Formation of Electron Beam Fields with 3D Printed Filters

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Abstract. In this research the electron beam traverse profiles beam before and after the application of the developed filter element was calculated and experimentally obtained. The article presents the calculated parameters of the unit form and geometrical dimension, forming the determined electron beam profile, and the physical configuration of the filter produced by 3D print method. The electron beam field distributions before and after filtration obtained with the help of GAFCHROMIC EBT2 radiographic films are illustrated. The calculation method of the filter actual density determination is presented. In the paper the comparison results of the electron beam experimental and calculated profiles are shown.

INTRODUCTION

It is known that cancer is among the most dangerous diseases with quite high lethality. One of the most common localization include: breast and skin. For their treatment electron beams are widely used, which allow to achieve good therapeutic results.

However, there is a risk of acute post-radiation complications from critical organs and healthy tissue, such as heart and lungs. As a consequence, there is a need to develop methods that improve the accuracy of dose delivery directly to the pathological focus and elimination of critical organs of the radiation field [1-2].

One of such techniques is the production of filter elements, the shape of which is designed to suit individual anatomical features of the patient. However, it has not found widespread due to the fact that the manufacture of these elements takes time, and one of the most important factors influencing the effectiveness of treatment for cancer is the speed of rendering aid to the patient, and the time spent on preparing for the radiation therapy should be minimized. In addition, the shape of the filter elements can be changed after each procedure by the virtue of the disease dynamics, which also imposes a restriction on their use [3-4].

The current state of the three-dimensional printing technology allows solving a wide range of tasks, both in industry and medicine due to its cheapness and rapidity of manufacturing products. Recent developments in this area meet the requirements of radiation therapy and will allow doing the rapid production of devices for the collimation of electron beams, forming their fields and dose intensity distribution in the amount according to the objectives [5-6].

In this paper we propose a method of formation of electron beam fields to the settings profile, using the flattening filter created by three-dimensional printing methods. Testing of the method was carried out on the extracted electron beam of the Tomsk Polytechnic University microtron for a further use of the results for the formation of clinical electron beams, for example, the extracted betatron beam.

Prospects of Fundamental Sciences Development (PFSD-2016)
AIP Conf. Proc. 1772, 060018-1–060018-7; doi: 10.1063/1.4964598
Published by AIP Publishing. 978-0-7354-1430-3/$30.00

As part of this, the correction of the developed model of the microtron extracted electron beam [5] was held; model-based filter elements, which changed the beam shape in a predetermined manner were calculated; flattening filters of the electron beam were produced by fused deposition modeling; experimental measurements of the electron beam profiles and shapes with the filter as well as without it were carried out; a comparison of the calculated and experimental data was conducted.

MATERIALS AND METHODS

Radiation source

In the study the investigation of the extracted electron beam from the microtron TPU with 6.1 MeV energy was carried out; the basic parameters of the source are given in Table 1 [7-8].

TABLE 1. The parameters of the electron beam extracted microtron TPU

Parameter	Value
Beam size at output	2.0 mm^2
Beam divergence	0.1 rad
Macro pulse duration	4 mks
Pulse-recurrence rate	1-8 Hz
Maximum energy of the electron	6.1 MeV

Modeling

Numerical simulation was carried out by the Monte-Carlo method by means of the software "Computer Lab (PCLab)» Version 9.6, allowing to model the character of the interaction of electrons, photons, protons and positrons with matter with desired characteristics [9]. The calculations were based on the previously developed model of the extracted electron beam of the TPU microtron [5].

The microtron components that are responsible for injecting, focusing and extraction of the electron beam have to debug for each vacuum pumping, accordingly the beam parameters are going through changes. For this reason, after realignment accelerator facility each time it is necessary to carry out the adjustment of the model. To this end, the work was divided into two phases.

The first step was experimental evaluation of the beam profile and shape, the second - to adjust the current model of the beam based on the experimental data obtained.

