KEK Preprint 96-29
June 1996
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High current density gun with a LaB_6 cathode

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Abstract:

To develop a high-current electron gun for an induction linac, a prototype of a Pierce-type electron gun using planar 12 mm-diameter lanthanum hexaboride(LaB_6) is being studied as a thermionic emitter at high current densities. The cathode is heated up to temperatures of $1,750^\circ\text{C}$ by electron bombardment and thermal radiation from a tungsten heater. The heater having the highest temperature in the gun is thermally isolated from the outer vacuum chamber by heat shields. A bombardment voltage of $\sim 1\text{ kV}$ is typically applied to a gap between the cathode and the heater. The gun has been operated up to voltages of 55 kV , obtaining a maximum current density of 20 A/cm^2 with a pulse width of 250 nsec at a cathode temperature of $1,600^\circ\text{C}$. High-voltage pulsing results show that the gun, with applied voltages of over 40 kV , is operated in a space-charge-limited region at temperatures of over $1,600^\circ\text{C}$; it is also operated in a temperature-limited region at temperatures of less than $1,500^\circ\text{C}$. An effective work function of 2.68 eV is obtained. The cathode, when heated up to $1,600^\circ\text{C}$, emits over 7 A of electrons with a $\sim 20\%$ reduction after 850 hours of continuous operation. These measurements were made between vacuum pressures of 10^{-6} to 10^{-7} Torr .

Submitted to Review of Scientific Instruments.

National Laboratory for High Energy Physics, 1996

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1. Introduction

A single-stage microwave free-electron laser (FEL) driven by an induction linac energized by magnetic compressors[1] is constructed at KEK (National Laboratory for High Energy Physics in Japan). The purpose is to develop a high-power microwave source for a future linear collider[2]. The large-area cathode used at KEK is a field-emission (cold) type, which emits an electron-beam current of 2 or 3kA with an energy of 1.6MeV and a width of 80nsec. We generated FEL output powers exceeding 100MW at 9.4GHz[3]. Electron beams have been generated using such cathodes, as metal cathodes, velvet-wool cathodes and graphite-felt cathodes[4]. However, since these kinds of cathodes evaporate the surface while emitting electrons, they have short operational lives of several hundred shots. It is very difficult to keep the emission current and spatial distribution under control. Also, such cathodes aren't suitable for high-repetition pulsed devices. Although thermionic dispenser cathodes are capable of producing high current density pulsed beams with a high repetition rate[5], they are limited to applications in devices where a high vacuum of below $\sim 10^{-9}$ Torr is maintained. Photocathodes are also capable of producing high current density pulsed beams with high repetition rates[6,7]. However, they have short operational lifetimes and require an ultrahigh vacuum environment of better than 10^{-10} Torr[8]. Because the vacuum of the KEK induction linac is poor for the use of the dispenser-type cathode, we have been developing a high current density gun with a reliable thermionic cathode since 1991[9].

We use lanthanum hexaboride (LaB_6) as the cathode material, because of its high current density, modest vacuum and resistance to chemical poisoning. Its basic properties as a cathode have been investigated by a number of authors[10-12]. However, there are unexpectedly only a few applications to high-current guns having large-area cathodes, regardless of their excellent properties.

Grigor'ev and Shanturin[13] obtained a beam current of 250A from a planar 50mm-diameter LaB_6 cathode at a voltage of 100kV, a cathode temperature of 1,700°C and a pulse duration of 300nsec. Loschialpo and Kapetanakis[14] measured an average current density of 12A/cm² and a normalized brightness of $3.4 \times 10^9 \text{A/m}^2 \cdot \text{rad}^2$ from a 50mm-diameter cathode. Hernitter and Getty[15] obtained a current of 90A from a 19mm-diameter

cathode at a voltage of 115kV and a temperature of 1,744°C. These cathodes were designed to be the electron source for high-power microwave tubes and FEL. Goebel et. al[16] obtained over 600A of electrons from a 63mm-diameter cathode at a temperature of 1,700°C and a hydrogen pressure of 4×10^{-4} Torr. This cathode was intended for use in a plasma source.

In this paper we first discuss a gun assembly heated to high temperature and a cathode heating system using electron bombardment and radiation from a heater. We then present results concerning the high-voltage operation of the gun and results which were analyzed in detail.

2. Electron gun assembly

The Piece-type electron gun comprises a planar cathode and an anode with an extraction hole. We designed the gun with the aid of the EGUN code[17]. According to the basic properties of the LaB_6 cathode[10-12, 16, 18], we designed a prototype gun, as described in the parameter list of the following Table.

