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PLASMA CATHODE FOR E-BEAM LASERS

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Hughes Research Laboratories

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13. ABSTRACT

The objective of this program is to develop a new type of plasma cathode electron gun and to demonstrate that it has properties suitable for operation with E-beam lasers. This device employs a plasma generated within a low-voltage hollow cathode discharge rather than a thermionic emitter as the source of electrons. Electrons extracted from the plasma pass through a triode-type control grid structure and are accelerated to high energies in a plasma-free region prior to emerging from the gun through a thin foil window. The device is characterized by ruggedness, low cost, low power consumption, and fast response in comparison to thermionic cathode E-guns.

Many of the basic characteristics of the plasma cathode concept have been previously demonstrated with devices producing beams of up to 30 cm^2 in area at beam energies of up to 140 kV and at pulsed current densities up to 1 A/cm^2. This work has included measurement of the beam current density distribution, verification that the beam is highly monoenergetic, and demonstration of triode-type electronic control characteristics.

Recently, devices which produce beams with areas up to 160 cm^2 have been evaluated and beam uniformities of typically ±5% (rms) have been achieved. Further demonstration of scalability has been undertaken with a 200-cm long hollow cathode discharge test vehicle. Finally, a new compact high-voltage feedthrough has been developed for the purpose of providing support and electrical insulation for the cathode portion of the E-gun. This component, which operates under the simultaneous constraints imposed by vacuum, Paschen and dielectric breakdown, has been successfully evaluated at voltages up to 200 kV in a gaseous environment similar to that encountered in the plasma cathode E-gun. The information gained from all of these experiments will be incorporated into a 5 x 125 cm E-gun which is presently being designed.

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SUMMARY

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1. INTRODUCTION

The objective of the plasma cathode program is to develop a new type of electron gun suitable for electron beam plasma conditioning of large volume electric discharge lasers.[1] This gun employs a plasma which is generated within a low-voltage hollow cathode discharge as the source of electrons rather than a thermionic cathode as in conventional electron guns. The beam current extracted from the discharge is controlled by means of a grid system in a manner very similar to that employed in standard vacuum triodes. This permits the generation of any desired pulse shape. After extraction from the discharge plasma, the electron beam is accelerated to energies in the range of 100 to 200 keV prior to passing through a thin metal foil window and into the active laser region.

The plasma cathode electron gun is characterized by its simplicity, and has advantages over conventional thermionic devices which include:

a. Simple, rugged construction — No inherently delicate heater elements are required, and since operation is obtained at near ambient temperatures, thermal stress problems are minimized.

b. Insensitivity to contamination — Since high temperature, low work function surfaces are not required, cathode poisoning is not possible; if the foil window ruptures, the plasma cathode will not be damaged.

c. Suitability for large area beam production — scaling to any desired size is achieved by simply enlarging the device dimensions without the constraints imposed by heater element design.

d. Instantaneous startup — No warm-up time is required since beam extraction can be obtained immediately after discharge ignition which occurs in about a microsecond.

e. Low power consumption — The plasma cathode consumes less power from power supplies floating at high voltage than do equivalent thermionic devices.

f. Low cost — The inherent structural simplicity of the plasma cathode and low part count is indicative of substantial cost savings in relation to thermionic devices.

Several plasma E-guns of various types are described in the literature, some of which have been used on lasers.[2] These employ either a high-voltage glow discharge or a low-pressure incipient vacuum arc. The plasma cathode gun is unlike either of these types and is expected to have advantages which include:

a. Good foil penetration for plasma conditioning — Efficient foil penetration is achieved due to the highly monoenergetic property of the beam generated by the plasma cathode gun. Other gas discharge devices, in which a plasma sheath exists in the region between the accelerating electrodes, produce a broader energy distribution with substantial amounts of electrons at lower energy; this results in reduced foil penetration ability.

b. Long pulse and cw capability — High-voltage glow discharge devices are only capable of pulsed operation at pulse lengths which are dependent on the beam voltage and current. The incipient vacuum-arc devices are inherently limited to short pulse ($\lesssim 5$ μsec) operation. The plasma cathode can operate in either pulsed or cw modes.

c. Long life — Since the plasma cathode incorporates a relatively low voltage (500 to 800 V) discharge, sputtering is greatly reduced in comparison to high voltage glow discharge devices in which ions with energies comparable to the E-beam energy strike the cathode.

