ELECTRON BEAM PROPERTIES FROM A COMPACT SEEDED TERAHERTZ FEL AMPLIFIER AT KYOTO UNIVERSITY

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Abstract

A compact seeded Terahertz FEL amplifier is started construction at the Institute of Advanced Energy, Kyoto University, Japan. The system consists of a 1.6 cell BNL type S-Band photocathode RF-gun, a magnetic bunch compressor in form of a chicane, triplet quadrupole magnets and a short planar undulator. Electron beams from the photocathode

RF-gun were measured and compared with the RARMELA simulation results. Numerical and experimental studies on the contribution of the space charge effect were carried out. By using the RF power of 9 MW, the RF phase of 40 degree, the laser pulse energy of 20 μJ and the solenoid magnet current of 135 A, the electron beam with a bunch charge of 50 pC, a beam energy of around 5 MeV and an RMS emittance of 6-8 mm-mrad was achieved.

INTRODUCTION

The Institute of Advanced Energy has developed the compact seeded THz-FEL (IR-FEL) amplifier [1]. The system was designed to be simple, compact and economical aimed to use in scientific researches. The system consists of a 1.6 cell BNL type S-Band photocathode RF-gun, a magnetic bunch compressor in form of a chicane, triplet quadrupole magnets and a short planar undulator. The photocathode RF gun succeeded to generate the first beam in May, 2015. The electron beam properties, i.e. a bunch charge, a beam energy and a transverse beam emittance from the photocathode RF gun were measured. These electron beam properties are compared with the simulation results using the program PARMELA [2] to check the system. Since the energy of the electron beam would be low, around 5 MeV, the space charge effect should affect the beam properties strongly and it might be difficult to obtain a short bunch beam to generate intense THz radiation. Therefore, the study on the beam properties from the RF gun is crucial both by experiment and by simulation.

The 1.6 cell BNL type S-Band photocathode RF-gun has been developed at KEK [3]. The gun has two cavities, the first cavity is a half-cell type and the second cavity is a full-cell type. The photocathode of the RF-gun is the copper one during this study. A high power microwave transported from a 10 MW klystron, travels through a waveguide, which is connected at the upper wall of the second cavity. The microwave is fed into the first cavity via the central iris between two cavities. The effective length of half-cell and full-cell are 3.4135 cm and 9.0405 cm, respectively. The microwave has a pulse duration of 2 μs with a maximum macro-pulse repetition rate of 10 Hz. The photocathode drive laser consists of a mode-locked Nd:YVO_4 laser (GE-100-VAN-89.25 MHz-CLX-Flexible AOM, Time-Bandwidth), two amplifiers, beam position stabilizers and SHG-FHG [4]. The laser wavelength is 266 nm with a pulse duration of 8 ps at FWHM. The repetition rate of the injected laser is one thirty second of the RF frequency (89.25 MHz), which is defined by mode-lock frequency and designed to synchronize the cavity frequency of the MIR-FEL system. This is because the laser system is also used for the photocathode mode operation of the existing S-band linac [4]. A solenoid magnetic field is used to compensate a very strong space-charge effect on the electron beam. The limitation of the power supply used for the solenoid magnet is 200 A with a solenoid field around 300 mT. Beside the experiments, numerical simulations using the program PARMELA were performed to study the electron motion in the RF gun as well as to investigate accelerated electron beam properties which are charge, energy, energy spread, emittance and pulse width.

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METHODOLOGY

To investigate a transverse profile, dark current and bunch charge of the electron beam produced from the photocathode RF-gun of a compact seeded terahertz FEL amplifier, we used a fluorescence screen, a CCD camera, an electron exaction window and a Faraday cup as shown in Fig. 1(left). The typical Faraday cup signal of the electron charge measurement is shown in Fig. 1(right). Unfortunately, we did not have enough time to prepare in vacuum measurement. Thus, the charge measurement was performed in air. The photoelectron beams hit the exaction window inside a vacuum chamber. The window made of copper with a thickness of 0.2 mm. The energy loss of electron at the copper window is calculated to be 230 keV at the kinetic energy of the beam of 4.5 MeV [5]. An emitted electron beam from the copper window traveled in the air, then, it is observed by using the Faraday cup. The cup itself is made of graphite for absorbing the electron beam by using the in air measurement technique. The electron bunch charge is obtained by using an Eq. 1:

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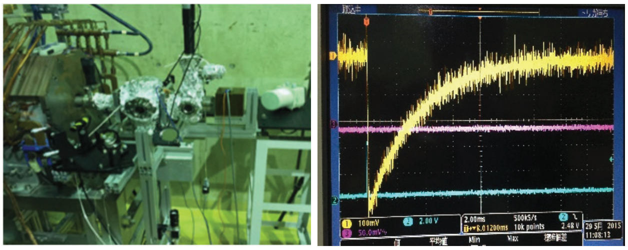

Figure 1: (left) Photogragh of the experimental set up for measurement of a dark current and electron bunch charges. (right) Typical Faraday cup signal of the electron charge measurement.

$$Q = \int I(t)dt = \frac{1}{R}\int U(t)dt\,, \qquad (1)$$

where *U(t)* is the measured voltage observed by the oscilloscope and *R* is a resistance of the measurement system. The dark current is a background current, which comes from an effect of the RF wave even the drive laser is switched off. The dark current dependence on the microwave power is shown in Fig. 2.

