ANALYSIS OF A DOUBLE-BEAM e,X-MODE AT AN IDUSTRIAL ACCELERATOR "EPOS"

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The main assignment of industrial plant with an accelerator "EPOS" providing the electron energy up to 30 MeV is radiation dyeing of gemstones. At treatment of them, the part of the electron energy is transformed into bremsstrahlung (X-) radiation. The energy characteristics of the electron beam were measured by a dosimetry wedge technique. On the basis of obtained results, the parameters of the mixed e,X-flux (the energy conversion coefficient and the factor of secondary radiation) along the path of radiation formation were calculated using a transport code GEANT4. The conditions for production of X-ray radiation in the state of electronic equilibrium have been determined. The spectrum of the X-ray photons as well as the dose rate and its distribution behind a target device for gemstone irradiation were calculated. A measured dose profile is satisfactory agreed with the data of the simulation. Implementation of a double-beam mode enables to conduct the extra radiation programs in the field of the bremsstrahlung radiation (modification of semiconductors and polymers, radiation tests, photonuclear activation of samples, etc.).

PACS: 87.56.bd; 41.50.+h; 81.40.Wx; 87.53Bn

INTRODUCTION

Industrial radiation plant with electron accelerator provides possibility of environmentally friendly product processing in wide span of absorbed dose. Depending on characteristics of a product, irradiation is conducted either directly by electrons or by bremsstrahlung (X-ray) radiation. For generation of the latter, an intermediary target-converter manufactured from a high-Z material (commonly tantalum) is applied. Only about 12% of the beam power is transformed into X-radiation at an electron energy of 7.5 MeV.

Considering the requirements imposed on the uniformity of the dose distribution, commonly only 30…40% of the beam power is utilized at industrial treatment of a product with the electrons. The last part is released as the heat in the elements of a plant, an also converted into the bremsstrahlung photons at interaction of accelerated electrons with a processed object and the elements of the output devices of an accelerator. As the treated products are manufactured predominantly from organic materials having atomic number ~7 (polymers, cellulose, etc.), the coefficient of energy conversion from the accelerated electrons into X-rays is appeared by several times less as compared with one for the tantalum at a similar electron energy. In the traditional installations, such radiation is regarded as the background and considered at the design of a radiation shield.

In the work [1], a method of computation of a path for formation of mixed e,X-radiation in the exit devices of an electron accelerator has been proposed. The technique makes possible to establish the conditions of production of an extra-source of the X-ray radiation in the state of electronic equilibrium and to rate its performances. The implementation of concept of a double-beam e,X-source at a linac LU-10 of NSC KIPT with electron energy in the spectrum maximum of 8…12 MeV, used for sterilization, was described in the work [2]. In the current work, the performances of the e,X-regime at a linac "EPOS" of NSC KIPT with electron energy up to 30 MeV, intended mainly for dyeing of gemstones (predominantly the topazes), are reported.

1. ELECTRON BEAM PARAMETERS

1.1. The linac "EPOS" (Table 1) includes the two accelerating sections and a beam scanner at its output. Unlike the LU-10 mashine, it isn't provided with a magnet analyser of the beam energy spectrum. So the study of energy characteristics of its beam was conducted with the use of an aluminium dosimetry wedge by 65 mm in thickness and meant for measurement of electron energy up to 25 MeV [3]. Earlier a thin wedge manufactured by a similar technology was applied for measurement of LU-10 beam parameters [4].

Table 1

Performance of accelerator "EPOS"

Electron energy span, MeV	10…30
Electron energy (nominal), MeV	20
Beam pulse duration, μA	4
Repetition rate, Hz	up to 300
Average beam current, mA	up to 1
Beam scanning frequency, Hz	3
Beam sweep amplitude (at output window), cm	±5

1.2. Preliminary analysis of accuracy of the electron energy measurement with the dosimetry wedge under the "EPOS" conditions was performed by a computer simulation technique using a GEANT4 package. In the calculations, the beam spectrum was described in the form that was obtained in the investigations conducted earlier (Fig. 1). The wedge was positioned at a distance of 134 cm from output window of the accelerator, corresponding to the conditions of the following experiment.

As a result of the calculations, the absorbed dose distributions along a dosimetry film set in the wedge were obtained and the metrological parameters R_{50}, R_p, R_{ex}. for determination of beam energy characteristics [3] were computed (Fig. 2). Whence the most probable E_p and average <E> values of the beam electron energy were calculated for different variants of the beam spectra using the formulae given in [3].

