INTENSIVE X-RAY SOURCE OPTIMIZATION

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Possibility of optimization of an intensive source of the electron radiation in crystals based on the Compton scattering of X-radiation is considered.

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1. INTRODUCTION

The radiation, arising as relativistic electrons pass through the crystal, is investigated very intensively [1-8] because can be used to create quasimonochromatic, polarized and spectrally intense X-ray and gamma source. But all known experimental results have been obtained only for very low electron current regimes, when the radiation is created by single electron passing through the crystal. As a result of this, the predictions of high current situation have discrepancies up to 5 orders [9] for X-radiation. The prospect and requirement of creation of intensive coherent x-ray sources causes the necessity of experimental techniques development for creation and measurement of the basic characteristics of such radiation: intensity of radiation; spectral and angular distributions, etc. The difficulties on optimisation of an intensive gamma-quanta source are connected with application necessity of the high current of the accelerated electrons and thick crystal converters.

In this work the method of optimization of intensive X-ray sources is proposed. The method is based on the results received by authors at investigations of gamma radiation of electrons in thick single crystals [10-12]. In the measurements are used the method of the nonlinear conversion of initial gamma radiation by a Compton scattering on the target - scatterer [10].

2. MEASUREMENTS OF INTENSIVE GAMMA-RADIATION SOURCE

Fig. 1 shows the experimental layout [10]. Gamma-radiation of electrons from the target 1 after cleaning magnets 3, 5 hit the scatterer 6. The Compton scattered photons after measuring-channel collimators 9,11,12 are registered by gamma-spectrometer 14. The transference of the scatterer along A-C allows the measuring of the spectral-angular distribution of the gamma-radiation. This technique was tested on Kharkov linear electron accelerator at electron energy 1 GeV [10, 11].

The method allows:

–to measure the "true" spectral - angular distributions of radiation without this radiation distortion in experimental conditions of a multiple production of gamma quanta by one electron;

– to measure the "true" spectral-angular distributions of radiation in experimental conditions of intensive pulse beam (impulse combination from gamma quanta in spectrometer).

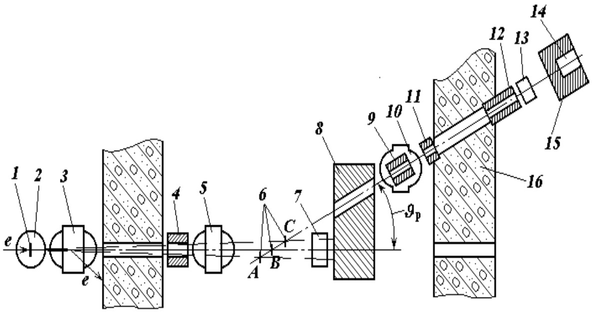

Fig. 1*. Scheme of the experimental setup: 1- target; 2- goniometer; 3- deflecting electromagnet; 4- photon beam collimator; 5, 10- cleaning electromagnets; 6- scatterer; 7- ionization chamber; 8- lead block; 9, 11, 12- measuring-channel collimators; 13- cleaning magnet; 14- gamma spectrometer; 15- lead shielding of the spectrometer; 16- concrete wall*

Figs. 2,3 show, for example, the experimental gamma-quanta spectra measured by technique [10]. The radiation spectra of 1.2 GeV electrons in 70 μm and 63 mm thick silicon single crystals are shown in Fig. 2.

The spectra have a prominent peak at ω=15 MeV, whose width is about 50 MeV. It is seen from Fig. 2 that the spectrum shape and the energy value at the intensity maximum are practically independent of the crystal thickness. The radiation spectrum from the tungsten crystals of various thickness averaged over experimental points, are presented in Fig. 3. It is seen from Fig. 3, that the spectrum curve for the tungsten crystals of 1.18 mm and 3.2 mm thickness have practically coinciding maximum at the gamma-quanta energy ω=22 MeV. But these spectra considerably differ from each other in intensity in the whole interval of gamma-quanta energy. The most visible decrease in intensity is observed in the hard part of spectrum, beginning from ω>20 MeV. This is likely to be caused by decrease in a number of gamma-quanta because of pair creation.

3. INTENSIVE X-RAY SOURCE OPTIMIZATION

Measuring X-rays spectrums with energy of some tens keV, it is necessary to take into account the Doppler broadening of scattered quanta spectrum caused by the non-zero initial momentum distribution of the atomic electrons.

