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A STUDY OF THE SKYSHINE NEUTRON DOSES WITH THE CODE GEANT4

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În prezenta lucrare au fost analizate cu ajutorul codului GEANT4 dozele de radiație skyshine de la două surse punctiforme de neutroni, cu energiile inițiale de 100 MeV şi 1 GeV. Componenta directă a câmpului de radiații prezintă o scădere exponențială cu distanța, dublată de un comportament de tip 1/r^2 , cu lungimea de atenuare de 582.7 m în cazul neutronilor cu energia inițială de 100 MeV şi 947.8 m pentru energia de 1 GeV. În cazul componentei de împrăştiere distribuția spațială a dozei îşi menține caracterul de scădere exponențială, însoțit de un comportament de tip 1/r. Lungimile de atenuare ale componentei de împrăştiere sunt de 420.16 m pentru energia de 100 MeV şi 696.8 m pentru energia de 1 GeV. Funcțiile de importanță ale neutronilor, calculate pentru 7 intervale ale unghiului de emisie în raport cu verticala (0^o - 5^o, 10^o - 20^o, 25^o - 35^o, 40^o - 50^o, 55^o - 65^o, 70^o - 80^o and 80^o - 90^o), sunt descrise cu 2 termeni exponențiali şi un comportament de tip 1/r. Introducerea celui de al doilea termen exponențial, cu o lugime de atenuare mai mare este impusă de faptul că spectrele neutronilor devin mai dure cu distanța.

The skyshine doses for point source neutrons with initial energies 100 MeV and 1 GeV were investigated through simulation with the code GEANT4. The direct component of the radiation field exhibits an exponential falling down with a 1/r^2 behavior and has attenuation lengths 582.7 m for the initial energy 100 MeV and 947.8 m for 1 GeV. In the case of the scattered component the dose distribution falls down exponentially and has a 1/r behavior. The attenuation length is 420.16 m for the initial energy 100 MeV and 696.8 m for 1GeV. The importance functions of the neutrons, calculated in 7 angular intervals of the vertical emission angle (0^o - 5^o, 10^o - 20^o, 25^o - 35^o, 40^o - 50^o, 55^o - 65^o, 70^o - 80^o and 80^o - 90^o) are described with two exponential terms with a 1/r behavior. The second exponential is due to the hardening of the neutrons spectra with the distance from the source and has a higher attenuation length.

Keywords: skyshine radiation, neutron effective dose, neutron importance functions

1. Introduction

Lindenbaum used for the first time the term “skyshine” in [1] to describe the propagation of neutrons through the atmosphere around high-energy proton

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accelerators. The term refers both to unscattered and scattered radiation which reaches a point in the vicinity of the source. . Lindebaum used for the flux of neutrons produced by a point source in an infinite isotropic medium the expression:

$$\phi(r) = \frac{Q \cdot \varepsilon(c,r)}{4\pi \cdot r^2} \cdot \exp(-\Sigma_t \cdot r) + \frac{Q \cdot k(c)}{4\pi \cdot D \cdot r} \cdot \exp(-k_0 \cdot r) \qquad (1)$$

where Q represents the intensity of the source (neutrons/s), Σ_t is the total macroscopic interaction cross section, D is the diffusion coefficient, $1/k_0$ is the diffusion length, c is the ratio between the scattering cross section and the macroscopic total cross section, and ε(c,r) and k(c) are functions of c.

The first term in equation (1) describes the propagation of the radiation from a point source in absorbing medium without scattering, and the second describes the radiation scattered from all the directions in the point of measurement.

In their work Stevenson and Thomas [2] analyze the neutron skyshine measured at different accelerators and propose to fit the spatial fluence distribution with the formula:

$$\phi(r) = \frac{a \cdot Q}{4\pi \cdot r^2} \cdot \left(1 - \exp(-\frac{r}{\mu})\right) \exp(-\frac{r}{\lambda}) \qquad (2)$$

where a is an empirical build-up factor, μ is the corresponding relaxation length, λ is an effective absorption length, Q is the fluence of the source , and r is the distance from the accelerator enclosure. λ depends on the neutron energy spectrum and they found values between 200 m and
830 m. Later works have shown that for extended non-isotropic sources λ can reach greater values, until 1300 m [3].

