ELECTRON BEAM ANALYSIS FOR CYCLOTRON HARMONIC AND FREE-ELECTRON LASER DEVICES

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Two separate experiments are described. The first was on the velocity distribution analysis of a gyrating electron beam. A retarding-potential analyzer was developed which operated at 75 kV and accepted gyrating electrons with large Larmor radii. Velocity distributons were compared with simulation results. The second experiment explored the possibility of forming a large-area electron beam from polycrystalline diamond film. Diamond, a negative electron affinity material in the crystalline <111> direction,has been observed to emit electrons into vacuum in certain configurations, but this effort was unsuccessful in obtaining emission.

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(Front Only)

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ELECTRON BEAM ANALYSIS FOR CYCLOTRON HARMONIC AND FREE-ELECTRON LASER DEVICES

1.0 INTRODUCTION

1.1. Time Period Covered by this Report

This report is a continuation of Final Technical Report No. 5 for Contract No. N00014-89-J-1417. That report covered the period from January 1, 1989 to October 31, 1989. It was for UM Account No. 026138. The present report is for the final three years of this project, which covers the period from October 1, 1989 to December 31, 1992. The contract number for that period was N00014-90-J-1065 and the UM account number was 027057.

1.2. General Background

The first two years of the time period covered by this report were devoted to an experiment in which we developed a high-voltage retarding potential analyzer that was used to measure the axial velocity distribution of an electron beam. The electron beam could be highly perturbed by passing the beam through an electromagnet wiggler to transform kinetic energy from the longitudinal direction to the transverse plane. This allowed us to observe the effect of the wiggler on the electron beam's velocity distribution.

The final year of the project was devoted to an attempt to obtain cold electron emission from polycrystalline diamond films. Diamond is known to have the property of negative electron affinity, which should lead to electron emission into vacuum from the surface of the diamond. This report presents the results of that investigation.

1.3. List of Papers and Theses

(1) Journal Articles

1. M. E. Herniter and W. D. Getty, "High Current Density Results From a LaB_6 Thermionic Cathode Electron Gun," *IEEE Trans. on Plasma Science*, Vol. 18, No. 6, pp. 992-1001 (December 1990).

2. M. E. Herniter and W. D. Getty, "Temperature-Limited Electron Bombardment Heating Method," *IEEE Trans. on Plasma Science*, Vol. 19, No. 6, pp. 1279-1289 (December 1991).

(2) Conference Paper

K. D. Pearce and W. D. Getty, "Retarding Field Analysis of a 90-kV, 70-A Electron Beam with Wiggler and Axial Magnetic Fields," presented at 32nd Annual Meeting, Division of Plasma Physics, *Amer. Phys. Soc.*, Cincinnati, Ohio, November 12-16, 1990. Abstract: *Bull. Amer. Phys. Soc.*, Ser. II, Vol. 34, p. 2072 (October 1990).

(3) Ph.D. Thesis

Kelly D. Pearce, "Retarding Field Analysis of Long Pulse Electron Beams Through Combined Bifurcated Bifilar Wiggler and Guide Magnetic Fields," Ph.D. Thesis, Nuclear Engineering, The University of Michigan, Ann Arbor, 1991.

1.4. General Plan of Final Report

Section 2.0 presents a brief overview of the electron beam analysis results. Section 3.0 presents the result on cold emission from polycrystalline diamond films. This section presents more detail since this work was not written up in detail in a thesis. The experimental apparatus is described in detail in case others wish to follow similar methods in the future.

2.0 RESEARCH ON ELECTRON BEAM VELOCITY ANALYSIS

The primary work done on this project was the measurement of the axial velocity distribution of an electron beam with an energy in the 75-kV range and appreciable transverse energy due to passage through an electromagnet wiggler. The measured distributions were compared with calculated distributions.

A special retarding analyzer was used which is known as a "filter lens" analyzer. The success of the project was largely due to the suitability of this type of analyzer for the 75-kV voltage range. Figure 1 shows the beam analyzer apparatus. A small Marx bank supplies a crowbarred 5-μs pulse to the electron gun in the 75-kV range. The gun uses a LaB_6 cathode which is heated by electron bombardment. The beam passes through a 1.5 inch diameter drift tube which holds the electromagnet wiggler. The gun, drift tube, and analyzer are in a uniform magnetic field of approximately 1000 G strength. Figure 2 shows the cross section of the electron gun.

The wiggler current is pulsed and the beam is fired at the peak of the wiggler current. A DC voltage is used on the retarding analyzer.

A cross section of the analyzer is shown in Figure 3. It consists of an on-axis entrance aperture at zero voltage, a retarding cylinder at a negative DC voltage, and a collector at zero voltage, except for the small voltage drop across the collector current-viewing resistor. The retarding cylinder voltage is varied from zero up to the full beam voltage in steps of 500 V, and the collected beam current is recorded at each voltage step. A retarding potential analyzer curve is then drawn by plotting the peak collector current versus the DC retarding voltage. Figure 3(b) shows how an electron is retarded if its axial energy is insufficient to overcome the retarding voltage.

The simulated retarding potential curves are calculated by integrating the equations of motion for single electrons from the anode aperture of the electron gun to the collector of the analyzer. Space charge and field distortion at the entrance aperture are neglected, but the velocity distribution at the gun-anode aperture is accounted for through the use of the EGUN code. The main special consideration found necessary to get good results was to use a very accurate value for the wiggler magnetic field at the location of the electron. Analytical values from Bessel function approximations to the field were not sufficiently accurate. It was found necessary to break the wiggler wires into small segments and to use the Biot-Savart law to calculate the field. This greatly increased the time required to calculate trajectories.

Results are shown in Figures 4 and 5 for standard operating conditions and reduced wiggler field conditions. The agreement between the simulation and the measurement is quite good. A large number of such curves were obtained. The experimental curve is taken on a single-shot basis so 12 to 14 different beam pulses are used to generate the experimental curve.

The simulation also showed that the electrons that pass through the on-axis analyzer aperture come from certain areas in the beam cross section at the gun anode. Most come from near the beam edge. The analyzer aperture has a diameter of 2 mm. Figure 6 shows the anode aperture positions of the electrons that pass through the analyzer aperture for a wiggler current of 160 A. The analyzer was also operated successfully at low beam currents without a pinhole entrance aperture.

The analyzer worked quite well for this application, and with precision voltmeters and beam-current signal averaging, it would be an excellent way to analyze gyrating beams. A detailed drawing of the analyzer is shown in Figure 7.

3.0 RESEARCH ON COLD ELECTRON EMISSION FROM DIAMOND FILMS

This project represented a large departure from the previous work. The intent was to use the existing beam-analyzer system to measure the velocity distribution and current density properties of electron beams emitted from cold diamond films. Unfortunately, we were not successful in obtaining any emission. In the following sections, our experiment is described in detail to aid others who may try similar experiments.

3.1. Background on Negative Electron Affinity Emitters

Negative electron affinity (NEA) in a material means that the bottom of the conduction band in the material is at a higher potential than the vacuum level potential outside the surface of the material. An n-type material with many negative carriers near the bottom of the conduction band has the potential capability to emit electrons directly into vacuum without heating above room temperature. p-type materials can also emit when fabricated into diodes. An example of an NEA emitter is GaAs with a monolayer of cesium oxide on its surface.[1] In this case, the vacuum level can be a few tenths of an eV below the conduction band in GaAs, energetically allowing electrons to leave the GaAs and flow into the vacuum. In p-type cesiated GaAs experiments these cathodes emit under illumination, but the cesium oxide layer is easily destroyed in poor vacuum. Most NEA emitters before diamond use a cesium oxide layer and are thus vacuum sensitive. Direct photoemission from diamond from its 111 crystalline surface has been observed.[2]

Direct emission from diamond $\langle 111 \rangle$ into vacuum has been observed[3] from diamond formed into pn junction diodes. Boron dopant was used to produce p-type diamond, and the carbon ion implantation method was used to induce a layer of n-type diamond on the p-type. An aluminum electrode was then deposited on the n-type surface to form a contact to the diode. Emission into vacuum was observed when the diode was forward biased. The emission is from the lateral edge of the diode junction, and consists of electrons injected into the p-type diamond from the n-type diamond under forward bias conditions.

3.2. Experimental Setup

The conditions in the experiment were quite different than those defined by the pn junction diode work. The approach was to seek emission directly from the bulk polycrystalline diamond surface in the form of a large-area planar emitter. This approach was taken because our goal was to produce cathodes for microwave devices, and we wished to investigate emission from a geometry suitable for this purpose.

Diamond films were obtained from Professor Roger W. Pryor, Diamond Materials Research Laboratory, Institute for Manufacturing Research, Wayne State University, Detroit, Michigan. Professor Pryor made these films using an Astex diamond CVD system, and provided Raman spectroscopy and electrical conductivity characterization of the films. He was in the process of developing a CVD doping procedure for n-type diamond, and some samples were n-type due to the results of this process. Samples of films were approximately 1 cm^2 in area and were made on ESPI molybdenum, AMAX molybdenum, Alfa molybdenum, or silicon substrates. Expenses for the production of these samples were reimbursed to Wayne State under a purchase agreement. Approximately a dozen samples were obtained. No samples from other sources were used in the project.

