The use of liquid xenon detectors in the conditions of intensive irradiation

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Abstract. The detectors based on liquid xenon have high radiation resistance. They are promising detectors for operation in the conditions of intense radiation. The recovery time of the spectrometric mode of the liquid xenon detector after intensive irradiation was investigated. We have studied the linearity range of the xenon detector in intensive irradiation. The operation of the liquid xenon spectrometer in the intervals between pulses of the radiation was investigated. The possibility of using the liquid xenon spectrometer for activation analysis for the short-lived nuclides was shown.

1. Introduction
At the present time, high-intensity pulsed-radiation sources are widely used in experimental studies. The operation of the detectors in intense radiation fields is limited to their radiation resistance. Intense radiation influence on the processes inside the detector and can lead to a violation of operating capacity.

Scintillation and semiconductor spectrometers do not satisfy the requirement of high radiation resistance. Inorganic scintillators would be inoperative for several hours at absorbed doses of ~ 1 Gy. In the semiconductor detectors dose of ~ 10^4 Gy leads to irreversible deterioration of the energy resolution. The ionization detectors based on condensed noble gases are characterized by a high radiation resistance [1]. The liquid xenon detectors have high detection efficiency of gamma rays. The energy resolution of the liquid xenon detector is at a level of scintillation detectors.

Therefore, the liquid xenon detectors are preferred detectors for projects:
- Industrial tomography
- Activation analysis for short-lived isomers (T_{1/2} < 1 s)

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. Detection of intense radiation
The high intensity radiation is used in the industrial tomography to enhance sensitivity and productivity. Detectors must register the high-intensity radiation with high efficiency.

The typical scheme of industrial tomography is shown in figure 1. Between the target and the sample is a collimator. The detector must detect photons that have passed through the sample. The main question is the range of linearity of the detector signal as a function of the irradiation intensity.
In the experiment, we used the liquid xenon ionization chamber [2]. A two-electrode flat ionization chamber with 1.8-cm-diameter electrodes, the distance between which is 0.53 cm, and a working volume is 1.35 cm$^3$ was placed inside a cryostat. The temperature of the chamber changed in the range 165–250 K. Purification of liquid xenon was carried out using the electric-spark method [3].

The setup is placed in the bremsstrahlung beam of the MT-25 microtron at the Flerov Laboratory of Nuclear Reactions (JINR, Dubna). The radiation pulse repetition frequency is 400 Hz, and the pulse duration is 2.5 $\mu$s. The pulse dose was measured with thermoluminescent dosimeters. The dose absorbed in liquid xenon per irradiation pulse varied from $10^{-7}$ to 0.1 Gy.

In the first series of measurements, we investigated the range of linearity of the signal of xenon detector in dependence on irradiation intensity. The liquid xenon detector was located in the direct beam of bremsstrahlung radiation of microtron. We recorded the electron current pulses of the xenon detector depending on the dose per pulse of radiation. Figure 2 shows the current pulse amplitude of the xenon detector as a function of pulse dose.

![Figure 1. The scheme of industrial tomography: 1 - electron accelerator, 2 - target, 3 - collimator, 4 - sample, 5 - detector.](image1)

![Figure 2. Current pulse amplitude as a function of the pulse dose. Dashed curve – current pulse amplitude calculated in the absence of a space charge.](image2)

As is seen in figure 2, the amplitude of the current pulse increases linearly up to a dose of 0.2 mGy per pulse. At higher doses the effect of the space charge becomes perceptible. The model of formation of the current pulse in the space charge conditions presented in the article [2].

If the dose per pulse of the radiation is 0.1 mGy, then the absorbed dose for 1 minute will be 2 Gy. At such doses, the scintillation detectors are not operational. Our experimental results showed that xenon detector can record an unlimited time the intense pulsed radiation. The liquid xenon detector has a linear output signal, if the dose of radiation pulse does not exceed 0.2 mGy.

3. Activation analysis for the short-lived nuclides

Activation analysis is widely used in various industries: mineral resource industry, geology, production of pure materials, ecology. A significant increase in productivity and profitability of activation analysis can be obtained by using the analysis for the short-lived nuclides ($T_{1/2} = 10^{-1} - 10^6$ s). Registration of short-lived nuclides will allow to explore the cross section and other parameters of the reactions in which they are formed.

