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Design of a photoneutron source based on 10 MeV electrons of radiotherapy linac

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ABSTRACT

The optimization of a compact, economical and simple photoneutron production, by using the tungsten as bremsstrahlung production target and heavy water serving as the dual purpose of photoneutron production and heat exchange medium, has been studied. The Monte Carlo code MCNPX has been used to optimize the targets geometry and reflectors geometry to increase the photoneutron yield as the highest possible rate. The process of bremsstrahlung production extremely heats up the tungsten target, making it necessary to be cooled down to below 350 K. The MATLAB code and jet impingement cooling method were used to obtain the temperature of tungsten target versus the electron current and also the velocity of heavy water coolant. The jet impingement cooling method was used to control the temperature of tungsten target versus the electron current and the jet velocity. Results showed that for the temperature of 350 K, the radius of tungsten was obtained to be 15.7 cm in accordance with the maximum electron current for 10 MeV electrons. Applying the optimized dimensions of the targets and a beryllium layer of 50 cm thick as a reflector and γ-contamination converter, the neutron yield was found to be 1.25×10^{11} n/mA/s for 10 MeV electrons.

1. Introduction

Researches on photoneutron production based on electron accelerators have been ongoing since 1950 (Barber and George, 1959; Berger and Seltzer, 1970; Seltzer and Berger, 1973) and vastly progressed in recent years. The so-called phenomenon has many applications in science, medicine and industry, such as Neutron Activation Analysis (NAA) (Oprea et al., 2011), Boron Neutron Capture Therapy (BNCT) (Nigg et al., 1997), detection of explosives, narcotics, and alcoholic beverages (Jones, 2003; Yang et al., 2007). There are several preferred aspects for photoneutron sources using accelerators rather than radioactive sources such as the high neutron intensity production (many orders of magnitude), the possibility of switching off without any need for shielding, and their low gamma ray contamination. Several studies have been conducted on neutron production using linear electron accelerator (linac) for radiography, tomography and BNCT (Rahmani and Shahriari, 2010; Huang et al., 2006; Auditore et al., 2005). They have introduced hybrid photoneutron target $BeD_2 + W$ as a proper target for BNCT since it has a high photoneutron cross section and low threshold energy for photoneutron production (Rahmani and Shahriari, 2010). Numerous calculations and measurements have been carried out on angular distributions, energy and flux of photoneutrons produced by microtron and betatron (Chakhlov et al., 1999; Jallu et al., 1999; Eshwarappa et al., 2005; Patil et al., 2010). A good agreement between measurements and MCNPX simulations has been found for neutrons that produced by sending 510 MeV electrons on different optimized targets (Quintieri et al., 2012). A few works have been carried out onto the measurement of photoneutron yield from heavy water (Coceva et al., 1988; Golovkov et al., 1989; Vasina et al., 1989). Dale and Gahl used from the MCNP code for modeling a photoneutron yield based on 10 MeV electron linac in a heavy water target and they compared the MCNP model with the experimental results (Dale and Gahl, 2001). The optimized converters, when fitted to the head of the linear electron accelerators, make the possibility use of them as a source of neutrons.

In the process of photoneutron production the geometry and properties of the electron impinging target and the photon impinging target can greatly affect the neutron production flux. In particular, the photon-energy threshold required to overcome the binding energy of neutrons in photoneutron target and photoneutron cross sections are of high importance. $^{2}D(\gamma,n)^{1}H$ and $^{9}Be(\gamma,n)^{8}Be$ reactions have the lowest threshold energies for photoneutron production and their cross sections have obtained by numerous researchers (Mobley and Laubenstein, 1950; Jakobson, 1961; Guth and Mullin, 1949).

On the other hand, the majority of the energy of the incoming electrons is converted into heat in photon production target and the target temperature quickly rise up and hence greatly affects its properties. To prevent the target oxidization and its collapse, it must

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be cooled down to temperatures less than 350 K. Various methods of cooling such as water-cooled targets (Korenev, 2004; Auslender et al., 2004), circular liquid lead (Altstadt et al., 2007) have been introduced. In recent years the use of impinging fluid jets for removing heat in the target has been proposed (Kim and Kim, 2009) in which the coolant is directed toward a nozzle and injected onto the target container. The MCNPX Monte Carlo Code was used to design a cylindrical container consisting of tungsten as the bremsstrahlung production target and D_2O as the photoneutron production target. Furthermore, to remove the huge amount of electron beam power converted to heat in the target and reach a more feasible photoneutron source, the jet impingement cooling method was used. In this method D_2O was employed as the coolant liquid and a numerical code in the MATLAB programming software was implemented. However, the proposed neutron source is relatively inexpensive, compact enough to be used in hospitals and the design promises to produce enough neutron flux for short treatment times.

2. Source design

2.1. The e–γ converter

The materials with high atomic numbers are suitable for the production of bremsstrahlung photons (Knoll, 2000). Because of high atomic number of tungsten and its physical properties, it was selected as a target material for photon production. For maximum bremsstrahlung production in a tungsten as an e–γ converter, the Monte Carlo code MCNPX was used to optimize the dimensions of a disc target. In SDEF card a small disk has been used as an monoenergetic electron source (10 MeV). Photon yields have been calculated by F1 tally. The LINAC beam parameters that have been considered in calculations are as follows:

Output beam energy: 10 MeV.
Output beam current: 50 mA.
Pulse repetition rate: 300 Hz.
Pulse duration: 3.6 µs.
Average beam power: 540 W.

