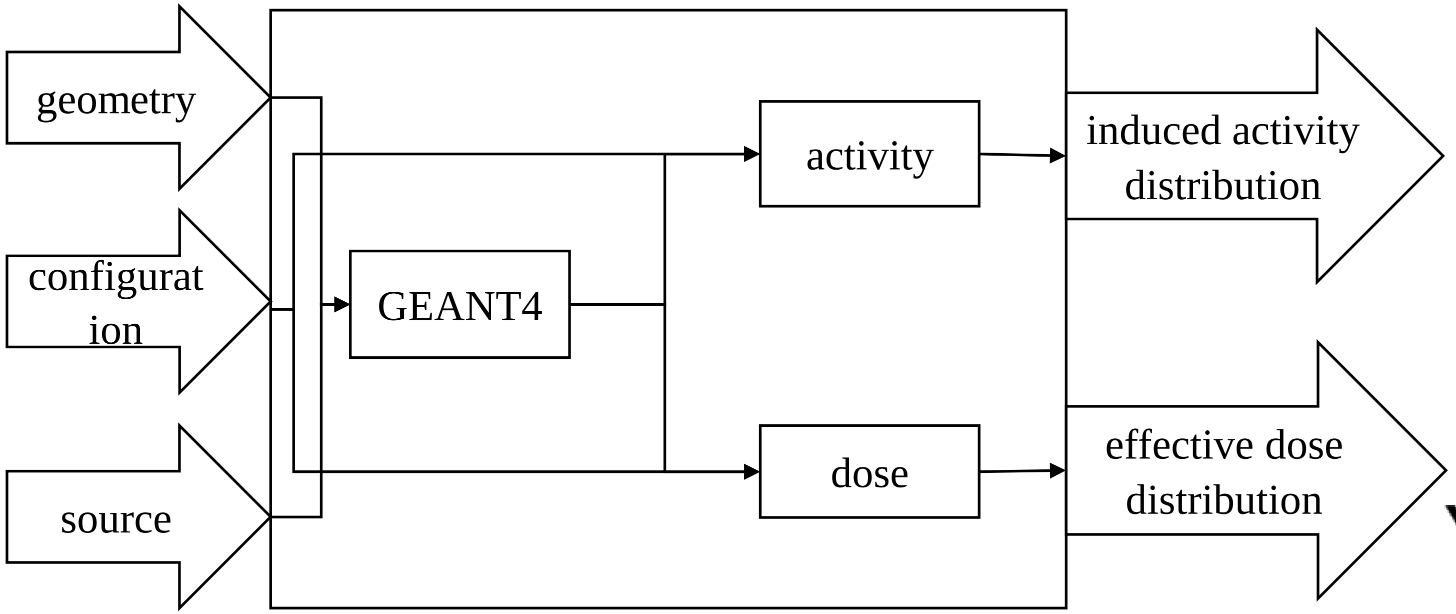
DEVELOPING OF A SOFTWARE FOR CALCULATIONS OF ACCELERATOR-INDUCED RADIATION ENVIRONMENTS USING THE GEANT4 TOOLKIT

