DEVELOPMENT OF A METHOD OF ABSORBED DOSE ON-LINE MONITORING AT PRODUCT PROCESSING BY SCANNED ELECTRON BEAM

R.I. Pomatsalyuk, V.A. Shevchenko, A.Eh. Tenishev, D.V. Titov, V.L. Uvarov, A.A. Zakharchenko

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

E-mail: uvarov@kipt.kharkov.ua

The conditions of the contact-free absorbed dose monitoring at industrial product processing by electron beam are investigated. The method is based on analysing the collected charge in a stack monitor (SM) mounted downstream of irradiated object. Using computer simulation on the basis of a modified transport code PENELOPE-2008, it is shown that by placing a filter of low-energy electrons before SM it is possible to obtain the one-to-one correlation dependence between the monitor charge and absorbed energy of radiation in the processed object. At a certain surface density of the filter, this dependence takes on the form similar to linear. The possibility to use an air gap between the object and SM as such a filter has been demonstrated. For the conditions of radiation plant with an electron accelerator LU-10 of NSC KIPT, the optimum distance of the SM location has been established. For the practical range of the electron energy, beam scan width and surface density of the irradiated product, the constants of the «product absorbed energy-to- SM charge » linear dependence have been determined. The capability to establish the average absorbed dose in the object moving trough the irradiation zone on the SM current is shown. The calculation data are in satisfactory agreement with the results of measurements.

PACS: 07.05Tp; 29.27.-a; 47.53.Bn, 81.40.Wx

INTRODUCTION

Key problem of any radiation technology is ensuring the absorbed dose value in any point of processed object satisfying the condition

$$D_{min} < D < D_{max}, \quad (1)$$

where D_{min} is the minimum dose providing the necessary result of the processing, D_{max} is the maximum permissible dose. E.g., at radiation sterilization, D_{min} corresponds to the sterilization dose [1].

Traditionally, the disposable chemical dosimeters are used. for technological dosimetry (see, e.g., [2]). They provide determination of absorbed dose only in the point of interest and only in the off-line mode. Unlike chemical ones, the calorimetric dosimeters make it possible the reusable application with determination of the dose value averaged over the sensitive volume of the calorimeter [3]. At the same time, the size of the sensitive volume is strictly fixed. Therefore, the calorimetric dosimeters are of little use in the wide range of size and density of the processed objects typical for radiation technology. Besides, dose measurements by calorimetric technique are carried out in off-line mode also.

Usually, industrial radiation sterilization of a product is executed directly in the transport boxes at their quantity in the one batch up to thousand or so. Therefore, it is practically impossible to provide the direct dose measurements in each box. In the work [4], a method for on-line dose monitoring at the product processing by scanned electron beam with energy 10 MeV is described. A principle of the method operation is based on comparison of charges of the electron radiation impinging on the front surface of an object and behind it using a special radiation absorber and the established correlation dependence between the energy of radiation absorbed in the object and the absorber charge. At the same time, the object area, in which the energy of radiation is absorbed, is uncertain. As a result, such measurements provide determination only so-called integrated dose, i.e. the part of the initial electron energy absorbed in the object. Moreover, in the offered geometry of the accelerator output device, the correlation dependence between the integrated dose and the charge collected in the absorber is one-to-one only for the objects, in which the losses of the initial electron energy exceed 60%. That takes place at a surface density of the object above 3 g/cm^2.

In the report, the results of development of a method for on-line monitoring of the absorbed dose at industrial processing of products over all the practical span of their surface density are described.

