The necessity and possibility of creating a dosimetric channel for determining the direction to the source of penetrating gamma-radiation in the nuclear situation monitoring system have been substantiated. The experimental assessment of a reduced error of the device for determining the direction to pulsed sources of radiation using a spherical absorber and CdTe detectors was carried out. These detectors can be used effectively only if there is appropriate electronic equipment, constructed in accordance with their characteristics and spectral-temporal characteristics of highly intense pulsed radiation. The direction to high-intensity pulsed radiation of linear accelerator Varian Clinac 600C (USA) by telluride-cadmium detectors was determined in the pulsed mode. This allowed conducting an experiment to determine the dependence of the coefficient of proportionality of recording pulses from each detector on the angle of direction to the source of pulsed radiation of the linear accelerator. A reduced error was assessed by comparing the received experimental data with a theoretical dependence based on a physical and mathematical model. It was recommended to divide the entire range of angles from 0° to 360° into five sub-ranges, in which three or two proportionality coefficients are responsible for determining the angle in space on gamma sources. The maximum reduced error does not exceed 10 % and the maximum angle error is not more than 8.4°. The most accurate determining of the angle to a radiation source can be carried out in the presence of a theoretically calculated and experimental database of proportionality coefficients for all angles in space and energy of radiation sources

Keywords: direction determination, gamma-radiation, semiconductor detectors, nuclear situation monitoring system

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EXPERIMENTAL EVALUATION OF ACCURACY IN DETERMINING THE DIRECTION TO A PULSED SOURCE OF GAMMA-RADIATION BY A SPHERICAL ABSORBER WITH CDTE DETECTORS IN A SYSTEM OF NUCLEAR SITUATION MONITORING

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1. Introduction

The basis of detection of a nuclear situation is the technology of monitoring (observation) of the state of the environment [1–3], associated with the precise determining the coordinates of a radiation source. The accuracy of existing means of determining the coordinates of a nuclear radiation source may vary widely. Radiotechnical means – up to 1 km, light-technical means – within 0.2 km, which against the background of the development of geoinformation technologies (geolocation technologies) and global positioning, requires revision and improvement. The error of light and technical means is related to the dependence of the registration zone on both the transparency of the atmosphere and the power of the explosion itself. This gives reasons to look for other more preventing and reliable ways of accurately determining the direction to the source of nuclear radiation, including pulsed radiation.

The most effective and promising method when determining the direction to highly intensive pulsed gamma-radiation in space is a dosimetric registration channel using detection units based on a spherical absorber [4–6]. CdTe detectors of the required size are placed in the vertices of a regular pyramid under the absorber. Calculated information-signal received from detectors are matched to each other. The found ratios depend on the angle to the source of gamma-radiation and are the ratios of transmission factors for detectors.

However, the accuracy of determining the direction to the sources of gamma-radiation is calculated at the level of general considerations. That is why these issues remain open for such devices. This is especially true of a high-intensity pulsed radiation source with the rigidity of the energy spectrum characteristic of gamma-emission of penetrating radiation.

On the other hand, according to preliminary estimates, the error of determining the direction to a pulsed source of gamma-radiation is associated precisely with the spectral-temporal characteristics of the applied CdTe detectors, as well as the signal processing equipment. CdTe detector of pulsed radiation should record the amplitude of pulses of high-intensity radiation with high precision, maintaining constant sensitivity throughout the entire duration of a pulse or a series of pulses. With the advent of modern methods of data processing, the development of the equipment, which will make it possible to research the accuracy of using the spherical absorber with CdTe detectors, is of considerable interest.

That is why studying the possibility to evaluate the reduced error of determining the direction to pulsed radiation by a spherical absorber is quite a relevant scientific and applied problem.

2. Literature review and problem statement

In paper [4], the possibility of determining the direction to pulsed gamma sources was tested experimentally by simulating it on a constant light source rotating at a certain rate.

The physical and mathematical model of determining the direction to point sources of gamma-radiation in space using a spherical absorber was developed in study [5]. A spherical absorber with four CdTe detectors inside was used as a receiving device. The flow of gamma-radiation from the linear accelerator I_0 will come to the point of a spherical absorber as a parallel beam (Fig. 1).

To determine the information coming from the detector, the law of exponential reduction of gamma-radiation in materials is applied:

$$I_i = I_0 \cdot e^{-\mu h_i}, \tag{1}$$

where I_i is the intensity of gamma-radiation that comes to i detector through the absorber h_i; μ is the linear attenuation factor of the absorber, cm^{-1}.

