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THE LINEARLY POLARIZED PHOTON BEAMS FOR PHOTONUCLEAR INVESTIGATIONS AT LOW ENERGY FACILITIES

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Intensity and polarization spectra of Coherent Bremsstrahlung (CB) for initial electron beam's energy 160-250 MeV are calculated. Beams of electrons with such energy are used in the laboratory MAX-lab (Lund, Sweden). Also it is planned to obtain the beams with such energies on the facility which have been created in NSC KIPT (project NESTOR). Calculations are executed in the CB theory with the use of the Born approximation and by consideration of experimental factors, such as sizes, divergence and energy spread of beam, sizes and form of collimator, thickness of crystal (consideration of multiply scattering). It is shown, at the use of collimation angle about $\theta_c \approx 0.5\theta_\gamma$ ($\theta_\gamma = mc^2/E_0$, m – mass of electron), it is possible to obtain beams of CB with polarization from 30% up to 60% in the range of energies about 100 MeV, that is opened by possibility of providing of nuclear–physical experiments with the polarized beams in the given range of energies.

KEY WORDS: coherent bremsstrahlung, polarized photon beam, diamond crystal, electron accelerators, nuclear physics researches

Fundamental nuclear physics investigations are of great importance from point of view of searching answers on substantial questions of natural science, such as elementary particles and nuclear structure, evolution of the matter in the universe, on one hand, and the possibility of practical application of the fundamental investigation results, on other hand [1]. For this goal wide programs of the nuclear physics investigations are carried in various scientific centers covering all energy ranges, from some tens MeV and up to hundreds GeV.

Substantial contribution to the problems decision is given by experiments performed at the intermediate energy range (up to some GeV) at MAMI, ELSA and MAX-lab. Fundamental problems that have been studied at these facilities are precision test and development of QCD approach in intermediate and low energy range, e.g. ChPT, study of nuclear and hadron structure and its changes in the nuclear matter etc., that suppose performing wide experimental programs on studying single and pair pion photoproduction on nucleon and nuclei near threshold, Compton scattering on nucleon and nuclei, nuclear disintegration etc., [2,3].

To provide such investigations the working accelerator facilities are regularly upgraded and new ones are proposed to be constructed. Thus, in MAX-laboratory the energy of the electron beam was increased from ~80 up to 250 MeV, the maximal energy at MAMI was increased from 850 MeV up to 1.5 GeV. Projects of new facilities for fundamental photonuclear investigations at intermediate energy range are discussed in NSC KFTI. One of them is the project of electron accelerator facility for energy up to 730 MeV (project SALO) [4,5]. The other possible facility on electron energy up to 160 MeV could be created on the base of storage ring "NESTOR" that is constructed at NSC KIPT [6].

The aim of this work was studying the linear polarized photon beam parameters produced on the base of the coherent bremsstrahlung radiation (CB) at SALO facility [7] and at "NESTOR" facility, using analytical code developed by P.Grabmayr and co-workers [8]. This is new more perfect code for the CB characteristics calculation. It was made on the base of Born's approximation [9,10,11 ch.2] and allows one to take into account most of the experimental factors: electron beam size and energy and angular divergence, multiple electron scattering in the crystal, photon beam collimation. Details are presented in Ref. [8]. Earlier characteristics of the linear polarized photon beam have been studied at the accelerators with the initial electron energy E_0=100 MeV in work [12] and for E_0=150-250 MeV in work [13] using our old code.

CHARACTERISTICS OF THE CB BEAM PRODUCED BY ELECTRONS WITH ENERGY 150-250 MEV

The most profitable parameters of the linearly polarized photon beam at electron accelerators with energies <1 GeV could be produced on the base of the coherent bremsstrahlung radiation generated by electrons in diamond crystal. The diamond crystal due to perfect crystal lattice and small volume of fundamental cell, high Debye temperature and small atomic number provides the highest operation parameters (intensity and polarization) of the beam.