The supplied films were viewed with a 1200 x optical microscope and photographs were taken of the surfaces. Most of the films, particularly those on silicon substrates, showed excellent randomly-ordered diamond crystals. A simple test with an ohmmeter was made to select samples with low surface resistance. Some of the samples which did not show good diamond crystal formation under the microscope were not used as much in the emission testing as those samples that did show good crystalline structures.

(1) Sample Mounting

Care was taken to obtain a good ohmic contact between the cathode electrode and the front face of the diamond film. Since the diamond film substrate was not necessarily a good conductor, we wanted to be sure that a good contact was made to the film itself. Figure 8 shows the arrangement used to hold the samples. One or more layers of thin copper foil was placed between the substrate and the stainless steel cathode holder to provide a compressive sandwich for the substrate. An indium foil cut into the shape of an annular ring was placed between the diamond film and the bottom ring of the cathode holder.

(2) Vacuum System

The basic vacuum system was pumped by a 510 ℓ/s turbopump. The base pressure is 10^{-7} Torr. It was set up so that glow discharges of oxygen or hydrogen could be run in the vicinity of the cathode for processing the diamond surface. Figure 9 shows the vacuum system layout. The diamond cathode electrodes were mounted in a 6-inch diameter stainless-steel cross that was connected through a short 6-inch tube to the main vacuum chamber. A butterfly valve was placed in the short tube to control the pressure. The glow-discharge gases were admitted into the cross through a needle valve, and with the butterfly valve closed pressures up to 50-100 mTorr could be obtained in the cross even with the turbopump running. This pressure range was high enough to give a good RF glow discharge around the diamond. When testing for emission, the gas was turned off and the butterfly valve was opened.

The RF power for the glow discharge was at 10-20 MHz and ranged up to 50 W.

(3) Anode-Cathode Electrodes and Instrumentation

The anode-cathode electrodes were in a traditional parallel-plate diode configuration as shown in Figure 10. The anode electrode could be rotated away from the cathode electrode to allow control of the glow discharge, which was affected by the anode-cathode spacing. The anode was moved back into position when glow-discharge processing was completed. The manipulator is shown in Figure 9 also. The anode plate could be run with or without the point.

Other configurations which were tried are shown in Figure 11. Since the diamond film is a poor conductor, we surrounded it with insulator in the form of boron nitride as shown in Figure 11(a). A pointed metal anode was then moved in close to the diamond film, as shown in Figure 11(b). The purpose of the pointed anode was to obtain a large electric field at the film surface.

The electrical circuit is shown in Figure 12. Both the anode and cathode electrodes were insulated so that either of the two connections shown in Figure 12(a) and 12(b) could be used. The ammeter was a Keithley Model 610B Electrometer with a full scale range from 10^{-3} to 10^{-11} A. The negative side of the electrometer was always grounded. The full scale setting was determined by a panel switch. The power supply was either an HP6209B, 0-320V, 0-0.1 A power supply, or a Spellman RHR 5PN50, 0-5 kV, 0-50 mA supply. One side of the power supply was also grounded. The ammeter was checked for proper operation with a 500 MΩ resistor which was inserted in place of the anode-cathode gap. With this setup, the electrometer could be checked for proper operation with regard to polarity and current level down to the 10^{-9} to 10^{-8} A scales. The resistor was not calibrated so we did not accurately calibrate the meter, but it was certain that the correct polarity was known and that the current was approximately correct.

In the configuration of Figure 11(b) and with the 5 kV power supply, it is estimated that field strengths of approximately 10^5 V/cm could be placed near the surface of the diamond film. A micrometer-screw translation unit was used to place the sharp point (estimated radius 0.025 cm) within 1 or 2 mm from the film. The purpose of the boron nitride shown in

Figure 11(a) was to attempt to prevent the nearby metallic cathode electrode from reducing the field strength.

A small ultraviolet lamp (Edmund Scientific Model A36875) was mounted inside the vacuum system in a position that allowed it to illuminate the diamond film at an angle. This lamp was powered with 60-Hz AC voltage through a fluorescent light ballast. It was quite intense but it did not produce any observable effect and its use was discontinued.

3.3. Experimental Results

Tests for emission were done on the native samples furnished by Wayne State University and after various sequences of processing in oxygen and hydrogen plasmas. It was known from Professor Pryor if the sample was doped n-type or undoped, and it was also checked that the topography looked good under the microscope. The RF voltage for glow-discharge processing was applied to the anode and the cathode was grounded. The glow discharges were run in the 50-500 mTorr range.

Sequences of ten minutes of oxygen discharge cleaning followed by 30 minutes of hydrogen discharge conditioning were performed, with checks for emission made between every discharge run. The electrometer had negligible drift or noise down to the 10^{-9} A scale and it was estimated to be possible to observe 0.03 to 0.05 nA easily. Total plasma discharge processing times of 30 minutes oxygen and 90 minutes hydrogen were used in a given run. These were then repeated later in the day or the next day or a new sample was installed.

All Teflon-coated wires were covered with ceramic tubes to avoid any sputtering of Teflon in the glow discharges.

Gradually, oxygen plasma exposure was increased to 18 minutes and mixed with a series of 30-minute hydrogen plasma exposures. Working pressures of hydrogen were increased to 400 mTorr, while oxygen pressures were kept at 20 mTorr or less. These pressures were adjusted to give good, intense glow discharges. Hydrogen plasma exposures were increased to 70 minutes in one series of tests.

Occasional small currents of the order of 0.1 nA were observed. These were ohmic leakage currents and could be easily identified by reversing the power supply voltage polarity.

Several variations of clamping of the diamond film were tried. The use of a pointed anode within 1-2 mm of the film had no effect even up to 1.5 kV.

3.4. Discussion of Results

It was unfortunate that we were unable to see any emission since we could do no optimizing of our process to maximize emission. It seems unlikely that a straightforward electron diode with a simple planar diamond cathode will work as a cold emitter without a more complicated diamond structure such as the mesa pn junction diodes of Reference 3. There is also the possibility that nearly single crystals of diamond ⟨111⟩ will be required. The question of doping is also an important one. Our approach was that n-type diamond exhibiting NEA would be most favorable, but we had no way to verify the doping polarity. It is clear from the literature that the conditioning of diamond films by exposure to a glow discharge has a large effect on the bulk properties and surface states of diamond films. It may be possible to find a proper recipe but our results and those of Reference 3 suggest that diamond device structure may be most important.

The application of appreciable field strengths near the diamond film by the use of pointed anodes did not yield any observable emission.

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1. M. D. Williams, et al., *J. Appl. Phys.*, 71(6): 3042-3044 (15 March 1992).
2. F. J. Himpsel, et al., *Phys. Rev. B*, 20(2): 624-627 (15 July 1979).
3. M. W. Geis, et al., *IEEE Electr. Dev. Lett.*, 12(8): 456-459 (August 1991).

