Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Instruments and Methods in Physics Research B 229 (2005) 339–347

NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Calculation of photoneutrons produced in the targets of electron linear accelerators for radiography and radiotherapy applications ☆

W.L. Huang *, Q.F. Li, Y.Z. Lin

Accelerator Laboratory, Department of Engineering Physics, Tsinghua University, Beijing 100084, China

Received 24 May 2004; received in revised form 10 December 2004
Available online 25 January 2005

Abstract

Photoneutron spectra produced by bremsstrahlung in electron linear accelerators for radiography and radiotherapy applications have been investigated. Calculations with the Monte Carlo code FLUKA were performed for electron beams of different energy values striking the same tungsten target, and a 15 MeV electron beam bombarding targets of different materials as well as different thicknesses to study the photoneutron spectra and the neutron dose equivalent at the isocenter. This work presents neutron yields and neutron energy spectra for targets under different conditions and compares these with the corresponding published results. The results show that the photoneutron average energy is below 1.0 MeV under the above mentioned conditions, which is much lower than the one published in NCRP Report No. 79. For a 4 mm tungsten target and incident electron energies of 9, 10, 15, 18 and 20 MeV, the photoneutron dose equivalents at the isocenter are 0.006, 0.016, 0.147, 0.231 and 0.261 mSv/GyX-ray, respectively. For copper, tantalum, tungsten and gold targets with different thicknesses, the photon doses at the isocenter are of the same order ($\sim 10^{-15}$ Gy/e), while photoneutron yields of copper targets are one order smaller than those of the other three materials, and so are the neutron dose equivalents of copper targets. The medium atomic number materials, such as copper with a thickness of about 0.56 radiation length, which is sufficient to prevent electron leakage, appeared to be good choices for sufficient photon production and lower neutron contamination.

PACS: 02.70.Uu; 25.20.Lj; 87.53.Pb
Keywords: Photoneutron; Neutron energy spectrum; Accelerator target; FLUKA code

1. Introduction

The electron linear accelerator, which produces bremsstrahlung by electrons bombarding the

☆ National Natural Science Fund: 10135040.
* Corresponding author. Tel.: +86 01062795424; fax: +86 01062795600.
E-mail address: huangwl00@mails.tsinghua.edu.cn (W.L. Huang).

0168-583X/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2004.12.117

target, is a good X-ray source for medical and industrial CTs or other nondestructive detecting systems [1]. But during its use in the above applications, photoneutrons are also produced if the photon energy exceeds the threshold energy of photonuclear reactions of the target material, such as ^{184}W, E_{th} = 7.41 MeV [2]. Photoneutrons are produced in the target, accelerator head, collimators and flattening filter, and other irradiated objects, causing a contamination of bremsstrahlung and bringing many problems, such as image resolution deterioration and radiation protection concerns. So as a type of converter, it is more important that the target should be optimized not only to achieve maximum bremsstrahlung intensity, but also to get minimum photoneutron production as well as complete absorption of primary accelerated electrons [3].

High Z materials are generally used as targets for high bremsstrahlung production, but the cross sections of photonuclear reactions of these materials, such as tungsten, gold and tantalum, have the maximum values when the photon energy reaches $14 \sim 15$ MeV. In order to get more information, the neutron energy spectrum is essential to calculate the neutron dose equivalent ratio and the induced activity. National Council on Radiation Protection and Measurement (NCRP) Report No. 79 addressed the spectrum of neutrons produced by a bremsstrahlung spectrum with a maximum energy E_b, which is given by summing (integrating over photon energy) the spectrum produced at each photon energy weighted with the bremsstrahlung spectrum [2]. However, this was published almost 20 years ago and has been superseded by new research and concepts [4]. For example, the photoneutron average energy is $\sim$1 MeV in this work, and other experiments [8–10] also got similar results, which are much lower than the one indicated in NCRP Rep. No. 79.