1. ANALYSIS OF THE OBJECT'S RADIATION SHADOW

1.1. From the condition (1), the requirement follows of maintenance of the sufficient uniformity of the dose distribution within the volume of the processed object. So at the use of the beam with energy 10 MeV, the one-sided processing of objects with surface density up to 3 g/cm^2 is permitted. In a case of greater density, the two-sided irradiation is recommended. Besides, the standards demand to provide the uniform distribution of the linear density of the scanned electron beam on front surface of the processed object [5]. It means, that behind its rear plane the radiation field includes the electrons of the primary beam, corresponding the edges of the irradiation zone, and also the particles passed through the object. Thus, the space-energy distribution of the particles behind the rear plane of the object, defined by the characteristics of the accelerator's radiation field, and also by the size and surface density of the object (the radiation shadow), is formed. In a case, when the length *l* of the object along the direction of its moving exceeds the beam width on the object surface (typical situation for radiation technology), it is possible to determine the value of the absorbed dose, averaged over the section of the object in the plane of beam scanning, using the formula

$$\bar{D} = \frac{P_{ab} \cdot l}{M \cdot V}, \qquad (2)$$

where P_{ab} – is the absorbed radiation power in the object; M – is the object weight; V – is the velocity of its movement.

1.2. The analysis of conditions of the dose measurement, described in the work [4], has shown that the ambiguity between the integrated dose and the charge collected in the absorber, is caused by presence of a flux of the low-energy electrons, generated by the primary beam in the surface layer of the processed object. As a result, at its surface density less than 3 g/cm^2, the electron flux, leaving the object, exceeds the beam current. So to obtain the one-to-one correlation dependence, it is necessary to place a filter of low-energy electrons between the object and the beam absorber.

At the initial stage, it was offered to use a plate from aluminium as such a filter. Its optimum thickness was established by computer simulation. In calculations, the verified program modules, developed on the basis of the transport code PENELOPE-2008, were used [6, 7]. As a beam absorber, a stack–monitor (SM), described in the work [8], was applied. In calculations, the geometry of a target device similar to the actual conditions of the radiation installation LU-10 [9] was reproduced (Fig. 1).

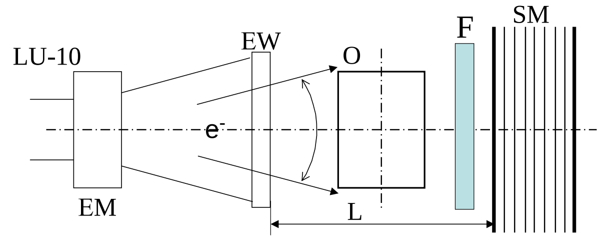


Fig. 1. Geometry of the LU-10 output device

The electron beam of 1 cm diameter with real energy spectrum having 9.35 MeV in maximum is swept by a scanning electromagnet with frequency 3 Hz and specified amplitude A_{sc} at an exit window of the accelerator EW. In the course of the beam sweeping, the alteration of its spectrum takes place considering a dependence of the angle α of beam deflection from electron energy E, which was described by the expression $\alpha(E) \sim E^{-1}$.

In calculations, it was supposed, that the horizontal axis Z coincides with the accelerator axis, the axis X is directed vertically upwards and lays in the plane of the beam scanning , and the axis Y is directed horizontally and corresponds to the direction of moving of the processed object O. The plane XOY coincides with the exit window EW of the accelerator. The irradiated object has the form of a parallelepiped from cellulose measuring 40×100×38 cm (X,Y,Z) and having surface density ρ_S=0; 0.76; 1.9; 3.8; 5.7 g/cm^2. The object's size is complied with the parameters of the LU-10 transport container. A filter F in the form of a plate from aluminum with thickness ΔZ=0.2; 0.4; 0.6; 0.8, and 1.0 cm was located behind the object at a distance L from EW.

In Fig. 2, the calculated data on the dependence between the absorbed energy in the object E_{obj} and collected charge in the monitor Q_{SM}, reduced to one electron of the primary beam, at various surface density of the object and thickness of the filter in case of direct beam (see Fig. 2,a), and also at its scanning with amplitude A_{sc}=10 cm at the exit window EW (see Fig. 2,b) are given.

