# LOW-ENERGY X-RAY RADIATION AFTER THE BIOLOGICAL SHIELDING OF ELECTRON ACCELERATORS

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The bremsstrahlung of electrons from thick converters and its passage through concrete shielding of accelerators at different angles to the axis of the electron beam were calculated using GEANT4. Numerical estimates of the residual low-energy component of X-ray radiation after passing through the biological protection were carried out at an electron energy of up to 300 MeV. Additional reasons for the possible appearance of soft X-ray radiation after the shielding are considered. Experimental measurements of the spectral and dosimetric characteristics were performed by a silicon uncooled detector with the energy resolution of ~ 1 keV and spectral sensitivity in the range 5...150 keV. The comparison of the estimated dose (using the number of counts in Si detector) with indications of dosimeters was made.

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## INTRODUCTION

Optimization of the composition, thickness and geometry of materials that provide effective protection against ionizing radiation remains an actual task of radiation physics [1 - 5]. Traditional applications of biological protection are the protection of nuclear power plants and reactors, containers with nuclear waste, neutron sources, electron accelerators etc.

Mixed gamma and neutron radiation can achieve any point outside the protection. Such radiation is strongly attenuated by layers of protection. There is also scattered radiation of gamma and X-ray quanta, after their multiple Compton scattering from the walls, floor, ceiling, structural elements and various labyrinths. Calculating such protection by analytical methods is rather cumbersome, because the accumulation factors depend on many parameters: gamma radiation energy, thickness and atomic number of the material, geometry of the layers of protection, etc. In addition, gamma radiation from neutron capture reactions is always present.

In [5], the main regularities of the formation of accumulation factors are considered and formulas are proposed for the mathematical calculation of the fluxes of reflected quanta.

To simulate the passage of radiation through the substance, computer codes GEANT4 and MCNP are also used, which offer adequate modeling of all the physical processes of ionizing radiation interaction with material, taking into account the geometry and chemical elements composition of the protection [6 - 10].

The purposes of this work were:

1. Calculation using GEANT4 the bremsstrahlung of electrons from thick converters and its passage through protection at different angles to the axis of the electron beam.

2. Numerical estimates of the residual low-energy component of X-ray radiation after passing through the protection.

3. Experimental measurements of the spectral and dosimetric characteristics by the silicon uncooled detector, with the energy resolution of ~ 1 keV and spectral sensitivity in the range 5...150 keV [11 - 13].

## 1. TRANSFORMATION OF BREMSSTRAHLUNG SPECTRA AFTER THE BIOLOGICAL SHIELDING OF ELECTRON ACCELERATORS

The energy and angular characteristics of the electrons bremsstrahlung for various electrons energy and converters were calculated similar to [14]. Calculations in GEANT4 were carried out for the spherical and flat geometry of the experiment. For spherical geometry inside the concrete ball (material G4_CONCRETE) in the cavity the converter was located, on which electrons with energy $E_e$ = 10...300 MeV were fall. Fig. 1 shows the detection surfaces that have the different angles of inclination to the axis of the electron beam. In the center of Fig. 1,a the trajectories of gamma quanta passing through concrete are shown. In Fig. 1,b there is no concrete, that’s why the trajectories of quanta are rectilinear. The electrons energy and type of the converter was changing.

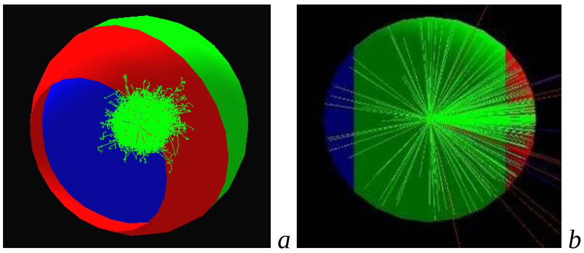

*Fig. 1. Visualization of the spherical geometry of the experiment: a – red and green color are the detecting surfaces. The concrete ball is blue. In the center the trajectories of gamma quanta passing through concrete are shown; b – there is no concrete, the trajectories of quanta are rectilinear, three directions of radiation are at angles: 0…45° (red – forward), 45…135° (green – sidewards) and 135…180° (blue – back)*

When the primary bremsstrahlung passes through the protective layers, the form of the spectrum changes significantly. First of all, the overall intensity of the radiation decreases. In addition, the form of the energy spectrum changes. The spectrum maximum was appeared in the 90 keV region, and the number of high energy quanta was decreased.