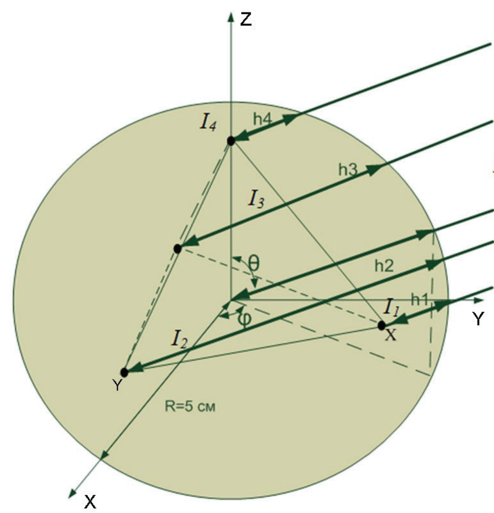

Fig. 1. Receiving device of pulsed gamma-radiation as a spherical absorber with four detection units [5]

Each detector will get the same density of gamma-radiation flow at the same angle. The method for direction determining implies obtaining the ratios of the amplitude of pulses on the detector, with different attenuation factor depending on direction, to the detector with a permanent attenuation factor for any direction.

These ratios will depend on many structural features of the implementation of the absorber itself and operation modes of the CdTe detectors. We will note that the analyzed sources did not study the problem of errors in determining the direction to pulsed sources of radiation using a spherical absorber and CdTe detectors.

Article [6] proposed the method and device [7] to determine the direction of a permanent source of gamma-radiation Cs-137 (0.661 MeV). They are based on the use of four multi-channel pulsed analyzers with CdTe detection units placed in asymmetrical absorbers. Detectors measure the amplitude energy of gamma quantum, which is recorded as a solitary pulse, and the direction to a radiation source is determined by the ratio of measured amplitudes of one to another. The limitations include the mismatch of the spectral-temporal characteristics of the used radiation sources and the characteristics of high-intensity pulsed emission of penetrating radiation.

Modeling of spectral characteristics of gamma-emission of penetrating radiation is associated with certain difficulties outlined in the papers on testing the protection against nuclear explosion radiation. First of all, it is a wide range of energies (0.05–6 MeV) with clearly expressed inequality of the spectrum [8].

In the literature, there are several studies on the use of the CdTe detector [9–12] and registration by it of high-intensity gamma-radiation in the range of energies of 0.06–1.2 MeV. In papers [12–15], CdTe detectors are studied together with operational characteristics, temperature stability, and reliability of the detector's measurements.

In addition, the results of research into temporal characteristics of CdTe-based detectors of type SPPD 29 on the accelerator of electrons SPIN 2 (Russia) were published in paper [12]. The temporal resolution of the measuring channel in the article was studied by recording pulses of X-ray radiation – softer radiation than the one typical for gamma-emission of penetrating radiation.

Among the existing powerful pulsed sources, linear electrons accelerators have these characteristics. They use bremsstrahlung radiation to obtain high-intensity and high-energy influences. According to the technical documentation for the medical linear accelerator Clinac 600C, the range of energy of photons of the bremsstrahlung radiation of this accelerator is 0–6 MeV (Fig. 2), with an average energy of the order of magnitude of 1.49 MeV [16].

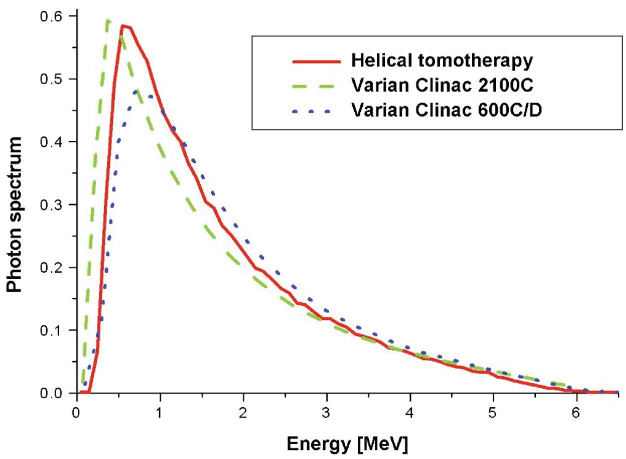

Fig. 2. Spectral distribution of photon radiation of a linear accelerator Varian Clinac 600C [16]

Analysis of the data published in [4–15], makes it possible to establish the following. In the studied sources, little attention was paid to the problems of assessment of the accuracy of the proposed methods. Improvement of the methods for automatically determining the direction to a pulsed source of gamma-radiation by semiconductor CdTe detectors is carried out without taking into consideration the necessary spectral-temporal characteristics of radiation inherent in penetrating radiation.

At the same time, there are prerequisites for creating such equipment based on a spherical absorber with CdTe detectors and an experimental assessment of the error of determining the direction to a pulsed source using radiation of a linear accelerator. However, this issue was not sufficiently studied, both theoretically and practically.

3. The aim and objectives of the study

The aim of this study is to experimentally assess the reduced error to determine the direction to pulsed sources of radiation using a spherical absorber and CdTe detectors.

To accomplish the aim, the following tasks have been set:

– to conduct an experiment to determine the dependence of the coefficient of proportionality of recording the amplitudes of pulses from each detector on the angle of direction to a pulsed radiation source of the linear accelerator Varian Clinac 600C (USA);

– to evaluate the reduced error of determining the direction to a pulsed source of radiation of the linear accelerator by comparing the obtained experimental data with theoretical dependence based on a physical and mathematical model [5].