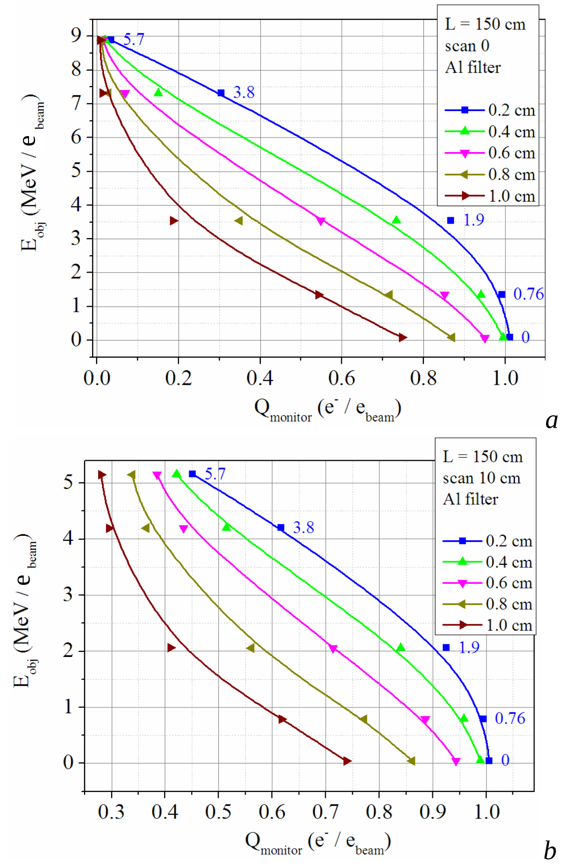


Fig. 2. Correlation dependence between the absorbed energy in object and the SM charge at presence of Al filter

It is seen, that at increasing filter thickness the obtained dependence alters its appearance. In particular, at some value of the thickness (ΔZ~0.6 cm) the dependence becomes close to linear.

In the sequel, the possibility to use an air gap between the irradiated object and SM as the filter was studied. The geometry of the output device was similar to the one given in Fig. 1, excepting the filter F. Calculation was conducted for a set of distances SM from the exit window, L=150; 180; 223, and 286 cm. The character of the dependences obtained (Fig. 3) is analogous to the ones shown in Fig. 2. So at a distance of 223 cm, the function $E_{obj}(Q_{SM})$ becomes close to linear in the all practical range of the ρ_S value (see Fig. 3,c and Table 1).

Table 1

Linearization coefficients of the $E_{obj}=a-b\times Q_{SM}$ dependence

A_{sc}, cm	a		b	
	value	std dev	value	std dev
0	9.09	0.13	9.35	0.2
10	7.92	0.11	8.76	0.17

1.3. In view of possible tuning the electron energy and scan width when irradiating the objects with different size and density, it was necessary to determine the respective change of the $E_{obj}(Q_{SM})$ dependence. In simulation, the various spectra of the LU-10 beam obtained in 2007 and in 2014 (after the change of some elements of the accelerator's feeding) were used (Fig. 4). The simulation results for the case L=223 cm are given in Fig. 5. It is seen, that the dependence $E_{obj}(Q_{SM})$ remains linear both for the direct beam and at its scanning with amplitude 10 cm.

