Optimization of bremsstrahlung characteristics for irradiating thick objects

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The possibility to form the bremsstrahlung (BS) characteristics, which provide the maximum thickness of the irradiated objects at a given value of the dose uniformity ratio (DUR), is studied. The electron beam is incident perpendicularly to the surface of the converter, while the transverse dimensions of the converter are larger than the diameter of the electron beam. The BS generation by 7.5 MeV electrons is calculated by the Monte Carlo method (PENELOPE package) in a three-layer converter with different thicknesses of Ta, water, and Fe. Figure 1 shows an irradiation scheme of large moving objects by BS radiation.

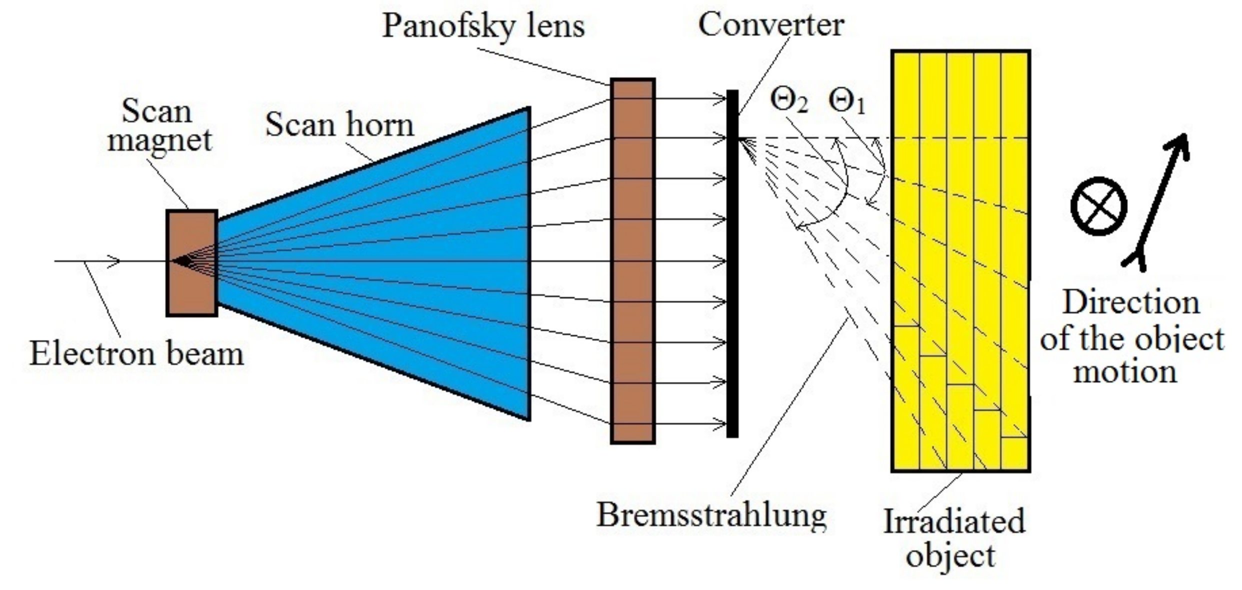

Fig. 1. Irradiation scheme of large moving objects by bremsstrahlung radiation**.**

The water thickness of 1.5 cm and steel of 2.5 mm in the converter are chosen so that the primary electrons do not reach the irradiated object. Changes in the photon yields and spectral characteristics of BS at different angles are investigated. Figure 2 shows the BS yields as a function of the Ta target thickness for the angular ranges Θ = 0÷30°, 0÷48°, 0÷90°(Total). The calculations show that increasing Ta thickness causes that γ-quanta with higher energy appear in the BS spectra due to the absorption of low-energy photons in the Ta target [1]. Figure 3 shows the dependences of the average photon energy on the angle of photon emission from the converter for different thicknesses of the Ta target. One can see that the average BS energy E_{av} decreases with an increase of the photon emission angle, and Ta layer increase in the thickness from 0.8 mm to 2.4 mm leads to increase of E_{av}.

