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REAL TIME LUMINESCENT DOSIMETRY SYSTEM FOR PRODUCT PROCESSING AT AN ELECTRON ACCELERATOR

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Quality control in industrial product processing at an electron accelerator requires continuous monitoring of critical parameters of the irradiation regime, first of all, of absorbed dose. The method of contact-free on-line measuring the surface distribution of absorbed dose in a processed object is described. The novel technique is based on the use of optical radiation induced in the object with the electron beam (cathodoluminescence, CL). It is shown, that the intensity of CL is proportional to the absorbed dose rate. An automated system for online measurement of the CL signal and determination of the scanning beam parameters (profile, width, offset) has been developed. The results of calibration of the absorbed dose by the CL signal in the industrial dose range are obtained. In contrast to the well-known methods of luminescent dosimetry based on thermo- or optically stimulated luminescence, the new approach does not require a special material for detector, as well as its extra stimulation to read out the dosimetry information.

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INTRODUCTION

The international standard ISO 11137 (Sterilization of health care products – Radiation) defines the requirements that ensure the proper performance of activities related to the radiation sterilization process, and also defines the control requirements for the conditions of radiation treatment of products [1]. At the same time the standard does not define the specific structure and implementation of the processing mode control and monitoring systems. It is emphasized that any reliable system that fully monitors and controls critical processing parameters can be used.

One of the main conditions of the radiation processing is the transfer the value of the absorbed dose of radiation to an irradiated product within the established limits. The dose distribution in processed products depends on:

- the electron beam energy;
- the linear current density distribution on the surface of the object being irradiated (the parameters of its sweep);
- the speed of the object transfer through the irradiation zone (conveyor speed).

Such parameters are defined as critical. Therefore, their monitoring should be carried out with special attention to ensure the reliable transmission of the product of a given sterilization dose.

Usually in the process of radiation treatment, the parameters of the beam are kept constant, and to ensure the required absorbed dose, the processed objects are moved through the irradiation zone with a conveyor at a given speed.

1. CL OF AN AMORPHOUS DIELECTRIC

The action of accelerated electrons on an amorphous dielectric is accompanied by incoherent optical radiation. Its nature is associated with the localization of electrons, injected by ionizing radiation from the valence band into the conduction band followed by their localization on deep traps in the forbidden band of the dielectric. The mechanism of the luminescence excited by a pulsed electron beam (cathodoluminescence, CL) in the technical dielectrics was described elsewhere [2]. Such materials include, in particular, cardboard, which is commonly used for manufacturing the shipping containers for the most types of products, and also a number of polymers (polypropylene, polyethylene, polystyrene, fluoroplastics, etc.).

If the duration of the beam pulse is shorter than the characteristic time, determined by the filling rate of deep traps and their concentration, the intensity of the prompt component of the optical radiation is proportional to the dose rate on the surface of the treated object. The integral of the radiant luminosity of the object over the exposure period (CL yield) is proportional to the absorbed dose on its surface. In a case of optically transparent material, the CL intensity increases with its thickness [3]. In this way it is possible to control the optical output of a given CL radiator. As an example, the glow generated by one pulse of 4 μs duration electron beam of the NSC KIPT LU-10 accelerator in a CL radiator (the polypropylene film 32 μm thick, wrapped in 3 layers around a cardboard sheet), is shown in Fig. 1.

Fig 1. The glow (white spot) generated with one pulse electron beam in CL radiator

2. AUTOMATED SYSTEM OF DETERMINING PARAMETERS OF A SCANNING ELECTRON BEAM

An automated system for online measurement of the CL signal and determination of the scanning beam parameters (profile, width, offset) has been developed. The system hardware is based on a commercial Canon EOS 400D digital single-lens reflex (DSLR) camera, a Raspberry Pi single-board computer and an optical path (Fig. 2). CL radiator (R) is located at a distance of 10 m from the Radiation shield (RS) of the accelerator. A hole has been made in the shield RS for the passage of optical radiation. A periscopic device (PD), consisting of two mirrors (m1 and m2), is positioned immediately behind the shield. The luminous flux at the PD output is focused by a lens on the sensor of the web-camera and digital camera. The camera, web-camera and single-board computer are placed behind a shielding wall in the accelerator bunker. The data are transferred from the single-board computer to the operator's server via an Ethernet network.

