Study of the spectra of parametric (quasi-Čerenkov) radiation by ultrarelativistic electrons in a diamond crystal

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The internal electron beam of the Tomsk synchrotron with energy $E = 900$ MeV has been used to search for and study the spectra of a new type of monochromatic x radiation in crystals. The measured photon spectra agree well with the theory, which permits us to conclude that the observed parametric (quasi-Čerenkov) radiation of relativistic electrons in crystals can be used as a source of monochromatic x rays up to energies about 10^2 keV.

1. INTRODUCTION

It is well known that the condition for Čerenkov radiation to occur is that the velocity $v = \beta c$ of a uniformly moving charge in a medium exceed the phase velocity of light in the medium, i.e., $\beta[\varepsilon(\omega)]^{1/2} > 1$.[1] For most materials this condition is satisfied only in the optical frequency region, and here radiation is emitted at large angles

$$\theta = \arccos\,[\beta\varepsilon^{1/2}(\omega)]^{-1} \gg \gamma^{-1},$$

where $\gamma = E/mc^2$ is the Lorentz factor. When a charge moves in a periodically varying medium a type radiation is observed which in many respects is similar to Čerenkov radiation. In particular, Faĭnberg and Khizhnyak[2] discussed a one-dimensional periodic medium consisting of layers of thicknesses a and b and permittivities ε_1 and ε_2. They showed that, in contrast to a uniform medium, photons are emitted even when $\beta[\varepsilon_i(\omega)]^{1/2} < 1$ for a layer taken individually. In addition radiation appears simultaneously at several angles.

The radiation emitted by an ultrarelativistic charged particle moving through a crystal, which is a three-dimensional periodic medium, has been discussed in many studies.[3–7] It has been shown that in the Bragg directions relative to the direction of the charged-particle beam quasimonochromatic x rays should be emitted whose frequency is determined by the type and orientation of the crystal relative to the velocity of the charge,

$$\omega_B = \pi cn/d \sin\theta, \qquad (1)$$

where $n = 1, 2, \ldots$ is the order of diffraction, d is the interplanar distance, and θ is the angle between the electron momentum and the crystallographic plane. In addition to these so-called "side spots of quasi-Čerenkov radiation" (the terminology of Ref. 3) which are propagated at large angles $\theta \gg \gamma^{-1}$, there is also a "central radiation spot" consisting of transition x rays arising at the crystal boundaries. In the case of a thick crystal, both in the side spots and in the central spot, narrow maxima appear in the radiation spectrum: $\Delta\omega/\omega \approx \gamma^{-1}$. The angular width of these maxima is determined mainly by the electron energy: $\Delta\theta/\theta \approx \gamma^{-1}$. In Ref. 3 the maxima in the spectra are called "dynamical," in Ref. 4 they are called "parametric Čerenkov radiation," and in Ref. 8 they are called "quasi-Čerenkov" radiation. If the crystal thickness satisfies the following inequality:

$$L(\omega/c)\,|\mathrm{Im}\, g_{00}| \gg 1, \qquad (2)$$

then the crystal is called thick. Here L is the crystal thickness and g_{00} is the Fourier component of the dielectric permittivity tensor of the crystal. In the x-ray frequency region the inequality (2) is satisfied for $L > 10^{-4}$ cm. In a thin crystal for which

$$L(\omega/c)\,|g_{00}| \ll 1, \qquad (3)$$

monochromatic radiation in the x-ray region (resonance radiation) was first dicussed by Ter-Mikaelyan.[7] The physical nature of parametric (quasi-Čerenkov) radiation is related to diffraction of the electromagnetic self-field of the charge particle at the atomic planes of the crystal. In contrast to Čerenkov radiation in a uniform medium, parametric (quasi-Čerenkov) radiation in a crystal has a number of distinctive properties: according to Ref. 4 there is no energy threshold for the radiation; when the particle energy E is less than $E_{\mathrm{eff}} = mc^2/|g_{00}|^{1/2}$, the intensity of the radiation drops rapidly, as $(E/E_{\mathrm{eff}})^4$; radiation with frequency ω_B is emitted simultaneously at all Bragg angles θ_B satisfying the condition (1). These types of radiation have in common that they result from uniform motion of a charge through a medium, that the radiation is emitted at large angles, and that the medium radiates under the influence of the electromagnetic field of a traveling charged particle.

