ASSESSMENT OF THERMIONIC EMISSION PROPERTIES AND BACK BOMBARDMENT EFFECTS FOR LaB_6 AND CeB_6

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Abstract

The emission properties of LaB_6 and CeB_6 materials as a thermionic cathode were determined experimentally in the range 1650 ~1900 K using an electrostatic DC gun. The determined emission properties were used in a developed numerical simulation model to investigate and compare the heating properties of LaB_6 and CeB_6 as cathode materials for thermionic RF gun against Back Bombardment (BB) electrons effect. The estimated work functions from the experimental results at 1600 K for LaB_6 and CeB_6 were 2.76 and 2.69 eV respectively. While, the simulation results for the BB effect showed that, for 6 μs pulse duration with 8 MW RF power, LaB_6 cathode experiences a large changes in the cathode temperature and 30% higher change in the current density compared with CeB_6.

INTRODUCTION

It is well known that, the high electric field in the RF gun cavity can be used to accelerate emitted electrons quickly to the state of v≈c (light velocity) [1] which enables the overcoming of the space charge effect problem existing in conventional guns. Thermionic RF guns don't require unique and expensive laser devices like photocathode RF gun. Generally speaking thermionic RF guns apparatus are considered one of the highest quality sources for supplying electron beams with a desired beam energy and current [2]. Due to the features of compactness, inexpensive and easy-handling compared with electrostatic guns; RF gun has been selected as electron beam injector to drive KU-FEL facility (Kyoto University Free Electron Laser) [3].

Back Bombardment (BB) effect on the other hand, is one of the main limitations of wide usage of thermionic RF guns. BB effect can be simply explained as next, in the RF cavity, electric field strength varies sinusoidally with the frequency of RF power fed to the gun. At the time when accelerating field exists in the cavity, electrons are extracted from the cathode and gain its kinetic energy. After the half period of RF cycle, the electric field changes its direction and electrons are decelerated to the cathode. These electrons are referred as back-streaming electrons [4]. The BB electrons induce not only ramping-up of a cathode's temperature and beam current, but also degradation of cavity voltage and beam energy during a macropulse. As a result, the macropulse duration with stable beam energy is reduced. However, high and stable electron beam energy in long macropulse is mandatory for generation of an oscillator FEL.

The performance of KU-FEL thermionic RF gun has been dramatically improved and high beam currents over longer macropulse have beam generated after replace the dispenser tungsten-base cathode with a single crystal of LaB_6 in 2007 [5]. The importance of the cathode material in BB effect reduction and gun performance improvement were discussed and clarified [6]. In the present paper two topics are discussed. The first one is the determination of LaB_6 and CeB_6 emission properties using an electrostatic DC gun under low beam current conditions. And the second one is to compare LaB_6 and CeB_6 as a thermionic RF gun cathode material numerically against the BB effect. In the next sections the experimental setup and the numerical simulation conditions are discussed and the results are presented as well.

DETERMINATION OF EMISSION PEROPERTIES OF LaB_6 AND CeB_6

Materials Preparation and Experimental Setup

The choice of gun cathode material is very important issue in electron beam acceleration technology and is mostly depends on applications cathode being considered. Thus, in operation point of view the cathode material is preferable to have the next properties: low work function, high current emission capability, long lifetime, high melting temperature and rapid recovery from contamination. The above mentioned properties may be realized by single crystals of LaB_6 and CeB_6 materials. While, from thermionic RF gun user's point of view additional property is required, which is material with less effect by BB electrons is preferable.

To determine the emission properties of LaB_6 and CeB_6, an electrostatic DC gun at Laboratory of Nuclear Science (LNS), Tohoku University was used [7]. Figure 1 shows a photograph for the experimental setup at LNS.

Two single crystals of LaB_6 and CeB_6 have been prepared using Inert Gas Arc Float Zone Refining method with 1.72 mm diameter and crystal orientation <100>. In the experiment, cathode materials were connected to the cathode heater and then attached to the gun ceramic feed

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through. The feed through is attached to the backside of the gun and the cathode is centered in the gun wehnelt; the bias voltage of the wehnelt was adjusted to zero in this experiment.

