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Calculation of doses from secondary neutrons during operating medical LINAC

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The relevance of research

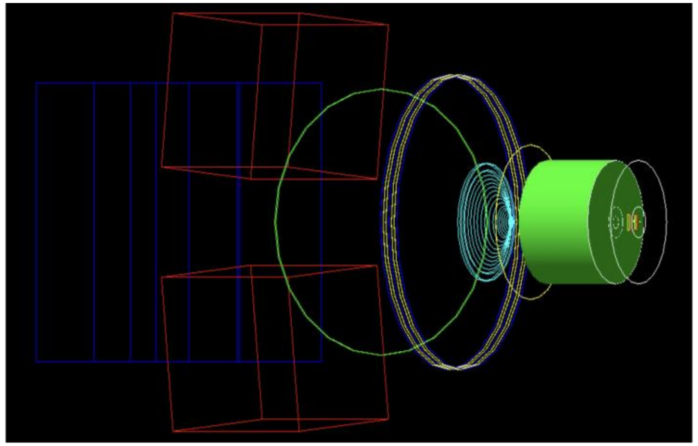
- At photon energies above 8 MeV, fluxes of secondary particles (mainly neutrons) in photonuclear reactions are appeared.
- Modern planning systems do not calculate this additional dose.
- The (γ, n) reaction threshold is 7.42 MeV.
- Substances with a large atomic number Z are characterized by a small cross section for the absorption of neutrons of various energies.

The relevance of research

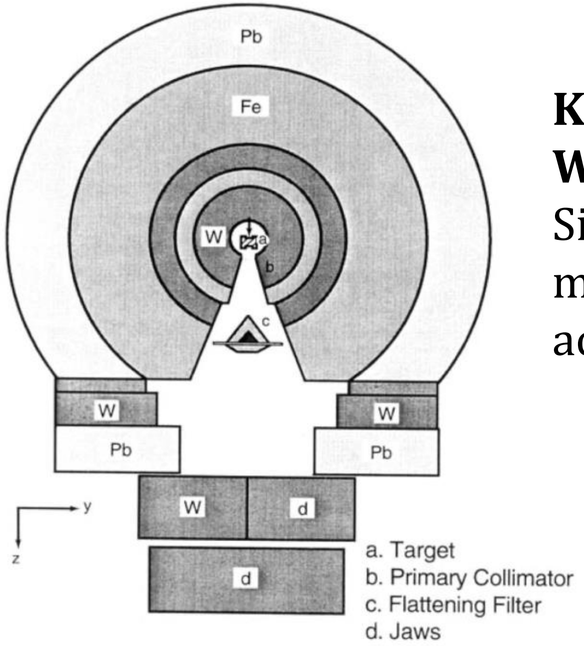
- In a treatment room, it is difficult to assess the contribution of secondary neutrons to the dose; however, the irradiation process can be simulated.

- The model of the head of the medical linac, verified by experiment, will make it possible to estimate the contribution of secondary particles to the dose.