Recently an experimental study has appeared[9] in which an attempt was made to observe the dynamical maxima of quasi-Čerenkov radiation in the central spot, i.e., at an angle $\theta \lesssim \gamma^{-1}$ to the electron beam axis. The electron energy was varied from 2.7 to 11 GeV. Polycrystalline LiF and mica of various thicknesses were used as targets. The background spectrum was measured by replacing the polycrystalline targets with polystyrene. As a result of the experiment it was found that for these electron energies the background spectrum and the spectrum from the polycrystalline samples coincided, i.e., dynamical maxima were not observed. The negative result of this experiment apparently can be explained as follows. According to theoretical estimates,[8] the photon yield in the dynamical maximum of the central spot reaches values of 10^{-4}–10^{-3} photons per electron, while the yield of x-ray transition radiation is about 10^{-2}. The resolution of

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the detectors used was low ($\Delta\omega/\omega \sim 10^{-1}$) and the spectral width of the dynamical maxima is $\Delta\omega/\omega \sim 10^{-3}$; consequently identification of these maxima in the background of intense transition x rays is very difficult. Therefore in spite of the fact that in a narrow region of spectrum and angle $\Delta\omega/\omega = \Delta\theta/\theta \approx 10^{-2}$–$10^{-3}$ the intensity of the dynamical maximum exceeds the intensity of the x-ray transition radiation by a factor of $|g_{00}/\mathrm{Im}\, g_{00}|$,[10] its contribution to the total radiation intensity is very small.

As for the maxima in the side spot of quasi-Čerenkov radiation, they have been observed recently in Refs. 11 and 12. For the purpose of observing them the detector energy resolution can be several tens of percent, since at large angles $\theta \gg \gamma^{-1}$ the contribution of background radiation with a continuous spectrum is considerably smaller than at an angle $\theta \sim \gamma^{-1}$. In addition in Ref. 13 it was shown experimentally that when 900-MeV electrons are channeled axially along the $\langle 110 \rangle$ axis of diamond (precisely this geometry was used in Refs. 11 and 12) there is a further suppression of the yield of background x rays at large angles.

In the present work we report detailed results of spectral studies of x rays at an angle $\theta = 2\theta_B = 90°$ to the electron beam in diffraction of the electromagnetic self-field of electrons in the (110) and (100) planes of diamond. Preliminary results have been published in Refs. 11 and 12.

2. METHOD OF MEASUREMENT

The measurements were made in the internal beam of the Tomsk synchrotron. A diagram of the experimental apparatus is shown in Fig. 1. The targets consisted of thick [according to the condition (2)] single crystals 1 of natural diamond with dimensions $10\times6\times0.35$ mm and $10\times6\times2$ mm cut from a single block (the $\langle 110 \rangle$ axis of the crystal was perpendicular to the large face). An electron beam with energy 900 MeV having an angular divergence about 10^{-4} rad and a monochromaticity 0.5% was directed onto a diamond crystal mounted in a two-axis goniometer. The angle step of the goniometer was $\Delta\psi_v = 3.6\cdot10^{-5}$ rad for rotation around the vertical axis and $\Delta\psi_h = 2\cdot10^{-5}$ rad for rotation around the horizontal axis. The crystal was mounted in the goniometer in such a way that the $\langle 001 \rangle$ axis and the vertical axis of the goniometer coincided with accuracy 1.5° or better. Spilling of electrons onto the target was accomplished by a slow ($\tau_{\text{spill}} = 15$ msec) decrease of the intensity of the accelerating high-frequency field, as a result of which the electron beam moved along a curved spiral and hit the edge of the diamond crystal, which was mounted at a radius $R = 416.5$ cm (the equilibrium orbit radius was $R_0 = 423$ cm). The uniformity of the beam spill was monitored on the basis of the shape of a synchrotron radiation probe signal (4 in Fig. 1). The characteristic dimensions of the electron beam at the target were determined Ref. 14 from the distribution of the density of blackening of the diamond crystal after 10^{16} electrons had passed through it. As a result we obtained the following characteristic horizontal and vertical dimensions of the electron beam at the target: $h_h = 0.8$ mm, $h_v = 0.65$ mm.