Improved control — The triode type grid control utilizes with the plasma cathode gun is expected to be simpler and more versatile than that of diode type high voltage discharge devices. The high acceleration voltage can be continuously applied in the present device and rectangular-pulsed beam operation is achieved by pulsing the hollow cathode discharge or the control grid. Operation with other pulse shapes can be obtained by proper temporal biasing of the control grid.

e. Higher power efficiency — Since electrons are produced in a low voltage gas discharge, the power efficiency of the plasma cathode is much higher than other plasma guns where ions reach the cathode at high energies.

f. Reduced power supply complexity — Pulsed operation of the plasma cathode is achieved simply by pulsing the low-voltage hollow cathode discharge. Other plasma guns require that the high voltage be pulsed, which is difficult to do efficiently and at high repetition rates.

Under the present contract, the plasma cathode concept is being developed to the point of demonstrating operation of a device which produces an electron beam having the following properties:*

a. Beam dimensions ≥10 cm x 15 cm

b. Beam current density ≥100 mA/cm^2

c. Beam energy ≥150 keV

d. Pulse length = 100 μsec.

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*This contract has been extended for the first half of 1974 with the objective of building a 5 x 125 cm E-gun designed primarily for cw operation.

II. TECHNICAL APPROACH

A diagram of the plasma cathode electron gun is shown in Fig. 1. The device consists of three major regions: (1) the plasma generation region in which the beam electrons originate, (2) the extraction and control region where electrons are removed from the plasma and transported in a controlled manner into the acceleration region, and (3) the high voltage acceleration region where the electrons are accelerated, without making collisions, to high energies prior to passing through a thin metal foil window and into the laser medium. These regions are comparable to the thermionic cathode, control grid, and the grid-to-anode space of a conventional vacuum triode.

The plasma generation region in the present device consists of a hollow-cathode discharge struck between the hollow cathode surfaces and the anode grid, G1. This type of discharge was chosen due to its stability, reliability, simplicity, and ability to operate at the low gas pressures required to preclude gas breakdown in the acceleration region. In the present application, the discharge operates at a voltage of typically 500 to 800 V with helium at pressures typically in the range 15 to 30 mTorr. Helium is used because He^+ ions have relatively low sputtering yields and because it has desirable high voltage breakdown characteristics.

The major characteristic of the hollow cathode discharge is that most of the plasma volume is surrounded by the cathode surface. The discharge is operated in a regime where the rate of ion generation by ionization in the discharge volume is sufficient to maintain the plasma potential at, or slightly above, anode potential. Under these conditions, the discharge is a cold cathode glow discharge sustained by secondary electron emission due to ion bombardment of the cathode surface. To first order, the applied discharge voltage V appears entirely across the cathode sheath. This results in two effects: (1) ions from the plasma are accelerated by the full discharge voltage through the cathode sheath, thus gaining the energy required for secondary electron emission, and (2) the secondary electrons emitted at the cathode

