STUDIES ON ELECTRON LINEAR ACCELERATOR SYSTEM FOR POLYMER RESEACH

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Abstract

This research focuses on modification of an electron linear accelerator system for irradiation of natural rubber latex and polymeric materials at the Plasma and Beam Physics Research Facility, Chiang Mai University, Thailand. This is in order to study the change of material properties due to electron beam irradiation. The main accelerator system consists of a DC thermionic electron gun and a short standing-wave linac. This system will be able to produce electron beams with variable energy in the range of 0.5 to 4 MeV. The linac macro pulse frequency is adjustable within the range of 20 to 1000 Hz. The macro pulse duration is 4 µs. The electron pulse current can be varied from 10 to 100 mA. This lead to the electron dose of about 0.44 to 4.4 Gy-m^2/min. In this paper, overview of the accelerator and the irradiation system is presented. Results of low-level RF measurements of the accelerating structure are also reported and discussed.

INTRODUCTION

Electron beam processing can be used to modify chemical and physical properties of materials with the aims to enhance their qualities, to promote commercial value and to reduce undesirable by-products [1]. Using electron beams produced from an accelerator is an alternative method to the conventional ones using gamma rays or chemical additives. In some applications, electron beam irradiation processing can produce unique effects that cannot be duplicated by other means. One of good examples, which is in our interest, is the natural rubber vulcanization. The cross-linking process can happen without heating and in the absence of chemical vulcanization agents [2]. Furthermore, the electron beam vulcanization has the advantages of being very low cytotoxicity and having potential in reduction of extractable protein, which is considered to be primary source of the allergic reaction.

This research aims to develop a linear accelerator system for natural rubber vulcanization and polymer cross-linking by using major parts of the accelerator system from a defunct medical linac donated to the Plasma and Beam Physics Research Facility, Chiang Mai University. This electron accelerator system will be used to define optimal conditions for natural rubber vulcanization and for polymer cross-linking with medium energy electron beams of 0.5 to 4 MeV for future development of a practical industrial unit of the electron beam processing system. Overview of the accelerator system and the processing unit as well as some study results concerning the accelerating structure are reported and discussed in this paper.

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METHODOLOGY

Electron Accelerator System

The completed system of electron beam irradiation for natural rubber vulcanization and polymer cross-linking consists of the electron linear accelerator system (as shown in Fig. 1), electron beam measurement and analysis components, the beam sweeper and the movable stage for the sample container, and the control system for the linac operation and for the electron beam treatment on the natural rubber and polymer. The whole system will be located inside the underground radiation shielding hall at the Plasma and Beam Physics Research Facility. The main components for the radio-frequency (RF) wave generator and the accelerating structure are adopted from a 4-MeV medical linac, which was donated from the Maharaj Nakorn Chiang Mai Hospital, Thailand. The systems for beam measurement and analysis, the beam sweeper and the rubber processing experimental station will be developed at the laboratory.

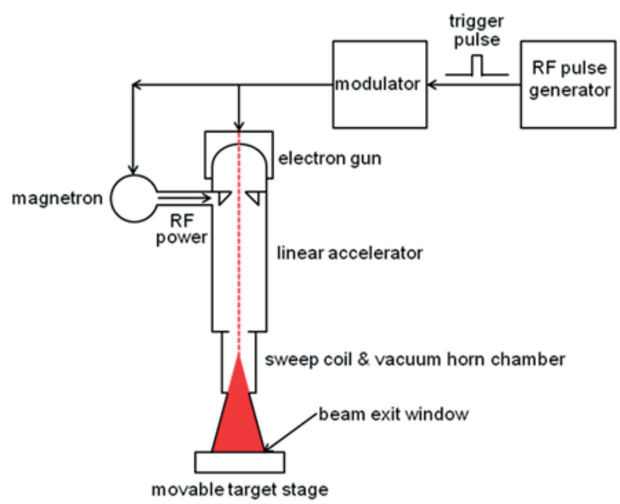

Figure 1: Schematic layout of the electron linear accelerator for rubber vulcanization.

