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EMISSION FROM CRYSTALS IRRADIATED WITH A BEAM OF RUNAWAY ELECTRONS

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An investigation of the spectral and amplitude-temporal characteristics of emission from different crystals, promising in terms of their application as detectors of runaway electrons, is performed. This emission is excited by subnanosecond electron beams generated in a gas diode. It is found out that at the electron energies of tens–hundreds of kiloelectronvolts, the main contribution into the emission from CsI*,* ZnS*, type IIa artificial and natural diamonds, sapphire,* CaF_2*,* ZrO_2*,* Ga_2O_3*,* $CaCO_3$*,* CdS*, and* ZnSe *crystals comes from the cathodoluminescence; the radiation pulse duration depends on the crystal used and sufficiently exceeds the Cherenkov radiation pulse duration. It is demonstrated that the latter radiation exhibits low intensity and can be detected in the short-wave region of the spectrum in the cases where a monochromator and a high-sensitivity photomultiplier tube (PMT) are used.*

Keywords: cathodoluminescence, Cherenkov radiation, beam of runaway electrons.

INTRODUCTION

Recently there has been an increased interest in designing energy detectors for registering high-energy runaway electrons, which rely on the Cherenkov radiation (CR) [1–3]. The CR is generated in the cases where the electrically charged particles (e.g., electrons) move at a velocity exceeding the phase velocity of light in this matter (i.e., velocity of optical wave propagation). The CR is universal radiation in the sense that under the action of particles possessing sufficient energies all transparent bodies in liquid, gaseous, and solid states glow. The Cherenkov-type detectors of fast electrons are primarily designed for registration of runaway electrons in tokamak facilities [2], which suffer from the influence of runaway electrons on plasma heating. A special feature of CR is its zero lag. Hence the shape of a CR signal would repeat that of the electron beam current. On the other hand, the electron energy has to be higher than the threshold energy, depending on the refractive index of the material. In [4–6] it was shown that when polymethylmethacrylate (plexiglass, PMMA) is excited by a beam of runaway electrons, it is the cathodoluminescence which makes the main contribution into radiation.

The purpose of this work is to investigate the spectral and amplitude-temporal characteristics of emission from a number of crystals and to determine which of them show promise in terms of their applications as detectors of runaway electrons.

CHARACTERISTICS OF CHERENKOV RADIATION

It is well known [7] that for the CR to be generated the electron energy has to exceed the value of the threshold energy E, which depends on the refractive index of a crystal. Figure 1*a* presents the plots of dependence of the electron

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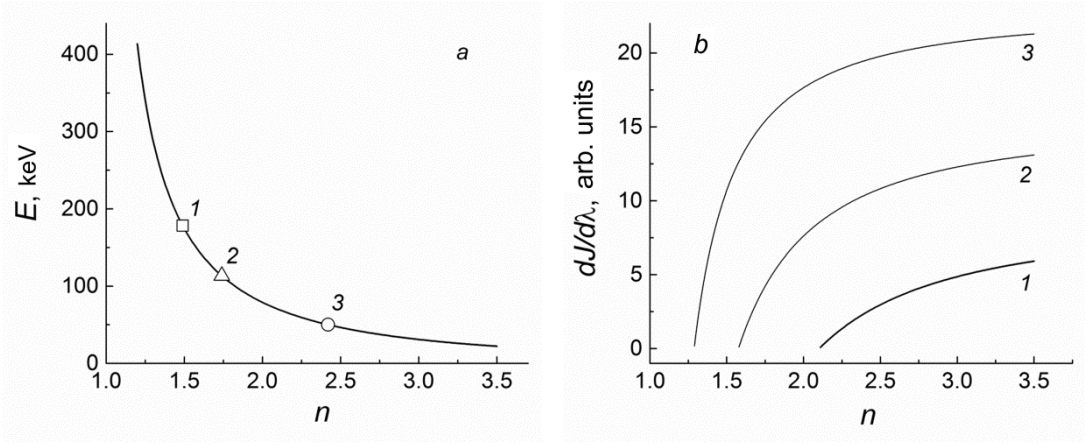

Fig. 1. Dependence of the threshold electron energy for the CR generation (*a*) and the CR spectral energy density for the electron energies 70 (curve *1*), 150 (curve *2*) and 300 keV (curve *3*) (*b*) on the refractive index. Emission of the CR from the PMMA (curve *1*), CsI (curve *2*), and diamond (curve *3*) crystals (*a*).

