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BEAM DYNAMICS SIMULATIONS OF LINEAR ACCELERATOR FOR NATURAL RUBBER VULCANIZATION AT CHIANG MAI UNIVERSITY

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Abstract

The Linear accelerator system for natural rubber vulcanization has been developed at the Plasma and Beam Physics Research Facility, Chiang Mai University, Thailand. The main components of the accelerator system consist of a DC electron gun with a thermionic cathode, an RF linear accelerator, an RF system, a control system, and an irradiation system. The electron beam properties for natural rubber vulcanization are predicted from the beam dynamics simulation starting from a cathode to the titanium exit window. The electron beam generation and the particle in cell simulation inside the DC electron gun are performed using CST Studio Suite software. The electron distribution at the gun exit from the CST output is covered to be an input distribution of the ASTRA beam dynamics simulation program. The electron beam enters the linac and is accelerated by RF filed inside the linac. The ASTRA simulation code is used to track electron trajectories including the space-charge interaction and the simulation starts from the linac entrance to the exit windows. The electron beam properties for various conditions are evaluated and will be used for further simulations.

INTRODUCTION

A linear accelerator (linac) system for rubber vulcanization has been developed at the PBP-CMU Electron Linac Laboratory (PCELL), Plasma and Beam Physics (PBP) Plasma and Beam Physics Research Facility, Chiang Mai University, Thailand. The system consists of a Pierce-type DC gun with a thermionic cathode, a radio-frequency linear accelerator (RF linac), electron beam diagnostic instruments, and an irradiation system. The layout of the accelerator and irradiation system is shown in Fig. 1. The accelerator system is modified from a medical linac system model Mitsubishi ML-4M. The modified accelerator system is expected to generate beam energy from 1 to 4 MeV [1, 2] with a pulse current of 10 – 100 mA and a pulse repetition rate of 20 – 200 Hz. Some specifications of the accelerator system are listed in our published articles [1, 2].

In this paper, the beam dynamic simulation in the DC gun and the linac are reported and discussed. The electron beam generation and the particle in cell (PIC) simulation inside the DC electron gun were performed using CST Studio Suite software [3]. The results of this simulation were used as the input particle distributions for the beam dynamic simulation in the linac to the exit window using software A Space Charge Tracking Algorithm (ASTRA) [4]. The simulation results for an average beam energy of 1.20 MeV and 3.75 MeV which are close to the expected minimum and maximum beam energy respectively are presented and discussed. the contents of the template.

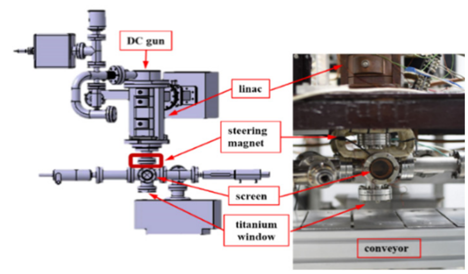
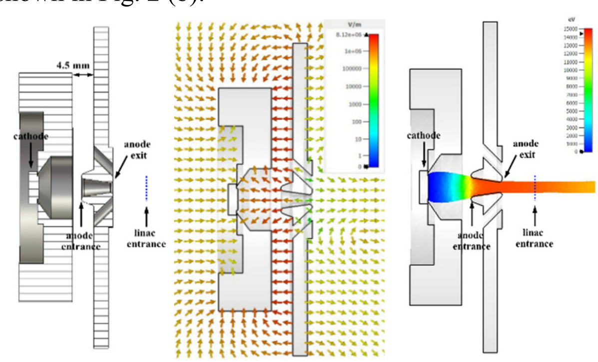


Figure 1: Layout of an accelerator unit.

ELECTRON BEAM DYNAMIC SIMULATION IN THE DC GUN

The simulations in the gun including electric field simulation, electron beam generation, and beam dynamic simulation were performed using CST Studio Suite 2022 software. The DC electron gun was taking a part for cathode and heating filament replacement, and dimension measurement. The simplified model of the DC gun for CST simulation is shown in Fig. 2 (a) which consists of a cathode, focusing electrode, and anode. The parallel gap between the focusing electrode and anode is 4.5 mm. For electric field simulation, the measured high voltage between two electrodes of 14.0 kV is applied since this value is normally used in machine operation. The simulated electric field is shown in Fig. 2 (b).



(a) (b) (c)

Figure 2: The DC electron gun: (a) the simplify model, (b) the simulated electric field, and (c) the electron beam trajectory.