In recent years, the Monte Carlo code FLUKA was developed for multiple purposes and all particles [5], so it is a powerful code for the calculation of photoneutrons produced in middle and high energy electron accelerators. Using FLUKA and neutron fluence-to-dose equivalent conversion factors published by NCRP Report No. 79, neutron dose equivalent ratios at the isocenter were calculated for electron beams of different energy values striking targets of different materials. It is estimated that the neutron dose equivalent ratio (DER), contributed by the target only, is 0.006, 0.016, 0.147, 0.231 and 0.261 mSv/GyX-ray and the average neutron energy is 0.401, 0.445, 0.713, 0.776 and 0.798 MeV for 9, 10, 15, 18 and 20 MeV electron beam, respectively, with a tungsten target thickness of 4 mm. In particular, for the 15 MeV electron beam, a copper target, with a thickness of 0.557 radiation lengths to prevent electron leakage, has a neutron DER much smaller than those of optimized targets of other materials and therefore produces enough bremsstrahlung and reduces neutron contamination effectively.

Using active foil detectors, measurements and unfolding the neutron spectra produced in electron accelerators for radiography and radiotherapy applications are undertaken, and a simulation with FLUKA for the whole accelerator system is planned for further study.

2. Simulation with FLUKA

The physics model used in early studies of neutron spectra, mentioned in NCRP Rep. No. 79 [2], considered only the production of neutrons. But in the whole accelerator facility, neutrons are transported through the target, scattered by heavy nuclei and moderated or absorbed by light nuclei. 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 information on bremsstrahlung production, electron leakage and neutron spectra.

Monte Carlo simulations with FLUKA for 15 MeV electron beams bombarding targets of different materials were carried out to study the photoneutron spectra and the neutron dose equivalent at the isocenter. Simulations of a tungsten target struck by electron beams of different energy values and of targets of different thicknesses with the same electron energy were also performed for target optimization. Neutron fluence-to-dose equivalent conversion factors advised in NCRP Rep. No. 79 [2] and photon fluence-to-dose conversion factors advised in MCNP4C [6] were used in this work.

2.1. Targets of the same material with different incident electron energy values

The 15 MeV electron beam hits the tungsten target perpendicularly, as shown in Fig. 1. Some of the electromagnetic energy is deposited in the target and the bremsstrahlung produced by primary and secondary electrons penetrated through the target. Fig. 2 shows that the bremsstrahlung spectrum changes with the energy of the incident electrons. More photons are contributed to the portion of low energy for 9 or 10 MeV incident electron beam than for ones 15 MeV and above. Still, photons with energy values above the tungsten photoneutron reaction threshold produce neutrons isotropically, as shown in Fig. 3.

For a continuous particle spectrum, the average energy can be calculated according to the following formula:

$$\overline{E} = \frac{\int E\phi(E)\,\mathrm{d}E}{\int \phi(E)\,\mathrm{d}E}, \tag{1}$$

where E is the particle energy, $\overline{E}$ is the average energy of the particles and $\phi(E)$ is the particle differential spectrum. If for a series of discrete energies E_i, and particle fluences $\phi(E_i)$ in the energy range $E_i < E < E_i + \Delta E_i$, the average energy $\overline{E}$ is given as follows:

$$\overline{E} = \frac{\sum_{i=1}^{n}\phi(E_i)E_i\Delta E_i}{\sum_{i=1}^{n}\phi(E_i)\Delta E_i}. \tag{2}$$

During the simulation, for photons, ΔE_i is invariably set to 0.2 MeV, while for neutrons, the energy group structure of the 72-neutron groups ENEA data set is adopted [5]. According to the

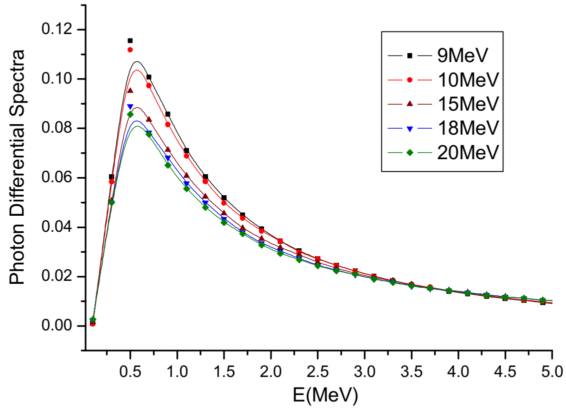

Fig. 2. Bremsstrahlung spectra at the isocenter.

