THE MODEL OF THE IRRADIATION OF A THREE-DIMENSIONAL OBJECT BY THE ELECTRON BEAM IN THE STERILIZATION INSTALLATION WITH THE LOCAL RADIATION SHIELDING

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The developed model of the process of three-dimensional object irradiation by electron beam in a compact installation with a local radiation shielding is presented. A methodology of description of this process is created and the computer code BEAM SCANNING for calculation of irradiation characteristics is modernized. Results of some the tests shown good calculation accuracy, are submitted. A preliminary modeling of a sterilized box irradiation process in the real operating regime of the installation is carried out. Places of sterilized box with minimal irradiation dose are determined. The mechanism of formation a nonmonotonous dose profile along an axis of system, consisting in the contribution of neighborhood layers of a continuous beam or neighborhood bunches of modulated beam creating pear-shaped distributions of a dose is revealed. The developed method and the created computer code allow to describe processes at work of installation, and also to give out recommendations on its optimization.

PACS: 29.27.Fh

INTRODUCTION

Operation of the sterilization installation based on linear electron standing wave accelerator with a compact local radiation shielding [1, 2] and the search for the optimal modes of operation requires the development of physical and mathematical model of processes in it. In [3] the results of the development of such a model for the exposing the upper surface of the three-dimensional object – a box filled by sterilized material. The computer code BEAM SCANNING, created on the basis of this method, and some results of calculations are described.

The paper presents a model of the process of irradiation of the volume of three-dimensional object, the method of its description and modernized computer code BEAM SCANNING for the calculation of the characteristics of exposure. The results of testing the program, as well as preliminary estimates of dose produced by an electron beam in the volume of the box are presented.

The basis of the sterilization installation – the electron accelerator is placed vertically inside the bell-shaped radiation shielding; the beam propagates from the top to bottom. At the end of accelerator the horn is placed with magnet of the scanning system which scans the electron beam in a one plane. At a distance of about 15 cm from the outlet window of the horn, covered with titanium foil with thickness of 50 microns, there is a surface of the irradiated box, located on the conveyor. To achieve a dose of 25…30 kGy the box with the mass of about 7 kg and with a sizes 30×40×60 cm takes four irradiation stages – two on top side and two on bottom side (after turning it with a special mechanical device). Conveyor velocity is 1.5…2 cm/s, scan frequency – about 4 Hz, scan angle – up to 28 degrees, the frequency of the 6-microsecond pulse beam – up to 300 Hz, the average energy of the beam spectrum – 5 MeV, the energy at the maximum of the spectrum – about 6 MeV, pulsed current of the accelerated beam – 250 mA.

1. THE MODEL OF IRRADIATION AND THE METHOD OF CALCULATION

The electron beam falling on the surface of the irradiated box penetrates inside it and creates an absorbed dose. The electrons in the process of their movement in the material gradually lose their energy due to spending it on the processes leading to the creation of the required dose in the sterilized object (ionization and excitation of molecules, etc.) and are scattered by the atoms of matter. Some of the electrons are lost, leaving the volume of the box as a result of entering into it under non-optimal angles, as well as due to scattering by atoms of the matter. The uniformity of the dose along the axis of the system (which coincides with the axis of the accelerator) is provided by both-sides irradiation.

The main method of measurement of the dose of irradiated objects in our installation is the use of plastic films, which change the light permeability under the influence of electron beam irradiation. The error of this method of measurement of the dose is 10…15%, which we took for the developed model. Therefore, to describe the energy loss and the scattering of the beam electrons in the material we use the Monte-Carlo method of so-called "enlarged collisions" [4]. This method, most often used in practical calculations of the radiation dose, is a simplification compared to the classical Monte-Carlo method. In the latter method a single scattering events and energy loses of individual electrons with the use of cross-sections of the corresponding processes and an averaging over a large number of these acts are calculated. In the method with the "enlarged collisions" the probability functions of the angular distribution and the energy loses characteristics as a result of multiple scattering events in a certain layer of the irradiated material are used. The solution of problems of this kind is made by modeling the trajectories of a large number of electrons within the material. The electrons penetrate the substance, experiencing the scattering and the energy losing. Their trajectory thus looks like broken lines, on each segment of which the energy loss and the angle of deviation is calculated in accordance with the used distribution functions. As a result of the summation of doses produced by all the electrons, the image of the dose distribution produced by the electron beam in the entire of the three-dimensional volume is created.

