EMITTANCE MEASUREMENT ON THE CEB6 ELECTRON GUN FOR THE SPRING-8 COMPACT SASE SOURCE

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Abstract

A 500 kV pulsed electron gun has been developed for the injector system of the X-ray FEL project at SPring-8. A single-crystal CeB_6 cathode is chosen as a thermionic emitter, because of its excellent emission properties, i.e., high resistance against contamination, uniform emission density, and smooth surface. A gun voltage of -500 kV was chosen as a compromise between the need for suppressing emittance growth and reducing the risks of high voltage arcing. We have succeeded in producing a 500 keV beam with 1 A peak current and 3 µsec width. A normalized rms emittance of 1.1π mm.mrad has been measured by means of double-slit method. In this paper, we report on the result of the emittance measurement and discuss improvements for X-ray FEL.

INTRODUCTION

In X-ray FEL theory, it is well known that the fine structure of the beam dominates the FEL gain. To achieve the SASE-FEL in Angstrom wavelength region, the sliced emittance of the beam should be very low and the peak current should be of the order of kA. Moreover from the application point of view, the FEL machine should be stable for long periods of operation.

In the SASE-FEL, the electron beam generated by the gun is accelerated in the main linac, then it is directly injected into the long undulator and generates the X-ray beam there. Therefore, any electron bunch fluctuation in transverse position, timing, size, charge, etc., will directly affect the X-ray lasing. This is markedly different from the storage ring type machine situation. As a result, the stability of the electron gun is essential for producing stable X-ray FEL light.

We decided to use a pulsed high-voltage gun with a single-crystal CeB_6 thermionic cathode followed by a buncher system [1]. A side view of the CeB_6 gun with an emittance monitor bench is shown in Fig. 1, and the beam design parameters at the gun exit are summarized in Table 1 [2].

Table1 : The beam design parameters at the gun exit.

Beam energy	500 keV
Peak current	3 A
Pulse width (FWHM)	1.6 µsec
Repetition rate	60 Hz
Normalized emittance (rms)	0.4π mm.mrad

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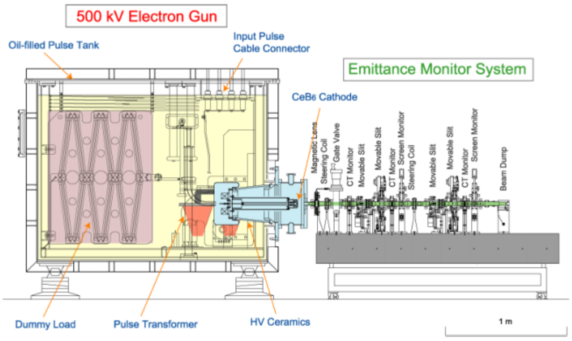

Fig. 1 : A side view of the CeB_6 electron gun with an emittance monitor bench.

THE CEB6 GUN

CeB_6 Cathode

The normalized rms thermal emittance of electrons emitted from a hot cathode is described by

$$\varepsilon_{n,rms} = \frac{r_c}{2}\sqrt{\frac{k_B T}{m_e c^2}} ,$$

where r_c is the cathode radius, k_B is Boltzman's constant, and T is the cathode temperature. From the above relation, in order to obtain the small emittance less than 1π mm.mrad required for the X-ray FEL, the diameter of the cathode must be in the range of a few mm at the temperature of 1000-1500°C. On the other hand, very high emission density (~50 A/cm^2) is required to produce a several ampere peak current from the small surface. Only the rare-earth hexaborides, such as LaB_6 or CeB_6 can emit such an intense current over long lifetimes. A single crystal is preferable for obtaining low emittance because of its extremely flat surface (roughness ≤1 µm) with low porosity after surface material evaporation [3]. The emission density is more uniform because the crystal orientation is the same over the whole surface. In recent years, single crystal CeB_6 cathodes are widely used for electron microscope and superior stability has been demonstrated [4]. We decided to use a single-crystal CeB_6 cathode with a [100] crystal face. The diameter of our CeB_6 cathode is 3 mm. 3 A peak current will be produced when heated to ~1400°C. The theoretical thermal emittance is 0.4π mm mrad.

