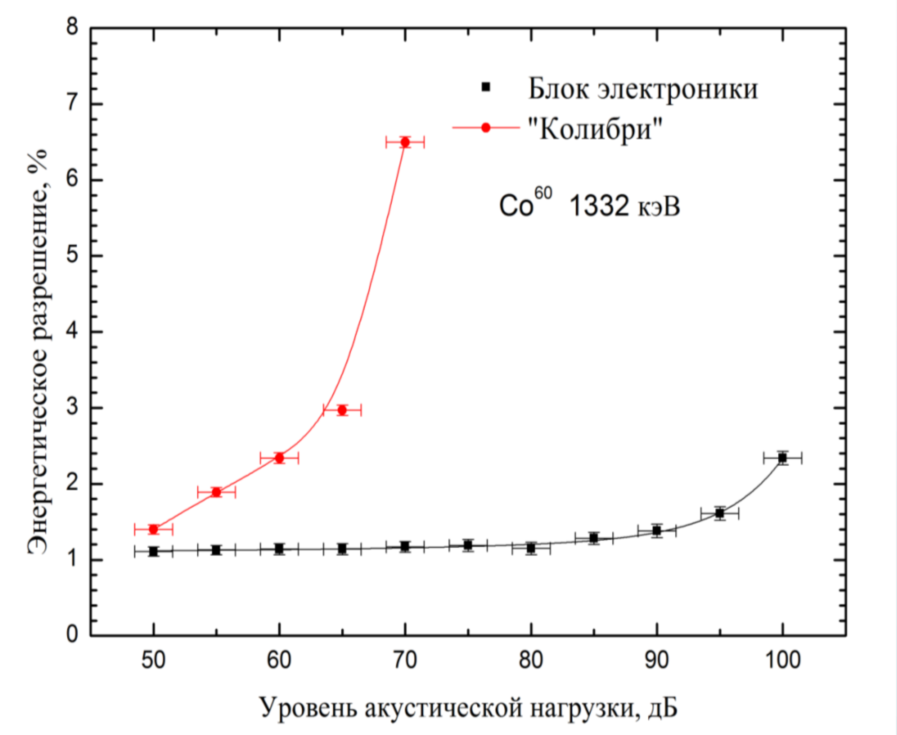
Xenon gamma-ray detector with a wall thickness of 0.5 mm stainless steel



- For a detector with a wall thickness of 0.5 mm fraction of absorbed gamma-rays with energy 59.5 keV (241Am) is three times smaller than for the detector with a wall thickness of 3 mm stainless steel.
- The range of detected gamma-rays extended to 30 keV-3 MeV.

The energy resolution of HPXe detector with the digital processing of electronic pulses at acoustic impact

