CHAPTER 5

Conclusion

Major results in this thesis are summarized in this chapter. Firstly, the procedure and results of start-to-end beam dynamic simulation by using programs PARMELA and ELEGANT are concluded in section 5.1. The simulation was done is in order to determine the appropriate operation parameters of the PBP-CMU Linac system for generating the coherent undulator radiation. Then, specifications of the undulator magnet and calculated results of the undulator radiation are briefly written in sections 5.2 and 5.3, respectively. The considered radiation properties including a spectrum range and a radiation power are used to compare the expected performance of the undulator radiation produced from the PBP-CMU Linac system.

5.1 Beam Dynamics Simulation

Start-to-end beam dynamics simulation was performed by using the program PARMELA for all components in the PBP-CMU Linac system except the simulation inside an alpha magnet, which the program ELEGANT was used. The electron beam dynamics simulation was divided into three parts including simulation inside the RF-gun, simulation from the gun exit to alpha magnet entrance (GTA), and simulation from the alpha magnet to the experimental station (ATE).

The electric field amplitude in the main full-cell of the RF-gun was optimized to be 41.7 MV/m in order to produce the electrom beam with the maximum energy of 2.5 MeV at the gun exit. When the accelerating electric field in the gun increases, more electrons can depart from the RF-gun and thus the Coulom force is larger. This leads to a larger rms transverse beam size at the gun exit. The rms divergence of the electron bunch decreases after the electrons depart from the RF-gun due to a focusing effect of the RF field. Low-energy electrons located off-axis at the tail of the bunch have smaller transverse size and larger divergence than the high-energy electrons, which are accumulated in the head of the bunch.

The transverse size and divergence of electron beam travelling along the GTA part was controlled by using quadrupole and steering magnets. To avoid the lengthening of the electron trajectories and larger transverse divergence, the quadrupole and steering magnetic fields were carefully employed to focus and guiding the electron beam in the beamline. The electron beam size starts to be larger than the vacuum chamber at the position of the first steering magnet (ST1). Some low-energy electrons with large transverse positions and large divergence angles are lost before the beam entering the alpha magnet. At the alpha magnet entrance, a large fraction of high-energy electrons are concentrated in the head of the bunch with a length of few picoseconds. They have a well correlation between energy and time that is suitable for the bunch compression by using the alpha magnet.

In the ATE part, an alpha magnet gradient, an energy filtering condition inside the alpha magnet and a linac RF phase were optimized to achieve the electron beam with short bunch length, high bunch charge and low transverse emittance at the experimental station. The number of longitudinal mesh for simulation in the ATE part was optimized to be 1800, while the maximum radial mesh number of 30 was applied in this simulation. The longitudinal phase space of the electron bunch is compressed and clockwisely rotated by the magnetic field of the alpha magnet. The compression of the longitudinal beam distribution obviously increases when the alpha magnet gradient is higher. The transverse beam distribution is focused in the vertical direction after the beam exiting the alpha magnet. The energy cut with low energy slit leads to the reduction of the transverse beam emittance and shorter bunch length at the alpha magnet exit. The optimal energy cut value is 2.1 MeV.

When the electron beam is accelerated through the linac, the beam transverse emittance reduces along the linac due to the reduction of the transverse momentum and the RF focusing effect. When the electron bunch entering the linac with on-crest phase (90°) of the RF wave, a large fraction of electrons in the bunch obtain similar linac RF phase and gain almost the same maximum energy from the accelerating field. Thus, this electron bunch exits the linac with small energy spread and short bunch length. For offcrest acceleration, electrons in the bunch enter the linac with different RF phases and gain different energies. Hence, the electron bunch in this case has larger energy spread and longer bunch length at the linac exit.

