Simulations and measurements of the dipole magnet using in the 4-MeV electron spectrometer

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Abstract. A dipole magnet is one of important components in particle accelerators. It can be used to transport a charged particle beam with desired deflecting angle and direction. Moreover, it is often utilized as a part of an energy spectrometer. This research focuses on simulations and measurements of the dipole magnet, which will be used to measure the electron beam energy produced from the 4-MeV radio-frequency (RF) linear accelerator (linac) for natural rubber vulcanization at the PBP-CMU Electron Linac Laboratory of the Plasma and Beam Physics (PBP) Research Facility in Chiang Mai University (CMU). The research activities are divided into three main parts. The first part focuses on three-dimensional (3D) simulation of the dipole magnet by using the RADIA program. The 3D field map of the magnetic field can be derived from the RADIA model. The second part is the magnetic field measurements of the magnet after the construction. The maximum magnetic field of 248.6 mT can be obtained with an excitation current of 3 A. The last part focuses on the electron beam dynamic study by using the program called ASTRA to track the particles though the 3D magnetic field distribution. The simulation data provides six-dimensional coordinates of the particles at the considered position downstream the dipole magnet. The optimal bending angle of the 4-MeV electron beam in the magnetic field of 0.22 T is 50° with an energy spread of 0.827 MeV.

1. Introduction
The RF linac for natural rubber vulcanization has been developed at the PBP-CMU Electron Linac Laboratory. It will be able to produce electron beams with kinetic energy up to about 4 MeV. Lower beam energies can also be achieved by varying the power of the RF wave supplied to the linac structure [1]. An energy spectrometer consisting of a dipole magnet, a phosphor screen and a CCD camera equipped with an optical readout system will be used to measure the beam energy and energy distribution of electron beams produced from the linac. In this paper, we present the results of the magnetic fields obtained from 3D simulation with RADIA program and from the experimental measurements. Furthermore, the motion of electron beam in the magnetic field was studied from beam dynamic simulations by using program ASTRA. Then, all information obtained from this
research is used to design the proper component positions and specifications for electron beam spectrometer. When an electron with a total energy $E$ moves through the gap of the dipole magnet as shown in figure 1, it will be bent by the magnetic force due to the dipole magnetic field intensity $B$ as [2]

$$\frac{1}{\rho [m]} = \frac{0.2998B[T]}{\beta E[GeV]},$$

where $\rho$ is the radius of the curvature trajectory of electron and $\beta = v/c$ is the normalized electron velocity. Electrons in the beam produced from the RF linac have different kinetic energies. Thus, they are bent with different bending radii at the same magnetic field value. Therefore, we can use the relation in Eq. (1) to define the energy spread of the beam. The layout of dipole magnet and its related devices for measuring the electron beam energy and energy spread are shown in figure 1.

![Figure 1. Layout of the system for measuring electron beam energy and energy spread.](image1)

![Figure 2. Three-dimensional (3D) RADIA model of the dipole magnet.](image2)

2. Simulations and measurement of magnetic field

![Figure 3. Normalized simulated magnetic field distribution in horizontal ($x$) and longitudinal ($z$) direction of the dipole magnet.](image3)

![Figure 4. Normalized simulated and measured vertical magnetic field of dipole magnet along the electron trajectory.](image4)

The dipole magnet was designed by using the program RADIA [3]. Three-dimensional model with dimensions in millimeter obtained from RADIA program are shown in figure 2. In this simulation, the dipole magnet is divided into ten sections. The suitable mesh size in Cartesian coordinates are $(7, 7, 7)$
mm for eight pieces of yoke and (7, 7, 140) mm for the two poles. These suitable mesh sizes were obtained from the optimization of mesh numbers that provides the magnetic field value converged to the constant and reliable value. The normalized magnetic field distribution in horizontal (x) and longitudinal (z) direction of the dipole magnet obtained from RADIA simulation is illustrated in figure 3. The normalized simulated vertical magnetic field (B_y) along the electron trajectory is shown in figure 4.

Magnetic field distribution of the dipole magnet can be obtained by using the magnetic field measuring system that consists of a linear actuator, a Hall probe, a shunt impedance, a Tesla meter, a Voltage meter, an Ammeter, a computer with control interface, a power supply and the dipole magnet. The Hall probe was set on the translating actuator and moved along the z-direction with the step size of 2 mm. The measured normalized vertical magnetic field along the electron trajectory are presented together with the simulated results in figure 4. Both data are comparable. The effective length of this magnet is equal to 57.1 mm. Specifications of the dipole magnet are shown in Table 1.