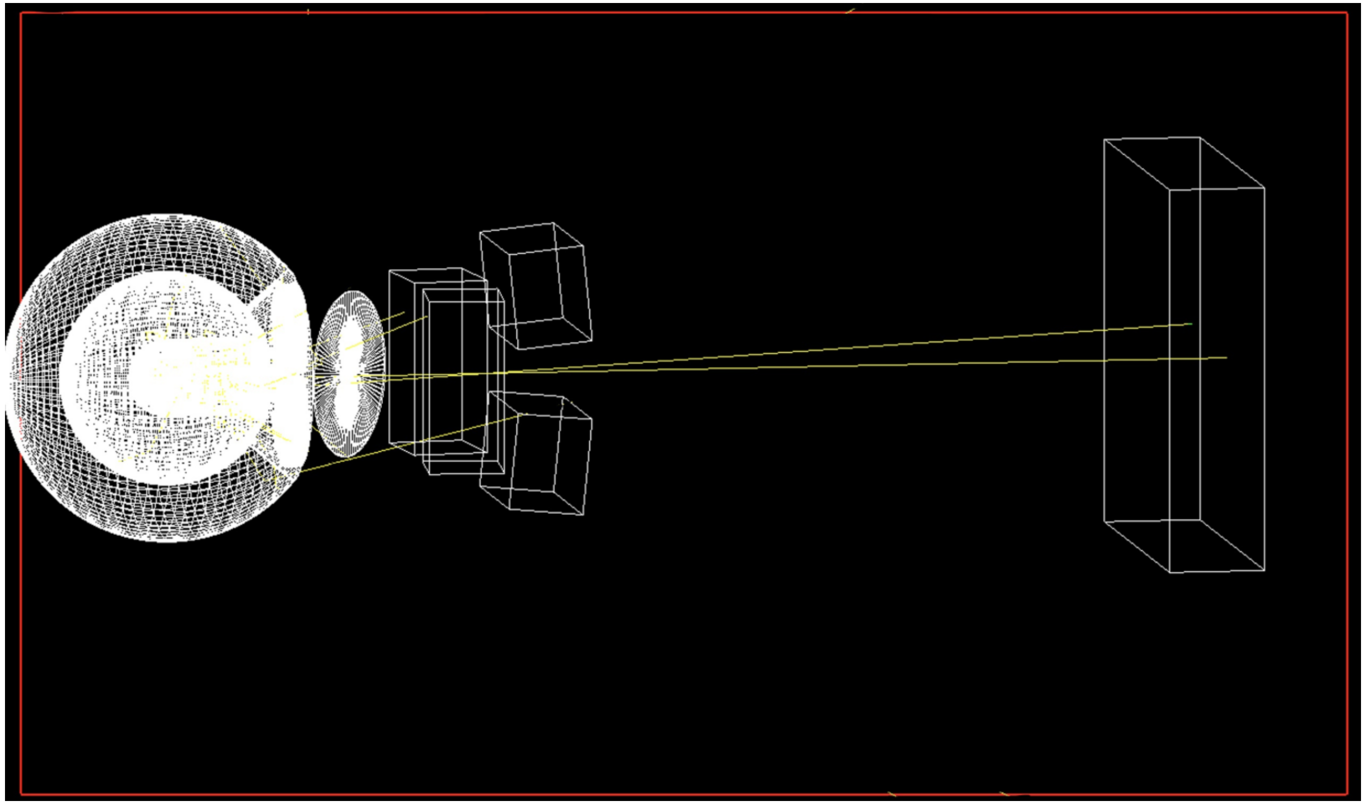
Medical linac simulation



Geant4 medicalLinac2
Advanced example geometry

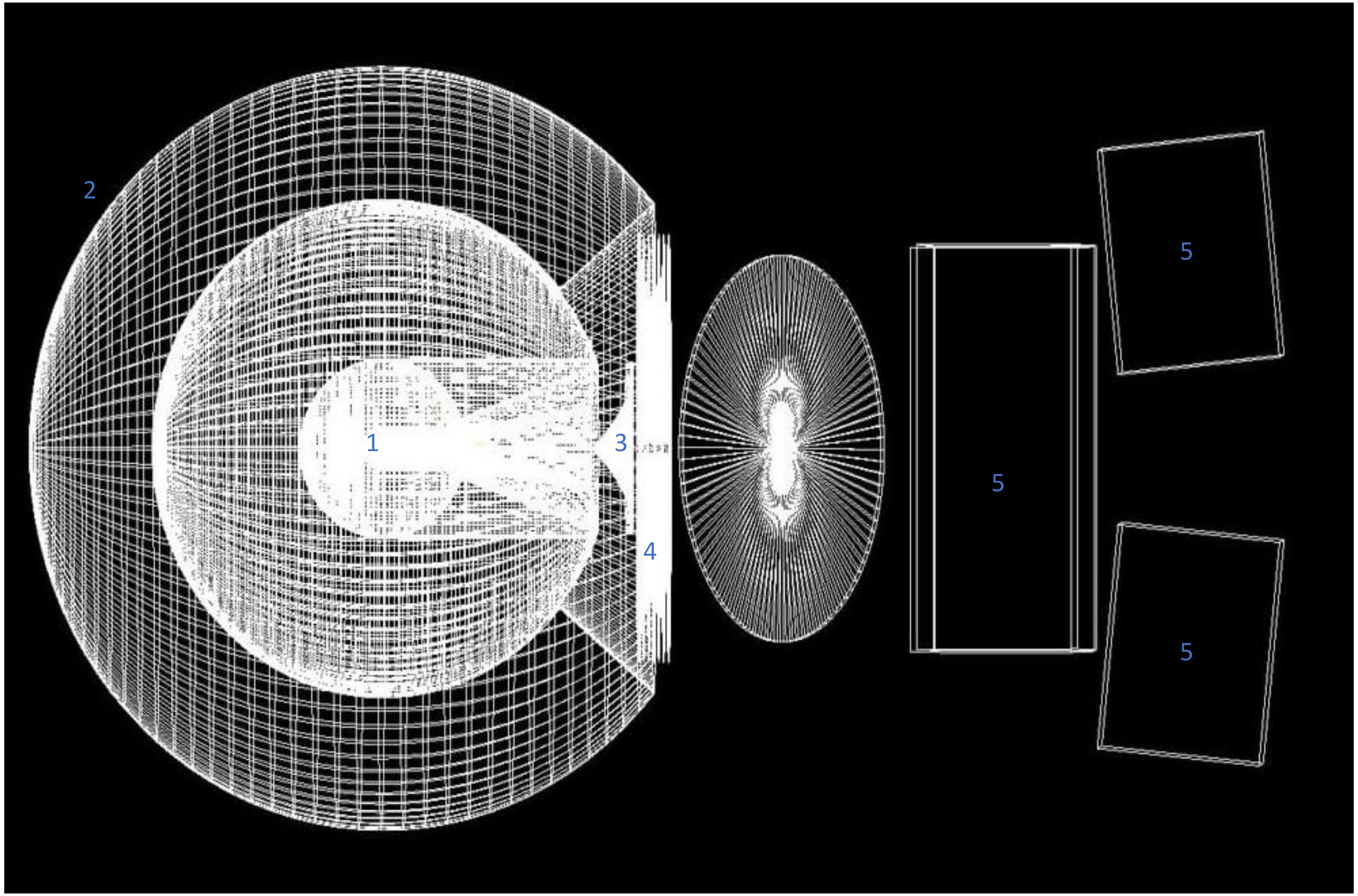


K. R. Kase, X. S. Mao, W. R. Nelson, 1998
Simplified geometry for medical linear accelerator modeling



Geometry of the realized model

Simulation model



EXPERIMENTAL SETUP:

1. BREMSSTRAHLUNG TARGET
2. PRIMARY COLLIMATOR
3. FLATTENING FILTER
4. IONIZATION CHAMBER
5. UPPER AND LOWER JAWS

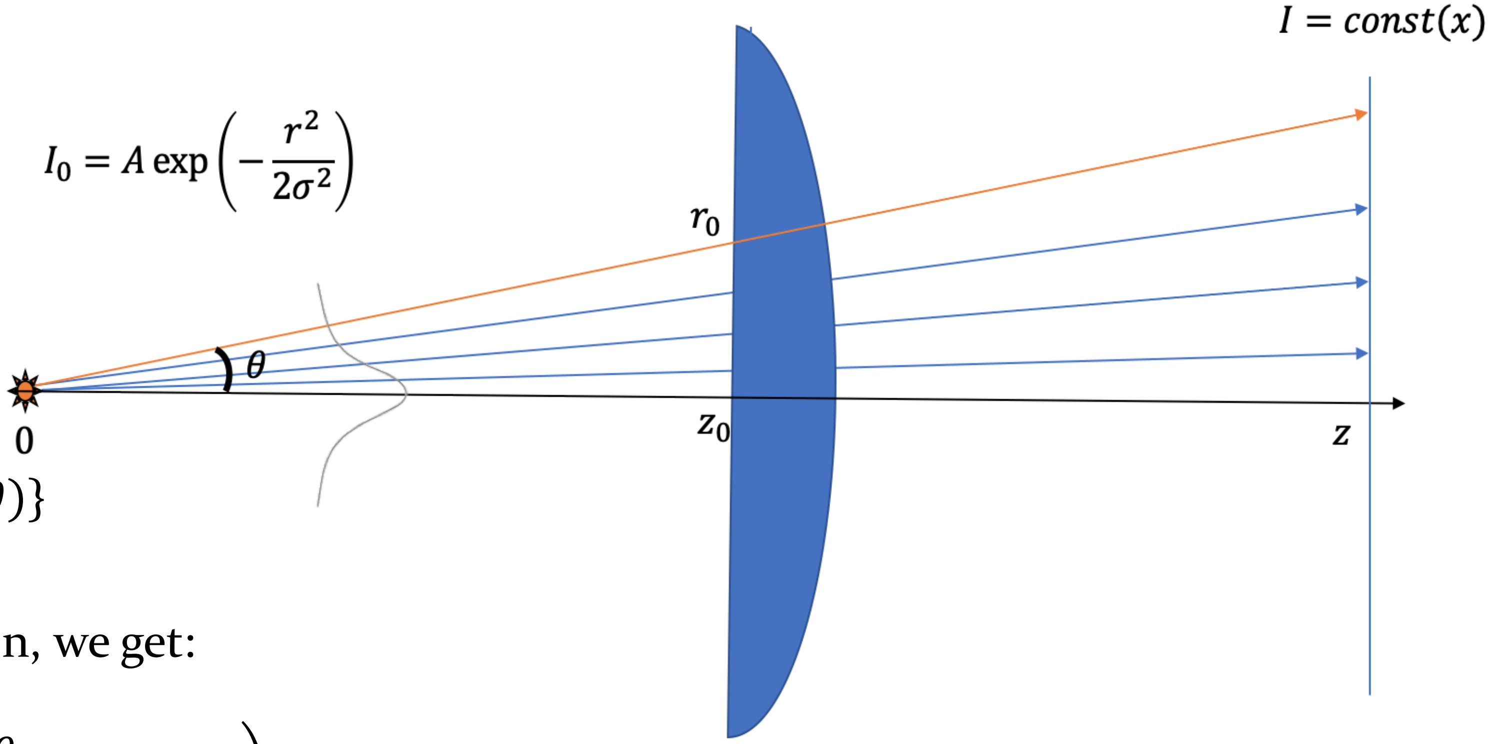
Flattening filter shape calculation

$$I(z) = I_0(r,z)\exp\big(-\mu\Delta(\theta)\big)$$

$$I(z_1) = I_0(r)\frac{S(z_0)}{S(z_1)}\exp\{-\mu\Delta(\theta)\}$$

$$I(z_1) = I_0(z_0\operatorname{tg}\theta)\frac{S(z_0)}{S(z_1)}\exp\{-\mu\Delta(\theta)\}$$

$$I(z_1) = A\exp\left(-\frac{z_0^2\operatorname{tg}^2\theta}{2\,\sigma^2}\right)\frac{S(z_0)}{S(z_1)}\exp\{-\mu\Delta(\theta)\}$$



Taking the derivatives of both sides of the equation, we get:

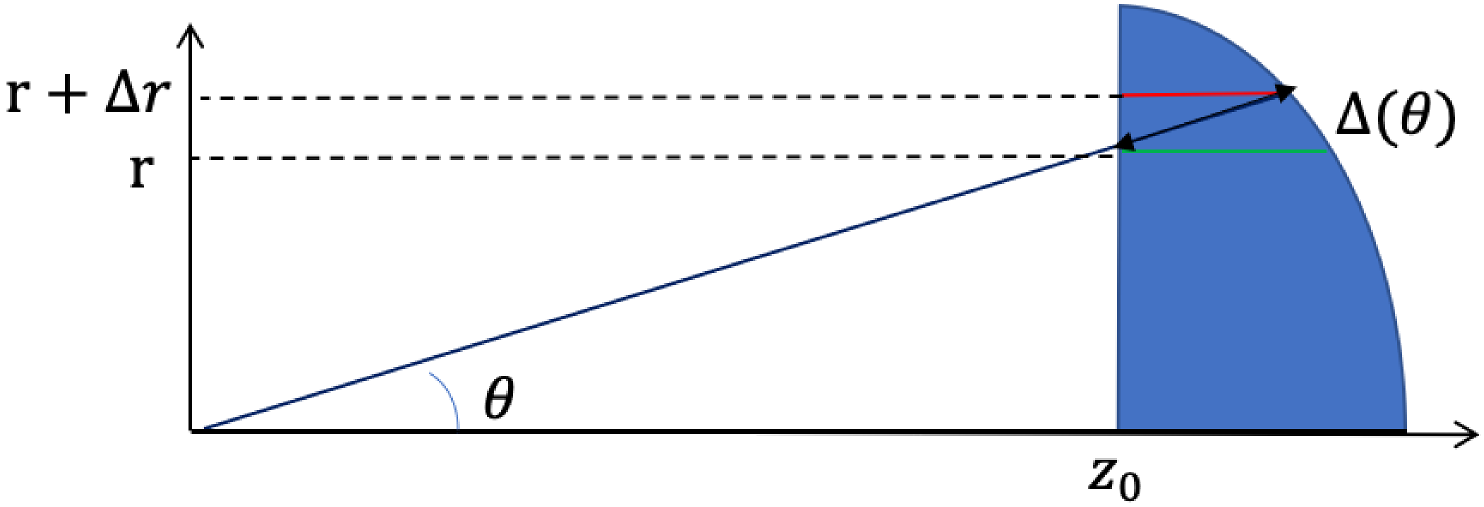
$$0 = A\frac{S(z_0)}{S(z_1)}\exp\left(-\frac{z_0^2\operatorname{tg}^2\theta}{2\,\sigma^2} - \mu\Delta(\theta)\right)\left(-\frac{2z_0^2\operatorname{tg}\theta}{2\sigma^2\cos^2\theta} - \mu\Delta'(\theta)\right)$$

$$\Delta'(\theta) = -\frac{2z_0^2\operatorname{tg}\theta}{2\mu\sigma^2\cos^2\theta}$$

$$\Delta(\theta) = \int -\frac{2z_0^2\operatorname{tg}\theta}{2\mu\sigma^2\cos^2\theta}d\theta = -\frac{z_0^2}{\mu\sigma^2}\int \operatorname{tg}\theta\, d\operatorname{tg}\theta$$

$$\boxed{\Delta(\theta) = -\frac{z_0^2}{2\mu\sigma^2}\operatorname{tg}^2\theta + C}$$

