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OPTIMIZATION OF THE BREMSSTRAHLUNG CONVERTER

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Variants of the formation of bremsstrahlung (BS) distributions along an extended converter, which ensures the maximum thickness of an object under two-sided and four-sided irradiation, are studied. For the target of the TaH_2OFe converter, the thicknesses of the Pb filter were determined, at which the average BS energy increases by more than 25%. In the PENELOPE package, the simulation of dose distributions in polyethylene produced by BS converters with optimal targets: previously used TaH_2OFe and proposed by us TaH_2OFePb, for 7.5 MeV electron energy, was performed. For four-sided irradiation, a technique for optimizing the distribution of the BS intensity along an extended converter is proposed. The combined use of the TaH_2OFePb target and optimal BS intensity distributions along an extended converter makes it possible to increase the thickness of objects by a factor of ~ 1.35 under four-sided irradiation, DUR < 1.5.

CONVERTER TARGET

The dependences of the bremsstrahlung (BS) yields on the thickness of the tantalum target for electron energies of 5…10 MeV were studied in a number of works [1–3]. For electrons with energy of 7.5 MeV, the Ta thickness is about 0.12 cm, at which the energy transferred by the BS is maximum. The paper [4] indicates that the target thickness exceeding the optimal value leads to a decrease in direct radiation due to an increase in the absorption of BS and scattering of electrons in the target. The thickness may be slightly greater than the optimal value, since the bremsstrahlung power gradually decreases with increasing target thickness. A thin tantalum target is usually cooled by a rapidly flowing water jet bounded by a thin sheet of stainless steel. The total thickness of tantalum, water, and stainless steel (Fe) must be sufficient to absorb incident electrons within the target assembly. In [5], the optimal parameters of such converter Ta1.2Wt2Fe2 (with thicknesses Ta = 1.2 mm, H_2O = 2 mm, Fe = 2 mm) are given. In [6], we presented the dependences of the average photon energy on the angle of photon emission from the converter for different thicknesses of the Ta target. It is shown that with increasing tantalum thickness, the average photon energy increases. For the Ta1.2Wt2Fe2 converter, the average BS energy across the full range angular distribution is ~ 1.14 MeV.

We have carried out a study of the BS characteristics generated by the Ta+H_2O+Fe+Pb converter depending on the thickness of Ta and Pb, where H_2O = 2 mm, Fe = 2 mm, and the electron energy is 7.5 MeV. Fig. 1 shows the dependences of the average energy E_{av} of BS photons and the ratio of the total photon energy E_{tr} to the electron energy E_0 for the angle range 0…90° at Pb layer thicknesses = 0, 1, 3 mm. The value $E_{tr}/E_0 = eff$ is essentially the efficiency of the converter, which characterizes the fraction of the energy of the initial electrons converted into bremsstrahlung photons. The Palletron irradiation scheme widely used in radiation technologies [5] uses a Ta1.2Wt2Fe2 converter, whose efficiency is 13.8% and the average BS energy across the full range angular distribution is ~ 1.15 MeV.

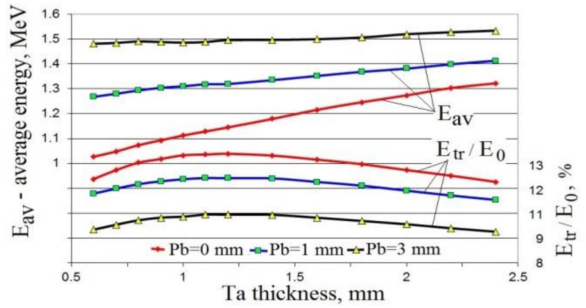

Fig. 1. The dependences of E_{av} and E_{tr}/E_0 for the angle range 0…90° at Pb layer thick = 0, 1, 3 mm

It follows from the data presented in Fig. 1 that the additional use of 1 and 3 mm Pb layers in the converter target reduces the efficiency of the converter by ~ 1 and 3%, but the average energy E_{av} increases from 1.14 to 1.32, and 1.5 MeV. Fig. 2 shows the average photon energies and intensities depending on the emission angle relative to the normal of converter surface for different Pb layer thicknesses of the Ta1.2Wt2Fe2 converter, denoted as Pal.

