PRELIMINARY MEASUREMENT OF EMITTANCE EVOLUTION USING EMITTANCE METER AT THE PAL*

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Abstract

A high-brightness electron beam is emitted from a RF photocatoode gun with 1.6 cell cavity from October 2005 at the Pohang Accereator Laboratory (PAL). The project of 4th Generation Light Source (4GLS) with the Spontaneous Amplification Sponteneous Emission Free-electron Laser (SASE FEL) in the PAL is called Pohang Accereator Laboratory X-ray Free-electron Laser (PAL-XFEL). In order to success of the PAL-XFEL project, it is necessary to research the high-brightness electron beam at the injector. A emittance meter (E-Meter) is installed for the high-brightness research in GTS (Gun Test Stand). The measurement of transverse emittance and beam size profile along the longitudinal direction was done by the E-Meter. Precise measurement of the emittance profile will be provided with a powerful tool for the commissioning of the 4GLS injectors based on the emittance compensation principle. We are going to achieve this with the use of slit-based E-Meter that can be moved along the longitudinal direction. In this article, we present a preliminary measurement of the emittance evolution with the E-Meter for the commissioning of the photocathode RF gun.

INTRODUCTION

The Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL X-FEL) is proposed with self amplifiered spontanous emision (SASE) lasging sheme that will use the final 3.7 GeV for the drive beam energy [1-2]. The performance of the PAL X-FEL in the 3.0 Angstrom regime is predicted on the capacity of 1 nC, 100 A beam at the end of the photoinjetor with transverse normalized rms emittance of 1.2 π mm mrad. For the low emittance beam, emittance compensation scheme is essential for the design and commitioning of the photoinjector.

In this paper, we review and report the emittance evolution in the beam drift region with emittance meter (E-Meter). This paper is composed of previous work on the subject of the emittance evolution measurements systems and the preliminary measuring of the beam emittance evolution of the photocathode rf gun. We then describe preliminary experimental result at the PAL where the slit based emittance measurement technique is used to measure the emittance evolution of the PC RF gun.

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The results of the experiment, which show that a possibility of the emittance evolution measurement found with the E-Meter, are compared with simulation.

EMITTANCE COMPENSATION

The emitance compensation is a technique used to reduce the normailzed rms emittance of the beam at the photoinjector. The emittance compensation typically involves two complementary stages: the rotation of phase space for each slice of the beam in the solenoid and the realignment of the slices and fast acceleration in the booster. Essentially, the principle of the emittance compensation by solenoid is the balance between the repulsive forces due to space-charge and external focusing forces. After the beam goes through the solenoid magnet region, the beam is blowed up by space-charge force if there is no booster linac [3-4]. Thus a booster is needed to fast accelrate the beam to a relatively high energy region at which the phase space is frozen and the beam is emittance dominated. To shift the second emittance minimum to the enterance of the booster where the beam is emittance dominated, Serafini and Ferrario suggested a matching condition [3-4] for properly matching the space-charge dominated beam from the gun to the booster,

$$\sigma' = 0, \quad \gamma' = \frac{2}{\sigma}\sqrt{\frac{I_P}{2 I_A \gamma}}, \tag{1}$$

where σ is the rms transverse spot size, I_P is peak current of the beam, I_A = 17 kA is the Alfven current. The booster matching point will be investigated by our experiments for optimizing the emittance compensation process i.e., by the emittance characterizations for various longitudinal position which will be performed with the Emittance-Meter using a slit based emittance measument technique. We use the rms emitance and the normalized rms emitance, defined by [5]

$$\varepsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}, \quad \varepsilon_{n,rms} = \beta\gamma\varepsilon_{rms}, \tag{2}$$

where β and $\gamma = 1/\sqrt{1-\beta^2}$ are the relativistic factors, the bracket denotes an average over the beam distribution at each location, the primes refer to axial derivatives, and

$\left\langle x^2 \right\rangle, \left\langle x'^2 \right\rangle$ are the second monents of the beam distribution.

A BNL GUN-IV type rf photo-cathode gun for far infra-red radiation (FIR) project is installed in the PAL. A resonant frequency of the gun cavity is 2856.0 MHz with 3.4 MHz mode separation. The photoelectron beam is emitted from the PC RF gun at the PAL since October 2005. The beam parameters are achieved 2.5 MeV beam energy with 2.5 % relative energy spread and 400 pC beam cahrge at the 30º laser injection phase. The emittance, the beam size, and the beam energy are simulated by the PARMELA code for the PAL XFEL injector with fullfilled emittance matching condition and the emittance compensation as shown in Fig. 1.

