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DESIGN OF LINAC BASED NEUTRON SOURCE

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Abstract

Neutron sources are of great utility for various applications, especially in the fields of nuclear medicine, nuclear energy and imaging. At SAMEER, we have designed a linear electron accelerator based neutron source via photo-neutron generation. The accelerator is a 15 MeV linac with both photon and electron mode and is capable of delivering high beam current to achieve beam power of 1 to 2 kW. Efforts are in place to achieve further higher beam powers. 15 MeV electrons are incident on a bremsstrahlung target followed by a secondary target to achieve neutrons. To further optimize and enhance the neutron yield, backing material is provided. In this paper, we present the simulation of (e, γ) and (γ, n) processes using the Monte Carlo code FLUKA. The optimization of Tungsten as the convertor target whereas of the Beryllium as the neutron target is discussed in detail. We have explored various backing materials in order to optimize the total neutron yield as well as the thermal neutron yield. The simulation results have been considered for the finalisation of all material parameters for the set-up of this neutron source activity.

INTRODUCTION

Neutrons have a wide range of applications, especially in the areas of imaging and medical isotope generation. Though reactors are the largely used method for neutron generation, using electron accelerators can be very efficient due to the low cost and compact size of the set-up. In this method, bremsstrahlung photons are generated when an electron beam irradiates a metal target. These photons then interact with a neutron source secondary target to generate neutrons via photo-nuclear reaction. The secondary target material has a threshold energy lower than that of the bremsstrahlung photons to produce neutrons [1].

At SAMEER, we have designed a linear electron accelerator based neutron source via photo-neutron generation. The accelerator is a 15 MeV linac with both photon and electron mode and is capable of delivering high beam current to achieve beam power of 1 to 2 kW.

To simulate the photo-nuclear interaction, we have used FLUKA which is a Monte Carlo code that can simulate transport and interaction of electromagnetic and hadronic particles in any target material over a wide energy range [2]. For imaging purposes, a high count of thermal neutrons is desired. So, we have studied the energy spectra of the photo-neutrons produced and based on that, we have explored various backing materials that can be used to further optimize the total neutron yield as well as thermal neutrons. Also, appropriate shielding has been applied to keep the doses within the radiation safety limits during operation.

ACCELERATOR AND TARGET DESIGN

The linac designed is a standing wave, side coupled structure operating at π/2 mode at 2998 MHz frequency [3]. The RF power comes from a Klystron with 6 µs pulse width operating at 0.1% duty cycle. Efforts are ongoing to enhance the duty cycle to 0.4%. When operating at maximum duty, the linac will be able to achieve a 15 MeV electron beam with an average current of about 350 µA at the exit [4]. The electron gun is a diode type gun with pulsed injection voltage of 20 kV. We have achieved high shunt impedance structure and demonstrated 15 MeV energy with 1 kW beam power. For the proposed neutron source, we are replacing the Klystron and modulator to achieve 0.004 duty cycle thus enhancing the beam power by a factor of four. The linac is already designed as per the high repetition rate operation and is thermally suitable to accept high average power from the source. The line type modulator developed in-house is being replaced by solid state modulator capable of high repetition rate with longer pulse width operation. The new RF system is under testing and once received we will initiate the beam trials. The linac is shown in Fig. 1 and the parameters are shown in Table 1.

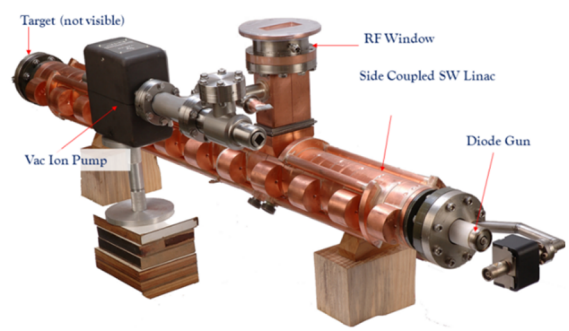

Figure 1: SAMEER made 15 MeV linac tube.

In a photo-neutron process, the neutrons are produced via (e, γ) and (γ, n) reaction. 15 MeV electrons are made incident on a bremsstrahlung target to produce photons which then interact with a suitable neutron target to generate neutrons through photo-nuclear reactions. The bremsstrahlung tungsten target is followed by a neutron source target along with a backing material which further optimizes the neutron yield. The backing material also

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Table 1: Measured Parameters for 15 MeV Linac Tube

Parameter	Simulated	Measured	
π/2 frequency	2998	2997.65	MHz
Side to main coupling	0.03	0.0278	%
Shunt Impedance	100	87	MΩ/m
Q (unloaded)	16000	15000	
VSWR	1.5	1.78	
Energy	15	15±0.5	MeV

enhances the thermal neutron count which is significant for imaging activity. Beryllium has been used as neutron source target. The entire target configuration is placed in a local shield inside a radiation facility to ensure no leakages are observed [5].

