Calibration of energy slits and simulation of electron trajectories in the alpha magnet’s 3D field

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Abstract. At the PBP-CMU Electron Linac Laboratory, high-brightness electron beams are produced from the radio-frequency (RF) linear accelerator (linac) system that consists of a thermionic RF electron gun, an alpha magnet, a traveling-wave linac structure, quadrupole magnets and steering coils. Several diagnostic devices are installed in the accelerator system to characterize electron beam properties. In this work, we study on measurement of electron beam energy downstream the RF gun using the alpha magnet equipped with energy slits in the vacuum chamber and a current transformer. Calibration of the energy slits’ positions for various stepper motor encoder numbers was conducted before installing the slits in the magnet’s vacuum chamber. The calibration result was imported into the energy calculation software that links to the stepper motor encoder and the energy value will then be automatically calculated. Moreover, dynamic simulations using a software ASTRA were performed to investigate electron’s trajectories in the alpha magnet’s field with different initial electron positions and angles. The results from this study will be used to estimate the result and accuracy of energy measurement using the alpha magnet. It was found that, for different initial horizontal and vertical positions at the alpha magnet entrance, the energy of electron will be measured to be lower than its actual energy by around 0.5% and the measured energy will decrease when the initial position is moving away from the middle point. In case of horizontal particle's angle, the error of energy measurement increases up to 1% at the angle of 3° before the beam hitting the alpha magnet chamber. For the vertical particle's angle, the electron that has the initial angle less than or larger than 1.5° will hit the vacuum chamber.

1. Introduction
The objective of research activities at the PBP-CMU Electron Linac Laboratory, Chiang Mai University, is to develop an electron accelerator system and experimental apparatus for production and applications of the coherent mid-infrared (MIR) and terahertz (THz) radiation. One of the main sections is the injector system consisting of a 1-1/2 cell standing-wave radio-frequency (RF) electron gun with a thermionic cathode, an alpha magnet as a magnetic bunch compressor with energy slits, a travelling-wave RF linear accelerator (linac), beam steering coils, quadrupole magnets, and a dipole magnet with a Faraday cup as an energy spectrometer. In order to generate high quality radiation, the high-quality electron beam is needed, especially the beam that produced from the electron source. One of critical beam properties is
electron beam energy. There are two locations that we need to measure electron beam energy in our injector system downstream the RF gun and the linac. The aim of this research focuses on the measurement of energy downstream the RF gun using the alpha magnet with its energy slits and the current transformer. We also analyzed the calibration of energy slits’ position and the stepping motor counter to calculate the electron energy. Furthermore, we estimated the accuracy of energy measurement by investigating electrons’ trajectories in the alpha magnet’s field using a particle tracking software ASTRA [1].

The alpha magnet has the structure like half-quadrupole magnet with a front iron mirror plate for terminating the magnetic field at the beam entrance. This magnet is placed downstream the RF gun as shown in figure 1 for magnetic bunch compression and energy filtering. The intensity of magnetic field linearly varies with the radius of the opening aperture between the magnetic poles. The electron beam is injected into the alpha magnet’s field in the x-z plane, thus the trajectory of each electron inside the magnetic field follows the Greek alphabet alpha as illustrated in figure 2.

| Figure 1. The alpha magnet (red object) installed downstream the RF gun. |
| Figure 2. Coordinates and trajectories of electrons with three different energies in alpha magnet’s field. |

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z_{\text{max}}(cm) = 75.051 \sqrt{\beta \gamma / g (G/cm)},
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where \( \beta = v/c \) and \( \gamma \) is the Lorentz’s factor. When the beam consisting of electrons with different energies moves through the magnetic field in the alpha magnet, the path length of higher energy electron is longer than that of lower energy electrons. Therefore, we can use the energy slits located in the alpha magnet vacuum chamber to select the part of electron beam with certain energy range. The current transformer is then used to measure the beam current downstream the alpha magnet exit.