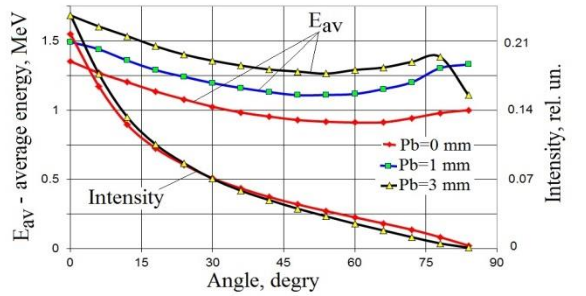

Fig. 2. The dependences of E_{av} and E_{tr}/E_0 on emission angle for different Pb layer thicknesses

Table 1 shows the average energies for several angular intervals and layers of Pb = 0, 1, 3 mm. From the data shown in Fig. 2 and Table 1 it follows that at small angles of emission of photons, their energy is significantly higher than the average energy across full range angular interval.

Table 1

Average energies for several angular intervals and layers of Pb = 0, 1, 3 mm

Angle interval	Pal	Pal+Pb1	Pal+Pb3
	Average energy, MeV		
0…30°	1.24	1.40	1.57
0…48°	1.19	1.35	1.53
0…90°	1.14	1.32	1.50

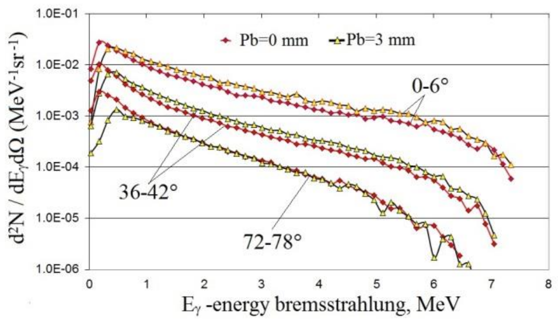

Fig. 3. The BS spectra at different angles

On Fig. 3 shows the BS spectra at different angles relative to the normal of the emission surface, produced by a 7.5 MeV electron beam incident normally on the target of a Ta1.2Wt2Fe2 converter and a similar converter + a three mm thick lead layer Ta1.2Wt2Fe2+Pb3.

It is shown that at photon emission angles of less than 50° in the energy range of 0.35…7.5 MeV, the use of a 3 mm lead layer increases the BS energy. In the energy range 0.35…7.5 MeV for all photon emission angles, a 3 mm lead layer significantly reduces the BS energy.

CALCULATION RESULTS WITH OPTIMAL CONVERTER PARAMETERS

In [7, 8], dose distributions in objects were calculated using quasi-analytical methods. The energy and angular spectra of BS were used as initial data. The characteristics of dose distributions during irradiation according to the Palletron scheme [5] were determined by the Monte Carlo method. To optimize the conditions for irradiation of objects of large volumes, a combination of the Monte Carlo method and the analytical method is used. In the PENELOPE and PHITS packages, the dose distributions in the object generated by a single element of the converter were calculated. The irradiated object is a cube with dimensions $X_O \times Y_O \times Z_O$ filled, for example, with polyethylene. Targets of two types with a thickness of Z_C = Ta1.2Wt2Fe2 mm and Ta1.2Wt2Fe2+Pb3 mm with dimensions $X_C \times Y_C$ are a single converter element. The center of a single element of the converter at a distance *h* from the center of the plane (XY). An electron beam with an energy of 7.5 MeV hits the target surface with dimensions $X_C \times Y_C$ along the normal and generates a BS flux, which forms an absorbed dose in the volume of the irradiated object. The PENELOPE and PHITS packages calculate the distribution of the absorbed dose in the irradiated volume using a given grid. However, the amount of data in a 3D grid is quite large. We believe that during real irradiation, the irradiated object moves on the conveyor relative to the converter element along the Y axis. By setting the procedure for integrating the dose of the variable Y in the PENELOPE and PHITS packages [10], we obtain data on the distribution of the absorbed dose in the plane (XZ).

Fig. 4 shows the change in the photon flux simulated by PHITS during the passage in air and polyethylene of BS radiation generated in the target Ta1.2Wt2Fe2 of the converter element irradiated by 7.5 MeV electrons.

