Liquid-xenon detector under the intensive pulse irradiation conditions

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Abstract. The effect of intense pulsed irradiation on the operation of the liquid xenon spectrometer was studied. The ionization chamber filled with liquid xenon was irradiated by bremsstrahlung pulses of the microtron. The pulse repetition rate was 400 Hz. The absorbed dose ranged from 10^{-7} to 0.1 Gy per pulse. Stable operation of the liquid xenon spectrometer in the intervals between the pulses of the accelerator was shown for a long time.

1. Introduction

At the present time the usage of the high-intensity pulsed sources of radiation, such as particle accelerators, synchrotrons, neutron generators and the pulse generators of the x-ray radiation are developing rapidly. The use of radiation detectors in intense radiation fields generated by such sources is limited by their radiation resistance.

The intense radiation can significantly affect the operation of the detectors and lead to a temporary malfunction of the detectors. Furthermore reversible effects after prolonged use under conditions of intense radiation accumulates unremovable defects which lead to deterioration of characteristics of the detectors. The usage of the noble gases as the working detector substance in the presence of a high-intensity radiation has good prospects. The detectors based on noble gases (both in the gaseous and liquid states) have the highest radiation resistance to prolonged intense irradiation [1]. As the noble gases have an atomic structure the radiation defects in traditional understanding do not arise in them and it is possible to use them long time without replacement. However, at high doses of radiation in ionization detectors based on liquid noble gases a special type of disruption may occur that is associated with the formation of a space charge and the flow of ion current.

To obtain experimental information on the effects of high-intensity pulsed radiation on the characteristics of the liquid xenon spectrometer such detector was located in the beam of bremsstrahlung of electron accelerator.

2. Processes in the liquid xenon detector under the intensive pulse irradiation conditions

The study of the liquid xenon detector operation was carried out on the beam of the microtron MT-25 in the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research. The parameters of the microtron: the energy of the electrons in the beam of 10-25 MeV, average beam current of up to 15 μA, the pulse repetition rate of 400 Hz, pulse duration of 2.5 μs. At its output, the electron beam bombarded a 2-mm-thick tungsten target with a 3-cm-thick aluminum absorber and generated bremsstrahlung with an appropriate spectrum and angular distribution.

Inside the cryostat there was a multifunction camera that contained researched ionization chamber, the xenon cleaning unit and the control unit of xenon purity. For chamber cooling in cryostat the vapors of the boiling nitrogen were used. The temperature of the chamber could be varied in the range 165-250 K. Most of the measurements performed at T=230 K. Purification of xenon was carried out using the electric spark method [2]. Liquid xenon is purified to a such level that the electron can traverse the distance between electrodes 10 times in average before capture.

In the first series of measurements the study of processes arising in liquid xenon under the influence of intense pulsed radiation was carried out. In this case, the research camera is a flat ionization chamber with two electrodes 1.8 cm in diameter, the area of the electrodes S = 2.54 cm^2 and the distance between the electrodes d = 0.53 cm. Working chamber volume V = 1.35 cm^3 [3]. The absorbed dose ranged from 10^{-7} to 0.1 Gy per pulse.

A space charge is produced in the chamber under high-intensity irradiation. If the formation time of the space charge significantly less than the time of his disappearance, it is possible to use the concept of the critical dose. The critical dose corresponds to a transition from the normal operation of the ionization chamber to the regime of space charge. The critical dose is given by the expressions [4]

$$D_{cr} = \varepsilon\varepsilon_0 wU / (fd^2 e\rho),$$

where e is the elementary electric charge, ε is the permittivity, ε_0 is the electric constant, ρ is the substance density, w is the average energy of production of an electron-ion pair, U is the potential difference between the electrodes, d is the interelectrode distance, and f is the ions yield coefficient from a track. Under our conditions, D_{cr} = 19 μGy at U = 5 kV.

The behavior of electrons in the chamber depends on the magnitude of the absorbed dose per pulse of radiation. When the dose is less than the critical the electrons leave the volume of the chamber within a few microseconds. When the irradiation dose above critical, the space charge reduces the electric field to zero in large parts of the chamber. In this case, the loss of electrons occurs due to the recombination. This process can last hundreds of microseconds. After the restoration of the electric field the electrons in a few microseconds leaving the chamber. In both cases after a complete collection of the electrons the positive ions remain in the chamber. The positive ions slowly drift to the cathode.