Flattening filter shape calculation



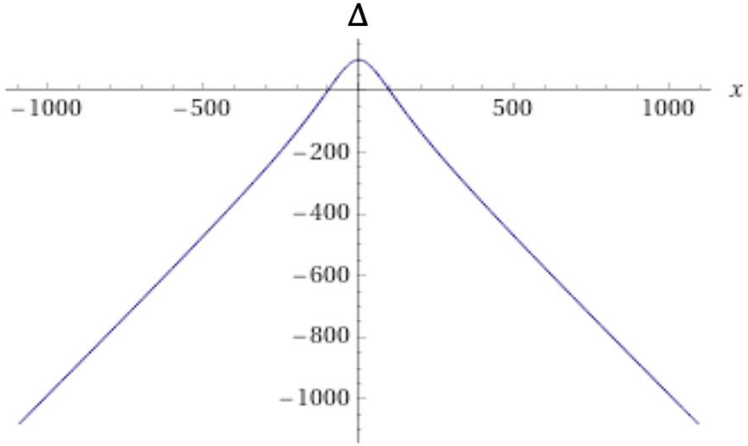
$$\Delta(r) = \Delta(\theta)\cos\theta = -\frac{r^2}{2\mu\sigma^2}\cos\theta + C\cos\theta$$

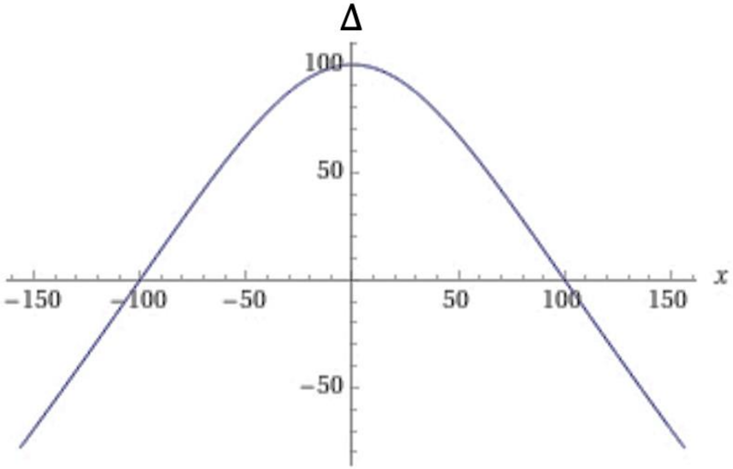
$$\Delta(r) = -\frac{r^2}{2\mu\sigma^2}\cos\left(\mathrm{arctg}\frac{r^2}{z_0^2}\right) + C\cos\left(\mathrm{arctg}\frac{r^2}{z_0^2}\right)$$

$$\Delta(r) = -\frac{r^2}{2\mu\sigma^2}\frac{z_0}{\sqrt{r^2+z_0^2}} + C\frac{z_0}{\sqrt{r^2+z_0^2}}$$

$$\Delta(r) = -\frac{z^0}{2\mu\sigma^2}\frac{r^2}{\sqrt{r^2+z_0^2}} + C\frac{z_0}{\sqrt{r^2+z_0^2}}$$

$$\Delta(r) = \frac{z_0}{\sqrt{r^2+z_0^2}}\left(C - \frac{r^2}{2\mu\sigma^2}\right)$$





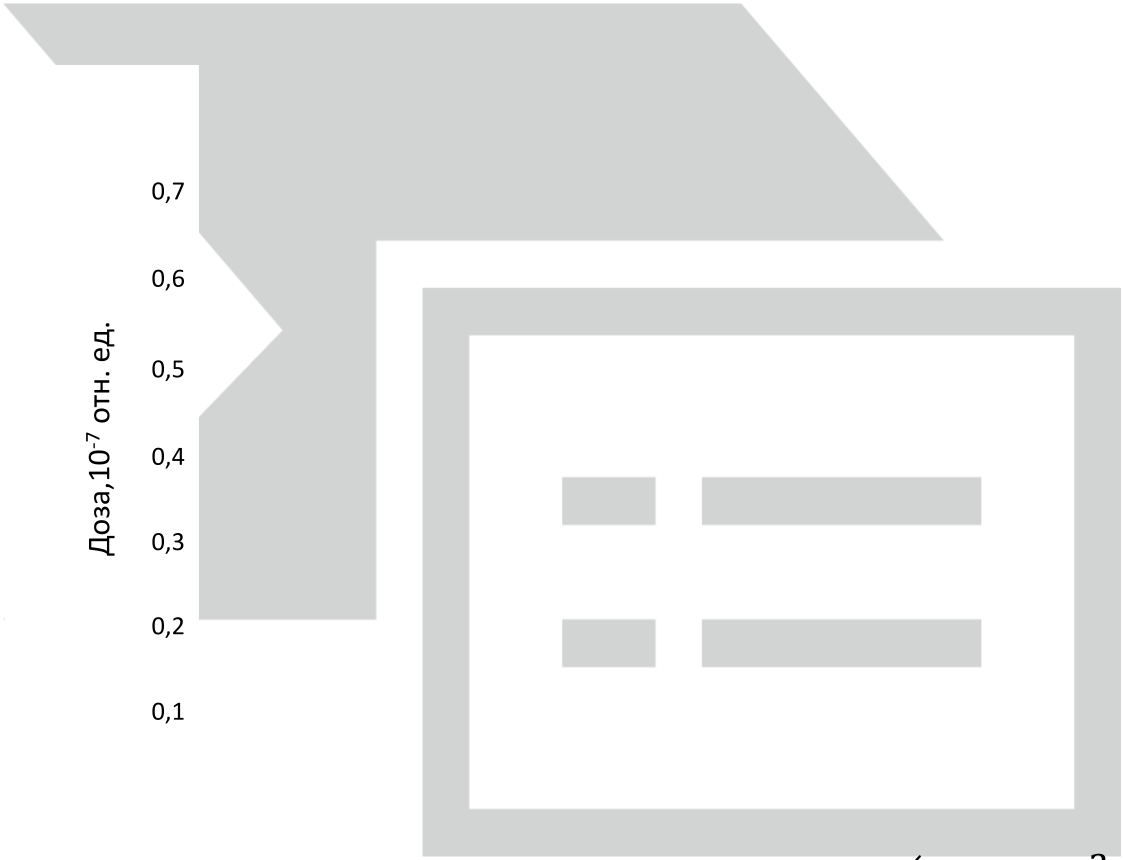
Function are presented on the figures on the right with the next values of constants

