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**HIGH-CURRENT-DENSITY THERMIONIC CATHODES AND
THE GENERATION OF HIGH-VOLTAGE ELECTRON BEAMS**

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**FINAL TECHNICAL REPORT
FOR THE PERIOD
SEPTEMBER 1, 1982 TO APRIL 30, 1989**

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HIGH-CURRENT DENSITY THERMIONIC CATHODES AND GENERATION OF HIGH-VOLTAGE ELECTRON BEAMS

1. INTRODUCTION

1.1 General Background

The project entitled "High-Current-Density Thermionic Cathodes" and "High Voltage Electron Beams From Thermionic Cathodes" is aimed at developing a thermionic cathode of high current density for use in intense electron-beam generators. The emitting material under study is lanthanum hexaboride (LaB_6). The project breaks down into 3 major parts:

1. Development of methods for heating LaB_6 disks to the emission-temperature range of 1800°C *dec.*
2. Measurement of the emission-current distribution over the cathode surface and correlation with thermionic-emission theory, *and*
3. Design and testing of an electron-gun diode with an LaB_6 cathode which would be a prototype for use in an intense beam generator. *Keywords: LaB₆, Lanthanum*

This Final Technical Report covers progress made on this project from September 1, 1982 to April 30, 1989.

The reason for choosing LaB_6 as a cathode material is that it does not require cathode activation and, in comparison to oxide cathodes, it is less sensitive to cathode poisoning when exposed to the atmosphere. These are important advantages when the cathode is used in a research device that must be opened frequently to air. Another important reason is that it can supply current densities in the 100 A/cm^2 range. High cathode current density is a desirable characteristic for intense beams because the beam brightness, a measure of beam quality, is proportional to current density. Also, less compression is required in a focussed gun.

The material used for LaB_6 cathodes is made by sintering LaB_6 powder. It is readily available in a variety of densities and shapes. In the present project, it was purchased as a solid cylinder and sliced in our shop with a diamond cutoff saw into wafers of the desired thickness (approximately 1/8-inch thick). Since the resulting wafer is like a ceramic material, it must be

*Hexaborides, High-Current Density Thermionic Cathodes,
High-Voltage Electron Beams*

heated slowly to avoid cracking. Part of the project was to develop a bombardment heating system suitable for heating these cathodes. The amount of heat radiated by the cathode and by the bombarding filament is considerable, and requires careful heat-flow control by proper use of heat shielding and water cooling.

1.2 List of Papers, Theses, Graduate Students, Invention Disclosure and Reports

Journal Articles

- (1) "Development of High-Current-Density LAB6 Thermionic Emitters for a Space-Charge-Limited Electron Gun," *Proc. 1987 IEEE Particle Accelerator Conference*, March 16-19, 1987, Washington, D.C., Vol. I, pp. 292-294.
- (2) "Thermionic Cathode Electron Gun for High Current Densities," M. E. Herniter and W. D. Getty, *IEEE Trans. on Plasma Science*, Vol PS-15, pp. 351-360 (August 1987).
- (3) "Pulsed Cathode Heating Method," G. A. Lipscomb, M. E. Herniter and W. D. Getty, *IEEE Trans. on Plasma Science*, Vol. PS-17, pp. 898-905 (December 1989).
- (4) "High Density Results from a LaB₆ Thermionic Cathode Electron Gun," M. E. Herniter and W. D. Getty, *IEEE Trans. on Plasma Science*, accepted for publication.

Conference Papers

- (1) "Current Density Distribution Measurements from Lanthanum Hexaboride Cathodes," (with A. Ashraf), presented at the 1984 IEEE International Conference on Plasma Science, St. Louis, Missouri, May 14-16, 1984.
- (2) "Demountable LaB6 Thermionic Cathode Operation in a Microperveance 2.8 Electron Gun," (with M. E. Herniter), presented at the Twenty Seventh Annual Meeting, Division of Plasma Physics, American Phys. Soc., San Diego, California, November 4-8, 1985. Abstract: *Bull. Amer. Phys. Soc., Ser. II*, Vol. 30, p. 1543 (October 1985).



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- (3) "Current Density Distribution Measurements on a LaB₆ Cathode in Space-Charge-Limited and Temperature-Limited Operation," (with M. E. Herniter), presented at the Twenty-Eighth Annual Meeting, Division of Plasma Physics, American Phys. Soc., Baltimore, Maryland, November 3-7, 1986. Abstract: *Bull. Amer. Phys. Soc., Ser. II*, Vol. 31, p. 1481 (October 1986).
- (4) "Development of High-Current-Density LaB₆ Thermionic Emitters for a Space-Charge-Limited Electron Gun," (with M. E. Herniter), presented at the 1987 Particle Accelerator Conference, Washington, D.C., March 16-19, 1987.
- (5) "Bombardment Heated Lanthanum Hexaboride Cathode Electron Gun for High Current Densities," M. E. Herniter and W. D. Getty, presented at the Twenty-Ninth Annual Meeting, Division of Plasma Physics, American Phys. Soc., San Diego, California, November 2-6, 1987. Abstract: *Bull. Amer. Phys. Soc.*, Vol. 32, p. 1887 (October 1987).
- (6) "Transient Heating Method for Thermionic Cathodes in REB Generators," W. D. Getty, M. E. Herniter and G. A. Lipscomb, presented at the 1988 IEEE International Conference on Plasma Science, Seattle, Washington, June 6-8, 1988.
- (7) "LaB₆ Cathode Operation up to 90 kV and 25 A/cm² in a Pierce-Type Electron Gun," M. E. Herniter and W. D. Getty, presented at the Thirtieth Annual Meeting, Division of Plasma Physics, American Phys. Soc., Hollywood, Florida, October 31 - November 4, 1988. Abstract: *Bull. Amer. Phys. Soc.*, Vol. 33, p. 1952, October 1988.

Ph.D. Theses

Marc E. Herniter, "A Bombardment Heated LaB₆ Thermionic Cathode Electron Gun," Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, 1989. (Abstract in Appendix)

Graduate Students

Marc E. Herniter, Ph.D. (Electrical Engineering), 1989.

George Lipscomb, M.S.E. (Electrical Engineering), 1989.

Aamir Ashraf, M.S.E. (Electrical Engineering), 1985

Kelly Pearce, Ph.D. Candidate, (Nuclear Engineering), 1989 -

Ronald Temske, M.S.E. Student, 1989 -

Disclosure of Invention

"Cathode Heating System," Marc E. Herniter and Ward D. Getty, March 14, 1987.

Reports

- (1) "High-Current-Density Thermionic Cathodes," Progress Report for the Period September 1, 1982 to October 31, 1983, ONR Contract No. N00014-82-K-0448, Ward D. Getty and A. Ashraf, Department of Electrical Engineering and Computer Science, The University of Michigan.
- (2) "High-Voltage Electron Beams From Thermionic Cathodes," Progress Report for the Period, 1 September 1987 to 1 April 1988, W. D. Getty, M. E. Herniter and G. A. Lipscomb, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48109-2122.

1.3 General Plan of Final Report

In the first phase of this study, we constructed a parallel plane diode with an LaB_6 cathode. The cathode was heated by electron bombardment from a temperature limited thoriated tungsten emitter (henceforth referred to as the "filament"). The measurements performed on this diode were cathode temperature, total i-v characteristic, and current density distribution. A second parallel-plane diode was constructed to improve the cathode holding method.

In the next stage, we used the same cathode heating technique on a cathode mounted in a Pierce-type electron-gun structure. In this case, we measured the current-density distribution of

the electron beam after exiting the anode aperture. A special inductively-isolated heating circuit was developed to supply cathode heating power and allow operation up to 40 kV.

A second Pierce-type gun was constructed to allow operation up to 120 kV.

This report traces the development of all four electron guns to show why and how the cathode heating scheme was developed. It concludes with a description of pulsed cathode heating method that greatly reduces the average cathode heating power requirement.

The appendix includes copies of all published papers and abstracts of a Ph.D. thesis and conference papers.

2. FIRST PARALLEL-PLANE DIODE

Parallel-plane diode geometry was chosen for the first diode because we can accurately calculate its expected performance as a space-charge-limited diode, and it was convenient to use while developing the electron bombardment heating circuit.

2.1 Anode-Cathode Design

A drawing of the diode is shown in Figure 1. The cathode is heated by a thoriated tungsten emitter made of 0.025-inch diameter wire. The emitting part of the wire is bent into a multiple hairpin form and is located 1/8 inch to 1/4 inch from the cathode. The cathode is held between two molybdenum disks, of which one is shown in Figure 1. The exposed diameter of the cathode is 3/4 inch, giving an area of 2.8 cm².

The molybdenum anode disk has a 0.020-inch diameter hole at its center for sampling the electron beam. This corresponds to sampling 0.07 percent of the beam area. An insulated Faraday-cup collector is located behind the sampling hole. The anode and cup are moved together when scanning across the beam cross-section.

The materials nearby the cathode are molybdenum and alumina (99.9 percent purity). Other parts of the supporting structure are approximately 1.5 inches away from the cathode and contain boron nitride and 304 stainless steel. No problems were experienced with any of these materials at cathode temperatures up to 1700°C.

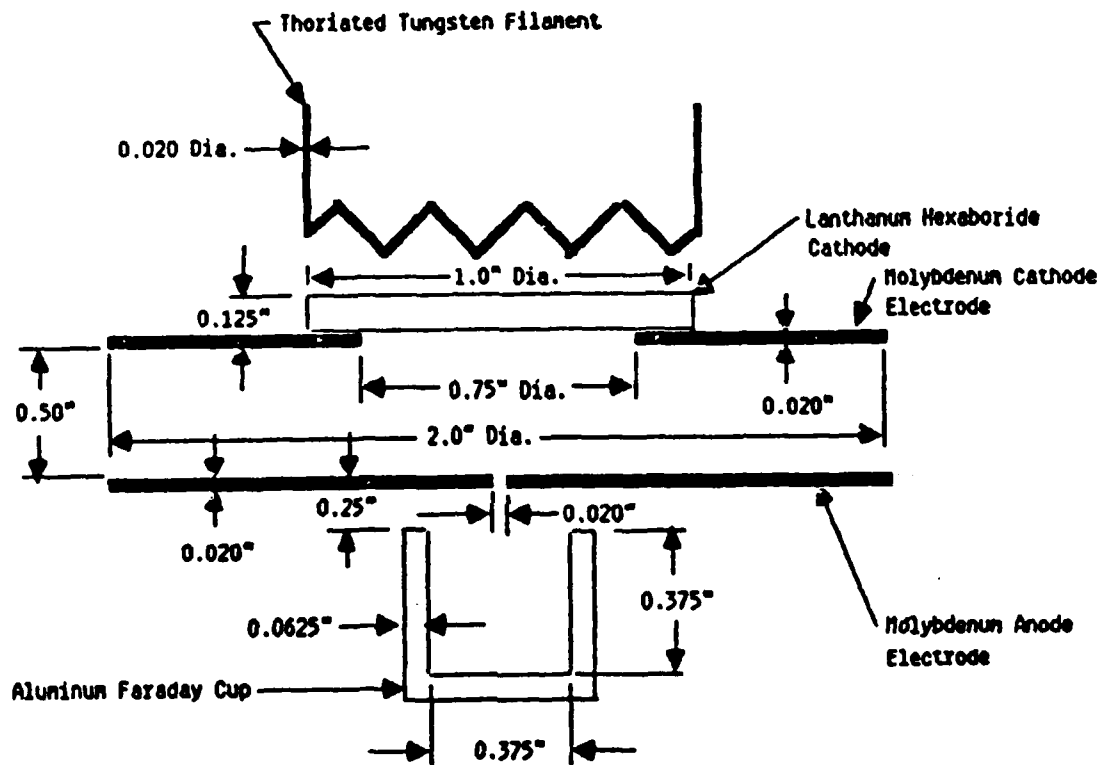


Figure 1: Cross-section of first diode. All dimensions are in inches.

The expected current for this diode can be calculated from the Child-Langmuir law. For plane-electrode space-charge-limited flow:

$$J = \frac{2.335 \times 10^{-6} V^{3/2}}{d^2} \quad (\text{A/m}^2)$$

$$I = J \frac{\pi D^2}{4} \quad (\text{A})$$

For our diode, $d \cong 1.25 \text{ cm}$ and $D \cong 1.9 \text{ cm}$, giving

$$J = 1.5 \times 10^{-6} V^{3/2} \quad (\text{A/cm}^2)$$

$$I = 4.2 \times 10^{-6} V^{3/2} \quad (\text{A})$$

Therefore, the expected microperveance is 4.2 for the experimental diode.

The diode has also been analyzed with the SLAC Electron Optics Program (Herrmannsfeldt code) and the results are shown in Figure 2. This code predicts a microperveance of 4.95 compared to the value of 4.2 found above. The code predicts a uniform current density over the cathode as can be seen by the electron trajectories in Figure 2.

2.2 First Cathode Heater Circuit

The cathode heater circuit provides power for the bombardment filament and the bombardment power. It contains a feedback loop that controls the filament temperature in such a way that the cathode bombardment power is constant. This prevents thermal runaway caused by back-radiation from the cathode onto the filament.

A block diagram of the first circuit used is shown in Figure 3. Power is supplied to the filament through a phase-controlled triac. A full-wave rectified voltage is applied between the cathode and the filament for the bombarding voltage. The filament is operated temperature-limited and therefore its emission current, which is the bombardment current, depends on the conduction angle of the triac. This angle is determined by a signal proportional to the instantaneous bombardment power which is obtained through an analog multiplier whose inputs are proportional to bombardment current and bombardment voltage. If back radiation from the LaB_6 cathode causes the filament to heat up and emit more current, the conduction angle of the triac is reduced to keep bombardment power constant. This, in turn, holds the cathode temperature constant.

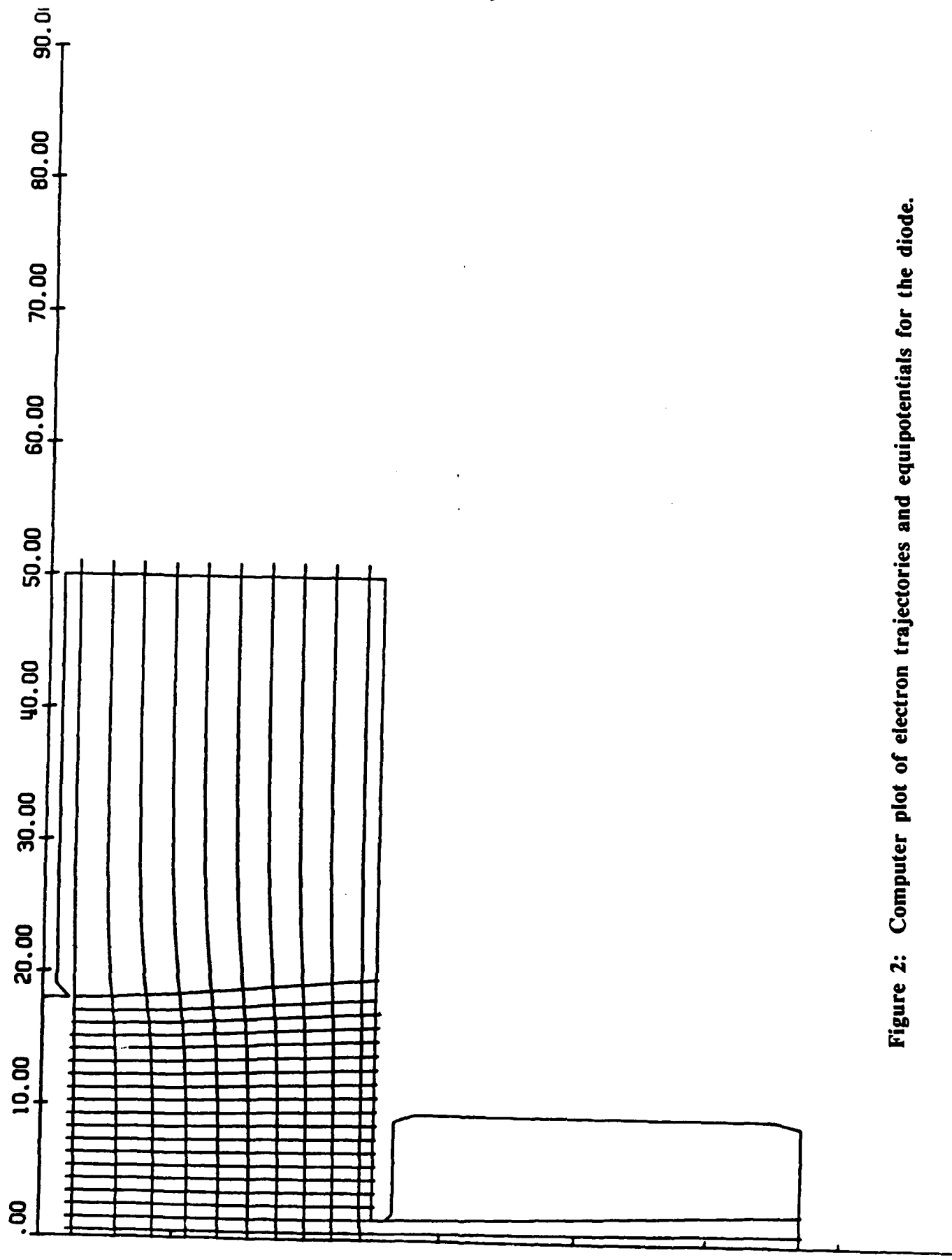


Figure 2: Computer plot of electron trajectories and equipotentials for the diode.

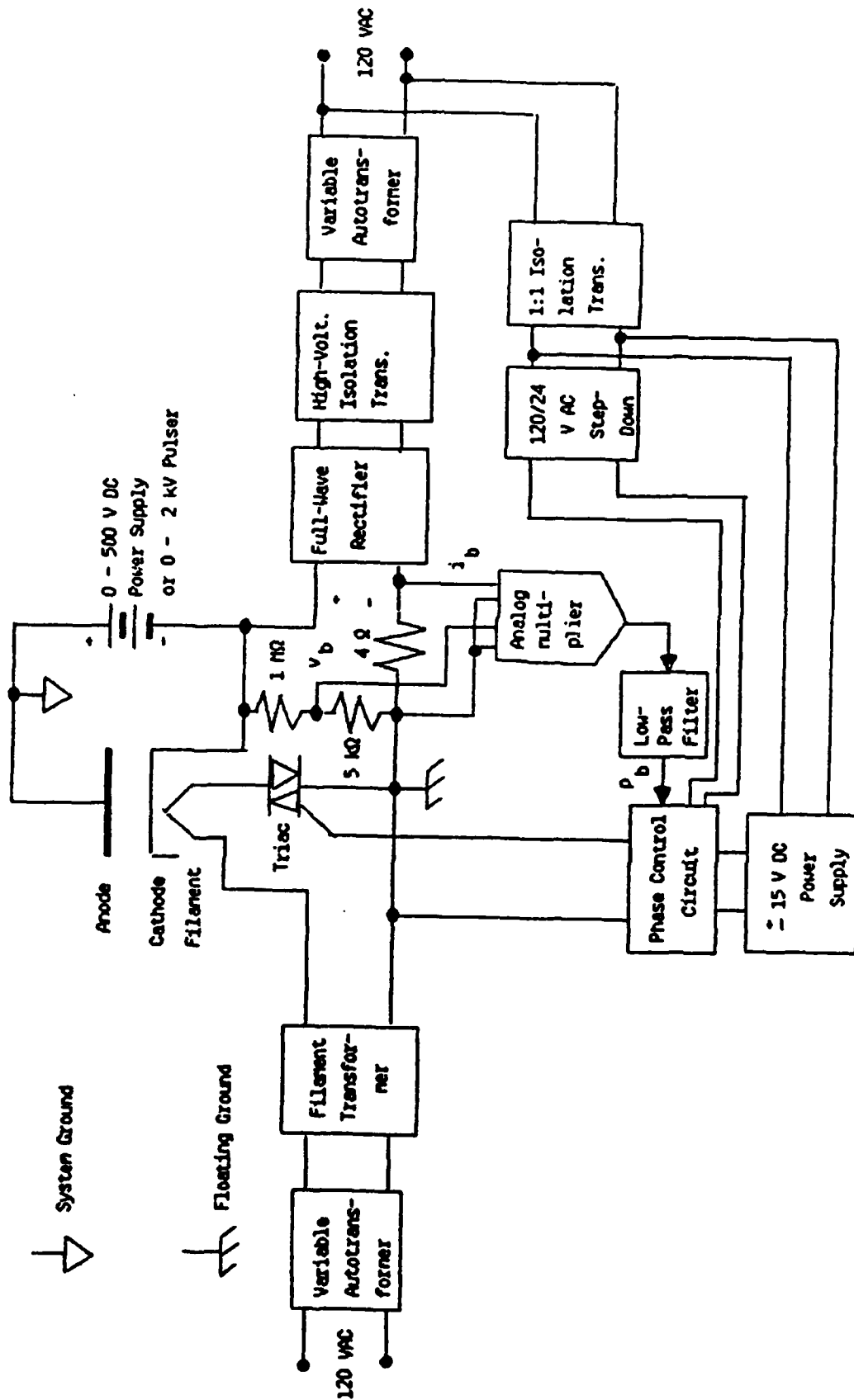


Figure 3: Block diagram of the cathode heating and control circuit.

2.3 Measurements of Diode Operation

Measurements were made of temperature, total emission, and emission distribution. In addition, measurements were made to confirm the operation of the bombardment circuit.

2.3.1 Cathode Heating

Initially, we used pure tungsten filaments but we found that too much power was required. Filament heating power up to 153 W. was used without reaching sufficient bombardment current. The emission current at this power was 28.5 mA. An optical pyrometer was used to measure filament temperature. A comparison of our filament temperature and emission current as a function of heating power was made with the published Jones and Langmuir table for pure tungsten. Fairly good agreement was obtained when we corrected for the power lost in the filament lead-in wire, but the results indicated a pessimistic extrapolation to reach the required emission current.

A 0.025-inch diameter thoriated tungsten filament was handwound in the multiple hairpin form, and the same measurements were performed. Thoriated tungsten was used in an effort to obtain sufficient bombardment current at a lower filament heating power. The new filament was located 1/8 inch from the back of the LaB_6 cathode, which was one-half of the spacing used for the first filament. This filament worked much better, and was used in all subsequent work with this diode. No evidence of poisoning of this filament was observed.

The thoriated tungsten filament could emit sufficient bombardment current at heating powers in the 30 to 40 watt range. For normal operation of the LaB_6 cathode, it was found that about 20 W of filament power was needed. This was 5 to 10 W less than expected, but there is some additional heating by radiation from the hot LaB_6 cathode. The average bombardment power delivered to the LaB_6 cathode was calculated to be 280 W. Thus, the total heat load on the diode structure was approximately 300 W when the LaB_6 was at a temperature of 1500-1600°C. The peak bombardment voltage was 700 V and the peak bombardment current was 0.8 A.

A plot of the resulting cathode temperature versus average bombardment current is shown in Figure 4. The peak bombardment voltage was approximately constant and the filament was operating temperature limited. The cathode temperature was measured with a Leeds/Northrup

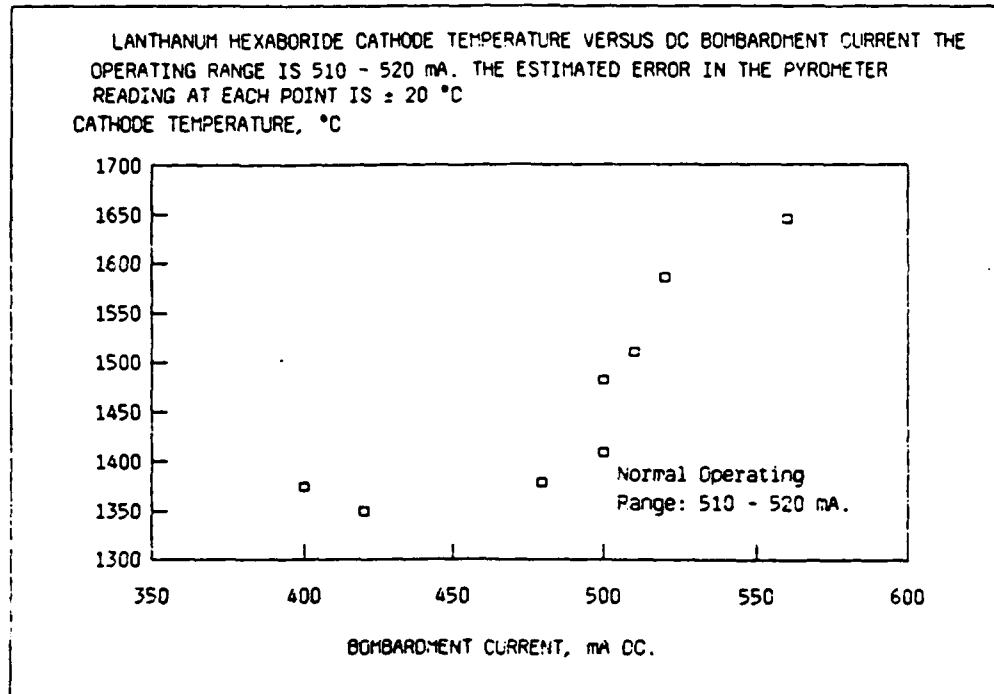


Figure 4: Lanthanum hexaboride cathode temperature versus DC bombardment current. The operating range is 510-520 mA. The estimated error in the pyrometer reading at each point is $\pm 20^{\circ}\text{C}$.

Optical Pyrometer, and no correction was made for the emissivity of LaB_6 . This correction would normally yield a higher actual temperature by a few tens of degrees.

Two thicknesses of LaB_6 cathode material were used ($1/8$ inch and $3/32$ inch) and it was found that the thinner one cracked into several pieces immediately upon heating. The thicker one developed a single crack after several heating/cooling cycles but was still usable. This cathode was used for several months and was exposed to air many times.

2.3.2 Emission Current Distribution

The emission current distribution was measured by sweeping the anode disk pinhole aperture across the cathode surface by moving the anode transversely. The arrangement is shown in Figure 5. The sampled cathode current (0.16 percent of the total) was recorded on an xy recorder whose x axis was driven by a voltage proportional to distance and the y axis was driven by a voltage proportional to the sample current. The orientation of the 13 scans is indicated in Figure 6(a). The translation stage was manually shifted in the y direction by steps of 0.025 inch for the first seven scans in the x direction and by 0.050 inch for the next five scans. The thirteenth scan was a repeat of Scan No. 1 but with zero anode-to-cathode diode voltage. The location of Scan No. 1 with respect to the cathode center is done by eye and its accuracy is ± 0.050 inch. The relative spacing of the scans is accurate to within ± 0.001 inch. The measuring circuit is shown in Figure 6(b). The average bombardment current was 520 mA for these measurements, and the cathode temperature was estimated to be 1600°C . The total cathode current was 89 mA and the diode voltage was 100 V.

The current detected by the Faraday cup as the pinhole is scanned across the cathode is shown in Figure 7 for scans along lines 1, 2, 3, 4, 5, 7 and 11 in Figure 6(a).

2.3.3 Conclusions

The i-v characteristics for this diode and the current distributions shown in Figure 7 are not consistent with parallel plane emission in a space-charge-limited diode. It was concluded that the cathode was operating temperature-limited, and that the temperature must be raised 100 to 200 degrees.

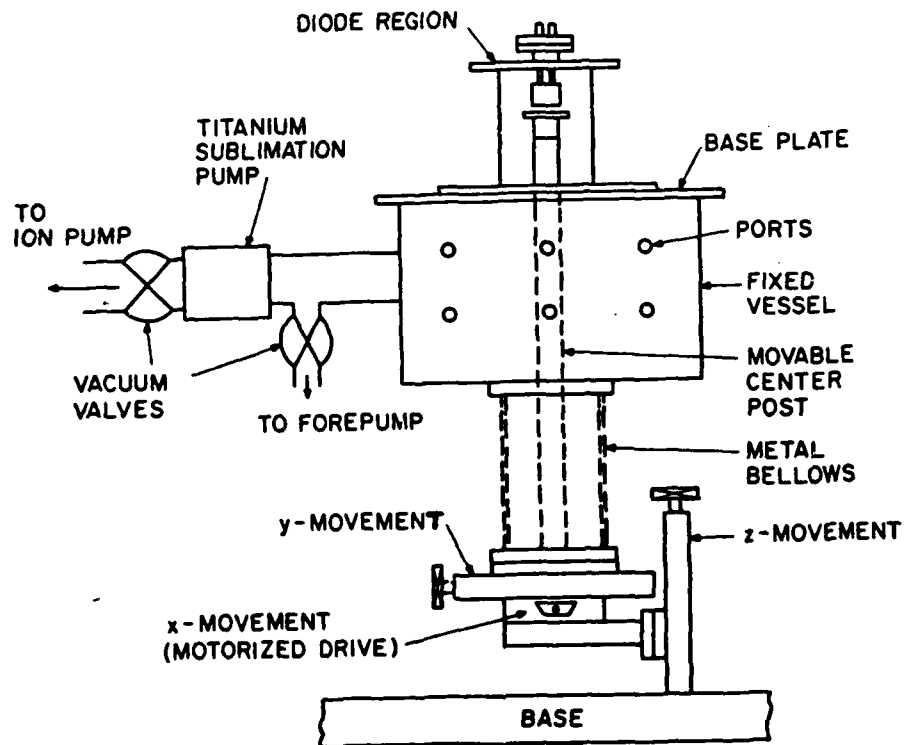


Figure 5: Overall view of the first vacuum system.

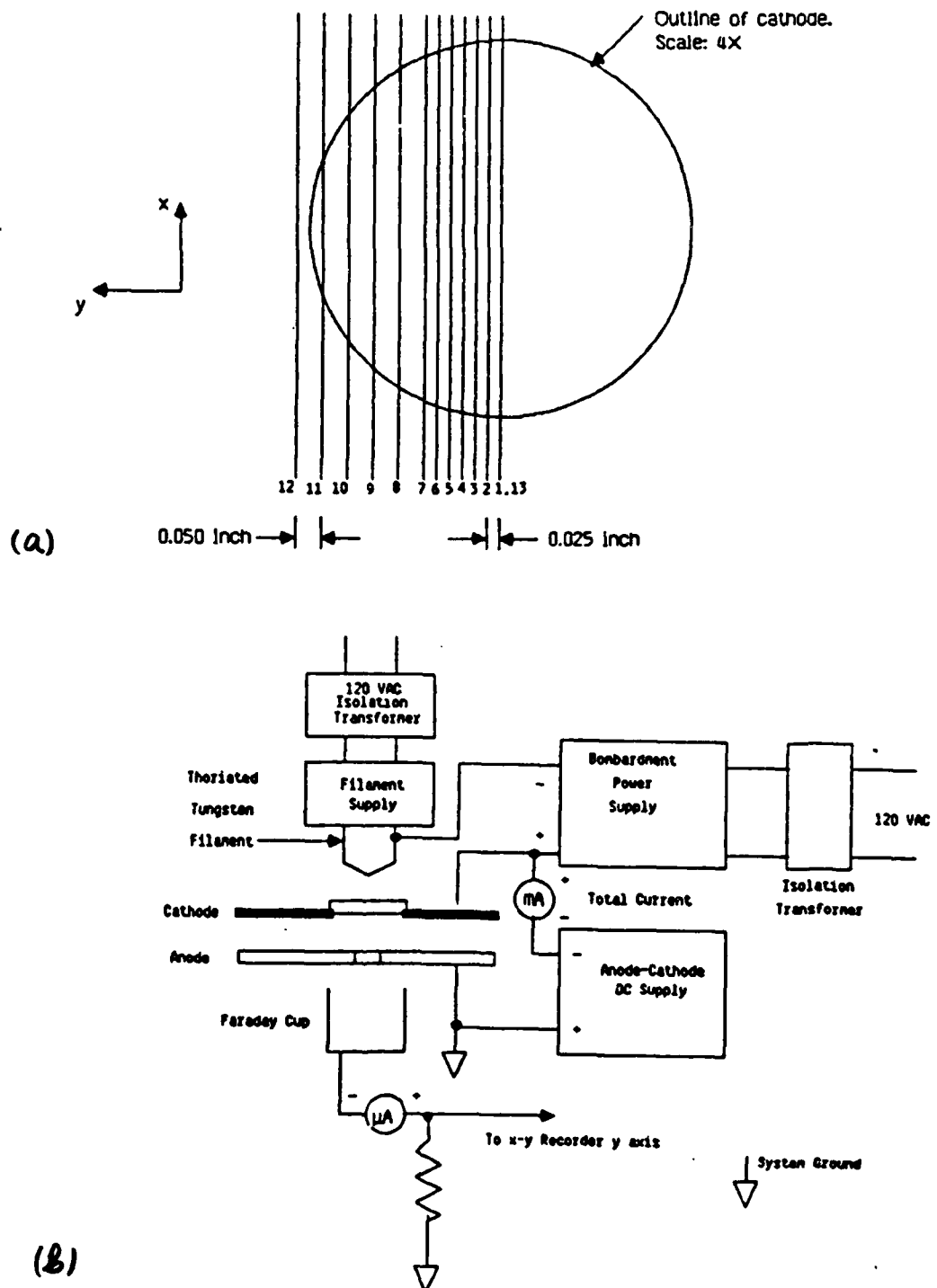


Figure 6: (a) Location of beam analyzer scans. (b) Circuit schematic.

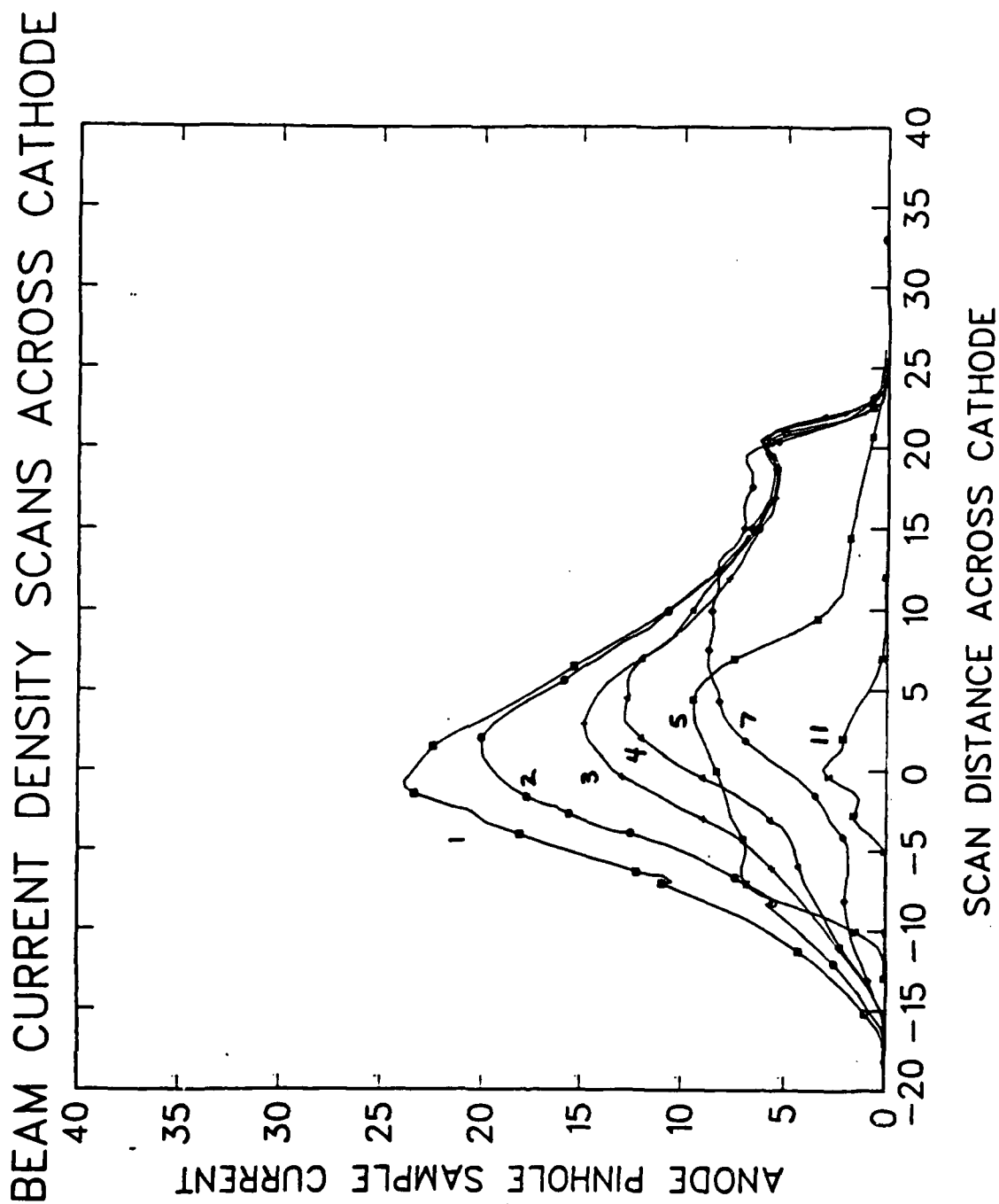


Figure 7: Beam current density scans across cathode.

3. SECOND PARALLEL-PLANE DIODE

The second diode was constructed with a better method for holding the LaB₆. Its design is shown in Figure 8. A LaB₆ disk of 0.125-inch thickness and 1.0-inch diameter was sandwiched between two molybdenum disks. A tungsten bombarding filament is located behind the disk. Two heat-shield disks made of molybdenum are located in back of the filament, and the whole structure is mounted on a boron nitride insulator and surrounded by a tantalum heat shield. All parts above the boron nitride are made of molybdenum, tungsten, tantalum, aluminum oxide, or LaB₆ to withstand the high operating temperature.

The vacuum vessel was set up as shown in Figures 5 and 9. The upper part where the diode was mounted consisted of a 6-inch diameter Pyrex tube 6 inches in length. The cathode structure was mounted on the top with the cathode emitting surface facing downward. The planar anode as supported by the translation-stage post extending up from the bottom of the vacuum system. The anode disk had a pinhole in it which could be moved across the entire cathode surface for emission distribution measurements. This diode was pulsed and a special sample-and-hold circuit was used to obtain a current input to the x-y recorder. The setup is shown in Figure 10. This diode was pulsed up to 2 kV.

4. FIRST PIERCE-TYPE ELECTRON GUN

Two Pierce-type electron guns were built. They both had the same basic anode-cathode gap with a perveance of $3.2 \times 10^{-6} \text{ A/V}^{3/2}$.

4.1 Structure of First Pierce Gun

An overall view of the system arrangement is shown in Figure 11. With the aid of the Herrmannsfeldt electron-optics code, a high perveance gun was designed which allowed us to reach 9 A at 20 kV and 25 A at 40 kV. These currents and voltages correspond to current densities of 3 A/cm² and 8 A/cm², respectively, and were within the range of our existing 5-μs pulser. A computer plot of the code result is shown in Figure 12 and the gun design is shown in Figure 13.

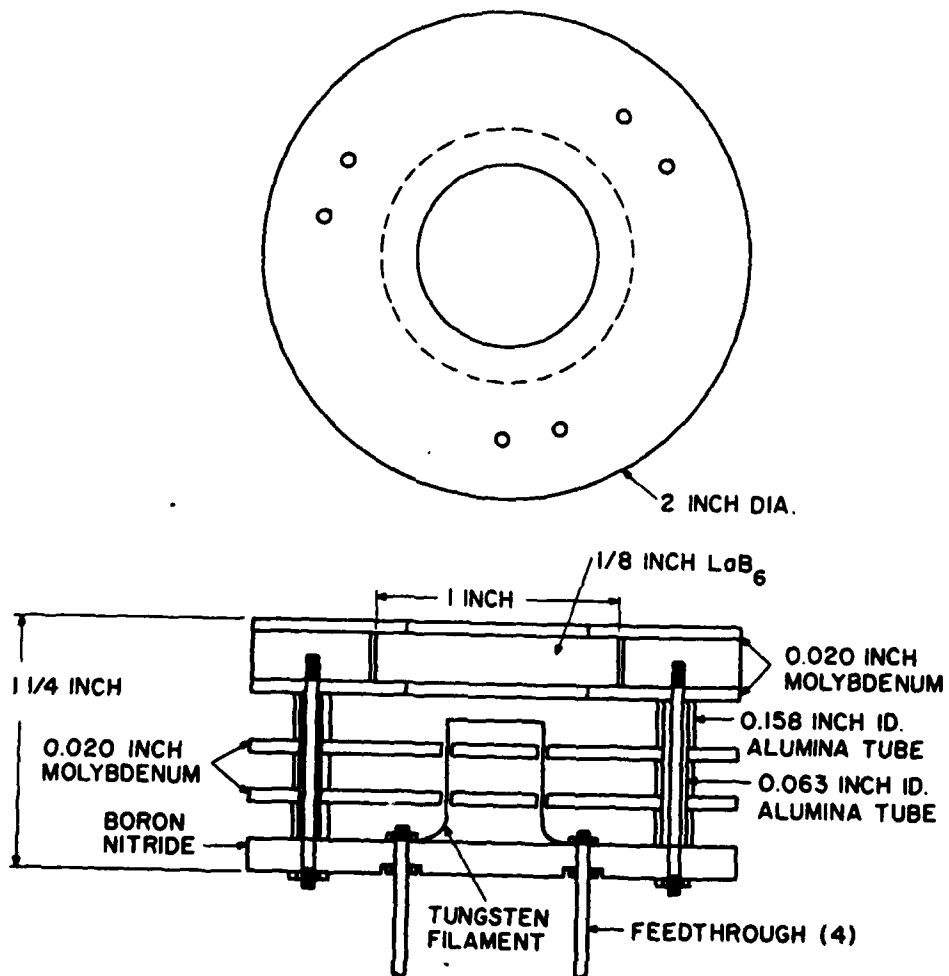


Figure 8: Second parallel plane diode assembly drawing

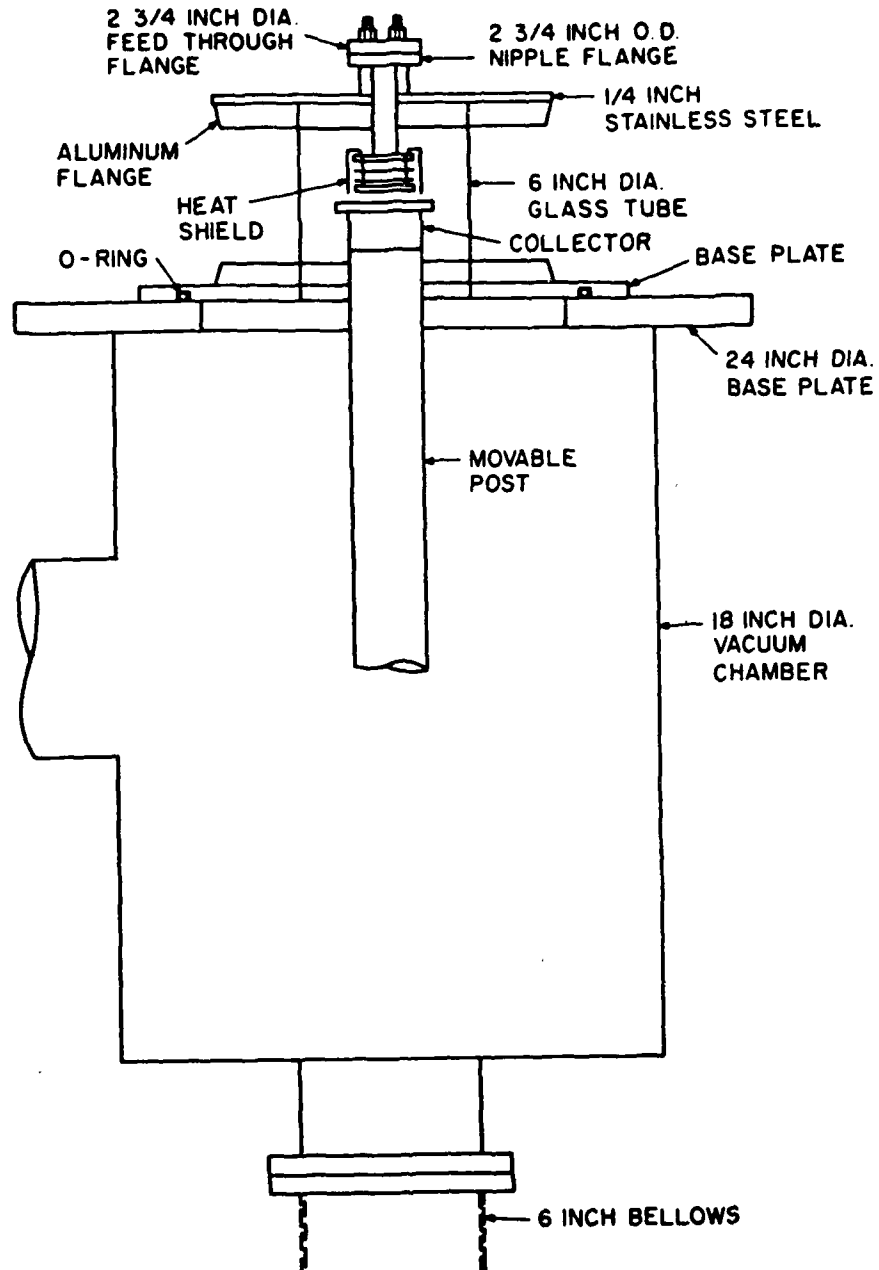


Figure 9: Upper part of beam analyzer vacuum vessel.

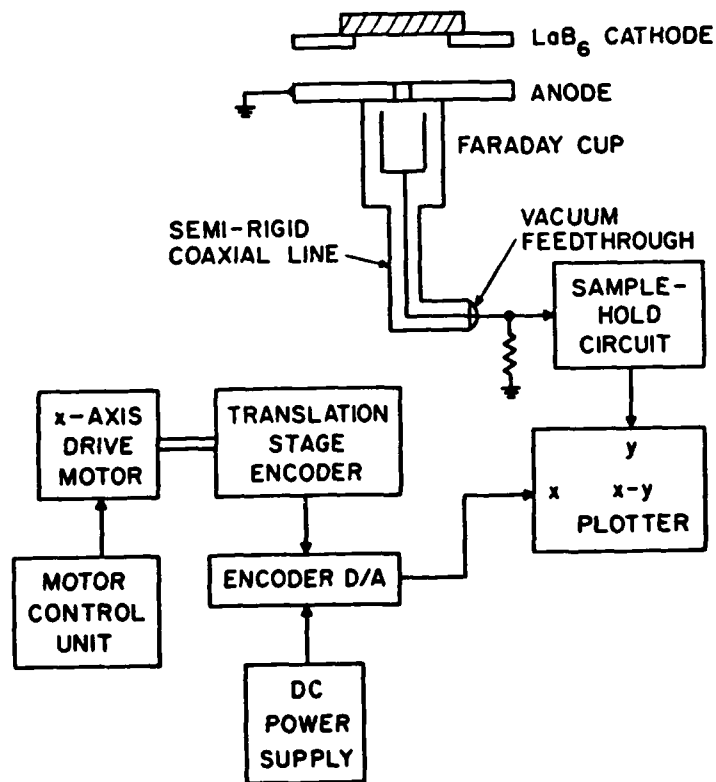


Figure 10: Anode and collector circuit

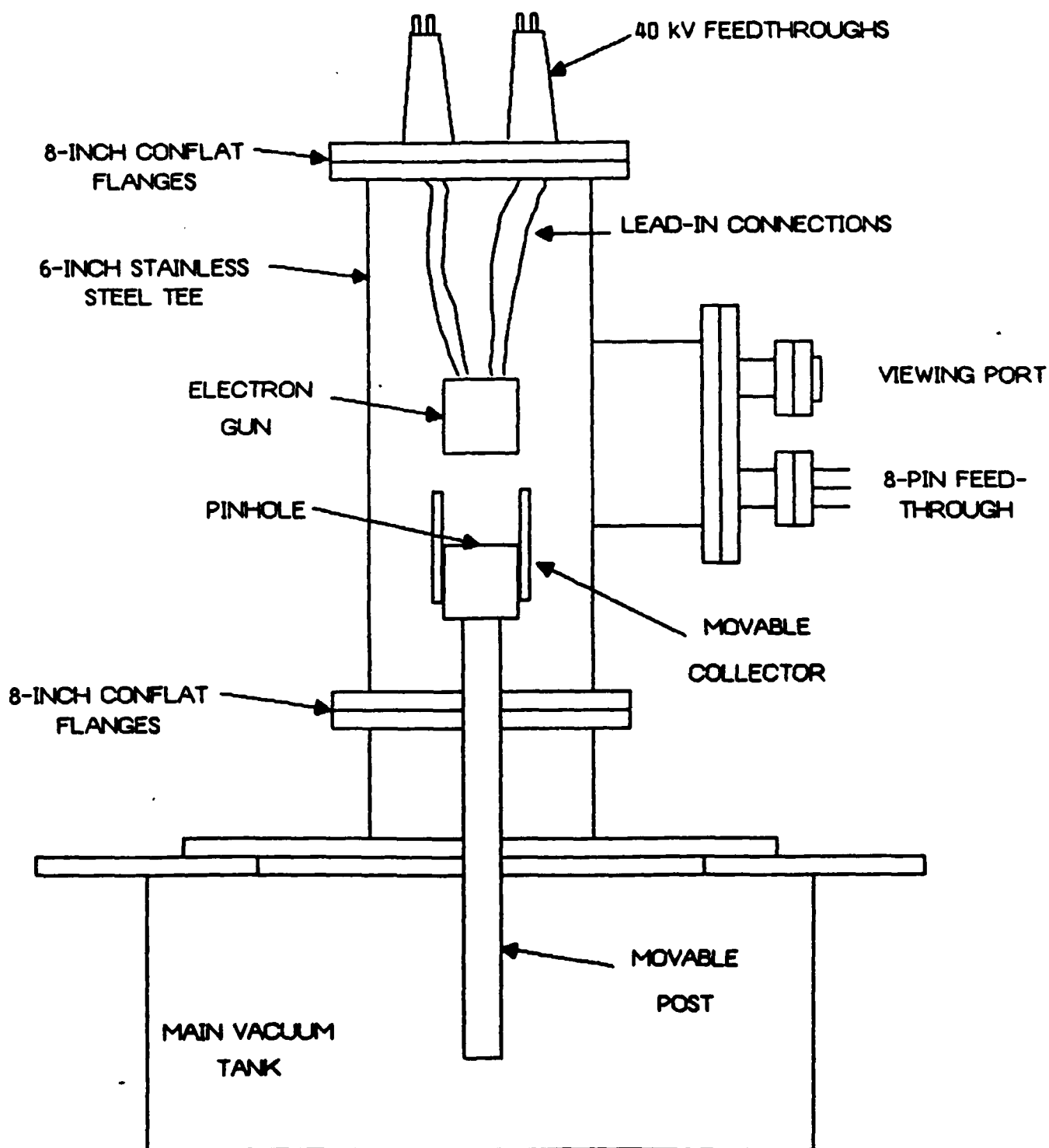


Figure 11: Main vacuum tank and 6-inch tee. The new all-metal system has feedthroughs rated at 40 KV and will be able to handle the heat load better than the glass system.