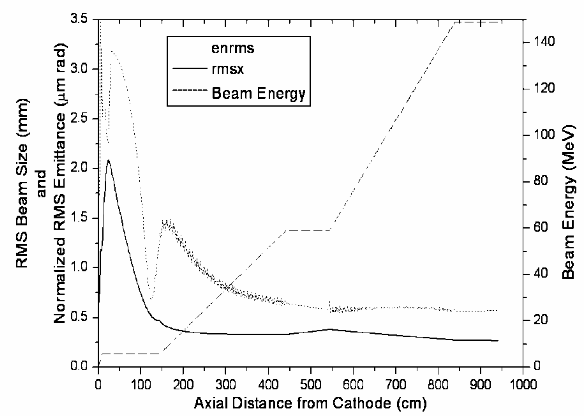

Figure 1. The beam size (solid line), the normalized rms emittance (dot line), and the beam energy (dash line) are simulated by PARMELA code for PAL-XFEL injector with fulfilled emittance matching condition.

EXPERIMENTAL SETUP

Our electron beam parameters are shown in Table1. The beam parameters depend on the laser parameters and rf power and phase.

Photocathode RF Gun and Basic Instruments

Figure. 2 shows the experimental setup with a 1.6 Cell photocathode S-band (2856 MHz) rf gun with 8 pancake-like solenoids. The PC rf gun was developed and constructed by collaboration of the BNL, KAIST, and PAL. The laser driven copper cathode rf gun consisted of 1.6 cell cavity with a half cell and a full cell. The half cell of the 1.6-cell rf gun is symmetrized by two laser ports which are rotated 45° from the waveguide, tuner, and pumping port in the full cell. The laser incident port, there is an angle of 67.5° between the laser propagation direction and the cathode normal vector, allows for ultra-violet (UV) laser to flash the cathode surface and to minimize the transmission loss. The gun is operated in pi-mode at S-band with multi-pole suppression achieved through cavity symmetrization. The coupling between the waveguide and the full cell is accomplished via the coupling slot on the full cell cavity. An electric coupling located between the half cell and full cell is utilized to couple rf power from the full cell to half cell. A home made klystron was proceeded to yield 80 MW at an rf pulse length of 1 μs of 2856 MHz. The klystron can be operated with maximum 60 Hz repetition rate at a 10MW rf power. The field gradient in the cavity was built by the rf power with 2856 MHz of 2 μs pulse width. The temperature of the cavity can be maintained by the precision cooling system for tuning the rf resonant condition. In order to reduce the space-charge induced emittance growth should be quickly accelerated in the gun. After the gun, a solenoid for the transverse emittance compensation is directly mounted with four ceramic key to prevent heat transmission. A steering magnet with maximum magnetic field of 80 Gauss is installed a space between inside the solenoid bore and outside the vacuum pipe. Immediately following the solenoid is an integrated current transformer (ICT) to measure the beam charge without beam dump.

After the ICT there was a screen to downstream for measurement and monitoring of the beam profile. The screen, which is about 15 μm layer of YAG:Ce doped on aluminium substrate of 100 μm thickness, is mounted on an aluminium holder at the 45° with respect to the beam axis. The position of the screen is 0.56 m from the cathode. A charged coupled device (CCD) camera to acquire of the electron beam image is synchronized to the electron beam for a shot-to-shot measurement. The spectrometer with a 60° sector dipole magnet for electron beam energy and the energy spread is located downstream of the screen.