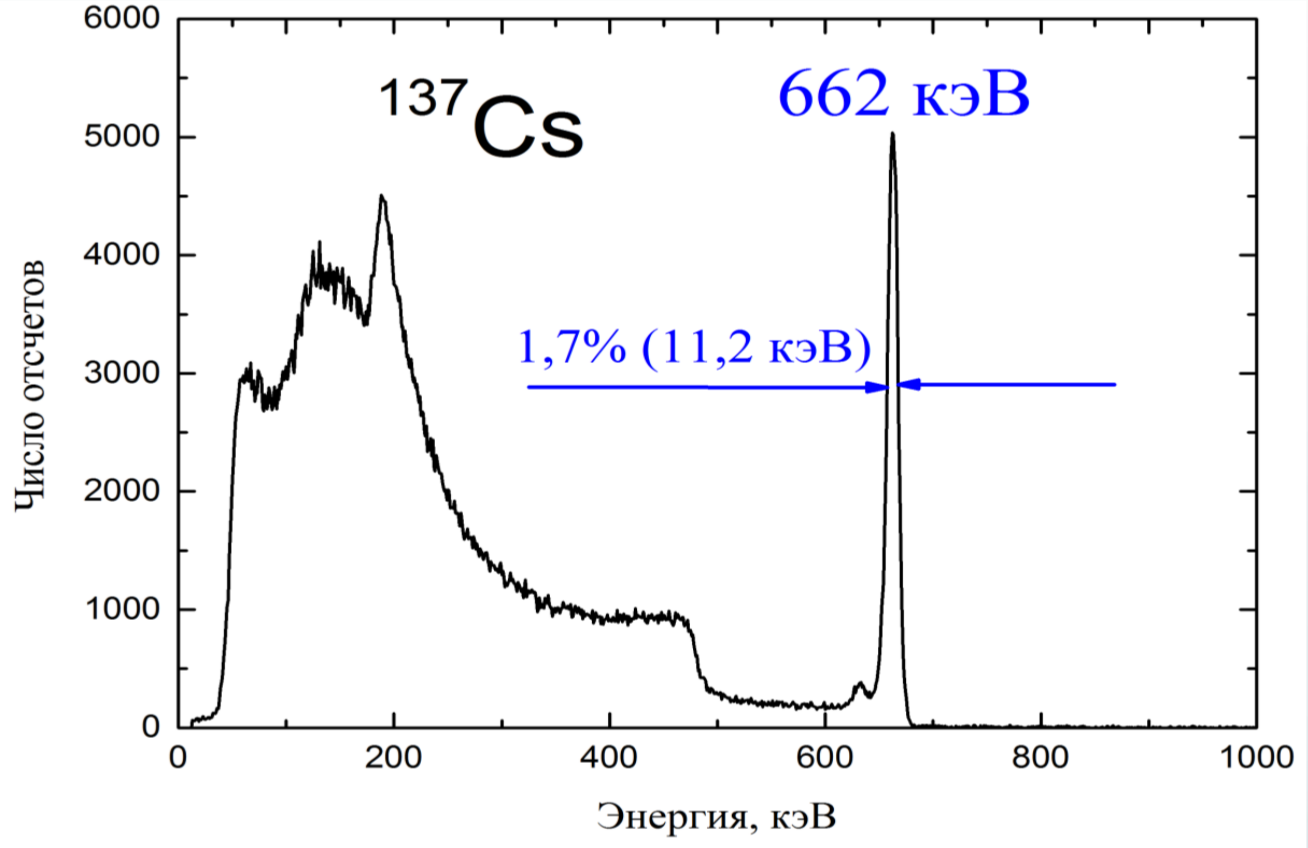




Using the digital pulse processing instead of analog allowed to make HPXe gamma-ray detector practically insensitive to the acoustic impact of up to 90 dB.

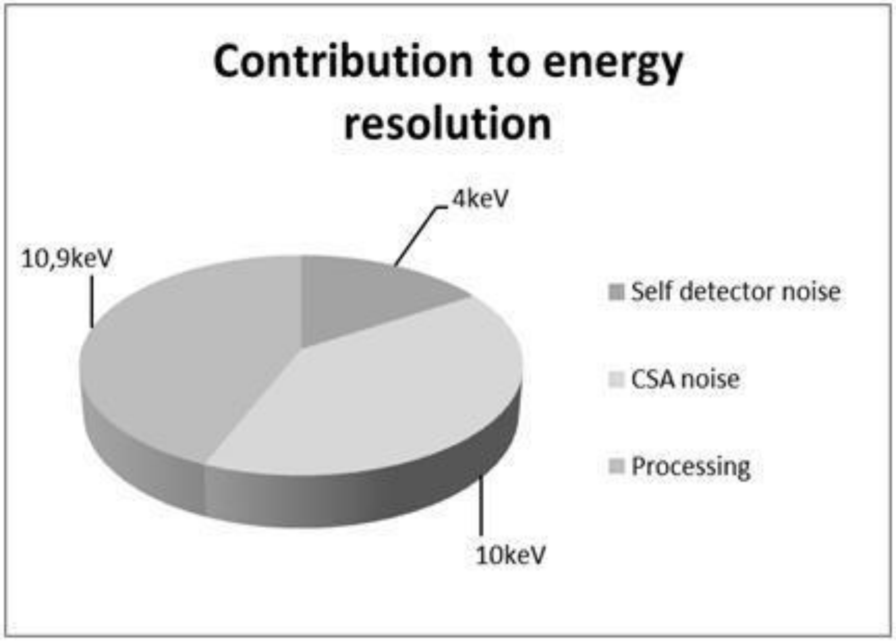
The results of the gamma-ray lines detection of with energies 662 keV and 1133 keV differ slightly.

