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RIDGE FILTER DESIGN FOR CARBON THERAPY

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Ката-Данил Г., Парайпан М., Тимошенко Г. Н. E16-2008-136
Расчет гребенчатого фильтра для углеродной радиотерапии

Представлен расчет гребенчатого фильтра для углеродной радиотерапии, предназначенного для формирования в опухоли модифицированной кривой Брэгга. Расчет формы гребенчатого фильтра проводился аналитическим методом и сравнивался с данными расчета методом Монте-Карло по программе GEANT4. Рассмотрены два варианта конструкции гребенчатого фильтра: стационарный и подвижный. Исследовано влияние на форму фильтра энергии пучка ядер углерода и вида зависимости относительной биологической эффективности от линейной передачи энергии ядер углерода в ткани.

Работа выполнена в Лаборатории радиационной биологии ОИЯИ.

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Ridge Filter Design for Carbon Therapy

The design of a ridge filter intended for forming the uniform spread-out Bragg peak within a tumour at carbon therapy is described. The computation of the ridge filter shape was carried out by an analytical algorithm and tested by MC simulation (GEANT4 code). Two kinds of the ridge filter were considered: stationary and movable. The influence on a ridge filter shape of the carbon beam energy and the type of relative biological effectiveness dependence on the carbon ion linear energy transfer in tissue were examined.

The investigation has been performed at the Laboratory of Radiation Biology, JINR.

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INTRODUCTION

High-LET* radiotherapy with protons and carbon ions is one of the most effective treatments for cancer. The medical advantages of carbon ions for treatments (i.e., an enhancement of the relative biological effectiveness and a reduction of the oxygen enhancement ratio) in comparison with protons make the carbon radiotherapy more attractive in spite of higher price and complexity. Carbon ions produce also the best physical dose distribution because of the decrease of longitudinal and lateral scattering compared to the protons.

Radiation intensity modulation is inherent to high-LET radiotherapy. At most operational proton therapy facilities, a flat depth–dose distribution throughout the irradiated volume simulates by the superposition of a fixed set of broad beam Bragg peaks, each modulated in range and intensity. The special range modulator (ridge filter) is employed for the forming of uniform spread-out Bragg peak (SOBP) within a tumour in this case.

The other perspective method of beam intensity modulation uses the active magnetic beam scanning — spot scanning technique (the raster or the pixel scan).

Different possibilities for design of a ridge filter to realize a SOBP of 2 cm with carbon ions in energy range from 135 to 400 MeV/u and in various tissues are investigated in this paper. Two variants of a ridge filter construction are considered as well: stationary and movable. The MC simulation of the ion transport through each element of a beam delivery system and tissue requires a lot of CPU time, and the iteration over different shapes and dimensions of a ridge filter is difficult. To shorten this time the problem was solved analytically, by convoluting the non-filtered Bragg curves with the ridge filter transfer functions. The Bragg curves without ridge filter were obtained by MC simulation with the GEANT4 code [1]. A comparison between simulation and experimental data is shown in Fig. 1.

The geometry used in the simulation (shown in Fig. 2) represents a simplified version of a beam delivery system. The carbon beam generated on a surface of 100×100 mm with a divergence of 1° penetrates through a scatterer (tantalum

**Linear energy transfer* (LET) is the physical quantity used to describe the density of ionization in particle tracks.

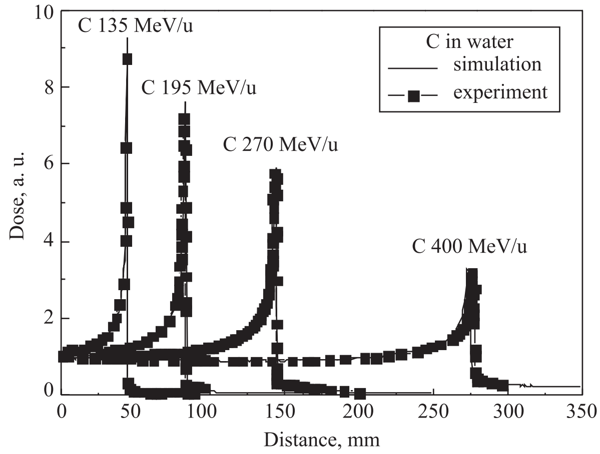

Fig. 1. Bragg curves for carbon beams with various energy, in water (experiment and simulation). The experimental data are taken from [7, 8]