Kuzmenko Anna Sergeevna

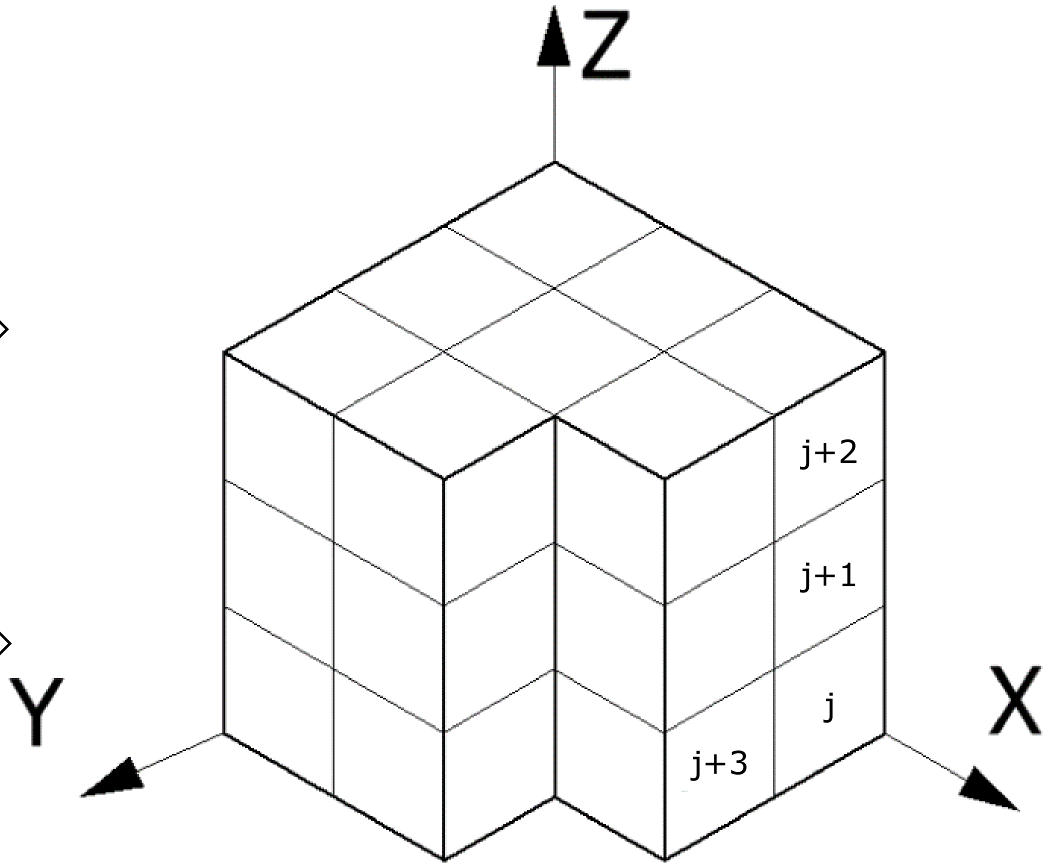
RELEVANCE

Due to the lack of certified programs for assessing the radiation environment during the operation of accelerator equipment, as well as advantages of using statistical toolkits for particle transport, the development and verification of a software for calculating the effective dose and induced activity is of current importance.

SOFTWARE



Structural scheme of the software



Reference system and numbering of sensitive volumes

EFFECTIVE DOSE METHOD

(1) $$\Phi_{ij} = \frac{\sum_{m=1}^{N} l_{imj}}{V_j}$$

(2) $$E_j = \sum_{i=1}^{n} k_{Ei} \cdot \frac{\sum_{m=1}^{N} l_{imj}}{V_j}$$

(3) $$k_E = k_p + \frac{k_{p+1} - k_p}{E_{p+1} - E_p} \cdot \left(e - e_p\right),\ E \in \left[e_p; e_{p+1}\right)$$

Indexes

j – volume number
i – particle
m – particle type (e^-, p…)
p – energy step

Quantities

E – effective dose, Sv
Φ – fluence, cm^{-2}
l – track length, cm
V – volume, cm^3
e – energy, MeV
n – types amount
N – amount particles

INDUCED ACTIVITY METHOD

(4) $$A_j = \sum_{i=1}^{n} \sum_{m=1}^{P} \frac{1}{\tau_i} \cdot N_{0imj} \cdot e^{-\frac{t_{cool}}{\tau_i}}$$