4. Determining the dependence of the coefficient of proportionality of recording pulses from each detector on the angle of direction to the source of pulsed radiation of a linear accelerator

The medical linear accelerator Varian Clinac 600C of the department of radiation therapy of the Institute of Medical Radiology named after S. P. Grigoriev of the NAMS of Ukraine was used as a source of pulsed high-intensity radiation. The direction to a radiation source was determined using the method described in [5].

To determine the dependence of the coefficient of proportionality of recording pulses from each detector on the angle of direction to a source of pulsed radiation of the linear accelerator Varian Clinac 600C, the special equipment was developed. CdTe detectors were located inside the spherical absorber (Fig. 1) on the edges of a regular polyhedron and are an electronic converter on the inside of which there is a protective screen, which allows achieving maximum sensitivity. The dimensions of the detection units are 20 mm in length and 10 mm in diameter, which is due to the location of CdTe detectors in them (Fig. 3).

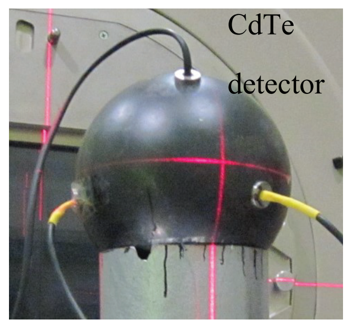

Fig. 3. Spherical absorber of pulsed gamma-radiation with four detection units with CdTe detectors

CdTe detectors with dimensions of 5×5×2 mm together with the previous amplifier with dimensions of 8×8×1.5 mm are under a layer of steel of the thickness d=10 mm. The detectors were placed in the absorber at the distance of one centimeter from its surface at the vertices of a regular pyramid, which ensures their maximum distance from each other. The amplitudes of pulses from the CdTe detectors of a spherical absorber were recorded by their automatic calculation with the intervals between measurements of 200 μs by a complex of hardware and software tools of automation of ITM measurements (https://www.itm.com.ua/) (version 4.4.1.2). The basis of the complex (Fig. 4) is a computer measuring device – an electronic unit (5), which includes a sixteen-digit ADC with a conversion time of 200 μs, a microcontroller, an interface of connection to the computer.

CdTe detectors (2) that work in the pulsed mode are connected to the electronic unit through amplifiers (4). The peak detector was included in the equipment to measure precisely the amplitudes of a separate pulse.

The experimental research was conducted at several stages. At the preparatory stage, the CdTe detectors with the peak detector, using a stabilized UV source, warmed up within three hours, were tested. In this case, the noises of the sensors, the amplifier and the ADC channel taking into consideration the noises of the signal source amounted to 8 units of ADC. Testing was conducted within 10 s.

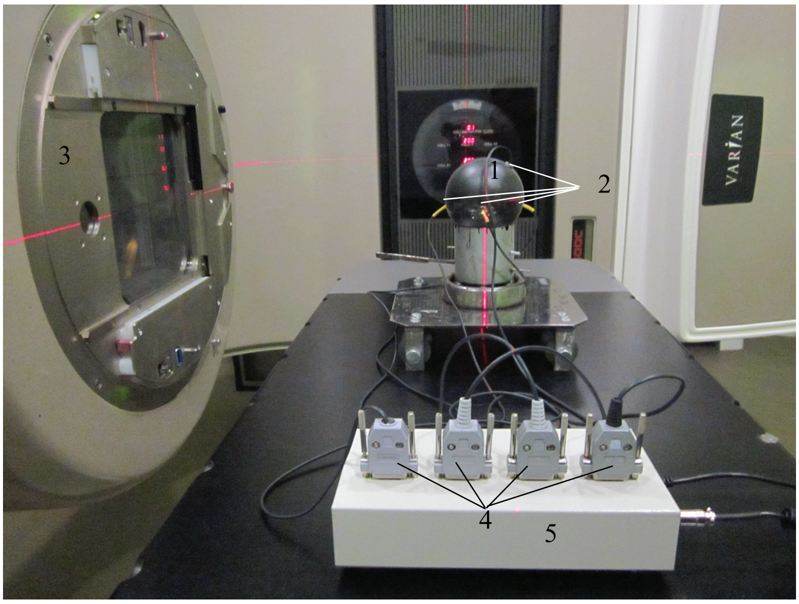

Fig. 4. Experimental setup for determining the direction to pulsed radiation of a linear accelerator: 1 — spherical absorber; 2 — four detection units from CdTe; 3 — medical accelerator Varian Clinac 600C; 4 — amplifier for detectors; 5 — 16-digit ADC

In addition, the orientation (attachment) of the spherical absorber to the coordinates of the linear accelerator was carried out. The spherical absorber was located at a distance of 1 meter from the source of radiation of the linear accelerator. The beginning of countdown during the experiment was chosen so that the *xy* plane (Fig. 1) should be orthogonal to the gravity vector. In this case, one of the pyramid's vertices was in the center of the sphere and the other, which was directed to the radiation source, was under axis *x* at the distance $\frac{r}{3}$ from the *xy* plane. Two more vertices were located at the vertices of the conditional regular triangle. This location corresponded to angle θ=90° and angle φ=0°, respectively, which was determined by the direction of the OX axis to a radiation source and enabled the attachment of the tool in space.