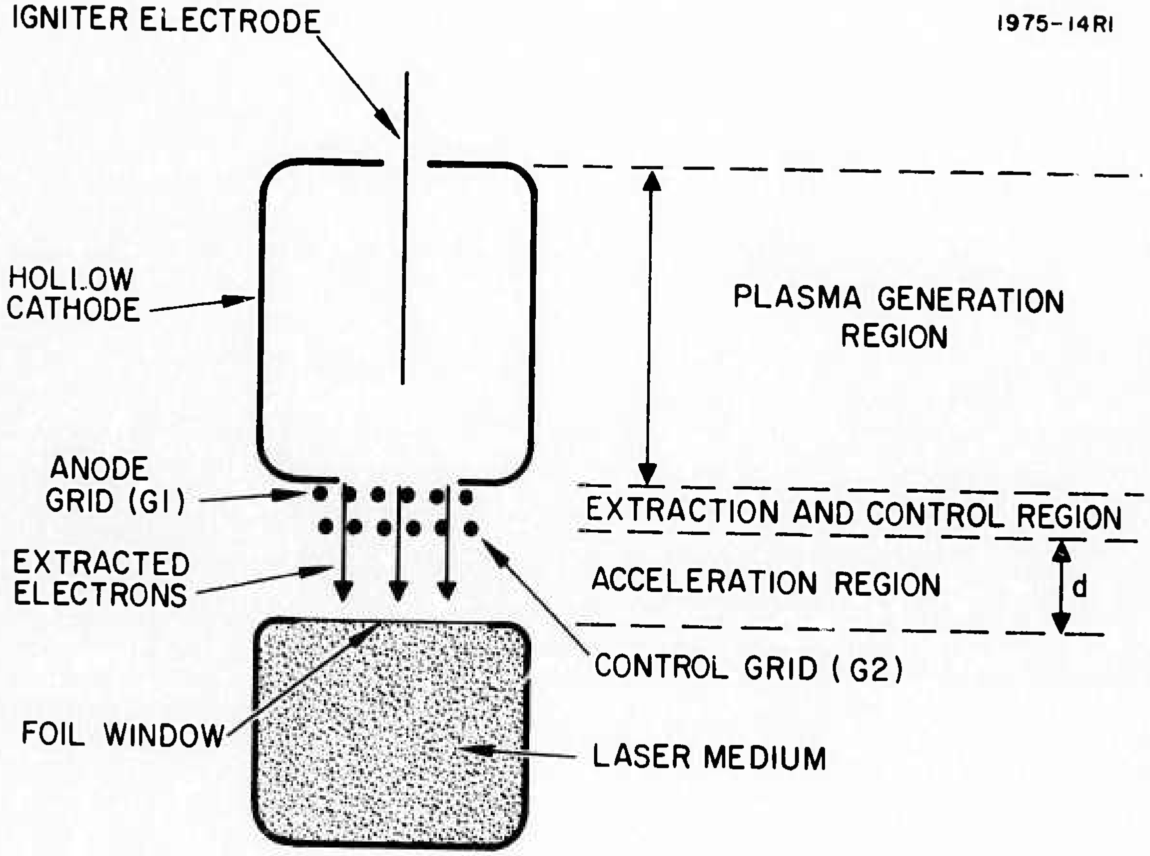

Fig. 1. Schematic of the plasma cathode electron gun.

are accelerated through the cathode sheath to the full discharge voltage, thus acquiring an energy at which the ionization cross section for gas atoms is near maximum.

Maintenance of the large cathode area-to-anode area ratio leads to the known result that: (1) most ions (generated by the secondary electrons) are sccelerated through the cathode sheath, intercepted by the surrounding cathode surfaces, and utilized with maximum efficiency for secondary electron emission, thus minimizing the rate of ion generation required per emitted electron; (2) for gas pressures where the electron ionization mean-free path exceeds the dimensions of the discharge chamber, the secondary electrons accelerated through the cathode sheath are not lost after their first transit through the discharge chamber; most of them are repeatedly reflected from opposing cathode surfaces, and have a high probability of making ionizing collisions before reaching the anode. The discharge is thus sustained at low pressures, where the electron ionization mean-free path exceeds the dimensions of the hollow cathode discharge region.

A minimum pressure exists, below which this mode of discharge cannot be sustained. This is believed to be due to the following circumstances: as the gas pressure is reduced, the number of oscillations which a secondary electron must perform before making an ionizing collision increases. As the number of oscillations increases, the probability for an oscillating electron to fall on the anode before making an ionizing collision increases; its probability of being captured rather than reflected by a cathode surface also increases.[3] Both effects result in a reduction of the percentage of oscillating electrons which are effectively utilized in making ionizing collisions. As the utilization efficiency of the oscillating electrons decreases with decreasing gas pressure, the energy which must be imparted to them increases to maintain the required rate of ion generation; this leads to the experimentally observed increase of discharge voltage with decreasing gas pressure. As the discharge voltage increases with decreasing gas pressure, the ionization collision cross section for the oscillating electrons decreases, and eventually the rate of ion generation per emitted secondary electron becomes smaller than the corresponding rate of ion loss. The gas pressure at which this happens is the minimum below which the discharge cannot be sustained in this mode.

Electrons are extracted from the discharge plasma through anode grid G1 and pass through the control grid G2 into the acceleration region. Voltages of typically 0 to -100 V relative to G1 are applied to G2 in order to control the beam intensity from 1 A/cm^2 to near cut-off. Grid G2 also serves to provide isolation between the low-voltage glow discharge region and the high-voltage acceleration region. Alternately, control of the beam current is possible through variation of the hollow cathode discharge current through the potential of G1.

The width d, of the acceleration region, is critical to the successful operation of the plasma cathode electron gun since the entire electron acceleration voltage is applied across this gas-filled gap. In order to produce a high-energy electron beam with a narrow energy distribution, the number of inelastic collisions which the electrons make with gas molecules in this region must be kept to a minimum. This is achieved by operating at low gas pressures, maintaining a small acceleration region width, and thus avoiding the formation of a gas discharge in this region. The width d, is determined primarily by the principles of vacuum breakdown. Previous experience has shown that parallel-plate electrodes will conservatively withstand applied fields of 70 kV/cm without breakdown in vacuum.[4] This result is not changed if gas, at sufficiently low pressures, is present in the interelectrode space. The vacuum breakdown voltage, V, is plotted as a function of d in Fig. 2.*

As the gas pressure is increased, the probability of gas or Paschen breakdown is increased. The present device operates to the left of the Paschen minimum, as shown in Fig. 2, for a helium pressure of 50 mTorr. As is well known, the Paschen breakdown voltage

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*There exists a wide scatter in data for vacuum breakdown as well as for Paschen breakdown in helium. The curves shown in Fig. 2 represent a conservative interpretation of this data, supplemened by our own measurements.

