THE NEW APPROXIMATION OF DOSE ATTENUATION CURVE IN CONCRETE

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Abstract

The analytical approach in shielding calculations is simple and fast method for quick estimations. But it provides less accuracy than Monte-Carlo one. Often the exponential attenuation of dose in shielding is considered. But also it is necessary to take into account the dose increase in the first layers of shielding due to initial accumulation of neutrons. The new approximation of dose attenuation curve in concrete is offered for quick analytical estimations of shielding of hadron accelerators. It allows to make fast estimation of shielding thickness enough correctly.

INTRODUCTION

The cost of building for accelerator complex is a significant part of the whole project cost, so the cost estimation is important before starting the project at Conceptual Design stage. Last years the hadron therapy of cancer is being actively developed. This paper was initiated by CBS (Cold Beam Synchrotron) project [1] developed at BINP. Later CBS was transformed into HITS (Heavy Ion Therapy System) project. It is designed for proton and heavy ion therapy (with carbon ions energy up to 400 Mev/u). Shielding calculations usually require comparatively big time and computer power resources due to using of codes based on Monte-Carlo methods. Direct analytical estimations are quicker but not so accurate due to complexity of taking into account build-up factor, real geometry and dependence of protection properties on energy of particles. However some information concerning the shielding calculations has been obtained and combined [2] and can be used in analytical approach. So, there was a necessity to make quick estimations of shielding of carbon therapy complex. It was made for relatively simple geometry, more complicate geometry was simplified. The critical places with significant beam losses were defined and wall thicknesses were determined. It allowed to create the conceptual layout of building.

SHIELDING ESTIMATIONS

Secondary neutron sources

At 400 MeV/u energy of the primary carbon ion beam the main contribution into dose behind the thick enough shielding is made by neutrons. Photons are usually damped by thick neutron shielding and give only several percents contribution into total dose.

The calculation of dose in the point at a distance r (enough big) from the target (bombarded by primary ion beam) in direction θ to the primary beam behind shielding with thickness d and at incidence angle on shielding ϑ_{sh} is made using the point kernel equation [3] p. 613:

$$H(r,\theta,\vartheta_{sh}) = \frac{1}{r^2}\int_{E\min}^{E\max} Y(E,\theta)g(E)f(E,d,\vartheta_{sh})dE \quad (1)$$

where $g(E)$ – neutron fluence-to-dose conversion factor, Sv·cm^2; $Y(E,\theta) = \dfrac{d^2n(E,\theta)}{dEd\Omega}$ – the double differential yield of neutrons (DDY) into unit energy and solid angle interval, MeV^{-1}·sr^{-1}·ion^{-1}. The data of neutron angular spectra is taken from [2]. $f(E,d,\vartheta_{sh})$ – the dose attenuation function depending on neutron energy and shielding thickness that differs significantly from the exponential one within the thickness of the first layer of a tenfold attenuation $\Delta_{10}^{(1)}$ (at $\vartheta_{sh} = 0$). Dose value above is normalized per one primary ion striking the target.

Approximations of the dose attenuation curve

In practice, when estimating thick shielding (d > 2 m), a simplified equation is used as well:

$$H(r,\theta) = \frac{1}{r^2}\cdot H_0(r,\theta)\cdot \exp(-d/\lambda_{eff}) \quad (2)$$

where

$$H_0(r,\theta) = \int_{E\min}^{E\max} Y(E,\theta)\cdot g(E)\cdot dE \quad (3)$$

is the "source term" representing DDY folded with conversion coefficient $g(E)$; λ_{eff} – some effective relaxation length (averaged over the spectrum taking into account shielding thickness). So the secondary neutron sources data (location, DDY or spectrums) is required for calculation. The dependence of the thickness of the first layer of a tenfold attenuation $\Delta_{10}^{(1)}$ was taken from [4]. In further calculations we use the values of exponential relaxation length calculated in [4] (see Fig. 8 there) for the neutrons with the energy of 1÷400 MeV for fitting of the data of neutron dose equivalent in concrete, example is given in Fig. 1. One can see from this figure that dose attenuation in reality differs from the exponential low (2) with depth d. It turned out that the dependences in Fig. 1 at normal hitting by neutrons the concrete shielding

$$f(E,d,\vartheta_{sh} = 0^0) = f_*(E,d) = H(E,d)/H(E,0) \quad (4)$$

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can be approximated for $0 \le d \le 0.56 \cdot \Delta_{10}^{(1)}$ by the dependence of the following type:

$$f_*(E,d) = a_1 e^{-\left(\frac{d}{2\lambda_e}\right)^2} - a_2 e^{-\frac{d}{\lambda_e}} + a_3 \qquad (5)$$

where coefficients a_1, a_2, a_3 and λ_e are functions of neutrons energy E and λ_e – is the exponential attenuation length.

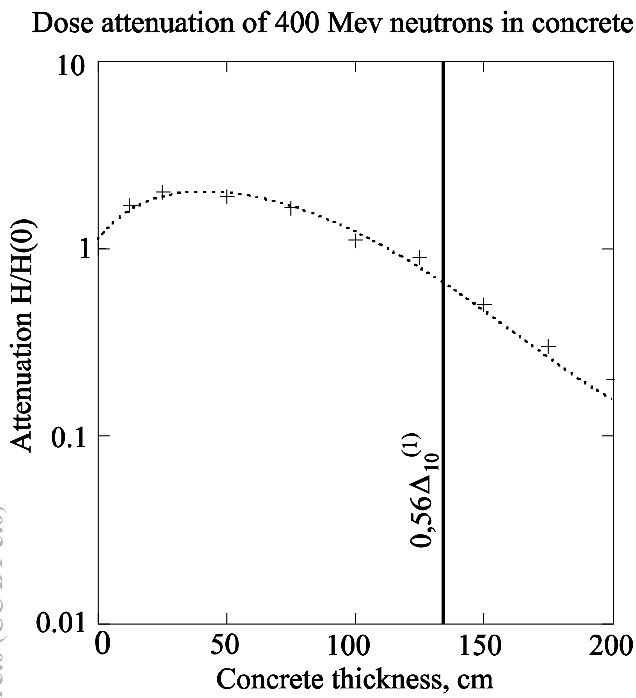

Figure 1: Attenuation of dose equivalent of 400 MeV neutrons by concrete with 2.5 g/cm^3 density. + – data from [4]; dashed line – the one being approximated.