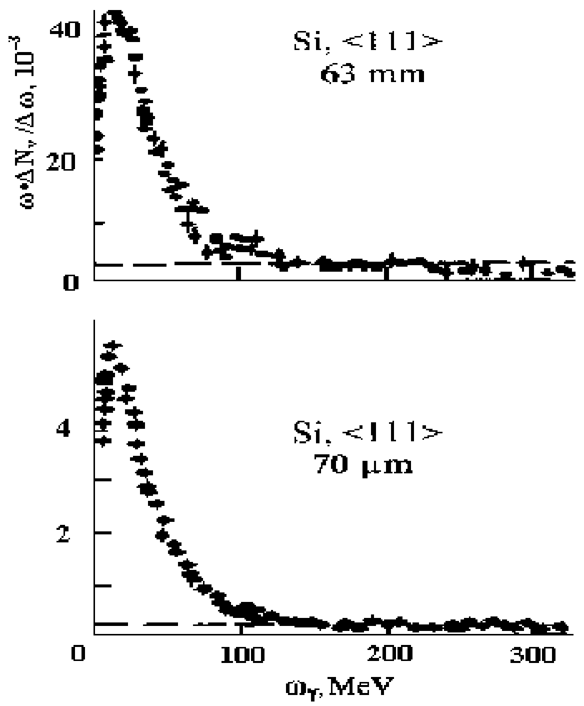

__Fig. 2.__ Spectra of gamma-radiation by 1,2 GeV electrons passing through the Si crystals along the <111> axis. The collimation angle ϑ_c = 0.213 mrad Dashed line – spectra levels for random crystals

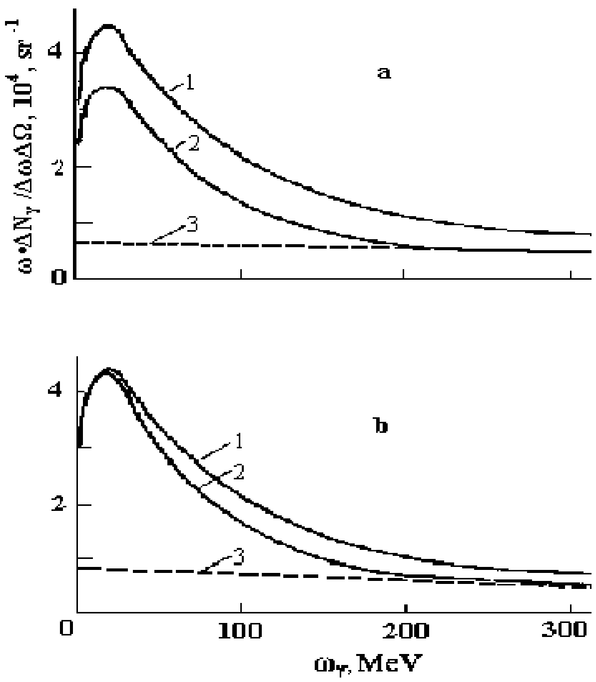

__Fig. 3.__ (a) –spectra of gamma-radiation by 1.2 GeV electrons passing through W crystals..
1– W (100), 1.18 mm ; 2– W (111), 3.2 mm thickness;
3 – W, random, 3.2 mm thickness
(b) – the same spectra, fitted at the energy ω=22 MeV

At photon scattering on free rest electron the energy of scattered photon is associated with initial photon energy and scattering angle by known Compton formula:

$$\omega_2 = \frac{\omega_1}{1+\frac{\omega_1}{m}\left(1-\cos\theta\right)}, \tag{1}$$

where ω_1 and ω_2 is the energy of initial and scattered photon, consequently, θ is scattering angle, m is electron rest mass.

Fig. 4 shows the dependence of scattered photons energy from the initial photon energy for two scattering angles 30° and 110°.

The cross-section of the photon scattering on angle ϑ in this case is (formula Klein-Nishina):

$$d\sigma = \frac{1}{2} r_0^2 \left(\frac{\omega_2}{\omega_1}\right)^2 \left(\frac{\omega_2}{\omega_2} + \frac{\omega_1}{\omega_2} - \sin^2\theta\right) d\Omega\ . \tag{2}$$

Compton equation (1) and formula (2) were obtained in assumption that the photon scattering occur on free rest electron. However, for energy electron less 100 keV this assumption is invalid at the photon scattering on atomic electrons, which have bond energy and impulse distribution.

