EMITTANCE MEASUREMENT OF A DC GUN FOR SMITH-PURCELL BACKWARD WAVE OSCILLATOR FEL*

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Abstract

A terahertz light source based on Smith-Purcell Backward Wave Oscillator FEL (S-P BWO-FEL) has been studied at Laboratory of Nuclear Science, Tohoku University. The DC gun employs a high voltage of 50 kV to extract electrons, which is suitable to drive S-P BWO-FEL [1]. Emittance measurement has been performed by means of a double slit technique. The deduced normalized rms emittance is about 2 π mm mrad. We present the results of emittance measurement and analysis.

INTRODUCTION

Currently, various sources of terahertz (THz) radiation are based on accelerator or laser and semiconductor technology. Especially, the accelerator based sources have the potential to serve the THz light with very high intensity. It is expected that such THz radiation will be very useful for many applications in molecular science, imaging and spectroscopy. The S-P BWO-FEL is considered to be one of the candidates of high intensity accelerator light sources.

Smith-Purcell Backward Wave Oscillator FEL

A numerical simulation using a 3-D FDTD method shows the characteristics of the S-P BWO-FEL, which results from the interaction between the DC beam and the evanescent waves supported by a conductive grating [2]. The simulation suggests the S-P BWO-FEL requires the beam should have beam current of higher than 150 mA, moderate kinetic energy around 70 keV and normalized rms emittance of less than 1 π mm mrad [3].

DC-gun

An electron DC gun capable for production of extremely low emittance is required for the S-P BWO-FEL. The DC gun we have developed has an additional bias voltage between a wehnelt electrode and a cathode to manipulate equi-potential surface near the cathode to make the transverse distribution of electrons an ideal Kapchinskij-Vladimirskij (K-V) beam, in which the space charge effect can be minimized. The DC gun employs the small cathode, which reduces the intrinsic emittance. In addition, the DC gun has no grid structure to avoid emittance growth [4]. Figure 1 shows the schematic cross section of the DC gun. Specification of the DC gun is shown in Table 1.

A reliable power supply composed of the high voltage power supply and cathode heater power supply with the feedback system is required to generate a high stability beam. The accelerating voltage was measured by a high voltage probe. It was found the fraction of the accelerating voltage is less than about ±0.4 % during one measurement of charge intensity profile. In addition the cathode has been operated for 6000 hours without failure.

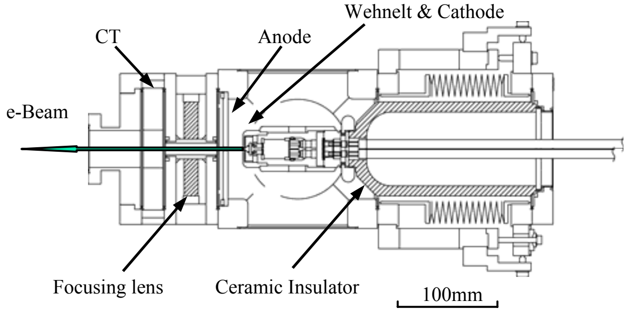

Figure 1: Side cutting view of the low emittance DC gun.

Table 1: Design parameters of the DC gun.

Beam energy	50keV
Beam current	>300mA
Pulse width (FWHM)	1 - 5 μs
Repetition rate	< 50 pps
Normalized emittance	< 1 π mm mrad.
Normalized thermal emittance*	0.25 π mm mrad
Cathode material	LaB_6 single crystal
Cathode diameter	1.75 mm

*theoretical

PHASE SPACE MEASUREMENT

Double slit technique

Considerable care should be required for a measurement system when the phase space is dominated by space charge effects. Since quadrupole (or solenoid) scan method may be much affected by the space charge effect, we have employed a double slit technique for phase space measurement to obtain trustworthy values of emittance. A schematic diagram of the measurement principle is shown in Fig. 2. The main components of the measurement system are a solenoid lens, an upstream slit, a downstream slit and a Faraday plate. The electron beam is cut into "beamlet" by the upstream slit. The downstream slit cuts the beamlet into "sub-beamlet". By scanning both slits throughout the whole beam area, a

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beam distribution in the transverse phase space can be obtained as shown in Fig. 3. Since the total charge in the beamlet would be very small, the space charge effect is small as well.

