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RF power commissioning and an electron beam diagnostic station for a new RF-gun at Chiang Mai University

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Abstract

This paper presents results of the RF power commissioning for a new thermionic RF electron gun of the linear accelerator system at the Plasma and Beam Physics Research Facility, Chiang Mai University. The research focuses on generation and measurements of a radio-frequency wave for using as a power source for electron acceleration. The low-level RF power measurements were conducted to study the performance of the system. Then, the commissioning of the RF-gun with the high-level RF power obtained from a new 7-MW klystron tube was performed to study the proper condition for the RF-gun operation. The gun temperature was optimized and the proper temperature was about 33^{o}C-34^{o}C. In nominal operation, the RF system produces the RF pulses with the repetition rate of 10 Hz for the proper RF pulse length of 3-4 μs and the maximum peak power of ~3.9 MW. The absorbed RF peak power is 2.7 MW, which leads to the average power of 81 W. In order to investigate the influence of the asymmetric electromagnetic field distribution inside the RF-gun, an integrated electron beam diagnostic station has been developed and is installed in the accelerator beam transport line. The results of the RF commissioning and development of the diagnostic system for measurements of the electron pulse current, the transverse beam emittance and the beam energy are reported and discussed.

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Keywords: RF power commissioning; RF system; thermionic RF-gun; beam diagnostic system

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1. Introduction

The electron linear accelerator (linac) system at the Plasma and Beam Physics (PBP) Research Facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, is used to produce femtosecond electron bunches for generation of terahertz (THz) radiation. The accelerator system consists of a thermionic RF electron gun, an alpha magnet for magnetic bunch compressor, a travelling wave linac structure and various diagnostic components [1, 2]. A radio-frequency (RF) wave with the frequency of 2856 MHz is used as a power source to accelerate the electrons in both RF-gun and linac. The thermionic RF electron gun consists of one and a half cell standing wave resonant cavities, which are coupled by a side-coupling cell. The cathode is placed at the center of the rear wall of the half-cell. An RF rectangular waveguide is connected at the radial wall of the full-cell. Both the side-coupling cavity and the RF waveguide input port lead to asymmetric electromagnetic (EM) field distribution inside the gun cavities [3].

The current RF-gun was fabricated under the collaboration with the High-energy Optics and Electronics (HOPE) Laboratory, National Tsing Hau University and the National Synchrotron Radiation Research Center (NSRRC), Taiwan, R.O.C [4]. Then, the cavity-tuning as well as low-level RF measurements were performed at PBP by following the optimized design of the previous PBP RF-gun [2]. After the low-level RF tests, the gun has been installed as the electron source of the PBP-CMU linac system. Experimental study to investigate the proper operation conditions for this RF-gun were performed. In this paper, we present the results of the RF measurements for both low and high power levels. An integrated electron beam diagnostic station (as shown in rectangular dash frame in Fig. 1) is developed for studying the properties of electron beams. Status of design and development of main components in the diagnostic station is reported in the second part of this paper.

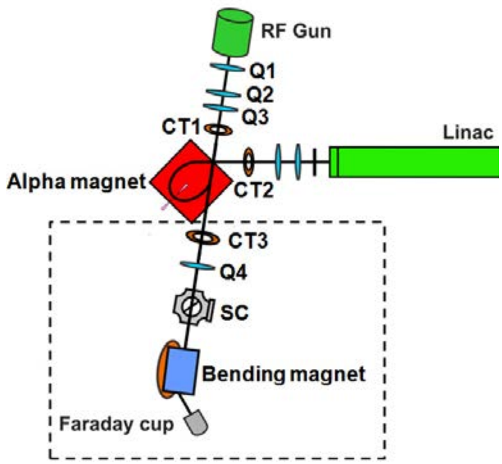


Fig. 1. Layout of the injector section of the PBP-CMU electron linear accelerator.

2. RF system and RF commissioning

The PBP-CMU RF-gun is powered by the 2856 MHz RF wave. The RF system of the whole accelerator composes of 2 sub-systems for RF-gun and linac. Each sub-system has 2 parts; low-level and high-level RF systems. An RF oscillator is used to generate the low power RF wave with the resonant frequency of 2856 MHz. Then, the RF signal is amplified by a pre-amplifier to have a peak power of about 60 W. A -3dB 90^{o} directional coupler is used to divide the RF signal for the RF systems of the RF-gun and the linac. The peak power of the output RF signals downstream the -3dB directional coupler is about 25-30 W. This signal is then increased by an amplifier to reach the maximum power of about 60 W. The measurements of the low-level RF signal were performed for 3 locations; upstream the -3dB directional coupler, downstream the -3dB directional coupler, and upstream the amplifier.