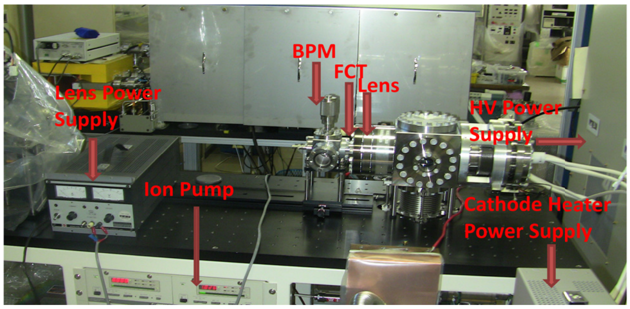

Figure 1: Experimental setup at LNS to determine the emission properties of LaB_6 and CeB_6.

Anode with 10 mm inner diameter located at 21 mm from the cathode surface is used to accelerate extracted electrons with applying acceleration voltage varying from -10 up to -50 kV by changing the DC power supply controller remotely with -2 kV step. A solenoid lens 14 mm from the anode aperture was used to confine the electron beam size by varying the solenoid current. The beam current was measured using a fast current transformer located at 50 mm from the anode exit. The beam size was measure using MgO screen employed as beam profile monitor. During the experiments the vacuum in the gun is lower than 6.5×10^{-8} Pa.

Experimental Results

At different cathode temperatures (1650 ~1900 K) V-I characterization curves were determined for LaB_6 and CeB_6 and the results are depicted in figure 2. It can be seen from figures 2-a, and 2-b, the investigated materials show beam current plateau for the low cathode temperatures. However, for 1900 K cathode temperature it was difficult to find the beam current plateau, due to the acceleration voltages is limited by the capability of the DC power supply up to -50 kV.

To determine the emission properties of the investigated materials, it well established that the relation between the emitted current density J (Acm^{-2}) from a hot material and the material temperature is given by Richardson-Doshman equation, Eq: 1, which includes Richardson work function and the effect of the material temperature in the total work function and given in the form [8]:

$$J = AT^2 \exp\left(-\frac{(\varphi_R+\alpha T)}{k_B T}\right) \qquad (1)$$

where A ($Acm^{-2}K^{-2}$), is Richardson constant, k_B (JK^{-1}) is Boltzmann constant, φ_R (eV) is the Richardson work function and α is the temperature coefficient and can be defined as, the relative change of a work function when the temperature is changed by 1 K. The term $Exp\ (-\alpha/k_B)$ is sometimes called Schottky-effect term or the responsible factor for the reduction of work function due to the existence of an external electric field at the cathode surface.

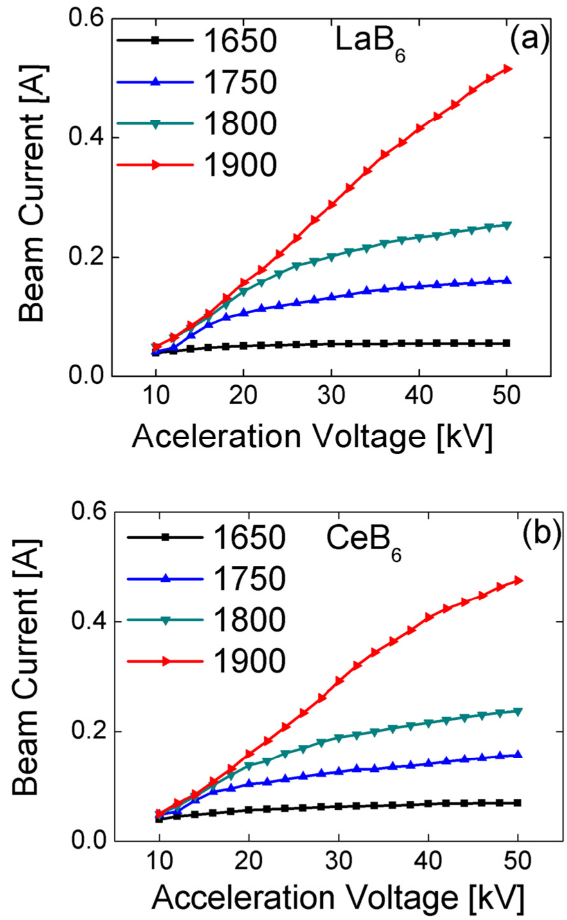

Figure 2: V-I characterization curves for LaB_6 and CeB_6 (a) and (b) respectively.

