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FLUKA simulation of 15 MeV linear accelerator based thermal neutron source for radiography

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FLUKA simulation has been carried out using 15 MeV LINAC to design thermal neutron source for radiography. In this case, a neutron collimator has been designed along with e-γ target, γ-n target, moderator and shielding. The γ-n target has been optimized based on their photonuclear reaction threshold. The moderating properties have been studied for a few light elements to optimize best suitable moderator for radiography system. To get best values of collimator parameters such as collimation ratio, gamma content, neuron fluence rate, cadmium ratio, beam uniformity etc., a FLUKA simulation was carried out. The collimator has been optimized with cadmium lining square cone to capture the scattered thermal neutrons and the collimation ratio to L/D=20. The neutron fluence rate and neutron to gamma ratio of the optimized facility at the object plane is 1.1×10^5 n cm^{-2} s^{-1} and 1.0×10^5 n cm^{-2} mR^{-1}.

Keywords: Neutron radiography, FLUKA simulation, Thermal neutron source, Linear accelerator, γ-n target

1 Introduction

Neutron radiography is a powerful non-destructive testing technique frequently used either on its own or as complementary to X-ray radiography for the analysis of objects. Most work in neutron radiography has been performed with thermal neutrons because neutrons within that energy range exhibit the useful attenuation characteristics and such neutrons can be obtained with relative ease from a variety of neutron sources. Neutrons are efficiently attenuated or absorbed by only a few specific elements such as hydrogen, boron, cadmium, samarium and gadolinium and many structural materials such as aluminium, steel are nearly transparent. This technique is widely used in security, engineering, medical, nuclear and industrial applications[1,2].

Basic requirements for neutron radiography system are a suitable neutron source providing high fluence rate of uniform thermal neutron beam at image plane, a neutron collimator having higher collimator ratio to increase image sharpness and a device to record the image of the object. The necessary neutron beams used today are provided by nuclear reactor, radioisotope and accelerator based sources. Nuclear reactors provide high-intensity neutron beam but are expensive, non-transportable and produce radioactive waste. Radioisotope based neutron sources, produce low neutron intensity in comparison to the accelerators and nuclear reactors. Because of the compactness, easy handling, adjustable fluence rate, no radioactive waste, less shielding requirement etc. the accelerator based neutron source is offering the possibility for *in-situ* testing of objects. In this work, a transportable unit for radiography using the accelerator based neutron source has been designed with FLUKA simulation. When electron beam from an accelerator incident on high Z e-γ target, it generates a cascade shower of bremsstrahlung radiations. Further interaction of these radiations with suitable photo neutron target γ-n results in emission of fast neutrons. Moderating material shifts these fast neutron to thermal region. In the design of neutron source, different materials and their dimensions for target and moderator are determined using Monte Carlo based FLUKA code.

2 Materials and Methods

In the whole accelerator facility electrons, bremsstrahlung radiations and neutrons are transported through various targets. These complex processes are difficult to study theoretically even on the basis of correct experiments. Therefore, simulations with an effective Monte Carlo code are very helpful to get such information on neutron spectra. As FLUKA can handle the accurate electron-nucleus, electron-electron bremsstrahlung and photo nuclear interactions over the whole energy range[3] and is therefore a good choice for simulation. For optimizing the collimator design for neutron radiography facility a FLUKA simulation was carried out until statistical error becomes less than 1%. The validation of the FLUKA code with experiments has already been carried out on 6 MeV Microtron accelerator and 6 MeV LINAC for neutron production[4,5].

Linear accelerator[6] which produces electron beam of energy 15 MeV has been used for the design of thermal neutron radiography facility. The parameters of the electron beam are pulsed current 130 mA, pulse width 4.5 μs and pulse rate 150 to 200 PPS. Therefore, the average current of the electron beam is ~ 100 μA.

3 Results

Initially, various Z materials were simulated at different target thicknesses as e-γ target. The variation of bremsstrahlung fluence with target thickness is shown in Fig. 1. From Fig. 1, it is observed that as the thickness of target increases, the photon fluence also increases till certain thickness and further decreases with increase in the thickness. The gold, uranium and tungsten provide maximum bremsstrahlung fluence. Therefore, tungsten was found to be best suitable for as e – γ target because of its availability and physical properties like melting point, heat conductivity and highest bremsstrahlung fluence.

