COLLIMATOR DESIGN OF 15 MeV LINEAR ACCELERATOR BASED THERMAL NEUTRON SOURCE FOR RADIOGRAPHY

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Abstract

Neutron Radiography is a powerful non-destructive technique used for the analysis of objects which are widely used in security, medical, nuclear and industrial applications. Optimization of the thermal neutron radiography facility has been carried out using 15 MeV Linear Accelerator based neutron source. In this case, a neutron collimator has been designed along with $\gamma - n$ target and moderator. The $\gamma - n$ target has been optimized based on their photonuclear reaction threshold. The moderating properties have been studied for 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 flux, 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=18. The neutron flux of the optimized facility obtained at the object plane is 3.1×10^4 n/(cm^2-sec^1) and neutron to gamma ratio is 1.0×10^5 n/(cm^2-mR^1).

INTRODUCTION

The thermal neutrons, are valuable for studying industrial components because of their high penetration depth in materials such as steel, aluminium and zirconium. Neutrons are efficiently attenuated 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. Neutron radiography (NR) 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. The technique is widely used in security, engineering, medical, nuclear and industrial applications [1, 2]. Inspection of ceramics or composite materials as well as detection of aluminium alloy corrosion damage is an example of effective applications of NR.

Neutron radiography comprises two principal components namely a suitable neutron source providing high flux of uniform thermal neutron beam at image plane and a device to record the image of the object. The necessary neutron beams used today are provided by nuclear reactors, radioisotopes and accelerators sources. Nuclear reactors provide high-intensity neutron beam but are expensive, non-transportable and having 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 flux, no radioactive waste, less shielding requirement etc. the accelerator based neutron source offering the possibility for in-situ testing of objects.

In this work, a transportable unit for radiography using the accelerator based neutron source and neutron collimator has been designed with FLUKA simulation. The dimensions of collimator were optimized such that it should provide maximum thermal neutron flux at the image plane.

MATERIALS AND METHODS

Simulation with FLUKA

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 handled the accurate electron-nucleus, electron-electron bremsstrahlung and photo nuclear interactions (described by Vector Meson Dominance, Delta Resonance, Quasi-Deuteron and Giant Dipole Resonance model) over the whole energy range [3] is the best choice for simulation. For optimizing the collimator design for neutron radiography facility a FLUKA simulation was carried out.

Photon Mode LINAC Machine

The linear accelerator(LINAC) [4] produces electron beam of energy of 15 MeV. 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 $\sim 100\,\mu A$. A Tungsten target having thickness 0.42 cm (range of the 15 MeV electron in W target) is mounted in path of electron beam for the production of bremsstrahlung radiations. LINAC is assembled with primary and secondary collimator to collimate the photon beam for industrial applications. The optimized assembly of neutron source is connected to this LINAC and produces neutrons.

RESULTS

15 MeV LINAC has been used for the design of thermal neutron radiography facility. To optimized the $\gamma - n$ target,

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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 $\gamma - n$ 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. 1. In addition, the results are also

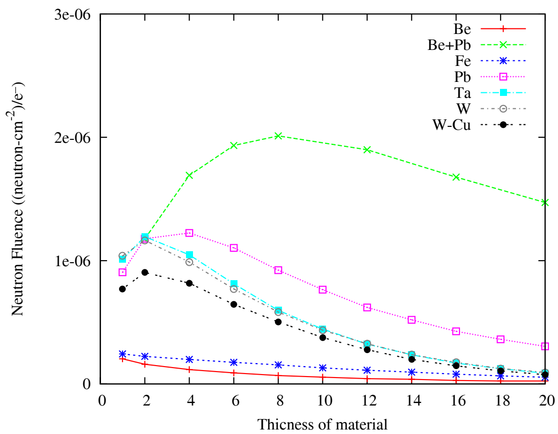

Figure 1: Variation in integrated neutron fluence as a function of $\gamma - n$ target thickness for different materials.

