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UNUSUAL ELECTRON EMISSION CHARACTERISTICS OF CeB_6 CATHODES

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Abstract

Thermionic electron guns that use borides of lanthanum or cerium as the electron emission surface are widely adopted for electron microscopes due to their high brightness. CeB_6 cathodes are known for their high environmental durability and can be used up to a vacuum pressure of 10^{-6} Pa. At MHI-MS, our company, we also adopt CeB_6 cathodes in the C-band compact accelerating structure units we manufacture, and we have shipped dozens of units so far.

As for the cathode assembly, we purchase Vogel-type cathodes and incorporate them into the thermionic electron guns. Before shipping, we bake the entire accelerating structure, including the electron gun, and confirm the electron emission characteristics. Recently, some of the procured cathodes have exhibited abnormal behaviour, such as a decrease in electron emission as the vacuum pressure of the electron gun decreases. Analysis of the CeB_6 crystal shows no significant differences between the normal and abnormal batches, and the cause is still unknown.

INTRODUCTION

The C-band accelerator unit, we manufacture, consists of 25 kV electron gun and side-coupled accelerating structure capable of accelerating the electron beam up to 6 MeV. The electron gun utilizes a direct-heated cathode type with a CeB6 crystal, and the entire unit is evacuated using a sputter ion pump (IP). The specifications of the unit are shown in Table 1.

Table 1: Specification of C-band Accelerator Unit

Item	Value
Accelerating frequency	5714 MHz
Structure type	Standing wave, APS and side-coupled
Unloaded Q	> 9000
Coupling β	1.6

Since high power RF tests are conducted at our customer's site, we are conducting the emission tests only on the electron gun. A schematic diagram of the test setup is shown in Fig.1.

Electron Gun

The electron gun consists of a cathode, Wehnelt electrode, and anode electrode. The cathode and Wehnelt electrode are at the same potential, and the anode is grounded. The gun is diode type and operated by controlling the output current of the heater current within temperature limited region. Diameter of the cathode is 2 mm and required beam current density is 48 mA/mm^2 so that we adopted a cathode made of CeB_6 single crystal with a (100) crystal face. The schematic image of this Vogel-type cathode assembly is shown in Fig. 2.

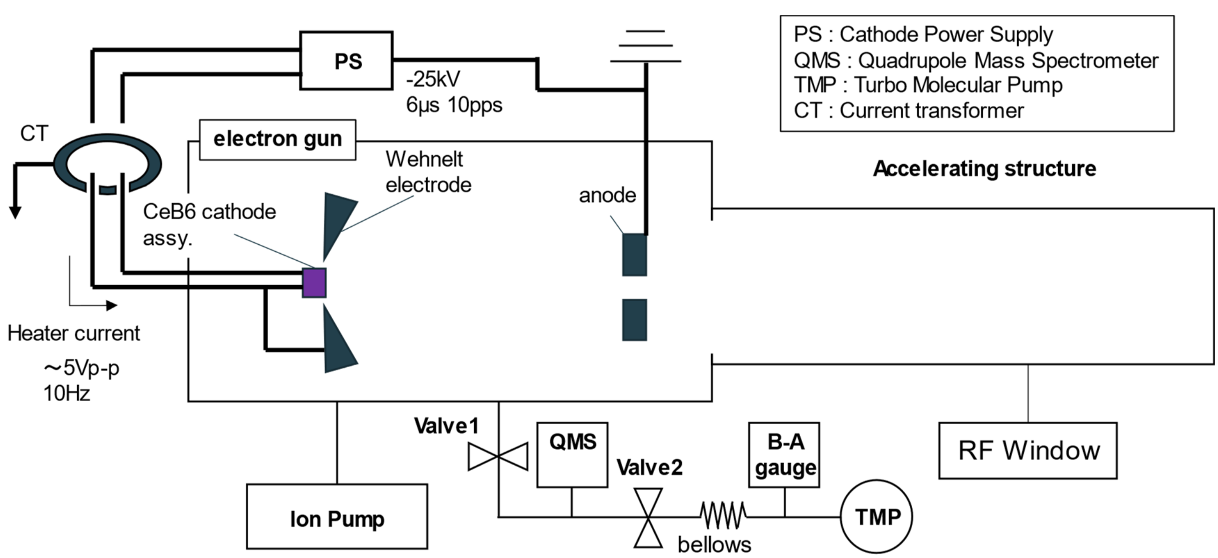

Figure 1: Schematic view of the emission test configuration.

