BREMSSTRAHLUNG CONVERTER FOR HIGH POWER EB RADIATION PROCESSING FACILITY

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Abstract

A radiation processing facility based on 10 kW Linac is being set up at RRCAT for radiation processing of food products and sterilization of medical items. The facility is planned to operate in electron (10 MeV) and X-ray (5 & 7.5 MeV) mode. The required X-rays will be generated by bombarding an optimized target with 5 or 7.5 MeV electron beam. The composite target is made of Ta, water & SS. Monte Carlo simulation with MCNP has been performed to optimize the design of the target for maximizing the X-ray output. Characteristics of the emerging X-ray field e.g. photon energy spectrum, angular distribution, radial dose and depth dose distribution in unit density material have been simulated & compared for 5 & 7.5 MeV. Our simulation results show that for optimized design, the fraction of the energy transmitted and useful for radiation processing at 5 & 7.5 MeV is 9.3% & 14.2 % respectively. The most probable energy of the photons is 0.3 MeV for both 5 and 7.5 MeV electrons and the average energy is 0.84 MeV & 1.24 MeV respectively. Large fraction of electron beam power is dissipated as heat in the targets. Necessary data has been generated to carry out thermal design.

INTRODUCTION

Four types of ionizing energy have been approved by regulatory authorities for radiation processing of food products. These are gamma rays from Co-60 and Cs-137, electrons with energy up to 10 MeV and X-rays with energies up to 5 MeV. FDA has recently approved use of X-rays generated by 7.5 MeV electron beam for food processing (*Federal Register 2004).* The selection of the energy source for a particular application is usually based on practical considerations like product shape, size, density, average dose requirement, dose uniformity ratio, processing rate and cost. Treatment with direct electron beam provides the highest processing rate and the lowest unit cost but electron has relatively short range. X-rays have higher penetration quality and hence permits the treatment of dense objects in large packages.

TARGET MATERIAL

X-rays are produced when energetic electrons strike any target material. The intensity and efficiency of X-ray conversion increase with the energy of incident electron and the atomic no of the target material. In order to maximize the X-ray output, Ta, W, Au are the suitable choice for the target material. Tungsten has high brittleness, hence difficult for machining and fabrication, while Au is not cost effective, so both are not considered for target material. Tantalum is the suitable choice as a compromise between photon yield, residual radioactivity, physical properties, mechanical properties and fabrication simplicity for commercial environment. At 5 MeV no activation will arise from the Ta target as the threshold energy level for two common isotopes of tantalum (Ta-180 and Ta –181) are 6.6 and 7.6 MeV respectively. When operated at 7.5 MeV i.e. above the threshold for γ-n reaction in target material, two radio nuclide Ta^{180} and Ta^{182} are formed respectively by (γ-n) and (n-γ) reaction on naturally abundant Ta^{181}. The former has half-life of 8.1 h mostly β emitter, and the latter has half-life of 114 days emitting γ of 1.2 MeV. Also, the order of saturation dose rate (due to the induced activity) measured immediately after the shut down of the accelerator is reported about 1 mGy/h for Ta target at 7.5 MeV (*J. Mckeeown et.al, 1998*). Extensive study have been performed to investigate the induced activity in the irradiated product and concluded that the amount of induced activity created by 7.5 MeV X-rays in food product is negligible small. The IAEA report *(IAEA-TECDOC-1287*) says that the possible radiation exposure from induced radioactivity to human, consuming 40 kg/yr of beef irradiated by 7.5 MeV beam on Ta target for a dose of 30 kGy (a dose more than 6 times the maximum permitted dose level of 4.5 kGy) is 300 times less than the yearly dose due to the natural activity present in the food. Keeping these points in view Ta is suitable & acceptable for X-ray converter at 7.5 MeV. In order to make cooling channel SS is suitable as the threshold energy for γ-n reaction in Fe, Ni the major constuient of SS is more than 10 MeV.

TARGET GEOMETRY

To obtain the basic data for the study, multi-layered composite target geometry is considered (see Figure 1). The shape of target for simplicity is cylindrical (radius 5 cm) and is made of three layers, tantalum, water, and stainless steel. Tantalum is used to generate the bremsstrahlung radiation from incident electron beam, while water is used to remove the heat deposited on the tantalum. The SS is used to make the water channel and stop the unwanted electron contamination coming out with the bremsstrahlung radiation. The thickness of tantalum is varied in the range 0-20 mm while the thickness of water channel and SS; each, is taken judiciously 2 mm (for both 5 MeV and 7.5 MeV). A water phantom of size 40 cm x 40 cm x 40 cm, placed 10 cm away from target, is simulate to study the dose profile in unit density material.