The x-ray spectrometer was a proportional counter 3 with xenon filling (Fig. 1). The entrance window of the detector was made of beryllium foil 300 μm thick and 50 mm in diameter. The energy resolution of the spectrometer for the Zn^{65} line ($E_\gamma = 8.2$ keV) was 14%. The threshold of the proportional counter corresponded to an energy $\omega_{\text{thr}} = 3$ keV. The spectrometer was placed in lead shielding of thickness $l = 20$ cm at a distance $L = 200$ cm from the target. Here the angular aperture of the detector was about 25 mrad. The x-ray photons passed through an exit window of Plexiglas which sealed the accelerator vacuum chamber and simultaneously served to cut off the charged component of the radiation. The thickness of the window was 0.6 cm. The photon spectra were measured in an AI-1024-90A analyzer which was opened during the electron spill onto the target. A block diagram of the electronics is shown in Fig. 1.

Since the angular divergence of the radiation investigated is of the order γ^{-1} (0.6 mrad in our case), orientation of the crystal, i.e., adjustment of the reflection from some crystallographic plane to coincide with the axis of the detector, is a very complicated problem. To solve it we used the following effect. For electrons moving along the $\langle 110 \rangle$ axis, the (100) planes are located at angles 45° to the electron momentum, and consequently at angles $\theta = 90°$ monochromatic x rays should appear (see Fig. 2a). In this geometry the procedure of alignment of the crystallographic axis with the direction of the electron momentum was based on use of the radiation effect in channeling (see for example Ref. 15). The criterion of coincidence of the electron beam with the $\langle 110 \rangle$ crystal axis was a rapid rise of the γ-ray yield in the directly forward direction in the soft part of the spectrum ($\omega \leqslant 0.01E$).[16] The intensity of the soft γ radiation was measured with a NaI(Tl) spectrometer set for Compton kinema-

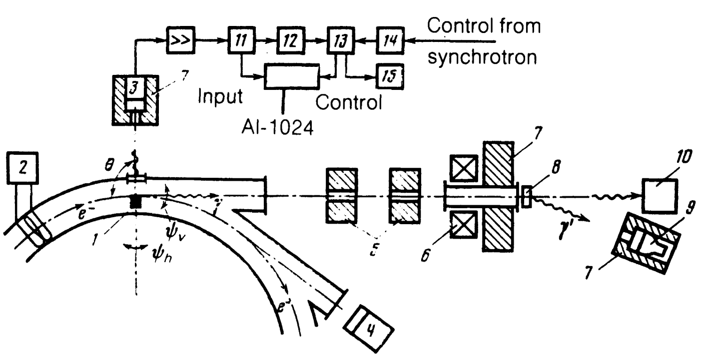

FIG. 1. Diagram of experimental apparatus: 1—single crystal, 2—inductive probe, 3—x-ray spectrometer, 4—synchrotron radiation probe, 5—collimators, 6—clearing magnet, 7—lead shielding, 8—scatterer, 9—Compton spectrometer, 10—Gauss quantameter, 11—splitter, 12 and 14—shapers, 13—gate, 15—scalar.

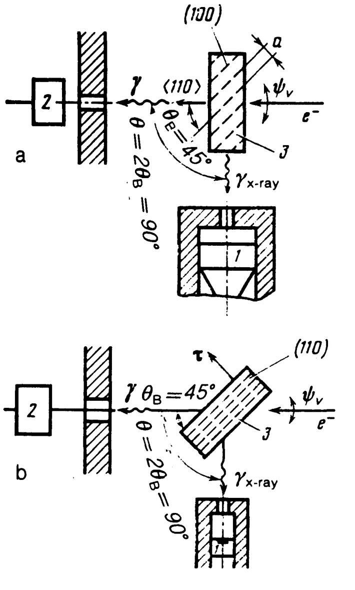

FIG. 2. (a)—Diagram of arrangement of single crystal and detecting apparatus for measurement of diffraction in (100) planes of diamond: 1—x-ray spectrometer, 2—apparatus for orientation of single crystal, 3—diamond crystal of thickness 0.35 mm. (b)—The same for measurement of diffraction in the (110) planes of diamond.

tics (see 8 and 9 in Fig. 1). For a more precise yield value on the axis we used the dependence of the total energy of the γ beam on the crystal disorientation angle, i.e., we measured the orientation dependence of the quantameter current (10 in Fig. 1) with a small collimation of the γ beam, normalized to the accelerated electron current. The accelerated electron current was recorded either by means of an induction probe 2 (Fig. 1) with an error 5% or with a synchrotron radiation probe with relative measurement error 10%.