Neutron skyshine represents a problem for most of particle accelerators, which have usually a thick lateral shielding, but a thinner roof. In this case, the neutrons which reach the point not directly from the shielding, but after multiple scattering in the air, have an important contribution to the dose.

The development of Monte Carlo transport codes allowed a more accurate study of the skyshine effect. The fluences realized by the neutrons emitted isotropically in the upward hemisphere from a point source in infinite air medium and at the air-ground interface were registered and it was found that near the source the fluences are higher in the presence of the ground [4]. The influence of the lateral shielding was studied by varying the upward angle subtended by the source [5,6,7]. The fluences and doses of skyshine neutrons depend both on the energy and on the vertical emission cone. In ref. [6] the authors generated neutrons from a point source situated at 15 m above the ground, which emits in different angular intervals. They used the DOT code to compute the doses at some selected distances from the source and tabulated them for neutrons with energies up to 400 MeV. They called the dose equivalent per neutron importance function.

2. Condition of the simulation and results

In the present work was used the Monte Carlo particle transport code GEANT4 [8] for the analyze of the spatial distribution of effective dose realized by skyshine neutrons with energy of 100 MeV and 1GeV. The energy of 100 MeV was chosen because the spectrum of high energy neutrons behind the shielding exhibits a peak around this energy, and the energy of 1 GeV was analized as its higher limit. The scheme of the geometry used in the simulation is presented in Fig. 1. Parameterization driven models from low energy package were used to simulate the elastic hadron nucleus interaction, the neutron capture and fission for neutron with energy above 20 MeV. The inelastic interaction was simulated with the binary cascade model. For neutrons with energy lower than 20 MeV the high- precision models based on evaluated neutron data library were used.

During a first set of simulations the neutrons were generated isotropically in a hemisphere with radius of 1500 m. The source was placed at two heights: once at the level of the detectors (1.5 m above the ground) and second at 2 m above the detectors. In this way was estimated the contribution of the scattered neutrons to the total dose. The detectors were situated at a height of 1 m from the ground.