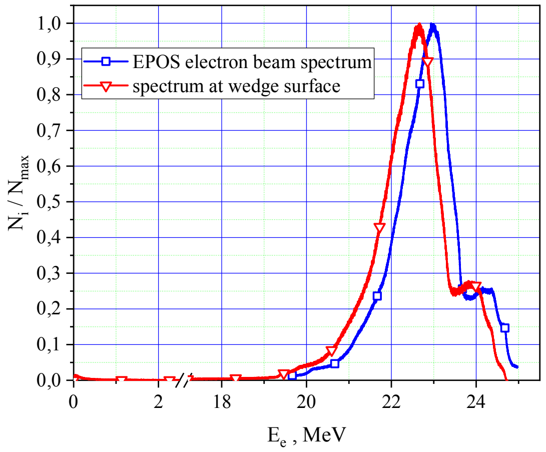

Fig. 1. "EPOS" beam spectra at its output window and at dosimetry wedge

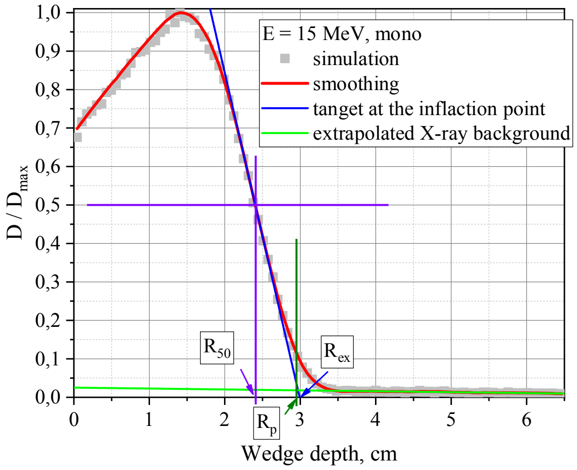

Fig. 2. Example of R_{50}, R_p, and R_{ex} parameter determination for monochromatic beam with energy 15 MeV

The results obtained are listened in Table 2, where E_e, is the most probable energy of the primary beam electrons, $<E>_{\text{inp wedge}}$ is the average electron energy at a front surface of the wedge determined by simulation, symbol "mono" denotes a monochromatic beam. The spectra with E_e=8.58; 9.90, and 10.88 MeV are related to measurement of the LU-10 beam. The statistical uncertainty of the simulation results did not exceed 0.4%.

Table 2

Average energy of beam electrons determined from R_{50} parameter (thick wedge)

E_e, MeV	$<E>_{\text{inp wedge}}$	R_{50}, cm	$<E_{50}>$, MeV ASTM51649
8.00 mono	7.65	1.22	7.87
9.00 mono	8.63	1.39	8.88
8.58	9.75	1.55	9.81
10.00 mono	9.61	1.56	9.89
9.90	11.09	1.78	11.19
10.88	11.86	1.92	12.01
15.00 mono	14.57	2.41	14.96
20.00 mono	19.54	3.24	19.96
23.00 EPOS	22.28	3.67	22.59
25.00 mono	24.51	4.03	24.87

The measurements conducted at the LU-10 machine with the use of thin wedge have demonstrated good precision in determination of average electron energy at high inaccuracy of measurement of its the most probable value [4]. For comparison, the similar procedures were simultaneously performed using the thick wedge as well. The both devices with the dosimetry film were disposed on the adjacent transport containers of a LU-10 conveyor and transferred through the irradiation zone. The results of the measurements are presented in Table 3.

It is evident, that the difference between the average values of the electron energy obtained by both wedges is not more than 3%. It meets the accuracy of the given measurement technique.

Table 3

Comparative results of measurement of LU-10 beam energy characteristics with two wedges

Measuring device	Electron energy, MeV	
	<E>	E_p
Thin wedge	12.99	10.30
Thick wedge	12.71	10.81

2. PATH OF e,X-RADIATION FORMATION

The output devices of the linac "EPOS" determinative composition of the e,X-radiation (Fig. 3) comprise a foil of the exit window EW (titanium, 50 µm) followed by a beam scatterer BS (the two 1mm thick aluminium foils separated by a gap of 2 mm), positioned at a distance of 90 mm from EW, and also a target vessel TV manufactured from alluminium and measuring 100×80×30 cm (W×H×Th) for irradiation of topazes with the electrons (e_Ob) located at a distance of 147 cm from BS. The thickness of the TV front wall makes 1 mm, when the rear of 5 mm. In simulations, the target e_Ob, disposed inside the vessel, was presented as a 2.5 mm thick vertical plate cooling with water. The mass fraction of the topazes in the plate makes 0.92, when the water of 0.08.