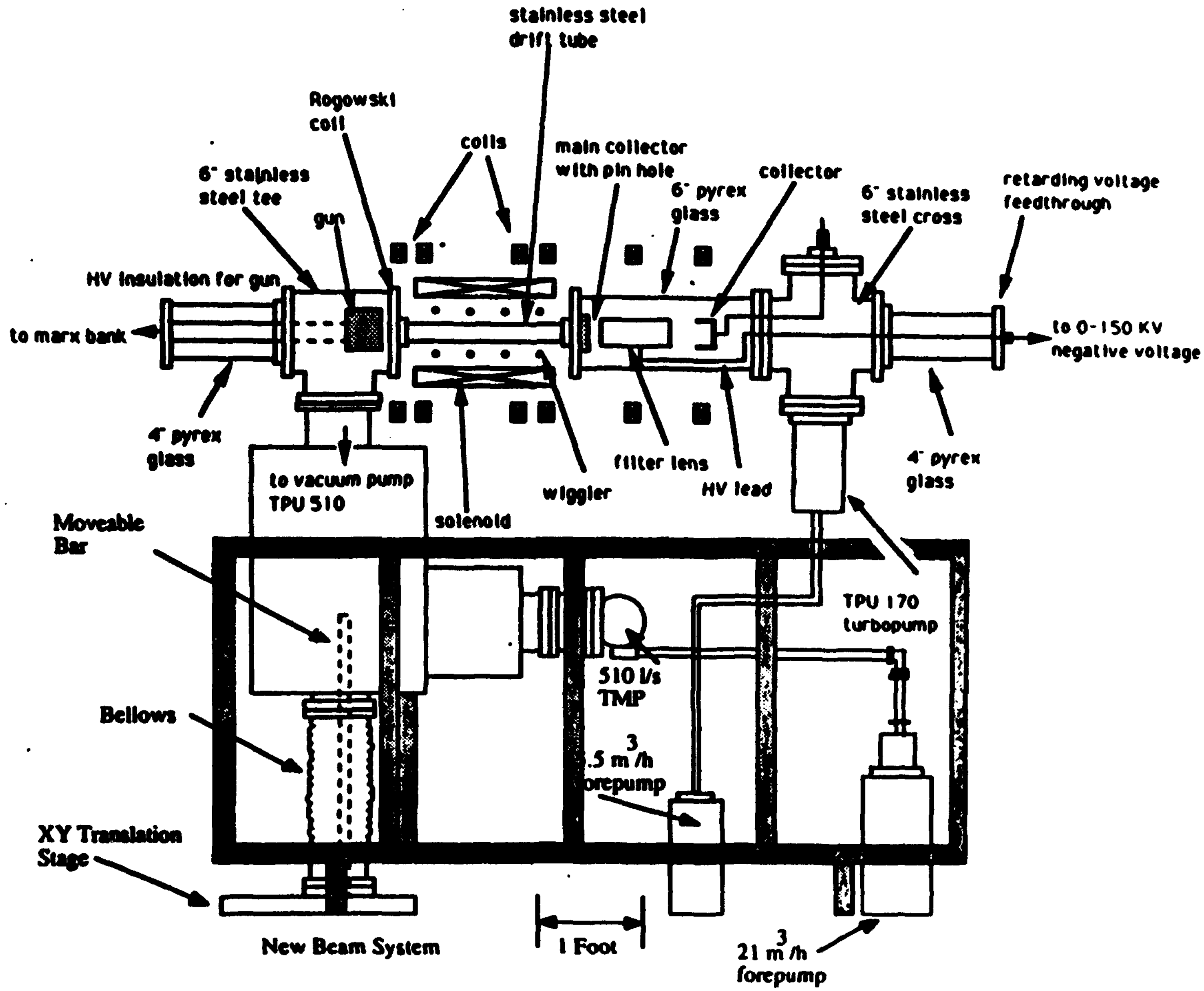


Figure 1 Beam-analyzer apparatus.

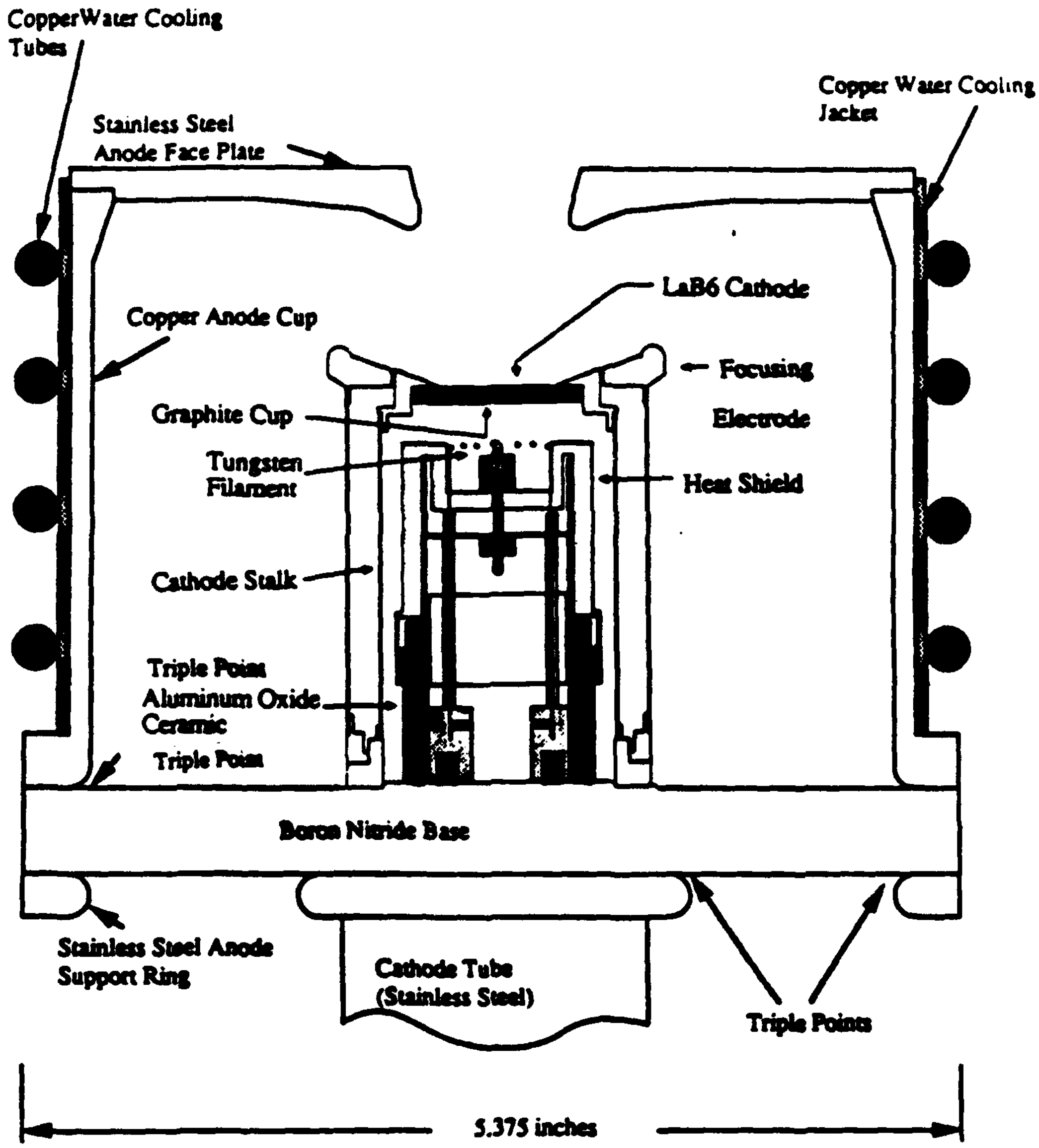


Figure 2 Cross section of LaB_6 electron gun. The one-inch diameter LaB_6 cathode is held inside a graphite cup. The boron nitride base has grooves (not shown) on both sides to increase its voltage standoff capability.

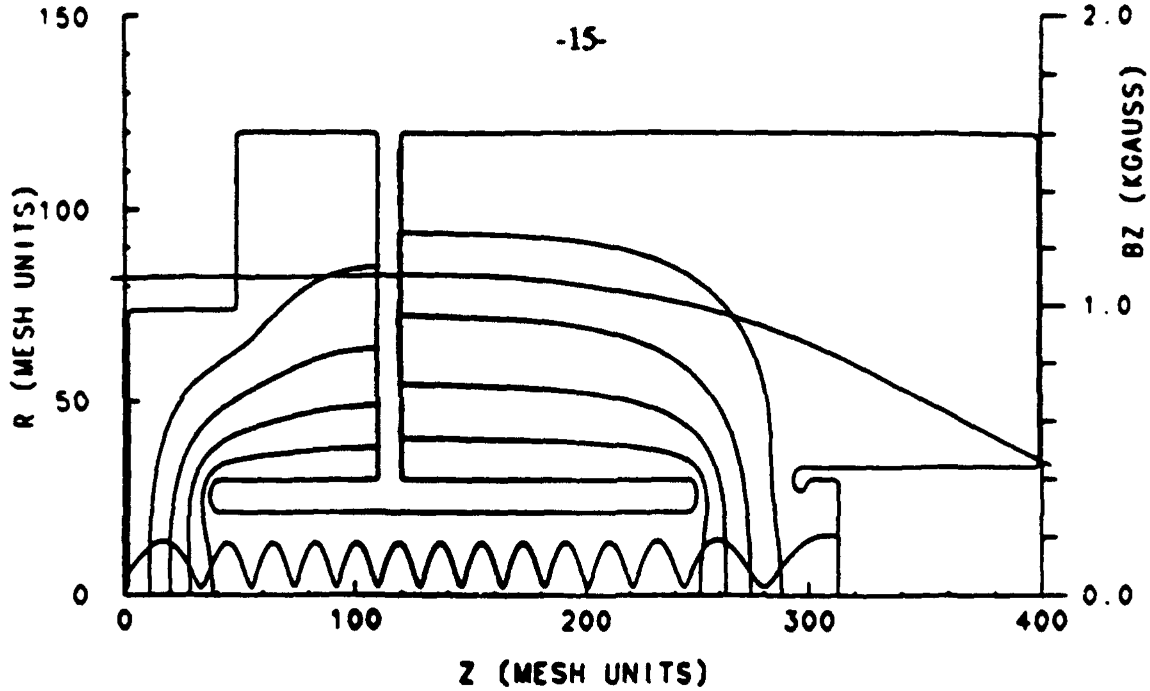


Figure 3 (a): EGUN simulation of the analyzer. Beam voltage = 75 kV; tube (filter lens) voltage = -30 kV; and α = 0.698. The electron is collected.

