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STERILIZATION INSTALLATION ELECTRON BEAM DYNAMICS OPTIMIZATION

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Abstract
Some methods to increase efficiency of electron beam usage and to improve the uniformity of irradiation dose in sterilization installation are proposed. Irradiation methods are simulated using the developed computer code "BEAM SCANNING". The need in correction of the saw-tooth shape of current in the deflecting magnet at wide amplitudes of beam deflection angle is confirmed. The efficiency of magnetic scanning system that creates not parallel but slightly convergent electron flow is shown. Dose drop near the lateral faces of the irradiated object is demonstrated. Configuration of magnets, that increases the dose in this area, is proposed. The possible benefit of using low-energy electrons in the spectrum is shown. This benefit is manifested in possibility of additional exposure of the lateral faces of the object.

Key words
Electron, beam, scanning, irradiation, dose, calculation.

1 Introduction

Currently, in MRTI the work is held to increase the efficiency and productivity of a compact radiation sterilization installation "Raduga". An important feature of the installation is the use of local radiation shielding, which essentially reduces the size of the installation. Installation can be used in a room without radiation protection, so that serving personnel can work in it. Figure 1 presents the photograph of installation. An essential part of installation is a bell-shaped dome of radiation shielding under which the accelerator is mounted. Maximum energy of the electrons at the accelerator output - 5 - 6 MeV, impulse beam current - up to 250 mA, the bunch duration of the beam 4 - 6 ms, repetition rate of bunches - up to 300 Hz [Belugin et. al., 2001, Belugin et. al., 2009].

Installation contains irradiation chamber, through which passes a conveyor on which the irradiated objects are moved. Objects are placed in boxes, which have dimensions of 30 x 40 x 60 cm and weight up to 7 kg. Irradiation takes place in four stages: two times one side of the box passes under the accelerator, and two times reverse side. The power of installation electron beam is 1.5 kW. At a dose of about 25 kGy productivity of the installation is 16 boxes per hour.

Figure 1. The photograph of the sterilization installation "Raduga".

An important part of the work on installation perfection is to increase the efficiency of the beam scanning system. The paper presents the results of studying the causes of the irradiation inhomogeneity of the sterilized substances, uniformly packed in rectangular boxes. Ways to get rid of them are proposed.

The location of beam scanning system can be seen on the scheme, shown in Figure 2. Beam scanning system contains deflecting magnet (item 8) and horn (3) integrated in one unit with the accelerator (1) under a vacuum. The magnet provides the deflection of the beam at an angle up to 45 degrees. The angle scanning distributes the beam bunches across the entire width of the box (4). The horn is terminated with the beam exit window, covered with thin titanium foil of thickness 50 mkm. The exit window width is 1.6 cm, length – 40 cm.

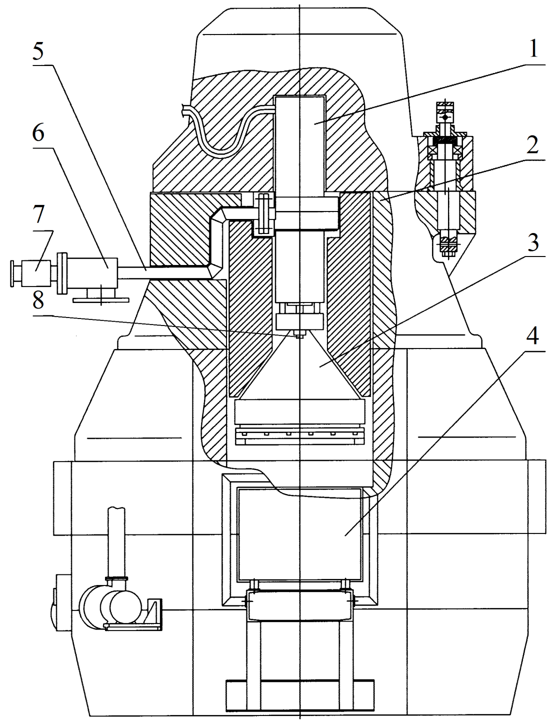

Figure 2. The scheme of the installation “Raduga” 1- accelerator; 2- local radiation shielding; 3- accelerator horn; 4- irradiated box; 5- waveguide; 6- magnetron; 7 – power supply; 8 – deflective magnet.

Within the work to increase the effectiveness of the beam scanning system, the computer code “Beam Scanning” was developed in MRTI [Bystrov and Rozanov, 2012 and 2014]. With this program the operation of installation “Raduga” was simulated. Particularly, the causes of substance irradiation inhomogeneity were investigated. To eliminate them, the following methods are proposed: the change of the particle trajectories at the entrance to the box, the selection of the current waveform of magnet power supply and exposure of the lateral faces of the box.

This paper presents the magnet configuration, which combines the methods listed above, for use in a beam scanning systems of sterilization installations. According to the calculations performed, the efficiency of the system increases, if the electrons, falling within the edge region of the box surface, are directed towards the central area of the box, rather than having divergent directions. This can be achieved by using compensating electromagnets (6), which windings are connected in series with a deflecting magnet (3). Such configuration of electromagnets, as shown in paper [Dmitriev et. al., 1980], provides the required trajectories for electrons with any energy.