In our model, we calculate the passing of bunches of the beam to the surface of the box, further the scattering and energy losses of electrons in the box material, created dose in it and beam losses due to getting out of the particles through all the faces of the box are calculated. In our program to speed up the calculations we use the tabulated functions for the energy loses and the scattering abilities of material. The program uses also the angle distribution probability function, developed by the authors, which is approaching to the widely used distribution of Moliere [4] and gives a good agreement with experimental data of the beam scattering on a thin titanium foil [3]. Although using these functions do not provide a very high accuracy of coincidence with the experimental results, but it allows to get a qualitative picture of the dose distribution and to fit into the margin of errors. For testing our model we use the experimental data and the results of calculations using a program based on the method proposed by T. Tabata et al. [5 - 7].

Below are the results of some calculations using the technique described above, which was implemented in the computer code BEAM SCANNING.

2. RESULTS OF CALCULATIONS

2.1. THE IRRADIATION BY THE THIN BEAM WITHOUT SCANNING

A three-dimensional configuration of the dose in the object is created by a contribution of a large number of beam bunches of relatively small diameter, that are falling on different places at different angles. Therefore, as first test we present simulation of experimental results [8] described in [9] of measure the dose generated by the electron beam with a small diameter – about 5 mm and small divergence angle – up to 3 degrees. Beam energy – 22 MeV, energy spread – 50 keV, the dose is created in water.

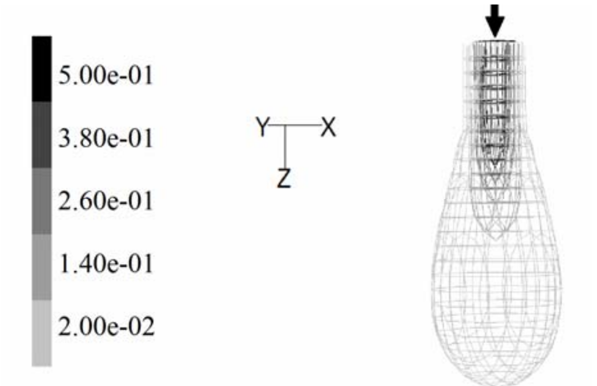

Fig. 1. Relative isodoses of object irradiation presented in the form of three-dimensional grids. The unit dose corresponds to a dose at a depth of 2 cm along the axis of system

Fig. 1 shows the results of calculations in a three-dimensional representation in the form of grids, corresponding to fixed levels of relative dose. The beam in the figure falls down on the surface of the box. As can be seen, at some part of plot the isodoses have a shape of a cylinder with constant diameter, and then the diameter of the cylinder is changing, forming the typical pear-shaped isodoses.

Fig. 2 (at right side) shows the same calculation results, but as an isodoses lines at a cross-sectional plane of symmetry of the system. At the left part of the figure the experimental results are shown by the similar way. Presented are isodoses for levels 2, 5, 10, 20 and 50% of the maximum dose.

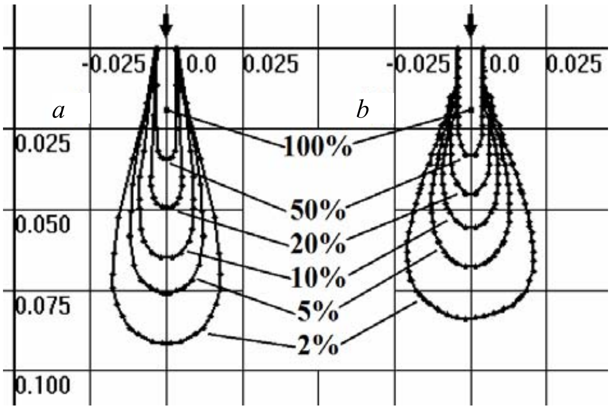

Fig. 2. Isodoses of irradiated object at the plane of symmetry: experimental (a) and calculated (b). The coordinates are measured in meters

It can be seen that the shapes of the calculated and experimental isodoses are qualitatively similar and have well-known pear-shaped form. At the same time, the quantitative differences are visible, displayed in a greater width and shorter length of calculated "pears". This is due to the fact that our model is focused on the description of the beams with energy of about 5 MeV, while the energy in the simulated experiment is much more. At this energy the calculation requires an accurate accounting of the secondary bremsstrahlung radiation and its contribution to the dose of the object.

