OPTIMIZING FAST NEUTRON SOURCES BY USING LINEAR ELECTRON ACCELERATORS

N. Baltateanu, V. Calian, Hyperion University, Bucharest, Romania

Abstract

We propose an optimized method to generate fast neutron fluxes by using linear electron accelerators. Both gamma radiation conversion targets (Pb, W, U, Au) and gamma-n reaction targets (Be, Deuterium) are studied. The Monte-Carlo simulation of the two processes in spatially extended targets with variable geometry allows us to optimize the set up in terms of material, dimensions and source position to obtain maximum fast neutron fluxes. We also performed extended experimental measurements, which confirm the theoretical simulations and prove the efficiency of the method.

1 DESCRIPTION OF EXPERIMENTAL METHOD

We propose a new design for primary and secondary conversion targets, which are used in experiments of neutron production by γ - n reactions.

The novelty of our method consists of optimizing the geometry of targets. We present the theoretical model and simulations, which were experimentally verified.

For this purpose, fast electrons provided by a linear accelerator and primary targets (Pb, W, U, Au) are used to generate gamma rays by electron induced bremsstrahlung radiation. Secondary targets (Be, D) are then γ - irradiated to produce photoneutrons.

The conversion efficiency for producing gamma radiation was computed and experimentally measured as a function of target material and electron energy.

It was verified that the conversion efficiency of the bremsstrahlung effect strongly depends on the target material and thickness.

The fast and thermal neutron flux were changing as a function of target thickness and material as well as of source position.

For instance, using the optimized Be target, the following values of the thermal neutron flux were measured: 2.14 x 10^5 n/cm^2 sec mA, for 3 MeV electrons; 2.29 x 10^7 n/cm^2 sec mA, for 7 MeV electrons; 10^{12} n/cm^2 sec mA , for 15 MeV electrons.

2 THEORETICAL MODELS

Appropriate models for the spatially extended target, for the spatial distribution and slowdown density of the neutrons were constructed.

One has to analyze two types of phenomena in order to be able to formulate the complete problem that leads to an optimized design of the experiment.

Firstly, we have to study the γ - photons generated in primary targets and take into account the occurrence of simultaneous phenomena as multiple Coulomb diffusion and ionization leading to auxiliary broadening or nonradiative loss of energy, respectively.

Secondly, the fast neutron emission has to be studied, establishing the most effective conditions in terms of target shape and dimensions, relative position of target and source, incident electron energy.

2.1 Primary conversion targets

The probability of gamma photon emission along the electron beam direction ($P(E_0,l)$) after multiple Coulomb diffusion is modeled as a function of the electron energy (E_0) and target thickness (l).

We use a semi – empirical formula :

$$P(E_0,l) = NE_0c_1\int_0^l f_1(l)f^2{}_2(E_0)\exp(-2c_2l)$$

$$-NE_0c_1\int_0^l f_1(l)[c_3f_2(E_0)\exp(-c_2l)+c_4]$$

where the functions $f_1(l)$ and $f_2(E_0)$ are given by:

$$f_1(l)=\frac{c_5}{1+c_6l}+\frac{c_7}{1+c_8l}$$

and

$$f_2(E_0)=c_9+c_2E_0$$

respectively. The parameters c_i (i =1, 2,…, 9) were experimentally determined.

The number of photons having energy values higher than the threshold energy corresponding to the photonuclear reaction (for target thickness smaller than electron mean free path) is then computed as:

$$N_\gamma = \int dx\left(\frac{dE_{rad}}{dx}\right)\frac{R_u}{\overline{\overline{E_\gamma}}}$$

where R_u is the ratio of the total effective photon energy and total bremsstrahlung energy while $\overline{E_\gamma}$ is the average energy of the effective gamma quanta.

2.2 Neutron generation in secondary targets

Two types of targets (Be, D) were used for the photoneutron generation. Their threshold energy values are 1.67 MeV and 2.2 MeV respectively.

We determined the optimum target spatial structure and dimensions, which provided a maximum fast neutron flux. The targets were then experimentally tested and the neutron flux was measured for different electron energy values.

The expression we use for the neutron flux takes into account the multiple phenomena and the experimental design conditions.

The expression of the neutron flux:

$$\Phi = \frac{\lambda\sigma N_\gamma n}{\varsigma(4\pi\tau)^{3/2}} \iiint_D d^3\vec{x} \exp\left(-\frac{\left(\vec{x}-\vec{x}_0\right)^2}{4\tau} - \lambda\left\|\vec{x}\right\| \right)$$

depends thus on: the variation of the probability of photoneutron production as a function of the reaction cross section and number of beryllium nuclei per cm^3; cross-section of the gamma - n reaction with the energy; probability of photon absorption as a result of electromagnetic interactions in the beryllium target (photoelectric effect, pairs generation, Compton effect); the influence of the slowing-down process on the neutron spatial distribution.