The spectral measurements were made in a geometry in which the x-ray detector was set at an angle 90° to the incident electron beam direction. Adjustment of the detector position was done as follows: the beam of an LG-78 laser placed on the axis of the bremsstrahlung beam (which coincides with the direction of the electron beam) was directed through a system of collimators onto a diamond crystal mounted in the goniometer. By rotation around two mutually perpendicular axis (ψ_h and ψ_v) the reflected beam of the laser was brought into coincidence with the incident beam to within an accuracy ± 3 mrad. After this the crystal was rotated with the goniometer about the vertical axis by an angle $\pi/4 \pm 0.1$ mrad. The detector shielding was arranged so that the laser beam reflected from the crystal passed through the center of the collimator. Then the crystal was returned to its initial position.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In Fig. 3 we have shown the radiation spectrum measured in the Bragg geometry (Fig. 2a) for electrons with energy $E = 900$ MeV after subtraction of the background in an exposure of $6.4\cdot 10^{11}$ electrons. The number $N_e \approx 10^8$ of electrons in a pulse was chosen so that the x-ray detector loading was less than 10^4 counts per second. We can see

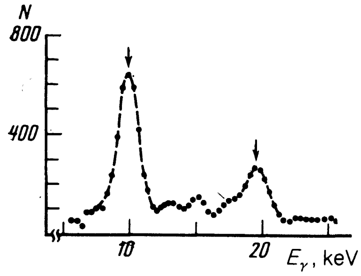

FIG. 3. The x-ray spectrum for angle $\theta = 90°$. The electron energy is $E = 900$ MeV, and the thickness of the diamond is $t = 0.35$ mm. Diffraction at (100) planes. The upper arrow coresponds to a value $E_\gamma = 9.9 \pm 0.15$ keV, and the lower corresponds to 19.7 ± 0.23 keV.

distinctly two maxima with photon energies $\omega_1 = 9.9 \pm 0.15$ keV and $\omega_2 = 19.7 \pm 0.2$ keV which coincide with the theoretically calculated values for the selected geometry. The width of the maxima coincides with the spectrometer energy resolution. Consequently the x rays with energy $\omega_1 = 9.9$ keV are significantly more monochromatic than the value $\Delta\omega_1$, which is 1.5 keV.

Figure 2b shows schematically the geometry of the experiment in which we measured the radiation spectrum in diffraction of the electron self field at (110) crystallographic planes. The required orientation of the crystal was achieved by adjusting the $\langle 100\rangle$ axis to coincide with the electron beam direction. In this case one should observe in the spectrum maxima with photon energies

$$\omega_n = 6.9;\ 13.8;\ 20.9;\ \ldots\ \text{keV}. \qquad (4)$$

To observe the (220) reflection with energy $\omega_1 = 6.9$ keV the Plexiglas exit window through which the x ray beam was extracted was replaced by a Mylar film of thickness 50 μm. In Fig. 4 we have shown the measured photon spectra: 1—the spectrum without background subtraction for an exposure of $2.84\cdot 10^{12}$ electrons, and 2—the background spectrum measured with disorientation of the target by 25 mrad about the vertical axis ψ_v.

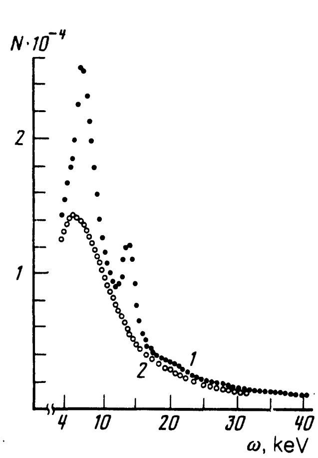

FIG. 4. X-ray spectra measured in the geometry shown in Fig. 2b: 1—spectrum without subtraction of background for an exposure $2.84\cdot 10^{12}$ electrons; 2—background spectrum. The thickness of the diamond is $t = 0.35$ mm.

