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Original Article

Determination of Tungsten Target Parameters for Transmission X-ray Tube: A Simulation Study Using Geant4

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ABSTRACT

Transmission X-ray tubes based on carbon nanotube have attracted significant attention recently. In most of these tubes, tungsten is used as the target material. In this article, the well-known simulator *Geant4* was used to obtain some of the tungsten target parameters. The optimal thickness for maximum production of usable X-rays when the target is exposed to electron beams of different energies was obtained. The linear variation of optimal thickness of the target for different electron energies was also obtained. The data obtained in this study can be used to design X-ray tubes. A beryllium window was considered for the X-ray tube. The X-ray energy spectra at the moment of production and after passing through the target and window for different electron energies in the 30–110 keV range were also obtained. The results obtained show that with a specific thickness, the target material itself can act as filter, which enables generation of X-rays with a limited energy.

1. Introduction

Because of its properties such as high atomic number and high melting point (3,422 °C), tungsten is used as the target material in X-ray tubes [1]. Recently, new technologies utilizing pyroelectric crystals [2] or carbon nanotubes (CNTs) [3–5] as electron emitters have been developed to produce X-rays. In the CNT method, electrons are emitted from a CNT when it is under an electric field [6]. This is a function carried out by filaments when they get warm. In X-ray tubes with old technology (of course nowadays, most X-ray tubes are of this kind), a heated filament is used to emit electrons and posteriorly produce X-rays. A warm-up time is needed for the filament to get hot and start emitting electrons. After collision with the target material, these emitted electrons produce X photons. As always, the X-rays are produced by a mechanism called the "bremsstrahlung phenomenon" and using characteristic X-rays (i.e., X-rays with specific energies) [7]. One advantage of the new technology utilizing CNT is that there is no warm-up time. In addition, warming filaments evaporate

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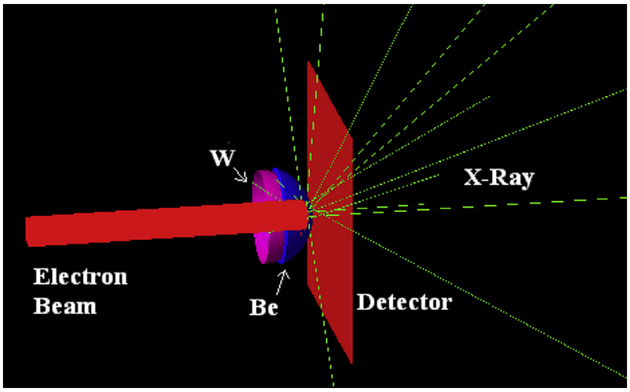

Fig. 1 – Virtual experiment setup.

and are destroyed over time but this will not happen in the CNT method. Therefore, compared with the filament kind, the working life of this kind of X-ray tube lasts longer. CNTs vary in stability and reliability because of the way they are made. There are different methods for making CNTs, with each having its own advantages and disadvantages [8]. Another advantage of CNT technology worth mentioning is its small size, because X-ray tubes made with CNTs are just a few centimeters long [9]. It is well-known that in X-ray tubes, heat is produced due to the collision of electrons on the target material. This can, however, cause many problems, especially when using small tubes. One of the solutions proposed to solve this issue is to use a transmission target instead of a reflective target, however, a reflective target is more efficient than a transmission target in producing X-rays. In addition, the angle of produced X-ray especially for low energies electron beam recommends the use of reflective target. Because of the technological reasons and problems related to the overheating of the target material, the transmission target is a better and a more suitable option [10]. In a transmission target, the amount of X-rays produced will increase with increasing thickness of the targets. It is obvious that, by increasing the thickness, the amount of self-absorption will also increase. Therefore, there is an optimal thickness that can produce the maximum amount of usable X photons. The optimal thickness of a tungsten target for different electron beam energies is obtained in this work. This is done using the well-known *Geant4* simulator code. The Geant4 code has a strong data library and its different models, such as the *Penelope* model, enable one to perform precise Monte Carlo calculations in the range of low electromagnetic energy [11]. Various samples for simulation of the bremsstrahlung phenomenon are available in the *Geant4* standard and low-energy electromagnetic packages. The electromagnetic package [12] consists of two processes for the simulation of electron bremsstrahlung. Geant4 is an object-oriented program, which takes advantage of several classes. For example, the *G4lowenergyBremsstrahlung* class [13], which is based on the Evaluated Electron Data Library [14], is used in the Livermore library for the estimation of cross-sections [15]. The *G4Penelope-Bremsstrahlung* class, which is based on the physics samples [16], was initially developed for the Penelope Monte Carlo model.