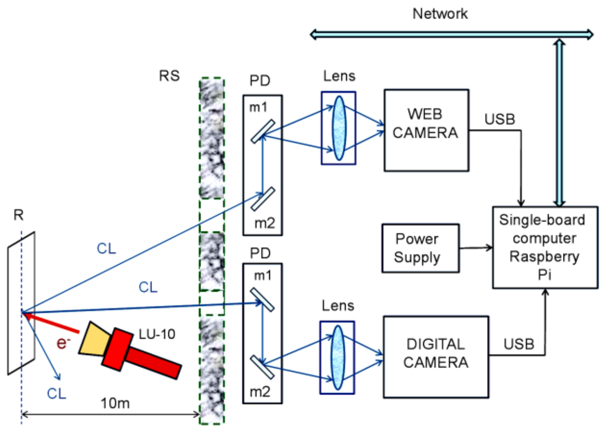

Fig. 2. Diagram of system of the CL signal remote recording

The software of the system is implemented as a set of functions in the Python programming language using the OpenCV (open source computer vision library) package [4].

The system automatically determines the following parameters of the scanning beam (Fig. 3):

• the position of the beam scan image in the photo (a, b);

• distribution of CL intensity (horizontal beam profile) in the middle part of the scan width (in 3 color channels: blue, red, green);

• approximation of the horizontal beam profile by a Gaussian and determination of its parameters (c);

• the CL intensity distribution (vertical profile) at the maximum of the horizontal distribution of the scanning beam (d);

• vertical scan width at 90% of the maximum of the CL signal;

• offset of the sweep from the lower edge of the transport container;

• minimum, maximum of intensity and uniformity coefficient over the scanning width.

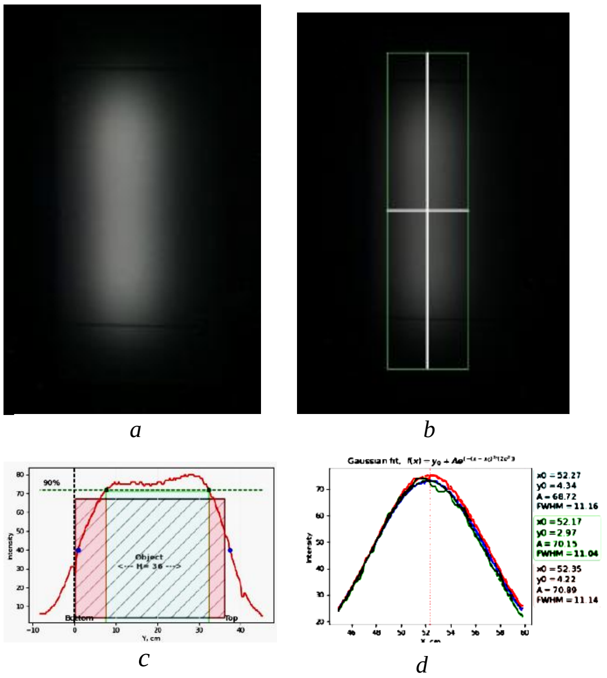

Fig. 3. Initial image of the scanning beam (a); position of the scanning beam image outlined by a contour in the photo (b); approximation of the horizontal profile of the beam by a Gaussian (c); distribution of the CL intensity (vertical profile) (d)

3. APPLICATION OF THE CATHODOLUMINESCENCE TECHNIQUE AT THE LU-10 ACCELERATOR

The radiators in the form of a sheet of white paper ~0.2 mm thick mounted on an aluminum plate 1mm thick measuring 59x26 cm were used in the experiment. They were placed on the 4 transport containers (1 radiator on each container) and passed through the irradiation zone. Dosimetry film B3 was placed vertically along the right edge of each radiator (Fig. 4). When a radiator passed the beam, 1–2 images of the CL signal were taken.