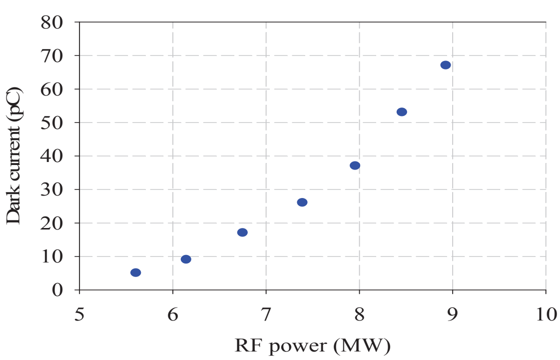

Figure 2: Relationship between the dark current and the RF power.

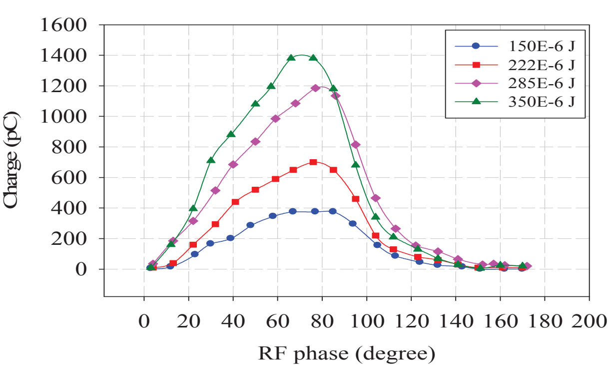

Figure 3: A relationship between the electron bunch charge and the RF phase.

We used an RF power of 9 MW and a solenoid current of 120 A to study the photoelectron bunch charge dependence on the RF phase. The relationships are shown in Fig. 3. Besides the bunch charge, the beam energy and beam emittance are other important properties of the electron beam. To study these properties, we used the measurement set-up as shown in Fig. 4.

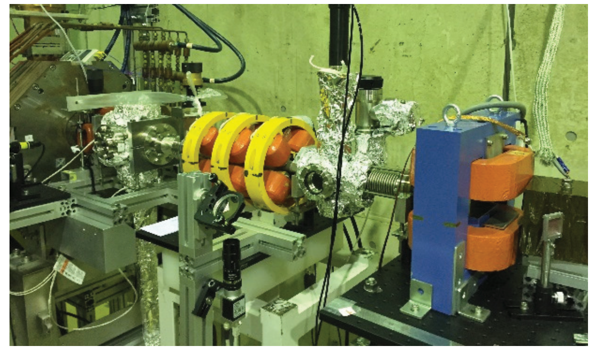

Figure 4: Photograph of the experimental set up for the measurements of beam energy and beam emittance.

The instrument system consists of a beam exaction window, which is a mylar window, a dipole magnet, three quadrupole magnets, a fluorescence screen and two CCD cameras. The energy measurement has been performed with the in air measurement as well. An emitted electron beam from the mylar window whose thickness is 0.3 μm traveled in the air. The mylar window is made of Aluminum coated one side with a polyimide [6]. The energy loss in the Aluminum window is calculated to be 110 keV at kinetic energy of the beam of 4.5 MeV [5]. On the other hand, the density of air inside the accelerator room is 1.20E-3 g/cm^3, the stopping power in the air is about 2.3 keV per 1 cm. When the beam travelling pass a dispersive region of the dipole magnet, which has the magnetic field perpendicular to a traveling path of the beam, the magnetic field acts on the electron beam related to the energy (E) of the beam [7] as

$$\frac{1}{\rho[m]} = \frac{0.2998 B_0[Tesla]}{\beta E_{total}[GeV]}\,, \qquad (2)$$

where B_0 is the peak magnetic field of the dipole magnet and ρ is the radius of curvature of the traveling path. Therefore, electrons with different energies bend in the dispersive region with different bending radii. A geometry length of the dipole magnet is 6.5 cm and an effective length is 11 cm. The beam energies are related to an RF power and phase.

