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X-RAY DOSE RATE OF 6/4 MeV EUROPEAN S-BAND LINAC STRUCTURE FOR INDUSTRIAL APPLICATION AT RTX

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Abstract

Recently, Radiation Technology eXcellence (RTX) has been developing a 6/4 MeV European S-band (= 2998 MHz) industrial linear accelerator (linac) by using a magnetron with a low RF power of about 3 MW for Container Inspection System (CIS). Its accelerating structure is designed to operate in $\pi/2$ mode by coupling 8 accelerating cells together through 7 side-coupling cells. In CIS, high dose rate X-ray from MeV-energy electron beam has been used to detect the possible presence of contrabands in cargoes or truck containers. The X-ray dose rate output can be simulated by using FLUKA Monte Carlo simulation. The aim of this work is to study the effects of thickness of X-ray target on dose rate as well as X-ray dose map at 1.0 m away from the X-ray target. This study gives the thickness of the target in which the dose rate can be highest with the lowest electron beam current.

INTRODUCTION

With rapidly increasing terrorist threats around the world, many Container Inspection Systems (CISs) have been installed at airports and seaports. CISs require a high dose of high energy X-rays to deeply penetrate a loaded container for clear information about the contents of cargo [1]. After consideration on a recent development in reliable and compact linear accelerators (linacs), Radiation Technology eXcellence (RTX) has been developing a dual energy linac as MeV energy X-ray generator for CIS [2]. This linac can accelerate electrons to two different energies (4 MeV and 6 MeV). Then the accelerated electrons hit an X-ray target, and the electron energy is converted into 4 MeV and 6 MeV energy X-ray beams through Bremsstrahlung radiation. X-rays of two different energies interact with material differently, and it depends on the atomic number of material. With those physical property, we can distinguish the materials inside the container. To improve material discrimination and image quality of CIS, electron linacs have to reliably generate MeV energy X-rays with a stable and high dose rate for both energies.

Bremsstrahlung radiation is based on the Coulomb force interaction between electron beam and nucleus of the target. It is indicated that the intensity of Bremsstrahlung X-ray is related to the beam current, the target atomic number, and the target thickness. The beam current is limited by the electron gun output and RF power source of the linac. Moreover, the space charge force plays a big role in the high current during an operation with a low energy. Only the thickness and material of the target can be changeable to obtain the high intensity X-ray. Generally, tungsten is widely used for linac X-ray target because it is a high atomic number and a high melting point material, and tungsten target with different thickness has different X-ray conversion efficiency for certain incident electron energy [3]. By optimizing the target thickness, we can obtain a high dose rate from a low beam current.

In this study, two electron beam energies of 6/4 MeV European S-band linac developed by RTX are used to estimate X-ray dose rate output. To optimize the target thickness with the highest conversion efficiency for a different beam energy, a scanning thickness simulation in FLUKA Monte Carlo code is performed.

INCIDENT ELECTRON BEAM

The dual energy European S-band (= 2998 MHz) electron linac for CIS was developed by RTX in 2018. This linac uses a magnetron with the maximum RF power of 3 MW as an RF source. It is operated at the maximum repetition rate of 250 Hz for a pulse width of 4 µs. The electron beams from a DC gun are accelerated up to the energy of 4 MeV and 6 MeV in the standing wave side-coupled linac structure. Then the beams hit the tungsten target to generate the X-ray Bremsstrahlung with a dose rate of 5 Gy/min for 4 MeV beam and a dose rate of 9 Gy/min for 6 MeV beam at 1 m away from the target. The average kinetic energies of low energy (LE) and high energy (HE) modes are 4.18 Me and 6.14 MeV at the target with the rms energy spread of 0.91 MeV and 1.39 MeV, respectively. The output beam has a Gaussian distribution in a transverse profile with the full width half maximum (FWHM) of 0.785 mm. Some of those beam parameters are summarized in Table 1.