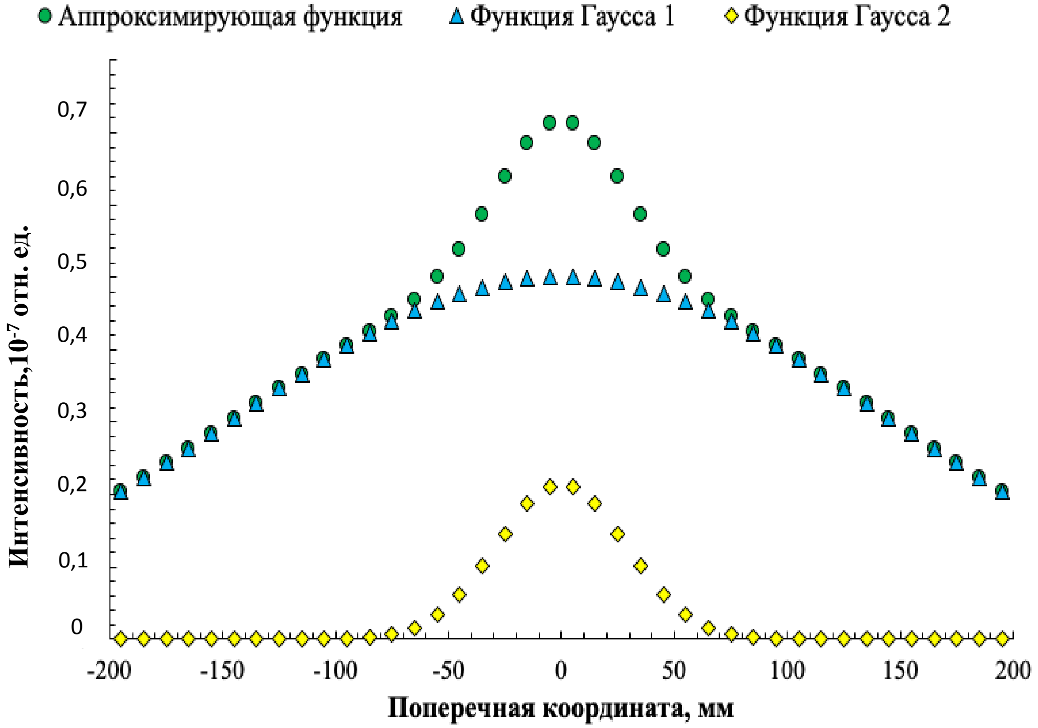
C = 100,

z_0 = 100,

$2\mu\sigma^2$ = 100.