foil with thickness 0.65 mm), a ridge filter, then is collimated by a collimator with opening 100×100 mm and reduces in a target with dimensions $200 \times 200 \times 300$ mm. The target material is soft tissue with density 1.05 g/cm^3 and with the composition defined by ICRU [2].

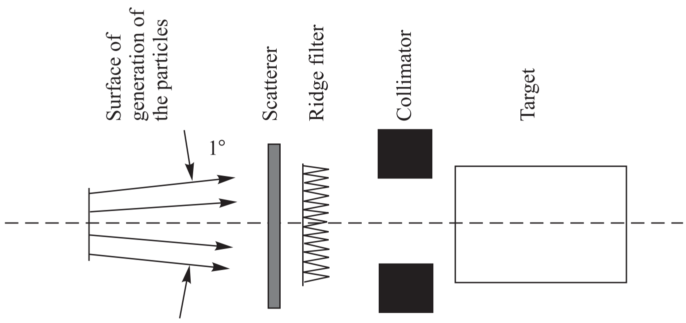

Fig. 2. Scheme of the beam delivery system used in simulation

The stationary ridge filter has a periodic structure consisting of great number of narrow ridges, where the mixing takes place via the multiple scattering in the ridge filter itself. Due to smaller scattering of the carbon ions compared to the protons the width of the every ridge is very narrow (typically 1.5–3 mm). The height of the ridge is defined by the necessary SOBP size. Plexiglas was chosen as material for the ridge filter in order to diminish the carbon ions fragmentation and the dose in the Bragg curve tails. The photo of a bar ridge filter for the proton beam is presented in Fig. 3.

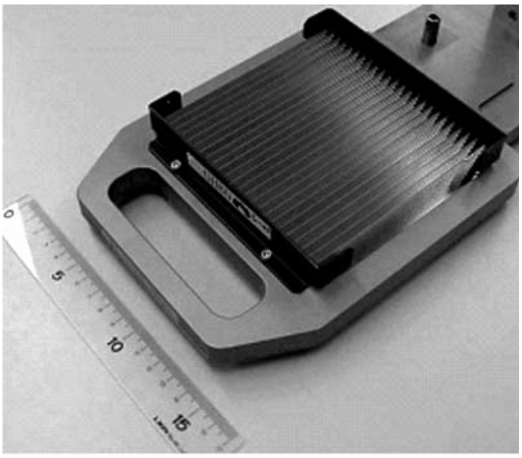

Fig. 3. A bar ridge filter for the therapeutic proton beam

ANALYTICAL COMPUTATION OF THE RIDGE FILTER SHAPE AND VERIFICATION BY MC CODE

The algorithm of the analytical computation is similar to [3, 4]. The modulated dose $D_{\mathrm{mod}}(y)$ at any point y in a SOBP region is

$$D_{\mathrm{mod}}(y) = \frac{1}{\lambda} \int\limits_{0}^{t_{\mathrm{max}}} d(y + c \cdot t) \cdot X'(t) \cdot B(x, t) \cdot F(t) \cdot dt, \qquad (1)$$

where $t(x)$ is the high of the ridge filter at the x position in direction Y, as it is shown in Fig. 4, c is a conversion factor (relation between density of the human tissue and density of the ridge filter material), λ represents the period of the ridge filter, t_{max} is a high of the ridge filter, $d(y)$ is the initial dose in tissue at the point y without the ridge filter. $B(x, t)$ function takes into account the influence of the beam lateral straggling on the ridge filter shape and $F(t)$ is a term that considered the decrease of the beam flux at the depth t. $X'(t)$ is the derivative of the $x(t)$ function determining the ridge filter shape.