2.2. THE INFLUENCE OF THICKNESS OF THE BEAM ON DOSE DISTRIBUTION

Analysis of the results of calculations with different thicknesses of the falling beam has revealed its influence on the form of the dose distribution in the direction of beam propagation.

Figs. 3,a-d show the two-dimensional distributions of the relative dose in the plane of symmetry for the four different thicknesses of the falling beam. The calculations were performed for beams with energy of 5 MeV, irradiated material has the characteristics of a sterilized object. On the figures, the beam is falling down to the object surface. The width of the object corresponds to the width of the picture and is equal to 30 cm. The density of the object is homogeneous. Fig. 3,e shows the dose distribution along the axis of the system for the same four thicknesses of the beam as in Figs. 3,a-d. Note that a different width of the irradiating beam is simulated by setting a different maximum deflection angle of the beam scanning system, while the other beam parameters – beam current and power, the number of bunches – remain unchanged. The beam width varies from very thin in the absence of scanning angle (3,a) up to thick enough to cover the whole object (3,d).

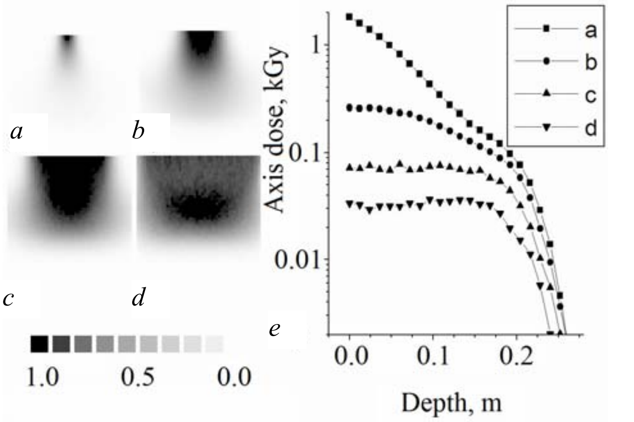

Fig. 3. Relative two-dimensional dose distributions in the plane of symmetry of the system for different width of the incident beam (a-d) and corresponded profiles of a dose in logarithmic scale (e) along the axis of the system

One can see that with the increase of the beam width the profile of dose along the axis of the system is changed. Monotonic decrease at the small width of the beam in Figs. 3,a,b is changed with a ("shelf") plateau-like profile with a decrease at the end in Fig. 3,c. Then, in Fig. 3,d (see also the presentation of this profile in a linear scale - curve "b" on Fig. 4,c) the profile became non-monotonic one, having the part of increase, and the maximum height at some distance from the object surface. Analysis shows that this maximum occurs not only because of the turning of some electron trajectories towards the surface of the object but also due to the contribution of electrons "arriving" to the plane of symmetry from the adjacent planes. One can say that it is a consequence of the addition of several pear-shaped dose distributions.

2.3. EFFECT OF THE ELECTRON BEAM ENERGY SPECTRUM

The above results refer to calculations and experiments with an electron beam with a negligible energy spread. However, the actual beam energy spectrum in the sterilization installation is relatively wide.

The role of the width of the energy spectrum of the beam is illustrated by the results of the calculations presented in Fig. 4. It shows the profiles of the doses received by a three-dimensional object irradiated by plane-parallel beam with all the parameters, listed in the previous section, and with the width corresponding to Fig. 3,d for two different energy spectrums. Figs. 4a,b are two-dimensional distributions of the relative dose in the plane of symmetry of the system, Fig. 4,c – dose distribution along the axis of the system. Fig. 4,a corresponds to the calculation with a monoenergetic beam, Fig. 4,b – with a beam with a "real" spectrum described in [10].

From the graph it follows that the dose distribution produced by the real beam is more uniform than in the case of a monoenergetic beam. The reason is that the low energy electrons create the maximum dose closer to the surface of the box than the electrons with high energy. As a result of the addition of doses produced by the fractions with different beam energies, the total dose is more uniform along the depth of the irradiated object.