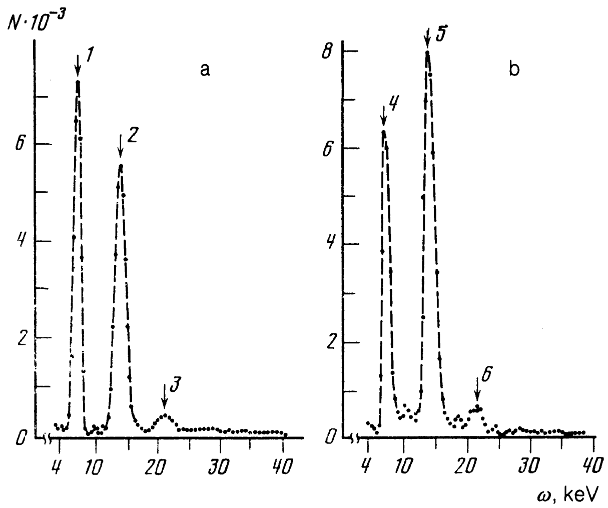

FIG. 5. The x-ray spectrum with subtraction of background in diffraction by the (110) plane of a diamond crystal 0.35 mm thick (a) and 2 mm thick (b). The numbers in the curves correspond to the following values of ω_γ: 1—6.85 ± 0.15 keV, 2—13.8 ± 0.15 keV, 3—21.0 ± 0.20 keV, 4—7.0 ± 4.1 keV, 5—13.9 ± 0.1 keV, 6—21.0 ± 0.15 keV.

In Ref. 13 it was shown that the yield of x-ray photons at large angles depends on the orientation of the target with respect to the electron beam. Therefore the measurement of the background spectrum during the same electron run is not completely correct. Subtraction of the background was carried out by fitting the background spectrum (disoriented diamond) to the effect + background spectrum (oriented diamond) by means of a normalization constant. In Fig. 5a we have shown the spectrum obtained after subtraction from the spectrum 1 shown in Fig. 4 of the corrected background spectrum. The spectrum was smoothed with a quadratic polynomial by the standard technique.[17] As can be seen from Fig. 5a, the location of the observed maxima in the spectrum is in good agreement with the theoretical predictions (4).

The subsequent measurements were made in diamond of thickness $t = 2$ mm. The experimental geometry was identical to that shown in Fig. 2b. The measured spectrum with subtraction of the background is given in Fig. 5b. The exposure in number of electrons was about $2.84\cdot10^{12}$. In contrast to the photon spectrum in 0.35-mm diamond (Fig. 5a), in the present case we obtained an unexpected result: the first peak with $\omega_1 = 7.0\pm0.1$ keV, which corresponds to the reflection from the (220) plane, is smaller than the second peak with $\omega_2 = 13.9\pm0.1$ keV [the reflection from the (440) plane].

The photon yield per electron at the second maximum did not change within experimental error in comparison with diamond of thickness 0.35 mm, although according to theoretical estimates the yield should increase in proportion to the crystal thickness, other conditions being equal. A possible explanation of this result is as follows. In Fig. 6 we have shown the arrangement of the targets (1—diamond of thickness 0.35 mm, 2—of thickness $t = 2$ mm) and the cross section of the electron beam. It is evident that the effective range of the photons in the 2-mm diamond in the direction of detection is greater than in the diamond with $t = 0.35$ mm, and consequently more photons with energy $\omega_1 = 6.9$ keV should be absorbed in the diamond with $t = 2$ mm.

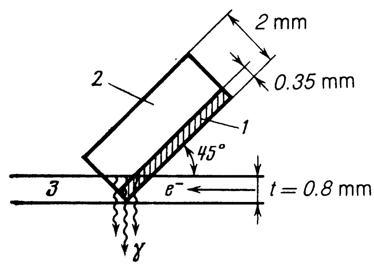

FIG. 6. Relative location of targets with respect to the electron beam: 1—diamond crystal of thickness 0.35 mm, 2—diamond crystal of thickness 2 mm, 3—electron beam.

An estimate of the yield of x rays from a crystal of thickness 0.35 mm carrried out with inclusion of absorption in air, in the exit windows, and in the detector entrance window gives the results listed in Table I.

Generally speaking, if in addition we take into account the absorption of radiation in the crystal material, the observed photon yield should increase. The number of photons was determined according to the following formula:

$$N_\gamma^n = S_n \exp\left(\sum_i \mu_i l_i\right) [N_e \eta_n(\omega)]^{-1}, \quad (5)$$

where S_n is the area under the nth peak in the spectrum, μ_i is the linear absorption coefficient, l_i is the length of the absorber (Mylar, air, Be), N_e is the number of electrons for a given run, and $\eta_n(\omega)$ is the efficiency of the detector for a photon with frequency ω_n. We note that the aperture of the detector is $\Delta\theta = 25$ mrad $\gg\gamma^{-1}$, where γ^{-1} is the charcteristic cone angle of quasi-Čerenkov radiation. Therefore in Eq. (5) the collimation of the radiation is not taken into account, since it is assumed that all photons emitted in a given peak are detected. Values of μ_i were taken from Ref. 18. The error in estimation of the photon yield is determined by the errors in the values of the absorption coefficients, the area of the peak, and the exposure in number of electrons. The main contribution is from the error in measurement of the number of electrons.