The use of compensative magnets leads to a significant increase in the amplitude of the angle created by the deflective magnet. The increase in the angle amplitude leads to a decrease in the radiation density at the edge areas of the box surface, using a sawtooth (linear) shape of deflective magnet current, therefore there is a need to change the waveform of the magnet current supply.

In development of magnets configuration special attention was given to improving efficiency of the scanning system while increasing the irradiation uniformity. To increase the dose in the areas of lateral faces, the additional exposure of material by the low-energy electrons, creating a dose near the surface, is proposed. The configuration of the magnets, proposed in this paper, not only provides this irradiation, but also increases the beam usage efficiency, because the low-energy electrons are directed into the box rather than on the wall of the accelerator horn. This configuration also decreases the risk of horn perforation by the beam in some emergency situations.

The scanning angle amplitude setting for the proposed system is simplified. This paper provides an example of a concrete installation and description of its operation.

2 Calculation of Dose

Perfection of the installation sets the problem of providing the uniform irradiation of the entire box volume with minimal loss of the beam electrons. That is why the initial step is the study of radiation dose distribution in the objects, irradiated in working conditions of present installation. To find the dose distribution, calculations were performed using the developed computer code “Beam Scanning” [Bystrov and Rozanov, 2012 and 2014]. The program allows the simulation of the object irradiation process in installation and takes into account the main factors, which influence the radiation dose. The program calculates the process of beam propagation in the scanning system, passing through the scattering foil and moving to the surface of the irradiated box, then beam propagation in the irradiated matter, where the scattering of electrons and energy loss takes place. The results of calculations are the dose distribution by volume of irradiated material, showing the level of homogeneity of irradiation, the value of scanning system efficiency and the channels of energy loss, allowing to understand the reasons for the lack of system efficiency.

Figures 3a, b show the calculation results of object irradiation (box of sizes 30 cm high, 40 cm wide and 60 cm long) in the working mode of installation functioning. In simulation model the dose is created by the electron beam, which propagates along the Z axis, and irradiates the top and bottom surfaces of the box. This models the process of both-sides irradiation in the installation. Beam scanning is carried out in one plane along X axis, the conveyor moves along the Y axis. The figure shows the value of relative dose of the box contents near the box surface and in its central cross-sections in accordance with given color scale. Figure 3a shows the entire box with dose distribution on its visible surfaces. Figure 3b shows the dose distribution in three mutually perpendicular planes passing through

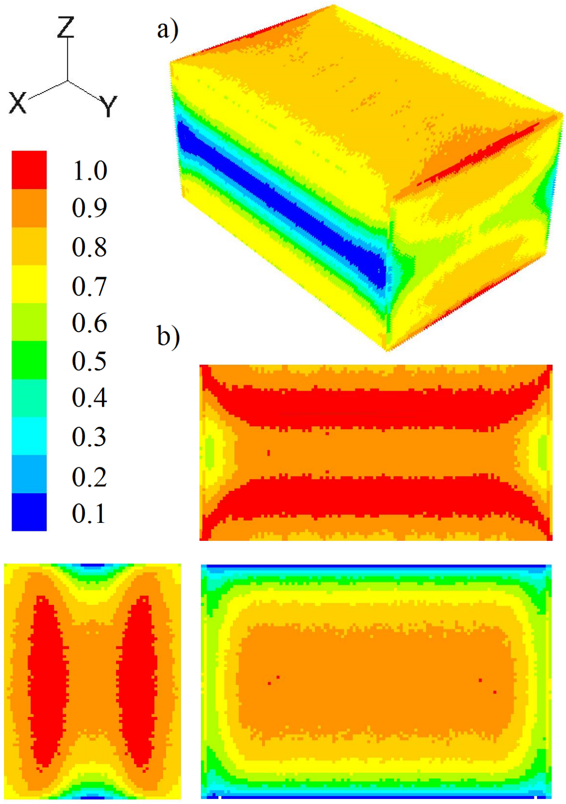

Figure 3. Relative dose in actual installation conditions: a - on the surface of the box; b – in three different central cross-sections of the box.

the center of the box. It is seen that the radiation dose is inhomogeneous in the volume of the box substance.

We can distinguish few types of the irradiation inhomogeneity. One is related to the decline in the radiation dose at the upper surface of the box near its side edges. This decline is 10-15% of the maximum dose and it can be called "edge decline". Another type is associated with the specifics of the formation of three-dimensional dose in volume of the material. One can see a noticeable dose decline in the region of the lateral edges and faces of the box, which are not under irradiation. This decline we can call the "side decline". "Side decline" is about 80%, that is significantly higher than the permissible amount and requires getting rid of. One can also see the essential inhomogeneity along Z axis. This inhomogeneity is due to specifics of the beam and will not be discussed in this paper. The values of relative inhomogeneities, caused by different types of declines, are significantly different. Nevertheless, perfecting the scanning system, we should get rid of both types of inhomogeneity. There is a possibility of simultaneous elimination of both of them, since they are interdependent.