Fig. 2 shows the CeB_6 crystal, the cathode assembly and the cathode being heated in the test chamber. The CeB_6 crystal is mounted in a graphite sleeve. This produces a uniform electric field over the entire cathode

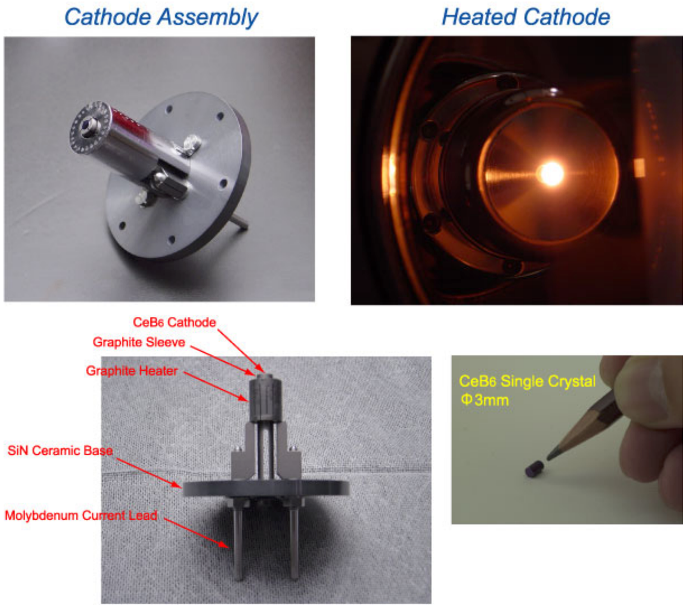

Fig. 2 : CeB_6 cathode assembly.

surface. This is quite important for elimination of any beam emission halo coming from the cathode edge, which could cause damage to the undulator magnets.

We use a graphite heater rather than the conventional metallic filament made of tungsten or the like. Graphite is mechanically and chemically stable even at very high temperatures and does not evaporate like other metals. Since its electrical resistance does not change much as a function of temperature, it is easy to control the heater power. The heater resistance is 0.18 Ω.

A tantalum cylinder covers the graphite heater to shield the thermal radiation from its surface. A base plate for the cathode assembly is made of silicon nitride, which is mechanically strong even when thermal stresses are applied.

The cathode was heated up to ~1400°C in the test chamber by applying 210 W of heater power (see the upper right side of Fig. 2). A reference temperature was measured from the graphite sleeve surrounding the cathode by means of a radiation monitor. We still need more study in order to determine the cathode temperature distribution precisely. Up to now, the cathode has been operated for 4000 hours without failure.

High-voltage Gun

Basically, the gun high-voltage tank follows the design conventional for a klystron tank. We use the same model C-band klystron modulator [5] to feed a -24 kV pulsed voltage to the gun high-voltage tank. The primary pulse is stepped-up to a -500 kV by a pulse transformer, with a turn's ratio of 1:21. In order to match the impedance of the gun to the modulator PFN output circuit, a 1.9 kΩ dummy load is connected in parallel with the cathode. Since we need to apply a -500 kV pulse voltage to the cathode, all the high-voltage components, namely, the ceramic insulator, pulse transformer, dummy load, etc., are immersed in insulating oil to eliminate discharge problems.

Fig. 3 shows the waveform of the gun voltage and beam current. The beam current was measured by a current transformer (CT) located in the beam line right after the gun. The beam energy is 500 keV, and the peak current is 1 A. The flat-top portion of the pulse is about 0.8 μsec, which is sufficient to generate a nsec bunch.

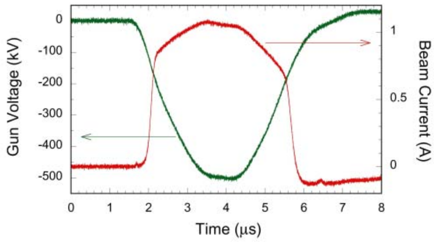

Fig. 3 : Waveform of the gun voltage and beam current.