Indexes

i – radionuclide
m – process
j – volume

Quantities

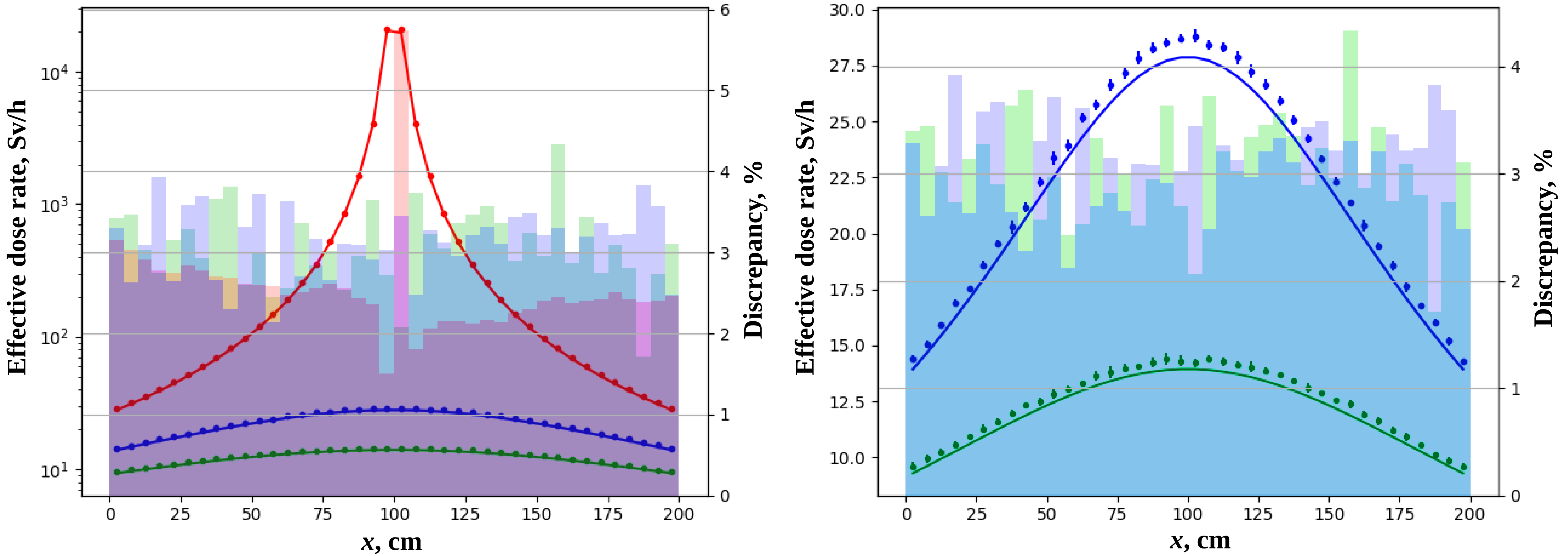
A – induced activity, Bq
τ – average lifetime, s
N_0 – number of nuclei
t_{cool} – cooling time, s
n – radionuclides amount
P – number of processes

Output example of neutron capture ^{98}Mo simulation results

Mo99	nCapture	18990	342660
Tc99	RadioactiveDecay	18990	9.61096e+12
Tc99[142.683]	RadioactiveDecay	16690	31197

GAMMA-INDUCED EFFECTIVE DOSE

^{60}Co
m = 1 g.



red (y = 102,5 cm; z = 102,5 cm); blue (y = 102,5 cm; z = 2,5 cm); green (y = 2,5 cm; z = 2,5 cm)

points – simulation in the GEANT4 toolkit; lines – analytical calculation

Dependence of the effective dose rate of isotropic decay of radionuclide on distance and relative simulation discrepancy (histogram)

NEUTRON CROSS SECTIONS, CM^{-1}

(5) $$\sigma_{tot} = \sigma_s + \sigma_a$$

(6) $$I(x) = I_0 e^{-\Sigma_{tot} x}$$

(7) $$\Sigma = \rho V N_A \sum_i \frac{\omega_i \sigma_i^{tot}}{\mu_i}$$

Natural iron

^{54}Fe	^{56}Fe	^{57}Fe	^{58}Fe
0.05845	0.91754	0.02119	0.00282

TOTAL (MT=1)

E, MeV	GEANT4	ENDF-VIII.0	Discrepancy, %
2	0.204445	0.208658	2.02
4	0.317292	0.317683	0.12
10	0.258789	0.255650	1.23
14	0.218180	0.219205	0.47

ELASTIC (MT=2)

E, MeV	GEANT4	ENDF-VIII.0	Discrepancy, %
2	0.157398	0.155779	2.03
4	0.208531	0.198163	4.73
10	0.137509	0.129906	5.45
14	0.098648	0.099890	1.76

NONELASTIC (MT=3) and INELASTIC (MT=4)

E, MeV	GEANT4	ENDF-VII.0, MT=3	ENDF-VIII.0, MT=4	ENDF-VIII.0, TOT-EL	Discrepancy, %
2	0.0463409	0.066535	0.067304	0.052879	31.35
4	0.109171	0.110789	0.109469	0.119520	1.46
10	0.121492	0.120421	0.109346	0.125744	0.89
14	0.119865	0.117625	0.063442	0.119315	1.90

INDUCED ACTIVITY VERIFICATION

(8) $$A = \frac{\ln 2}{T_{1/2}} \cdot N \cdot e^{-\frac{\ln 2}{T_{1/2}} \cdot t_{cool}}$$

(9) $$N = \sigma \cdot N_{\text{target}} \cdot t \cdot \Phi_0$$

(10) $$N_{\text{target}} = \frac{\rho_{\text{target}} \cdot V}{\mu_{\text{target}}} \cdot N_A$$