After the adjustment based on experimental data for the simulation of the character of the electron beam interaction with ABS plastic, the following parameters of the beam were used: size of the beam at the output - 2.0 mm^2, the divergence of the beam - 0.085 rad, electron energy – 6.1 MeV.

In the next step based on the received data, the flattening filters geometry calculation was conducted. For simulating the flattening filter was located 15 cm from the microtron output window, the electron beam profile analysis was done on a distance of 20 cm from the output window. Analysis of the shape and profile of the beam was performed in air.

Experiment geometry

For divergence angle estimation the vertical and horizontal dimensions of the extracted electron beam were measured by scanning frame and the Faraday cup. Faraday cup is located such that the whole beam would hit in its working area. When moving the frame transversely to the axis of the beam a part of the electrons is absorbed or scattered therein, this affects to the level of Faraday cup signal. Scanning is done in increments of 2 mm. The cross-scan was performed at distances of 10, 15, 20 and 25 cm from the output window.

To obtain more accurate information about the shape and profile of the electron beam GAFCHROMIC EBT2 radiographic film (Ashland Advanced Materials, US) were used. This film consists of a yellow marker dye in the active layer and a synthetic polymer as the binder component. Dose range is from 1cGy -10Gy for measuring in red color channel up to 40Gy for measuring in green color channel. The GAFCHROMIC EBT2 film is energy independent from 50 keV into the MeV range [10-12]. The use of film dosimeters made it possible to estimate the profile and shape of the beam directly from the output window of the accelerator. These measurements were made in increments of 5 cm. For receiving of two-dimensional distribution in the plane of the beam axis, the film was placed perpendicular to the beam transmission axis. Since the microtron electron beam has a high intensity, exposure time is chosen taking into account the sensitivity of the film, and corresponds to one pulse of the accelerator.

At the final stage, an experimental analysis of the beam profile formed by flattening filter obtained by scanning frame and GAFCHROMIC EBT2 radiographic films was carried out. Flattening filter was located at 15 cm from the output window of the accelerator, the electron beam profiles were obtained at a distance of 20 cm from the output window.

RESULTS AND DISCUSSION

Figure 1 presents the spatial distribution of electron beams obtained by the GAFCHROMIC EBT2 radiographic films at distances 5 and 20 cm.

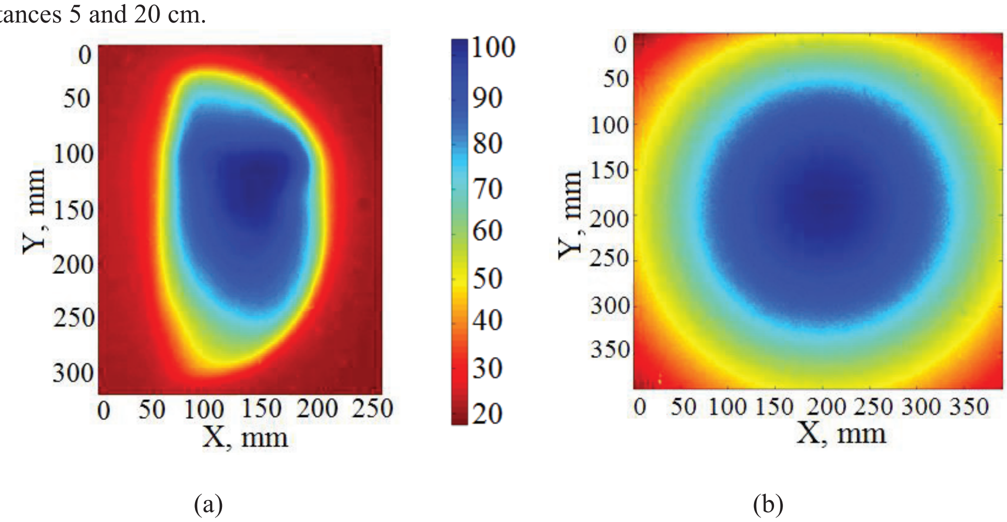

FIGURE 1. The spatial distribution of electron beams obtained by the GAFCHROMIC EBT2 radiographic films at distances 5 (a) and 20 cm (b)