The CB is generated when relativistic electrons fall onto the crystal at a small angle ψ relatively to the crystal axes but exceeding substantially critical angle of axial channeling, $\psi >> \psi_c$. Under this conditions interference maxima appear in the radiation spectra due to periodicity of atom locations in the crystal lattice. The radiation intensity in these maxima substantially exceeds the radiation intensity in an amorphous material and in addition it has significant linear polarization. The CB process is well described by theory based on Born approximation, and its cross section can be represented as a sum, [9,10,11 ch.2]:

$$d\sigma_{CB} = d\sigma_{coh} + d\sigma_{in}, \tag{1}$$

where $d\sigma_{coh}$ is the interference part of the CB cross section depending on the crystal orientation relatively to the electron beam; $d\sigma_{in}$ is the non-coherent part of the cross section, which does not depend on the crystal orientation and represents itself a cross section of usual bremsstrahlung in the amorphous substance. Thus, CB beam spectrum consists of two parts: coherent part with interference maxima and usual bremsstrahlung. The interference peaks have a sharp upper border and are reduced slowly in the low-energy area. With increasing angle ψ the radiation intensity in the peaks falls, the peaks are displaced to higher energy range and at large ψ they are not observed.

The results of the calculations [12,13] performed for electrons with initial energies E_0~100-250 MeV have shown that the photon energy range in which the CB polarized beam could be applied to photonuclear researches is extended up to 30-40 MeV, that is, it covers the giant dipole resonance range if initial electron beam energy E_0 is about 100 MeV and it is spread out up to 100-120 MeV for initial electron beam energy E_0 about 250 MeV. The polarization of the coherent bremsstrahlung at the CB maximum can reach large magnitudes (P~0.5-0.6) if the photon beam is collimated in the angle $\theta_c \approx 0.5\theta_\gamma$ ($\theta_\gamma = mc^2/E_0$, m is the electron mass).

The present calculations have been made with new code [8] for diamond crystal with thickness 0.1 mm and they are in agreement with the results of the previous estimations [13]. As in the previous case the crystal orientation was chosen in a such a way that main contribution to the CB cross section was produced by point (0, 2, -2) of the crystal reciprocal lattice due to special selection of two angles values, θ and α, where θ is the angle between electron momentum $\mathbf{P}_0$ in beam and crystal axis $\mathbf{b}_1$=<100>, α is the angle between planes ($\mathbf{P}_0$,$\mathbf{b}_1$) and ($\mathbf{b}_1$,$\mathbf{b}_2$), where $\mathbf{b}_2$=<010>. The electron beam energy spread was assumed to be ~0.1%, diameter of the electron beam spot on the target was 5 mm. Collimation angles are determined by the distance between the crystal and photon collimator (~2.14 m) and diameter of the collimator holes which vary from 4 to 19 mm.

Calculated spectra of the polarization, relative β and total intensity I_{sum}

$$\beta = (I_{coh} + I_{in}) / I_{in},$$
$$I_{sum} = I_{coh} + I_{in}, \tag{2}$$

where I_{coh} and I_{in} are intensities of the coherent and incoherent part of the radiation which are determined as

$$I_{coh,in} = \frac{E_\gamma}{\sigma_0} \frac{d\sigma_{coh,in}}{dE_\gamma}, \tag{3}$$

where $\sigma_0 = 0.5794 \cdot 10^{-27} Z^2 cm^2$ are shown in Fig. 1 for initial electron energies E_0=160, 200 and 250 MeV and the CB peak energies $E_{\gamma,d}$=40, 60, 80 MeV ($X_d = E_{\gamma,d}/E_0$=0.25, 0.3 and 0.32 that corresponds approximately to the middle of the effective energy range) and some collimation angles $\theta_c \sim 0.5\theta_\gamma$. Some preliminary results were presented in [14]. One can see that at these comparatively low electron energies the CB spectra have all features present at the higher electron energies, E_0~1 GeV: distinctive CB maximum with essentially high photon polarization (P_γ~0.6) and coherent effect value in the CB maximum β_{max}~2.5-3.