It was found that $a_1 - a_2 \cong 1.1$, and $a_3 = 0$, the linking at $d = 0.56\Delta_{10}^{(1)}$:

$$f_*(E,d) = f_*\left(E, 0.56\Delta_{10}^{(1)}\right) \cdot \exp\left(-\frac{d - 0.56\Delta_{10}^{(1)}}{\lambda_e(E)}\right) \qquad (6)$$

Thus, for estimations we have only one parameter the values $a_2(E)$ and can approximate the function at a normal hitting the concrete by monoenergetic neutrons; $a_1(E)$ is calculated as follows:

$$a_1(E) \cong a_2(E) + 1.1 \qquad (7)$$

The "linfit" function of Mathcad was used, it finds the coefficients for set of given functions in least-squares sense.

The linking of attenuation curves (Fig.1) takes place at the thickness of $0.56\Delta_{10}^{(1)}$ and provides a good coincidence of an integral attenuation coefficient (Fig. 2) at $d > \Delta_{10}^{(1)}$ in comparison with an approximation linking at $d=\Delta_{10}^{(1)}$.

Integral attenuation coefficients were calculated by the integration over neutron spectrum (for Cu target is shown in Fig.3 (for a normal hitting).

$$K(d) = \frac{\int_{E\min}^{E\max} Y(E,\theta) \cdot g(E) dE}{\int_{E\min}^{E\max} Y(E,\theta) \cdot g(E) \cdot f_*(E,d) dE} \qquad (8)$$

The value of integral in numerator represents the "source term", i.e. the dose calculated for a unit distance from the neutron source at a zero thickness of the shielding.

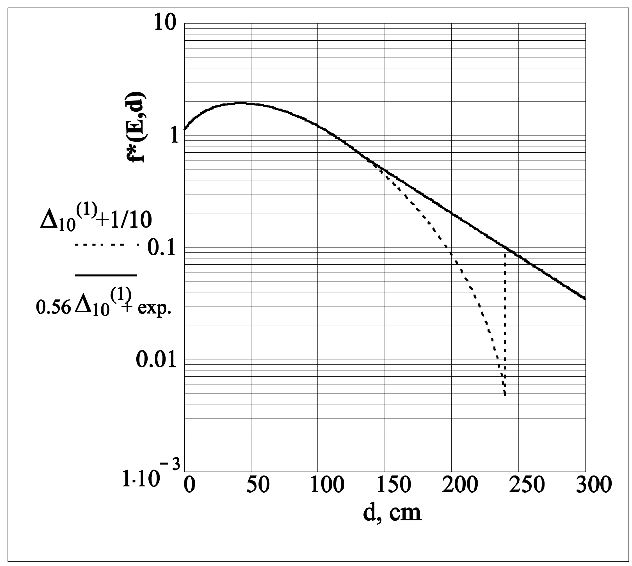

Figure 2: Two variants of linking of the found approximation of $f(E,d)$ in comparison: linking at $d=\Delta_{10}^{(1)}$ and at $d = 0.56\Delta_{10}^{(1)}$ with exponential attenuation after linking points.

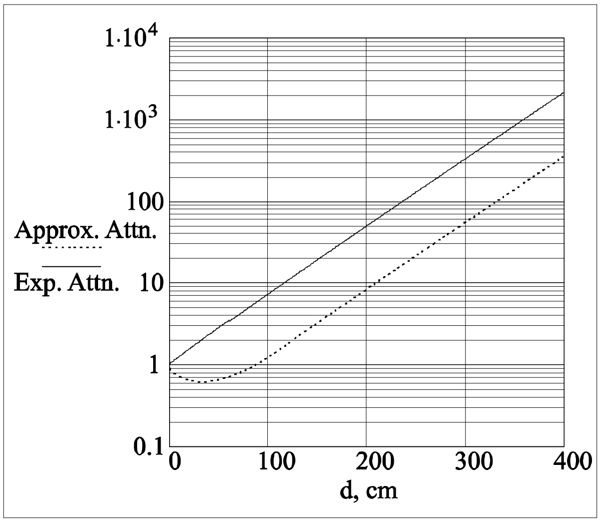

Figure 3: Dose attenuation factor averaged over the spectrum from 400 MeV/u carbon ion beam striking Cu target ($\theta = 0°$, $\theta_{sh} = 0°$) in comparison with purely exponential attenuation.

SUMMARY

It was shown that the use of a purely exponential dose attenuation in estimations gives several times underestimation of the dose behind shielding of typical proton and heavy ion therapy accelerators.

The new approximation of dose attenuation curve in concrete offered in this paper allows more adequate estimations of the dose equivalent attenuation by concrete shielding, first of all, within the thickness less than 200 cm. It can be useful for shielding estimations for proton and heavy ion accelerators with energy up to 400÷500 MeV/u. The results of approximation are moderately sensitive to exponential attenuation lengths which are dependent on the total shielding thickness and energy. Thus more careful investigation is required.

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