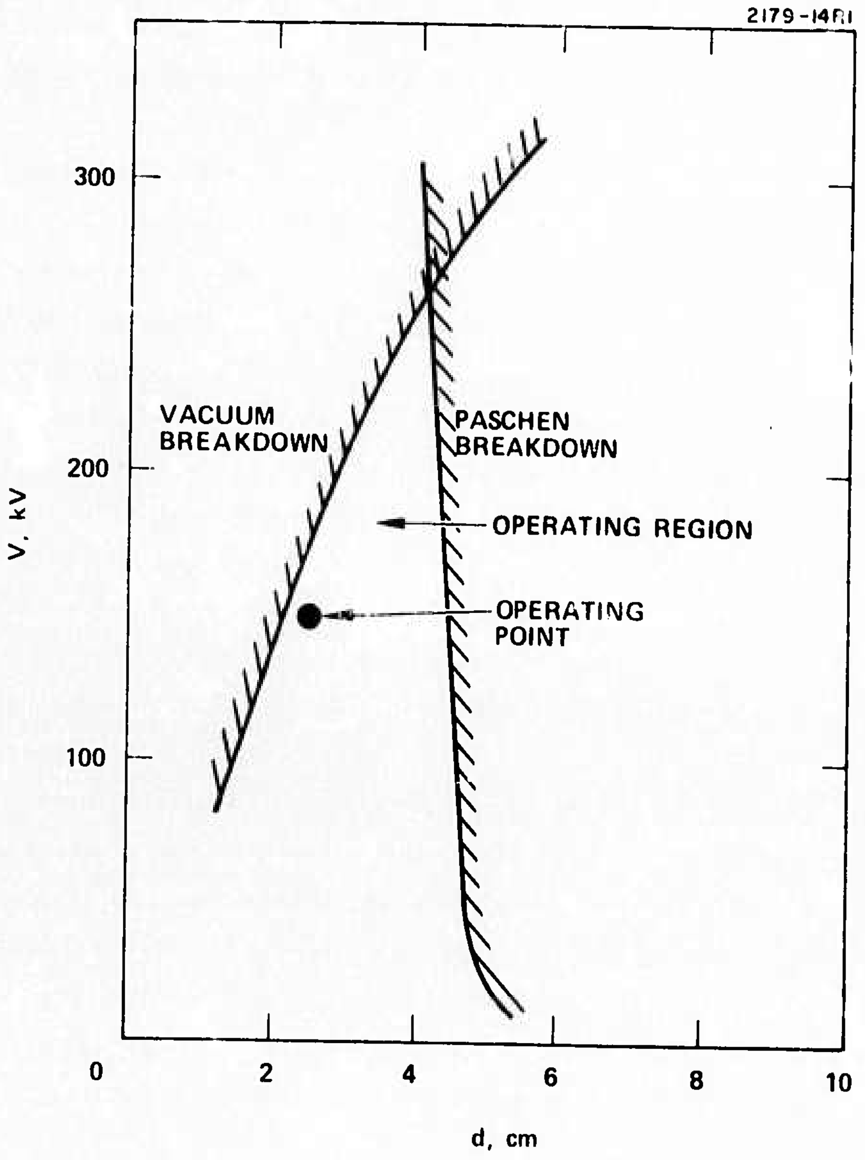

Fig. 2. Low pressure breakdown voltage in the plasma cathode accelerating region as a function of the gap width, d.

depends on the product pd and, thus, a reduction in pressure results in a proportional increase in width d for which breakdown occurs at a given voltage.[5] It has been experimentally demonstrated under the present program that, as expected, the Paschen breakdown characteristic is unaffected by the presence of an electron beam in the acceleration region.

As seen from Fig. 2, there is a region between the two breakdown characteristics where high voltage operation is possible without incurring breakdown. In the present device, width d is chosen for a given maximum operating voltage (150 kV for this example) so that the operating point will lie nearer to vacuum breakdown characteristic. This is desirable since this characteristic is expected to be more stable in time than the Paschen curve which is sensitive to the presence of outgassing products. As can be seen from Fig. 2, this design is conservative and accelerating voltages up to 250 kV may be possible with a helium pressure of 50 mTorr; even higher voltages may be possible at lower pressures.