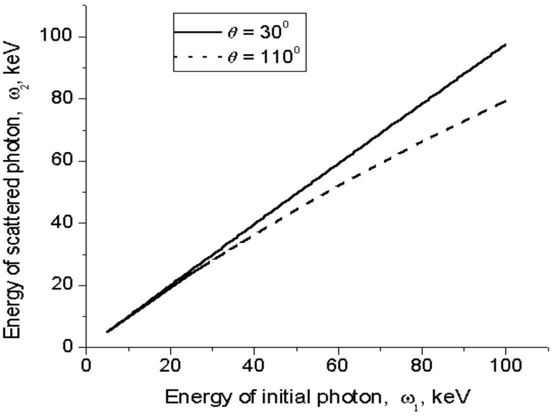

__Fig. 4__. The dependence of scattered photon energy vs the initial photon energy for two scattering angles 30 ° and 110 °

If initial photon energy is small on the comparison with rest electron energy the Compton cross-section may be written in form:

$$\frac{d^2\sigma}{d\omega\, d\Omega} = \left(\frac{d\sigma}{d\omega}\right)_{Th} \frac{\omega_1}{\omega_2} \frac{m}{\left|\vec{k}_1 - \vec{k}_2\right|} J(q), \tag{3}$$

where $\left(\frac{d\sigma}{d\omega}\right)_{Th}$ -nonrelativistic Tomson cross-section, $J(q) = 2\pi \int_0^\infty n(p_0)\, p_0\, dp_o$ – Compton profile, $q = (k_1 - k_2)\cdot p_0 / \left|k_1 - k_2\right|$, and $\int\limits_{-\infty}^{\infty} J(q)dq = 1$ for one electron. Here $n(p_0)$ is the probability that an electron in the ground state of the system will have momentum p_0.

The authors of work [13] on the visualization systems simulation are used the relativistic equation for double differential cross section for scattering at angle ϑ per differential solid angle $d\Omega$, per differential energy $d\omega'$ from work [14]:

$$\frac{d^2\sigma}{d\omega' d\Omega} = \frac{1}{2} m r_0^2 \sqrt{\omega_1^2 + \omega'^2 - 2\omega_1 \omega' \cos\theta} \times$$

$$\left(\frac{\omega'}{\omega_1}\right)\left(\frac{\omega'}{\omega_1} + \frac{\omega_1}{\omega'} - \sin^2\theta\right) \cdot J(q), \qquad (4)$$

where ω' is the energy of scattered photon. Compton profiles in this work was used from published calculations with use of the precise Hartree-Fock wave functions [15]. Equation associating energy of scattered photon with q is

$$q = \frac{\omega' \omega_2 (1 - \cos\theta) - m(\omega' - \omega_2)}{(\omega'^2 + \omega_2^2 - \omega' \omega_1 \cos\theta)^{1/2}}, \qquad (5)$$

where ω_2 is energy of scattered photon predicted by Compton equation (1).

The presence of a bound electron momentum results in the energy distribution of scattered photons for a fixed scattering angle and the violation of a single valued bond between the scattering angle and the photon energy (Compton spectra).

Fig. 5 and 6 show the Compton spectra for hydrogen systems with different Z=1 and 3 for two values of energy ω_1 calculated in impulse approximation [16].

The widths of the distributions on the half-height are about 1.5 % and 7 %, accordingly.

The spectrum of the scattered photons measured in experiment is bound with the initial spectrum of scattered photons by equation [17]:

$$N_{\mathrm{EXP}}(\omega_2) = \Phi(\omega_2) +$$

$$+ \int N(\omega'_2) S(\omega_2 - \omega'_2)[J(\omega'_2) + M(\omega'_2)] A(\omega'_2) C(\omega'_2) \eta(\omega'_2) d\omega'_2 \qquad (6)$$

$$\int N(\omega'_2) S(\omega_2 - \omega'_2)[J(\omega'_2) + M(\omega'_2)] A(\omega'_2) C(\omega'_2) \eta(\omega'_2) d\omega'_2,$$

where $N(\omega_2)$ – the initial spectrum of scattered photons, $S(\omega_2)$ – detector system's response, $J(\omega_2)$ – Compton profile, $M(\omega_2)$ – the multiple scattering function, $A(\omega_2)$ – probability of photoelectric absorption in scatterer, $C(\omega_2)$ – Compton scattering cross-section on free electrons, $\eta(\omega_2)$ – detector efficiency function, $\varphi(\omega_2)$ – background distribution.

With point of view of the experiment the appearance of these Compton distributions (Figs. 5,6) leads to aggravation of the energy resolution of the measuring system, which perhaps removed, in principle, by deconvolution procedure [18] for inverting the equation (6).

In the case of coherent polarization radiation the photons have the high degree of linear polarization [19,20].