FLUKA SIMULATION DETAILS

A 15 MeV electron beam is incident on a 0.42 cm thick tungsten target followed by a 4 cm thick beryllium target. A 4 cm thick D_2O target is further attached as a backing material. The geometry of the target is shown in Fig. 2.

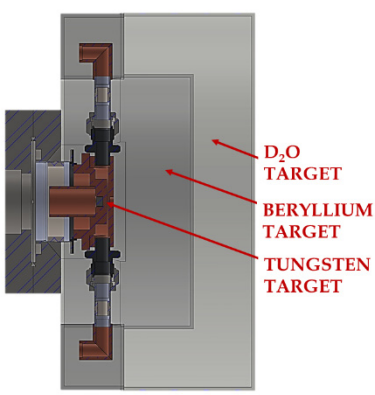

Figure 2: Target geometry.

We use USRBIN, USRBDX and USRYIELD to define the detectors to score fluence and dose. Spatial distribution of dose was scored using USRBIN and the yield was scored using USRYIELD detectors. The number of primaries run are set to 10^6.

PHOTON PRODUCTION

The geometry and parameter settings are defined in FLUKA and photon flux is computed which is then converted to dose. The relationship between absorbed dose rate and particle flux is given by [6]:

$$\dot{D} = \frac{\Phi E_0 \mu_a \times 1.6 \times 10^{-6}}{100} \quad (1)$$

where, $\dot{D}$ is the dose rate, Φ is the particle flux (quanta/cm^2/s), μ_a is the mass absorption coefficient of gamma rays in air (cm^2/g), 1.6×10^{-6} is the energy equivalent in ergs of 1 MeV, 100 is the energy equivalent in erg/g of 1 rad.

The photon dose rates from FLUKA are compared with the standard source term values as shown in Table 2 [7].

Table 2: Photon Source Term for Tungsten Target

Energy (MeV)	Bremsstrahlung Output - Forward (Gy/h/m²/kW)	
	NCRP	FLUKA
15	3500	3878.51
20	6000	5706.76
30	8500	7569.14

NEUTRON OPTIMIZATION

Photo-neutron generation occurs above a threshold energy defined for each material and is in the range of 6 MeV to 13 MeV but, beryllium has a low threshold energy of 1.67 MeV [8]. Figure 3 shows the thickness vs neutron yield plot for Be. We see that even with huge increment in thickness of Be, the yield does not increase significantly beyond 4 cm.

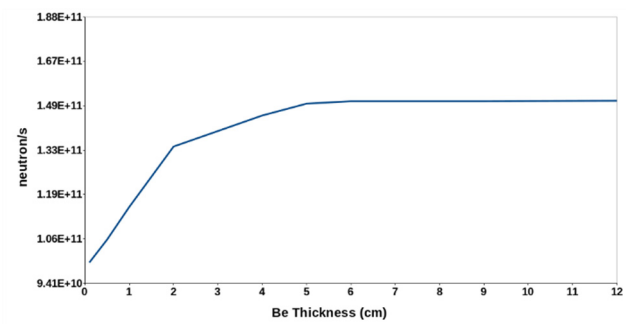

Figure 3: Beryllium thickness vs neutron yield.

To further enhance the neutron yield it was decided to try various other backing materials. Cadmium, Depleted Uranium and Heavy Water were some of the materials considered. It was found that a suitable backing material can be used to further optimize the total neutron yield and generate a good count of thermal neutrons as well. Figure 4 shows that the highest total neutron yield is given by D_2O. Figure 5 presents a comparative analysis of neutron yield from various backing materials. We see that the best results for thermal neutrons are achieved with Be target backed by D_2O.

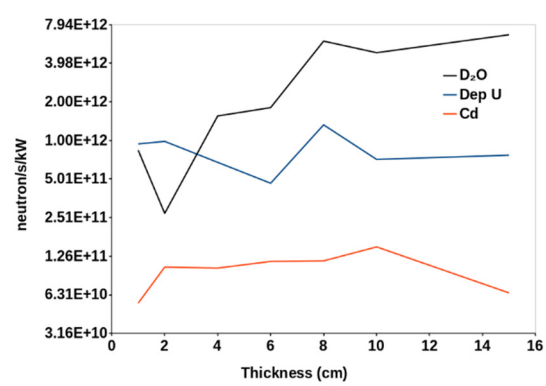

Figure 4: Total neutron yield for varying thickness of backing materials.

