STUDY ON COMPACT DC ELECTRON GUN USING SINGLE CRYSTAL CATHODE OF LaB_6*

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Abstract

A novel, compact DC gun has been developed and is currently on a test bed at LNS. Applying 50 kV high voltage for the gun, it is expected to supply a high brightness beam which the beam current of 300 mA and the variable pulse duration from 1 to 5 µsec. In addition, a floating bias voltage can be applied between the cathode and the wehnelt to manipulate electric field near cathode surface. In order to produce lower emittance beam, the size of thermionic cathode should be very small, but the cathode should be higher current density. Consequently we have chosen single crystal LaB_6 as the thermionic cathode, which can provide higher current density with good homogeneity electron emission. The design parameters and initial operating experience of the DC gun are discussed. This DC gun will be used for Smith-Purcell FEL [1], advanced accelerator researches and other experiments.

INTRODUCTION

Recently, electron guns with high brightness are of great interest to achieve many applications in the field of electron beam technology such as Smith-Purcell FEL , for example. The low emittance DC electron gun at LNS is one of the candidates. The prominent point of this DC electron gun has no grid which would degrade beam emittance. The cathode is made of a single crystal material with the low work function, and heated to higher for producing electrons. We have chosen a low applying voltage (50 kV) to reduce the size of the entire system. 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, and the bias voltage apply between wehnelt and cathode can manipulate the beam property. 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 or CeB_6 [2,3]. The design parameters and the drawing of the low emittance DC electron gun with solenoid lens are shown in Table 1 and Fig.2, respectively.

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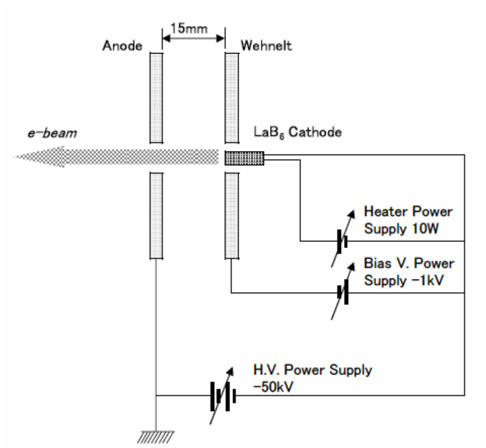

Figure 1: The schematic diagram of DC gun power supply.

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	<10 π mm mrad.
Normalized thermal emittance	0.25 π mm mrad* *theoretical
Cathode diameter	1.75 mm.

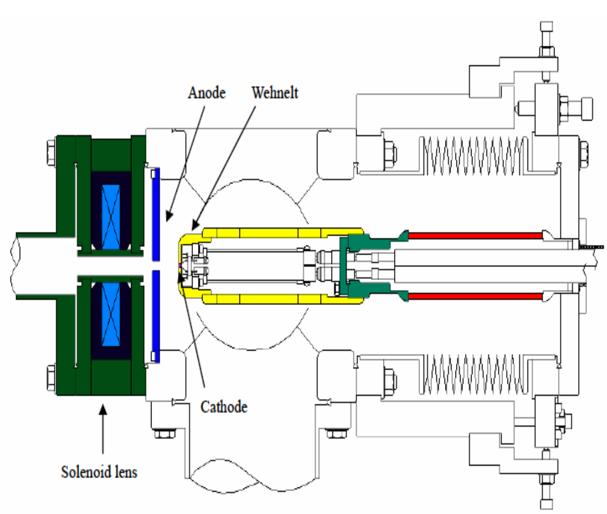

Figure 2: The low emittance DC electron gun.

DC GUN DEVELOPMENT

LaB_6 cathode

The thermal limit of normalized rms emittance of electrons emitted from a hot cathode is given 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 Boltzmann 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, the diameter of the cathode must be in the range of a few mm. On the other hand, high emission density is required to produce a several hundred miliampere peak current from the small surface. The LaB_6 can emit such an intense current over the long lifetime. 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 much more uniform because the crystal orientation is the same over the whole surface. So, we decided to use a single-crystal LaB_6 cathode with a flat crystal surface shown in Fig. 3.