The $F(t)$ term is described by equation:

$$F(t) = \frac{\Phi(t)}{\Phi(0)} = \exp\left(-\frac{t}{\mu_1}\right) \cdot \exp\left(-\frac{(y - c \cdot t)}{\mu_2}\right), \qquad (2)$$

where $\Phi(t)$ is the particle flux at the filter thickness t, μ_1 and μ_2 are the attenuation lengths for ridge filter material and for tissue accordingly.

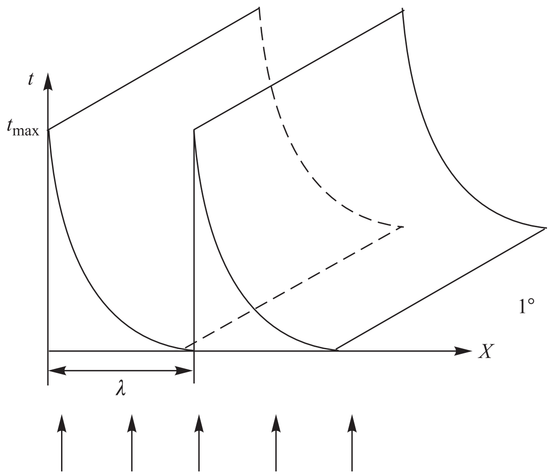

Fig. 4. The schematic view of the ridge filter geometry. Axes t and Y are collinear

In the case of a static ridge filter the shape of the ridge filter strongly depends on lateral straggling of the particles in its material. The term $B(x,t)$ expresses this dependence by the following equation:

$$B(x,t) = \sum_{k=0}^{N} \int_{x_1}^{x_2} \exp\left(-\frac{(x + k \cdot \lambda - \nu)^2}{2 \cdot \sigma^2(t)}\right) \cdot d\nu. \tag{3}$$

Here x_1 and x_2 are the limits of the slice of the tissue along the X-axis, N is the number of «teeth» of ridge filter and $\sigma(t)$ is the variance of the particles lateral scattering in the filter and tissue layer before the SOBP (in assumption of the Gaussian distribution). $\sigma(t)$ is estimated as

$$\sigma^2(t) = \sigma_f^2 + \sigma_{\mathrm{tis}}^2, \tag{4}$$

where σ_f^2 expresses the scattering in the ridge filter and σ_{tis}^2 expresses the scattering in the tissue.

In the present paper we design the plexiglas ridge filter for forming of the SOBP curve with length $l = 2$ cm within the tissue and carbon ion energy range 135–400 MeV/u.

The verification of the analytical computation was carried out by the MC code GEANT4.

The values of $\sigma(t)$ for the carbon ion with the above-mentioned energy range are less than for protons with similar energies and are in limits 0.88–0.9 mm at the level of SOBP. These values are lower than the period λ of the ridge filter. As a result, from Eq. (3) we can retain only 3 terms (corresponding to the 3 «teeth» of the filter):

$$B(x,t) = \int_{x_1}^{x_2} \left[\exp\left(-\frac{(x+\lambda-\nu)^2}{2\cdot\sigma^2(t)} \right) + \exp\left(-\frac{(x-\nu)^2}{2\cdot\sigma^2(t)} \right) + \right.$$
$$\left. + \exp\left(-\frac{(x-\lambda-\nu)^2}{2\cdot\sigma^2(t)} \right) \right] \cdot d\nu. \quad (5)$$

In the analytical computation of the ridge filter shape a slice in the tissue with the thickness λ and the parallel particle beam approaches were considered.