Equation (1) can be rearranged and written in the form:

$$Log\left(\frac{J}{T^2}\right) = \left(Log\ A - \frac{\alpha}{k_B}\right) - \frac{\varphi_R}{k_B T} \qquad (2)$$

By plotting the relation between $log\ (J/T^2)$ against $1/T$ yields a straight line of slope (φ_R/k_B) and intercept of $(Log\ A-\alpha/k_B)$, this plot is called Richardson plot. In this method to determine the work function and heat coefficient, the Richardson constant A is assumed to have its numerical value as $(4\pi m_e e k_B^2)/h^3$=120.173 $Acm^{-2}K^{-2}$, where m_e (kg) is the electron mass. Then, the total work function of hot material can be determine as ($\varphi=\varphi_R+\alpha T$).

Richardson plot for the investigated materials were prepared at 50 kV (as an example) acceleration voltages (2.38 MV/m) for the materials temperature range 1650~1900 K and the results are depicted in figure 3. It is important to mention here that, the dependency of the beam current on the materials temperature which introduces increase of the beam current with increase the acceleration voltages is not deeply considered in this

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paper. Moreover, the analysis of the experimental results showed that the variation of the estimated work functions at different acceleration voltages is not exceeding 0.05 eV. Therefore, in this paper the analysis to determine the emission properties is carried out at 50 kV acceleration voltages.

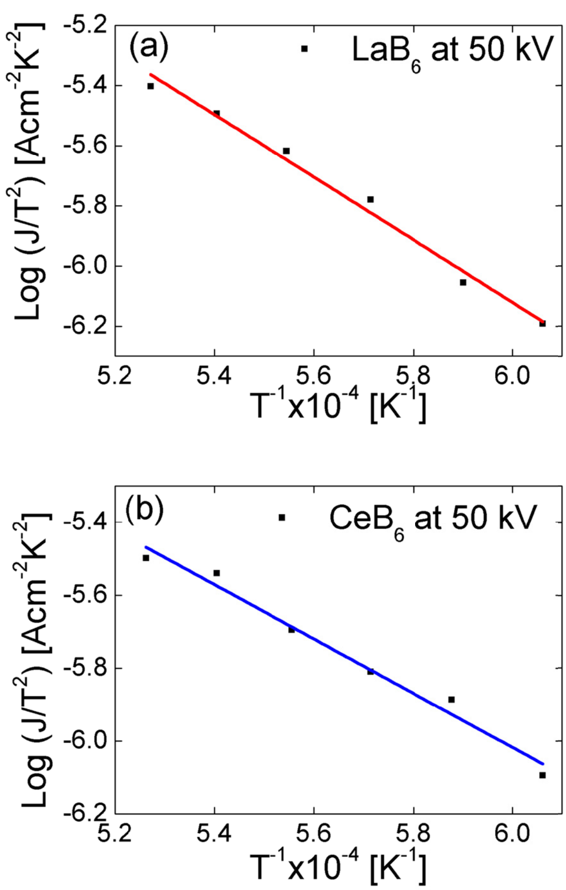

Figure 3: Richardson plots for LaB_6 and CeB_6 (a) and (b) respectively, at acceleration voltage 50 kV.

The total work functions are estimated from the fitting functions in figures 3-a, and 3-b as φ=2.07+4.38×10^{-4}T eV and φ=1.48+7.58×10^{-4}T eV for LaB_6 and CeB_6 respectively. The determined work functions from the experimental results conducted herein are agrees well with the previous measured values for LaB_6 and CeB_6 prepared using the same growth method and have <100> orientation in Refs. [9,10]. At temperature 1600 K, the present results predict the total work functions to be 2.76 eV and 2.69 eV compared with 2.70 ± 0.05 eV and 2.62 ± 0.05 eV from the references for LaB_6 and CeB_6 respectively. The work functions determined herein are used again in equation 1, to determine the emission curve for LaB_6 and CeB_6 and depicted in figure 4.

The data for the work function determined from these experiments are used in the numerical simulation model to compare LaB_6 and CeB_6 cathodes from the BB effect point of view.

BB EFFECT FOR LaB_6 AND CeB_6

Conditions of the Simulation Model

A numerical simulation method was used to study the dependency of BB effect on the cathode material in a thermionic RF gun [11]. This method is used to compare LaB_6 and CeB_6. In the simulation model, a semiempirical equation [12] was used to investigate and determine the stopping range and deposited heat power by BB electrons in cathode materials. A numerical simulation code has been used to determine the change of LaB_6 and CeB_6 cathodes temperatures and current densities during a single macropulse [6]. This was done by solving two differential equations for the RF gun cavity equivalent circuit and one dimensional thermal diffusion equation [11].