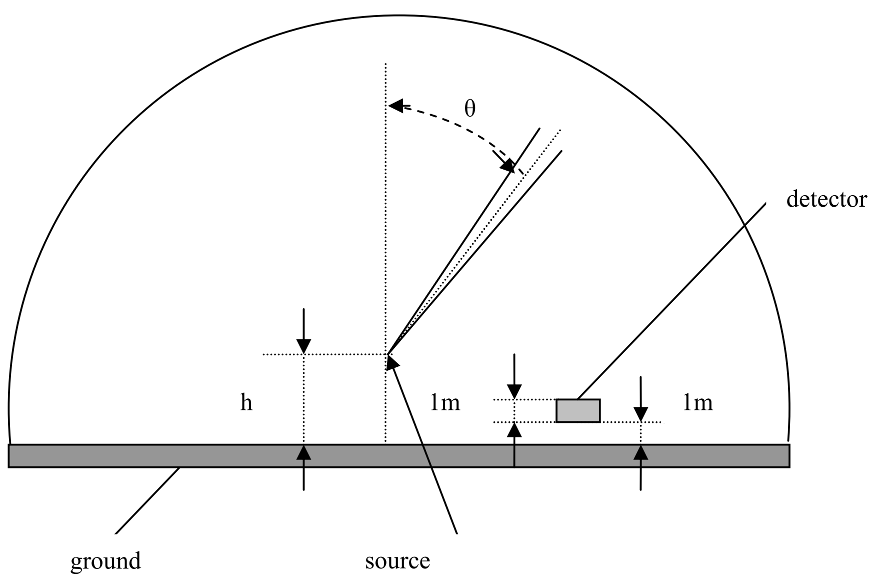

Fig. 1 The scheme of the geometry

The air density decreases on a distance of 2000 m with about 18 % from the value registered at see level. The program GEANT4 does not allow the definition of materials with variable density. The effect of the altitude can be taken into account in two ways. One manner is to divide the volume in layers, and to decrease the density in steps from a layer to another. Another manner is to compute the density of the air at each step, corresponding with the current position (height) of the particle and to adjust the macroscopic cross section for each model used, in the case of material air. The last variant was chosen in this work. The variation of the air density with the altitude (h) was calculated with the formula:

$$\rho(h) = \rho_0 \cdot \left[\frac{T_0 + L \cdot h}{T_0}\right]^{-\frac{g \cdot M}{R \cdot L} - 1} \tag{3}$$

where T_0 is the standard temperature, ρ_0 represents the air density at see level and standard temperature, L is the temperature lapse rate, g is the gravitational acceleration, M is the molar mass of the air, and R is the universal gas constant.

The results obtained are shown in Fig. 2, with the effective doses reported on primary neutron.

For the situation with the source at the level of the detectors (height 0 m) the spatial dose distribution *D(r)* is described with a function of the form:

$$D(r) = p_0 \cdot \frac{1 - \exp(-p_2 \cdot r)}{r^2} \cdot \exp(-p_1 \cdot r) \tag{4}$$

where p_0 , p_1 , p_2 are fit parameters and r is the distance from the source. The values for the parameters are given in table 1 and the fit functions are shown on the graphics in the figure 2.

In all the cases the fit functions describe the dose distributions with errors lower than 10%. The $1/r^2$ factor from the formula 4 shows that in the case of the source placed at the same height with the detectors the direct component of the radiation dominates. The attenuation lengths are 582.7 m for neutrons with initial energy 100 MeV and 947.8 m for the initial energy 1 GeV.

For the source situated at 2 m above the detectors (height 2 m) the form of the fit function differs from the first case by the replacement of $1/r^2$ term with 1/r. In this case, only neutrons scattered in air or ground arrive at the detectors. The attenuation lengths for the scattered component are lower, with values of 420.16 m for the initial energy 100 MeV and 696.8 m for 1GeV.

The 1/r dependence generates a slower decrease of the scattered component, which is negligible at distances close to the source, but reaches 32.13 % from the total dose at 500 m, 45.8 % at 1000 m, 49.2 % at 1500 m for neutrons with initial energy 100 MeV, respective 24.2 % ,40.1 % and 49.4 % the initial energy 1GeV.

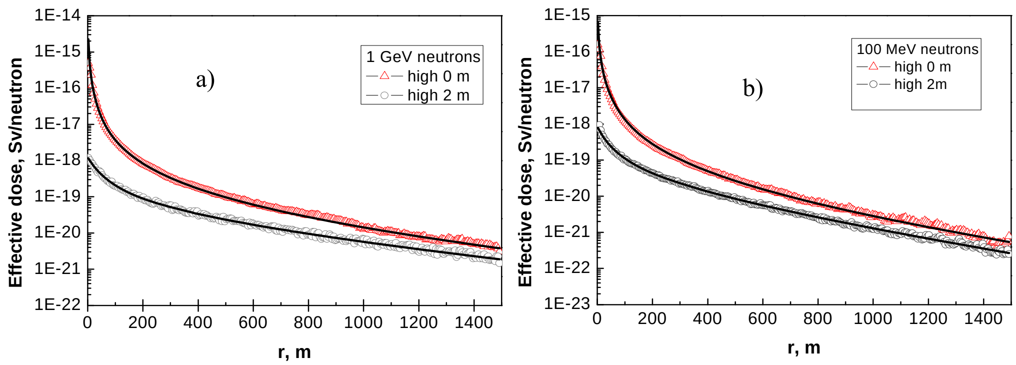

Fig.2 The effective dose distribution for neutrons with initial energy 1 GeV (a) and 100 MeV (b) generated isotropically from high 0 m and 2 m