A stopper (ES) of electrons passed the TV unit is located at a distance of 53 cm from the latter. It comprises a 1mm thick tantalum plate (390×110 mm) followed by a set of 10 foils from duralumin D16 by 37 mm in total thickness separated with the 2 mm gaps. A 10 mm thick polystyrene plate playing the role of a target for X-radiation (X_Ob) is positioned behind ES at a distance of 20 cm. The two strips of the dosimetry film B3 (GEX Corp., USA) by 40 cm in length were fixed crosswise at the rear surface of the plate with centrum on the electron beam axes.

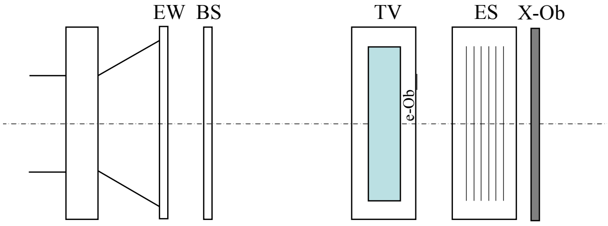

Fig. 3. Chart of "EPOS" output devices

3. RESULTS AND DISCUSSION

The conditions of formation of the e,X-radiation in the "EPOS" output devices were preliminary studied by a computer simulation technique (Fig. 4). On the draft, the following signs are used: A – the beam scanner; B – the electron beam scatterer (ES); C – the front wall of the target vessel; D – the target irradiated with the electrons (e,-Ob); E – the rear wall of the target vessel; F – the electron beam stopper (ES), G – the plate from polystyrene (X_Ob); the red lines denote the electron trajectories; the yellow points show the places of the interaction of electrons and gammas with a medium; the green lines correspond to the trajectories of gammas.

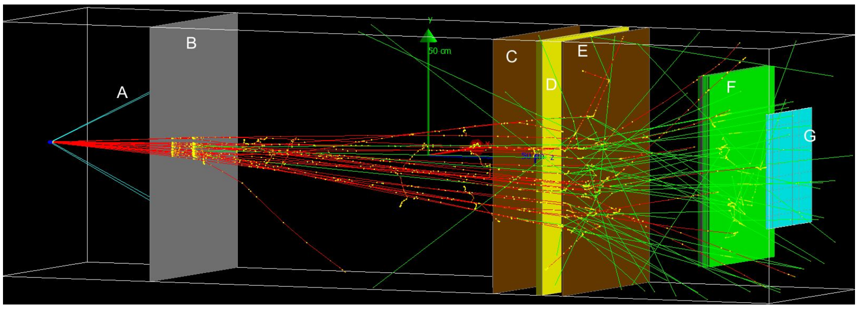

Fig. 4. Draft of path of X-ray generation in exit devices of accelerator EPOS (modelling)

In simulations, a dosimetry film was not considered as its small thickness does not allow to obtain a smooth dose distribution for tolerable counting time. Instead of it, the absorbed dose in the 1mm thick rear layer of X_Ob was calculated. It was believed, that the results obtained in such a way are close to the ones drown with the film but at speeding up the computations.

Before modelling, the energy characteristics of the electron beam corresponding to a topazes irradiation mode were measured using the thick wedge positioned in front of the target vessel. Thus it was established, that the spectral energy maximum makes 25.0 MeV at an average energy of 23.8 MeV.

The results of simulation of $3{\cdot}10^8$ electron trajectories for such a beam at a sweep amplitude on the accelerator exit window of ±4 cm are presented in Figs. 5-7.

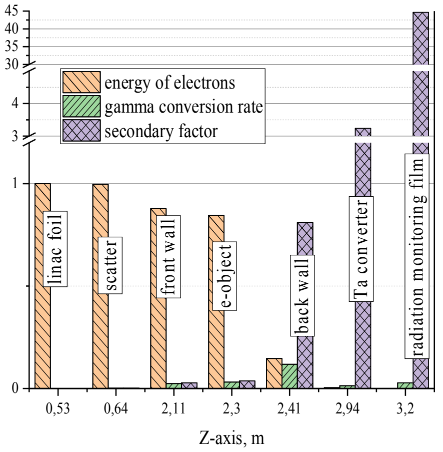

Fig. 5. Distribution of energy of e,X-radiation (rel. units) along axis of exit devices of "EPOS" plant

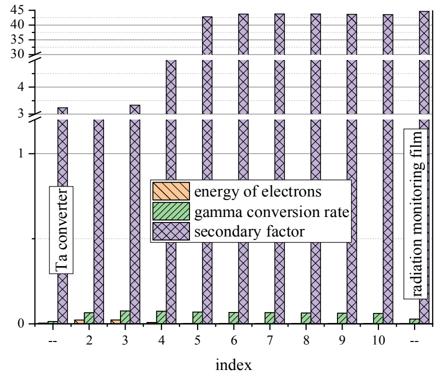

Fig. 6. Characteristics of radiation energy transfer in stopper of electrons

The transformation of energy of the electron beam into epy X-ray radiation in the elements of the accelerator exit devices is shown in Figs. 5, 6. It is evident, that the major part of the primary electron energy is absorbed in e_Ob.