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Depleted Uranium is rare and also difficult to machine. Cadmium lining can be made but the yield is poor. Hence from the simulation point of view, Heavy Water appears to be a good choice. To make use of such a material, the secondary target geometry is being designed so as to ensure ease of handling. A hollow target assembly with an easy to use mechanism is under design stage.

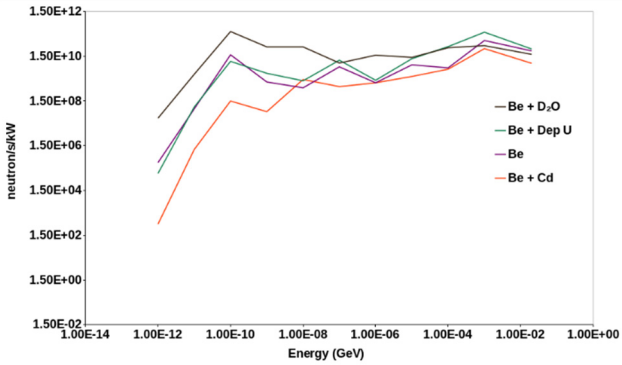

Figure 5: Comparison of neutron yield from various backing materials.

SHIELDING ESTIMATION

Figure 6 presents the spatial distribution of neutron dose with 0.42 cm of tungsten and 4 cm beryllium backed by 4 cm of D_2O inside the concrete walls of radiation lab. The neutron dose outside the D_2O region is ~ 10^{10} µSv/h/kW. Figure 7 shows the spatial distribution of neutron dose at 90° port inside the radiation lab. It was found that with this configuration, neutron dose in the outside area is in the range of 10^{-5} µSv/h/kW and the photon dose is below 10^4 µSv/h/kW which are well within the acceptable safety limits.

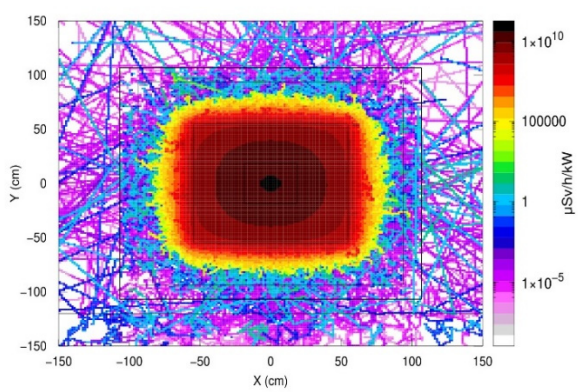

Figure 6: Neutron dose inside the radiation lab.

RESULTS AND DISCUSSION

From our simulations, it can be seen that for a 15 MeV electron beam irradiating on the source target configuration, we achieve a total neutron yield of 1.55 x 10^{12} neutron/sec and thermal neutron yield of 5.36 x 10^8 neutron/sec with the D_2O backing. Thus, the target configuration comprising of tungsten with beryllium backed by D_2O gives us a total neutron yield and thermal neutron count suitably large for imaging activities. Efforts are being made to achieve higher beam powers in order to obtain further higher neutrons.

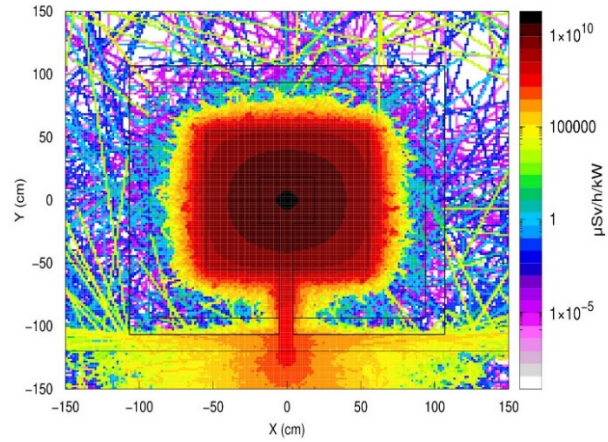

Figure 7: Neutron dose at 90° port inside the radiation lab.

Based on the results, it was concluded that a local shielding of 6 TVL lead in beam direction and 2.5 TVL on all sides surrounded by 3 TVL of HDPE along with 1 TVL of 5% borated HDPE and a 0.3 cm of 40% boron rubber sheet is effective in reducing the leakage radiation to attain safety limits for both photons and neutrons.

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