A comparison between the measurement and simulation results of the beam energy dependence on the RF phase is shown in Fig. 5. The blue plots are the measurement results and other plots are the example of simulation results. The measurement results of the beam energies depending on the RF powers and the RF phases are shown in Fig. 6. An expected ratio of the accelerating gradient between the half-cell and the full-cell of the RF-gun is 1:1.

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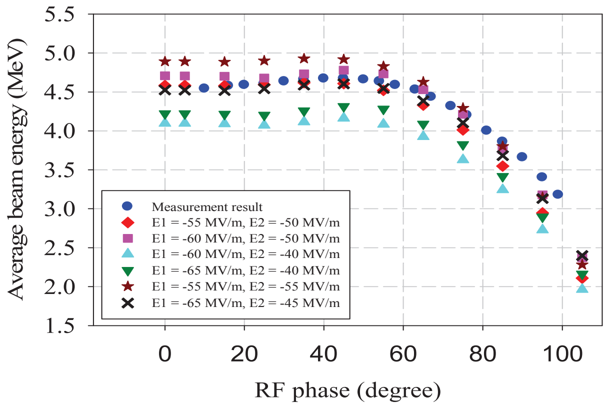

Figure 5: Measurement and simulation results of the beam energy dependence on the RF phases.

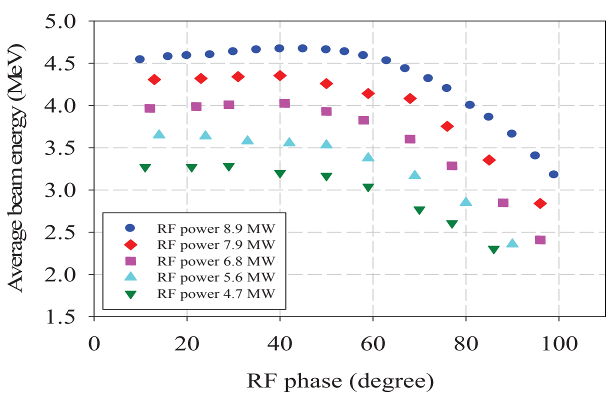

Figure 6: Measurement results of the beam energy dependence on the RF powers and the RF phases.

According to the measurement results in Fig. 6, at the RF phase lower than 40 degree, the beam energy slowly increases and it is almost constant around 40-50 degree for each RF power. The beam energy rapidly decreases at the phase larger than 50 degree. The beam energy for each phase are proportional to the RF power. The relationship of the beam energy and the RF phase for each RF power shows the same tendency.

Beam emittance is an important quantity for evaluation of the transverse electron beam quality. The emittance relates to area or volume of the phase space diagram, which is occupied by electrons. The emittance are defined as [8]

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}\,,\ \varepsilon_y = \sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2}\,, \quad (3)$$

where x, y are electron horizontal and vertical positions in Cartesian coordinate system. The angles x', y' are defined by the transverse momenta divided by the total momentum.

A measurement system is prepared in form of a quadrupole scan method with a thin lens approximation. The quadrupole magnets focus the electron beam in vertical or horizontal direction. A focal length of quadrupole magnet is given by this following equation

$$f[m] = 1/(k[m^{-2}]l[m])\,, \quad (4)$$

where k is the strength of the magnet and l is the effective length of the magnet, which is related to [7]

$$k = (0.2998G[T/m])/(p[GeV/c])\,, \quad (5)$$

where G is the gradient of the magnet and p is the momentum of the electron. An effective length of the quadrupole magnets in this experiment is 55 mm. We used an RF power of 9 MW with an RF phase of 40 degree and a solenoid current of 130 A to study the beam emittance dependence on the bunch charge and the drive laser pulse energy. The relationships of these parameters are shown in Fig. 7.

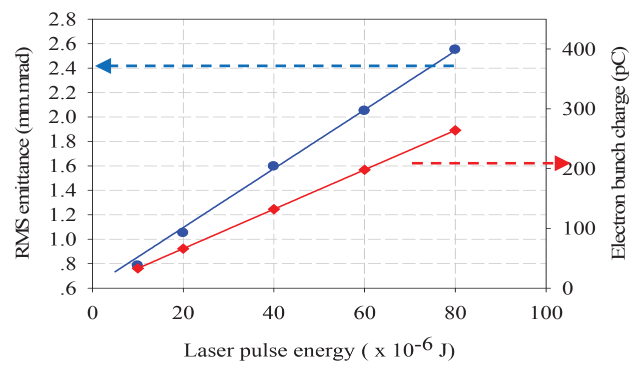

Figure 7: The beam emittance dependence on the bunch charge and the drive laser pulse energy.

As is shown in the Fig. 7, the bunch charges are proportional to the laser pulse energies. It is noted that the space charge effect, which is larger with a higher bunch charge, makes the beam getting a large divergence. Therefore, the beam emittance is getting larger according to the laser pulse energy.