Subsequent studies were devoted to measuring pulsed amplitudes on each detector at the rotation of the spherical absorber with the pitch of φ=15°.

The linear accelerator Varian Clinac 600C at the distance of 100 cm from the focus formed a standard rectangular field of 40×40 cm. Symmetry and uniformity of the irradiation field was not more than 1.5 %. At maximum power of accelerator radiation (400 Mu/min, which corresponds to the power of the absorbed dose at the location of the detector 4 Gy/min (6.6 P/s)), the spherical absorber was irradiated with the power of 0.8 Gy/min. Duration of a separate pulse and the period of pulses measured by oscillograph SDS1000CML/CNL/DL amounted to 3.5 μs (Fig. 5) and 18 μs (Fig. 6), respectively.

Fig. 7 shows the result of the operation of the CdTe detector in the pulsed mode. At the doze power of 0.8 Gy/min, assigned by an operator, the detector recorded the distribution of pulsed amplitudes in time. The mean value corresponds to the amplitude of 14,000 relative units of the AFC and the cumulative dose was 7.84 Gy per 10 s.

The recorded shapes of pulses on four CdTe detectors in the spherical absorber from steel of the thickness of *h*=1 cm for angles of 45° and 30° are shown, respectively, in (Fig. 8) and (Fig. 9). Channel 1 (Fig. 8) recorded 348 pulses from the detector, channel 2 – 392 pulses, channel 3 – 1,267 pulses, channel 4 – 1,364 pulses.

For each angle in the horizontal plane, we calculated proportionality coefficients K_p, which determine the relative numbers of recorded amplitudes of pulses of one detector to another at assigned geometry of irradiation of these detectors:

$$\mathrm{K}_{p1}=\frac{N_1}{N_2},\quad K_{p2}=\frac{N_1}{N_3},\quad \mathrm{K}_{p3}=\frac{N_1}{N_4},$$
$$K_{p4}=\frac{N_2}{N_3},\quad \mathrm{K}_{p5}=\frac{N_2}{N_4},\quad \mathrm{K}_{p6}=\frac{N_3}{N_4}. \qquad (2)$$

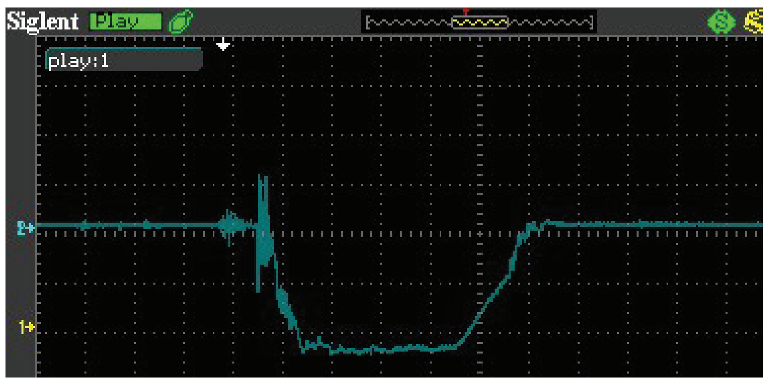

Fig. 5. Pulses of current of loading on targets of linear accelerator Varian Clinac 600C

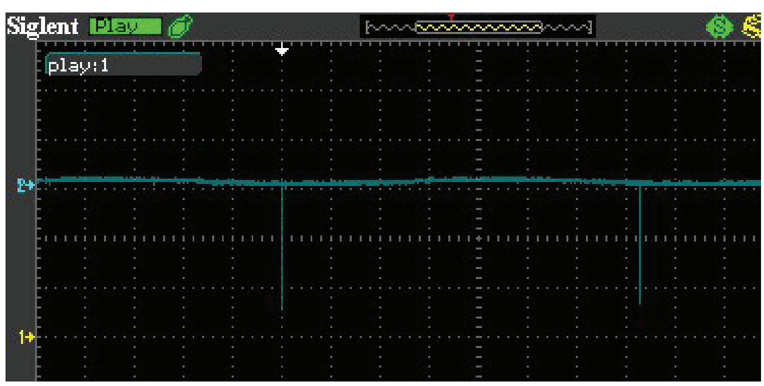

Fig. 6. Frequency of pulse passing from the linear accelerator Varian Clinac 600C

Calculated proportionality coefficients K_p for each angle in the horizontal plane are given in Table 1.

At the final stage of the study, the dependence of proportionality coefficient on the angle in space in the horizontal plane was obtained (φ=0–360°), at angle θ=90° (Fig. 10).