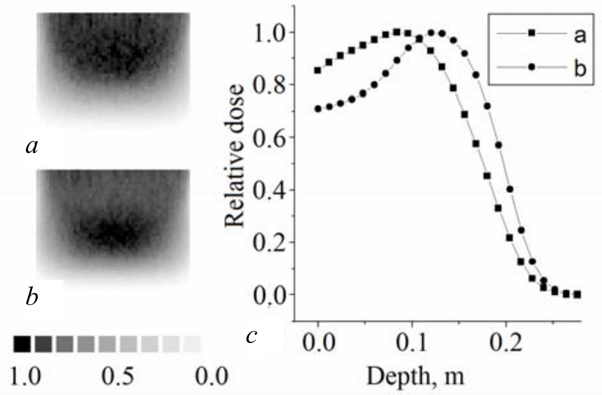

Fig. 4. Relative dose distribution in the plane of symmetry of the system (a, b) and along the axis of the system (c), created by monoenergetic beam (a) and the beam with the actual spectrum (b)

2.4. TEST CALCULATION FOR THE PLANE-PARALLEL BEAM

An important test for the sterilization installation is the irradiation of object with a plane-parallel beam front.

Fig. 5 shows the dose distribution along the axis of the system created by plane-parallel beam with an energy of 10 MeV in polystyrene. It shows the results of measurements on the accelerator IMPELA [11] in comparison with the results of calculations by the method [5, 6] and with the use of the program BEAM SCANNING.

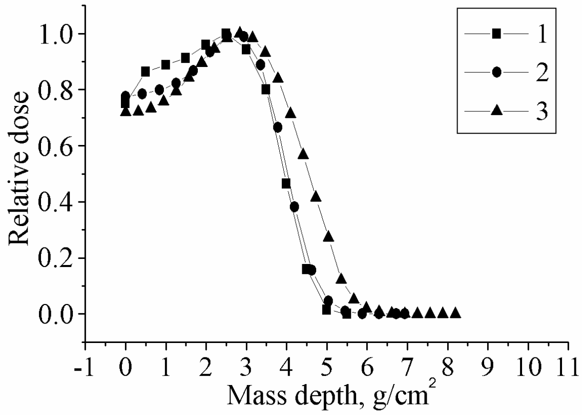

Fig. 5. Dependence of relative dose on the mass penetration depth of the plane-parallel beam with energy of 10 MeV in the target of polystyrene. Curve 1 – experimental data; 2 – calculation by program BEAM SCANNING; 3 – calculations by the method [5, 6]

As one can see, the result obtained with our program BEAM SCANNING differs from the experimental result not more than by 10…15%, and exceed the accuracy of the result obtained by the method [5, 6].

Another test made for comparison the calculation and experimental results obtained on our sterilization installation for the irradiation of the target consisting of a number of aluminum plates with the film dose meters between them. In our installation the electron beam is not monoenergetic, so the preliminary work is required to model and restore the energy spectrum of the beam (by the method described in [10]). Fig. 6 shows the dependence of the measured and calculated dose as function of penetration depth of the electron beam into the aluminum target.

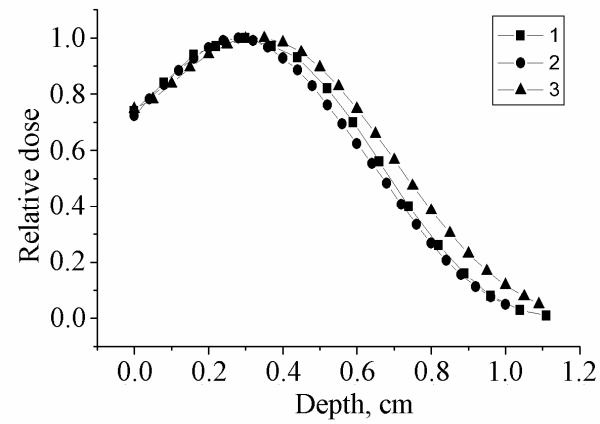

Fig. 6. Dose dependence on the depth of penetration of a wide electron beam in sterilization installation in an aluminum target. Curve 1 – experimental data; 2 – calculation by program BEAM SCANNING; 3 – calculations according to method [5, 6]

A comparison of experimental and calculated curves shows that the difference between them is within the experimental error of the measurements that is 10…15%. It is also seen that the method [5, 6] gives a little more difference from the measurements results.