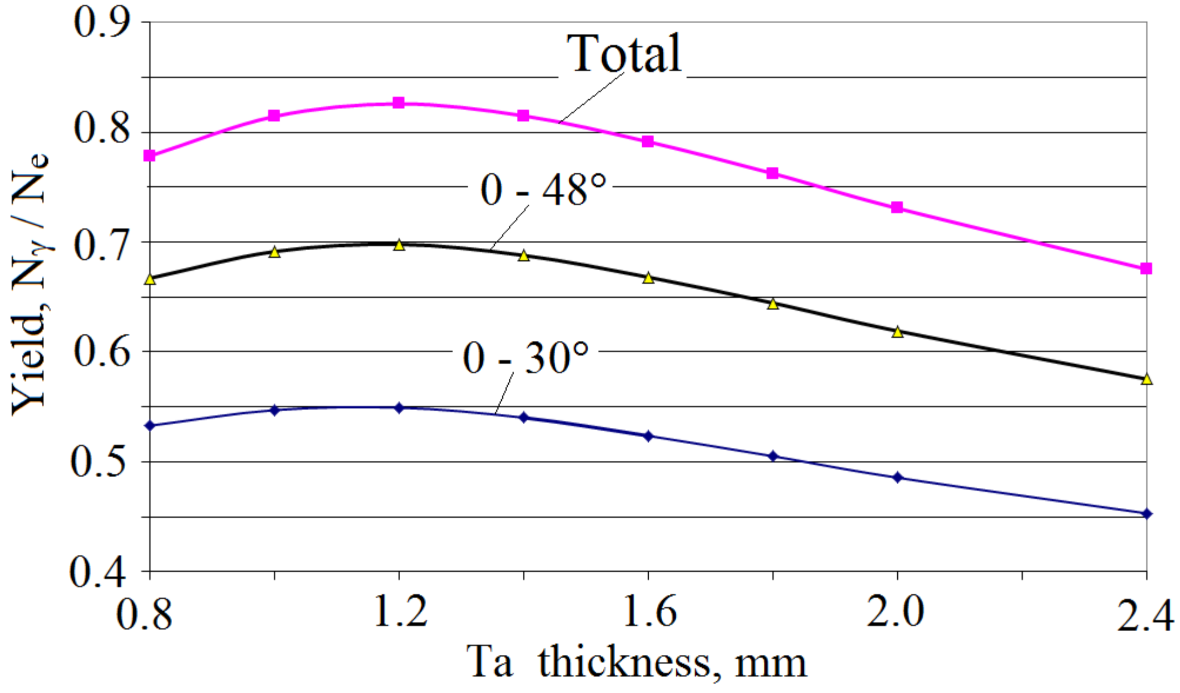

Fig. 2. Dependences of the BS yields on the Ta target thickness for the angular ranges Θ = 0÷30°, 0÷48°, 0÷90°(Total).

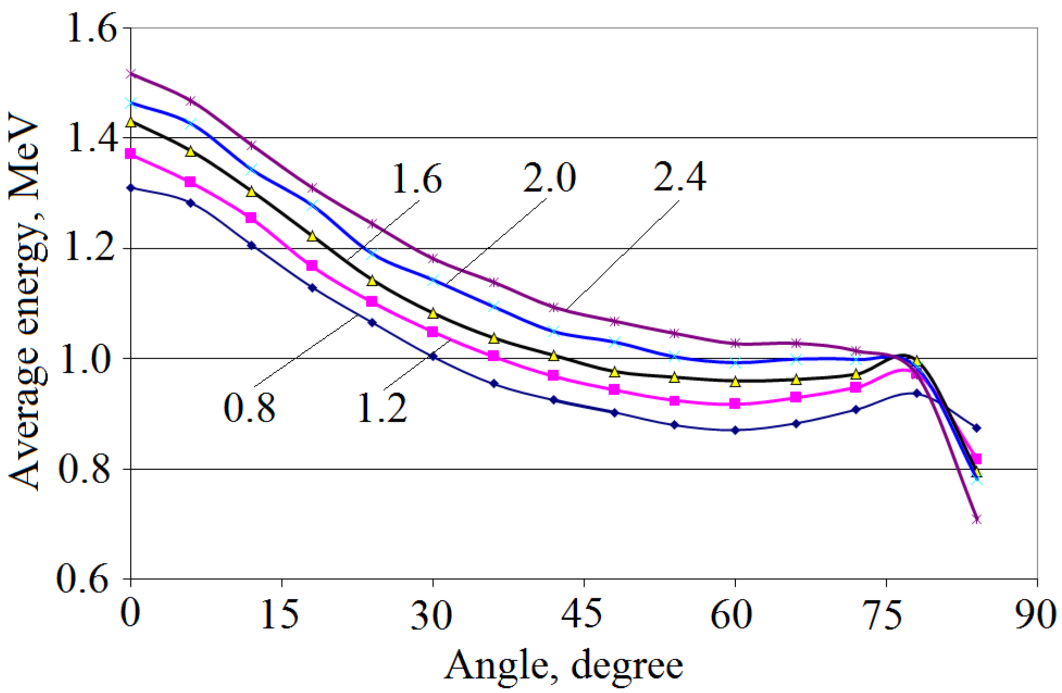

Fig. 3. Dependences of the average photon energy on the angle of photon emission from the converter for different thicknesses of the Ta target.

