Electrons accelerator for research Cherenkov radiation in different specimens

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Abstract. Cherenkov radiation is widely used to register charged particles with high energy. This paper describes the design and parameters of an electrons accelerator, as well as the results of studies of the spectra and amplitude-time characteristics of sapphire and quartz KU1 radiation under the excitation of electrons with an energy of up to 350 keV. It was shown that in the UV and visible spectral regions a wide band is recorded, the intensity of which increases with decreasing wavelength. It was established that the duration and shape of the radiation pulse of this band coincides with the pulse of the electron beam. All this allows us to attribute the registered emission to the Cherenkov radiation.

1. Introduction

Cherenkov radiation (CR) [1] is generated via the motion of electrically charged particles (e.g. electrons) in a substance at a velocity exceeding the phase velocity of light (i.e. lightwave propagation velocity) in this substance. CR is universal in a sense that under the impact of particles with a sufficiently high energy all transparent substances (solids, liquids, and gases) emit the light. CR is applied to detect high energy particles [2–4], in particular, to study particles with energies of ~0.1–10 GeV, which arrive from space and affect the Earth's atmosphere. The refractive index, energy and type of particles effect on the propagation angle of CR. Thanks to this, it is possible to measure the parameters of high-energy particle beams. For example, the feasibility of transverse electron beam profile measurements for a few MeV energy and low intensity beams using Cherenkov radiation generated in a bulk of optical fibers was demonstrated in experiments presented in [5].

In recent decades, the detectors of Cherenkov radiation have been actively developed for Tokamaks. They are used to detect runaway electrons and measure their parameters [6, 7]. As has been shown, the energy of runaway electrons in Tokamak systems can range from tens of kilo- to tens of mega-electron volts [8] and they can damage the walls of chamber [8, 9]. The use of CR in the detector of runaway electrons can help to understand the physics of high-temperature plasma. However, the spectra of the detected radiation were not presented usually. Only in [7], the Cherenkov detector was calibrated at an electron energy of 2.3 MeV. But, the presented radiation spectrum does not correspond to Cherenkov radiation. An intense band is observed in the spectrum of diamond in the range 500–700 nm with a maximum at a wavelength of 637 nm. In [10–12] it was shown that to detect CR, it is best to use specimens transparent in the UV range and characterized by the absence or low

intensity of cathodoluminescence bands. As is known [3], an increasing in the CR intensity with a decrease in wavelength is one of the fundamental properties of this type of radiation. In our papers, this CR property was demonstrated using ordinary Ocean Optics spectrometers with beam current pulses of 12 ns [13, 14] and 4 μs [15]. Moreover, CR in the UV spectral range up to 220 nm was observed in leucosapphire and quartz [13–15]. As we have already noted, in [7] only the emission band in the region of 500–700 nm corresponding to cathodoluminescence was observed. The characteristic features of CR described in [10–14] were absent in the spectra in [7]. In earlier works of this scientific group [6], the emission spectra of CR were not presented.

The purpose of this work is to create an electron accelerator with a pulse duration of about 1 ns and electron energy of up to 350 keV and to check the presence of CR in the UV spectral range for sapphire and quartz KU1. The refraction indices of sapphire (n = 1.77) and quartz (n = 1.46) are lower the refraction index of diamond (n = 2.42) and hence these materials feature a lower intensity of CR and a higher electron energy threshold for its generation [13]. However, the fundamental absorption edge in sapphire and quartz lies in the vacuum ultra violet (VUV) region (λ_{VUV} <200 nm).

2. Experimental setup

The experiments were carried out on setup which was created to study Cherenkov radiation. An accelerator was specially developed that provided electron energy of hundreds of keV with a beam current pulse duration of about 1 ns. The design of the created accelerator, the high-voltage block of which consists of two sections and a gas-filled diode, are shown in figure 1.

