DEVELOPMENT OF HIGH-CURRENT-DENSITY LAB6 THERMIONIC EMITTERS FOR A SPACE-CHARGE-LIMITED ELECTRON GUN

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Summary

An electron gun has been developed for investigation of high current density, space charge limited operation of a lanthanum hexaboride (LaB_6) thermionic cathode. The 2.8 cm^2 cathode disk is heated by electron bombardment from a tungsten filament. For LaB_6 cathode temperatures greater than 1600 °C it has been found that evaporation from the LaB_6 causes an increase in the tungsten filament emission, leading to an instability in the bombardment heating system. This instability has been investigated and eliminated by using a graphite disk in place of the LaB_6 cathode or by shielding the filament from the LaB_6 cathode by placing the LaB_6 in a graphite cup and bombarding the cup. The graphite disk has been heated to 1755 °C with 755 W of heating power, and the shielded LaB_6 cathode has been heated to 1695 °C. This temperature range is required for emission current densities in the 30 A/cm^2 range. It is believed that the evaporation of lanthanum lowers the tungsten work function. In electron-gun use, the LaB_6 cathode has been operated up to 6.7 A/cm^2 at 36 kV. A 120 kV Marx generator has been built to allow operation up to 40 A/cm^2.

Introduction

The electron gun described in this paper has been built to investigate the use of LaB_6 cathodes at high current densities. A thermionic cathode that is capable of 40 A/cm^2 or more emission current density in space charge limited operation would be an excellent candidate for use in generating high brightness electron beams for free electron lasers. The properties of LaB_6 of greatest interest are its capability of producing high current densities at relatively low temperatures, and resistance to chemical poisioning upon exposure to the atmosphere.

A bombardment heating system offers the advantage of precise control of the heating and cooling sequence of the cathode. Bombardment heating can be thermally unstable, and a feedback control system must be used for stabilization. This paper describes a digital control system used for this purpose.

Since the heating control system depends on temperature limited operation of the bombardment filament, the system is highly dependent on the work function of the filament. Changes in the filament work function during operation can cause instabilities in the heating system. A description of this effect and a method of eliminating it is given in this paper.

Electron Gun and Heating System Construction

Since the cathode must operate at temperatures around 1800 °C to obtain the desired current density, the electron gun was designed to maximize the thermal insulation of the cathode. The beam forming electrodes are designed to obtain a microperveance $P=I/V^{3/2} \times 10^6$ of 3.2 with a planar cathode. The SLAC electron gun trajectory code [1] was used to optimize the design.

Figure 1 shows the cross section of the assembled electron gun. The LaB_6 cathode is held in a graphite cup at the end of a thin-walled tantalum tube called the cathode stalk. The cathode beam forming electrode is split into two rings. This feature allows the outer ring to operate at a lower temperature than the inner ring, thereby reducing radiated power losses. The cathode stalk has 1-inch diameter holes in the tantalum tube to lower conduction losses. A heat shield around the tungsten filament provides good thermal coupling between the filament and the cathode, and a large percentage of the radiated filament power heats the cathode. The useful cathode diameter is approximately 1.9 cm.

The measured perveance of the electron gun is the same as the design value. Measurements have been made of the beam current density and cathode temperature across the cathode surface, and filament and bombardment power as a function of cathode temperature. These results will be presented in a future publication. In the present paper, the operation of the bombardment heating system will be described for cathode temperatures up to 1755 °C.

The heating and isolation system is shown in Fig. 2. The heating power supply and controls are at ground potential and power is passed to the gun through three 120 kV isolation inductors. Filament power is passed through the inductors as 240 V 60 Hz and then stepped down to 24 V and rectified at the gun potential. Filament power is regulated by opening and closing a power MOSFET switch. Control signals for the power MOSFET are sent through a fiber optic link which provides high voltage isolation between the gun and the control circuit.

The tungsten filament is heated to a temperature where it can source a bombardment current of 500mA RMS. The filament is biased negatively with respect to the LaB_6 cathode by bombardment voltages of 700V to 1800V RMS.

In temperature limited operation the bombardment current from the filament can be directly controlled by the electrical filament heating power. Since radiated power from the LaB_6 cathode also heats the filament, when the filament emits a temperature limited beam, a positive feedback loop is formed between the cathode and the filament.

Digital Control Circuit

The positive feedback loop in the heating system can be eliminated by reducing the the electrical heating power to the filament to balance an increase

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in the radiated power from the cathode. In the circuit of Fig. 2, the heating power to the filament can be turned on and off by closing and opening the power MOSFET switch. When the bombardment current is too large the switch is opened to reduce the filament power and lower the bombardment current. When the bombardment current is too small the switch is closed to increase the filament heating power and increase the bombardment current. The switching action of the power MOSFET is controlled by a digital controller.