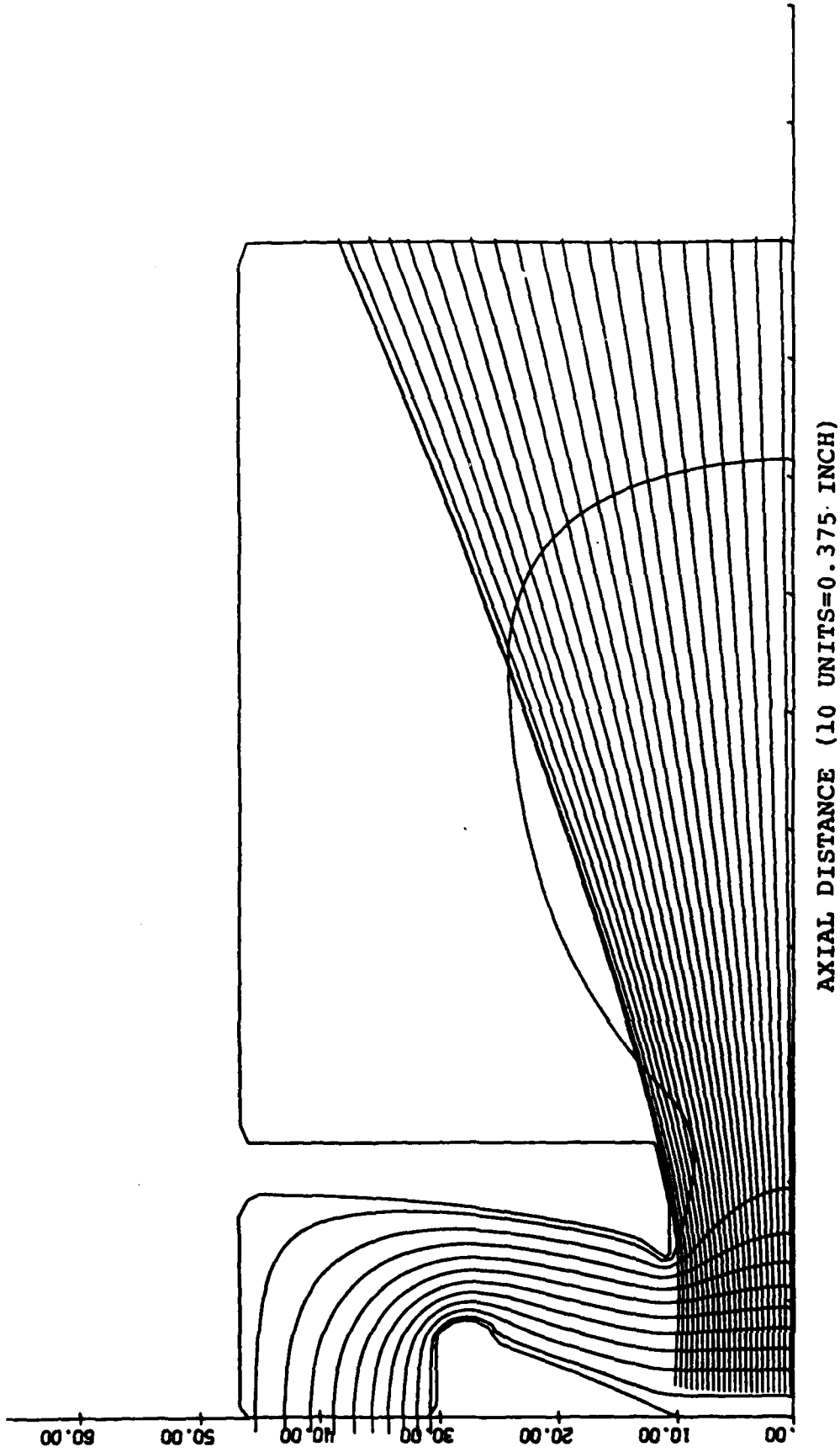
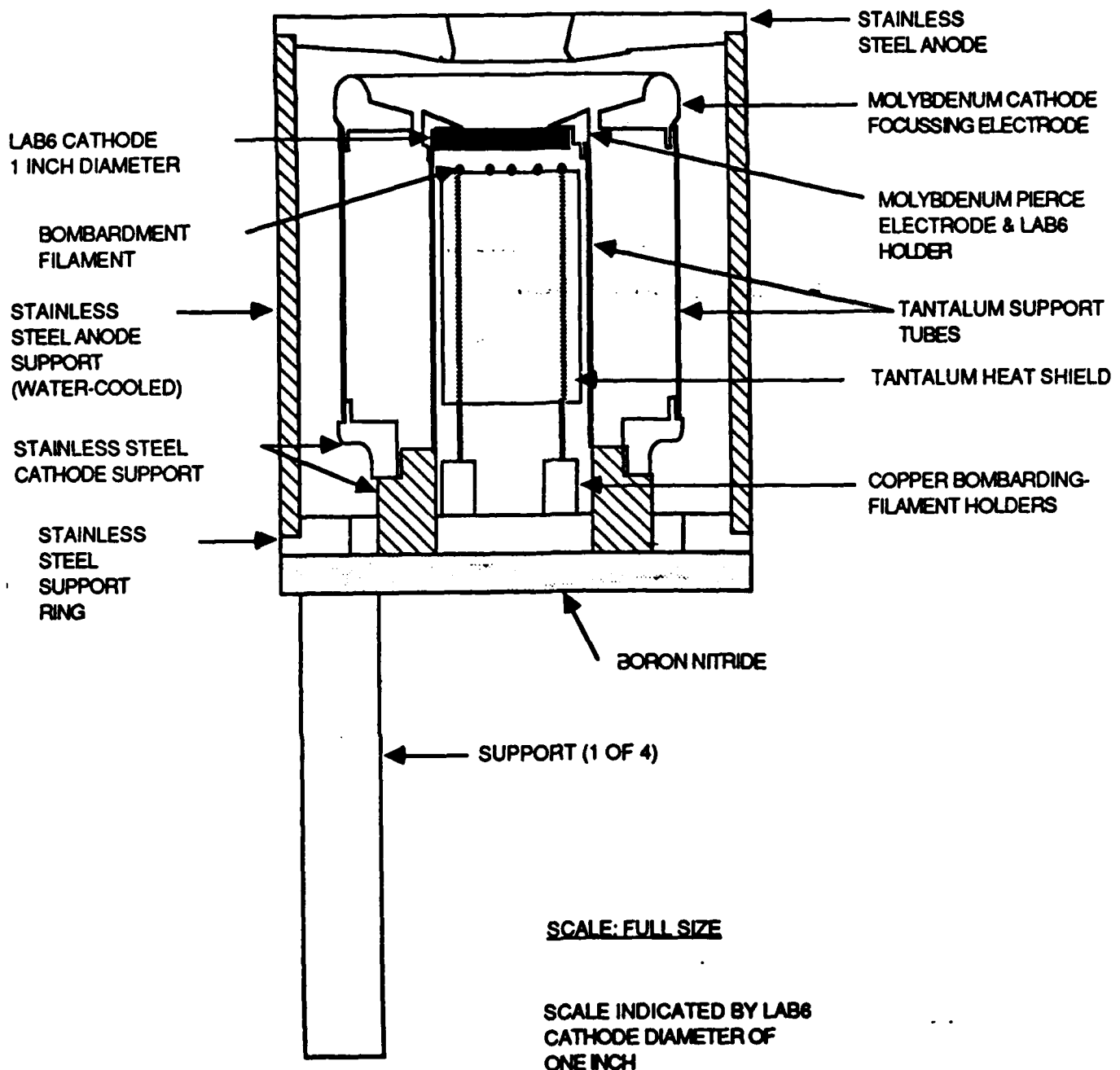


Figure 12: Computer plot of equipotentials and trajectories for new electron gun using Herrmannsfeldt code.



Assembly drawing of the UM LAB6 bombardment-heated electron gun

Figure 13: Assembly drawing of the UM LaB₆ bombardment-heated electron gun.

A pulse transformer was purchased which is rated at 40 kV and 30 A for 5- μ s pulses. This transformer has a bifilar secondary winding rated at 120 VAC and 9 A, and this supplied the AC power required by the cathode bombardment heating circuit. The heating control circuit used was the same as that of Figure 3, except the cathode pulser range was 0-40 kV.

4.2 Beam Measurements

This demountable, 3.2-micropervance, Pierce-type electron gun had a 1.9 cm diameter lanthanum hexaboride (LaB_6) cathode. It was operated in 5- μ s pulses up to 36 kV, giving cathode current densities of 6.7 A/cm². Measurements were made under both space-charged-limited (SCL) and temperature-limited (TL) operation. Measurements of current distribution were made by sweeping a pinhole across the beam at a distance of $z = 4$ cm from the cathode and using the circuit of Figure 10. Complete profiles in the x-y plane or single sweeps across the diameter were made for various cathode heating powers and the effect on the current distribution of changing from TL to SCL operation was observed.

The cathode was heated by electron bombardment and thermal radiation from a tungsten filament. The cathode was heated to 1755°C with 744 W of power. The measured micropervance was found to be very close to the design value as shown in Figure 14, as long as the cathode was space-charge limited.

The analog phase control circuit of Figure 3 was used to achieve stable operating temperatures.

Results of the sweep measurements are shown in Figures 15 through 17. It was found that peaking occurred near the cathode edges at low temperature and/or at high voltage. This effect was traced to temperature limitation by using the SLAC code for simulation. It was shown that the beam constricts in the anode aperture and the current density peaks near the edges, as shown by the simulation results in Figures 18 and 19.

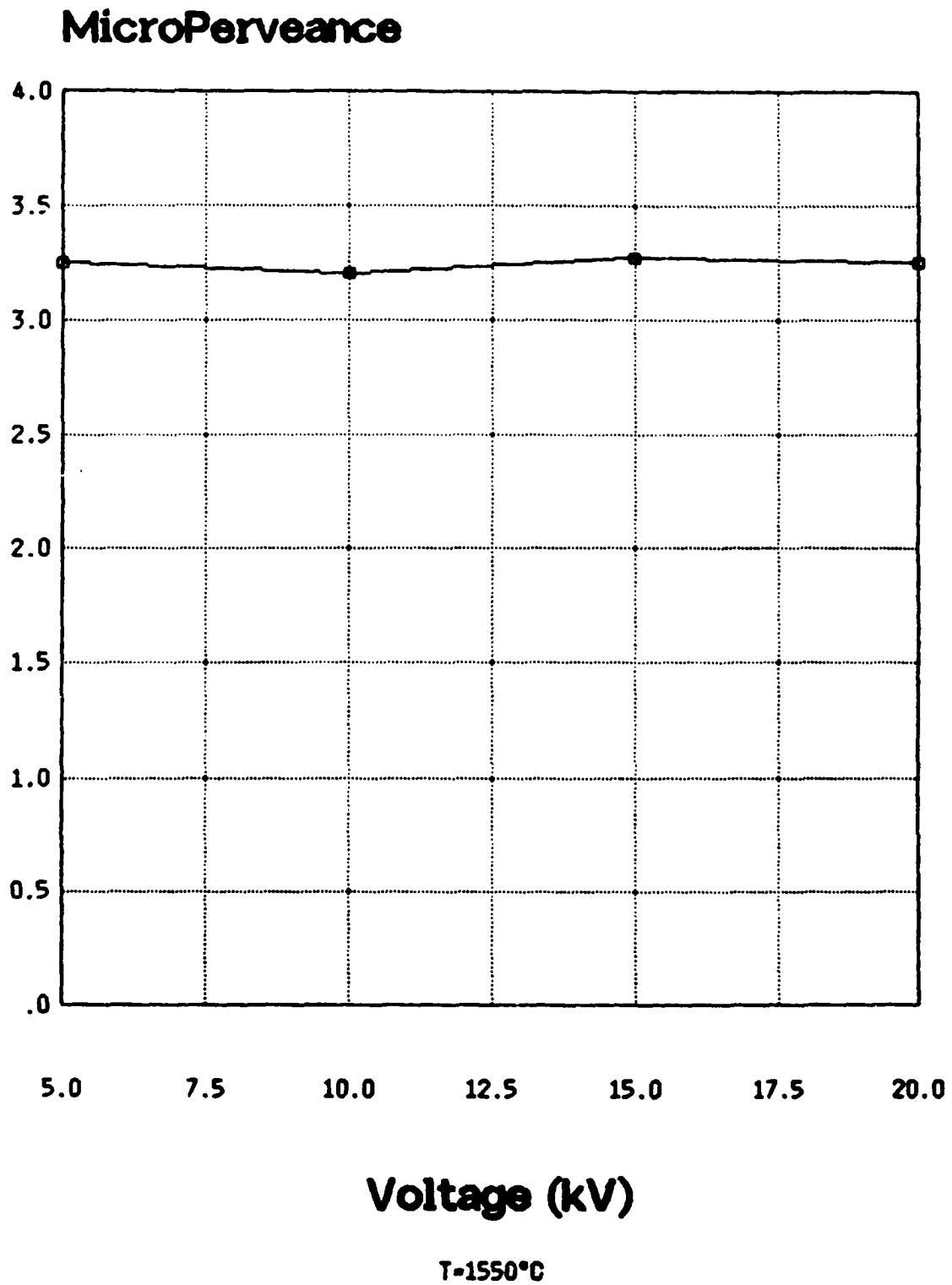


Figure 14: Average microperveance vs. voltage.

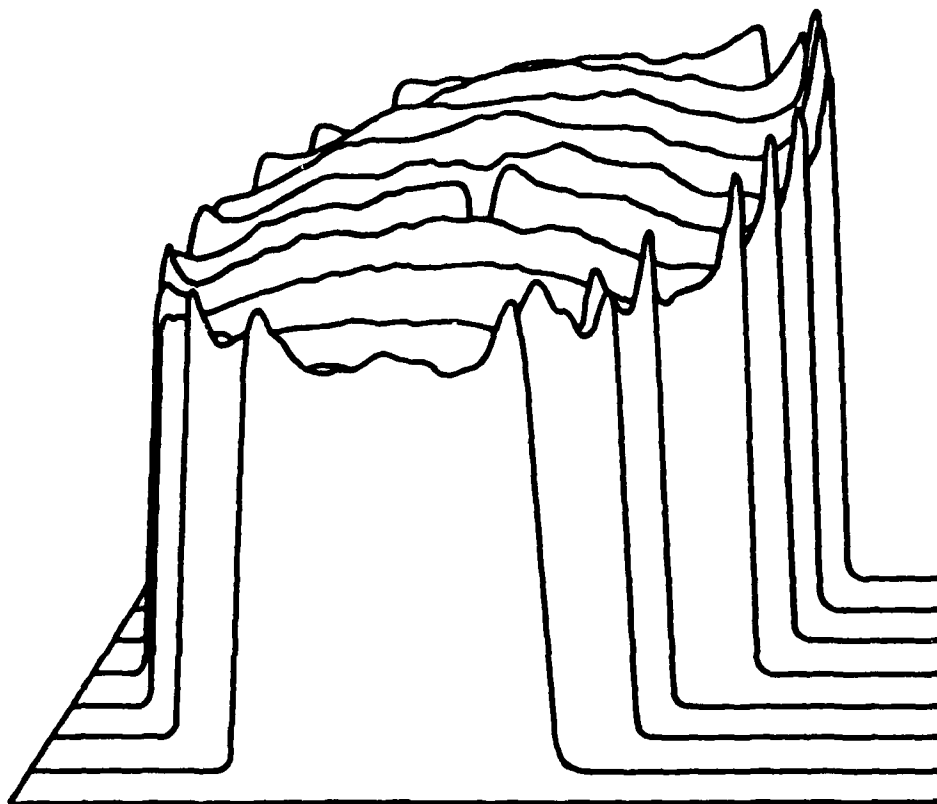


Figure 15: LaB₆ electron gun emission profile of the entire beam cross section. The approximate diameter of the beam at the location of the measurement ($z = 4$ cm) is 3 cm. Eleven pinhole sweeps were made across equally spaced chords. Pinhole 0.0135-inch diameter, at $z = 4$ cm from cathode.

Current Density Distribution Increasing Voltage

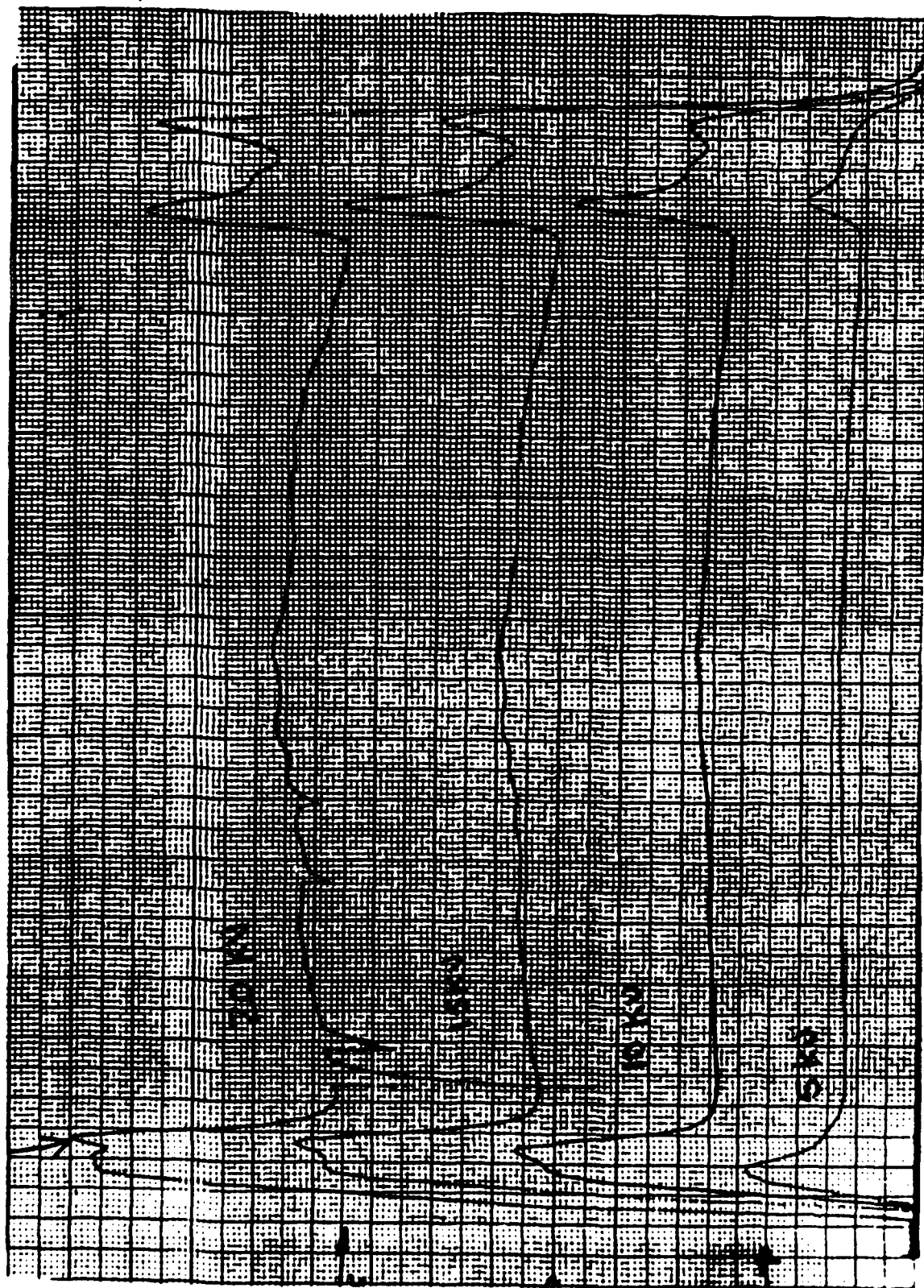


Figure 16: Current density distribution increasing voltage.

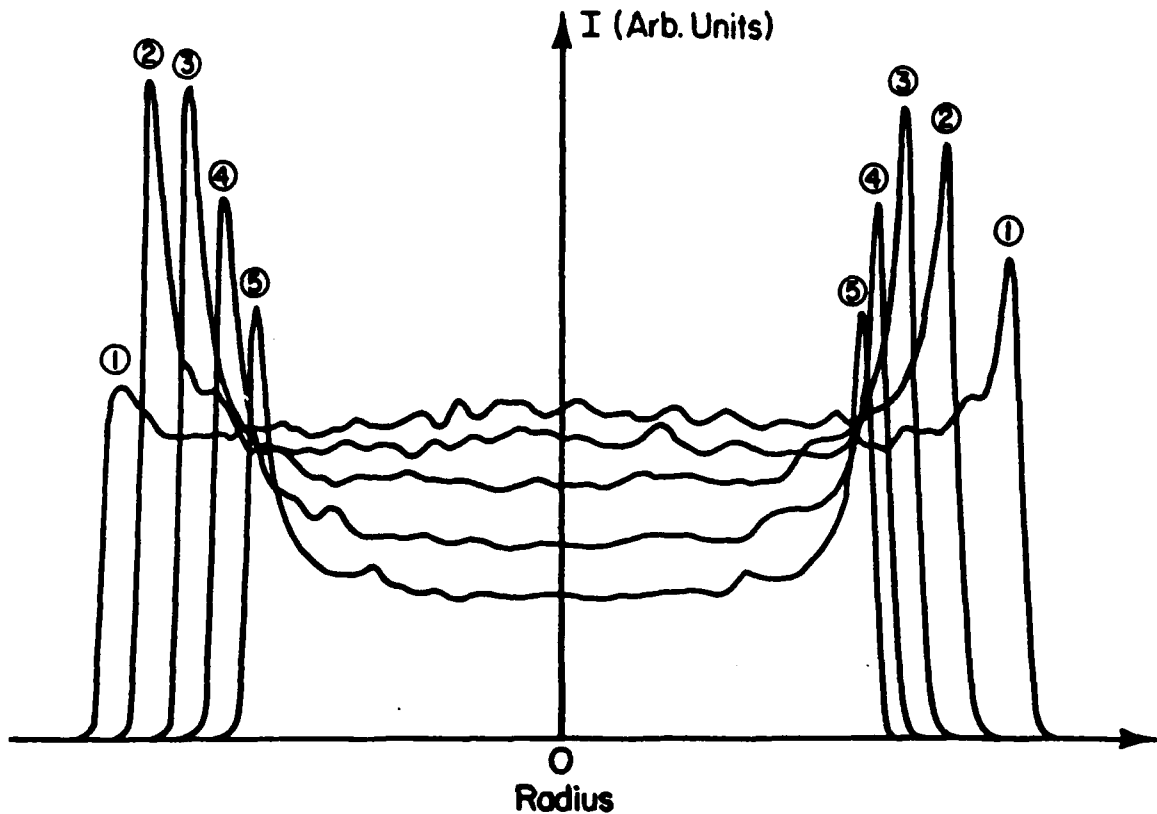


Figure 17: Electron gun emission profiles across the beam center diameter showing the effects of temperature limitation. Profiles were made at a gun voltage of 15 kV. Scans 1 to 5 are in order of increasing temperature limitation. The microperveance of the profiles are: (1) $\rho = 2.83 \text{ A/V}^{3/2}$, (2) $\rho = 2.18 \text{ A/V}^{3/2}$, (3) $\rho = 1.58 \text{ A/V}^{3/2}$, (4) $\rho = 1.09 \text{ A/V}^{3/2}$, (5) $\rho = 0.67 \text{ A/V}^{3/2}$. Profile (1) is essentially the same as the space-charge-limited profile.

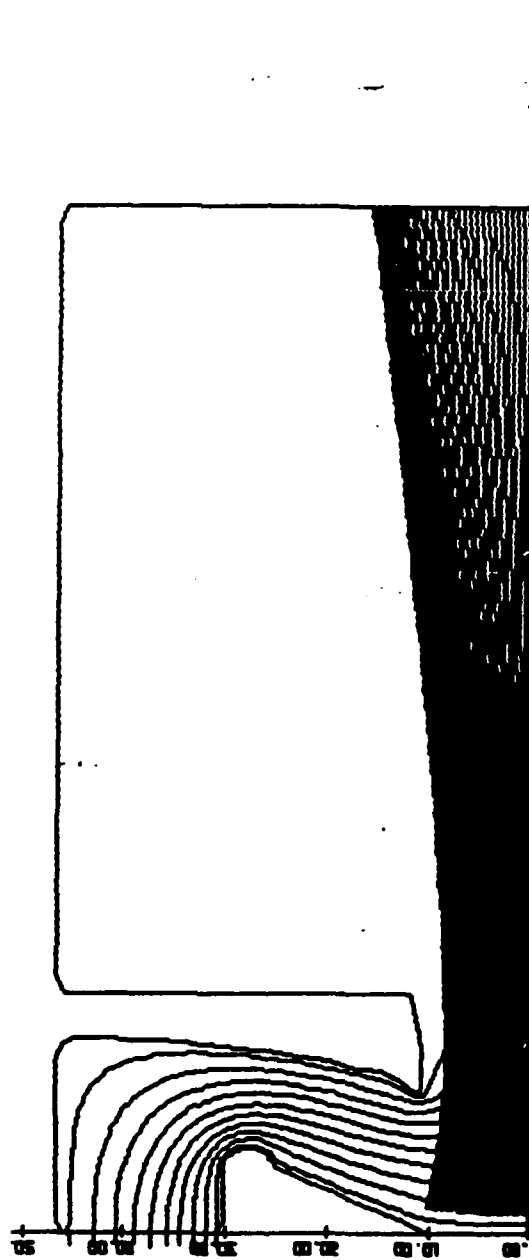


Figure 18: SLAC computer simulation temperature-limited emission.

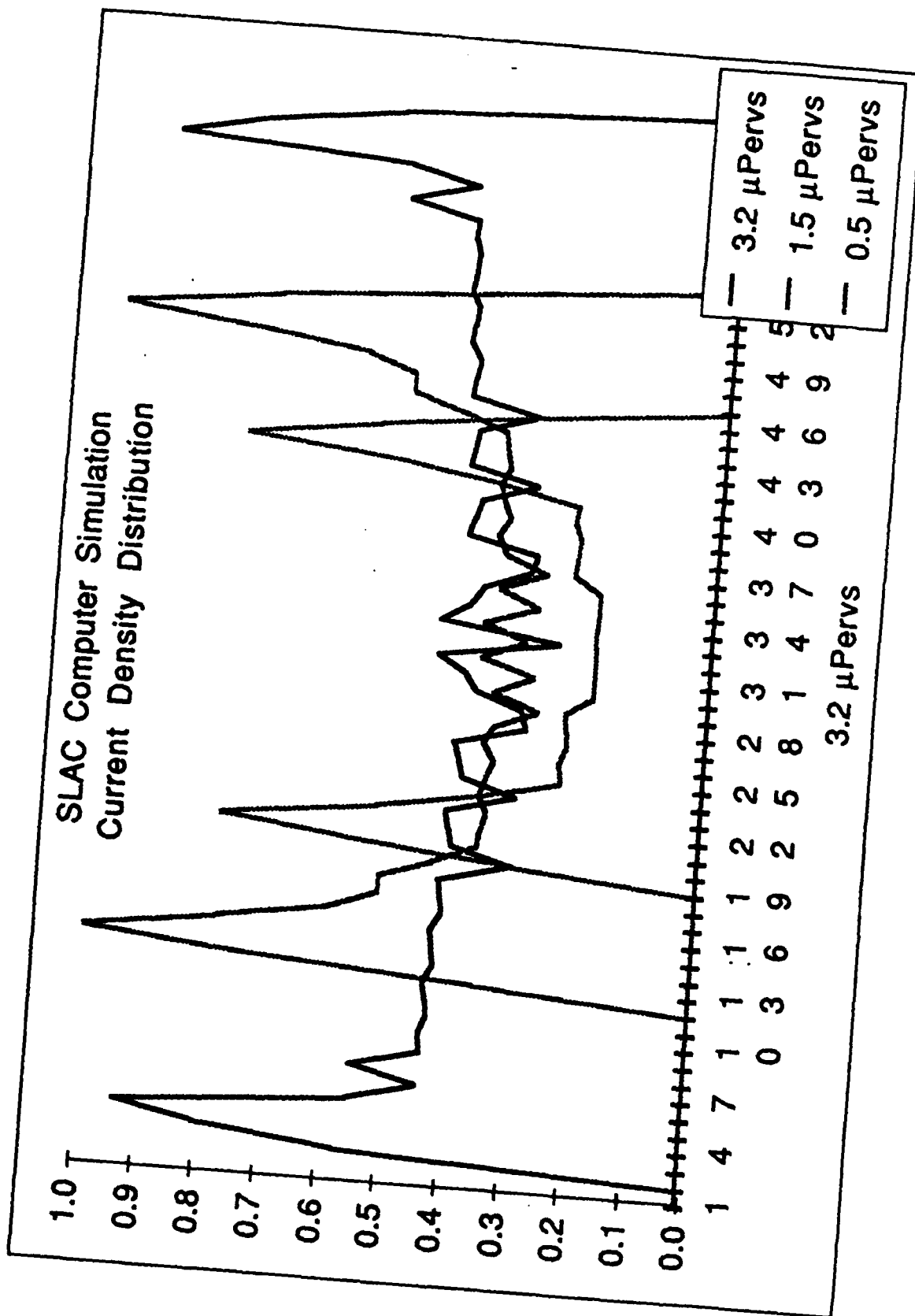


Figure 19: SLAC computer simulation current density distribution.

4.3 Cathode Heating Measurements

The basic heating control method was to control the bombardment current by changing the filament temperature. If the filament is operating temperature-limited, the bombardment current will increase if the filament power is increased. By sensing the bombardment current, feedback could be used to vary the filament power and thereby hold the bombardment current constant. The new control circuit is shown in Figure 20. It replaces the analog multiplier and low pass filter shown in Figure 3. It was found to be more effective to control current rather than power, which was sensed by the multiplier.

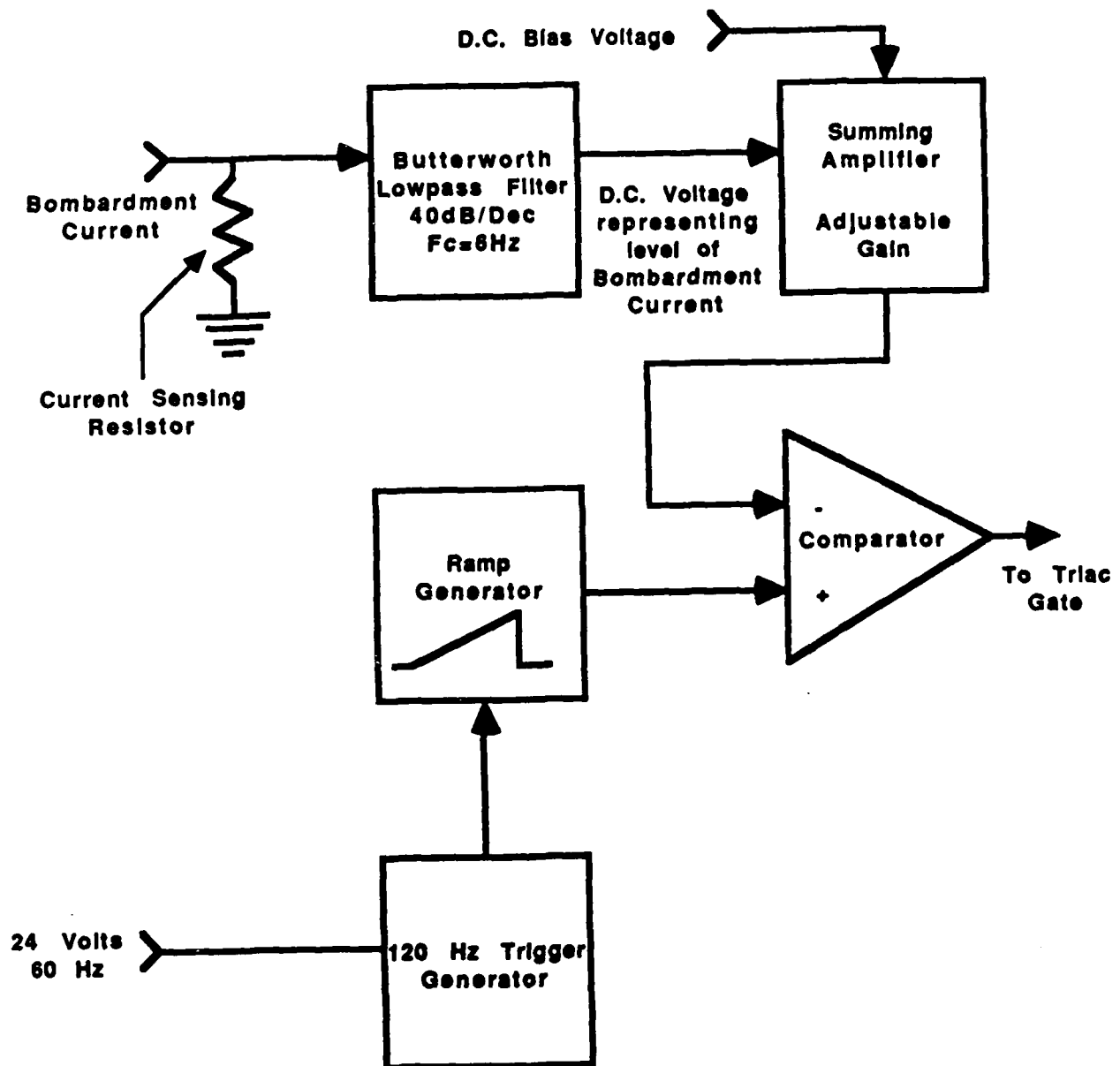
The power levels were typically 744 W total at a cathode temperature of 1755°C. Of this power, 519 W were from bombardment and 225 W were supplied to the filament. The cathode temperature was measured with an infrared detector made by Vanzetti Corporation. It could be scanned across the cathode and detected the temperature in a spot of 1/8-inch diameter. A typical profile is shown in Figure 21.

A heating model was developed which could be used to predict cathode temperature. The basic model was made by dividing the gun into different regions, as shown in Figure 22, and solving the steady-state heat flow equations. By adjusting parameters in the equations, a reasonable fit to the measured temperature curve could be obtained. The result is shown in Figure 23.

5. SECOND PIERCE-TYPE ELECTRON GUN

5.1 Description of Gun

A larger gun structure was built to prevent arcing at voltage up to 120 kV. The new gun has the same cathode diameter and the same perveance. It consists of a lanthanum hexaboride planar cathode in a conventional Pierce-diode gun geometry. The cathode is heated by electron bombardment from a tungsten filament. The electron gun is driven by a conventional 4-stage Marx generator rated at 30 kV per stage. With the gun-diode load, the expected RC decay time of the Marx generator is 16 μ s. The voltage pulse can be terminated anytime by a crowbar spark gap.



Control Circuit Block Diagram

Figure 20: Control circuit block diagram

Cathode Temperature Scan

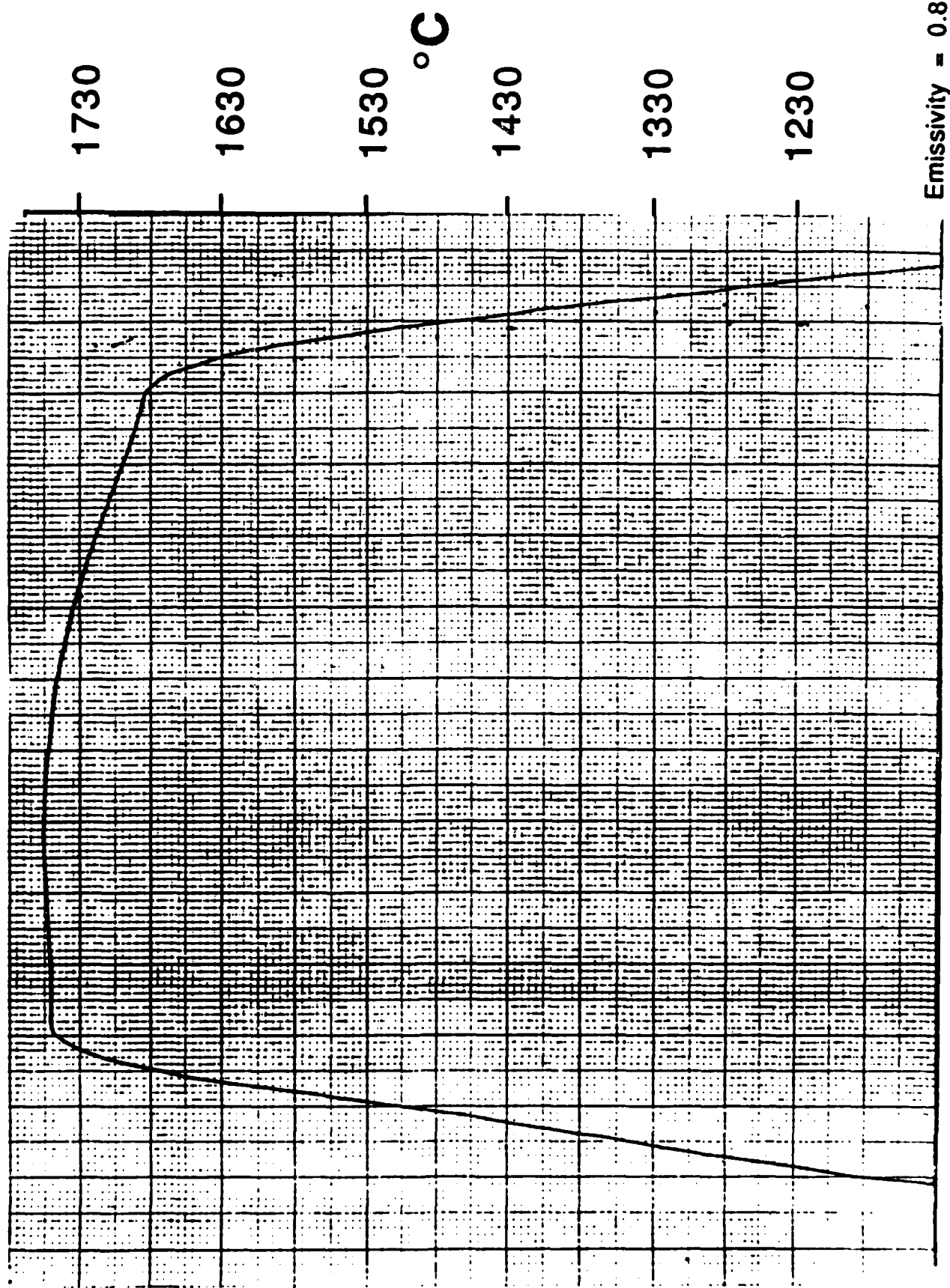


Figure 21: Cathode temperature scan.

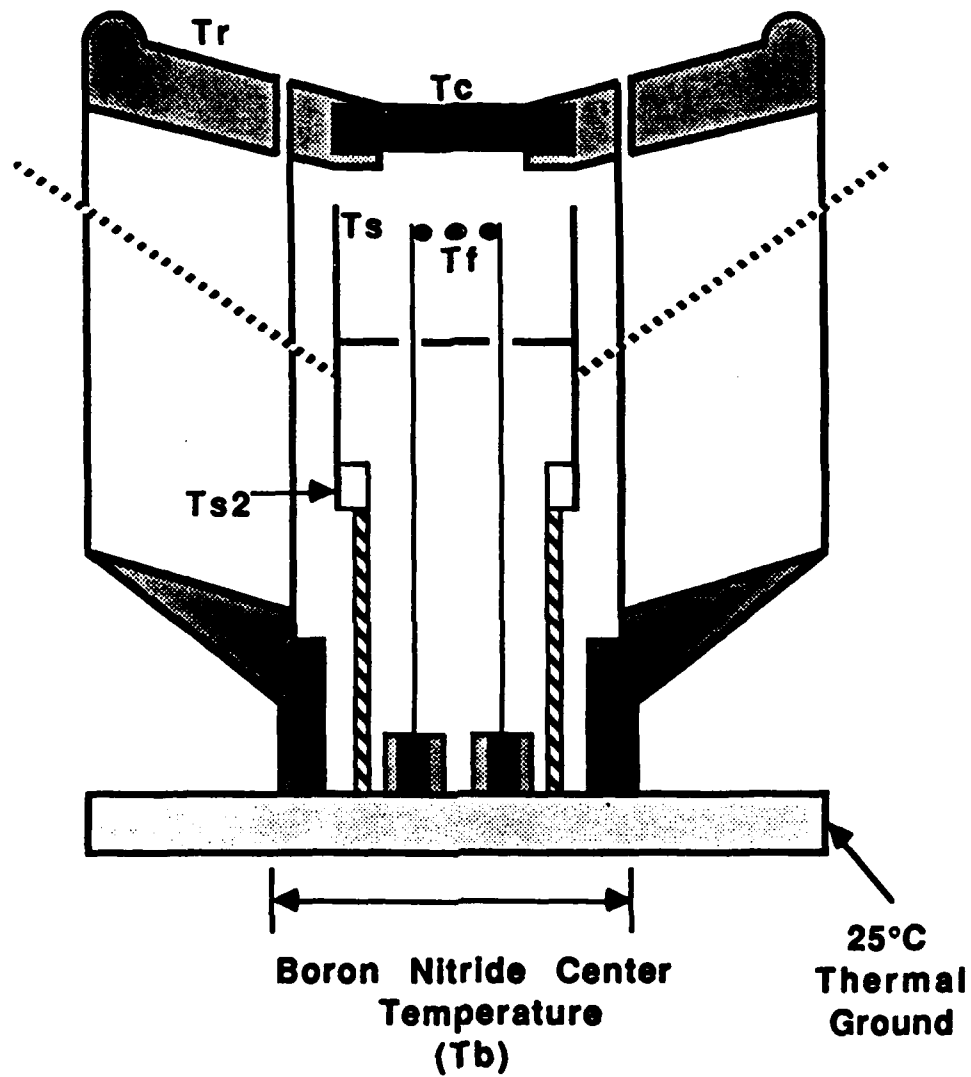


Figure 22: Bombardment heating system steady state model.

Heating Power Vs. Cathode Temperature

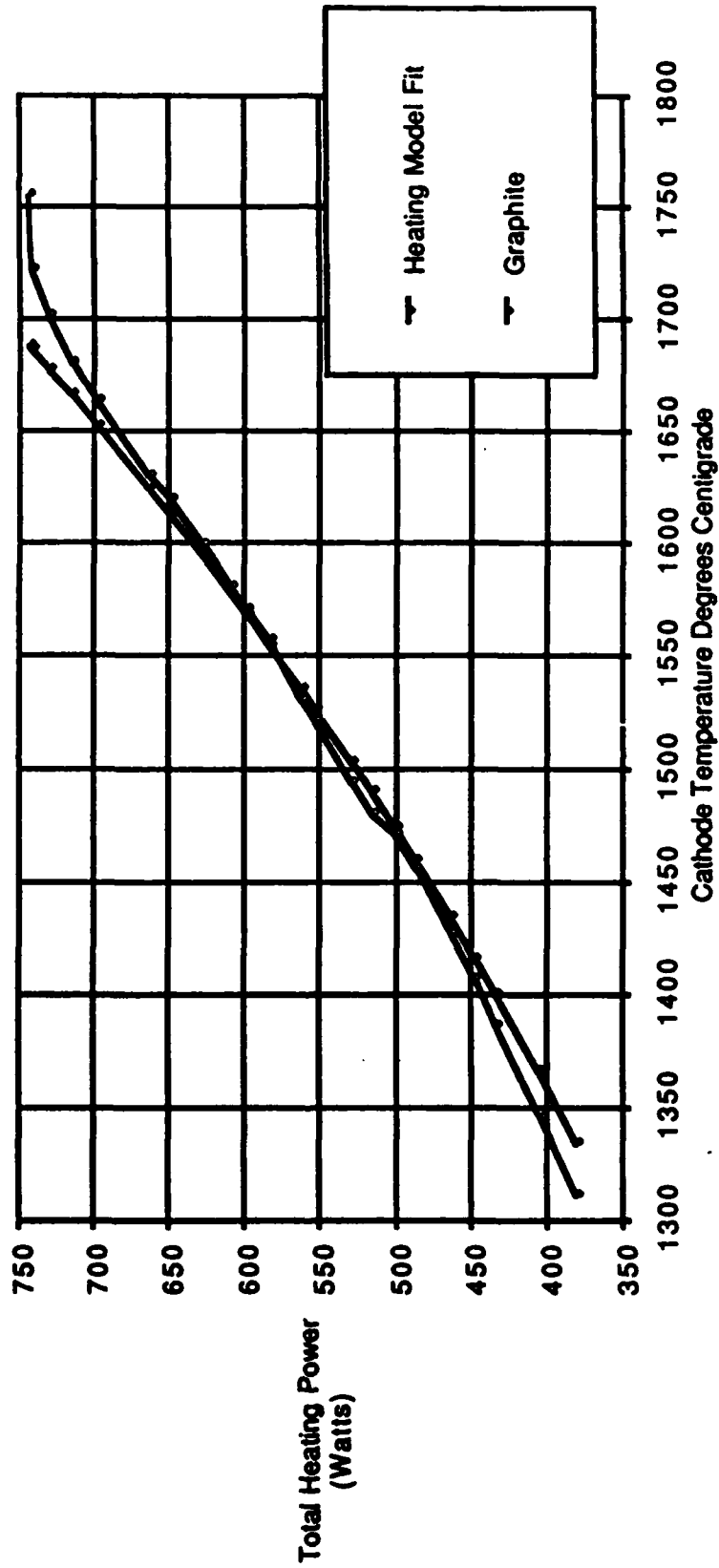


Figure 23: Heating power vs. cathode temperature.