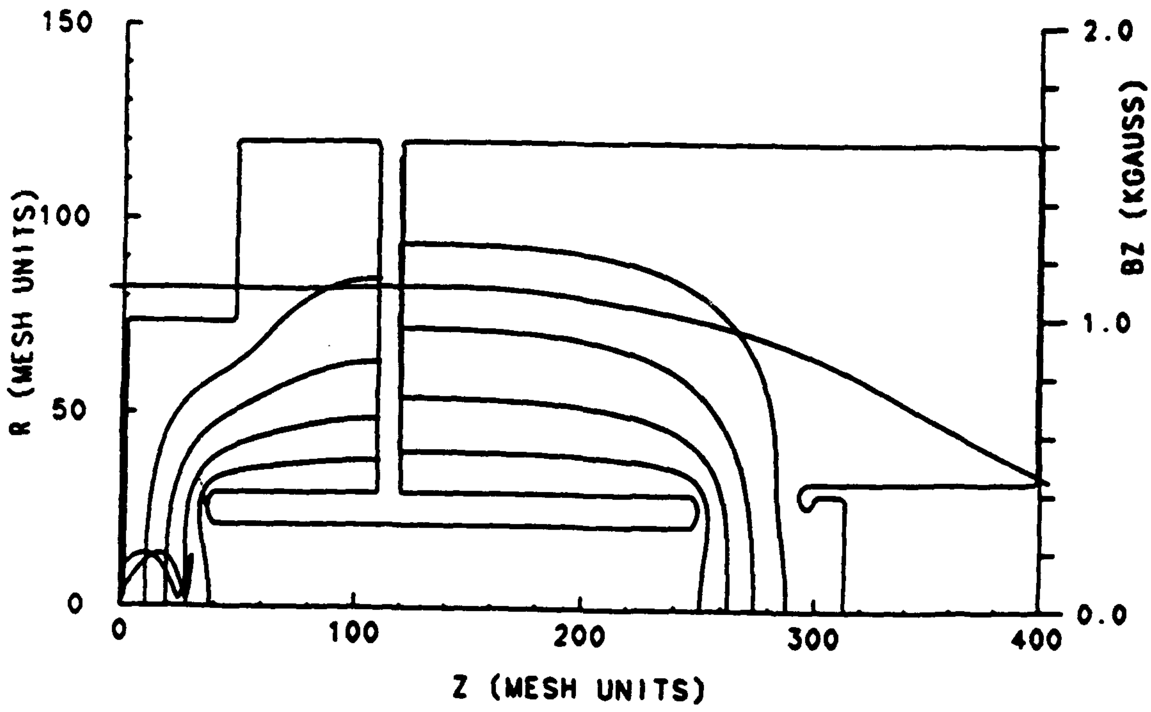


Figure 3 (b): EGUN simulation of the analyzer. Same conditions as (a) except tube (filter lens) voltage = -65 kV. The electron is reflected and not collected.

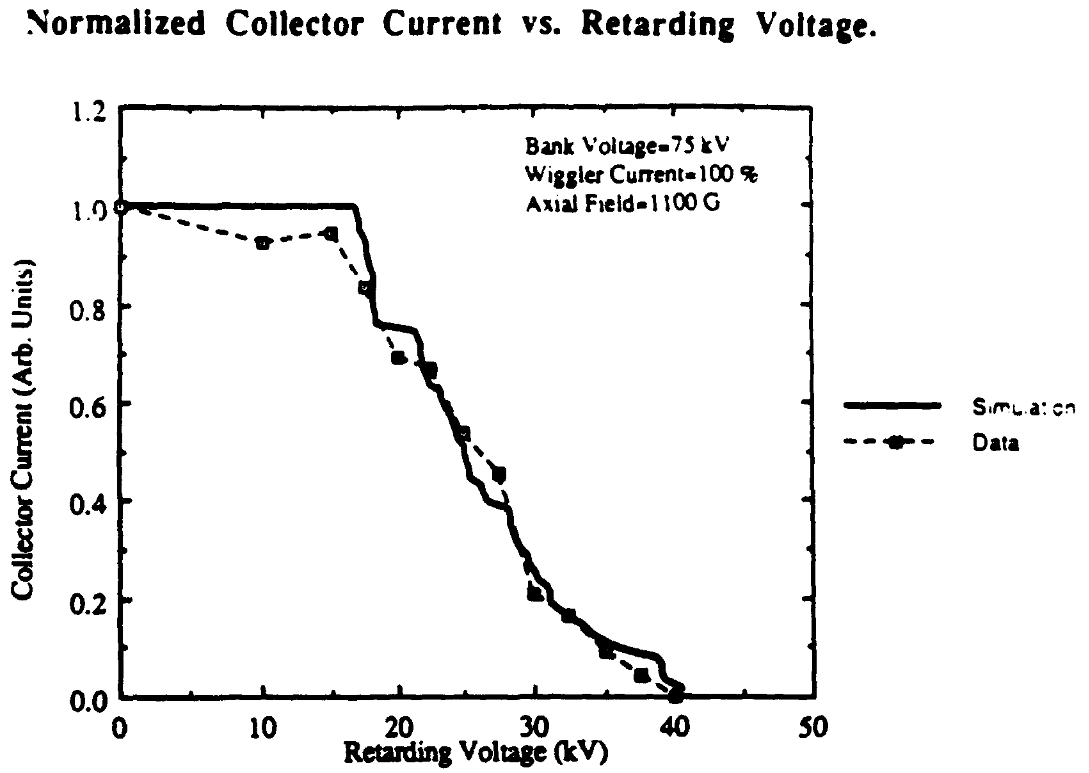


Figure 4 : Measured and simulated retarding potential curves. The simulation uses the Biot-Savart law to calculate the wiggler field. Wiggler current = 160 A.

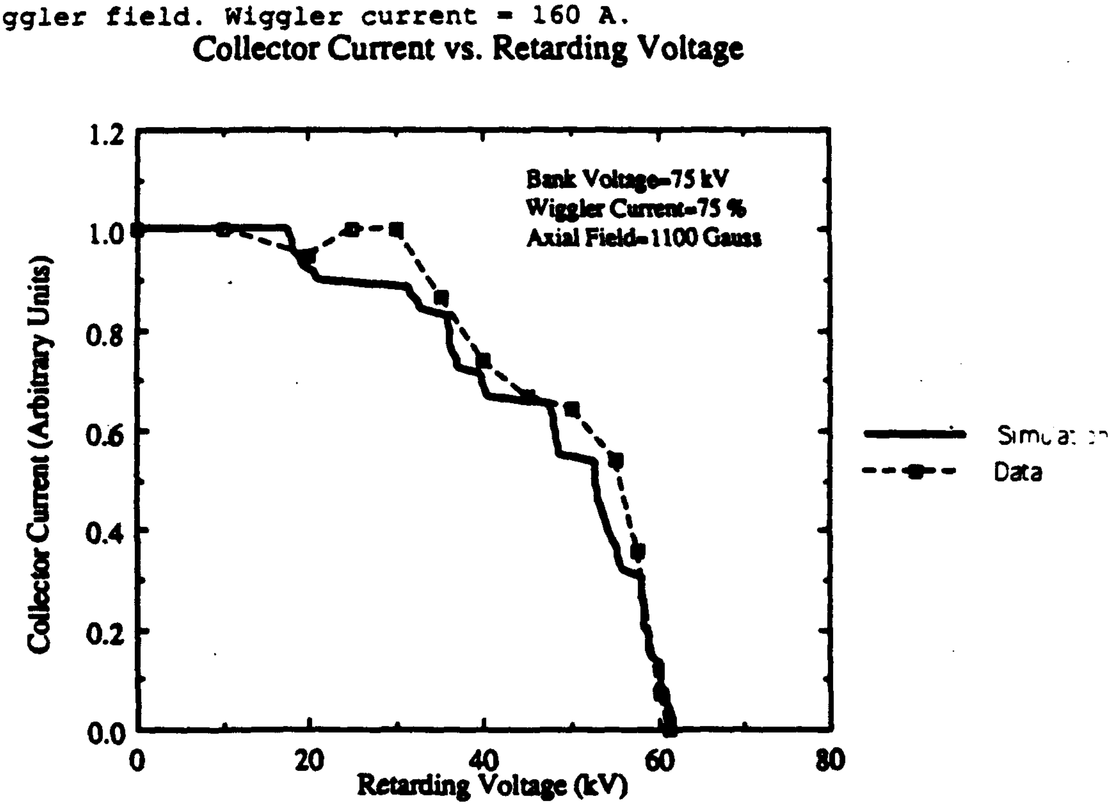
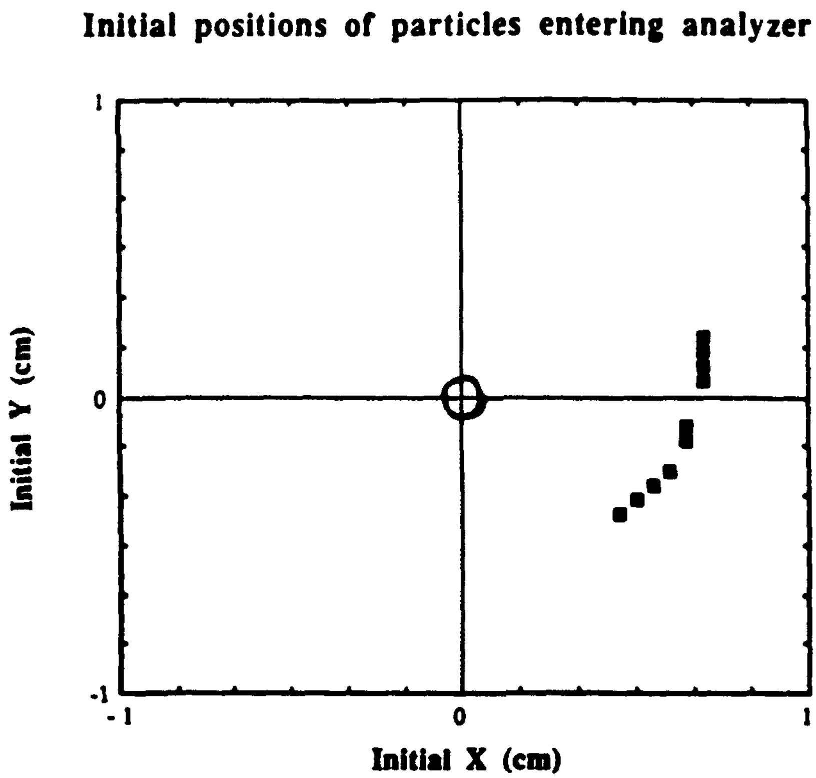