The controller samples the bombardment current and stores one 60 Hz cycle in RAM. The stored cycle is the desired bombardment current waveform, and has a peak value selected by the operator. After the desired waveform has been stored, the controller then samples the bombardment current and continously compares the real time samples to the samples stored in the RAM. When the real-time sample is less than the stored sample the power MOSFET switch is closed to increase the bombardment current. When the real time sample is greater than the stored sample the switch is opened to lower the bombardment current.

The circuit is consistent with temperature limited operation of the filament. By forcing the filament to emit a real time bombardment current waveform which is a fraction of the stored waveform current, the filament must operate temperature limited and its emission current is controllable by the filament power input.

Another benefit of the digital control algorithm is that for portions of the bombardment waveform cycle where the filament operates space charge limited the electrical heating power to the filament will be zero. The filament will operate space charge limited during low voltage portions of the bombardment voltage cycle. Because of this property the filament will be heated only when operating temperature limited and only when the bombardment current is too small. This method heats the filament with the minimum amount of power required to achieve a desired amount of bombardment current.

The digital circuit also has logic to automatically warm up and outgas the cathode. The warm up time is adjustable and can be set to warm the cathode as fast as possible without cracking the cathode or exceeding a pre-set vacuum pressure setpoint.

The digital circuit has been tested up to 1695 °C with the LaB_6 cathode. The system heated the cathode from 25 °C to 1695 °C in 30 minutes. This time may be lengthened or shortened by selecting different clock rates provided by the circuit.

Heating System Model

A simple model showing the dynamics of the system is shown in Fig. 3. For simplicity the bombardment voltage V_B is assumed to be a DC source. Power is exchanged between the filament and the cathode by bombardment and radiation. Power losses are by radiation only, i.e., $P = CT^4$. The power balance equations for the cathode and filament are

$$C_c dT_c/dt = I_B V_B + P_{fb} - P_{rc} \quad (1)$$

$$C_f dT_f/dt = P_H - P_{fb} - P_{rf} \quad (2)$$

where $P_{fb} = C_0(T_f^4 - T_c^4)$, C_c and C_f are specific heats, and P_H is the filament electrical heating power. Since V_B is a DC voltage and the filament operates temperature limited, I_B can be obtained from the Richardson - Dushman equation:

$$I_B = CT_f^2 \exp[-q\phi/kT_f]. \quad (3)$$

Substituting this into Eqs.(1) and (2) and expressing the radiated power as a function of temperature, we obtain the nonlinear system of equations

$$dT_c/dt = C_1 T_f^2 \exp[-q\phi/kT_f] + C_2 T_f^4 - C_3 T_c^4 \quad (4)$$

$$dT_f/dt = P_H + C_4 T_c^4 - C_5 T_f^4 \quad (5)$$

The positive feedback loop arises from the term $C_4 T_c^4$. The positive feedback can be eliminated by making the electrical filament heating power a function of the filament temperature.

The digital circuit achieves control by monitoring the bombardment current and turning P_H on and off. P_H can be expressed as:

$$P_H = P_{fmax} (1 - u(I_B - I_{Bo})) \quad (6)$$

where $u(I_B - I_{Bo}) = 1$ when $I_B \geq I_{Bo}$
0 when $I_B < I_{Bo}$.

I_{Bo} is the desired bombardment current and P_{fmax} is the electrical heating power when the filament is turned on. The bombardment current is given by Eq. (3). Equation (6) becomes

$$P_H = P_{fmax} (1 - u(CT_f^2 \exp[-q\phi/kT_f] - I_{Bo})) \quad (7)$$

Subsitituting Eq. (7) into Eq. (5) gives the heating system state equations with feedback stabilization,

$$dT_c/dt = C_1 T_f^2 \exp[-q\phi/kT_f] + C_2 T_f^4 - C_3 T_c^4 \quad (8)$$

$$dT_f/dt = P_{fmax} (1 - u(CT_f^2 \exp[-q\phi/kT_f] - I_{Bo})) + C_4 T_c^4 - C_5 T_f^4 \quad (9)$$

The following conclusions can be drawn from from the heating model:

1) P_{fmax} must be greater than zero to use this type of control. An uncontrolled solution may exist where the feedback term $C_4 T_c^4$ provides enough power to heat the filament to a temperature where it can emit the desired amount of current with $P_H = 0$.

2) For small values of the work function ϕ, the filament temperature required for the desired emission may be sufficiently small so that the feedback power $C_4 T_c^4$ is large enough to maintain this temperature with $P_H = 0$.

Thoriated Tungsten Operation

The heating system has been tested with both thoriated tungsten and pure tungsten. When the system is initially heated, with pure tungsten, approximately 18 A of current is required to heat the filament until it can source the required current. As the cathode warms up, less power is radiated from the filament to the cathode, and therefore less electrical heating power is required to keep the filament at this temperature. When the cathode temperature is around 1600 °C the filament current required is between 14 and 15 A. Electrical power is always required to heat the pure tungsten filament because the pure tungsten filament must operate at a higher temperature than the cathode.