Operation of the plasma cathode electron gun in either high current pulsed or cw modes is possible. However, cw operation results in much greater heating of the cathode surfaces due to ion bombardment than is encountered for pulsed operation at similar discharge current levels and low duty cycles. It is, therefore, necessary to operate at lower discharge currents and correspondingly reduced beam currents in the cw case. This requirement is also imposed by the inability of thin metal foil windows to withstand high average energy deposition rates resulting from high-energy electron scattering within the foil.

Figure 3 summarizes the voltage and current requirements for the plasma cathode E-gun which are based on data obtained under typical operating conditions. For pulsed operation, the 500 V grid supply would provide current pulses.

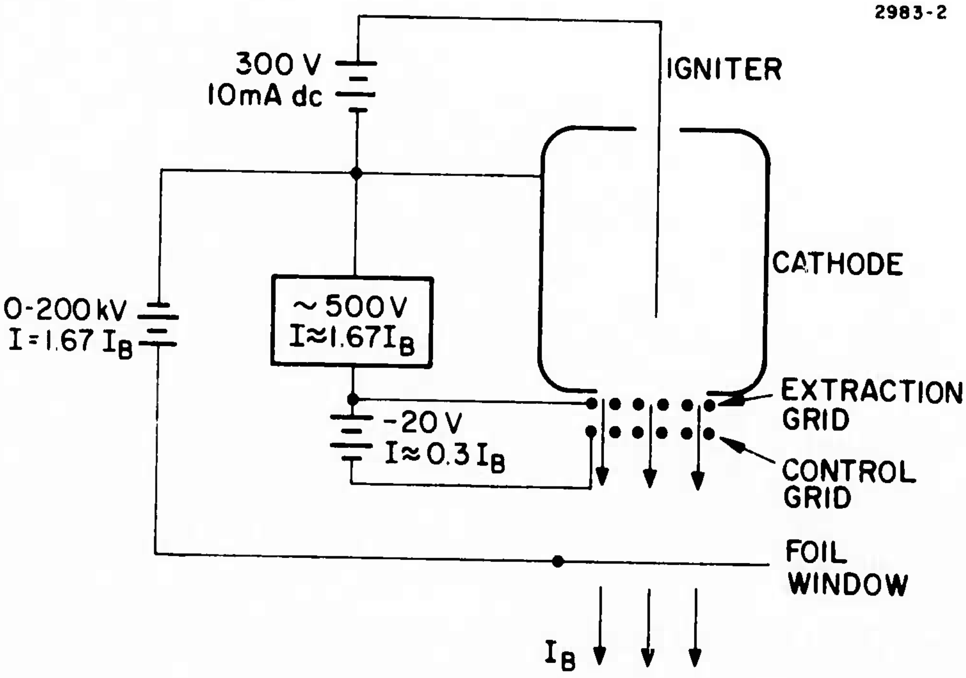

Fig. 3. Plasma cathode power supply schematic.

III. PLASMA CATHODE EVALUATION PROGRAM

This section discusses the details of the program undertaken to experimentally evaluate the plasma cathode E-gun concept. The following areas will be discussed below:

a. Previous Experimental Evaluations

b. The 10 x 15 cm Device

c. The 4 x 40 cm Coaxial Device

d. Compact High-Voltage Feedthrough Development

e. Scaling Experiments

f. The 5 x 125 cm E-Gun

A. Previous Experimental Evaluations

The previous experimental work, described in the two previous semiannual reports, has been divided into two basic areas. The first area involved an assessment of various possible basic design alternatives. This led to the choice of the hollow cathode discharge as the low pressure plasma source and the thin-wire ignition electrode. The second area was concerned with the experimental evaluation of the basic plasma cathode design. This latter area, which was the major subject of the previous semiannual report, is reviewed below in order to provide a basis for the new work described in this report.

The purpose of the prior evaluation effort was to systematically verify the basic operating characteristics of the plasma cathode E-gun with devices which permitted maximum flexibility. This flexibility was necessary in order to be able to quickly incorporate design changes indicated by the experimental results. Thus, this work was performed with relatively small devices which produced beams with cross-sectional dimensions of 1 x 11 and 3 x 10 cm.