Figure 5 Measured and simulated retarding potential curves. The simulation uses the Biot-Savart law to calculate the wiggler field. Wiggler current = 120 A.

Initial positions of test particles which pass through wiggler and enter analyzer aperture and their final radii vs. initial radii, Iwiggler = 160 A



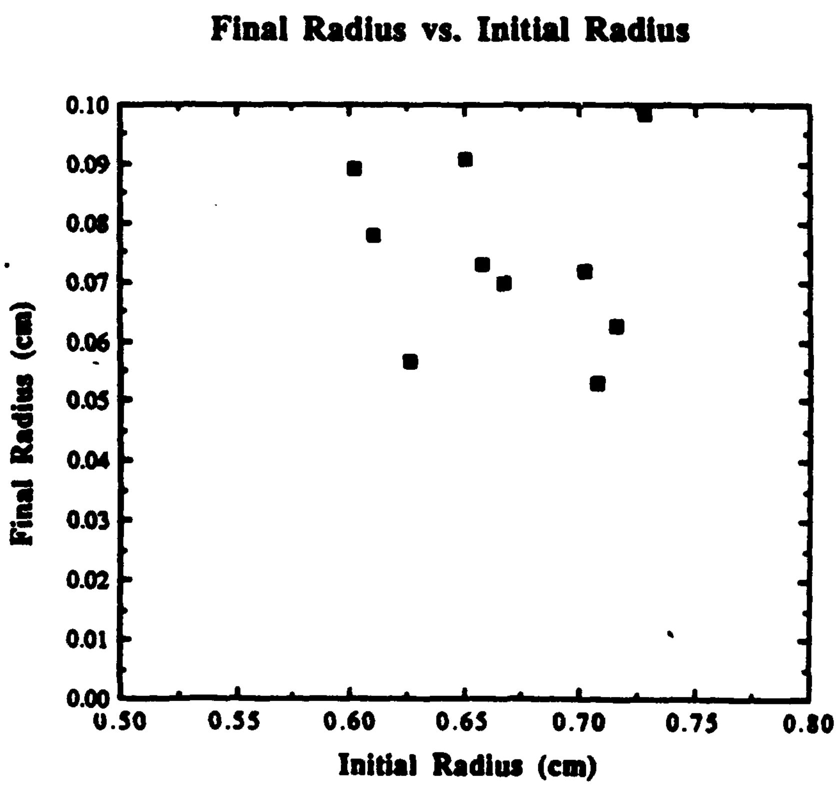


Figure 6 Anode aperture positions of electrons that pass through the analyzer aperture. The aperture is shown to scale on the initial-position plot. The analyzed electrons come from a radius near the beam edge.

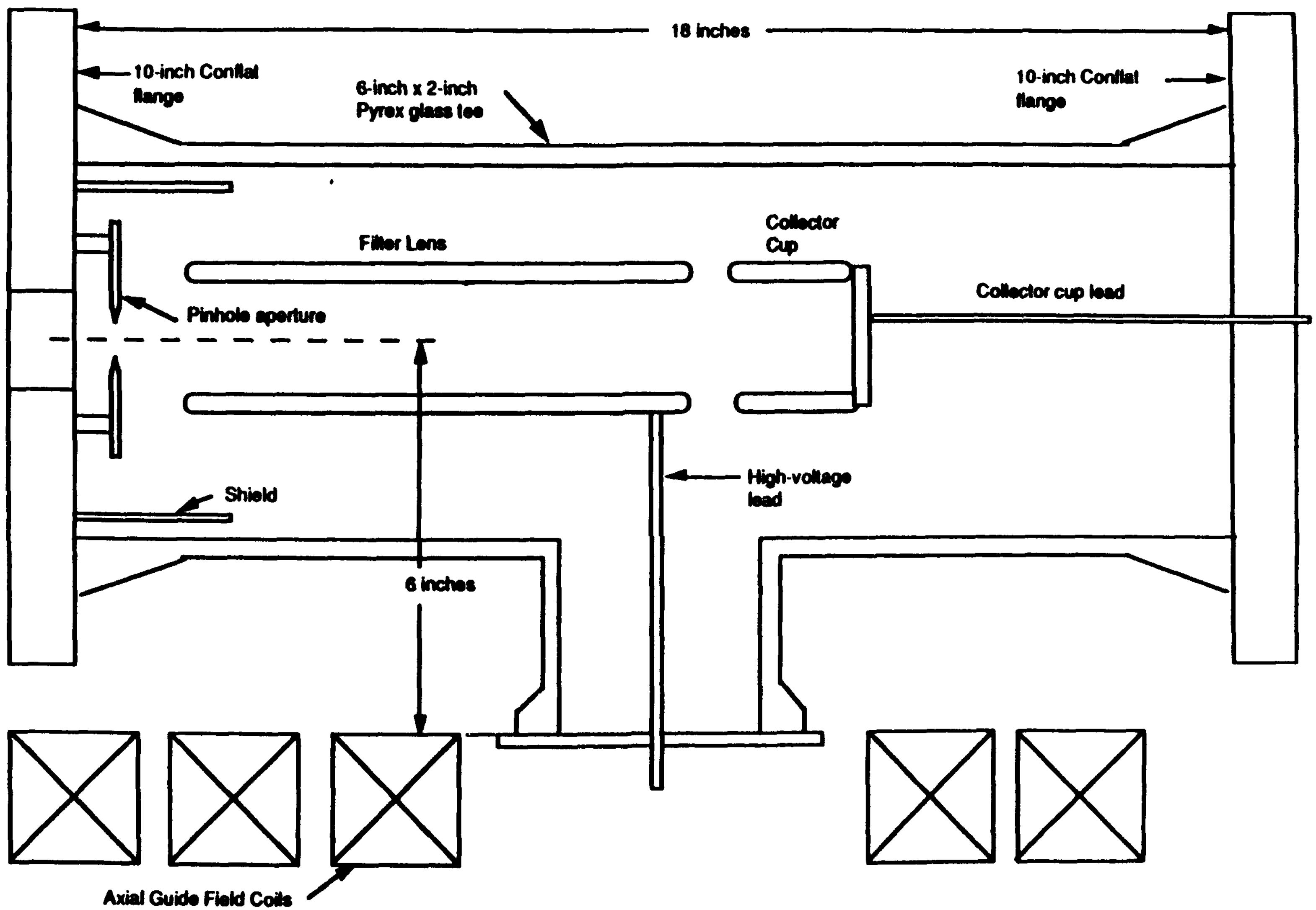


Figure 7 Drawing of the analyzer cross section. In the actual analyzer, the high-voltage lead came in from the right-hand side as shown in Figure 1.

