ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS041

DESIGN AND PARAMETERIZATION OF ELECTRON BEAM IRRADIATION SYSTEM FOR NATURAL RUBBER VULCANIZATION

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Abstract

Electron beam irradiation is a process to modify or improve the properties of materials with less chemical residue. In natural rubber vulcanization, a proper electron absorbed dose is about 50 - 150 kGy. In this study, the experimental station is designed to investigate the deposition of the electron beam in natural rubber. Electron beams generated from an RF linac are used in this study. This accelerator can generate the beam with energies in the range of 1 - 4 MeV and an adjustable repetition rate of up to 200 Hz. We can optimize these parameters to maximize the throughput and uniformity of electron dose in the vulcanization. The simulation results from GEANT4 were used to narrow down the appropriate parameters in the experiment. In the early stage of the study, water was used as a sample instead of natural rubber. The dose distribution was obtained by placing a B3 film dosimeter under a water chamber. The water depth was varied from 0.5 to 2.0 cm. The simulation results provide the dose distribution to compare with the experimental results. In a further study, the beam irradiation in natural rubber with these optimal parameters and vulcanization tests will be performed.

INTRODUCTION

The electron radio-frequency linear accelerator (RF-linac) with an irradiated station for rubber vulcanization has been developed at the Plasma and Beam Physics Research Facility, Chiang Mai University, Thailand [1]. The electron beams generated from this RF-linac have energies in the range of 1 - 4 MeV. Difference electron beam energies provide different absorbed doses along penetration depths in the material. In the case of rubber vulcanization, the suitable absorbed dose is in the range of 50 - 150 kGy. The main objective of the work is to design the irradiation station for rubber vulcanization. The throughput is aimed to be maximum and uniform in quality. In the early stage, water is employed instead of rubber latex to set up a proper depth dose study for further rubber vulcanization experiments. In this study, the water depths were varied to investigate the absorbed dose in the water volume along with the Monte Carlo simulations.

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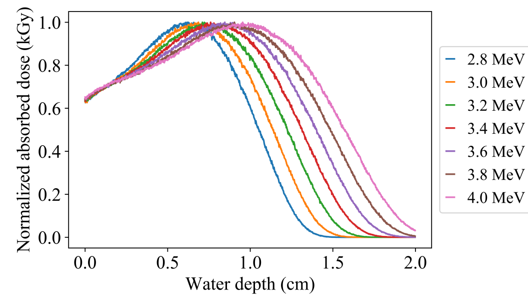

Figure 1: Normalized depth dose distributions in water volume thickness of 2 cm using monoenergetic point source of 3 - 4 MeV beams.

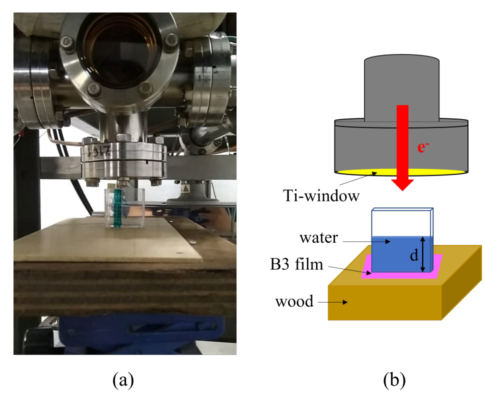

Figure 2: Dose deposition experimental set up for rubber vulcanization at the Plasma and Beam Physics Research Facility, Faculty of Science, Chiang Mai University.

DOSE DEPOSITION MEASUREMENT

Performance of an irradiation system is determined by the electron absorbed dose in water (sample) volume and related directly to the electron beam parameters. To demonstrate the effect of beam energy, different depth dose distributions in water volume using monoenergetic point source beams of 3 - 4 MeV are illustrated in Fig. 1. To prepare for vulcanization experiments, the experimental station for dose deposition was set up by placing the water container downstream of the accelerator system, after the Ti-window, as shown in Fig. 2. The electron absorbed dose was measured using B3 radiochromic film from GEX cooperation [2] so the B3 film was placed under the water c ontainer. The water container and the B3 film were then placed on a wood

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS041

plate, a good electron absorbent material. In the experiment, the time for each irradiation was 30 minutes due to very low beam current and the distance from Ti-window to B3 films were set to 5 cm. In order to obtain the optimum depth, water depth in the container varied from d = 0.5 to 2.0 cm. After being irradiated by electron, B3 film turns from colour less to a different shade of pink, where the colour intensity depends on the amount of absorbed dose. The difference in water depths provide different dose distribution on the B3 film as shown in Fig. 3. The amount of absorbed dose on B3 film can be obtained by converting the colour response to numerical data using a calibration curve in RisøScan software [2].