The edge decline is caused by the decrease in irradiation density at the edges of the box at large angles of the beam deflection. This decline occurs when using a saw-tooth current waveform in deflective magnet, which causes the linear growth of the magnetic field in the scanning period. Technically it is quite simple to get rid of this inhomogeneity. To do this, one should choose the non-linear waveform of feeding magnet current. This current curve should provide an increase in the density of falling beam bunches at large deflection angles, so that their density along the width of the box surface will be in accordance with required uniform irradiation of the surface layer.

The "side decline" is due to electrons scattering in the irradiated matter. Scattered electrons leave the box through its lateral sides without returning back. There is a decrease in density of the scattered electrons in the irradiated material near these faces. To eliminate this decline it is not enough to correct the magnet current waveform, as the essential dose increase in this zone is required. Current waveform correction in this manner will cause the undesirable extra dose in the box surface area and also will significantly decrease the efficiency of the beam usage. Therefore most optimal method of eliminating this inhomogeneity is the additional exposure of lateral sides of the box.

The efficiency of the optimally tuned beam scanning system is 63% without the account of the beam losses, caused by the gaps between the boxes traveling on conveyor. Investigation of channels of energy loss shows, that the beam loses 10% of energy, while propagating in the horn. The main losses occur due to the beam miss falling into a box for large values ??of the angle of deflection. This loss is about 17%. About 10% of the energy is lost due to incomplete transfer of electrons energy to the material. The electrons leave the box, losing only part of the energy due to non-optimal angle of falling at area, close to the box edges, where they are directed from the center. The nature of these losses is illustrated schematically in Figure 6-1.

Nonoptimality of falling angle also contributes to the side decline in dose. To improve the efficiency of the scanning system additional magnets should be used, which influence on the electrons trajectory near the box surface, optimizing the beam falling angle.

3 Magnet Current Waveform Correction

Getting rid of "edge decline" of dose by adjusting the current curve of the magnet is the most simple in terms of technical execution. For "Raduga" installation it is possible to set any desired current waveform in digital form.

The "edge decline" is due to a decrease in the density of uniformly following beam bunches falling on the surface of the box with growth of the beam deflection angle in the scanning system. This occurs when magnet current and accordingly deflecting magnetic field are linearly dependent on time, that is at a saw-tooth current waveform, used in installation. To compensate the inhomogeneity of irradiation, one should make a non-linear dependence of the field from time.

At first, consider a simple geometrical scheme, showing the operation of the scanning system. This scheme

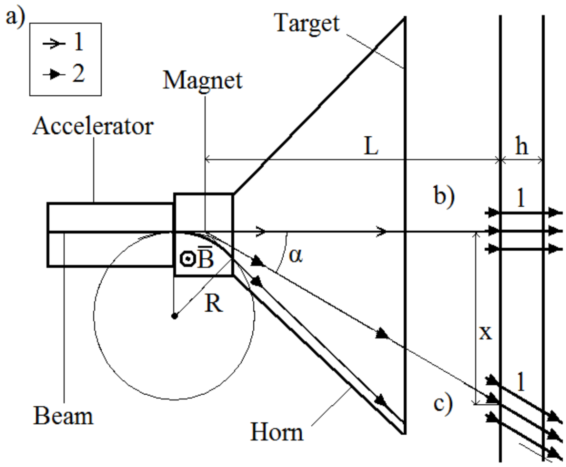

Figure 4. a - geometrical parameters of the system model; b - irradiation of the target with a perpendicularly falling beam; c – with a beam, falling at some angle. 1 - trajectory of the undeflected beam; 2 - trajectories of the deflected beam; α — angle of deflection: x - the deviation of the beam from the center of the target; R - cyclotronic radius; B - direction of magnetic field; L - distance from the center of the magnet to the target surface: h - the thickness of the surface layer of the target; l - length of the trajectories of particles in the layer.

is presented on Figure 4. The system contains a magnet which deflects the beam to an angle α. For simplicity, we assume that the deflection angle depends linearly on the magnetic field, current of the magnet and time. The intensity of the beam will be assumed constant, that is, the accelerator is considered as a source of a thin beam of particles with energy ε and uniform beam current I. Beam irradiates a thin layer of the surface. The thickness h of this layer is small, so that the beam direction and energy of the electrons in it can be taken constant.

If we assume that the beam comes from the center of the magnet at an angle α, defined by the magnet and hits the target located at a distance L from the center of the magnet, then the deflection of the beam from the center X on the surface of the box and its differential *dx* can be written as:

$$x = L\,tg\,(\alpha) \tag{1}$$

$$dx = \frac{L}{\cos^2(\alpha)} d\alpha \tag{2}$$

In our model, search for the current curve is reduced to search for the dependence of angle on time α(t) which provides the uniform irradiation. At a short time interval *dt* of irradiation beam passes to the target surface layer of the thickness h its energy *dE*, equal to:

$$dE = \frac{I\,S_\varepsilon\,\rho\,h}{\cos(\alpha)}\,dt \tag{3}$$

Where S_ε – stopping power of electrons in the material, ρ – density of the irradiated substance. The formula includes a path length h in the layer in which energy transfer occurs, and which increases in accordance with a deflection angle α, as one can see at Figure 4b, c. If we assume that the beam has a width of y (in a plane perpendicular to the figure) then the differential of irradiated mass can be written as:

