GAMMA-RADIATION SPECTRA OF $1200\,MeV$ ELECTRONS IN THICK BERYLLIUM, SILICON AND TUNGSTEN SINGLE CRYSTALS

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Gamma radiation spectra of 1200 MeV electrons from the single crystals of the beryllium 1.2 mm thick, silicon 1.5 mm and 15 mm thick and tungsten 1.18 mm thick along of the crystallographic axes were measured. Also spectral-angular distributions of gamma radiation from the silicon single crystals 1.5 mm thick along of the crystallographic axes $< 100 >$, $< 110 >$ and $< 111 >$ were measured. On the basis of these measurements the γ-radiation spectra for the different solid angles up to 6.97×10^{-6} sr were obtained.

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1. INTRODUCTION

In recent decades the electromagnetic radiation (x-ray and gamma range) of the relativistic electrons in single crystals is object of numerous theoretical and experimental studies for the electron energy from several MeV to hundreds GeV.

Interest to the channeling radiation of the electrons was amplified after the idea about a possibility of its application as intensive and easily tunable source quasi monoenergetic X-ray and gamma radiation [1-15] and also as the positrons source for the linear supercolliders [16].

For example, at the plane channeling of electrons with energy about 50 MeV in the radiation spectra intensive narrow spectral lines are observed. They can be used in the applications which require the intensive and quasi monoenergetic gamma radiation source.

In the paper [2] the detailed theoretical analysis was performed of all possible factors which influence on the parameters of an intensive X-ray source (atomic number, crystal structure, heat conductivity, radiation resistance etc.). Such source of radiation can be based on the channeling radiation in Be, C, Si, Ge and W single crystals and the high-current electron beams with energy about 50 MeV.

In particular, it is shown that from all considered materials the diamond crystal provides of the greatest gamma radiation intensity. However, Be crystal not much more concedes to a diamond crystal.

At energy range of electrons 10...100 MeV systematic experimental study of gamma radiation spectra at the electrons plane channeling was performed, generally on C and Si single crystals. The gamma radiation spectra from Be crystal are given in paper [12]. The main attention was paid to optimization of the yield and the spectral line width of the gamma radiation [2, 11] and [13-15].

Range of the electrons energy of about 1000 MeV is interesting by that in the gamma radiation spectra of electrons at their moving along crystallographic axes is observed noticeable increasing of the yield of gamma quanta with energy in the region of "giant resonance" in the cross section of photonuclear reactions.

Transition from traditional amorphous converters to the crystal targets of "optimal thickness" can help to solve the problem of the transformation coefficient increase of electron energy into the gamma radiation energy [17-19].

It is known that at initial electrons energy 1200 MeV for the silicon crystal 15.0 mm thick the transformation coefficient reaches 6% that significantly exceeds the value of this parameter for the amorphous target. This circumstance can be used in various applied and scientific nuclear and physical researches from [17-25].

The comprehensive theoretical analysis of the experimental data obtained on linacs in various scientific centers ($KIPT, SLAC, YerPhI, NPITPU$ etc.) was performed. It made possible to conclude about the considerable (in case of electrons - crucial) influence of the dynamics of the charged particles beams in the thin crystal on the formation of the main gamma radiation characteristics, such as the spectrum and intensity.

In thick crystals as a result of the process of electrons multiple scattering and their fast dechanelling [26], the main radiation mechanism is the gamma

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radiation of above-barrier electrons. The important role of particle beam dynamics in a crystal in determining the main radiation mechanisms was clarified, and, as a consequence, the main characteristics of this radiation were evaluated.

Presently the new opportunities for obtaining the intensive electromagnetic radiation of the sub-GeV electrons when using bent crystals and crystal undulators are studied. The gamma radiation of electrons was studied experimentally for the electrons energy 855 MeV [27], and theoretically by means of simulation [28].

It should be noted that all the experimental results known so far were obtained at very small electrons current. In this conditions no more than one photon in an accelerator current impulse are registered.

However, during creation of the intensive gamma radiation sources there can be difficulties because of big heat load on the single crystals when using high-current electron beams.

The investigation of the influence of the impulse current of the linac beam on the gamma radiation yield from the single crystal at the electrons channeling and evaluation of the ionization energy losses of the electrons with energy 300 and 1200 MeV from the silicon single crystal 15.0 mm thick was given in paper [29].