A 7-MW klystron is used to amplify the RF power from watt scale to megawatt scale. The output RF wave has a pulse width depending on the functionalities of the modulator system and the Pulse Forming Network (PFN) system. The output wave is then transported to the RF-gun via a rectangular waveguide. To protect the klystron from the reflected RF wave, an RF circulator is installed between the klystron and the RF-gun. A crystal detector is used to transform a digital signal of the RF wave to an analog signal, which can be read by an oscilloscope.

2.1. Low-level RF commissioning

The low level RF measurements reveal that the maximum RF peak powers measured downstream the RF oscillator and the -3dB directional coupler are 60.5 W and 27.5 W, respectively. The RF pulse downstream the oscillator has nearly rectangular shape, while its shape is close to the triangle pulse after the signal was divided by the -3 dB directional coupler. Then, the signal becomes rectangular pulse again after the amplification by the amplifier. The measurement results for the input power and the output power of the amplifier are illustrated in Fig. 2, which show that the output power starts to be constant at 60 W when the input power is above 18 W.

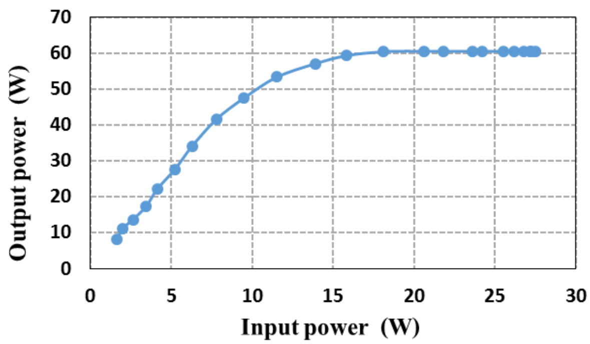


Fig. 2. Output RF-power as a function of the input power of the RF amplifier.

2.2. High-level RF commissioning

In this study, the high power RF system produces the RF pulses with the repetition rate of 10 Hz. The pulse width can be adjusted in the range of 1-8 µs. In the production of the electron beam the RF pulse width was set at about 3-4 µs. A directional coupler upstream the RF-gun is used to measure forward and reflected RF waves. The measured signals were attenuated by RF attenuators to reduce the peak power to be lower than the readout limit of the crystal detector, which is 200 mV [5]. Then, the RF signals were measured with high resolution oscilloscope. The high-level RF measurements were performed for 2 processes. The first process is the measurements of the RF signals before and after the power amplification by the klystron. Another process is the optimization of the RF-gun temperature by adjusting the water temperature of the cooling system.

Two new 7-MW klystron tubes were delivered from the Research Center for Electron Photon Science, Tohoku University, Japan. One new klystron tube has been installed in the klystron housing of the RF-gun in 2014. The commissioning of the klystron was performed and it successfully delivers an RF wave at 2856 MHz with appropriated parameters. Measurements of the RF signals before and after the power amplification by the klystron for three different high voltage levels were conducted. A semi-linear relation between the input and the output powers of the klystronfor all three high voltage levels is shown in Fig. 3.

To optimize the operating temperature of the RF-gun, the water cooling temperature of the gun was varied from 25^{o}C to 50^{o}C. Results in Fig. 4 show that the optimal gun temperature was 34^{o}C for the RF pulse length of 3 µs. As shown in Fig. 5, the maximum forward, reflected and absorbed RF powers are 3.9, 1.1, and 2.7 MW, respectively. The average absorbed RF power is evaluated to be about 81 W. In addition, the high-level RF tests for the RF pulse width of 4 µs were conducted. The results show that the optimal gun temperature for this case is at 33^{o}C, which is

1°C lower than the case of 3 μs pulse width. High-power RF measurement results for two RF pulse widths are reported and compared in Table 1.

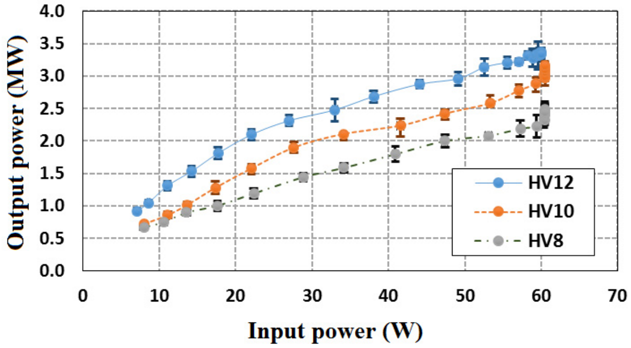


Fig. 3. Output power as a function of the input power of the RF wave with a pulse width of 3 μs for 3 high voltage levels; HV12, HV10 and HV8.