The integral from Eq. (1) is computed as a superposition of doses displaced in steps of $c \cdot dt = 0.5$ mm with different weights w_j representing the product between the values of the derivative X'_j at $y_j = j \cdot dy$ and the terms counting for the lateral scattering B_j:

$$w_j = X'_j \cdot B_j.$$

The modulated dose at the position y can be written:

$$D_{\mathrm{mod}}(y) = \frac{c\cdot dt}{\lambda} \sum_{j-0}^{j_{\max}} w_j \cdot d(y + c\cdot j\cdot dt) \times$$
$$\times \exp\left(-\frac{j\cdot dt}{\mu_1} \right) \cdot \exp\left(-\frac{(y - c\cdot j\cdot dt)}{\mu_2} \right). \quad (6)$$

Here, $j_{\max} = \frac{t_{\max}}{dt}, d(y + c\cdot j\cdot t)$ are the values of the dose without ridge filter at the point $y + c\cdot j\cdot t$. The weights w_j are obtained by the minimization of the function f:

$$f = \sum_{i=0}^{n} [D_0 - D_{\mathrm{mod}}(y)]^2,$$

where n is the number of points in which the dose was calculated and D_0 is the uniform dose which we intend to obtain in the SOBP region. The dependence $x(y_j)$ is obtained from the values of the derivative w_j by integration:

$$x_j = x(t_j) = \lambda \frac{\sum\limits_{k=0}^{j} w_k}{\sum\limits_{k=0}^{j_{\max}} w_k}.$$

The set of points (x_j, t_j) determines the necessary shape of the ridge filter.

COMPUTATION OF RBE

The destination of the ridge filter is to realize a constant distribution of the biological dose. The biological dose D_b is defined from the absorbed dose D_a and the relative biological effectiveness (RBE) as

$$D_b = \text{RBE(LET)} \cdot D_a.$$

RBE depends on the particle linear energy transfer (LET) and varies in large limits for different types of biological cells. In Fig. 5 the dependence RBE on LET for 3 cell lines is presented (from [5, 6]).

The RBE1 values were derived from the survival curve for HSG tumor cells irradiated *in vitro* with carbon ions [6], using the linear-quadratic (LQ) model. Conformity of this model to the survival fraction of the irradiated cells has a quadratic dependence of the dose:

$$S = \exp\left(-\alpha \cdot D - \beta \cdot D^2\right).$$

The dependences of α and β parameters on LET are shown in Fig. 6.

The RBE values were calculated from the ratio between the dose of carbon necessary for a rate of survival of 10% ($D_{10,C}$) and the dose of 200 keV X-rays that determines the same biological effect ($D_{10,R} = 4.08$ Gy). $D_{10,C}$ at each position i was obtained from the equation:

$$\alpha_i D_{10,C_i} + \beta_i D_{10,C_i}^2 + \ln 0.1 = 0.$$

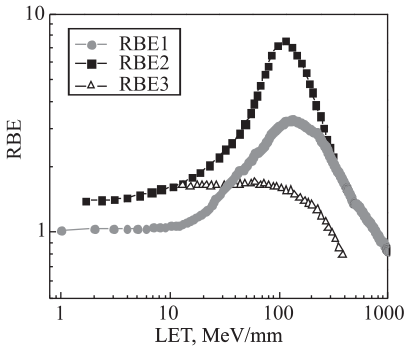

Fig. 5. The dependence of RBE on LET for HSG (RBE1), V79 (RBE2) and xrs5 (RBE3) cells

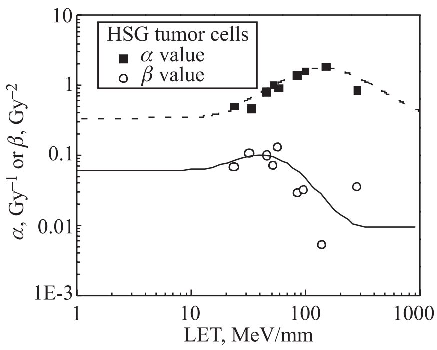

Fig. 6. Parameters α and β as a function of LET. The circles represent empirical results for HSG tumor cells

