Russian Technological Journal. 2023;11(5):71–80 ISSN 2500-316X (Online)

UDC 681.2.0821.083:535.2:543.063
https://doi.org/10.32362/2500-316X-2023-11-5-71-80

RESEARCH ARTICLE

Synchrotron radiation of a single electron application for optical spectroradiometry

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Abstract

Objectives. The investigations of optical radiation sources and metrological detector characteristics in the infrared (IR), visible, and air ultraviolet (UV) spectral regions are partially based on the unique metrological properties of synchrotron radiation. The aim of this work is to develop a high-precision method for determining the storage ring accelerated electron number with synchrotron radiation of a single electron to establish spectroradiometry and photometry units.

Methods. By determining the number of accelerated electrons, any storage ring can be used to calculate the synchrotron radiation characteristics at wavelengths of many large then the critical wavelength in the visible, air UV, and IR regions of the spectrum. This makes it possible to determine the main metrological characteristics normalized to the number of electrons, such as luminous intensity, luminance, illuminance, radiant power, radiance, irradiance, etc., regardless of the energy of the electrons.

Results. When applying the method for determining the number of accelerated electrons at low currents of the electronic storage ring, a total standard deviation of the number of accelerated electrons is less than 0.01% for an exposure range of the CCD matrix from 10^{-2} to $3 \cdot 10^3$ s in a wide dynamic range of $1–10^{10}$ electrons per orbit.

Conclusions. The use of a CCD-based radiometer-comparator calibrated by responsivity on a synchrotron radiation source is particularly relevant in monitoring luminance contrast thresholds and spatial distribution of object and background brightness, as well as determining metrological characteristics of optoelectronic measuring instruments, including CCD cameras, radiometers, spectroradiometers and photometers.

Keywords: synchrotron radiation, responsivity threshold, luminance contrast, luminance spatial distribution, measuring instruments

• **Submitted:** 05.06.2023 • **Revised:** 23.06.2023 • **Accepted:** 11.07.2023

For citation: Sigov A.S., Lazarenko E.R., Golovanova N.B., Minaeva O.A., Anevsky S.I., Minaev R.V., Pushkin P.Yu. Synchrotron radiation of a single electron application for optical spectroradiometry. *Russ. Technol. J.* 2023;11(5):71–80. https://doi.org/10.32362/2500-316X-2023-11-5-71-80

Financial disclosure: The authors have no a financial or property interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Использование синхротронного излучения отдельного электрона для спектрорадиометрии оптического диапазона

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Резюме
Цели. Исследование метрологических характеристик источников и приемников оптического излучения в инфракрасной (ИК), видимой и ближней ультрафиолетовой (УФ) областях спектра в значительной мере основано на использовании уникальных метрологических свойств синхротронного излучения. Целью работы является развитие высокоточного метода определения числа ускоренных электронов накопительного кольца, основанного на использовании синхротронного излучения отдельного электрона для воспроизведения единиц величин спектрорадиометрии и фотометрии.
Методы. Определение числа ускоренных электронов позволяет для любого накопительного кольца рассчитать характеристики синхротронного излучения на длинах волн, намного бóльших критической длины волны, т.е. в видимой, ближней УФ- и ИК-областях спектра. Это обеспечивает возможность, вне зависимости от энергии электронов, определить нормированные на число электронов основные метрологические характеристики, такие как сила света, яркость, освещенность, сила излучения, энергетическая освещенность, энергетическая яркость и другие.
Результаты. Применение метода определения числа ускоренных электронов при малых токах электронного накопительного кольца позволяет обеспечить в широком динамическом диапазоне $1–10^{10}$ электронов на орбите значение суммарного среднеквадратического отклонения не более 0.01% для диапазона экспозиций приборов с зарядовой связью (ПЗС-матрицы) от 10^{-2} до $3 \cdot 10^3$ с.

Выводы. Применение радиометра-компаратора на основе телескопа с ПЗС-матрицей, откалиброванного по чувствительности на источнике синхротронного излучения, особенно актуально при контроле пороговых значений яркостного контраста и пространственного распределения яркости объекта и фона, а также определения метрологических характеристик оптико-электронных средств измерений, включая ПЗС-камеры, радиометры, спектрорадиометры и фотометры.

