BEAM QUALITY MEASUREMENTS OF A LOW EMITTANCE DC GUN

EMPLOYING A SINGLE CRYSTAL of LaB$_6$ CATHODE

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Abstract

The low emittance compact DC gun employing a single crystal of LaB$_6$ cathode has been developed for the application of high brightness beam such as Smith-Purcell free electron lasers [1] and advanced accelerator researches. Achieved maximum beam energy and maximum emission current in the initial beam test were 50 keV and 1.5 A, respectively [2]. Beam quality measurements have been carried out to study the characteristic of the DC gun. The slits with of 50 μm in both horizontal and vertical axis are used for a measurement of a small beam size at the downstream of a DC gun. The horizontal and vertical rms beam sizes focused by solenoid lens are less than 2 mm at a location of 173 mm from the anode exit. The details of measurement results are described.

INTRODUCTION

In recent years, FEL application has been extensively conducted in many laboratories. Electron guns for production of high brightness are generally required toward such applications. The low emittance DC gun at Laboratory of Nuclear Science (LNS) is one of the choices. Our DC gun has been designed without a grid electrode to avoid emittance growth by through the grid mesh. The single crystal LaB$_6$ cathode has been chosen to produce the high current density [3]. The simulation results show that we can manipulate the transverse phase space by applying negative bias voltage at the wehnelt electrode [4]. The schematic diagram of DC gun power supply is shown in Fig.1. We have chosen a low applying voltage (50 kV) to reduce the size of the entire system. The fabrication of the DC gun had been finished and we succeeded to extract the electron beam over 300 mA followed by our designed target. The main design parameters are shown in Table 1. This DC gun is now under evaluation of beam qualities. In this paper, we examine the measurement of the beam size and analyze the normalized rms emittance by means of solenoid scanning method. In order to measure precisely such a small beam size, the installation of the slit in the beam line and precision of the movement are very important. The measurement results of the DC gun are described together with data analysis.
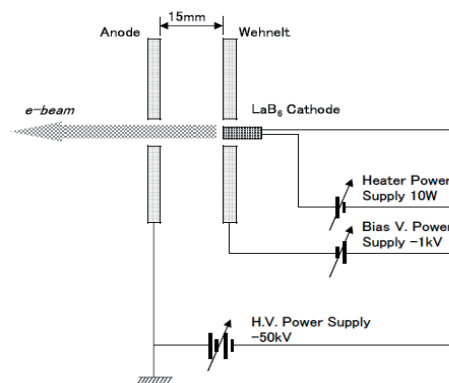
Figure 1: The schematic diagram of DC gun power supply.

Table 1: Design parameters of electron gun.

Beam energy	50 keV (Max.)
Peak current	>300 mA
Pulse width (FWHM)	1-5 μsec
Repetition rate	50 pps
Normalized emittance	< 1 π mm mrad.
Normalized thermal emittance	0.25 π mm mrad* *theoretical
Cathode diameter	1.75 mm.

MEASUREMENT AND ANALYTICAL RESULTS

Beam size measurement

The beam size was measured at downstream of the DC gun. Figure 2 shows the configuration of the beam size measurement. The main components in this section are solenoid lens, current transformer (CT), and slit. The beam current was measured by the CT installed at the downstream of the solenoid lens.

The slit is located at 173 mm downstream of anode exit. The slit foil with thickness 50 μm made of SUS 316L and consists of 2 perpendicular slits in X and Y direction with slit width 50 $\pm$ 2 μm. The slit was manufactured by wire cut method and its width was measured by a high precision microscope. The moving direction of the slit stage is 45 degree between X and Y axis has an advantage

of that the only one move direction is necessary for 2 axis scans. The end of the slit mover stage is powered by a 5-phase stepping motor stage assembly (Oriental Motor PK545AW-P7.2). This stage is driven by a ball bearing spindle of 1 mm pitch for one revolution. The stepping motor performs one rotation by 3600 steps. Combining the ball bearing spindle and the precise stepping motor, the maximum resolution of step is 1/3600 mm.