Table 1

Values of the fit parameters for the isotropic source

Energy (MeV)	100		1000	
Height (m)	0	2	0	2
p_0 [Sv·m^2]	$1.57\cdot10^{-14}$	$1.4\cdot10^{-17}$	$4.07\cdot10^{-14}$	$2.39\cdot10^{-17}$
p_1 [m^{-1}]	$1.16\cdot10^{-3}$	$2.82\cdot10^{-3}$	$1.05\cdot10^{-3}$	$2.38\cdot10^{-3}$
p_2 [m^{-1}]	0.091	0.06	0.123	0.051

The role of the height at which the source is situated, and the influence of the ground were investigated, too. In Fig. 3 a comparison between the dose distributions obtained with the source placed at 2 m and 20 m, in the presence of a layer of the ground is shown. For the height of 20 m the dose distribution calculated in the absence of the ground is also presented.

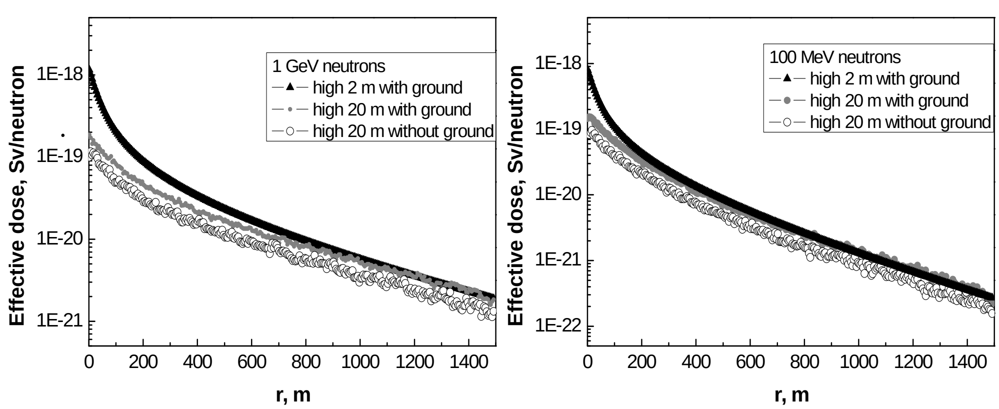

Fig. 3 The spatial distributions of the effective dose for neutrons with initial energy 100 MeV and 1GeV, with the source at 20 m height (with and without layer of the

The height of the source has a significant influence on the doses close to it. At 10 m distance from the center the ratio between the dose realized with the source at 2 m height and the dose at 20 m is 6.6 for 100 MeV neutrons and 6.14 for 1 GeV. The differences are present until 200 m for the initial energy 100 MeV, respective 800 m for 1 GeV. The doses of the neutrons backscattered from the ground represent about 30% from the total dose.

In a second set of simulations the importance function are calculated. In this case the source was positioned at 10 m above the ground, which is a reasonable height for neutrons leaving the building through the roof. The neutrons are generated in 7 intervals of the vertical emission angle: 0^o - 5^o, 10^o - 20^o, 25^o - 35^o, 40^o - 50^o, 55^o - 65^o, 70^o - 80^o and 80^o - 90^o azimuthally symmetric. The volume of air is a hemisphere with radius of 2000 m.

For both the energies and all the angles the curves have a 1/r and they can be fitted with the formula

$$D(r) = \frac{1-\exp(-p_4 \cdot r)}{r} \cdot \left[p_0 \cdot \exp(-p_1 \cdot r) + p_2 \cdot \exp(-p_3 \cdot r)\right] \qquad (5)$$

where the parameters p_0 , p_1, p_2 , p_3 and p_4 depend on the energy and the emission angle. The second exponential in the brackets, with a higher attenuation length, is due to the hardening of the spectra with the distance. The effect appears at all the emission angles and energies.