From the figures it is clear that at the exit of the microtron the divergences of the extricated electron beam in horizontal and vertical directions are different, this can be explained by influence of quadrupole magnets which set before the output window. Therefore, this effect should be considered in future simulation of the filter parameters. However, such strong asymmetry mitigated at the distance beginning from 15 cm from the window. In this connection, the position of the filter elements must be at least 15 cm.

To calculate the parameters of the filter elements and the estimation of the electron beam intensity distribution before and after filtration an adjusted model has been used. A filter element made of ABS plastic (Table 2, Fig. 2) was designed to form a predetermined beam profile.

TABLE 2. The dimension of the flattening filter layers

Layer	Radius, mm	Layer thickness, mm
1	3	0.5
2	4	0.7
3	6	0.7
4	12	1

FIGURE 2. The physical configuration of the flattening filter

Figure 3 shows the calculated profiles in transverse plane (h) of the electron beam at 20 cm with and without filtration.

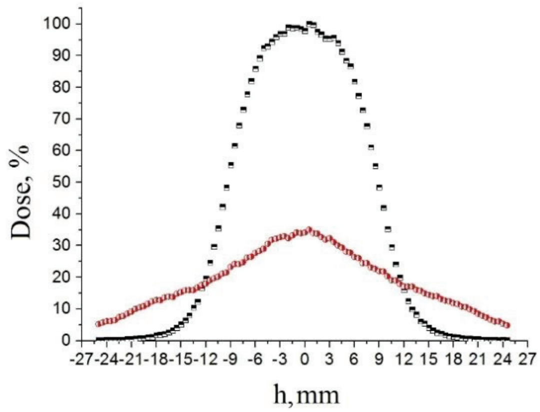

FIGURE 3. Calculated profiles of electron beams:
■ – without a filter, ◑ - with a filter

The flattening filter with calculated geometrical parameters was made with the help of three-dimensional printing technology from ABS plastic and an experimental analysis of the microtron shaped electron beam profile was conducted. Figure 4 shows the experimental and calculated profiles in transverse plane (h) of the electron beam without a filter element and with it. Experimental results obtained by scanning frame.

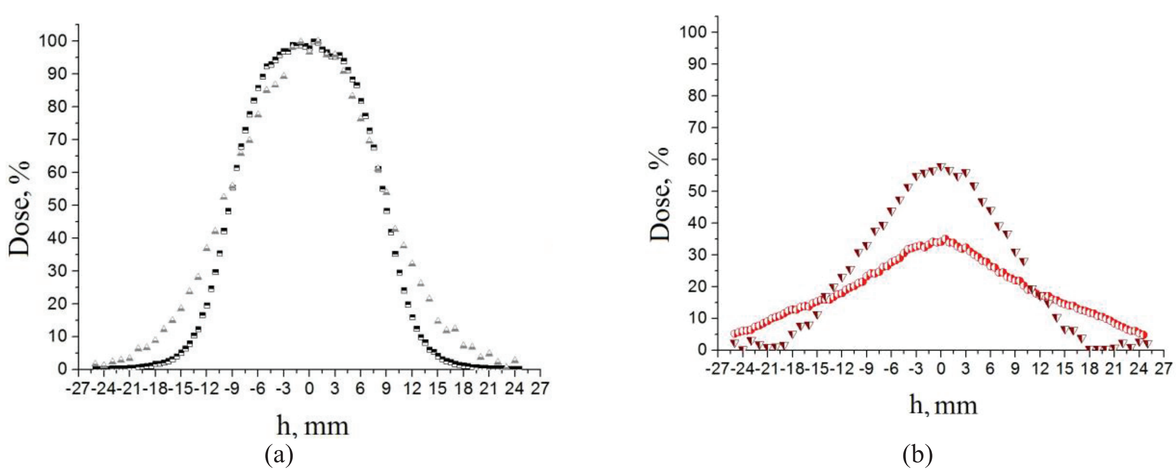

FIGURE 4. The experimental and calculated profiles of the electron beam:
■, ◑ - Modeling; △, ▼ - Experiment
a - without a filter; b - with a filter