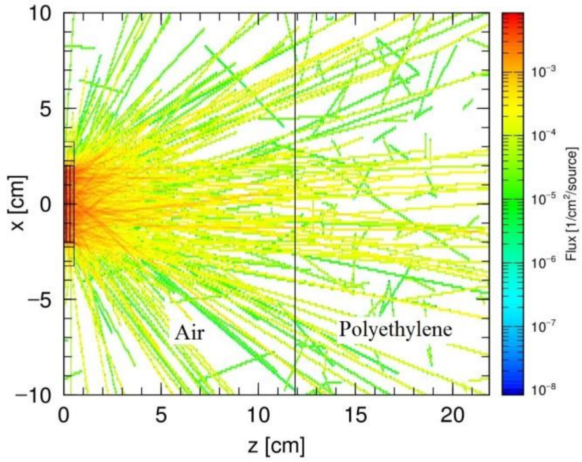

Fig. 4. BS flux of the converter element irradiated by 7.5 MeV electrons

When irradiating large objects by BS, extended converters are used, for example, for Palletron, the length of the converter is more than 2 m [5]. Given the data on absorbed doses from an individual element of the converter in the form of a matrix in the (XZ) plane, the distribution of absorbed doses along an extended converter of length L is a superposition of doses from individual elements of the converter in the procedure below. In PENELOPE or PHITS [9, 10], absorbed doses are calculated inside an object with a volume of $X_O \times Y_O \times Z_O$ and, taking into account integration over the Y coordinate, data on the dose distribution are given in the form of a matrix $d_{(i,jz)}$, where i = 1…Nx, iz = 1…Nz, and the coordinates of the points xi = (i-1) X_O/(Nx+1), zj = (iz-1) Z_O/(Nz+1). Using the values of $d_{(i,jz)}$, a continuous dose distribution function D(x,y) from an individual element of the converter in the plane (XZ) is constructed in the form of a two-dimensional spline. The distribution of the absorbed dose in the object generated by the BS from an extended converter of length L is determined by the relation:

$$Ds(x,z) = \sum_{j=1}^{N} \left[D(|x - L_x \cdot (j-1)|, z) \cdot Ie_j \right], \quad (1)$$

where N = L/L_X is the number of individual converter elements that make up an extended converter; L_X is the length of an individual converter element; Ie_j is the intensity of the electron beam incident on the j-th individual converter element.

The analytical procedure for calculating absorbed doses both along an extended converter and along the depth of the irradiated object using relation (1) is based on the Monte Carlo calculation of an individual element of the converter. This makes it possible to optimize the dependences of the intensity of the electron beam Ie(x) incident on the extended converter to minimize the absorbed dose inhomogeneity (DUR) in the irradiated object. A study was made of changes in dose distributions in polyethylene objects (density 0.8 g/cm^3) for volumes from 0.5×0.5×0.5 to 0.8×0.8×0.8 m. We used Ta1.2Wt2Fe2 and Ta1.2Wt2Fe2+Pb3 targets (L_X = 2.5 cm, L_Y = 1.5 cm) for an individual element of the converter and optimized the dependences of the electron beam intensity Ie(x) along the extended converter. It is known that at the same intensity of the electron beam incident on an extended converter, BS produce a dose distribution along the converter in the irradiated object with a maximum in the center and a minimum at the edges. In [11], in order to equalize the dose distribution, it was proposed to increase the intensity of the electron beam incident on the edges of the converter.

Using relation (1) for two variants of targets, Ta1.2Wt2Fe2, where Pb = 0 and Ta1.2Wt2Fe2Pb3, where Pb = 3, using relation (1), the optimal thicknesses of the object under double-sided irradiation were determined to achieve DUR < 1.5. Fig. 5 shows the dependences of the electron beam intensity Ie(x) and the absorbed dose on the object surface D(x,z = 0) for the Pb = 3 variant on the distance along the converter.

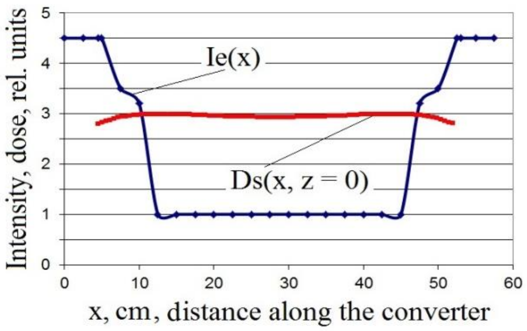

Fig. 5. Intensities Ie(x) and absorbed dose D(x,z = 0) for variant Pb = 3 depending on the distance along the converter

Fig. 6 (Pb = 3) and 7 (Pb = 0) show dose distributions in the (XZ) plane for two-sided irradiation of objects with DUR < 1.5.