SIMULATION MODEL

FLUKA is a multipurpose Monte Carlo code to simulate the interaction and transport of 60 different particles in the matter [4]. Although FLUKA is a FORTRAN based simulation code, there is a user friendly graphical interface, called FLAIR to write input files, to run the code and to visualize output files in FLUKA [5]. The simple head geometry of 6/4 MeV European S-band linac is modelled in FLUKA. Figure 1 shows main components of linac head including a tungsten target, a collimator, and a detector. The tungsten

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Table 1: Incident Electron Beam Parameters

Parameters	LE mode	HE mode
Kinetic energy (MeV)	4.183	6.137
RMS energy spread (MeV)	0.91	1.39
Peak current (mA)	150	100
FWHM (mm)	0.785	0.785
Divergence (mrad)	0.93	0.53
Duty factor (%)	0.1	0.1
Normalized transverse emittance (µm)	11.2	14.1
Dose rate at 1 m (Gy/min)	5	9

target is a disk with a radius of 20 mm and adjustable thickness from 0.2 mm to 10 mm. The 0.3 m-long collimator is defined using lead in the simulation. A water detector with a volume of $0.3 \times 0.3 \times 0.01$ m^3 is defined at 1 m away from the target.

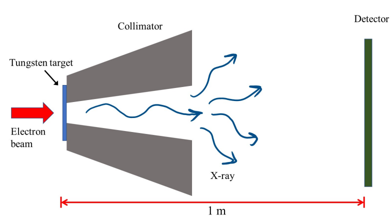

Figure 1: A simple simulation model in FLUKA.

In FLUKA, there are many types of interaction, transport, and energy threshold, called card, to be set in the physics and transport section of FLUKA input file. PRECISIO is used as a DEFAULTS card in FLUKA code. The production threshold energy of 50 keV for electron and 1 keV for photon are used by EMFCUT card. Moreover, the maximum energy loss per an electron step of 10% is set by EMFFIX card. The number of primary electrons for this study is set at 5×10^7 for 5 cycle simulations. With those primary electrons, the statistic error of the output is lower than 5%. To score the simulation output, the USRBIN and USRBDX cards are used. The USRBIN in FLUKA is used to calculate the energy stored in the region of interest. The USRBIN scoring output is given in GeV/cm^3 per an electron unit. To obtain the dose rate in Gy/min unit, the USRBIN results must be multiplied by $6 \times 10^7 I/\rho$, where I is the average beam current in µA unit and ρ is the density of detector in g/cm^3 unit. The USRBDX output supplies the energy distributions of the X-ray photon and electron particles, which pass through the surface of interest in unit of particle/cm^2 per an electron.

RESULTS

FLUKA simulation is performed for 4 MeV and 6 MeV electron energies with 18 different tungsten target thicknesses separately. For each simulation, the detector scores a dose rate, an X-ray energy distribution and an escaped electron rate per a surface area of 1 cm^2.

Target Thickness for Single Energy Operation

The dose rate of various target thicknesses from FLUKA simulation is shown in Fig. 2. It is found that a thinner target can generate a higher X-ray dose rate than a thicker one. It means that the thin target has a high X-ray conversion efficiency. With a high conversion efficiency of a thin target, it requires a low beam current to generate the designed dose rate. However, the target can't be too thin. Higher energy electrons can penetrate through the thinner target. Therefore, the X-ray Bremsstrahlung output will be contaminated with those escaping electrons. To avoid this contamination, the electron leakage ratio has to be considered. Figure 3 shows the electron energy leakage ratio for different target thicknesses. Generally, the electron energy leakage ratio per 1 cm^2 surface area should be lower than 0.005%. The results from Fig. 3 indicates that the electron leakage ratio can rapidly be reduced as the target thickness is increased.

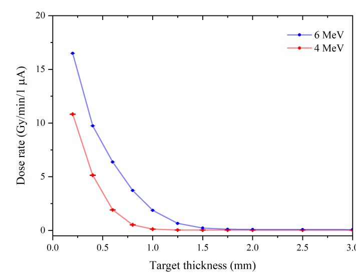

Figure 2: X-ray dose rate for different target thicknesses.

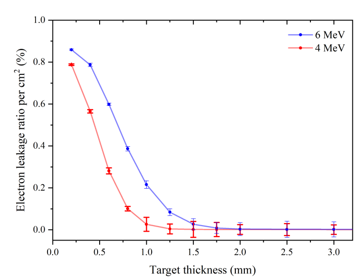

Figure 3: Electron leakage ratio for different target thicknesses.

