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PROMPT RADIATION AND SHIELDING CALCULATION FOR THE COMPACT PULSED HADRON SOURCE

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Abstract

The design of the 13-MeV proton linac-driven Compact Pulsed Hadron Source (CPHS) at Tsinghua University in Beijing, China is currently under study. Prior to construction, a proper assessment of the ionizing radiation hazards and consequently the requirement of shielding for the safety of the facility is an essential prerequisite. The source terms include six components: LEBT, RFQ, DTL, HEBT, target station, and beam dump, while the neutrons emitted from the beam loss in HEBT and the relevant attenuation are of most important and mainly discussed in this paper. The Monte Carlo simulations were performed with FLUKA 2008 code. The neutron angle-differential and energy-differential yield were analysed, and the total yield were calculated and compared with the published data. The ambient dose equivelent rates behind the concrete shielding of different thicknesses were calculated and fitted with a classical two parameter formula. The attenuation lengths and source terms for incident neutrons of different energies were summarized and compared with published data. The results then permit the estimate of required shielding dimensions, from the immediate enclosure of the sources to the perimeters of the experimental building.

1. Introduction

Studies of the prompt radiation from the beam loss along the beam tunnels should be done and reasonable shielding design should be given before the construction of the 13-MeV proton linac-driven Compact Pulsed Hadron Source (CPHS) at Tsinghua University in Beijing, China. The source terms mainly including the following six parts: LEBT (Low Energy Beam Transport), RFQ (Radio Frequency Quadrupole）, DTL (Drift Tube Linac), HEBT (High Energy Beam Transport), the target station and the beam dump. The prompt radiation from the beam losses of the HEBT is of the most important because for the target station and the beam dump, enough local shielding will be adopt, and for LEBT、RFQ and DTL, the transport proton is of lower energy. So the prompt radiation and the shielding consideration for the beam losses in the HEBT tunnel will be analyzed and discussed mainly and firstly in this paper.

To evaluate the effect of the prompt radiation field, the ambient dose equivalent H*(10) was adopt. The ambient dose equivalent H*(10) at the point of interest is the dose equivalent which would be generated in the associated oriented and expanded radiation field at a depth of 10 mm on the radius of the ICRU sphere (30 cm diameter tissue equivalent) [1] which is oriented opposite to the direction of incident radiation. The ambient dose equivalent behind the shield should include the contributions from neutrons, photons, charged particles and their secondaries produced in the shielding material itself. The fluence-to-ambient dose equivalent conversion factors reported in the ICRP Publication 74 [2] were adopted.

For the HEBT beam losses, the primary particle (13 MeV protons) strike at the beam tunnel (3mm thick iron), where the projected range of proton in iron is about 0.4mm, calculated by the software SRIM 2008[3], the ambient dose equivalent is mainly contributed by neutrons and photons with energy lower than 13 MeV. As photons could be attenuated quickly by enough local iron shielding, meanwhile the neutron will only be slowing down and penetrate the iron shielding, the production and attenuation of neutrons are of most concern and will be mainly studied in this paper.

The calculations were performed with the Monte Carlo code FLUKA 2008 [4, 5]. The neutron yield of angle-differential and energy-differential were given respectively; also the total yield was calculated and compared with the formerly published data. The attenuations of the 2 to 13MeV neutron in concrete of different thicknesses were studied and the attenuations of the total ambient dose equivalent were fitted with the classical two parameter formula [6-8] :

$$H(d) = \frac{H_0}{r^2}\, exp^{-d/\lambda}, \tag{1}$$

where H is the ambient dose equivalent beyond the shield, $\mu Sv/h$, d is the shield thickness, m, r is the distance between the radiation source (the target stopping the protons) and the scoring position, m, H_0 is the source term, $\mu Sv \cdot m^2/h$, λ is the attenuation length for the given shielding material, m.

Consulting the results from the Monte Carlo simulation and the fitting calculations, a conservative and reasonable shielding design was given for CPHS.

2. Monte Carlo Simulations

The simulations were performed with the version 2008 of the FLUKA Monte Carlo code [4, 5]. For improving the calculative efficiency, the calculation procedures were divided into two steps.

Firstly, we considered the dominant secondary radiation field created by the beam losses in the HEBT tunnel. In this step, the target element is iron with the natural components pre-defined in FLUKA, which is the main constituent of accelerator components and also representative of other materials of similar density and atomic number (such as stainless steel and copper). The geometry was set as a right circular torus (the HEBT beam tunnel) with an inner radius of 5 cm and outer radius of 5.3 cm, a height of 10 cm. A 13MeV pencil-like proton beam strikes the centre of the torus perpendicularly, which represented the worst scenario for the beam losses.