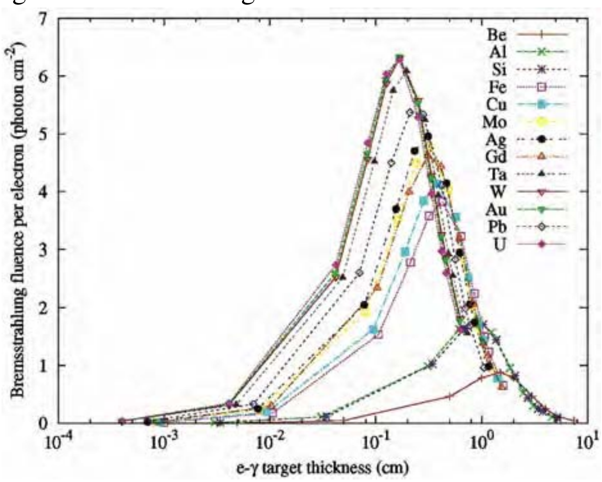

Fig. 1 — Variation in integrated bremsstrahlung fluence as a function of e-γ target thickness for 15 MeV electron incidents on different materials

Photons produced in this way can be redirected towards a suitable photo neutron target and get absorbed in the target. If the absorbed photon has energy greater than the binding energy of the neutron to the target, then a neutron is emitted. The materials those having photo nuclear reaction threshold below 15 MeV were simulated in FLUKA and the integrated neutron fluence was calculated for different thickness of γ-n target. The different materials such as beryllium, iron, lead, tantalum, tungsten were simulated for various target thickness and the variation in integrated neutron fluence is shown in Fig. 2. The results are also simulated for the most commonly used e-γ target such as W-Cu. In general, it is observed from Fig. 2 that the neutron fluence increases with thickness up to certain thickness and then decreases with increase in thickness of γ-n target.

In an individual target case, the lead produces the highest neutron fluence at thickness of 4 cm. The bremsstrahlung spectrum generated from the e-γ target contains maximum number of bremsstrahlung radiation of energy less than 6.74 MeV. Therefore, to utilize lower energy bremsstrahlung radiation (E < 6.74 MeV), it was decided to use combine target of beryllium with lead. From the simulated results, it was decided to use equal thickness for both the targets. The variation of neutron fluence with thickness for Be+Pb target is also shown in Fig. 2. It is observed that the Be+Pb target generates highest neutron fluence at 8 cm thickness. The integrated neutron fluence estimated from FLUKA simulation for individual beryllium (4 cm thick), individual lead

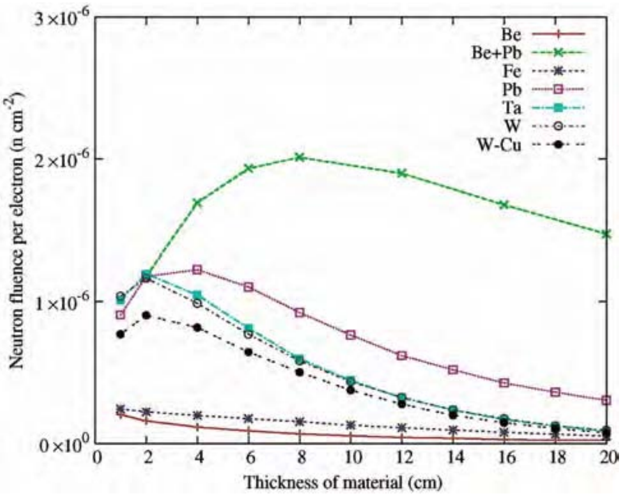

Fig. 2 — Variation in integrated neutron fluence as a function of γ-n target thickness for different materials

(4 cm thick) and combine beryllium + lead (4 cm Be + 4 cm Pb) target is 3.045×10^{-7}, 1.124×10^{-6}, 2.099×10^{-6} n cm^{-2} per electron, respectively. It is also observed from simulated results that in backward direction the neutron fluence is more as compared to forward and orthogonal direction. Since the backward direction gives maximum neutron fluence, the respective target was divided into two parts. First part of the target was mounted before the neutron collimator and subsequently second one was mounted after the collimator opening. Both the targets were mounted along the incident electron beam axis.

Next in the design is to optimize the moderator by varying different materials and optimize the thickness. The moderator material must have properties like high average logarithmic energy loss (ξ), large moderating ratio R_m, large scattering cross-section, and small value of thermalization factor. The geometric configuration used for the optimization of moderator is shown Fig. 3. Center of the circle acts as a source of electron which emits beam isotropically. The electron interacts with e-γ target sphere and generates bremsstrahlung radiation. Then the bremsstrahlung radiations interact with γ-n target sphere to generate neutrons through photonuclear reaction. Further, they scattered and moderated in moderating material of radius (r_m) and subsequently detected at the detecting sphere. The moderation efficiency, defined as the fluence rate of thermal neutrons obtained in the moderator per neutron source rate is shown in Fig. 4.