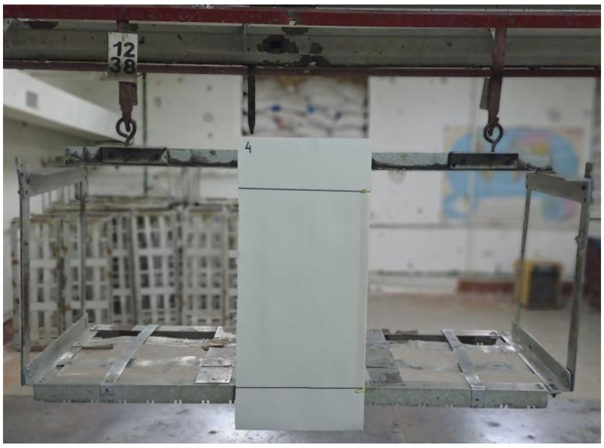

Fig. 4. Radiator No.4 with B3 film attached to the container

In the experiment, the accelerator parameters were as follows: the electron beam energy – 9.6 MeV, the pulse current – 0.760 mA, the beam pulse frequency – 250 Hz, the beam sweep frequency – 3 Hz.

Digital camera parameters: ISO speed=200, Shutter speed=1s, number of captured frames per radiator=2. The conveyor speed is set to 1.87 cm/s.

During measurements, the scan amplitude offset of the master sweep generator was constant and set to 0.11 V. At the same time, the specified scan width was changed to: 50, 46, 42, 40 cm, respectively.

The measured parameters of the vertical beam scan profile are listed in Table 1, the corresponding distributions are shown in Fig. 5.

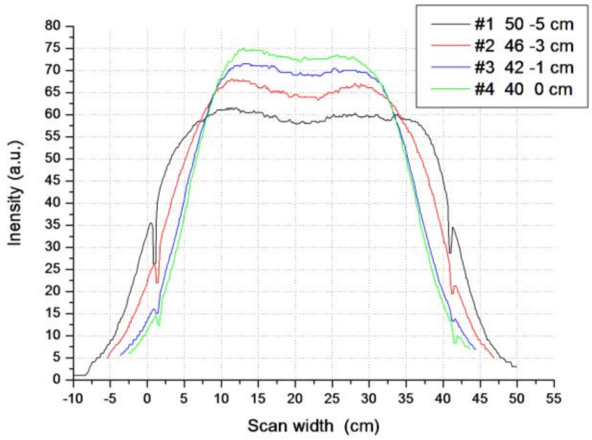

Fig. 5. Vertical beam scan profiles averaged over 2 frames for different scan widths

Table 1

Measured parameters of the vertical profile of the beam scan (M1)

Radi-ator №	Scan width set, cm	Profile Scan width (90%), cm	Profile Scan offset (90%), cm	Ununi-formity (90%), %	Max Intens, a.u.	Min Intens (90%), a.u.
1	50	32.7	3.8	10.6	61.1	54.6
1	50	33.1	3.1	11.5	62.1	55.0
2	46	26.4	5.9	11.4	67.6	59.9
2	46	25.9	6.1	11.3	68.7	60.9
3	42	23.3	7.1	11.2	72.1	64.0
3	42	23.8	7.3	11.5	72.1	63.8
4	40	22.0	7.7	11.1	75.1	66.8
4	40	22.0	7.9	11.2	75.1	66.7

It can be seen from Fig. 6 that with a decrease in the beam sweep width, the intensity of the CL signal increases due to an increase in the beam density along the scan sweep.

The horizontal profile of the beam was measured in the middle part of the vertical scan (19.5 cm from the bottom of the container). The profile was approximated by the Gaussian function in the form**:**

$$y = y_0 + A \cdot e^{-\frac{1}{2}\left(\frac{x-x_0}{\sigma}\right)^2}, \qquad (1)$$

where y_0 is the displacement along the Y axis; A is the height of the peak; x_0 is the position of the center of the peak; σ is the standard deviation, FWHM is the width at half maximum of the peak determined as: FWHM=2.355·σ.

The horizontal beam profiles are presented in Fig. 6.