To solve these tasks need detectors with high radiation resistance. The liquid xenon spectrometer is a promising detector for solving the problem of registration of the activation photons of short-lived nuclides. The photons generated in the sample as a result of nuclear reactions initiated by the pulsed radiation of the accelerators. In this case, the detector should record the activation photons in the intervals between the pulses of the accelerator. Therefore, the detector should be located near the target accelerator and operate in spectrometric mode. The problem of the recovery rate of the spectrometric mode of operation of the detector after intense pulse irradiation is the most important. The scheme of the activation analysis for the short-lived nuclides is presented in figure 3.
To investigate the spectrometric characteristics of the xenon detector during operation in the intervals between the pulses of intense radiation, we used a cylindrical ionization chamber [4]. The sizes of the cylindrical chamber: the cathode radius is 0.52 cm, the anode radius is 0.01 cm, the height is 2.8 cm, the sensitive volume is 2.4 cm$^3$. The cylindrical chamber located at a right angle to the brake target of microtron MT-25. Passive protection, which consisted of lead and borated polyethylene, is between the brake target and the chamber.

A space charge is produced in the chamber under high intensity irradiation [2]. At low radiation doses electrons leave the volume of the detector for several microseconds after the end of irradiation. At high doses, the electrons are in the chamber several hundred microseconds, since recombination of charges is slow. Our experiments have shown significant result: for all doses, electrons leave the volume of the detector during the time that is less than the interval between the radiation pulses. Thus, electrons are not accumulated in the chamber.

Because the ions have a low mobility, they accumulate in the chamber even at low intensity of pulse irradiation. Therefore, the registration of gamma rays in the interval between pulses of the accelerator occurs on the ion current. This can lead to a deterioration of the energy resolution of the xenon spectrometer [5].

The stable operation of the xenon spectrometer in the intervals between the pulses of the accelerator has occurred at the dose per pulse < 2·10$^{-7}$ Gy/pulse. A special electronic circuit protected the spectrometric preamplifier from overloading during the pulse accelerator. The blocking time was 500 μs after the pulse accelerator.

The liquid xenon detector registered gamma rays from $^{137}$Cs source in the intervals between pulses of the accelerator. When the accelerator is off the energy resolution of the detector was 9.5%. When the accelerator is running resolution of the detector was 14% [6]. 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.

We measured gamma spectra of nuclide with small half-life ($^{207m}$Pb) between pulses of the electron accelerator MT-25. This nuclide was formed by bremsstrahlung in the lead sample: $^{208}$Pb($\gamma$,n)$^{207m}$Pb [7]. The isomer $^{207m}$Pb has a half-life $T_{1/2} = 0.8$ s and emits two gamma lines (0.57 MeV and 1.06 MeV). The liquid xenon detector measured these gamma rays in the intervals between pulses of the
accelerator. Figure 4 shows the spectrum of the isomer 207mPb, which was registered by the xenon detector in the intervals between the pulses of the microtron MT-25.

Our experiments have demonstrated that xenon spectrometer is a promising detector for activation analysis for short-lived nuclides and studies of reaction cross sections in which they are formed.

4. Conclusion
The radiation resistance of the liquid xenon detector under conditions of intense pulsed irradiation was investigated. For the first time, we experimentally studied the question of the range of linearity of the xenon detector signal depending on the radiation intensity. The liquid xenon detector quickly restores spectrometric properties after intense pulsed radiation. The ability of the liquid xenon detector to operate in the spectrometric mode in the intervals between the accelerator pulses was shown. We found that the liquid xenon detector has a high long-term resistance to radiation. The possibility of using the liquid xenon spectrometer for activation analysis for the short-lived nuclides was shown.

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References
[1] Kirsanov M A et al. 1991 (in Russian) Atomic Energy 70 131 (Original Russian title: Atomnaya Energiya)
[2] Kirsanov M A and Obodovskiy I M 2008 Instr. Exp. Techn. 51 358
[3] Pokachalov S G et al. 1993 Nucl. Instrum. Meth. A 327 159
[4] Kirsanov M A et al. 1991 (in Russian) Instruments and Experimental Techniques 1 75 (Original Russian title: Pribory i Tekhnika Eksperimenta)
[5] Kirsanov M A and Obodovskiy I M 2010 Instr. Exp. Techn. 53 185
[6] Kirsanov M A 2016 Journal of Physics: Conference Series 675 042014
[7] Kirsanov M A, Obodovski I M and Gangrski Yu P 1993 Nucl. Instrum. Meth. A 327 48