Using these small area test vehicles, results in the following areas were obtained:

1. Discharge Characteristics — The current, voltage, and pressure characteristics of the hollow cathode discharge were mapped. This indicated that the discharge can operate at discharge voltages consistent with tolerable sputtering levels (i.e., below ~1 kV) at helium pressures as low as 15 mTorr. The discharge operates at approximately constant voltage and with plasma parameters consistent with our model of the hollow cathode discharge.

2. Paschen Breakdown — Measurements of the Paschen breakdown characteristics were obtained with and without the presence of an electron beam which was produced by a small thermionic E-gun. It was found, as expected, that the pressure at which breakdown occurred was reduced by less than 20% at 100 kV with the beam on. A value of Pd = 0.20 Torr-cm was established for design purposes.

3. Beam Extraction — Beam extraction was obtained at 140 keV and 91 mA/cm (all current densities are upstream of the foil window location) in 100 μsec pulses with the 1 x 11 cm device. In other tests, pulsed and cw current densities of up to 1 A/cm^2 and 0.7 mA/cm^2, respectively, were obtained.

4. Beam Current Density — Preliminary measurements of the current density distribution with the small devices indicated that good uniformity could be expected with large devices.

5. Electron Energy Distribution — A retarding Faraday probe was used to measure the electron energy distribution of a small portion of the beam. The energy spread was measured to be monoenergetic to within ±1.4%. The actual energy spread is expected to be less than these measurements indicate on the basis of instrumentation effects.

6. Life Tests — Preliminary life tests demonstrated that device lifetimes in excess of tens to hundreds of hours can be expected for operation at average beam current densities of 1 mA/cm^2. Calculations indicate that lifetimes on the order of 1000 hours can be expected.

B. The 10 x 15 cm Device

A 10 x 15 cm high-voltage test device has been built and evaluated with the objective of extending the previous single module work performed with 1 x 11 and 3 x 10 cm units to a size capable of demonstrating scalability. Figure 4 shows a schematic of this device. The hollow cathode is formed from stainless steel and has inside dimensions of 5 cm deep x 12.5 cm x 17.5 cm. Six igniter electrodes (not shown) protrude into the discharge volume from the upstream cathode surface. The grid structure consists of two identical 44% transparent stainless steel meshes spaced 0.8 cm apart. The open area of the structure has dimensions of 10 x 15 cm. The hollow cathode and grid assembly are mounted in the end of a re-entrant electrode, shown partially completed in Fig. 5, which protrudes into the cylindrical ceramic standoff. This standoff also serves as part of the vacuum enclosure. The collector electrode shown in Fig. 6 is re-entrant from the opposite end of the ceramic cylinder and is spaced 3.5 cm from the opposing electrode. In actual usage, with a laser, the solid collector would be replaced by a thin foil window. With this device, the characteristics of beam extraction and acceleration can be studied without involving the unrelated complicating factors of foil transmission. In the experimental studies, the cathode was grounded and the collector was biased at up to 150 kV. Suitable corona shields were fitted to the exterior of the device and the assembly was mounted on an LN_2 trapped oil diffusion pump station. The system was first evacuated, then filled with helium, and finally gettered in order to remove outgassing products. During the experimental program, an array of 25 Faraday probes, mounted as part of the collector, were employed in measurements of the beam current density distribution.