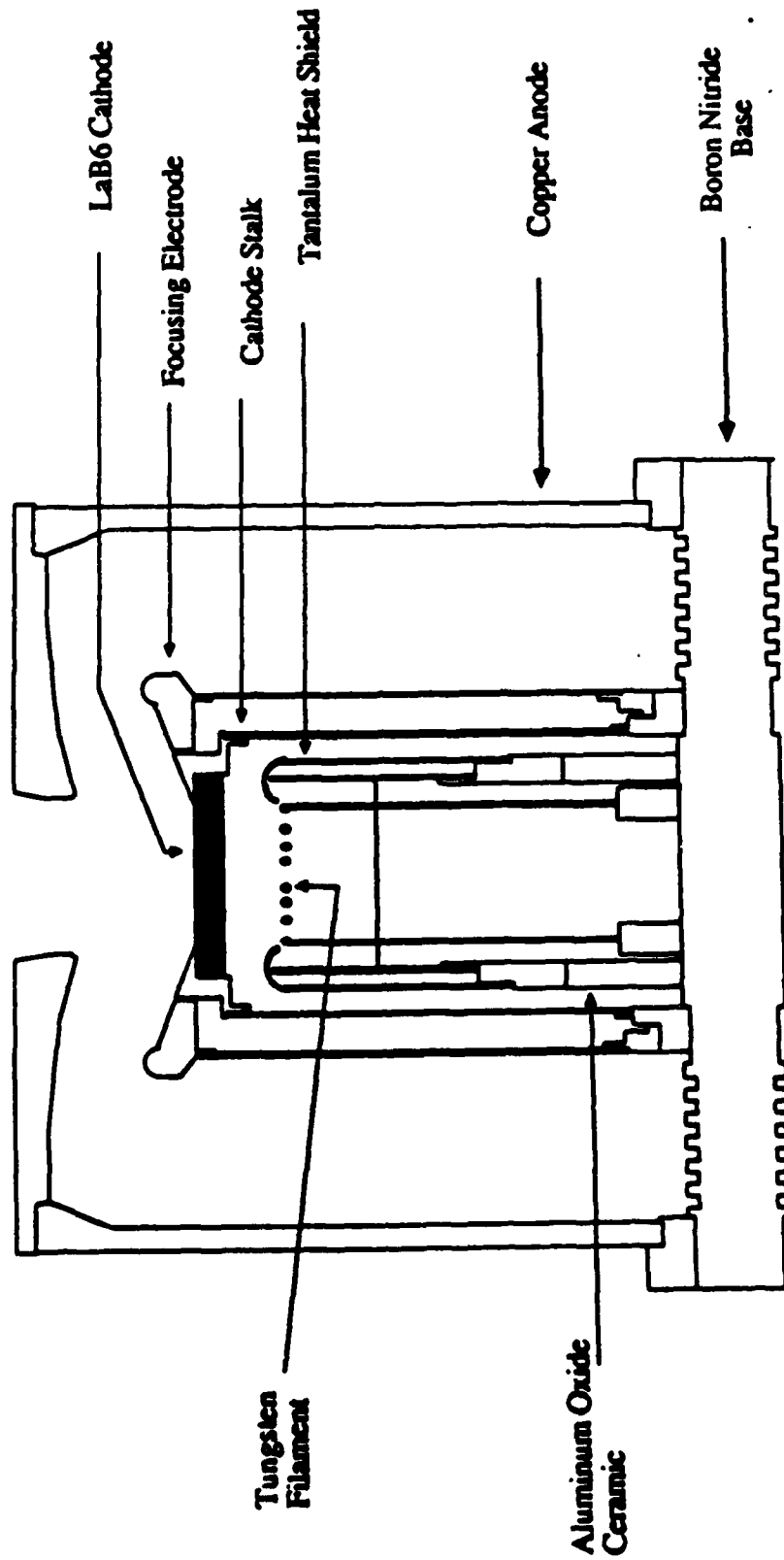


Figure 24: UM LaB6 electron gun cross section. The scale is set by the LaB6 cathode disk diameter which is 1.0 inch. The boron nitride base is grooved to prevent surface breakdown.

The second Pierce-type electron gun design is shown in Figure 24. This design was made larger than the first gun to provide more space inside the cathode stalk. The cathode diameter and Pierce electrodes are the same as in the first gun. The boron nitride base is larger and is grooved to improve its voltage standoff capability. The copper anode is water cooled. The scale of the drawing in Figure 24 is given by the cathode diameter, which is 1.0 inch.

5.2 Cathode Heating Instability Studies

The LaB_6 cathode is heated by temperature-limited electron bombardment from a tungsten filament. Temperature-limited operation reduces the dependence of the bombarding electron beam on the filament-cathode geometry, and allows control of bombardment power by control of filament power. The system is unstable because radiated power from the cathode to the filament raises the filament temperature, causing it to emit a larger current. The increased current is an increase in the bombardment power to the cathode, which raises the cathode temperature and the radiated power back toward the filament.

The control circuits stabilize the system. These circuits reduce electrical filament heating power to balance radiated power from the cathode. As noted in Section 4.3, they require the electrical filament heating power to be non-zero.

It is possible for the filament electrical power to be zero when the desired bombardment current requires the filament to operate at a temperature lower than the cathode temperature. In this case, radiation from the cathode is sufficient to heat the filament to the emission temperature. This system will be uncontrollable.

In tests of the heating system, both a LaB_6 cathode disk and a graphite disk of the same size were used. In the case of a tungsten filament bombarding a graphite disk with the objective of reaching a disk temperature of 1800°C , the filament may run several hundred degrees higher than the graphite disk. The filament may require 100 W of heating power or more to maintain this temperature difference. This system is controllable.

If a filament with a lower work function than tungsten is used, the filament temperature required for emission is reduced. The emission area of the filament becomes important. The

filament area must be reduced to require a high enough current density from the filament to force it to operate at a higher temperature than the cathode. This consideration has an effect on the design of the filament shape.

The case of a tungsten filament bombarding a LaB_6 cathode to a temperature of 1800°C may seem to be a similar case to that of the graphite disk. However, for cathode temperatures above 1600°C , evaporation of lanthanum from the cathode lowers the work function of the filament and causes the system to become uncontrollable. This system has been made controllable by using hairpin filaments with reduced area, thereby forcing the filament to run hotter to get the same emission current.

Another problem with lanthanum evaporation from the LaB_6 cathode is that metal parts inside the cathode stalk will have their work function lowered. The tantalum heat shield and molybdenum filament holders have been observed to emit current at LaB_6 cathode temperatures above 1600°C . Emission from parts other than the filament may not bombard the cathode and may make the system less efficient and uncontrollable. This problem has been solved by enclosing all parts that are inside the cathode stalk which are not intended to emit in a boron nitride heat shield.

The evaporation of lanthanum from LaB_6 cathodes was first measured by Lafferty. The evaporation rate increases rapidly above 1600°C , which is in agreement with our observation.

Lafferty also observed the activation of tungsten by evaporated lanthanum. In fact, he used this effect to measure the evaporation rate of lanthanum hexaboride.

By using a graphite "cathode," the activation effect could be stopped. A comparison of graphite and LaB_6 is given in Table 1.

5.2.1 Observation of Metal Activation by LaB_6

An indirect observation of metal thermionic activation by lanthanum was made by observing the power to the filament and the bombardment power as functions of temperature.

Filament electrical heating power and bombardment power versus cathode temperature are shown in Figures 25, 26 and 27 for both a graphite disk and LaB_6 cathode. With the LaB_6 cathode at 1620°C , the filament became activated and filament heating power was reduced by

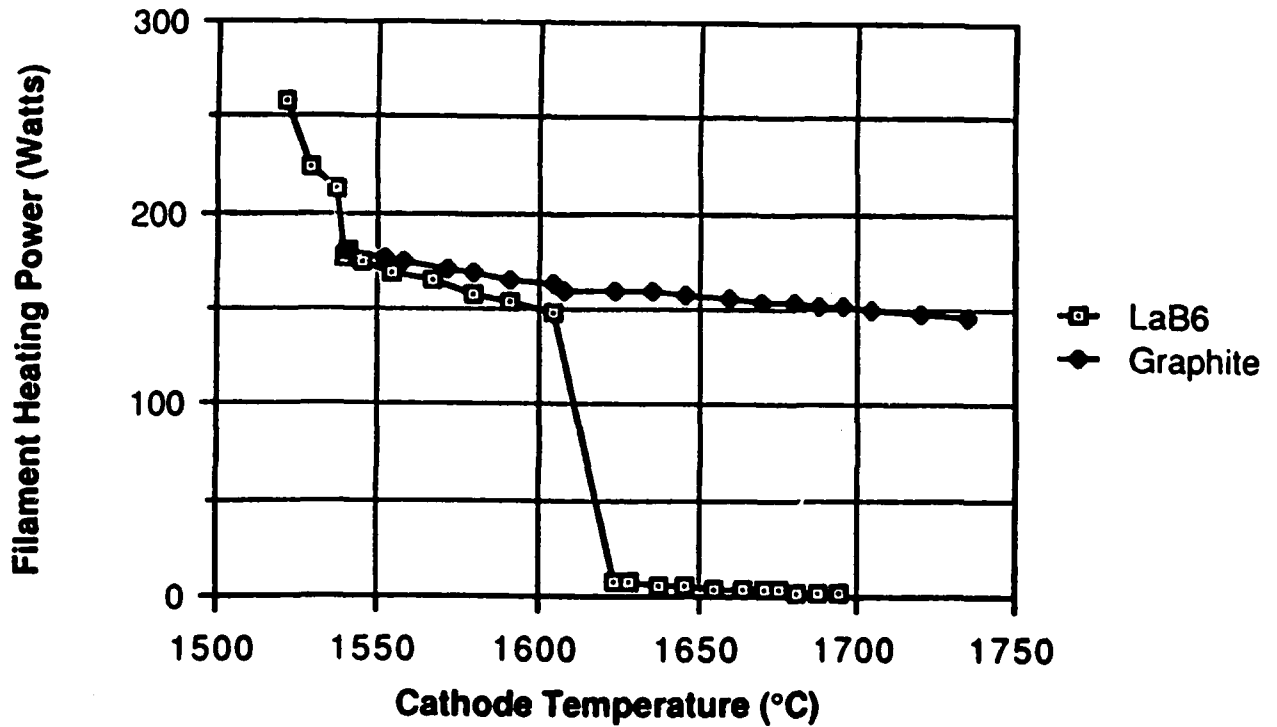


Figure 25: Measured curves of filament heating power as a function of temperature for a LaB₆ cathode and a "fake cathode" graphite disk. Filament power tends to decrease because back radiation from the cathode is substituted for electrical heating power. When the LaB₆ activates the filament in the 1600-1620°C range, essentially zero electrical power is required.

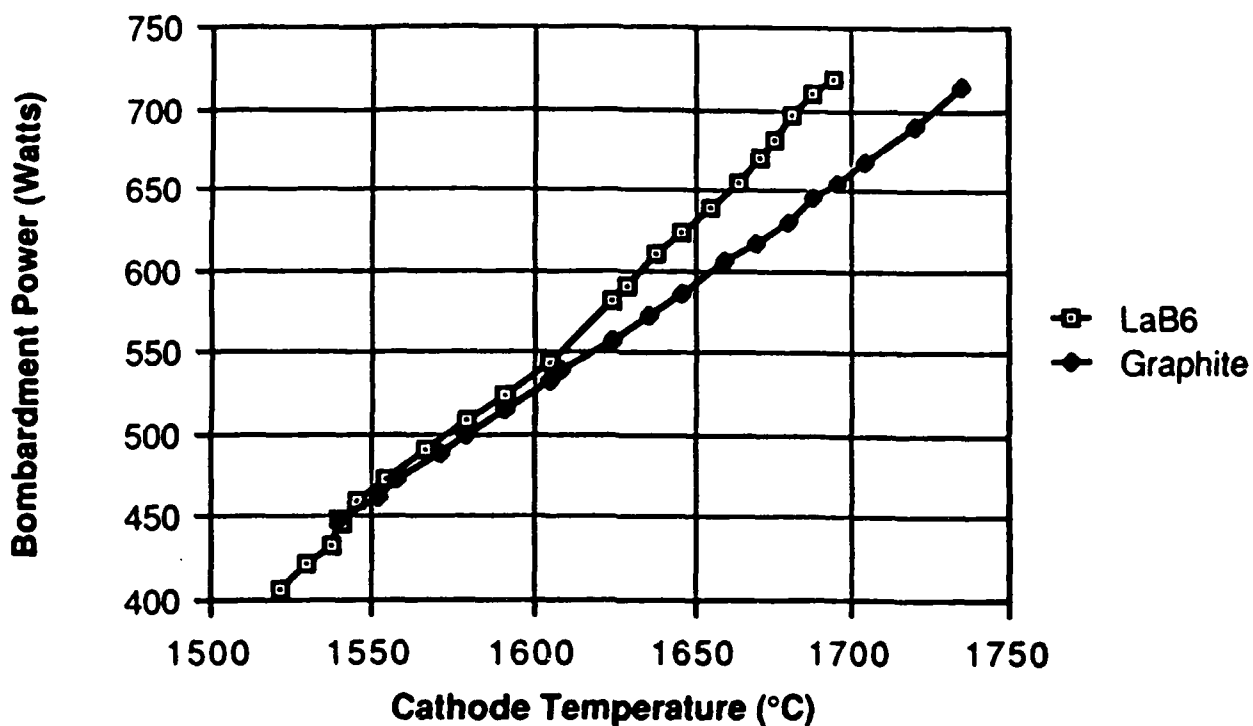


Figure 26: Measured total power as a function of temperature.

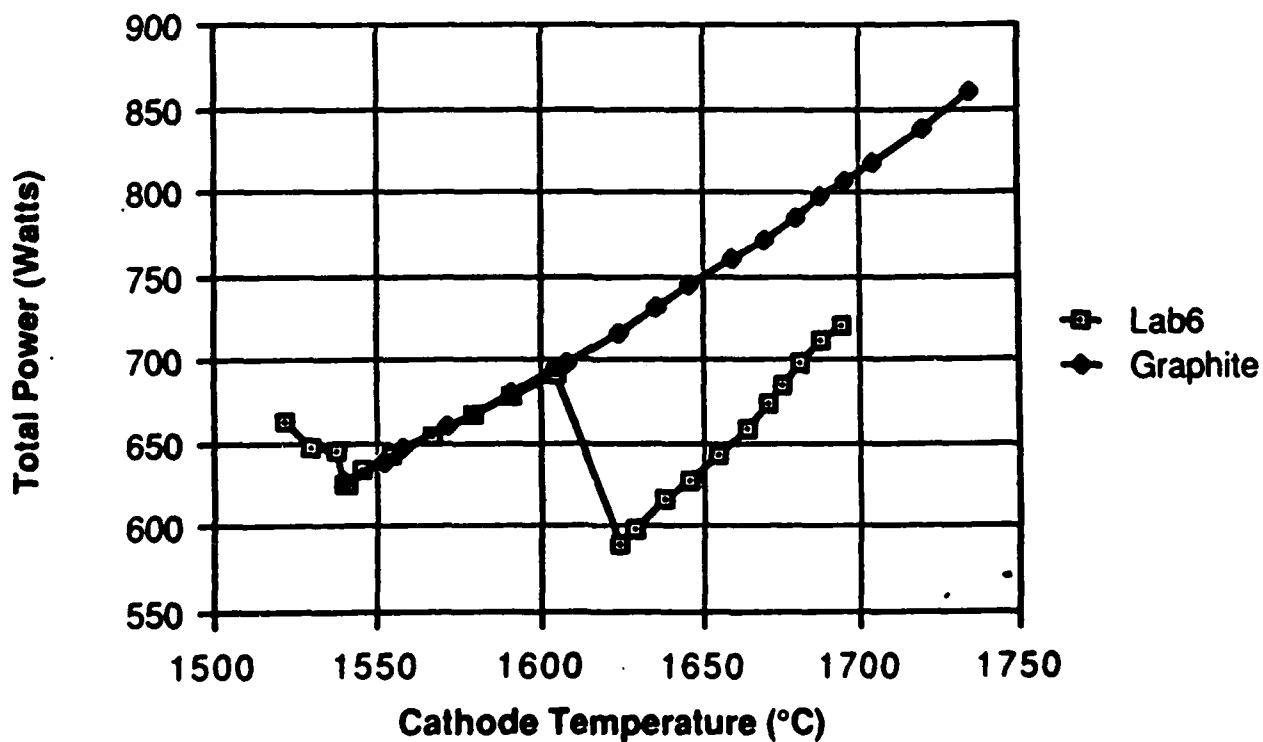


Figure 27: Measured total power (filament plus bombardment) as a function of temperature.

almost 140 W as shown in Figure 25. At temperatures above 1620°C, filament power was reduced by the controller to eliminate the instability. When the filament power was reduced to zero, the system became unstable. When the graphite disk was used in place of the LaB₆, the activation did not take place and the power decreased slowly, as shown in Figure 25.

The bombardment power is plotted in Figure 26 for the two cases. At 1600°C, the bombardment power starts to increase more rapidly in the case of the LaB₆ cathode. This is because activation by LaB₆ reduces the filament power requirement to zero and the difference in

TABLE 1
UM LaB₆ Electron Gun Cathode Heating Results

	<u>LaB₆ Cathode</u>	<u>Graphite "Cathode"</u>
Highest Cathode Temperature	1800°C	1756°C
Bombardment Power	756 W.	739 W.
Filament Heating Power	2 W.	147 W.
Total Power	758 W.	886 W.

radiation power to the cathode must be made up by increasing the bombardment power. Figure 27 shows the total power and the decrease due to activation in the LaB₆ case. As the temperature increases, the total power requirement increases and filament power tends to become a relatively small part of the total. Consequently, the two curves in Figure 27 tend to approach each other at high temperatures.

Note that the filament power is only 2 W in Table 1 when the LaB₆ cathode is used. The system is marginally stable in this condition.

The digital data acquisition system can be used to record a time history of the activation process over the 25-30 minute cycle time of the process. Figure 28(a) shows a typical record. The bombardment current is plotted at the top and increases in the downward direction. The cathode temperature is plotted at the bottom. The total trade time is 25 minutes. The LaB₆ cathode is

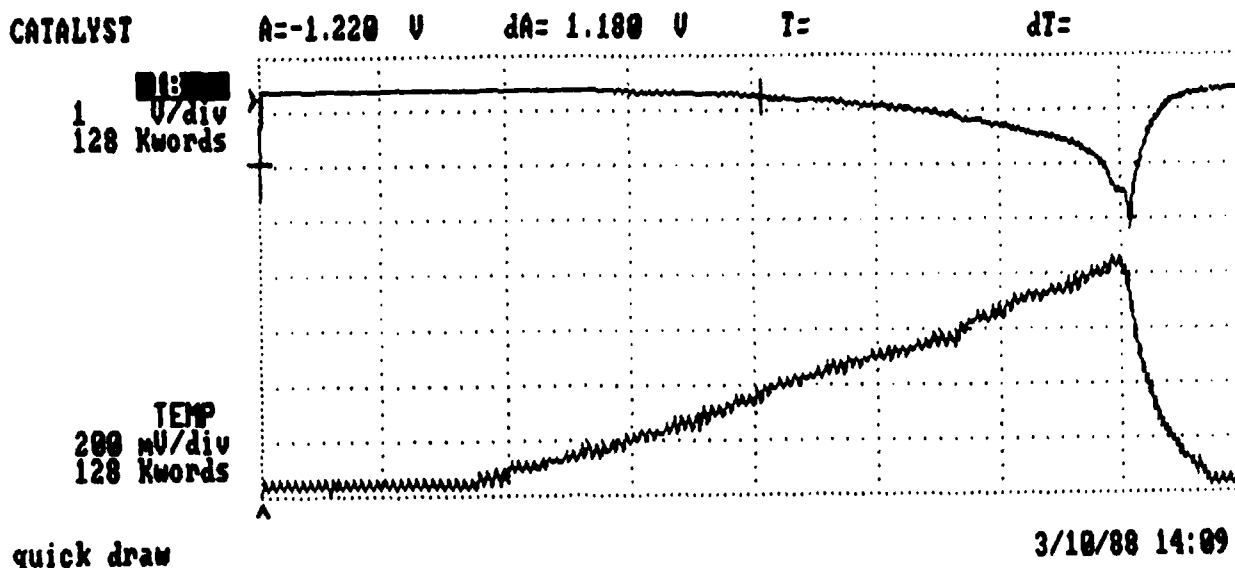
bombarded with electrons from a relatively large tungsten filament. At a cathode temperature 1550°C (just below the peak in Figure 28(a)), evaporation of lanthanum from the cathode activates the filament causing it to emit a large current. The system shuts off and the cathode cools.

Figure 28(b) shown a blow-up of the peak temperature region in Figure 28(a). It can be seen that the bombardment current reaches the control set point and is held constant by the control circuit. During this time, the filament becomes activated and the controller reduces the filament power to compensate for increased emission due to a lower work function. Eventually the filament power is reduced to zero and the system becomes uncontrollable. The bombardment current increases rapidly and then the system shuts off. The cathode temperature is 1557°C at the time of the runaway.

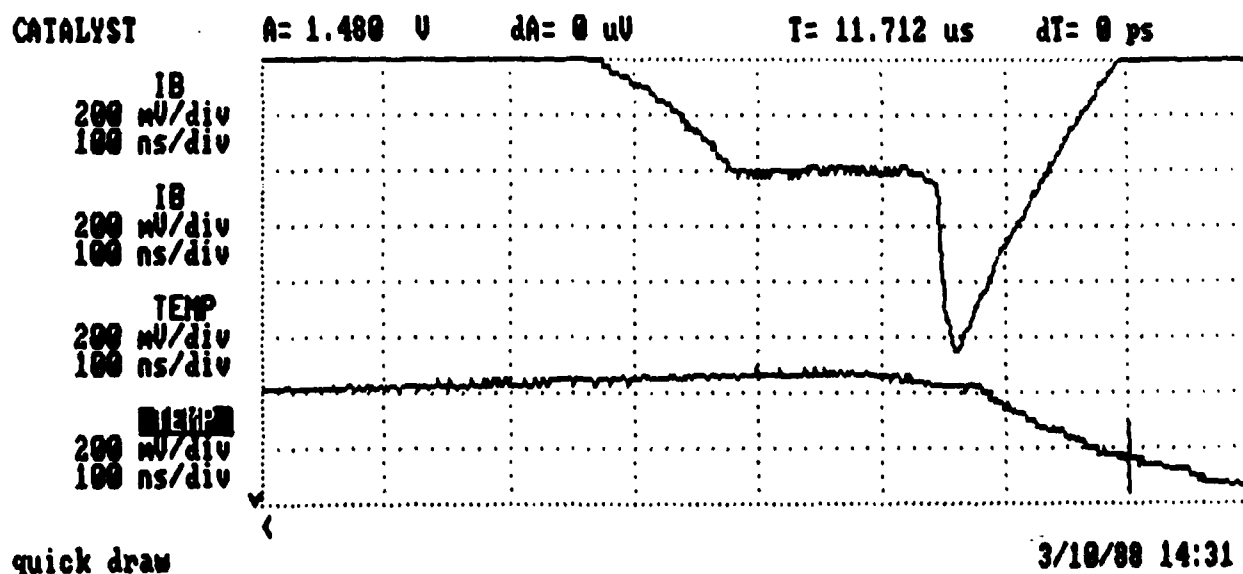
Figure 29(a) shows the initial surge in bombardment current when the system is first turned on because of a residual coating of lanthanum on the filament. After a few minutes, the lanthanum burns off and the filament emits like an ordinary tungsten filament. The trace in Figure 29(a) was taken an hour after that in Figure 28(a).

Figure 29(b) is a similar situation to that in Figure 29(a), except the bombardment voltage is set a little higher. When the filament becomes activated, there is so much radiated power from the cathode onto the filament that the control circuit cannot stabilize the system even for a short time as in Figure 28(b), and the bombardment current runs away. The initial surge also occurs in Figure 29(b) due to residual activation. The runaway occurs at a temperature of approximately 1550°C.

By reducing the filament area, a higher filament temperature can be forced and the system will be controllable for higher cathode temperatures. The difficulty found with hairpin filaments was that bombardment power was too concentrated and the cathode was heated nonuniformly.



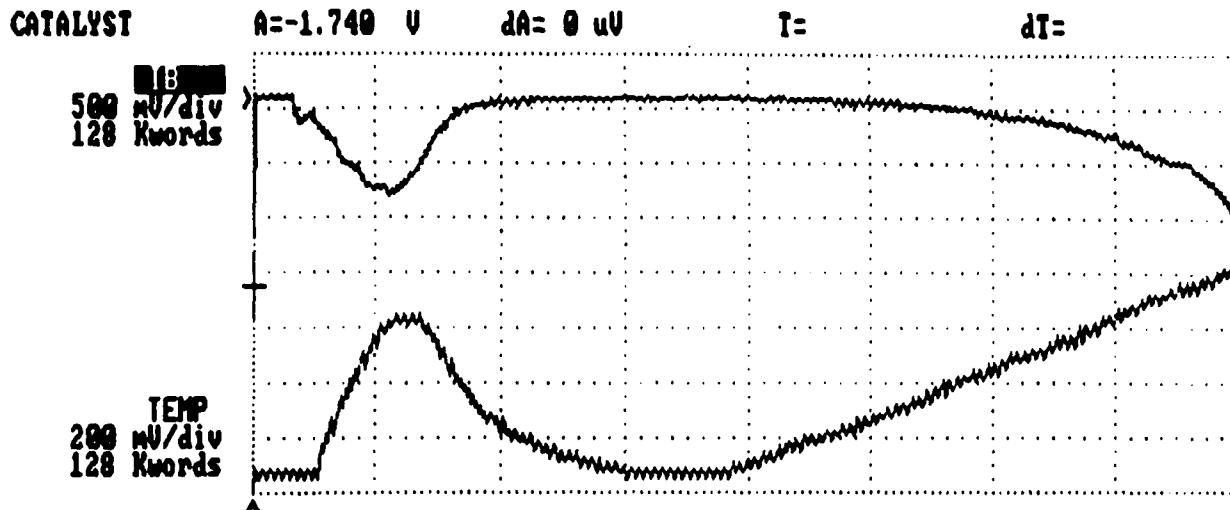
(a)



(b)

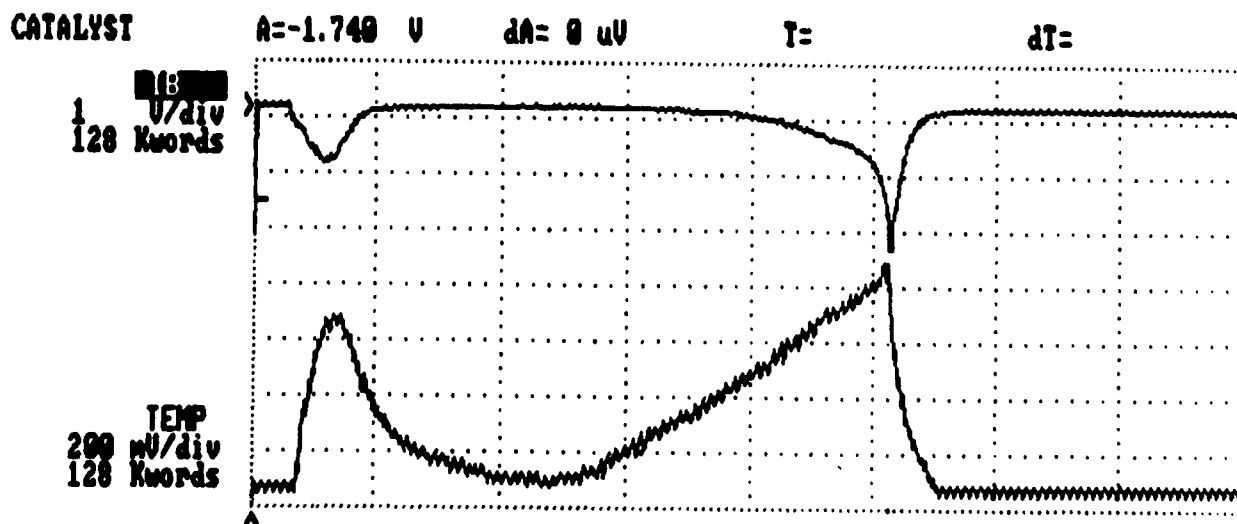
Figure 28(a): Bombardment current (top curve) and cathode temperature (bottom curve) as functions of time. The time scale is 3.125 minutes/div. The vertical scale for current is 250 mA/div and zero circuit is at the ">" mark near the top grid line. Current increases in the downward direction. The temperature curve scale is 200°C/div but it has an offset so the zero temperature line is not shown.

(b): Blown up plot of Figure 28(a) near the temperature peak. The current scale is 50 mA/div and the baseline of the curve is offset. The time scale is 0.8 seconds/div.



quick draw 3/10/88 14:36
 $V_b = (80/130) \times 1800 \text{ Vrms}$. Trace start at 12:43, Peak at 11.5 W Filament power.
 Vacuum < 10^{-7} Torr. ITrace not complete. Stored in temp2.dat, temp1.dat

(a)



quick draw

3/10/88 14:40

(b)

Figure 29(a): An initial surge of bombardment current due to a coating of lanthanum on the filament. This trace was taken one hour after that in Figure 28(a). The current scale (top trace) is 125 mA/div. The temperature scale (bottom trace) is 200°C/div . The time scale is 3.875 minutes/div.

(b): Same effect observed at a slightly higher bombardment voltage than that in Figure 28(a). In this case, the current runs away because of re-activation of the tungsten by lanthanum.

5.2.2 Heat Shield and Filament Design

Several heat shield designs were constructed in an attempt to eliminate emission from components inside the cathode stalk. Tantalum, tungsten, and molybdenum metal would become activated by lanthanum evaporating from the cathode. The original setup of heat shields is shown in Figure 24.

With the arrangement of Figure 24, a "cathode" temperature of 1800°C was achieved with a graphite disk in place of the LaB₆ cathode. Even with graphite, it was found that at 1800°C, the outer heat shield would become an emitter. The rounded upper portion of the outer shield has a large area which "sees" the cathode clearly and becomes hot enough to emit a substantial current. At cathode temperatures in the 1800°C range, the rounded part of the shield was hot enough to emit even without lanthanum activation (although it may have retained some activation from previous exposure to LaB₆). When used with a LaB₆ cathode, it was an excellent emitter after activation.

After extensive trials, the best way to suppress activation by evaporated LaB₆ was found to be a graphite cup holder for the cathode.

The lanthanum evaporation was controlled but not completely eliminated by placing the LaB₆ disk in a small graphite cup. The bombardment filament "sees" only the graphite cup. This arrangement increases the amount of bombardment power required because of poor thermal transfer across the graphite-LaB₆ interface, but not enough to preclude the use of the cup. The total power required with the graphite cup in place was 955 W, which is 26 percent higher than the power required for the plain LaB₆ cathode as given in Table 1. The graphite cup has a disadvantage in that enough graphite evaporates to cause a nuisance inside the cathode-filament region. A graphite cup is presently in use and eliminates filament activation. The present gun and heat shield is shown in Figure 30. Details of the heat shield are given in Figure 31.

5.2.3 Control Circuit

The second Pierce gun was initially used with a digital circuit to gate a MOSFET switch in the filament circuit, thus providing chopper control of filament current. The MOSFET switch is shown in Figure 32. The logic diagram of the complete system is shown in Figure 33. Basically,

one cycle of the desired waveform for the bombardment current is digitized and stored in memory. The stored waveform at a given sample time is compared to a digitized sample of the real-time waveform. If the real-time sample is less than the stored sample, the MOSFET is turned on to increase the filament temperature and provide more bombardment current. If the real-time sample is greater than the stored sample, the MOSFET is turned off to decrease the filament temperature. The circuit can make up to 1000 comparisons during each 60-Hz cycle. It was found to be necessary to use a fast chopper because the triac control of Figure 3 was too slow.

The digital controller is interfaced to the vacuum gauge controller to provide automatic warm up while outgassing a new cathode after making changes in the electron gun. The automatic warm-up circuit is shown in Figure 34.

5.3 Other System Components

5.3.1 Isolation System

Bombardment and filament power is supplied to the electron gun through an inductive isolation system shown in Figure 35. This system uses three 120-kV isolation inductors that are large enough to prevent appreciable current from flowing during a 16- μ s pulse. A large number of MOV (varistor) elements are used to suppress transient spikes. The Marx generator connection is at the lower right in Figure 35.

5.3.2 Marx Generator Operation

The 3-stage or 4-stage Marx generator operates up to 120 kV into a 1000 ohm dummy load without a crowbar. Three stages are used when it is desired to operate in the 75 kV to 90 kV range.

A 120-kV vacuum feedthrough was designed and fabricated. It is designed along the lines of a cathode stalk as used in REB machines, and its perfection was an important step toward the use of the thermionic cathode up to 120 kV. A sketch of the system is shown in Figure 36. A 4-inch inside diameter, 12-inch long Pyrex tube is used to provide the basic insulation. The cathode connection and two filament leads are inside centered within the Pyrex tube. the two filament leads are inside a stainless steel tube that provides the cathode connection and carries the

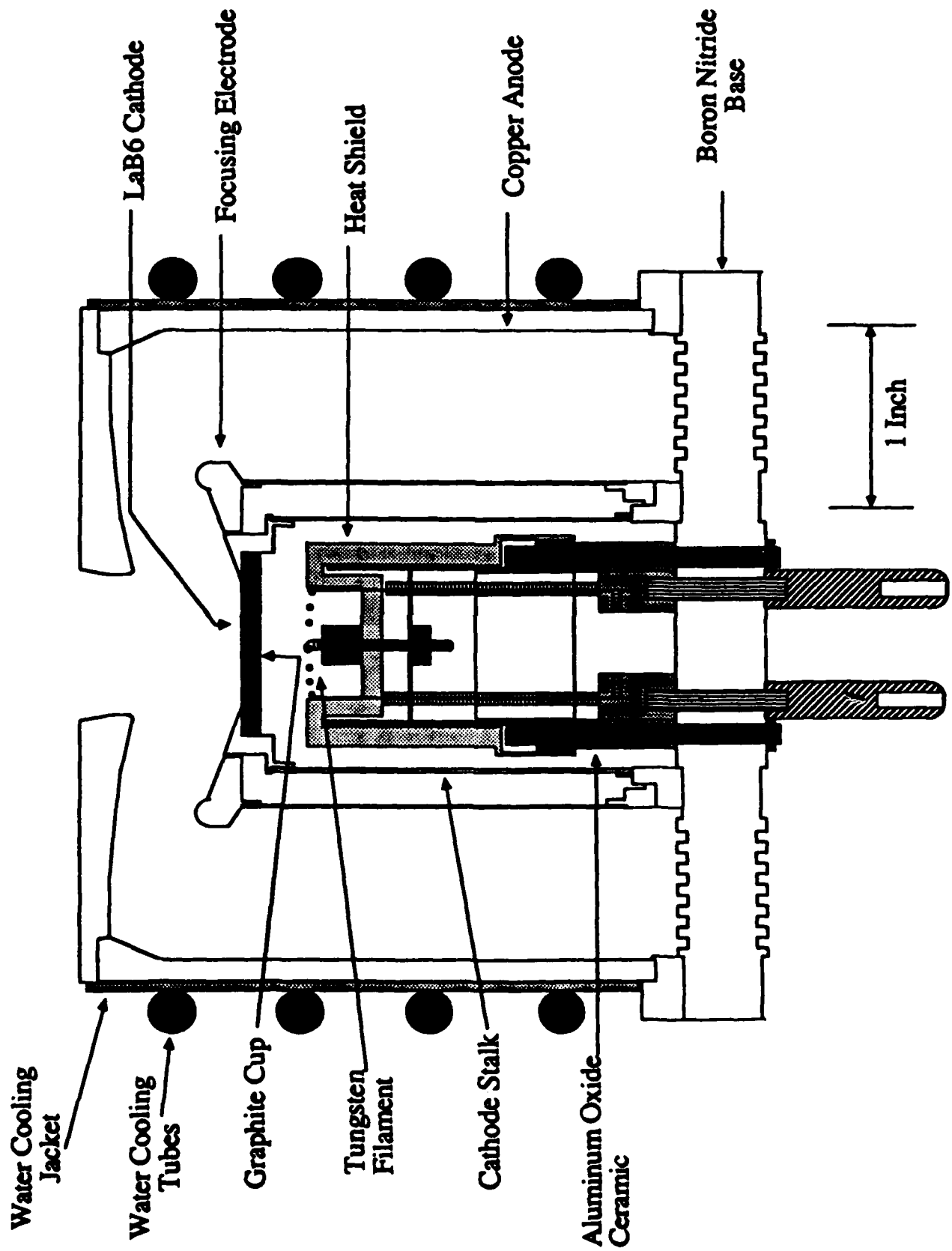


Figure 30: UM LaB6 Electron Gun.

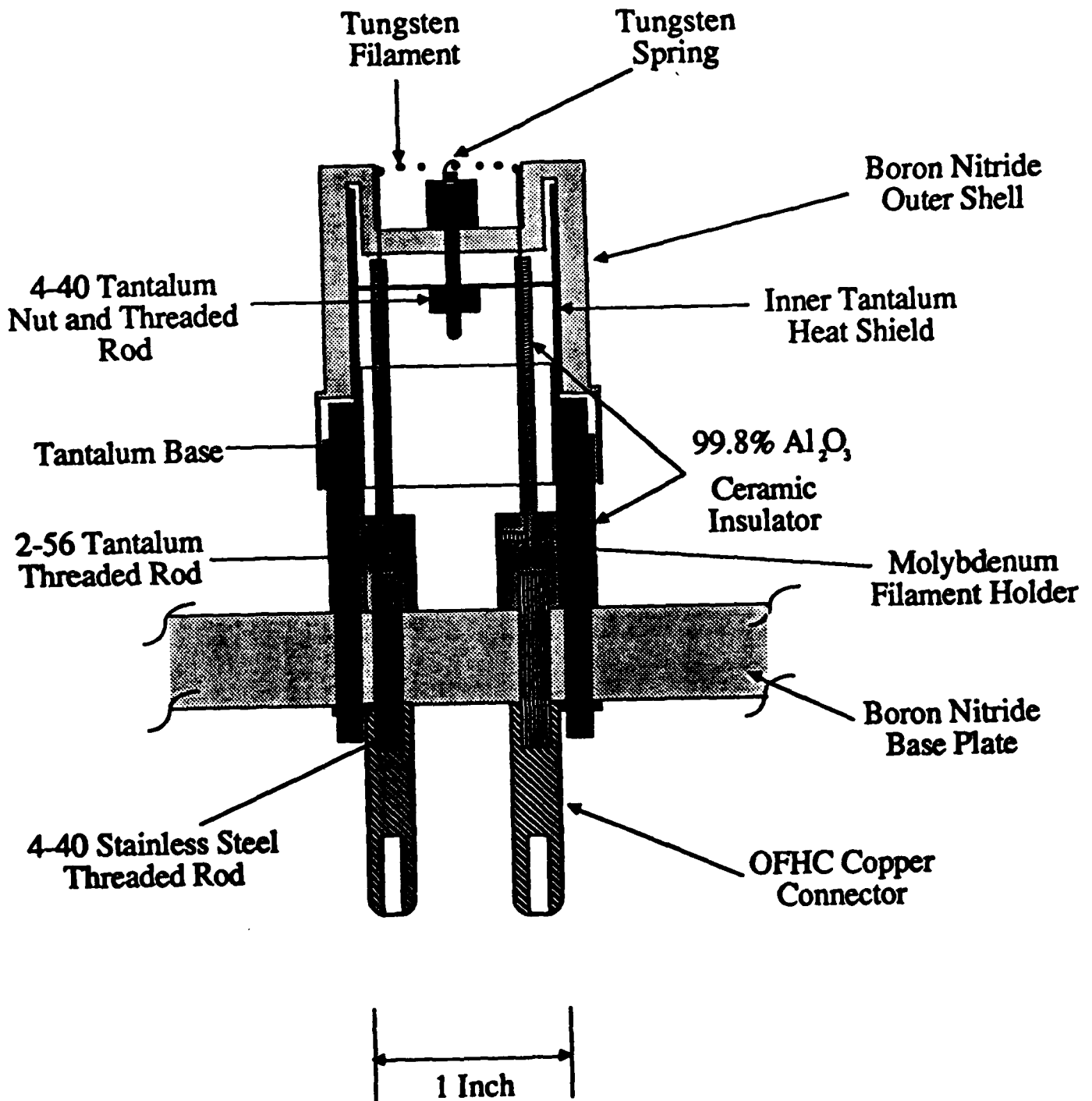


Figure 31: Heat shield assembly.

MOSFET control

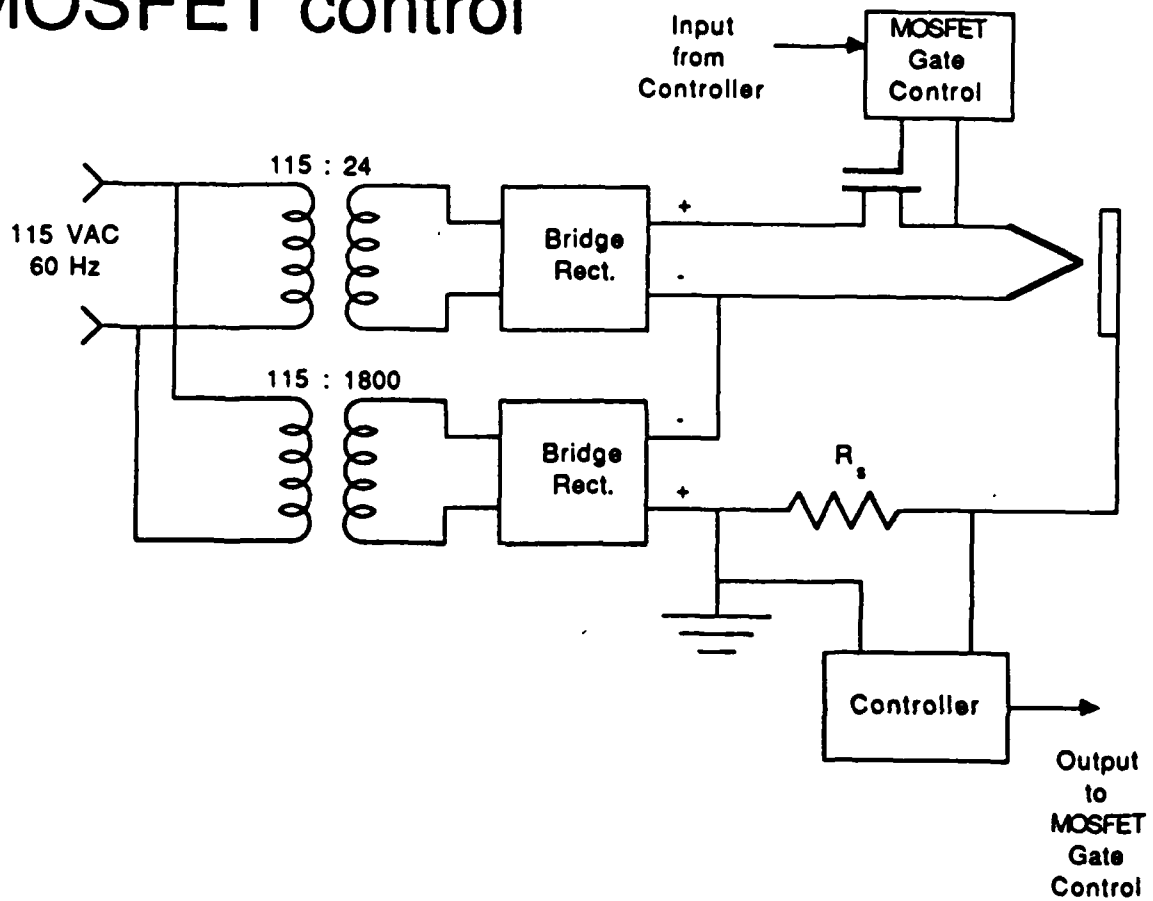


Figure 32: Second bombardment control system with power MOSFET used for chopper control of filament current.

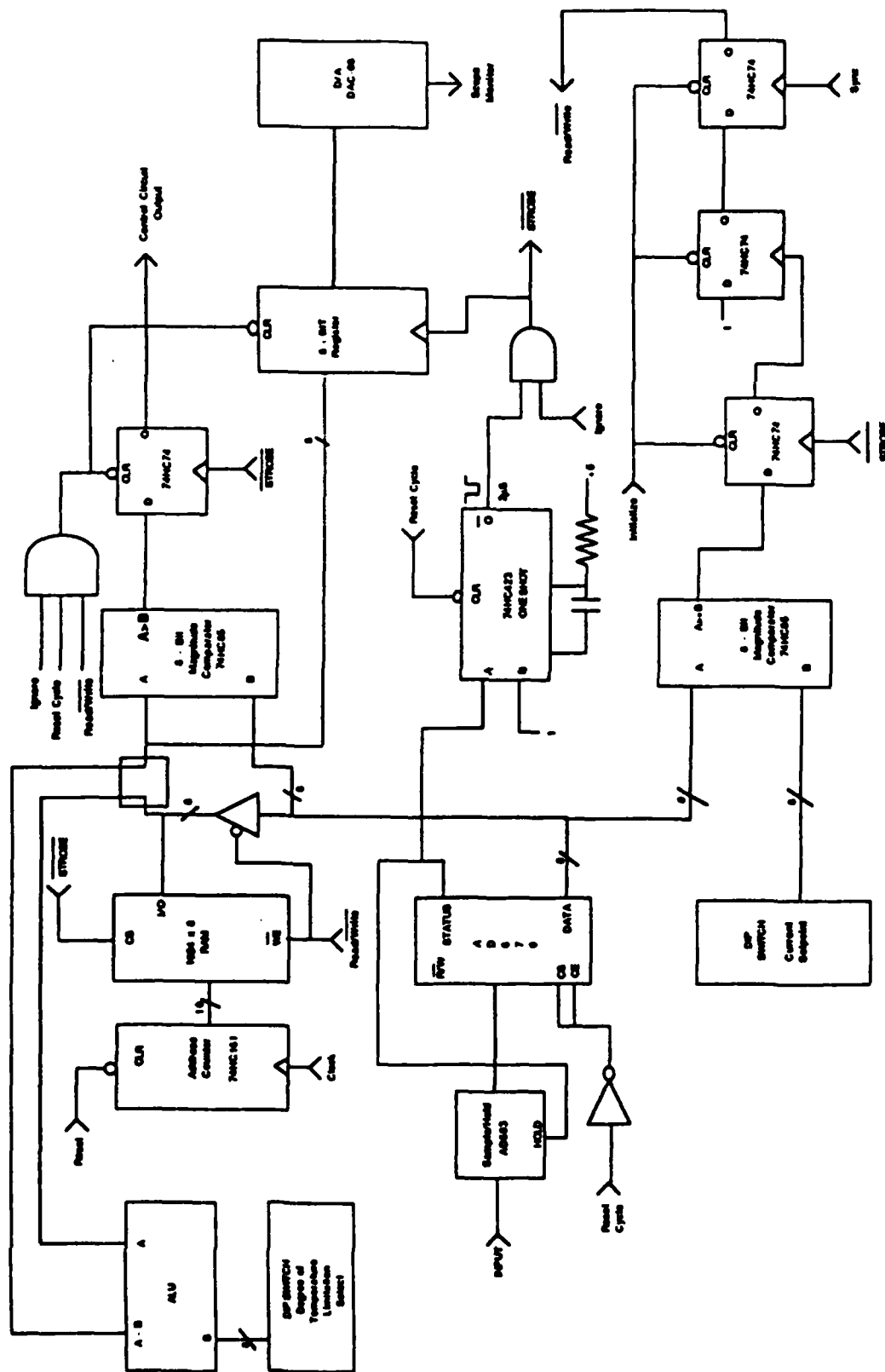


Figure 33: Digital control circuit logic diagram.