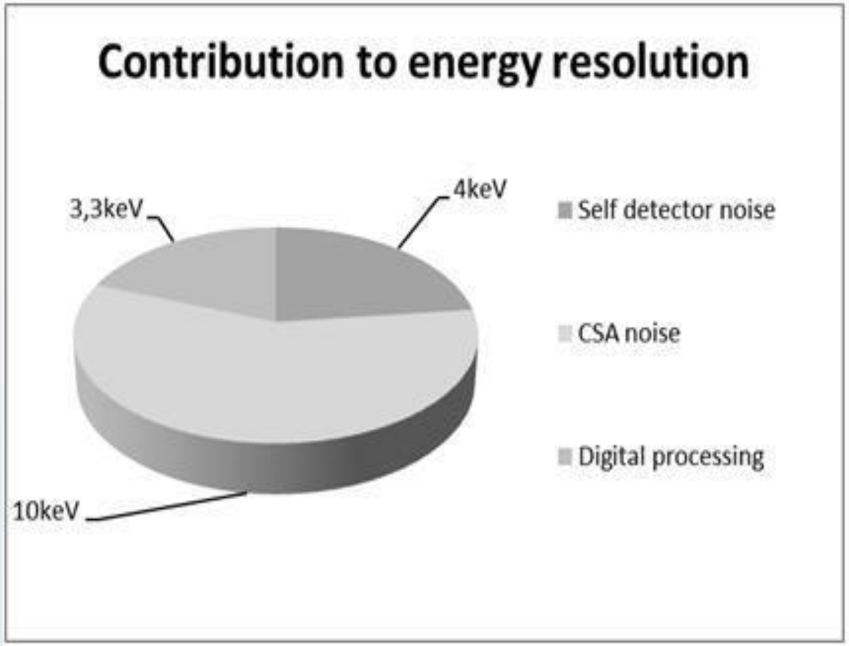
The energy resolution of HPXe gamma-ray detector with digital pulse processing



The values obtained for the energy resolution of HPXe gamma-ray detector, in particular the value of (1,7 ± 0,1)% or 11,2 keV for the 662 keV gamma-line are by far a record for this type of equipment.

Contribution to energy resolution in case using analog and digital signal processing





Contribution to energy resolution in case using analog signal processing. It shows data for the energy 662 keV. The resulting energy resolution – 15,3 keV (2,3 %).

Contribution to energy resolution in case using digital signal processing. It shows data for the energy 662 keV. The resulting energy resolution – 11,3 keV (1,7 %).