Fig. 2 shows the bremsstrahlung spectrum produced by electrons with an energy $E_e$ = 300 MeV for Ta target 6 mm thick. The spectrum of gamma radiation passing through 52 cm thick Si flat layer is also presented.

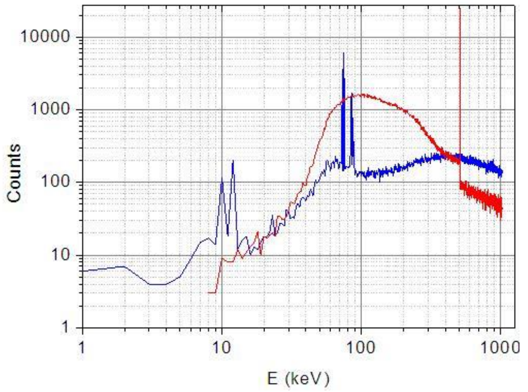

*Fig. 2. The bremsstrahlung spectrum of 300 MeV electrons for Ta target 6 mm thick (blue). The spectrum of gamma radiation which passed through 52 cm thick Si flat layer (red)*

In the target the characteristic X-lines Ta were generated, the maximum of the bremsstrahlung distribution is located in the 400 keV region. After the gamma radiation passes through the Si layer, the maximum was appeared in the region of 90 keV, the number of quanta with energies above 1 MeV decreases in 3.7 times, respectively, the increase in the soft part is 1.85 times. Thus, the Compton multiple scattering of the high-energy quanta is the source of soft X-ray radiation beyond the biological protection of electron accelerators.

Calculations of the attenuation of primary bremsstrahlung for different concrete protection thickness (G4_Concrete) were performed. Fig. 3 shows the low-energy part of the gamma radiation up to 300 keV. The range of concrete thickness is 0…200 cm. Geometry is spherical, registration angle is 4π.

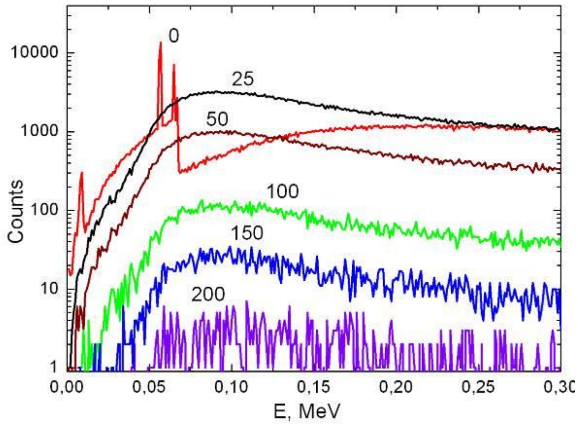

*Fig. 3. Bremsstrahlung spectra for different thickness of concrete protection from 0 to 200 cm. Ta = 1 mm, $E_e$ = 100 MeV*

The changing of the spectrum was observed for small concrete thickness. The gamma radiation spectra have the similar form, the number of passed quanta decreases with thickness. The flux of the bremsstrahlung of the 100 MeV electrons for the concrete 50 cm thick is attenuated in 5 times, for 100 cm thick in 50 times, and for 200 cm in 5 000 times, which corresponds to the data reported in [4].

In Fig. 4 shows three spectra of the bremsstrahlung passed through concrete with 60 cm thickness in three directions – at angles 0...45° (forward), 45...135° (sidewards) and 135...180° (back).