As shown in Fig. 1, the accelerator system consists of a DC electron gun, a standing-wave linear accelerator equipped with a related radio-frequency (RF) system and a sweeping coil with a vacuum horn chamber. The DC electron gun is a Pierce-type electron gun with a circular thermionic cathode with diameter of 4.86 mm. The linear accelerator (linac) composes of five TM_{010}-mode standing-wave resonant cavities that can be used to accelerate electron to reach the maximum energy of about 4 MeV for the supplied RF power of 2 MW. The RF wave is transported from a 2-MW magnetron to the linac via a

ISBN 978-3-95450-147-2

WR-284 rectangular waveguide system with an RF window for separation of the SF_6 pressurized part and the vacuum part. Between each resonant cavity, the RF wave is coupled through a side-coupling cavity. Hence, the whole linac structure is operated in π/2-mode. Low-level RF measurements for the linac were performed to investigate its RF properties and the results are presented in the next section.

It is aimed that this accelerator system will be able to produce electron beams with tunable energy of 0.5 – 4 MeV and the electron pulse current of 10 – 100 mA. Specifications of the electron linac and expected beam parameters, which will be obtained from the developed system are listed in Table 1.

Table 1: Expected Specifications of the Electron Linac and Electron Beam Parameters

Specification	Value
RF power from magnetron	2 MW
RF frequency	~2996-2998 MHz
Beam energy	0.5-4 MeV
Electron pulse repetition rate	20-1000 pulse/s
Electron pulse duration	4 µs
Electron pulse current	10-100 mA
Average current at 1000 pulse/s	40-400 µA
Electron power at 1000 pulse/s	1600 W

Electron Beam Processing

The electron beam processing system (as shown in Fig. 2) consists of a dipole magnet to sweep electron beam for irradiate on the sample in x-direction and the moving state move in y-direction. This system is controllable by using the computer interface and software. Preliminary, the sweeping area will be 20×20 cm^2. The electron dose at the sample chamber will be 0.44-4.4 Gy-m^2/min.

The choice of electron energy and average current in the irradiation process is usually based on practical considerations, such as absorbed dose, dose uniformity ratio, material thickness, density and configuration, processing rate, capital and operating costs. Practically, the electron dose will be adjusted by varying the electron beam energy and/or the beam average current. In general, the incident electron energy determines the maximum material thickness, while the electron beam current and beam power determine the maximum processing rate. Low electron energies in keV scale will lose excessive beam power in the vacuum-window and in air. Electron with higher beam energy will penetrate deeper into the materials. However, they can induce radioactivity when hitting the material. Thus, the medium electron energy range seems to be the most practical. Moreover, using the minimum electron energy will benefit in reducing the physical size and cost of the accelerator, as well as reducing the thickness and cost of the radiation shielding [3]. Therefore, the electron energy range of 0.5 MeV to 4 MeV is appropriated for this application.

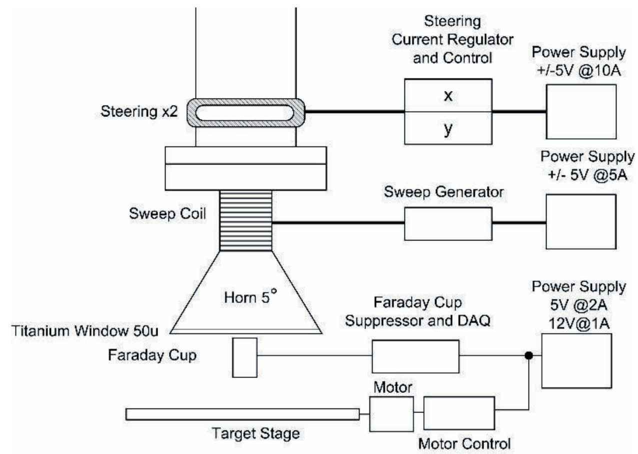

Figure 2: Schematic layout of the electron beam sweeper, the charge measurement system and the movable stage for the rubber liquid container.

RESULTS AND DISCUSSION

In this study the properties of the standing-wave linac are investigated. Since the linac is a part of the medical linac system, which we had lack of physical and technical information. Therefore, we dissembled the system to study all parts. Low-power RF measurements were performed by using an S-parameter Hewlett Packard Vector Network Analyzer model HP 8753E, which has the input frequency range of 30 kHz - 6 GHz. During the measurements the input power was 0 dB, which is equivalent to 1 mW. Four main measurements were done with the S_{11} reflection measurement method. There are the measurements of the resonant frequency for the operating mode, the quality (Q-factor), the RF-coupling coefficient (β_{rf}) and the normalized longitudinal field profile.