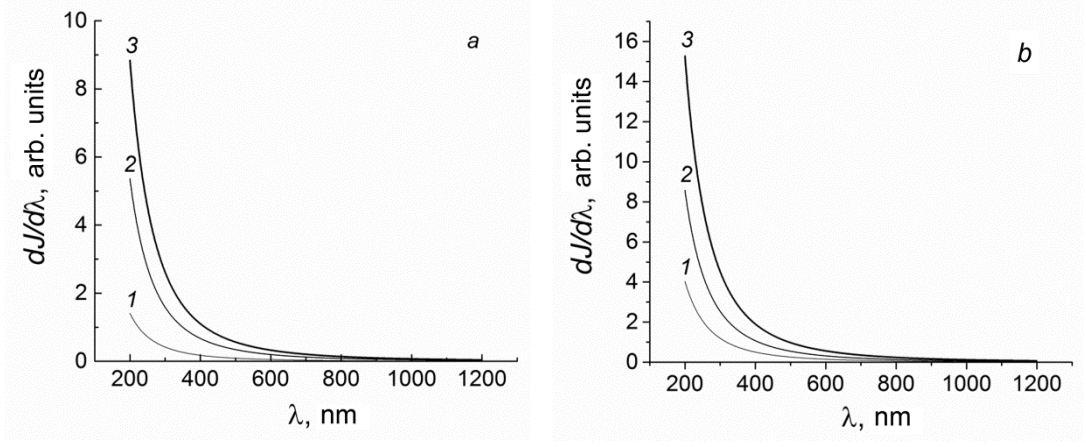

Fig. 2. Dependence of the CR spectral energy density on the wavelength in PMMA (curve *1*), CsI (curve *2*), and diamond (curve *3*) for the electron energies 200 keV (*a*), and in CsI for the electron energies 150 (curve *1*), 200 (curve *2*), and 300 (curve *3*) keV (*b*).

threshold energy on the refractive index, obtained via a formula reported in [8] and used in [5, 6]. In order to produce the CR radiation at the electron energy ~50 keV, one needs the crystals with the refractive indices ≥2.42. Figure 1*b* plots the spectral densities of the CR energy versus the refractive indices for different electron energies of monoenergetic beams. An increase in the refractive index allows not only decreasing the electron threshold energy for the CR to be generated but also, given the same electron energies, makes it possible to multiply increase its spectral density.

In order to get an insight into the origin of the detected radiation, it is critical to bear in mind that the CR spectral energy density considerably increases with a decrease in the wavelength and when the electron energy is increased in the wavelength range up to 200 nm for most crystals. This offers a possibility of differentiating the CR in the UV region from the cathodoluminescence background. Thus to design the CR detectors we have to use the crystals transparent in the UV spectral region. Figure 2 presents the plots of dependence of the CR spectral density in diamond, CsI crystals, and, for comparison, PMMA on the wavelength and the electron energy. It is evident that the CR spectral

density increases with a decrease in the wavelength. Similar dependences for polymethylmethacrylate specimens are reported in [5, 6] for the electron energies 200, 250, and 300 keV.

It should be noted that in designing the high-energy detectors it is preferable to use the crystals characterized not only by large refractive indices but also by high heat conductivity and thermal stability.

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

The crystals were excited by a supershort avalanche electron beam (SAEB) [9, 10] formed in a gas-filled diode, to which voltage pulses were supplied from a RADAN-220 generator. Operating on a high-resistance load (>1 kΩ), RADAN-220 formed voltage pulses with the amplitude up to 250 kV. Two modes of SAEB generation were used, which were determined by the pressure and gas type in the diode. Mode 1 allowed achieving a SAEB current density of $j \approx 75$ A/cm^2 at FWHM $\tau \approx 180$ ps and pulse repetition frequency $f = 1$ Hz. Mode 2 used the following SAEB parameters: $j \approx 1.1$ A/cm^2, $\tau \approx 100$ ps, $f = 1$ Hz. In both regimes, more than 95% electrons in the beam had the energy higher than 50 keV and the electron energy distribution had two peaks at the energies ≈80 and 150 keV. Note that a small portion of electrons, <1% of those registered behind the foil, had the energy higher than 200 keV [11].

The emission and transmission spectra of the crystals under study were measured with an OceanOptics HR2000+ES spectrometer (spectral range 190–1100 nm, resolution ~0.9 nm) with a rated sensitivity. The amplitude-temporal characteristics of the integral emission within the range 200–700 nm were investigated with a subnanosecond time resolution using a Photek PD025 photodiode (LNS20 cathode, rise time of the transient response ~80 ps). The short-wavelength limit of the detected emission was determined by the absorption of the crystal in question, and the long-wavelength limit (~700 nm) – by the decreased photodiode sensitivity. In these experiments, in contrast to those reported in [12], we did not use any light guides to transfer the emission from the specimen to the diode, which allowed registering it in short-wave region of the spectrum (down to 200 nm). The signal from the PD025 photodide and the electron collector were registered with an Agilent DSO-X6004A oscilloscope (6 GHz, 20 S/ns) and the PMT signals – with a Tektronix TDS3054B oscilloscope (0.5 GHz, 5 S/ns). The schematic designs of the experiments on measuring the emission spectra and the amplitude-temporal characteristics are reported elsewhere [4–6, 12].