Secondly, we simulated the attenuation of the secondary particles, dominantly neutrons, which are attenuated by the concrete shielding of different thicknesses. The neutrons as a pencil-like beam are histogrmed over energy range from 2 MeV to 13 MeV, in intervals of 1 or 2 MeV, impact the concrete shielding perpendicularly. The elemental composition of the concrete was taken from the report NCRP51 for NBS-5.0 type [10], and the density is $2.35 g/cm^3$. The length and width of the concrete shielding both are 100 cm, with the thicknesses increasing from 10 to 70 cm, in steps of 20 cm. The ambient dose equivalent behind the concrete shielding was valuated. The fluence-to-ambient dose equivalent conversion factors adopted in FLUKA are according to ICRP Publication 74 [2] and could be found detailed in [11].

With the two-step calculations and the experimental formula fittings, the simulative results will have a widespread of applicability and could also indicate the shielding design for other source terms such as DTL and RFQ, or other proton accelerators of the same energy range.

3. Results and Discussion

3.1. Neutron Yield

The energy-differential and angle-differential neutron yield from a 13 MeV-proton beam striking the iron beam tunnel were calculated by FLUKA and showed in Fig.1 and Fig.2. From the energy-differential neutron yield figure we could see the neutron resonance peaks very obvious. The emitted neutron energies do not exceed 8 MeV and mostly less than 6 MeV. From the angle-differential neutron yield figure we could see the emitted neutrons are not only isotropic but also have some forward emission and backward reflection. That arises from the fact that there are two important proton-nucleus interactions producing the neutrons: nuclear evaporation and intra-nuclear cascades [6]. In the nuclear evaporation, the incident proton is absorbed into the target nucleus to create a new compound nucleus. This compound nucleus is in an excited state with a number of allowed decay channels. The decay of this compound nucleus then emitted the secondary particles isotropically. In the intra-nuclear cascades, the process is described by the interaction cross sections, and the emitted directions of the secondary particles are relative to the direction of the incident proton. At proton energies below 10 MeV the nuclear evaporation is primary, and at high energies (> 50 MeV) the intra-nuclear cascade becomes important. The total angular and energy integral neutron yield is 7.35×10^{-4} (±0.42%) per 13 MeV proton calculated by FLUKA. In references [6] and [9], the published results for thick Fe target or Cu target, the number of neutrons produced by per 10 MeV proton is about 1.2×10^{-3}. So, the results from the FLUKA simulation are generally in reasonable agreement with the earlier pubished data, and will be adopt in the subsequent shielding calculations.