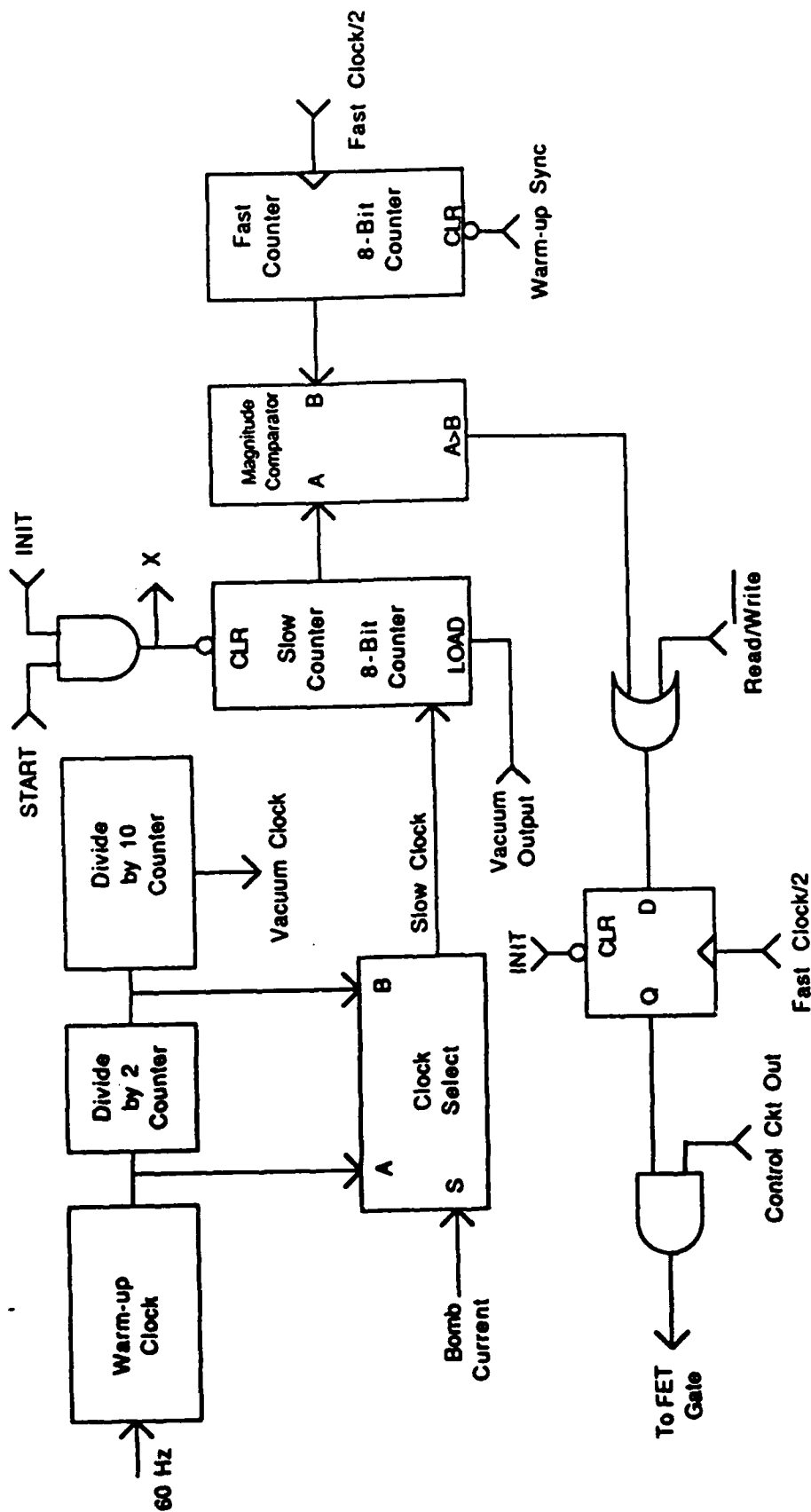


Figure 34: Digital controller interface to the ionization gauge and MOSFET. This feature allows the operator to automatically heat the cathode slowly while keeping the system pressure below some pre-set limit.

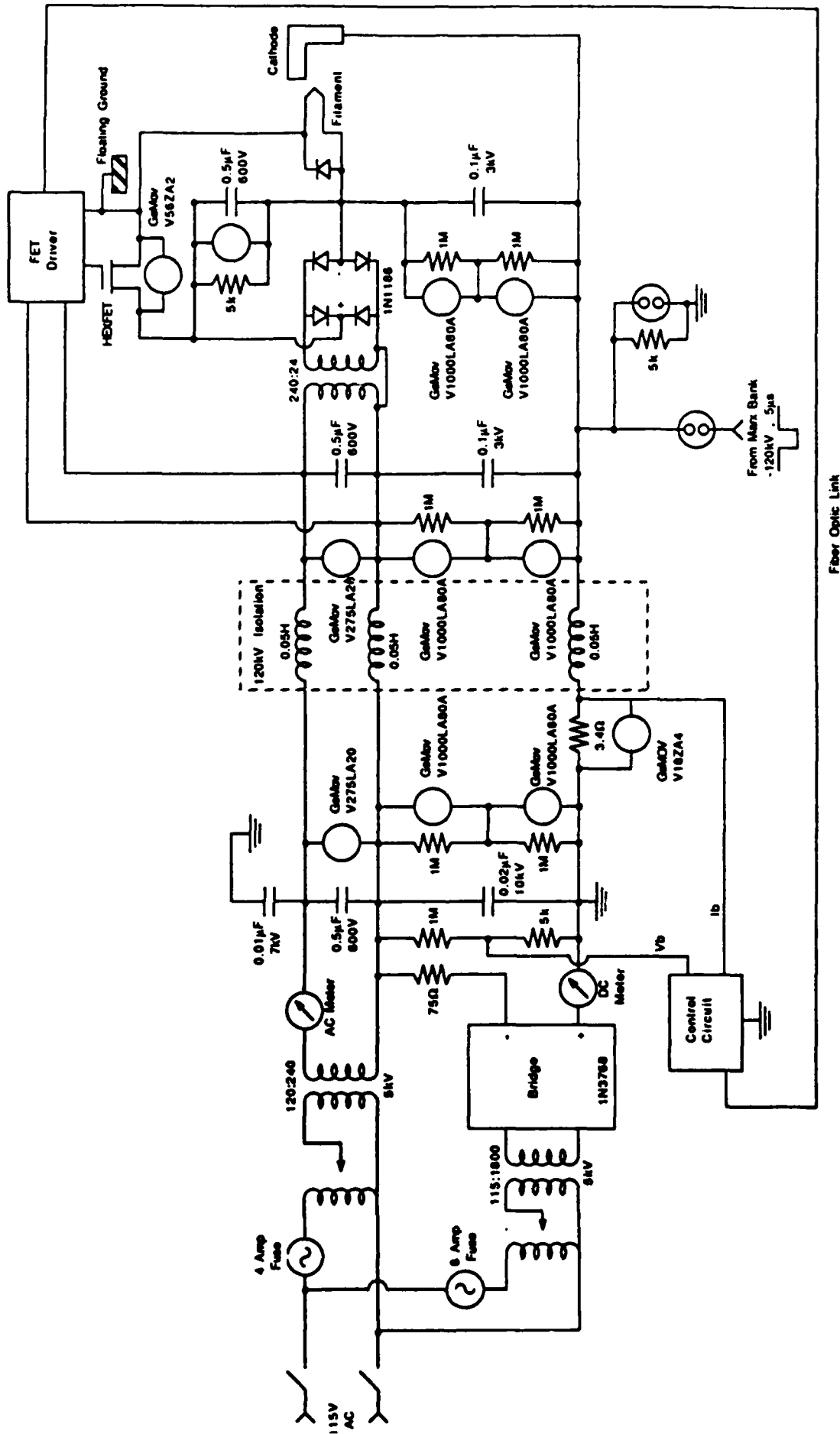


Figure 35: Heating and isolation system schematic. The basic high-voltage isolation of the cathode heating circuit is provided by the three 120 kV isolation inductors.

cathode voltage to the gun. The diameter of the tube was chosen to minimize electric field gradients.

5.3.3 Data Acquisition System

The data presented in this report were obtained with a LeCroy/Catalyst digital data acquisition system. This system contains two fast channels for recording the instantaneous beam voltage and current, and 32 slow channels for recording various 60-Hz signals in the bombardment heating system. This data acquisition system has proven to be invaluable for analyzing the bombardment system.

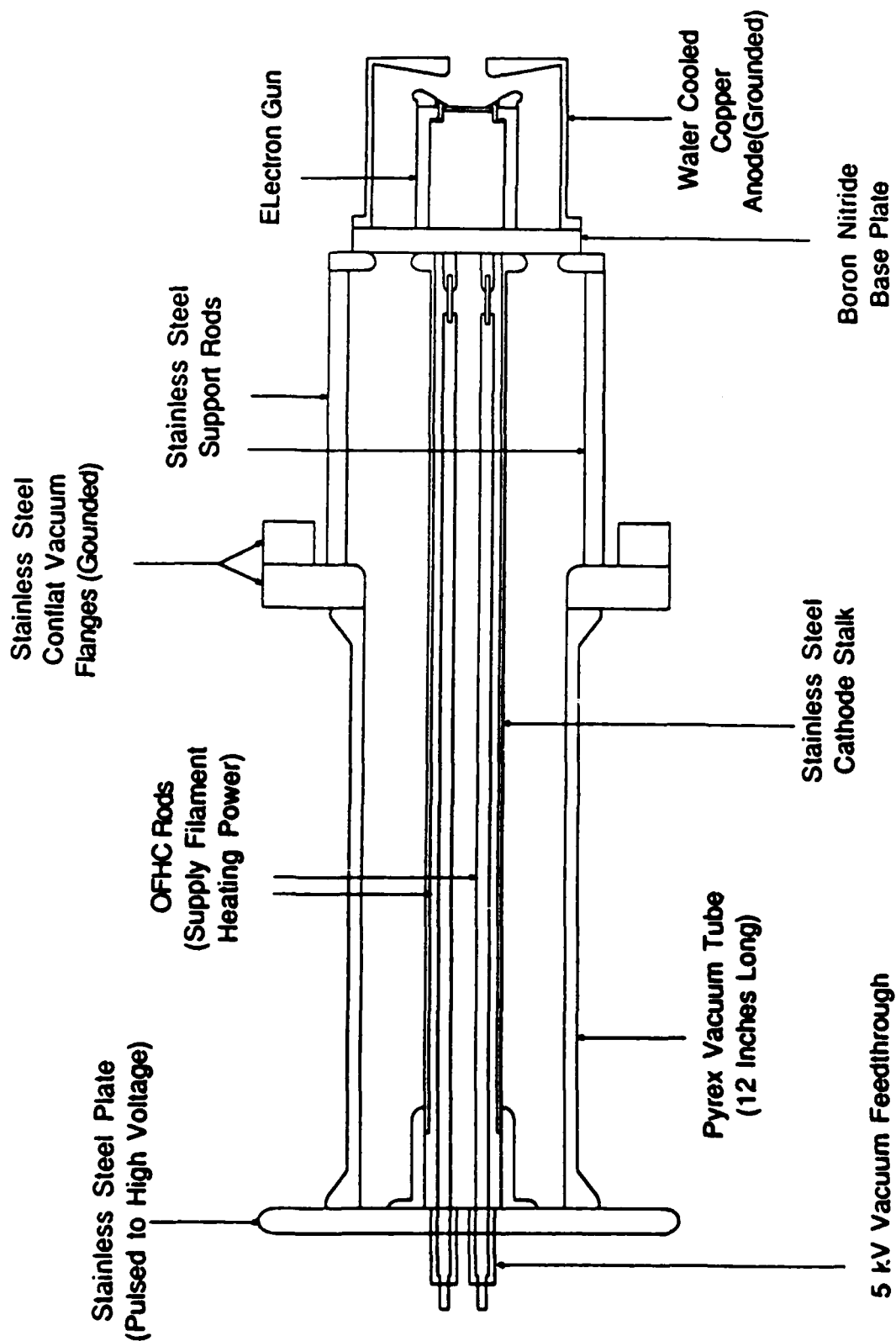


Figure 36: New 120 kV cathode insulation system. Insulation is provided by a 12 inch long, 4 inch diameter pyrex tube. This system has been tested to 100 kV thus far, and it is felt that it can reach 120 kV with additional conditioning.

6. HIGH VOLTAGE OPERATION OF SECOND PIERCE GUN

6.1 Voltage and Current Time Variation

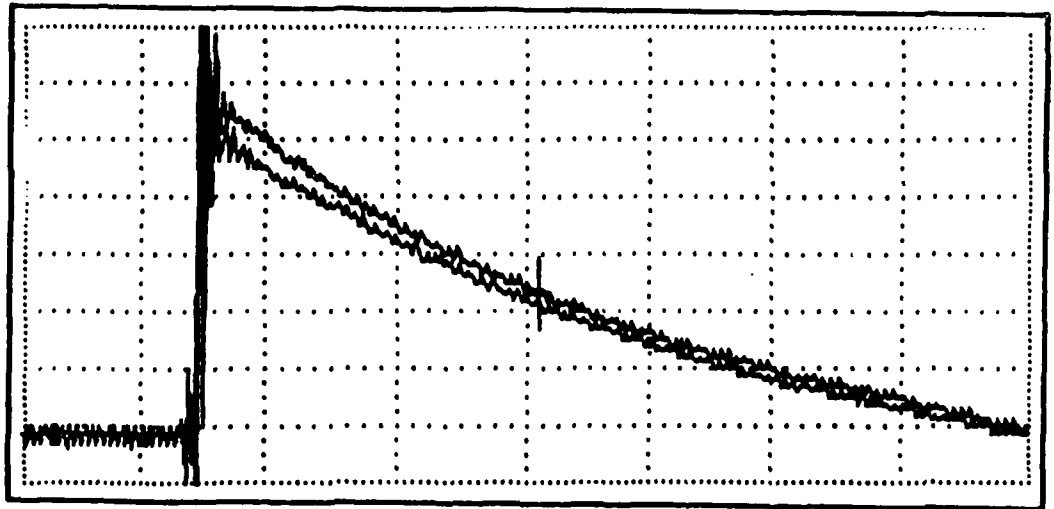
The second Pierce gun with heat shield and graphite cathode holder was operated up to 115 kV peak pulse voltage. The transmitted current (through the anode hole) was 90 A, corresponding to a cathode current density of 30 A/cm² (assuming 100% transmission) and a beam power density at the anode hole of 3.4 MW/cm². Operation at this voltage level was limited by gun breakdown, and only about 10-20% of the shots did not arc.

The gun operated reliably with no arcing up to 90 kV. Typical values for this voltage range were transmitted current of 75 A and anode hole power density of 2 MW/cm². Anode transmission was very good at all voltages. Examples of gun (cathode) current and transmitted current are shown in Figure 37 for operation at 90 kV. The beam pulse is not crowbarred. At the higher temperature shown in Figure 37, there is emission from the cathode molybdenum holder because of coating by evaporated LaB₆. The portion of the beam from this holder strikes the anode and causes gas evolution, leading to anode-cathode gap closure. Other examples of transmitted and cathode currents are shown in Figures 38 and 39. The latter figure shows A-K gap closure at $\approx 8\mu\text{s}$. The transmission as a function of cathode temperature is shown in Figure 40. As soon as the temperature exceeds 1600°C, LaB₆ evaporation becomes significant and the cathode holder emits, giving lower transmission. The SLAC code was used to verify that electrons from the cathode holder intercepted the anode.

Examples of current and voltage traces at high voltage operation are given in Figures 41, 42, and 43. Figure 41 shows a very clean example with a peak voltage of approximately 95 kV and a peak current of 50 A. The cathode temperature is 1621°C and it is temperature limited. Figures 42 and 43 show examples at the highest voltage achieved. The signals are noisy because the A-K gap is on the verge of breakdown, and only 10-20% of the shots do not arc. In Figure 42, the peak transmitted current is 79 A at a beam voltage of 116 kV at the time of 1.4 μs , giving a power density at the anode aperture of 3 MW/cm². Figure 43 shows a current of 89 A and a voltage of 115 kV at 1.4 μs , giving a beam power density of 3.4 MW/cm².

Gun Current
10 A/div

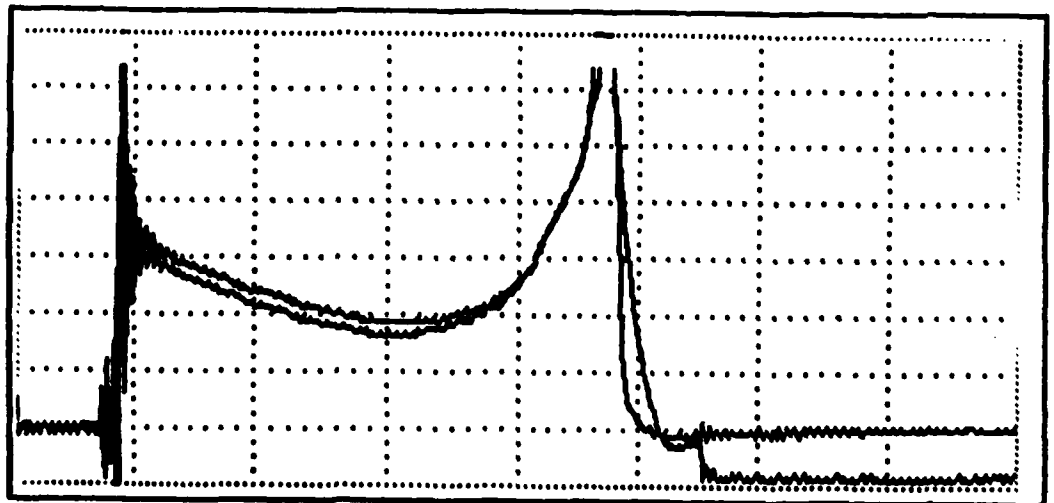
Transmitted
Current
10 A/div



Time 5 μ Sec/div
Cathode Temperature ≈ 1650 $^{\circ}$ C

Gun Current
20 A/div

Transmitted
Current
20 A/div



Time 5 μ Sec/div
Cathode Temperature ≈ 1700 $^{\circ}$ C

Figure 37: Peak gun voltage = 90 kV

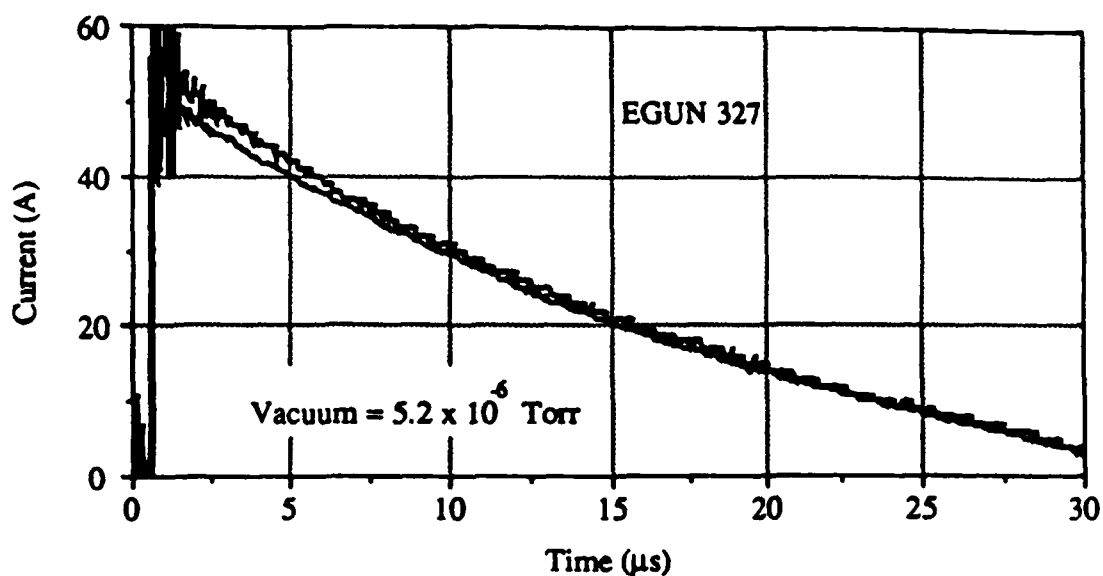


Figure 38: Electron gun total current and transmitted current traces at 1621°C. This shot is the companion shot to EGUN325.

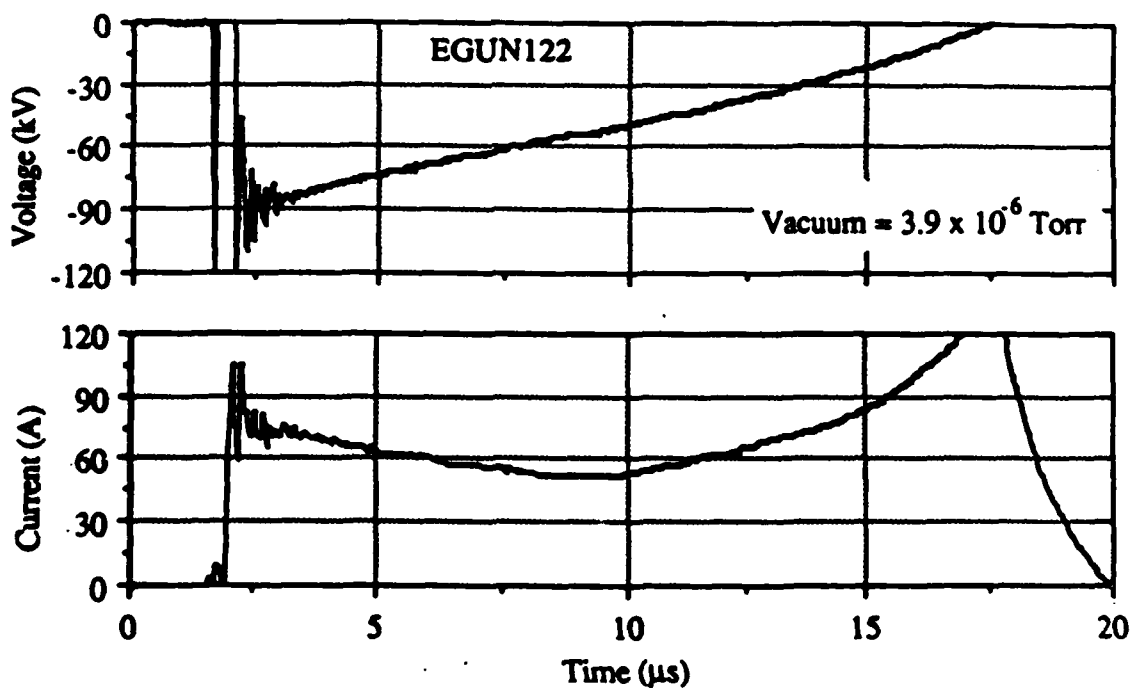


Figure 39: Electron gun voltage and total current traces at 1653°C.

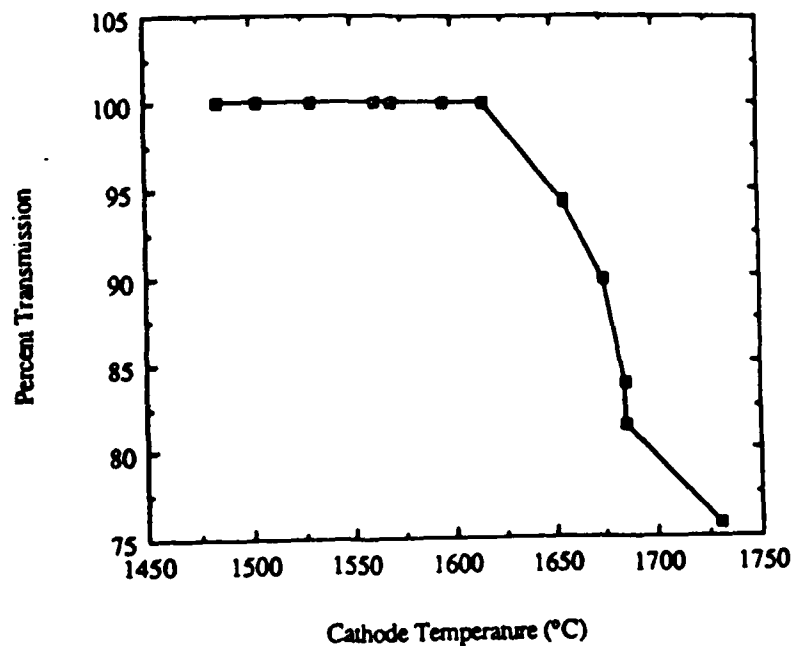


Figure 40: Electron beam percent transmission as a function of temperature.

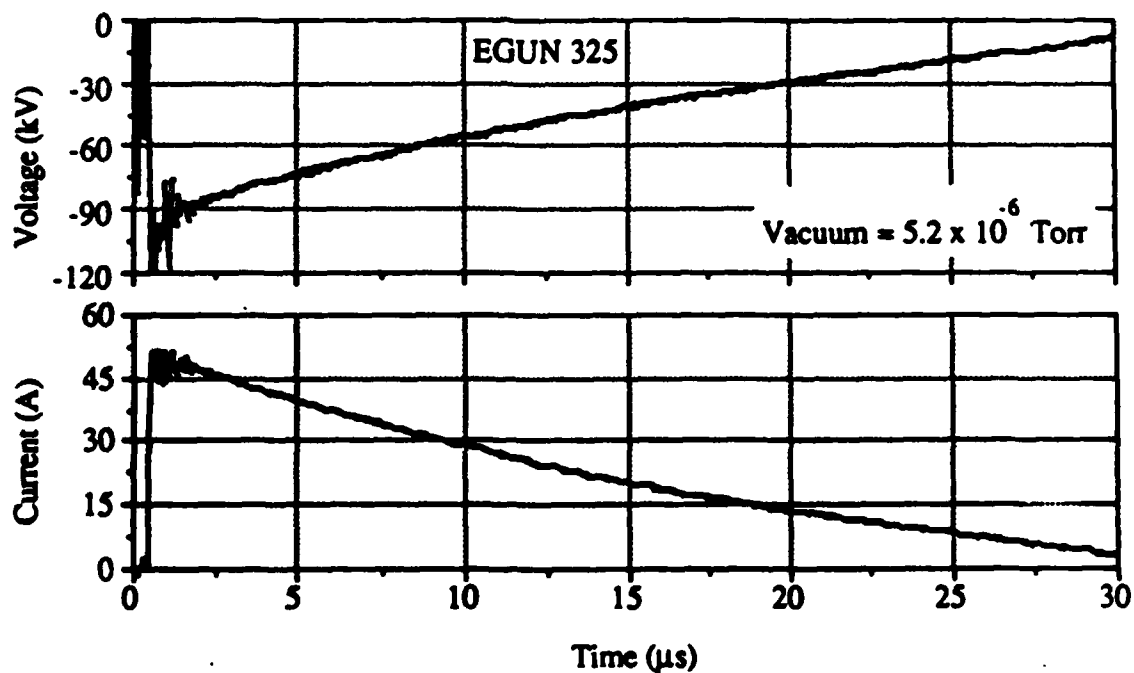


Figure 41: Electron gun voltage and transmitted current traces at 1621°C.

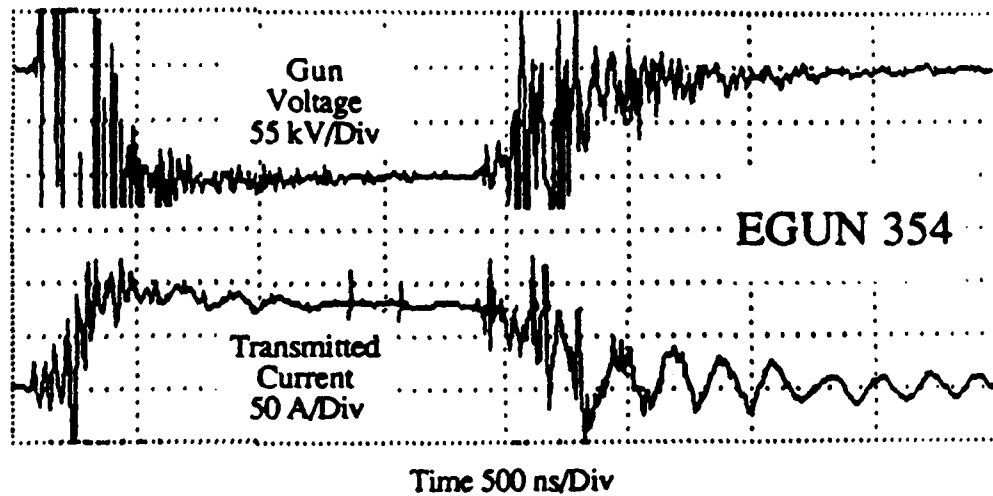


Figure 42: Electron gun voltage and transmitted current traces at 1700°C.

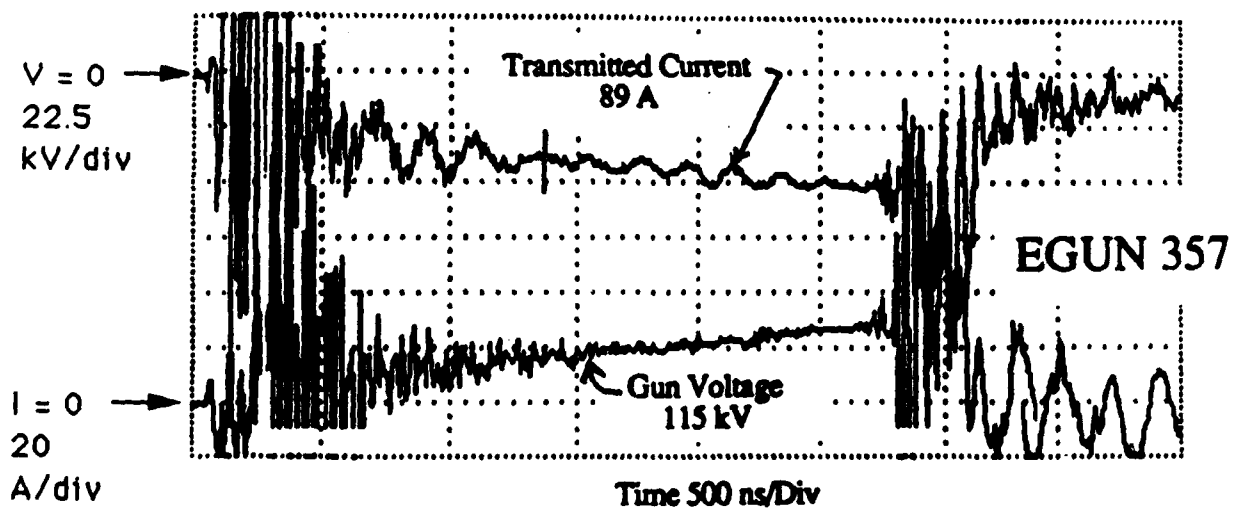


Figure 43: Electron gun total current and transmitted current traces at 1744°C.

6.2 Comparison with Thermionic Emission Theory

A large number of comparisons of I-V characteristics were made between measured curves and theoretical curves. The theoretical curves were derived from the Longo equation

$$I = \frac{I_{TL} I_{SCL}}{I_{TL} + I_{SCL}} \quad (1)$$

where I_{TL} and I_{SCL} are the temperature-limited and space-charge-limited currents of the diode. These comparisons are crude because of the exponential dependence of I_{TL} on work function and temperature, and the uncertainty about emission area caused by LaB_6 activation.

An example is shown in Figure 44 for operation at 1326°C . The measured curve agrees well with Eq. (1) when the actual cathode area of 2.85 cm^2 is used with a work function of $\phi = 2.33 \text{ eV}$. This is slightly lower than Lafferty's value of 2.66 eV . The other curves in Figure 44 use this value and two different areas. The area of 8 cm^2 is for the case when the entire cathode holder area emits. In Figure 44, the low voltage part of the curve is the SCL regime. Small errors in temperature, work function, and area can account for the differences between Eq. (1) and measured I-V curves.

6.3 Cathode Heating Results

The second Pierce-gun cathode was heated to 1800°C successfully. The highest temperature was 1801°C with a total power of 955 W . Of this, 828 W were bombardment power and 127 W were filament power. A plot of cathode temperature versus total power is shown in Figure 45. The temperature across the cathode is very uniform as shown in Figure 46. It is more uniform with the carbon cup holder than with direct bombardment, which is the case in Figure 21, because the heat is deposited on the carbon cup and spreads out as it flows into the cathode.

The digital control circuit for cathode heating has proven to be robust and dependable. An important improvement was made by moving the MOSFET chopper in the filament circuit to the ground side of the isolation inductors. This removed all of the electronics from the high-voltage

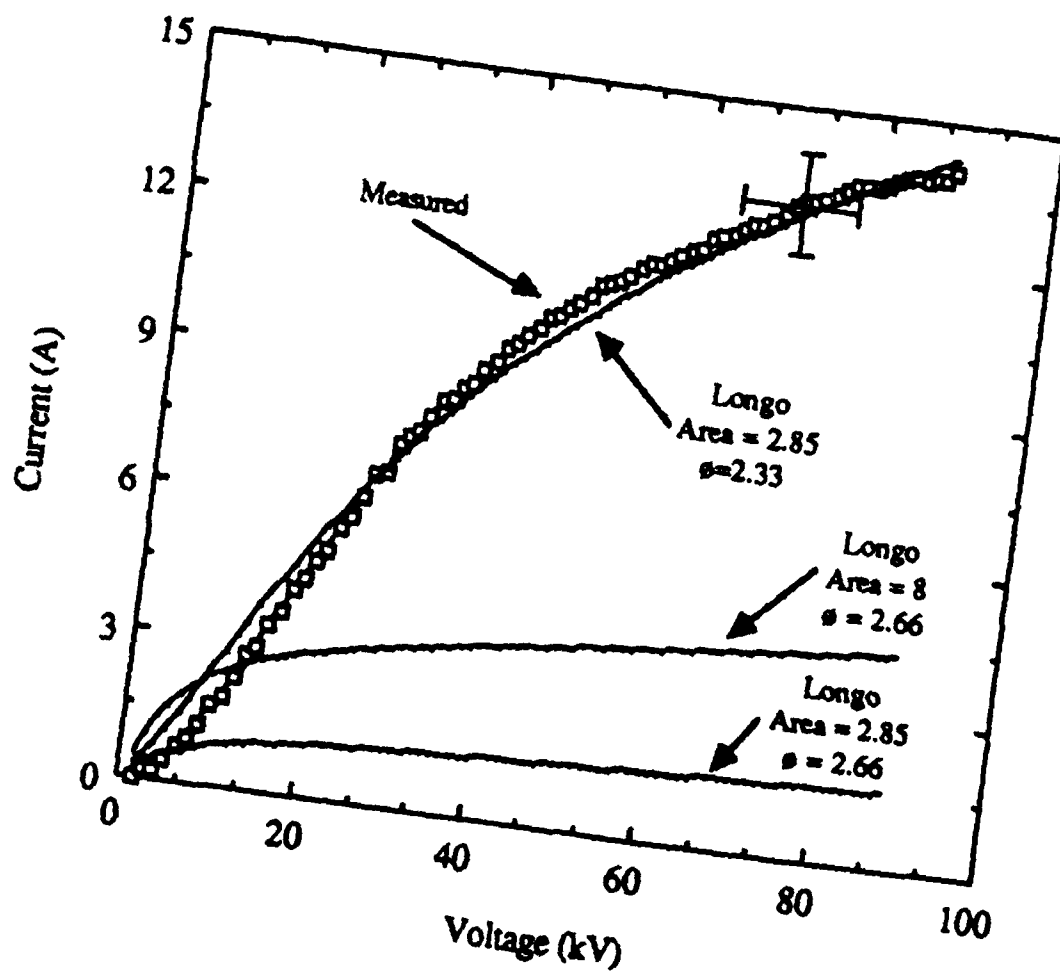


Figure 44: IV characteristic of the electron gun generated from shot EGUN 191.
Cathode temperature = 1326°C.

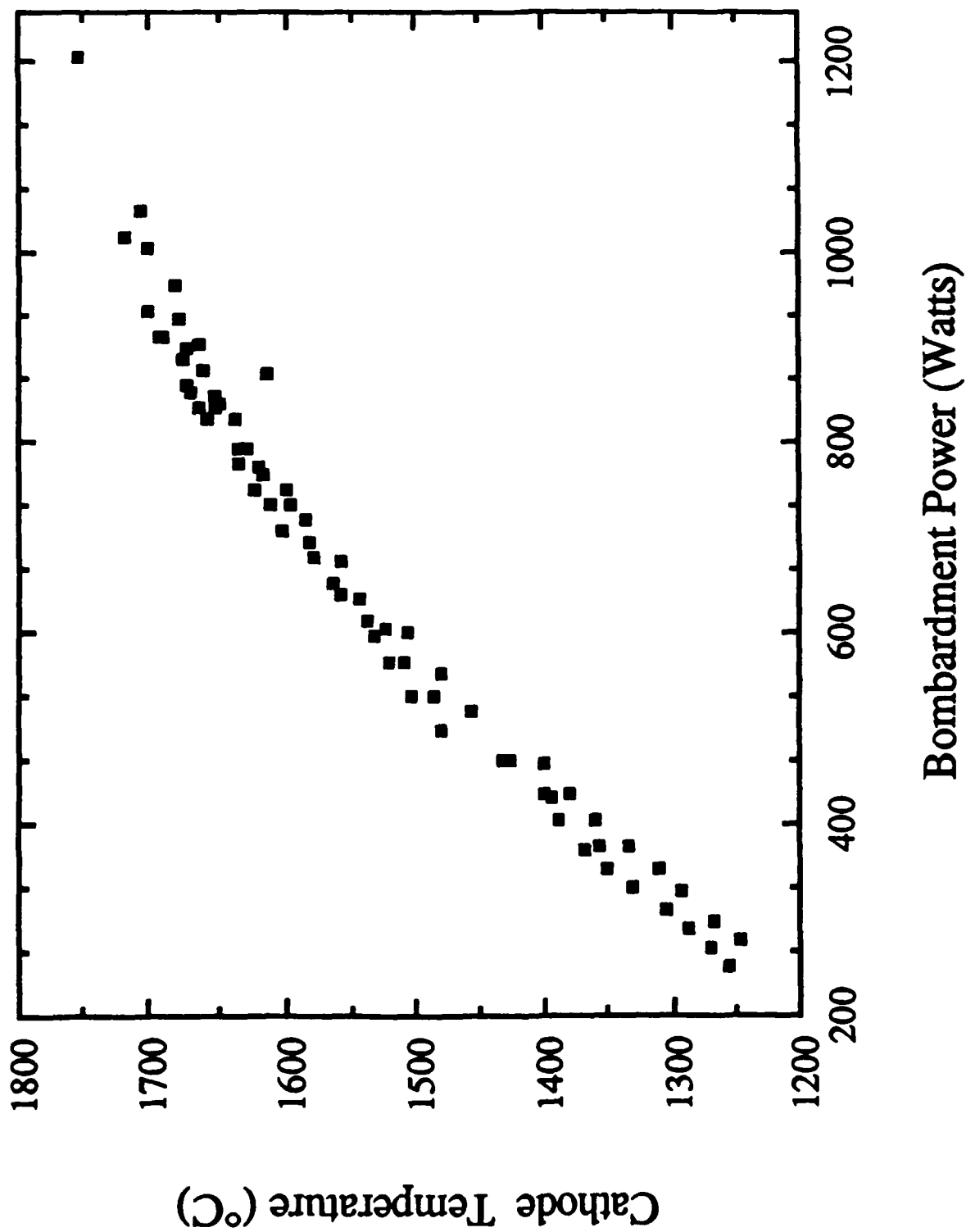
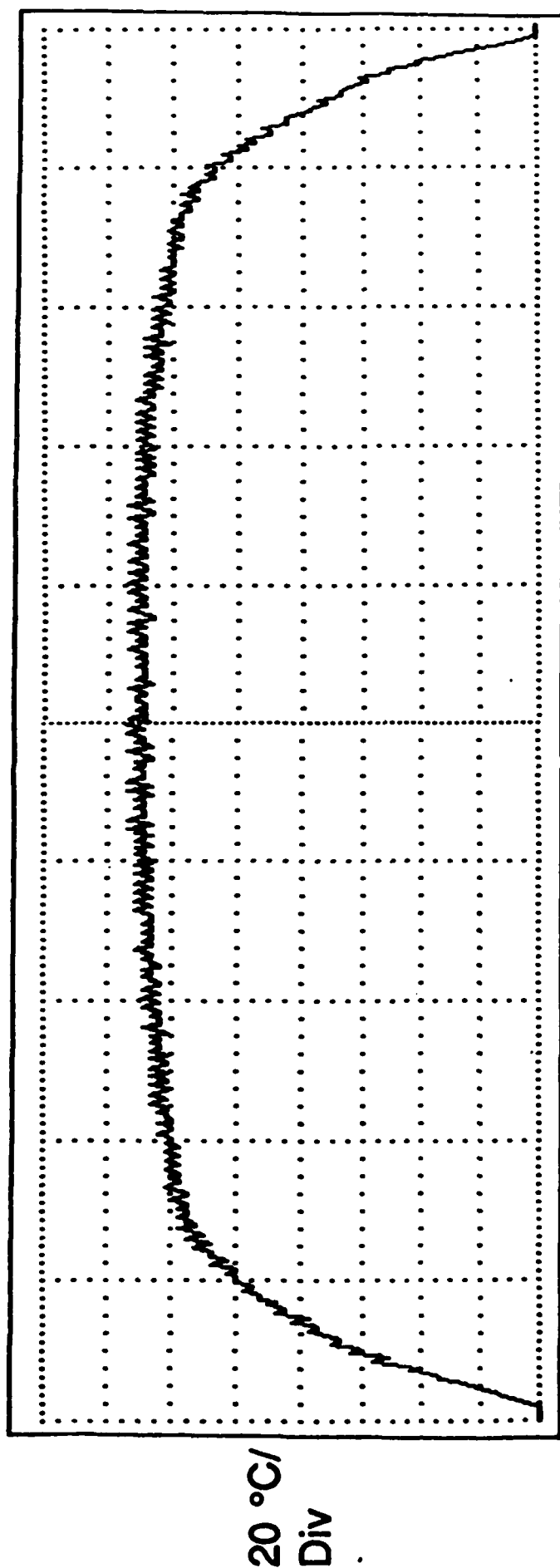


Figure 45: Cathode temperature vs. bombardment power



Cathode Temperature = 1700 °C, $\varepsilon = 0.8$
Temperature Variation Across Cathode = 10°C

Figure 46: Cathode temperature distribution

side. The only component left is the 10:1 step-down transformer. The circuit is shown in Figure 47. Some capacitors and MOV's are on the high-voltage side to tie the three filament-cathode leads together for the duration of the high-voltage pulse.

The heating cycle is illustrated by the traces shown in Figure 48. Under automatic control with the heating circuit slaved to the pressure gauge, the cathode starts from 740°C (filament-only radiant heating) and rises to 1600°C. The control set point of 400 mA is reached after approximately 8 minutes and the constant current control locks in. During this time, the digital circuit compares an 8-bit digitized sample of the bombardment current with a memorized set-point value approximately 100 times during each half-cycle of the 60-Hz bombardment current. The control principle is illustrated in Figure 49. When the bombardment current sample exceeds the reference value, the filament heating power is turned off. When it is too low, the power is turned on. Frequent sampling was found to be necessary because of the fast risetime of the thermal runaway.

7. PULSED CATHODE HEATING STUDIES

A study was performed on a method for drastically reducing the average thermal power requirement for heating a LaB₆ cathode to 1800°C. The method also eliminates the need for inductive isolation and feedback control to supply heating power to a thermionic cathode.

It requires approximately 800 W to heat the present one-inch-diameter cathode to 1800°C. Most of this power is carried off by a water-cooled jacket on the gun anode. However, if a two-inch diameter cathode is used, the heating requirement goes up to 3 to 4 KW, and it becomes more difficult to handle this amount of heat.

A method has been investigated theoretically which reduces the heat load by an order of magnitude and is also suitable for very high voltage operation of a thermionic cathode electron gun. It is most effective when the electron gun is pulsed every few minutes. Since the cathode stays at 1800°C for several seconds, several thousand pulses of a few microseconds duration each could be generated on every cathode heating pulse if a suitable beam-pulse driver were available. The

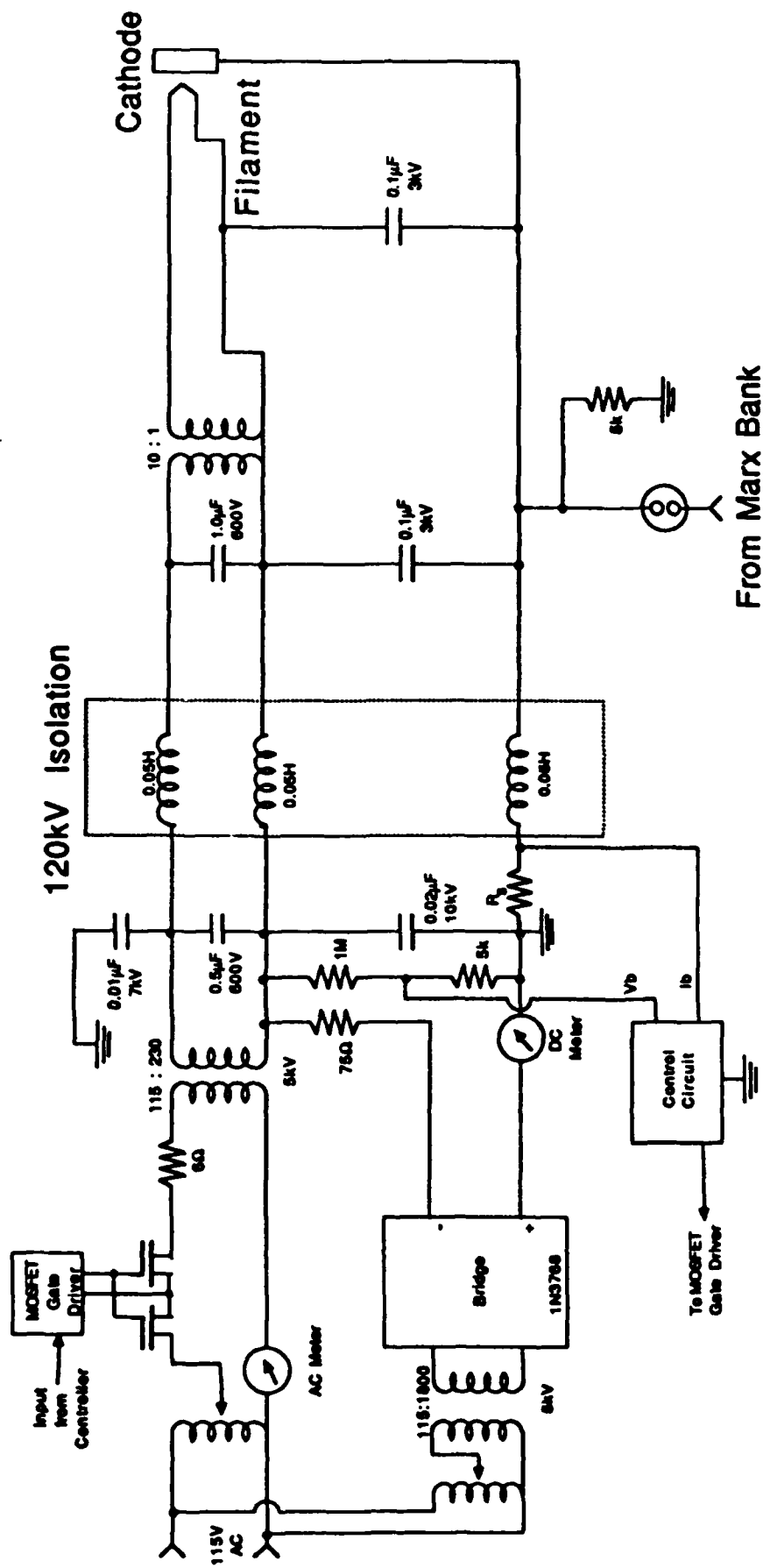
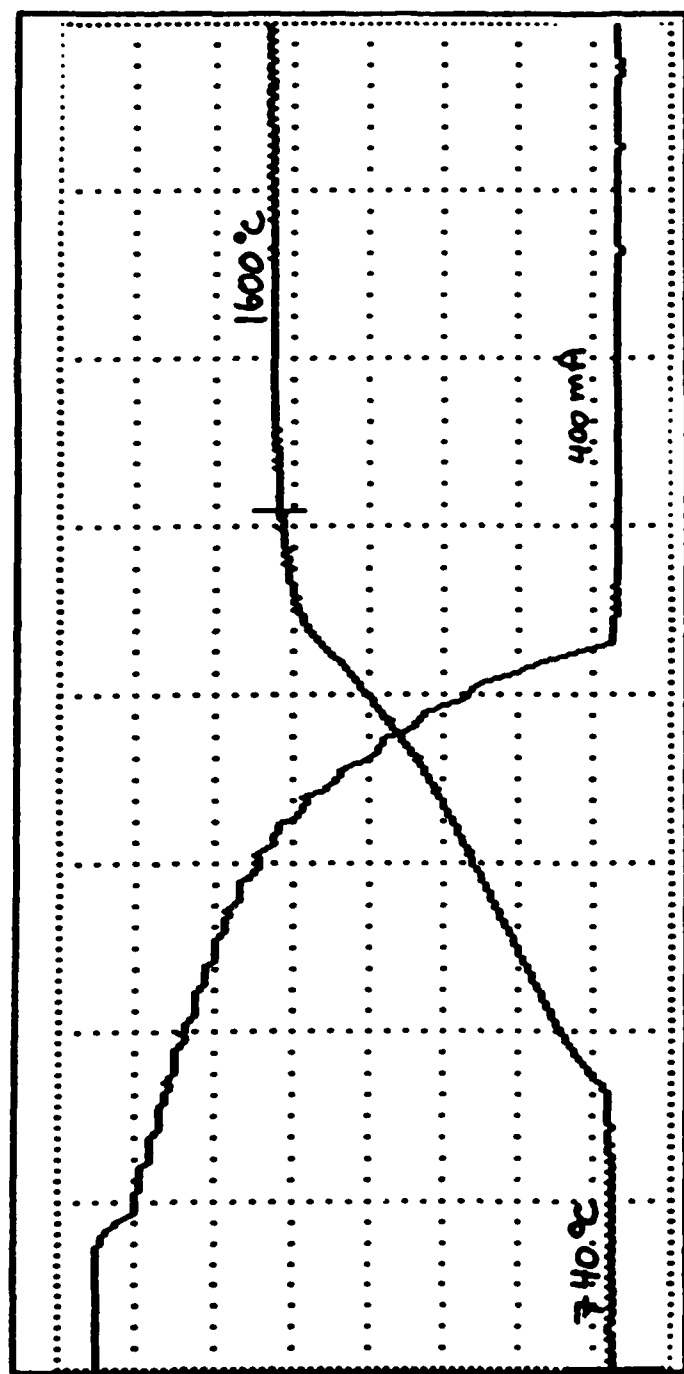


Figure 47: Three inductor isolation circuit



Bombardment
Current
50 mA/div

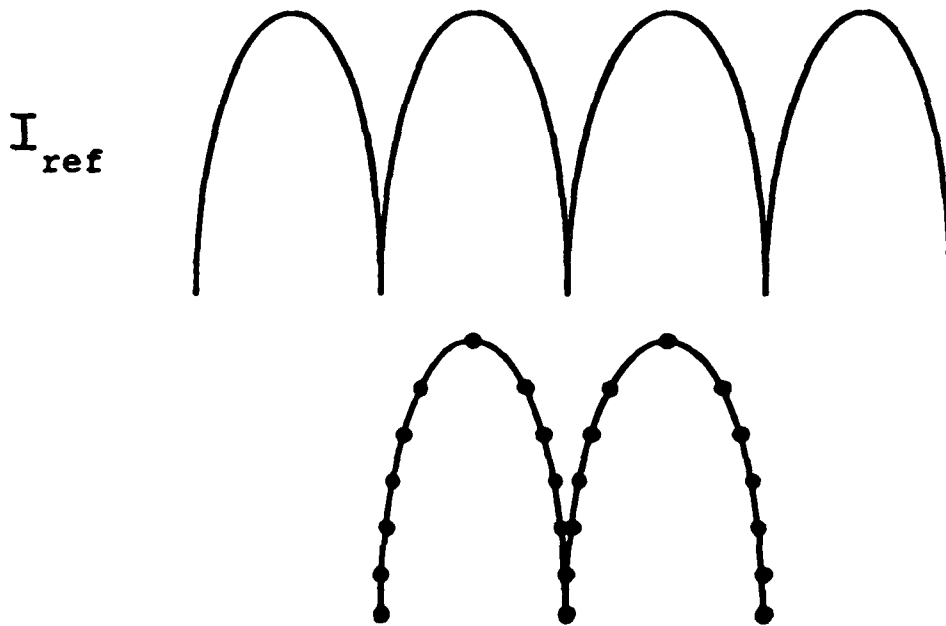
Cathode
Temperature
200 °C/div

Trace Time = 17 Minutes

Bombardment Voltage = 1800 Vrms

Figure 48: Typical heatup period under automatic control.