$$dm = \rho\,y\,h \frac{L}{\cos^2(\alpha)}\,\alpha'(t)\,dt \tag{4}$$

Where $\alpha'(t)$ — derivative of the deflection angle. Dividing (3) to (4) we can get the absorbed dose:

$$D(t) = \frac{I\,S_\varepsilon \cos(\alpha(t))}{L\,y\,\alpha'(t)} \tag{5}$$

The required dependence of the angle on the time can be found by solving the differential equation (5) for $\alpha(t)$ in which the dose is constant. For a linear scanning time dependence, as it follows from (5), if we take $\alpha'(t)$ as constant, then edge decline occurs due to the acceleration of motion of the beam on the surface of the irradiated object with increasing scan angle. This inhomogeneity produces the edge decline by the decrease in the density of beam surface irradiation with a coefficient equal to *cos* α.

In the sterilization installation “Raduga” the distance from the foil to the center of the magnet is 42 cm, the distance from the foil to the surface of the box – 17 cm, and the half-width of the box – 20 cm. Maximum angle of deflection of the beam is thus 19 degrees. This corresponds to a decrease of the density ratio of the beam falling up to 0.9 when irradiating the edge of the box (the coefficient falls from 1 to 0.9 when moving from the center to the edge of the box). To get rid of “edge decline” one should adjust the magnet current waveform so that more beam bunches propagate at high magnetic fields.

For the “Raduga” installation, a detailed simulation of the box surface irradiation was performed with the help of computer code “Beam Scanning”. The dose distribution on the surface was investigated. The curve of dose decline at the edges of the box surface due to the increase of the deflection angle of the beam was found. From this curve the magnet current waveform was calculated which allowing to flatten this dose. This curve is constructed so that the derivative of the deflection angle at the time was reduced by the decline coefficient, which depends on the angle of deflection. The decline in dose along the width of the object at a linear dependence of the current on time is shown in Figure 5, curve 1. Curve 2 represents the dose profile, created using the corrected current waveform.

From these curves one can see, that the current waveform correction may be performed in installation and cause a good improvement in the dose uniformity in

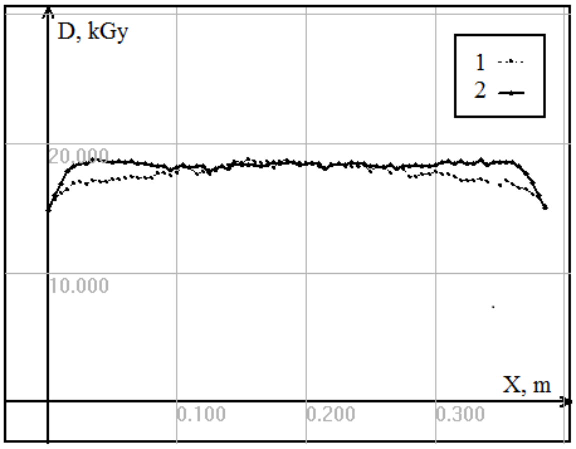

Figure 5. Alignment of the surface dose by changing the magnet current waveform: 1 – dose at saw-tooth current, 2 – dose at matched current waveform.

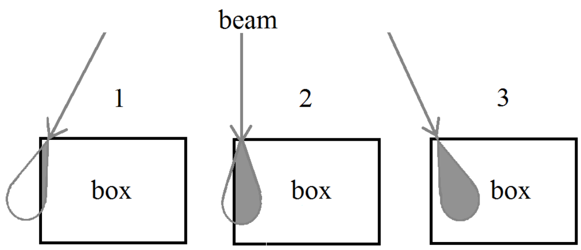

Figure 6. Typical pear-shaped contours of dose produced by the beam and the efficiency of the beam usage depending on the falling angle at area near the edge of the box: 6-1 divergent beam, 6-2 parallel beam, 6-3 converging beam.

the surface area. However, the use of this curve in the installation "Raduga" does not promise a substantial payoff. Decline of dose at the edge of the box does not exceed 10-15% that is permissible, while increase in the density of bunches, that fall on the edge of the box, may result in a noticeable reduction in system efficiency, since the direction of the electrons at the box edge is not optimal. Falling near the box edge, the electrons penetrate through small volume of irradiated matter in the box and fly away, leaving only a small amount of their energy, as shown schematically in Figure 6-1.

As to "side decline", it cannot be eliminated by adjusting the current curve, since the electrons that fall near the box edge, do not penetrate deep into the box. Side decline can be eliminated by using additional compensative magnets which influence the trajectory of the electrons near the box surface and allow irradiating the box lateral faces. Although the current curve adjustment does not give the desired effect in currently used beam scanning system, it is necessary when using additional compensative magnets. Usage of these magnets requires increasing the amplitude of beam scanning angle, and the inhomogeneity of irradiation, associated with the edge decline, grows. Moreover, the adjustment of the current waveform can be a simple and efficient way to influence the ratio of doses at the center and at the edges, whereby to achieve better uniformity of the irradiation, and, hence, to increase the installation productivity.

