Design of dual flattening filter for 4-MeV electron beam irradiation system

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Abstract. A 4-MeV electron radio-frequency linear accelerator (RF linac) at the Plasma and Beam Physics Research Facility is used to irradiate electron beam on the natural rubber latex for vulcanization process. The irradiation area and uniformity of electron dose have significant influence on the vulcanization quality and throughput. This research focuses on the design of electron beam flattening filter to enlarge the transverse beam size with more uniform energy and dose distribution. The flattening filter system consists of two different filters. The primary one is used to increases the transverse beam size while the secondary one is used to modify the beam for achieving more uniform transverse distribution. Optimization of the filter system was performed for 4 MeV electron beam by using the GEANT4 Monte Carlo simulation program. The initial electron beam has a pencil shape with transverse Gaussian distribution and an RMS radius of 2 mm. The optimized parameters of the filters are thickness, shape and position. The results of the optimization suggest that the primary filter should have high atomic number. The tantalum (Ta) sheet with a thickness of 30 micron was chosen. The material and shape of the secondary filter were also studied. It is found that the aluminium (Al) plate with a shape of the truncated cone can smear the beam to uniformly distribute over the irradiating area. The output of this work can be used to construct the flattening filter system in the electron beam irradiation system for increasing the vulcanization throughput.

1. Introduction
At the PBP-CMU Electron Linac Laboratory, an RF linac is developed to irradiate electron beam on natural rubber latex for vulcanization process. The expected electron beams produced from the accelerator has small irradiating area, which leads to small irradiating throughput. This research aims to enlarge the electron beam transverse size with uniform dose distribution at the rubber surface. A dual flattening filter system can be used to fulfil this task. A primary filter will scatter the beam to have a larger transverse size while a secondary one will smear the beam to have more uniform transverse distribution.

This considered RF linac system can produce electron beam with variable energies in a range of about 0.7 to 4 MeV. Electron beams with different beam energies have different transverse and longitudinal distributions [1]. Design of the flattening filter depends greatly on these properties. In this
study, we focus only for the electron with an average energy of 4 MeV. For simplicity, the beam with uniform energy and Gaussian transverse distribution were applied. The aims of this study is to design the electron beam filtering system and to investigate the behaviour of the transverse beam dose distribution after passing through the filters.

2. Methodology
A Monte Carlo based program GEANT4 [2] was used to simulate the passage and energy deposition of electrons when they pass through the components in the beam irradiation system. There are three steps to modify electron beam. Firstly, an initial electron beam was generated to have a pencil shape with 2 mm RMS transverse Gaussian distribution as shown in fig. 1 (a). The beam contains 300,000 electrons with uniform energy of 4 MeV. Secondly, a suitable position and thickness of the primary filter were selected. Lastly, a position and shape of the secondary filter were optimized based on the distribution of energy deposition at the surface of the natural rubber latex. The geometry set up used in GEANT4 simulation is shown in fig. 1 (b). The simulation process starts with the injection of initial electron beam at the position \( z = 6 \) cm in front of the 50-μm titanium vacuum window. Then, the beam moves through the 18 cm air gap before reaching the surface of the rubber latex. Positions of the primary and secondary filter are between the titanium foil and the rubber.

![Figure 1](image1.png)

**Figure 1.** (a) The initial transverse distribution of electron beam. (b) Geometry in GEANT4 simulation. The electron beam source is located at \( z = 0 \) cm in vacuum, a titanium foil is placed at \( z = 6 \) cm and the rubber latex is positioned at \( z = 20 \) cm.

![Figure 2](image2.png)

**Figure 2.** (a) Total energy at positions along the beam passage. (b) Transverse energy deposition in air.
Simulations of the electron beam transportation from the initial position to the rubber surface were done. The results in fig. 2 (a) present the total energy that remained with the beam along the beam passage in vacuum, titanium foil and air. The beam lost the total energy of 0.83% and 0.87% in the titanium foil and in air, respectively. At the rubber surface the beam has 98.3% of its initial total value. The transverse energy deposition at three positions; 8, 16 and 23 cm are displayed in fig. 2 (b). It is obvious that the energy deposition distribution is flatter at a longer distance.