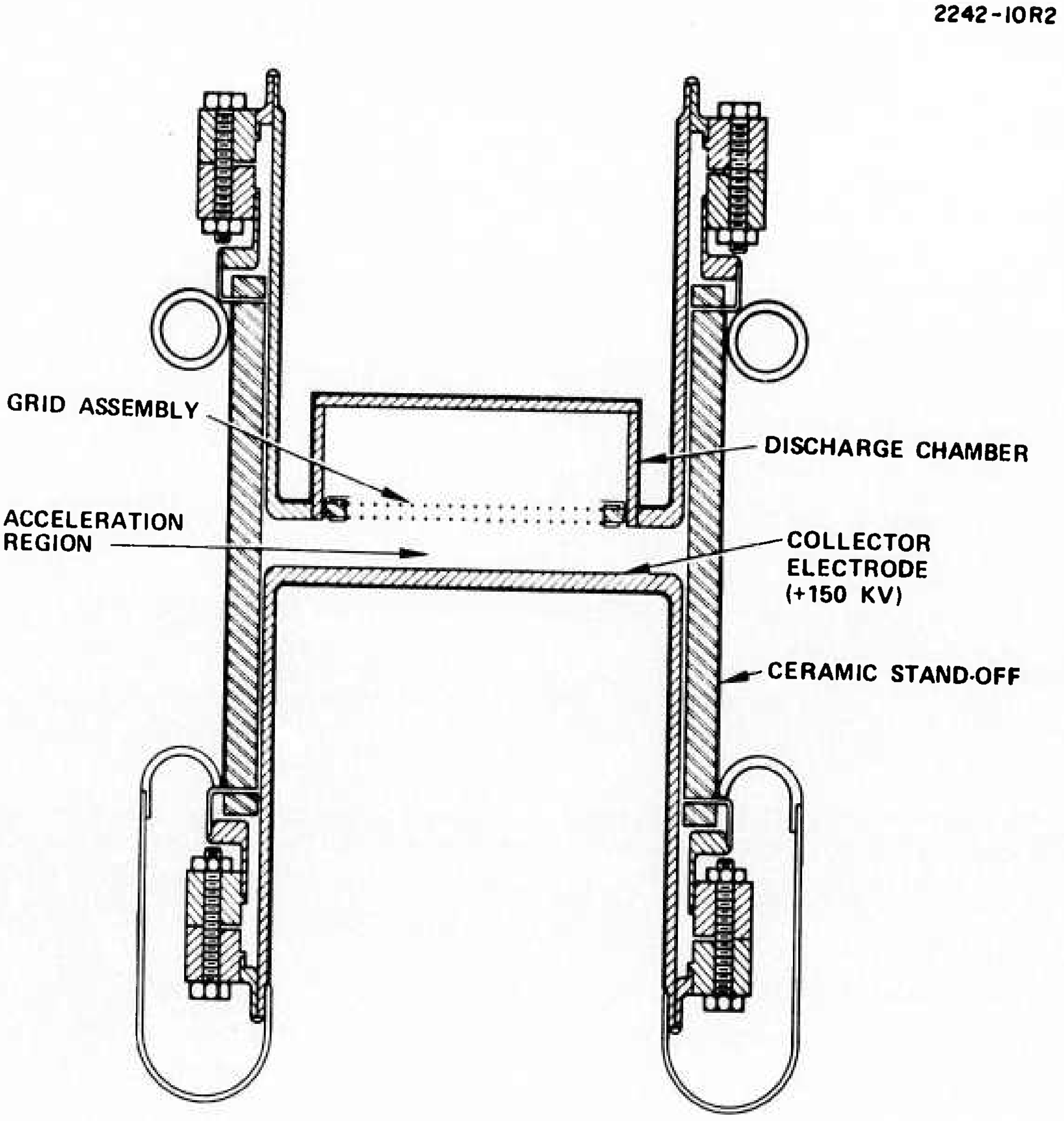

Fig. 4. Schematic diagram of 10 x 15 cm plasma cathode device.

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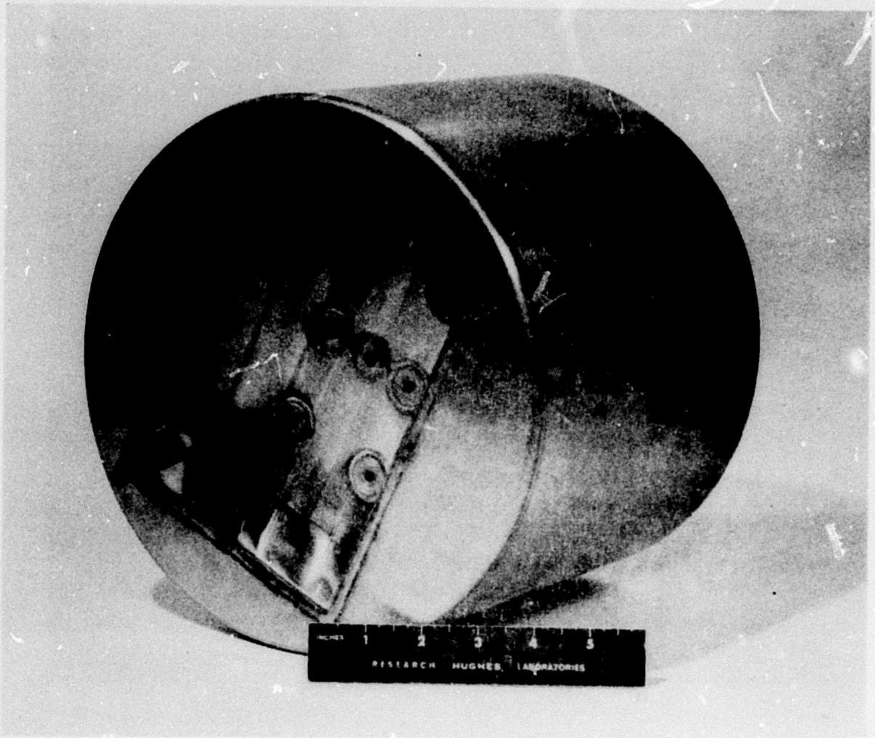

Fig. 5. Partially completed re-entrant electrode containing the plasma cathode discharge region.