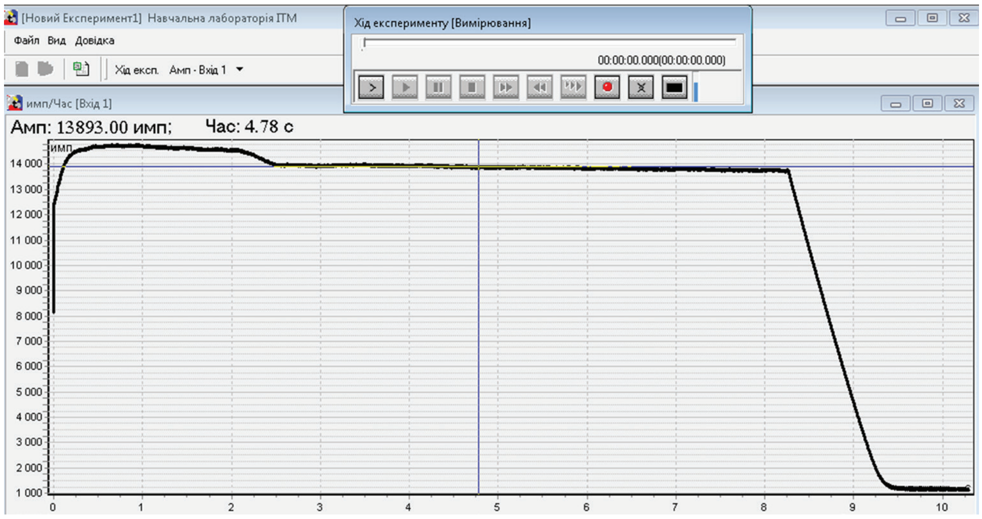

Fig. 7. Amplitude-temporal distribution of pulses from the linear accelerator at dose power 0.8 Gy/min during measurement time of 10 s

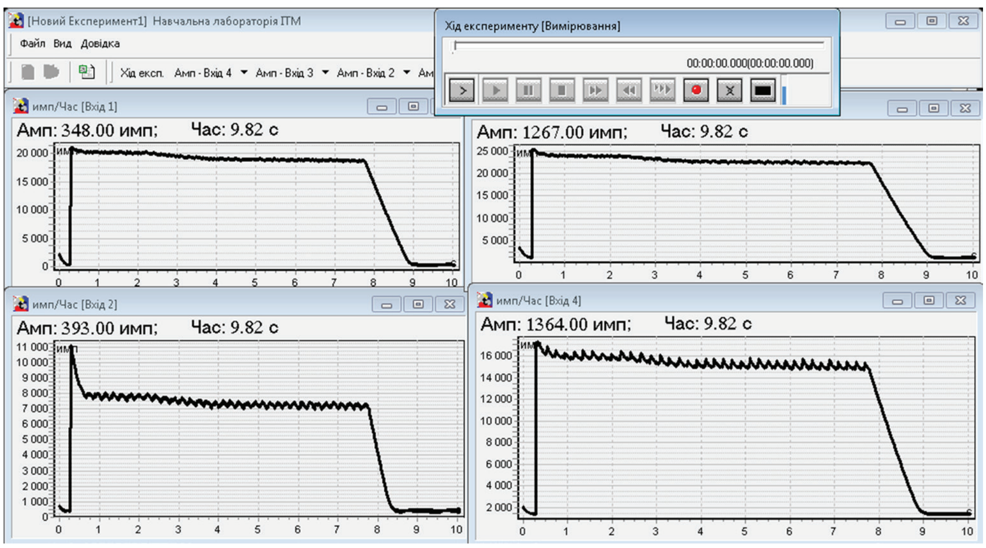

Fig. 8. Shapes of the recorded pulses of gamma-radiation on four CdTe detectors in the spherical absorber from steel of a thickness of h=1 cm at 45° angle

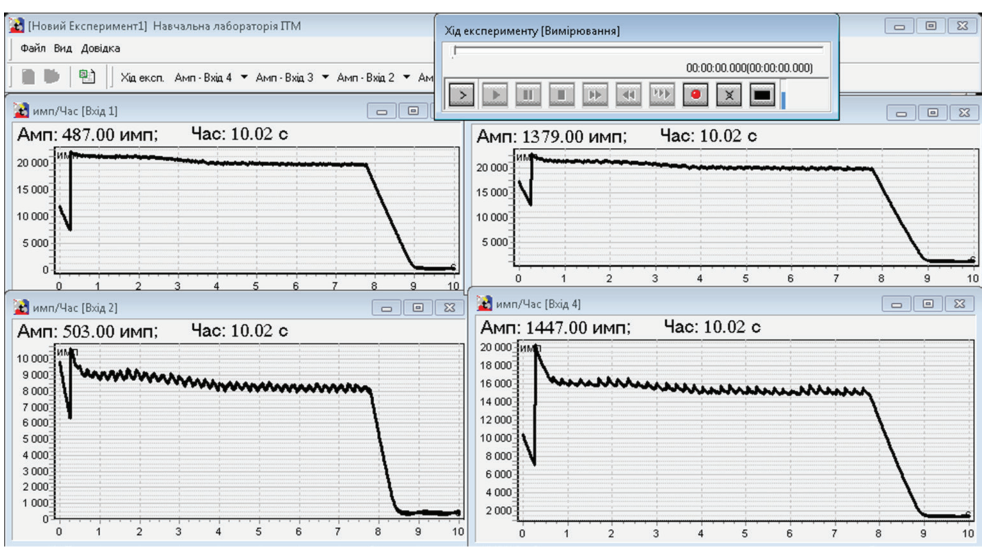

Fig. 9. Shapes of recorded pulses of gamma-radiation on four CdTe detectors in the spherical absorber from steel of a thickness of h=1 cm at a 30° angle