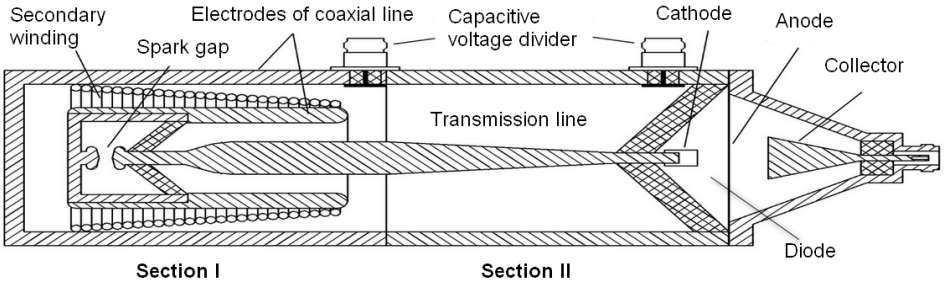

Figure 1. The design of accelerator with two high voltage sections, gas-filled diode and collector

In the first section, as in [16], a double forming line is used. However, instead of an adjustable spark gap, which is located between the high-voltage and grounded electrodes of coaxial line, the industrial high-pressure two-electrode spark gap R-49 was used. The spark gap was connected to the high voltage and inside electrodes of second coaxial line. The wave impedances of both forming lines of the section I were ≈20 ohms. The resistance of the transmission line was 50 ohms. After a short transmission line, the section II of the accelerator was installed, which consisted of an inhomogeneous transmission line 20 cm long, the wave resistance of which gradually varied from 50 to 100 Ohms. The diameter of the inner electrode at the input of the inhomogeneous line into the gas diode was 8 mm. A tubular cathode with an inner diameter of 8 mm was made of stainless steel foil with a thickness of 100 μm. The gap could vary from 2 to 13 mm. Diode was filled with atmospheric air with a humidity not higher than 50%. The pressure of air in diode was ranged from 0.1 to 10 torr. The beam current was extracted through an anode (AlMg foil 40 μm thick). The beam current was recorded using a conical collector with a time resolution of no worse than 100 ps. Measurements of voltage pulses at the output from the first and second sections of the accelerator were carried out using a capacitive voltage divider (CVD). The electrical signals from the collector and CVD were recorded with a Keysight Tech MSOS804A digital oscilloscope (8 GHz, 20 GS·s^{-1}).

The photograph the high-voltage block of the created accelerator, which consists of two sections and a gas-filled diode, are shown in Figure 2.

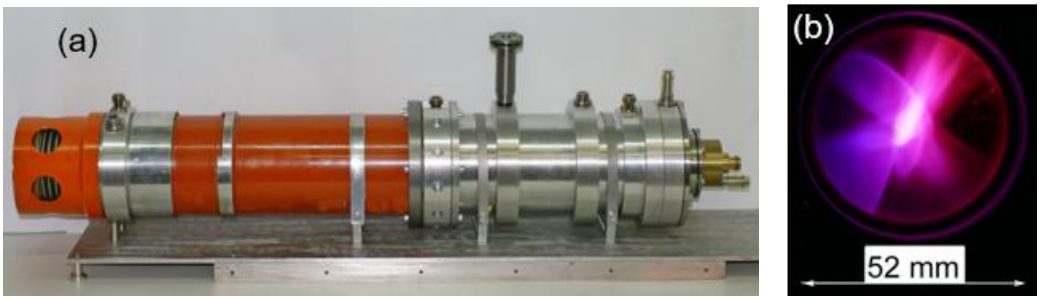

Figure 2. The photograph of accelerator with two high voltage sections, gas-filled diode and collector (a), and the photograph of the emission of a sapphire plate excited by an electron beam (b)