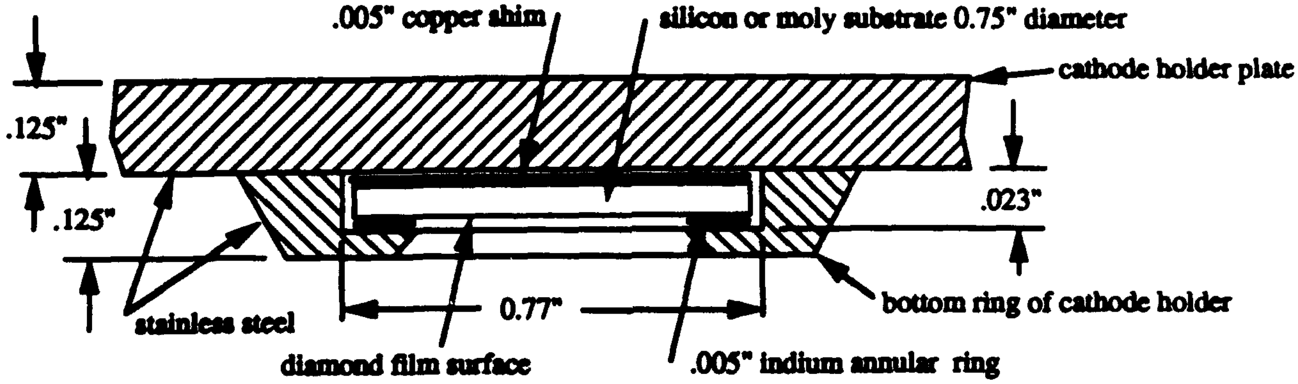


Figure 8: Diamond sample holder.

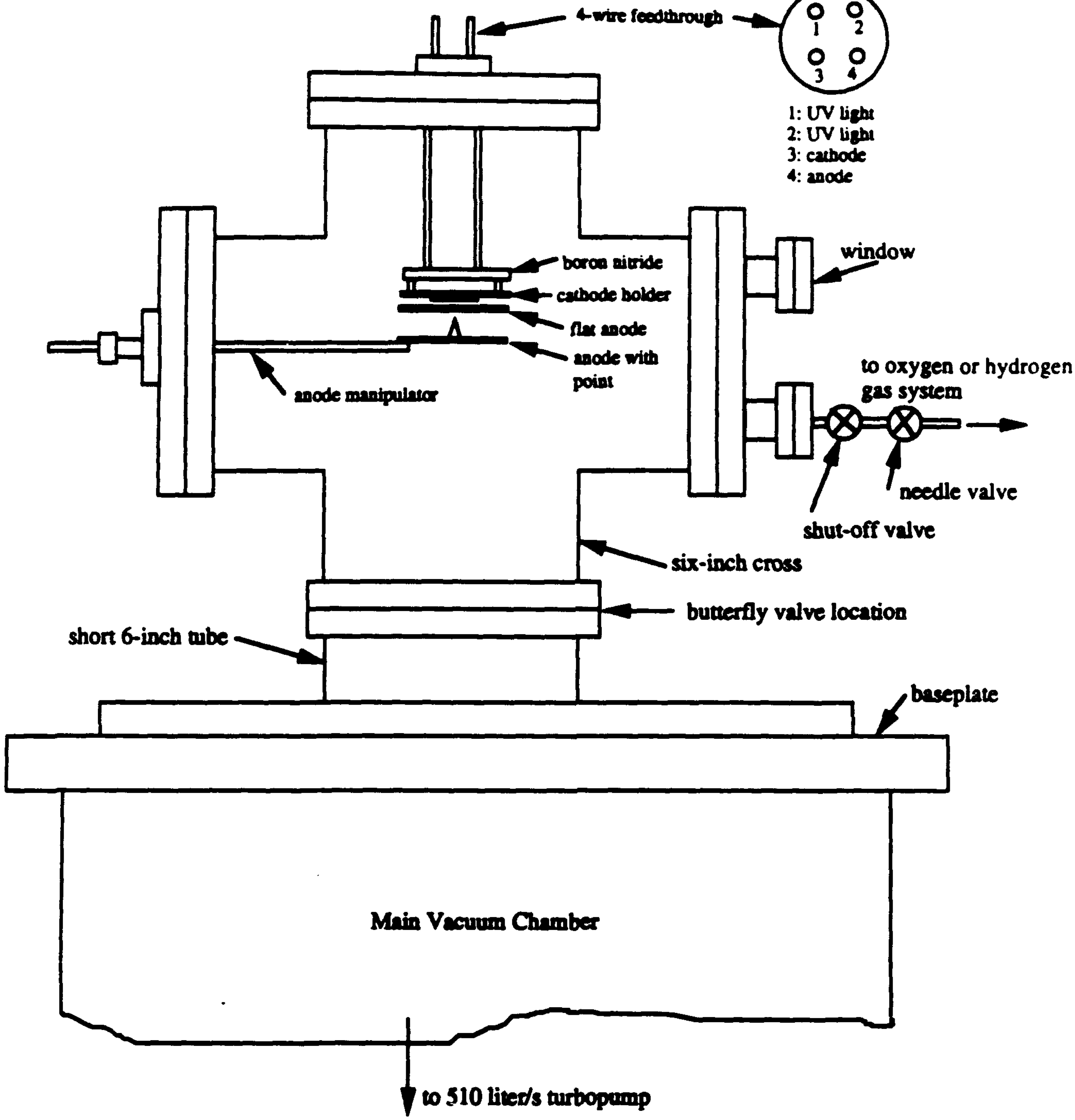


Figure 9: Vacuum system and electrode mount for diamond emission. Two anodes could be used: a flat plate or a sharp point.

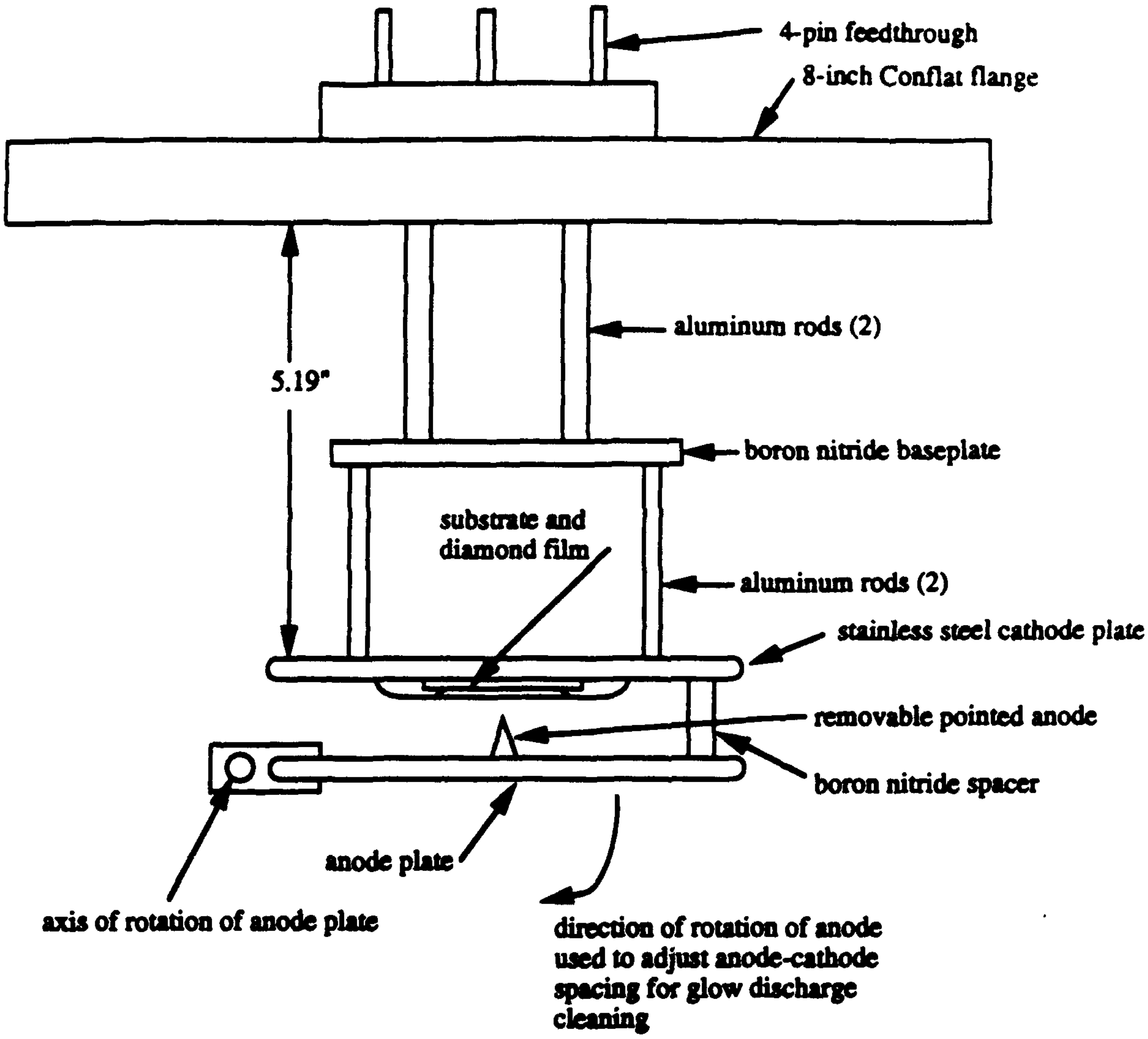


Figure 10: Anode-cathode electrodes.