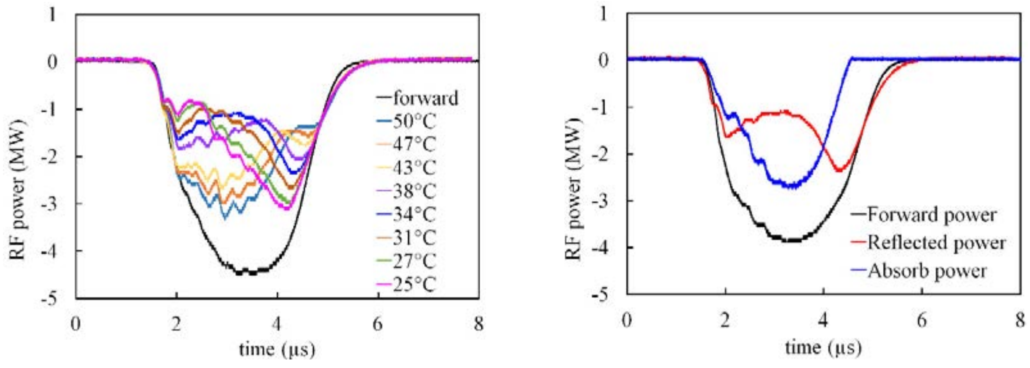


Fig. 4. (a) Forward and reflected RF-signals at 2856 MHz for the gun temperatures of 25°C to 50°C; (b) Forward, reflected, and absorbed RF powers for the gun with the temperature of 34°C.

Table 1. High-power RF measurements for the RF pulse widths of 3 μs and 4 μs.

Parameters	RF pulse width of 3 μs	RF pulse width of 4 μs
Operating temperature (°C)	34	33
Forward RF peak power (MW)	3.9	4.3
Reflected RF peak power (MW)	1.1	1.0
Absorb RF peak power (MW)	2.7	3.3
Absorb average RF power (W)	81	132

3. Electron beam diagnostics station

The electron beam dynamic simulation inside the RF-gun was performed by using the 3D-field distribution from the code CST Microwave Studio 2012© [6]. The particle tracking code PARMELA [7] was used to investigate the particle distribution, transverse profiles, and phase spaces of electron bunch. In the simulations, an electron bunch with a total charge 0.91 nC per RF period are tracked through the RF-gun and the whole beam diagnostic station with radial and longitudinal meshes of 0.42 mm and 0.89 mm, respectively.

The beam with a maximum kinetic energy of 2.63 MeV and a total bunch charge of 0.21 nC is achieved at the gun exit. Due to the typical feature of the thermionic RF-gun, the electron bunch at the gun exit has large energy spread. In order to have efficient post acceleration in the linac, and good beam transportation to the experimental station downstream the linac, energy slits inside the alpha magnet vacuum chamber can be used to filter the electrons with kinetic energies lower than 1.58 MeV [8]. The output beam distributions from the PBP RF-gun show asymmetric transverse shape with the emittance value higher than the beam from the symmetric gun. The problems can be enlarged when the beam is transported from the gun through the accelerator system.

An integrated electron beam diagnostic station has been developed at the PBP-CMU linac facility to study the effect of the asymmetric EM field distribution inside the gun cavities. This station will be installed after the alpha magnet as shown in Fig. 5. The system consists of a current transformer for measuring of the electron beam pulse current, a view screen station, a quadrupole scan setup for the measurements of the transverse beam emittance, and a dipole magnet equipped with Faraday cup for the measurements of electron beam energy and energy spread. This compact beam diagnostic station can be conveniently installed or removed from the main beam line. Detailed study and development of the main components have been conducted and the results are reported in this section.

