OPTIMAL FAST NEUTRON SOURCES USING LINEAR ELECTRON ACCELERATORS

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Abstract

Fast neutron sources are designed and experimentally tested, based on optimized conversion targets and linear accelerator as electron suppliers. Both gamma radiation and fast neutron emissions are studied, establishing the most effective characteristics of the targets in terms of material, spatial dimensions, relative position of target and source, incident electron energy. A numerical procedure is implemented in order to obtain optimum values of the conversion efficiency and neutron flux, respectively.

1 INTRODUCTION

We proved that the electron beams provided by a linear accelerator can be efficiently used in order to produce fast neutrons by photonuclear reactions in appropriately designed targets (Be) due to the bremstrahlung radiation generated by corresponding conversion targets (Pb, W, U).

Two types of applications were performed:

i) Firstly, we compute and experimentally measure the conversion efficiency of the Bremsstrahlung generated gamma radiation as function of target material and electron energy.

ii) Secondly, the optimum fast and thermal neutron flux are calculated and measured, exhibiting a strong dependence on the target thickness and material as well as on the source position.

We took into account an appropriate model for the spatially extended target, for the spatial distribution and slowdown density of the neutrons.

2 CONVERSION PROCESSES AND SIMULATION

2.1 Bremstrahlung radiation

A set of conversion targets (W, Pb, U) was used in order to obtain gamma radiation by fast electron irradiation process. It was thus proved that the conversion efficiency in Bremstrahlung effect strongly depends on the target material and thickness.

Both the estimation and the measurement of the generated photon number in this type of processes is recognized as a difficult problem ([6] and reference therein). One must take into account the occurrence of simultaneous phenomena as multiple Coulomb diffusion and ionization leading to auxiliary broadening or nonradiative loss of energy, respectively.

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

$$N = \sum_{i}^{n} \left(\frac{dE_{rad}}{dx} \right) \frac{R_u}{\langle E_\gamma \rangle} \Delta x \qquad (1)$$

where: n is the number of target layers which correspond to electron energy loss equal to the threshold energy, E_g is the average energy of the effective gamma quanta, R_u is the ratio of the total effective photon energy and total bremstrahlung energy.

The experiments were designed in order to perform a complete analysis for an entire set of targets with different materials and thickness values. The conversion efficiency as a function of electron energy is proved to be better for the U-target, providing quanta energy higher than 7 MeV, followed by Pb and W targets which give lower energy values but allowing us to use simple cooling methods.

2.2 Fast neutron generation

We investigated two types of target materials (Be and deuterium) due to the threshold energy values (1.67 MeV and 2.2 MeV respectively), designing the optimum target spatial structure and computing the corresponding dimensions in order to provide maximum fast neutron flux. The targets were then experimentally tested and the neutron flux was measured for different electron energy values.

The following factors were taken into account:

a) the variation of the cross-section of the $\gamma - n$ reaction with the energy;

b) the spatial dimesions and shape of the accelerator exit window;

c) the design of the cooling system;

d) the probability of photoneutron production as a function of the reaction cross section and number of beryllium nuclei per cm^3 ;

e) the probability of photon absorption as a result of electromagnetic interactions in the berylium target (photoelectric effect, pairs generation, Compton effect);

f) the slowing-down influence on the neutron spatial distribution which in turn is connected to the neutron flux.

The general optimization problem we were thus confronted was to find the extremum of a 3D integral for variable integration domains and an auxiliary parmeter in the integrated function which give the neutron flux:

$$\phi = \frac{\lambda N_\gamma n\sigma}{\zeta(4\pi\tau)^{3/2}} \iiint_D d^3\mathbf{r} \exp\left[-\frac{(\mathbf{r}-\mathbf{r}_0)^2}{4\tau} - \mu r\right] \qquad (2)$$

where $(x-x_0)$ is the distance, along the electron beam propagation direction, between the source position and the plane where the neutron flux is evaluated.

Considering the spatial extension of both source and target, without symmetry constraints, would provide a problem which is not well-defined. On the contrary, if one uses the conditions imposed on the symmetry of the spatial structures (rotation around the propagation axis *x*), the 3D domain may be parametrized as well as the integrated function, reducing the degree of uncertainty. We must emphasize here the role of the interplay of modelling and optimization procedures.

On the other hand, the 3D integration step might generate high values of the memory and computing time if one uses the standard quadrature methods. This is avoided in our approach by the implementation of a Monte-Carlo based procedure at this stages.