Experimental results showed that under the conditions of this work, the escape of electrons from the chamber occurs for a time shorter than the interval between pulses of radiation. Accumulation of electrons in the chamber does not occur.

Because the ions have a low mobility, they accumulate in the chamber even at low intensity of pulse irradiation. Therefore, the registration of gamma-quanta in the interval between pulses of the accelerator occurs on the falling ion current. In this case, the following factors give the deterioration of the energy resolution of gamma spectrometer: 1) fluctuations in the ion current; 2) a change in the ion current over time between pulses of radiation; 3) the presence of the internal field of the space charge of positive ions. Each of these factors gives the contribution of ω_i to the total relative energy resolution of the detector. The values of these factors are determined by the expressions [4]:

$$\omega_1 = 2.35\frac{\sqrt{D\rho V f T_e / 2t_{int} w}}{Ef / w}; \quad \omega_2 = \frac{2.35}{\sqrt{12}}\frac{D\rho V}{E}\frac{RCT_{dif}}{T_+^2}; \quad \omega_3 = \frac{2.35}{\sqrt{12}}\frac{f_c - f_a}{f_0}, \qquad (1)$$

where D is the absorbed dose; V is the chamber volume; T_e is the electron drift time; t_{int} is the interval between pulses; E is the photon energy; R is the load resistance; C is the equivalent capacitance of the detector; T_{dif} is the differentiation time of the amplifier; T_+ is the ion drift time, f_c and f_a is the coefficient of ion yield from the track near the cathode and anode, respectively; f_0 is the ion yield in the absence of irradiation pulses.

The dependence of the contributions to the energy resolution ω_i on the dose per irradiation pulse is shown in figure 1. The calculations were performed for the photon energy E = 0.662 MeV.

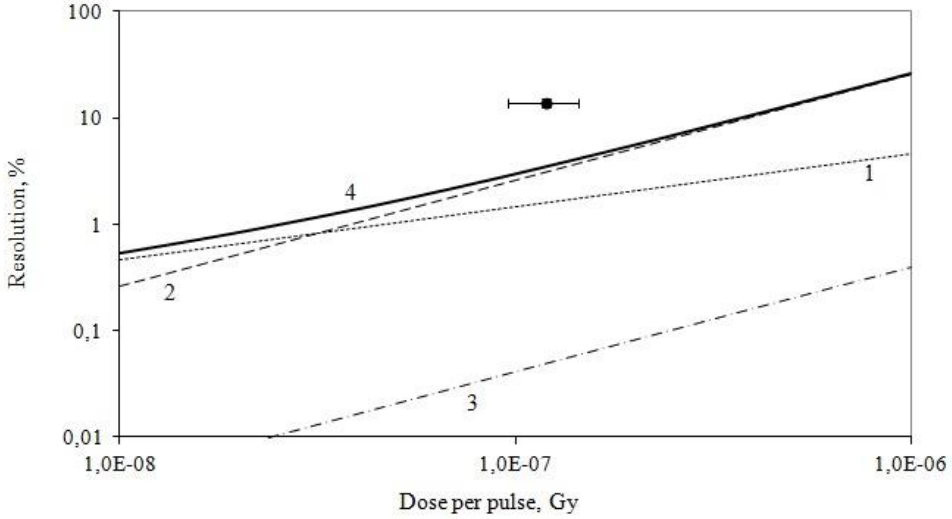

Figure 1. Contributions of different factors to the energy resolution of the our chamber: 1 - ion current fluctuations; 2 - changes in the ion current with time; 3 - electric field of the ions; 4 - total energy resolution.

From the equations (1) it is evident that each of these factors depend on the absorbed dose and the volume of the detector in different ways. In our detector (small volume) factors 1 and 2 have a major role, the impact factor of 3 is very small. In a large detector ($V = 10^3$ cm^3) factor 1 retains a major role, a factor 3 is more important than factor 2. In our detector, the total contribution of the ions to the energy resolution at a dose of 0.1 μGy is 3%, and at a dose of 1 μGy reaches 26%. Thus the accumulation of ions deteriorates the energy resolution of the detector at doses much lower than the critical dose.

3. The operation of the detector in spectrometric mode in the intervals between the pulses of intense radiation

In the second series of measurements we studied the spectrometric properties of the liquid xenon detector during operation in the intervals between the pulses of intense radiation . In this case, research chamber was a cylindrical ionization chamber, the working volume of which was equal to V = 2.4 cm^3 [5]. The detector was surrounded by a protective shield consisting of lead and borated polyethylene.