At individual wavelengths, the amplitude-temporal characteristics were investigated using an MDP-23 monochromator (grating – 1200 lines/mm, inverse linear dispersion – 13 Å/mm, width of the entrance and exit slits– 400 μm) and a Hamamatsu H7732-10 PMT with a rated sensitivity (wavelength range 185–900 nm, range of PMT sensitivity variation 10^3–10^7, rise time of the transient response 2.2 ns).

RESULTS AND DISCUSSION

The cathodoluminescence spectra from the crystals irradiated with SAEBs were obtained for eleven specimens (type IIa artificial and natural diamonds, CsI, ZnS, sapphire, CaF_2, ZrO_2, Ga_2O_3, CdS, ZnSe and $CaCO_3$). Due to the cathodoluminescence and its high intensity, the spectrometer did not register any CR from the specimens under study. This finding is consistent with our earlier data [12]. On the other hand, it was found that there is a large spectral region between the absorption and emission band edges in the spectra from the natural and artificial diamonds, ZnS, $CaCO_3$, and Ga_2O_3. In this region, there was no emission noticeable at the level of noise in the spectrograms. In the CsI crystals, the short-wave absorption-band and cathodoluminescence edges practically coincide, which makes the CR detection in this range difficult. Though in CaF_2 the short-wave absorption band edge lies in the VUV spectral region, the short-wave edge of the luminescence band reaches 215 nm. Nevertheless, based on the spectra obtained one might expect a registration of the CR by more sensitive detection techniques in the short-wave spectral region. In the latter region, the intensity of cathodoluminescence for most crystals is essentially lower, while that of CR increases, according to the calculations (see Fig. 2).

In order to detect the CR, we measured the amplitude-temporal characteristics using a PMT placed behind a monochromator. Due to a high sensitivity of the former, the radiation pulses could be measured at individual wavelengths even in the cases of low radiation intensity in these regions. Unfortunately, the temporal resolution in the

latter case was more than 2 ns. As noted above, the most appropriate region for the registration of the CR is that between the short-wave absorption band edge of the crystals and the short-wave cathodoluminescence limit, which is due to the impurity-defect centers. From the plot of dependence of the spectral energy density on the wavelength during excitation by a SAEB it was found out for the natural diamond specimen that, for instance, in the region 250–310 nm its spectral energy density did not change with a decrease in the wavelength, and in the region 225–250 nm it even increased. The radiation pulse duration of the diamond specimens in these regions remains unchanged and corresponds to the PMT temporal resolution. Moreover, the radiation pulse delay in the diamond specimen is minimal with respect to the voltage pulse rise time, with which the SAEB pulse was synchronized to subnanosecond accuracy. The optical radiation registered in the region 225–310 nm could be treated as the CR (more specifically, in this case we observe an overlapping of the CR on the short-wave wing of cathodoluminescence). Nevertheless, as the wavelength is increased starting from the wavelength 310 nm, for the natural diamond specimen the spectral energy density is observed to increase, and there is a manifold increase in the radiation pulse duration. In addition, in this wavelength range there appears a delay of radiation pulses with respect to those associated with the CR, which gradually increases up to 4–5 ns. Using a PMT and a monochromator, in the short-wave region we registered the CR not only in the diamond (natural and artificial) specimens but also in ZnS, ZrO_2, Ga_2O_3, sapphire, and CsI. The sensitivity of the PMT used in this study was found to be sufficient for a reliable registration of the CR in these crystals. The CdS and ZnSe crystals are unfit for applications in the CR detectors, due to their high absorption in the spectral region <500 nm. A registration of the CR in CaF_2 and $CaCO_3$ requires the use of higher-energy electron beams (>200 keV).

CONCLUSIONS

The results obtained in this study have demonstrated that in order to use the advantage of the CR, associated with its zero lag, it is necessary to take into consideration the influence of cathodoluminescence in the detectors of runaway electrons. In order to register the electrons with the energies ~50 keV based on the CR, it is recommended to use the crystals whose refractive indices are >2.4. It should also be borne in mind that the CR could be most readily detected in the short-wave region between the crystal absorption band edge and the cathodoluminescence band edge. Furthermore, there should be no other strong emission bands in the crystals in this region. In the experiments carried out in this work, the CR has been registered in diamonds (natural and artificial), ZnS, ZrO_2, Ga_2O_3, sapphire, and CsI. The most suitable materials, in terms of their overall physical and luminescent properties, for designing the CR detectors are the artificial diamond crystals containing a small number of impurities. In the experiments performed, use was made of a type IIa artificial diamond crystal grown by the CVD process.

Our experiments also suggest that the intensity of cathodoluminescence observed during registration of the signals in a wide spectral range is essentially higher than that of the CR and also depends on the current and energy density of runaway electrons. This offers a possibility of designing more sensitive detectors, relying on the cathodoluminescence, for registration of runaway electrons in the tokamak-type facilities. A promising machine for their calibration is a runaway electron accelerator with gas diodes forming electron beams with the current density ~100 A/cm^2, where the pulse duration is ~100 ps and could be changed by varying the gas pressure in the diode [12].

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