### Table 1. Specifications of the dipole bending magnet.

| Parameter                        | Value          |
|----------------------------------|----------------|
| Dipole gap (h)                   | 1.84 cm        |
| Number of coil turns (n)         | 1234 turn      |
| Maximum applied current (I)      | 3.0 A          |
| Maximum magnetic field (B)       | 248.6 mT       |
| Magnetic field effective length  | 57.1 mm        |

3. Beam dynamics simulations

Electron beam dynamic simulations were performed by using program ASTRA [4] to track electrons through the magnetic field of the dipole magnet. This study aims to find the relationship between the bending angle, the magnetic field intensity and the transverse distribution of the electron beam with kinetic energy of about 4 MeV. As mentioned in equation (1), when the magnetic field intensity is fixed, the radii of the electrons’ trajectories depend on their kinetic energies. Therefore, in the experiment the positions of electrons on the screen are at different positions. The transverse beam positions on the screen and the corresponding kinetic energy values can be used to calculate the energy spread ε of the electron beam from [5]

$$\varepsilon = \pm \frac{E_{k,\text{max}} - E_{k,\text{min}}}{2E_{k,\text{avg}}} \times 100\%,$$

(2)

where $E_{k,\text{max}}$ is the maximum kinetic energy, $E_{k,\text{min}}$ is the minimum kinetic energy, and $E_{k,\text{avg}}$ is the average kinetic energy. Furthermore, the beam dynamic simulation was done in order to estimate the trajectory of electron beam though the 3D magnetic field distribution obtained from the RADIA simulation (figure 3). The essential parameter for simulation is the dependence of magnetic field intensity (B) on the applied current (I) as shown in figure 5 (left). The magnetic field has a linear relationship with the applied current in the considered range of 0 to 3 A.

The simulation of electron trajectory through the dipole magnetic field was done for different electron beam energies. As an example, the simulated trajectory of electron traveling through the dipole magnet with an average kinetic energy of 3.995 MeV and the magnetic field intensity of 0.22 T is shown in fig. 5 (right). Furthermore, to investigate the bending angle and energy spread of electron beam for average energy of 3.995 MeV, the magnetic field intensity of the dipole magnet was varied from 0.06 to 0.22 T with the step of 0.02 T. The simulation results in fig. 6 show that when the magnetic field intensity increases, the bending angle increases while the energy spread of electron beam at $z = 530$ mm decreases. Thus, the optimal bending angle was chosen for the lowest energy spread that is about 50°.
The optimal screen position should be at the $x = 80$ mm and $z = 480$ mm. The optimal magnetic field intensity for this energy is 0.22 T, which is equivalent of the applied current of 2.61 A.

![Graph](image)

**Figure 5.** Simulated excitation curve for the dipole magnet (left) and simulated trajectory of an electron traveling through the dipole magnet with an average kinetic energy of 3.995 MeV and the magnetic field intensity of 0.22 T (right).

The resolution of the electron spectrometer at this energy can be calculated from the average kinetic energy and the energy spread. For the average kinetic energy of 3.995 MeV, the energy spread after passing through the dipole magnet is $\pm 0.827$ MeV. Then, the maximum and minimum kinetic energies has the different value of 1.654 MeV. As a result, the resolution $(\Delta E/E)$ of this spectrometer is equal to 0.414 MeV. The resolution of the spectrometer depends greatly on energy spread. Thus, the resolution of the spectrometer can be improved by adding energy slit in the experimental setup to cut electron beam before it travels through the dipole magnetic field.

![Graph](image)

**Figure 6.** Relationships between the bending angle and energy spread for different magnetic fields. The simulated beam has average kinetic energy of 3.995 MeV.

4. **Conclusion**

The spectrometer system including the dipole magnet, the phosphor screen and the CCD camera with proper optical readout was designed and optimized for measurements of electron beam with the maximum kinetic energy of about 4 MeV. According to the study results, the effective length of the
dipole magnet is equal to 5.71 cm. The magnetic field intensity from simulation and measurement are comparable. The optimal bending angle of electron beam in the magnetic field of 0.22 T is 50° with the energy spread of 0.827 MeV. The positions of dipole magnet and the phosphor screen were defined. The results of this research can then be used to design a proper spectrometer system for measurements of electron beam energy and energy spread. The energy resolution of 0.414 MeV can be expected from of this spectrometer.

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