Design and Development of Emittance Measurement Device by Using the Pepper-pot Technique

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Abstract. Transverse emittance of a charged particle beam is one of the most important properties that reveals the quality of the beam. It is related to charge density, transvers size and angular displacement of the beam in transverse phase space. There are several techniques to measure the transverse emittance value. One of practical methods is the pepper-pot technique, which can measure both horizontal and vertical emittance value in a single measurement. This research concentrates on development of a pepper-pot device to measure the transverse emittance of electron beam produced from an accelerator injector system, which consists of a thermionic cathode RF electron gun and an alpha magnet, at the Plasma and Beam Physics Research Facility, Chiang Mai University. Simulation of beam dynamics was conducted with programs PARMELA, ELEGANT and self-developed codes using C and MATLAB. The geometry, dimensions and location of the pepper-pot as well as its corresponding screen station position were included in the simulation. The result from this study will be used to design and develop a practical pepper-pot experimental station.

1. Introduction

Emittance measurements using the pepper-pot technique is widely used to measure transverse emittance of charged particle beams at several laboratories [1-5]. This method has several advantages. First, it can provide information about a beam profile and a beam divergence in one measurement. Second, in a single measurement it can measure both horizontal and vertical emittance values. Furthermore, the pepper-pot technique is not prone to space charged effect. This is a strong advantage of this technique compared to other techniques e.g. the quadrupole scan method. Thus, it is a suitable method to measure the transverse emittance of electron beams with high charge and low energy.

At the Plasma and Beam Physics (PBP) Research Facility, Chiang Mai University (CMU), the electron beam is produced from a thermionic cathode RF electron gun with a maximum energy of around 2.5 MeV and a maximum charge of about 0.2 nC per micro-bunch [6]. Since the electron beam has quite low energy and large bunch charge, the emittance measurement of the beam has to be careful, especially for the space charged effect. Therefore, this study is interested in using the pepper-pot technique to measure the transverse emittance. In this paper, we describe the overview of the experimental station, the design of the pepper-pot device and the simulation of the emittance measurement.

The pepper-pot device consists of a pepper-pot plate with identical holes and an observation screen station at a distance L from the plate as shown in figure 1. The concept of the pepper-pot method is that
when the beam incidents the pepper-pot plate, the plate stops the main part of the beam and allows only small beamlets passing through the holes and traveling to the screen. The images of the beamlets on the screen are detected and analysed. The angular displacement ($x'$) can be obtained in terms of a slope from the point ($x,y$) at the pepper-pot plate to the point ($u,v$) on the screen [7], which is

$$x' = \frac{(u-x)}{L}, \quad y' = \frac{(v-y)}{L}. \quad (1)$$

![Figure 1. The diagram of the pepper-pot device and its corresponding screen station.](image)

We can plot the angular displacements of electron beamlets versus the hole positions as an ellipse phase space. Then, the emittance value can be defined by using equation (2), where $A$ is the area of the phase space ellipse and $\varepsilon$ is the geometric emittance.

$$\varepsilon = \frac{A}{\pi}. \quad (2)$$

In this research, the beam dynamics simulation of electron beam travelling through the RF-gun and the alpha magnet was firstly performed by using programs PARMELA [8] and ELEGANT [9]. Then, the pepper-pot plate and its holes as well as the position of the observation screen station were designed based on the results of the electron beam dynamics simulation. The calculation of the emittance value was done with a self-developed C code. Finally, the self-created MATLAB script [10] was used to analyse the simulation data.

2. Methodology

The PARMELA program was used to specially study the beam dynamics inside the RF gun. The output of PARMELA simulation was converted to be the input of program ELEGANT, which was employed to study the beam transportation through the beamline. Figure 2 shows the accelerator setup used in this study. The RF electron gun with a thermionic cathode was utilized to produce electron beam. While electron beam travelling in the vacuum tube, the quadrupole and steering magnets were used to focus the beam and to control the beam direction, respectively. The beam pulse current was measured by using current transformers CT1 and CT2. The pepper-pot plate and its observation screen position are downstream the alpha magnet. A dipole magnet at the end of the accelerator system was used for electron beam dumping. From the beam dynamics study, we obtained the particle distributions for both transverse and longitudinal directions.