Laser Systems

The laser system consists of an active mode-locked Ti:Sapphire oscillator, a regenerative amplifier, a second harmonic generator (SHG), a third harmonic generator (THG), and a custom designed UV stretcher system. The laser system for the rf PC gun is installed in a clean room which temperature stability is dynamically controlled within 0.5 °C for stable operation. The oscillator is operated at a frequency of 79.33 MHz by using a frequency divider (/36) with the master oscillator of 2856 MHz for the lock-to-clock between the master and laser oscillator. The oscillator output is phase-locked with a reference 79.33 MHz divided rf frequency by dynamically adjusting the cavity length of the oscillator with piezo mirror by lock-to-clock module. The timing jitter is measured to within an rms value of 130 fs using a phase detection method. The measured energy stability of the oscillator output using by infra-red (IR) power meter is 1 % peak to peak. From the oscillator, 105 fs width with a full width at half maximum (FWHM) value, 800 nm wavelength pulse is generated with 79.33 MHz repetition rate. These laser pulses come into the regenerative amplifier to amplify the pulse energy up to about 2.5 mJ with 1 kHz repetition rate. After the regenerative amplifier, the amplified laser pulse comes into the THG with a pair of frequency conversion non-linear crystals to obtain 266 nm UV light with maximum laser energy of 250 μJ. The UV laser pulse still has an ultra short pulse width. An UV pulse stretcher with a pair of prisms is installed in order to stretch the pulse width of the UV laser to 10 ps FWHM. In addition, the UV pulse stretcher has a capability to change the pulse duration of the UV laser from 1 ps (FWHM) to 10 ps (FWHM). A cross correlator with a BBO crystal is installed in order to measure the pulse width at the UV region using cross correlation method.

Emittance Meter

We have designed the Emittance-Meter which has the movable slits chamber and screen chamber along the beam axis with bellows independently, which will be used to demonstrate the emittance evolution predicted by theory and simulation [3-4]. The transverse emittance evolution after solenoid magnet to compensate of the beam emittance along the beam axis can be measured by this Emittance-Meter. Designed Emittance-Meter was shown in Fig. 2, the left side part was the PC RF gun, and the right side part was the Emittance-Meter. The Emittance-Meter consisted of three long bellows, the slit plate chamber with the YAG screen to make beamlet and to measure the main beam size, at the downstream of the slit chamber YAG screen chamber to measure of the beamlet size. The long bellows is used for the transverse emittance measurement from 0.9 m to 2.1 m position measured from the cathode. The length of the bellows can be changed from 0.54 m to 1.54 m without vacuum breaking. The distance from pin-hole chamber to screen chamber can be moved along to the beam divergence. If the beam has a big divergence, the distance should be short and the other case it should be large to make an optimized image size at the screen. In the last part, we put another bellows to make the vacuum force balance in the front part bellows. We will check the position of the slit plate chamber and the screen chamber with CCD cameras and a long scale attached on the shelf. The slits are fabricated by high power Laser micro-drilling with 30 μm, 40 μm, and 50 μm silt widths in tungsten plate with 0.5 mm thickness. The plates in the Emittance-Meter are designed to be changeable at the specific experimental position with stepping motor. We can compare the emittance value to each slit width along to a space-charge dominance factor [6]. The sizes of the slit are determined by considering the signal to noise ratio (SNR) and the acceptance angle when the beam goes through the plate [7]. Also, very small size hole should be aligned on the beam axis for beam measurement, because if the hole is not aligned, the beam is dumped on the tungsten plate. We designed to realize an alignment technique with goniometric motion, rotary motion, and linear motion with high accuracy stepping motor. The single slit scanning method will be used in usually with x and y directional linear motion which method is needed precision moving control, however the analysis of the data files is easy [8].

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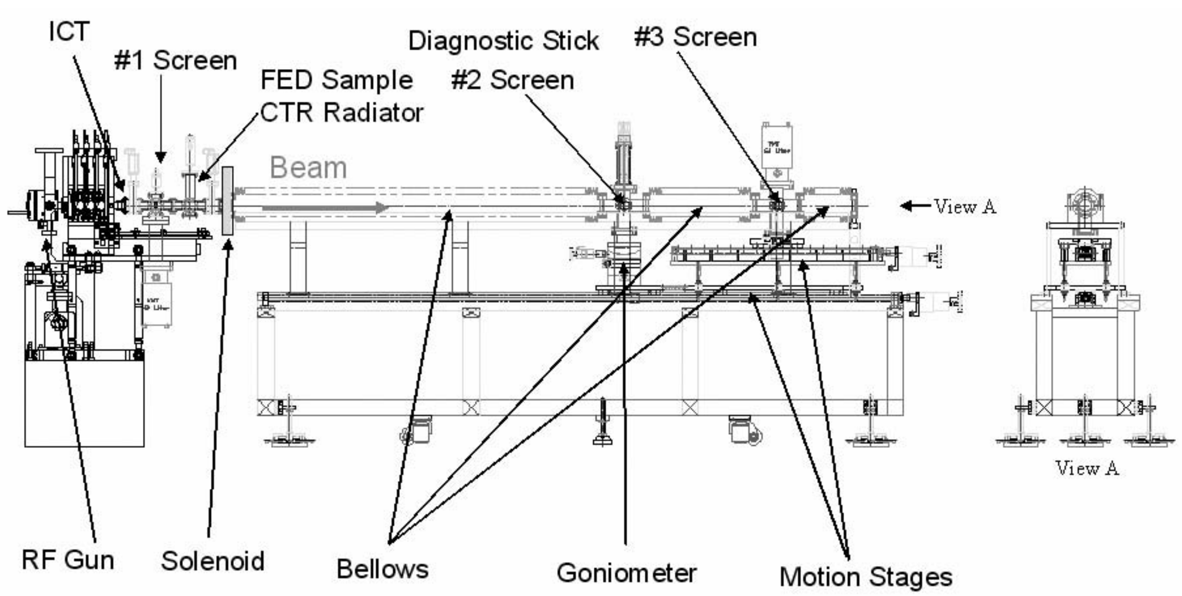