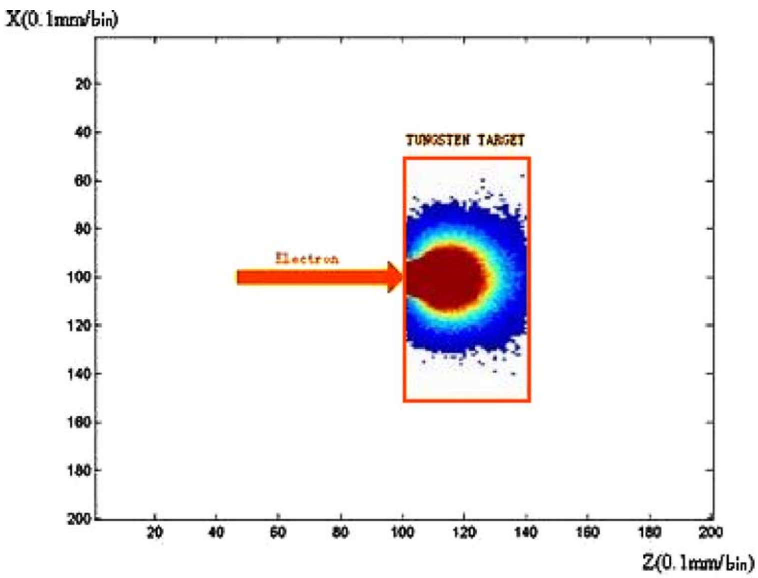

Fig. 1. Electromagnetic energy deposited in a 4 mm-thick tungsten target hit by a 15 MeV electron beam.

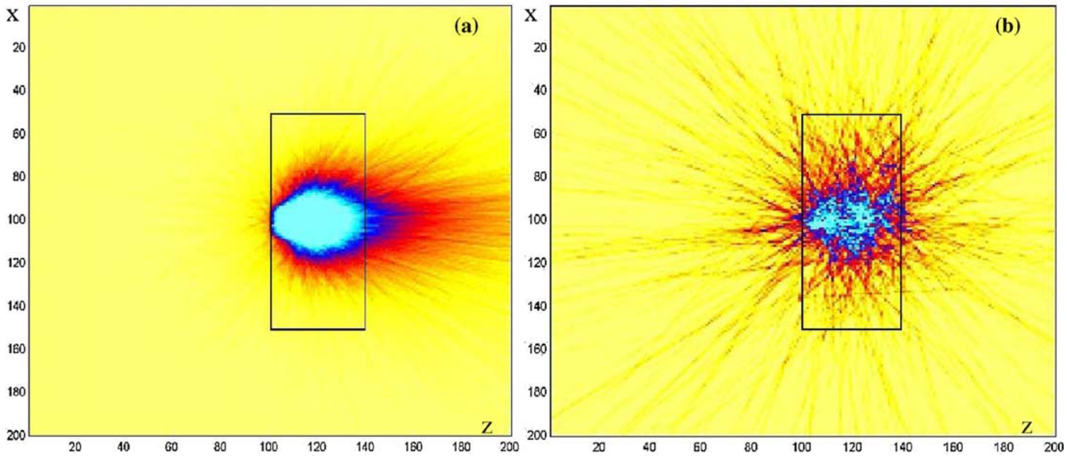

Fig. 3. Particle fluence distribution in a 4 mm-thick tungsten target (2 cm × 2 cm, 0.1 mm/bin). (a) Photon fluence distribution; (b) neutron fluence distribution.

simulation, the photon and neutron average energies at the isocenter for different incident electron beam energies are listed in Table 1.

For an electron beam of energy below 20 MeV, the photoneutron average energy is less than 1 MeV, as shown in Table 1. Other works [8–10] also reported similar results, which are much smaller than the one indicated in NCRP Rep. No. 79. In the old theoretical analysis of photoneutron average energy, the production of photoneutrons was easy to take into account, but the transport, moderation and absorption of neutrons were difficult to analyze in detail; thus low energy neutrons were not considered sufficiently in the neutron spectrum. Modern computer technologies with appropriate biasing methods compensate for the low efficiency of Monte Carlo methods for simulating large numbers of particles. For the same number of particle histories, CPU time will be more than 100 times shorter than 20 years ago. So these results are closer to the experiment data (Fig. 4).

Table 1
Secondary particle average energy for a 4 mm-thick tungsten target

Incident electron beam energy (MeV)	9	10	15	18	20
Average photon energy (MeV)	2.07	2.25	2.98	3.48	3.72
Average neutron energy (MeV)	0.401	0.445	0.713	0.776	0.798

The simulated target thickness was 4 mm, about 1.143 radiation length of tungsten. At the isocenter (1 m away from the target along the beam direction), the photon dose and the neutron dose increased with the energy, as shown in Table 2. The photoneutron dose equivalent ratios for comparison with corresponding experiment data of Varian Clinacs are also given for different incident electron energy values. It was estimated that the neutron dose contributed by the target will be 70% of the total neutron dose. The neutron yield per source electron increased rapidly at the giant resonance (12 MeV ~ 18 MeV for ^{184}W (γ, xn) [2]), as shown in Fig. 5.