CONCLUSIONS

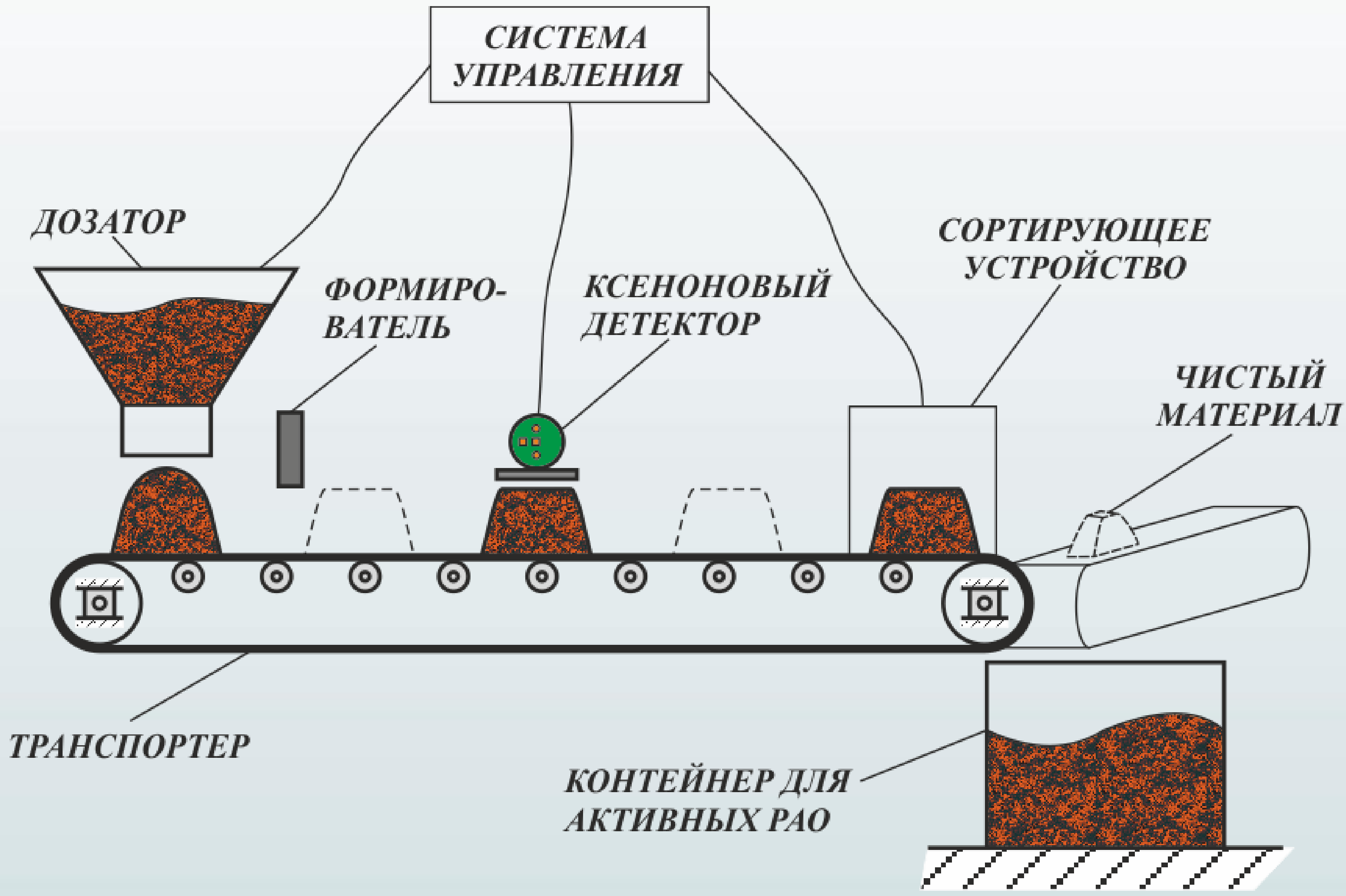
- Xenon gamma-ray spectrometers have high spectrometric and performance characteristics and in many cases can successfully compete with existing gamma-ray spectrometers.

- Numerous testes of Xenon gamma-ray spectrometers carried out at different organizations confirmed the reasonability to use them more widely.

- there are some perspective in further developing of spectrometric and performance characteristics of Xenon gamma-ray spectrometers.

