CHAPTER 5

Conclusion

The photocathode RF-gun of the compact accelerator for generation of the THz-FEL at Kyoto University is operated in the π-mode with the RF frequency of 2856 MHz. The high power RF system transfers the RF wave into the RF-gun with repetition rate of 10 Hz and the RF pulse duration of 2 μs. During this study, the RF peak powers of 4.7 to 8.9 MW were used. In this study, the copper cathode was used. The photocathode drive laser is produced from the mode-lock laser system. It injects 1-4 laser pulses to the cathode with the frequency of 89.25 MHz. The laser media is a neodymium-doped yttrium orthovanadate, which produces laser pulses with a fundamental wavelength of 1064 nm. Then, the laser with the fundamental wavelength is converted by SHG and FHG crystals to reach the wavelength of 266 nm.

Electrons are produced when laser pulses hit the cathode surface at a suitable RF phase for acceleration of electrons inside the RF-gun. After emitted from the cathode surface, electrons are accelerated in the first half-cell resonant cavity to reach a maximum kinetic energy of around 1.4 MeV. Then, they are further accelerated inside the second full-cell resonant cavity and reach the RF-gun exit with the average kinetic energy of about 4.6 MeV. In this reseach, several electron beam paramaters were studied. Both simulations and measurements were performed to investigate the properties of electron beams produced from the photocathode RF-gun.

5.1 Study of Electron Bunch Charge

A measurement called the phase scan method, which is a bunch charge measurement as a function of the laser injection phase, was performed. Electrons are produced when the drive laser with a pulse duration of 8 ps shines upon the cathode surface. Then, the electron bunch charge was measured by using a Faraday cup. Since the laser pulse energy is proportional to the laser intensity, the amount of bunch charge is proportional to both the laser intensity and pulse energy. In addition, the work function of the cathode material is reduced by an influence of the high electric field in order of tens MV/m at the cathode surface due to the Schotty effect. This results in increasing of emitted electrons for certain laser energy.

A magnitude of the electric field on the cathode surface is related to the laser injection phase. The measurement results show that near a zero-crossing phase the bunch charge linearly increases with the laser injection phase. The amount of bunch charge is maximum at the phase of around 70-80 degree for all laser pulse energies. Then, the bunch charge decreases when the laser injection phase is larger than 90 degree.

5.2 Study of Electron Beam Energy

In this study, the energy of electron beam after exiting the RF-gun was measured by using a dipole magnet and a fluorescent screen. The measurements were performed in air environment. The Mylar window was attached to the end of the vacuum chamber for keeping a vacuum condition in the accelerator system. The energy lost in the Mylar window and in air is very small in this study. A numerical calculation was used to investigate the traveling path of an electron inside a 3-D dipole magnetic field distribution by using the PARMALA program. The calculation results are used to determine the electron energy from the beam image on the fluencent screen in the dispersive section. The beam energy dependence on the RF powers and the laser injection phases were studied for the RF power from 4.7 to 8.9 MW and the laser injection phase from 10 - 100 degree. The beam energy stated in this study refers to an average energy of entire electrons in the bunch.

According to definition of the zero phase in this study, the measured results show that the mean maximum momentum gain (MMMG) phase is around 40 degree when using the RF power of 7.0-8.9 MW. The beam energy is almost constant at the laser injection phases of around 40-50 degree. At the phase larger than 60 degree, the beam energy rapidly decreases and the energy spread increases. The energies of electrons in the bunch are not uniform depending on the laser injection phase and a longitudinal and a transverse profile of the drive laser. Unfortunately, the energy spread of electron beam cannot estimated in this research due to limitation of the measurement equipment.

For simulation part, we studied the influence of the accelerating gradients in the half-cell and the full-cell cavities by using the gradient values of 37 – 52 MV/m and the laser injection phase of 10-100 degree. A simulated reference phase was determined from the maximum mean momentum gain (MMMG) phase. For the gradients of 44-52 MV/m, the MMMG phase is equivalent to the measured laser injection phase of 40 degree. The simulation results show that the tendencies of the beam energy on the accelerating gradient and the laser injection phase are similar to the measurements. The results show that the electron beam with an energy of around 4.6 MeV is produced when the accelerating gradient of around 52 MV/m and the laser injection phase of 40 degree. The minimum beam emittance of around 0.22 mm-mrad is obtained at the position 112 cm downstream the cathode when the solenoid magnetic field is 150 mT.

5.3 Study of Transverse Beam Emittance

The beam emittance is an important property to define the transverse beam quality. It can be estimated from the transverse phase space, which is related to transverse and angular displacements of electrons in the bunch. The beam emittance strongly depends on other beam properties including the beam energy, the energy distribution and the bunch charge. It also depends on the external influence such as the focusing from a solenoid and a quadrupole magnet. For this research, the beam emittance measurement was performed with a quadrupole scan method. The beam emittance dependences on the electron bunch charge, the solenoid magnetic field and the RF phase were studied. The measurement location is around 1 m downstream the photocathode.

The beam energy distribution and the space charge effect have an effect on the beam emittance. Since, the space charge force is a defocusing force and it is inversely proportional to the beam energy, the beam getting a large divergence when the space charge effect is large. The study results show that the transverse beam size and the beam emittance are proportional to the bunch charge.

The solenoid magnetic field changes the transverse beam properties and the focusing condition. Thus, the beam emittance depends greatly on the solenoid field. In case of the MMMG phase of 40 degree, the minimum beam emittance is around 0.6-0.8 mm-mrad when using the solenoid magnet field of 200 mT. Both simulation and measurement results show that the beam emittance values are low at the laser injection phases lower than 50 degree, where the beam energy is high and the energy spread is small. Therefore, the beam is well focus at the optimal solenoid magnetic field.

The simulation results suggest that at the emittance measurement position of 112 cm, the electron beam with the energy of 4.6 MeV has the minimum beam emittance of around 0.22 mm-mrad. This beam is accelerated from the RF-gun by using the accelerating gradient of 52 MV/m and the laser injection phase of 40 degree when the solenoid magnetic field is 150 mT. Summary of optimal measurement conditions of the accelerator system for electron beam production and acceleration obtained from this research are shown in Table 5.1. The optimal properties of the electron beam, which are produced from the photocathode RF-gun, are summarized Table 5.2.

Table 5.1: Optimal measurement conditions for the electron beam production and acceleration.

Properties	**Value**
Laser pulse energy	20 μJ
Laser pulse duration at FWHM	8 ps
Laser transverse size at FWHM	1.37 mm
Number of laser macropulse	1-4 pulses
Laser repetition rate	89.25 MHz
RF peak power	9 MW
RF resonant frequency	2,856 MHz
RF macro-pulse repetition rate	10 Hz
RF macro-pulse duration	2 μs
Laser injection phase	40 degree
Solenoid magnetic field	200 mT

Table 5.2: Optimal properties of electron beams, which are produced from the photocathode RF-gun.

Properties	Value
Beam average energy	4.6 - 4.7 MeV
RMS transverse beam emittance	0.6 – 0.8 mm-mrad
RMS transverse beam size	0.56 mm
Bunch charge	50 pC