4 Known Constructions of Compensative Magnets

In spite of possibility of eliminating the edge decline by adjusting the current waveform, the problems of side decline (when considering the matter in the volume of the box) and insufficient efficiency of scanning system remain. The reason for side decline, as discussed earlier, is the scattering of electrons in the material of the box and the electron density decrease near the side faces due to departure through them. The reason for insufficient efficiency is non-optimal angle of propagation of the beam at the edge of the box, which cause a decrease in the length of the path in which the energy of the electrons is transferred to the irradiated matter.

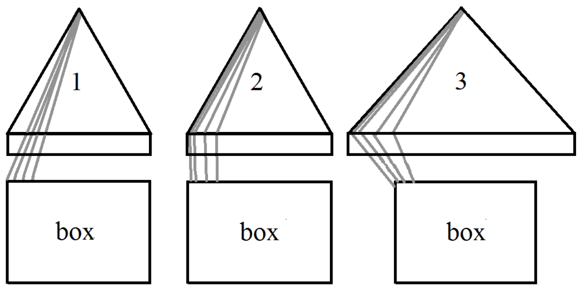

Figure 7. Use of compensative magnets located at the exit window of the horn allows changing the angle of the beam falling on the box surface and increase the efficiency of the scanning system. 7-1 divergent beam, 7-2 parallel beam, 7-3 converging beam.

As already noted, to increase the efficiency of scanning system one should use additional magnets to change the trajectories of the electrons near the surface of the irradiated box. Trajectories should be changed so that the electrons from the edge of the box propagate in the direction of its center, which is schematically shown in Figure 7-3. This will cause a more complete transfer of the electron energy into matter. The use of compensative magnets should be done in conjunction with the corrected current curve of the deflective magnet. Changing the angle of direction of the electrons at the edge of the box surface makes effective the correction of the magnet current curve to eliminate the edge decline. In turn, the use of compensating magnets leads to the need for correcting the current waveform due to increasing amplitude of the scanning angle.

Figure 7 presents the schemes of various types of beams, which can be formed by compensative magnets. In the absence of such magnets, box is irradiated by a divergent beam flow, as shown on Figure 7-1. When using the compensative magnets, convergent or parallel flow can be created, as shown on Figure 7 - 2,3.

With the help of the computer code "Beam Scanning" the preliminary calculations of irradiation by the beam,

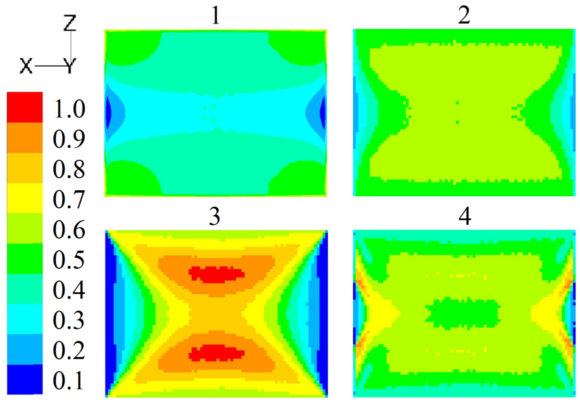

Figure 8. Results of irradiation by a beam, distributed uniformly over the surface of the box, presented in the cross-section plane of scanning: 8-1 - divergent beam, 8-2 - parallel beam, 8-3 - converging beam, 8-4 - converging beam that covers lateral faces.

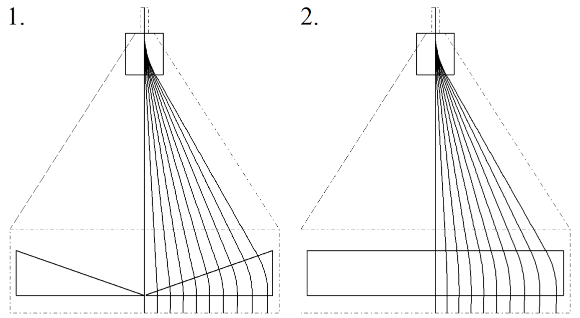

Figure 9. Types of compensative magnets and beam trajectories: 1 - based on permanent magnets with triangular pole shape; 2 - on the basis of an electromagnet connected in series with the deflection magnet.

uniformly distributed over the surface, were carried out for all three scanning systems, the results of which are presented in Figure 8. The efficiency associated only with the loss of the beam electrons through the side walls, is 79% for the diverging beam (Figure 8-1), 91 % for a parallel beam (Figure 8-2) and 96% for a converging beam (Figure 8-3). The best dose uniformity is achieved for divergent and parallel beam, the best efficiency - for convergent. Thus, using the compensative magnets increases the efficiency, but also increases the dose drop near the side edges. This entails the need to provide additional irradiation of the lateral faces of the box. Presented on Figure 8-4, the calculation results of box irradiation by a broader converging beam, which covers the lateral faces. The figure shows that the uniformity of irradiation significantly improved, while the efficiency maintains near 95%.

There are known two types of compensative magnets in scanning systems. One such device, protected by a patent [Pirozhenko et. al., 1995], has permanent corrective magnets in its basis. These magnets are arranged so that their magnetic field is constant in time but varies in space. Magnets scheme is presented in Figure 9-1. Induction of the magnetic field between the magnets is constant. Beam path traversed in the field of the magnets is maximal near the edges and minimal at the axis of the accelerator. With the passage of electrons through a field their direction changes: the farther the electron flies from the accelerator axis, the greater the turning angle of its trajectory. This ensures parallelism or convergence of trajectories of electrons at the box surface.