The thickness of the pepper-pot plate was defined by using the Monte Carlo program GEANT4 [11]. Then, the pepper-pot geometry and dimensions were designed by using a self-developed C code. The hole spacing was optimized to obtain the appropriated spacing value for separating the beamlets at the screen position. For the optimal hole spacing, the hole radius was varied to define the optimal value that provides the transverse emittance close to the value obtained from ELEGANT simulation. The peak positions of the beamlets spots on the screen were compared to the hole positions at the pepper-pot plate.
to calculate the angular displacement by using equation (1). Then, the position and the angular displacement value of each hole were plotted. Finally, the phase space distribution was constructed by using the ellipse fitting with least square method. The emittance values were then calculated from the area of the ellipse phase space.

![Accelerator setup and the pepper-pot station.](image)

**Figure 2.** Accelerator setup and the pepper-pot station.

### 3. Results and discussion

The pepper-pot device is designed to be located at 64.65 cm downstream the alpha magnet, which is used for energy filtering and bunch compression [12]. In this study, we used alpha magnet energy slits to filter out electrons with energy lower than 1.70 MeV because their position are outside the vacuum tube. The parameters of electron beam used in ELEGANT simulation are shown in table 1. The transverse distributions and phase spaces of electron beam at the pepper-pot plate before passing through the holes are shown in figure 3. The area of the phase space ellipses yield the emittance values of 24.89 and 20.92 mm.mrad for horizontal and vertical directions, respectively.

**Table 1.** Electron beam parameters at the pepper-pot plate used in ELEGANT simulation.

| Parameter                    | Value | Unit |
|------------------------------|-------|------|
| Maximum Energy               | 2.50  | MeV  |
| Minimum Energy               | 1.70  | MeV  |
| Average Energy               | 2.29  | MeV  |
| Horizontal rms beam size     | 2.39  | mm   |
| Vertical rms beam size       | 2.61  | mm   |
| Charge per micro-bunch       | 0.15  | nC   |

![Simulated transverse distributions of electron beam at the pepper-pot plate.](image)

**Figure 3.** Simulated transverse distributions of electron beam at the pepper-pot plate.
The pepper-pot plate made of tungsten due to its properties that can prevent the electron beam to passing though. The thickness of the plate must be thick enough to stop the beam and also thin enough to minimise the beam scattering. The energy absorption at each distance in tungsten was studied with program GEANT4 and the simulation result is shown in figure 4. The thickness of 0.5 mm is chosen because it can stop most of the beam.

![Energy absorption as a function of distance in tungsten.](image)

**Figure 4.** Energy absorption as a function of distance in tungsten.

The results from beam dynamics simulation show that the optimal spacing between the pepper-pot holes is 3 mm. With this spacing value, the beamlets’ images are well separated on the screen as shown in figure 5. Then, the holes radius was varied from 0.2 mm to 0.5 mm to define the optimal hole radius. The results show that the hole radius of 0.25 mm provides the emittance value obtained from the pepper-pot method close to the value obtained from ELEGANT simulation. The least square method of ellipse fitting is used to define the phase space ellipses of the electron beam at the pepper-pot plate and the results are shown in figure 6. The horizontal and vertical phase ellipses obtained from ELEGANT simulation are smaller than the phase space ellipses obtained from the pepper-pot method. This leads to 6.3% and 3.6% smaller emittance values for horizontal and vertical axes, respectively. The results are compared in table 2.

![Transverse distributions of the electron beam at the pepper-pot plate (left) and at the screen position (right).](image)

**Figure 5.** Transverse distributions of the electron beam at the pepper-pot plate (left) and at the screen position (right).

![Phase space ellipses of electron beam at the pepper-pot plate.](image)

**Figure 6.** Phase space ellipses of electron beam at the pepper-pot plate.
Table 2. Emittance values obtained from ELEGANT simulation and from simulated pepper-pot method.

| Emittance value (mm.mrad) | ELEGANT | Pepper-pot |
|----------------------------|----------|------------|
| Horizontal emittance       | 24.89    | 26.56      |
| Vertical emittance         | 20.92    | 21.71      |

4. Conclusion
The pepper-pot device was designed for measuring the transverse emittance value of electron beam produced from the injector system of the PBP-CMU Linac Laboratory. The material, geometry and location of the pepper-pot plate and its observation screen were studied. We found that the tungsten plate with the thickness of 0.5 mm is suitable for using as the pepper-pot plate. The optimal hole spacing and radius are 3 mm and 0.25 mm, respectively. The horizontal and vertical emittance values, which were calculated from the phase space ellipses by using the pepper-pot method, are 6.3% and 3.6% larger than the values obtained from the ELEGANT simulation. The results of this study will be used to develop the experimental station for the emittance measurement in the near future.

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6. References
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