It is shown that in the range of impulse current 1...100 mA the gamma radiation yield of the 1200 MeV electrons increases in proportion to the value of the impulse current. This demonstrates the preservation by the crystal converter of the single crystal properties up to the impulse current of electrons for 100 mA.

Similar investigations at the low electrons energy are given in papers [5-8] and in the recent years in papers [13-15].

For various applications it is important to have the gamma quanta beams with small divergence and the maximal brightness in the given spectral interval. For such applications it is necessary to know the spectral and angular distribution of the gamma radiation and find optimum parameters of the beam - crystal system on the corresponding exit beam parameters.

The purpose of the given paper is further studying of the gamma radiation characteristics of the electrons from single crystals for the solution of such problems as the choice of the crystal material, the crystallographic axes and minimum energy of electrons at which the use of the crystal radiator can be considered reasonable.

In the paper the experimental gamma radiation spectra of the 1200 MeV electrons in the single crystals of the beryllium 1.2 mm , silicon 1.5 mm and 15.0 mm and tungsten 1.8 mm thick are presented. About the use prospects of the beryllium crystal as the radiator it was indicated also in paper [19].

The gamma radiation spectra of the 1200 MeV electrons in various radiation solid angles are presented for the electrons motion along the crystallographic axes: $< 100 >$, $< 110 >$ and $< 111 >$ of the silicon single crystals 1.5 mm thick.

The paper is the continuation of the earlier performed the experimental investigations of the spectral and the spectral - angular distributions of the gamma radiation of the electrons with energy about 1000 MeV at their motion along the single crystals axes of the silicon and tungsten in the wide range of the crystals thickness [23, 29-31].

1.1. MINIMUM ELECTRONS ENERGY FOR THE GAMMA QUANTA SOURCE ON THE CRYSTAL TARGET BASIS

In Ref.[23] the experiments were made to identify of minimum energy at which application of the crystal radiator as the gamma quanta source for the radiation technologies can be considered still reasonable. The measurements of the gamma radiation spectra of the electrons with energy 1200 600 and 300 MeV from the silicon single crystals 15.0 mm

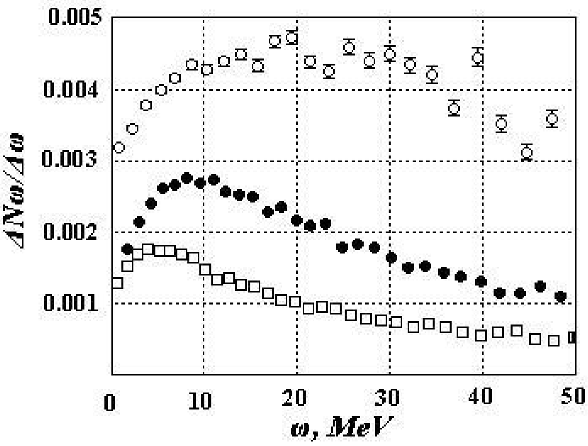

Fig.1. The gamma radiation spectra of electrons from Si crystal 15.0 *mm thick along axis* $< 111 >$ *in solid angle* $\Delta\Omega = 0.14 \times 10^{-6}$ *sr:* ○ – 1200 *MeV;* ● – 600 *MeV;* □- 300 *MeV*

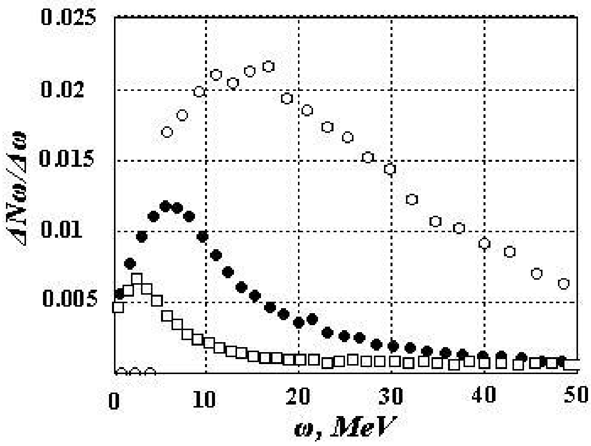

Fig.2. The gamma radiation spectra of electrons in W crystal 3.0 *mm thick along axis* $< 100 >$ *to solid angle* $\Delta\Omega = 0.14 \times 10^{-6}$ *sr:* ○ – 1200 *MeV;* ● – 600 *MeV;* □– 300 *MeV*

thick and the tungsten 3.0 mm thick in solid angle $\Delta\Omega = 0.14 \times 10^{-6}$ sr were performed. Results are given in Figs.1 and 2.