TABLE I.

Reflection	Energy, keV		Photon yield N_γ/N_e
	Experiment	Theory	
(220)	6.8±0.1	6.96	$(1.0\pm0.4)10^{-6}$
(440)	13.8±0.1	13.9	$(5.4\pm1.0)10^{-8}$
(660)	21.0±0.2	20.9	$(8.5\pm2.0)10^{-9}$
(400)	9.9±0.1	9.85	$(3.4\pm1.0)10^{-7}$
(800)	19.7±0.2	19.7	$(1.0\pm0.3)10^{-8}$

In the experiment the number of accelerated electrons was measured with absolute calibration of the synchrotron radiation probe readings by means of a quantameter measurement of the total cone $\theta_c = \gamma^{-1}$. The error was about 20%. From the results given in the table we can conclude that the spectral density of radiation of photons with energy corresponding to the maximum ω_n exceeds the corresponding value for radiation in channeling, transition radiation, or bremsstrahlung, in agreement with the estimates of Refs. 19 and 20. In these studies a theoretical comparison of the characeristics of the different types of radiation was carried out in the x-ray region.

4. CONCLUSIONS

Our measurements of the x-ray spectra are in good agreement with the theoretical values, which permits us to conclude that a new phenomenon of parametric (quasi-Čerenkov) radiation of relativistic electrons passing through single crystals has been observed in the x-ray region. The new type of monochromatic x radiation is distinguished by monodirectionality, a narrow energy line, and the possibility of smooth variation of the photon energy.[10] With a high spectral and angular density this type of radiation apparently may present interest for x-ray fluorescence analysis, the Compton-profile method in study of the electron structure of solids, and other techniques where an intense monodirectional beam of monochromatic photons is necessary.

Another attractive feature of quasi-Čerenkov (parametric) radiation is the possibility of obtaining it in contemporary relativistic proton accelerators such as that at the Institute of High Energy Physics at Protvino, where by this method a practically background-free source of monochromatic x rays can be produced, since the bremsstrahlung mechanisms of the electromagnetic radiation for protons are suppressed. Especially promising here are the accelerators being built at the present time for relativistic beams of heavy nuclei (for example, at the High Energy Laboratory at the Joint Institute for Nuclear Research[21]). The increase in the intensity of parametric radiation when relativistic electrons are replaced by relativistic nuclei occurs as a result of the fact that the nuclear charge increases by a factor of Z the Coulomb self-field of the nucleus scattered by the crystal in comparison with the charge of electrons. Accordingly the intensity of the radiation of nuclei is Z^2 times higher, other conditions being equal. Already with a nuclear charge $Z_A = 2$ and a Lorentz factor $\gamma_A = 5$ (the parameters of the synchrotron at the High Energy Laboratory of the Joint Institute for Nuclear Research[22]) the same intensity of monochromatic x rays is obtained per accelerated nucleus as in the recent experiment with $\gamma_e \approx 10^3$, i.e., their ratio is $R \approx 1$. Furthermore, for heavier nuclei such as Fe^{56} (a beam of such nuclei has been produced in Berkeley[22]) the photon yield will be more than two orders of magnitude higher than the photon yield per accelerated electron.

For construction of practical sources of parametric radiation it is possible to use numerous methods and devices of x-ray optics based on curved crystals. For example, by using curved plates of single crystals appropriately arranged in a charged-particle beam, it is possible to achieve focusing of parametric radiation to spot sizes limited by the natural photon-beam divergence γ^{-1}. By placing several crystal radiators in a broad beam of charged particles it is possible to obtain several x-ray beams separated in space.

At the present time it is obviously essential to carry out detailed studies of the spectral and angular characteristics of parametric (quasi-Čerenkov) radiation with different types of crystals in order to check the theory of this radiation and optimize its characteristics (including the possibility of realization of the Borrmann effect).

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