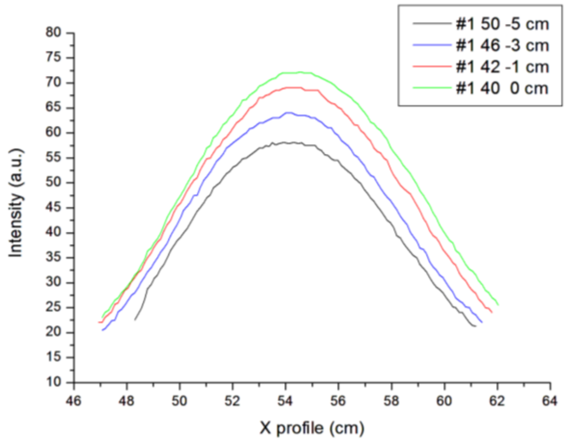

Fig. 6. Horizontal beam profiles for 4 radiators (averaged over 2 frames)

The length of film B3 was 42 cm, width 1.5 cm. Transverse marks of 0 cm (bottom of the container), 20 and 40 cm were made on the films with a black pen. Film B3 was located (vertically) along the right edge of the radiator. The B3 absorption coefficient was measured with a photo scanner (in the green color channel). The dose was determined using calibration factors.

Table 2 shows the parameters of the vertical beam profile measured with film B3. The dose distributions along the B3 film for the different beam sweep are shown in Fig. 7.

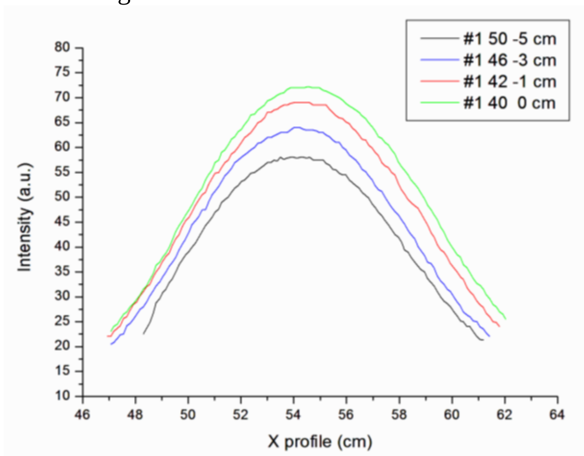

Fig. 7. Dose distribution along the B3 film for different scan width

Table 2

Parameters of vertical beam profile measured with the B3 film (M1)

Radi-ator №	Profile Scan width (90%), cm	Profile Scan offset (90%), cm	Ununi-formity 90%, %	B3 max Dose, kGy	B3 min Dose 90%, kGy
1	32.4	3.7	10.0	15.8	14.2
2	25.7	6.1	10.0	17.9	16.1
3	22.2	8.0	10.0	19.9	17.9
4	21.1	9.0	10.0	20.7	18.6

4. DOSE CALIBRATION

To provide a number of dose values, the measurements were performed also with different conveyor speed (M2: 1.22, 2.46 cm/s) and different average beam current (M3: 0.4 mA, 0.2 mA). From the obtained data, one can get the dependence of the dose in a certain place on the surface of the irradiated object at a certain beam energy on the intensity of the CL signal. The intensity of the CL signal on the captured image by digital camera is depended on camera exposure settings (aperture, shutter speed, ISO speed). The amount of light captured by a lens is proportional to the area of the aperture, equal to:

$$A=\pi\cdot(F/2N)^2, \quad (2)$$

where N=F/d camera f-number (aperture); F – focal length; d – aperture diameter.

The area of the aperture is A=0.001 m^2 for camera f-number N=5.6 and focal length F=0.2 m.

In this way, it is possible to determine the relationship between the dose (D) on the surface of the irradiated object and the intensity of the CL signal, measured by the optical method as:

$$D=C\cdot I_{CL}/(A\cdot S\cdot t_{exp}) = C\cdot I_N, \quad (3)$$

where I_{CL} is the intensity of the CL signal (a.u.); t_{exp} is the exposure time (shutter speed) (s); C is the coefficient; A is area of the aperture (m^2); S is camera ISO number; I_N – is the normalized intensity of the CL signal.

Fig. 8 shows the dependence of the dose (in the area of (15±0.25) cm from the bottom of the transport container) on the normalized intensity of the CL signal at the same location. The dose measurement uncertainty with B3 film was ~5% (shown in the plot).

Table 3 shows the results of all 3 measurements (M1, M2, M3). The values of dose and CL signal intensity are shown for an area of 15 cm from the bottom of the container. The CL signal intensity values for measurements at conveyor speeds 1.22 cm/s (M2-1) and 2.46 cm/s (M2-2) are corrected relative to the conveyor speed of 1.87 cm/s.