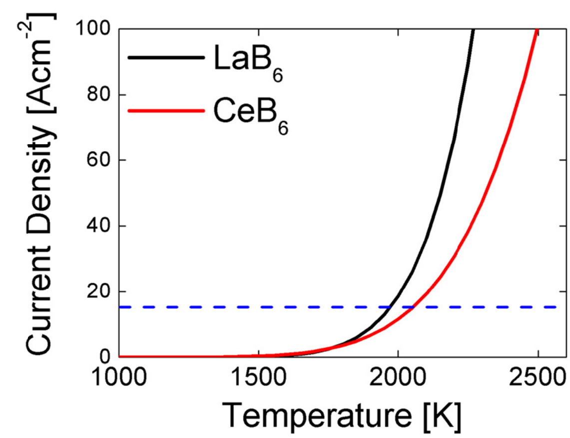

Figure 4: Emitted current density for LaB_6 and CeB_6 determined from equation (1).

Table (1) shows the KU-FEL thermionic RF gun parameters and the RF power pulse specifications used in the simulation code.

Table: 1 Input Parameters for the Numerical Model

Parameter	Value
Resonant Frequency [MHz]	2856
Coupling Coefficient β	2.79
Q Value	1500
R/Q [Ω]	980
Accelerating Mode	π
Gun Body Temperature C	62
Cathode Radius [mm]	0.86
RF Power Pulse-flat [MW]	8
Macropulse Duration [μs]	6

When the BB electrons hit a cathode material during a macropulse, the cathode temperature and consequently current density increase from initial operation values. Therefore, sitting a minimum value of the initial current density is crucial for the comparison. To have a high emission current with stable and long life time operation for thermionic RF gun cathode, let us assume the minimum required current density (J_{min}) is criterion to be

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15 Acm^{-2}. In this criterion the thermionic gun can be employed for electron beam applications with high peak current with long macropulse requirements, and in the same time far from the material melting temperature for target materials. The main properties of LaB_6 and CeB_6 used in this simulation are listed in table 2.

Table: 2 LaB_6 and CeB_6 Input Parameters.

	LaB_6	CeB_6
Molecular Weight (g mol^{-1})	203.77	204.98
Density (g cm^{-3})	4.72	4.80
Melting Temperature (K)	2483	2463
Work Function (V)	2.93	3.04
Effe. Atomic Number	40.45	41.23
Effe .Molecular Weight ($gmol^{-1}$)	94.74	96.04
Initial Temperatures K	1968	2050

The initial cathodes temperatures used in the simulation code are 1968 and 2050 K for LaB_6 and CeB_6 respectively which is picked from figure 4 corresponding to 15 Acm^{-2}. The initial work functions used in the simulation to calculate the change in the current density during the macropulse are determined corresponding to 1968 and 2050 K operation temperatures for LaB_6 and CeB_6 respectively and listed in table 2.

Simulation Results

The numerical simulation code mentioned above has been used to determine the change in LaB_6 and CeB_6 temperatures and corresponding changes in the current densities by BB electrons. The results indicated that the temperatures changes are 275 and 229 K, while the corresponding current densities changes are 144 and 97 Acm^{-2} for LaB_6 and CeB_6 respectively. This means the change in CeB_6 temperature is producing change of its current density much smaller than for LaB_6. The difference in the temperature change of CeB_6 compared with LaB_6 can be related to the consistence of the materials properties as listed in table 2, which introduces a small difference in the heat deposition by BB electrons as determined from the semiempirical equation. While, the corresponding changes in the current density for CeB_6 is 30% less than that for LaB_6. This behaviour can be explained as; the high work function of CeB_6 as listed in table 2 implies higher temperature required to extract electrons compared to LaB_6. Therefore, the increase of the current density for CeB_6 is less than for LaB_6. Therefore, the BB electrons effect in LaB_6 is much higher than CeB_6. Experimental results for CeB_6 as a thermionic RF gun cathode are required to satisfy and confirm the numerical simulation results.

CONCLUSIONS

We investigated two hexaboride materials to determine the emission properties and then compare their effect by BB electrons. The strategy started with determines the emission properties of LaB_6 and CeB_6 using an electrostatic DC gun. And then the determined work functions are used in numerical simulation code to compare the materials effect by BB electrons. Based upon the findings of this investigation, the work functions for LaB_6 and CeB_6 are determined and effect of BB electrons in LaB_6 and CeB_6 is studied. LaB_6 has higher change in the cathode temperature and 30% higher in the current density compared with CeB_6. As a result, the numerical simulation predicts that, CeB_6 experiences less effect by BB electrons than LaB_6.

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