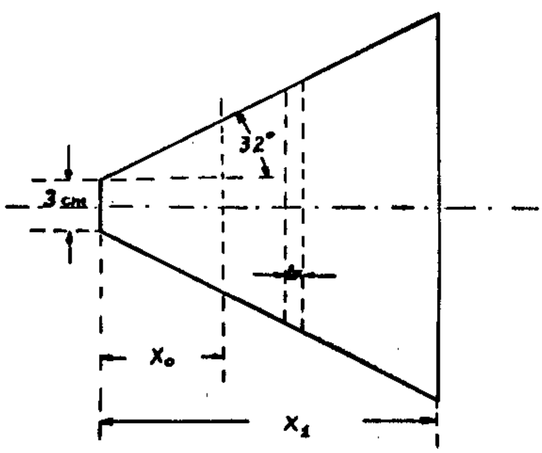

Figure 1: Target geometry.

The Monte-Carlo method may offer the chance to calculate multidimensional integrals which obviously occur while we solve this type of problems. If the spatial configuration of the system is described by a 3A-dimensional vector (R) and we have to integrate a function of R ($F(R)$), then we need a suitable real, positive and normalizable weight function $W(R)$, so that it can be used as a probability distribution in order to write:

$$\int F(R)dR = \lim_{N_c\to\infty} \overline{F/W} \int W(R)dR \qquad (3)$$

for N_c - the number of configurations $[R_i]$ distributed with the weight $W(R)$ and the average

$$\overline{F/W} = \frac{1}{N_c}\sum_{i=1}^{N_c} F(R_i)/W(R_i)\,. \qquad (4)$$

The value of the integral, computed by Monte-Carlo technique where N_c is certainly finite will then be:

$$\int F(R)dR = \left(\overline{F/W} \pm \delta\right)\int W(R)\,dR \qquad (5)$$

with

$$\delta = \sigma/\sqrt{N_c}$$

and

$$\sigma^2 = \frac{1}{N}\sum\left[F(R_i)/W(R_i) - \overline{F/W}\right]^2$$

These formula are valid if the $F(R_i)/W(R_i)$ values have a normal distribution. However, if is not the case, block averages must be first performed. The weight we use, as resulted from equation (2), is a Gaussian type one.

The configurations $[R_i]$ are obtained by sampling the weight function $W(R_i)$ and when this is not a simple function the Metropolis algorithm based on the principle of detailed balance has to be used.

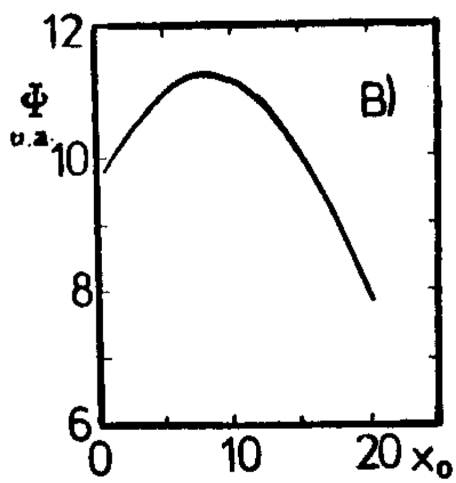

Figure 2: Neutron flux dependence on source position.

The optimum spatial domain, which also satisfies the constructive conditions, is given in figure 1 while the dependence of the flux ϕ on the x_0, x_1 plane positions is shown in figures 2, 3.

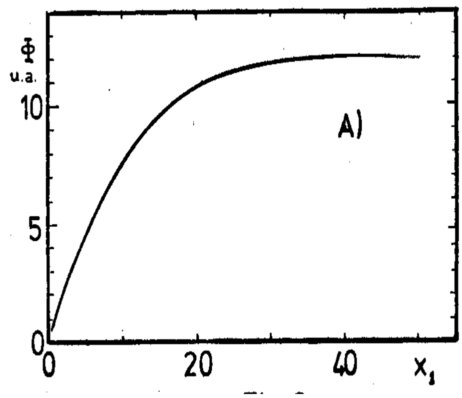

Figure 3: Neutron flux dependence on evaluation plane position.

3 CONCLUSIONS

The simulation results, obtained after the optimization problem for the target geometry is solved and after the fast neutron flux was computed, are in very good agreement with the experimental tests.

The optimized conversion targets provided the following thermal neutron flux values: $2.14 \cdot 10^5 n/cm^2 \sec mA$ for 3MeV electrons; $2.29 \cdot 10^7 n/cm^2 \sec mA$ for 7MeV electrons; $10^{12} n/cm^2 \sec mA$, for 15MeV electrons.

In conclusion, our method provides an efficient technique for obtaining pulsed fast neutrons beams as a result of photonuclear reactions in optimal targets (Be). In a first stage, gamma radiation was generated in conversion targets (Pb, W, U), using the fast electrons supplied by a linear accelerator.

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