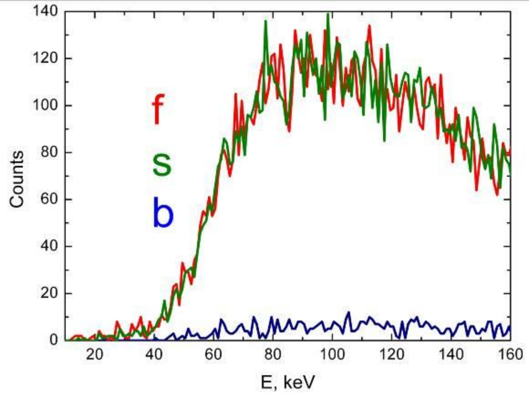

*Fig. 4. Bremsstrahlung spectra which passed through concrete in three directions – at angles 0…45° (forward), 45…135° (sidewards) and 135°…180° (back). CONCRETE = 60 cm, Ta = 4 mm, $E_e$ = 15 MeV*

Low-energy soft X-ray radiation is observed in the range of 20…100 keV, but its fraction in the total spectrum is relatively small.

## 2. THE TRANSFORMATION OF BREMSSTRAHLUNG SPECTRA FOR SINGLE- AND DOUBLE-REFLECTION

In Fig. 5 shows the scheme for calculating gamma radiation scattered on the concrete wall. Quanta fall normally to the surface in the direction of the arrow. Quanta scattered at large angle are recorded at the rear by a hemisphere counter.

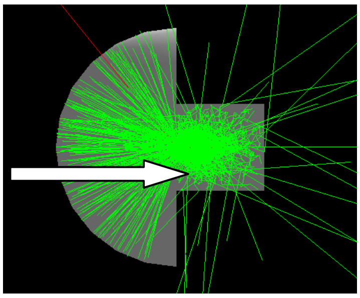

*Fig. 5. The scheme for calculating gamma radiation scattered on the concrete wall*

The spectra of scattered quanta from a thick wall differ greatly from the case of scattering for a thin layer. The energy of singly scattered quanta is rigidly determined by the scattering angle (for angles 90…180°): for initial energy $E_\gamma$ = 60 keV, energy of the reflected quanta is from 53 to 48 keV, for 500 keV – from 252 keV to 169 keV, for 1000 keV – from 338 to 203 keV, for 5 MeV – from 463 to 243 keV.

In the case of a thick wall, a complex structure of reflected spectra is formed from two scattering peaks – single and multiple scattering (Figs. 6, 7).

As a result of multiple scattering, the energy of scattered quanta is reduced up to 30 keV. The spectra depend on the energy of the incident quanta and the wall thickness.

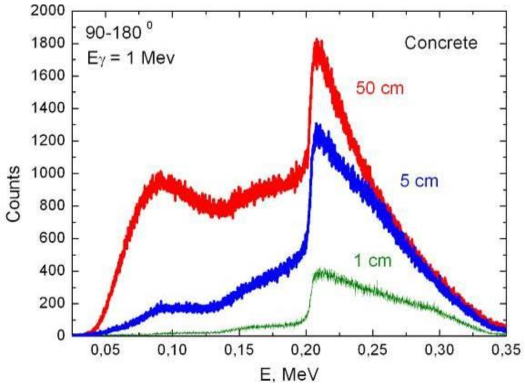

*Fig. 6. Backscattered spectra of quanta for angles of 90…180°, $E_\gamma$ = 1 MeV. The thickness of concrete is 1, 5, 50 cm*

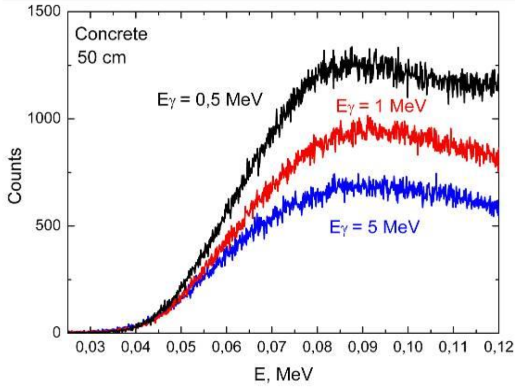

*Fig. 7. Backscattered spectra of quanta for angles of 90…180°, $E_\gamma$ = 0.5, 1, 5 MeV. The thickness of concrete is 50 cm*

Twice scattered radiation was simulated in structures of the "labyrinth" type (Fig. 8). Such the distribution of the walls allows one to reduce the transmission coefficient of scattered radiation, but the yield of scattered radiation must be accurately estimated.