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The cathode of the DC gun is an indirect heating cathode with a diameter of 4.96 mm. It is a 532 cathode [5] manufactured by Heat-Wave Labs, Inc. At our facility, the maximum brightness temperature of 1,419 K (1,146 °C) was observed using an IGA 10 pyrometer at the heating filament power of 95 W. The Electrostatic Particle-in-Cell (Es-PIC) Solver was used for the simulation in the gun. The DC emission model was used to generate an electron beam with the extraction voltage of 14 kV and the emission temperature of 1,340 K. The emission temperature is converted from the brightness temperature using formula explained in [5]. For this study, the emission temperature of 1,340 K corresponds to the brightness temperature of 1,328 K (1055 °C) at the heating filament power of 65 W was applied to the emission model. The current density was calculated from the Richardson's law and the Child–Langmuir's law explained in [6]. The calculated current density of 14,950 A/m^{2}was carried out for the emission temperature of 1,340 K and the extraction voltage of 14 kV. Consequently, the emission current of 289 mA should be extracted from the cathode with a diameter of 4.96 mm.

The Es-PIC Solver tracks macro-particles through the electric field distribution starting from the cathode surface (z = 0.2 mm) to 25 mm away from the surface. The 25 planes of particle 2D monitor were set up to evaluate the electron beam properties along its trajectory. The anode has a conical hole for electron beam focusing where the entrance is at z = 9 mm and the exit is at z= 16.0 mm. The anode entrance has a diameter of 4.1 mm while the anode exit has a diameter of 2.1 mm. The simulated beam trajectory is shown in Fig. 2(c) and the electron beam properties along z are shown in Fig. 3. The electron beam was accelerated and focused due to the non-uniform electric field from the cathode to the anode entrance. Although the beam spot size at the anode entrance was smaller than the entrance aperture and was continuously focused however some parts of the beam still hit the anode wall. Consequently, the simulated beam current of 285 mA was reduced to 179 mA at the anode exit as shown in Fig. 3(a). Figure 3(b) shows the focused beam envelope along z starting from the cathode to the end of the simulation. It is clearly see that the spot size after the anode exit is focused to has the smaller spot size.

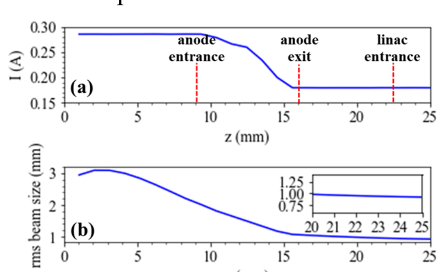
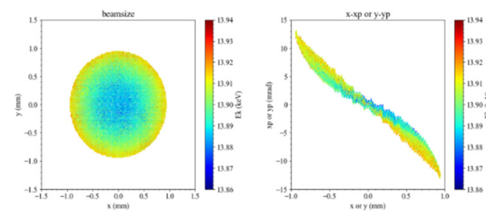


Figure 3: The electron properties along the simulation beamline: (a) the beam current, and (b) the rms beam size.

At the position z = 22.5 mm which is approximately the position of the linac entrance, the other particle 2D monitor was set up to accumulate macro-particles in one RF period or 333 ps. The distribution of this monitor was converted to be an input distribution of the beam dynamics simulation in RF linac which will be explained in the next section.

The continuous electron beam at the linac entrance has a beam current of 179 mA which contains a total charge of 59.2 nC in one RF cycle (333 ps). The transverse distribution of the beam is shown in Fig. 4(a) with an rms transverse beam size of 0.471 mm. The transverse phase-space of the beam is shown in Fig. 4(b) with the normalized emittance of 0.0855 π mm.mrad. The electron beam has an average kinetic energy of 13.9 keV with 426,824 macroparticles.



(a) (b)

Figure 4: The electron beam distribution at the linac entrance in (a) the transverse xy plane, and (b) transverse x or y phase space.

ELECTRON BEAM DYNAMIC SIMULATION IN THE LINAC

The beam dynamic simulation in the linac was performed using ASTRA simulation code. In this section, the simulation starts from the linac entrance (z = 0.00 mm) where the accelerating field is equal to zero until the titanium exit window (z = 42.95 mm). The linac exit locates at the position z = 22.15 mm where the accelerating field is equal to zero. The accelerating field along the linac axis used in this simulation had been measured with the bead-pull technique and presented in our publications [1, 2]. The accelerating field gradients used in this study were based on the available RF power which delivers to the linac. The relation between the RF-power and the accelerating field gradients can be founded in [2]. In this work, the field gradients of 18 and 38 MV/m were used in the ASTRA simulations to generate electron beams with an average beam energy of 1.20 and 3.75 MeV, respectively.