It is shown that BS generated by an extended converter with an additional filter Pb = 3 mm has a high penetrating power. With double-sided irradiation, the thickness of the object increases from 27 to 48.5 cm. In case of double-sided irradiation of an object in the form of a parallelepiped, bremsstrahlung processes the 1st and 3rd sides of the object, see Figs. 6 and 7.

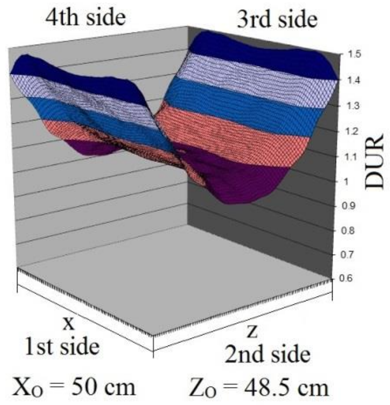

Fig. 6. Dose distributions in the (XZ) plane for variant Pb=3 for two-sided irradiation of objects with DUR < 1.5

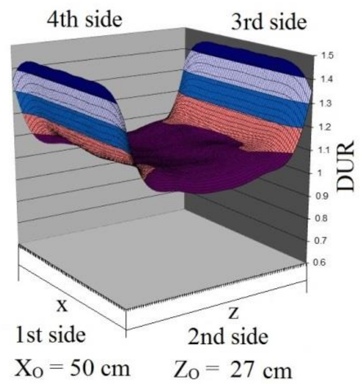

Fig. 7. Dose distributions in the (XZ) plane for variant Pb=0 for two-sided irradiation of objects with DUR < 1.5

From the data on the distribution of the absorbed dose given in Figs. 6 and 7, it follows that if additional irradiation from the 2nd and 4th sides, then the DUR of the total dose distribution will decrease. We have carried out the optimization of the conditions of four-sided irradiation. For converters with Ta1.2Wt2Fe2 and Ta1.2Wt2Fe2Pb3 targets, the optimal distributions for the intensity of electron fluxes used for processing the 1st and 3rd sides of the object, and then after turning the object by 90° the 2nd and 4th sides of the object were determined.

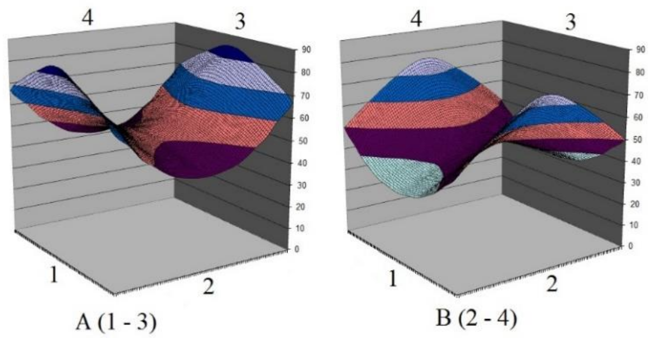

Fig. 8. Dose distributions inside an object with dimensions of 60×60 during sequential irradiation of the 1st and 3rd sides A (1–3), as well as the 2nd and 4th sides B (2–4)

Fig. 8 shows the dose distributions inside an object with dimensions of 60×60 with sequential irradiation of the 1st and 3rd sides A (1–3), as well as the 2nd and 4th sides B (2–4), target Ta1.2Wt2Fe2Pb3. The optimal dependences of the change in the intensity Ie(x) of the electron beam along the converter are shown in Fig. 9.

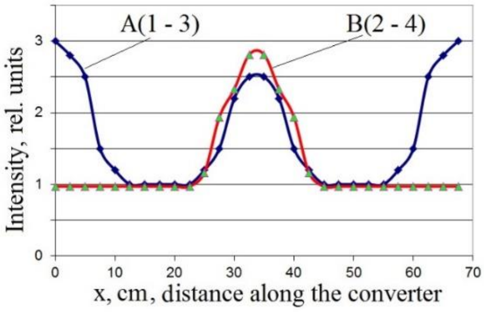

Fig. 9. Optimal dependences of the change in the intensity Ie(x) of the electron beam along the converter