Digital Control Method



-Point by point comparison to I_b

- At a single point :

If $I_b \geq I_{ref}(i)$ power off
If $I_b < I_{ref}(i)$ power on

Figure 49: Digital control method

use of a thermionic cathode in an REB machine would be a great advantage over plasma cathodes for long pulses because there could be no anode-cathode breakdown.

The method under study uses a capacitor to store the cathode heating energy. This capacitor must "float" at the high voltage provided by the Marx bank to pulse the gun anode-cathode voltage and therefore would be located in the same oil insulation tank as the Marx bank. It can be charged through a resistive isolation circuit in the same way as the Marx bank capacitors, and therefore inductive isolation is not needed for supplying cathode heating power.

The method takes advantage of the lanthanum activation of the tungsten filament as described in this report. Starting with a cold activated tungsten filament, a low-voltage capacitor is discharged into the filament. This starts emission from the filament and the emission heats the cathode by bombardment. The energy for bombardment is supplied by a second capacitor that has been pre-charged. Since the gap between the filament and the cathode is a thermionic diode, the cathode capacitor will not begin to discharge until the filament is hot. This forms a "thermionic switch" that switches on the main capacitor for supplying bombardment energy. This allows the use of only one switch in the system, and it is used for turning on the low-voltage filament. This switch will only have to switch a few tens of volts.

After the bombardment current starts to flow, the LaB_6 cathode heats up within a few seconds and heats the filament by back radiation. If the filament has a sufficiently low work function, the back radiation will keep it hot enough to emit the bombardment current. The low work function is provided by lanthanum activation of tungsten. A LaB_6 -coated tungsten filament could be used to start the system initially, and lanthanum activation would take over as the cathode is repeatedly heated.

Two scenarios for this process have been simulated with our bombardment heating model. In the first the cathode is assumed to start at a given initial temperature, heated by one pulse up to 1800°C , and allowed to cool back to ambient temperature. This is the most costly in terms of energy. In the second case, the cathode is heated on a 120-second cycle, and cools down to

approximately 700°C between pulses. Half as much bombardment energy is used in the second case.

7.1 Model

The model is based on the one developed for analyzing the present bombardment heating system. The thermal model is shown in Figure 50. The cathode and filament are assumed to lose heat by thermal radiation only. The filament capacitor C_f discharges into the filament when the switch closes. The cathode capacitor C_c discharges through the filament-cathode thermionic diode. The cathode and filament are assumed to have constant emissivities and specific heats with temperature. The work function of the filament can be varied. The mass densities of the filament and cathode are assumed to be constant. Radiation view factors between the cathode and filament and the areas and volumes of the filament and cathode are estimated.

The dynamic thermal equations used to describe this system are given in the appendix of this report in the article by Lipscomb, et al. The bombardment I_B is given by the Longo equation with

$$I_{SCL} = \rho V_B^{3/2}$$

$$I_{TL} = a_f A T_f^2 \exp\left(-\frac{11600\phi}{T_f}\right)$$

ρ = perveance of filament-cathode gap

ϕ = work function of filament

A = Richardson-Dushman constant for the filament

V_B = bombardment voltage.

The electrical equation for the filament is given by

$$R_f C_f \frac{dV_f}{dt} + V_f = 0 \quad (2)$$

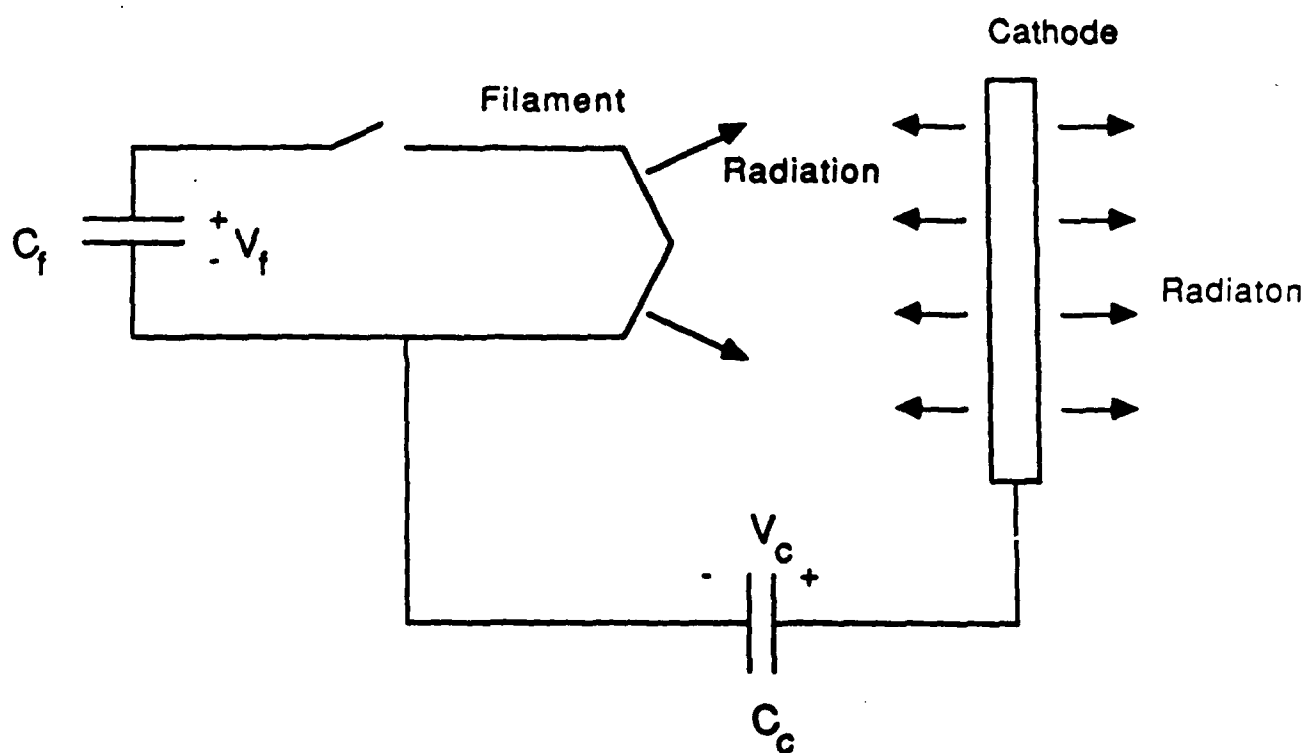


Figure 50: Model for bombardment system with transient bombardment heating.

with the initial condition $V_f(t = 0) = V_{f0}$. The resistance of the filament is allowed to change with the filament temperature according to the equation

$$R_f = R_{f0} [1 + \alpha (T_f - 2500)] \quad (3)$$

where R_{f0} is the filament resistance at 2500°K and α is the temperature coefficient of resistivity. The value of α is estimated to be 0.00041 per °K, and the value of R_{f0} is taken to be the measured value of 0.7 ohms for the hot filament. The electrical power to the filament, P_H , is calculated from

$$P_H = V_f^2 / R_f. \quad (4)$$

The complete electrical circuit is shown in Figure 51. The cathode bombardment capacitor C_c is charged through the 35 K ohm charging resistor R_{ser} and the 5 K ohm dummy load resistor R_{sh} . The filament capacitor only uses 24 volts and could be charged from a battery. The heating circuit is drawn in a more compact form in Figure 52. The resistance R_{gap} is the nonlinear thermionic diode resistance from filament to cathode. Using this circuit, we can write down the relationship between V_B and I_B .

$$C_c = \frac{dV_B}{dt} = \frac{V_c - V_B}{R_{ser} + R_{sh}} - I_B \quad (5)$$

The relationship between I_B and V_B represented by the nonlinear resistance R_{gap} is given by Eq. (1).

The main equations for the system are Eqs. (1) through (5). These equations are integrated by the Runge-Kutta method to obtain solutions for T_c and T_f as functions of time along with other parameters of interest. The main parameters that were varied are V_c , V_f , C_c , C_f , ρ and ϕ .

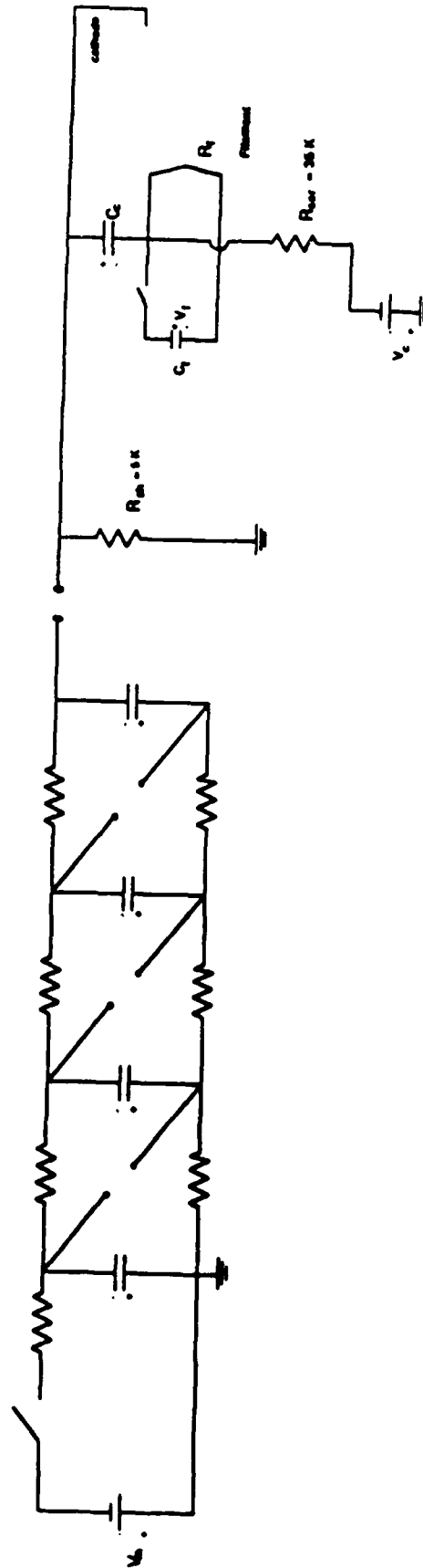


Figure 51: Marx circuit and filament-cathode diode circuit.

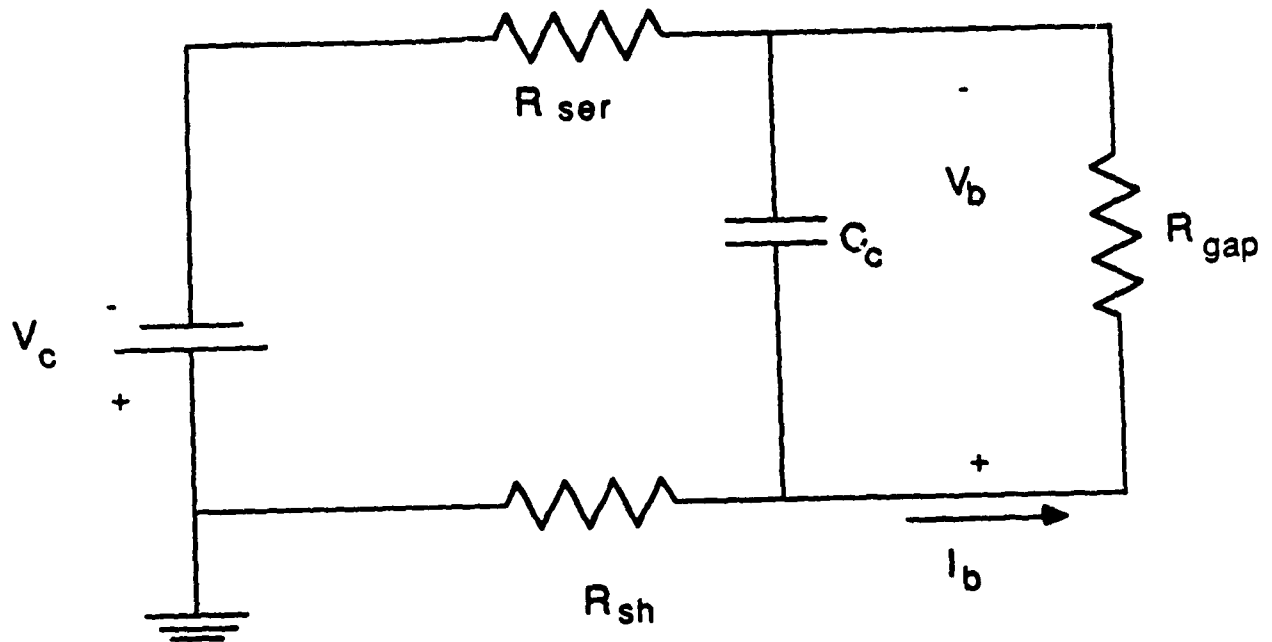


Figure 52: Charging circuit and discharging circuit for filament-cathode thermionic diode (R_{gap}).

7.2 Results of Calculations

A variety of test cases were studied. The initial study used a simplified version of the model, and progressively more detail was added.

7.2.1 Results for Simplified Model

In this case it is assumed that the filament simply operates space-charge limited at all times and that the cathode capacitor discharges through the filament-cathode thermionic diode according to the Child-Langmuir 3/2-power law. Under these assumptions, Equations (3) and (7) reduce to

$$C_c \frac{dV_B}{dt} = - \rho V_B^{3/2}$$

two initial cathode temperatures were used: 25°C and 1200°C. Cathode capacitor size and initial voltage were varied. The diode perveance was also varied. A search was made for minimum bombardment energy requirements using a bombardment voltage and current similar to the values presently in use in the experiment. Equation (2) is used to calculate the cathode temperature, with T_f assumed to be a constant that is high enough to always give space-charge-limited emission and T_a assumed to be 25°C. A typical time plot of the cathode temperature is shown in Figure 53.

Typical results of this basic case are shown in Table 2. With a higher initial bombardment current and voltage, the cathode is heated faster and a little less total energy is required. Starting from a temperature of 1200°C reduces the energy by a factor of 2 or 3. The cathode temperature is at 1800°C for approximately 2 seconds. During this time the main electron beam could be fired many times.

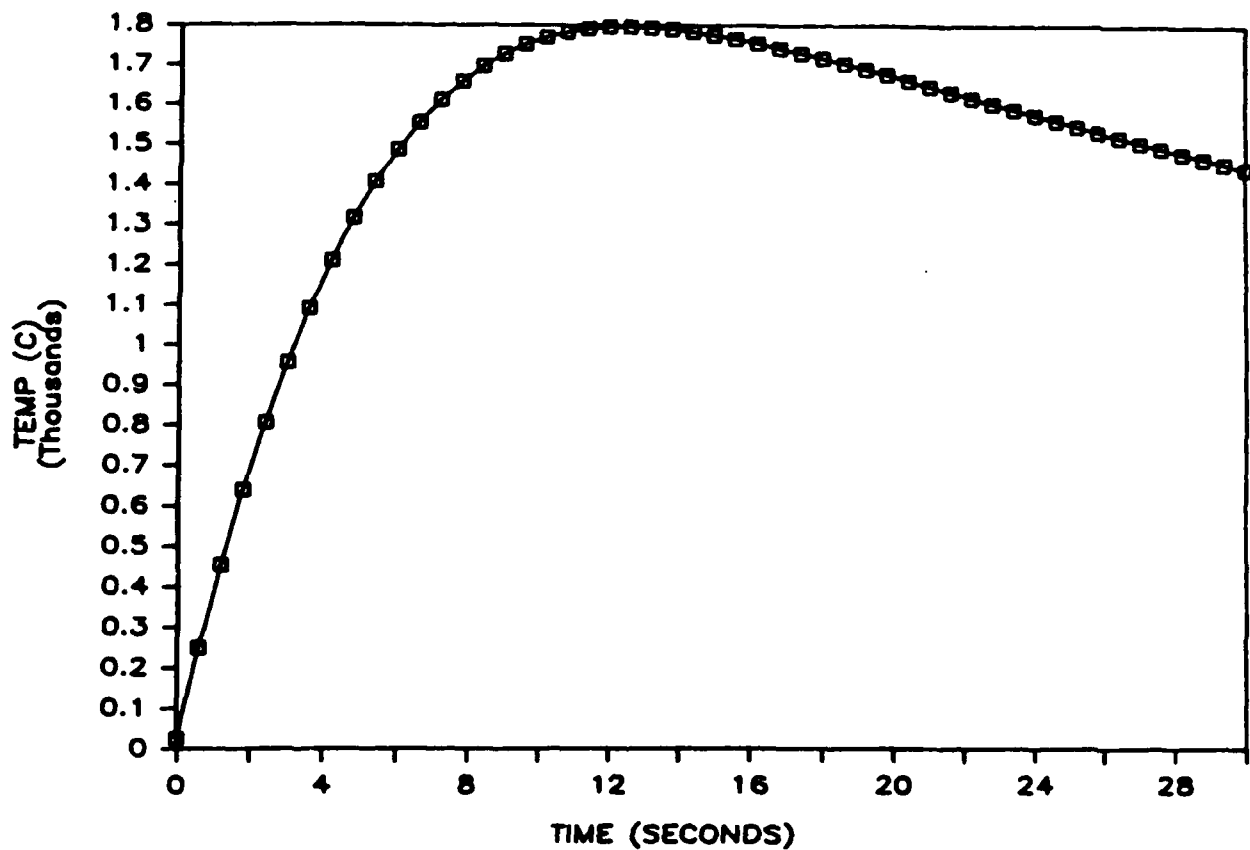


Figure 53: Basic case of pulsed bombardment heating. The filament-cathode gap is assumed to be governed by the Child-Langmuir $3/2$ -power law, the filament temperature is assumed to be high enough for space-charge limited emission at all times, and the cathode is assumed to start at 25°C . The cathode and filament lose power by radiation.

TABLE 2
Basic Model with Space-Charge Limited Filament Emission

	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	<u>Case 4</u>
T_c (initial) ($^{\circ}\text{C}$)	25	25	1200	1200
T_c (max) ($^{\circ}\text{C}$)	1800	1800	1800	1800
t_{max} (sec.)	8.4	6.6	6.0	2.2
V_B (initial) (kV)	3.5	4.0	2.5	4.0
Perveance(ρ) $\times 10^6$ (A/ $V^{3/2}$)	7.24	7.91	8.0	7.91
$I_B(=\rho V_B^{3/2})$ (A.)	1.5	2.0	1.0	2.0
E (kJ)	19.9	18.2	10.2	6.52
C_c (mF)	3.25	2.275	3.25	0.815

The highest energy required in Table 2 is approximately 20 kJ from a 3250 μF capacitor bank at 3500 volts. This assumes the cathode starts from room temperature. If it starts at 1200 $^{\circ}\text{C}$, the energy requirement is reduced to 10.2 kJ which could be obtained from 3250 μF at 2500 volts. This could be done with 4 capacitors rated at 3000 J each. When cyclic operation is considered, the energy requirement is considerably reduced.

7.2.2 Complete Model Operation

The complete set of equations were solved for single shot and cyclic operation. In this case the circuit of Figure 52 is included, so that C_c can begin to recharge through R_{ser} and R_{ch} when the "thermionic switch" opens. The process is started by discharging C_f into the filament. This turns on the filament-cathode "thermionic switch" diode and bombardment heating begins. The cathode back radiation continues to heat the filament until the cathode capacitor is nearly 100% discharged. As the filament cools the thermionic switch opens and the cathode capacitor recharges.

This operation was studied for an initial charge voltage on the filament capacitor of 24 V. The filament work function had to be in the range of 2.6 to 3.5 eV for the system to work.

Otherwise, back radiation heating could not keep the filament hot enough to provide sufficient bombardment current. The filament resistance was allowed to vary with temperature, but this did not have a large effect. Both single shot and 120-second cycle operation were studied. The ambient temperature was assumed to be 25°C, and the maximum cathode temperature reached was chosen to be 1800°C. The filament temperature was kept under 2300°C. It was also attempted to have the cathode reach its maximum temperature in as long a time as possible to prevent cracking the LaB₆ cathode by heating it too rapidly.

Typical cyclic operation is found to be very efficient. In a 120-second cycle, several seconds of flat-top time on the cathode temperature at 1800°C are obtained. The average power required is 50-60 W., or less than 10% of the steady heating power requirement. The method takes full advantage of the thermionic switch and filament activation by lanthanum.

Typical results are shown in Table 3. The first 2 cases are for a filament work function of 2.6 eV (activated). The third case assumes $\phi = 3.5$ eV (partially activated). The system would not work for higher work functions. The cathode capacitor voltage is fully recharged in 120 seconds because the thermionic switch opens and allows it to recharge through the 40 K ohm charging resistor ($R_{ser} + R_{sh}$). These two resistors would have to be able to withstand the full electron gun cathode-anode voltage. The cathode capacitor is in the range of 950 to 2000 μ F at 3.5 kv. The total energy storage is approximately 6000 J. for the low work function case. This is a reasonable amount of capacitance and energy storage to float on the main cathode voltage pulse. The most advantageous savings is the average heat load. Only 60 W. are needed for the low work function case, compared to 700-800 W. for steady heating.

A plot of T_c , T_f , and V_c is given in Figure 54. The cathode temperature peaks in 2-3 seconds, which raises the possibility of cathode cracking. This may have to be prevented by providing some relief of thermal stresses in the cathode by choice of cathode thickness, the graphite cathode holder design, and possibly stress-relief cuts in the cathode disk. Note the small increase in T_f in Figure 26 at a time of approximately 5 seconds. This is due to the radiation heating of the filament by the cathode.

Similar results were found with 2-inch diameter LaB_6 cathodes. These results and experimental verification of the above calculations are described in the paper included in the appendix.

TABLE 3

cases 1, 2 : $f = 2.6 \text{ eV}$ case 3 : $f = 3.5 \text{ eV}$

C_c (mF)	C_f (mF)	V_{∞} (kV)	I_{∞} (A.)	V_c			T_f			T_c			E_c (kJ)	E_f (J)	P_{cAve} (W.)	P_{fAve} (W.)
				start (kV)	end (kV)	endpoints (°C)	peak (°C)	peak (°C)	endpoints (°C)	peak (°C)	t_{Tcmax} (sec.)	t_{Tcmax} (sec.)				
1.37	473	3.0	2.0	3.0	2.636	390	2300	1796	528	1796	3.2	3.2	6.165	113	51.4	9.4
0.95	472	3.48	2.5	3.48	3.38	388	2299	1803	526	1803	2.6	2.6	5.756	112	48.0	9.4
2.00	463	3.48	2.5	3.48	3.29	380	2299	1784	517	1784	1.4	1.4	12.12	110	101	9.2

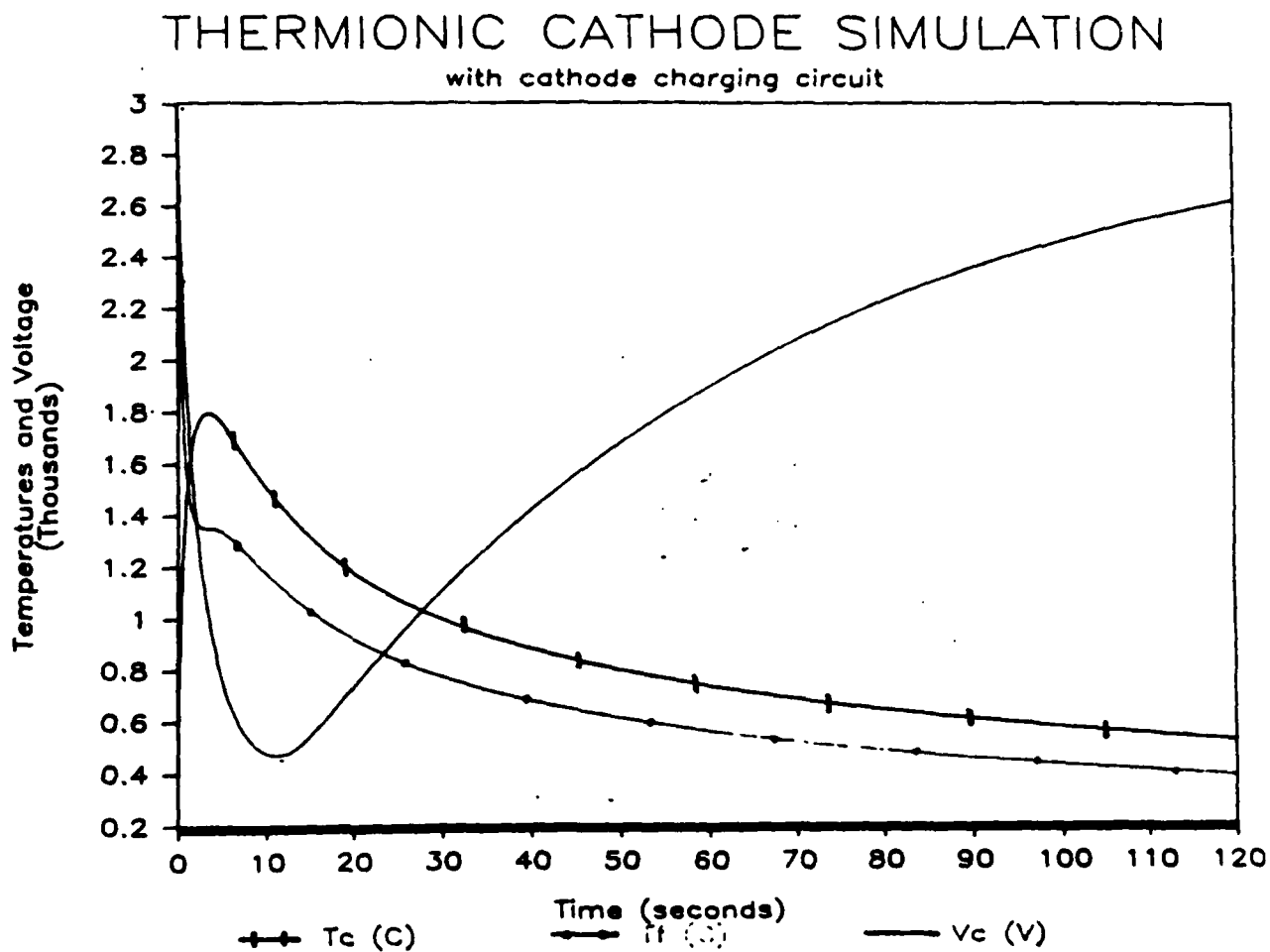


Figure 54: An example of the operation of the complete circuit of Figures 51 and 52 in which the cathode capacitor begins to re-charge after the "thermionic switch" opens.

APPENDIX

- A. Journal and Proceedings Articles (list on page 3)
- B. Conference Paper Abstracts (list on pages 3 and 4)
- C. Ph.D. Thesis Abstract
- D. Disclosure of Invention

PROCEEDINGS OF THE 1987 IEEE Particle Accelerator Conference

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DEVELOPMENT OF HIGH-CURRENT-DENSITY LaB_6 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 poisoning 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 $240 \text{ V } 60 \text{ Hz}$ 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 500 mA RMS . The filament is biased negatively with respect to the LaB_6 cathode by bombardment voltages of 700 V to 1800 V 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 electrical heating power to the filament to balance an increase

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 continuously 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 LaB₆ 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:

$$P_H = P_{fmax} (1 - u(I_B - I_{B0})) \quad (6)$$

where $u(I_B - I_{B0}) = 1$ when $I_B \geq I_{B0}$
0 when $I_B < I_{B0}$.

I_{B0} 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

$$P_H = P_{fmax} (1 - u(CT_f^2 \exp[-q\phi/kT_f] - I_{B0})) \quad (7)$$

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

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

$$dT_f/dt = P_{fmax} (1 - u(CT_f^2 \exp[-q\phi/kT_f] - I_{B0})) + C_4 T_c^4 - C_5 T_f^4 \quad (9)$$

The following conclusions can be drawn 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.

LaB₆ Instability

Heating system operation with a pure tungsten filament and the LaB₆ 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 LaB₆ 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 LaB₆ 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 LaB₆ cathode in a graphite cup, the filament is not directly exposed to the cathode and the effect was eliminated.

Acknowledgement

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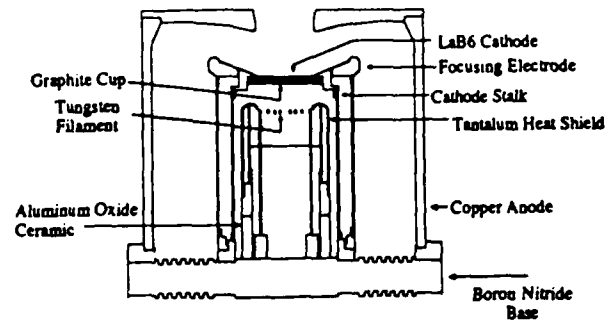


Fig. 1 : Electron Gun Assembly

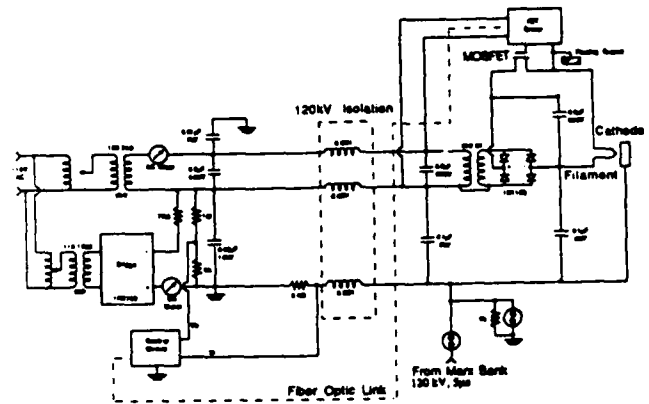


Fig. 2 : Heating and Isolation System

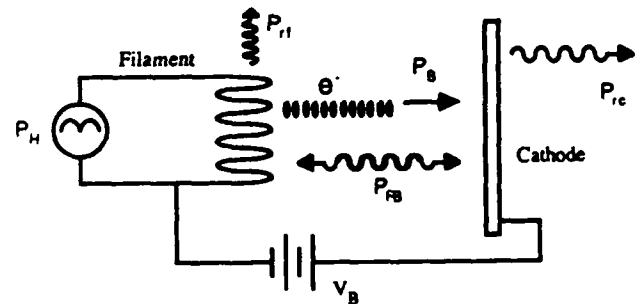


Figure 3: Heating System Model

Thermionic Cathode Electron Gun for High Current Densities

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Abstract—An electron gun using lanthanum hexaboride (LaB_6) as a cathode material is being studied for use as a robust thermionic emitter at high cathode current densities. It has a standard planar cathode, Pierce-type electron gun design with a space-charge-limited permeance of $3.2 \times 10^{-6} \text{ A/V}^{3/2}$. Thus far it has been operated up to 36 kV in the space-charge-limited regime. The cathode is heated by electron bombardment and radiation from an auxiliary tungsten filament. The total heating requirement is found to be 202 W/cm^2 of cathode area at a cathode temperature of 1626°C . These observations are found to be in reasonable agreement with a thermal steady-state power balance model. Beam current distribution measurements are made with a movable collector and Faraday cup, and are found to be in agreement with an electron-gun computer code. The cathode temperature distribution is also measured.

I. INTRODUCTION

LANTHANUM HEXABORIDE (LaB_6) is used as a cathode material in applications where high current density and resistance to chemical poisoning are important. Its basic properties as a cathode were first investigated by Lafferty [1]. More recently, Storms and Mueller [2] have investigated its thermionic properties in detail. They compared measurements of the work function by several authors. These and other authors have given values for the Richardson-Dushman constant A , the emissivity ϵ , and the work function ϕ . Representative values for these constants are $A = 30 \text{ A/cm}^2/\text{K}^2$ [1], [3], [4], $\epsilon = 0.7$ – 1.0 [3]–[6], and $\phi = 2.6 \text{ eV}$ [1], [3], [4]. These values of A and ϕ have been used to compare the results of this paper with the Richardson-Dushman equation prediction, and $\epsilon = 0.8$ has been used in the measurement of the cathode temperature with an infrared thermal monitor. To obtain the range of current density of interest for this paper, cathode temperatures of 1500°C to 1800°C are required.

Recent work with LaB_6 cathodes in electron guns and plasma sources has used several methods for cathode heating. These are generally either joule heating of LaB_6 (direct heating), joule heating of a tungsten coil with conduction heat transfer to the LaB_6 (indirect heating), radiation heating, or a combination of radiation and electron bombardment heating. Shintake *et al.* [7] used indirect heating of an LaB_6 cathode in a Pierce-type electron gun

with a highly concave spherical cathode of area 5.5 cm^2 , achieving a relatively low current density of 0.3 A/cm^2 at 1300°C . Others have used small LaB_6 cathodes for CRT and electron microscope applications. Schmidt *et al.* [5] have developed an indirectly heated single-crystal LaB_6 cathode for use as an interchangeable electron source in a variety of electron microscopes and similar instruments. Emission currents as high as 50 A/cm^2 were observed from 3×10^{-5} - mm^2 cathodes. Broers [8] obtained current densities of 0.8 – 40 A/cm^2 from a 1-mm^2 LaB_6 cathode over the temperature range of 1400 – 1800°C . In direct heating, a heating current of 100 A or more is passed through the LaB_6 cathode. This type of cathode has been developed by Leung *et al.* [3] and Leung and Pincosy [6] for plasma sources. In these cathodes, sintered LaB_6 plates are cut into a hairpin shape and connected to molybdenum electrodes. In another LaB_6 cathode for plasma sources, Goebel *et al.* [4] used radiative heating from a tungsten filament placed directly behind the LaB_6 disk. They obtained emission current densities of up to 20 A/cm^2 from a 30-cm^2 cathode at 1700°C . This cathode was not used in a Pierce gun geometry. In all of these applications, the objective was to produce rugged cathodes that are resistant to poisoning and are capable of producing high current densities.

Conventional dispenser and tungstate cathodes of the type used in Pierce guns in traveling wave tubes have been operated at current densities up to 30 A/cm^2 at 1100°C [9], but are usually operated at 2 A/cm^2 or less [10]. The choice of operating current density is a compromise between the required cathode lifetime and cathode heating power.

An application that requires high current density and high beam quality is that of the free-electron laser (FEL). It has been shown that high cathode current density is an important factor in achieving high beam brightness [11]. Interest in using LaB_6 cathodes in Pierce-type electron guns to obtain high current density beams has centered around a cathode heating method using a combination of radiation and electron bombardment heating [12]–[15]. Free-electron laser applications require cathodes with current densities of up to 100 A/cm^2 . The resistance to poisoning characteristic of LaB_6 cathodes is also a desirable cathode property for prototype FEL devices.

In the work reported in this paper, the radiation-bombardment heating method has been studied for a Pierce

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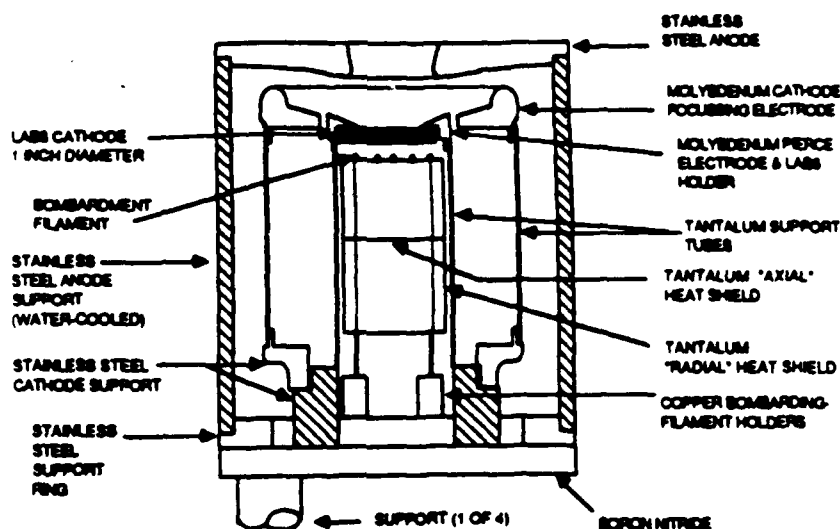


Fig. 1. Assembly drawing of the LaB_6 bombardment-heated electron gun. Design microperveance of this gun is 3.2. The size scale is indicated by the 1-in diameter of the LaB_6 cathode.

type electron gun with an LaB_6 cathode area of 2.87 cm^2 . The area of application for this gun is the FEL, and therefore the goal of the work has been to develop a cathode heating method that will allow the cathode to reach the necessary temperature to provide current densities of at least 40 A/cm^2 . It is also desired to operate the electron gun in the space-charge-limited regime. Since in this regime the current density is proportional to the three-halves power of the gun voltage, it is necessary to use an electron gun design with high perveance (perveance p is the ratio $I/V^{3/2}$ and is a function of gun geometry only) and to operate at voltages of approximately 100 kV to obtain 40 A/cm^2 . In the work reported here, a control system was developed which allows the stable control of the cathode temperature. An efficient heat shield is used which traps 75 percent of the heating filament radiation power for use in cathode heating. The results reported here include measurements of current density and temperature distribution across the cathode, and comparisons of the gun operation with the predictions of an electron-gun computer code. A description of the control and bombardment heating system is also given.

II. ELECTRON GUN DESIGN

A Pierce-type electron gun with a planar cathode and an anode extraction hole was designed with the aid of the Hermmannsfeldt-SLAC electron trajectory computer code [16]. The electrode shapes from Pierce's original design were used as a starting point [17]. A planar cathode gun with a microperveance of 3.2 and acceptable anode-cathode spacing was designed. The cathode diameter was chosen so that cathodes could be cut from 2.5-cm-diameter LaB_6 rods. Taking into account the cathode edge area covered by the cathode holder, an effective cathode diameter of 1.91 cm was obtained. The remaining dimensions of the anode-cathode region were scaled from the code results.

A. Electron Gun Assembly

An assembly drawing of the present electron gun is shown in Fig. 1. It is mounted on a 7.6-cm-diameter 0.64-cm-thick boron nitride baseplate. A cathode support tube of 3.18-cm-diameter 0.051-cm-wall tantalum tubing contains the bombardment-heating tungsten filament and heat shield and supports the cathode at one end. The cathode is mounted in a molybdenum holder and held in place by tantalum set screws. There is a tantalum heat shield inside the cathode support tube between it and the bombardment filament. The bombardment filament is made of 0.051-cm-diameter pure tungsten wire. The outer part of the cathode-focussing electrode is made of molybdenum and is mounted on a separate tantalum support tube to thermally insulate it from the cathode. The water-cooled gun anode structure is made of stainless steel and is also mounted on the boron nitride. The entire structure is connected to the stainless steel vacuum flange by four copper rods. Three electrical connections are made through two dual high-voltage feedthroughs mounted on the same 20-cm flange. The electrical connections consist of two wires for the bombardment filament and one for the cathode. The entire gun structure and flange can be removed as a unit for servicing.

B. Heat Shield Assembly

The present heat shield design is shown in the schematic of Fig. 2. A tantalum cylinder (the "radial" heat shield) is supported from the boron nitride by 99.8 percent Al_2O_3 insulators and molybdenum threaded support screws. The cylinder is open at both ends, but at its midsection a solid tantalum sheet (the "axial" heat shield) is spot-welded in place to completely block the cross-section, except for two small holes for the filament lead wires. These wires are insulated by Al_2O_3 tubes and are supported and held by set screws in copper connectors.

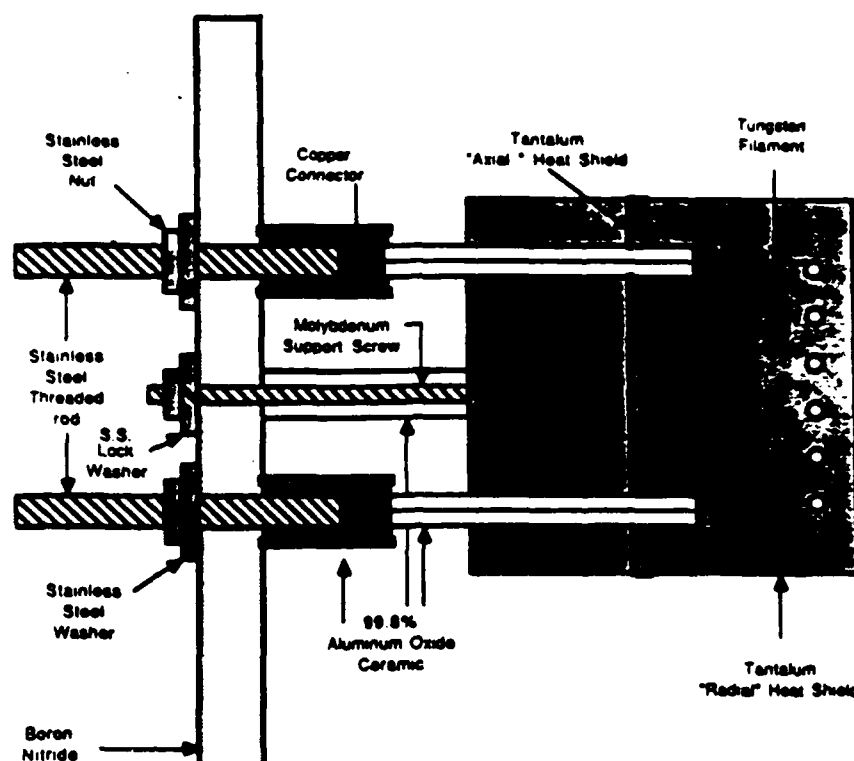


Fig. 2. Heat shield assembly.

the boron nitride baseplate. It was found that because of close spacing, arcing occurred between the copper connectors and the stainless steel cathode support ring for the cathode support tube. This was eliminated by placing short Al_2O_3 tubes over the copper connectors. Electrically the heat shields are connected to one terminal of the filament.

The radial and axial tantalum heat shields combine to enclose the filament in a small pillbox bounded on one end by the axial heat shield and on the other by the LaB_6 cathode. This geometry improves the efficiency of use of the filament heating power because radiation from both the filament and the cathode is partially trapped in the pillbox.

The heat shield is supported by two molybdenum threaded support screws inside Al_2O_3 tubes to take advantage of the differential coefficient of thermal expansion for these two materials. It was found that the stainless steel threaded rod expanded too much and the support loosened, allowing the shield to droop and to short to the cathode support tube. The voltage difference between these two parts is the bombarding voltage, which varies up to 1200 V rms. The electrical characteristics of the heating system will be discussed in Section IV.

III. ELECTRON GUN OPERATION

The electron gun has been pulsed with 5- μs pulses up to 36 kV in space-charge-limited operation, producing a maximum current density of 6.7 A/cm² from the 2.87-cm² LaB_6 cathode. The total current at 36 kV was 19 A. Higher current densities were not achieved because the electrical insulation and voltage pulser were limited to 40

kV. The current density distribution of the entire beam has been measured by sweeping a Faraday cup with a pin-hole entrance aperture across the beam at a distance of 4 cm from the cathode. The measured microperveance of the gun is 3.4.

The effects of temperature limitation on the electron beam have been investigated and are compared to results generated by the SLAC code.

A. Space-Charge-Limited Operation

The gun current is measured using a pulse current transformer. The placement of the transformer is shown in Fig. 3. The current transformer output voltage has components due to cathode emission, charging of the gun and vacuum feedthrough stray capacitance, and noise from the filament and bombardment currents. With zero pulse voltage, the output from the current transformer is a 2-mV peak, 120-Hz voltage corresponding to 20-mA noise current from the heating system. All current measurements from the pulse transformer may be off by ± 20 mA due to the noise from the heating system.

Fig. 4 shows the total gun current for voltages of 5, 10, 15, and 20 kV with a repetition rate of 20 Hz. The microperveance calculated from these data is 3.4. In general, the microperveance is found to be close to the design value of 3.2. The beam diameter at various distances beyond the anode hole has also been observed and is the same as the value expected from the SLAC code.