Thoriated tungsten emitters have a much lower work function than do pure tungsten emitters. With a thoriated tungsten filament, upon initial warm up, 12 A of filament current was required to heat the filament to the temperature of emission. However, with the cathode at 1620 °C, no electrical filament power was required. The power radiated back from the cathode was enough to heat the filament to the temperature required for the desired emission level. In this mode of operation 0 W of electrical filament power and 414 W of bombardment power were required to heat the cathode to 1620 °C. This mode of operation is not desirable because the system is no longer controllable from the electrical filament power input.

LaB_6 Instability

Heating system operation with a pure tungsten filament and the LaB_6 cathode has been observed to operate in a mode similar to the mode observed with the thoriated tungsten filament. The emission current of the pure tungsten filament was observed to increase at a rate which at times could not be stabilized by the control circuit. The heating system has been operated with only 1 to 2 A of filament current and a cathode temperature of approximately 1600 °C for about 20 minutes before losing heating control. This mode of operation suggests that the filament was operating with a work function similar to that of thoriated tungsten. The difference in operation between this mode and operation with thoriated tungsten was that the tungsten filament was initially heated with 18 A of current and reduced down to 1 to 2 A. With the thoriated tungsten, the filament was initially heated with 12 A of current and then reduced to 0 A. This behavior suggests that the work function of the filament has been reduced.

It is hypothesized that the increase in filament emission is due to a monolayer coating of lanthanum on the tungsten filament. Published evaporation rates [2,3] for LaB_6 show a rapid increase in the 1600-1800 °C range. Lafferty [2] has observed that a monolayer of La on tungsten will increase the thermionic emission from tungsten at 800 °C, which is low enough to allow a monolayer to form readily. At the higher temperatures used in the present work, the increase in evaporation rate may be sufficient to produce the same effect. The evaporation rate at elevated temperatures is low enough to not appreciably affect the cathode lifetime.

The hypothesis was tested by replacing the LaB_6 disk with a graphite disk. This eliminated the effect and the graphite disk could be heated stably to 1755 °C, the limit of the bombardment heating power supply. By placing the LaB_6 cathode in a graphite cup, the filament is not directly exposed to the cathode and the effect was eliminated

Acknowledgement

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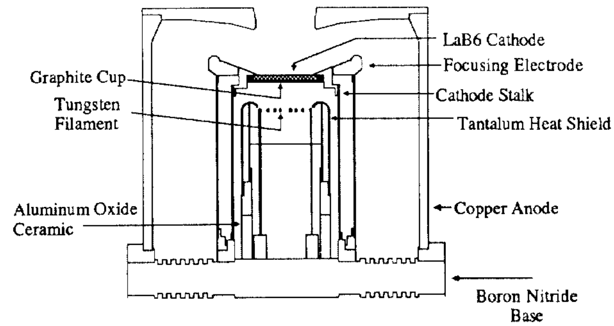

Fig. 1 : Electron Gun Assembly

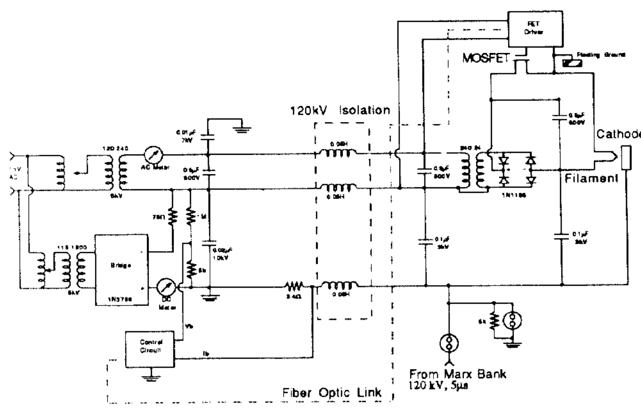

Fig. 2 : Heating and Isolation System

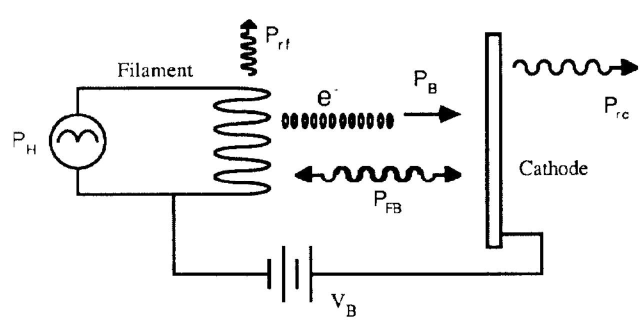

Figure 3: Heating System Model