Ключевые слова: синхротронное излучение, порог чувствительности, яркостный контраст, пространственное распределение яркости, средства измерений

• **Поступила:** 05.06.2023 • **Доработана:** 23.06.2023 • **Принята к опубликованию:** 11.07.2023

Для цитирования: Сигов А.С., Лазаренко Е.Р., Голованова Н.Б., Минаева О.А., Аневский С.И., Минаев Р.В., Пушкин П.Ю. Использование синхротронного излучения отдельного электрона для спектрорадиометрии оптического диапазона. *Russ. Technol. J.* 2023;11(5):71–80. https://doi.org/10.32362/2500-316X-2023-11-5-71-80

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

The solution of topical spectroradiometry and photometry problems is based on the use of reference sources and receivers of radiation in the infrared (IR), visible and ultraviolet (UV) regions of the spectrum [1–3]. Spectroradiometry methods play an important role in various fields of science and technology, including plasma diagnostics, photochemistry and photobiology, as well as astronavigation, Earth remote sensing, solar activity diagnostics, the study of fluid properties in the terahertz range, localization of remote objects, and nanoelectronics [4, 5].

Despite the success of national metrology institutes (NMIs) in creating spectroradiometry standards, significant difficulties are faced when assessing the quality of radiometers and photometers used in scientific research, as well as when evaluating efficiency and risks involved in UV radiation and photometric characteristics of emitters in areas of production, transport, labor protection, sanitary and epidemiological surveillance, etc. [6–8]. International key comparisons of K2c absolute spectral sensitivity of reference detectors UV radiation conducted by the International Bureau of Weights and Measures (BIPM) showed that, out of 14 participants, NMIs Physikalisch-Technische Bundesanstalt[1] (Germany), VNIIOFI[2] (Russia), and NIST[3] (USA) meet accuracy requirements in the spectral range of 200–400 nm [9, 10].

Blackbody models and synchrotron radiation sources are used as primary standards for photometry and spectroradiometry units in the infrared, visible, and air-ultraviolet regions of the spectrum [11, 12]. However, due to the limitation of the radiance temperature of the blackbody model to 3500 K, it is not possible to extend the working spectral range into the short-wave UV region of the spectrum, while the radiance temperature of synchrotron radiation is regulated by changing the energy of the electrons from thousands to tens of millions of degrees Kelvin.

The determination of photometry and spectroradiometry units by primary standards are associated with a number of problems on which leading NMIs have been working for many years. For example, the blackbody model requires a determination of the radiation temperature, accurate registration of weak fluxes of UV radiation against the background of powerful IR radiation, and ensuring the equal luminance of the emitting area. When using a synchrotron as a reference emitter, it is necessary to ensure the accuracy of electron beam diagnostics.

When using cryogenic radiometers as primary reference receivers, the main errors are related to low responsivity and heat exchange between the receiving cavity, housing and superconducting elements, as well as the need to compare radiation fluxes across a wide dynamic range [13]. The high intensity of synchrotron radiation, absence of lines in the spectrum, and high radiance temperature allow the use, along with a cryogenic radiometer, of an ionization chamber and a Golay detector [14]. In addition, synchrotron radiation can be used to conduct metrological studies of the characteristics of multilayer surface coatings and calculate the spectral responsivity of secondary reference radiation detectors using the dependence of detectors signals on the energy of accelerated electrons [15, 16].

Thus, in order to solve the problems arising in the investigations of sources and detectors metrological characteristics in the infrared, visible, and air-ultraviolet regions, the development of techniques based on the use

[1] https://www.ptb.de/cms/en.html. Accessed June 05, 2023.

[2] All-Russian Research Institute of Optical and Physical Measurements. https://www.vniiofi.ru/ (in Russ.). Accessed June 05, 2023.

[3] National Institute of Standards and Technology. https://www.nist.gov/. Accessed June 05, 2023.

of the unique metrological properties of synchrotron radiation is of particular interest.

SYNCHROTRON RADIATION RADIOMETRY

The spectral characteristics of synchrotron radiation are calculated with high-accuracy measurements of the electron orbital radius, energy, and number of accelerated electrons [17]. The distribution of the spectral radiance of synchrotron radiation over the emitting area is described by the following expression:

$$L(x,y)=\frac{27Ne^2c}{32\pi^3R^3D\sigma_{x'}\sigma_{y'}}\left(\lambda_{\tilde{n}}/\lambda\right)^4\gamma^8\left[1+\left(\gamma\Psi\right)^2\right]^2\times$$
$$\times\left\{K^2{}_{2/3}(\xi)+K^2{}_{1/3}(\xi)(\gamma\Psi)^2\Big/\left[1+(\gamma\Psi)^2\right]\right\}\times \qquad (1)$$
$$\times\exp\left[-\frac{\left(x'-x'_0\right)^2}{2\sigma_{x'}{}^2}-\frac{\left(y'-y'_0\right)^2}{2\sigma_{y'}{}^2}\right],$$