The solenoid magnetic field changes a focusing condition of the beam. Therefore, it changes the RMS beam emittance. We used an RF power of 9 MW, an electron bunch charge of 50 pC and an RF phase of 40 degree for studying the beam emittance dependence on the solenoid field. The relationship is shown in Fig. 8. Blue and red plots refer to a property in x-axis and y-axis, respectively. The beam emittance is minimum at a solenoid current of 135 A. The results in both x-axis and y-axis show similar tendency with small difference in values.

A magnitude of the electric field inside the RF-gun changes with the time. Then, the beam energy depends on an accelerating gradient of the RF as a function of the RF phase. Therefore, the RMS emittance also related to the RF phase. We used the RF power of 9 MW, the solenoid current of 135 A and the bunch charge of 50 pC for this

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investigation. The measurement and simulation results are shown in Fig. 9.

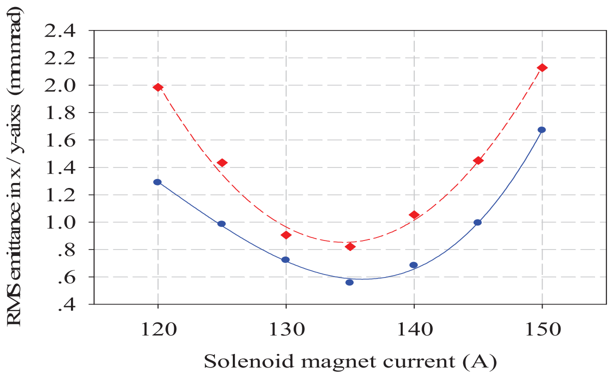

Figure 8: Relationship between the beam RMS emittance and the solenoid magnetic current.

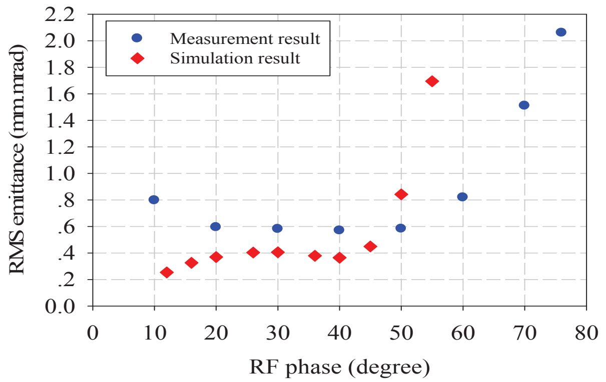

Figure 9: Relationship between the beam emittance and the RF phase.

It is clearly seen that the beam energies are high and almost constant at low RF phase region, where the space charge effect is low. Therefore, the beam emittance almost constant at this region. On the other hand, the beam energy rapidly decreases at high RF phase region, where the space charge effect is high. Therefore, the beam emittance rapidly increases.

CONCLUSTION AND OUTLOOK

The numerical and experimental studies on the electron beam properties have been carried out. Results of the investigation show that the electron beam with a bunch charge of 50 pC, a beam energy of around 5 MeV and an RMS emittance of 6-8 mm-mrad can be obtained by using the RF power of 9 MW, the RF phase of 40 degree, the laser pulse energy of 20 µJ and the solenoid magnet current of 135 A. Further investigation will be performed in order to improve the quality of the RF-gun, the measurement systems and the calculation methods for the better performance of the 1.6 cell BNL type photocathode RF-gun.

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REFERENCE

[1] S. Suphakul et al., “Development of Compact THz-FEL system at Kyoto University”, TUP057, FEL2014, Basel, Switzerland (2014).

[2] L.M. Young and J.H. Billen, Los Alamos National Laboratory Technical Note LA-UR-96-1835, 2002.

[3] N. Terunuma et al., “Improvement of an S-band RF gun with a Cs_2Te photocathode for the KEK-ATF”, Nucl. Instrum. Methods Phys. Res. A 613 1(2010).

[4] H. Zen et al., “Development of Photocathode Drive Laser System for RF Guns in KU-FEL”, THP045, FEL2014, Basel, Switzerland (2014)

[5] Stopping-power and range tables for electrons: http://physics.nist.gov/cgi-bin/Star/e_ta ble. pl

[6] Sheldehl materials, “The red book”: http://www. sheldahl.com/documents/RedBook.pdf

[7] J. Holmes, S. Henderson, Y. Zhang, “Magnetic Field and Magnet Design”, USPAS, Vanderbilt (2009): http://uspas.fnal.gov/materials/09VU/Lectu re2.pdf.

[8] T. Rao and D. H. Dowell, An Engineering Guide to Photoinjectors, (New York, 2012).

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