The energy released in the spectrometer during the accelerator pulse was higher than the energy of the detected quanta (~1MeV) by several orders of magnitude. Developed electronic circuit blocking of the preamplifier in the momentum of the accelerator pulse allowed the detector to operate in a spectrometric mode, in the intervals between pulses. Under our conditions, the blocking time was 0.5 ms. In test measurements, the detector registered gamma-quanta from ^{137}Cs source. The corresponding spectra are shown in figure 2. When the accelerator is off the energy resolution of the detector was 9.5%. The registration of gamma-quanta in the intervals between pulses of the accelerator occurs in the presence of ion current. The ion current deteriorates the energy resolution of the detector. When the accelerator is running resolution of the detector was 14%. This experimental point is shown in figure 1. In the cylindrical geometry the resolution for the above factors increases approximately two times. This means that the experimental result does not contradict our calculations.

This detector has been used to study short lived isomer ^{207m}Pb ($T_{1/2}$ = 0.8 s), which is under the action of gamma rays formed in the reaction ^{208}Pb(γ,n)^{207m}Pb. The yield of the ^{207m}Pb isomer as a function of the energy of the bremsstrahlung spectrum maximum was measured in [6].

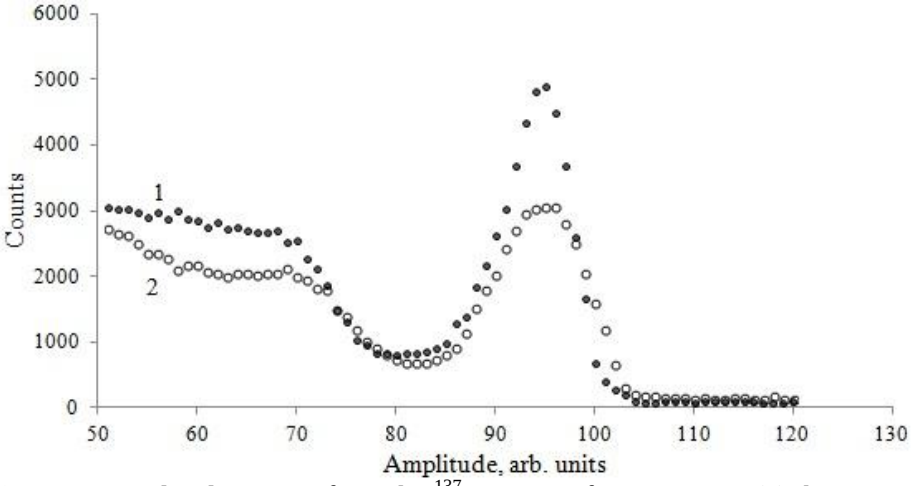

Figure 2. Amplitude spectra from the ^{137}Cs source for two cases: (1) the accelerator is turned off and (2) the accelerator is turned on.

The total absorbed dose in the liquid xenon detector during operation on the accelerator MT-25 for 2 years was 10^7 Gy. There were no change in the spectrometric properties of the detector.

4. Conclusion

The ionization detectors based on noble gases have the high radiation resistance. The effect of intense pulsed irradiation on the operation of the liquid xenon detector was studied. The electrons formed under pulsed irradiation are not accumulated in the detector volume. Due to the low mobility positive ions are accumulated in the detector form a space charge creating an ion current. This leads to a deterioration of the energy resolution of the detector, which depends on the absorbed dose per pulse and the volume of the detector.

It was shown that the liquid xenon detector is able to operate in the spectrometric mode during the intervals between pulses of intense radiation. Cylindrical liquid xenon detector was applied to study short lived isomer ^{207m}Pb.

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References

[1] Kirsanov M A *et al.* 1991 (in Russian) *Atomic Energy* **70** 131 (Original Russian title: *Atomnaya Energiya*)
[2] Pokachalov S G *et al.* 1993 *Nucl. Instrum. Meth.* A **327** 159
[3] Kirsanov M A and Obodovskiy I M 2008 *Instr. Exp. Techn.* **51** 358
[4] Kirsanov M A and Obodovskiy I M 2010 *Instr. Exp. Techn.* **53** 185
[5] Kirsanov M A *et al.* 1991 (in Russian) *Instruments and Experimental Techniques* **1** 75 (Original Russian title: *Pribory i Tekhnika Eksperimenta*)
[6] Kirsanov M A, Obodovski I M and Gangrski Yu P 1993 *Nucl. Instrum. Meth*. A **327** 48