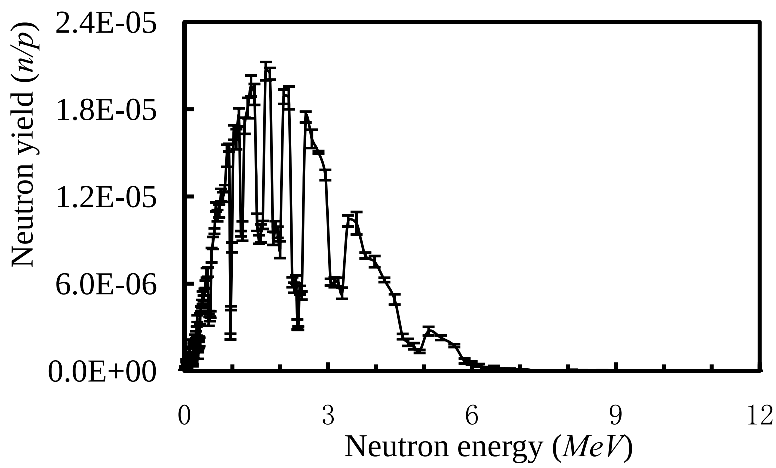

Fig.1 Energy-differential neutron yield for the iron target per 13MeV proton

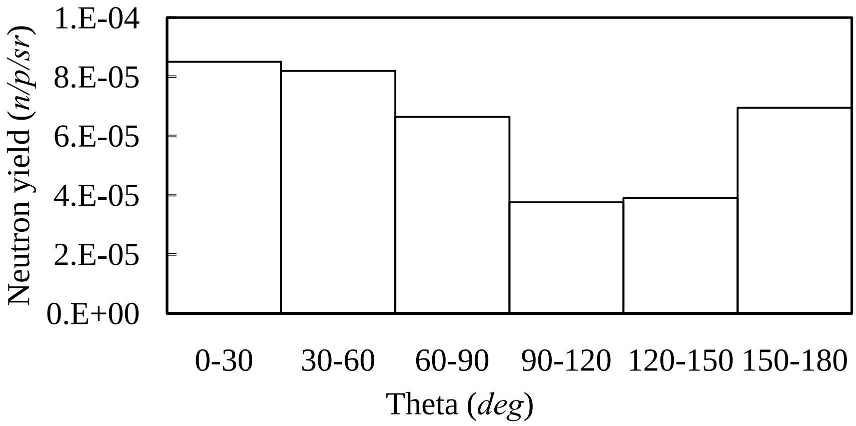

Fig.2 Angle-differential neutron yield for the iron target per steradian and per 13MeV proton. Theta is the polar angle respect to the beam direction. The error is within 2.5%

3.2. Shielding Data for Concrete

The attenuation of the ambient dose equivalent at the 0 degree emission angle are plotted in Figs.3 for 3, 7, 9 and 13 MeV neutrons impinging on the NBS-5.0 type concrete shielding with different thicknesses. The statistical uncertainties on the data points are less than 1% at depths less than 50cm and 3% at the largest depths. For the sake of clarity only the 3, 7, 9 and 13 MeV neutrons attenuation curves were plotted but the calculation were performed also case for 2, 5, 6 and 11 MeV neutrons. The fitted results of source terms H_0 and attenuation lengths λ are showed in Fig.4 and Fig.5. The FLUKA simulating source terms H_0 are exactly equal to the data recommended in ICRP report 74. For the attenuation lengths, the fitting relation coefficients are all higher than 0.9999. A recommended attenuation length for neutron energies from 2 to 10 MeV in [6] is $300\,kg/m^2$ for $2.4 g/cm^3$ concrete, equal to 12.5 cm. The FLUKA simulation results are changing from 6 cm to 11 cm for 2 to 13 MeV neutrons, with good agreement to the published data, and will be applied to the shielding design for CPHS.

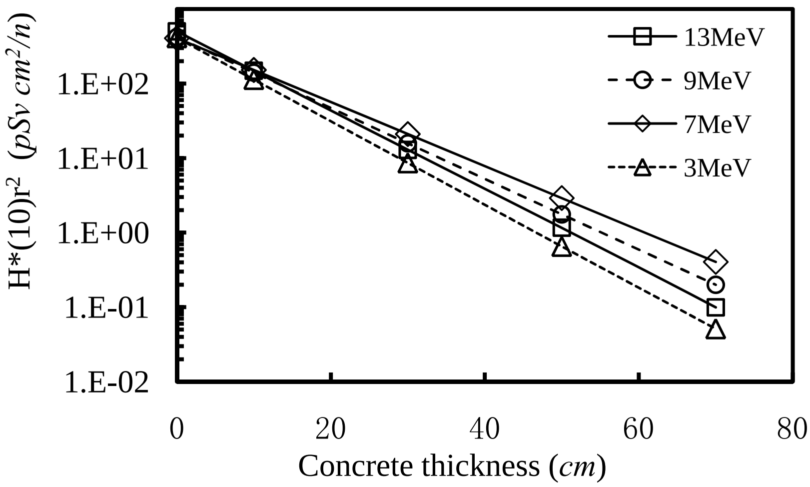

Fig.3 Attenuation of the ambient dose equivalent for neutrons of different energy impinging on the concrete shielding of different thicknesses. The statistical uncertainties of the data are smaller than the size of the symbols

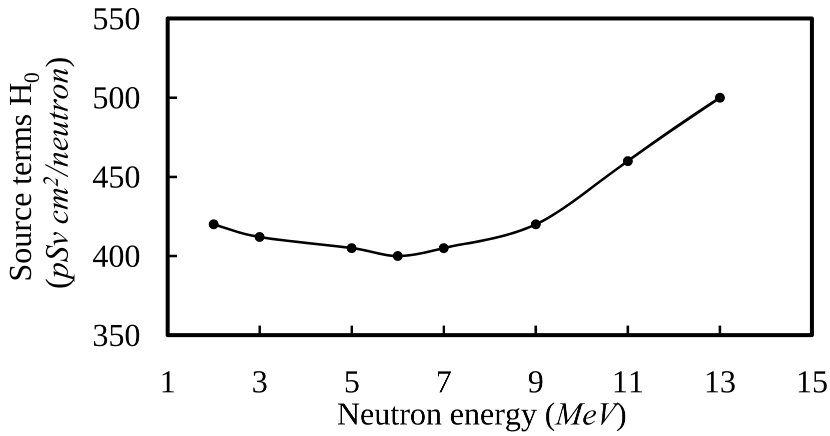

Fig.4 The source terms H0 in fitting formula Eq. 1, the FLUKA simulating results are equal to the data recommended in ICRP report 74