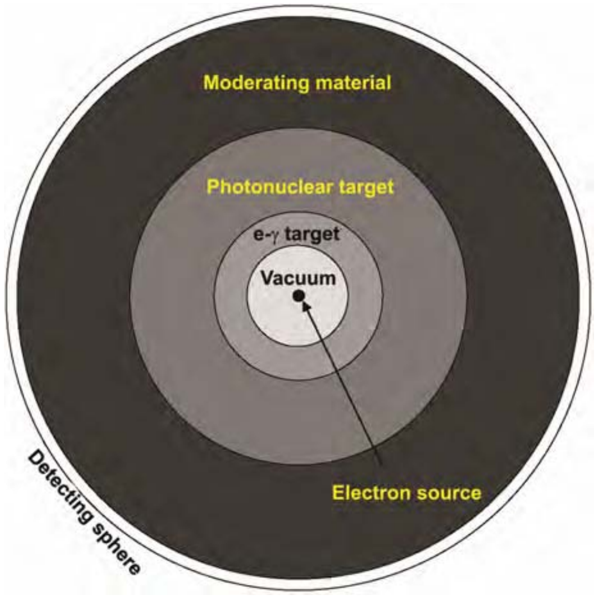

Fig. 3 — Geometric configuration for optimizing moderating materials

It has been observed that the normalized thermal neutrons fluence rate, ϕ_{th}, for paraffin ($C_{25}H_{52}$), high density polyethylene (HD-PE) (C_2H_4), zirconium hydride (ZrH_2) and light water (H_2O) is about the same, since they possess approximately the same number of hydrogen atoms per unit volume. In association with these materials, the fluence rate of thermal neutrons decreases very rapidly as the thickness of the moderating material increases. For moderators with higher moderating ratios (R_m), such as beryllium (Be), beryllium oxide (BeO), heavy water (D_2O) and graphite (C), a gradual decrease is observed as a function of moderating thickness, due to lower absorption of thermal neutrons. Since HD-PE shift the fast neutron energy to thermal energy very quickly, therefore, the HD-PE has been optimized as a moderator.

The schematic of the optimized thermal neutron radiography facility is shown in Fig. 5. The optimized e-γ and γ-n targets (two parts) are placed in the electron beam axis for the generation of neutron. It has been observed that at 4.5 cm distance between the first γ-n target and collimator, a maximum thermal neutron fluence rate is obtained. To minimize the gamma content at image plane, neutron collimator has been designed in perpendicular direction to the incident beam. Especially, the collimator opens at the beam axis to get the maximum neutron fluence. The neutron absorbing lining of collimator has been started at 30 cm from the beam axis. To minimize the gamma contamination in the thermal neutron beam, the lead having 5 cm thickness was kept as a gamma filter. Moreover, the second γ-n target was placed at 1.5 cm from collimator along the electron beam axis.

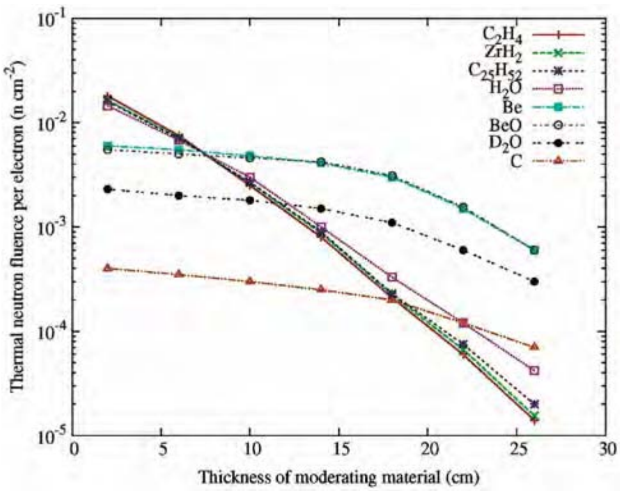

Fig. 4 — Variation in thermal neutron fluence as a function of radius of moderating sphere, r_m