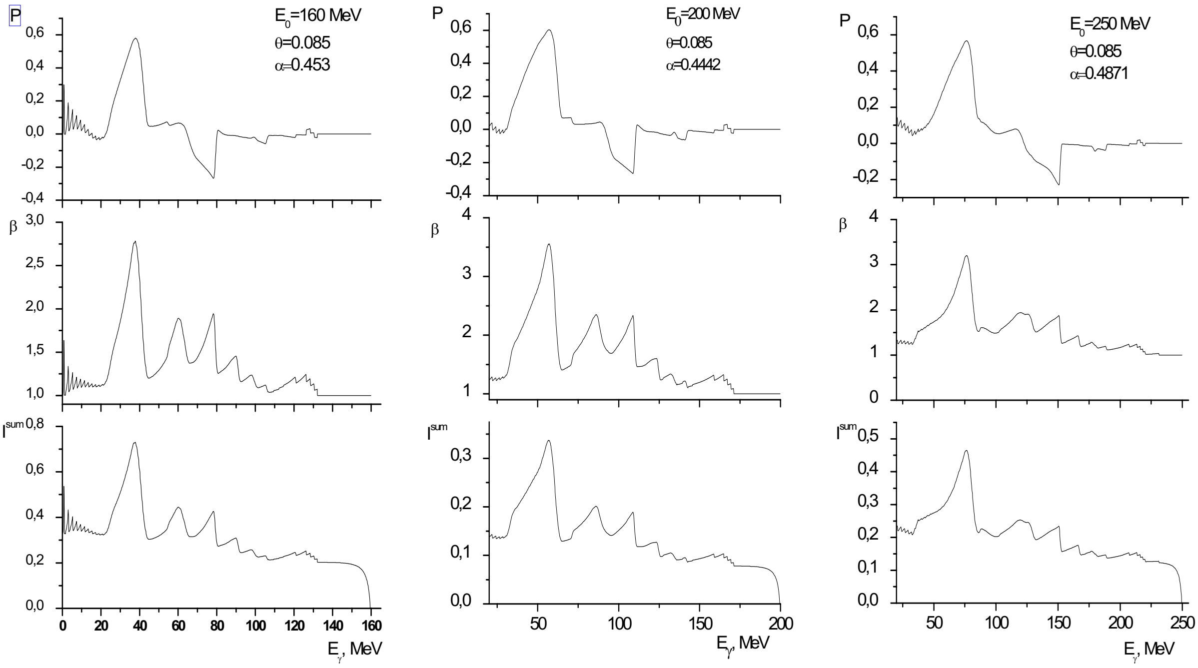

Fig. 1. Polarization, coherent effect and full intensity of the CB for E_0=160 MeV (collimation angle $\theta_c \sim 0.31\theta_\gamma$), 200 MeV (collimation angle $\theta_c \sim 0.36\theta_\gamma$) and 250 MeV (collimation angle $\theta_c \sim 0.45\theta_\gamma$).

Collimation dependence of the CB characteristics

To obtain CB beam with good operational parameters the important factor is the collimation of the γ-radiation. Its influence has been considered in detail in many papers, see, e.g. Refs. [8-14]. It is determined by the fact that for a fixed recoil momentum there is a kinematical relation between the photon emission angle and its energy. That is, with decreasing photon energy its emission angle is increased. If this angle is limited to θc by the collimator then also the lower energy of the photons, which pass the collimator, is limited. In the ideal case therefore the collimation, firstly, narrows the spectrum of the coherent part of the radiation without decreasing its intensity in a maximum, and secondly, reduces the intensity of the incoherent part, thereby increasing the coherent effect. Furthermore, collimation increases the polarization as well, because it depends on the coherent effect value.

However, in a real situation collimator limits not the angle of photon emission, but the angle between the photon and axis of the electron beam. So, firstly, if there is a divergence of the electron beam and multiple scattering then any deviation of the radiating electron relative to the beam axis “smears” the collimation angle and the boundaries of the spectrum. Secondly, the angular dispersion of the electrons in a beam results in a dispersion of the incidence angle of electrons relative to the crystal axes. It leads to a dispersion of the transferred momentums, which contribute to the CB cross section. After averaging over them some smoothing of the sharp maxima and reduction of their size as well as displacement and broadening occur.

As was shown in [13] in the case of initial electron energies of the MAX-lab scale (E_0<250 MeV) it will not be possible to get an essentially monochromatic CB spectrum due to collimation because of multiple scattering even for diamond crystal of thickness 0.1 mm. At the same time, the essential decrease of the CB incoherent part can be achieved. It will increase the values of the polarization and coherent effect, which are more important for experiments. The real magnitude of the incoherent part decrease depends on the collimation angle θ_c and the effective divergence of the electron beam.