Flattening filter shape calculation



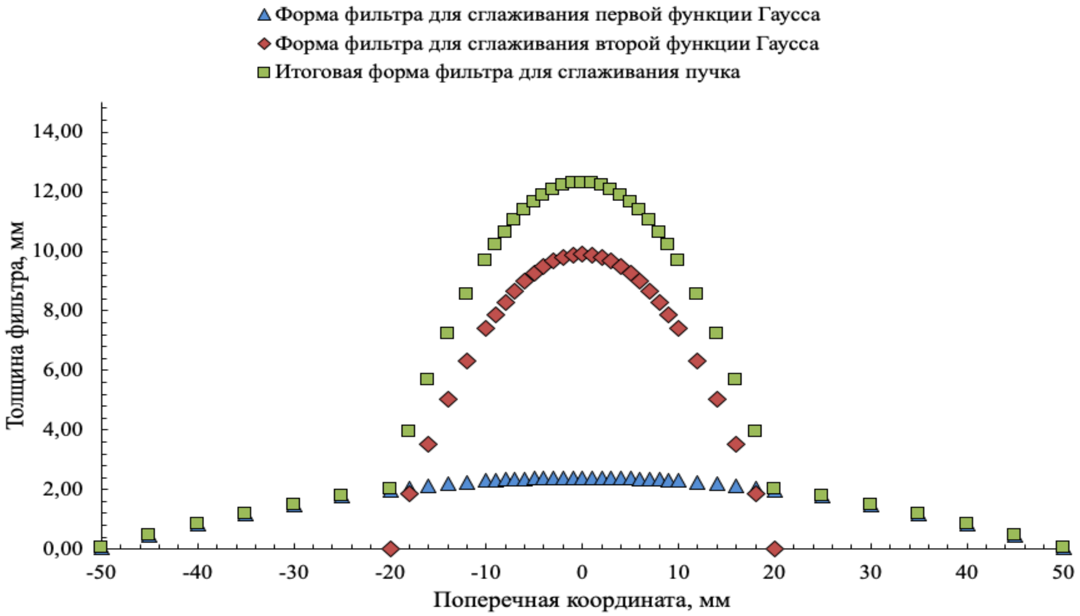


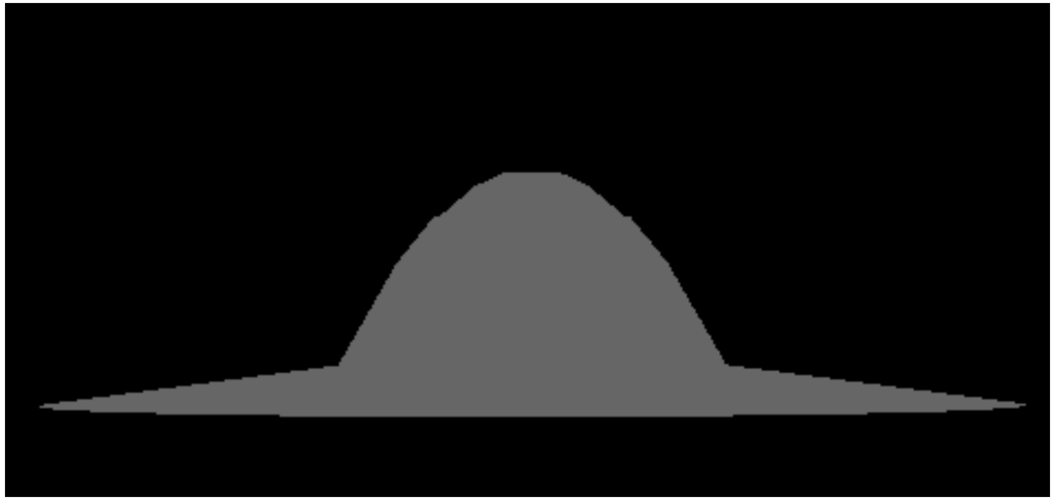
$$D = 5{,}00856 * 10^{-7} \exp\left(-\frac{x^2}{2 * 145{,}76^2}\right) + 2{,}14801 * 10^{-7} \exp\left(-\frac{x^2}{2 * 28{,}449^2}\right)$$