Another way is to install an electromagnet, which is powered by the same current as the deflecting magnet of scanning system, but has the opposite direction of the field. Using such a magnet makes possible to align the beam path to a fully parallel or converging. One patent proposes to use the compensative magnet in the form of O-shaped electromagnet wherein the height of the pole and the air gap are equal to the corresponding values in the deflective electromagnet. The windings of both electromagnets have the same number of turns and connected in series to the scanning power supply. Because supply currents and poles dimensions are equal, the electrons are turned in the compensative magnet at the same angle as in the deflective magnet, so their trajectories become parallel to the axis of the accelerator [Dmitriev et. al., 1980]. The scheme of the system is presented in Figure 9-2.

System with additional magnets (permanent magnets), was tested on the installation, but did not allow to reach the desired result, as it led to extra dose in the surface area in the center of the box. This occurs for two reasons. Firstly, because the linear current through the deflective magnet was kept, while the scanning angle amplitude was significantly increased by using the compensative magnets, that led to the growth of the edge decline. Secondly, because the low-energy electrons in spectrum made the contribution to increasing the dose in the center. These electrons are turned by permanent magnets stronger than the main beam and dropped toward the center of the box. When such a system was tested, the side decline maintained and the edge decline increased, also new types of inhomogeneity appeared. This caused the further work on improvement of the scanning system.

For our purposes of improving the efficiency of scanning system and eliminating the side decline the convergent beam should be used. As a prototype, the second type of compensative magnet should be taken, since it operates correctly with the low-energy electrons. However, when using a converging beam, while increasing the efficiency, the inhomogeneity of dose also increased in the form of side decline, since the electrons are directed towards the center, as seen on Figure 8-3. To solve this problem, one should use a horn that is wider than the box width, on which to install the electromagnets, which turn the beam in the opposite direction along the axis of the scanning as on Figure 7-3. The width of the horn and the electromagnet should provide the possibility for electrons to fall not only on the box edge, but also on its side face.

In the case of a system with a converging beam this can be achieved by increasing the amplitude of the scanning angle. The amplitude is adjusted so that the beam not only covers the edge region, but also the side face of the box. The density of falling bunches on this face can be controlled by adjusting the current waveform of the magnets. The results of calculations for such system are presented on Figure 8-4.

Installation of compensating magnets results in considerable increase in the angle scanning, created by a deflective magnet. In contrast to the divergent flow, when creating a parallel or convergent flow, the beam must reach the deviation greater than half of the box width at a distance of the arrangement of compensative magnet. This distance is less than the distance to the box. The amplitude of the deflection angle, thus reaches 30 degrees or more. With this amplitude, edge decline will be more than 20 percent. This inhomogeneity should be eliminated by correcting the magnet current curve simultaneously with defining the degree of the side face irradiation.

On Figure 8-3 one can see, that it may be effective to use the converging beam with a quadripartite box irradiation. With such irradiation the uniform dose can be achieved with very high efficiency. Unfortunately, it is not easy to implement the quadripartite irradiation on the installation “Raduga” because of its design features. So the best solution is to use a parallel or slightly convergent beam with bilateral irradiation. The option of a wide horn and large convergence angle, as shown in Figure 7-3 is not suitable for installation “Raduga”, because the horn width is limited by radiation shield size, that do not allow to create a strongly convergent beam..

5 Proposed Design of Compensative Magnets

In the previous part the option of box irradiation by a converging beam with the angle amplitude, allowing irradiating the lateral face was considered. Such a device is expected to demonstrate a good uniformity of irradiation in conjunction with the high efficiency of beam usage. However, the use of a wide converging beam does not exhaust all the possibilities for improving the installation.

It is known that the beam of the accelerator, which used in the installation, has a wide energy spectrum. This causes the loss of the low-energy electrons, as they are deflected to excessively large angles, when scanning the beam along the object. This loss leads to lower efficiency and it is desirable to utilize these electrons for irradiation.

When injected into the surface of the box the low-energy electrons lose their energy in the thin layer of the surface region, creating the dose in it. For example, in a system with permanent magnets, these electrons created the excessive irradiation of the surface in the center of the box. As ”side decline” takes place in a thin zone, which lies near the side faces of the box, it is desirable to direct the low-energy electrons to the additional exposure of the side faces of the surface of the box. Due to the small thickness of weakly irradiated zone, these electrons are most suitable for additional exposure.

Setting the amplitude of the magnetic field is not an easy task. In case of large scanning angle amplitude, the installation efficiency is decreased. In case of small amplitude of scanning angle the edges of the box are not irradiated enough. The main problem is to find the minimum amplitude of the magnetic field which provides the required uniformity. It would be desirable to have a more convenient way to adjust the amplitude of the field of scanning system which makes the loss of electrons impossible.

Solving the above described problems and implementing the proposed ideas is possible by using new device, described in [Belugin et. al., 2014], containing the developed system of magnets. The proposed device can be used to increase the efficiency when irradiated not only by convergent but by parallel or divergent beam. However, the best results are achieved with a converging beam.