The small current spike at the beginning of the pulse shown in Fig. 4 is due to the charging of the gun and vacuum feedthrough stray capacitance. The typical pulse

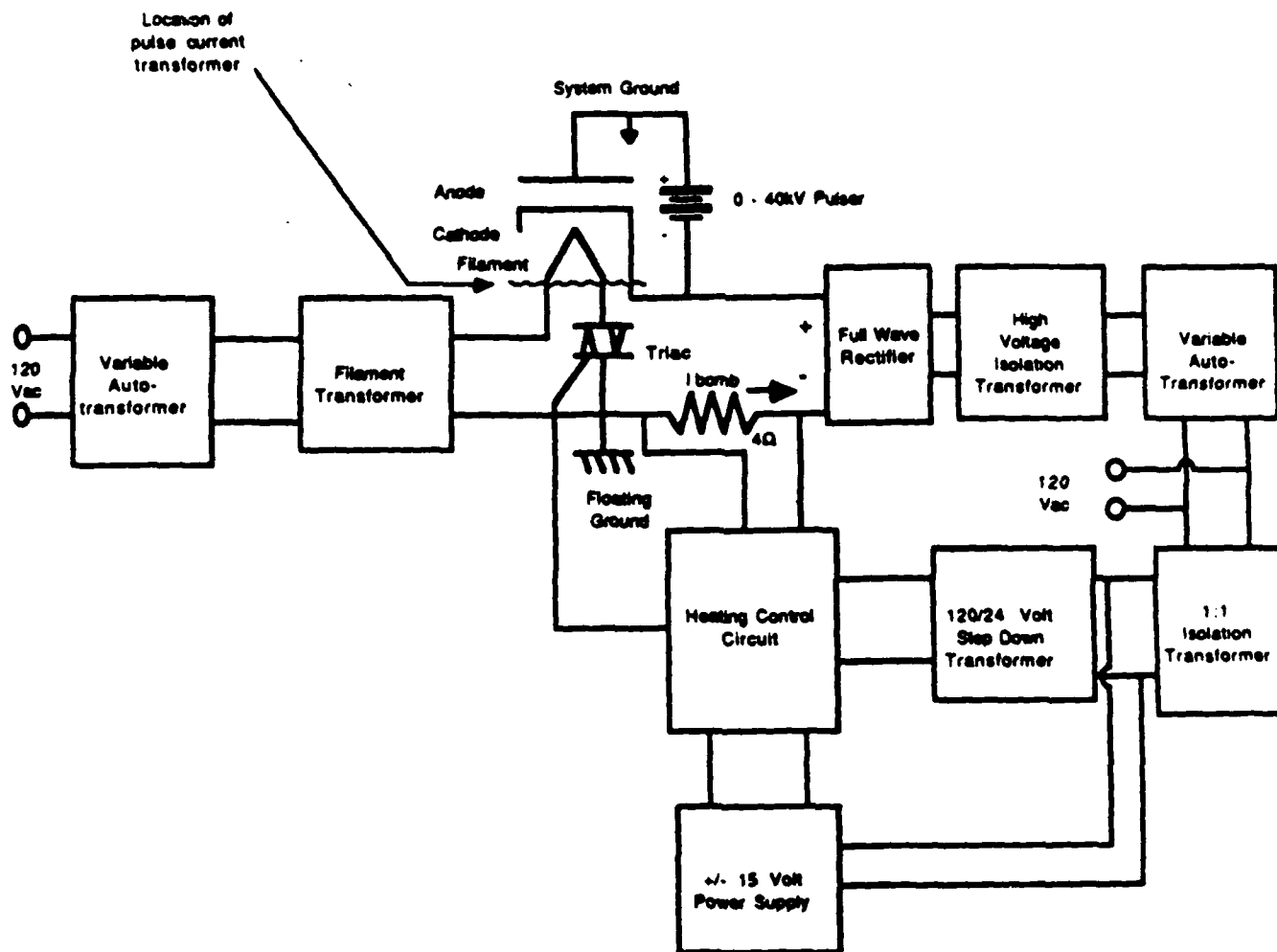


Fig. 3. Bombardment and radiation heating system. 120-VAC 60-Hz power is fed through a bifilar-wound 40-kV isolation inductor. The configuration shown is for constant bombardment current.

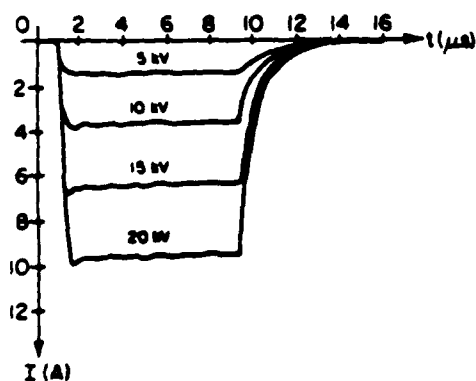


Fig. 4. Total electron gun current for 5- μ s pulsed gun voltages of 5, 10, 15, and 20 kV at 20-Hz pulse repetition rate

nitude of the spike indicates that the stray capacitance is 50-100 pF.

The current density distribution of the electron beam under space-charge-limited operation at 15 kV is shown in Fig. 5. Current density plots are generated using a Faraday cup with a pinhole diameter of 0.0343 cm. The Faraday cup pinhole was placed a distance $z = 4$ cm from the cathode and was swept over the entire beam cross sec-

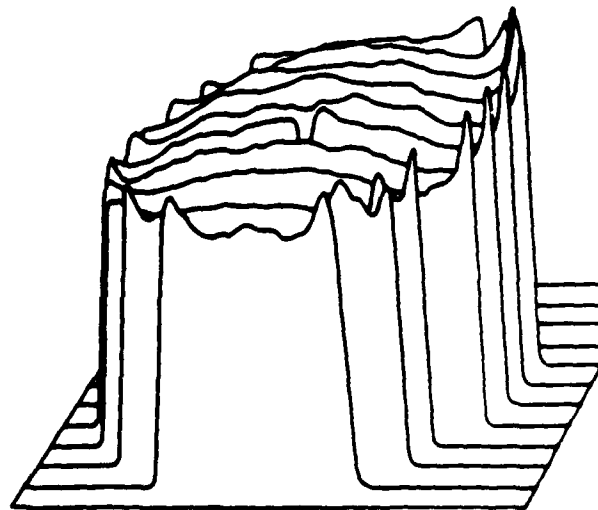


Fig. 5. Lab₂ electron-gun emission profile of the entire beam section. The approximate diameter of the beam at the location of measurement ($z = 4$ cm) is 3 cm. Eleven pinhole sweeps were made equally spaced chords

tion. The output of the Faraday cup is fed to a 50- Ω impedance boxcar integrator whose output drive a plotter. The asymmetry of the scan in Fig. 5 is

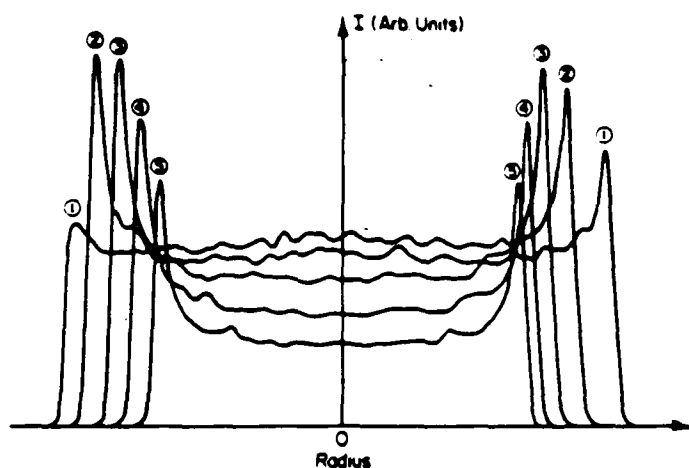


Fig. 6. Electron gun emission profiles across the beam center diameter showing the effects of temperature limitation. Profiles were made at a gun voltage of 15 kV. Scans 1 to 5 are in order of increasing temperature limitation. The microperveance of the profiles are: ① $\rho = 2.83 \text{ A/V}^{3/2}$; ② $\rho = 2.18 \text{ A/V}^{3/2}$; ③ $\rho = 1.58 \text{ A/V}^{3/2}$; ④ $\rho = 1.09 \text{ A/V}^{3/2}$; and ⑤ $\rho = 0.67 \text{ A/V}^{3/2}$. Profile ① is essentially the same as the space-charge-limited profile.

machining tolerances and uneven expansion of the gun electrodes at elevated temperatures. It was observed that the edge peaks became larger at higher cathode temperatures while still operating space-charge-limited due to greater thermal expansion. They are also larger under temperature-limited operation.

B. Temperature-Limited Operation

Temperature-limited current density distributions were generated by scanning across the beam several times at a gun voltage of 15 kV with different cathode temperatures. Fig. 6 shows that as the cathode becomes more temperature limited, the diameter of the beam becomes smaller and large peaks in the distribution appear at the edges.

The peaks in the current density plot and the narrowing of the beam agree with the current density plots and trajectories generated by the SLAC computer code [16]. Fig. 7 shows the calculated electron ray trajectories of the electron gun for space-charge-limited (SCL) and temperature-limited (TL) operation. For increased temperature limitation, the diameter of the beam decreases and the electron rays become bunched at the edges of the beam. Current density distribution plots given in Fig. 8 are generated from the electron trajectory plots by smoothing the current contained in each ray across the diameter of the beam. In Fig. 8, the space-charge-limited case is indicated by a microperveance of 3.2, and it exhibits smaller peaks at the edge than in the temperature-limited case. Small peaks are also seen across the diameter in the computed distribution, but these appear because the distribution is generated from the discrete rays of the electron trajectory plot.

IV. CATHODE HEATING SYSTEM

The LaB_6 cathode is heated by a bombardment and radiation method. A general diagram of the heating system

is shown in Fig. 3. In this method, a 0.051-cm-diameter tungsten filament is directly heated by a 24-VAC filament transformer to a temperature where it can source a maximum electron beam current of 500 mA rms. The filament is biased negatively with respect to the LaB_6 cathode by bombardment voltages of 700–1200 V rms, causing a temperature-limited electron beam to bombard the cathode (the bombardment current). The heating system has a floating ground. The 120-VAC 60-Hz power for it is fed through a bifilar-wound 40-kV isolation inductor.

A temperature-limited beam is used so that the amount of bombardment current the filament can source can be directly controlled by the electrical filament heating power, independent of geometry and the bombardment voltage. Radiated power from the LaB_6 cathode is also a heating power input to the filament. This power causes an increase in the filament temperature which allows the filament to source more bombardment current. The increased bombardment current results in an increase in the bombardment power, which raises the cathode temperature and the power radiated back toward the filament. Thus, when the filament emits a temperature-limited beam, it forms a positive feedback loop between the cathode and the filament.

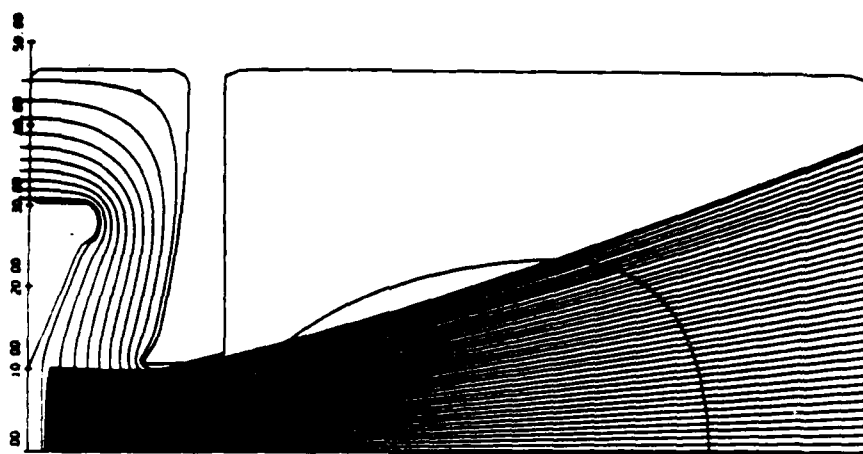
A. Heating System Controllers

To eliminate the positive feedback loop, a constant bombardment current control circuit has been developed. This controller monitors the bombardment current and reduces electrical filament heating power for increasing bombardment current. The controller forces the net power input to the filament, electrical heating power plus radiated power from the cathode minus filament losses, to remain constant. An increase in radiated power is balanced by a reduction in electrical heating power.

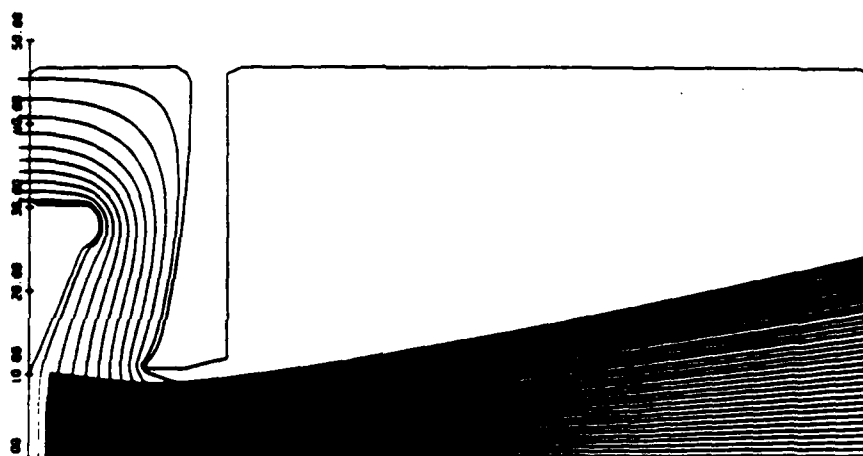
Since the filament operates in the temperature-limited regime, the bombardment current is independent of the bombardment voltage. This freedom makes the heating system easy to use and allows the operator to choose the bombardment current and voltage to utilize the maximum rated power from the bombardment supply.

A variation of the constant current controller is the constant bombardment power controller. The controller monitors the bombardment power and reduces electrical filament heating power for increasing bombardment power. With this controller, the positive feedback is eliminated and bombardment power fluctuations due to line voltage variations are minimized. For constant line voltages, the constant power controller is equivalent to the constant current controller. With the constant power controller, the bombardment current and voltage are no longer independent, but subject to the constraint $V_b \times I_b$ equals a constant.

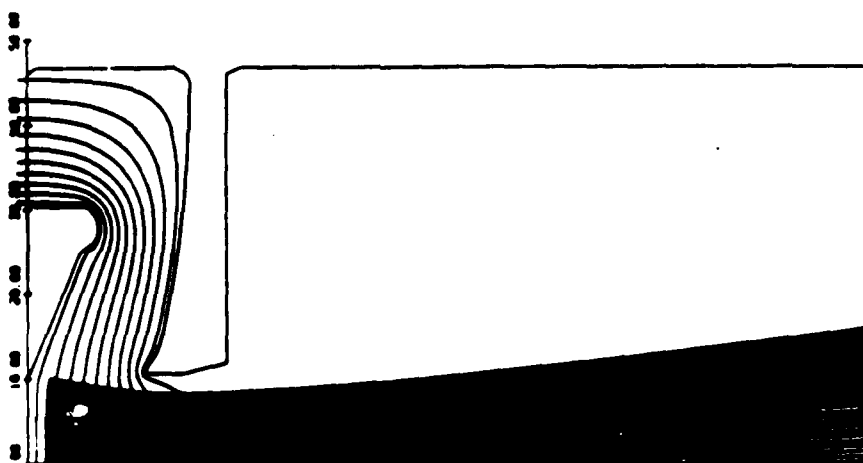
The controllers are realized by a phase control triac. Increasing bombardment current or power causes an increase in the triac firing angle which lowers the electrical heating power to the filament. A block diagram of the control circuit is shown in Fig. 9. For the constant power



(a)



(b)



(c)

Fig. 7. Electron trajectories and equipotentials, generated from the SLAC Electron Trajectory Program, showing the electron trajectories when the gun is operated space-charge limited—(a) $\rho = 3.2 \times 10^{-6} \text{ A/V}^{1/2}$ —and temperature limited—(b) $\rho = 1.5 \times 10^{-6} \text{ A/V}^{1/2}$, (c) $\rho = 0.5 \times 10^{-6} \text{ A/V}^{1/2}$.

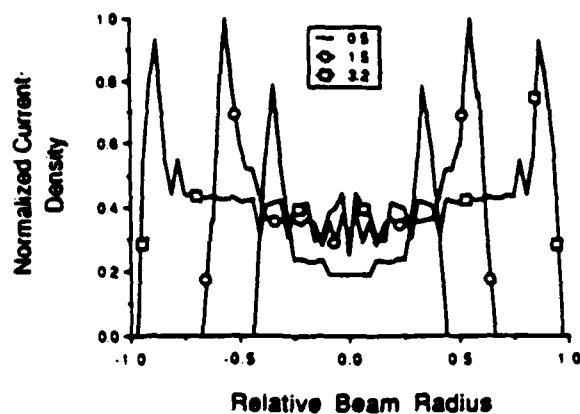


Fig. 8. Electron gun emission profiles generated from the results of Fig. 7. The narrowest profile corresponds to a microperveance of 0.5 and the widest profile to a microperveance of 3.2.

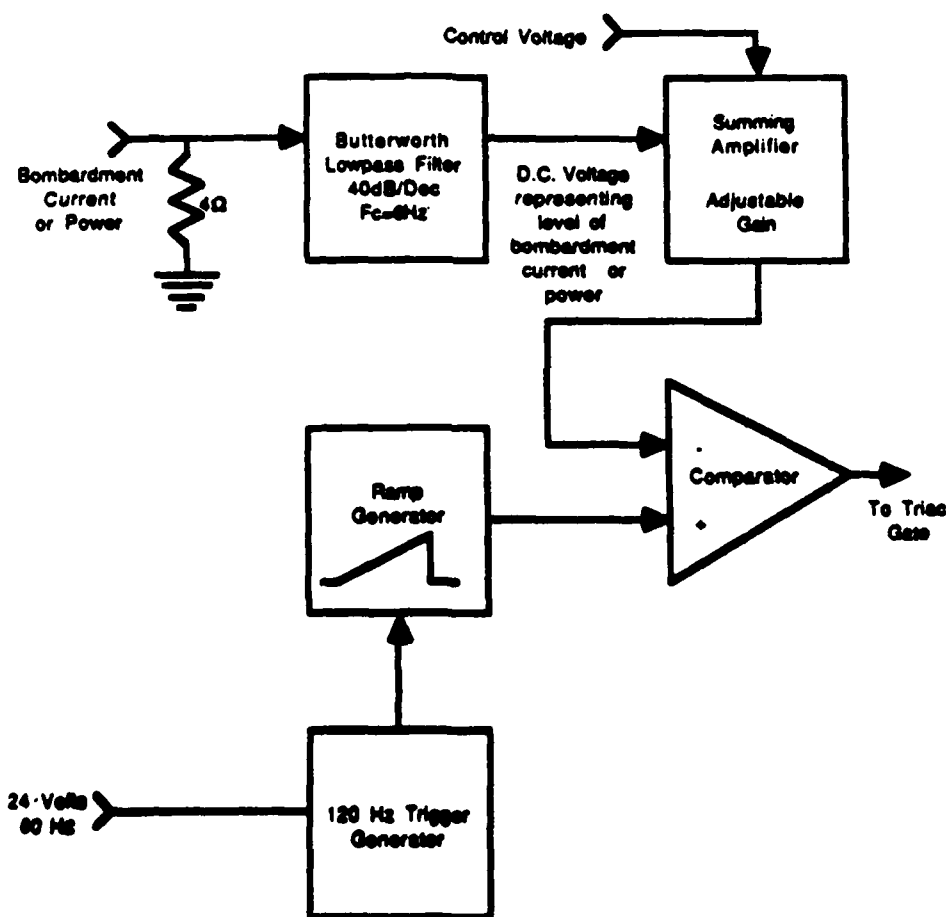


Fig. 9. Bombardment and radiation controller block diagram.

controller, the power signal in Fig. 9 is obtained from the bombardment current and voltage with an analog multiplier.

The control system in Fig. 9 only allows modification of the triac firing angle twice during the 60-Hz heating cycle. Also, the average bombardment current or bombardment power is used to control the firing angle. The controlling signal is averaged by a low-pass filter with a cutoff frequency of 6 Hz. The rate of growth of the ther-

mal instability is slow compared to the 6-Hz time scale so that the time constant of the low-pass filter can be neglected and average electrical power can be used in the analysis.

B. Cathode Temperature Measurements

In studies of the heating system, both the LaB₆ cathode and a graphite disk of the same size have been used. The

emissivity and thermal conductivity of graphite are similar to those of LaB_6 , so the heating power requirements are similar. The difference between the two materials is that LaB_6 vapor increases the thermionic emission of the tungsten bombardment filament [1] and thereby affects the heating system control. This effect becomes apparent at approximately 1610°C , where the vapor pressure of LaB_6 is 10^{-5} torr [18]. A study of the heating system without the effects of LaB_6 vapor present in the system was done by using the graphite disk in place of the LaB_6 . The effects of the LaB_6 vapor on the heating system are the subject of present investigation.

The highest temperature achieved with the LaB_6 cathode was 1626°C , requiring 196 W of filament heating power and 383 W of bombardment power. With the graphite disk, the highest temperature achieved was 1755°C , requiring 225 W of filament heating power and 519 W of bombardment power. Higher temperatures could not be achieved because the power required at 1755°C was the maximum available from the present system.

Temperature distribution scans of the LaB_6 cathode and the graphite disk were made using an infrared detector thermal monitor with a 0.21-cm-diameter spot size on the cathode. It views the cathode through the anode aperture at a distance of 25 cm from the cathode. A scan at 1755°C is shown in Fig. 10. The cathode temperature ranges between 1755°C and 1680°C across the diameter. The temperature falls on the edges as the viewing spot moves out of the anode aperture. The temperature gradient is caused by improper focussing of the bombarding electron beam. When the electron gun was disassembled, it was observed that one side of the filament had drooped, allowing it to come closer to the cathode. The closest portion of the filament to the cathode would emit the most current, allowing one part of the cathode to receive a disproportionate amount of bombarding power.

C. Heating System Analysis and Measurements

A steady-state model has been developed to predict gun element temperatures and heating power requirements. In the drawing of Fig. 11, all continuous surfaces above the partition surface (the dotted lines) are assumed not to contain a temperature gradient. Heat is exchanged between these surfaces by radiation only. For surfaces below the partition surface, radiated power is assumed to be negligible and heat is carried by conduction only. The temperatures that are calculated in the model are defined in Fig. 11.

The cathode is assumed to be a black body when absorbing radiation; there is no reflected radiation from the cathode. For emitted radiation, the emissivity of the cathode is assumed to be the actual value of the emissivity of cathode material.

Radiated power back toward the filament is either absorbed by the filament, absorbed by the axial heat shield, or reflected back toward and absorbed by the cathode. The fraction of radiation passing between the cathode and axial heat shield which is absorbed by the filament is called

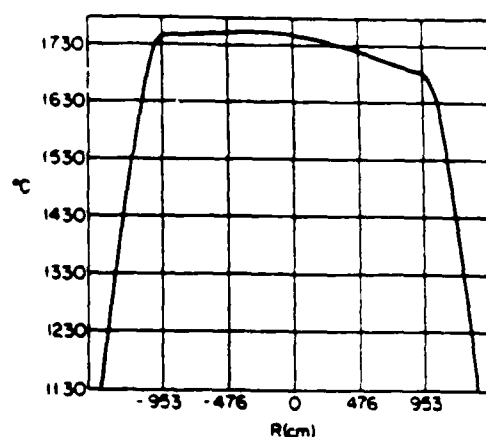


Fig. 10. Temperature scan across the diameter of the graphite disk. The peak temperature of the scan is 1755°C . The emissivity of graphite is assumed to be 0.8. The power required is 519 W of bombarding power and 225 W of filament heating power.

the screening factor, and may have values between 0 and 1.

The final approximation of the model is that, for surfaces that exchange energy by radiation, only the first and second reflections carry a significant amount of power.

These approximations avoid the calculation of view factors between radiating surfaces. The placement of the partition surface in Fig. 11 and the screening factor are free variables of the model and are chosen to fit calculated results to experimental data. The model is used to predict required total heating power (bombardment plus filament power) of the cathode at higher temperatures. A sample fit is shown in Fig. 12.

The observed roll-off of heating power at higher temperatures in Fig. 12 is not predicted by the heating model, which only considers heat transfer due to radiation and conduction. The roll-off of power may be due to a convective heat transfer which may appear at higher temperatures when the evaporation rate of the cathode material increases.

D. Heating System Efficiency

Although the bombardment power is very efficient in heating the cathode, it may appear that only a small amount of the filament heating power goes toward heating the cathode. However, because of the efficient design of the heat shield, it was found that the filament radiation alone was able to heat the cathode to 1050°C with the bombardment power turned off, and that this accounts for 75 percent of the filament power.

The radiated power from the cathode causes a thermal instability which is eliminated by the controller by exchanging electrical heating power for radiated power. At higher temperatures more power will be radiated toward the filament, requiring less electrical heating power. Thus, at higher cathode temperatures, less filament power is required and the heating system becomes more efficient. It has been observed that as the cathode temperature was increased from 1311 to 1630°C , the electrical filament

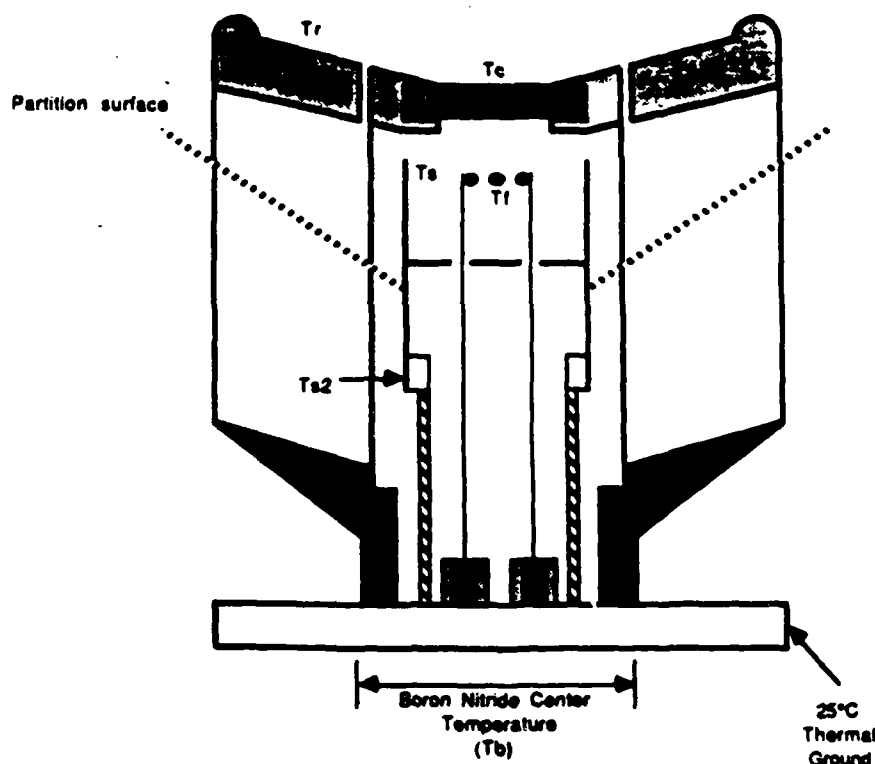


Fig. 11. Steady-state heating model used for the prediction of cathode heating power. Heat transfer above the partition surface is dominated by radiation and heat transfer below the partition surface is dominated by conduction. The dotted lines define the partition surface.

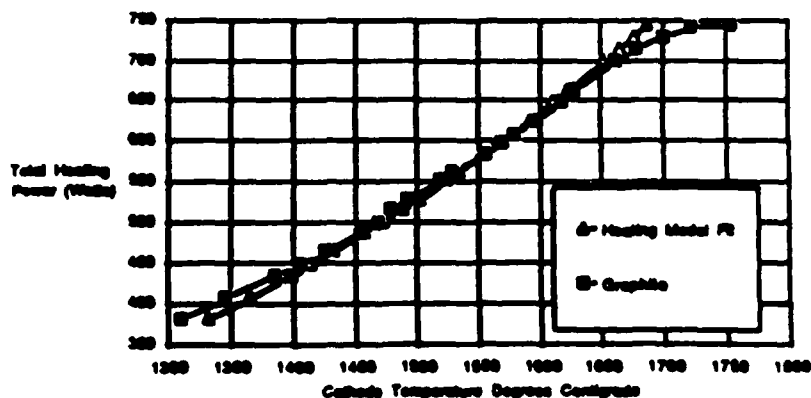


Fig. 12. Total electrical heating power (bombardment plus filament power) versus cathode temperature. The black squares are measured data from a graphite disk and the open triangles are generated from the model of Fig. 11.

heating power decreased from 238 to 221 W while the bombardment power increased from 140 to 440 W.

It is important to couple closely the thermal exchange between the filament and the cathode to use the radiated power as much as possible to reduce the electrical filament heating power. Heating system efficiency can also be increased by using smaller diameter filaments which require less filament heating power.

V. SUMMARY

A Pierce-type electron gun with a 1.91-cm-diameter LaB₆ thermionic cathode has been constructed. The gun

has been designed to achieve current densities of 40 A/cm² at cathode voltages of 108 kV. The gun has been operated up to 36 kV with current densities of 6.7 A/cm². The operation of the electron gun in both the space-charge-limited and temperature-limited regimes agrees well with the Richardson-Dushman equation and the results of the SLAC electron trajectory program.

To achieve current densities of 40 A/cm², the required cathode temperature is 1800°C. The heating system has been operated up to 1755°C with the graphite disk and has been shown to provide a stable heating method having run several times at 1755°C for continuous periods of

up to 5 h. The heating power required at 1755°C was 744 W and was the limit of the heating power supply. The cathode temperature distribution and current distribution have been measured.

The most important part of the electron gun is the cathode heating system. The electron bombardment and radiation heating method provides an efficient high-impedance controllable heating system. A controller has been developed to stabilize the system. This controller can be expanded to provide additional functions such as automatic warm-up and cool-down.

A steady-state thermal model has been developed which successfully predicts the variation of the cathode temperature with heating power. A transient model has also been developed which can be used in the analysis of the heating controller.

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Pulsed Cathode Heating Method

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Abstract—One drawback in the use of lanthanum hexaboride thermionic cathodes at high current density is the amount of steady-state heating power needed to heat the cathode to the desired temperature range ($\approx 1800^\circ\text{C}$). With continuous heating, approximately 1000 W of power are required to keep a 1-in diam cathode at 1800°C . For 2-in diam cathodes, the power requirement rises to 3 to 5 kW. Cathode evaporation is significant with continuous heating at 1800°C . To reduce the average power requirement and evaporation in pulsed experiments, a transient heating scheme has been investigated which allows single shot or slow, cyclic heating of the cathode. This scheme gives a few seconds of peak temperature during which many microsecond-length beam pulses can be fired with a suitable pulse modulator. For a 1-in diam cathode heated at a 120-s repetition period, the average power requirement drops by over an order of magnitude. This scheme provides average power reduction for larger cathodes to the same extent, and simplifies the voltage isolation problem in supplying cathode heating power. In this paper we present calculations based on a thermal model with electron bombardment heating, and compare these calculations with a pulsed-heating experiment.

I. INTRODUCTION

FREE-ELECTRON Lasers (FEL's) have employed a variety of cathodes in their electron beam sources. Cathodes in use or under development for FEL's include lanthanum hexaboride (LaB_6) thermionic cathodes [1], [2], cold field-emission cathodes [3], thermionic dispenser cathodes [4], plasma cathodes [5], and metal photocathodes [6]. In the present research a thermionic cathode of LaB_6 has been developed for high current density operation in a Pierce-type electron gun [1], [7]. An objective of the development has been to heat the cathode to 1800°C , the temperature where the Richardson-Dushman equation predicts that 40 A/cm^2 emission current should be obtained. The electron gun has a perveance of $3.2 \times 10^{-6} \text{ A/V}^{3/2}$ and has been constructed with a 1-in diam LaB_6 cathode for operation up to 120 kV. The achieved cathode temperature range was 1650°C – 1800°C .

The use of a thermionic cathode in a relativistic electron-beam machine would be a great advantage over plasma cathodes for long beam pulses because there would be no anode-cathode gap closure problem. In order to reduce the average cathode heating power, we have ana-

lyzed and tested a pulsed heating scheme for a LaB_6 cathode which is suitable for the cyclic or single-shot pulsed operation of an electron gun in a FEL, CARM (Cyclotron Autoresonance Maser), or similar device requiring a high cathode current density and relativistic beam energies. The method greatly reduces the average cathode heating power and uses a relatively simple electrical heating circuit. It is suitable for very high-voltage electron guns because the problem of isolating the cathode heating supply is simplified.

A. Continuous-Mode Cathode Heating

Steady-state cathode heating [1], [7] is done by continuous electron bombardment of the LaB_6 cathode from a temperature-limited tungsten filament. Temperature-limited electron bombardment heating is open-loop unstable [7] and requires a control circuit to eliminate the instability [1], [7]. Bombardment and filament power is supplied to the electron gun through an inductive isolation system. This system uses three 120-kV isolation inductors that are large enough to prevent damaging current from flowing through the control circuit during the high-voltage electron-gun pulse. A 4-stage Marx generator is used to drive the gun cathode approximately 120 kV negative to produce the main beam pulse.

Steady-state heating results [1], [7] show that the 1-in cathode requires up to 1050 W of heating power to heat it to 1800°C . The electron-gun anode is water cooled, and cooling fans are used on the vacuum system near the gun region. There is significant evaporation from the LaB_6 cathode which affects the bombardment heating system by activating the tungsten filament. If a 2-in diam cathode is used [2], the measured total heating requirement is 3 to 4 kW and it becomes more difficult to handle the heat load. In single-shot or low duty-cycle systems, it is possible to significantly reduce the average cathode heating power by pulsed heating.

B. Pulsed-Mode Cathode Heating

A theoretical and experimental study has been performed on a method for drastically reducing the average power requirement for heating a LaB_6 cathode to 1800°C . The method also eliminates the need for inductive isolation and heating control which are required for continuous heating. The reduced average heating power and cathode temperature lower the vacuum vessel temperature and reduce outgassing and cathode evaporation.

The pulsed-mode heating method reduces the heat load by an order of magnitude and is suitable for very high voltage operation of a thermionic cathode electron gun. It

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is most effective when the electron gun is pulsed every few minutes. Since the cathode stays at or near 1800°C for several seconds, several thousand microsecond-length beam pulses could be generated on every cathode heating pulse if a suitable beam-pulse driver were available. Since the cathode is only at a high temperature for a few seconds, the cathode lifetime is greatly increased due to the decrease in evaporation.

The pulse-heating method uses two capacitors or one capacitor and a battery to store the cathode and filament heating energy. These capacitors must "float" at the beam anode-cathode gap voltage provided by a Marx bank and therefore would be best located in the same oil insulation tank as the Marx bank. The cathode capacitor supplies 97 percent of the heating energy and can be charged through a resistive isolation circuit in the same way as the Marx bank capacitors; therefore, inductive isolation is not needed for supplying the cathode heating power. The filament capacitor supplies the remaining energy and could be charged by a floating storage battery, or the battery could be used directly through a simple switch.

The pulsed-heating method takes advantage of lanthanum activation of the tungsten filament. At temperatures above 1600°C, LaB₆ evaporates fast enough to coat the tungsten filament and raise its thermionic emission [7], [8]. The effective tungsten work function drops to the range of 2 to 3 eV with a LaB₆ coating [9]. Starting with a cold, activated tungsten filament, a low-voltage capacitor or battery is discharged into the filament. This starts emission from the filament, and the current heats the cathode by electron bombardment. The energy for bombardment heating is supplied by a second capacitor that has been pre-charged. Since the gap between the filament and cathode is a thermionic diode, the cathode capacitor will not begin to discharge until the filament is hot. This forms a "thermionic switch" that switches on the cathode capacitor to supply bombardment energy. This allows the use of only one switch in the heating system, and it is used for turning on the low-voltage filament. This switch will only have to switch a few tens of volts.

After the bombardment current starts to flow, the LaB₆ cathode heats up within a few seconds and heats the filament by thermal radiation. If the filament has a sufficiently low work function, the thermal radiation from the cathode will keep it hot enough to emit the bombardment current even without the continued filament electrical heating power [7]. Cathode radiation can reduce the required electrical filament heating energy to zero. The required low filament work function is provided by the LaB₆ activation of tungsten.

Activation requires a LaB₆ layer on the tungsten filament. Continuous-heating operation has shown that above 1600°C, cathode evaporation will rapidly coat the filament; the effect can be observed as the aforementioned thermal instability in the bombardment-heating system. The longevity of the coating has been tested by turning off the bombardment power and re-applying it 30 min later [7]. It was observed that the filament remained activated for at least this period of time. In pulsed heating opera-

tion, the accumulation of evaporated LaB₆ will occur in a start-up phase that consists of several initial activation shots. To minimize the number of required shots in this phase, the cathode capacitor voltage could be increased to supply additional cathode-heating energy and higher peak cathode temperatures. Additional start-up aid can be supplied by coating the filament with LaB₆ powder before its installation in the electron gun. This technique has been used to prepare directly heated cathodes consisting of LaB₆ powder coated on tungsten or other refractory metals [10].

The model used to study the heating method takes into account temperature-limited and space-charge-limited emission from the filament, dynamic changes in filament and cathode temperatures, and the recharging of the cathode capacitor. Many combinations of circuit parameters have been varied to minimize the energy requirements of the system. The model has been used for both single-shot and cyclic operation. In the single-shot mode, the cathode is heated from a given initial temperature (usually room temperature) and then allowed to cool back to the same initial temperature. In cyclic operation the cathode is heated at a 120-s repetition period and has an average temperature of several hundred degrees.

Cyclic operation also models the experimental situation where 60-Hz filament power is continuously supplied to the filament through isolation inductors, and the bombardment heating energy is stored in the cathode capacitor. Continuous filament radiation will heat the cathode to approximately 900°C, and the cathode capacitor energy heats the cathode for the remaining amount up to 1800°C. This scheme is different in the important detail that continuous filament ac heating power must be supplied and therefore isolation inductors are required, but a control circuit is unnecessary. It models the experiment to be discussed in the present paper.

Verification of the pulse-mode simulation was obtained with the same apparatus used to heat the LaB₆ cathode to 1800°C in the steady state by electron bombardment [1], [7]. Minor modifications of the apparatus allowed it to be used for the pulsed heating tests. Trial runs in the peak temperature range of 1100° to 1200°C gave close agreement between the experiment and model. Peak cathode temperature predictions were within 2 percent of experimental results, while bombardment current predictions were within 25 percent.

II. PULSE HEATING SIMULATION

A. Thermal and Electrical Models

The thermal and electrical model is shown in Fig. 1. The cathode and filament are assumed to lose heat by thermal radiation only. The filament capacitor C_f discharges into the filament when the filament switch closes. The cathode capacitor C_c discharges through the filament-cathode "thermionic switch." The cathode and filament are assumed to have emissivities and specific heats that are independent of temperature. The work function of the filament is varied as a program input because of the lanthanum activation effect. It is a critical parameter because

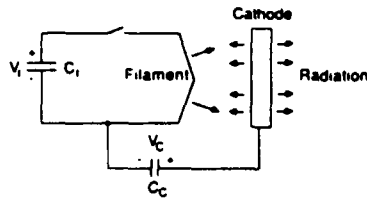


Fig. 1. Model for transient electron bombardment heating. Cathode heating energy is stored in C_c . Filament heating energy is stored in C_f , which could be replaced with a storage battery.

it appears in the exponent of the Richardson-Dushman equation. The mass densities of the filament and cathode are assumed to be constant. Radiation view factors [11], [12] between the cathode and filament, the filament-cathode gap perveance, and the areas and volumes of the filament and cathode are estimated from formulas using the actual dimensions of the system.

The dynamic thermal equations used to describe this system are as follows:

Filament Heat Balance:

$$H_f \frac{dT_f}{dt} = P_H - a_f \epsilon_f \sigma (2 - F_{fc}) (T_f^4 - T_a^4) + R^{-1} \sigma (T_c^4 - T_f^4) \quad (1)$$

Cathode Heat Balance:

$$H_c \frac{dT_c}{dt} = V_B I_B - a_c \epsilon_c \sigma (2 - F_{cf}) (T_c^4 - T_a^4) - R^{-1} \sigma (T_c^4 - T_f^4) \quad (2)$$

where

$$R = \frac{1 - \epsilon_f}{a_f \epsilon_f} + \frac{1}{a_c F_{cf}} + \frac{1 - \epsilon_c}{a_c \epsilon_c}$$

P_H	filament electrical heating power,
$V_B I_B$	bombardment power,
T_f	filament temperature (K),
T_c	cathode temperature (K),
T_a	ambient temperature (K),
F_{cf}, F_{fc}	radiation view factors,
a_f, a_c	filament, cathode view areas,
ϵ_f, ϵ_c	filament, cathode emissivities,
H_f, H_c	filament, cathode heat capacities,
σ	Stefan-Boltzmann constant.

The equivalent geometry used for the filament-cathode gap is shown in Fig. 2. The view factors and perveance are calculated from the following equations in terms of the diameter of the cathode, radius of the filament, and filament-cathode separation. The radiation view factor for two parallel disks is given as [12]

$$F_{fc} = \frac{r_f^2 + r_c^2 + z^2 - \sqrt{(r_f^2 + r_c^2 + z^2)^2 - 4r_f^2 r_c^2}}{2r_f^2}$$

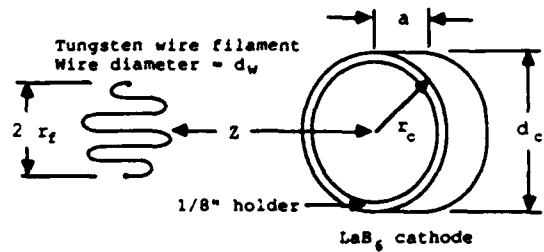


Fig. 2. Filament and cathode disk model for perveance and view factor calculation. The actual filament consists of 6 hairpin turns of tungsten wire lying in a plane. The filament equivalent disk radius is $r_f = 0.564$ cm, the wire diameter is $d_w = 0.508$ mm, the LaB₆ diameter is $d_c = 2.54$ cm, the LaB₆ thickness is $a = 0.317$ cm, and the filament-cathode separation is $z = 0.565$ cm.

The cathode-to-filament view factor can be obtained by the reciprocity relation [11]:

$$F_{cf} = (a_f/a_c) F_{fc}$$

The perveance of the filament-cathode gap is given by

$$\rho = (9.341 \times 10^{-6}) r_f^2 / z^2$$

where z = filament-cathode separation; r_f = filament equivalent-disk radius; r_c = cathode radius; and ρ = filament-cathode gap perveance. The value used for r_c accounts for the area of the cathode covered by the molybdenum cathode holder. The numerical constant in the equation for ρ and the view factor equations are obtained by modeling the filament as a thin disk. The shape of the actual filament is sketched in Fig. 2. The EGUN code [13] is used to calculate the perveance of the disk-cathode diode, giving the constant in the equation for ρ .

The heat capacities are given in terms of the specific heat capacities, volumes, and mass densities by

$$H_f = h_f \cdot \rho_{mf} \cdot \text{Vol}_f$$

$$H_c = h_c \cdot \rho_{mc} \cdot \text{Vol}_c$$

The bombardment current I_B is given by an empirical equation [14] that allows a continuous transition between the space-charge-limited and temperature-limited operation of the filament. It is given by

$$\frac{1}{I_B} = \frac{1}{I_{TL}} + \frac{1}{I_{SCL}} \quad (3)$$

where

$$I_{SCL} = \rho V_B^{3/2}$$

$$I_{TL} = a_f A T_f^2 \exp(-11600\phi/T_f)$$

ϕ work function of filament,

A Richardson-Dushman constant for the tungsten filament,

V_B bombardment voltage.

The electrical equation for the filament voltage is given by

$$R_f C_f \frac{dV_f}{dt} + V_f = 0 \quad (4)$$

with the initial condition $V_f(0) = V_{f0}$. The resistance of the filament is allowed to change with the filament temperature according to the equation

$$R_f = R_{fh} - \alpha(2300 - T_f) \\ \alpha = (R_{fh} - R_{fc})/(2300 - 25) \quad (5)$$

where R_{fh} is the filament resistance at 2300°C. R_{fc} is the resistance at 25°C. α is the approximate temperature coefficient of resistivity, and T_f is in °C. The value of α is estimated to be 0.000214 Ω/K for a filament length of 12.5 cm and wire diameter of 0.508 mm, and the values of R_{fh} and R_{fc} are calculated to be 0.5264 and 0.0389 Ω , respectively. The electrical power to the filament P_H is calculated from

$$P_H = V_f^2/R_f. \quad (6)$$

The complete electrical circuit, including the charging resistor for the cathode capacitor, is shown in Fig. 3. The cathode capacitor C_c is charged through the 35-k Ω charging resistor R_{ser} and the 5-k Ω dummy load resistor R_{sh} . The filament capacitor only uses 24 V and could be charged from a battery, or a battery and switch could be used instead of a capacitor. The load on C_c is the nonlinear thermionic diode resistance from filament to cathode. There is no resistance in series with the diode, and therefore in this case the capacitor voltage V_{sc} and the bombardment voltage V_B are equal. Using this circuit we can write down the relationship between V_B and I_B :

$$C_c \frac{dV_B}{dt} = \frac{V_{sc0} - V_B}{R_{ser} + R_{sh}} - I_B. \quad (7)$$

The relationship between I_B and V_B is given by (3).

The dynamic equations for the system are (1) through (7). These equations are integrated with a fourth-order Runge-Kutta method [15] to obtain solutions for V_B , I_B , T_c , and T_f as functions of time along with other parameters of interest. The main input parameters that were varied are the initial values of the filament temperature T_{f0} , cathode temperature T_{c0} , cathode capacitor voltage V_{sc0} , filament capacitor voltage V_{f0} , cathode capacitor C_c , filament capacitor C_f , and filament work function ϕ . Various constants and calculated parameters are listed in Table I.

B. Results of 1-in Cathode Simulations

The complete set of equations (1)–(7) were solved for single-shot and 120-s cyclic operation. In the circuit of Fig. 3, C_c recharges through R_{ser} and R_{sh} when the thermionic switch opens ($I_B = 0$) after both capacitors are discharged. The process is started by discharging C_f into the filament. This turns on the filament–cathode diode and bombardment heating begins. The cathode back radiation continues to heat the filament until the cathode capacitor is nearly 100 percent discharged. As the cathode and filament cool, the thermionic switch opens and the cathode capacitor recharges.

This operation was simulated for an initial charge voltage on the filament capacitor of 20 or 24 V in all cases

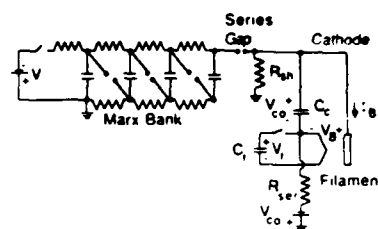


Fig. 3. Complete circuit showing the Marx generator for pulsing the gun anode-cathode gap and the bombardment cathode-heating circuit.

presented here. The filament work function had to be less than 3.5 eV for the system to work, signifying the importance of an activated filament, since the normal work function of tungsten is 4.55 eV. Otherwise, back radiation heating could not keep the filament hot enough to provide sufficient bombardment current. The filament resistance was allowed to vary with temperature through (5), but this did not have a large effect. The ambient temperature was assumed to be 25°C, and the maximum cathode temperature reached was chosen to be 1800°C. The filament temperature was kept under 2439°C. It was also attempted to have the cathode reach its maximum temperature in as long a time as possible to prevent cracking the LaB₆ cathode by heating it too rapidly.

Single-shot operation is defined as one heating pulse which raises the cathode temperature from ambient temperature to 1800°C. The cathode is then allowed to cool back to ambient temperature. Operation in this mode with a variety of special cases of the above model was studied. It was found that for certain circuit parameters a minimum heating energy could be found. For example, a 1-in cathode required 9900 J of energy for heating to 1800°C with a 3-kV charging voltage. The required cathode capacitance was 2200 μF , and the time required to reach the maximum temperature was 7 s. The filament was heated initially by 160 J of energy from a 800 mF capacitor charged to 20 V, but after approximately 0.5 s radiation from the cathode became the dominant heating source for the filament. The maximum bombardment current was 1.5 A.

A typical 120-s cyclic operation with a base temperature of approximately 600°C was found to be very efficient. Several seconds of flattop time on the cathode temperature at 1800°C are obtained and provide a relatively long time to fire electron beam pulses at the peak cathode temperature. The average total power required is 59 to 67 W, or less than 10 percent of the steady heating power requirement. The method takes full advantage of the thermionic switch and tungsten filament activation by lanthanum.