Some examples of the calculated spectra and polarization for some collimation angles in the range θ_c/θ_γ~0.3…1 are presented in Fig.2 for initial electron energy E_0=160 MeV and CB peak energy X_d=0.25. As expected, with decreasing collimation angle, the CB spectrum becomes somewhat sharper due to cutting off the low energy part of the coherent peak. The coherent effect increases (from β_{max}~1.5 to ~2.5) with decreasing collimation angle (from θ_c~θ_γ to $0.3\theta_\gamma$). However, its magnitude is also significantly less than what follows under these conditions for an ideal spectrum. The polarization at the CB maximum under these conditions is rather high and varies from P_γ~0.25 at θ_c~θ_γ up to P_γ~0.6 at θ_c~$0.3\theta_\gamma$. As expected, the CB beam monochromatization even for strong collimation is not better than 0.2-0.25.

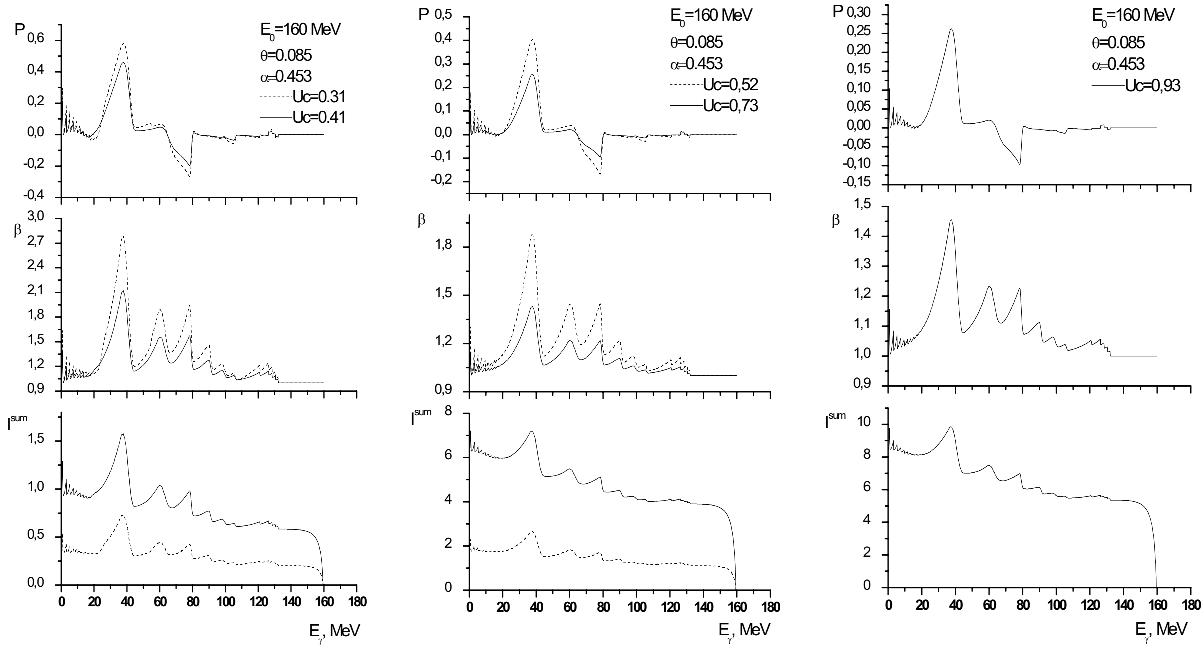

Fig. 2. Spectra of the coherent effect and polarization. E_0=160 MeV, X_d=0.25 for some collimation angles.

The dependence of the intensity and polarization in the CB maximum as a function of the collimation is shown in more details in Fig. 3 for electron energies E_0=160, 200 and 250 MeV and CB peak energies X_d=0.25, 0.3, 0.32. Calculations demonstrate fast decreasing of the polarization and coherent effect values from P~0.6 and β_{max}~3-3.5 up to P~0.25 and β_{max}~1.5 with the collimation angle increasing from θ_c~$0.4\theta_\gamma$ up to θ_c~θ_γ respectively. The CB beam can be successfully used in experiments if the polarization and coherent effect are not less than P_γ~0.3 and β~1.5, so the CB beam parameters for this electron and peak photon energies are also good enough for using in polarized experiments even at collimation θ_c~θ_γ. The essential improvement of the beam parameters begins at collimation angles $\theta_c \leq \theta_\gamma$ and collimation θ_c~$0.5\theta_\gamma$ is more suitable for obtaining the operative CB beam for photonuclear experiments.