$T_{1/2}$ – half-life of the reaction product, s
N – the number of product nuclei formed
t_{cool} – cooling time, s

σ – microscopic reaction cross section, cm^{-2}
N_{target} – number of nuclei in the target
t – radiation time, s
Φ_0 – fluence, particles/cm^2·s

ρ_{target} – target's density, g/cm^3
μ_{target} – target's molar mass, g/mol
N_A= 6.022·10^{23} mol^{-1} – Avogadro number

Induced activity of reaction neutron capture on ^{98}Mo nuclei

Neutron energy, MeV	Induced activity, Bq		Discrepancy, %
	GEANT4	Analytical calculation	
0.1	0.0901±0.0003	0.0881	2.29
0.5	0.0903±0.0004	0.0889	1.60
1	0.0532±0.0004	0.0514	3.63

^{98}Mo(*n*, *γ*)Mo^{99}

Neutron fluence – 10^7 n./cm^2·s

Number of experiments – 10

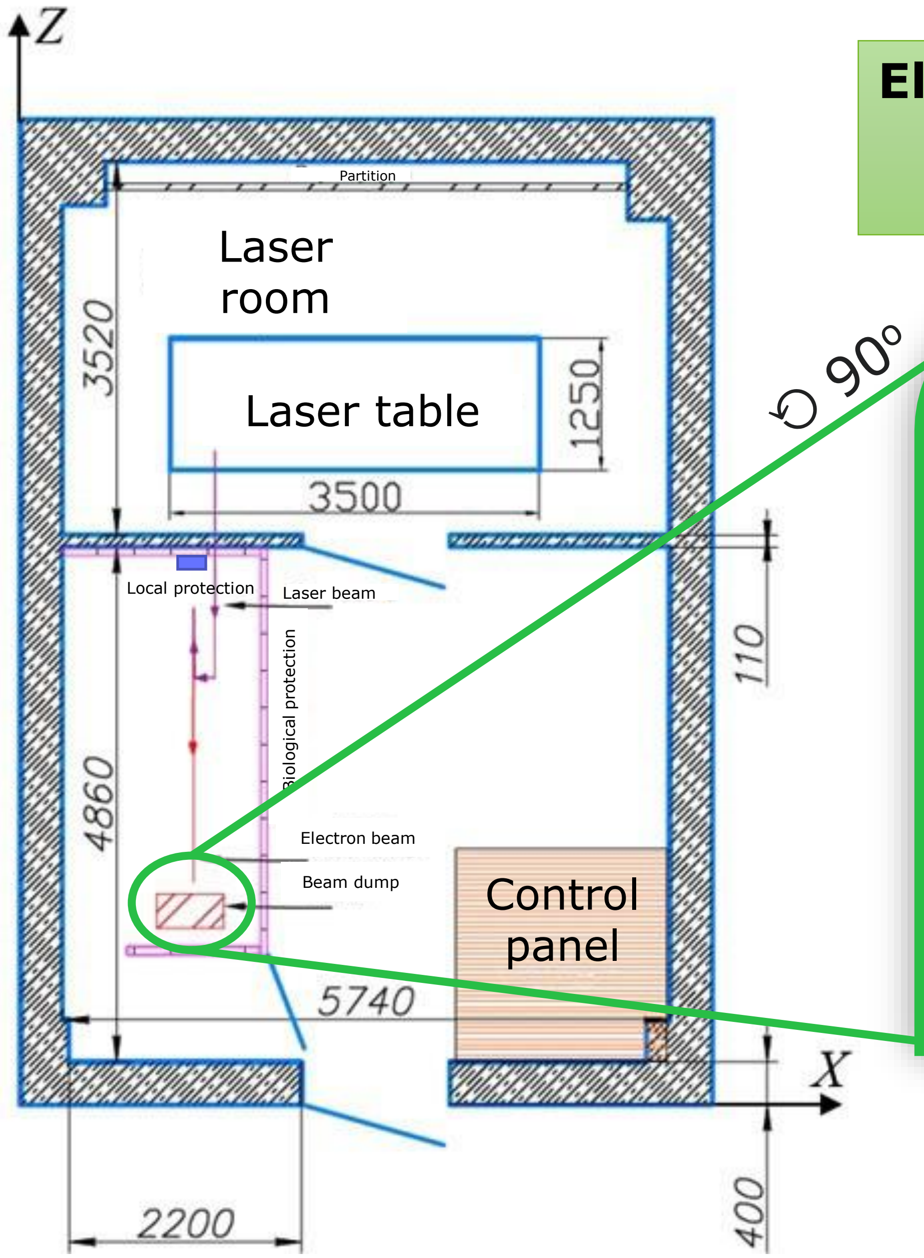
$T_{1/2}$ = 65.976 h

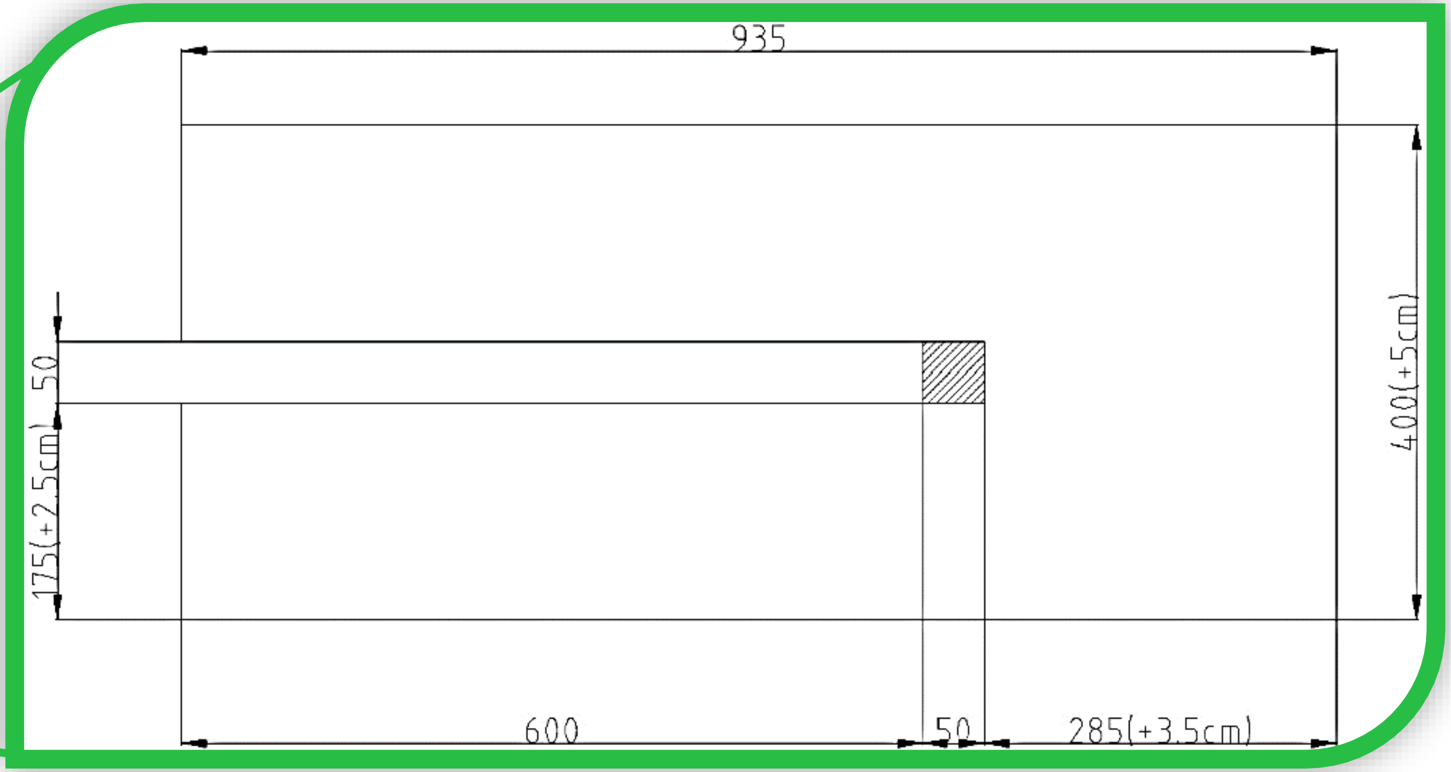
A PHOTOINJECTOR TESTBENCH ROOM

Electron beam
E = 6 MeV
I = 0.5 μA

biological protection – 1 mm Pb

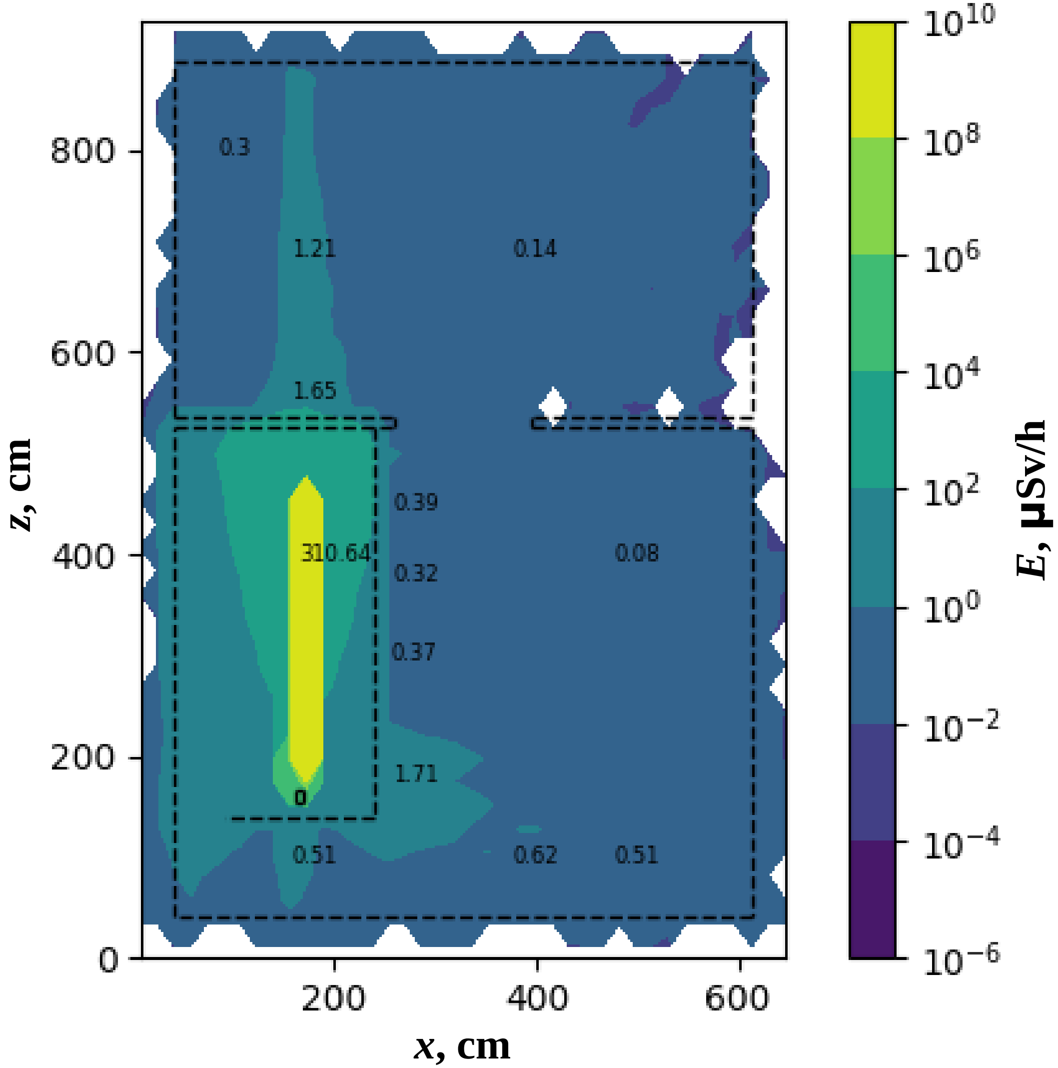
local protection – 4 cm Pb, 50x50 cm

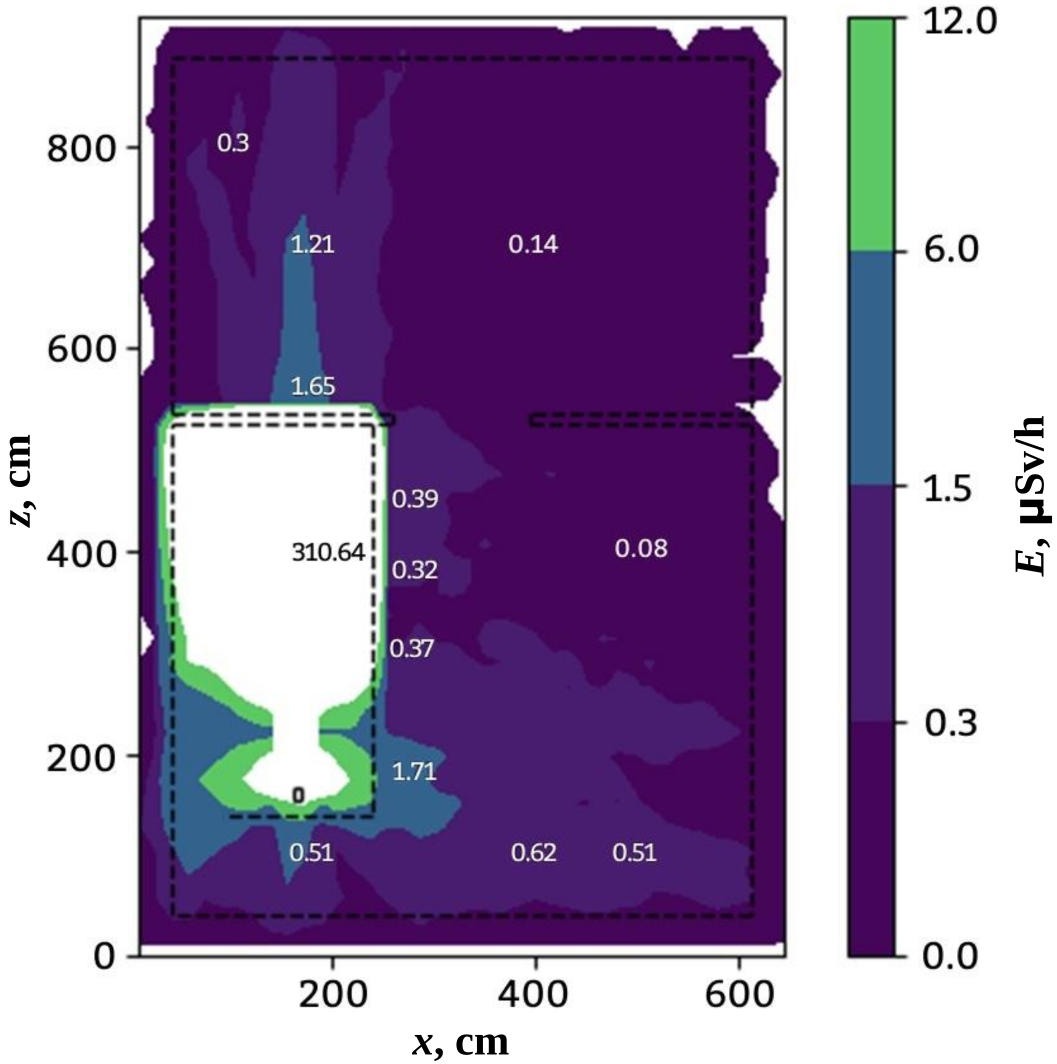




shaded part is **aluminum**, the rest is **lead**
Beam dump geometry

RADIATION ENVIRONMENT IN A PHOTOINJECTOR TESTBENCH ROOM





Effective dose rate distribution at a height of *165 cm* (beam level)

CONCLUSIONS

1. Methods for calculating the spatial distribution of the effective dose and induced activity of installations with complex geometry by placing active volumes in a «parallel world» have been developed and implemented in software using GEANT4 toolkit.
2. Verification of the simulation of the spatial distribution of the effective dose of photon radiation in the air from isotropic radiation sources with anterior-posterior irradiation geometry showed agreement with the analytical calculation for the gamma constant within 6 %.
3. The attenuation of the monoenergetic neutron fluence according to the Beer-Lambert’s law showed that the simulation discrepancy does not exceed 3 % of the analytical calculation based on the total cross sections of the ENDF database.
4. Comparison of simulation of induced activity in a reaction $^{98}Mo(n, \gamma)Mo^{99}$ with analytical calculations showed agreement between the simulation results and the analytical ones within 5 %.
5. The study of the radiation environment in the photoinjector testbench room with an electron energy of 6 MeV and a maximum average current of 0.5 μA showed that with biological protection of 1 mm of lead and local 4 cm lead protection, the effective dose rate outside the installation does not exceed the permissible 6 μSv/h for personnel of group A.

THANK YOU FOR YOUR ATTENTION!

Developing of a software for calculations of accelerator-induced radiation environments using the GEANT4 toolkit

Kuzmenko Anna Sergeevna