The photons polarized perpendiculars to scattering plane are scattered stronger then the photons polarized parallel to scattering plane [21]. This fact can to lead to distortion of the measuring X-ray spectra and has to be taken into account on measuring of the spectral characteristics of the X-ray intensive source.

The estimations are showing that on the using of scatterer from 1 mm beryllium and registration solid angle 10^{-6} sr it is possible to measure the spectral distributions of continuos X-ray radiation on the fluency $10^{12}...10^{13}$ quanta per second.

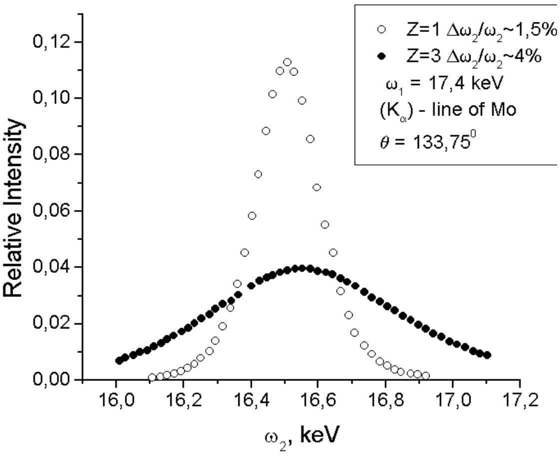

***Fig. 5**. Compton spectra for hydrogen systems with different Z for No $K_{\alpha 1}$ radiation ($\omega_1 \approx 17{,}4$ keV) calculated in impulse approximation [16]*

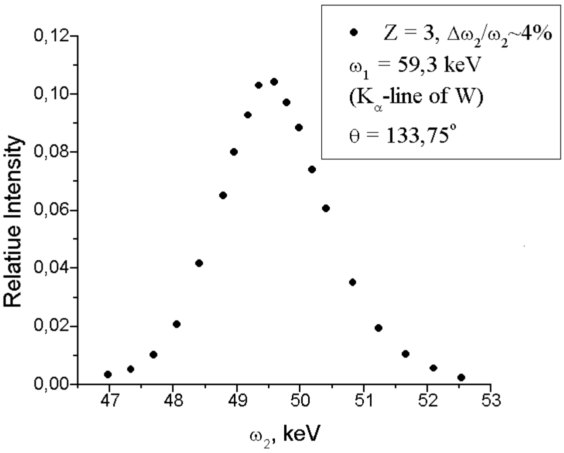

***Fig. 6**. Compton spectra for hydrogen systems with Z=3 for W $K_{\alpha 1}$ radiation ($\omega_1 \approx 59{,}3$ keV) calculated in impulse approximation [16]*

4. CONCLUSIONS

The method of the measuring of spectral-angular distributions of gamma-quanta on base of the Compton scattering on the atomic electrons is allowed the spectral characteristics measuring of the X-ray radiation with energy more 10 keV, but with insufficiently high energy resolution about 5…7 % caused by Doppler broadening. On measuring with use of the Ge(Li) detector the energy resolution is determined, in the main, by the Doppler broadening, as the modern semiconductor detectors have high-energy resolution.

The method allows to measure the "true" spectral - angular distributions of X-radiation in experimental conditions of intensive pulse beam without this radiation distortion in conditions of a multiple production of gamma quanta in thick crystals by one electron .

The resolution corrected X-ray spectra of scattered quanta may be obtained by using of the deconvolution procedure with using of the experimental Compton profile and resolution function of detector.

To obtain the initial “true” spectrum of X-radiation, it is necessary to restore the spectrum of the measured scattered radiation through the use of the inverse Compton transforms.

On the using of scatterer from 1 mm beryllium and registration solid angle 10^{-6} sr it is possible to measure the spectral distributions of continuos X-ray radiation on the fluency $10^{12}…10^{13}$ quanta per second.

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ОПТИМИЗАЦИЯ ИСТОЧНИКОВ ИНТЕНСИВНОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ

Г.Л. Бочек, В.И. Кулибаба, Н.И. Маслов, В.Д. Овчинник

Рассматривается возможность оптимизации источников интенсивного рентгеновского излучения ускоренных электронов с использованием методики на основе комптоновского рассеяния.

ОПТИМІЗАЦІЯ ДЖЕРЕЛ ІНТЕНСИВНОГО РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ

Г.Л. Бочек, В.І. Кулібаба, М.І. Маслов, В.Д. Овчинник

Розглядається можливість оптимізації джерел інтенсивного рентгенівського випромінювання прискорених електронів з використанням методики на основі комптонівського розсіяння.