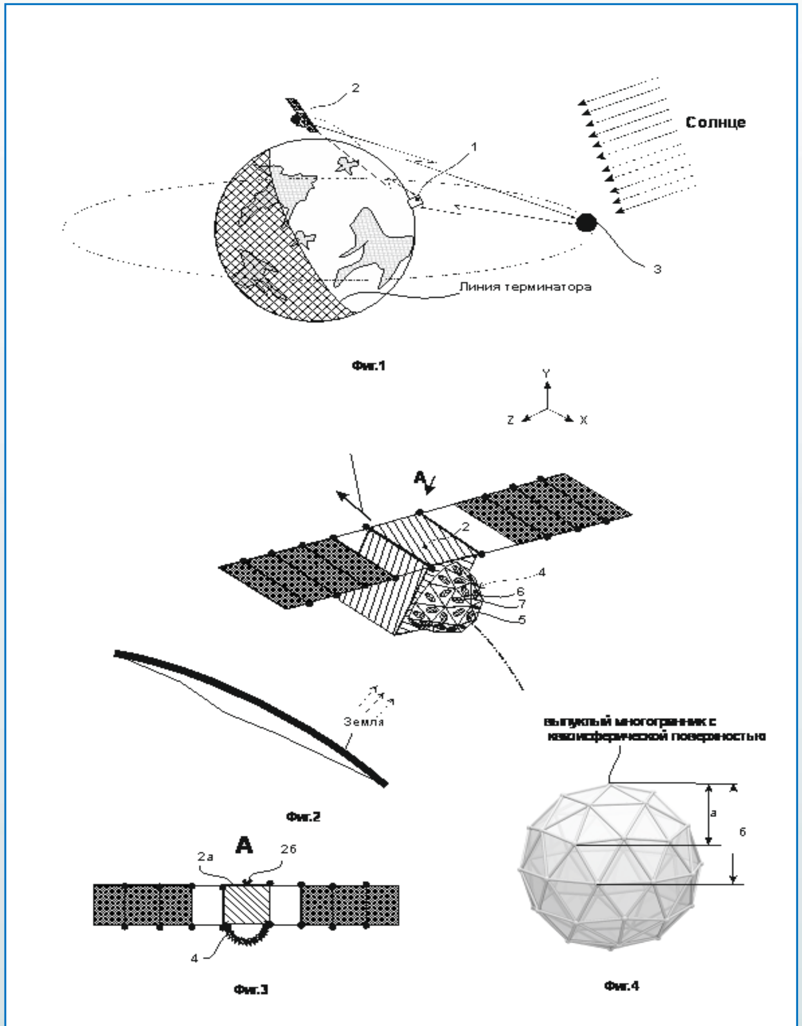
- **THANK YOU FOR YOUR ATTENTION**

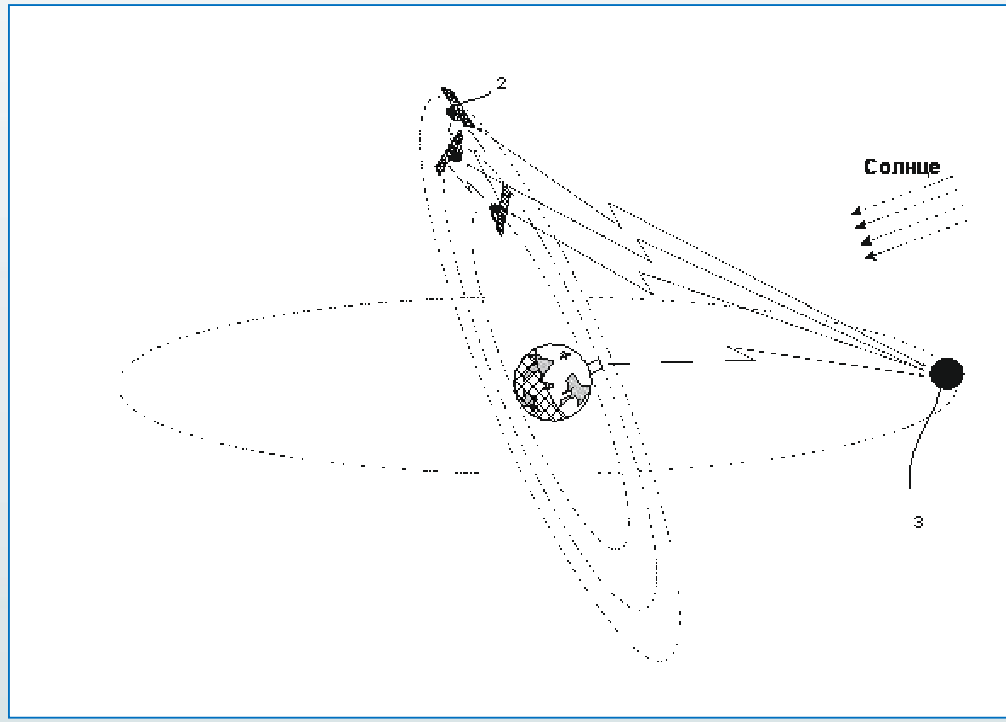
МОБИЛЬНАЯ УСТАНОВКА ДЛЯ СОРТИРОВКИ РАО



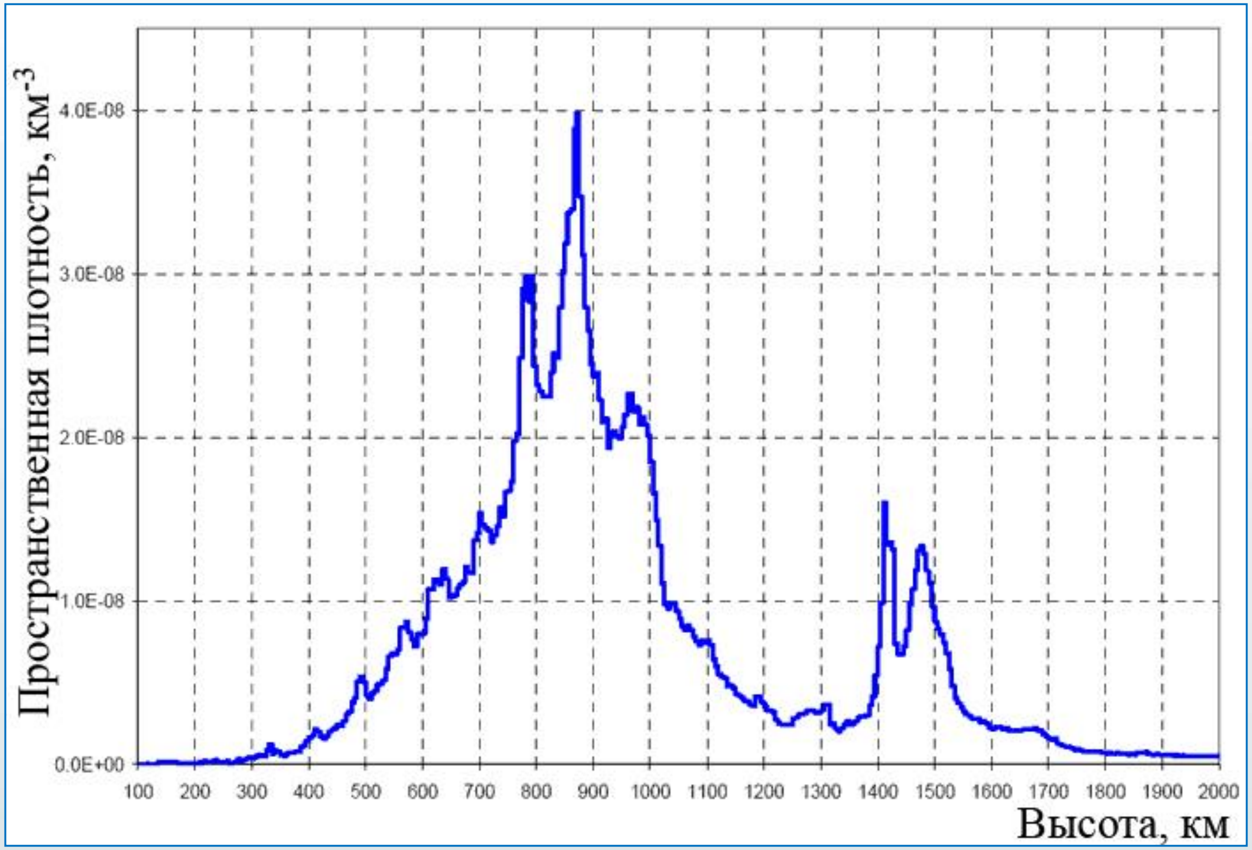