The current-voltage characteristic of the CeB_6 gun has been measured for various cathode temperature (Fig. 4). The gun is operated in temperature limited region. In this region, the beam current is dominated by Schottky effect ($I \propto exp(\sqrt{V})$) rather than Child's law ($I \propto V^{3/2}$), that is, the slope of the current-voltage curve becomes gentle. Therefore, it is expected that the beam intensity jitter caused by the gun voltage jitter is suppressed.

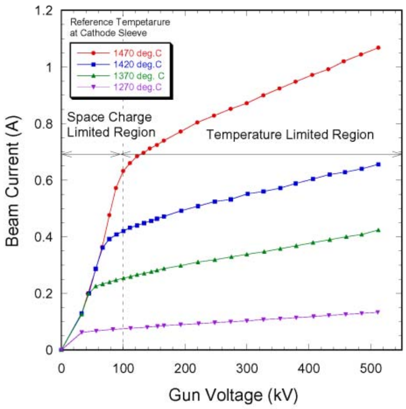

Fig. 4 : Current-voltage characteristic of the CeB_6 gun.

EMITTANCE MEASUREMENT

Double-slits Method

We measured the beam emittance by the so-called double-slits method (Fig. 5) [6]. The upstream slit cut out a sheet shaped beamlet from the round beam, which spreads after passing through the drift space due to transverse thermal motion and space charge. The downstream slit measures the beamlet profile. By scanning the both slits throughout the whole beam area, the intensity profile in the phase space can be obtained.

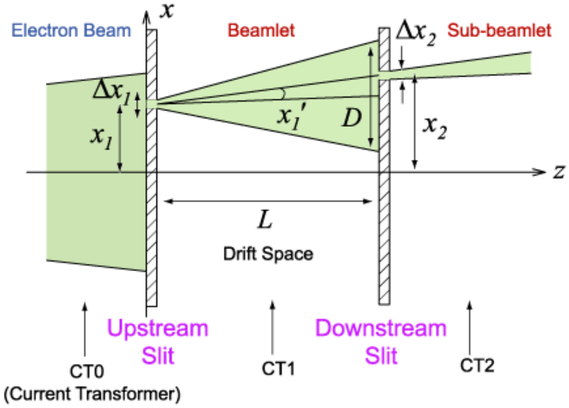

Fig. 5 : Principle of emittance measurement.

We prepared four slits, two for horizontal (x-direction) scan and two for vertical (y-direction) scan. The upstream x-slit are located at 50 cm downstream from the cathode, followed by a 60 cm drift space and the downstream slit. The opening width must be narrow enough to ignore the beamlet broadening due to space charge. Fig. 6 shows the beamlet intensity profiles for several upstream slit width (25, 50, 100, 200 μm). The original beam energy and current was 400 keV and 0.9 A, respectively. The downstream slit width was set to 25 μm. Accuracy of the width and position is better than 10 μm. The profile became Gaussian for the narrow width less than 100 μm, as expected from the thermal spread. The beamlet broadening due to space charge is ~15% of the thermal spread at 50 μm width in the experimental condition.

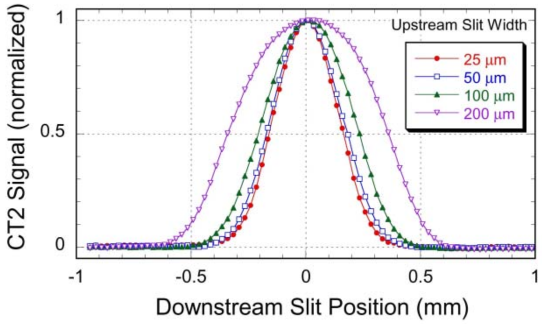

Fig. 6 : Beamlet profiles for different upstream slit width.