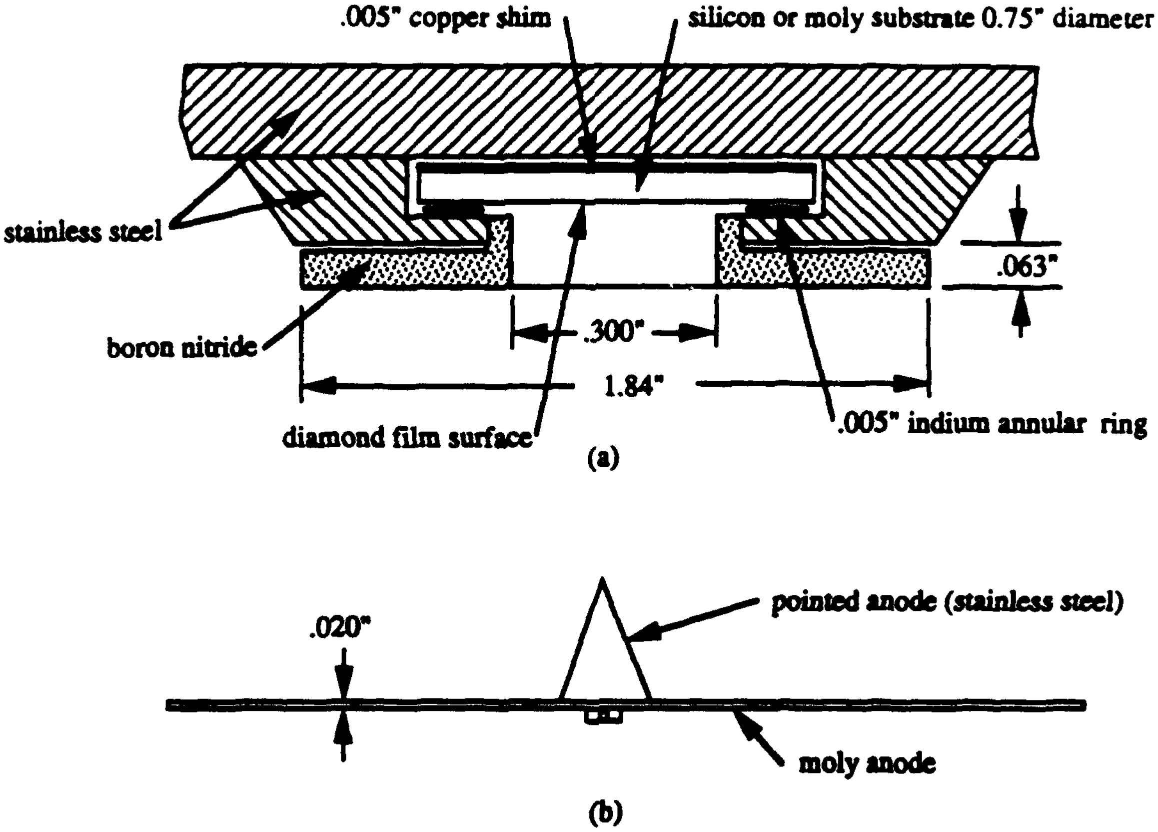


Figure 11 Other configurations of the (a) diamond film holder with insulator surface and (b) pointed anode.

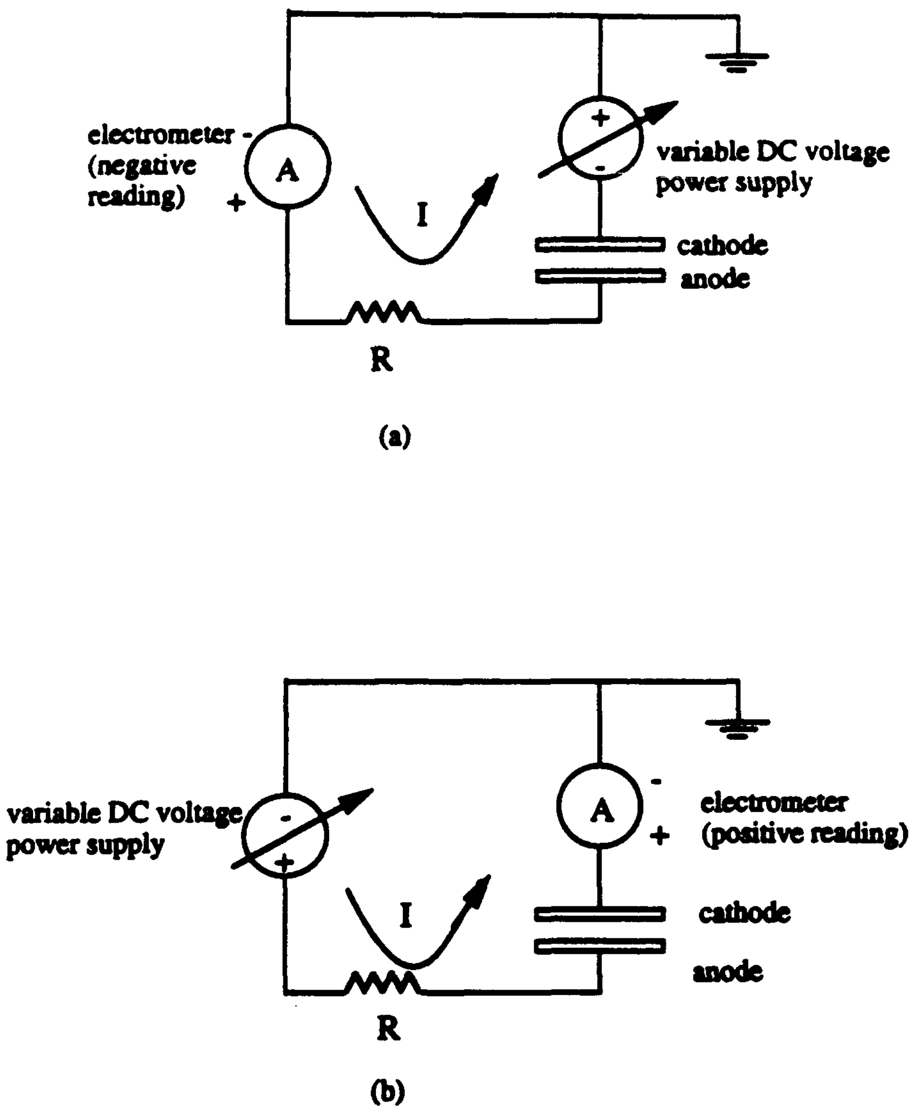


Figure 12: Electrical circuit for measuring emission. (a) anode grounded through electrometer; (b) cathode grounded through electrometer. R is a 1 MΩ current-limiting resistor.

APPENDIX A

Journal Article Abstracts

1. M. E. Herniter and W. D. Getty, "High Current Density Results From a LaB_6 Thermionic Cathode Electron Gun," *IEEE Trans. on Plasma Science*, Vol. 18, No. 6, pp. 992-1001 (December 1990).

2. M. E. Herniter and W. D. Getty, "Temperature-Limited Electron Bombardment Heating Method," *IEEE Trans. on Plasma Science*, Vol. 19, No. 6, pp. 1279-1289 (December 1991).

High Current Density Results From a LaB_6 Thermionic Cathode Electron Gun

MARC E. HERNITER, MEMBER, IEEE, AND WARD D. GETTY, MEMBER, IEEE

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/cm^2. 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/cm^2.

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/cm^2. The results presented here are for gun voltages up to 115 kV and transmitted current densities up to 30 A/cm^2. 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 cathode material in applications where high current density and resistance to chemical poisoning are important. Its thermionic properties were first investigated by Lafferty in 1951 [2]. Lafferty determined the thermionic emission constants of LaB_6 to be $A = 29$ A/cm$^2 \cdot$ K^2 for the Richardson-Dushman constant and $\phi = 2.66$ eV for the work function [2]. Since this 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/cm$^2 \cdot$ K^2 and ϕ in the range of 2.4 to 3.2 eV [3], [4].

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IEEE Log Number 9040082.

Other properties of LaB_6 that are important for cathode operation are its emissivity and evaporation rate. The emissivity of LaB_6 has been reported to be in the range of $\epsilon = 0.7$ to 1.0 [5]–[8]. Storms [9] has determined the emissivity of LaB_6 at 650 nm as a function of temperature. 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/cm^2 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]. A low evaporation rate is important for increased cathode lifetime.

An advantage of LaB_6 is its modest vacuum requirements. Ahmed and Broers [3] reported that LaB_6 can be operated in vacuum around 10^{-5} torr. 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 [5], [6]. 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 [2], [10]. 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 [5], [6] for the material 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 × 10^{-3}-mm^2 cathodes. Broers [11], [12] obtained current densities of 0.8 to 40 A/cm^2 from a 1-mm^2 LaB_6 rod cathode over a temperature range of 1400° to 1800°C.