2.2. Targets of the same material with different thicknesses

More neutrons will be produced with increasing target thickness when source electrons exceed the threshold energy of the target material. For 15 MeV incident electrons and tungsten targets of different thicknesses (now being used in some accelerators for industrial and clinic CTs), neutron yields per source electron and neutron spectra are given in Figs. 6 and 7.

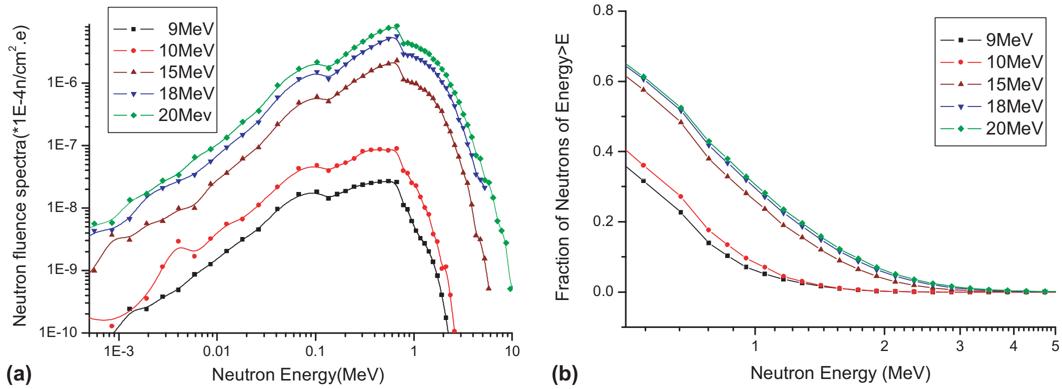

Fig. 4. Neutron fluence spectra and integral spectra at the isocenter.

Table 2
Neutron dose equivalent ratio at the isocenter, compared with cited experimental data

E (MeV)	Photon dose (Gy/e)	Neutron dose (mSv/e)	Neutron DER (mSv/Gy X-ray) This work	Neutron DER (mSv/Gy X-ray) Varian rep. [7]
9	8.54E−16	5.37E−18	0.006	–
10	1.16E−15	1.82E−17	0.016	0.02
15	3.74E−15	5.50E−16	0.147	0.17
18	6.35E−15	1.46E−15	0.231	0.31
20	8.39E−15	2.19E−15	0.261	–

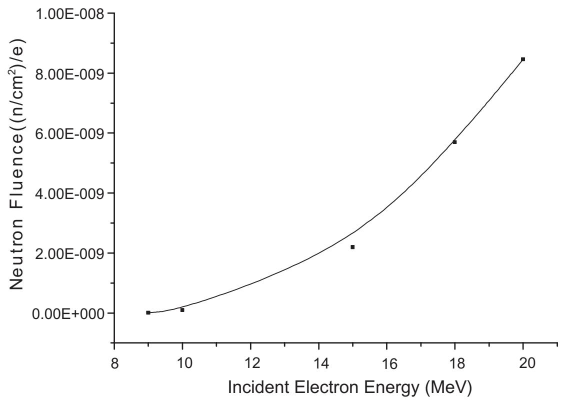

Fig. 5. Neutron fluence (per source electron) at the isocenter from 4 mm tungsten slabs bombarded by electron beams of different energy values.

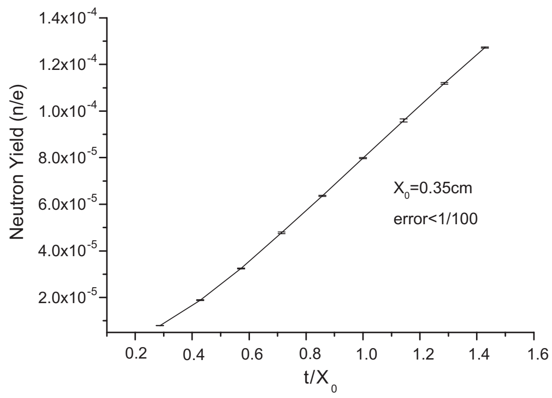

Fig. 6. Neutron yields (per source electron) for tungsten targets of different thicknesses.

