Beam Dynamics Simulation of Photocathode RF Electron Gun at the PBP-CMU Linac Laboratory

K. Buakor [1], S. Rimjaem [1,*]

Plasma and Beam physics research facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand
E-mail: khachiwanb@gmail.com, sakhorn.rimjaem@cmu.ac.th[*]

Abstract. Photocathode RF electron guns are widely used at many particle accelerator laboratories because of the high quality of the produced electron beams. By using a short-pulse laser to induce the photoemission process, the electrons are emitted with low energy spread. Moreover, the photocathode RF guns are not suffered from the electron back bombardment effect, which can cause the limited electron current and accelerated energy. In this research, we aim to develop the photocathode RF gun for the linac-based THz radiation source base on the existing gun design. The gun consists of a one and a half cell S-band standing-wave RF cavities with a maximum electric field of about 60 MV/m at the centre of the full cell. We study the beam dynamics of electrons traveling through the electromagnetic field inside the RF gun by using the particle tracking program ASTRA. The laser properties i.e. transverse size and injecting phase are optimized to obtained low transverse emittance. In addition, the solenoid magnet is applied for beam focusing and emittance compensation. The proper solenoid magnetic field is then investigated to find the optimum value for proper emittance conservation condition.

1. Introduction

The linac-based THz Free-electron laser is under the development at the Plasma and Beam Physics (PBP) Research Facility, Chiang Mai University. To improve the quality of produced THz radiation, the electron beam quality from the injector system is needed to be considered. Due to several advantages of a photocathode RF-gun, the plan to operate the present thermionic gun via the photoelectric effect with a short laser pulses in ongoing. Unlike thermionic RF-guns, the electron emission of photocathode guns is controlled by a short-pulses laser system. Moreover, the injected time of the laser can be adjusted such that electrons are not emitted when the RF phase is not suitable for electron acceleration. Thus, there is no electron back-bombardment effect, which can affect the electron beam loading and can damage the surface of a cathode as well as shorten its life time. In addition, the photocathode guns can generate an electron beam with smaller transverse beam emittance and high bunch charge.

An S-band thermionic radio-frequency (RF) electron gun has been developed at the PBP-CMU Linac Laboratory. It was optimized to generate the electron beam with a short bunch length. The gun has one and a half cell standing-wave cavities, which were designed to resonate at 2856 MHz in π-mode. The RF wave from the klystron passes from the full-cell to the half-cell through a side-coupling cavity. Thus, the whole RF-gun is operated in $\pi/2$ mode. In order to generate the electron beam with a maximum kinetic energy of about 2-2.5 MeV, maximum electric fields in the full- cell and the half-cell have to be 64.29 and 31.91 MV/m, respectively [1]. In this research, we study on a possibility to

adopt the thermionic RF gun for the photocathode operation via beam dynamics simulation with program ASTRA [2]. The electric field distribution that we input in this simulation was obtained from SUPERFISH program [3]. The wavelength and time duration of laser pulses that we used in the simulation are 266 nm and 7.5 ps FWHM, respectively [4].
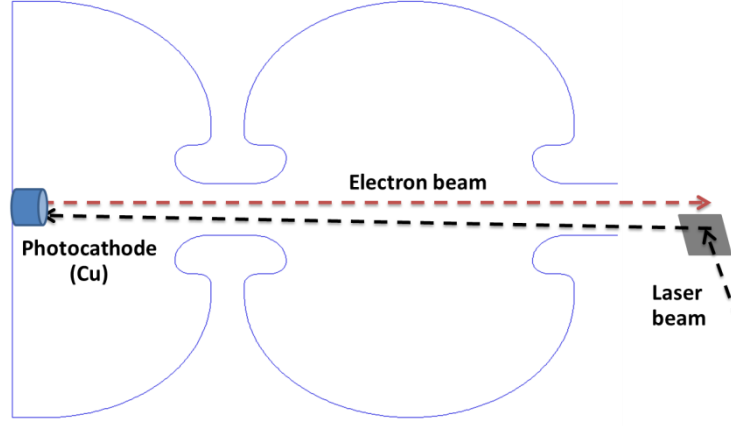

Figure 1. The adaptation of the thermionic RF electron gun to be operated as a photocathode RF gun.

The performance of a photocathode RF gun depends greatly on the properties of cathode material especially the quantum efficiency (QE), which is defined as a ratio of the emitted electron to the absorbed incident photon. For preliminary study, a copper (Cu) cathode was used in this study. The parameters of atomically clean copper for the simulation are listed in Table 1 [5]. Quantities $\emptyset_w$, $\emptyset_{Schottky}$ and E_{ph} are the work function of the material, the Schottky correction and the photon (laser) energy, respectively.

Table 1. Properties of atomically clean copper used in simulation [5].