Figure 1 shows an assembly drawing of the gun. The gun is made of a sintered LaB_6 disk of 12mm diameter and 3mm thickness. It is set in a 20mm-diameter graphite cup that doesn't react with refractory metals, such as tungsten, molybdenum or tantalum, at elevated temperatures[10], because of having the same coefficient of thermal expansion. The graphite cup is supported by small pins on a tantalum holder that serves as a focusing electrode. Further, the holder is mounted on a 56mm-diameter, 0.5mm wall tantalum tube. The tip of this tube is drawn by spinning to form a Wehnelt electrode. The tube contains a heating tungsten heater (filament) and heat shields. The spiral filament is made of 0.7mm-diameter pure tungsten wire. The filament and the heat shields are mounted on a 46mm-diameter, 5mm thick boron nitride(BN) base plate. We leave a 3mm spacing the graphite cup including the cathode and the filament at room temperatures to apply a bombardment voltage. The spacing reduces to about 1mm at elevated temperatures because of a thermal expansion of heater-current leads. The anode is made of molybdenum, and is mounted on the outer vacuum chamber. Water-cooling jackets are fitted to the chamber, which is heated by radiation from the inner filament and cathode.

To confined heat radiated from the filament, which has the highest

temperature of over 2,000°C, we set radial and axial heat shields inside the tantalum tube. They are combined so as to enclose the filament in a small pillbox bounded on one end by the axial heat shield and on the other by a graphite cup. The radial shield is five-fold wound by a thin sheet having many dimples. The dimples maintain the gap between the neighboring sheets for thermal isolation. The axial shield is stacked with six thin disks with the same dimples. Both shields are made of 0.1mm thick tantalum sheets.

3. Cathode heating and high-voltage system

The LaB₆ cathode is heated by the electron-bombardment and radiation method. Figure 2 shows a block diagram of the heating system. The tungsten filament is directly heated by a DC current to a temperature at which it can serve as a source having a maximum electron-bombardment current of 430mA. The filament is negatively biased relative to the cathode by a bombardment voltage of 1.0~1.5kV. The bombardment current is a temperature-limited electron beam, which is directly controlled by the electrical-filament heating power. Radiation from the heated cathode also heats the filament. Since this power causes an increase in the filament temperature, the bombardment current increases when a constant-voltage bombarding power supply is used. The increased current still raises the cathode temperature, and the cathode radiates back to the filament. Thus, in a temperature-limited beam, it forms a positive feedback loop between the cathode and the filament[19]. On the other hand, when the constant-current power supply is used for bombardment, the cathode temperature decreases to a lower value. We eliminated this difficulty by using the power supply controlled to a constant heating power in order to keep the filament temperature constant.

The pulse power supply for high voltage is a pulse-forming network (PFN) type with a single thyatron switch[20]. We use a coaxial 20mm-diameter cable of 25m length as the PFN. To protect the DC power supplies, blocking coils between the DC power supplies and the pulse power supply electrically isolate pulses from the high-voltage power supply. Figure 2 schematically shows the high-voltage circuit. To increase the voltage and to invert the sign of the voltage, a step-up transformer is connected between a dummy load(resistor) and the thyatron.

4. Heating and high-voltage pulsing results

Figure 3 shows the measuring result of the cathode temperature versus the total heating power(P_t). Here, P_b represents the bombardment power. We measured the cathode temperatures using an infrared radiation thermometer (0.95μ) calibrated by an optical pyrometer. The thermometer could be focused directly onto the cathode surface through the anode hole. The cathode temperature is raised up to 1,070°C by only radiation when the heating power of the filament reaches 290W. Further, when the bombardment power plus the filament power reaches 670W, the cathode temperature attains a maximum of 1,750°C (=2,020K) without any serious problem. The first heating of the cathode to temperatures of 1,600°C or more requires long outgassing of the higher temperature parts, such as the filament, cathode and thermal shields. Subsequent heating doesn't require any further outgassing unless the vacuum is broken. We measured the vacuum pressure using a B-A type ionization gauge. The pumping unit was a turb-molecular pump assisted by a rotary pump.