As a bremsstrahlung converter, the target should be optimized to achieve the maximum bremsstrahlung intensity and the minimum photoneutron production. So the photon dose and the neutron dose at the isocenter were calculated separately according to the corresponding spectrum and fluence-to-dose conversion factors, as shown in Fig. 8. The photon dose declined when the tungsten target thickness was over 1/3 radiation length, while the neutron dose increased gradually and reached saturation. As the quotient of the former

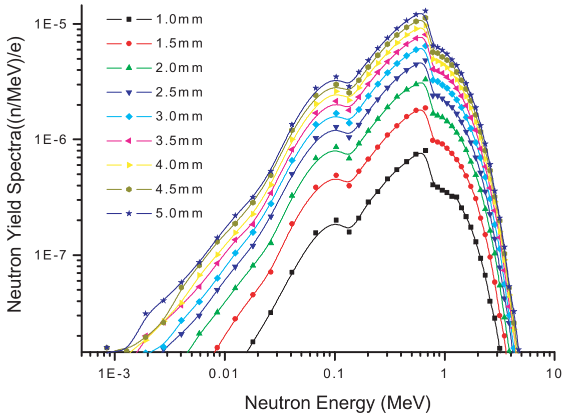

Fig. 7. Neutron yield spectra (per source electron) from tungsten targets of different thicknesses.

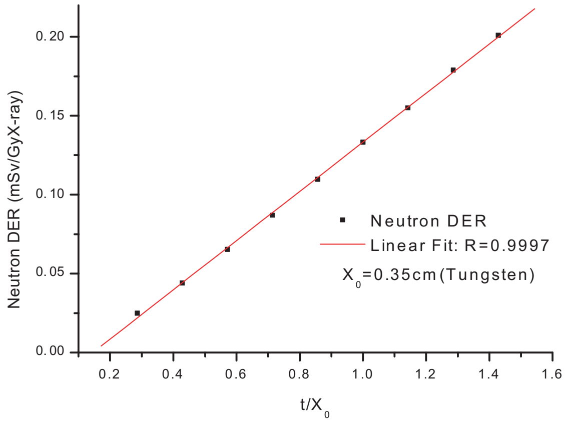

Fig. 9. Neutron dose equivalent ratio at the isocenter for tungsten targets of different thicknesses.

two quantities, the neutron DER (dose equivalent ratio) at the isocenter appeared to increase proportionally to the target thickness, as shown in Fig. 9. To ensure minimal electron leakage, the target should be thick enough to stop most electrons or an absorber made of light material should be added after the converter.

2.3. Targets of different materials with incident electron energy of 15 MeV

For 15 MeV incident electron beams, the bremsstrahlung spectrum varied with the atomic numbers of the targets, as shown in Fig. 10. Photon average energy increased with Z. Radiation length decreases with Z, so if the target thickness was 4 mm, the photon dose could not reach the

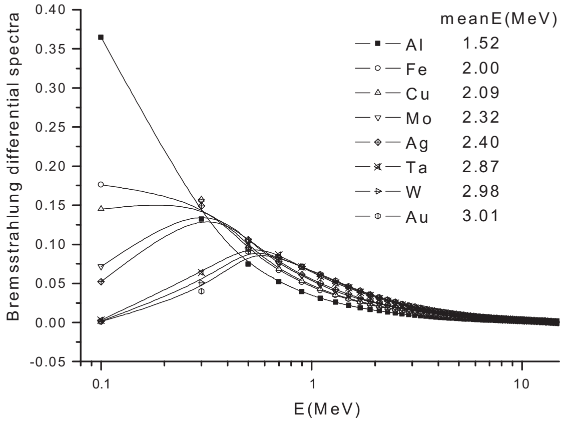

Fig. 10. Bremsstrahlung spectra and photon average energy at the isocenter, for the targets of different materials with the same thickness $t = 4$ mm (15 MeV incident electron beam).