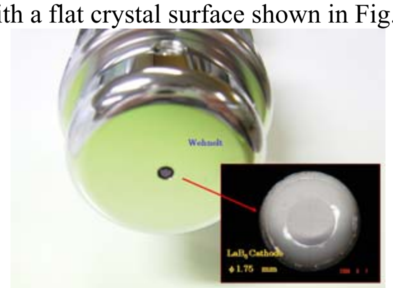

Figure 3: The assembly of single-crystal LaB_6 cathode.

Gun High Voltage

The high voltage power supply was tested by loading with the electron gun. The beam current was measured by the Faraday plate. The cathode was heated up to ~1900 K by applying 10 W of heater power and the DC pulsed current, 1.5 A, was measured in the test chamber. Fig. 4 shows the measured waveforms of the accelerating voltage and beam current. Up to now, the cathode has been operated for 4000 hours without failure.

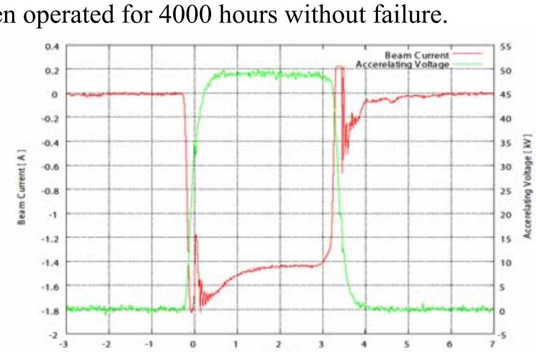

Figure 4: The measured waveforms of the accelerating voltage and beam current.

Gun simulation

We developed the 3 dimensional self-developed code. The simulation showed the small value of normalized emittance. The result of electron beam extraction and normalized emittance with bias voltage of 600 V is shown in Fig. 5 (above), and the macro-particle distribution and phase space distribution at the end point are shown as well (below).

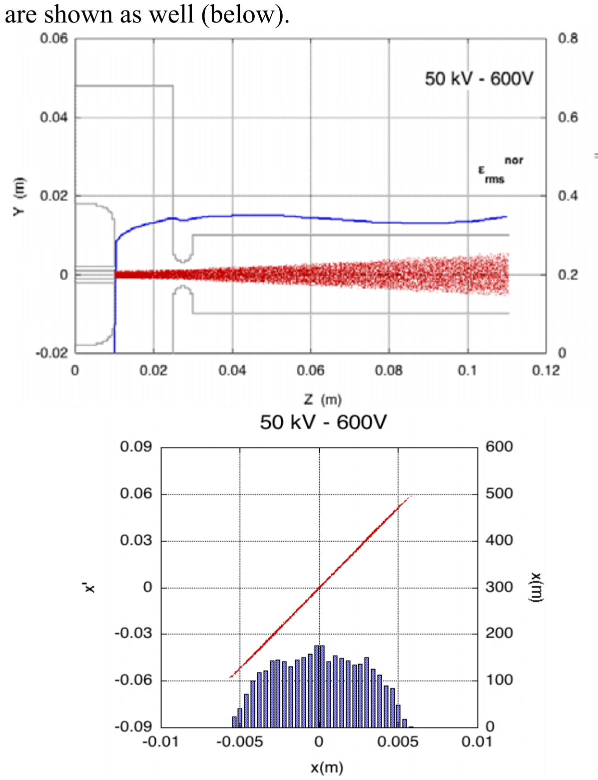

Figure 5: An electron beam extraction and normalized emittance of 300 mA (above) and the macro-particle distribution including phase space distribution (below) at the end point according to a simulation.

In the simulation, we applied bias voltage of 600 V between wehnelt and cathode to manipulate the electric field around the cathode surface. The 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 [4]. An extremely low emittance less than 1 π mm mrad is obtained by the simulation.

MEASUREMENT RESULTS

We measured gun characteristics at the test bench. The first measurement of the LaB_6 gun is V-I characteristics. The measurement was done for various cathode temperatures, which is shown in Fig. 6. From V-I characteristic curve, our gun should be operated at 1800 K in temperature limited region to avoid the space charge effect from high emission current. In this region, the beam current is dominated by Schottky effect rather than Child's law. Accordingly, the slope of the current-voltage curve becomes very smooth.