As an example the dependence of the mean energy of neutron spectra on the distance from the source is presented in figure 4. In figure are shown the mean energies for the emission angles 0^o - 5^o and 80^o - 90^o. It can be seen that the mean energy at a distance of 2000 m is almost 2.5 times higher than at 1500 m.

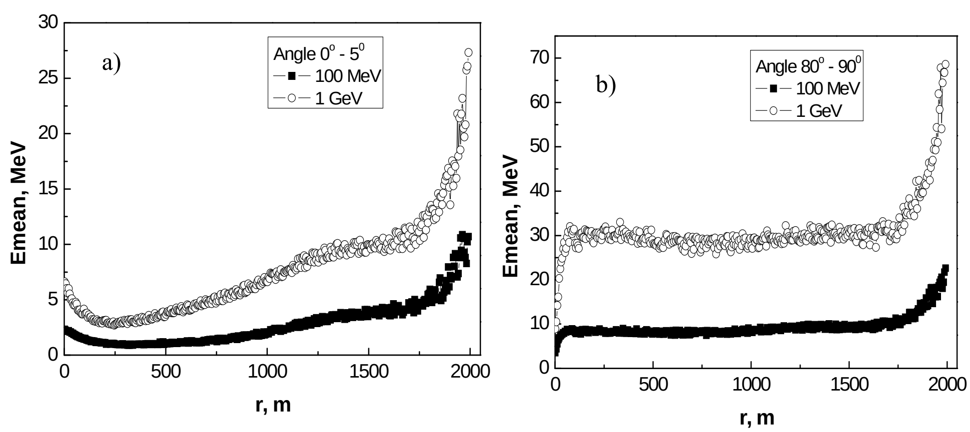

Fig. 4 The mean energy of the neutron spectra as function on the distance from the center for emission angle 0^o - 5^o (a) and 80^o - 90^o (b).

The importance functions obtained for the two studied energies are shown in the figure 5. The dependence of parameters from formula (5) on the emission angle of the neutrons is expressed with the following formulas

$$p_0(\cos\theta) = c_{00} \cdot \exp\left[c_{01} \cdot \cos\theta + c_{02} \cdot \exp(c_{03} \cdot \cos\theta)\right] \quad (6.a)$$

$$p_1(\cos\theta) = c_{10} + c_{11} \cdot \cos\theta + c_{12} \cdot \cos^2\theta + c_{13} \cdot \cos^3\theta \quad (6.b)$$

$$p_2(\cos\theta) = c_{20} \cdot \exp\left[c_{21} \cdot \cos\theta + c_{22} \cdot \exp(c_{23} \cdot \cos\theta)\right] \quad (6.c)$$

$$p_3(\cos\theta) = c_{30} \quad (6.d)$$

$$p_4(\cos\theta) = c_{40} + c_{41} \cdot \cos\theta + c_{42} \cdot \cos^2\theta + c_{43} \cdot \cos^3\theta \quad (6.e)$$

The values for the coefficients c_{ij} are given in table 2 and the fit functions are shown in the graphics from Fig. 5.