The electron bunch length at the experimental station is determined in three definitions that are the statistic rms bunch length, the FWHM bunch length and the width of the Gaussian fitting. Simulation results show that electron bunch lengths at the experimental station increase as the gradient of the alpha magnet is raised. The energy filtering influences significantly on both transverse and longitudinal beam properties. The simulation results indicate that each linac RF phase corresponds to different alpha magnet gradient and different energy filter condition. The optimal operating parameters of the PBP-CMU Linac system to obtain the electron beam with low energy spread, short bunch length and high bunch charge at the experimental station are the acceleration with the linac RF phase of 87° with the alpha gradient of 209 G/cm and the minimum energy filter of 2.1 MeV.

In this study, the beam dynamic simulation inside the alpha magnet was performed by using the program ELEGANT, which the space charge calculation was not included. However, the influence of this effect can lead to the increase of the bunch length and the beam transverse size after the electron beam moving through the alpha magnet. Consequently, the optimal gradient of the alpha magnet is expected to be higher when the simulation in the alpha magnet includes the space charge calculation. Similar influence is also expected in practice.

5.2 Undulator Magnet

An electromagnetic undulator with 30 periods and 64 mm period length will be installed downstream the linac structure at the PBP-CMU Linac Laboratory for generation of coherent THz undulator radiation. The undulator magnet prototype was designed and constructed by K. Thaijai-un. It has a peak magnetic field of 50 - 167 mT corresponding to undulator parameters of 0.3 - 1.0.

The measurement results of the undulator prototype show that the magnetic field of the end poles was uncompensated. This will significantly affect to the deflecting angle and the electron displacement along the magnetic field. It also results in small angular flux density of the undulator radiation. The uncompensated end-poles' field will cause the electron beam to leave from the undulator magnet with non-zero deflecting angle and off-axis at the end of the magnet. In addition, the angular flux density does not contribute at a certain photon energy. Therefore, the magnetic field integral at two ends of the undulator magnet will be compensated in the future in order to transport the electron beam in and out from the undulator on the central axis with parallel trajectory. In practice, steering magnets also used to correct the electrons' trajectory upstream and downstream the undulator magnet.

5.3 Undulator Radiation

The undulator radiation in a central cone from the electron beam with longitudinal Gaussian distribution was considered and the spectral bandwidth of 3%BW was used to calculate the average power of the radiation in this study. For the electron beam with measured properties and the specifications of the undulator magnet, the estimated average power of about 20 nW to 63 mW for 3%BW corresponding to the radiation wavelengths of around 100 - 1000 μm can be obtained.

Incoherent radiation occurs when the electron bunch length is longer than the wavelength by a factor of 2π or more where the phase of the emitted radiation is random and thus the total power becomes proportional to the number of electrons. In contrast, the total power of the coherent part scales with the number of electron squared. Therefore, the PBP-CMU Linac system should produce the electron beam with the bunch length equal or shorter than 45 μm (150 fs) in order to achieve the coherent undulator radiation at the central wavelength of longer than 100 μm.

The dependency of the spectral power and the electron beam properties including a kinetic energy, a bunch length, and a bunch charge, were studied in this section. The results show that when the undulator parameter is considered in the range of 0.3 - 1, the undulator radiation of higher beam energy covers shorter wavelengths with lower spectral power. The radiated power is higher as the bunch charge of the electron increases. Furthermore, the electron beam with shorter bunch length provides more coherent radiation with higher total power. In case of the electron beam with the optimal operating parameters, the estimated average power of about 2.81 mW/3%BW can be produced for the radiation wavelengths of about 120 µm. The calculated average power of the simulated beam with optimal operating parameters is about 10^4 times higher than the case of the measured beam properties for an undulator parameter of 1.

The undulator radiation is collimated in forward direction and has narrow spectral range at a well specified wavelength. Nevertheless, the required spectral regime of the undulator radiation can be shifted by changing the electron beam energy and/or the undulator parameter, which can be varied by adjusting the current of the undulator conducting coils. The comparison between the undulator radiation and the transition radiation reveals that the average power of the coherent undulator radiation is about 50 times higher than the coherent transition radiation. This indicates that the high intensity of the undulator radiation originates is due to the superposition of the radiation from individual poles of the undulator magnet.