Figure 4 shows the high-voltage pulsing results of the gun. Here, we observed the transmitted currents as a function of the voltage for the cathode temperatures. The gun has been operated with pulsing voltages up to 55kV at various cathode temperatures from 1,400°C (=1,670K) to 1,750°C (=2,020K). We measured the transmitted current using a wall-current monitor (WC) placed downstream of the anode. The ambiguity of the current due to noise induced by high-voltage pulsing was below ±0.5A. We obtained a transmitted current of 18A at a temperature of 1,750°C when the high voltage reached 55kV. The measured currents in the space-charge-limited region can be fitted well with the Langmuir-Child law, except for at currents of over 15A as described later. The solid line in Fig.4 is the Langmuir-Child equation fitted for 1,700°C (=1,970K); $I_a = 1.38 \times 10^{-6} \times V_a^{3/2}$. According to increasing the cathode temperature, the transmitted current increases at the same voltages. This phenomenon is explained by the fact that the cathode becomes nearer to the anode because of thermal expansion due to the increasing temperature of the cathode; thus, the perveance gradually increases. The perveance of the gun is $1.13 \times 10^{-6} \text{ A/V}^{3/2}$ at 1,600°C, and increases to 1.50×10^{-6} at 1,750°C. On the assumption that the emission constant in the Richardson-Dushman equation

is the theoretical value ($A=120\text{A}/\text{cm}^2\cdot\text{K}^2$), the effective work function, calculated from the measured values in the temperature-limited region[21], is 2.73~2.77eV for the LaB_6 cathode. The measurements have been made over a vacuum-pressure range of $10^{-7}\sim 10^{-6}$ Torr.

After replacing the cathode with a new one, we again measured the transmitted currents in the same way. Figure 5 shows the high-voltage pulsing results. When the high voltage reached 55kV, we obtained a maximum current of 23A at a temperature of 1,600°C(=1,870K). The current density had a maximum of $20\text{A}/\text{cm}^2$. Figure 6 shows the waveform for a beam current of 23A at a high voltage of 55kV. The upper and lower traces represent the outputs of the WC and high-voltage probe, respectively. The solid line in Fig.5 is the Langmuir-Child equation for the 1,600°C: $I_d = 1.90 \times 10^{-6} \times V_d^{3/2}$. We increased the perveance to 1.90×10^{-6} by reducing the distance between the cathode and the anode. To obtain a higher perveance, we moved the cathode so as to be close to the anode. Due to the high field at the tip of the focusing electrodes, the gun arced two~three times for a voltage of 55kV. We didn't try to apply higher voltages, fearing a breakdown. The effective work function obtained is $2.68\pm 0.05\text{eV}$ for the new cathode under the same assumption. From the high-voltage pulsing results given in Figs.4 and 5, the electron gun, at applied voltages of over 40kV, is operated in the space-charge-limited region at temperatures of over 1,600°C(=1,870K), while it is operated in the temperature-limited region at temperatures of less than 1,500°C(=1,775K).

To investigate the lifetime of the cathode, long-duration emission tests were made at a temperature of 1,550°C while applying a voltage of 28kV with a repetition rate of 2Hz. The cathode emitted over 5A of electrons without any appreciable reduction in the emission after 420 hours of operation. The cathode was exposed to air several times because of a short of the bombardment circuit. After outgassing it, the emission current always recovered to the above-mentioned level. The short problem is worked out by taking away the disk insulator that supported the heater-current lead of stainless steel, because powders of Fe, Cr, ... attached to the disk surface and formed a conducting material. The cathode, after being heated up to 1,600°C, emitted 8.8A of electrons at first, then slowly decreased, and emitted 7A with about a 20% reduction after 850 hours of continuous operation (Fig.7). The decrease is the cathode temperature (within 30°C) caused a reduction in the

transmitted current during 300~700 hours. We observed that the initial buildup of emission from the cathode was under 10%. These results indicate that the LaB_6 cathode operated below 1,600°C has stably emitted the electron beam over a long period of 35 successive days or more. The measurements were made over the vacuum-pressure range of $2 \times 10^{-7}\sim 10^{-6}$ Torr.

5. Discussions

The deviation from the Langmuir-Child law at over 15A, as shown in Figs.4 and 5, is due to the beam loss at the anode wall. A simulation using the EGUN code shows that the outer electrons deviate from the beam center and then strike the anode wall as the number of electrons increase. We also found traces showing how electrons struck the surface of the anode hole. Based on the measured results and simulation, the emission current is expected to be 1.1-times as large as the transmitted one, about 20~23A.

Since the obtained effective work function is 2.68eV, the current densities calculated from the Richardson-Dushman equation are $26.1\text{A}/\text{cm}^2$ at 1,600°C and $67.0\text{A}/\text{cm}^2$ at 1,700°C, respectively. This shows the excellent property of the LaB_6 cathode at a high current density. The results can be compared to previous work with the work function[10,11]. J. Pelletier et. al[22] obtained a work function of 2.36eV from a hot-pressed porous LaB_6 cathode of 20mm in diameter after molybdenum decontamination by iodine attacks. We think that the difference in the work function between our old and new cathodes was caused by contamination of the cathode surface by the molybdenum vapor provided at above 1,400K, because the holder mounting for a graphite cup, when measured the transmitted currents in Fig.4, was made of molybdenum.