where L is the spectral radiance of the synchrotron radiation (W/m^3·sr); x' and y' are coordinates of two-dimensional emitting region in the orbital and perpendicular planes; x'_0 and y'_0 are coordinates of maximum of synchrotron radiation spectral radiance distribution; N is the number of accelerated electrons; $\gamma = E/E_0$ is the relativistic factor; E is the energy of the accelerated electron, E_0 = 0.511 MeV is the rest energy of the electron; e is the charge of the electron; c is the speed of light; R is the radius of the electron orbit in the radiation point; D is the integral of the two-dimensional Gaussian distribution; $\sigma_{x'}$ and $\sigma_{y'}$ is the standard deviation of the spatial distribution of the spectral radiance of the electron clot in the orbit plane and perpendicular plan; $\lambda_c = (4/3)\pi R\gamma^{-3}$ is the critical wavelength; λ is the wavelength; Ψ is the deflection angle from the orbital plane; $K_{1/3}$ and $K_{2/3}$ are modified Bessel functions (McDonald functions); $\xi = [\lambda_c/(2\lambda)][1 + (\gamma\Psi)^2]^{3/2}$ is the argument.

The two-dimensional Gaussian distribution integral D is calculated according to the formula:

$$D=\iint\frac{1}{2\pi\sigma_{x'}\sigma_{y'}}\exp\left[-\frac{\left(x'-x'_0\right)^2}{2\sigma_{x'}{}^2}-\frac{\left(y'-y'_0\right)^2}{2\sigma_{y'}{}^2}\right]dx'dy'.$$

Figure 1 shows the dependence of the modified Bessel functions (McDonald functions) $K_{1/3}$, $K_{2/3}$ on the wavelength normalized to the critical wavelength λ_c of the synchrotron radiation spectrum [17].

Equation (1) describes the spectral and angular distribution of the spectral radiance in the polarization σ- and π-components of synchrotron radiation. The polarization vector of the σ-component, which lies in the

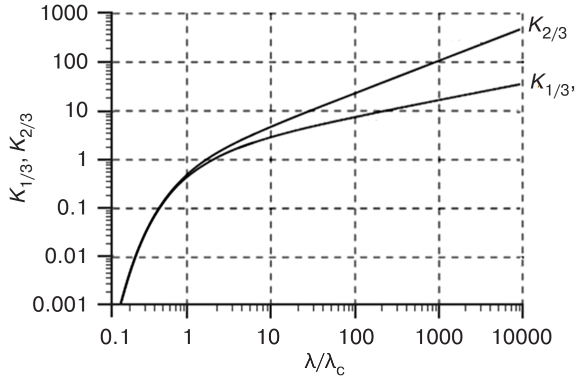

Fig. 1. Dependence of modified Bessel functions (McDonald functions) $K_{1/3}$, $K_{2/3}$ on wavelength

plane of the electron orbit perpendicular to the induction vector of the deflecting magnetic field, is described by the first term of Eq. (1), while the polarization vector of the π-component lying in the plane parallel to the magnetic field induction vector is described by the second term.

A universal function $f(\lambda/\lambda_0)$ of the spectral distribution of the synchrotron radiation flux is obtained by integrating Eq. (1) over the emitting region of the electron clot and the deflection angle from the electron orbital plane [18].

The universal function shown in Fig. 2 is used to calculate the characteristics of synchrotron radiation by specifying the critical wavelength λ_c of the electron storage rings.

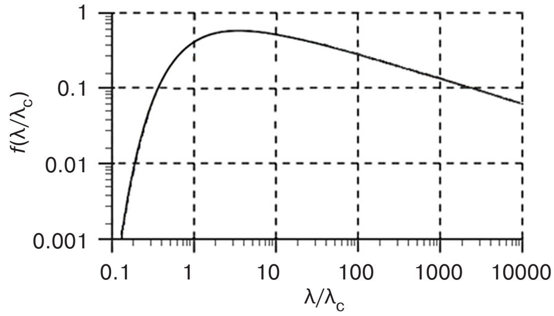

Fig. 2. Universal spectral distribution function of the synchrotron radiation flux

The energy of the electrons in the electron storage ring is determined by absolute measurements of the magnetic field induction at the emitting point of the electron orbit, by the wavelength of the Compton backscattering of photons on accelerated electrons, or by relative spectral measurements of the synchrotron radiation flux. The orbital radius of the electron storage ring is determined by the frequency of the accelerating high-frequency field.