smcXe

РАДИОАКТИВНЫЙ КОСМИЧЕСКИЙ МУСОР



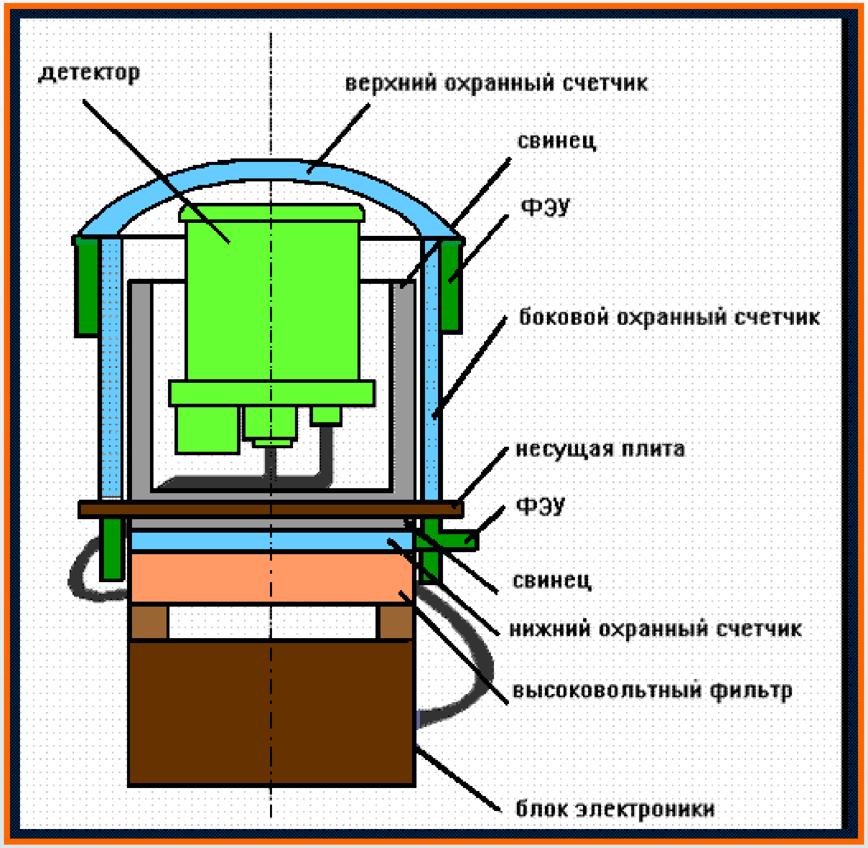


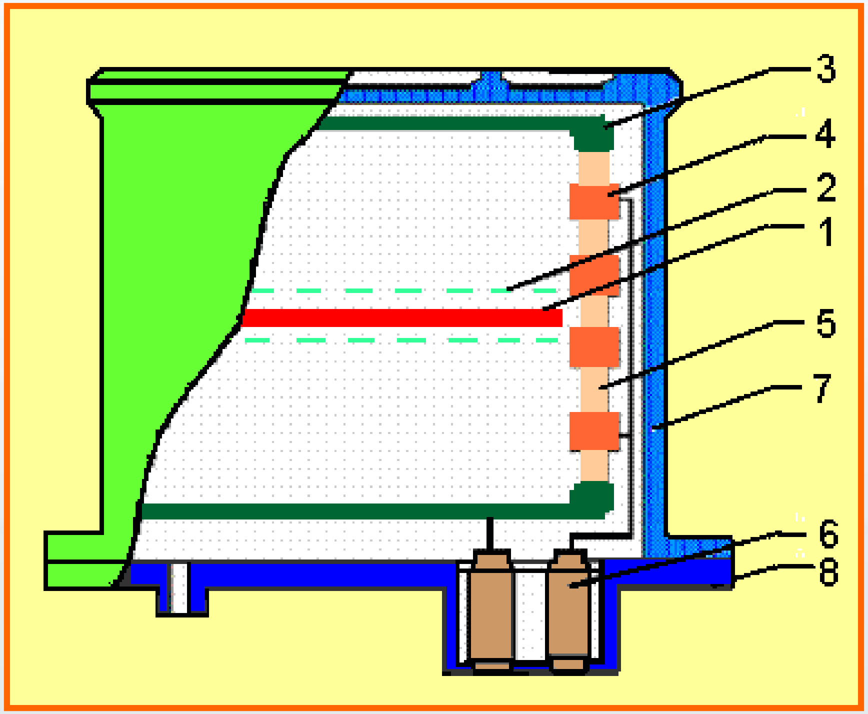
РАДИОАКТИВНЫЙ КОСМИЧЕСКИЙ МУСОР



Распределение космического мусора на высотах от 100 до 2000 км

Gamma-ray telescope "Xenia"





1. anode,
2. shielding grid,
3. cathode,
4. drift electrodes,
5. ceramic isolator,
6. stainless still vessel,
7. high-voltage feethrough,
8. flange.