Table 1

Dependence of proportionality coefficients on angle φ at θ=90°, calculated theoretically for a spherical absorber

Angle φ, degrees	K_{p1}	K_{p2}	K_{p3}	K_{p4}	K_{p5}	K_{p6}
0	13.48692	13.48692	1	10.44684	0.774591	0.774591
15	27.67308	6.084594	0.219874	10.26233	0.370842	1.686609
30	48.36711	2.965424	0.061311	9.728114	0.201131	3.280514
45	64.70769	1.647007	0.025453	8.793739	0.135899	5.339222
60	61.70469	1.005958	0.016303	7.314802	0.118545	7.271481
75	39.28803	0.610779	0.015546	5.339222	0.135899	8.741659
90	16.31035	0.335223	0.020553	3.280514	0.201131	9.786071
105	4.548057	0.163376	0.035922	1.67662	0.368645	10.26233
120	0.862	0.074146	0.086016	0.774591	0.898598	10.44684
135	0.219874	0.035922	0.163376	0.368645	1.67662	10.26233
150	0.061311	0.020675	0.33722	0.201131	3.280514	9.728114
165	0.025453	0.015546	0.610779	0.135899	5.339222	8.741659
180	0.016206	0.016206	1	0.118545	7.314802	7.314802
195	0.015454	0.025302	1.637253	0.135899	8.793739	5.371032
210	0.020675	0.061311	2.965424	0.201131	9.728114	3.280514
225	0.035922	0.221184	6.15731	0.368645	10.26233	1.666691
240	0.074146	1.005958	13.56727	0.774591	10.44684	0.770004
255	0.163376	4.548057	27.83794	1.67662	10.26233	0.368645
270	0.335223	16.31035	48.65526	3.280514	9.786071	0.201131
285	0.607162	39.28803	64.70769	5.339222	8.793739	0.135899
300	1	61.70469	61.70469	7.314802	7.314802	0.118545
315	1.647007	64.70769	39.28803	8.793739	5.339222	0.135899
330	2.983091	48.36711	16.21376	9.786071	3.280514	0.202329
345	6.120844	27.83794	4.548057	10.26233	1.67662	0.368645
360	13.48692	13.48692	1	10.44684	0.774591	0.774591

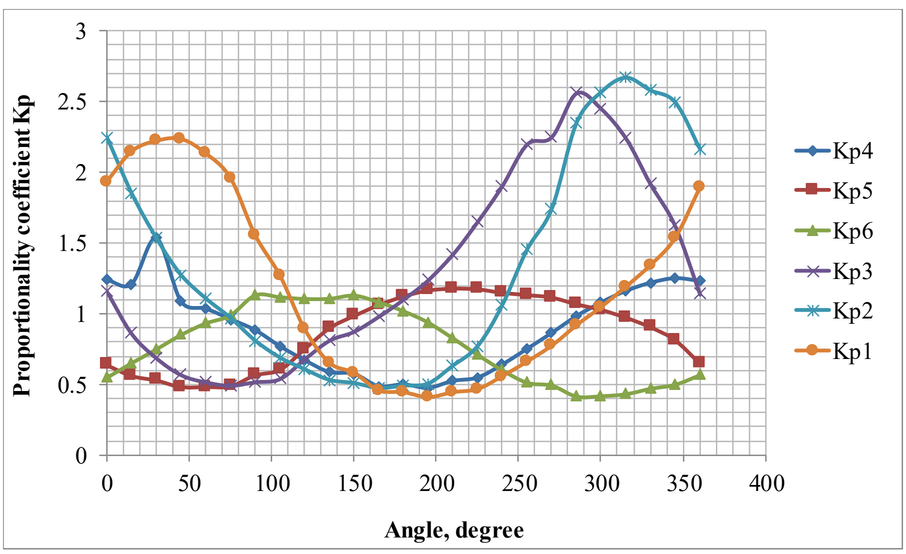

Fig. 10. Experimental dependence of K_p on the angle to pulsed radiation, where θ=90°, φ=0° – 360°

5. Estimation of reduced error of determining the direction to a pulsed source of radiation of the linear accelerator

The method for finding the reduced error of determining the direction to a pulsed source of radiation involves comparing the obtained experimental data K_p (Table 1) with the theoretical dependence (Fig. 11) based on the physical and mathematical model [5].