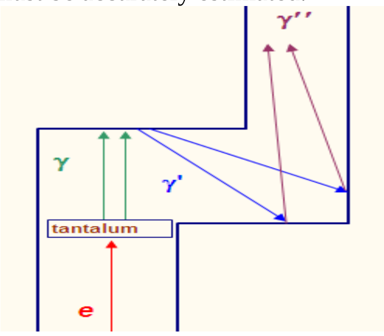

*Fig. 8. The scheme for simulating double reflection: γ – output (quanta yield) from the tantalum target forward; γ′ – after single reflection; γ″ – after double reflection; e – electrons*

Fig. 9 shows the transformation of the spectral distribution, according to the scheme shown in Fig. 8. The spectra are presented in the relative units.

When primary photons are reflected, soft gamma radiation is generated and the hard part of the radiation disappears.

Calculations for two successive reflections of the gamma radiation with the fixed energy in the range from 50 keV to 1 MeV were performed. Fig. 10 presents the gamma quanta spectra obtained with single and double reflection from the semi-infinite concrete medium.

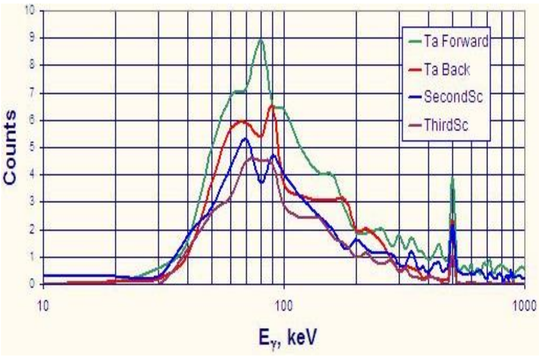

*Fig. 9. Spectral distributions of bremsstrahlung and scattered gamma radiation. Green curve – yield from the Ta target forward; red – yield from the Ta target back; blue – the single reflection; brown – the double reflection. $E_e$=15 MeV*

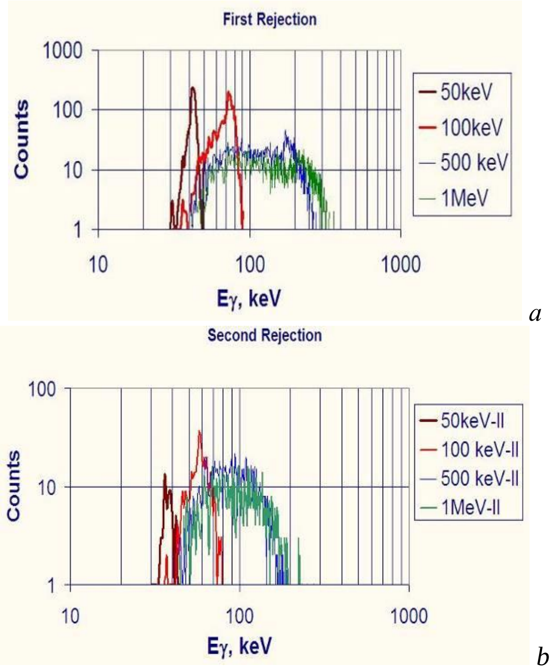

*Fig. 10. Spectral gamma quanta distributions for one- and two-fold reflection from a semi-infinite concrete. a – is single reflection; b – is double reflection. Primary photon energy: brown line – 50 keV; red – 100 keV; blue – 500 keV; green – 1 MeV*

Table 1 shows the number of reflected quanta (as a percentage of the incident quanta number) for single and double reflection from the semi-infinite concrete.

***Table 1***

*The number of reflected quanta (as a percentage of the incident quanta number) for single and double reflection from the semi-infinite concrete*

| $E_\gamma$, keV | *single* | *double* |
|---|---|---|
| 50 | 9% | 0.6% |
| 100 | 25% | 4% |
| 500 | 34% | 11% |
| 1 000 | 28% | 9% |

The important consequence of multiple scattering of the high-energy quanta is the decrease of their energy up to 30 keV. Thus, scattered gamma radiation in structures of the "labyrinth" type also gives a expressed low-energy X-ray radiation.