Thus, the optimization between dose rate and electron leakage has to be determined to get the best target thickness which provides a high dose rate at a low beam current as well as a low electron leakage. From Fig. 2 and Fig. 3, we can make a conclusion that the best thicknesses for LE mode and HE mode are 1.25 mm and 2 mm, respectively. The dose rates and electron energy leakage ratios for those thickness are summarized in Table 2.

Target Thickness for Dual Energy Operation

During dual energy (DE) operation mode, the linac is switched to produce two different energies of electron beam from the macropulse to the macropulse. It is a simple design

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Table 2: The Optimized FLUKA Simulation Results

Parameters	LE	HE	DE
Energy (MeV)	4	6	6/4
Average electron beam current (μA)	120	100	100/150
Target thickness (mm)	1.25	2	2
Electron leakage ratio (%)	0.004	0.004	0.004
Dose rate at 1 m (Gy/min)	5	9	9/5
Average beam power (kW)	0.48	0.6	0.6

and a cost effective way to use only one target thickness which can be used to generate a high dose rate and low electron leakage for two different energies. To meet those requirements, the target thickness should be 2 mm. With that thickness, the requirement of average beam current for LE mode is increased by about 25% to generate the same dose rate when the target thickness is changed from 1.25 mm to 2 mm. When the beam current of LE mode is increased, the power consumption is also increased. But this increasing power consumption is still small due to a low beam energy.

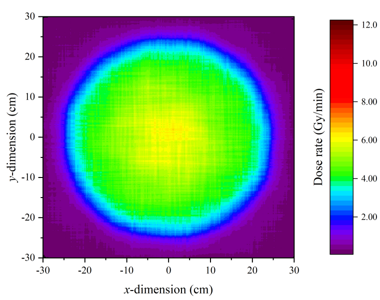

Figure 4: X-ray dose map generated from 2 mm thick target at 4 MeV.

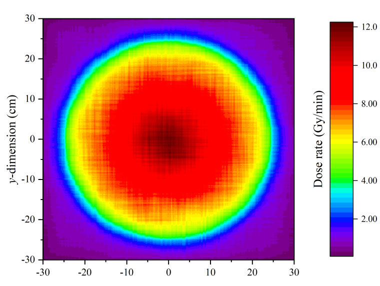

Figure 5: X-ray dose map generated from 2 mm thick target at 6 MeV.

At 1 m away from a target,the dose maps generated from 2 mm thick target for HE mode (6 MeV) and LE mode (4 MeV) are shown in Fig. 4 and Fig. 5, respectively. The results show that the full width (FW) spot size of X-ray for

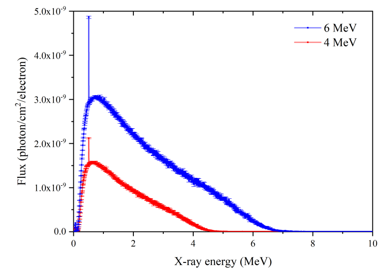

Figure 6: Bremsstrahlung X-ray energy spectra at 4 MeV and 6 MeV.

both high and low energy modes is about 0.5 m in diameter. The high dose rate occurs within a solid angle of 10° of the linac axis. Figure 6 shows the X-ray energy spectra from the low and high energy modes at 1 m away from the target. It is shown in Fig. 6 that the output X-ray photons have energies from 0 MeV to the maximum energy of electrons for each operating mode.

CONCLUSION

The X-ray target of 6/4 MeV European S-band linac for CIS is made with tungsten. The tungsten thickness is varied in FLUKA simulation to optimize the dose rate and the electron leakage. From FLUKA results, we can make a conclusion that the thinner X-ray target can generate a higher dose rate. However, the thicker target is required for a higher energy electron beam to prevent electron escaping from the target. The minimum target thicknesses which provide both a high dose rate and a low electron leakage ratio are 1.25 mm and 2 mm for 4 MeV and 6 MeV electron beam, respectively. For dual energy operation, it is a simple way to use target thickness of 2 mm. Although the required beam current of LE mode is increased, the beam power is not increased so much due to the low beam energy.

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