The emission spectra of specimens were taken with a HR2000+ES spectrometer (the FWHM of the instrumental function is ≈12 Å, spectral range of 190–1100 nm; Ocean Optics, Inc.). A P600-1-SR optical fiber (core diameter is 600 μm, spectral range of 200–1100 nm, Ocean Optics, Inc.). The emission produced in specimen per pulse was transmitted via optical fiber to the spectrometer, and its spectra were processed with taking into account the spectrometer sensitivity and optical fiber transparency. The transmission spectra of the specimens were measured with a deuterium-halogen source emitting in the range of 200–850 nm (Stellar-Net SL5). The specimens from sapphire and quartz KU1 were in the form of plates with diameter 60 mm and thickness 5 and 8 mm, respectively. The amplitude-time characteristics of the emission were measured using a high-speed photodiode (Photek PD025, time resolution is 0.1 ns). UFS-1 or UFS-2 optical filters were used to separate the UV component of the emission.

3. Parameters of the electron accelerator

When optimizing the parameters of the electron beam, a regime was used in which the diode was filled with air at pressures from 10^{-1} to 10 torr. In figure 3a shows the dependence of the amplitude and pulse duration at half maximum (FWHM) when filling the diode with air.

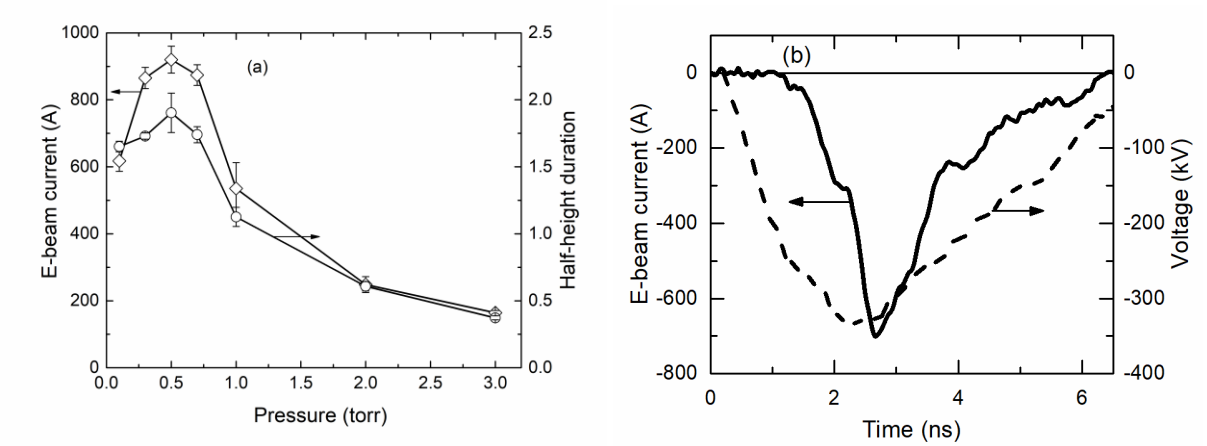

Figure 3. The dependence of the amplitude and pulse duration at half maximum when filling the diode with air (a). Waveforms of voltage and e-beam current pulse measured behind the foil (b)

As shown in [17], the use of generators with a nanosecond front and a voltage pulse duration allows one to change the beam current pulse duration from 0.1 to several nanoseconds. The pulse duration (FWHM) and amplitude of the beam current increases with decreasing pressure. As was established in this work, the beam current has a maximum at an air pressure of 0.5 Torr. However, the duration of the current pulse at half maximum at maximum amplitude was 2.2 ns. Therefore, to excite

the samples, we used a regime with an air pressure in the diode of about 0.8 Torr, at which the beam current pulse duration decreased. Waveforms of voltage and e-beam current are presented in figure 3b. The amplitude of the voltage pulse on the diode was 350 kV, and that of the e-beam current pulse was 700 A. The FWHM of the e-beam current pulse was ≈1.25 ns. According to calculations as described elsewhere [18], the electron energy distribution of the e-beam current pulse reveals two peaks at 50–150 keV and 150–350 keV, with the electron energy measuring 50–350 keV at a level of 0.2. The e-beam current density downstream of the foil was up to 220 A/cm^2. The image of the integral emission of a sapphire plate irradiated by a single e-beam pulse is shown in Fig. 2b. The highest brightness is observed in the center, where the e-beam mainly affected. The emission far from the center is also observed, which is associated with the scattering of the e-beam in the material. Similar was observed in other samples.