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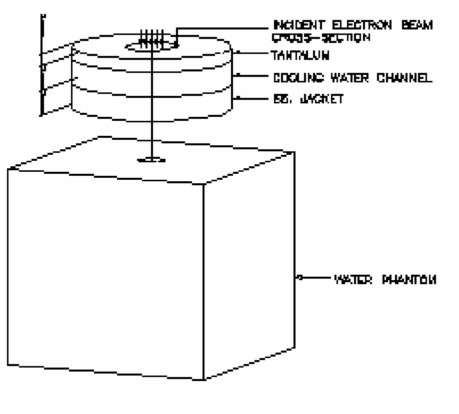

Figure 1. Target Geometry

METHOD OF CALCULATION

Three-dimensional photon and electron transport calculation is performed with MCNP. The MCNP uses continuous energy nuclear and atomic data libraries. The data in the photon/electron cross-section tables allow MCNP to account for coherent and in-coherent scattering, photoelectric absorption with the possibility of fluorescent emission and pair production.

The incident electron beam is taken to have a circular cross-section of diameter 25-mm ($\pm 2\sigma$) and is considered to fall normally on the target surface. The distribution of electrons in side the beam is taken Gaussian with mean at $r = 0$ and $\sigma = 6.25$. For electron sampling from 25-mm dia surface, the total surface is divided into 7 circular regions of radius 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, and 12.5 mm. The sampling from different region is done to meet the requirement of Gaussian distribution. The probability of electron sampling from first region (i.e. encircled by 2mm-radius circle) is taken 0.251. For the successive annular region sampling probability is taken as 0.226, 0.185, 0.136, 0.091, 0.054, 0.029 respectively. The initial number of electron histories is taken 10^6, which reduces the statistical errors involved in the calculation below 2%. Contribution from electrons down to 10 keV and photons down to 20 keV has been included.

RESULTS AND DISCUSSION

Figure 2 shows the variation of the transmitted X-ray output with the Ta thickness. The optimum thickness of Ta for maximum bremsstrahlung yield at 5 MeV and 7.5 MeV is 0.9 and 1.4 mm respectively. As the thickness of Ta is increased beyond the optimum thickness the transmitted intensity decreases due to self-absorption in the target material. At 7.5 MeV the X-ray yield increases 50.3 % that of the yield achieved at 5 MeV. Useful data required for thermal analysis and throughput calculation are given in Table1 & Table 2. The cooling water and SS channel helps in reducing the electron contamination in the X-ray field by absorbing the low energy electrons (10% of incident energy) leaving the Ta target. The cooling water and the SS channel also absorb 5-8 % of the photon yield hence needs careful design consideration.

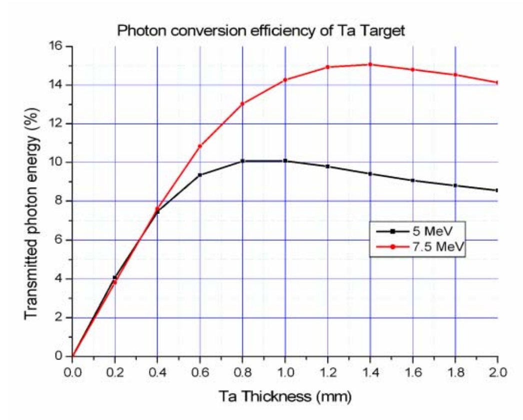

Figure 2. Transmitted X ray output as function of Tantalum thickness

Table 1. Data for 5 MeV electrons

Ta thick. (mm)	% of incident energy transmitted through various mediums in the form of photons				% of energy deposited in the Ta sheet
	Ta	Water	SS	10 cm air	
0.8	10.12	9.92	9.23	8.60	60.74
0.9	10.14	9.92	9.29	8.60	65.26
1.0	10.02	9.76	9.17	8.54	68.61
1.2	9.76	9.55	8.86	8.31	72.44
1.4	9.38	9.18	8.55	8.05	74.02

Table 2. Data for 7.5 MeV electrons

Ta thick ness (mm)	% of incident energy transmitted through various mediums in the form of photons				% of energy deposited in the Ta sheet
	Ta	Water	SS	10 cm air	
0.8	13.52	13.40	13.72	12.82	40.12
1.0	14.69	14.49	14.16	13.26	50.66
1.2	15.20	14.94	14.17	13.30	58.92
1.4	15.24	14.97	14.18	13.33	64.92
1.6	15.02	14.74	13.88	13.10	68.98
1.4*	15.24	15.08	13.07	12.38	65.05

The conversion efficiency calculated above with MCNP agrees within 5% with the calculation done with the Integrated TIGER Series of Coupled Electron/Photon Monte Carlo Transport Code [*J. Meissner et al*].

The photon energy spectra transmitted from the target is shown in figure 3. The total number of photon and proportion of high-energy photons increases with electron energy. The most probable energy for both spectrums is at 0.3 MeV and the average photon energy ($\Sigma\, n_i E_i/n_i$) for 5, 7.5 MeV is 0.84 and 1.14 MeV respectively. The angular dose distribution of the photon beam is shown in figure 4, which is forward peaked in the direction of electron beam and this effect becomes more pronounced as energy increase. FWHM for 5 and 7.5 MeV beam are 20° &13° respectively.