The RBE values were obtained from the following relation:

$$\mathrm{RBE}_i = \frac{D_{10,R}}{D_{10,C_i}} = \frac{4.08 \cdot 2 \cdot \beta_i}{-\alpha_i + (\beta_i^2 - 4 \cdot \alpha_i)^{\frac{1}{2}}}.$$

α_i and β_i are mediated as follows:

$$\alpha_i = \frac{\sum\limits_j \alpha(\mathrm{LET}_{i,j}) \cdot e_{i,j}}{\sum\limits_j e_{i,j}} \qquad \sqrt{\beta_i} = \frac{\sum\limits_j e_{i,j} \cdot \sqrt{\beta(\mathrm{LET}_{i,j})}}{\sum\limits_j e_{i,j}},$$

where $\alpha(\mathrm{LET}_{i,j})$, $\beta(\mathrm{LET}_{i,j})$ and $e_{i,j}$ are the LQ parameters for monochromatic radiation as a function of LET and the energy deposited in the slice i in the incidence of ion j. The parameters $\alpha(\mathrm{LET}_{i,j})$ and $\beta(\mathrm{LET}_{i,j})$ were taken from [5]. In the computation the same dependence RBE(LET) for the resulting fragments was assumed as for initial carbon ions, because of the lack of experimental data. This approximation has low influence on the result because most of the fragments are low-LET particles and give a small contribution in the SOBP region.

The tissue has an influence on the performances of the ridge filter mostly through the variations in RBE. The changes in chemical composition and density are less important. The most part of the tumors has a composition and density like soft tissue.

RESULTS

The dependences of the ridge filter shape on the energy of the incident carbon beam and on the RBE type were analyzed and shown in Fig. 7. The filter shape was computed and tested by MC simulation for three energies of the carbon beam: 135, 270 and 400 MeV/u considering the different RBE types from Fig. 5. The weights w_j were practically the same for the energy range 135–270 MeV/u, so the weights corresponding to each step of the filter height are shown in Fig. 7 only for beam energy 270 MeV/u. A beam with energy 400 MeV/u requires the other ridge filter shape in order to obtain an acceptable SOBP plateau. The RBE type exerts more significant influence on the filter shape in comparison with the beam energy, as it can be seen in Fig. 7, c, d, f.

The calculations presented in Fig. 7 are performed at the presence of small gap between the «teeth» in order to obtain the sharp SOBP end. The maximums in figs. a, b, c, e correspond to the last slice in the tissue at the SOBP end. The gap's length is obvious from figs. d and f

The uniformity of the SOBP in the beam direction and in the transversal direction was analyzed analytically and by MC simulation. In Fig. 8 the doses