2. Methodology

In the experiment, calibration of the energy slits was conducted before installing them in the vacuum chamber. The setup of alpha’s magnet energy slits used in the calibration is shown in figure 3. The positions of low and high energy slits were measured for various stepper motor encoder numbers. Then, the calibration result was imported into the energy calculation software that links to the stepper motor. When the stepper motor moves the energy slits to cut the beam, the energy value will then be automatically calculated with equation (1). The calibration data is presented in figure 4. The linear fitting equations of the calibration lines are \( z \ [mm] = 0.0053 \ C + 9.5337 \) for high energy slit and \( z \ [mm] = -0.0054 \ C + 12.829 \) for low energy slit.
The electron dynamic simulations using a particle tracking software ASTRA were performed to investigate electron trajectories in the alpha magnet’s field with different initial conditions of electron transverse position and angle at the magnet entrance. The 3D magnetic field distribution inside the alpha magnet is obtained from the simulation with software CST EM Studio [3] as described in [4]. Finally, the simulation results were used to estimate the value and accuracy of energy measurement using the alpha magnet.

3. Results and discussion
To estimate the accuracy of energy measurement using alpha magnet, the electron’s trajectory inside the alpha magnet’s field was investigated for the case of without the fringe field effect, the injection angle of 40.71° was adjusted to inject the electron to the vertex of the alpha magnet, which was obtained from [2]. The alpha’s magnetic field gradient of 2.05 T/m was used to all simulations in this study. This gradient provides the shortest electron bunch length [4]. The diameter inside the vacuum chamber at the alpha magnet entrance is about 22 mm, therefore the possible entering electron positions in horizontal and vertical directions were varied from -11 to 11 mm.

The electron trajectories with different initial horizontal positions for various electron energies are shown in figure 5. The simulation results show that there are different maximum distances in z axis of particles with different horizontal entrance positions. Thus, from equation (1) there are several energy values that can be measured by using energy slits. The error of energy measurement from horizontal position with different electron energies is presented in figure 6(a). At the middle point (x = 0), the energy of electron will be measured to be lower than its actual energy and the measured energy decreases when the distance is moving away from the middle point. Therefore, the energy of electron that has lower energy will be measured with larger error than the value obtained for higher energy electron.

In the vertical direction, the characteristic of energy measuring error is similar to the results for the horizontal direction. Nevertheless, the energy measurement error in the vertical direction is smaller than the horizontal direction as shown in figure 6(b). An example of the trajectories of electrons with different initial vertical positions in z axis and along the path length s in the alpha magnet’s field for the case of 2.5 MeV beam are shown in figure 7. The results indicate that the vertical beam size is almost the same in z axis while the vertical beam is focused inside the alpha magnet along the path length s. This leads to smaller beam size in vertical direction after the beam passing through the alpha magnet.
Figure 5. Electron trajectories inside the alpha magnet’s field with different initial horizontal positions for four beam energies.

Figure 6. The energy measurement errors obtained from electrons with different horizontal positions (a) and different vertical positions (b).

Figure 7. The 2.5 MeV electrons’ trajectories along z axis (a) and along the longitudinal path (b) inside the alpha magnet’s field for different initial vertical positions.
The effect of particle’s angle at the alpha magnet entrance was investigated by determining the initial angle of electrons with the same energy from -3° to 3° in horizontal and vertical axis. The investigation result of initial horizontal angle in figure 8(a) shows that the error of energy measurement increases up to 1% when the initial horizontal angle is increased to 3°. The plot of electron’s trajectories inside the alpha magnet’s field with different horizontal angles in figure 8(b) presents that electrons exit the magnet with slightly different vertical positions. The result for vertical angles in figure 9(a) shows that the error is almost constant around -0.5 % for all initial vertical angles. From the plot of electron’s trajectories inside the alpha magnetic field with different initial vertical angles in figure 9(b) shows that the electrons that have the initial angles less than or larger than 1.5° hit the vacuum chamber before the beam exiting the alpha magnet.

**Figure 8.** The 2.5 MeV electrons’ trajectories inside the alpha magnet’s field with different initial horizontal angles.

**Figure 9.** The 2.5 MeV electrons’ trajectories inside the alpha magnet’s field with different initial vertical angles.

4. Conclusion
In this research, we studied on calibration and estimation of energy measurement accuracy using the alpha magnet. The electrons’ trajectories in the alpha magnet’s field with different initial positions were investigated. We can conclude that the error of energy measurement caused by initial positions is about -0.5%. The error of energy measurement for the initial horizontal positions are larger than the vertical ones. The study on the effect of particle’s angles at the middle of alpha magnet entrance shows that the energy measurement errors increase, respectively, up to 1% and -0.5% when the initial horizontal and vertical angles are increased to 3°.
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