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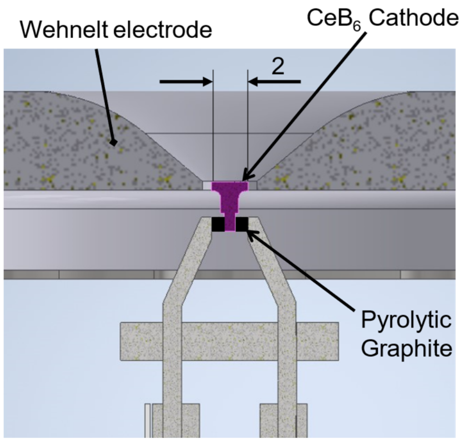

Figure 2: Schematic image of the cathode assembly.

BEAM EMISSION TEST

Setups and Conditions

In our emission tests, high voltage of -25 kV is applied to the cathode with a pulse duration of 6 µs and a repetition rate of 10 pps. The heater current is supplied with AC of approximately 5 Vp-p and a frequency of 10 Hz. Electron beam current is indirectly measured by passing the heater cable through a current transformer (CT).

A detachable turbo molecular pump (TMP) and oil-free scroll pump unit system, and IP are used for vacuum evacuation. After baking, operating under high vacuum level conditions is possible by using the IP for evacuation. Table 2 shows the combinations of each evacuation device and its typical vacuum levels. Due to the presence of bellows, we know that the pressure in the electron gun is typically one order of magnitude higher than indicated by a B-A gauge located near the TMP. In addition, the IP controller shows a pressure approximately one-fifth lower than the pressure in the electron gun.

In order to obtain stable electron beam, vacuum level is an important factor. Operating under higher pressure residual gas contamination and surface roughness due to ion bombardment can lead to performance degradation and cathode failure. For example, when using LaB_6 cathodes, it is said that the pressure should be below 10^{-4} Pa. CeB_6 is known to be more resistant to carbon contamination compared to LaB_6, and sufficient emission current can be obtained at the pressure is around 1×10^{-4} Pa. However, it is desirable to operate under lower pressure.

Table 2: Typical Vacuum Levels

Evacuation condition	Egun Pressure [Pa]
TMP	$> 1\times10^{-5}$
TMP and IP	$> 5\times10^{-6}$
IP (after baking)	$> 3\times10^{-7}$
IP (QMS and after baking)	$> 1\times10^{-6}$

Test Sequence

Beam emission tests are conducted before and after baking the unit. When the pressure change reaches equilibrium, the test begins from the vacuum level shown in Table 2. The usual sequence is to heat the cathode up to 1800 K in several minutes, hold it for 10 minutes, and verify that beam current exceeds the criteria. In some cases, the heating rate are adjusted during the test for the pressure do not exceed the criteria. After verifying that the beam current exceeds the criteria, the heater current is decreased before finishing the test. The cycle of the emission test is defined as the period between the start of cathode heating and the end of cooling.

UNUSUAL EMISSION CHARACTERISTICS

Unusual Behaviour of the Beam Current

Typically, the beam current increases in response to an increase in the heater current. However, we observed the beam current decreases with time for certain cathodes. Alternatively, the beam current is no longer obtained after baking process. The decrease time constant varies depending on each cathode and test conditions, with fluctuations ranging from a few minutes to about an hour.

When the heater current and voltage are kept constant, there are two behaviors after the beam current decreases. One is that the current decrease monotonically until it reaches zero. The other is that decrease in beam current followed by a peak and subsequent increase. In the latter case, the time constant of the beam current change tends to increase with each emission test cycle. Figure 3 shows the change over four cycles.

In Fig. 3, (i)~(iv) represent time evolution in beam current and pressure in each cycle. The tests were conducted in the order of (i) to (iv). In this case, the first test performed the same as the normal cathode, but the second and subsequent tests did not reproduce the first behavior. The cathode temperature was heated up to 1800 K, maintained for 10 minutes, cooled down to 1790 K, and then maintained until the beam current reached equilibrium. The interruption points in each graphs indicate end points of test. (v) shows the temperature and heater current of the cathode in cycle (iv), and (i) ~ (iii) were conducted by the same procedure except for the time to maintain 1790 K. The temperature of cathode was calculated from the heater current during the test using the previously measured relationship between heater current and cathode temperature.

Investigation

Visual Inspection Generally, the emission capability of cathode decreases due to structural damage or roughening of electron emission surface. Visual inspection showed no damage to the crystals or support components. We also requested cathode supplier to observe the surface, but no significant differences were observed compared to the normal ones.