The incidence angles and the spectral composition of BS, which depends on the incidence angle, are the initial data for calculating the depth-dose distributions of polyethylene in the PENELOPE package. Figure 4 shows the BS spectra for the converter with a 1.4 mm thick Ta target.

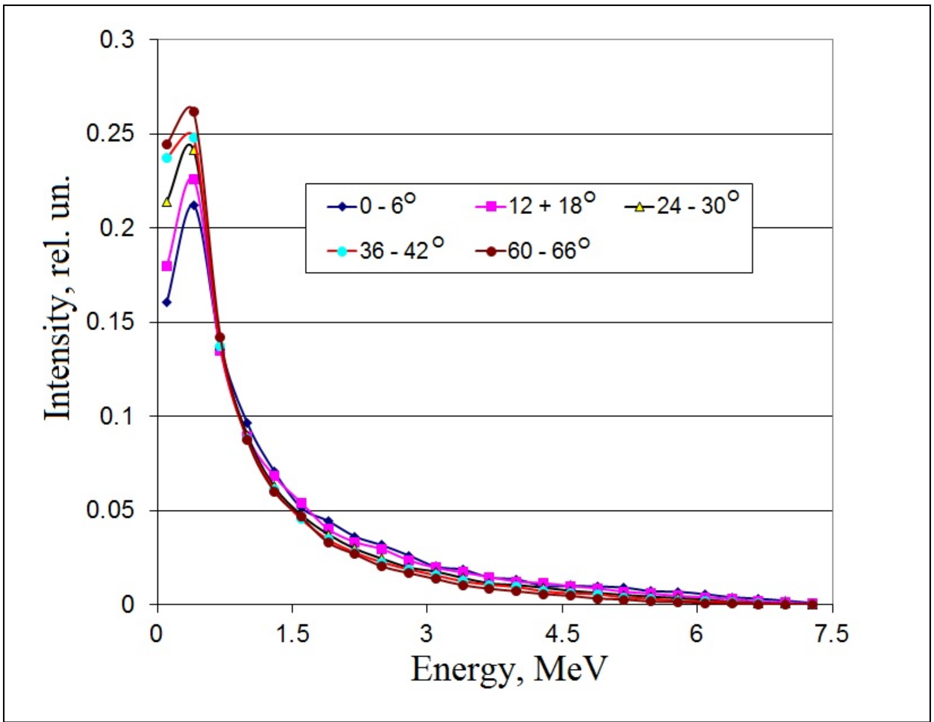

Fig. 4. BS spectra for the converter with 1.4 mm thick Ta target.

Calculations of deposited depth-doses in polyethylene, caused by BS falling on the surface of an object at different angles, are carried out [2]. Figure 5 shows the dependences of the specific (per unit area) deposited depth-dose in polyethylene for different incidence angles of BS within the angular intervals of angles $\Delta = 6°$.