Temperature-Limited Electron Bombardment Heating Method

Marc E. Herniter, *Member, IEEE*, and Ward D. Getty, *Member, IEEE*

***Abstract*—A temperature-limited electron bombardment heating method capable of heating LaB_6 cathodes to 1800°C has been developed. This method heats LaB_6 cathodes in a Pierce-type electron gun which is pulsed to 115 kV. 1.9-cm-diam LaB_6 cathodes have been heated to 1800°C, with 370 W/cm^2 of heating power. This method has been successfully used in a pulsed power environment where the bombardment filament and LaB_6 cathode are simultaneously pulsed to high voltages to produce electron beams. The heating system has produced cathode temperatures in excess of 1750°C, while the electron gun has been pulsed up to voltages of 115 kV. A dynamic model of the bombardment heating system has been developed. This model shows that the temperature-limited bombardment heating system is open-loop unstable. A digital control method is presented which stabilizes the heating system.**

I. Introduction

THIS paper describes the temperature-limited electron bombardment heating system used to heat Lanthanum Hexaboride (LaB_6) cathodes in a Pierce-type electron gun. The steady state and transient operation of the heating system, the operation of a digital controller which stabilizes the heating system, and the mechanical design of the heating system are presented. The possibility exists that this heating method may become uncontrollable. The conditions under which this may occur are discussed and design rules which avoid an uncontrollable system are outlined. This heating system operates while the electron gun is being pulsed to high voltages. The high voltage pulsing results of the electron gun have been discussed previously [1]–[3].

Several heating methods have been used to heat LaB_6 cathodes. These are generally either Joule heating of the LaB_6 cathode (direct heating), Joule heating of a tungsten coil with conduction heat transfer to the LaB_6 cathode (indirect heating), radiation heating, or a combination of radiation and electron bombardment heating.

The thermionic properties of LaB_6 have been compared to those of metals, thoriated tungsten, and barium oxide by Lafferty [4] in Richardson plots of current density versus temperature. Using data from Gewartowski and Watson [5], the dispenser cathode can be similarly compared. These comparisons show that in the temperature range of interest the LaB_6 current density lies above that of thoriated tungsten, and below those of dispenser and barium oxide cathodes. LaB_6 has other properties such as high current density capability at high temperatures and resistance to poisoning which make it advantageous for some applications.

A. Direct Heating

Direct heating is accomplished by passing a current through the LaB_6 cathode. This method has been used extensively by Williams *et al.* [7], Leung *et al.* [7], and Pincosy and Leung [8]. Due to the high electrical conductivity of LaB_6, large heating currents are required. Leung and Pincosy worked with directly heated LaB_6 cathodes that were made by cutting sintered LaB_6 plates into hairpin filaments. Heater currents up to 160 A were passed through the filaments. The taper of the filaments was chosen to achieve a uniform temperature distribution.

B. Indirect Heating

The indirect heating method heats the LaB_6 cathode by thermal conduction from a directly heated tungsten filament. Shintake [9] used this method to heat a 30-mm-diam LaB_6 cathode to 1340°C. The heater consisted of a tungsten wire wound around a boron nitride tube. The tube was directly connected to a graphite rod which held the LaB_6 cathode. The cathode was heated by conduction through the graphite rod and boron nitride tube. The advantage of this method is that lower heating currents are required than in direct heating, because of the higher resistance of the tungsten filament. The main disadvantage is the possibility of poor thermal conduction at the interfaces between the different materials.

C. Radiative Heating

A third cathode heating method is thermal radiation from a tungsten filament. The filament is heated to high temperatures and the thermal radiation emitted by the filament is focused onto the cathode. This method requires lower heating currents than a directly heated LaB_6 cathode. Goebel *et al.* [10] used radiative heating from a tungsten filament made with 0.32-cm-diam wire placed directly behind a 6.3-cm-diam LaB_6 cathode. To achieve a cathode temperature of 1650°C, a heater current of 510 A at 17 V was required.

One subtle problem with radiative heating is that electron bombardment heating may also occur. Depending on the magnitude and bias of the filament potential with respect to the cathode, the filament may bombard the cathode with electrons or the cathode may bombard the filament. This extra heating may cause difficulties in achieving uniform

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APPENDIX B

Conference Paper Abstract

1. K. D. Pearce and W. D. Getty, "Retarding Field Analysis of a 90-kV, 70-A Electron Beam with Wiggler and Axial Magnetic Fields," presented at the 32nd Annual Meeting, Division of Plasma Physics, *Amer. Phys. Soc.*, Cincinnati, Ohio, November 12-16, 1990. Abstract: *Bull Amer. Phys. Soc.*, Ser. II, Vol. 34, p. 2072 (October 1990).

Abstract Submitted for the Thirty-second Annual Meeting
Division of Plasma Physics
November 12-16 1990

Category Number and Subject 5.1.1

__ Theory _x Experiment

Retarding Field Analysis of a 90 kV, 70 A Electron Beam with Wiggler and Axial Magnetic Fields. K. D. PEARCE and W. D. GETTY, Univ. of Michigan.* A 5 μs, 90 kV, 70 A square output pulse electron beam is produced by a 3-stage, crowbarred, Marx generator with a 10-90% risetime of less than 1 μs. The electron gun contains a lanthanum hexaboride (LaB_6) cathode which is heated by electron bombardment in a Pierce electron-gun geometry. The cathode is immersed in a collimating axial magnetic field of 1.2 kG which extends over the entire length of the beam. The electromagnetic bifilar wiggler has a period of 4.0 cm and is 7 wavelengths long. The beam is transported to a collector 5 cm beyond the wiggler. Diagnostics consist of a capacitive-divider Marx voltage monitor, a resistive-divider beam voltage monitor, a Rogowski coil beam current monitor, and a post-wiggler current collector. A pinhole in the current collector allows part of the beam to enter a newly-developed retarding potential velocity analyzer which is being used in studies of the effect of the wiggler on the beam velocity distribution.

* Work supported by the Office of Naval Research.

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RLM 11.234
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Austin, TX 78712

APPENDIX C

Ph.D. Thesis Abstract

K. D. Pearce and W. D. Getty, "Retarding Field Analysis of Long Pulse Electron Beams Through Combined Bifurcated Bifilar Wiggler and Guide Magnetic Fields," Ph.D. Thesis, Nuclear Engineering, The University of Michigan, Ann Arbor, 1991.

ABSTRACT

RETARDING FIELD ANALYSIS OF LONG PULSE ELECTRON BEAMS THROUGH COMBINED BIFURCATED BIFILAR WIGGLER AND GUIDE MAGNETIC FIELDS

by

Kelly Douglas Pearce

Co-chairs: Ward D. Getty, Mary L. Brake

In the past several years, the free electron laser (FEL) has been used to produce frequency tunable coherent radiation in the millimeter to submillimeter wavelength range. The reasonably high efficiency and power levels already achieved have spurred further work to refine and improve the FEL, particularly for lower wavelength applications.

In a free electron laser, the electron beam is given a substantial transverse velocity component by passing it through a transverse periodic magnetic field commonly referred to as a wiggler. Recent work includes analytical and experimental investigations of beam propagation dynamics in the wiggler field. The present investigation is an experimental and numerical study of a type of wiggler called the bifurcated bifilar wiggler.

In the present investigation a retarding field energy analysis is performed upon a long-pulse, mildly relativistic electron beam after it passes through combined bifurcated bifilar wiggler and axial magnetic fields. A 5-μs, 75-kV, 0-20 A, square output pulse electron beam is generated by a 3-stage, crowbarred Marx generator with a 10-90% risetime of less than 1 μs.

The electron gun contains a lanthanum hexaboride (LaB6) cathode which is heated by electron bombardment in a Pierce electron-gun geometry. The cathode is immersed in a

collimating axial guide field of 1.1 kG which extends over the length of the beam. The variable pitch wiggler has an entrance pitch of 5.65 cm and is 30 cm long.

Diagnostics include a resistive-divider beam voltage monitor, a Pearson coil cathode current monitor, and a post-wiggler current collector. An aperture in the current collector allows part of the beam to enter a newly-developed retarding potential velocity analyzer. This analyzer is able to operate at full beam voltage of up to 85 kV.

Numerical methods were used to produce computer generated retarding potential curves for operation at various combinations of system parameters. It was shown by simulation that the analyzer gives good selection of axial velocity, and that it could operate properly when the electrons had large Larmor radii. A code was also used to compare three-dimensional realizable wiggler operation with existing one-dimensional idealized wiggler theory.

The experimental and numerical retarding potential plots were compared and demonstrated good agreement. The wiggler demonstrated a high level of axial-to-transverse energy conversion. However, it also greatly increased the axial velocity spread of the beam as it passed through the wiggler.