From Fig.1 and Fig.2 it is seen that at the decrease of the electrons energy the maximum of the gamma radiation intensity is shifted in the range of the less energy and the application of the silicon crystal at the electrons energy lower than 600 MeV it is already inexpedient.

However, in the case of the tungsten crystal it is seen that else at the electrons energy 300 MeV the application of the tungsten crystal as the radiator can be still efficient.

A preliminary version of this work is located in [41].

2. SPECTRA AND THE SPECTRAL-ANGULAR DISTRIBUTIONS OF THE ELECTRONS GAMMA RADIATION IN THE BERYLLIUM, SILICON AND TUNGSTEN SINGLE CRYSTALS

In the experiment the gamma radiation spectra of the 1200 MeV electrons in the beryllium single crystal and the spectral-angular distributions in thick single crystals of the silicon and tungsten in the range of the gamma quanta radiation angles $\Theta_\gamma = 0...1.28$ mrad were measured.

Data are obtained with use of the technique allowing to measure of the gamma quanta spectra without the distortions because of the multiple photons production by one electron in thick single crystals [32, 35].

In Fig.3 the intensity spectra $\Delta N\omega/\Delta\omega$ of the gamma radiation of 1200 MeV electrons are given for the Be single crystal 1.2 mm thick in the solid angle $\Delta\Omega = 0.14 \times 10^{-6}$ sr at their passing along the axis $< 0001 >$ and plane (0110). Here ΔN – number of the quanta on one incident electron in the channel of the analyzer with width on energy $\Delta\omega$, ω – average energy of the relevant channel.

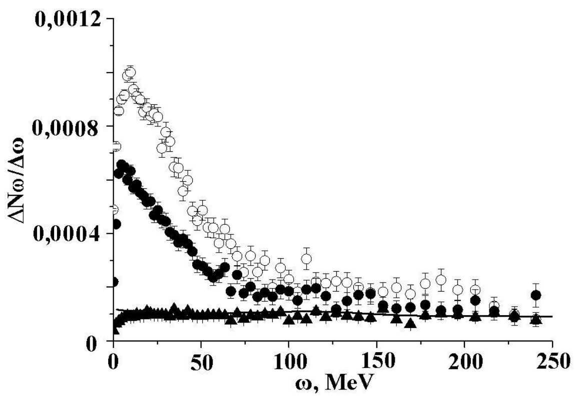

Fig.3. *The gamma radiation spectra of* 1200 *MeV electrons in the solid angle* $\Delta\Omega = 0.14 \times 10^{-6}$ *sr from the Be crystal* 1.2 *mm thick:* ○ *– axis* $< 0001 >$, ● *– plane* (0110), *black triangle – random crystal. Solid line – GEANT*4 *calculation for random crystal*

As can be seen from Fig.3 intensity in the maximum of the gamma radiation spectrum at the axial electron motion approximately by 10 times exceeds intensity for the random crystal, and for the plane motion - approximately by 7 times. The maximum in the intensity spectrum is at the gamma quanta energy $\omega_{max} \sim 10$ MeV in the case of the axial electrons motion and $\omega_{max} \sim 5$ MeV in case of the plane motion.

Spectral-angular distributions of the gamma radiation was measured for the silicon and tungsten single crystals. From this distributions the radiation spectra in the solid angles $\Delta\Omega = 0.14 \times 10^{-6}, 1.28 \times 10^{-6}, 3.55 \times 10^{-6}$ and 6.97×10^{-6} sr from this distributions was obtained.

Gamma radiation spectra of the 1200 MeV electrons from the silicon crystals 1.5 mm and 15 mm thick and from the tungsten crystal 1.18 mm thick in the solid angles 0.14×10^{-6} and 6.97×10^{-6} sr are shown in Figs.4 and 5, respectively.