In the resonant frequency measurements, there are 8 peaks observed corresponding to degenerated modes of 8 resonant cavities including the side coupling cavities. The resonant frequencies of these modes are 2969.565, 2978.925, 2986.435, 2996.395, 3005.545, 3014.310, 3021.090, and 3024.890 MHz, respectively. In this research the π/2-mode is used as the operating mode. The Q-factor of the π/2-mode can be measured by obtaining the resonant frequency (f_0) at the peak of the S_{11} reflection peak and the frequencies bandwidth (Δf) at the half - power points (-3.0 dB points). Then, a loaded Q-factor is calculated to be [4]

$$Q_L = \frac{\omega_0}{\Delta\omega} = \frac{f_0}{\Delta f}\,. \tag{1}$$

An unloaded Q-factor, which is the characteristic quality factor of the linac, is obtained from the following relation

$$Q_0 = Q_L(1+\beta_{rf})\,. \tag{2}$$

The RF-coupling coefficient and the Q-factor of the π/2-mode were measured. The measured resonant frequency at the room temperature of 27.2°C and in ambient air was 2996.395 MHz. Based on the ability of the cooling system, the operating temperature of the linac will be 30°C. Therefore, the resonance frequency in the linac operation will change to be 2996.256 MHz. Results of the RF measurements performed in air and in the room temperature of 27.2°C are listed in Table 2.

Table 2: Measured RF Parameters at the π/2-mode of the Linac at the Room Temperature of 27.2°C and in Ambient Air

Parameter	Value
Resonant frequency (f_0)	2996.395 MHz
RF-coupling coefficient (β_{rf})	1.6528
Unloaded Quality factor (Q_L)	5732
Loaded Quality factor (Q_0)	15198

The longitudinal RF field distribution inside the linac can be obtained by introducing a small object into the resonant cavities and observing the coupling to electric and magnetic field components at various positions. This phenomenon can be described by the Slater perturbation theorem [5], which states that the change in resonant frequency leads to a change in electric field (E) and magnetic field (M) stored energy $U = U_M + U_E$ as [5]

$$\frac{\Delta\omega}{\omega} = \frac{\Delta f}{f} = \frac{\Delta U_M - \Delta U_E}{U} = \frac{\int(\mu H^2 - \varepsilon E^2)dV}{\int(\mu H^2 + \varepsilon E^2)dV}. \quad (3)$$

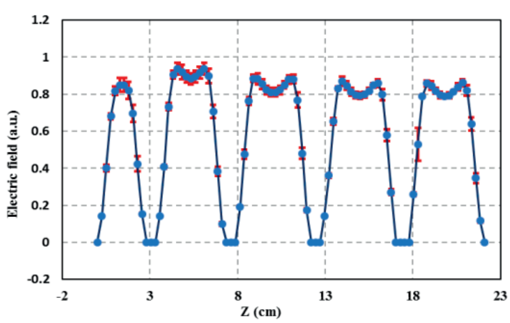

Figure 3: Measured normalized longitudinal electric field distribution in the linac obtained from the bead-pull measurements.

In this study, a dielectric bead with diameter of 4.50 mm was used in the bead-pull measurements. Then, the change in the resonant frequency is proportional to the amplitude of the longitudinal electric field as $E_z \propto \sqrt{f - f_0}$. The relation between the position in the linac cavities and the normalized electric field amplitude are shown in Fig.3.

CONCLUSION

The electron linear accelerator for natural rubber vulcanization and polymer cross-linking is developed at the plasma and Beam Physics Facility. Overview of the whole system including the accelerator and the electron beam irradiation system was presented. The RF measurements of the linac structure were performed and the results show that the linac has five resonant frequencies, which has five degenerated modes and each cell has its own resonant frequency. The resonant frequency of the π/2 operating mode is 2996.256 MHz for the operating temperature of be 30°C. The unloaded quality factor is 15198 and the RF-coupling coefficient is 1.6781 The result from the bead-pull measurements reveals that the first cell has shorter cavity and lower electric field than the others, while the second cell seems to have the highest field amplitude. Furthermore, to understand the beam properties, beam dynamic simulations of electrons travelling through the whole accelerator will be performed. Then, the results will be used to define optimal conditions for natural rubber vulcanization and polymer cross-linking with medium energy electron beams for future development of a practical industrial system.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support by the Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, the Thailand Center of Excellence in Physics, and the Science Achievement Scholarship of Thailand.

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ISBN 978-3-95450-147-2