The most important and challenging task of synchrotron radiation spectroradiometry is determining the number of accelerated electrons with high accuracy. At synchrotron radiation sources, the number of accelerated NMI electrons is measured by comparing the spectral radiance of the blackbody model and the synchrotron in the visible region of the spectrum; i.e., for spectroradiometry, the relative spectral distribution of synchrotron radiation spectral radiance with absolutization in the visible range is used according to the black body model. Over a number of years, an accurate method for measuring the number of electrons with an error not exceeding a hundredth of a percent was developed using synchrotron radiation sources for spectroradiometry and photometry. The method of particle number measurements is based on Fourier-transformation of the signal of a telescope with a charge-coupled device (CCD) matrix proportional to the spectral radiance of synchrotron radiation; here, isolation of a single electron in a relativistic orbit of an electron storage ring is used with filtering of high-frequency spatial harmonics to ensure a wide linear range of responsivity of the detector.

RADIOMETER–COMPARATOR

A radiometer–comparator (made in Russia) includes an achromatic refractor telescope with a focal distance of 6 m and an aperture of 150 mm, containing a cooled CCD matrix, a set of interference filters for the UV, visible, and IR spectrum ranges, as well as filters for spectral responsivity correction according to the relative spectral luminous efficiency of monochromatic radiation [19]. The use of a cooled CCD matrix for dark signal subtraction ensures the possibility of measurements at decreasing beam current in a wide range of exposures from 0.1 to 4000 s. A general view of the comparator radiometer on the synchrotron radiation channel is shown in Fig. 3.

Fig. 3. General view of the radiometer comparator on the synchrotron radiation channel

The cooled CCD matrix comprises 3326 × × 2504 pixels of 5.4 × 5.4 μm with 16-bit sampling of signal values. The comparator radiometer is mounted on the white channel of the electron storage ring without monochromatization of synchrotron radiation at a fixed distance from the emitting point of the orbit.

MEASUREMENT OF THE NUMBER OF ELECTRONS IN THE ORBIT

Synchrotron radiation flux, which is characterized by a uniform angular distribution in the horizontal plane of the electron orbit, has a complex angular dependence of the intensity of polarization components and the degree of polarization in the vertical plane [18]. The influence of axial oscillations of the clot electrons further complicates the angular dependence of the intensity of polarization components in the vertical direction, as determined by the convolution of the angular distribution of the synchrotron radiation of an individual electron and the distribution of clot electrons by angles of deviation from the orbital plane. The choice of telescope aperture is determined by the need to integrate the flux of synchrotron radiation in the vertical plane over the receiving surface of the CCD matrix.

To exclude distortions in the distribution of the energy illumination recorded during the integration of the CCD matrix pixel signals, the pixel responsivity is equalized to eliminate the zone inhomogeneity of the telescope transmission coefficient. Figure 4 shows the distribution of CCD matrix pixel signals corresponding to the Gaussian distribution of spectral radiance over the emitting region of the synchrotron.

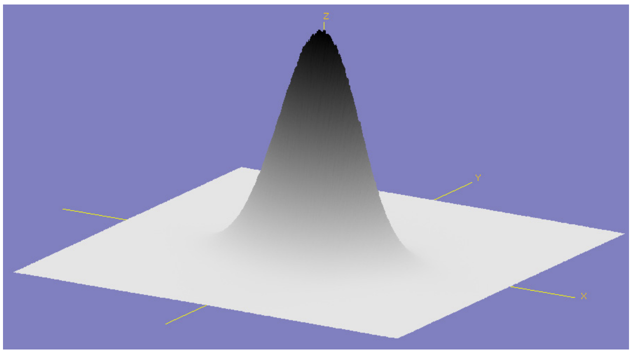

Fig. 4. Distribution of the CCD matrix pixel signals

The image on the CCD matrix is formed by multiple passage of electrons through a relativistic orbit. To reduce the influence of the CCD matrix noise when recording small fluxes of synchrotron radiation, forward and reverse Fourier transforms with filtration of high-frequency spatial harmonics are used. Calculation of energetic characteristics of synchrotron radiation of a single electron allows estimating the noise level and responsivity threshold for the comparator radiometer which does not exceed 10^{-10} W/(nm·m^2·sr). An important metrological property of synchrotron radiation is the perfect Gaussian distribution of the spectral radiance over the radiating region of the electron storage ring due to the axial, radial, and phase oscillations of the clot electrons. As the number of electrons decreases, the integral signal decreases proportionally. In this case, the relative distribution of the spectral radiance over the emitting region does not change, allowing the Gaussian distribution to be used to obtain a uniform responsivity of the comparator radiometer over the receiving surface of the CCD matrix.