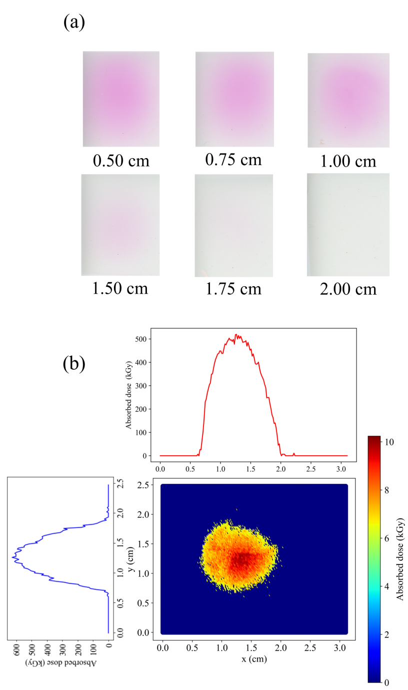

Figure 3: The examples of the irradiated B3 film (a) the colour response at different depths of water (b) the converted dose data map and their projection onto the x or y-axis for a water depth of 1.0 cm.

COMPUTATIONAL MODEL

The computational simulation of the irradiated station was modelled by the Monte Carlo simulations using the GEometry ANd Tracking 4 (GEANT4) [3]. The geometries, positions and materials in the simulation were mimicked from the actual experimental station described earlier and is shown in Fig. 4. The initial electron beams in simulation were used monoenergetic point source beams with 3.0 and 4.0 MeV. Moreover, the another set of initial electron beams were obtained from beam dynamic simulation using the software ASTRA (A Space Charge Tracking Algorithm) [4]. These beams contain essential properties such as the beam distribution and energy spread following the RF-linac conditions. The study of beam dynamic simulation for this RF linac was reported in [5]. The beam with average energies of 2.94 and 4.06 MeV were obtained and used as the initial beam source in the simulation. The energy distributions of electron beams with average energies of 2.94 and 4.06 MeV are shown in Fig. 5. The water depth in the container varied from 0.5 - 2.0 cm in the simulation to compare the dose distribution on B3 film from the experiments.

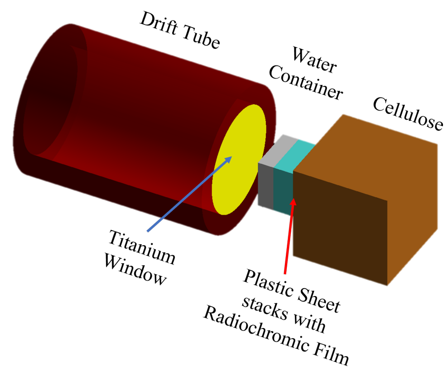

Figure 4: Simulation setup of electron beam irradiation station for rubber vulcanization in GEANT4.

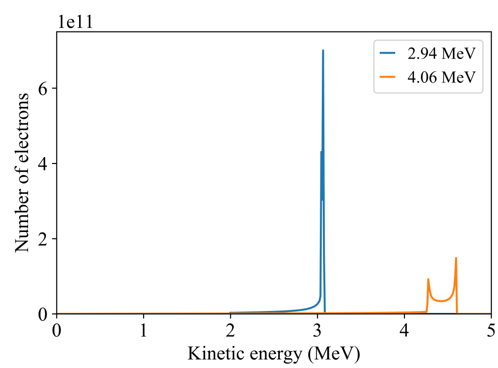

Figure 5: The energy distributions of electron beams with average energies of 2.94 MeV and 4.06 MeV.

RESULTS AND DISCUSSIONS

Two irradiation experiments were conducted. In the set A, water depth of 0.5, 1.0, 1.5 2.0 cm were varied. The set B was conducted to check the irradiation stability and collect more data points of water depths that need to clarify at 0.75 and 1.75 cm. The colour response of irradiated B3 film was converted to dose using two sets of calibration curves. The two sets of calibration curves are the program default and in house calibration using known beam energies, beam currents and deposit doses. From the experimental results, the maximum water depth that B3 film can still be sensitive to the electron beam is around 1.75 cm. Therefore, the maximum energy of the electron beam can possibly be between 3.4 -4.0 MeV by using the depth dose distribution in Fig. 1. The absorbed dose data from the experiment were analyzed by projecting the dose data onto the x or y-axis. This can