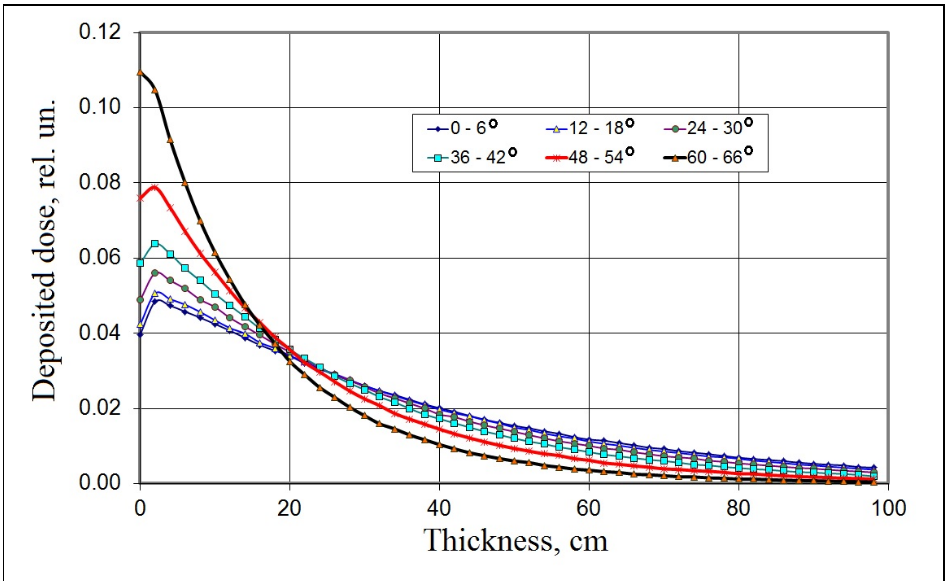

Fig. 5. Dependences of the deposited depth-dose in polyethylene for different incidence angles of BS.

It follows from the data shown in Fig. 5 that with a significant deviation of the BS incidence angle from the normal, the near-surface deposited dose is much higher, and at thicknesses greater than 20 cm it is less than for BS incident perpendicularly to the object. The distribution of the depth-dose in the irradiated polyethylene depends on the incidence angles and the BS spectra corresponding to these angles, as well as the angular distribution of BS generated by the converter.

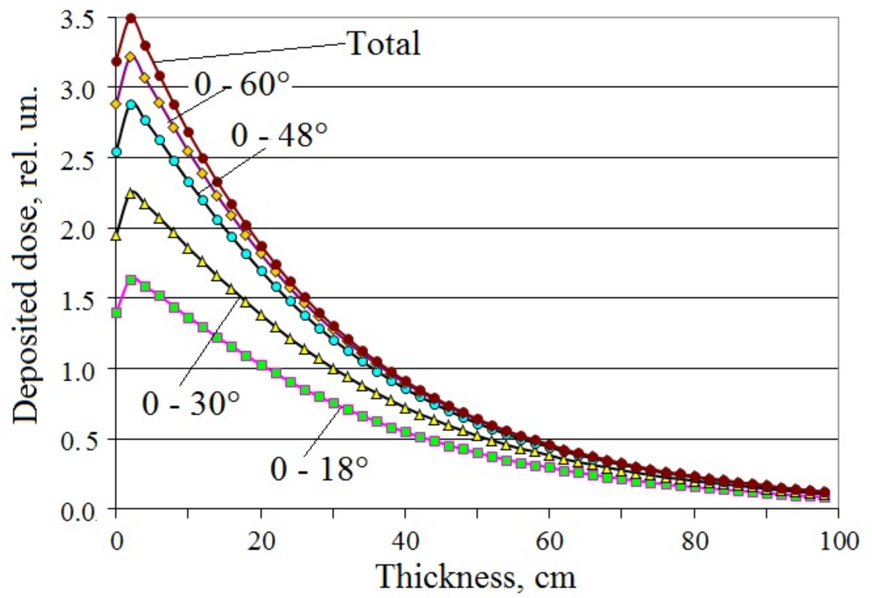

Fig. 6. Dependences deposited depth-dose on thickness of polyethylene for different intervals of the BS incidence angles.

Using the technique proposed in [3], the calculations of dose distributions for double-sided irradiation under bremsstrahlung radiation from an extended converter were completed. The deposited depth-dose at a depth X with double-sided irradiation is determined by the ratio:

$$D_{ds}(X,\Delta\Theta,Xo) = D(X,\Delta\Theta) - D(Xo - X,\Delta\Theta), \quad (1)$$

where D (X, ΔΘ) is the deposited depth-dose in polyethylene for the incidence angles interval ΔΘ of BS, Xo is the thickness of the object. The dependences of the deposited depth-dose on the thickness of polyethylene under double-sided irradiation for different ranges of the BS incidence angles with inhomogeneity DUR = 1.5 are shown in Fig.7.