Adjustment of the electron beam current of the storage ring in a wide dynamic range is carried out while controlling the relative number of electrons by the integral flux of synchrotron radiation keeping the spectral and angular distribution constant. For the first time, registration of a single electron in orbit was carried out on a first-generation electron storage ring using a photomultiplier tube. When a single electron is singled out in orbit for high-precision reproduction of spectroradiometry and photometry units the spectral radiance of synchrotron radiation has Gaussian distribution due to high frequency of electron circulation, which allows higher spatial harmonics to be excluded during signal registration, radically reducing noise level and increasing accuracy when integrating pixel signals in a wide exposure range from milliseconds to one hour using direct and inverse Fourier transform with high-frequency filtering.

First, it is necessary to provide a responsivity linearity range of CCD matrix in ten orders of magnitude taking into account random and systematic errors of shutter response time, signal reading noise and possible saturation of pixel charges. The CCD matrix signal is measured when the exposure time changes, but at a constant value of the synchrotron radiation flux. The high stability of energy characteristics of synchrotron radiation at fixed electron beam current allows CCD matrix signals to be compared even at maximum exposures.

At the beginning of the cycle of absolute electron number measurements using the synchrotron radiation flux of a single electron, the choice of the minimum exposure of the CCD matrix corresponds to the maximum beam current of the electron storage ring. The sequential decrease in the electron-beam current along with the decrease in the signal proportional to the synchrotron radiation flux is compensated by increasing the exposure time. The difference in the signals obtained before the current decrease and following the exposure time increase indicates the nonlinear dependence of the CCD matrix responsivity on the exposure time, thus requiring the introduction of correction coefficients. To reduce the electron-beam current, a scriber is used, which allows electrons to be removed from the orbit of the storage ring in steps, so that the last electron remains on the orbit, which can be held for several hours.

Figure 5 shows the step change of the CCD matrix signals when the electrons are removed from the orbit of the electron storage ring.

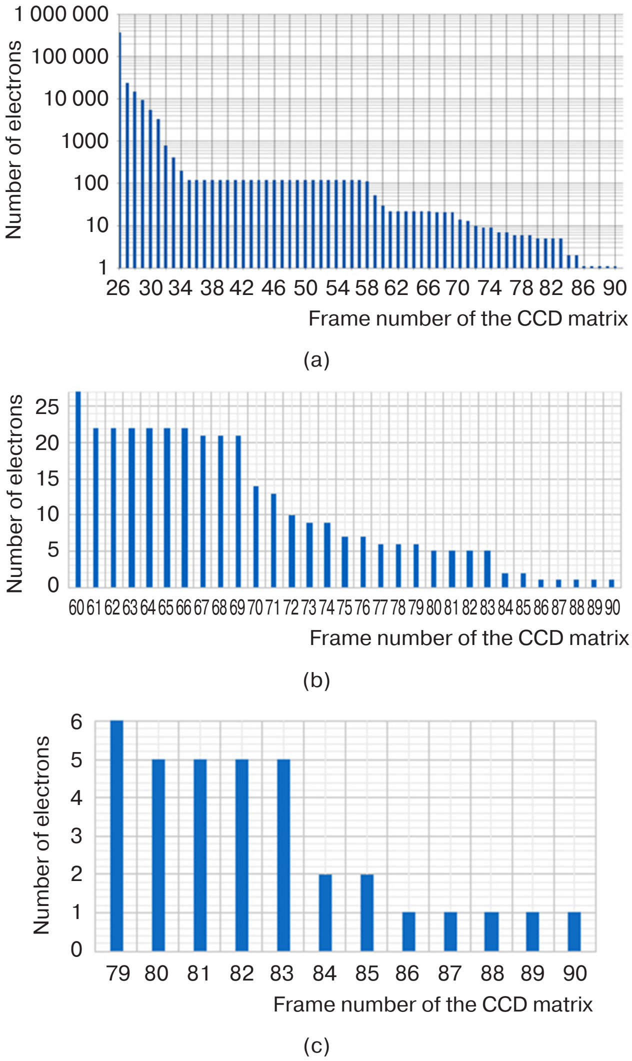

Fig. 5. Diagram of the step decrease of the CCD matrix signals when electrons are removed from the orbit: (a) diagram from 400 000 to 1 electron; (b) fragment of the diagram from 27 to 1 electron; (c) fragment of the diagram from 6 to 1 electron

Figure 5a shows the step change in the CCD matrix signal proportional to the number of electrons in the orbit on a logarithmic scale, starting at frame 26, with a signal of 400 000 relative units. According to the scriber, the signal decreased rapidly from frame 26 to frame 35 to 110 units. The stability of the synchrotron radiation flux was checked for several hours to estimate the standard deviation of the CCD matrix signals from frame 35 to frame 57. During this time, the electron clot did not lose a single electron; the signal standard deviation did not exceed 0.01%. Frames 58 and 60 illustrate a signal decrease by a factor of 5; from frame 61, synchrotron flux stability was repeated with estimation of the signal standard deviation.