## 3. MEASUREMENT OF LOW-ENERGY X-RAY RADIATION

In Fig. 11 shows the nuclear-physical power plant, fragment of the linear accelerator (linac) LUE-300.

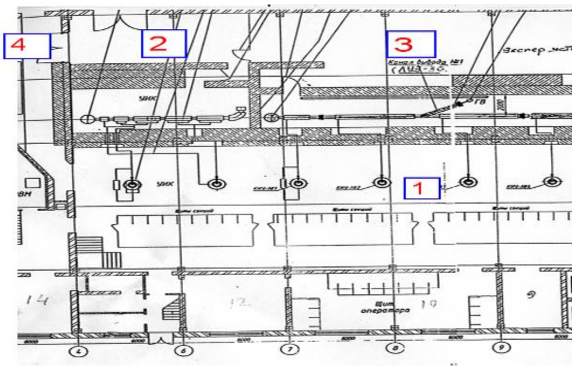

*Fig. 11. Fragment of the linac LUE-300*

Experimental measurements of the spectral and dosimetric characteristics by the silicon uncooled detector, with the energy resolution of ~ 1 keV and spectral sensitivity in the range 5...150 keV were performed. The measurements were carried out at points 2, 3, 4 on the side of Zone 1 of the linear accelerator LUE-300 (Fig. 12).

*Fig. 12. Fragment of Zone 1 of the linear electron accelerator LUE-300. Detector and power supply located on the chair – point 2*

The concrete thickness at different points is different, at the narrowest place is 60 cm. The accelerator worked with parameters: electron energy $E_e$ = 12 MeV, beam current $I_e$ = 18 μA.

Note that in real measurements with the thin planar detector, the incident gamma-ray spectrum is converted into the deposited energy ED in the Si detector 300 μm thick. In Fig. 13 shown: the bremsstrahlung spectrum (converter U, thickness 1 mm, $E_e$ = 100 MeV), passed through 50 cm of concrete; b – energy ΔE released in Si detector (really measured radiation spectrum). Such spectra should be obtained experimentally.

In Fig. 14 shows the gamma radiation spectra measured at point 2 (without the Cd and with the Cd layer 0.8 mm thick).

When the protective layer Cd was used, the spectrum was attenuated in 3.2 times. Such attenuation corresponds to photons energy of 80...90 keV. This means that the spectrum consists of soft X-ray quanta. CXR of Cd appeared (line $K_\alpha$ = 23.17 keV), which is excited by the soft X-ray.

In Fig. 15 shows the gamma radiation spectra measured at point 3. The number of registered quanta increased significantly, because position 3 is closer to the target-converter.

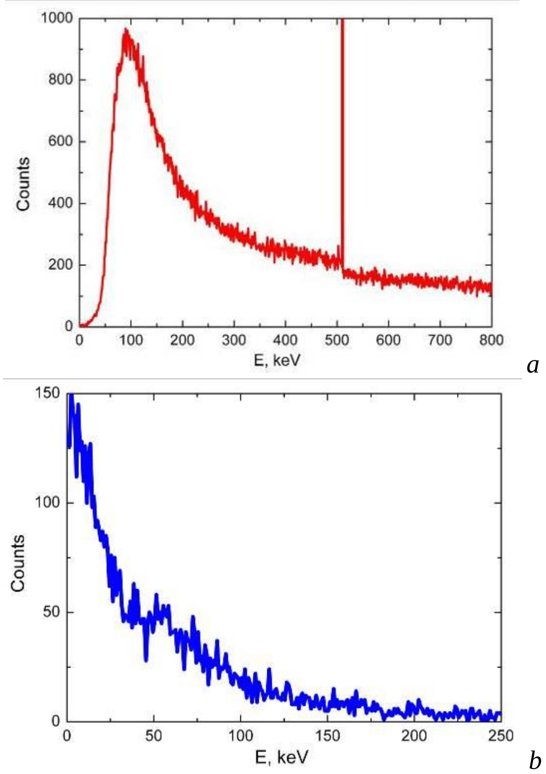

*Fig. 13. a – bremsstrahlung spectrum (converter U, thickness 1 mm, $E_e$ = 100 MeV), passed through 50 cm of concrete; b – energy ΔE released in Si detector*