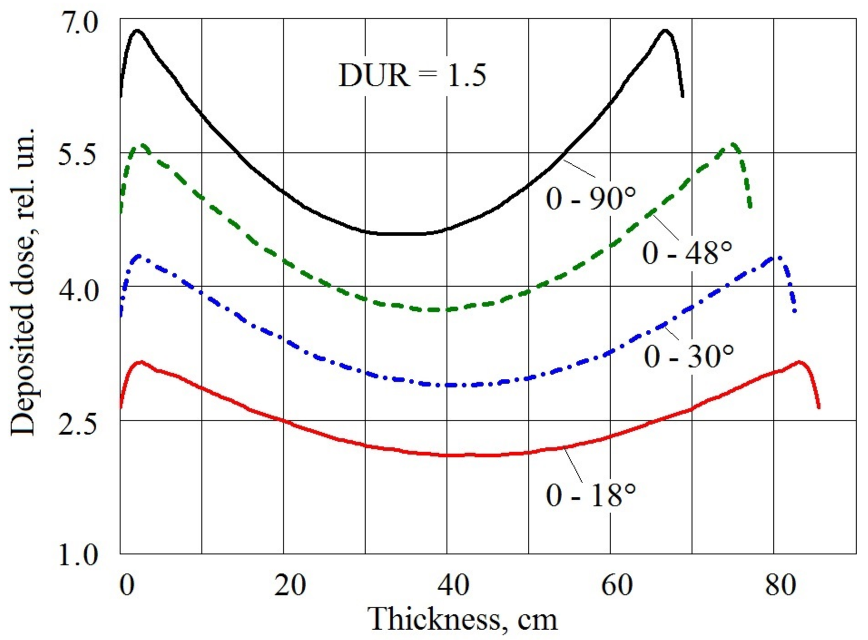

Fig. 7. Dependences of the deposited depth-dose on the thickness of polyethylene under double-sided irradiation for different ranges of BS incidence angles.

The thickness of polyethylene significantly depends on the BS incidence angle ranges for a fixed value of DUR. In our case, double-sided irradiation at DUR = 1.5 is considered. Table 1 shows the dependences of the thickness t, the ratio of the thicknesses t(ΔΘ)/t(0-90°) and the ration of the deposited energies $E_{dep}(\Delta\Theta)/E_{dep}(0\text{-}90°)$ in the object on the intervals of the incidence angles for double-sided irradiation of polyethylene.

Table 1. Polyethylene thickness vs incidence angle ranges, DUR = 1.5.

ΔΘ	0-18°	0-30°	0-48°	0-90°
t = Thickness, cm	85.5	82.6	77.1	68.8
t(ΔΘ)/t(0-90°)	1.24	1.20	1.12	1.00
$E_{dep}(\Delta\Theta)/E_{dep}(0\text{-}90°)$	0.573	0.763	0.919	1

In radiation technologies, the inhomogeneity of the deposited depth-dose DUR = 1.5 is usually used for food irradiation processing by BS radiation. In technological processes connected with a change in the properties of the irradiated materials, the DUR value should be smaller than 1.15. Under the condition of maximum thickness under double-sided irradiation, the minimum inhomogeneity of the deposited depth-dose distribution is determined by the ratio of D_{max} to D_{min}, where D_{min} is the dose on the surface of the object [1]. In [1], filters made of light elements (in particular, Al) are used to equalize the depth distribution of the dose under electron irradiation. In the case of irradiation by BS photons, Pb is used as a filter, which well absorbs low-energy photons. Figure 8 shows the dependences of the deposited depth-dose on the thickness of polyethylene irradiated without filter and with Pb filter for different ranges of the BS incidence angles.