Typical results for cyclic operation are shown in Table II. The two cases presented are for an activated filament work function of $\phi = 2.6$ eV. There is a slight increase in energy requirements for $\phi = 3.0$ eV; however, the energy requirements double for $\phi = 3.5$ eV. For higher values of ϕ , the system did not work because the filament could not emit enough bombardment current at the temperature it was heated to by the energy stored in C_c and

TABLE I
CONSTANTS AND CALCULATED PARAMETERS USED FOR HEATING
CALCULATIONS

Constants:			
A	Richardson-Dushman constant for tungsten	120	A/cm ² /°K ²
ρ_{-f}	Mass density of tungsten	19.35	gm/cm ³
ρ_{-c}	Mass density of LaB ₆	2.61	gm/cm ³
h_f	Specific heat capacity of tungsten	0.2694	J/gm-°K
h_c	Specific heat capacity of LaB ₆	1.046	J/gm-°K
ϵ_f	Emissivity of filament	0.2	
ϵ_c	Emissivity of cathode	0.7	
Calculated Parameters:			
F_{cf}	View factor, cathode-filament	0.240	
F_{fc}	View factor, filament-cathode	0.684	
a_f	View area of filament	1.0	cm ²
a_c	View area of cathode	2.85	cm ²
Vol_f	Volume of filament	0.0254	cm ³
Vol_c	Volume of LaB ₆ cathode	1.61	cm ³

TABLE II
SIMULATION RESULTS WITH EQUAL INITIAL AND FINAL (ENDPOINT)
FILAMENT AND CATHODE TEMPERATURES ON A 120-s CYCLE*

Cathode Parameters ($T_{cmax} = 1800^\circ\text{C}$)								
C_c (mF)	T_{c0} end- pts (°C)	$t @$ T_{cmax} (s)	$V_B(0)$ (V)	V_{Bmin} (V)	$V_B @$ 120 s (V)	$I_B(0)$ (A)	E_c (J)	P_{Nave} (W)
1.57	581	4.3	3000	472	2473	1.531	7065	58.9
2.57	588	5.9	2500	510	1709	1.164	8031	66.9

Filament Parameters					
C_f (mF)	T_{f0} end- pts (°C)	T_{fmax} (°C)	$t @$ T_{fmax} (s)	E_f (J)	P_{Nave} (W)
770	486	2425	0.5	222	1.85
780	493	2439	0.5	225	1.87

*Filament work function: $\phi = 2.6$ eV.

thermal radiation from the cathode. The cathode capacitor voltage is recharged in 120 s because the thermionic switch opens and allows it to recharge through the 40-k Ω charging resistor ($R_{err} + R_{sh}$). These two resistors must withstand the full electron gun cathode-anode voltage. The cathode capacitor is 1.57 mF and the total energy storage in cyclic operation is approximately 7300 J for the 3-kV case. The most advantageous savings is the average heat load. Only 60 W are needed for the 3-kV case, compared to 700 to 1000 W for steady heating.

A plot of T_c , T_f , I_B , and V_B is given in Fig. 4. Although not apparent from the curve, the filament temperature curve of Fig. 4(a) includes filament heating by back radiation from the cathode. The rate of decrease in T_f in Fig.

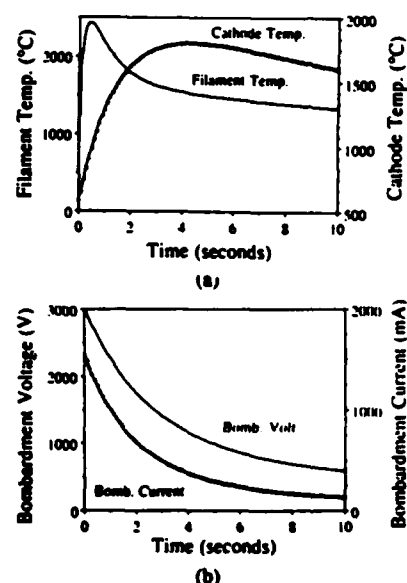


Fig. 4. Simulated 1-in. cathode 120-s cyclic operation for $V_{c0} = 3$ kV. Other parameters and energy requirements for this case are given in the first line of Table II. (a) Transient filament and cathode temperatures with cathode peak at 1800°C . (b) Transient bombardment voltage V_B and current I_B . These waveforms repeat every 120 s.

4(a) is slower than would be the case without back radiation. The cathode temperature peaks at approximately 4 s. Cathode heating at this rate raises the possibility of cathode cracking, which could be prevented by providing relief of thermal stresses in the cathode by the choice of cathode thickness, cathode holder design, and stress-relief cuts in the cathode disk. Another possibility is to place the cathode in thermal contact with another material to raise the effective specific heat and slow down the rate of rise of the temperature.

The model has been applied to calculations for cyclic heating of a 2-in diam cathode. It is found that a more massive cathode gives as large an advantage in terms of the average power needed for cyclic pulse heating in comparison to the power needed for steady heating. Numerical results for a 2-in cathode are given in Section IV.

III. PULSE-HEATING EXPERIMENT

An experiment was performed using the pulse-mode heating technique on an existing continuously heated electron gun [7]. The gun system was modified to resemble the simulated system. The match was not exact because the filament is continuously heated by 60-Hz current, but is similar enough to model the cathode capacitor discharge and resulting temperature rise. The continuous filament heating makes the operation similar to the 120-s cyclic case, since the filament heats the cathode to a base temperature of approximately 900°C by radiation alone. The filament was heated enough to make it operationally space-charge limited. The cathode capacitor energy raises the cathode to a temperature greater than the base temperature by an amount that depends on the initial energy stored in C_c .

A. Experimental Configuration

The configuration used is much the same as in Fig. 3, with the exception of an added resistor R_{pn} placed in series with the cathode capacitor to protect the digitizer against possible gap arcing, and the use of a switch to allow single-shot bombardment heating. The resistors R_{sh} and R_{ser} of Fig. 3 are omitted. The new circuit is shown in Fig. 5.

The filament current is set by the variable transformer. When the cathode temperature is at steady state, the cathode capacitor is charged to the desired voltage from the dc power supply with switch $S1$ open. The capacitor is isolated from the power supply by opening switch $S2$, and then discharged through the filament-cathode gap by closing $S1$, which is a vacuum relay high-voltage electromechanical switch. This switch remains closed until C_c completely discharges (about 30 s). As the capacitor discharges, the LaB_6 cathode is heated by electron bombardment. The digitizer samples the capacitor voltage V_{ac} by the use of a resistive voltage divider, and the bombardment current is sampled across the 1- Ω resistor R_B . The temperature is read by the use of a rapidly responding infrared temperature monitor. All signals were digitized at a 200-Hz sampling rate for approximately 40 s. The next capacitor discharge was initiated after the cathode had returned to its steady-state temperature.

B. Model Simulation

The model used to reproduce the experimental apparatus is a modified version of the 120-s cyclic model presented in Section II. The filament temperature is assumed to be constant for the duration of the capacitor discharge. In reality, a maximum temperature increase of about 10°C would be encountered in the filament due to back radi-

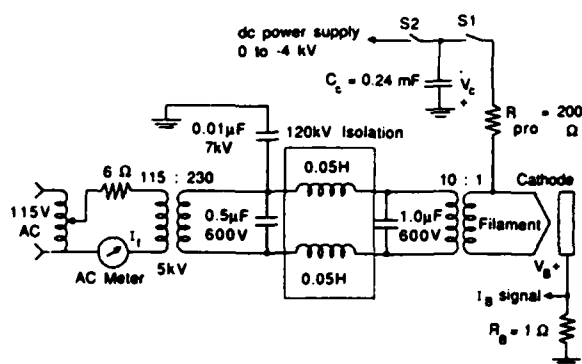


Fig. 5. Actual single-shot test circuit with continuous filament heating. V_c is measured through a resistive voltage divider. S1 is a high-voltage vacuum relay.

tion from the cathode; however, the resulting increase in the space-charge-limited filament emission current and hence the increase in the cathode temperature would be small.

Of the original seven equations from Section II, all are applicable in the present model except (7), which must be modified because of R_{pn} . Assuming that the filament temperature is constant, the steady-state cathode temperature can be found from (2) with $dT_c/dt = 0$:

$$T_c = \frac{[T_f^4 + a_c \epsilon_c (2 - F_{cf}) R T_a^4 + R \sigma^{-1} V_B I_B]^{1/4}}{[a_c \epsilon_c (2 - F_{cf}) R + 1]^{1/4}}. \quad (8)$$

The temperature-limited component of the bombardment current is assumed to be constant for the duration of the discharge and is given by I_{TL} in (3). The net bombardment current is found from (3) and is approximately the same as the space-charge limited current I_{SCL} . The determination of V_B , however, is different (since the bombardment voltage is not the same as the capacitor voltage). If the capacitor voltage V_C is known, the bombardment voltage V_B is found from

$$V_B = V_C - R_{\text{pm}} I_B \quad (9)$$

by solving the algebraic equations (3) and (9) for V_B and I_B by the method of bisection. The capacitor voltage is related to I_B by

$$dV_C/dt = -I_A/C_C \quad (10)$$

The cathode temperature and capacitor voltage are found by integrating (2) and (10) by the Runge-Kutta method. The code is designed to calculate V_C , V_B , T_c , I_{SCL} , and I_B as they vary with time.

C. Comparison of Experimental and Calculated Results

Despite the slight differences between the model and the experiment in geometry, the results are in good quantitative agreement.

Experimental values of I_f from 2.5 to 3.3 A were used to vary the steady-state temperature. Initial cathode capacitor voltages V_{C0} ranging from 500 to 3300 V were used. Plots of the measured bombardment currents and cathode temperatures from the four highest filament cur-

TABLE III
COMPARISON OF EXPERIMENTAL AND CALCULATED CASES

V_{C0} (V)	I_f (A)	T_{16} (°C)	T (°C)	T (°C)	T_{max} (°C)	T_{max} (°C)	T_{16} (°C)	T_{16} (°C)	I_{max} (A)	I_{max} (A)
3074	2.7	2150	884	884	1101 @ 1.04 s	1080 @ 1.10 s	944	999	1.1346 @ 150 ms	1.102
3082	2.7	2214	916	916	1128 @ 0.91 s	1127 @ 1.10 s	984	1000	1.147 @ 75 ms	1.104
3087	3.1	2318	943	943	1163 @ 0.98 s	1157 @ 1.60 s	1016	1064	1.198 @ 50 ms	1.307
3053	3.3	2439	999	999	1206 @ 0.88 s	1208 @ 1.60 s	1067	1109	1.314 @ 0 ms	1.287

* = experimental data; $\phi = 2.6$ eV; T_{16} = cathode temperature at $t = 16$ s.

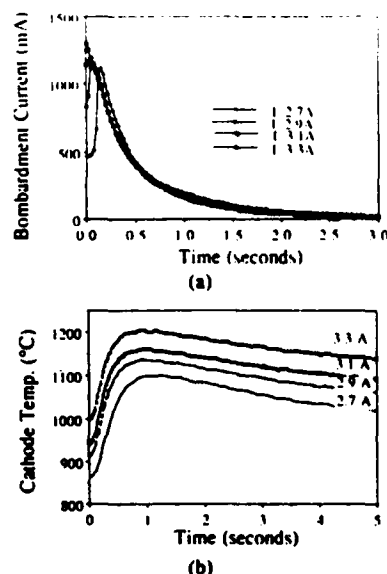


Fig. 6. (a) Experimental bombardment current for various filament currents. $V_{C0} = 3$ kV. (b) Experimental cathode temperature for the same parameters as (a).

rent runs at $V_{C0} = 3$ kV are shown in Fig. 6. At early times they show the gradual transition from temperature-limited to space-charge-limited bombardment current as I_f is raised.

A comparison study was done between the 3-kV experimental runs and a 3-kV solution with the model. Before this comparison could begin, consistent values were needed for the filament separation and the temperature of the filament. To estimate these values, data from the $I_f = 3.3$ A run, which is most clearly space-charge limited, were used. Using the experimental initial bombardment current, which is equal to the space-charge-limited current for high filament temperatures, the separation z was varied until the initial bombardment current of the model matched that of the experiment. This separation was then used for all the model runs. Calculation of the filament temperature for each of the filament current values was obtained by changing the model's filament temperature until the initial cathode temperature of the model, as given by (8) with $V_B I_B = 0$, matched that of the experiment.

Despite the estimates that had to be made, the differences between the model calculations and experimental results are small. A comparison for the 3-kV cases is shown in Table III. With the initial cathode temperatures set to be the same in the model and experiment, the peak temperatures differ by less than 2 percent, although the peak times are off by a factor of 1.75. This indicates a complete transfer of energy, but at a different rate than predicted. The cooling of the cathode also exhibits this rate difference.

The experimental and calculated peak bombardment currents are within 25 percent of each other. The main difference is the time of occurrence of the peak bombardment current. In the model the temperature-limited filament emission current for the lower filament current case is over 100 A. This is consistent with space-charge-limited operation at bombardment currents of approximately 1 A. Space-charge-limited operation is observed in both experimental and calculated results.

A sample comparison of the transient cathode capacitor voltage, cathode temperature, and bombardment current between the model and experiment for the case of $V_{C0} = 3$ kV, $I_f = 2.7$ A is shown in Fig. 7. The largest disagreement between the measured and calculated cathode temperature curves is in the rates of heating and cooling. It is believed that the major contributing factors to this are incorrect values of emissivities, poorly defined geometry for the hottest parts of the system, and neglect of heat losses by conduction and heat-shield radiation. The main goal of the simulation was to predict the peak cathode temperature obtained for a given amount of bombardment energy, and there is good agreement for that calculation.

IV. SUMMARY

Cathode heating in a thermionic LaB_6 electron source can be a major problem from a power and cooling perspective. Steady-state heating to temperatures in the 1800°C range can require excessive power for cathode sizes of 1-in diam or more. A pulsed-mode heating method has been developed and tested for a 1-in diam cathode which reduces the average filament power by over an order of magnitude. The method allows cyclic operation

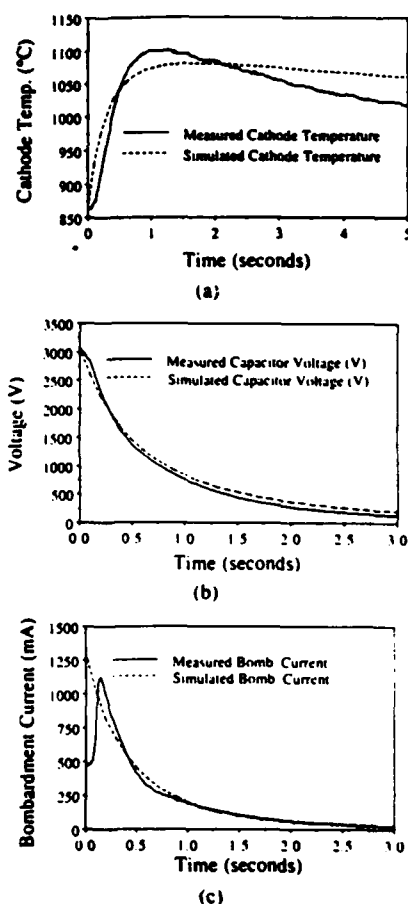


Fig. 7. Comparison of simulation model and experiment for a single heating pulse at $V_{CO} = 3$ kV and $I_f = 2.7$ A. (a) Cathode temperature. (b) Capacitor voltage V_C . (c) Bombardment current I_B .

with a few seconds of peak cathode temperature, which would allow many microsecond-duration electron pulses to be fired at the peak cathode temperature in each cycle. For a 2-in diam 0.125-in-thick LaB_6 cathode the savings is just as great. A 1.68-mF capacitor at 6 kV can cycle the larger cathode from 494° to 1800°C and back in 120 s. The energy requirement is 30.2 kJ, which is an average power of 252 W. This is still a savings of over an order of magnitude from the case of steady heating. The assumption of the same cathode thickness as in the 1-in case is utilized in this prediction.

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High Current Density Results From a LaB_6 Thermionic Cathode Electron Gun

Marc E. Herniter¹ AND Ward D. Getty²

Abstract - A Pierce-type electron gun using a planar 1.9-cm-diameter lanthanum hexaboride cathode is being studied as a robust thermionic emitter at high cathode current densities. The gun has been operated up to voltages of 115 kV achieving beam current densities of 30 A/cm². The electron gun operated dependably up to voltages of 90 kV achieving temperature-limited currents of 50 A. Due to the high fields at the tip of the Pierce-focusing electrode the gun would usually arc at voltages greater than 90 kV. Ten shots were obtained at a gun voltage of 115 kV achieving transmitted currents up to 89 A, transmitted beam power up to 10.2 MW, and transmitted power densities up to 3.4 MW/cm².

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I. INTRODUCTION

This paper describes the high-voltage operation of a Pierce-type electron gun with a lanthanum hexaboride (LaB_6) thermionic cathode. The cathode is heated by an electron bombardment method. The heating system and low-voltage operation of this gun were discussed in a previous article [1]. The results previously presented were for a maximum gun voltage of 36 kV and a current density of 6.7 A/cm². The results presented here are for gun voltages up to 115 kV and transmitted current densities up to 30 A/cm². To operate the gun at these higher voltages, modifications to the electron gun assembly and electrical isolation were necessary. These modifications are discussed here. Several modifications to the heating system have also been made. These changes and an analysis of the bombardment heating system will be discussed in a future article.

Lanthanum Hexaboride is used as a cathode material in applications where high current density and resistance to chemical poisoning are important. Its original properties were first investigated by Lafferty in 1951 [2]. Lafferty originally determined the thermionic emission constants of LaB_6 to be $A = 29 \text{ A/cm}^2 \cdot ^\circ K^2$ for the Richardson-Dushman constant and $\phi = 2.66 \text{ eV}$ for the work function [2]. Since the original work several authors have reported various values for the work function and the Richardson-Dushman constant. A sampling of reported values gives A in the range of 29 to 73 A/cm²·°K² and ϕ in the range of 2.4 to 3.2 eV [3,4].

The emissivity of LaB_6 has been reported to be in the range of $\epsilon = 0.7$ to 1.0 [5,6,7,8]. Storms has determined the emissivity of LaB_6 at 650 nm as a function of temperature [9]. Typically the value is between 0.7 and 0.8 for temperatures of interest.

The evaporation rate of LaB_6 is lower than other conventional thermionic cathodes when compared at the same emission density. At an emission density of 5 A/cm² the evaporation rate of LaB_6 is approximately 100 times less than the evaporation rate of tungsten at the same emission density [2]. Uniform evaporation of LaB_6 takes place from the surface [3]. Low evaporation rate is important for increased cathode lifetime.

An advantage of LaB_6 is its modest vacuum requirements. Ahmed and Broers reported that LaB_6 can be operated in vacuum around 10^{-5} Torr [3]. LaB_6 is suitable for demountable systems since it is atmospherically stable [2]. LaB_6 cathodes do not require activation. Usually the temperatures required to outgas the cathode are sufficient to activate the cathode [2].

A difficulty with LaB_6 is that boron reacts with refractory metals at elevated temperatures [6,5]. When LaB_6 is used with metals such as tungsten, molybdenum, or tantalum, the boron diffuses into the metal lattice forming boron alloys with it [10,2]. When the diffusion starts the boron lattice which holds the lanthanum collapses, allowing the lanthanum to evaporate [2]. The reactions can be minimized by using rhenium or tantalum-carbide, or eliminated by using graphite [6,5] for the materials which must come in contact with LaB_6 at elevated temperatures.

A. Previous Work With LaB_6 Cathodes

Because of its low work function and evaporation rate much work has been done with LaB_6 cathodes. Shintake *et al.* [10] used a LaB_6 cathode in a Pierce-type electron gun with a highly concave spherical cathode of area 5.5 cm^2 achieving a current density of 0.3 A/cm^2 at 1300°C . Schmidt *et al.* [7] have developed a single-crystal LaB_6 cathode for use as an interchangeable electron source in a variety of electron microscopes and similar instruments. Emission currents as high as 50 A/cm^2 were observed from $3 \times 10^{-5} - \text{mm}^2$ cathodes. Broers [11,12] obtained current densities of 0.8 to 40 A/cm^2 from a $1 - \text{mm}^2$ LaB_6 rod cathode over a temperature range of 1400 to 1800°C . This cathode was designed as a long-life electron source suitable for electron microscopes. The LaB_6 cathode has at least a two order of magnitude greater life-time than the conventional tungsten hairpin filament at the same emission density [11]. Goebel *et al.* [6] obtained current densities up to 20 A/cm^2 from a $30 - \text{cm}^2$ cathode at 1700°C . This cathode was intended for use in a plasma source. The emission levels obtained were in the presence of hydrogen at a pressure of 4×10^{-4} Torr. Loschialpo and Kapetanakis measured an average current density of 12 A/cm^2 from a $5 - \text{cm}$ -diameter LaB_6 cathode [13]. This cathode was designed to be the electron source for gyrotrons and free-electron-lasers.

B. Recent Work With High Current Density Cathodes

Along with LaB_6 , other cathodes are also being researched as possible high current density sources. Most of the work has focused around LaB_6 , dispenser, and photo cathodes.

Friedman and Eninger [14] achieved $30 A/cm^2$ from a 100-cm^2 porous tungsten matrix dispenser cathode. The actual emission area was shown to be approximately 70 cm^2 . This cathode is driven by a 300-kV pulse forming network producing $1\text{-}\mu s$ pulses at a repetition rate of 25 Hz . Successive runs with an average of 1000 pulses at 25 Hz were made. During these runs the vacuum pressure rose to $2 \times 10^{-6}\text{ Torr}$ with no degradation in the output current.

Shih *et al.* [15] achieved current densities up to $50 A/cm^2$ with an osmium-coated impregnated dispenser cathode. The vacuum was maintained below $2 \times 10^{-8}\text{ Torr}$ at all times. Life studies indicated that at an emission level of $40\text{-}50 A/cm^2$ over 800 hours of life is obtainable [15].

Lee *et al.* [16] achieved $200 A/cm^2$ from a 1-cm^2 Cs_3Sb photocathode irradiated by a Nd:glass laser. The experiment was performed in a vacuum chamber pumped to 10^{-9} Torr . The duration of the electron pulse was 50 ns . Stable shot-to-shot operation was noted.

Massey *et al.* [17] achieved $30 A/cm^2$ from a 1-cm^2 organic film photocathode. The cathode was illuminated with a 1-MW -peak power nitrogen laser. The output current pulse width was 5 ns .

C. Free Electron Lasers

An application that requires high current density and high quality is that of the free-electron-laser (FEL). It has been shown that high current density is an important factor in achieving high beam quality [18]. Beam quality is defined as [19]:

$$B_Q \equiv \frac{J}{\Delta\gamma_z/\gamma}. \quad (1)$$

J is the beam current density and $\Delta\gamma_z/\gamma$ is a measure of the energy spread in the direction of propagation. The beam quality can be increased by increasing the beam current density or lowering the energy spread. Cathode contributions to the energy spread are initial velocities of the electrons leaving the cathode

(thermal spread), surface roughness, and non-uniform emission [20,21].

The output power of a free-electron laser is proportional to the total beam current. To achieve high output power a high total current is required. This requirement implies the use of a large area cathode to achieve large total current.

The cathode requirements for a free-electron laser are high current density and low energy spread from a large-area cathode.

II. THE ELECTRON GUN ASSEMBLY

An assembly drawing of the electron gun is shown in Fig. 1. The perveance of this gun as predicted by the E-GUN program [22] is 3.2×10^{-6} . The gun is mounted on a 11.4-cm diameter, 1.27-cm thick boron nitride baseplate. The cathode stalk is made from 3.8-cm diameter, 0.0508-cm wall tantalum tubing. It contains the bombardment-heating tungsten filament and heat shield, and supports the cathode at one end. Large holes are bored into the cathode stalk at its base to reduce thermal conduction through the stalk. The LaB_6 cathode is placed in a graphite cup that is mounted in a molybdenum holder. The emission area of the cathode is 2.85 cm^2 . The original purpose of the graphite cup was to shield the filament from evaporation of lanthanum when the cathode is heated. The cup has the desirable side effects of providing even heating of the cathode and eliminating cathode cracking. The focusing electrode is made of molybdenum and is mounted on a separate 5.08-cm diameter tantalum tube to thermally insulate it from the cathode. The focusing electrode and cathode holder are separated by a 0.05-cm vacuum gap. The gap allows the focusing electrode to run at a lower temperature than the cathode stalk which reduces heating power requirements. The bombardment filament is made of 0.0381 to 0.0508-cm diameter pure tungsten wire. The gun anode is made of OFHC copper and is also mounted on the boron nitride.

The main function of the baseplate is to support the cathode stalk and the heat shield. Boron nitride is a good thermal conductor, a good electrical insulator, and has a high melting temperature. These properties allow large voltages to be applied across the baseplate surface between the copper anode and focusing electrode support tube, and allow the baseplate to serve as a low thermal resistance path for

removing heat from the gun assembly. The length of boron nitride between the focusing electrode support tube and the copper anode is approximately 2.5 cm. Grooves are machined into the baseplate to increase the breakdown strength across its surface. In cold pulsing results, up to 140 kV was applied across this length of boron nitride without surface flashover.

The anode face plate is made of stainless steel. The plate was machined to a smooth surface and then electro-polished to remove all burrs. A smooth surface is required because of the high fields present in the anode-cathode region. Any burrs on the anode, the cathode holder, or the focusing electrode could cause electrical breakdown.

Surrounding the anode is a removable water cooling jacket. The jacket is constructed from a 0.102-cm thick sheet of OFHC copper rolled into a tube with an inside diameter the same as the anode's outside diameter. Copper refrigeration tubing is silver soldered to the tube to provide cooling. A mounting bracket is provided for clamping the cooling jacket on the anode to provide good thermal conduction between the cooling jacket and the anode.

III. ELECTRICAL ISOLATION

In order to operate the electron gun at high pulsed voltages while the cathode is being heated, an electrical isolation system is needed. This system allows power at ground potential to be passed to the bombardment heating filament which is pulsed up to high voltages with the electron gun. A system with three isolation inductors was used which allowed the heating system controls and most of the electronics to reside at ground potential.

The isolation system is shown in Fig. 2. Filament power is obtained through two impedance transformations. The 115 VRMS line is converted to 230 VRMS by a 5000 V isolation transformer with the 230 V side floating at the bombardment potential. The 230 V power is passed through two isolation inductors to a 10:1 transformer which supplies 23 V filament power at the gun potential. The 10:1 transformer is the only electrical component which is pulsed to high voltage with the electron gun.

The impedance transformations were needed so that power could be passed through the isolation

inductors. The resistance of the filament is less than one Ohm. Had the power been passed at the filament voltage of 23 V, the filament-isolation inductor loop would be mostly inductive permitting only a small amount of power to be dissipated by the filament. With the impedance transformations the equivalent filament resistance is 100 times the impedance of the filament.

The bombardment power is converted from 115 to 1800 VRMS and rectified on the ground side of the isolation. It is passed to the filament-cathode diode gap through two isolation inductors. The bombardment current sensing resistor, R_s , is placed on the ground side of the isolation with one side of R_s grounded. Since R_s is grounded it is easily connected to electronics which are also grounded. This placement of R_s allows the use of semiconductor electronics in the control circuit.

A 75 Ω resistor is shown in series with the output of the bombardment voltage bridge rectifier. The purpose of this resistor is to limit the current through the bridge rectifier when there is an arc between the filament and the cathode. A 6 Ω resistor is shown in series with a MOSFET switch. The purpose of this resistor is to limit the current through the switch during high frequency switching. The input impedance of the 115:230 transformer is capacitive at high frequency and will cause large surge currents through the MOSFET switch. The 6 Ω resistor limits these surge currents.

Several capacitors are shown in Fig. 2. These are small enough to be considered open circuits to the heating system but large enough to be considered short circuits to the pulse voltage. The purpose of the capacitors on the high voltage pulsed side of the inductors is to maintain the heating system voltages between the isolation inductors during the voltage pulse. If these capacitors were not in the circuit, only the inductor directly connected to the Marx generator output would be raised to the pulse voltage. The entire pulse voltage plus the bombardment and filament voltages would appear across the filament-cathode gap. The capacitors do not change their voltage instantaneously and attempt to maintain a low voltage across the filament-cathode gap. The purpose of the capacitors on the ground side of the inductors is to prevent current surges through the inductors from reaching the heating system electronics.

This isolation system allows all of the heating system electronics except the 10:1 transformer to reside

at ground potential. This feature allows semiconductor electronics to be used in this high-voltage-pulse environment.

IV. HIGH VOLTAGE PULSING RESULTS

High voltage pulsing results of the electron gun are now presented. The gun has been operated with single shot voltage pulses up to 115 kV and cathode temperatures up to 1740 °C. Traces showing the gun voltage, transmitted current, and total current are shown. Total current is the current emitted by the cathode, cathode holder, and the focusing electrode. Transmitted current is the fraction of the total current that is focused through the anode aperture.

A. Low Temperature Transmitted Current and Voltage Traces

Several digitizer traces were taken to observe the gun voltage and transmitted current for varying cathode temperatures. The low-temperature operation of the gun was explored for transmitted gun currents from 1 A to 48 A. The current density from these shots are compared to predictions from Longo emission equation [23]. For the design perveance of the electron gun and the work function given by Lafferty the measured data do not fit the predictions of the Longo equation. Several possibilities for this discrepancy are suggested and include temperature measurement errors, a different LaB_6 work function from the one given by Lafferty, electron emission by surfaces other than the cathode, and increased fields at the cathode due to field enhancement.

Two sample traces of the electron gun voltage and transmitted current are presented in Figs. 3 and 4. The trace of Fig. 3 was taken at a temperature of 1326 °C. The gun voltage starts at a peak voltage of 88 kV. The change in the decay rate of the voltage pulse at 25 μ s is due to saturation of the isolation inductors. At low voltages the gun appears to operate space-charge-limited while at higher voltages the current levels off and is limited by the temperature of the cathode. During the temperature limited portion of the trace the current is seen to vary with the gun voltage. This variation is due to the large fields present at the cathode surface during temperature-limited operation. The fields lower the work function of the

cathode due to the Schottky effect [23,24,25]. The higher the voltage the more the work function will be reduced. With a cathode emission area of 2.85 cm^2 the space-charge-limited current predicted by the E-GUN program at 88 kV should be 83 A . A current of 14 A at 88 kV indicates that this trace is temperature limited at the higher gun voltages when compared to the predicted space-charge-limited current. Figure 4 shows the transmitted current and voltage at a cathode temperature of 1621°C and indicates a current of approximately 48 A at 88 kV .

The data presented in Figs. 3 and 4 can be presented as current versus voltage plots to observe the I-V characteristic of the electron gun. Figure 5 shows a composite I-V characteristic constructed from Figs. 3 and 4 and four other current and voltage traces. The space-charge-limited current of the electron gun given by the Child-Langmuir law assuming a microperveance of 3.2 is also shown. For cathode temperatures below 1498°C the gun operates as expected for varying cathode temperatures. At voltages below 20 kV the gun operates space-charge-limited and all I-V characteristics for temperatures at or below 1498°C indicate a gun perveance of 1.9×10^{-6} . The design perveance of the electron gun is 3.2×10^{-6} . The I-V characteristic with a cathode temperature of 1621°C indicates that the perveance of the gun has changed. For low voltages the space-charge-limited current indicates that the perveance of the gun has increased to the expected value of $3.2 \mu\text{P}$. This change in perveance may be due to emission from parts of the electron gun other than the cathode. At temperatures around 1600°C , evaporation of LaB_6 from the cathode was observed to affect the operation of the heating system by coating the heat shield with LaB_6 causing it to emit electrons. At 1600°C it may be possible that the cathode holder becomes coated with LaB_6 and emits electrons. Data presented later indicates that the 1326°C to 1498°C traces in Fig. 5 were at 100% beam transmission and the 1621°C trace was below 100% transmission. This reduced transmission may also indicate electron emission from the cathode also.

The I-V characteristic of Fig. 5 shows that the perveance of the gun changes at 1621°C . This change could be the result of variations in the anode-cathode spacing due to thermal expansion, or electron emission from the cathode holder which runs at a high temperature. Emission from the cathode holder could be

tested by constructing an electron gun which allows the cathode holder to run at a lower temperature. Emission from the cathode holder is indicated by other measurements which will also be discussed.

Figure 6 shows the I-V characteristic of the electron gun generated from shot EGUN191 in Fig. 3. Also plotted is the current predicted by the Longo thermionic emission equation [23] assuming emission areas of 2.85 and 8 cm², with the thermionic emission constants measured by Lafferty [2], $A = 29 \text{ A/cm}^2 \cdot ^\circ\text{K}^2$ and $\phi = 2.66 \text{ eV}$. An emission area of 2.85 cm² corresponds to electron emission by the cathode only. An emission area of 8 cm² corresponds to electron emission by the cathode and the entire cathode holder and is the largest possible emission area. It is seen that the Longo equation with either area predicts currents less than the measured current. The difference between the measured and predicted currents could be explained by a lower LaB_6 work function or a higher than measured cathode temperature. Another explanation could be greater fields at the cathode surface than expected due to field enhancement. The Longo equation predicts current densities by taking into account the electric field at the cathode surface when space-charge is not present. The higher the electric field the higher the current density. The electric field is calculated assuming a smooth cathode surface. However, the cathode surface is rough and the electric field at the surface may be larger than expected due to field enhancement. With a work function of 2.66 eV, an emission area of 2.85 cm², a field enhancement factor of 25 is required to fit the experimental data to the Longo equation. A field enhancement factor of 25 requires hair like protrusions from the cathode and may be an unreasonable value to expect from a machined cathode surface.

Figure 7 shows the I-V characteristic of the electron gun generated from shot EGUN325 in Fig. 4. Also plotted is the current predicted by the Longo equation with emission areas of 2.85 cm² and 4.9 cm². An emission area of 2.85 cm² successfully predicts the measured current during the low voltage portion of the I-V characteristic where the gun operates space-charge limited. At higher voltages the gun enters the temperature-limited regime of operation and an area of 4.9 cm² gives a better fit. Simulations of the electron trajectories with the E-GUN program show that as the gun becomes more temperature-limited a larger fraction of the electrons emitted by the cathode holder will be focused through the anode aperture.

If the cathode holder emits electrons then the emission area of transmitted electrons will increase as the voltage increases. The Longo equation with an emission area of 4.9 cm^2 successfully predicts the current at the highest voltage. Simulation of the electron trajectories show that electrons emitted from an area of 4.9 cm^2 will be focused through the anode aperture. For this reason, the area of 4.9 cm^2 is more realistic than the maximum possible area of 8 cm^2 . The measured current is bounded by the two curves of the Longo equation with these areas.

It was previously mentioned that a lower LaB_6 work function could explain the difference between the theoretical and measured current. The work function of LaB_6 has been reported to be in the range of 2.4 to 3.2 eV, and the Richardson-Dushman constant A in the range of 29 to 70 $A/cm^2 \cdot K^2$ [2,3,4]. Figures 6 and 7 show plots of the Longo equation using an emission area of 2.85 cm^2 , $A = 29 A/cm^2 \cdot K^2$, and various values of the work function. The measured current can be matched to the Longo equation with an emission area of 2.85 cm^2 by assuming a LaB_6 work function in the range of 2.33 - 2.5 eV. A work function 2.33 eV successfully matches Fig. 6 and a work function of 2.5 eV matches Fig. 7. With the variation in the reported work function it is not unreasonable to assume a lower work function. The Richardson-Dushman constant A was not changed to fit the Longo equation to the measured data since a variation of A will have the same effect as a variation in the emission area.

The measured data can also be fitted to the predicted curves by changing the cathode temperature. It is not unreasonable to assume higher than measured temperatures due to the uncertainties present in temperature measurement. However, assuming a cathode work function of $\phi = 2.66 \text{ eV}$ and an emission area of 2.85 cm^2 , the temperature must be increased by 100 to 200 $^\circ C$ to achieve a fit.

In summary, it is believed that the higher than predicted current is due to the combination of increased emission area, a lower work function than 2.66 eV, and a higher than measured temperature.

B. Transmitted Current versus Temperature

To observe the emission characteristics of the cathode the transmitted current versus temperature at constant voltage was measured over a number of shots. Two plots were constructed from shots 168 to

325. One plot was at a gun voltage of 46 kV and the other was at 88 kV. The plots are compared to the Longo emission equation. For the design perveance of the electron gun and the work function given by Lafferty the measured data do not fit the predictions of the Longo equation. Several possibilities for this discrepancy are suggested and include temperature measurement errors, a different LaB_6 work function from the one given by Lafferty, or electron emission by surfaces other than the cathode,

Figure 8 shows the transmitted current density versus cathode temperature at a gun voltage of 46 kV. Also shown are two plots of the Longo emission equation assuming the LaB_6 thermionic constants presented by Lafferty, $\phi = 2.66$ eV and $A = 29$ A/cm²·°K², with emission areas of 4 cm² and 8 cm². These areas assume that electrons are emitted by the cathode holder and that 100 percent of these electrons are transmitted through the anode aperture. The plot with a 4-cm² emission area matches the measured current plot at high temperatures where the gun approaches space-charge-limited operation but differs considerably from the temperature-limited portion of the measured plot. By increasing the emission area to 8 cm², the maximum possible thermionic current from the cathode and holder is plotted. From the E-GUN program simulations, a large fraction of this current would not be transmitted and the actual transmitted current assuming an area of 8 cm² would be less than this plot. Even with this larger emission area the measured transmitted current is greater than the current predicted by the Longo equation at low temperatures.

Figure 9 shows a similar plot to Fig. 8 but at a gun voltage of 88 kV. Figure 9 shows similar results to Fig. 8. At high temperatures where the gun approaches space-charge-limited operation, an emission area of 5 cm² matches the Longo equation to the measured data. At the lower temperatures where the gun operates temperature limited, an emission area of 8 cm² with the Longo equation cannot account for the measured current.

In Figs. 8 and 9 the Longo equation is plotted with an emission area of 2.85 cm² and thermionic constants $\phi = 2.4$ eV and $A = 29$ A/cm²·°K². This plot provides a better fit than can be obtained by varying the emission area but does not follow the general curve of the measured data.

As with the I-V characteristic plots, the cathode temperature can also be changed to achieve similar results as changing the work function. The cathode temperature had to be increased by 6% to 15% to fit experimental data to the Longo equation. These results are consistent with the I-V characteristic plots. It is believed that the higher than predicted current is due to a combination of increased emission area, a lower work function than 2.66 eV , and a higher than measured temperature.

C. Low Temperature Transmitted and Total Current

Companion shots to the voltage and transmitted current shots which show transmitted current and total current versus time were also taken. These shots were taken at the same time as the voltage and current shots, and were at the same cathode temperature and gun voltage. Since only two digitizer channels were available, transmitted current, total current, and gun voltage could not be measured simultaneously. These shots show how the transmitted and total current vary versus gun voltage and cathode temperature. A sample trace is shown in Fig. 10. This trace was taken at the same cathode temperature and gun voltage as shot EGUN325.

The total gun current is the sum of all currents emitted by the gun structure. The transmitted current is the current emitted by the gun structure that is focused through the anode aperture. The transmitted current is not always equal to the current emitted by the cathode and may contain current emitted by the cathode holder that is not intercepted by the anode.

All of the traces displayed the same characteristic. At low voltages the traces indicate 100 percent transmission while at the high voltages the transmission is approximately 90 percent. This characteristic is contrary to what would be expected from the focusing properties of the electron gun. If the cathode holder was emitting electrons then the percent transmission is expected to decrease as the gun operated more space-charge-limited. Thus at lower voltages or at higher cathode temperatures it would be expected that the percent transmission would decrease. However, shots showing transmitted and total current indicate that the percent transmission appears independent of temperature and increases as the voltage decreases.

The transmission characteristic may be explained by the Schottky effect. It may be that only a small

portion of the cathode holder emits electrons at low voltages and all of these are focused through the anode aperture. At higher voltages the fields on the holder will be large and the holder work function will be reduced due to the Schottky effect. The lowered work function will allow a larger portion of the holder to emit a significant amount of current. This current may not be transmitted through the aperture and may account for the lowered transmission at high voltages.

D. High Temperature Pulsing Results

Figures 11 and 12 show the electron gun voltage, total current, and transmitted current at cathode temperatures greater than 1650 °C. In Fig. 11 it is observed that the gun operates as expected with a thermionic cathode at the beginning of the pulse, but at the end of the pulse the current increases unexpectedly. Figure 12 shows that the current transmission at the beginning of the pulse is about 90 percent. It is believed that the 10 percent which is not transmitted through the anode aperture impacts the anode and forms a plasma. The plasma increases the gun perveance and eventually shorts the anode to the cathode. It is interesting to note that as the perveance increases the gun focusing is maintained. The percent transmission increases during the pulse and approaches 100 percent transmission before the cathode and anode short.

Figure 13 is a composite graph generated from shots 130 to 167 showing the percent beam transmission as a function of temperature. The gun voltage for the data presented in Fig. 13 was approximately 85 kV. It is observed that at a cathode temperature of 1620 °C the percent transmission begins to decrease. Lafferty reported that the thermionic emission current from a tungsten filament increased in the presence of evaporating LaB_6 [2], and that the evaporation rate becomes significant at 1600 °C. It is believed that at 1620 °C evaporation of LaB_6 from the cathode coats the gun electrodes enabling them to emit current at lower temperatures. The cathode holder, which is in good thermal contact with the cathode, is especially suspect as an unwanted electron emitter. The holder would not emit electrons in normal operation because of the high work function of molybdenum. With a LaB_6 coating its work function would be reduced and may be able to emit electrons. As the cathode temperature increases the holder temperature also increases,

allowing it to source more electrons. A large fraction of these electrons would impact the anode face plate causing a reduction in the percent transmission.

Several simulations of the electron trajectories were run using the E-GUN program. Simulations which assumed electron emission from only the cathode show 100% beam transmission independent of cathode temperature. The only effect of increasing temperature limitation was narrowing of the electron beam. From these simulations it can be expected that if only the cathode emits electrons then beam transmission should be 100% for all temperatures. E-GUN simulations were also run such that the cathode holder could emit electrons. These simulations showed that some of the rays which originated at the cathode holder would be focused through the anode aperture. As in above simulations, as the amount of temperature limitation was increased the electron trajectories were focused into a narrower beam allowing more of the trajectories to be emitted through the anode aperture. These simulations show that if the cathode holder is also an electron emitter than as the amount of temperature-limitation increases the percent transmission will increase. The percent transmission graph in Fig. 13 starts with a large amount of temperature limitation which decreases as the cathode temperature is increased. The decrease in percent transmission as the amount of temperature limitation decreases suggests that the cathode holder may be emitting electrons.

E. High Current Density Results

Figures 14 and 15 show the highest transmitted currents obtained with the electron gun. About ten successful shots were obtained. To achieve these currents the gun had to be pushed to voltages up to 115 kV causing the gun electrodes to arc on most of the shots. Figure 14 shows a transmitted current of 79 A at a gun voltage of 115 kV at a time of 1.4 μ s corresponding to a beam power density of 3 MW/cm². Figure 15 shows a transmission current of 89 A at a gun voltage of 115 kV at a time of 1.4 μ s corresponding to a beam power density of 3.4 MW/cm². Unfortunately the gain settings on shot EGUN357 make it difficult to differentiate between the current and voltage traces. The original display of the shot was in color and the waveforms appeared to be close to those in shot EGUN354. The top trace is the transmitted current

which starts in the lower left corner. It is positive in magnitude and decreases with time. The calibration for this trace is 20 A/div. The bottom trace is the gun voltage at 22.5 kV/div. This trace starts in the upper left corner and is negative in magnitude.

V. SUMMARY

A Pierce-type electron gun with a 1.9-cm-diameter LaB_6 cathode has been operated to 115 kV achieving transmitted beam current densities of 30 A/cm². The electron gun operated dependably up to voltages of 90 kV achieving temperature-limited currents of 50 A. Due to the high fields at the tip of the Pierce focusing electrode the gun would usually arc for voltages greater than 90 kV. The gun was pushed up to voltages of 115 kV but only one in several shots would not arc. Ten shots were obtained at these high voltages achieving transmitted currents up to 89 A, transmitted beam power up to 10.2 MW, and transmitted power densities up to 3.4 MW/cm². This problem of arcing can be reduced by further work on the electrode shapes to reduce the field strength at the tip of the Pierce focusing electrode.

These results can be compared to previous work with large-area LaB_6 cathodes. Goebel *et al.* [6] obtained 20 A/cm² from a 30-cm² cathode intended for use as a plasma source. Loschialpo and Kapetanakis [13] measured an average current density of 12 A/cm² from a 5-cm-diameter cathode. This cathode was used in a parallel plate diode and pulsed with voltages up to 10 kV.

Transmitted and total electron gun current were measured. It was found that at higher cathode temperatures the percent transmission began to decrease. It is believed that at the higher temperatures the cathode holder becomes activated by a coating of LaB_6 . The evaporation of LaB_6 from the cathode is the source of the problem and can not be eliminated. In the present electron gun design the cathode holder is in direct thermal contact with the cathode causing the holder to run at high temperatures. The holder becomes hot enough to emit electrons when activated. In the present design the holder both holds the cathode and forms part of the Pierce focusing system. A new design could use two parts to perform the separate functions. The holder would support the cathode and run at high temperatures but not form the part of the focusing system. The Pierce focusing electrodes would be thermally isolated from the cathode.

The design should allow the focusing electrodes to run at low enough temperatures so that they do not emit electrons even with a LaB_6 coating.

A transmitted current density of 30 A/cm^2 was obtained. Due to the uncertainty of the emission area the emission density from the LaB_6 cathode is not known. However, if it is assumed that the transmitted current originates from the cathode only, then the cathode current density is 31 A/cm^2 . Current versus temperature at constant voltage, and current versus voltage at constant temperature were measured but did not agree with the Longo equation. The measured data could be made to fit the Longo equation by manipulating the emission area or the work function of LaB_6 .