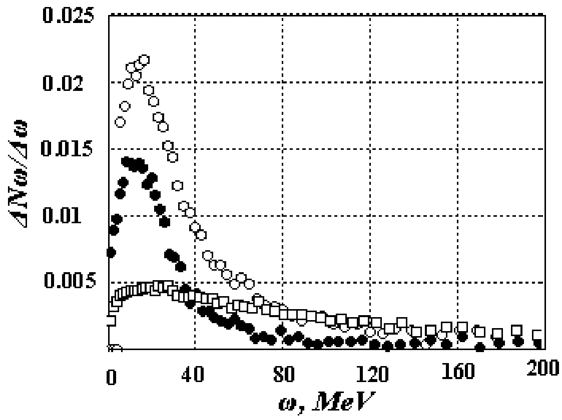

Fig.4. *The gamma radiation spectra of* 1200 *MeV electrons in the solid angle* $\Delta\Omega = 0.14 \times 10^{-6}$ *sr from the Si crystal along axis* $< 111 >$*:* ● *–* 1.5 *mm thick:* ○ *–* 15 *mm thick,* □ *– from W crystal* 1.18 *mm thick along axis* $< 100 >$

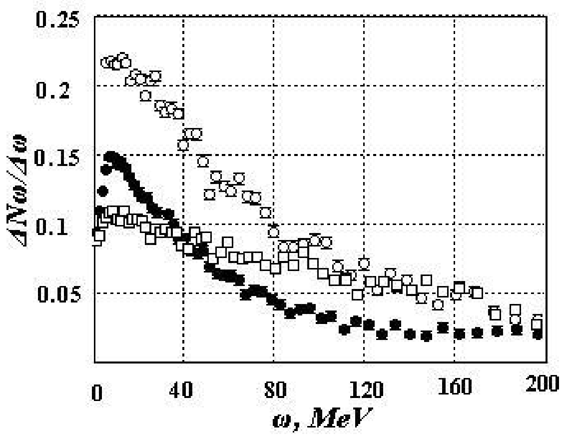

Fig.5. *The gamma radiation spectra of* 1200 *MeV electrons in the solid angle* $\Delta\Omega = 6.97 \times 10^{-6}$ *sr from the Si crystal along axis* $< 111 >$*:* ● *–* 1.5 *mm thick:* ● *–* 15 *mm thick,* □ *– from W crystal* 1.18 *mm thick along axis* $< 100 >$

As can be seen from Figs.4 and 5, the gamma radiation yield from the silicon crystals in the range of the gamma-quanta energy 10...30 MeV is larger, than for the tungsten crystal. Higher energy in the maximum of the gamma radiation intensity spectra from the tungsten crystal in comparison with the silicon crystal makes it more preferable to the positrons generation [16].

From Fig.4 it is visible that upon the transition from the crystal thickness 1.5 mm to the thickness 15 mm at the thickness increase by 10 times and the gamma quanta yield increases only approximately by 1.5 times while the ionization losses of electrons increase in proportion to the crystal thickness. This circumstance needs to consider at the choice of the crystal thickness.

3. SPECTRAL-ANGULAR DISTRIBUTIONS OF THE ELECTRONS GAMMA RADIATION FOR THREE MAIN AXES OF THE SILICON CRYSTAL

Practically all experimental data on the investigation of the electromagnetic electrons radiation in the silicon single crystal are obtained for the case of the electron beam passing along the axis $< 111 >$. However, from the point of view of obtaining the maximum yield of gamma radiation, this axis may not be optimal.

Therefore, spectral-angular distributions of the gamma radiation of the 1200 MeV electrons from three silicon crystal targets 1.5 mm thick were measured. *Si* crystal targets were cut out from the central part of the silicon ingot so that the direction of the axes $< 100 >, < 110 >$ and $< 111 >$ was perpendicular the geometrical plane of the targets. Spectral-angular distributions of gamma radiation were measured for the angles radiation relatively of the initial electrons beam direction $\Theta_\gamma = 0, 0.42, 0.85$ and 1.28 mrad. Spectral-angular distributions of the gamma radiation from the $< 111 >$ silicon crystal 1.5 mm thick for the 1200 MeV electrons also were measured earlier [31, 32].

From these distributions the gamma radiation spectra of the electrons were obtained in the solid angles $\Delta\Omega = 0.14 \times 10^{-6}, 1.28 \times 10^{-6}, 3.55 \times 10^{-6}$ and 6.97×10^{-6} sr at their passing along three main axes $< 100 >, < 110 >$ and $< 111 >$. Results are shown on Figs.4-7. The solid line - calculation for the random crystal on the *GEANT* program.