Figure 5b shows on a linear scale the smallest reduction in signals at frames 67, 72, 78, and 80, which comprises a multiple of the step changes in signals corresponding to the synchrotron emission flux of a single electron.

Figure 5c portrays the results of comparing the signals of the last frames on a linear scale; in frame 80, one electron was removed and five electrons remained in the orbit. After checking the stability of the signals on frame 84, three electrons are removed using the scriber; the signal corresponds to the remaining two electrons. After frame 85, another electron is removed from the orbit, while in frame 86, the CCD matrix signal corresponds to one electron which is kept in the orbit for a long time. This allows the responsivity of the CCD matrix to be connected with the synchrotron radiation flux of a single electron. By determining the ratio of signals in the last frames shown in Fig. 5c, it becomes possible to precisely specify the number of electrons for each captured frame and select in the graphs the scale at which the relative unit of the signal corresponds to the synchrotron radiation flux of a single electron.

CONCLUSIONS

The method for determining the number of accelerated electrons of the storage ring based on the use of synchrotron radiation of a single electron is designed to diagnose an electron clot for establishing the spectroradiometry and photometry units based on the fundamental physical constants: electron charge and the speed of light in a vacuum. When determining the number of electrons from 1 to 10^{10} in the exposure range from 10^{-2} to $3 \cdot 10^3$ s, the total standard deviation does not exceed 0.01%.

According to the developed method, the spectral radiance of synchrotron radiation can be calculated for any electron storage ring at wavelengths significantly longer than the critical wavelength, i.e., in the visible, air UV, and IR regions of the spectrum. By this means, basic metrological characteristics can be determined normalized to the number of electrons regardless of electron energy, given in terms of luminance intensity, luminance, illuminance, radiant power, radiance, irradiance, etc. Thus, the spectroradiometric and photometric characteristics of synchrotron radiation in the visible, air UV, and IR regions of the spectrum, normalized to the number of accelerated electrons serve as constants for each electron storage ring.

The use of a comparator radiometer based on a telescope with a CCD matrix, which is calibrated by sensitivity at a synchrotron radiation source, is especially relevant for controlling the threshold values of luminance contrast and spatial luminance distribution of the object and background, as well as for determining the metrological characteristics of optoelectronic measuring instruments, including CCD cameras, radiometers, spectroradiometers and photometers.

Authors' contribution. All authors equally contributed to the research work.

REFERENCES

1. El'kin G.I., Salamatov V.Yu., Krutikov V.N., Novikov N.Yu. The state and main directions of work in the field of ensuring the uniformity of measurements in the Russian Federation. *Zakonodatel'naya i prikladnaya metrologiya = Legislative and Applied Metrology*. 2010;3:5–10 (in Russ.). Available from URL: https://metrob.ru/html/Stati/metrolob/napravlenia.html
2. Anevskii S.I., Minaeva O.A., Krutikov V.N., Minaev R.V., et al. *Metrological Support of Nanotechnologies and Nanoindustry Products*. Moscow: Logos; 2011. 592 p. (in Russ.).
3. Richter M., Ulm G. Metrology with Synchrotron Radiation. In: Jaeschke E., Khan S., Schneider J., Hastings J. (Eds.). *Synchrotron Light Sources and Free-Electron Lasers*. Springer; 2020. P. 1–35. https://doi.org/10.1007/978-3-319-04507-8_63-1
4. Shevelko A.P. Spectral instruments for x-ray and VUV plasma diagnostics. *J. Phys.: Conf. Ser*. 2018;1115(2):022042. http://doi.org/10.1088/1742-6596/1115/2/022042

СПИСОК ЛИТЕРАТУРЫ

1. Элькин Г.И., Саламатов В.Ю., Крутиков В.Н., Новиков Н.Ю. Состояние и основные направления работ в области обеспечения единства измерений в Российской Федерации. *Законодательная и прикладная метрология*. 2010;3:5–10. URL: https://metrob.ru/html/Stati/metrolob/napravlenia.html
2. Аневский С.И., Минаева О.А., Крутиков В.Н., Минаев Р.В. и др. *Метрологическое обеспечение нанотехнологий и продукции наноиндустрии.* М.: Издательство «Логос»; 2011. 592 с.
3. Richter M., Ulm G. Metrology with Synchrotron Radiation. In: Jaeschke E., Khan S., Schneider J., Hastings J. (Eds.). *Synchrotron Light Sources and Free-Electron Lasers*. Springer; 2020. P. 1–35. https://doi.org/10.1007/978-3-319-04507-8_63-1
4. Shevelko A.P. Spectral instruments for x-ray and VUV plasma diagnostics. *J. Phys.: Conf. Ser*. 2018;1115(2):022042. http://doi.org/10.1088/1742-6596/1115/2/022042