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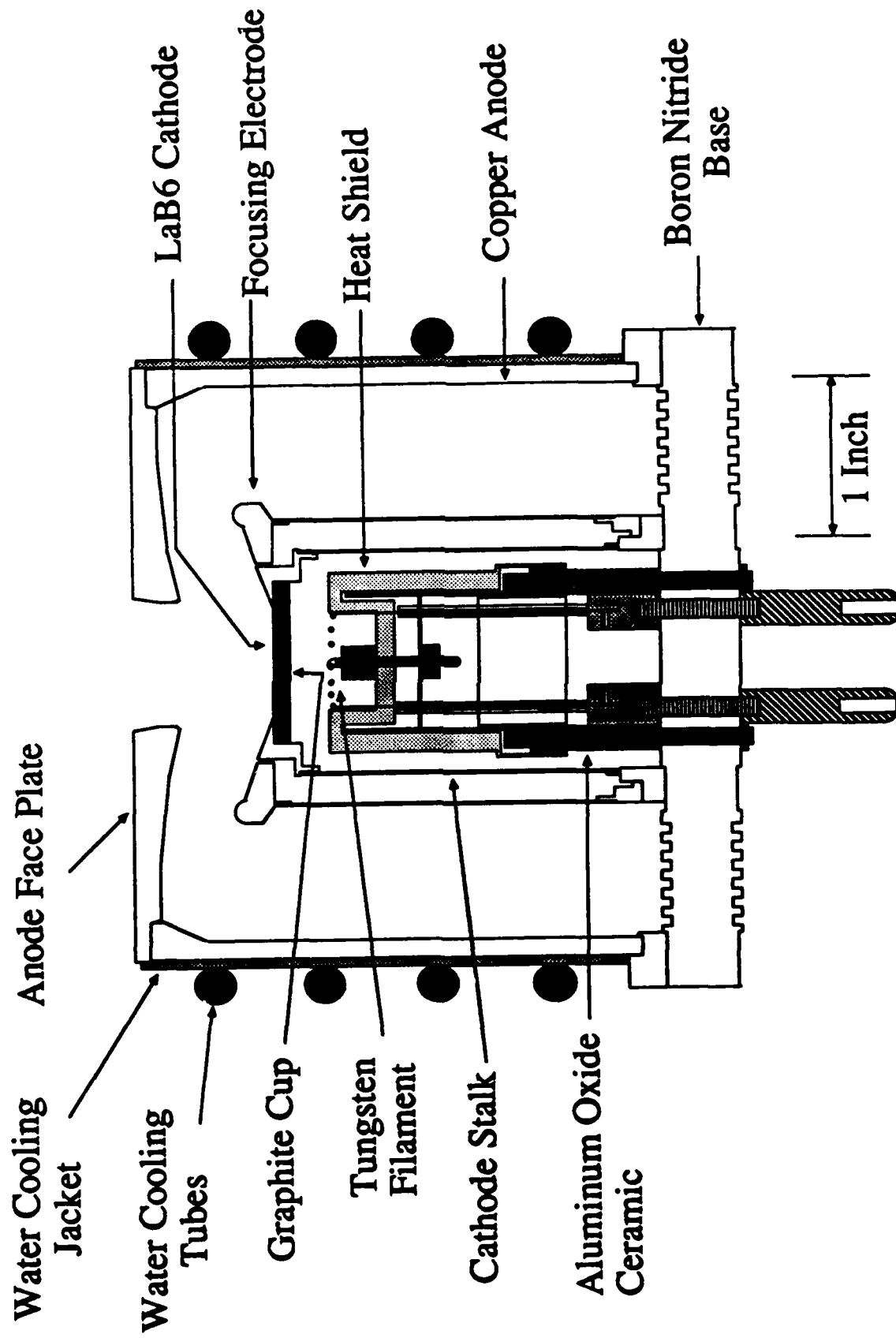
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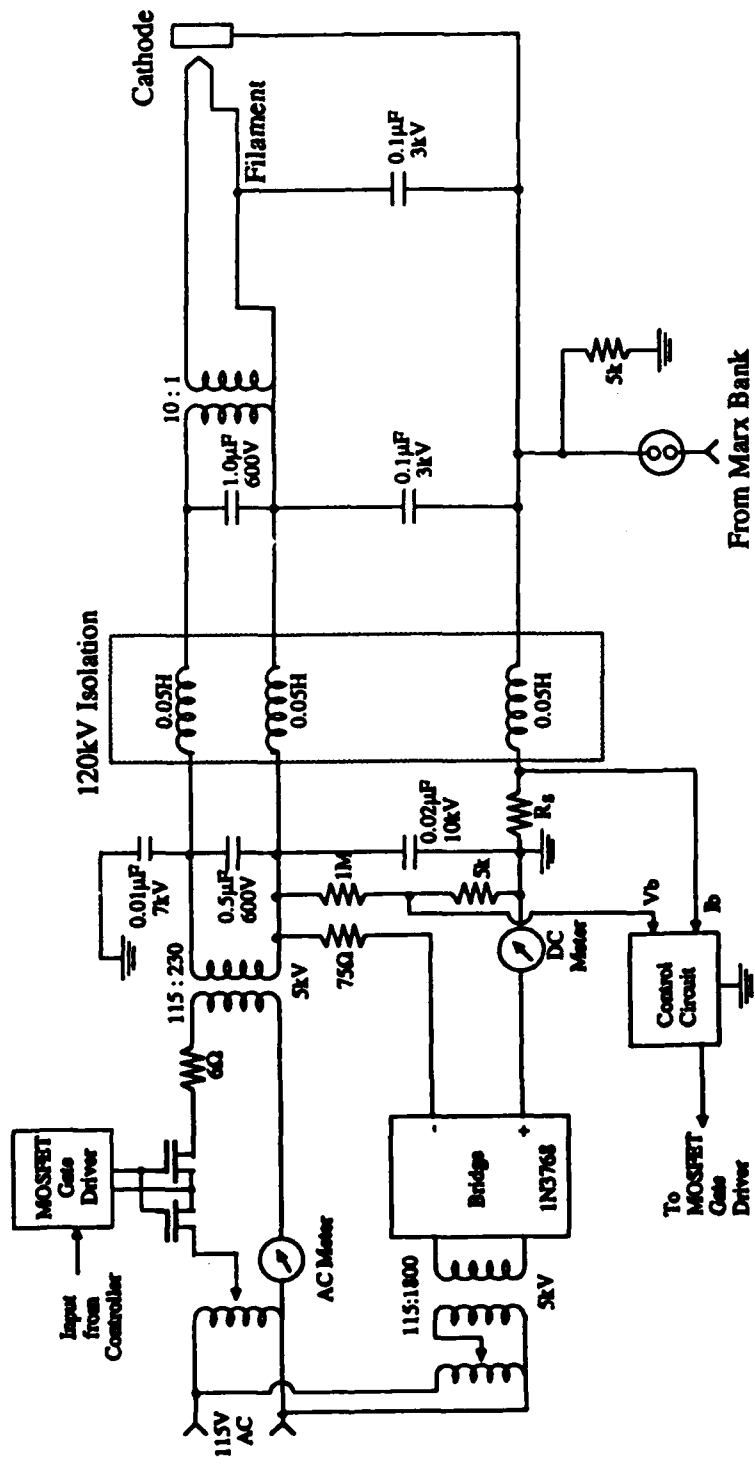
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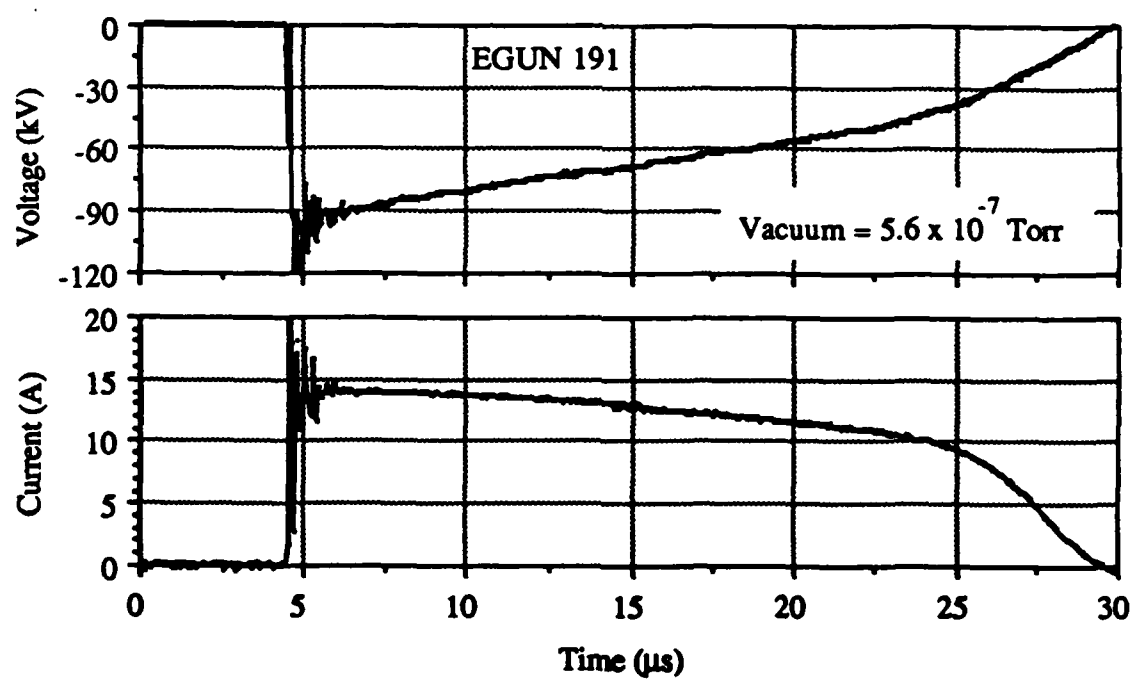
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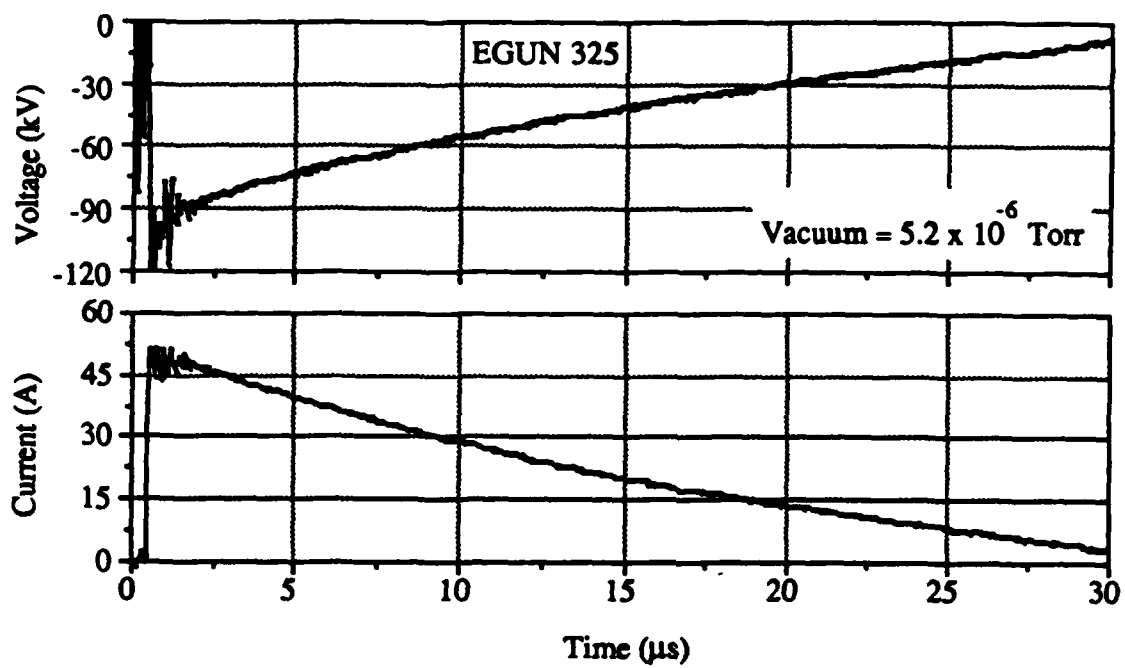
FIGURE CAPTIONS

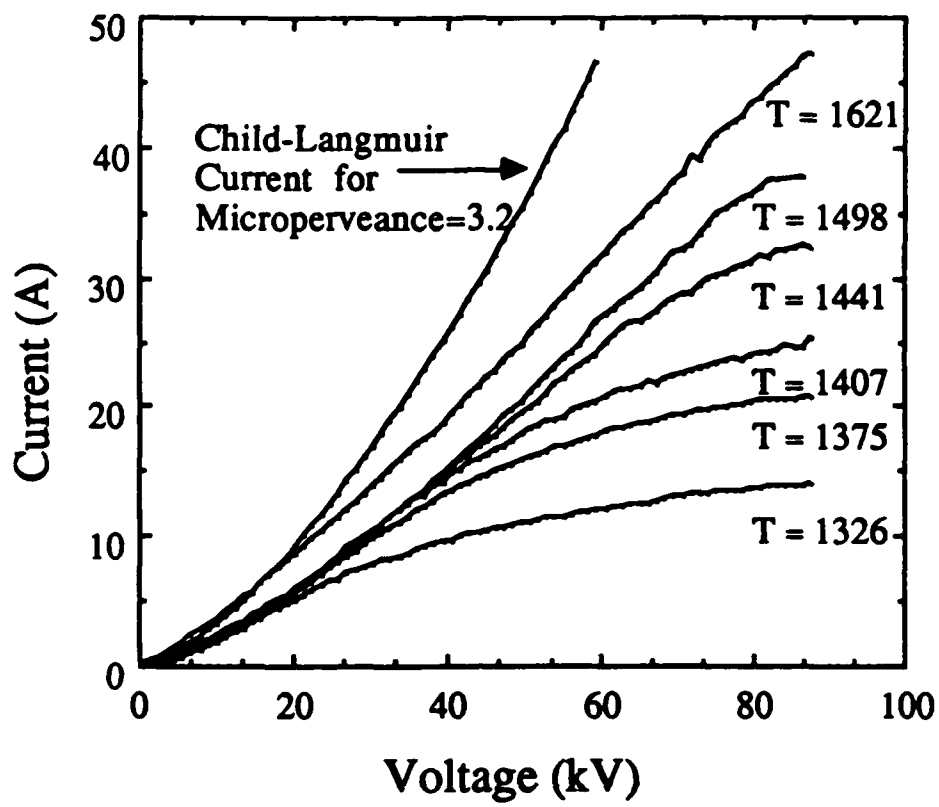
- Fig. 1 Assembly drawing of the electron gun. The perveance of this gun is $3.2 \times 10^{-6} A/V^{3/2}$.
- Fig. 2 Three inductor isolation system.
- Fig. 3 Electron gun voltage and transmitted current traces at 1326 °C.
- Fig. 4 Electron gun voltage and transmitted current traces at 1621 °C.
- Fig. 5 I-V characteristic of the electron gun generated from shots EGUN191 to EGUN325. The current shown is transmitted current.
- Fig. 6 I-V characteristic of the electron gun generated from shot EGUN191. Cathode temperature = 1326 °C.
- Fig. 7 I-V characteristic of the electron gun generated from shot EGUN325. Cathode temperature = 1621 °C.
- Fig. 8 Transmitted current versus cathode temperature at 46 kV.
- Fig. 9 Transmitted current versus cathode temperature at 88 kV.
- Fig. 10 Electron gun total current and transmitted current traces at 1621 °C.
- Fig. 11 Electron gun voltage and total current traces at 1653 °C.
- Fig. 12 Electron gun total current and transmitted current traces at 1675 °C.
- Fig. 13 Electron beam percent transmission as a function of temperature.
- Fig. 14 Electron gun voltage and transmitted current traces at 1700 °C.
- Fig. 15 Electron gun total current and transmitted current traces at 1744 °C.

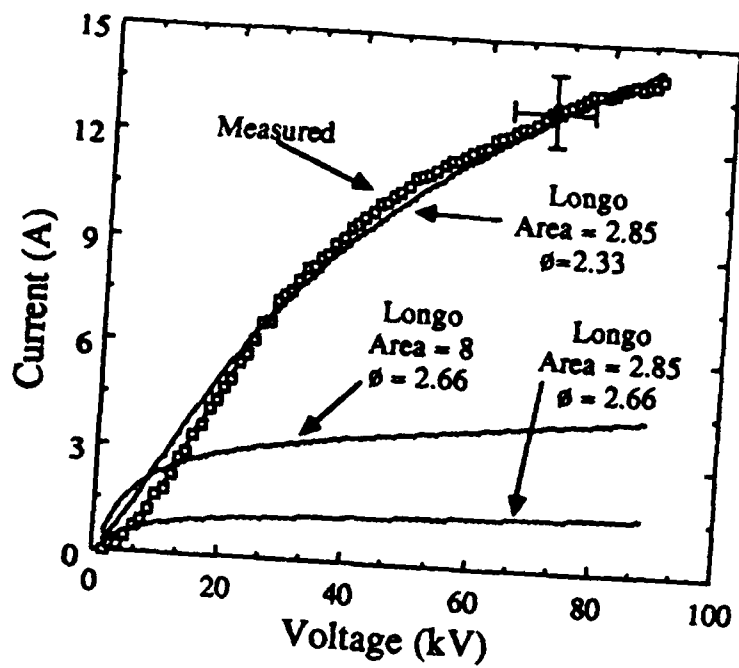


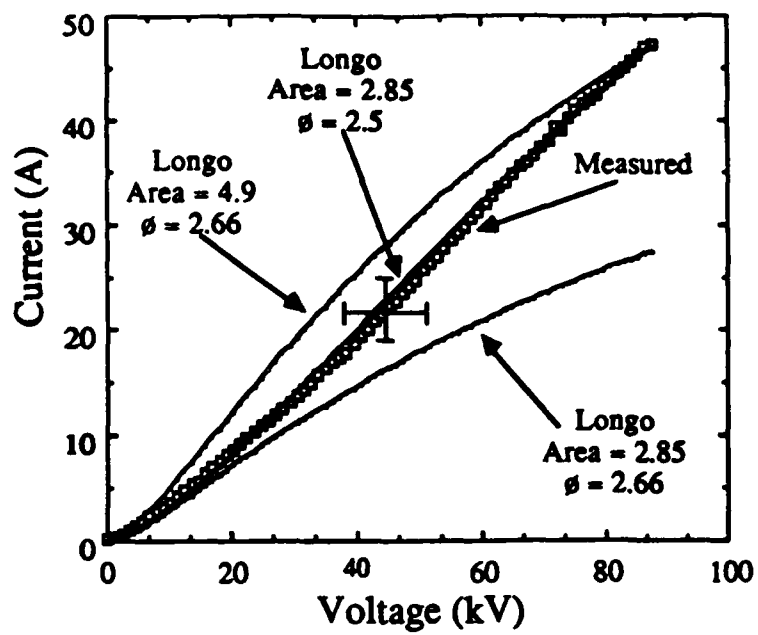


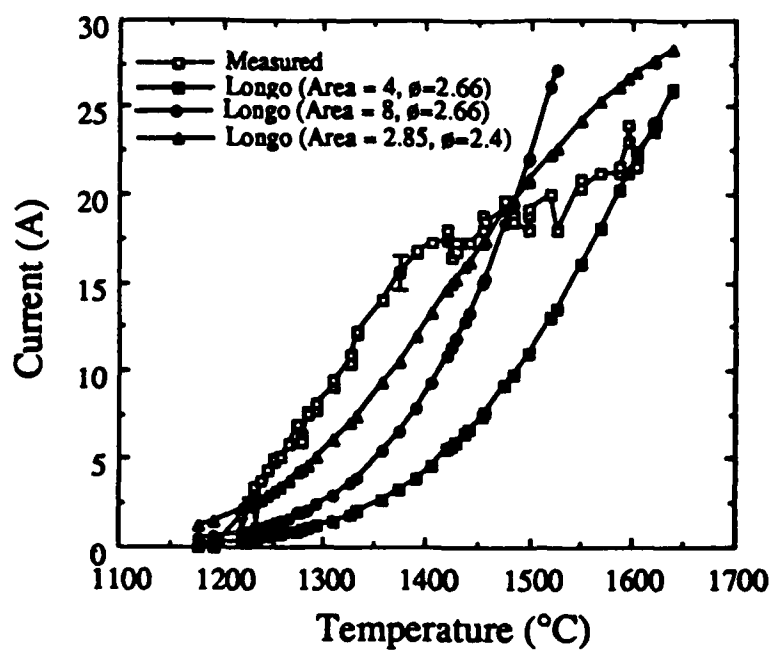


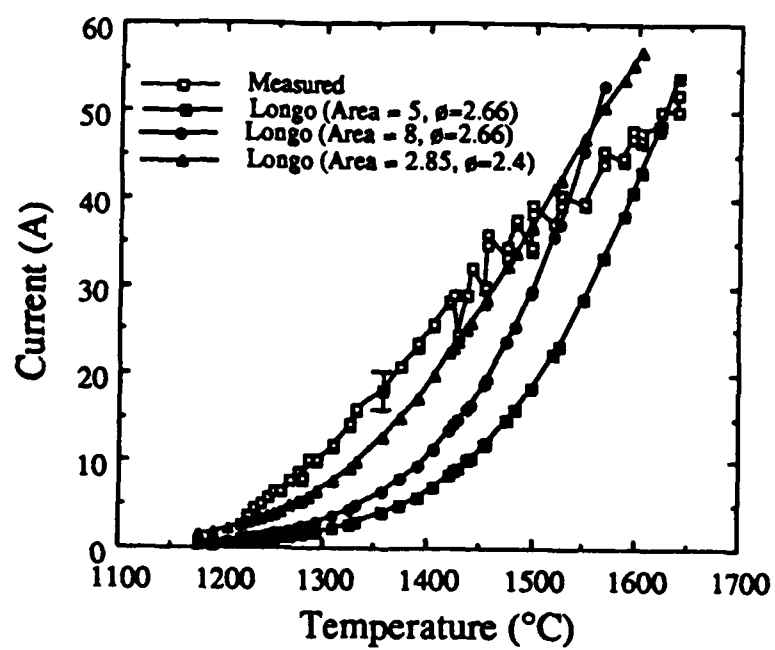


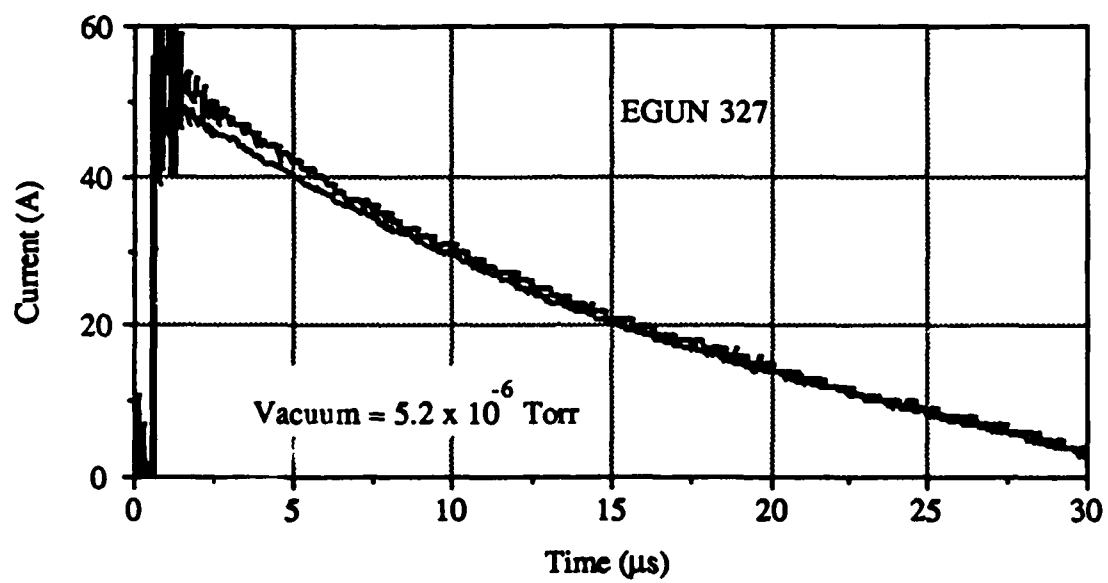


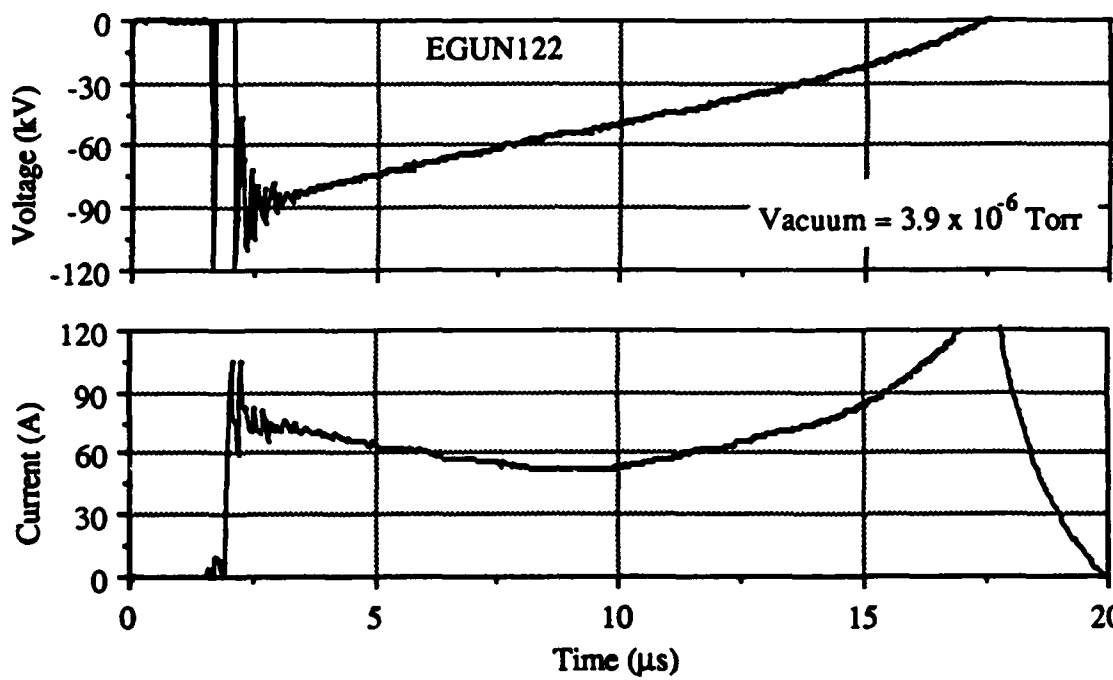


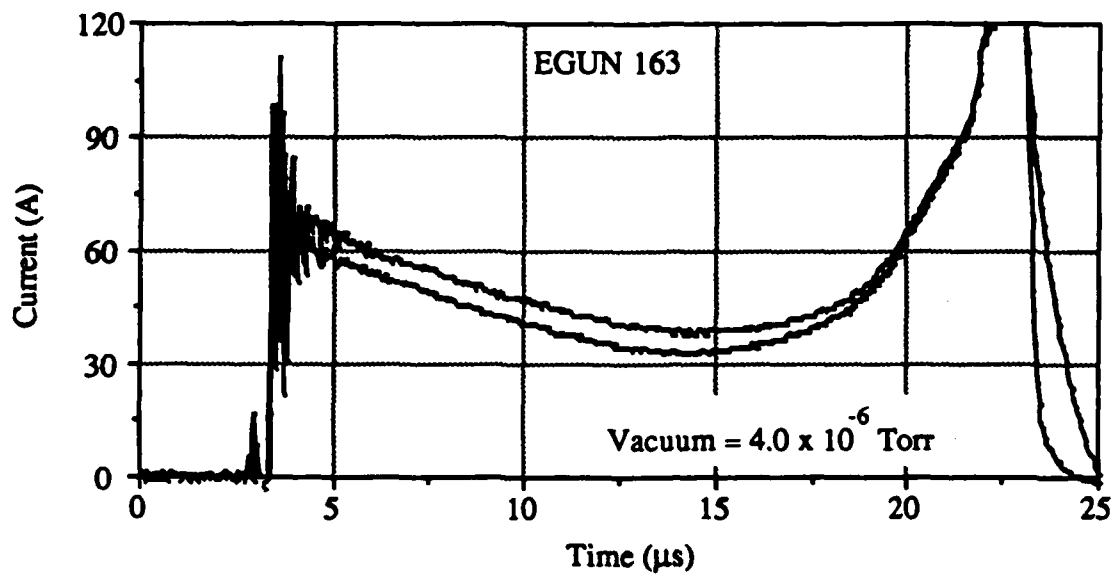


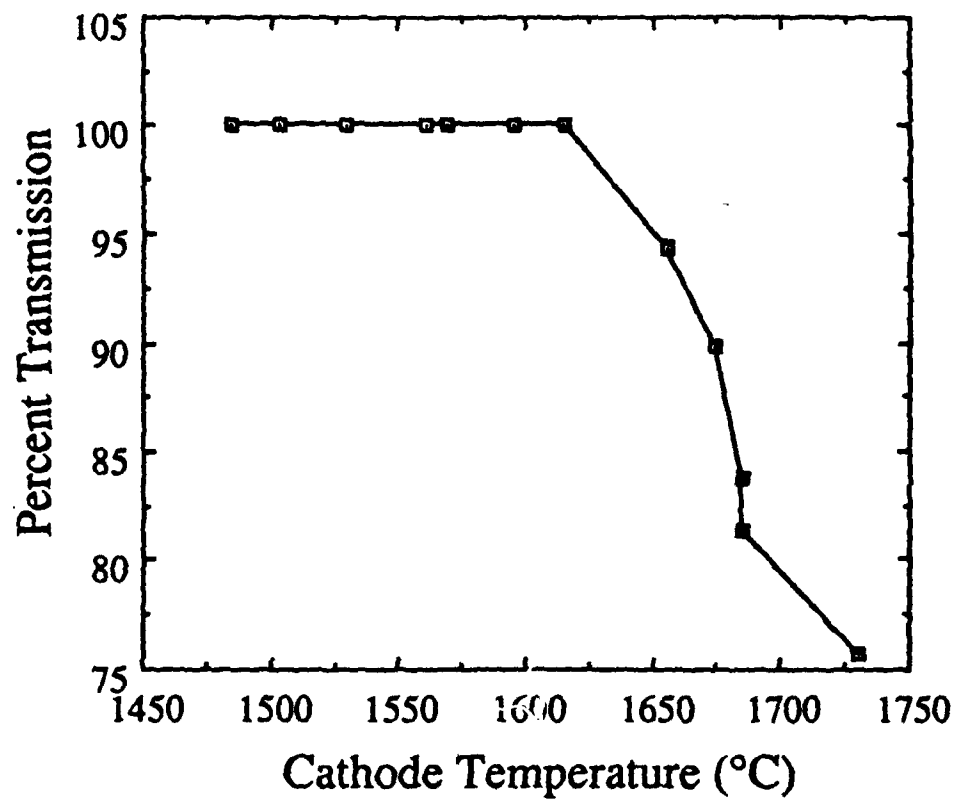


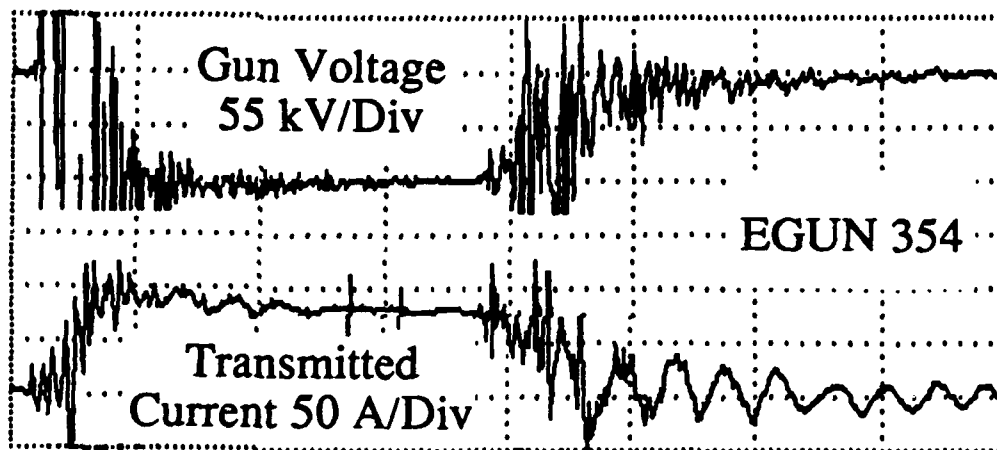




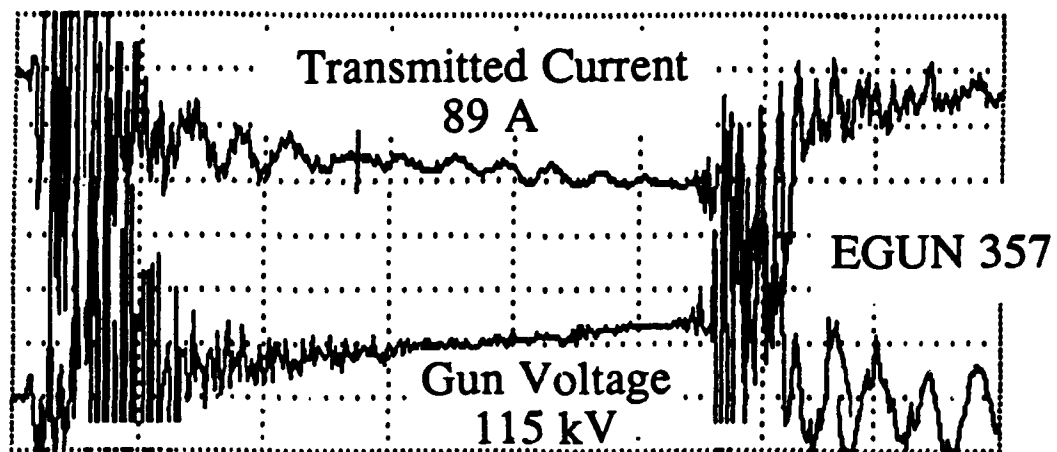








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Abstract Submitted
For The Twenty-Sixth Annual Meeting
Division of Plasma Physics
American Physical Society
October 29 to November 2, 1984

Category Number and Subject: 4.9.3, Physics and Technology of Free-Electron Lasers

 Theory

 X Experiment

Operation of a Pierce-Type Electron Gun With a Bombardment-Heated Lanthanum Hexaboride Cathode*. W.D. Getty and A. Ashraf, Univ. of Michigan.--A one-inch diameter lanthanum hexaboride (LaB_6) cathode has been used in a Pierce-type electron gun structure. The emission uniformity of the resultant electron beam is being studied in a beam analyzer for the purpose of developing a LaB_6 cathode for free-electron lasers and other e-beam devices. The cathode is heated by electron bombardment from a tungsten filament. The LaB_6 cathode requires approximately 280 W of bombardment power to heat it to the 1600 °C range, and the filament requires 20 W.

A pulse transformer with a bifilar-wound secondary is used to supply a 5- μs pulse to the electron gun. Present operation level is at 2 kV and the goal is to reach 20 kV. The bombardment circuit is on a floating deck and receives power at 120 V AC through the bifilar winding. The bombardment power is controlled by a feedback circuit.

The present Pierce gun has been optimized using the SLAC Electron Optics Code¹. The structure has been designed to minimize the bombardment heating power. The beam current density is measured by scanning a collector pinhole across the beam. An optical pyrometer for measuring the cathode temperature is located in the collector and views the cathode through 2 pinholes.

*Work supported by ONR.

¹W.B. Herrmansfeldt, SLAC Report No. 226, Stanford Univ.

 X Prefer Poster Session

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 Theory X Experiment

Demountable LaB₆ Thermionic Cathode Operation in a Microperveance 2.8 Electron Gun*. W.D. Getty and M.E. Herniter, Univ. of Michigan.--A planar cathode, Pierce-type electron gun with a design perveance of 3.2×10^{-6} A/V^{3/2} has been operated with a lanthanum hexaboride (LaB₆) cathode. The cathode (useful diameter 1.9 cm) is heated by bombardment by electrons from a small tungsten filament. The bombardment heating system is stabilized by a feedback control circuit. The power required to heat the cathode is 315 W bombardment power and 200 W filament power. Heating power has been reduced by careful heat shielding and reduction of heat conduction losses. Significant additional reductions should be possible. The sintered LaB₆ cathode disk is 2.5 cm in diameter, 3.2 mm thick, and has a density of 94 %. No problems have been encountered with cracking of the disk. Cathode emission is insensitive to repeated exposure to air after allowing the cathode to fully cool. The measured perveance and anode transmission of the gun are 2.8×10^{-6} and 94 %, respectively. Measurements were made at cathode temperatures of 1300 to 1600 °C. The difference between design and measured perveance is at least partially due to assembly inaccuracy in the anode-to-cathode spacing.

*Work supported by ONR.

 X Prefer Poster Session

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Current Density Distribution Measurements On a LaB₆ Cathode

In Space-Charge-Limited and Temperature-Limited Operation.

M.E.Herniter and W.D.Getty, Univ. of Michigan.^{*} - A demountable,

3.2-micropervance, Pierce-type electron gun has been developed with a 1.9cm diameter lanthanum hexaboride (LaB₆) cathode. This

electron gun has been operated in 5- μ s pulses upto 36kV, giving cathode current densities of 6.7A/cm². The cathode is heated by a feedback-controlled electron bombardment circuit. Results are presented on current density measurements under both space-charged-limited (SCL) and temperature-limited (TL) operation. Measurements are made by sweeping

a pinhole across the beam at a distance of $z=4\text{cm}$ from the cathode. Complete profiles in the x-y plane or single sweeps across the diameter are made. Current profiles are measured for various cathode heating powers and the effect on the current distribution of changing from TL to SCL operation is observed. The measurements are compared with simulations made with the SLAC computer code[1]. Calculations and measurements made for the bombardment heating system, the most critical part of the electron gun, are also presented.

1.W.B.Herrmannsfeldt, SLAC Rep.226, Stanford Univ., Nov.1979.

Abstract Submitted for the
1987 Particle Accelerator Conference
Washington, D. C.
March 16-19, 1987

DEVELOPMENT OF HIGH-CURRENT-DENSITY LAB₆
THERMIONIC EMITTERS FOR A SPACE-CHARGE-LIMITED
ELECTRON GUN*, M.E. HERNITER and W.D. GETTY, Intense
Energy Beam Interaction Laboratory and Electrical Engineering &
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MI 48109

An electron gun has been developed with a lanthanum hexaboride (LaB₆) cathode for investigation of high-current-density operation of LaB₆ cathodes in a space-charge-limited electron gun environment. The 2.8-cm² cathode is heated by electron bombardment from a tungsten filament. Cathode temperatures of 1755 °C have been reached with approximately 740 watts of total (bombardment + radiation) heating power. This temperature range is required for emission current densities in the 30 A/cm² range. Cathode temperature scans are made with a movable infrared thermal monitor. In this range of cathode temperatures it has been found that evaporation from the LaB₆ increases the tungsten emission, causing an instability of the bombardment system. This has been investigated by shielding the filament from the cathode with a carbon disk. It is believed that evaporated La lowers the tungsten work function. Thus far the cathode has been operated up to 6.7 A/cm². A 120-kV Marx generator is under construction to allow operation up to 40 A/cm².

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category:

AO3 Particle Sources

session:

poster session preferred

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Division of Plasma Physics

November 2-6, 1987

Category Number and Subject 4.11 /E Physics and Technology of Coherent Radiation Generation

☐ Theory

☒ Experiment

**Bombardment Heated Lanthanum Hexaboride Cathode
Electron Gun for High Current Densities***, M. E.

Herniter, W. D. Getty, Univ. of Michigan. A Pierce-type electron gun has been developed with a 1.9-cm diameter lanthanum hexaboride (LaB_6) cathode. The electron gun has been operated to 36 kV, giving current densities of 6.7 A/cm². A Marx generator has been constructed and tested to 108 kV, the voltage required by the gun to achieve 40 A/cm². The cathode is bombardment-heated by electrons emitted from a lanthanum(La) activated tungsten filament. La activated filaments require much less electrical heating power than pure tungsten filaments. They are activated by evaporation of LaB_6 from the cathode when it is heated to temperatures above 1600°C. The cathode has been heated to 1800°C, the temperature required to achieve 40 A/cm², with 756 W bombardment power and 2 W filament heating power. A digital control circuit has been developed to automate the heating system. It controls the bombardment power by controlling the filament emission current.

*Work supported by ONR.

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Submitted by:

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This form, or a reasonable facsimile, plus TWO XEROX COPIES, must be received by NO LATER THAN NOON, Friday, July 17, 1987, at the following address:

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Abstract Submitted for the 1988
IEEE International Conference on
Plasma Science

6-8 June 1988

Subject Topic and Number:
4. Electron, Ion and Plasma
Sources

Prefer Poster Session

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Transient Heating Method for Thermionic Cathodes in REB Generators, W.D. Getty, M.E. Herniter, and G.A. Lipscomb, Univ. of Michigan, Ann Arbor, MI 48109. -- A major problem in using thermionic cathodes in high-voltage electron beam systems is that of supplying power to heat the cathode while maintaining voltage insulation at megavolt levels. This insulation is usually provided by inductive isolation. Recently there has been interest in the use of lanthanum hexaboride (LaB₆) as a cathode material to obtain high current density. LaB₆ must be operated near 1800 °C to obtain the desired current density, and therefore requires significant heating power.

This paper describes a transient heating method suitable for pulsed high-voltage machines. It reduces the average cathode heating power and does not require inductive isolation, which becomes increasingly difficult as the beam pulse length extends into the μ s regime. This proposed method uses resistive isolation and capacitively-stored energy in the same manner as in a Marx generator. The cathode heating method is by electron bombardment, and LaB₆ is used as the cathode material.

In an experiment on a bombardment-heated LaB₆ cathode it has been observed that evaporated La thermionically activates the tungsten bombardment filament¹, and that back radiation from the cathode is sufficient to heat an activated filament to emission temperatures, allowing filament electrical heating power to be reduced to zero. Based on these observations, we have developed a system in which a small amount of stored energy is used to heat the filament initially until the back radiation from the cathode takes over. A second capacitor provides the energy needed for bombardment heating of the cathode. Both capacitors can be charged at the same time that the Marx bank used to drive the main electron beam is charged.

Calculations were made that are based on a thermal bombardment model that has given good results for a 2.8-cm² LaB₆ cathode heated by bombardment at 2.0 kV and 850 W steady state power¹. It was required that the cathode reach 1800 °C and that the filament temperature not exceed 2300 °C. The filament/cathode gap operates continuously over the temperature and space charge limited regimes. The temperature dependence of the filament resistance is taken into account. In cyclic operation with a 120 second cycle time (which does not allow the cathode to fully cool) it was found that 5.8 kJ bombardment energy (50 W average) and 80 J filament energy (0.7 W average) were required. These energies were supplied with 950 μ F at 3.5 kV for bombardment and 470 nF at 24 V for the filament. The peak cathode temperature is reached in 2.6 s. In single-shot operation where the cathode is allowed to cool to room temperature the required energy increases by approximately 50 %. The only switching requirement (other than the Marx bank) is for the 24 volt filament capacitor since the filament/cathode gap is open when the filament is cold. Results of simulations over a wide range of parameters will be presented.

* Work supported by the Office of Naval Research.
1: M.E. Herniter and W.D. Getty, IEEE Trans. on Plas. Sci., vol. PS-15, pp. 351-360, October, 1987.

Abstract Submitted for the Thirtieth Annual Meeting

Division of Plasma Physics

October 31 - November 4, 1988

Category Number and Subject 4.11 Physics and Technology of Coherent Radiation Generation

 Theory

 ☒ Experiment

LaB₆ Cathode Operation up to 90 kV and 25 A/cm² in a Pierce-Type Electron Gun, M. E. HERNITER and W. D. GETTY, Univ. of Michigan, Ann Arbor.* -- A Pierce-type electron gun with a 1.9-cm diameter lanthanum hexaboride (LaB₆) thermionic cathode is being studied at voltages up to 90 kV and cathode current densities greater than 25 A/cm². Typical total emitted currents of 100 A and anode-transmitted currents of 75 A are obtained. The beam power density at the anode aperture is typically 2 MW/cm² in this current range. Measurements of transmitted current versus emitted current have been made over a range of emitted current up to 100 A to investigate focusing. Emitted current has been measured as a function of cathode temperature to investigate TL and SCL operation, and to compare with the Richardson - Dushman equation.

The cathode is held in a graphite cup that is bombardment-heated by electrons from a tungsten filament. The graphite cup reduces the effect of evaporation of LaB₆ on the heating system, and eliminates cathode cracking by distributing the bombardment power uniformly.

*Work supported by ONR.

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ABSTRACT

A BOMBARDMENT HEATED LaB_6 THERMIONIC CATHODE ELECTRON GUN

by
Marc Efreem Herniter

Chairperson: Ward D. Getty

This dissertation concerns the development and operation of a high current density Pierce-type electron gun with a 0.75-inch-diameter lanthanum hexaboride (LaB_6) thermionic cathode. The objective of this research is to achieve as high a current density as possible from the lanthanum hexaboride cathode. The topics which are addressed are the cathode heating and control system, the Pierce-type electron gun design, and the high voltage pulsing and isolation system.

Lanthanum hexaboride is used as a cathode material in applications where high current density and resistance to chemical poisoning are important. Applications include free electron lasers and high power microwave generation.

A four stage Marx generator capable of producing 140-kV-peak pulses with a 16 μs decay time constant is used to pulse the electron gun. The cathode is heated to temperatures greater than 1800 °C by electron bombardment from a tungsten filament. Both temperature-limited and space-charge-limited bombardment methods have been investigated. The temperature-limited method is open-loop unstable. Analog and digital control circuits have been developed to control this instability. A simple heating model has been

developed and criteria for constructing a controllable system have been established.

An instability in the heating system which is caused by evaporation of lanthanum hexaboride from the cathode is discussed. This evaporation reduces the work function of the bombarding filament and makes the temperature-limited bombardment system uncontrollable.

The gun has been operated up to voltages of 115 kV achieving beam current densities of 30 A/cm². The electron gun operated dependably up to voltages of 90 kV achieving temperature-limited currents of 50 A. Due to the high fields at the tip of the Pierce-focusing electrode the gun would usually arc at voltages greater than 90 kV. Electron gun operation has been observed in the temperature-limited and space-charge-limited regimes. The current density profile has been measured across the entire beam cross section.

Disclosure of Invention
March 14, 1987

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Disclosure of Invention

1. Inventor's Names: Marc E. Herniter, Ward D. Getty

2. Title of Invention: Cathode Heating System

3. Research Sponsor: Office of Naval Research

4. Stage of Development:

Invention's date of conception: Jan. 1, 1986

Date and name of prior publications, if any: None

Date and name of expected future publications: Conference

Proceedings, 1987 Particle Accelerator Conference, Washington
DC, March 119, 1987.

Dormant: blank

Date of University of Michigan Disclosure: March 14, 1987

To Whom Disclosed: Eric J. Pitcher

Date of Disclosure to Sponsor: None

Detailed Disclosure:

5. General Objectives of the Invention

To heat a cathode material to a temperature at which it will emit electrons by thermionic emission.

6. Potential Market For the Product

a. The product could be used in producing electron beams for lasers or for industrial applications such as welding. It provides a robust cathode that can emit high current densities and withstand exposure to contaminants.

b. There are no old methods for performing the specific function of this invention.

c. This product will allow the use of a rugged cathode because it allows the user to heat the cathode in a more efficient, stable manner.

d. It is not disposable.

7. Present Status of Project

The project is presently funded through August 31, 1987. An extension has been proposed to the sponsor. In the next six months the heating method will be perfected and an analysis of it will be made.

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8. Detailed Description

There are two parts to the invention. The first part is as follows.

The invention allows the use of lanthanum hexaboride (LaB_6) as a cathode (C) material at temperatures above 1500°C when electron bombardment is used to heat the LaB_6 . The bombarding electrons are generated by an auxiliary emitter or filament (AE), usually tungsten. The invention prevents a thermal instability that can occur in such systems. This instability occurs because of heat radiation from the cathode that is absorbed by the filament. The AE and C form a diode which is operated in the temperature-limited regime. This is done so that the electrical power into the AE can control the electron emission from the AE. The electrical power into the AE is controlled by a feedback signal that is proportional to the bombarding current between the AE and the C. This the same as the AE/C diode current. Thus because the AE /C diode is temperature limited the AE power can control the diode current. The problem is that vaporization of LaB_6 at temperatures above 1500°C deposits material on the AE that lowewrs its work function, allowing the AE/C diode current to increase even though the AE heating power is decreased. Thus control is lost.

The invention is to insert a material between the AE and the C that intercepts the evaporants but does not prevent the bombarding power from heating the C. The material used thus far for this is graphite, but other materials such as tantalum, rhenium, or boron nitride may serve this purpose. Insertion of this material allows the AE/C diode to operate in the temperature limited regime and to be stabilized by controlling the AE electrical heating power. Being temperature limited allows the feedback system to precisely control the bombardment current.

The second part of the invention is as follows.

The second part of the invention is a way to ccntrol the C temperature with a digital control system. The control system consists of two parts. These parts are the circuit that is used and the algorithm that guides the operation of the circuit. The circuit part of the invention is to use a power MOSFET as a switch in series with the AE to pulse modulate or chop the AE current and thereby control the AE temperature. Either an AC or DC voltage supply can be used. The power MOSFET is turned on or off by a pulse from a digital circuit. The pulse is derived according to the algorithm part of the invention.

The algorithm part of the invention consists of the following steps:

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- a. Sample the bombardment current waveform and store the samples digitally.
- b. Compare real time bombardment current with the saved value.
- c. Force the real time value to be less than the stored value by chopper control of the AE current. This guarantees that the bombardment current will be temperature limited. The system requires being temperature limited to be stabilized; therefore this algorithm guarantees that the system will be temperature limited and stabilized.
- d. Send a signal to the power MOSFET or other chopper device to control the AE current.

As an auxiliary feature, the control system can provide automatic warm-up capability by using the temperature-limited condition. The rate of warm-up can be controlled by the digital clock.

9. Alternative Methods of Constuction

Other materials than LaB_6 could be used as a cathode.

10. Each inventor contributed equally to the invention.

Signatures:

Marc E. Herniter

Marc E. Herniter

Title: Graduate Student
Research Assistant

Date: 3/14/87

Ward D. Getty

Ward D. Getty

Title: Professor

Date: 3/14/87

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March 14, 1987

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Total number of pages in this disclosure: 4
Attachments: none

Disclosed and understood by me this 14 day of March 1987
Witness:

Eric J. Patcher