2. Virtual Experiment

In this virtual experiment setup, tungsten was chosen as the target material. Because the thickness of the target material is very low in transmission X-ray tubes, the target should be coated onto another material that can play the role of window. The material generally used for this purpose is beryllium. Therefore, different thicknesses of tungsten on a 1-mm layer of beryllium was used. Hemisphere geometry with a diameter of 5 mm was used for both materials. Fig. 1 shows the virtual experiment layout. Electron beams (intensity 10^7 electrons with 1-mm^2 cross-section) with different energies of 30 keV, 50 keV, 70 keV, 90 keV, and 110 keV are fired from a distance of 5 cm to the inner layer of the hemisphere.

The experiment shows that the largest numbers of usable X photons (especially, the ones that exit forward from the beryllium window in the same direction of electron beam) are produced for different electron energies in different thicknesses of the tungsten target. This is shown in Fig. 2.

Therefore, it seems that a linear equation like $Y = -1.45 + 0.075 \times X$ can be used to calculate the maximum output of X-rays versus the target thickness. In this equation, Y is the target material thickness (μm) and X is the energy of collided electrons (keV). The fitted linear equation is shown in Fig. 3.

It can be useful to know about the output X-ray spectra resulting from the hit of electrons on tungsten (target) at different electron energies especially after passing through the window layer. The X-ray spectra at the moment of production and after passing through the target and 1 mm of beryllium for 30 keV and 110 keV energies are shown in Figs. 4 and 5, respectively. If the energy for electrons is lower than 30 keV, characteristic X-rays do not have a significant role in spectra formation. However, with an increase of electron energy, characteristic X-rays present themselves as sharp peaks. This is shown in Fig. 5 by creating more peaks in the spectrum. Another finding from these figures is that, for a certain electron energy, the number of X-rays produced is only based on the specific target thickness. In other words, using a greater

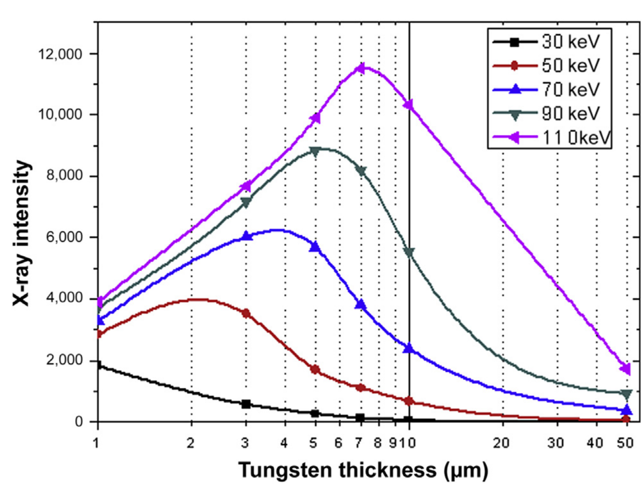

Fig. 2 – The number of output X-ray photons for different thicknesses of target material.

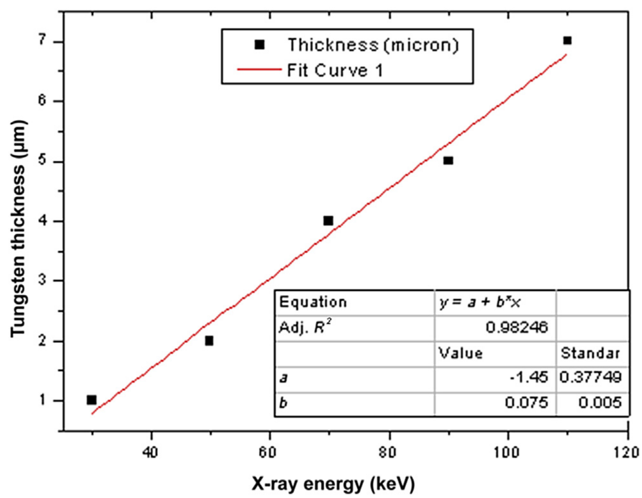

Fig. 3 – Maximum X-rays produced for different energies of electron beam have a linear ratio with the thickness of target material.

