A COMPACT LOW EMITTANCE DC GUN EMPLOYING SINGLE CRYSTAL CATHODE OF LaB_6*

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Abstract

Development of an electron gun capable of producing low emittance is in the interests of further applications of high brightness electron beam such as Smith-Purcell FEL [1] for example. A prominent point of this DC gun is that operation high voltage is very low (50 kV). Since a higher beam current of the macropulse is required in general, a cathode should have higher current density, while the smaller size of the cathode is preferred for lower emittance. Consequently we have chosen single crystal LaB_6 as the cathode, which can provide higher current with good homogeneity emission. Some numerical calculations have also been performed. There are some good agreement in calculated results between them. Numerical calculations show a normalized rms emittance is expected to be less than 5 π mm mrad. A state-of-the-art electron source will possibly open new scientific opportunities in the many fields.

INTRODUCTION

Nowadays, the demand for high-brightness electron gun has increased dramatically to achieve many applications in the field of electron beam technolygy. The low emittance DC electron gun at LNS is one of the candidates. This DC electron gun has no grid which would degrade beam emittance. The cathode is made of materials with the low work function, and heated to 1700 - 1900 K for producing electrons. We have employed the cathode voltage of -50 kV with respect to grounded anode and variable pulse duration from 1 to 5 μsec. This low voltage choice can make the entire system to compact. The schematic diagram of DC gun power supply is shown in Fig.1. In spite of such low voltage, the emittance can be reduced to very small because of a very short distance between the cathode and the anode. In order to produce low emittance beam, the cathode size should be small, so that the higher current density is required. Such high current density can be realized by some cathode materials such as single crystal LaB_6 [2] or CeB_6 [3].The design parameters and the drawing of the low emittance DC electron gun are shown in Table 1 and Fig.2, respectively.

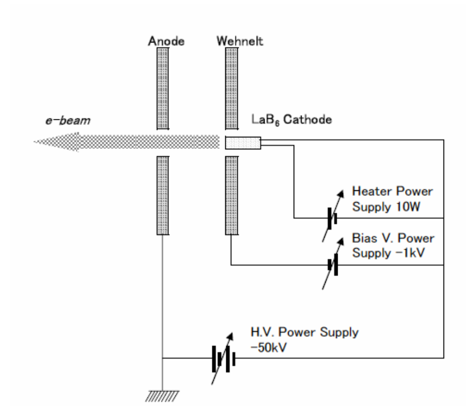

Figure 1: The schematic diagram of DC gun power supply.

Table 1: Design parameters of electron gun.

Beam energy	50 keV (Max.)
Peak current	>300 mA
Pulse width (FWHM)	1-5 μsec
Repetition rate	300 pps (Max.)
Normalized emittance	<10 π mm mrad.
Normalized thermal emittance	0.25 π mm mrad* *theoretical
Cathode diameter	1.75 mm.

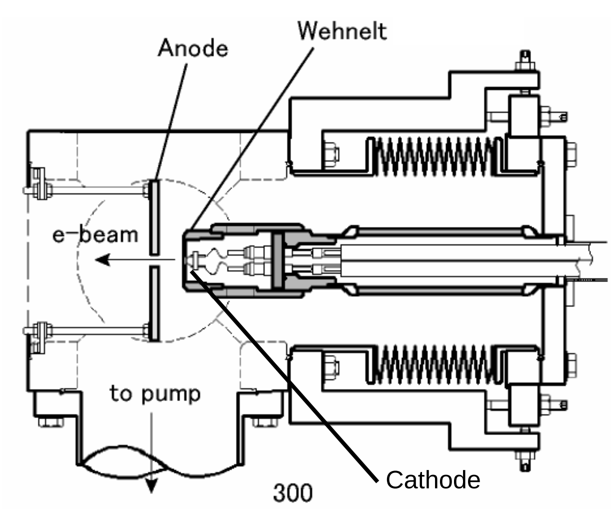

Figure 2: The low emittance DC electron gun.

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THE LOW EMITTANCE DC GUN

LaB_6 cathode

The normalized rms thermal emittance of electrons emitted from a hot cathode is followed by equation (1):

$$\varepsilon_{\mathrm{n,rms}} = \frac{r_c}{2}\sqrt{\frac{k_B T}{m_o c^2}} \quad , \tag{1}$$

where r_C is the cathode radius, k_B is Boltzman's constant, m_0 is electron rest mass and T is the cathode absolute temperature. From the above relation, in order to obtain the small emittance less than 1 π mm mrad required for an example, the X-ray FEL application, the diameter of the cathode must be in the range of a few mm. On the other hand, high emission density (~12 A/cm^2) is required to produce a several hundred miliampere peak current from the small surface. The 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 with low porosity after surface material evaporation. The emission density is more uniform because the crystal orientation is the same over the whole surface. In recent years, single crystal LaB_6 cathodes are widely used for scanning electron microscope (SEM) and superior stability has been demonstrated. So, we decided to use a single-crystal LaB_6 cathode with a flat crystal surface shown in Fig.3. The diameter of our LaB_6 cathode is 1.75 mm. The 300 mA peak current will be produced when the cathode is heated to ~1900 K at vacuum level of 10^{-8} torr or better. The theoretical thermal normalized emittance is 0.25 π mm mrad.