The average approximation error is 3,13%

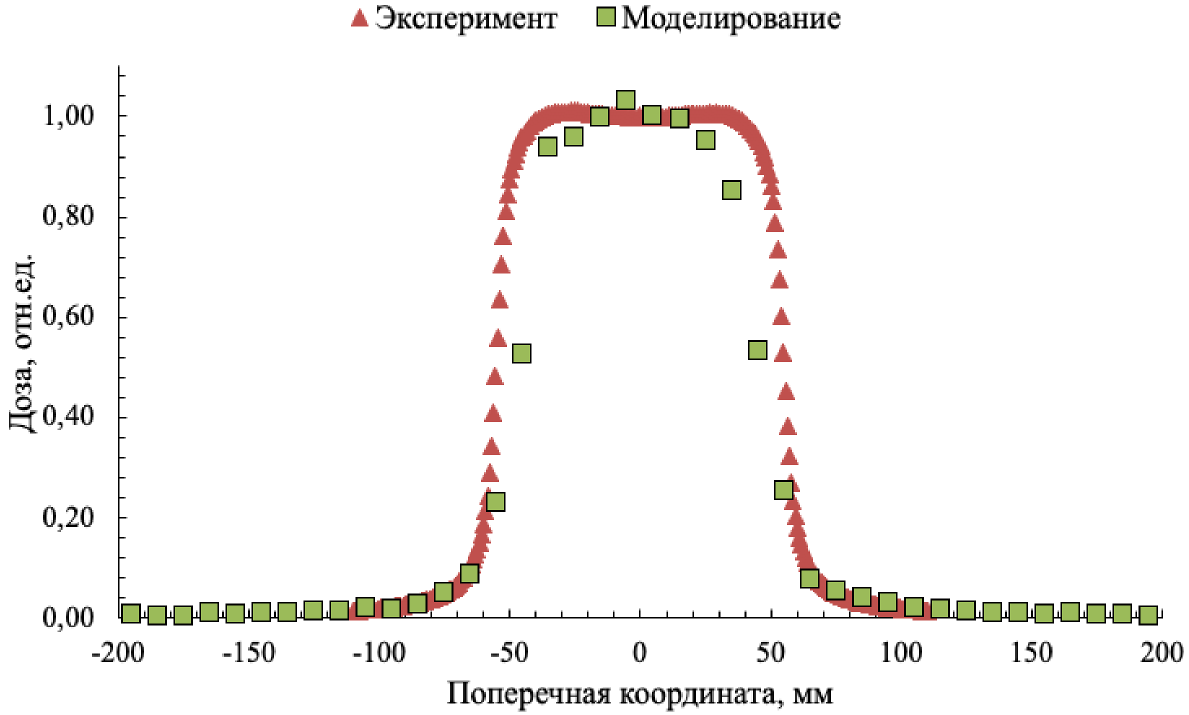
Model verification

Dependence of the filter thickness on the transverse coordinate



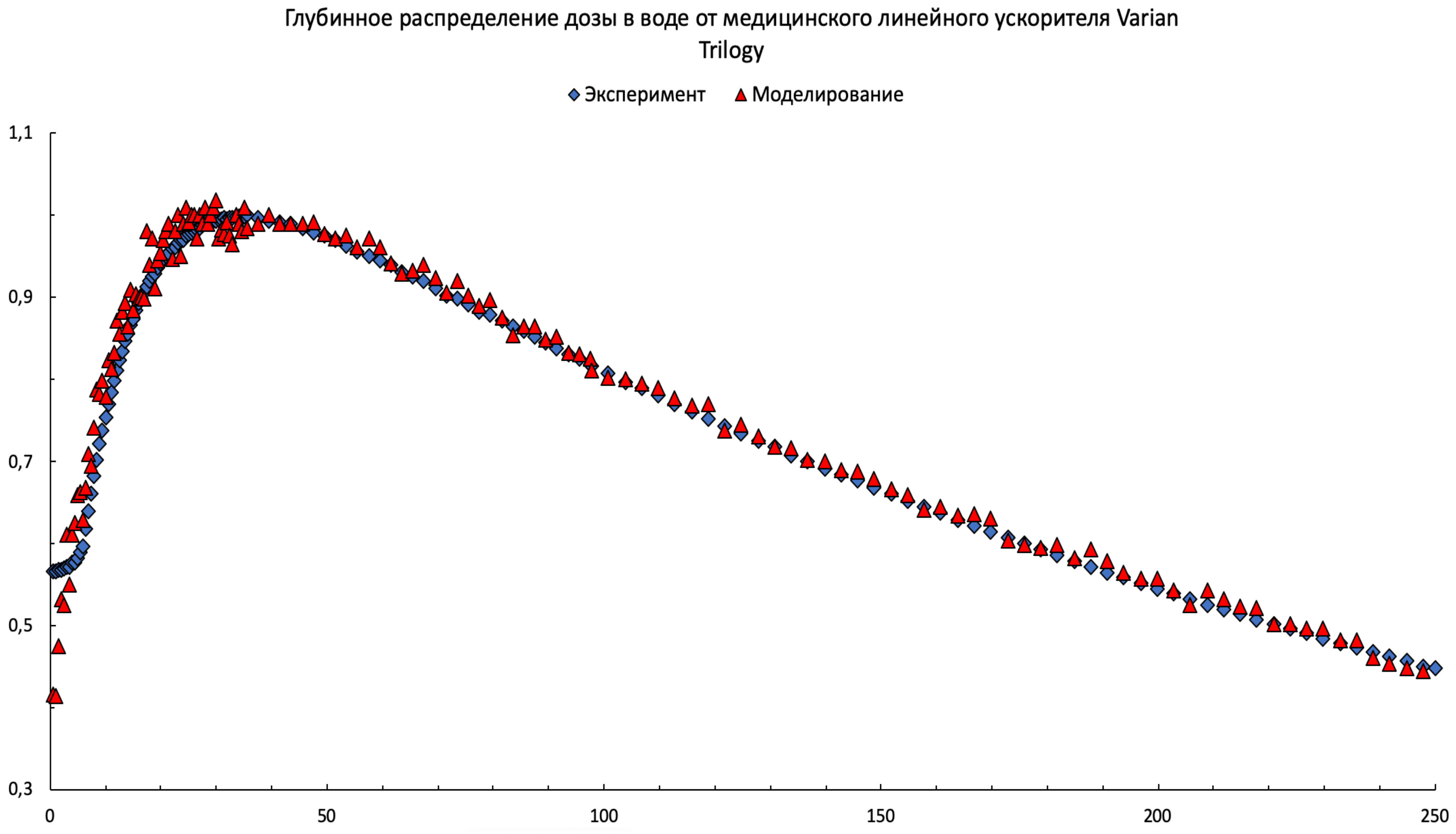


Dose profile of the beam at the depth of 10 cm in a water phantom



Despite the large numbers of assumptions in the theoretical flattening filter shape calculations and in its practical realization in the model, the model profile is in sufficient agreement with the experimental data.

Model verification

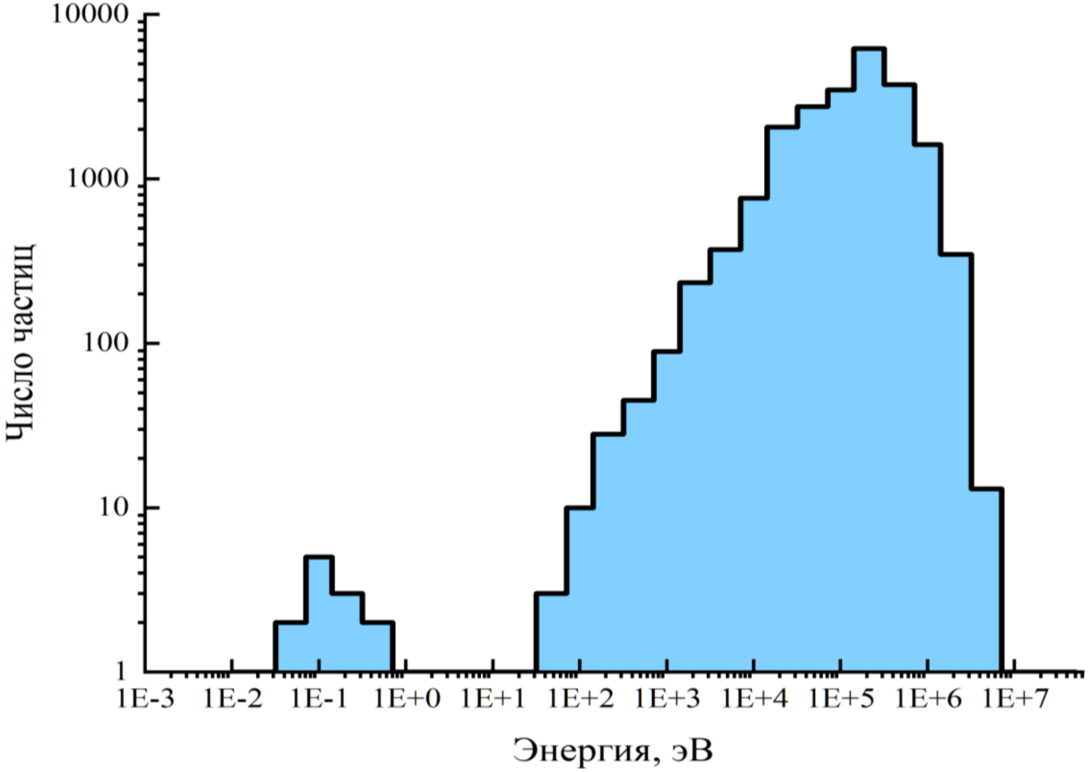


- For a cylindrical detector with an inner diameter of 5.5 mm, the simulation results converge with the experimental ones with a high accuracy.