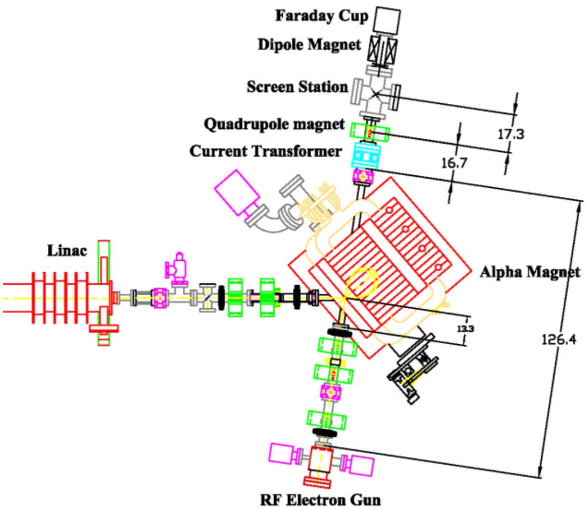
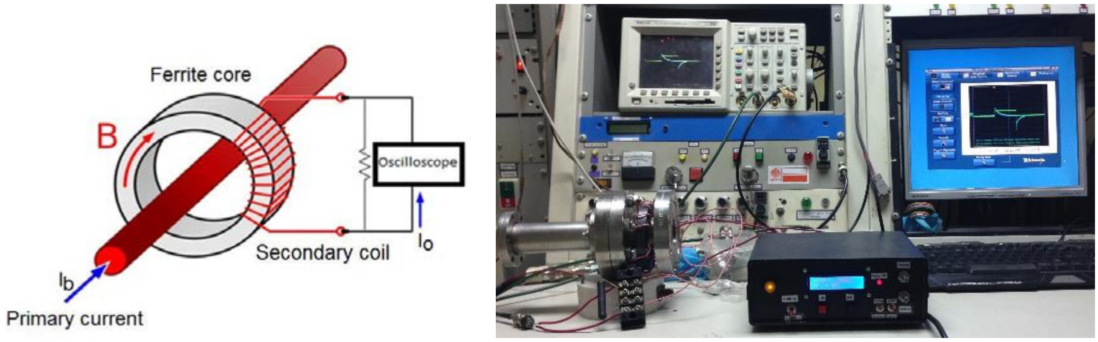


Fig. 5. Drawing layout of the diagnostic station to measure properties of electron beams from the RF-gun.

3.1. Current transformer

A current transformer is used to measure and analyze a pulse current of electron beams. It consists of a ferrite core with high-permeability, a conductor wire wounded around the core forming a secondary coil, and an external resistor to terminate the transformer circuit, which is shown in Fig. 6 (a). The electron current that runs through the transformer acts as the current in the primary coil and it induces an electromotive force in the secondary coil. Therefore, the output signal from the secondary winding can be measured and analyzed to be a current value of the electron beam. In order to develop a reliable current transformer, we investigated the dependence of transformer characteristics on the type of the ferrite core, a number of wounding turns of the secondary coil, a resistance value of the external resistor, and a cross-sectional area of the secondary wire. The test setup of the current transformer is illustrated in Fig. 6 (b).

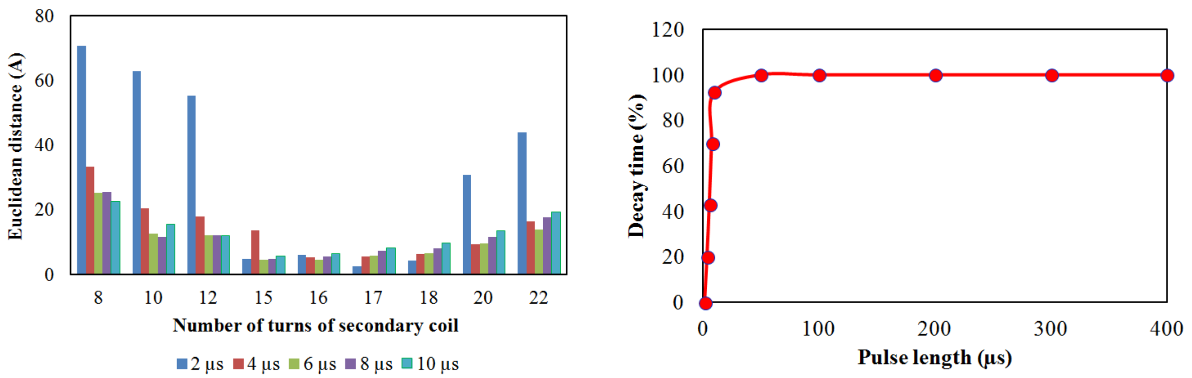
The study results show that the higher the ferrite permeability, the better output signal from the current transformer. The optimum numbers of wounding turns of the secondary coil are 15-17 turns as shown in Fig. 7 (a). In addition, it was found that within the variation range of this study, the external resistances (20-70 Ω) and the cross-sectional area of the secondary wire (0.35-1.27 mm^2) have no significant effect to the measured output signal of the current transformer.