The initial distribution for the ASTRA simulations in the previous work [1, 2] was generated from the *generator* program [4], while the output from the Es-PIC simulation described in the previous section was used as the initial particle distribution for this work. The distribution was set up to have radial grid rings of 30 and longitudinal grids of 100. The main monitoring screen was located at the position of the titanium window for the electron beam properties evaluation. When the electron beam travelled into the first cell of the linac and experienced RF field in 1 cycle (333 ps), about half of the particles were accelerated and moved in the forward direction while about haft were decelerated and travelled back. Consequently, the electron beam was first bunched in the first linac cell and then an electron bunch continue to travel into the rest of the linac cells for accelerating and bunching process. According to the simulation, some electrons can form additional bunches as

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shown in Fig. 5 (a) and (b) for the accelerating gradient of 18 MV/m and 38 MV/m respectively when the main bunch arrived position of the titanium window. For the accelerating gradient of 38 MV/m, it can be seen that the additional bunches are well separated and each additional bunches have a small number of electrons. For the accelerating gradient of 18 MV/m, the additional bunches are not well separated and the number of electrons in each additional bunches is higher than that of the other case. Note that the distance between each bunch is about 10 cm which corresponds to one RF period (333 ps). The additional bunches will combine with the main following bunches and the simulation results will be carried out in near future.

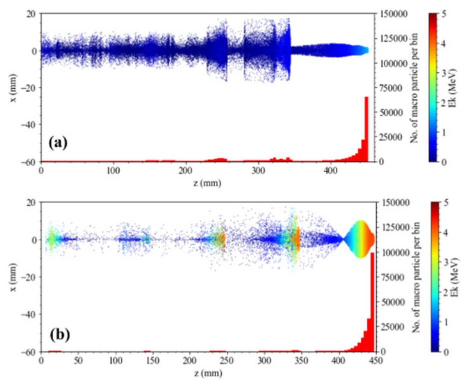

Figure 5: 2D distribution and histogram of electron bunch recorded on the monitoring screen at the titanium window for accelerating gradient of (a) 18 MV/m and (b) 38 MV/m.

Considering only main bunch, the bunch properties are shown in Figs. 6 and 7, and Table 1. Figure 6 (a)-(c) are particle distributions for an accelerating gradient of 18 MV/m, which can achieve the average beam energy of 1.20 MeV, and Fig. 7 (a)-(c) are particle distributions for an accelerating gradient of 38 MV/m, which can achieve the average beam energy of 3.75 MeV.

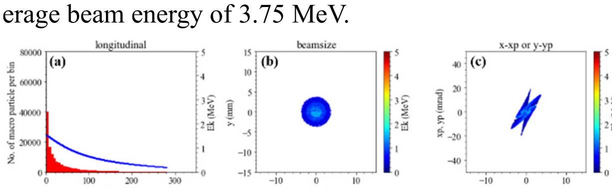

Figure 6: particle distributions at the titanium window: (a) electron energy distribution, (b) transverse distribution, and (c) phase space distribution for an accelerating gradient of 18 MV/m.

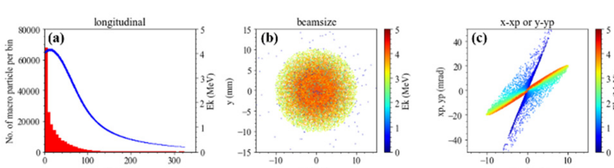

Figure 7: particle distributions at the titanium window: (a) electron energy distribution, (b) transverse distribution, and (c) phase space distribution for an accelerating gradient of 38 MV/m.

According to the beam properties in Table 1, the electron beam with the average beam energy of 3.75 MeV has a larger rms beam size and rms normalized emittance than that of the 1.20 MeV electron beam. The 3.75 MeV electron bunch has a higher bunch charge but lower bunch length than that of the other due to the bunching mechanism in the linac. Therefore, the 3.75 MeV electron bunch has twice higher bunch current.

Table 1: Paramerters of the Electron Bunch

Parameters	**Value**	**Value**
Accelerating gradient [MV/m]	18.0	38.0
Average energy [MeV]	1.20	3.75
Rms beam size [mm]	0.785	1.905
Rms normalized emittance [π mm.mrad]	6.80	34.29
Bunch charge [pC]	18.8	26.2
Bunch length [ps]	115	80
Bunch current [mA]	163	327

CONCLUSION

The beam dynamics simulation in this work was performed by using the combination between the CST Studio Suite software and the ASTRA simulation code. The Es-PIC Solver in CST Studio Suite was used for the simulation in the DC gun. The output distribution from the gun was converted as an input distribution of the beam dynamics simulation in RF linac using the ASTRA simulation. The simulation results from this work are very useful for further simulations to predict electron beam generation in various conditions.

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