From Figs.6-9 can be seen that the gamma radiation spectra of the electrons for different crystal axes significantly differ for all the radiation solid angles. The maximal gamma radiation intensity takes place on the electrons passing along the silicon crystal axis $< 110 >$. The gamma radiation intensity for axis $< 110 >$ exceeds, for example, the radiation intensity for the axis $< 100 >$ approximately by 1.24 in the radiation solid angle $\Delta\Omega = 0.14 \times 10^{-6}$ sr and by 1.38 in $\Delta\Omega = 6.97 \times 10^{-6}$ sr.

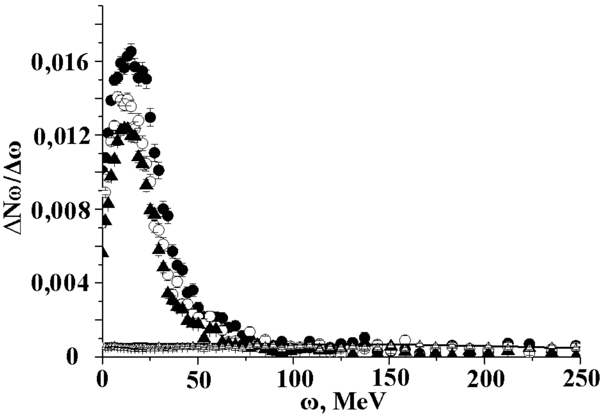

Fig.6. *The gamma radiation spectra of* 1200 *MeV electrons from Si crystals* 1.5 *mm thick:* • *– axis* $< 110 >$*,* ∘ *–* $< 111 >$*, black triangle –* $< 100 >$ *,* ▽ *– random crystal;* $\Delta\Omega = 0.14 \times 10^{-6}$ *sr*

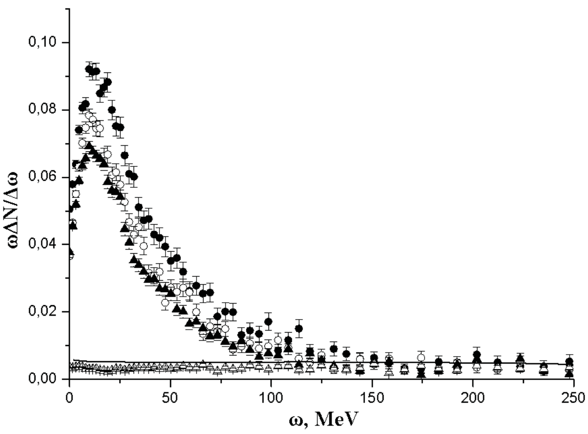

Fig.7. *The same that Fig.6,* $\Delta\Omega$=1.28×10^{-6} *sr*

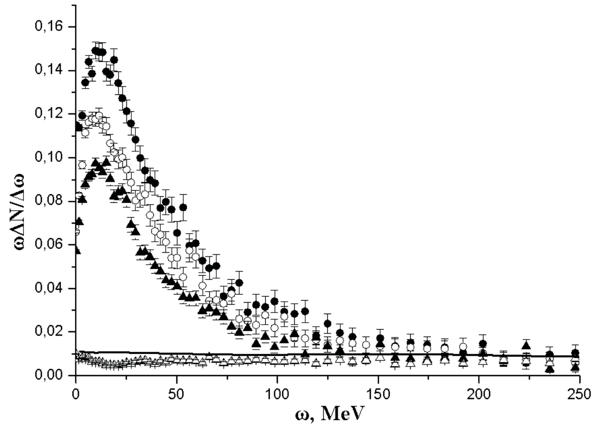

Fig.8. *The same that Fig.6,* $\Delta\Omega$=3.55×10^{-6} *sr*

With decrease of the radiation solid angle is observed also some improvement of the radiation monochromaticity in the range of the radiation intensity maximum.

Measurement of the absolute values of the spectral-angular distributions of the electrons gamma radiation in thick crystals opened the possibility of quantitative comparison of experimental results with the predictions of the theoretical models and hypotheses verification which are the basis of these models.