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reduce the misleading interpretation of the dust on B3 film that occurred in the experiment. Moreover, the absorbed dose on B3 film from simulation was obtained and compared to the peak value of the projected dose at each water depth. In set A and B, both default and in house calibration fell in between the 3 and 4 MeV beams curve. This corresponds well to the maximum electron beam energy approximated from the depth dose curve. The dose beyond the depth of 1.5 cm cannot be interpreted numerically because of the insufficient response of B3 film to a very low dose. The data points at 0.75 cm depth on set B displayed large deviation from the expected curve. This error can be caused by the accelerator system has not reached an optimum condition before conducting the experiment. The normalized absorbed dose from simulations and experiments using two sets of calibration (a) set A and (b) set B are illustrated in Fig. 6. To investigate the size of transverse dose distribution, the full width at half maximum (FWHM) from both simulation and experiment were compared. Since the beam current for experiment was much lower, the results can be compared qualitatively. The default calibration provides the FWHM of about 1.79 - 1.94 cm on the x-axis and 1.50 - 1.58 cm on the y-axis, respectively. The FWHM was about 1.01 - 1.10 cm on the x-axis and 0.86 - 1.00 cm on the y-axis when using the in house calibration, respectively. From the simulation, the FWHM is in the range of 0.90 - 1.14 cm for a 2.94 MeV beam and 0.83 - 1.33 cm for a 4.06 MeV beam, respectively. The FWHM from experiment and simulation in different water depths are shown in Fig. 7. The FWHM from experiments revealed a nearly constant dimension along the water depths, resembling those from the 2.94 MeV simulation.

CONCLUSION AND FURTHER WORK

The investigation of dose deposition and dose distribution was performed in order to initiate the irradiated station for rubber vulcanization. The current study aims to test the performance of the irradiation system by employing B3 radiochromic film to measure the dose distribution. Moreover, the GEANT4 simulation was used to give some insightful information and to analyze the experimental results. The maximum water depth that the beam in the experiment can penetrate is around 1.75 cm. The maximum beam energy is therefore between 3.4 - 4.0 MeV according to the depth dose curve. The normalized absorbed dose from experiments using two sets of calibration curves fit well to the simulation between the curve 3 MeV and 4 MeV beams from simulation. The experiment shows that the FWHM of the dose distribution is nearly constant along the 1.5 cm water depth. To obtain more clarifying experimental results, the beam stability should be tested before conducting the long run irradiation experiments. The size of B3 film should be large enough and the irradiation time should be optimized in order to obtain an overall dose on the B3 film and be able to identify the edge of the beam. Finally, the container for rubber latex vulcanization with this electron beam can be designed from the constant FWHM and optimal depth.

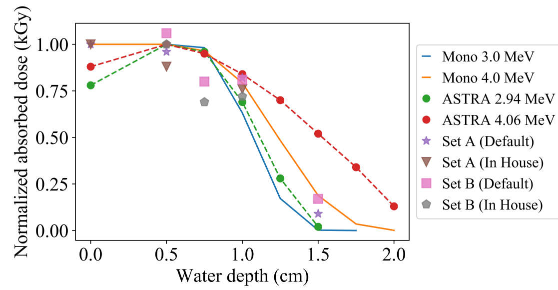

Figure 6: Normalized electron absorbed dose for monoenergetic beams and for the beams from beam dynamics simulation and measurement results with two sets of calibration (Default, In house).

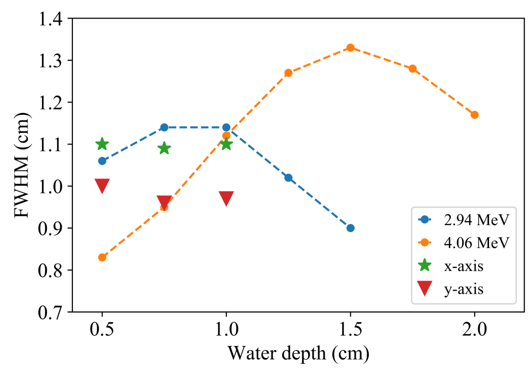

Figure 7: The FWHM of the dose distribution from experiment (set B) using in house calibration and from simulation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding supports by Chiang Mai University, the Thailand Center of Excellence in Physics (ThEP Center), the Science and Technology Park Chiang Mai University (CMU STeP), and the NSRF via the Program Management Unit for Human Resources & Institutional Development, Re-search and Innovation (grant number B16F630068).

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[2] B3 RisøScan Dosimetry System, `https://www.gexcorp.com/risoscan.html`

[3] GEANT4 a simulation toolkit, `http://geant4.web.cern.ch`

[4] K. Flöttmann, “A Space Charge Tracking Algorithm (ASTRA)”, `http://www.desy.de~mpyflo/`.

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