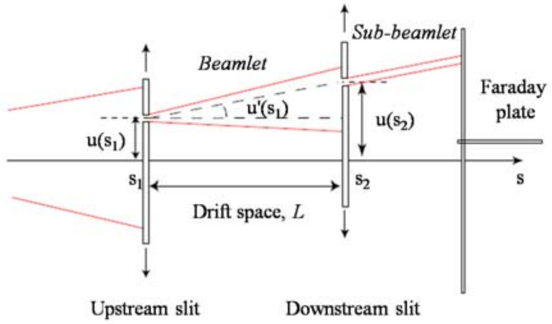

Figure 2: Principle of emittance measurement using double slits technique.

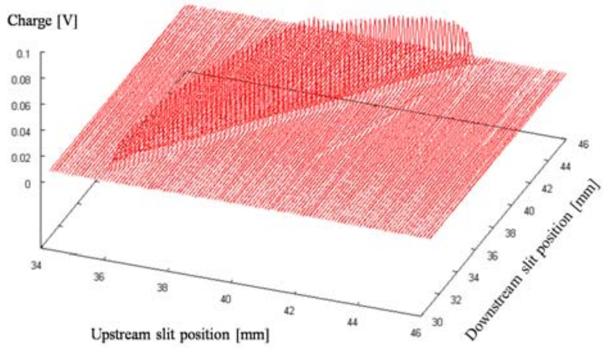

Figure 3: Two-dimensional charge intensity profile of the beam by double slits technique.

In our experimental set-up, the upstream slit was located 190 mm from the cathode. The drift space L between the upstream and the downstream slits was set to be 142 mm. Sub-beamlet current is measured by the Faraday plate. The slit width in both the vertical and the horizontal slits was chosen to be 100 μm, and the material of the slit was tungsten.

The rms emittance of the beam is calculated from the sub-beamlet as,

$$\varepsilon_{rms} = \sqrt{\langle u^2\rangle\langle u'^2\rangle - \langle uu'\rangle^2}\ , \qquad (1)$$

where $<u^2>$, $<u'^2>$, $<uu'>^2$ are the mean square values of position, angular divergence and those product, respectively, weighted by charge density.

In our experimental set-up case, as a result of the structure of slit and the distance of free space, the position resolution is 0.1 mm, and the resolution of the angular divergence is $2 \times \tan^{-1}\theta \approx 2 \times (0.1/142) = 1.41 mrad$.

Measurement of phase space distribution

After focusing the beam in a proper size by adjusting the current of solenoid lens, we have measured the charge density profile at a cathode voltage of 50 kV and a beam current of 300 mA. The scanning step was 100 μm. It took around 6 hours to measure one beam profile.

The sub-beamlet current passing through downstream slit was picked up by the Faraday plate and its signal was fed to an oscilloscope. Using an averaging mode of the scope, the signal voltage at the flattop of the macropulse was measured. Figure 4 and 5 show the phase space distribution for the horizontal and vertical spaces, respectively.

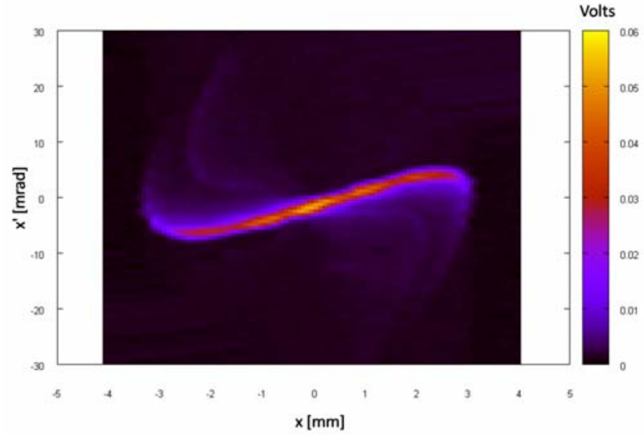

Figure 4: Horizontal phase space of 300 mA beam current obtained from the double slits measurement. The cathode voltage is 50 kV.