The spectra of the bremsstrahlung radiation incident on elements the accelerator exit devices are given in Fig. 7. The results of simulation are normalized to the number of the beam electrons.

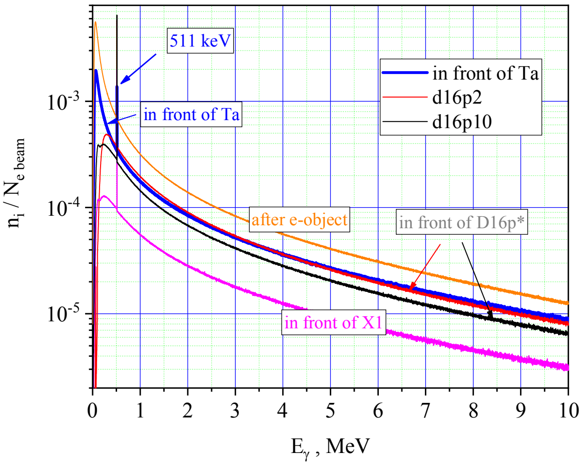

Fig. 7. Spectra of X-ray photons on elements of secondary radiation path

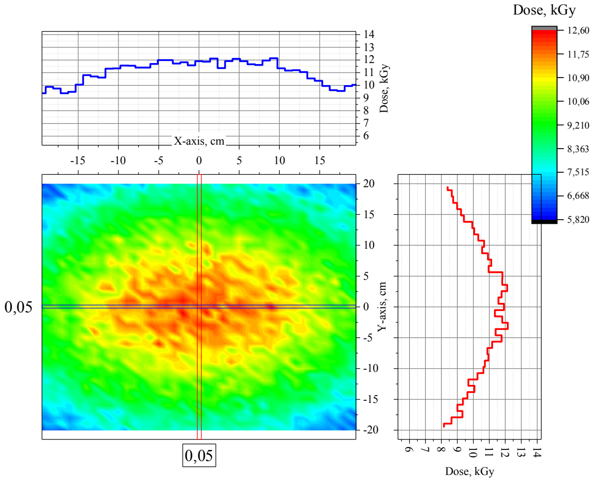

Fig. 8. Distribution of absorbed dose on rear surface of X_Ob plate

The dose calculation data were reduced to the actual conditions of the experiment – an irradiation for 1h at a mean beam current of 0.45 mA. The results of measurement of dose distributions drown under those conditions with the use of B3 film are given in Fig. 9.

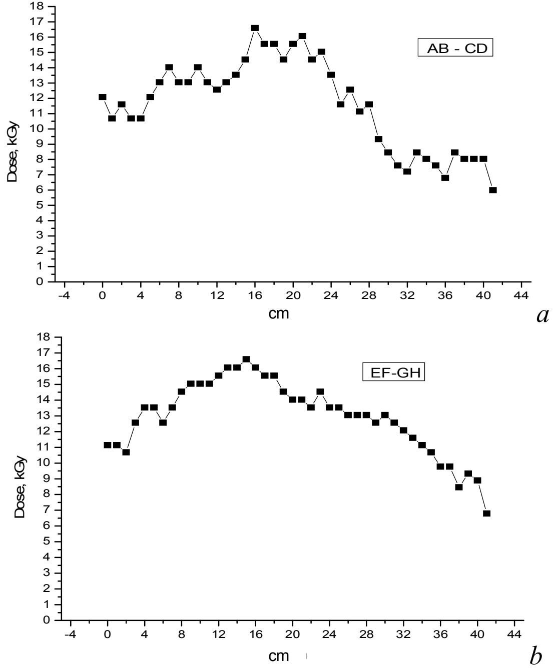

Fig. 9. Absorbed dose distribution on rear surface of PS plate (experiment): a – vertically; b – horizontally

The scatter of calculated dose data (see Fig. 8) can be explained by the limited counting time and so by the insufficient statistical assurance of the simulation results. In a case of measurement with the use of a dosimetry film (see Fig. 9), the non-uniformity of the dose profile can be connected with the granularity of the topaz distribution in the target, and also with the features of reproduction of the film optical density in an ORIGIN medium. Considering those remarks, the calculated maximum (12.2 kGy) and minimum (8.2 kGy) of the dose distribution are in satisfactory agreement with their experimental values (16.6 and 6.8 kGy respectively).