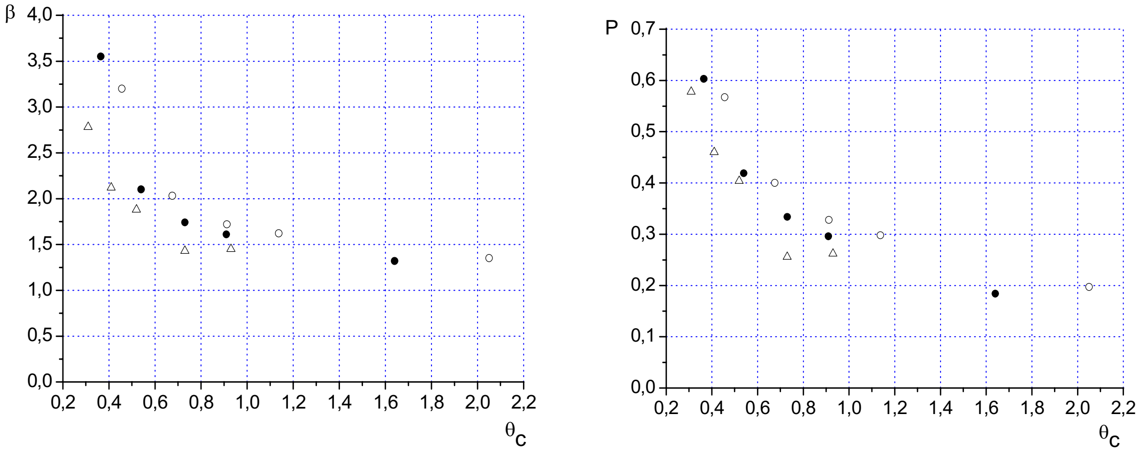

Fig. 3. Dependences of the coherent effect and polarization at the CB maximum from collimation of the γ radiation. Triangles- E_0=160 MeV, X_d=0.25; full circles - E_0=200 MeV, X_d=0.3; empty circles - E_0=250 MeV, X_d=0.32. Left panel: coherent effect, right panel: polarization.

Expected effective energy range

Both the coherent effect and polarization of the CB beam decrease when the coherent peak is shifted towards larger energies. The expected energy dependence of these parameters is plotted in Fig. 4 for initial electron energies E_0=160, 200 and 250 MeV and some collimation angles. Calculations show that at small energies of the peak, about $E_{\gamma,d}$~20-30 MeV, these parameters can achieve high values ($\beta_{max} \approx 3$-3.5 and $P_\gamma \approx 0.6$-0.7) even at an electron energy E_0~150 MeV but under condition of strong collimation gamma radiation, θ_c~$0.3\theta_\gamma$. When the collimation angle increases up to θ_c~θ_γ, their magnitude drops down to $\beta_{max} \approx 2$ and $P_\gamma \approx 0.4$ even for low energies.

Using collimation θ_c~$0.5\theta_\gamma$ one can obtain suitable CB beam parameters for photonuclear experiments, $P_\gamma \geq 0.3$ and $\beta_{max} \geq 1.5$, even for electron with energy E_0=200 MeV for energy interval E_γ<80 MeV, but for experiments higher energy range (E_γ>80 MeV) the maximal electron energy E_0=250 MeV is needed. So, increasing the initial energy of the electron beam up to E_0=250 MeV allows one to considerably improve the parameters of the CB beam and to expand the effective energy range practically up to pion photoproduction threshold.