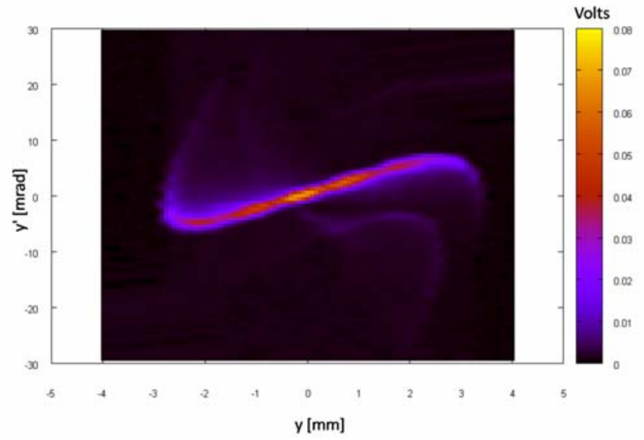

Figure 5: Same as Fig.4 but for vertical phase space.

ANALYSIS

Since the total charge of the extracted beamlet is quite small, S/N ratio of the observed signal was not sufficient level. Figure 4 and 5 actually include the significant amount of background noise which is very sensitive to the emittance estimation. One of useful approach in this situation would be a “core emittance” estimation to deduce the actual emittance. At first the obtained phase space distribution is applied a thresholding in order to remove a given fraction of the particles after the background subtraction. An average value of the background noise is used for the background subtraction. The background noise was measured at the same timing as the beam signal measurement on the standby position of the slits where slits shut out the entire beam. Then the rms emittance is calculated for the remaining core part (core emittance). The threshold level is varied from 0 to 100 % of the total charge in every 10 % step. The results of calculated normalized rms emittances are shown in Fig. 6 and 7 as a function of subtraction level for x and y emittances, respectively. The calculated core emittance decreases steeply in the region of subtraction level from 0 to ~ 50 % as increasing the subtraction level of the background, which implies this region still contains a large amount of the background noise. At the subtraction level higher than 50 %, the decreasing slope of core emittance becomes much gentler.

To deduce the actual emittance which corresponds to no subtraction and no background, a linear fitting was carried out for the region of higher subtraction level of 50 to 100 % and extrapolated to 0 % subtraction. The solid lines in Fig. 6 and 7 show the result of the fitting.

The double slit measurement and the emittance estimation process was repeated for 3 times. The results are summarized in Table 2.

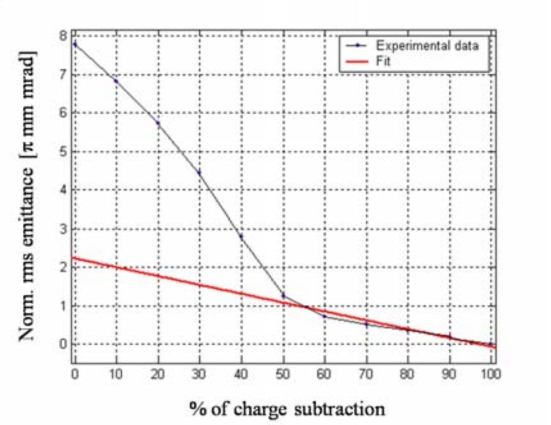

Figure 6: Calculated horizontal normalized rms emittance with respect to the subtraction level. Red solid line shows a result of linear fitting.

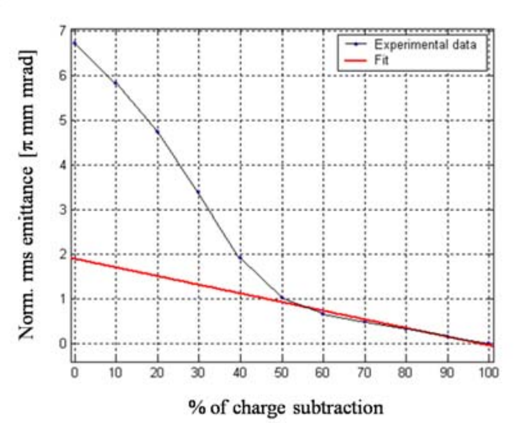

Figure 7: Same as Fig. 6 but for vertical normalized rms emittance.