Figures show that the shapes of the calculated and experimental profiles have differences. This is due to the fact that the passage of electrons through a target material depends on the elemental composition, which can vary from a manufacturer to manufacturer. Also the effect of quadrupole magnets which set before the accelerator exit window and affect to the beam shape (Fig. 1) is not considered in this simulation.

Besides, in the manufacture of objects by fused deposition modeling their actual density is lower than that of the material, since small voids are formed in the product inevitably. On this basis, the next stage of the work was to determine the actual density of the filter element. For this purpose, the profiles were obtained by electron beams generated by the same filter elements but having different density: 0.424 g/cm^3; 0.530 g/cm^3; 0.636 g/cm^3; 0.742 g/cm^3; 0.848 g/cm^3; 0.954 g/cm^3. Figure 5 shows examples of profiles obtained in transverse beam plane (h).

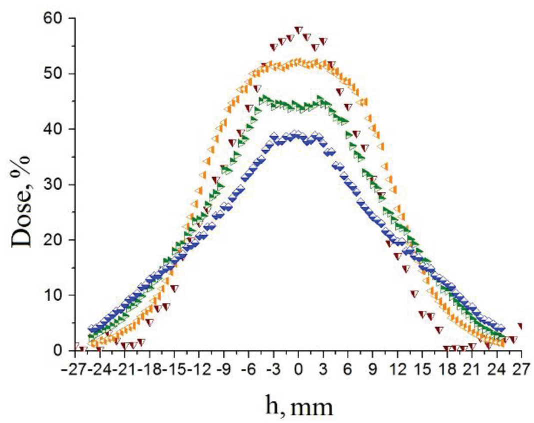

FIGURE 5. Experimental and calculated profiles of electron beams generated by filters with different densities: ▼ - Experiment; ◀ - Modeling, filter density 0.530 g/cm^3; ▶ - Modeling, filter density 0.742 g/cm^3; ◆ - Modeling, filter density 0.954 g/cm^3

After modeling for each density, the ratio of the number of electrons passed through the filter to the number of electrons without filter (k) was obtained, the amount of which is calculated by integrating the respective profiles. The values obtained were approximated by a straight line. Figure 6 shows the dependence of the coefficient k from the density of the filter element, this dependence can be approximate by following mathematical function: $k = -0.4x + 0.9$, where x is filter density.

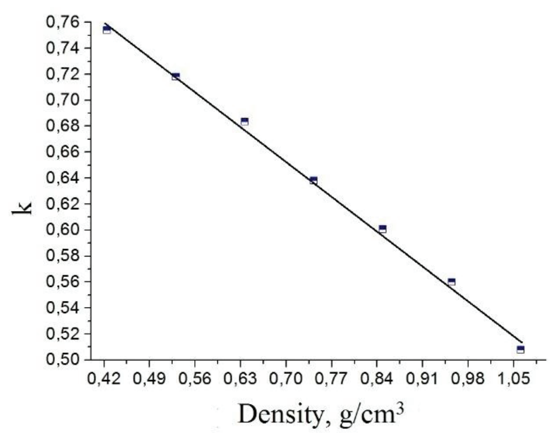

FIGURE 6. The dependence of the rate k to the density of the filter element

The experimentally obtained value of k is 0.58, which means that the actual density of the filter element is equal to 0.90 g/cm^3. Figure 7 shows the experimental and calculated profiles of electron beams formed filter element with a density of 0.90 g/cm^3. In the filter density measurement by standard method of weight to volume ratio the similar value was obtained, but it was determined with insufficient accuracy. It can be explained by fact that the layers thickness of the produced filter is comparable to printing fidelity of 3D printer being used; accordingly, the element edges have a complex shape, which contributes to inaccuracy at density determination.