3. Design of the primary filter
Tantalum was selected as the material for the primary foil due to its high density, which can scatter the electron beam more than low density material. However, its thickness should be thin to reduce the energy lose. The flat Tantalum plates with thicknesses of 30, 40, 50 and 60 µm were examined. The position of the primary filter was considered at 8, 12, 16 and 20 cm. The results are listed in Table 1. The optimum position and thickness of the primary foil are 20 cm and 30 µm, respectively. The total energy lose in the primary foil is 16,697 MeV.

| Primary filter thickness (µm) | Energy loss of electron beam in primary filter (MeV) |
|------------------------------|-----------------------------------------------------|
| 30                           | z = 8 cm 1.52 z = 12 cm 1.50 z = 16 cm 1.47 z = 20 cm 1.41 |
| 40                           |                                                      |
| 50                           |                                                      |
| 60                           |                                                      |

4. Design of the secondary filter
In this study, the thickness of the secondary filter was varied from 0.6 cm to 2 cm. Since the position of the primary filter is at z = 20 cm and the rubber surface is at z = 24 cm, the positions of the secondary filter can be only between z = 21 cm to z = 22 cm. The position at z = 23 cm was excluded from this consideration because when the thickness of the secondary filter was adjusted to be 2 cm, some part of the secondary filter will be in the rubber latex. The required radius of the irradiated beam that has quite uniform energy deposition was set to be 2 mm. Shapes of the filters and their setup in GEANT4 simulation are shown in fig. 3. Examples of transverse energy deposition distributions at the rubber surface are presented in fig. 4. The optimal shape and dimensions of the secondary filter are listed in Table 2.

![Figure 3](image-url)

**Figure 3.** Examples of transverse energy deposition distribution at the position z = 21 cm for the cases with (a) and without (b) the secondary filter.
The simulation results in fig. 5 show the total energy of electron beam from \( z = 0 \) to \( z = 24 \) cm for the cases that the secondary filters are at \( z = 21 \) cm and at \( z = 22 \) cm. Both graphs show that there is sudden loss of the total energy at \( z = 20 \) cm where is the position of the primary filter. The beam transportation in the whole system for the optimal case is shown in fig. 6.

**Figure 4.** (a) Shape of the secondary foil, where \( r \) is the small radius, \( R \) is the big radius and \( h \) is the height of the filter. (b) Geometry setup in GEANT4 simulation with dual filter system.

![Figure 4](image)

**Figure 5.** (a) Total energy at positions along the beam passage with dual flattening filter system. The blue and orange graphs show the results for the positions of the secondary filters at 21 and 22 cm, respectively. (b) Dose deposition along the beam passage without (gray) and with the dual flattening filter system, where the secondary filter at 21 cm (blue) and at 22 cm (orange).

![Figure 5](image)

**Table 2.** Optimal dimensions of the secondary filter.

| Position (cm) | \( r \) (cm) | \( R \) (cm) | \( h \) (cm) | Total energy loss \( \times 10^5 \) MeV |
|---------------|-------------|-------------|-------------|-------------------------------------|
| 21            | 0.5         | 2.0         | 0.5         | 4953.30                             |
| 22            | 0.5         | 2.0         | 0.6         | 5924.83                             |

**Figure 6.** Illustration of beam transportation in the irradiation system with the dual filter system.
5. Conclusion
A dual flattening filter system can be used to enlarge the electron beam transverse size with uniform dose distribution at the rubber surface. Based on the Monte Carlo simulation results we found that the primary filter with flat shape should have the optimal position at 20 cm with the optimal thickness of 30 µm. A solid truncated cone can be used as the secondary filter. Its position is selected to be at 22 cm for providing high dose deposition at the rubber surface. With dual flattening filter system, the volume of the electron beam irradiation is 6.285 cm³ with a cylindrical shape that has 0.5 cm of depth and 12.57 cm² circle area. The calculated dose deposition is 1.4 kGy/s.

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