Table 2: Results of double slit measurement for beam current 300 mA

Measurement No.	Normalize rms emittance [π mm mrad]	
	X-emittance	Y-emittance
1st	2.35	1.81
2nd	2.23	1.90
3rd	2.22	1.87
Average value	2.27	1.86
Error	±0.07	±0.05

We studied the validity of this emittance estimation by a simulation. The measured noise distribution was added to a simulated charge intensity profile. Similarly the rms emittance is calculated for the remaining core part with changing the threshold level. The results of estimated normalized rms emittance are shown in Fig. 8 as a function of the background subtraction level. The behaviour of the estimated emittance in the noise added case is well consistent with the experiment.

In order to estimate the validity, the same fitting procedure as the measurement is carried out for this simulation data. The solid line in Fig. 8 shows the result of the fitting. In Fig.8, no noise case is also shown.

As a results of simulation study, the emittance of 1.38 π mm mrad would be produced by this DC gun, where the decreasing slope of core emittance become more flat in the lower background subtraction level. Therefore it might be considered that this deduced value may give upper limit of the emittance. Some sources such as alignment error of the cathode and the focusing lens etc. can be also considered, which will interpret the difference between measurement and simulation.

Figure 9 shows the phase space distribution for 80 % of charge subtraction for the measurement data. The tail part of phase space is considered due to the effect of a non-linear force by the focusing lens.

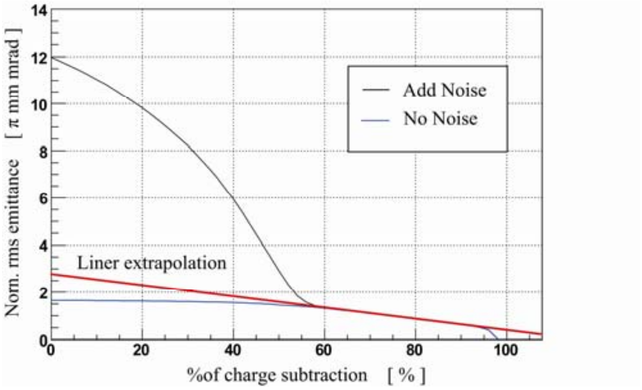

Figure 8: Subtraction estimate for simulation result. Solid line shows a result of linear fitting. The true rms emittance is smaller than the deduced rms emittance by liner extrapolation.

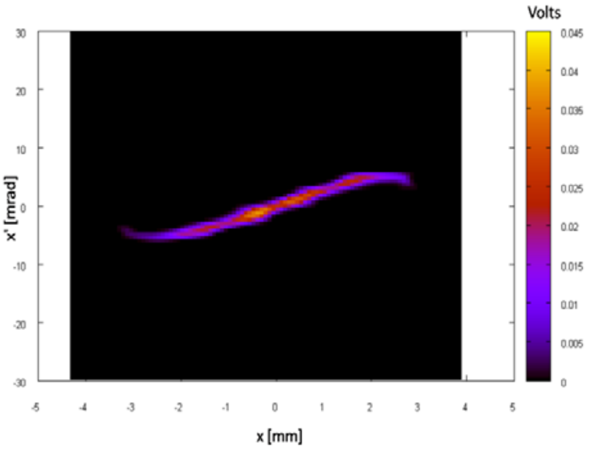

Figure 9: Phase space distribution for 80 % of charge subtraction.

SUMMARY

We have developed a very low emittance DC gun for the S-P BWO-FEL driver. The DC gun has three distinctive features: (1) a single crystal LaB_6 cathode with the small diameter; (2) no grid structure; and (3) special bias between a wehnelt and the cathode. We have measured the beam emittance by using the double slit technique at the cathode voltage of 50 kV and the peak current of 300 mA. The deduced normalized emittance at the upstream slit position was around 2 π mm mrad. We have concluded that the DC-gun will possibly qualify the requirement for the S-P BWO-FEL by performing further improvement. We will design a beam transport system for the S-P BWO-FEL for the next step.

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