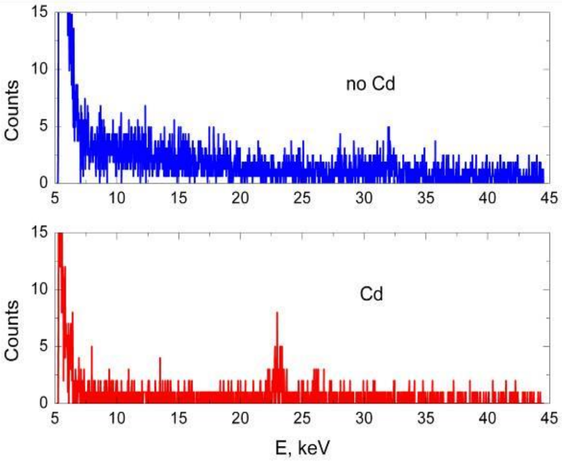

*Fig. 14. The gamma radiation spectra measured at point 2 (without the Cd – above and with the Cd layer 0.8 mm thick – below)*

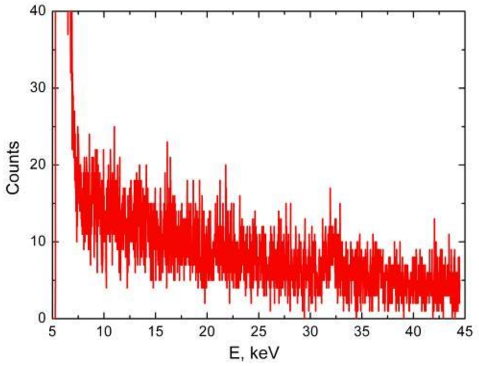

*Fig. 15. The radiation spectra measured at point 3*

Also for measurements the two-channel detector based on the Si detector (without Gd foil and with Gd foil thickness 0.4 mm) was used [16]. In Fig. 16 shows the gamma radiation spectra measured at point 4.

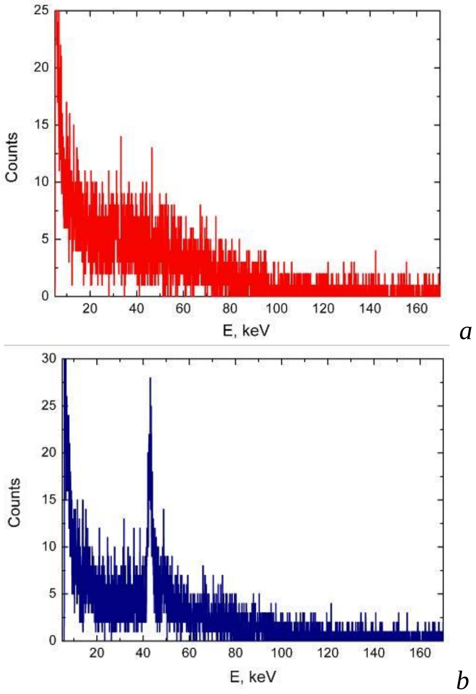

*Fig. 16. Gamma radiation spectra measured at point 4 (a – without Gd and b – with Gd foil thickness 0.4 mm)*

In the spectrum, the gadolinium CXR lines with the energy $K_{\alpha}$ =42.99 keV are registered, which indicates the presence of soft X-radiation with energy slightly higher than this value.

In addition, the background was measured when the accelerator was turned off.

The measured spectra were compared with the dosimeter indications. In this case, the sum of the accounts in the Si detector in the background was equated to the value of 12 μR/h, which corresponds to the background value in the accelerator building. Table 2 presents the comparison of the estimated dose and the number of counts in the Si detector with the dosimeter indications. Agreement is quite good.