Fig. 10 shows the dose distributions inside an object 60×60 cm in size for 4-sided irradiation with a converter with a Ta1.2Wt2Fe2Pb3 target, DUR = 1.19. For comparison, Fig. 11 shows the dose distributions inside an object with dimensions of 60×60 cm during 4-sided irradiation with a converter with a Ta1.2Wt2Fe2 target without using Pb, with such a target DUR = 1.48

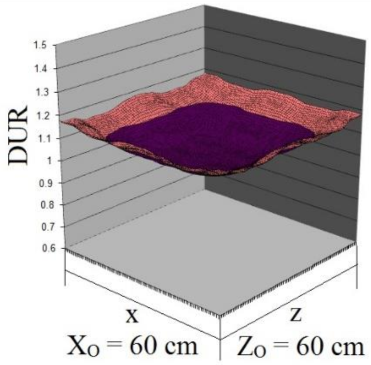

Fig. 10. Dose distributions for 4-sided irradiation with a converter with a Ta1.2Wt2Fe2Pb3 target

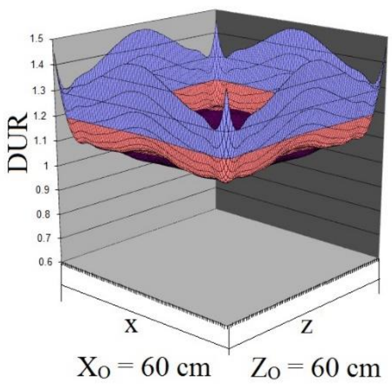

Fig. 11. Dose distributions for 4-sided irradiation with a converter with a Ta1.2Wt2Fe2 target without using Pb

Table 2 lists the DUR values in an object made of polyethylene with a density of 0.8 g/cm^3 under BS irradiation depending on the sizes for targets of converters Ta1.2Wt2Fe2Pb3 and Ta1.2Wt2Fe2, electron energy is 7.5 MeV.

Table 2

DUR values depending on sizes for Ta1.2Wt2Fe2Pb3 and Ta1.2Wt2Fe2 converters

Converter target	Dimensions of objects, cm			
	50×50	60×60	70×70	80×80
	DUR			
Pb=3 mm	1.09	1.19	1.34	1.50
Pb=0 mm	1.32	1.48	1.68	2.04

CONCLUSIONS

Variants of the formation of BS distributions along an extended converter, which ensures the maximum thickness of an object under two-sided and four-sided irradiation, are studied. For the target of the TaH_2OFe converter, the thicknesses of the Pb filter were determined, at which the average BS energy increases by more than 25%. In the PENELOPE package, the simulation of dose distributions in polyethylene produced by BS converters with optimal targets: previously used TaH_2OFe and proposed by us TaH_2OFePb, electron energy is 7.5 MeV, was performed. For four-sided irradiation, a method for optimizing the distribution of BS intensity along an extended converter is proposed. For sizes of objects made of polyethylene up to 60×60 cm, the use of optimal target and operating modes of the converter makes it possible to reduce the inhomogeneity of the dose distribution to DUR < 1.2. The combined use of the proposed TaH_2OFePb target and optimal distributions of BS intensities along an extended converter makes it possible to increase the thickness of objects by a factor of ~ 1.35 under four-sided irradiation with DUR < 1.5.

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ОПТИМІЗАЦІЯ КОНВЕРТЕРА ГАЛЬМІВНОГО ВИПРОМІНЮВАННЯ

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Досліджено варіанти формування розподілів гальмівного випромінювання (ГВ) вздовж протяжного конвертера, що забезпечує максимальну товщину об'єкта при двосторонньому та чотиристоронньому опроміненні. Для мішені конвертера TaH_2OFe визначено товщини фільтра з Pb, при яких середня енергія ГВ зростає більш, ніж на 25%. У пакеті PENELOPE виконано моделювання дозових розподілів у поліетилені створюваних ГВ конвертерами з оптимальними мішенями: раніше використовуваним TaH_2OFe та запропонованим нами TaH_2OFePb, енергія електронів 7,5 МеВ. Для чотиристороннього опромінення запропоновано методику оптимізації розподілу інтенсивності ГВ вздовж протяжного конвертера. Комбіноване використання мішені TaH_2OFePb та оптимальних розподілів інтенсивностей ГВ вздовж протяжного конвертера дозволяє збільшити у ~ 1.35 рази товщину об'єктів при чотиристоронньому опроміненні, DUR < 1,5.