(a) (b)

Fig.6. (a) Schematic picture of the current transformer; (b) Current transformer test setup.

Study on the attenuation of the output signal along the length of the pulse was also perfomed. The results in Fig. 7 (b) show that the longer the pulse, the more decay of the signal at the end of the pulse. For the short pulse of a few microseconds, the current pulse shows almost no attenuation of the signal. The attenuation of the signal increase to 100% at the pulse length of longer than 50 μs. By analyzing the exponential decay curve, the fitting coefficients can be obtained and can be used as the correction terms to improve the value of the measured signal. However, the electron pulses produced from the PBP-CMU linac have the pulse length of about 1-3 μs, thus it is not necessary to add the correction terms to improve the output signal for the current transformers in the accelerator system.



(a) (b)

Fig. 7. (a) Optimization results of number of turns of the secondary coil; (b) Decay time of the current transformer output signal along the pulse.

3.2. Emittance measurement setup

The transverse emittance measurement using the quadrupole scan technique was studied by using the beam dynamics simulation program PARMELA. The technique is used to evaluate the transverse beam emittance by measuring the electron beam size as a function of the quadrupole focal length. In this study, a quadrupole magnet with a maximum gradient of 7.09 T/m is placed downstream the alpha magnet (see Fig. 5). As shown in Fig. 8, the distance from the quadrupole magnet to the screen station (D) is 17.3 cm. The fluorescent screen with dimensions of 4.8 cm × 4.8 cm is planed to be installed in the screen station.

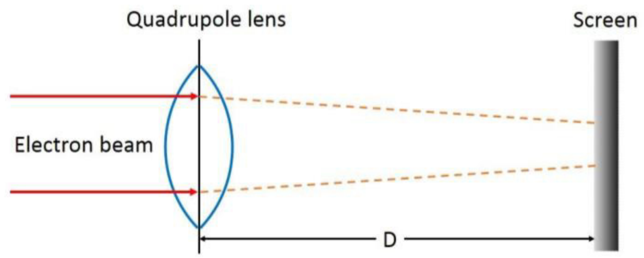


Fig. 8. Emittance measurement setup.

In the simulation of the emittance measurement, the quadrupole magnet focal length (f) was varied and the beam transverse distribution was monitored at the screen position. Two methods were applied to analyze the beam transverse size; the direct calculated rms beam size and the Gaussian fitted beam size obtained from the Beam Emittance Analysis Tool (BEAT) [9]. Examples of the relation between the simulated rms beam size squared and the quadrupole focal length are shown in Fig. 9. The horizontal and vertical emittance values in the case of simulations including space charge effects (with sp) are 15.41 and 10.19 mm·mrad, respectively. The emittance values in the case of simulations without space charge effects (without sp) are 6.84 mm·mrad for the horizontal direction and 5.57 mm·mrad for the vertical one. The estimated emittance values have large error bars due to the large energy spread of the beam, which contributes to uncertainty in defining of the quadrupole focal length.