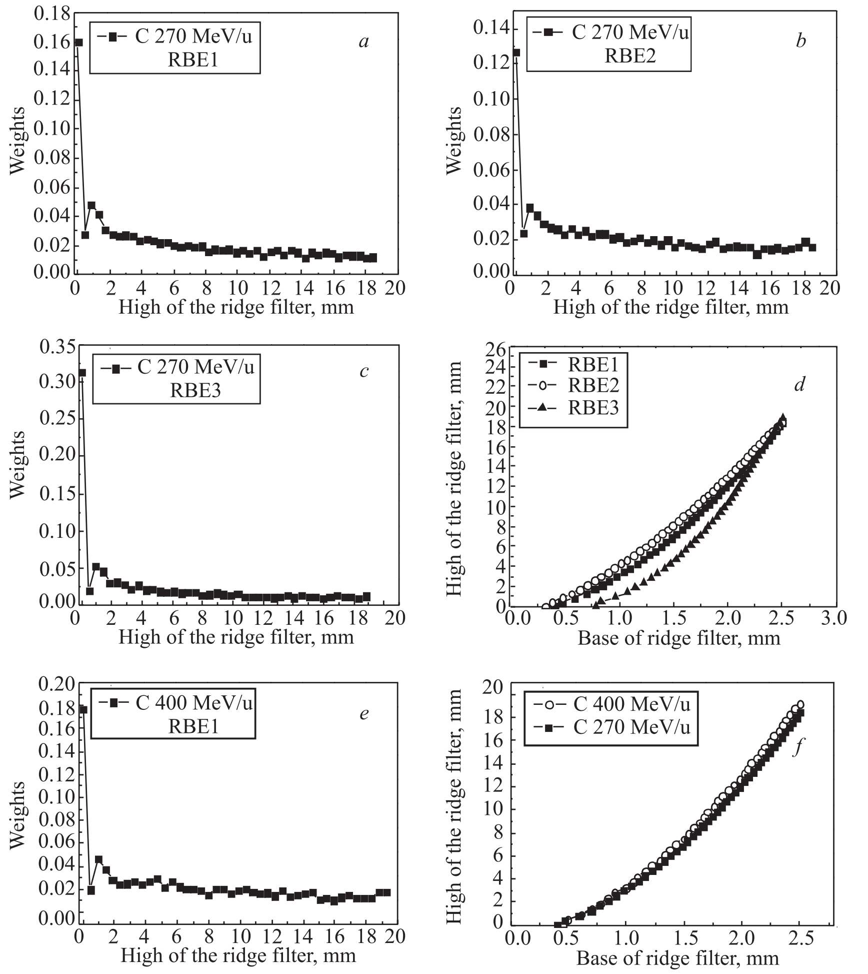

Fig. 7. The dependences of the ridge filter shape on the energy of the carbon beam and on the RBE type. a, b, c — the weight dependences on the RBE type at beam energy 270 MeV/u; d — the $t(x)$ dependences on different types of RBE; e — the weight dependence on the RBE1 at beam energy 400 MeV/u; f — the $t(x)$ dependences at the energies 270 and 400 MeV/u for RBE1

deposited in 3 slices with thickness 0.1 mm, situated at the beginning, in the middle and at the end of the «tooth», are presented in comparison with the dose deposited in slice with length of the whole «tooth» (2.5 mm) for incident beam energy 270 MeV/u. As it is obvious, the detailed partition of the tissue at the SOBP calculation shows the ununiformity of the SOBP in comparison with rough