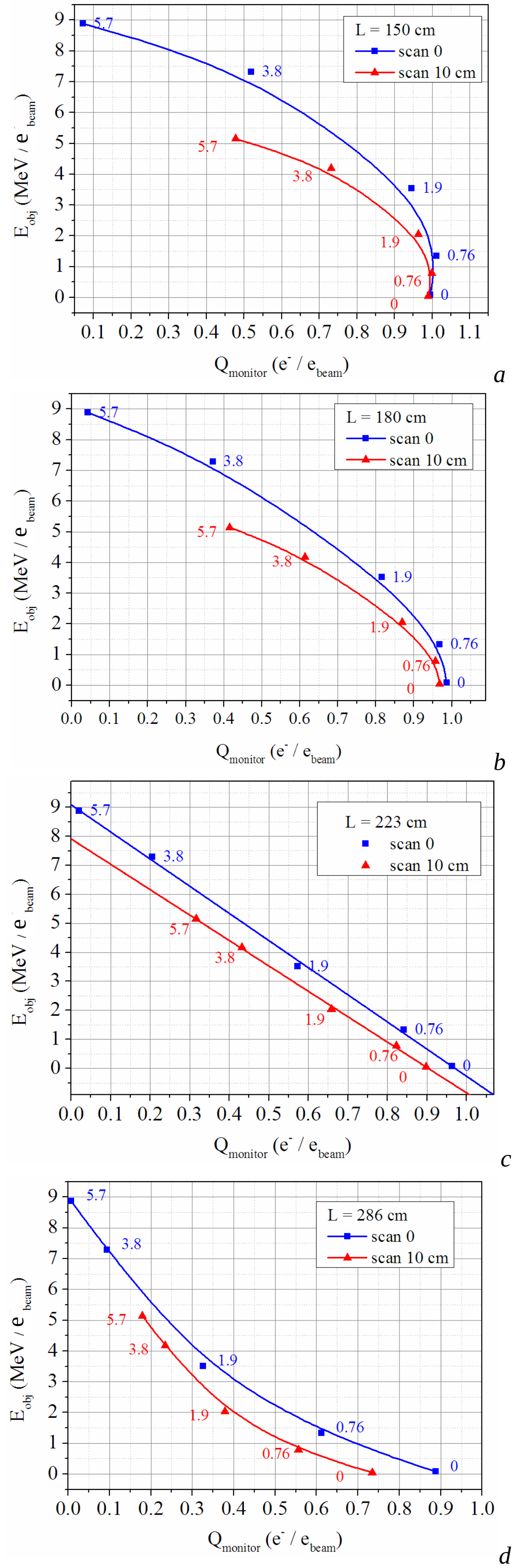


Fig. 3. Dependence $E_{obj}(Q_{SM})$ at various SM distance from exit window of the accelerator

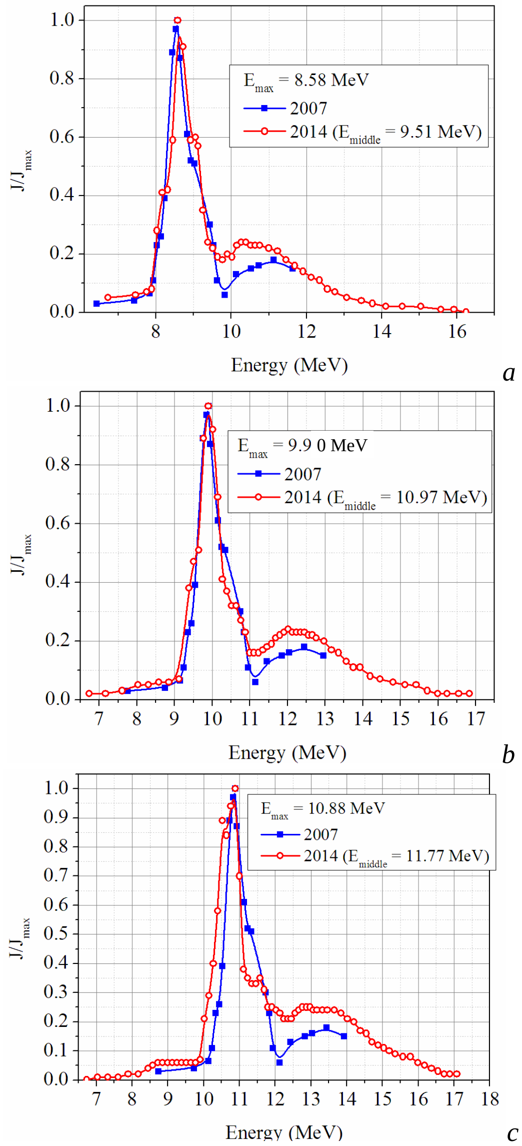
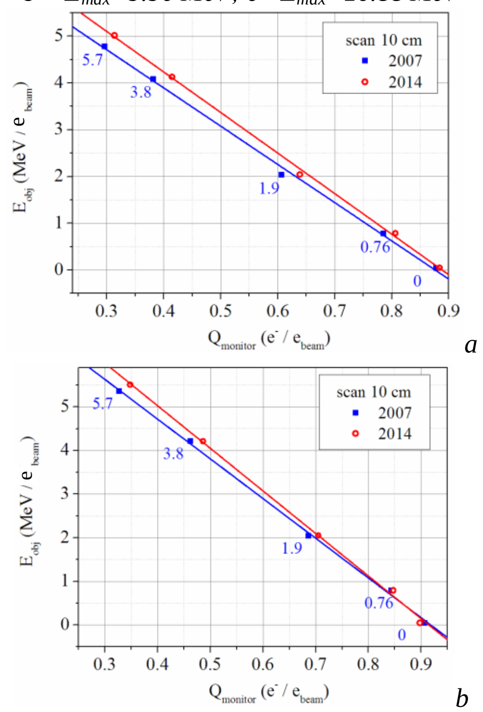
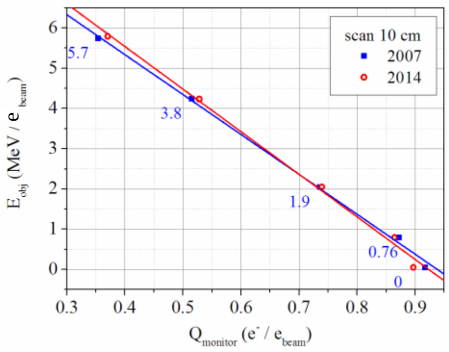