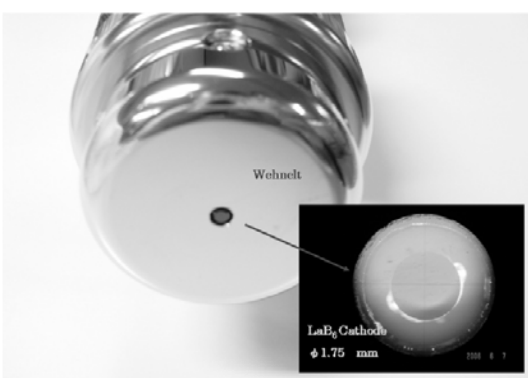

Figure 3: The assembly of single-crystal LaB_6 cathode.

High-voltage power supply

A high voltage DC thermionic gun uses a heated cathode to produce electrons, which are then initially accelerated with a DC pulse voltage. A low energy electron gun high-voltage power supply was developed for 0~-50 kV with 300 mA a peak current, a pulse width of 1-5 μsec, and pulse droop 0.1%, respectively. The wehnelt voltage can be adjusted from 0~-1 kV. In addition, a floating bias voltage can be applied between the cathode and the wehnelt to optimize the electric field for achieving the lowest emittance. In the case of the heater power supply, we use 1 V_{dc} and 12 A maximum current to feed the LaB_6 cathode.

The high-voltage power supply was tested by loading at an electron gun system to generate an electron beam.The beam current was measured by the Faraday plate. The cathode was heated up to ~1800 K and the current, 200 mA, was measured in the test chamber by applying 10 W of heater power. So, one of reasons to achieve peak current, 300 mA, is that we have to increase the absolute temperature of the cathode. Up to now, the cathode has been operated for 1000 hours without failure. Fig. 4 shows the measurement waveform of the accelerating voltage and beam current.

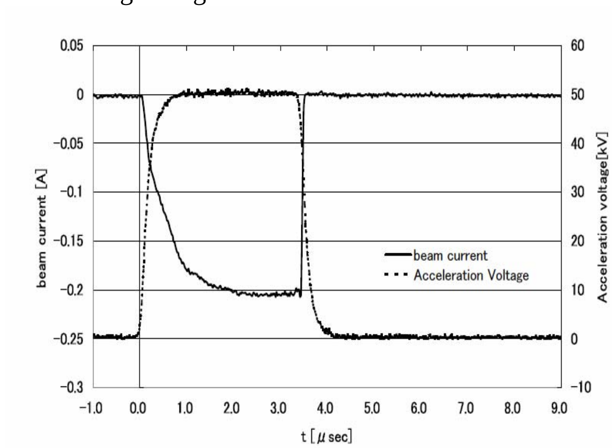

Figure 4: The measurement waveform of the accelerating voltage and beam current.

NUMERICAL CALCULATION RESULTS

We performed a computer simulation using 2 dimensional simulation code [KUAD2 v2.21] developed by Kyoto University [4,5] for 50 keV, 300 mA beam current and 15 mm cathode-anode distance in simple model. As shown in Fig.5, the beam trajectories diverge too much including the emittance growth due to space charge, which would result in a rapid increase in beam spot size. Nevertheless, the normalized emittance from the anode exit still has a small value (4 π mm mrad) at the longitudinal position far from the anode. Fig.6 shows the macro-particle distribution and the phase space distribution at the position 200 mm from the cathode. In addition, the simulation result shows electric field near the cathode surface is very sensitive to the emittance growth, which means the mechanical positioning of the cathode is very important. So we need special bias voltage between cathode and wehnelt to manipulate the electric field around cathode surface. On the other hand, we developed the 3 dimensional self-developed code 3-D FDTD [6] and compared with 2 dimensional simulation code. The trend of position dependence of the emittance is good agreement between them, and both of them still result in the small value of normalized emittance. The result of electron beam extraction and normalized emittance is shown in Fig.7, and the macro-particle distribution and phase space distribution at the end point are shown in Fig.8.

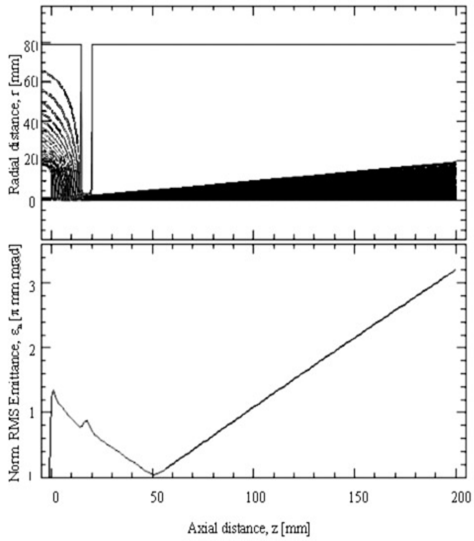

Figure 5: An electron beam extraction and normalized emittance of 300 mA in a DC gun according to a simulation with KUAD2.