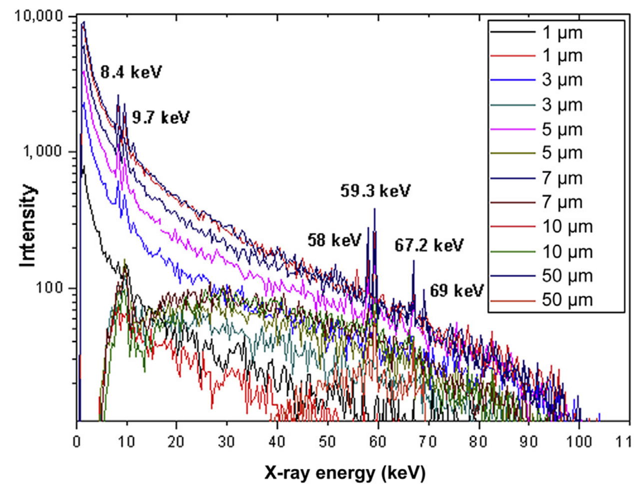

Fig. 5 – X-ray spectra for 110-keV electron energy at the moment of production and after passing through different thicknesses of tungsten target.

thickness for that material will not change the X-ray amount produced. Therefore, for a specific electron energy, one cannot increase the number of X-rays by increasing the thickness of the target material.

The output X-ray angular distribution can be of great importance in designing a tube. Electron beams at different energies caused the production of X-rays with different angular distributions, as shown in Fig. 6. According to this figure, with the increase of electron energy, X-ray angles become smaller in comparison with electron beam direction while exiting the window. Fig. 6 also shows that by increasing the electron energy, the output X-ray beam profile will become more focused or the X-ray tends to take a more focused state.

3. Conclusion

To design a transmission X-ray tube, it is necessary to determine the thickness of the target material. This article studied tungsten as a target material. The highest amounts of output X-rays are produced for different electron energies in different thicknesses of the target. The thickness has a linear ratio with the electron energy. The X-ray spectra produced are strongly dependent on the electron energy and the output X-ray spectra are strongly dependent on the thickness of the target material. Figs. 4 and 5 show the output spectra for different energies and thicknesses, and this information can be used to design tubes for different applications. In addition, at high electron energies more focused X-rays can be produced.

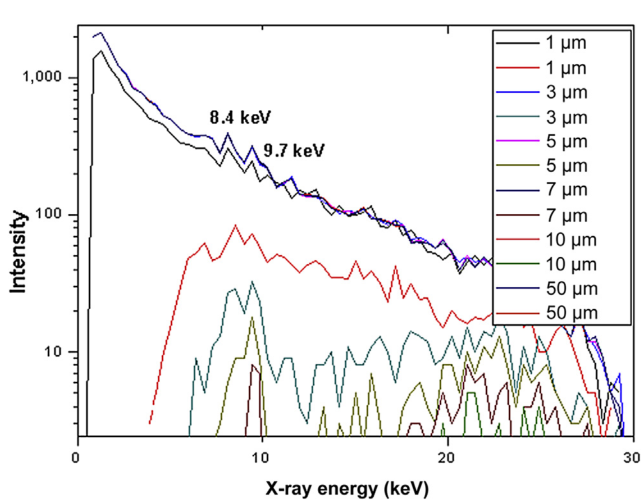

Fig. 4 – X-ray spectra for 30-keV electron energy at the moment of production and after passing through different thicknesses of tungsten target.

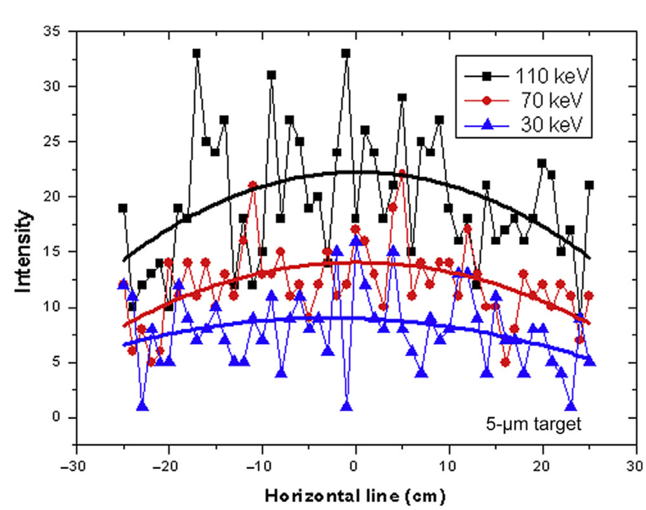

Fig. 6 – Angular distribution or beam profile of output X-rays for different electron energies.

Conflicts of interest

The author declares no conflicts of interest.

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