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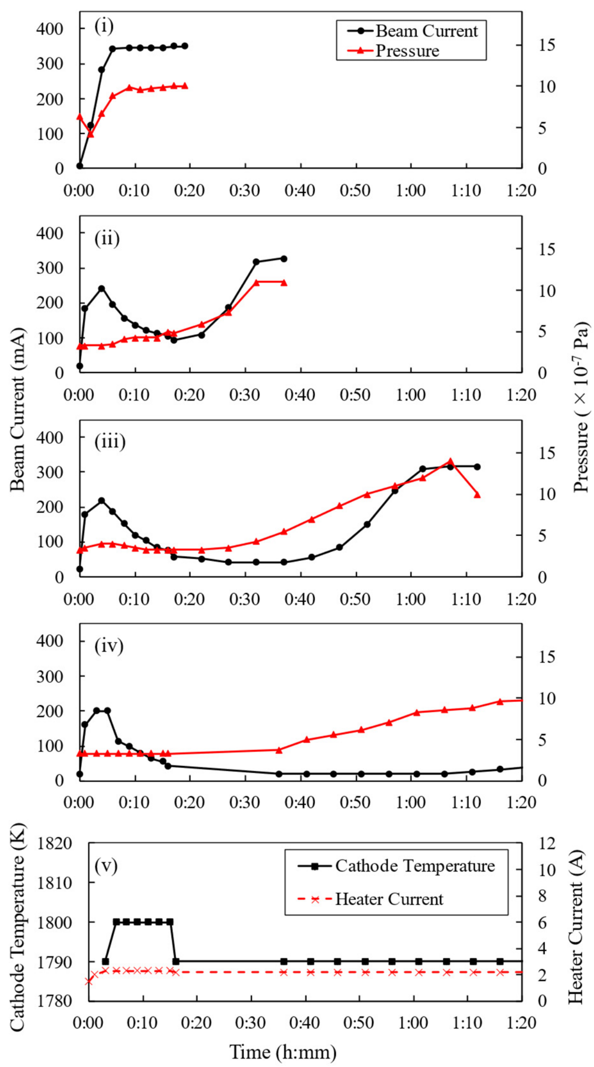

Figure 3: (i)~(iv); The variation of beam current and pressure during four cycle of emission tests. (v) Cathode temperature and Heater current of (iv) test.

Surface Inspection According to [1], the thermionic current density of a cathode is represented by the Richardson-Dushman equation:

$$I = AT^2 \exp\left(-\frac{w}{kT}\right) \quad (1)$$

where: w – work function;
T – cathode temperature;
A – Richardson constant;
k – Boltzmann's constant.

By equation (1), when the work function of a cathode increases under constant temperature conditions, the resulting beam current decreases. The factors that can increase the work function are:

(a) Presence of impurities in CeB_6 crystal;
(b) Crystal orientation of CeB_6 not being (100);
(c) Adsorption of residual gas on the electron emission surface.

We compered the surface spectra of normal and unusual cathode using Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS), and we find no significant differences in the peak patterns of the spectra between them. Furthermore, using Electron Back-Scatter Diffraction (EBSD), both cathodes were found to have a crystal orientation of (100).

During repeated emission tests, we found that the problem occurs only when vacuum is evacuated using the IP after baking process. We also observed that the beam current increased as the pressure of the gun increased. For example, valves 1 and 2 were opened and TMP was used for vacuum evacuation, beam current increased. We analysed residual gas components for M/Z < 100 using QMS, but no significant peaks were found under the condition of decreasing beam current.

Discussion

We have not been able to understand the process in which the beam current decreases when performing vacuum evacuation by IP after baking process. We speculate that the increase in work function is caused by the absorption of certain gases onto the cathode surface. This adsorbed gas can be removed through processes such as ion bombardment with carbon dioxide [2]. After baking, it is believed that a gas absorption rate exceeds the cleaning effect on the cathode surface due to the low partial pressure of carbon dioxide. However, the existence of certain gas species and compounds that do not evaporate at the operating temperature has not been verified, and the exact cause is still unknown. It is desired that measuring the work function during the cathode heating could provide clues for understanding the cause.

Furthermore, we found that this matter occurs only in specific cathode batches. Table 3 shows the acceptance rates for the two batches. The reason is not yet understood.

Table 3: Acceptance Rate for Cathode Batches

Batches	**Number of accepted cathodes**	**Acceptance rate**
Normal batches	40 of 40	100 %
Abnormal batches	21 of 40	53 %

CONCLUSION

We observed peculiar phenomena in which the beam current decreased under certain conditions, using certain CeB_6 cathodes in electron guns. This occurred after baking process and vacuum evacuating using IP at pressures in order of 10^{-7} Pa. We found that the beam current restored when the test system is evacuated using TMP or operating at pressure above 10^{-6} Pa without baking process. However, the exact process causing this phenomenon is still unknown. Although we resolved temporarily this problem by using different cathode batches, at least it is necessary to consider a screening process that can eliminate cathodes that cause such phenomena.

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