Fig. 4. Spectra of the beam: a – E_{max}=8.58 MeV; b – E_{max}=9.90 MeV; c – E_{max}=10.88 MeV

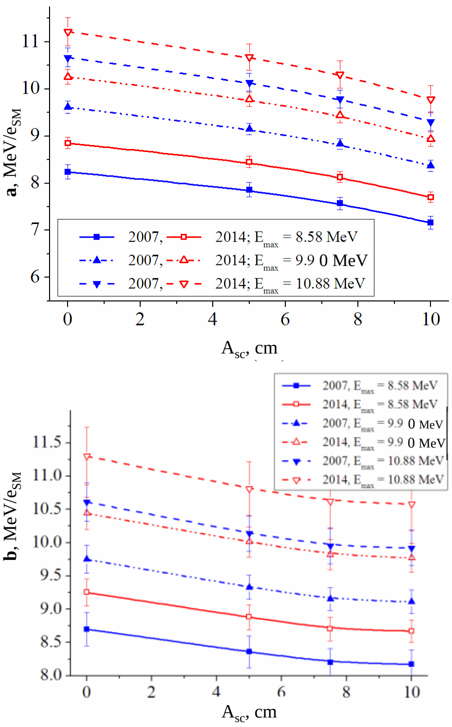




c

Fig. 5. Dependence $E_{obj}(Q_{SM})$ at various electron energy, L=223 cm, A_{sc}=10 cm: a – E_{max}=8.58 MeV; b – E_{max}=9.90 MeV; c – E_{max}=10.88 MeV

The summary data on the dependence of the linearization coefficient from the electron energy and amplitude of scanning are given in Fig. 6. As the latter is changed in the practical span 0…7.5 cm, those dependences remain close to linear.



b

Fig. 6. Linearization coefficients of the $E_{obj}(Q_{SM})$ dependence

Hence, with due regard to formula (2), it follows the possibility to determine the averaged value of the absorbed dose in the processed object at the time t using the expression

$$\bar{D}(t)=\frac{\left[a\left(E_{max},A_{sc},\rho_S\right)\cdot I_b(t)-b\left(E_{max},A_{sc},\rho_S\right)\cdot I_{SM}(t)\right]\cdot l}{M\cdot V(t)}, \quad (3)$$

where I_b – is the average beam current, $I_{SM}(t)$ – is the average SM current at the time *t*.

2. TESTING OF METHOD

2.1. To verify the proposed technique, a phantom from heavy cellular polystyrene (ρ=0.11 g/cm^3) measuring 32.5×70×17.5 cm (X×Y×Z) was fabricated. Choice of phantom thickness was stipulated by the condition of correspondence its surface density to the characteristics of a standard polystyrene calorimetric dosimeter [3]. That provides the identical averaged values of the absorbed dose in the phantom and calorimeter at their irradiation in the same mode. Those conditions ensure the possibility to calibrate the offered method using a reference calorimetric dosimeter by direct determination of the *a* and *b* coefficients from the formulae