simulated for the most commonly used $e - \gamma$ target (W-Cu). In general, it is observed from figure that the neutron fluence increases with thickness up to certain thickness and then decreases with increase in thickness of $\gamma - n$ target. In an individual target, the lead produces the highest neutron fluence at thickness of 4 cm. The bremsstrahlung spectrum generated from the tungsten target contain maximum number of bremsstrahlung radiation of energy less than 7.37 MeV. Therefore, to utilize lower energy bremsstrahlung radiation (E < 7.37 MeV), it was decided to use combine target of beryllium with lead. The thickness for both the targets were kept same. The variation of neutron fluence with thickness for Be+Pb target is shown in Fig. 1. It is observed that the Be+Pb target generates highest neutron fluence at 8 cm thickness. The neutron spectra for beryllium (4 cm thick), lead (4 cm thick) and combine target of beryllium + lead (4 cm Be + 4 cm Pb) is shown in Fig. 2. The integrated neutron fluence for individual beryllium, lead and combine beryllium + lead is 3.045 $\times 10^{-7}$, 1.124 $\times 10^{-6}$, 2.099 $\times 10^{-6}$ (n–cm^{-2}–sec^{-1})/e– and mean energy is 150, 562, 400 keV respectively.

The neutron spectra calculated in forward, orthogonal and backward direction for combined target of beryllium + lead is shown in Fig. 3. It is observed that in backward direction the neutron fluence is more as compared to forward and orthogonal direction. The integrated neutron fluence for Be+Pb is 2.099 $\times 10^{-6}$, 1.846 $\times 10^{-6}$, 2.798 $\times 10^{-6}$ n–cm^{-2}–sec^{-1} at forward, orthogonal and backward direction respectively. Since the backward direction gives maximum neutron fluence, the respective target was divided in to two parts. First part of the target was mounted before the neutron collimator and subsequently second one

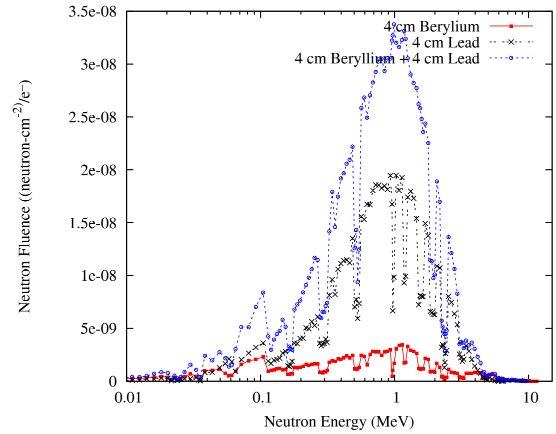

Figure 2: Neutron fluence spectra for beryllium, lead and beryllium + lead targets.

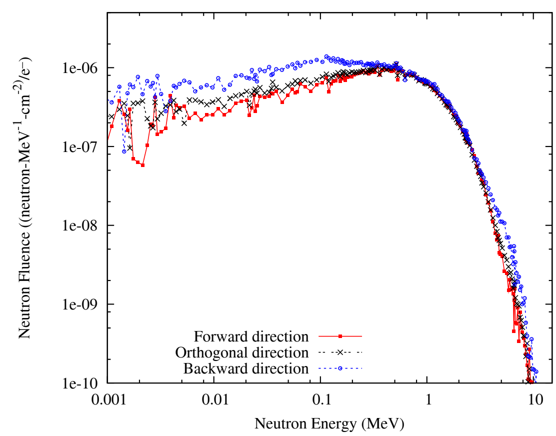

Figure 3: Neutron fluence spectrum for 4 cm thick beryllium and 4 cm lead at forward, orthogonal and backward direction.