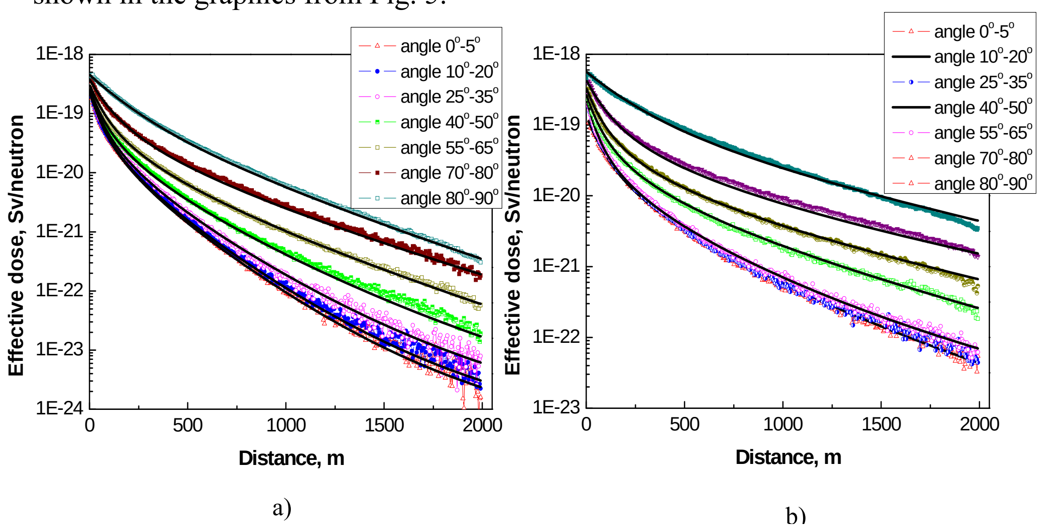

Fig. 5 The neutron importance functions for the energy 100 MeV (a) and 1

The radiation field around an accelerator of protons or ions with energies of a few GeV/n is dominated by neutrons. They are responsible of more than 90% of the dose [9,10]. In this paper the effective doses realized by other particles other than neutrons were also calculated. The effective doses obtained for protons, pions, muons and gammas produced in the air or ground and are entering in the detectors are shown in table 3 for a few distances until 500 m in the case of primary neutrons with energy 1GeV. The doses are given for one incident neutron.

Table 2

Values of the coefficients from formulas (5)

Coefficient	100 MeV	1000 MeV
C_{00} [Sv·m]	$1.77\cdot10^{-17}$	$2.02\cdot10^{-17}$
C_{01}	-0.86	-1.61
C_{02}	2.36	2.83
C_{03}	-6.49	-9.34
C_{10} [m^{-1}]	$2.43\cdot10^{-3}$	$1.13\cdot10^{-3}$
C_{11} [m^{-1}]	$-4.26\cdot10^{-3}$	$-1.45\cdot10^{-3}$
C_{12} [m^{-1}]	$1.013\cdot10^{-2}$	$2.68\ 10^{-3}$
C_{13} [m^{-1}]	$-4.07\cdot10^{-3}$	$-1.2\ 10^{-5}$
C_{20} [Sv·m]	$5.12\cdot10^{-17}$	$7.92\cdot10^{-19}$
C_{21}	7.31	0.515
C_{22}	-5.18	$-8.52\ 10^{-2}$
C_{23}	1.02	2.55
C_{30} [m^{-1}]	$1.27\cdot10^{-3}$	$8.74\ 10^{-3}$
C_{40} [m^{-1}]	$-1\cdot10^{-10}$	$-2.62\ 10^{-3}$
C_{41} [m^{-1}]	0.12	0.14
C_{42} [m^{-1}]	-0.15	-0.21
C_{43} [m^{-1}]	$7.5\cdot10^{-2}$	0.12

Table 3

Effective doses realized by different particles

Particle/ Distance [m]	Effective dose [Sv/neutron]			
	10	100	200	500
neutron	$5.3\cdot10^{-19}$	$3.27\cdot10^{-19}$	$2.12\cdot10^{-19}$	$8.14\cdot10^{-20}$
gamma	$1.24\cdot10^{-20}$	$3.25\cdot10^{-21}$	$1.78\cdot10^{-21}$	$9.4\cdot10^{-22}$
proton	$1.02\cdot10^{-19}$	$2.35\cdot10^{-20}$	$1.54\cdot10^{-21}$	$3.57\cdot10^{-22}$
pion	$1.07\cdot10^{-20}$	$8.5\cdot10^{-22}$	$2.91\cdot10^{-22}$	$7.61\cdot10^{-23}$
muon	$1.37\cdot10^{-20}$	$3.65\cdot10^{-21}$	$2.13\cdot10^{-21}$	$8.76\cdot10^{-22}$

.

