Thermal stability analysis of miniaturized targets for bracytherapy x-ray tubes

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1. Introduction

Conventional x-ray targets render relatively larger effective focal spot size when incident upon by electron beams. The increase in the effective focal spot size, which is also called as x-ray source size, is due to the broadening of the electron beam inside the target material and consequently image resolution is affected [1]. Transmission type targets which are composed of thin foil have been found very promising in minimizing the electron beam broadening [2]. The miniaturized x-ray targets, composed of micro-particles attached to a relatively thicker substrate, can cause further reduction in the effective x-ray source size. It is because of its lateral dimension of the miniaturized structure which minimizes the beam broadening to a further extent. By virtue of its micron-ordered geometric dimensions, an x-ray target composed of miniaturized structure would greatly suit to a super miniature x-ray tube to be used for brachytherapy or cancer therapy.

However, there are two associated concerns. First, the focusing of electron beam on such a small scaled dimension of the target is very difficult for an ultra-small sized x-ray tube. This issue can be resolved by irradiating the miniaturized target with a large sized electron beam. The useful portion of the beam would be that which strikes the target and the rest of the beam would be dumped into the bulk of the substrate material. The second concern is however much serious from the real engineering viewpoint. It is about the thermal stability of the miniaturized target and the associated substrate irradiated by large sized electron beam. Irradiation of miniaturized target by large sized electron beam can cause melting [3]. For stable operation of an x-ray tube, the integrity of target should always be maintained. Here in this research work, we have carried out a thermal stability analysis of miniaturized target and the associated substrate.

2. Methods and Results

In this section the specifications of the geometry of miniaturized target and the simulation models used for the analysis are described. The results of the analysis have also been enclosed.

2.1 Geometry Description

The x-ray target is composed of a micro-particle attached to a thicker substrate. Various morphologies of micro-structured particles, with their dimensions of the order of a few microns, have been analyzed. Molybdenum has been used as the material of miniaturized target in the analysis, whereas the energy of electron beam is taken as 50 keV. Since a large portion of electron beam is to be dumped in the substrate assembly, a substrate with a low Z number such as Beryllium is preferred to minimize the bremsstrahlung production inside the substrate. The results of thermal stability analysis for a miniaturized target with conical geometry have been shown in the later sections. Fig. 1 shows a brief description of the basic simulation model.

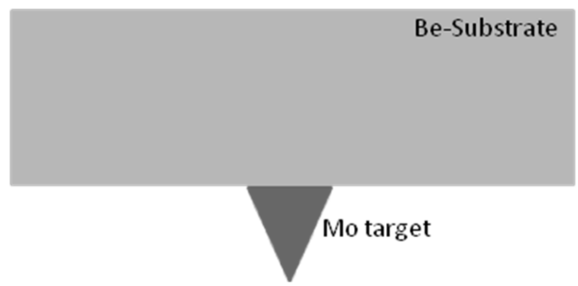

Fig. 1. Schematic of the basic simulation model.

2.2 Calculation and Simulation Methods

Following the irradiation of large sized electron beam, huge amount of thermal energy is imparted to the miniaturized target and the substrate. For stable operation, the maximum electron beam current should be defined such that the melting of target/substrate assembly would never take place and hence the target integrity remains intact. Therefore, thermal stability analysis of the assembly is performed. In order to perform thermal stability analysis, it is important to know the distribution of the imparted energy inside the target and substrate. Monte Carlo simulation code MCNPX [4] has been used to determine the distribution of the imparted energy in target/substrate following the irradiation by electron beam. This energy distribution is input to COMSOL Multiphysics [5] in order to carry out finite element analysis to calculate the temperature profiles both for steady state operation and under transient conditions.

2.3 Thermal Stability Analysis – Steady-state Condition

Based on the power loading as described in previous section, temperature profile within the miniaturized target and substrate was calculated using COMSOL Multiphysics. These simulations were performed for axial symmetric 2-D geometry. For the simulation, it was assumed that an electron beam with a beam size of 1 mm is incident upon the target/substrate assembly. The substrate thickness was 500 μm. The temperature of the circular peripheral region and the backside of substrate were assumed to be maintained at 300 K. Only conduction heat transfer was taken into account.

According to these calculations, quite interestingly, it is found that melting takes place in the Be substrate and not in the Mo miniaturized target. The maximum beam current which the target/substrate assembly can withstand without melting was calculated as 13.5 mA. An axial-symmetric temperature profile of the target part is shown in Fig. 2. Although the total beam current is very high, but the useful current which is responsible for x-ray production, also termed as target current, is however very small and consequently x-ray brightness would be significantly minimized.

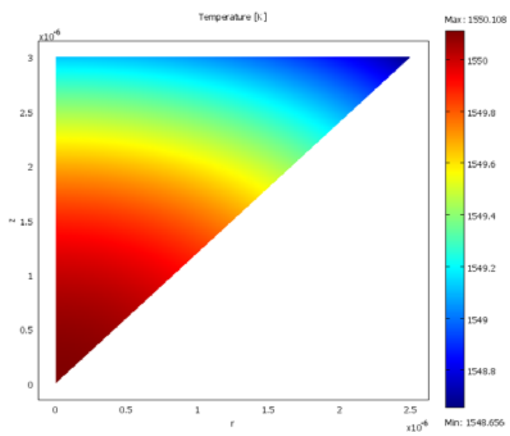

Fig. 2. Axial-symmetric temperature profile of the conical target portion.

2.4 Thermal Stability Analysis – Transient Conditions

Since the target current remains very low under steady-state operation, an alternate approach to enhance the x-ray brightness can be pulsed operation. Under pulsed operation, the electron irradiation is initiated momentarily and is switched off after a specified time period. Thermal stability analysis was performed under transient conditions with the same boundary conditions and beam parameters as described in the previous subsection. The maximum current which the target can sustain without being melted is calculated with pulses of different durations. The result of the analysis is indicated in Table 1.

Pulse Duration	Max. Beam Current
5 ms	13.5 mA
2 ms	15.5 mA
1 ms	19.0 mA
10 μs	0.4 A
5 μs	0.8 A
2 μs	1.8 A
1 μs	3.4 A

Table 1: Maximum beam current (transient mode).

According to the results of transient operation, the beam current is greatly increased without target damage. Again the maximum beam current is limited by the melting temperature of Be. The maximum temperature of the Mo miniaturized target remains below 1570 K which is much lesser than its melting point. The variation in the maximum beryllium temperature as a function of time (for 1 μs pulse) is shown in Fig. 3.

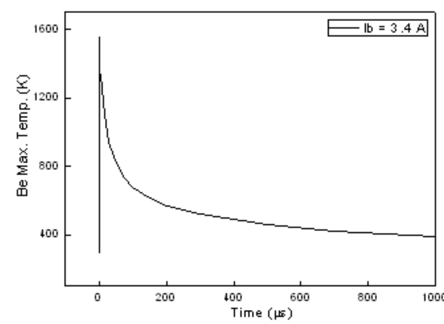

Fig. 3. Max. Be temperature as a function of time in μs.

3. Conclusions

Miniaturized target geometries composed of particles with micron order dimensions can effectively be utilized as targets for super miniature x-ray tubes. These geometries, by virtue of their dimensions can efficiently be used for bracytherapy and cancer therapy x-ray tubes. Miniaturized structures can not only limit the electron beam broadening as well as they can also be loaded with excessively high beam currents under pulsed operations.

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