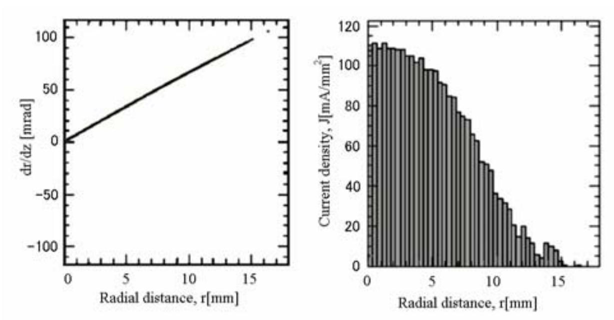

Figure 6: The macro-particle distribution and phase space distribution at the position 200 mm from cathode according to a simulation with KUAD2.

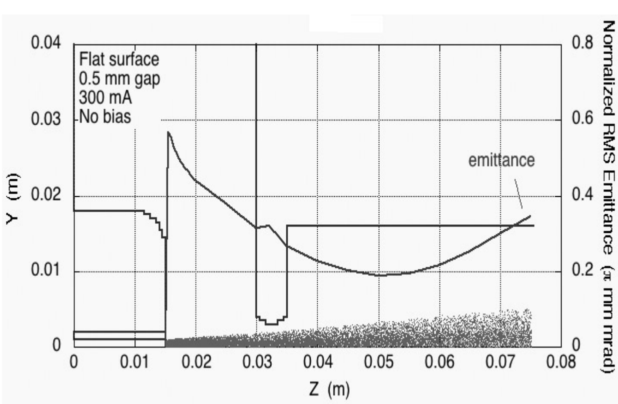

Figure 7: An electron beam extraction and normalized emittance of 300 mA in a DC gun according to a simulation with 3D FDTD.

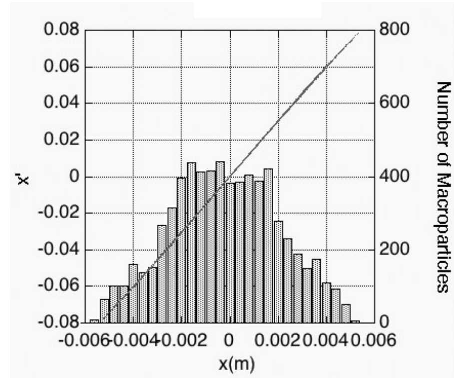

Figure 8: The macro-particle distribution and phase space distribution at the end point according to a simulation with 3D FDTD.

In another result of the 3D FDTD simulation, we applied bias voltage between wehnelt and cathode to manipulate the electric field around the cathode surface as shown in Fig.9. At the low bias voltage, a little focussing action, therefore, the emittance is gradually grow and become smoothly when the bias voltage was increased from 200 V to 400 V. The minimum point of emittance was shifted backward to cathode side by increasing of special bias voltage. At the high bias voltage, the negative field from wehnelt predominates and deflects the electron beam away from anode, so the 600 V case shows the over correction of emittance. This result shows that we can manipulate the equipotential line near the cathode surface by adjusting the special bias voltage to optimize the extracted beam emittance.

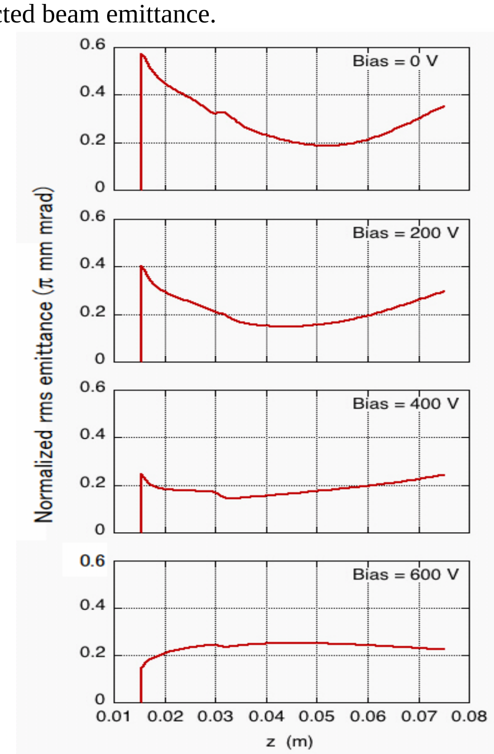

Figure 9: The bias voltage dependence of normalized emittance.

SUMMARY

Presently the DC gun has been examined on a test stand, and characteristics of the extracted beam from the gun are measured. Some numerical calculations have also been performed using 2 dimensional code and 3 dimensional self-developped code. There are some good agreement in calculated results between them. Moreover, both of them show the small value of normalized emittance. So that, the beam transportation after the gun should be carefully designed to keep such small emittance and utilize the beam. We can also apply special bias voltage to manipulate the electric field near the cathode surface.

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