In Fig. 1, variation of photon yield as a function of target thickness was shown, using tungsten radius of 1 cm. This figure shows a maximum photon yield at target thickness of ~0.15 cm. Similarly, Fig. 2 shows the variation of photon yield as a function of the radius of target at the optimum thickness. This figure shows a photon yield saturation at a disc radius of ~1.5 cm. The obtained optimum thickness of the electron target (~0.15 cm) is less than the electron ranges (0.32 cm) in the target. This difference is attributed to the optimum dimensions of the tungsten target for maximum bremsstrahlung production at its front face. Hence some of the electrons will escape from the tungsten target and enter the D_2O target. Fig. 3 shows the bremsstrahlung spectrum produced by 10 MeV electrons with the optimized dimensions obtained for the tungsten e–γ converter.

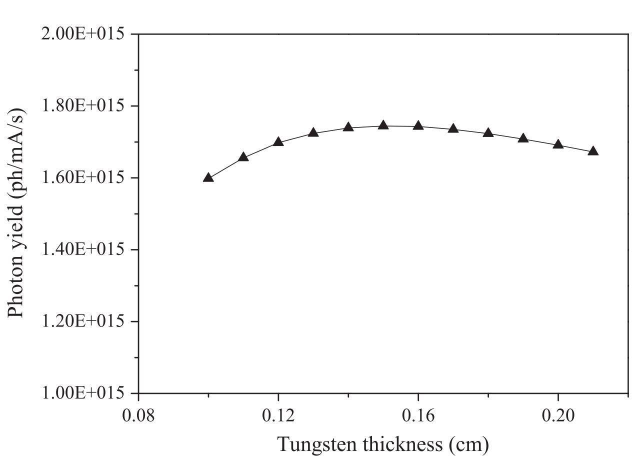

Fig. 1. Photon yield in a cylindrical target of tungsten as a function of its thickness.

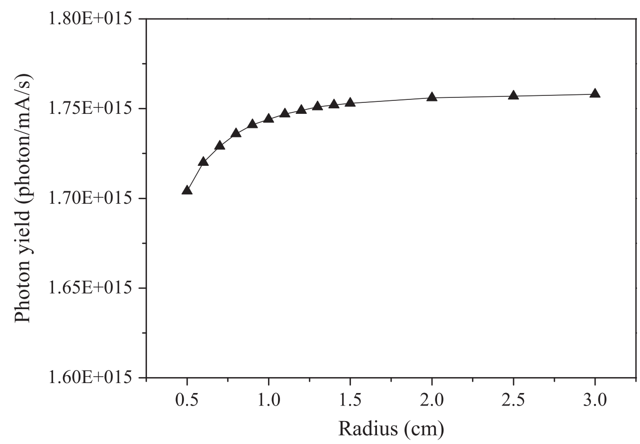

Fig. 2. Photon yield in tungsten target (disk) as a function of disk radius.

2.2. The γ–n converter

To produce photoneutrons, a gamma ray photon with an energy of at least the binding energy of the neutrons to the γ–n converter is required to make the reactions energetically possible. Applying the conservation laws of energy and linear momentum, neutron energy is obtained to be (Knoll, 2000):

$$E_n(\theta) \cong \frac{M(E_\gamma + Q)}{m + M} + \frac{E_\gamma[(2mM)(m + M)(E\gamma + Q)]^{0.5}}{(m - M)^2}\cos\theta \quad (1)$$

where

Q = Q-value of the photoneutron reaction (MeV).
θ = angle between gamma photon and neutron direction.
E_γ = gamma energy (assumed $\ll$ 931 MeV).
M = mass of recoil nucleus $\times$ c^2.
m = mass of neutron $\times$ c^2.

The threshold energy of photon reaction for light nuclei is greater than that of heavy nuclei. For light nuclei is given to be

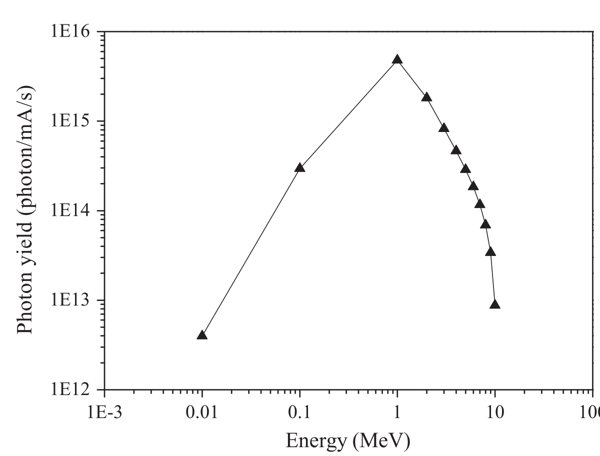

Fig. 3. Bremsstrahlung spectrum produced by the optimized dimensions at the front surface of the tungsten target.