We found that the combination of a slit and a CT monitor with a digital scope is a very powerful tool to analyse the beam dynamics in time domain. The sub-beamlet current waveform provides the information about the time evolution of the phase space intensity at a certain point. From about 1500 waveforms stored by the slit scan, the time evolution of the phase space profile can be reconstructed. Fig. 7 shows an example of the animation screens of the phase space profile evolution.

Using a pair of vertical and horizontal slits, a time-resolved beam profile can be also measured by the same method.

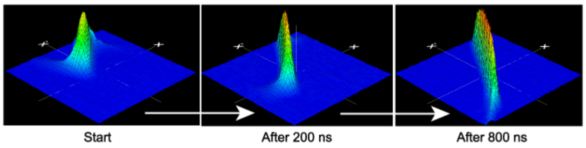

Fig. 7 : Time evolution of the phase space profile.

Experimental Result

We have measured the current density profile for the 500 keV beam with 1.0 A peak current. Fig. 8 shows the 3-dimensional plot of the current density profile. The width for both the x- and y-slits was set to 0.5 mm × 0.5 mm and the scan step was 0.5 mm. It shows fairly flat top shape as we expected from the cathode geometry.

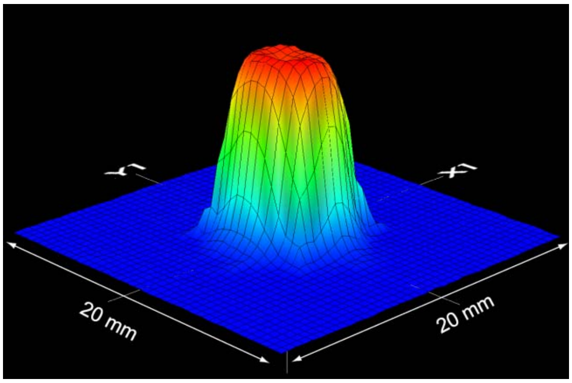

Fig. 8 : Current density profile of the 500 keV, 1.0 A beam.

Fig. 9 shows the 2-dimensional plot of the phase space profile (x-direction) measured for the same beam parameters. The width for both the upstream and downstream slits was set to 50 μm and the scan step was 0.25 mm for the upstream slit and 0.1 mm for the downstream slit. From the phase space profile, we analysed the normalized rms emittance, defined as

$$\varepsilon_{n,rms} = \beta\gamma\sqrt{<x^2><x'^2> - <xx'>^2} ,$$

where $<x^2>$, $<x'^2>$ and $<xx'^2>$ denote mean square values weighted by current. The result was 1.1π mm mrad. The demonstrated beam parameters at gun exit are summarized in Table 2

The measurement of the rms emittance was very sensitive to the background noise. The noise signal of the CT monitor became a source of false emittance increase. The noise level (3σ) was ~1% of the peak intensity. To reduce the noise influence, we analysed the emittance using the signal, which was larger than that of the noise level, then corrected it to the expected value without noise. In order to overcome this ambiguity, we will improve the noise reduction and study the method of emittance analysis.

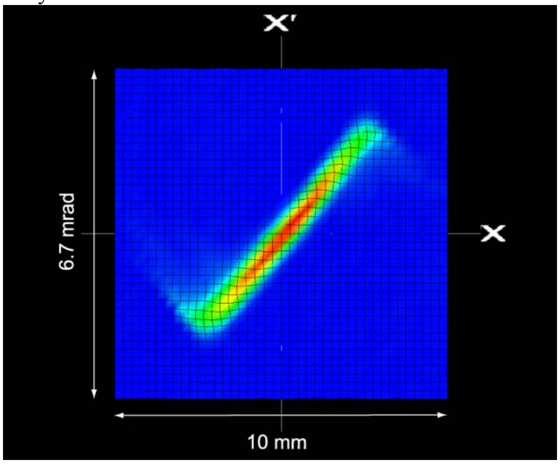

Fig. 9 : Phase space profile of the 500 keV, 1.0 A beam.

Table 2: Demonstrated beam parameters at gun exit.