4. Registration of the spectrum and pulse duration of Cherenkov radiation

As was shown in [10, 11], one of the main features of Cherenkov radiation is an increase in intensity with a decrease in wavelength. In this case, the electron energy must exceed the threshold for the appearance of Cherenkov radiation, which depends on the refractive index of the substance. In addition, the studied samples should be transparent and they should not contain intense cathodoluminescence bands in the region of registration of Cherenkov radiation. In figure 4 shows the emission and transmission spectrums of sapphire and quartz KU1 under the excitation of an electron beam.

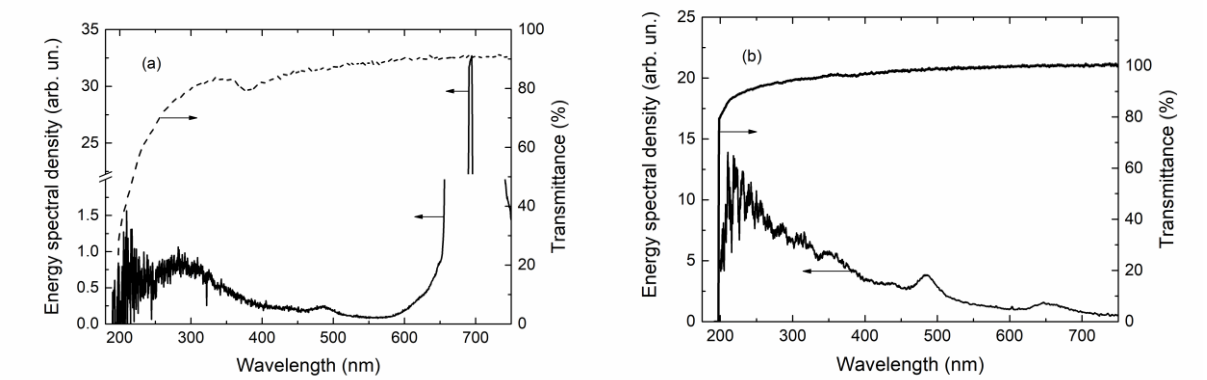

Figure 4. Emission and transmission spectra of sapphire (a) and quartz KU1 (b)

In sapphire, energy density $dE/d\lambda$ increases monotonically with decreasing wavelength in the range of 280–450 nm. It associated with CR. An intense narrow line at 693 nm and a broad band at 650–800 nm of which both are likely due to uncontrolled Cr^{3+} impurity ions was found in sapphire. The broad band is due to overlapped N and S bands. In quartz, the same behavior of $dE/d\lambda$ was observed in the range of 230–450 nm (figure 4b). It can also be associated with CR. For additional identifying the nature of radiation in the UV range, the amplitude-time parameters of the emission were studied with using the PD0125 photodiode. The measurements in the range of 240–400 nm with UFS-1 and UFS-2 filters show that the radiation pulse in all specimens approximates the e-beam current pulse duration.

5. Conclusion

This paper describes the design and characteristics of the electron accelerator, which was created to study Cherenkov radiation. Due to the use of two sections and a gas-filled diode, an accelerator operating mode was obtained with an electron energy of up to 350 keV and a beam current density of 220 A/cm^2 at a pulse duration at half maximum ≈1.25 ns. The experimental studies confirmed that CR is quite easy to detect in specimens transparent in the spectral region of 230–450 nm and in which there are no intense cathodoluminescence bands. CR in sapphire and KU1 quartz was reliably detected by an ordinary spectrometer.

Acknowledgments
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