$$a=\frac{P_{ab,ph}}{I_{SM,o}-I_{SM,ph}}\cdot\frac{I_{SM,o}}{I_b}, \quad (4.1)$$

$$b=\frac{P_{ab,ph}}{I_{SM,o}-I_{SM,ph}}, \quad (4.2)$$

where $I_{SM,o}$, $I_{SM,ph}$ – are the SM currant values in absence of an object and at the phantom irradiation respectively. Then the radiation power, absorbed in the phantom, $P_{ab,ph}$, can be determined from the expression

$$P_{ab,ph}=\frac{D_{cal}\cdot V\cdot M_{ph}}{l_{ph}}, \quad (5)$$

where D_{cal} – is the dose measured with the calorimetric dosimeter, M_{ph} and l_{ph} – are the phantom weight and length along the direction of its moving respectively.

2.2. The phantom was placed into a transport container of the conveyor jointly with the polystyrene calorimetric dosimeter RISO and transferred via the irradiation zone with specified velocity V. The data on the irradiation mode and the results of the dose measurement by the standard technique and proposed method with the use of formulae (3-5) are given in the Table 2.

Table 2

Results of the on-line dosimetry trial

N	V, cm/s	E_{max}, MeV	I_b, μA	$I_{SM,o}$ μA	$I_{SM,ph}$ μA	Dose RISO, kGy	Dose SM, kGy
1	4.88	8.65	816	670	439	6.26	6.37
2	3.65	8.68	817	671	451	8.77	8.96
3	2.44	8.83	827	683	462	13.12	13.02
4	1.82	8.99	836	693	472	18.54	18.39
5	1.22	8.97	822	679	471	27.51	27.83
6	0.92	8.95	819	677	450	36.61	36.32

In a number of experiments, the routine dosimeters Harwell Red 4034 and B3 were placed into a special slot located in the centre of the vertical median plane of the phantom. The measurements have shown, that within the uncertainty u=6% (k=2) their readings are agreed with the data of the RISO calorimeters.

CONCLUSIONS

Application of charge absorbing monitor behind an object being processed at an electron accelerator, providing the preliminary filtering of a low-energy part of the radiation spectrum, enables to establish the one-to-one correlation dependence between the monitor charge and absorbed dose in the object. At a specified velocity of the object moving trough the irradiation zone, it makes possible to determine in on-line mode the absorbed dose averaged over the object's section in the beam scanning plane.

A gap between the object and the monitor can be used as a filter of low-energy electrons. At its certain thickness, the correlation dependence becomes close to linear within all the practical range of the electron energy, as well as of the beam scanning width, and also of surface density of the processed products. It allows also prompt calibration of the measuring channel by means of joint traveling trough the irradiation zone of a system composing the calorimetric dosimeter and phantom with identical surface density. On the condition of preliminary dose mapping, it provides the possibility of continuous on-line dose monitoring and its maintenance within predetermined limits over the volume of the processed object.

REFERENCES

1. ISO 11137-1 (2006). Sterilization of health care products. Radiation sterilisation. Part 1: Requirements for development, validation and routine control of a sterilization process for medical devices.
2. Dosimetry for Radiation Processing. IAEA-TECDOC-1156.2000.
3. ISO/ASTM 51631:2011(E). Practice for Use of Calorimetric Dosimetry Systems for Electron Dose Measurements and Routine Dosimetry System.
4. Patent USA. Method for Monitoring Absorbed Dose in an Electron Beam // 1997, № 5661305.
5. Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies between 300 keV and 25 MeV / ISO ASTM 51649-2015.
6. Fernández-Varea and J. Sempau. *"PENELOPE-2008. A Code System for Monte Carlo Simulation of Electron and Photon Transport"*. OECD, NEA, Issy-les-Moulineaux, France, 2008.
7. V.I. Nikiforov, R.I. Pomatsalyuk, Yu.V. Rogov, V.A. Shevchenko, A.Eh. Tenishev, V.L. Uvarov. Development and Validation of Software for Simulation of Product Processing Regimes at an Electron Accelerator // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2013, № 6, p. 156-160.
8. S.A. Vanzha, V.I. Nikiforov, R.I. Pomatsalyuk, A.Eh. Tenishev, V.L. Uvarov, V.A. Shevchenko, I.N. Shlyakhov. Development of a "Radiation Shadow" Technique for Monitoring Product Sterilization Regime by Electron Beam // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations" (53)*. 2010, № 2, p. 150-153.
9. V.N. Boriskin, S.A. Vanzha, V.N. Vereshchaka, et al. Development of radiation technologies and tests in "Accelerator" // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2008, № 5, p. 150-154.