From the table 3 we can see that at small distances the protons have an important contribution to the dose (the dose delivered by the protons represents 19.2 % from the dose delivered by neutrons at 10 m from the center), but the dose from protons is falling down quickly with the distance. The dose from other particles than neutrons represents 9.5% at 100 m from the source, and 2.8% at 500 m.

The influence of the air volume used in the simulation and the ground layer on the dose was studied also. For this purpose the neutron were generated isotropic at a high of 20 m. The air surround the generation point was a hemisphere with radius 300 m, 500 m and 1000 m. The results are shown in Fig. 6.

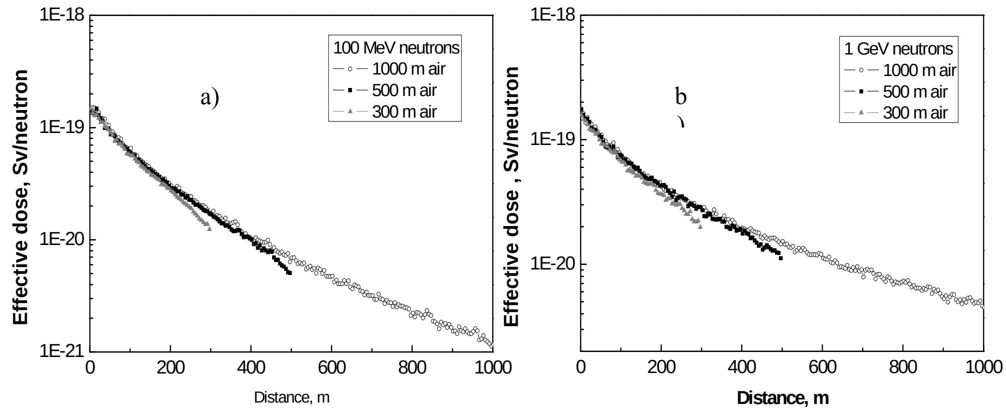

Fig. 6 The spatial distribution of the effective dose for neutrons with energy 100 MeV (a) and 1 GeV (b), in different volumes of air.

It can be seen from the figure that the doses registered with a volume of air with radius 500 m are the same as for the 1000 m radius, excepting the last 50m near the boundary. The doses for radius 300 m are a little smaller. For points not to close to the boundary a radius of about 500 m (an interaction length) is enough.

3. Conclusions

The neutrons are the principal constituent of the radiation field around an accelerator of protons and ions. The dose in a point in the vicinity of the source has two components: the radiation that reaches the point directly and the radiation that arrives at the point after multiple scattering in air, ground, buildings. In this work the radiation field from a point source of neutrons with initial energy 100 MeV and 1 GeV was studied.

In the case of unshielded source (or with equal shielding on all sides) the direct component of the radiation dominates the field, and the spatial dose distribution exhibits an exponential falling down with the distance and a $1/r^2$ behavior. The attenuation length of neutrons in the air is 582.7 m for the initial energy 100 MeV and 947.8 m for 1GeV. At small distances the scattered component plays a negligible role, but becomes important at higher distances (at 1500 m is responsible of about 50% of the dose).

In the situation of unequal shielding (thick lateral shielding and less or no up shielding) the most part of the dose is realized by the scattered radiation. The dose falls down exponentially and has a 1/r behavior. The attenuation length is 420.16 m for the initial energy 100 MeV and 696.8 m for 1GeV.

The importance functions of the neutrons, calculated in 7 angular intervals of the vertical emission angle (0^o - 5^o, 10^o - 20^o, 25^o - 35^o, 40^o -:50^o, 55^o - 65^o, 70^o

- 80^o and 80^o - 90^o) are described with two exponential terms with a 1/r behavior. The second exponential is due to the hardening of the neutrons spectra with the distance from the source and has a higher attenuation length.

The analyze of the role played by the volume of air used in the simulation shows that for points not to close to the boundary the use of a volume with radius about one attenuation length of neutrons in the air is enough.

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