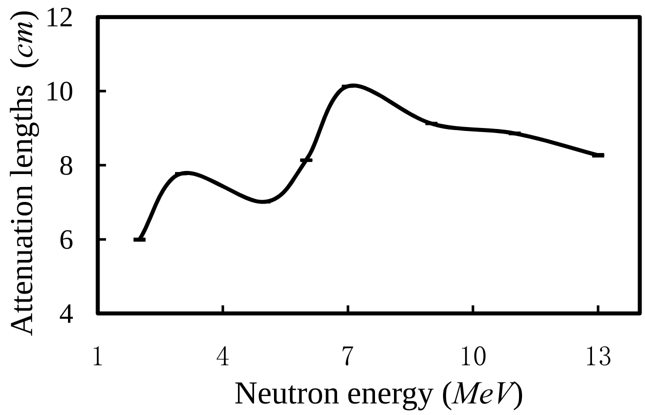

Fig.5 Attenuation lengths for neutrons of different energies impinging on the concrete shielding. The fitting relation coefficients are all higher than 0.9999.

3.3. Shielding Design for CPHS

With the above results and analysis, the shielding design for CPHS should be considered as follows. For conservative and for produced neutron energy will not exceed 8 MeV, take the maximum attenuation length $\lambda = 10.13\,cm$ at 7 MeV, the maximum source term $H_0 = 420\,pSv \cdot cm^2/n$ at 2 MeV, and the neutron yield $8.5 \times 10^{-5}\,n/p/sr$ at $0 \sim 30°$. The ambient dose equivalent rate outside the concrete shielding could be calculated by the Eq.2:

$$H(d) = \frac{N_p Y H_0}{r^2} e^{-d/\lambda}, \quad (2)$$

where Np is the proton number from the beam losses per second, $7.8 \times 10^{12}\,p/s$ for CPHS's HEBT; Y is the neutron yield, $n/p/sr$; others are the same as the definition in Eq. 1.

The calculated ambient dose equivalents beyond the shield of different thicknesses are showed in Fig.6. Suppose the distance r between the radiation source and the scoring position is 2 m. So, with 1.5 m thick common concrete, the neutron ambient dose equivalent from the normal beam losses of HEBT will be lower than $1 \times 10^{-2}\,\mu Sv/h$.

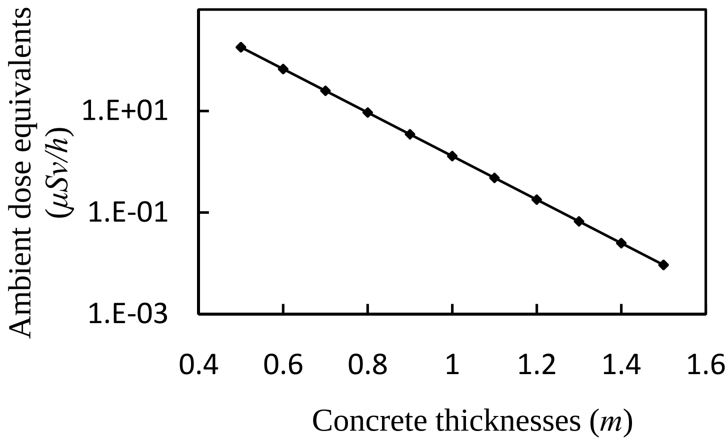

Fig.6 Ambient dose equivalent beyond the shield, the distance between the radiation source and the scoring position is 2m

4. Conclusions

By FLUKA simulations, the neutron yield from a 13 MeV proton striking the iron target, the sourece terms and attenuation lengths of $2 \sim 13$ MeV neutron impinging on the concrete shielding were calculated and compared with the published data. The results then permit the estimate of required shielding dimensions for CPHS, from the immediate enclosure of the sources to the perimeters of the experimental building. Furthermore, as the calculations are performed for different energies seperately, the results could also be adopted for the DTL、RFQ and other proton accelerators of the same energy range. For the shielding design of CPHS, with sufficient local shielding for target station and beam dump, and proper local iron shielding for photon outside the beam tunnels, 1.5 m concrete will be very enough for the neutron prompt radiation, achieve a ambient dose equivalent rate lower than $1 \times 10^{-2}\ \mu Sv/h$.

5. Acknowledgements

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