***Table 2***

*Comparison of the estimated dose and the number of counts in the Si detector with the dosimeter indications*

| Estimated dose | Si, μR/h | Si counts/ min | Dosimeter, μR/h |
|---|---|---|---|
| Background | 12 | 0.5 | 12 |
| 2 | 2450 | 102 | 3000 |
| 3 | 20060 | 836 | 5 000…15 000 |
| 4 | 720 | 30 | 200…400 |

## CONCLUSIONS

In GEANT4 were calculated the bremsstrahlung of electrons from thick converters and its passage through accelerators biological protection at different angles to the axis of the electron beam. Numerical estimates of the residual low-energy component of X-ray radiation after passing through the protection were carried out. The energy of accelerated electrons was up to 300 MeV.

When the primary bremsstrahlung passes through the protective layers, the form of the spectrum changes significantly. First of all, the total intensity of the radiation decreases. In addition, the form of the energy spectrum is changing. The spectral maximum was appeared in the 90 keV region, and the number of the high – energy quanta was decreased.

Low-energy radiation is observed in the range of 20…100 keV, but its fraction in the total spectrum is relatively small.

In the case of the thick wall, the complex structure of reflected gamma spectra is formed from two scattering peaks – single and multiple scattering. As the result of multiple scattering, the energy of scattered quanta is reduced up to 30 keV. The gamma spectra depend on the energy of the incident quanta and the wall thickness.

Twice scattered gamma radiation was simulated in structures of the "labyrinth" type. When primary photons are reflected from walls, soft gamma radiation is generated and the hard part of the radiation disappears. Calculations for two successive reflections of the gamma radiation with energy in the range from 50 keV to 1 MeV were performed.

Experimental measurements of the spectral and dosimetric characteristics by the silicon uncooled detector, with the energy resolution of ~ 1 keV and spectral sensitivity in the range 5...150 keV were performed. The measurements were carried out at three points on the side of Zone 1 of the linear electron accelerator LUE-300.

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## НИЗКОЭНЕРГЕТИЧЕСКОЕ РЕНТГЕНОВСКОЕ ИЗЛУЧЕНИЕ ПОСЛЕ БИОЛОГИЧЕСКОЙ ЗАЩИТЫ УСКОРИТЕЛЕЙ ЭЛЕКТРОНОВ

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В GEANT4 рассчитаны тормозное излучение электронов из толстых конверторов и прохождение излучения через бетонное экранирование ускорителей под разными углами к оси электронного пучка. Проведены численные оценки остаточной низкоэнергетической составляющей рентгеновского излучения после прохождения биологической защиты при энергии электронов до 300 МэВ. Рассмотрены дополнительные причины возможного появления мягкого рентгеновского излучения после прохождения защиты. Экспериментальные измерения спектральных и дозиметрических характеристик выполнялись кремниевым неохлаждаемым детектором с энергетическим разрешением ~ 1 кэВ и спектральной чувствительностью в диапазоне 5...150 кэВ. Проведено сравнение оценочной дозы (с использованием количества отсчетов в детекторе Si) с показаниями дозиметров.

## НИЗЬКОЕНЕРГЕТИЧНЕ РЕНТГЕНІВСЬКЕ ВИПРОМІНЮВАННЯ ПІСЛЯ БІОЛОГІЧНОГО ЗАХИСТУ ПРИСКОРЮВАЧІВ ЕЛЕКТРОНІВ

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У GEANT4 розраховано гальмівне випромінювання електронів з товстих перетворювачів і проходження випромінювання через бетонне екранування прискорювачів під різними кутами до осі електронного пучка. Проведені численні оцінки залишкової низькоенергетичної складової рентгенівського випромінювання після проходження біологічного захисту при енергії електронів до 300 МеВ. Розглянуто додаткові причини появи м'якого рентгенівського випромінювання після проходження захисту. Експериментальні виміри спектральних та дозиметричних характеристик виконувалися кремнієвим неохолодженим детектором з енергетичним дозволом ~ 1 кеВ і спектральною чутливістю в діапазоні 5...150 кеВ. Проведено порівняння оціночної дози (з використанням кількості відліків у детекторі Si) з показами дозиметрів.