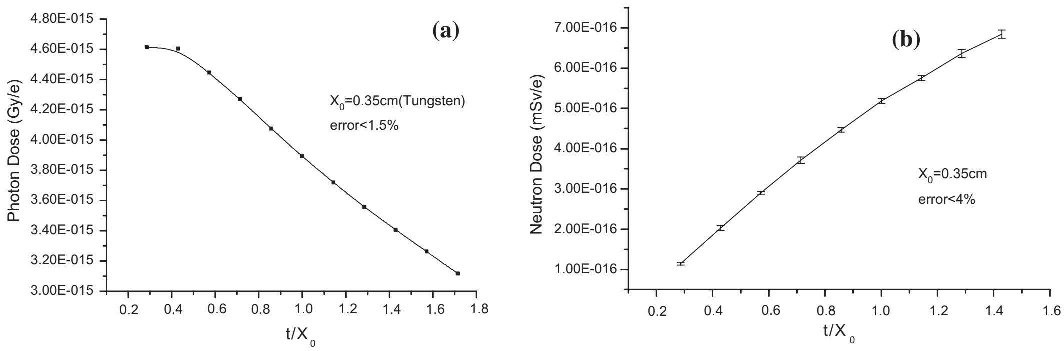

Fig. 8. Photon doses (a) and neutron doses (b) at the isocenter for tungsten targets of different thicknesses (per source electron).

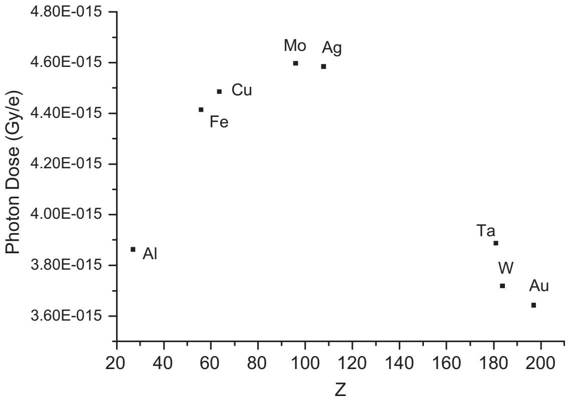

Fig. 11. Photon dose (per source electron) at the isocenter, for targets of different materials with the same thickness $t = 4$ mm (15 MeV incident electron beam).

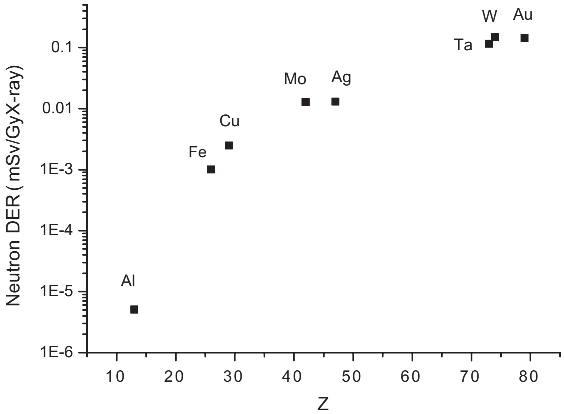

Fig. 13. Neutron dose equivalent ratio at the isocenter for targets of different materials with the same thickness $t = 4$ mm (15 MeV incident electron beam).

maximum for some light materials, while more photons were attenuated in the target for heavy materials, as shown in Fig. 11. Materials of medium atomic numbers, such as copper and molybdenum, resulted in better bremsstrahlung production.

Photoneutrons produced in targets of different materials increased generally with the atomic number, as shown in Fig. 12. Neutron average energies were all below 1 MeV, as shown in the neutron integral spectra. Fig. 13 shows the neutron DER for different materials of the same thickness. Targets of high Z materials had a much higher neutron DER than low Z materials.

Considering the different radiation lengths of different materials, a series of calculations for commonly used materials (copper, tantalum, tungsten and gold) were performed for better comparison. It was found that to reduce the electron leakage to about 1.0%, a copper target thickness t of 0.6 radiation length was required, and for the other three materials, a thickness of 0.9 radiation length was necessary, as shown in Fig. 14. At the isocenter, the photon doses due to the four materials were of the same order ($\sim 10^{-15}$ Gy/e), while the photoneutron yields of copper targets were one order of magnitude smaller than the other three materials, and so were neutron dose equivalent