The device contains a wide (in plane of scanning) horn, which enables irradiation of sterilized objects in form of boxes with converging electron beam. The width of the horn allows irradiating both the upper and the side faces of the box. Convergence angle of the beam is determined by the characteristic angle of electrons scattering in a material of the object. The device comprises one deflective and a few correcting magnets. Compensative magnets are designed to convert a divergent beam into a convergent beam. In the proposed device, compensative electromagnets are fed by the same current as the deflective magnet and form the electron beam trajectories, converging at the desired angle.

The device differs from its prototype [Dmitriev et. al., 1980] by the shape of the magnet poles. Also the difference is in using the additional electromagnets at the edges of the main compensative magnet. The triangular shape of the deflective magnet pole, creating a triangular-prismatic field profile, provides a limitation of the deflection angle of the electrons and the preservation of low-energy electrons of the beam spectrum. Edge compensative magnets provide useful utilization of the entire electron beam and the additional exposure of the side faces.

Poles of additional compensative magnets also have a triangular shape and create a prismatic profile of field in the horn. Poles of these magnets are adjacent to a rectangular pole of the basic compensative magnet by a base of the triangle, while triangle vertex is directed to the edges of the horn.

The feature of the proposed system is that possible deflection angle of the electron is limited and determined by the shape of the pole. Electrons under an overvalued field of deflective magnet, as well as the electrons of low-energy part of the spectrum under the nominal values of field are deflected by this angle. The advantage of the proposed system is that the electrons are not lost, falling to the horn wall, but propagate on parallel trajectories along this wall at a short distance. The edge compensative magnets turn these electrons in the direction of the lateral face of the box. The triangular shape of the poles of the magnets and their arrangement provide turning all of these electrons at one angle and parallel propagation to the side face, thus, increasing the dose in the region where it is usually low. This is the way, how side decline near the surface of the lateral faces, being compensated.

The angles of the triangles of deflecting electromagnet pole and compensative electromagnets as well as the location of the magnets are found from the geometrical calculations. The optimal magnet current amplitude and waveform in scanning system are defined based on the fact that at small amplitudes of magnet current, there is a good exposure of the central area of the box surface, and at large amplitudes box edges and side faces get more irradiation, which makes it convenient to configure the system to ensure uniform irradiation. At a large magnet current amplitude there is a significant increase in number of electrons, propagating parallel in a narrow region from the edge of the additional compensating magnet pole. This may demand some actions to protect the exit window foil from overheating and perforation. These actions involve the defocusing of the beam, which can be accomplished by adjusting the current waveform or the pole shape of additional magnets in order to reduce the load on the foil to acceptable values. The optimal width of compensative magnet is found from the calculations for convergence angle of the beam, which is determined by the characteristic angle of electrons scattering in irradiated matter. The device can also be operated with parallel or divergent beam flow, by irradiating the edge of the box instead of a side face, but the efficiency of system will be lower.

Proposed compensative and deflective magnets increase efficiency of the beam usage, as well as improve the uniformity of irradiation, since they use low-energy electrons by directing them to the side faces and edges of the box, where according to calculations, there is a decrease in dose at a surface area. In known systems, these electrons are lost. The efficiency of usage of high-energy part of the beam spectrum also increases due to the fact that the electrons pass into the box at an angle, directed toward the center, which is optimal, as it reduces the number of electrons leaving the irradiated object through the side walls of the box.

6 Proposed Design Implementation Example

As an implementation example of the proposed construction one can consider an electron beam scanning device for electrons with energy of 5 MeV. Angle of a deflective magnet pole at vertex is 16 degrees, scanning angle amplitude is 32 degrees. Dimensions of the irradiated object are 400 mm wide and 300 mm high. The height of the triangle pole of a deflecting magnet is 50 mm. The main compensative magnet has a length of 450 mm and a height of 60 mm. Additional magnets have poles, which have triangular shape with a height of 80 mm, base 60 mm, with the base closely adjacent to the side faces of the basic magnet pole. The blocks of compensative magnets are located at a distance of 35 cm from a deflective magnet.

Figure 10 presents the scheme of proposed system in plane of scanning. The scanning system contains the horn (item 1), beam exit window (2), deflective magnet (3), magnet current power supply (4), blocs of compensative magnet, each of them contains one basic electromagnet (7) and two additional electromagnets (6). The irradiated box (5) is placed below the system. The horn (1) is connected to electron accelerator (9) by its narrow end and forms the entire vacuum volume with it. The wide end of the horn is terminated with the sealing exit window (2), covered with a thin titanium foil. The horn is made of a nonmagnetic material such as stainless steel. At the narrow end of the funnel the deflecting electromagnet (3) is installed in such a manner that the poles are on opposite sides of the horn. The two blocks of compensating magnets are installed near the wide end of the horn on opposite sides. Each block contains electromagnet (7) in the form of a rectangular bar, and two electromagnets (6) in the form of triangular side extensions of basic magnet. The power source (4) and electromagnets (3), (6) and (7) are connected in series by the wire (10). Poles of the magnets are made of magnetically soft material (eg, iron Armco)