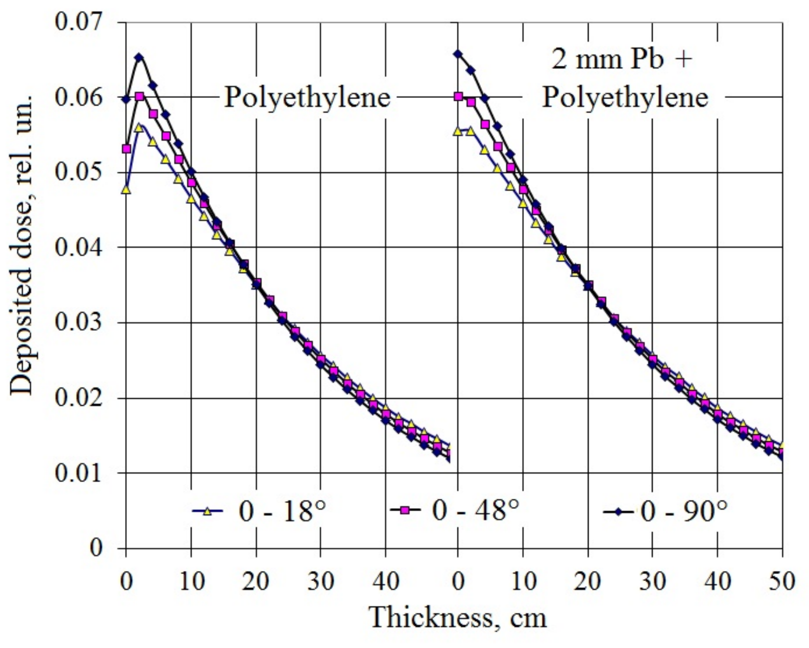

Fig. 8. Dependences of the deposited depth-dose on the thickness of polyethylene irradiated without filter and with Pb filter for different intervals of the BS incidence angles.

The optimal magnitudes of Xo were determined from the doses equality on the surface and in the center of the object, and is determined by the following relation:

$$D_{ds}(0,\Delta\Theta,Xo) = D_{ds}(Xo/2,\Delta\Theta,Xo). \quad (2)$$

Figure 9 shows the dependences of the deposited depth-dose on the thickness of polyethylene under double-sided irradiation with 2 mm Pb filter for different ranges of the BS incidence angles.

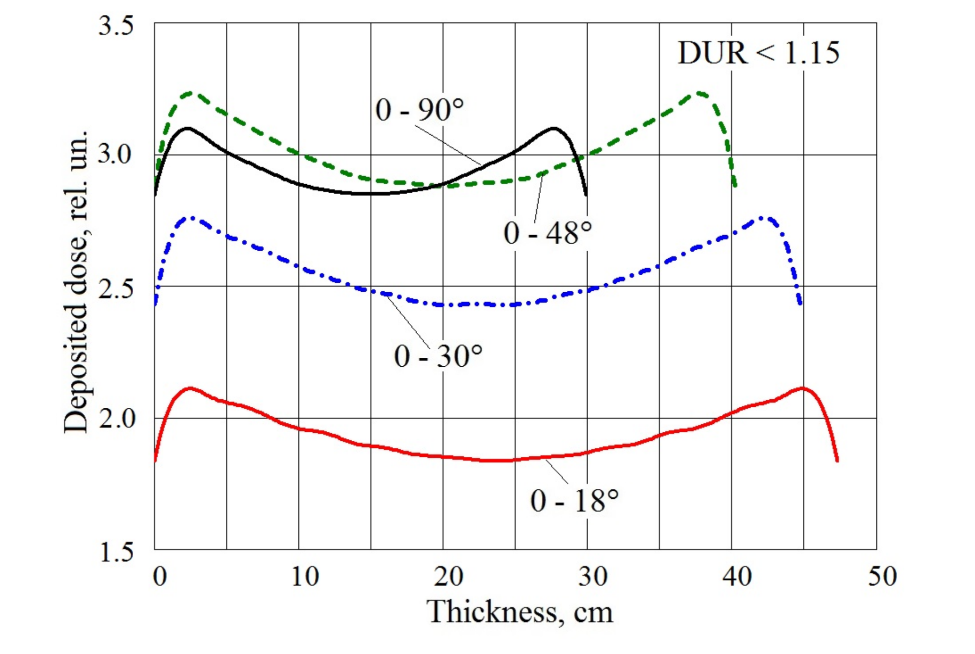

Fig.9. the dependences of the deposited depth-dose on the thickness of polyethylene under double-sided irradiation with 2 mm Pb filter for different ranges of the BS incidence angles.

Conclusions

The characteristics of BS produced by electrons with 7.5 MeV energy in a three-layer converter with different thicknesses of Ta, water, and Fe target are investigated. Changes in the yields and spectral characteristics of BS at different angles are calculated. It is shown that the average energy of BS decreases with increasing angle relative to the electron trajectory. An increase in the Ta layer thickness leads to increase of the energy E_{av}. Taking into account the spectra, the distributions of deposited depth-doses of polyethylene by BS incident on the surface of the object at different angles are calculated. The incidence angles and the BS spectra corresponding to these angles are shown to affect the formation of the depth-dose distribution of the irradiated polyethylene. For double-sided irradiation at a fixed value of the dose inhomogeneity DUR, the thickness of the object depends on the BS angle range. For technological processes related with a change in the properties of irradiated materials requiring high dose uniformity (low DUR values), the use of BS filters made of heavy materials is proposed.

References

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