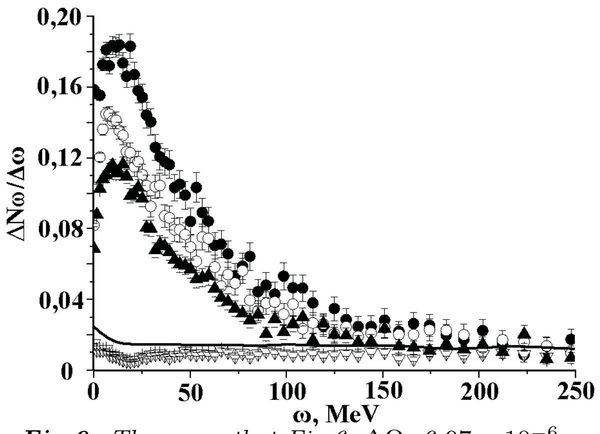

Fig.9. *The same that Fig.6,* $\Delta\Omega$=6.97 × 10^{-6} *sr*

In our case the calculations were performed taking into account the angular distribution evolution of the electron beam in the crystal, which is bound with the multiple scattering of the particles on the lattice atoms. For the particles passing at the angle ψ to the crystallographic axis exceeding the critical angle of the channeling ψ_c the calculation was performed on the formulas of the modified theory of the coherent radiation; at ψ less ψ_c the electron trajectory curvature in the field of the crystal atoms row was considered [34, 36, 37, 38]. The contribution of the channeled particles to the gamma radiation was not considered.

The results of the measuring and calculation of the quantity $(\Delta\, N \times \omega/(\Delta\omega)/(\Delta\Omega) \times 10^{-4}$ are presented in Table for three Si axes, ($\omega = 10\, MeV$, radiation angle $\Theta\gamma = 0$).

The results of the measuring and calculation of the quantity $(\Delta\, N \times \omega/(\Delta\omega)/(\Delta\Omega) \times 10^{-4}$ *for three Si axes,* ($\omega = 10\, MeV$, *radiation angle* $\Theta\gamma = 0$)

Axis	Experiment	Calculation
< 111 >	9.2	9.5
< 110 >	10.3	10.7
< 100 >	8.3	8.7

The satisfactory quantitative agreement of the results of the calculation and experiment demonstrates correctness of the assumptions made for the calculations simplification. It means that the regularities of the spectral-angular distributions of the electrons gamma radiation in a thick crystal which were observed in the experiment are caused by the coherent radiation features of the above-barrier electrons in the field of the crystal atoms raw.

Thus, we can see that in the considered area of the particles energy and the crystals thickness the above-barrier particles give the main contribution to the angular distributions formation of the gamma radiation. The reason of it, apparently, consists that in the considered energy range the electron motion in the field of the atoms row in the channeling conditions is extremely unstable. Therefore, there is the fast particles dechanneling, i.e. their transition from sub-barrier to above-barrier states [39].

4. INFLUENCE OF THE FOIL AT THE EXIT OF THE ACCELERATOR VACUUM CHAMBER

One of the principle opportunities to increase the electrons current on the crystal target, and, respectively, the maximum achievable gamma radiation intensity is the forced crystal cooling. For this, it is necessary to install a goniometer with a crystal outside the vacuum chamber of the accelerator [40].

To check the effect of the foil at the exit of the vacuum chamber on the radiation parameters in front of the crystals the aluminum foil 0.16 mm thick was installed. This simulated the foil at the exit of the accelerator vacuum chamber. In this geometry gamma-ray spectra were measured. On Fig.10 the gamma radiation spectra of the 1200 MeV electrons are shown for the axis < 111 > in the silicon crystals 3.0 mm thick (Fig.10,a) and 1.5 mm thick (Fig.10,b) before and after the installation of aluminum foil in front of the crystal.

From Fig.10 it is seen that the installation of the goniometer with the crystal out the accelerator vacuum chamber leads to the decrease of the gamma radiation intensity: about by 1.21 for the crystal 3.0 mm and about by 1.28 for the crystal 1.5 mm thick. However, this decrease of the intensity can be compensated by the increase of the electrons current due to the possibility of the forced cooling of the crystal target and simplicity of the goniometer maintenance.

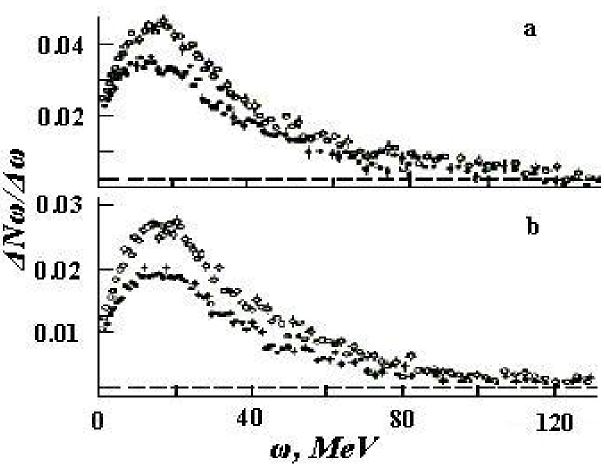

Fig.10. *The gamma radiation spectra of* 1200 MeV *electrons along axis* < 111 > *from* Si *crystals* 3.0 mm *thick (Fig.10,a) and* 1.5 mm *thick (Fig.10,b), before* (○) *and after* (●) *the installation of aluminum foil* 0.165 mm *thick in front of the crystals. Dush line - random oriented* Si *crystal*