First, the corresponding difference of six experimentally obtained K_p from six theoretically calculated K_p, which is an absolute error of K_p, is found Then, the measurement range for each of the six theoretically calculated K_p, which is the difference between the maximum and minimum K_p values, is determined. According to the conducted calculations, the reduced error depending on the angle is calculated as the ratio of absolute error K_p to the measurement range for each K_p, multiplied by 100. The derived absolute error K_p as the difference of six experimentally obtained K_p from six theoretically calculated K_p is given in Table 2.

The measurement range for each of the six theoretically calculated K_p, which represents the difference between the maximum and minimum value K_p, is given in Table 3.

The reduced error, depending on the angle as the ratio of absolute error K_p (Table 2) to the measurement range (Table 3) for each K_p was calculated. The dependence of reduced error on the angle to a pulsed source of radiation for the spherical absorber is shown in Fig. 12.

It is advisable to divide the entire range of angles φ into five sub-ranges, where the direction to a source of pulsed radiation will be determined by three and two K_p with a minimum error (Table 4).

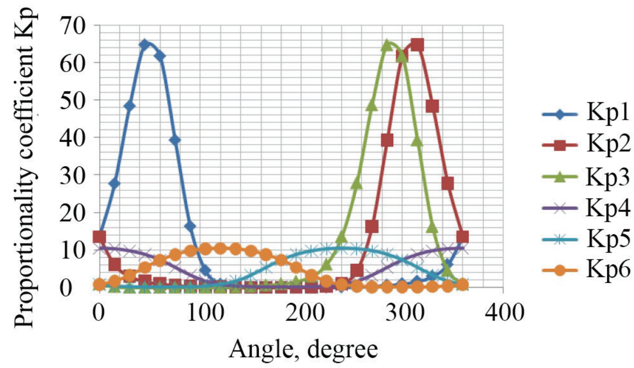

Fig. 11. Theoretically calculated dependence of K_p on the angle to gamma-radiation source, where θ=90°, φ=0° –360° [5]

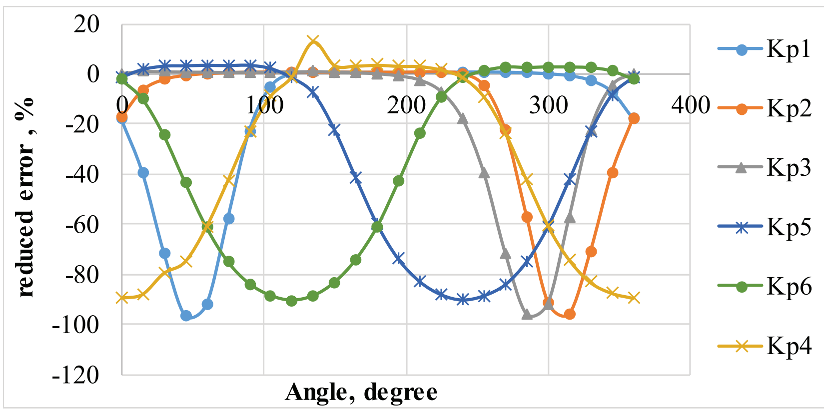

Fig. 12. Dependence of the reduced error on the angle to a pulsed radiation source for a spherical absorber

Table 2

The absolute error of proportionality coefficients for a spherical absorber

Angle degree	K_{p1}	K_{p2}	K_{p3}	K_{p4}	K_{p5}	K_{p6}
0	–11.5529	–11.2399	0.161	–9.20984	–0.13559	–0.22459
15	–25.5271	–4.23359	0.642126	–9.05333	0.192158	–1.03361
30	–46.1461	–1.43342	0.627689	–8.19611	0.329869	–2.52951
45	–62.4737	–0.37601	0.543547	–7.70874	0.349101	–4.48622
60	–59.5727	0.100042	0.501697	–6.2808	0.366455	–6.33748
75	–37.332	0.356221	0.478454	–4.38022	0.354101	–7.74966
90	–14.7584	0.470777	0.498447	–2.39851	0.366869	–8.65307
105	–3.28106	0.522624	0.505078	–0.90862	0.237355	–9.14333
120	0.026	0.529854	0.593984	–0.10559	–0.1456	–9.33984
135	0.430126	0.492078	0.648624	0.216355	–0.77662	–9.15433
150	0.516689	0.485325	0.53778	0.370869	–2.29351	–8.59811
165	0.429547	0.455454	0.370221	0.348101	–4.27522	–7.65766
180	0.425794	0.470794	0.102	0.378455	–6.1898	–6.2948
195	0.390546	0.477698	–0.39725	0.337101	–7.62674	–4.43103
210	0.421325	0.567689	–1.54342	0.320869	–8.54811	–2.45151
225	0.428078	0.545816	–4.50531	0.177355	–9.08633	–0.95469
240	0.480854	0.052042	–11.6613	–0.13659	–9.29684	–0.167
255	0.495624	–3.09606	–25.6369	–0.92762	–9.12733	0.146355
270	0.436777	–14.5694	–46.4033	–2.41751	–8.66907	0.293869
285	0.308838	–36.94	–62.1457	–4.35822	–7.72374	0.281101
300	0.046	–59.1377	–59.2527	–6.2368	–6.2848	0.301455
315	–0.45801	–62.0397	–37.045	–7.63374	–4.36422	0.298101
330	–1.64009	–45.7891	–14.2948	–8.56807	–2.37351	0.269671
345	–4.58484	–25.3449	–2.92606	–9.01233	–0.86262	0.132355
360	–11.5919	–11.3269	0.139	–9.21684	–0.12659	–0.20559