2.5. CALCULATION OF THE BEAM CURRENT TRANSMISSION COEFFICIENT

One of the main operational methods of measuring the energy of the accelerated beam is the use of coefficient of beam current transmission through an aluminum plate. To find it, one should measure the current, coming to the plate, and the current passing through it and entering the Faraday cup, located behind the plate. The ratio of current from Faraday cup to the sum of these currents is called the current transmission coefficient. Its calculation is performed with the values of these currents, taken from the waveforms, mostly for the values on the plateau of 6-microsecond beam pulses. The characteristic energy of the beam is obtained using a known dependence of the transmission coefficient on an energy of a monoenergetic beam. Therefore, one of the test calculations is to compare the experimental and calculated dependencies of transmission coefficient through an aluminum plate on its thickness. Fig. 7 shows the graph of the transmission coefficient of a monoenergetic electron beam with an energy of 5 MeV through aluminum plates of different thicknesses obtained from the calculations and the experimental data [12] described in [7].

It can be seen that the result calculated using the BEAM SCANNING is in excellent agreement with the experimental data.

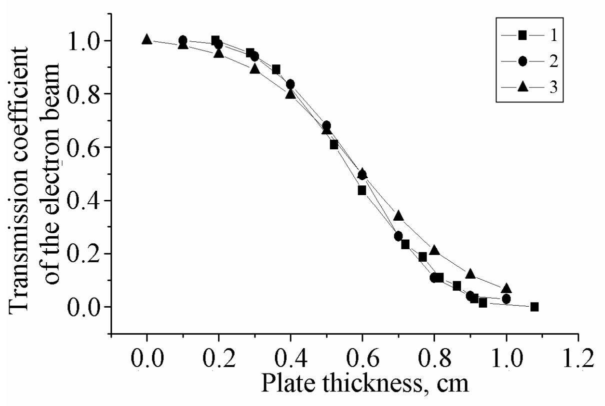

Fig.7. Dependence of transmission coefficient of the electron beam with energy of a 5 MeV through an aluminum plate on its thickness. Curves: 1 – experimental data; 2 – calculations by program BEAM SCANNING; 3 – calculation according to [7]

2.6. PRELIMINARY CALCULATION OF THE DOSE IN THREE-DIMENSIONAL OBJECT

Let's describe the results of preliminary calculations of the dose distribution produced by an electron beam in a three-dimensional target (box) to model the actual regime of operation of our sterilization installation. The calculations are carried out for the box with the dimensions 30x40x10 cm^3, i.e. for the length in the direction of the conveyor less than actual one. The results for the irradiation of the box with the beam with spectrum calculated for the working regime is shown in Fig. 8. The left part of the figure presents the whole box with the distribution of the dose on its visible faces. In the right figure part, the dose distributions on the three mutually perpendicular central cross-section planes of the box are presented. Electron beam is moving along the axis Z and enters the upper and lower faces of box, thus simulating the double-sided irradiation. Beam is scanned along the X axis, the conveyor moves along the Y axis.

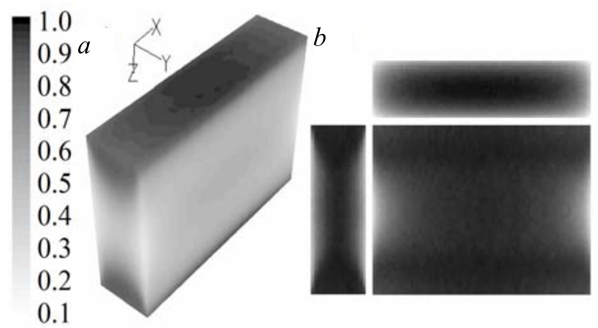

Fig. 8. Relative radiation dose for actual installation conditions on the box surface (a) and in three different central cross- sections of the box (b)

One can see relatively small dose inhomogeneity in the direction of scanning (along the X axis), which is due to an increase of linear velocity of the beam on the surface of the box when the angle of its deflection is large. This effect occurs when "sawtooth"-shape of waveform of the current in the magnet of scanning system is used. This inhomogeneity can be eliminated by optimizing the current waveform of the magnet.