5. CONCLUSIONS

Gamma radiation spectra of the 1200 MeV electrons in various solid angles from crystals: beryllium

$1.2\,mm$ thick along $< 0001 >$ axis, silicon $1.5\,mm$ and $15\,mm$ thick along $< 111 >$ axis and tungsten $1.18\,mm$ thick along $< 100 >$ axis are measured.

It is shown that for the silicon crystals in the energy range of gamma quanta $10...30\,MeV$ were produced larger gamma radiation yield than for the tungsten crystal. Higher energy in the maximum of the gamma radiation intensity for W crystal in the comparison with Si crystal does W more preferable for the positrons generation.

Spectral-angular distributions of the gamma radiation spectra of the $1200\,MeV$ electrons from three silicon crystals $1.5\,mm$ thick with the orientation of the $< 100 >, < 110 >$ and $< 111 >$ axes along the electron beam direction were measured in the range of the gamma radiation angles from 0 to $1.28\,mrad$. From this distributions the gamma radiation spectra of the electrons in the solid angles $\Delta\Omega = 0.14 \times 10^{-6}, 1.28 \times 10^{-6}, 3.55 \times 10^{-6}$ and $6.97 \times 10^{-6}\,sr$ are obtained.

It was established that the maximal gamma radiation intensity takes place on the electrons passing along the silicon crystal axis $< 110 >$. The gamma radiation intensity for axis $< 110 >$ exceeds, for example, the radiation intensity for the axis $< 100 >$ approximately by 1.24 in the solid angle $\Delta\Omega = 0.14 \times 10^{-6}\,sr$ and by 1.38 in $\Delta\Omega = 6.97 \times 10^{-6}\,sr$. With decrease of the solid angle is observed also some improvement of the radiation monochromaticity in the range of the radiation intensity maximum.

The above results complement the previously obtained experimental and theoretical data and can be used to create a source of intense gamma-ray beams for radiation technologies on the basis of the crystal targets and linac with electrons energy about $1000\,MeV$.

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СПЕКТРЫ ГАММА-ИЗЛУЧЕНИЯ 1200 МэВ ЭЛЕКТРОНОВ В ТОЛСТЫХ МОНОКРИСТАЛЛАХ БЕРИЛЛИЯ, КРЕМНИЯ И ВОЛЬФРАМА

Г. Л. Бочек, А. С. Деев, В. И. Кулибаба, Н. И. Маслов, В. Д. Овчинник, С. М. Потин, Б. И. Шраменко

Измерены спектры гамма-излучения электронов 1200 МэВ из монокристаллов бериллия толщиной 1,2 мм, кремния толщиной 1,5 мм и 15,0 мм и вольфрама толщиной 1,18 мм вдоль кристаллографических осей. Измерены также спектрально-угловые распределения гамма-излучения монокристаллов кремния толщиной 1,5 мм вдоль кристаллографических осей <100>, <110> и <111>. На основе этих измерений были получены спектры гамма-излучения для разных телесных углов до $6,97 \times 10^{-6}$ стерадиан.

СПЕКТРИ ГАМА-ВИПРОМІНЮВАННЯ 1200 МеВ ЕЛЕКТРОНІВ У ТОВСТИХ МОНОКРИСТАЛІВ БЕРИЛІЮ, КРЕМНІЮ І ВОЛЬФРАМУ

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Виміряно спектр гамма-випромінювання електронів 1200 МэВ із монокристалів берилію товщиною 1,2 мм, кремнію товщиною 1,5 мм та 15,0 мм і вольфраму товщиною 1,18 мм вздовж кристалографічних осей. Вимірюються також спектрально-кутові розподіли гама-випромінювання монокристалів кремнію з товщиною 1,5 мм вздовж кристалографічних осей <100>, <110> та <111>. На основі цих вимірів були отримані спектри гама-випромінювання для різних телесних кутів до $6,97 \times 10^{-6}$ стерадиан.