Characteristics of semiflex chambers	
Ventilated sensitive volume	0,125 см^3
Inner diameter	5,5 мм
Nominal usable energy range	30 кэВ – 50 МэВ

Results

Photoneutron spectrum recorded in a thin layer of water in the center of the phantom 2 mm thick in the isocenter

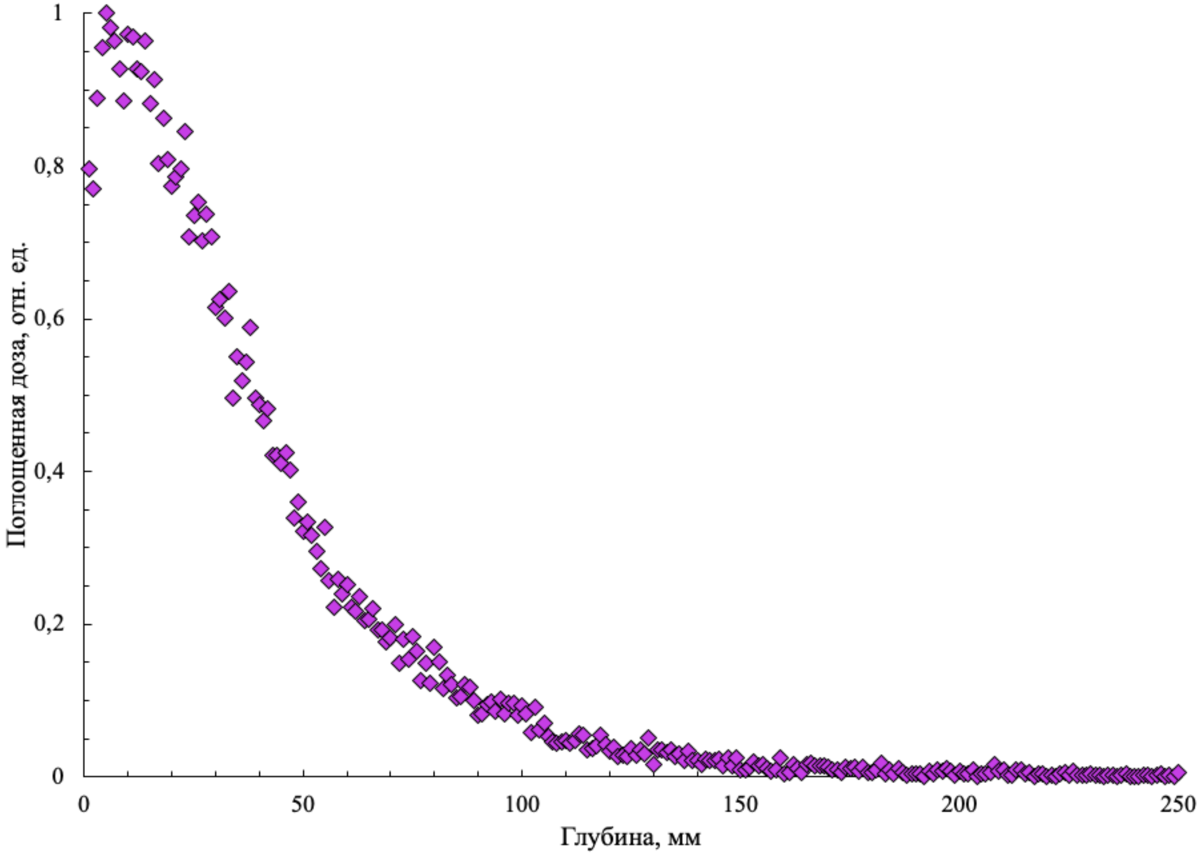


As the result of simulation, an estimate of the average energy o secondary neutrons was obtained.

$\langle E \rangle$ = 0,76 MeV

$\langle E \rangle_{exp}$ = 0,89 MeV

PDD for neutrons



The dose maximum falls at a depth of 5 mm.

Results

To estimate the equivalent dose, the average absorbed dose in a thin layer of water in the center of the phantom was estimated for neutrons and photons, respectively. A layer of water with linear dimensions of 5 x 5 x 0.2 cm3, located at the isocenter in the center of the phantom, was considered.

Radiation	Average dose	Quality factor
Photones	$2{,}98 \cdot 10^{-10}$ Gy	1
Neutrons up to 10 keV	$4{,}03 \cdot 10^{-13}$Gy	5
Neutrons from 10 to 100 keV	$6{,}61 \cdot 10^{-14}$Gy	10
Neutrons from 100 keV to 2 MeV	$1{,}64 \cdot 10^{-14}$Gy	20
Neutrons from 2 MeV to 20 MeV	$1{,}48 \cdot 10^{-16}$Gy	10

The contribution of neutron radiation to the absorbed dose was estimated as the ratio of the total dose from neutron radiation to the total dose from all radiation.

$$\omega_{N_{\text{abs}}} = 0{,}20\%$$

$$\omega_{N_{\text{abs},exp}} = 0{,}25\%$$

The contribution to the equivalent dose was calculated as the ratio of the weighted sum of doses from all types of neutron radiation to the weighted sum of doses from all radiation.

$$\omega_n = 1{,}63\%$$

Conclusions

- A theoretical flattening filter shape was calculated;
- The model was verified on the dose profile and depth dose distribution, the results agreed with experiment with a high degree of accuracy;
- The spectrum of secondary neutrons was obtained. The average neutron energy was estimated. **<E> = 0,76 MeV**
- Neutron PDD has been obtained. The maximum dose is at a depth of 5 mm.
- The contribution of neutron radiation to the dose is estimated. The contribution to the absorbed dose was $\boldsymbol{\omega_{N_{погл}} = 0,20\%}$ (experimental value is $\omega_{N_{погл,эксп}} = 0{,}25\%$). This value corresponds to the contribution at the equivalent dose at the level of $\boldsymbol{\omega_n = 1,63\%}$

Thanks for your attention

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