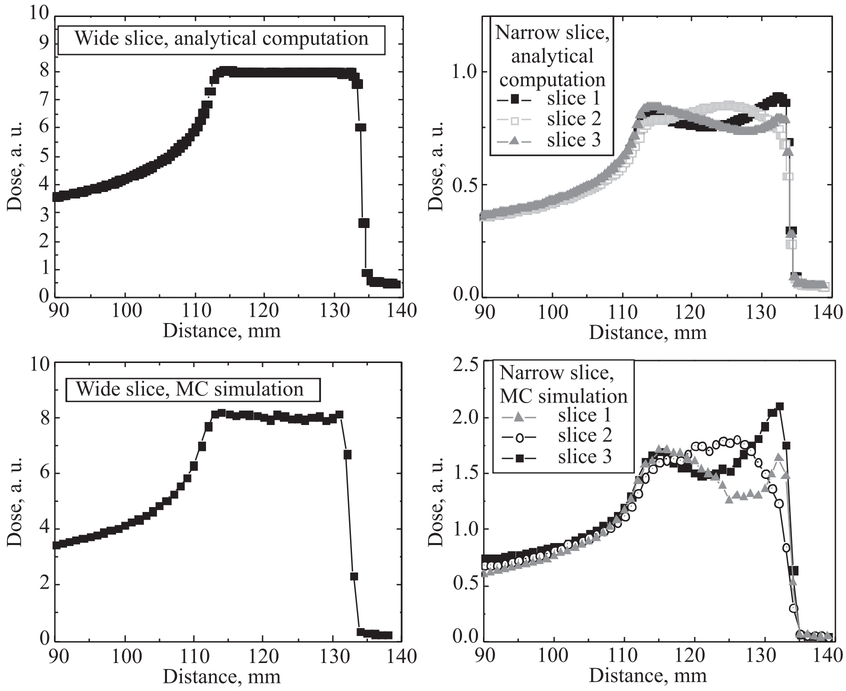

Fig. 8. The verification of the SOBP quality by the detailed partition of the tissue at the SOBP calculations. The wide slice — 2.5 mm, the narrow slices — 0.1 mm. Carbon beam energy is 270 MeV/u

partition. For the stationary ridge filter this disadvantage is unavoidable since a uniform SOBP is not realized in each of the small tissue slices in the beam direction. It is more important for carbon beam in comparison with a proton beam because of the smaller lateral scattering of the carbon ions. The other disadvantage of the stationary filter with numerous thin «teeth» is the necessity for very high precision technology of manufacturing (and the big cost accordingly).

In principal, better result can be obtained with the moving ridge filter. A frequent periodic movement of the ridge filter in the transversal direction to the beam (or its rotation) allows obtaining a flat spatial distribution of the dose in the SOBP limits, even with a large filter period.

The movable assembly of 2 large «teeth», each of them with a length higher than the beam diameter, was considered as well. The distance between the «teeth» was chosen equal to 100 mm including the gap. The weights in this case were the same as for stationary filter. At the MC simulation the ridge filter moved in the beam transversal direction by steps of 1 mm. At each step 1000 carbon ions

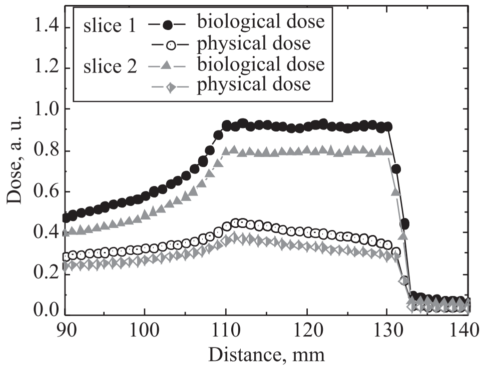

Fig. 9. The SOBP shapes of the movable ridge filter for two thin slices in tissue. The carbon beam energy is 270 MeV/u

with a Gaussian distribution ($\sigma_x = \sigma_y = 50$ mm) were generated randomly. The beam time structure was ignored.

In Fig. 9 the SOBP is realized in 2 slices of 0.5 mm thickness in the beam direction. First of them is positioned in the average of the beam distribution ($x = 0$ mm), another is at $x = 45$ mm. The beam energy was 270 MeV/u, the RBE1 was used.

For this type of the ridge filter the SOBP shape does not depend on tissue slice position. The same feature was observed also for other beam energies and RBE types.

The next task that we considered was a check of the necessary precision in the filter production with maintenance of a good SOBP shape. The verification of the SOBP shape at the variations of the filter height $(y_{\max})$ and the period (λ) in the limits of ± 1 mm was done for beam energy 270 MeV/u and RBE1. The MC simulation has shown that precision of 0.1 mm is sufficient for suitable SOBP shape maintenance.

CONCLUSION

A good SOBP cannot be achieved in the beam energy range 135–400 MeV/u with the same kind of the ridge filter. For the same tissue and RBE type the shape of the ridge filter is stable in a range of energy 135–270 MeV/u only.

It is difficult to ensure the good SOBP in all necessary tissue volume with the stationary ridge filter for the carbon beam. The better result can be obtained with the movable kind of the ridge filter.

The needed precision in the filter construction has to be better than 0.1 mm for suitable SOBP shape.

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