Figure 2: Schematic diagram of experimental setup of the gun test stand (GTS) for photo-injector developments of the PAL-XFEL.

THE PRELIMINARY MEASUREMENT OF TRANSVERSE EMITTANCE EVOLUTION

The transverse emittance evolution was measured by a pair of a singe slit with 30, 40, and 50 μm slit width and an YAG screen downstream of the slit. The beamlet.is created by the slit plate, which is made by 0.5 mm tungsten plate. The beamlet distribution is then imaged on the screen downstream of the slit plate at a distance of 71 cm from the slit. The width of the beamlet has a connection with a measure of the width of the transverse momentum distribution at the slit. The beamlet yield the correlated beam divergence and the rms transverse divergence,

$$x'_c = < x - w > / L,$$

$$\sigma' = \sqrt{\frac{\langle x^2 \rangle}{L^2} - (x'_c)^2},$$

where L is the distance between the slit and the YAG screen, x is the measured beamlet size on the screen, and w is the slit width. Here the average is performed over the distribution in the measured beamlet. The beamlet size

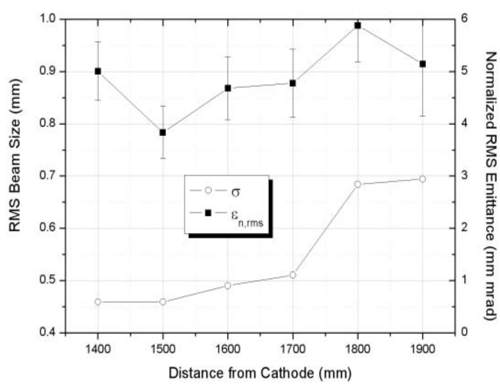

Figure 3: Preliminary measurement of the emittance evolution (solid circle) and the beam evolution (empty circle).

is measured about 10 times larger than the slit width to reduce the space-charge effect in the emittance measurement In generally, quad technique for beam emittance measurement was reported over-estimated due to the purely space-charge dominated region [refer insert]. The position of the slit from the cathode can be changed with stepping motor without vacuum break which of the least position of the slit is 1.4 m from the cathode. The distance between the slit and the YAG screen can be changed for optimizing of the beamlet measuring on the YAG screen.

The distance is 0.71 m between the slit chamber with the screen and the screen chamber for measuring of a beamlet size. The main beam size on the #2 screen at the slit chamber and beamlet size on the #3 screen at the screen chamber are measured by the synchronized CCD camera. From measured the beam size and the beamlet size the beam gradient is calculated which for the beam emitance calculation. The evolution of the beam emitance and beam size is shown in Fig.3.This experiment is performed with the condition of 2.0 MeV beam energy and 350 pC beam charge with 30º laser injection phase.

SUMMARY

The experimental measurement by the E-Meter is to measure the emittance evolution in the drift region for many experimental conditions to find optimized operating condition for our injector. We measure the first measurement of the emittance evolution at the drift region of the photo-injector. For better results of the emittance evolution, we need to improve data analysis methodology, and to automate data acquisition processes. For advanced experiments, we need to improve high energy (more than 5 MeV at the gun) beam experiment or normal laser incidence.

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