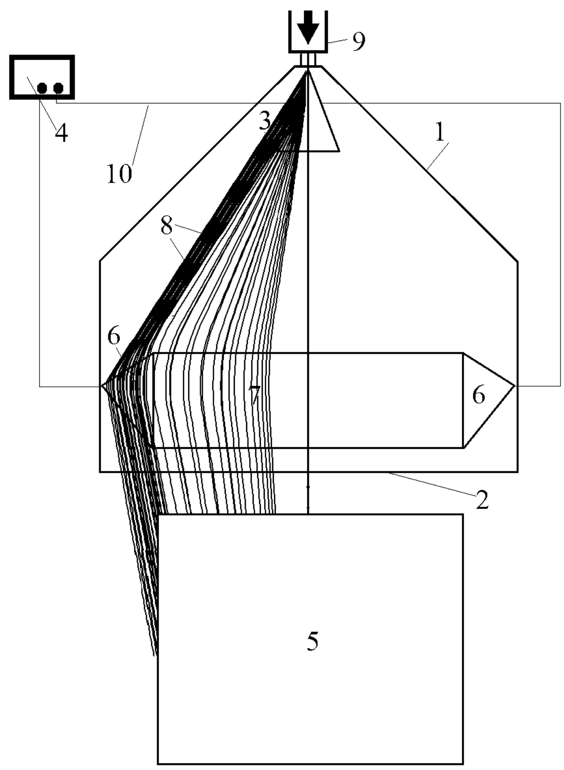

Figure 10. The scheme of scanning system and the trajectories of the beam electrons.

Poles of all the magnets are adjacent to the horn. The height and thickness of the basic compensative electromagnet (7) are constant along the center line of the accelerator and along the scanning direction. The magnetic field, created between the blocks of deflective (3) and compensative (6,7) magnets, located in the vacuum cavity of the horn (1). The direction of magnetic field is perpendicular to the wide side of the horn for all magnets. The direction of the magnetic field for blocks of each magnet is the same. The basic compensative magnet (7) is following the deflecting magnet (3) along the electrons motion trajectories. It creates a magnetic field, equal in magnitude, but opposite in direction to the field of the deflective magnet. The length of the trajectory in the magnetic field of compensative magnet is slightly greater than the length of the trajectory in the field of deflective magnet. This field changes the trajectories of the electrons on such a way, that they form a converging beam, which covers the entire width of the irradiated object surface (5) during a scanning period.

The main compensative magnet (7) is placed in such a way, that all the electrons propagating at angles less than the maximum and moving from the base of the triangle pole of the deflective magnet (3) fall into the area of its field. Additional electromagnets (6) are placed so that only those electrons, which propagate on parallel trajectories with a maximum angle of deflection, fall in the area of the field, produced by them. Field of additional electromagnets turns these electrons in the direction of the lateral faces of irradiated boxes (5). As a result, all the electrons in the beam for all values ??of the magnetic fields of the magnets in system are traveling by the trajectories (8) which fall into the irradiated box under optimal angles.

The beam scanning system shown in figure works as follows. The electron beam, emerging from the accelerator (9) passes through a magnetic deflection field of the electromagnet with a triangular shape pole (3). The beam is deflected and expands in the plane of scanning in accordance with the beam electron energy spectrum. Maximum possible deflection angle of the electron in deflecting field is limited by the magnet pole geometrical form; thereby electrons deflected on maximum angle do not fall onto the horn wall (1). Electrons with different energies are distributed along different trajectories (8), but all of them are falling into the box (5). The desired angles of electrons trajectories with the box surface are provided by compensating magnet (7) having additives (6). The pole shape of additional magnets (6) provides turning the electrons, flying along the horn wall, on an equal angle.

If small amplitude of the scanning magnetic field is set, the beam electrons with a typical energy are deflected within the limits of maximum angle, determined by magnet pole, and pass through the field of main compensative magnet. If the amplitude is increased, or for low-energy electrons, the trajectories of some electrons are going outside the deflective magnet field. Leaving the field of deflective magnet, these electrons propagate further along parallel paths with a maximum deflection angle in a narrow area along horn wall to its bottom edge. In that area, they fall into the scope of the field of additional compensating magnets, which provide reverse rotation of the beam electrons. Triangular shape of the poles of the magnets (6) provides a turn of all these electrons at a predetermined angle and their targeting to the edge area and lateral wall of the box. The irradiation of the lateral faces of the box, as required, is done by the electrons of the low-energy part of the spectrum.

With the growth of the amplitude of the scanning field, an increasing number of electrons will leave the deflecting magnet field area, spread with a maximum deflection angle and fall into the edge area and lateral face of the box, increasing the irradiation dose of this region. Thus, all beam electrons always fall into the box, but are distributed between central and edge regions in accordance with amplitude of magnets current. This is the essence of simplification of magnet current adjustment.

7 Conclusion

From calculations, carried out using the “BEAM SCANNING” computer code, characteristic zones of objects radiation dose inhomogeneity (decline) in the sterilization installation “Raduga” are found. The causes of these inhomogeneities are analyzed. Proposed solutions, such as the correction of the magnets current, mounting additional magnets, changing the shapes of the magnets poles and adjusting the dimensions of horn of beam scanning system are considered. The optimal combination of the proposed methods, which provides the maximum efficiency in conjunction with a uniform irradiation of the object is found.

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