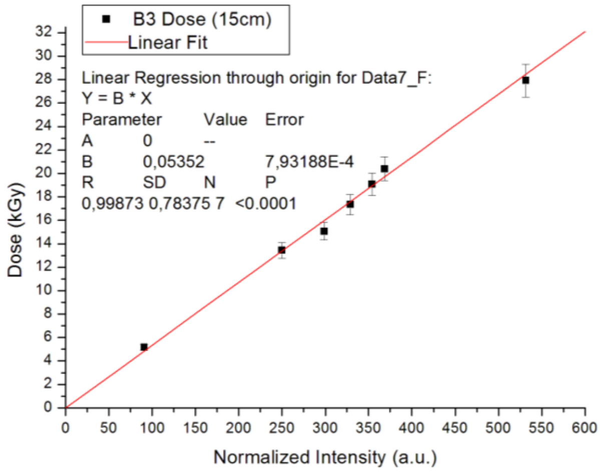

Fig. 8. Dependence of dose on normalized CL signal intensity

Table 3

Results of CL dosimeter calibration

Meas. №	Acceler. current, mA	Conv. speed, cm/s	Scan Width, cm	I_{CL}, a.u.	I_N, a.u.	B3 Dose, kGy	B3 Dose error, kGy
M1-1	0.763	1.85	32.9	59.7	298.7	15.1	0.8
M1-2	0.764	1.87	26.1	65.8	328.8	17.3	0.9
M1-3	0.763	1.88	23.5	70.8	354.0	19.1	1.0
M1-4	0.762	1.87	22.0	73.7	368.5	20.4	1.0
M2-1	0.796	1.22	25.9	106.4	531.7	27.9	1.4
M2-2	0.796	2.46	26.0	50.0	250.0	13.4	0.7
M3-3	0.401	1.84	26.3	67.5	168.7	–	–
M3-4	0.203	1.88	21.1	36.3	90.8	5.2	0.3

CONCLUSIONS

Radiation processing, in particular, sterilization of medical devices, as well as products and raw materials of the pharmaceutical and food industries, is usually carried out directly in the cartons. When using an electron beam as a sterilizing agent, its effect on a carton is accompanied by the generation of optical radiation (Cathodoluminescence, CL). The conducted studies have been established, that the CL radiant exitance is proportional to the surface absorbed dose rate. Based on this effect, a system for contactless real-time monitoring of main parameters of the product processing, namely, the absorbed dose and its distribution on a transport box, has been developed. The system hardware includes an optical path for remote registration of the CL signal with the digital and web camera. The processing of their signals is performed by a single-board computer. The system software provides a graphical representation of the vertical and horizontal dose profile created by the scanning electron beam. Calibration of the system has shown the possibility of its application for on-line dose monitoring without the use of standard disposable dosimeters.

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СИСТЕМА ЛЮМІНЕСЕНТНОЇ ДОЗИМЕТРІЇ У РЕАЛЬНОМУ ЧАСІ ДЛЯ ОБРОБКИ ПРОДУКЦІЇ НА ПРИСКОРЮВАЧІ ЕЛЕКТРОНІВ

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Контроль якості радіаційної обробки продукції вимагає постійного моніторингу критичних параметрів режиму опромінення, насамперед поглинутої дози. Описано систему безконтактного оперативного вимірювання поверхневого розподілу поглинутої дози на об'єкті, який оброблюється на промисловому прискорювачі електронів. Новий підхід заснований на використанні оптичного випромінювання, індукованого пучком електронів (катодолюмінесценція, КЛ). Показано, що інтенсивність КЛ пропорційна потужності поглинутої дози. Розроблено автоматизовану систему онлайн-вимірювання сигналу КЛ та визначення параметрів скануючого пучка електронів (профілю, ширини, зміщення). Отримано результати калібрування дози за сигналом КЛ у промисловому діапазоні її значень. На відміну від відомих методів люмінесцентної дозиметрії на основі термо- або оптично-стимульованої люмінесценції, новий підхід не потребує спеціального матеріалу для детектора, а також його додаткової стимуляції після опромінення для зчитування дозиметричної інформації.