Article received 03.03.2016

РАЗРАБОТКА МЕТОДА ON-LINE МОНИТОРИНГА ПОГЛОЩЁННОЙ ДОЗЫ ПРИ ОБРАБОТКЕ ПРОДУКЦИИ СКАНИРУЮЩИМ ПУЧКОМ ЭЛЕКТРОНОВ

Р.И. Помацалюк, В.А. Шевченко, А.Э. Тенишев, Д.В. Титов, В.Л. Уваров, А.А. Захарченко

Исследованы условия бесконтактного мониторинга поглощённой дозы при обработке продукции на ускорителе электронов. Метод основан на анализе поглощённого заряда в пластинчатом мониторе (ПМ), размещённом за облучаемым объектом. С использованием компьютерного моделирования на базе модифицированного транспортного кода PENELOPE-2008 показано, что путём размещения перед ПМ фильтра низкоэнергетичных электронов можно получить однозначную корреляционную зависимость между зарядом монитора и энергией излучения, поглощённой в обрабатываемом объекте. При определённой поверхностной плотности фильтра эта зависимость становится близкой к линейной. Показана возможность использования в качестве такого фильтра воздушного промежутка между объектом и ПМ. Для условий радиационно-технологической установки с ускорителем электронов ЛУ-10 ННЦ ХФТИ установлено оптимальное расстояние размещения ПМ. Определены коэффициенты линейной зависимости «поглощённая энергия в объекте/заряд ПМ» для практического диапазона значений энергии электронов, ширины развёртки пучка и поверхностной плотности облучаемых объектов. Показана возможность установления по току ПМ усреднённого значения поглощённой дозы в объекте, перемещаемом через зону облучения с заданной скоростью. Полученные данные удовлетворительно согласуются с результатами измерений.

РОЗРОБКА МЕТОДУ ON-LINE МОНІТОРИНГУ ПОГЛИНУТОЇ ДОЗИ ПРИ ОБРОБЦІ ПРОДУКЦІЇ СКАНУЮЧИМ ПУЧКОМ ЕЛЕКТРОНІВ

Р.І. Помацалюк, В.А. Шевченко, А.Е. Тєнішев, Д.В. Титов, В.Л. Уваров, О.О. Захарченко

Досліджено умови безконтактного моніторингу поглинутої дози при обробці продукції на прискорювачі електронів. Метод заснований на аналізі поглинутого заряду в пластинчастому моніторі (ПМ), розміщеному за опромінюваним об'єктом. З використанням комп'ютерного моделювання на базі модифікованого транспортного коду PENELOPE-2008 показано, що шляхом розміщення перед ПМ фільтра низькоенергетичних електронів можна отримати однозначну кореляційну залежність між зарядом монітора і поглинутою в оброблюваному об'єкті енергією випромінювання. При певній поверхневій щільності фільтра ця залежність стає близькою до лінійної. Встановлена можливість використання в якості такого фільтра повітряного проміжку між об'єктом і ПМ. Для умов радіаційно-технологічної установки з прискорювачем електронів ЛУ-10 ННЦ ХФТІ встановлена оптимальна відстань розміщення ПМ. Визначені коефіцієнти лінійної залежності «поглинута енергія/заряд ПМ» для практичного діапазону значень енергії електронів, ширини розгортки пучка і поверхневої щільності опромінюваних об'єктів. Показана можливість визначення за струмом ПМ усередненого значення поглинутої дози в об'єкті, що переміщується через зону опромінення з наданою швидкістю. Отримані дані задовільно узгоджуються з результатами вимірювань.