The slit is used for cutting a round beam in a sheet shape of the transverse beam profile after the solenoid lens confined the beam. Faraday plate is attached behind the slit to pick up the signal after cut by slit. All of signal from current transformer and Faraday plate is connected to digital oscilloscope and analyzed by software (MEXPO1).
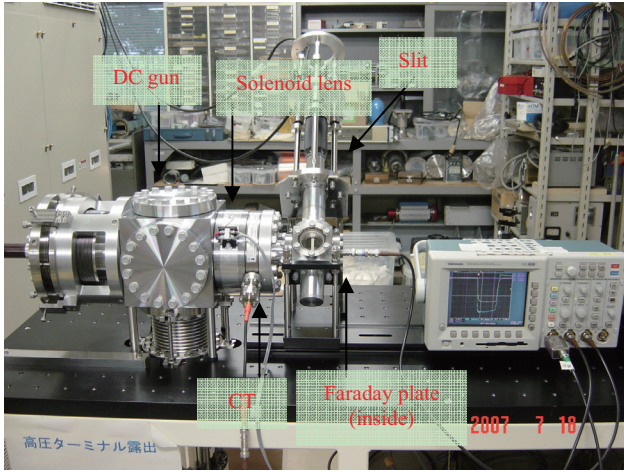

Figure 2: The DC GUN configuration of beam size measurement

From V-I characteristic curve of our DC GUN [4],we have chosen 8 A of heater current for operating condition, so that the cathode was heated up to ~1800 K by applying 10 W of heater power and the beam current, 430 mA, was measured by current transformer. The result from scanning slit throughout whole beam area shows the minimum rms beam size less than 2 mm in both X and Y directions. Figure 3 shows the minimum beam diameter in X and Y directions at the beam current of 430 mA confined by solenoid lens.
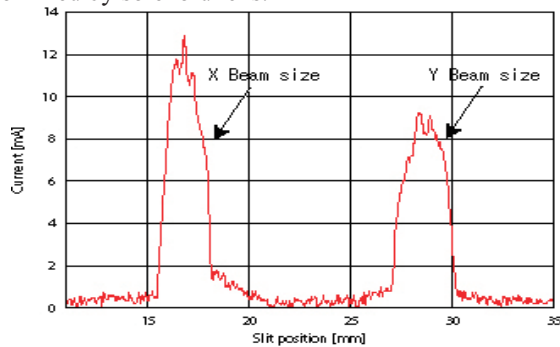

Figure 3: The minimum rms beam diameter in X and Y direction at 430 mA of beam current focused by solenoid lens.

Furthermore, beam size measurements were performed in various beam currents of 50 and 180 mA corresponding to heater current of 7 and 7.5 A, respectively. The results of beam profiles are shown in Fig. 4. One can notice the shifting of a beam position in each case. Possible reasons are alignment error of cathode and unsymmetrical field of solenoid lens. Moreover, the beam size becomes bigger when the beam current increases and a stronger focusing strength from solenoid lens is required to confine the beam. From this result it seems the space charge effects play a significant role for the beam size.
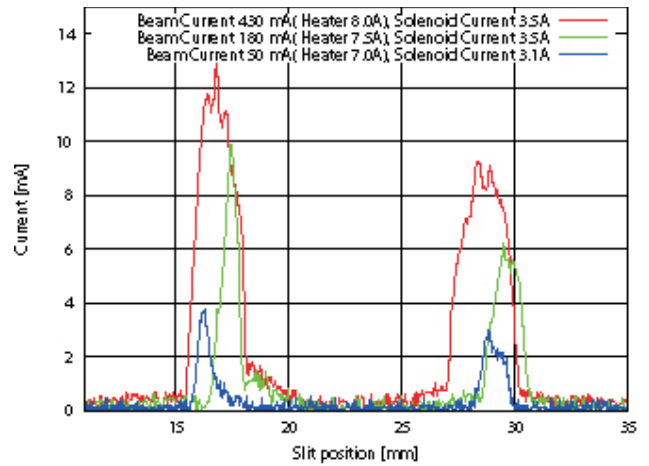

Figure 4: The minimum beam diameter in various cases of beam current.

Transverse beam emittance

The solenoid scanning method is used to deduce a tentative beam emittance of the DC gun. The measurement can be understood by examining the evolution of the rms beam size in a drift length following a thin lens of focal length *f*. So the beam matrix transforms at the slit position given by equation (1)

$$\sigma^1 = R\sigma^0 R^T, \tag{1}$$

where R is the transfer matrix in drift space (L) and solenoid lens (the magnetic strength, Q) followed by equation (2)

$$R = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -Q & 1 \end{pmatrix} = \begin{pmatrix} 1-QL & L \\ -Q & 1 \end{pmatrix}. \tag{2}$$