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. It has been observed that the normalized thermal neutrons flux, 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 flux 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. 4. The optimized $e - \gamma$ and

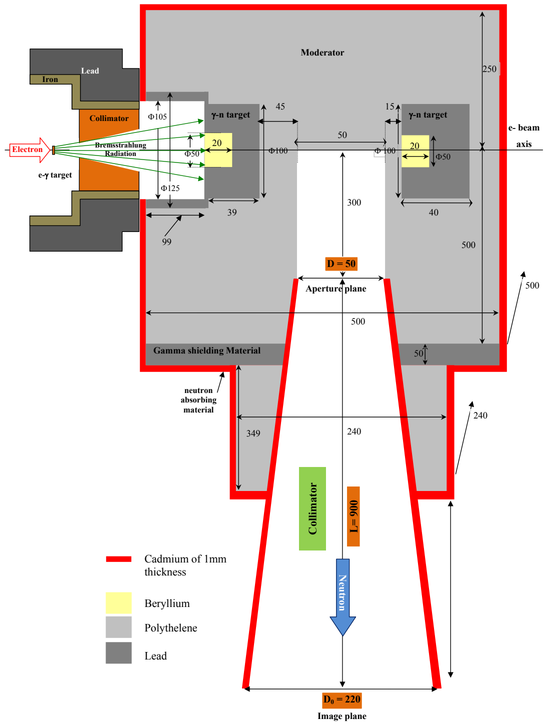

Figure 4: Schematic diagram of the optimized thermal neutron radiography facility. Not to the scale. Dimensions are in mm.

$\gamma - n$ targets (two parts) are placed in the electron beam axis for the generation of neutron. The position at which the peak of the thermal neutron flux occurs is observed using polyethylene as a moderator. It is found that at 4.5 cm distance from the first $\gamma - n$ target, the peak of thermal neutron flux is observed. 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 $\gamma - n$ target was placed at 1.5 cm from collimator along the electron beam axis.

The best results derived on variation of L and D are given in Table 1. 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 flux at the image plane. The table also shows the divergence angle of the beam (θ). From the results it was optimized to use L/D ratio of the collimator equal to 18, diameter of the aperture 5 cm and length of the collimator 90 cm. The thermal neutron flux calculated on the image plan is 3.1×10^4 n$-$cm$^{-2}-$s^{-1} at 80 μA current of 15 MeV electron beam.

The specifications of the optimized 15 MeV accelerator based neutron radiography facility are as follows:

Table 1: Thermal neutron flux at image plane for different L/D ratio.

D cm	**L** cm	**D$_0$** cm	ϕ_{th} n$-$cm$^{-2}-$s^{-1}	θ (°)	**L/D**
1	16	22	5.9×10^4	34.5	16
1	18	22	5.4×10^4	31.4	18
1	20	22	5.0×10^4	28.8	20
2	32	22	5.5×10^4	18.9	16
2	36	22	5.0×10^4	17.0	18
2	40	22	4.5×10^4	15.4	20
3	48	22	5.1×10^4	12.9	16
3	54	22	4.5×10^4	11.5	18
3	60	22	3.9×10^4	10.4	20
4	64	22	4.6×10^4	9.7	16
4	72	22	3.8×10^4	8.7	18
4	80	22	3.0×10^4	7.8	20
5	80	22	4.0×10^4	7.8	16
5	90	22	3.1×10^4	7.0	18
5	100	22	2.2×10^4	6.3	20
6	96	22	3.5×10^4	6.5	16
6	108	22	2.4×10^4	5.8	18
6	120	22	1.3×10^4	5.2	20

1. Useful beam area = 22 cm ×22 cm square cone
2. Thermal neuron flux = 3.1 $\times 10^4$ n$-$cm$^{-2}-$s^{-1}
3. L/D ratio = 18
4. Neutron / gamma ratio = 1 $\times 10^5$ n$-$cm$^{-2}-$mR^{-1}
5. $e - \gamma$ target = tungsten
6. $\gamma - n$ target = beryllium in combination with lead
7. Moderator = high density polyethylene
8. X-ray shielding = lead
9. Neutron shielding = polyethylene with cadmium lining

CONCLUSION

A successful study on the design of 15 MeV Linear accelerator based thermal neutron radiography facility was carried out. The optimized design of radiography provide thermal neutron flux of 3 $\times 10^4$ n$-$cm^{-2}.s^{-1} at 80 μA current of electron beam. L/D ratio is 18, the beam size is of 22 $\times$ 22 cm on image plane and the neutron to gamma ratio is 1 $\times 10^4$ n$-$cm$^{-2}-$mR^{-1}. A divergent type collimator of cadmium lining has been optimized in the proposed neutron radiography facility.

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