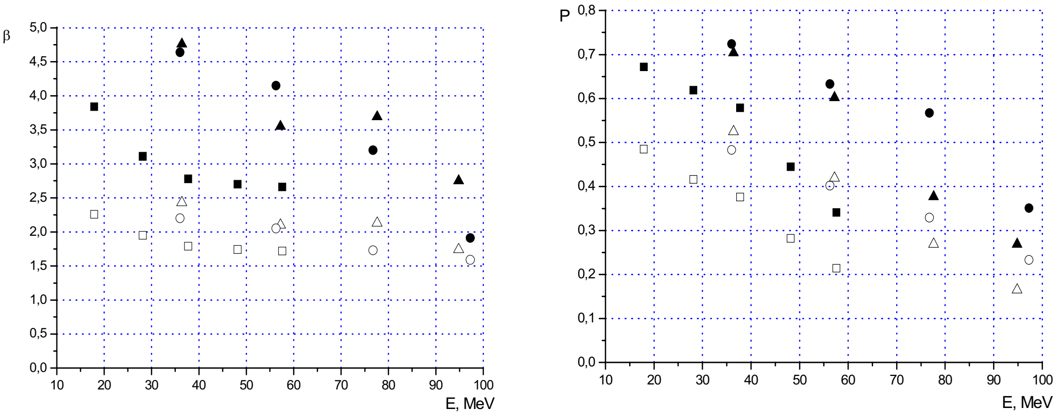

Fig. 4. Dependences of the coherent effect and polarization at the CB maximum from peak's energy. Initial electron energies are: E_0=160 MeV (full squares - collimation angle $\theta_c=0.31\theta_\gamma$, empty - $\theta_c=0.63\theta_\gamma$.); E_0=200 MeV (full triangles - $\theta_c=0.36\theta_\gamma$, empty - $\theta_c=0.54\theta_\gamma$); E_0=250 MeV (full circles - collimation angle $\theta_c=0.46\theta_\gamma$, empty - $\theta_c=0.91\theta_\gamma$.). Left panel: coherent effect, right panel: polarization.

As was shown in Ref.[13] using the more thick crystal at the collimation angle θ_c~$0.5\theta_\gamma$ practically does not reduce the characteristics of the beam. It is therefore possible to partially compensate some of the loss in intensity due to strong collimation by increasing the target thickness.

CONCLUSION

In summary, the calculations show that for electron energies $E_0 \leq 250$ MeV the spectrum and polarization of the CB still have properties, which are usually observed at the higher electron energies, about $E_0 \geq 1$ GeV. The coherent effect and the polarization in the CB maximum can reach rather large magnitudes and essentially depend on the collimation of the γ radiation. To obtain a CB beam which could be used in experimental research on accelerators with initial energy $E_0 \sim 150\text{-}250$ MeV, it is necessary to have a rather strong collimation of the γ radiation, $\theta_c \approx 0.3\text{-}0.5\theta_\gamma$. In order to compensate the intensity decrease due to strong collimation, one can in some cases increase the thickness of the crystal.

The calculations demonstrate that acceptable energy ranges for nuclear physics investigation with linearly polarized photons at electron energy $E_0 \sim 250$ MeV will cover the range up to 10-120 MeV and could be increased up to pion photoproduction threshold if strong collimation ($\theta_c \approx 0.3\theta_\gamma$) will be applied. The CB beam for electrons with $E_0 \sim 160$ MeV could provide the investigations in the giant dipole resonance region.

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ЛИНЕЙНЫЙ ПОЛЯРИЗОВАННЫЙ ФОТОННЫЙ ПУЧОК ДЛЯ ФОТОЯДЕРНЫХ ИССЛЕДОВАНИЙ ПРИ НИЗКИХ ЭНЕРГИЯХ

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Рассчитаны спектры интенсивности и поляризации когерентного тормозного излучения (КТИ) для начальной энергии электронного пучка 160-250 МэВ. Пучки электронов с такой энергией используются в лаборатории MAX-lab (г. Лунд, Швеция). Также пучки данного диапазона энергий планируется получать на создаваемой в ННЦ ХФТИ установке (проект NESTOR). Расчеты выполнены в теории КТИ с использованием борновского приближения и учетом экспериментальных факторов, таких как размеры, дивергенция и энергетическое разрешение пучка, размеры и форма коллиматора, толщина кристалла (учет многократного рассеяния). Показано, при использовании коллимации порядка $\theta_c \approx 0.5\theta_\gamma$ ($\theta_\gamma = mc^2/E_0$, m – масса электрона), возможно получение пучков КТИ с поляризацией от 30% до 60% в диапазоне энергий до 100 МэВ, что открывает возможность проведения ядерно–физических экспериментов с поляризованными пучками в данном диапазоне энергий.

КЛЮЧЕВЫЕ СЛОВА: когерентное тормозное излучение, поляризованные пучки фотонов, кристалл алмаза, ускорители электронов, ядерно-физические исследования.