Here we have explicitly ignored space-charge. By applying initial conditions to equation (1), we can solve the equation for the square of the rms beam size in the term of focal length of the solenoid lens as:

$$\sigma_{11}^1 = <x_1^2> = L^2\sigma_{11}^0 \cdot \frac{1}{f^2} - 2[L\sigma_{11}^0 + L^2\sigma_{12}^0] \cdot \frac{1}{f} + \tag{3}$$

$$L^2\sigma_{22}^0 + 2L\sigma_{12}^0 + \sigma_{11}^0.$$

In this form, we can see that the square of the rms beam size at the end of the drift should follow the square of the

focal length of the solenoid lens. The scan process then, is to vary excitation current of the solenoid lens and measure the beam size at the fixed distance from the lens. The magnetic strength of solenoid lens given by equation (4)

$$Q = \frac{1}{f} = \frac{1}{4}\left(\frac{e}{cp}\right)^2 B_z^2 D,$$ (4)

where Q is magnetic strength of solenoid lens, f is focal length , e is charge density of electron, c is speed of light , p is electron momentum, B_z is longitudinal magnetic field at the center of solenoid lens, and D is effective length of solenoid lens, respectively. From equation (4), we can calculate the magnetic strength of solenoid. So the equation (3) can be simplified to the form of equation (5)

$$\sigma_{11}^1 = <x_1^2> = aQ^2 + bQ + c.$$ (5)

The normalized rms emittance is calculated by equation (6)

$$\varepsilon_{n,rms} = \beta\gamma\sqrt{<x_0^2>.<x'_0^2> - (<x_0.x'_0>)^2} = \beta\gamma\frac{\sqrt{4ac-b^2}}{2L^2},$$ (6)

where β is the beam velocity divided by light velocity, γ is the relativistic mass factor, and a, b, c are coefficients of quadratic function from curve fitting.

At the beam current of 430 mA, the results of emittance calculations are shown in fig. 5 and fig. 6. The data sets (square of rms beam size vs. magnetic strength of solenoid) were combined and analyzed to obtain a polynomial fit. The X and Y normalized rms emittances, 2.46 and 2.66 π mm mrad respectively, are obtained by this method.
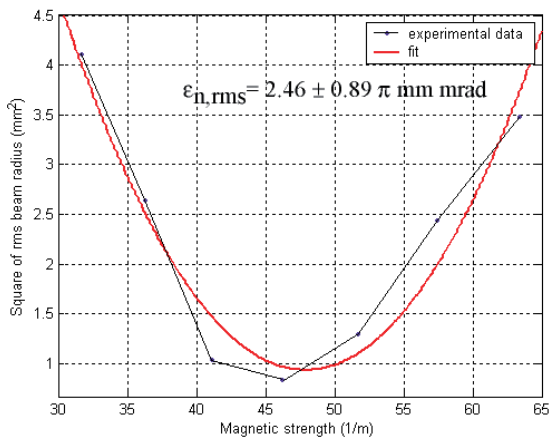

Figure 5: A square of beam radius in X-direction plotted as a function of magnetic strength of solenoid lens.
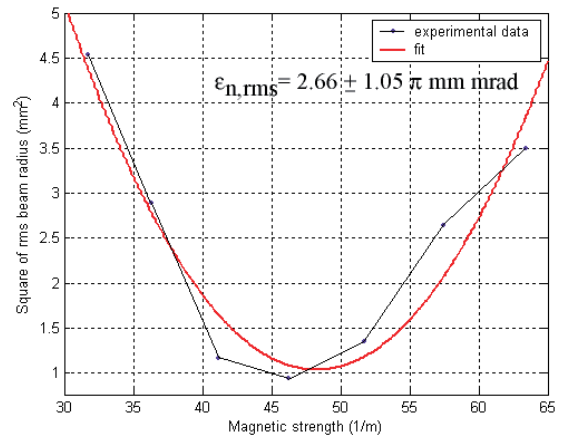

Figure 6: A square of beam radius in Y-direction plotted as a function of magnetic strength of solenoid lens.

A rigorous error analysis was not performed in the analysis of the slit scan data. The different errors that contribute to the analysis uncertainty have been estimated. These errors result from the analysis uncertainty of quadratic fit coefficients from thin lens approximation and the distance measurement of the drift space. The deduced errors are $\pm$ 0.89 and $\pm$ 1.05 π mm mrad for the X and Y normalized rms emittances, respectively. These errors seem to be high compared with expected values of normalized rms emittance. So we need more precise technique for emittance measurement to confirm the emittance value.

SUMMARY

We have measured the beam size at 50 keV. The data have been taken at various beam currents by varying magnetic strength of solenoid lens. At our target designed value of beam current, we achieved the minimum rms beam size in both horizontal and vertical direction less than 2 mm, and the preliminary data analysis of the normalized rms emittance can be carried out by the rms beam size evolution at the slit in the drift space. Nevertheless, we need to clarify the beam emittance by double slit method and apply special bias voltage to manipulate the phase space of the beam.

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