As simulations showed, the maximum intensity of X-rays is provided behind e_Ob (see Fig. 7). The rest elements contribute only to the increase of index of the secondary radiation and so to establishing its electronic equilibrium.

CONCLUSIONS

In an industrial electron accelerator by proper transformation of mixed e,X-radiation behind a processed object, an extra-source of the X-ray radiation in state of electronic equilibrium with photon energies up to the beam electron energy E_e can be obtained. In the E_e. span 8…30 MeV, the conversion coefficient of energy of the primary beam into the bremsstrahlung radiation is approximately proportional to E_e, when the dose rate ~ E_e^3.

An extra-source of the X-ray photons can be used for carrying out of radiation tests, photonuclear activation of samples, modification of semiconductors and polymers, etc.

REFERENCES

1. V.L. Uvarov, A.N. Dovbnya, N.A. Dovbnya, V.I. Nikiforov. Electron Linac Based e,X-Facility // *Proc. of the EPAC 2006 Conf.* 2006, p. 2257-2259.
2. V.A. Shevchenko, A.Eh. Tenishev, V.L. Uvarov, et al. Operation of an Industrial Electron Accelerator in a Double-Beam e,X-Mode // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2019, № 6, p. 163-167.
3. R.I. Pomatsalyuk, V.A. Shevchenko, I.N. Shlyakhov, et al. Measurement of electron beam energy characteristics at an industrial accelerator // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2017, № 6, p. 3-7.
4. ISO/ASTM 51649. *Practice for dosimetry in an electron beam facility for radiation processing at energies between 300 keV and 25 MeV.*

Article received 18.01.2020

ИССЛЕДОВАНИЕ ДВУХПУЧКОВОГО e,X-РЕЖИМА НА ПРОМЫШЛЕННОМ УСКОРИТЕЛЕ "ЭПОС"

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Основным назначением технологической установки с ускорителем "ЭПОС", обеспечивающим энергию электронов пучка до 30 МэВ, является радиационное окрашивание ювелирных камней. В процессе их обработки часть энергии электронов трансформируется в тормозное излучение. С помощью дозиметрического клина измерены энергетические характеристики пучка. На основе полученных данных методом моделирования с использованием транспортного кода GEANT 4 рассчитаны параметры смешанного e,X-излучения (энергетический коэффициент конверсии и фактор вторичного излучения) вдоль тракта его формирования. Определены условия получения тормозного излучения в состоянии электронного равновесия. Рассчитаны спектр фотонов, а также мощность поглощенной дозы тормозного излучения и ее распределение. Результаты измерения последнего удовлетворительно согласуются с данными моделирования. Реализация двухпучкового режима обеспечивает возможность, наряду с облучением продукции электронами в основном радиационном канале, проводить также дополнительные программы в поле тормозного излучения (радиационные испытания, фотоядерную активацию образцов, модификацию полупроводников и полимеров и т. д.).

ДОСЛІДЖЕННЯ ДВОПУЧКОВОГО e,X-РЕЖИМУ НА ПРОМИСЛОВОМУ ПРИСКОРЮВАЧІ "ЕПОС"

В.Л. Уваров, О.О. Захарченко, Л.В. Зарочинцев, А.Е. Тєнішев, Д.В. Тітов, В.Ю. Тітов

Основним призначенням технологічної установки з прискорювачем "ЕПОС", що забезпечує енергію електронів пучка до 30 МеВ, є радіаційне фарбування ювелірних каменів. У процесі їх обробки частина енергії електронів трансформується в гальмівне випромінювання. За допомогою дозиметричного клину зміряні енергетичні характеристики пучка. На основі одержаних даних методом моделювання з використанням транспортного коду GEANT 4 розраховані параметри змішаного e,X-випромінювання (енергетичний коефіцієнт конверсії і показник вторинного випромінювання) уздовж тракту його формування. Визначені умови отримання на виході тракту гальмівного випромінювання в стані електронної рівноваги. Розраховано спектр фотонів, а також потужність поглинутої дози гальмівного випромінювання та її розподіл. Результати вимірювання останнього задовільно узгоджуються з даними моделювання. Реалізація двопучкового режиму забезпечує можливість, разом з опромінюванням продукції електронами в основному радіаційному каналі, проводити також додаткові програми в полі гальмівного випромінювання (радіаційні випробування, фотоядерну активацію зразків, модифікацію напівпровідників і полімерів, тощо).