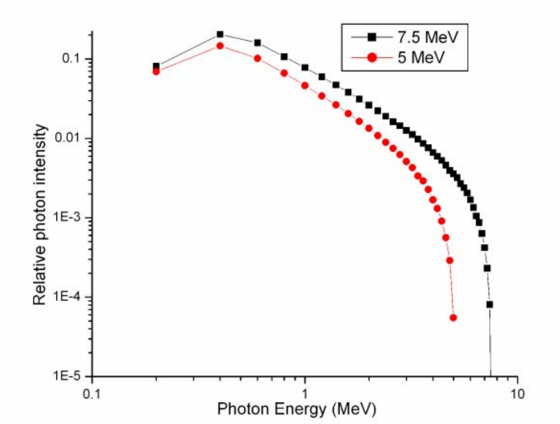

Figure 3. Spectrum of Photons Transmitted from optimised Ta Target

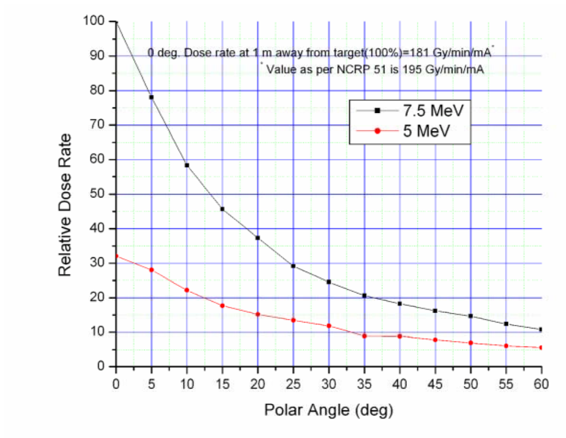

Figure 4. Angular dose distribution for 5 and 7.5 MeV X-rays

To calculate the radial dose distribution and depth dose distribution in product a water phantom of 30 cm x 30 cm x 30cm is simulated at 10 cm away from the target. Respective dose distributions are shown in figure 5 & 6. The depth dose fall rapidly in the initial part of the curve, which is due to the narrow beam geometry and soft energy x-ray components present in the beam. To improve the depth dose characteristics there is need to introduce some filter in the path of X-ray beam, which absorb the soft energy X-ray components and allow high energy component without much attenuation.

CONCLUSION

Tantalum is suitable target material to generate X-rays for radiation processing of food products. Optimum thickness of the Tantalum for 5 and 7.5 MeV beam is 1 mm and 1.4 mm corresponding to which the X-ray conversion efficiency is 10.1% and 15.2 % respectively. Analysis of photon spectrum shows that the most probable energy for both 5 and 7.5 MeV beam is 0.3 MeV and the average energy is 0.84 MeV and 1.24 MeV respectively. Due to the presence of low energy components surface dose to the products becomes severe, which cause poor dose uniformity ratio within the product. Hence to improve dose uniformity there is need to introduce a suitable filter, which absorb the low energy components from the X-ray field with least attenuation of high-energy components.

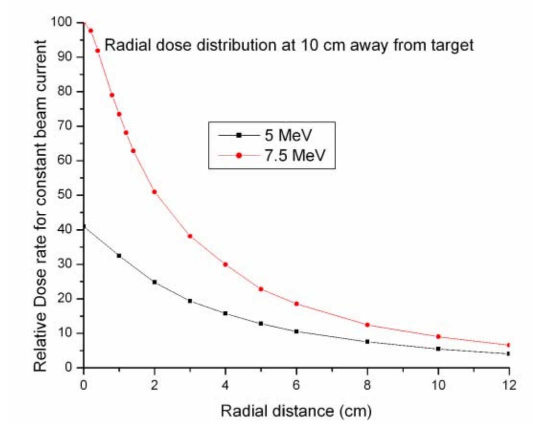

Figure 5. Radial dose distribution of 5 and 7.5 MeV X-rays

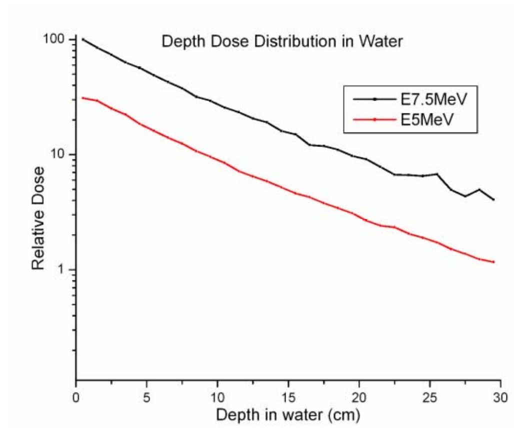

Figure 6. Depth dose distribution of 5 and 7.5 MeV X-rays in water

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[5] MCNP A General Purpose Monte Carlo N-Particle Transport Code. Los Alamos National Laboratory. Briesmeister JF.