5. Torretti F., Liu F., Bayraktar M., Scheers J., Bouza Z., Ubachs W., Hoekstra R., Versolato O. Spectral characterization of an industrial EUV light source for nanolithography. *J. Phys. D: Appl. Phys.* 2019;53(5):055204. http://doi.org/10.1088/1361-6463/ab56d4
6. Berni L.Â., Vilela W.A., Beloto A.F., de Sena F.O. System for measuring the angular response of radiometers. In: *Proc. 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers, and Applications*. 2013. V. 8785. https://doi.org/10.1117/12.2019888
7. Fryc I. Spectral correction of detector used in illuminance measurements. In: *Proc. 11th Slovak-Czech-Polish Optical Conference on Wave and Quantum Aspects of Contemporary Optics* (*SPIE 3820*). 1999. V. 3820. P. 343–348. https://doi.org/10.1117/12.353083
8. Han L. The principle and characteristics of photoelectric sensors. *Science and Technology Innovation and Application*. 2020;10:77–78.
9. Lutz W. The CCPR K2.c key comparison of spectral responsivity from 200 nm to 400 nm. *Metrologia.* 2014;51(6):S336. http://doi.org/10.1088/0026-1394/51/6/S336
10. Anevskii S.I., Zolotarevskii Y.M., Ivanov V.S., et al. Spectroradiometry of ultraviolet radiation. *Meas. Tech.* 2016;28(11):1216–1222. http://doi.org/10.1007/s11018-016-0873-9
[Original Russian Text: Anevskii S.I., Zolotarevskii Yu.M., Ivanov V.S., Krutikov V.N., Minaeva O.A., Minaev R.V. Spectroradiometry of ultraviolet radiation. *Izmeritel''naya Tekhnika*. 2015;11:26–30 (in Russ.).]
11. König S., Gutschwager B., Taubert R.D., Hollandt J. Metrological Characterization and Calibration of Thermographic Cameras for Quantitative temperature measurement. *Sens. Sens. Syst*. 2020;9(2):425–442. https://doi.org/10.5194/jsss-9-425-2020
12. Gottwald A., Krumrey M., Scholze F., et al. Metrology with synchrotron radiation at PTB. *Eur. Phys. J. Plus.* 2022;137(11):1238. https://doi.org/10.1140/epjp/s13360-022-03417-9
13. Woods S., Neira J., Proctor J., Rice J., Tomlin N., White M., Stephens M., Lehman J. Generalized Electrical Substitution Methods and Detectors for Absolute Optical Power Measurements. *Metrologia.* 2022;59(4):044002. https://doi.org/10.1088/1681-7575/ac72dc
14. Anevsky S., Ivanov V., Kuznetsov V., Minaeva O., et al. Primary UV-radiation detector standards. *Metrologia*. 2003;40(1):S25. http://doi.org/10.1088/0026-1394/40/1/307
15. Sigov A.S., Minaeva O.A., Anevsky S.I., Lebedev A.M., Minaev R.V. Metrological studies of the characteristics of multilayer surface coatings using synchrotron radiation. *Russ. Technol. J.* 2021;9(1):38–47 (in Russ.). https://doi.org/10.32362/2500-316X-2021-9-1-38-47
16. Sigov A.S., Golovanova N.B., Minaeva O.A., Anevsky S.I., Shamin R.V., Ostanina O.I. Solution of topical specroradiometric problems using synchrotron radiation. *Russ. Technol. J.* 2022;10(3):34–44 (in Russ.). https://doi.org/10.32362/2500-316X-2022-10-3-34-44