Beam energy	500 keV
Peak current	1 A
Pulse width (FWHM)	3 μsec
Repetition rate	10 Hz
Normalized emittance (rms)	1.1π mm.mrad

IMPROVEMENTS FOR X-RAY FEL

Based on the experimental results, the following improvements will be done for the real injector system:

1) Beam current: we need to increase the beam current by a factor of 3 for operation. The current cathode emission may not be activated well as possible. The increase in cathode temperature to obtain a 3 A peak current is estimated to be ~120°C.

2) Pulse width: the high-voltage pulse width turned out to be two times longer than the design value. The fairly big stray capacitance of the dummy load resistors no doubt causes the pulse to be stretched out to this long duration. As a result, the heat load that must be removed from the high-voltage tank was higher than the design expectation. The large size of the high-voltage tank is also determined by the resistors. In order to shorten the pulse width and to make the tank more compact, we are now developing an electron tube dummy load, which will replace the load resistors.

3) Emittance: we successfully achieved a very small emittance, but even so, it was somewhat larger than the theoretical predicted value. A small tail at the profile edge is a source of the emittance increase. It may be generated in the following mechanism. The electrons around the beam edge diffuse to the outside of the beam by the transverse thermal motion. In this region, radial electric field generated by the space charge is not linear, that is, it decreases in inverse proportion to radius. Therefore, the diverging angles of the diffusing electrons become smaller than that of the electrons in the beam edge. As a result, the phase space profile becomes S-shape after travelling in the drift space. The concept of the mechanism is shown in Fig. 10.

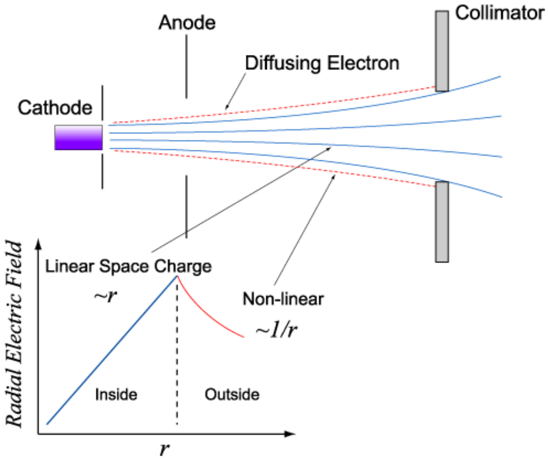

Fig. 10 : Mechanism of the emittance increase by thermal diffusion and space charge force.

The emittance without this tail can be roughly estimated by making the product of the rms diverging angle at the beam centre ($\sigma_{x'}$) and the rms beam radius (~$r/2$). The 0.6π mm.mrad value obtained is near the theoretical thermal emittance. Since the nonlinear tail comes from the edge region of the round beam, it could be removed by using a beam collimator. We expect that doing that we should realize the required small emittance of less than 1π mm.mrad.

REFERENCES

[1] T. Shintake et al., "SPring-8 Compact SASE Source, SPIE2001, San Diego, USA, June 2001

[2] K. Togawa et al., "CeB_6 Electron Gun for the Soft X-ray FEL Project at SPring-8", FEL2003, Tsukuba, Japan, Sept. 2003, Nucl. Instr. Meth. A 528 (2004) 312

[3] H. Kobayashi et al., Emittance Measurement for High-Brightness Electron Guns, 1992 Linear Accelerator Conference, Ottawa, Canada, August 1992

[4] http://www.feibeamtech.com/

[5] H. Matsumoto et al., "A Closed Compact Modulator for 50 MW C-band (5712 MHz) Klystron" 25th International Power Modulator Symposium and 2002 High Voltage Workshop, Hollywood, USA, 2002, ISBN 0-7803-7540-8

[6] K. Togawa et al., "Emittance Measurement on the CeB_6 Electron Gun for the SPring-8 Compact SASE Source FEL Project", APAC2004, Gyeongju, Korea, March 2004