We used the following notations:
x_1 –axis is along the electron beam propagation direction, x_{10} is the coordinate of the source position, λ - the neutron mean free path, σ - the cross - section of the γ - n reaction, ς - the logarithmic decrement of the neutron slow-down for the given target material, τ - the age of the neutrons having energy ε.

3 OPTIMIZATION OF THE CONVERSION TARGETS

Given the conditions imposed by the symmetry of the spatial structures (rotation around the propagation axis x_1), the 3D domain may be parametrized as well as the integrated function, reducing the degree of uncertainty in the expression of the neutron flux. We must note here the role of the interplay of modeling and optimization procedures.

We use a Monte – Carlo method to calculate the multidimensional integrals and to move in the large space of possible geometrical structures of the targets.

The value of the integral, computed by this technique will be:

$$\int F(\vec{x})d^3\vec{x} = \left(\left\langle \frac{F}{G} \right\rangle \pm \delta \right) \int G(\vec{x})d^3\vec{x}$$

with:

$$\delta = \sigma / N_{config}$$

and:

$$\sigma^2 = N_{config}{}^{-1} \sum \left(F(\vec{x}) / G(\vec{x}) - \langle F/G \rangle \right)^2$$

while:

$$\langle F/G \rangle = N_{config}{}^{-1} \sum F(\vec{x}) / G(\vec{x})$$

The sums are computed over the entire space of configurations $(\vec{x})$.

We found the optimum spatial domain, which respects all the constructive constraints, having conical symmetry and we denote by x_0 the x - coordinate of the source and by x_1 – the x –coordinate of the plane where the fast neutron flux is measured

The computed values of the neutron flux were then compared with the experimental data obtained by using the designed optimum target, and the best positions of the source and plane of measurement for the neutron flux were obtained.

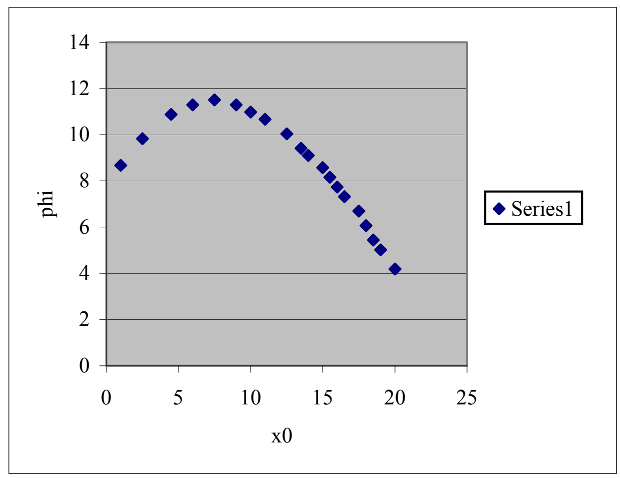

Figure 1: The neutron flux dependence on the position of the source, for the Be target.

As an example, we give the dependence of the flux on the source position and measurement plane position in figure 1 and figue 2, respectively, for the optimum Be target.

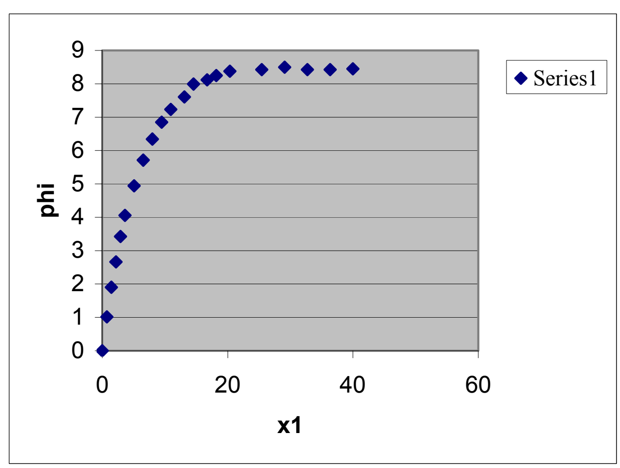

Figure 2: The neutron flux dependence on the position of the measurement plane, for the Be target

4 CONCLUSIONS

We designed and we tested a new type of pulsed neutron sources. They are based on two main phenomena, the γ ray generation by irradiating primary targets with fast electrons provided by a linear accelerator and the photoneutron generation in secondary optimized targets by γ - n reactions.

We used a numerical method in order to search for the optimum geometry of the targets and then to calculate the best positions corresponding to a maximum neutron flux.

We can thus conclude that the linear accelerator can be successfully used as a low cost pulsed neutron source.

The performances of the proposed method can be further improved by using fissionable target materials and higher electron energies.

5 REFERENCES

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