5. Torretti F., Liu F., Bayraktar M., Scheers J., Bouza Z., Ubachs W., Hoekstra R., Versolato O. Spectral characterization of an industrial EUV light source for nanolithography. *J. Phys. D: Appl. Phys.* 2019;53(5):055204. http://doi.org/10.1088/1361-6463/ab56d4
6. Berni L.Â., Vilela W.A., Beloto A.F., de Sena F.O. System for measuring the angular response of radiometers. In: *Proc. 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers, and Applications*. 2013. V. 8785. https://doi.org/10.1117/12.2019888
7. Fryc I. Spectral correction of detector used in illuminance measurements. In: *Proc. 11th Slovak-Czech-Polish Optical Conference on Wave and Quantum Aspects of Contemporary Optics* (*SPIE 3820*). 1999. V. 3820. P. 343–348. https://doi.org/10.1117/12.353083
8. Han L. The principle and characteristics of photoelectric sensors. *Science and Technology Innovation and Application*. 2020;10:77–78.
9. Lutz W. The CCPR K2.c key comparison of spectral responsivity from 200 nm to 400 nm. *Metrologia.* 2014;51(6):S336. http://doi.org/10.1088/0026-1394/51/6/S336
10. Аневский С.И., Золотаревский Ю.М., Иванов В.С., Крутиков В.Н., Минаева О.А., Минаев Р.В. Спектрорадиометрия ультрафиолетового излучения. *Измерительная техника*. 2015;11:26–30.
11. König S., Gutschwager B., Taubert R.D., Hollandt J. Metrological Characterization and Calibration of Thermographic Cameras for Quantitative temperature measurement. *Sens. Sens. Syst*. 2020;9(2):425–442. https://doi.org/10.5194/jsss-9-425-2020
12. Gottwald A., Krumrey M., Scholze F., et al. Metrology with synchrotron radiation at PTB. *Eur. Phys. J. Plus.* 2022;137(11):1238. https://doi.org/10.1140/epjp/s13360-022-03417-9
13. Woods S., Neira J., Proctor J., Rice J., Tomlin N., White M., Stephens M., Lehman J. Generalized Electrical Substitution Methods and Detectors for Absolute Optical Power Measurements. *Metrologia.* 2022;59(4):044002. https://doi.org/10.1088/1681-7575/ac72dc
14. Anevsky S., Ivanov V., Kuznetsov V., Minaeva O., et al. Primary UV-radiation detector standards. *Metrologia*. 2003;40(1):S25. http://doi.org/10.1088/0026-1394/40/1/307
15. Сигов А.С., Минаева О.А., Лебедев А.М., Минаев Р.В. Метрологические исследования характеристик многослойных поверхностных покрытий с использованием синхротронного излучения. *Russ. Technol. J.* 2021;9(2): 38–46. https://doi.org/10.32362/2500-316X-2021-9-1-38-47
16. Сигов А.С., Голованова Н.Б., Минаева О.А., Аневский С.И., Шамин Р.В., Останина О.И. Решение актуальных задач спектрорадиометрии с использованием синхротронного излучения. *Russ. Technol. J.* 2022;10(3):34–44. https://doi.org/10.32362/2500-316X-2022-10-3-34-44
17. Schwinger J. On the Classical Radiarion of Accelerated Electrons. *Phys. Rev*. 1949;75(12):1912. https://doi.org/10.1103/PhysRev.75.1912
18. Wiedemann H. *Particle Accelerator Physics*. Springer Science & Business Media; 2007. P. 815–894.

17. Schwinger J. On the Classical Radiarion of Accelerated Electrons. *Phys. Rev*. 1949;75(12):1912. https://doi.org/10.1103/PhysRev.75.1912
18. Wiedemann H. *Particle Accelerator Physics*. Springer Science & Business Media; 2007. P. 815–894.
19. Anevskii S.I., Zolotarevskii Y.M., Krutikov V.N., et al. The Use of a Standard Source of Synchrotron Radiation for Calibration of the Sensitivity of a Telescope with CCD Array and High Angular Resolution. *Meas. Tech.* 2015;58(5):520–525. https://doi.org/10.1007/s11018-015-0747-6
[Original Russian Text: Anevskii S.I., Zolotarevskii Yu.M., Krutikov V.N., Lebedev A.M., Minaev R.V., Senin D.S., Stankevich V.G. The Use of a Standard Source of Synchrotron Radiation for Calibration of the Sensitivity of a Telescope with CCD Array and High Angular Resolution *Izmeritel'naya Tekhnika*. 2015;5:33–36 (in Russ.).]

19. Аневский С.И., Золотаревский Ю.М., Крутиков В.Н., Лебедев А.М., Минаев Р.В., Сенин Д.С., Станкевич В.Г. Использование эталонного источника синхротронного излучения для калибровки чувствительности телескопа с ПЗС-матрицей с высоким угловым разрешением. *Измерительная техника*. 2015;5:33–36

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Translated from Russian into English by Lyudmila O. Bychkova
Edited for English language and spelling by Thomas A. Beavitt