Parameters	Value
Work function, $\emptyset_w$	4.31 eV
$\emptyset_{Schottky}$ at 31.91 MV/m	0.214 eV
Photon energy at 266 nm	4.66 eV

2. Optimization of simulation setup

To obtain reliable beam parameters from beam dynamics simulation, we need to optimize the input parameters i.e. number of macro-particles and mesh size of space-charge calculation. Gaussian and radial uniform distributions were considered to be used as transverse distributions of initial electron pulses. Both distributions were generated with program Generator [2]. Simulation with different bunch charges was performed to investigate the performance of the gun with different beam loading. Thus, we study and compare the results of 100 and 400 pC per bunch.

Optimization of particle numbers

To optimize the number of macro particles, both longitudinal and transverse properties are considered. Besides, the space-charge calculation is switched off for this optimization. The laser spot size and the RF phase of 1 mm and 0 degree were used, respectively. Simulation results as shown in an example in fig. 1 reveal that the beam properties for both transverse and longitudinal directions are constant when

the macro-particle number is larger than 200,000 for both radial uniform and Gaussian distributions as well as for a bunch charge of 100 pC and 400 pC.
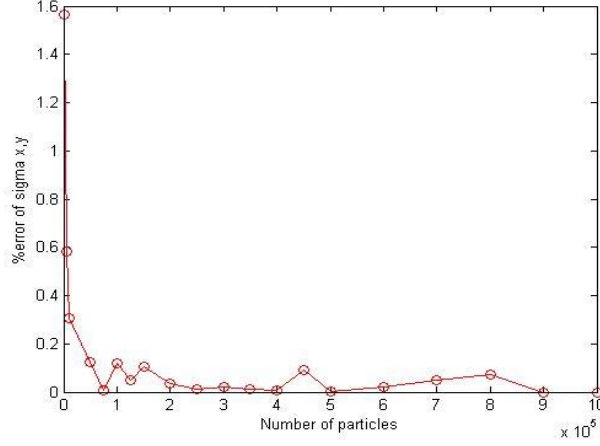

Figure 2. An example of percentage error for a transverse beam size in macro-particle number optimization. This simulation was done with radial uniform distribution and a bunch charge of 100 pC.

Optimization of space charge mesh size

In this study, we used a cylindrical grid algorithm for the space-charge calculation. Thus, three parameters, which are time steps of emitted electron, radial mesh number and longitudinal mesh number, were considered. To optimize the time steps of emitted electrons, we only consider the longitudinal properties, which are average kinetic energy, energy spread and bunch length. Results of simulation with the radial uniform distribution suggest that the longitudinal beam properties are constant when the time steps of emitted electrons are more than 1000 for a bunch charge of 100 and 400 pC. In addition, the simulation with Gaussian distribution was performed and the results show that the longitudinal beam parameters are constant when the time steps of emitted electron are more than 1000 for the bunch charge of 100 pC, while the time steps should be larger than 2500 for 400 pC.

For the radial mesh size optimization, the transverse properties of the electron beam i.e. beam size, divergence and emittance were considered. The optimal radial mesh size of the electron bunch for both radial distributions are 0.7151 and 0.4767 mm, respectively. To optimize the longitudinal mesh size, we only consider the longitudinal properties, which are average kinetic energy, energy spread and bunch length. From the results of simulation with 100 pC bunch charge, the optimum longitudinal mesh size for both radial uniform and Gaussian distributions is 1.480 mm. The simulation results of 400 pC bunch charge show that the optimal longitudinal mesh sizes for both radial distribution are 0.9868 mm and 1.7762 mm, respectively.

3. Beam dynamics simulation

In this research, we firstly considered the transverse emittance, which relates to the transverse beam size and the divergence, of electron bunch after accelerating along the gun. A laser spot size and a solenoid magnetic field, which affect significantly on the beam emittance, were optimized to obtain the smallest transverse beam emittance that can be achieved from this considered RF-gun. Dependencies of average energy and energy spread on a maximum accelerating phase were investigated and the results are shown in fig. 3. The simulation was done with transverse Gaussian and radial uniform distribution for the bunch charges of 100 pC and 400 pC.