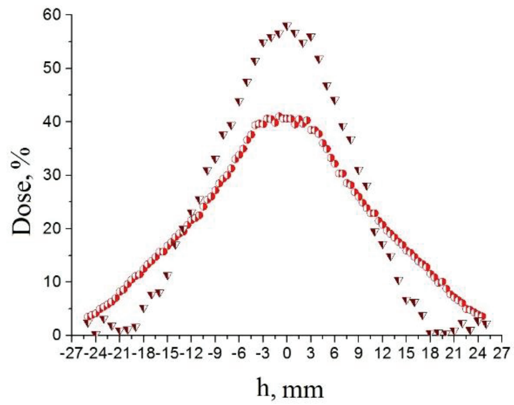

FIGURE 7. The experimental and calculated profiles of electron beams generated by filters at a density of 0.90 g/cm^3

Figure 8 presents the spatial distribution of electron beams obtained by GAFCHROMIC EBT2 radiographic films before and after applying the created filter element.

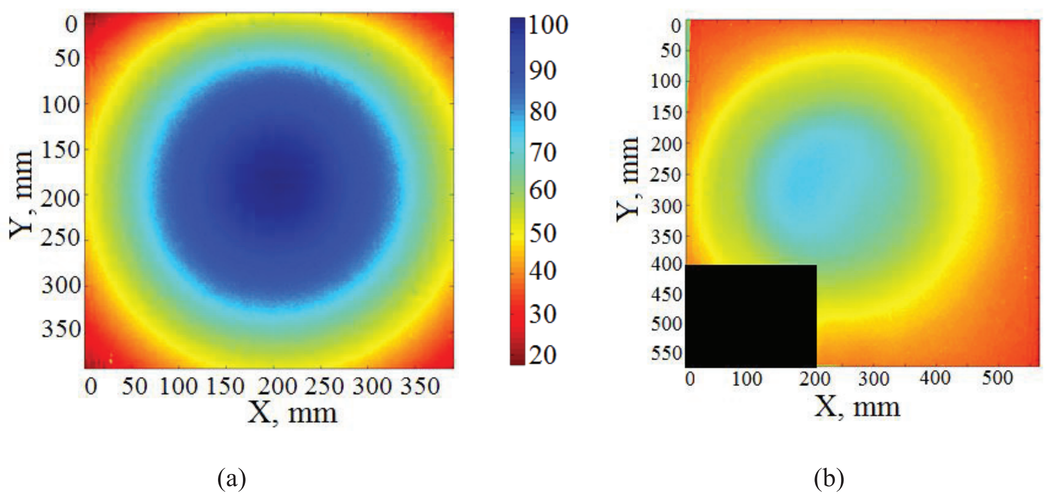

FIGURE 8. The spatial distribution of electron beams obtained by GAFCHROMIC EBT2 radiographic films before (a) and after (b) applying the created filter element

A black rectangle in the lower left corner is a part of the marking film dosimeters.

CONCLUSION

The comparison of experimental and calculated data (Fig. 4-5) showed the following facts. Filled density of the finished elements made by fused deposition modeling differs from the density of the filament from which they are made. Unevenness in the distribution of the intensity of an electron beam in cross-section and the energy distribution of electrons in the beam affects the experimental profile and should be considered in future simulations.

The differences in the experimental and calculated profiles of a shaped electron beam depend on the ultimate composition of the filter. Since the exact chemical composition of the filaments varies with the manufacturer, for different materials it is necessary to carry out further adjustments.

ACKNOWLEDGMENTS

This work was partly supported by Competitiveness Enhancement Program of Tomsk Polytechnic University.

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