6. Summary

To develop a high-current electron gun for the induction linac intended for a microwave FEL, a prototype gun with the LaB_6 cathode studied at high current densities. The summary is as follows:
850 hours of continuous operation.

- 1) We obtained a maximum temperature of 1,750°C at the cathode surface by using electron bombardment and thermal radiation from the heater.

- 2) Applying a high voltage of 55kV, we obtained a maximum-transmitted current of 23A at 1,600°C. Also, the obtained perveance was $1.9 \times 10^{-6} \text{ A/V}^{3/2}$.
- 3) The effective work function was 2.68eV for a cathode, assuming that $A=120 \text{ A/cm}^2 \cdot \text{K}^2$.
- 4) The cathode, after being heated up to 1,600°C, emitted 7A of electrons with a 20% reduction after

Based on these results, we have somewhat confirmed that the high current density gun will be put to practical use for the induction linac. First, the cathode can emit at a high current density of over 20 A/cm^2 in a vacuum-pressure range of 10^{-6} ~ 10^{-7} Torr. If we have a large area-cathode of $\sim 50 \text{ cm}^2$, the cathode will emit electrons of over 1,000A. Second, after it is exposed to air, the emission current always recovers to the above level due to heating at temperatures of over 1,500°C. The resistance to poisoning makes it more attractive than the other thermionic cathode. To obtain a higher temperature compared to the other cathode, however, we must pay special care in designing the gun and selecting its components.

Acknowledgment

The authors thank Associate Director Prof. Y. Kimura and the Director of the Accelerator Department, Prof. K. Takata of KEK for their continuous support of our R&D work. They also thank Dr. S. Fukuda of KEK-PF for useful discussions concerning the gun design and thermal shield. They further thank the members of the FEL group for providing useful suggestions and helpful assistance during the construction and experiment.

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21) Because of the Schottky effect(electric field-assisted thermal emission), the measured densities don't equal to current densities calculated for zero-electric field at the cathode surface J_0 , for example, in the Fig.4. So, we take the J_0 's as intersects of the Langmuir-Child equation fitted for and the line extrapolated from the measured densities in the temperature-limited region for the same temperature.

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Table captions:

Table Design parameters of the prototype gun

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Cathode diameter	12 mm
Cathode temperature	1900 K(=1,630°C)
Current density ^{a)}	10 A/cm ²
Anode voltage	40 kV
Beam current ^{b)}	11 A
Emittance ^{b)}	7.2 cm*mrad
Pulse width	250 nsec.
Repetition rate	20 Hz

a) Temperature-limited current density calculated for a zero-electric field at the cathode surface.

b) Simulation results computed using EGUN (gun design program).

Figure captions:

Fig.1 Assembly drawing of the prototype gun with a LaB_6 cathode.

Fig.2 Cathode heating and high-voltage system.

Fig.3 Total electrical heating power (P_t) versus the cathode temperature for the gun. Here, P_b represents the bombardment power.

Fig.4 Transmitted currents (I_d) as a function of the high voltages (V_d) for the cathode temperatures among $1,400^\circ\text{C}(=1,670\text{K})$ and $1,750^\circ\text{C}(=2,020\text{K})$. The solid line is the Langmuir-Child equation fitted for $1,700^\circ\text{C}(=1,970\text{K})$; $I_d = 1.38 \times 10^{-6} \times V_d^{3/2}$.

Fig.5 Transmitted currents (I_d) as a function of the high voltages (V_d) for the cathode temperatures after being replaced by a new cathode. The solid line in this figure is the Langmuir-Child equation for the $1,600^\circ\text{C}$; $I_d = 1.90 \times 10^{-6} \times V_d^{3/2}$.

Fig.6 Oscilloscope display of the beam current (the lower) and the high voltage (the upper). The lower trace represents an output of the WC of which the calibrating constant is 1A/V . The upper also represents one of the high-voltage probe of which is 20kV/V . The vertical axes: 5V/div for the lower(ch.1), and 10V/div for the upper(ch.2), The horizontal (time scale): 100ns/div .

Fig.7 Long-duration emission tests for cathode temperature of $1,600^\circ\text{C}$.

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High voltage pulsing test

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High voltage pulsing test II

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Measured lifetime of the LaB_6 cathode

Fig.6 Oscilloscope display of the beam current (the lower) and the high voltage (the upper). The lower trace represents an output of the WC of which the calibrating constant is 1 A/V. The upper also represents one of the high-voltage probe of which is 20kV/V. The vertical axes: 5V/div for the lower (ch.1), and 10V/div for the upper (ch.2), The horizontal (time scale): 100ns/div.

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