The highest dose inhomogeneity occurs in the center of the edges connecting the narrow and wide side faces of the box. It is due to the following effect, manifested most strongly in the plane located at the mid-depth of the box (i.e., along the axis Z). Namely in this plane the most of the electrons leave the box through side faces. Non-uniformity in these areas of the box is beyond the permissible and requires finding the solutions to delete it.

CONCLUSIONS

The model of the process of irradiation of the three-dimensional objects by the electron beam in the compact sterilization installation based on standing wave linear electron accelerator with the local radiation shielding is developed. The method of describing this process is created and the program BEAM SCANNING for the calculation of the irradiation characteristics is modernized. The presented test results show good accuracy of calculations.

A possible positive role of the beam energy spread, which may give an equalizing of the dose in the irradiated box is demonstrated.

The mechanism of formation of non-monotonous dose profile along the axis of the system is found. It is due to contribution to the axial dose profile of neighborhood layers of a continuous beam or neighborhood electron bunches of modulated beam, each of which creates a pear-shaped dose. Contribution of the neighborhood "pear" to the dose leads to the appearance of a dose maximum located at a certain distance from the surface of the object (namely, at the distance of expansion of the "pear").

The preliminary modeling of the box irradiation in an actual operating regime of a sterilization installation is performed. The areas of the box with minimum dose are determined.

Finally, the physical-mathematical tool (computer code) is developed which allows studying the physics of the processes in the sterilization facility, in particular, to describe the mechanism of the dose creation in the box volume. It gives an opportunity to improve the installation, to make it easier a tuning and a testing of the facility.

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Article received 17.02.2014

МОДЕЛЬ ОБЛУЧЕНИЯ ЭЛЕКТРОННЫМ ПУЧКОМ ТРЕХМЕРНОГО ОБЪЕКТА В СТЕРИЛИЗАЦИОННОЙ УСТАНОВКЕ С МЕСТНОЙ БИОЗАЩИТОЙ

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Представлена разработанная модель процесса облучения трехмерного объекта электронным пучком в компактной стерилизационной установке с местной биологической защитой. Разработана методика описания этого процесса и модернизирована программа BEAM SCANNING для расчета характеристик облучения. Представлены результаты ряда тестов, показавшие хорошую точность расчетов. Проведено предварительное моделирование процесса облучения коробки в режиме реально работающей установки. Определены места коробки с минимальной дозой облучения. Выявлен механизм формирования немонотонного профиля дозы вдоль оси системы, состоящий во вкладе соседних слоев непрерывного пучка или соседних сгустков модулированного пучка, создающих грушеобразные распределения дозы. Разработанный метод и написанная программа позволяют описывать процессы при работе установки, а также выдавать рекомендации по ее оптимизации.

МОДЕЛЬ ОПРОМІНЕННЯ ЕЛЕКТРОННИМ ПУЧКОМ ТРИВИМІРНОГО ОБ'ЄКТА В СТЕРИЛІЗАЦІЙНІЙ УСТАНОВЦІ З МІСЦЕВИМ БІОЗАХИСТОМ

П.А. Бистров, Н.Є. Розанов

Представлено розроблену модель процесу опромінення тривимірного об'єкта електронним пучком у компактній стерилізаційній установці з місцевим біологічним захистом. Розроблена методика опису цього процесу і модернізована програма BEAM SCANNING для розрахунку характеристик опромінення. Представлено результати ряду тестів, що показали хорошу точність розрахунків. Проведено попереднє моделювання процеса опромінення коробки в режимі реально працюючої установки. Визначені місця коробки з мінімальною дозою опромінення. Виявлено механізм формування немонотонного профілю дози уздовж осі системи, що полягає у вкладі сусідніх шарів безперервного пучка або сусідніх згустків модульованого пучка, що створюють грушоподібні розподіли дози. Розроблений метод і написана програма дозволяють описувати процеси при роботі установки, а також видавати рекомендації з її оптимізації.