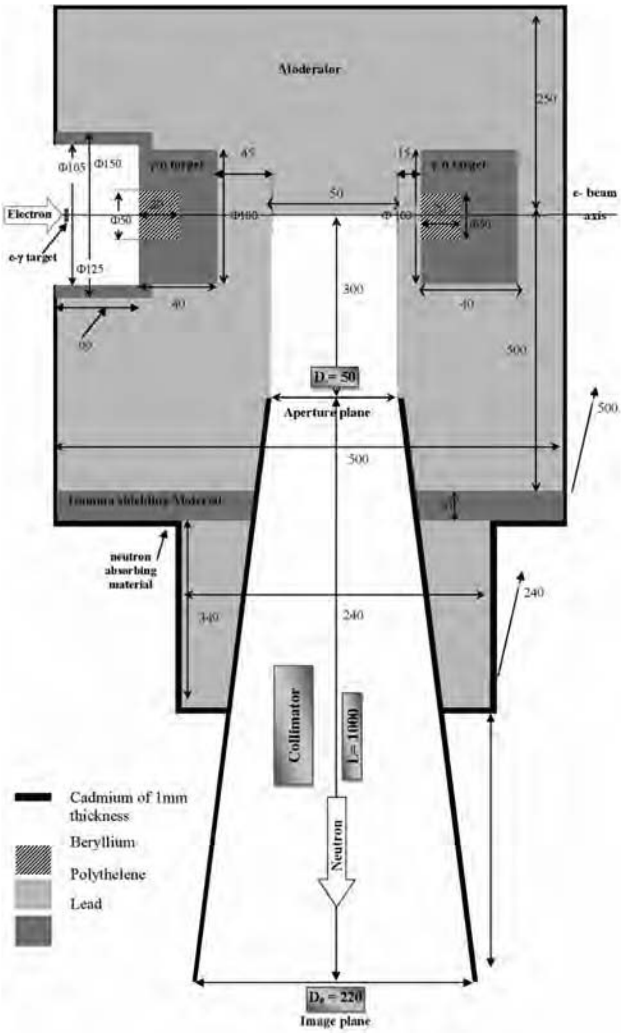

Fig. 5 — Schematic diagram of the optimized thermal neutron radiography facility. Not to the scale. Dimensions are in mm

In optimization process of collimator, collimator length L, inlet aperture D and diameter of the collimator inlet next to the image plane, D_O, were varied in order to attain the maximum thermal neutron fluence rate at the image plane. It is observed in the simulation results of the collimator design that as increase in collimation ratio (L/D), the image sharpness of radiograph also increases due to less scattered neutron beam, but subsequently, the neutron fluence rate at the object plane decreases. Therefore, it is optimized the L/D ratio of the collimator equal to 20, diameter of the aperture 5 cm and length of the collimator 100 cm. The thermal neutron fluence rate calculated on the image plan is 1.1×10^5 n cm^{-2} s^{-1} at

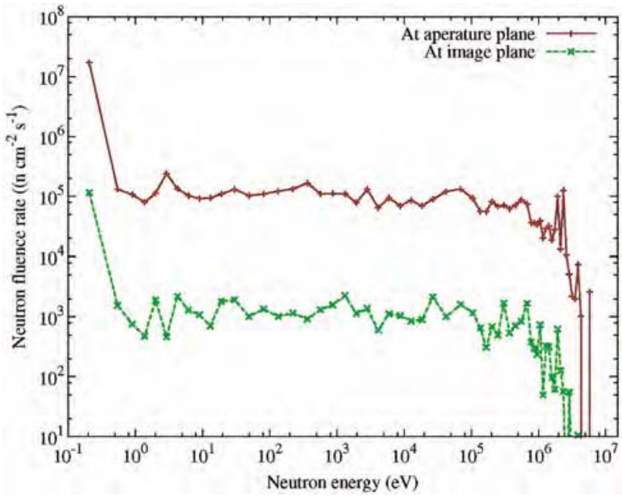

Fig. 6 — Neutron energy spectrum calculated at aperture and image plane for the optimized design of 15 MeV accelerator based neutron radiography facility

80 μA current of 15 MeV electron beam. The neutron spectra calculated on the aperture plane and image plane are shown in Fig. 6.

4 Conclusions

A successful study on the design of 15 MeV Linear accelerator based thermal neutron radiography facility was carried out with the following specifications, (i) useful beam area is 22 × 22 cm^2 square cone, (ii) thermal neuron fluence rate is 1.1×10^5 n cm^{-2} s^{-1}, (iii) L/D ratio is 20, (iv) neutron/gamma ratio is 1×10^5 n cm^{-2} mR^{-1}, and following materials are optimized for the facility (i) e-γ target: tungsten, (ii) γ-n target: beryllium + lead, (iii) moderator: high density polyethylene, (iv) X-ray shielding: lead, (v) neutron shielding: polyethylene, cadmium, (vi) collimator: divergent type with cadmium lining.

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