We have deduced the work function of LaB_6 cathode by measuring the thermal emission current varying the cathode temperature. In the ideal case Richardson-Dashman's formula shows the emission current density given by equation (2)

$$J = 120.4T^2 \exp\left(-\phi' / k_B T\right) \quad , \qquad (2)$$

where J is emission current density, T is cathode temperature , k_B is Boltzmann constant, and ϕ' is effective work function, respectively. From equation (2), we can calculate the work function of LaB_6 cathode to be 2.4 eV. This measured value is not far from the previous value [5].

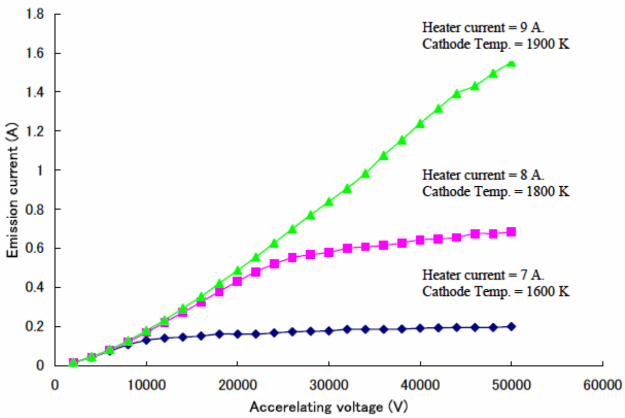

Figure 6: Current-voltage characteristic curve of the LaB_6 gun.

One of the most important characteristics of an electron gun is its perveance (P) express by equation (3)

$$P = \frac{I}{V^{3/2}} \quad , \qquad (3)$$

where I is the beam current and V is the anode potential with respect to the cathode. For guns with flat cathodes, current density inhomogeneity becomes large when the perveance is high value. However, electron beams with higher perveance are needed in number of applications where charge or current density is a key parameter. From curve fitting function, we can obtain 0.155 $\mu A/V^{3/2}$. This result shows that this DC gun has high emission current density.

In order to focus the beam and to compensate space-charge blow-up the DC solenoid lens has been designed and installed downstream of the anode structure. The solenoid is capable of delivering high magnetic field strength on axis. Through proper tuning of the solenoid current beam focus can be produced at any location within the diagnostic module which is built around a 104 mm long drift section behind the solenoid magnet. We can achieve the minimum beam size diameter of 1.6 mm at solenoid current 2.5 A. The beam profile at plastic scintillator [EJJEN TECHNOLOGY, EJ-212] is shown in Fig. 7. Fig. 8 shows the effect of solenoid current that induces the magnetic field strength to confine the electron beam.

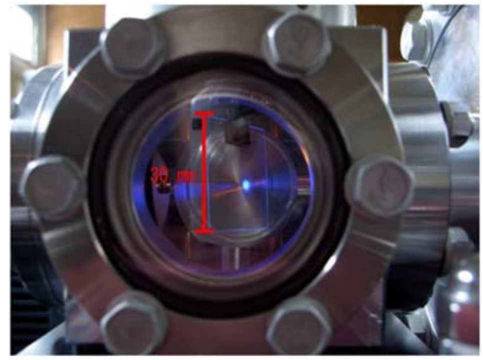

Figure 7: The beam profile at 45 kV confined by solenoid current 2.5 A.

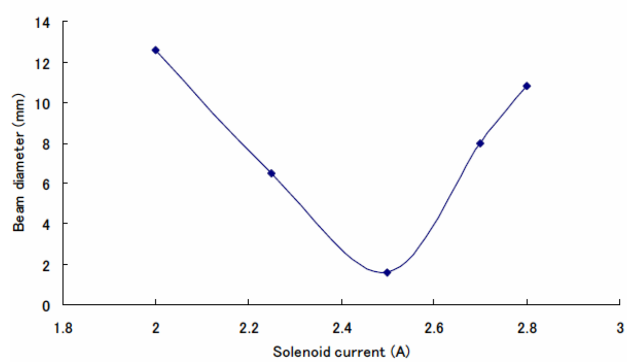

Figure 8: The beam diameter plotted as a function of solenoid current.

SUMMARY

At the present the DC gun has been examined on a test stand, and characteristics of the extracted beam from the gun are measured. The simulation shows that a fairy simple and compact system have a capability to fulfil the design goals.The measurement results show high emission current density of DC gun with LaB_6 cathode ,and we can also control the beam size at downstream of gun exit by solenoid lens. As the next step, we are planning to measure other beam parameters including the beam emittance.

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