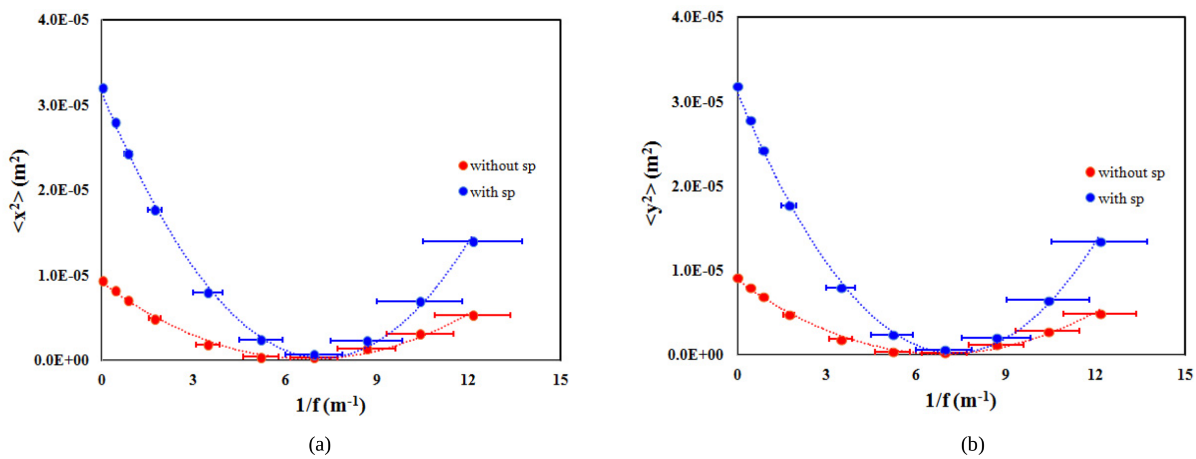


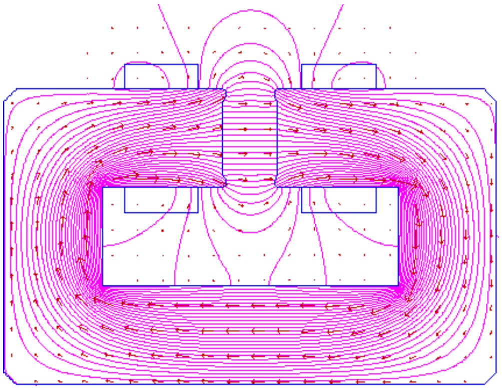
Fig. 9. Calculated horizontal (a) and vertical (b) rms beam size squared versus the quadrupole focal length.

3.3. Dipole magnet

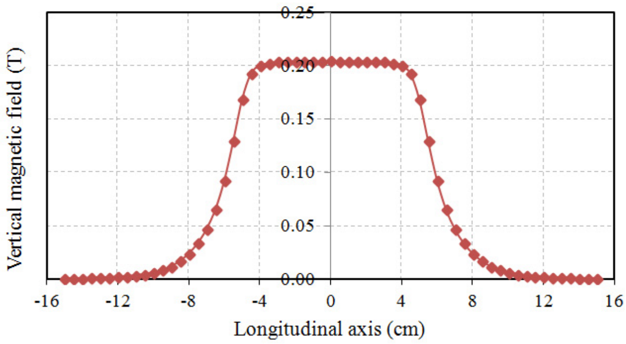
To measure energy and energy spread of electron beams, a dipole magnet and a Faraday cup are installed at the end of the integrated diagnostic station. Two well-known computer programs POISSON [10] and RADIA [11] were used to simulate 2D and 3D magnet models. The optimized magnet model has C-shape, which is convenient for installation in the accelerator beamline. It has a gap between the magnetic poles of 2.2 cm and can produce the field with a maximum magnetic field intensity up to 0.2 T. The length of uniform magnetic field within 5×10^{-4} in the horizontal direction is 1.62 cm. The 2D POISSON model of the new design dipole magnet is shown in Fig. 10 (a).

The 3D field map of the magnet was obtained from the RADIA model. The vertical magnetic field along the longitudinal axis is shown in Fig. 10 (b).

The electron trajectory tracking though the 3D magnetic field map was conducted. The calculated trajectory shows that the deflecting angle of 61 degree can be achieved for the electron energy of 6 MeV when the magnet is rotated by 8 degree. Two conducting coils with total 1,234 winding turns were constructed and tests. The test results show that the maximum current can be increased up to 3 A for the maximum temperature of 59^{o}C. The simulation results from 2D and 3D models are used as the based information to construct the real dipole magnet. This magnet can be utilized in the spectrometer system to measure the energy and energy spread of electron beams in the integrated diagnostic station.



(a)



(b)

Fig. 10. (a) 2D POISSON model of the dipole magnet; (b) Vertical magnetic field along the longitudinal axis of dipole magnet.

4. Conclusion

Commissioning of the RF power system and the RF performance of the thermionic RF electron gun at the Plasma and Beam Physics Research Facility were reported. The study results provide the useful information on the appropriate conditions for using the RF pluses with the resonant frequency of 2856 MHz. Results of high-power RF measurements using the new klystron tube reveal that the maximum RF peak power of about 3.9-4.3 MW with the reflected RF peak power of about 1 MW can be obtained for the RF pulse widths of 3-4 μs. Components of the integrated beam diagnostic station including the current transformer, the dipole magnet, the emittance measurement setup consisting of the quadrupole magnet and the view screen have been designed and developed. These components together with their related system and control will be installed in the accelerator beam transport line for studying the effect of the asymmetric EM field distribution inside the RF-gun on the electron beam properties.

Acknowledgements

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