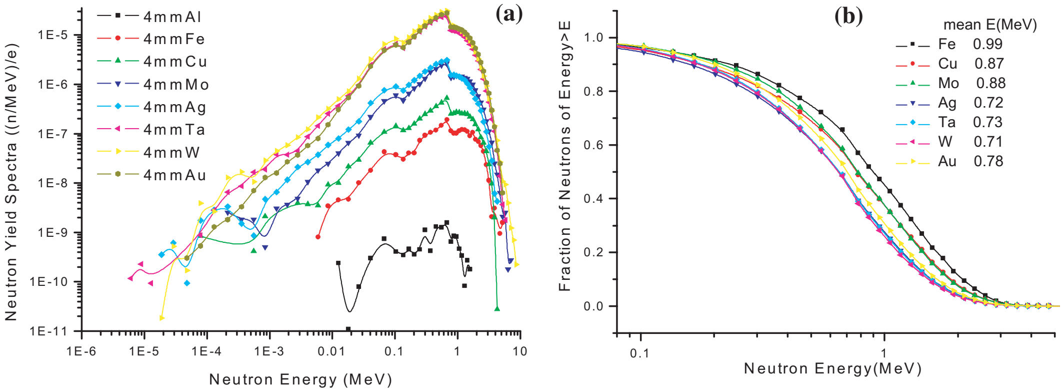

Fig. 12. Neutron fluence spectra (a) and integral spectra (b) from the target, for targets of different materials with the same thickness (15 MeV incident electron beam).

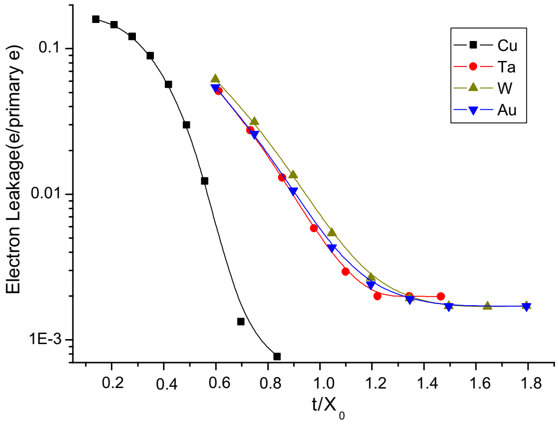

Fig. 14. Electron leakage from targets of different materials (15 MeV incident electron beam).

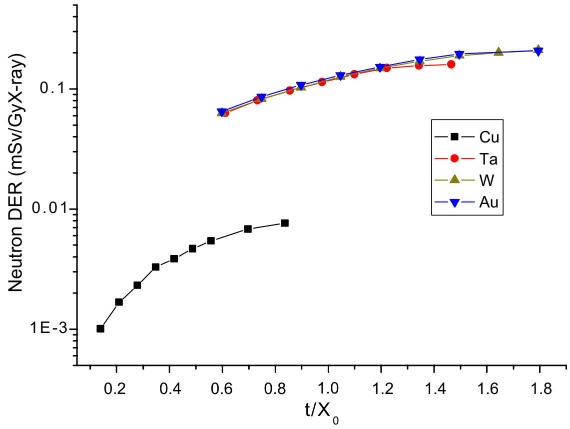

Fig. 16. Neutron dose equivalent ratios at the isocenter for targets of different materials and thicknesses.

ratios, as shown in Figs. 15 and 16. A summary of electron leakage, photon dose and neutron dose equivalent at the isocenter is shown in Table 3. According to these figures, medium Z materials with adequate bremsstrahlung production and lower photoneutron contamination are good choices for the design of targets used in high energy accelerators. In addition, the heat elimination factor of copper (4.01 W/cmK) is higher than the other three materials (0.575 W/cmK for Ta,

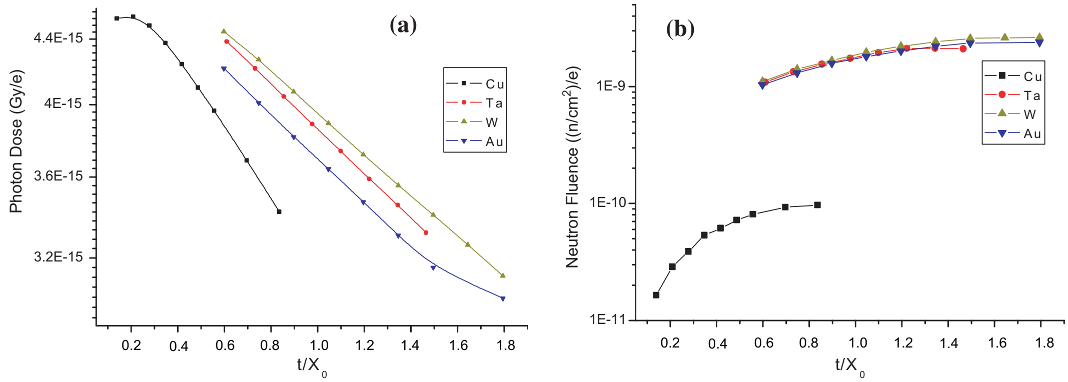

Fig. 15. Photon dose (a) and neutron fluence (b) at the isocenter for targets of different materials and different thicknesses t (per source electron (15 MeV)).