Optimization of the laser transverse size with the initial radial uniform distribution was conducted. The minimum emittance values of 0.34 and 0.76 mm.mrad are achieved for the laser spot sizes of 1.085 and 3.099 mm at a bunch charge of 100 and 400 pC, respectively.
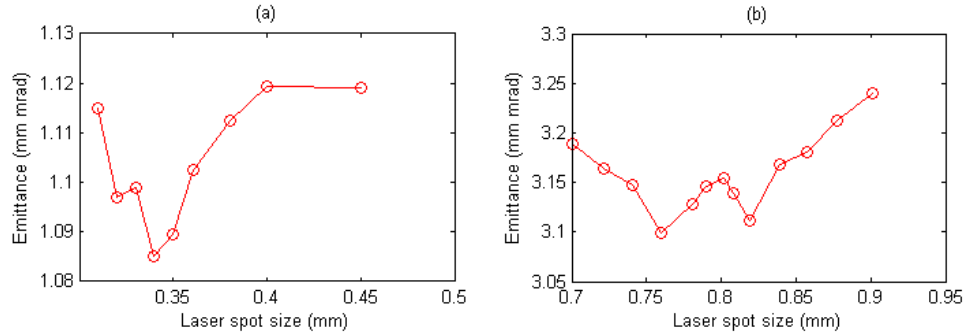
Figure 3. Results of laser spot size optimization for the radial uniform distribution with a bunch charge of 100 pC (a) and 400 pC (b).

The solenoid magnet is applied for beam focusing and transverse emittance conservation. In this research, proper solenoid magnetic field was investigated in order to generate the electron bunch with a charge of 100 pC for the radial uniform distribution. The results are shown in fig. 4.
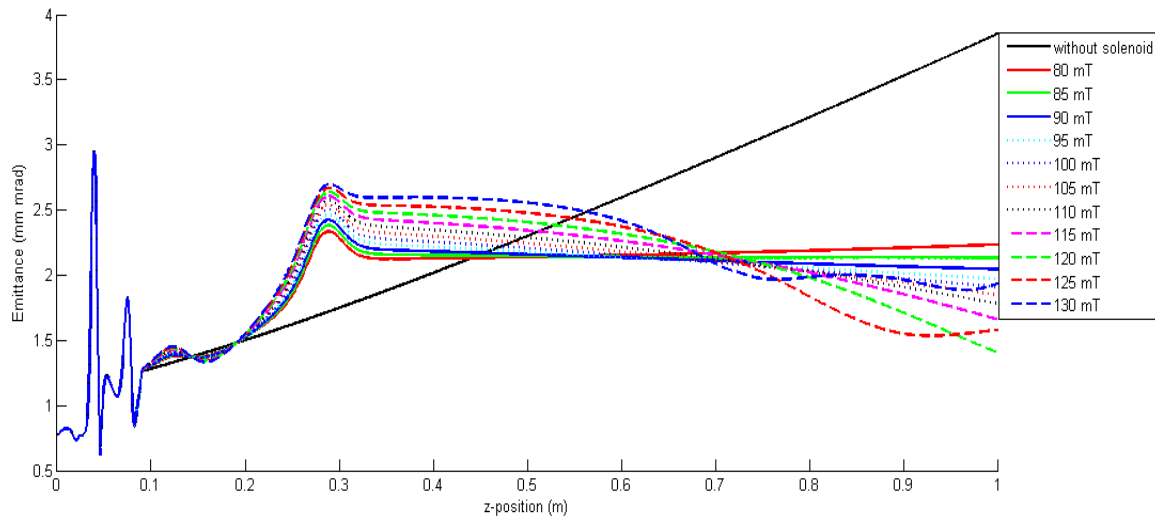

Figure 4. Simulated transverse emittance along the z-position for different solenoid magnetic fields with a bunch charge of 100 pC.

4. Conclusion

The thermionic RF electron gun at the PBP-CMU Linac Laboratory can be adopted to operate as a photocathode gun by using a laser system with a pulse duration of 7.5 ps (FWHM) and laser wavelength of 266 nm. From simulation results, the emittance of an electron bunch with initial radial uniform distribution is smaller than the one with the Gaussian distribution. Therefore, the laser injection with an aperture much smaller than the rms transverse width of the laser pulse is chosen. The laser spot sizes of 1.085 and 3.099 mm are suitable for the bunch charge of 100 and 400 pC, respectively. Moreover, the emittance of the electron bunch is influenced from an applied solenoid field. This results in conservation of emittance after passing through the solenoid magnet. From simulation with a bunch charge of 100 pC, the emittance of 2.2 mm.mrad can be obtained at 0.6 m downstream the cathode by applying the solenoid magnetic field of 85 mT.

5. Acknowledgements

References

[1] Rimjaem S et al. 2014 RF study and 3-D simulations of a side coupling thermionic RF-gun *Nucl Instrum Methods A* **736** 10

[2] Flottmann K, ASTRA Particle Tracking Code< http://www.desy.de/~mpyflo/ >

[3] Young L.M. and Billen J.H 1999 Los Alamos National Laboratory Technical Note LA-UR-96-1834

[4] Zen H et al. 2014 *Proc of FEL2014 (Basel:Switzerland)* p 828-831

[5] Dowell D and Schmerge J 2009 Quantum efficiency and thermal emittance of metal cathodes *Phys. Rev. ST Accel. Beams* **12** 119901