Table 3

Measurement range of each K_p

K_{p1}	K_{p2}	K_{p3}	K_{p4}	K_{p5}	K_{p6}
64.69223	64.69214	64.69214	10.3283	10.3283	10.3283

Table 4

Distribution of angle φ around sub-ranges with minimal error

Range of angles φ, degrees	345°–15°	15°–105°	105°–225°	225°–255°	255°–345°
K_p, responsible for determining the angle in the above range	K_{p3}, K_{p5}, K_{p6}	K_{p2}, K_{p3}, K_{p5}	K_{p1}, K_{p2}, K_{p3}	K_{p1}, K_{p2}, K_{p6}	K_{p1}, K_{p6},
The module of reduced error K_p does not exceed, %	10	6.6	6.96	9.3	7.1
Error of determining the direction in sub-ranges of angles, degrees	3	6	8.4	2.8	6.4

This makes it possible to determine the angle to a pulsed source with an error of not more than 8.4° from the explored sub-range. The maximum reduced error does not exceed 10 %.

6. Discussion of results of experimental assessment of the reduced error of the device for determining the direction to pulsed radiation of the linear accelerator Varian Clinac 600C

In the course of the studies into the accuracy of determining the direction of pulsed gamma-radiation by a spherical absorber with CdTe detectors, the following facts were established:

– operation of CdTe detectors in the pulsed mode makes it possible to record accurately the amplitude-temporal distribution of pulses from the linear accelerator in the range of energies of 1–6 MeV. When working with a spherical absorber, it was established that the most optimal voltage for CdTe is 5–7 V;

– the developed equipment makes it possible to record a unique combination of pulse amplitudes (Fig. 8, 9), which determines the spatial position of a pulsed source at the given configuration of the CdTe detectors in a spherical absorber;

– experimental studies of the device for determining the direction to a pulsed source of radiation using a spherical absorber showed the correctness of the physical and mathematical model [5]. Some difference between experimental and theoretically calculated proportionality coefficients is explained by the existence of optimal filter thickness for certain energy of gamma-radiation, with respect to which, a relative error increases at a decrease and an increase in the thickness of the absorber. In addition, such difference may be explained by the established discrimination by the energy of gamma-radiation. The proportionality coefficient of K_p also depends on the energy of gamma-radiation. This is caused by the fact that the linear attenuation factor of the material of the absorber (steel) μ depends on the energy of gamma-radiation (expression 1). The sensitivity of CdTe detectors is dependent on radiation energy, which causes an additional error due to the so-called in literature "rigidity rate" in the literature.

An analysis of the obtained results (Fig. 12) shows that it is advisable to split the entire range of angles φ into five sub-ranges, where the direction to the source of pulsed radiation will be determined by three and two K_p with a minimum error (Table 4). This makes it possible to determine the angle to a pulsed source with an error of no more than 8.4° from the sub-range under review. The maximum reduced error does not exceed 10 %. This fact opens up wide opportunities not only in the systems of nuclear situation monitoring, observing the parameters of nuclear explosions but also for the research into gamma-bursts in space, the possibility of their use as miniature detectors in sub-critical assemblies.

The limitation of the study is the use of a steel absorber and four CdTe detectors by the number of ADC channels.

It is possible to determine the angle to pulsed radiation most accurately if there is a theoretically calculated and experimental database of proportionality coefficients for all angles in the space and energy of a radiation source. This assumption is the object of subsequent research.

7. Conclusions

1. The dependence of the coefficient of proportionality of recording pulses from each detector on the angle of direction to a source of pulsed radiation of linear accelerator Varian Clinac 600C (USA) was found. The dependence proved the existence of a unique combination of pulsed amplitudes, which determines the spatial position of a pulsed source at the given configuration of the CdTe detectors in the spherical absorber. In addition, experimental studies of the device for determining the direction to a pulsed source of radiation using a spherical absorber demonstrated the correctness of the used assumption regarding the physical-mathematical model.

2. It has been recommended to divide the entire range of angles from 0° to 360° into five sub-ranges, in which three or two proportionality coefficients are responsible for determining the angle in space on a gamma-source. The maximum reduced error does not exceed 10 % and the maximum angle error is less than 8.4°. The angle to a radiation source can be determined more accurately if there is a theoretically calculated and experimental database of proportionality coefficients for all angles in space and energy of radiation sources.

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