Table 3
Comparison of radiation length, electron leakage, photon dose and neutron dose equivalent at the isocenter for targets of different materials

Target material	Radiation length X_0 (cm)	t (cm)	t/X_0	Electron leakage (e/primary e)	Photon dose at the isocenter (Gy/e)	Neutron DER at the isocenter (mSv/GyX-ray)
Cu	1.436	0.8	0.5571	0.01234	3.964E−15	0.0054
Ta	0.4094	0.35	0.8549	0.01306	4.046E−15	0.0969
W	0.3507	0.3	0.8554	0.01347	4.075E−15	0.1025
Au	0.3344	0.3	0.8971	0.01062	4.009E−15	0.0862

1.74 W/cmK for W and 3.17 W/cmK for Au). Therefore, copper targets have excellent heat exchange properties.

3. Conclusion

In this work, calculations using the Monte Carlo code FLUKA were performed for different energy electron beams bombarding targets of different materials to study the photoneutron spectra and the neutron dose equivalent at the isocenter. The results indicate that the photoneutron production increases with the incident electron energy and target thickness, and medium atomic number materials such as copper appear to be a good choice for sufficient photon production and lower neutron contamination.

For a 9, 10, 15, 18, 20 MeV electron beam, the neutron dose equivalent ratio, contributed by the target only, is 0.006, 0.016, 0.147, 0.231, 0.261 mSv/Gy X-ray, and the average neutron energy is 0.401, 0.445, 0.713, 0.776 and 0.798 MeV, respectively, with a tungsten target thickness of 4 mm. Compared with the corresponding published experimental results, neutron DERs are of the same order and the average neutron energy is below 1.0 MeV, which is different from that reported in NCRP Rep. No. 79. For instance, for a 15 MeV electron beam, a copper target, with a thickness of 0.557 radiation length to prevent electron leakage, has a neutron DER one order of magnitude smaller than those of optimized targets of other materials, and therefore is a better choice of target material.

References

[1] P. Ni, X. Li, Industrial CT Technique(VI), NDT 18 (6) (1996).
[2] NCRP Report 79, Neutron contamination from medical accelerators, 1984.
[3] Y.G. Teterev, A.G. Belov, Induced activity of a tungsten target in a 10 MeV electron accelerator, Atomic Energy 91 (3) (2001) 745.
[4] D.S. Followill, M.S. Stovall, S.F. Kry, G.S. Ibbott, Neutron source strength measurements for Varian, Siemens, Elekta and General Electric Linear Accelerators, J. Appl. Clin. Med. Phys. 4 (2003) 189.
[5] FLUKA: A. Fasso, A. Ferrari, J. Ranft, P.R. SalaProceedings of Monte Carlo 2000, Lisbon, 23–26 October 2000, Springer, Berlin, 2001, p. 159 and 955.
[6] MCNP: MCNP – A general Monte Carlo N-particle transport code, LosAlamos Report LA-UR-03-1987, 2003.
[7] P.H. McGinley, J.C. Landry, Neutron contamination of X-ray beams produced by the Varian clinac 1800, Phys. Med. Biol. 34 (6) (1989) 777.
[8] J.R. Bading, L. Zeitz, Phosphorus activation neutron dosimetry and its application to an 18-MV radiotherapy accelerator, Med. Phys. 9 (6) (1982) 835.
[9] P. Kliauga, H. Amols, Photoneutrons from high energy medical linear accelerators: measurement of the spectrum and dose using a miniature proportional counter, Int. J. Radiat. Oncol. Biol. Phys. 31 (3) (1995) 629.
[10] O. Chibani, C. Ma, Photonuclear dose calculations for high-energy photon beams from Siemens and Varian linacs, Med. Phys. 30 (8) (2003) 1990.