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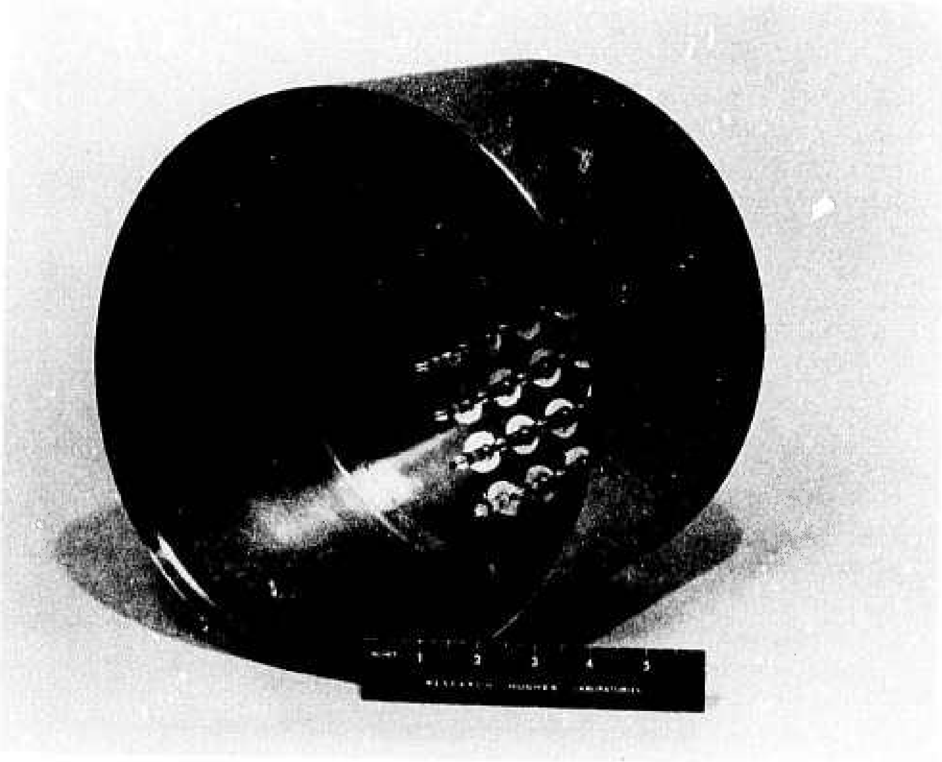

Fig. 6. Partially completed re-entrant beam collector electrode showing the arrangement of the current density probe system.

This device was initially operated with two 5-cm wide partitions which were placed to form three 12.5-cm long modules. Each of these was similar to the single modules evaluated earlier. However, difficulty was encountered in igniting all three modules. This occurred because the modules had a common anode grid and because slight differences in cathode surface conditions from module to module led to slightly different I-V current-voltage characteristics. Such differences then led to ignition of that module which operated at the lowest voltage.

Subsequently the partition widths were reduced to 2 cm in order to provide coupling between modules while, at the same time, providing a sufficiently large cathode-to-anode area ratio to permit stable discharge operation at reasonably low helium pressures. With these modifications, uniform ignition and stable operation was obtained.

Operation of this device was obtained at beam energies of 150 keV in 100 µsec pulsed operation at 60 mA/cm^2. At lower beam energies the device operated at up to 170 mA/cm^2. Difficulty was encountered in achieving operation at greater than 60 mA/cm^2 at 150 keV due to the presence of oscillations which appear to be peculiar to this device. Although no explanation has been verified, this may be due to plasma instabilities resulting from the modular construction. On the basis of this expectation, further large area experiments have been deferred until the coaxial devices to be described later can be completed.

Figure 7 illustrates the current density distribution measured with the 10 x 15 cm device in 100 µsec, pulsed operation at 105 keV and 50 mA/cm^2. The probe current data, shown for the long and short dimensions of the beam, were obtained with the Faraday probe array visible in Fig. 6. Each probe comprised an area of 0.052 cm^2. The shoulders of the curves have been drawn in, based on the results previously obtained with the smaller devices, and on the basis of a comparison between the probe currents and average beam current density. It is seen that the deviation from the average is about ±5%. This indicates the efficacy of the plasma cathode for the production of uniform large area electron beams.

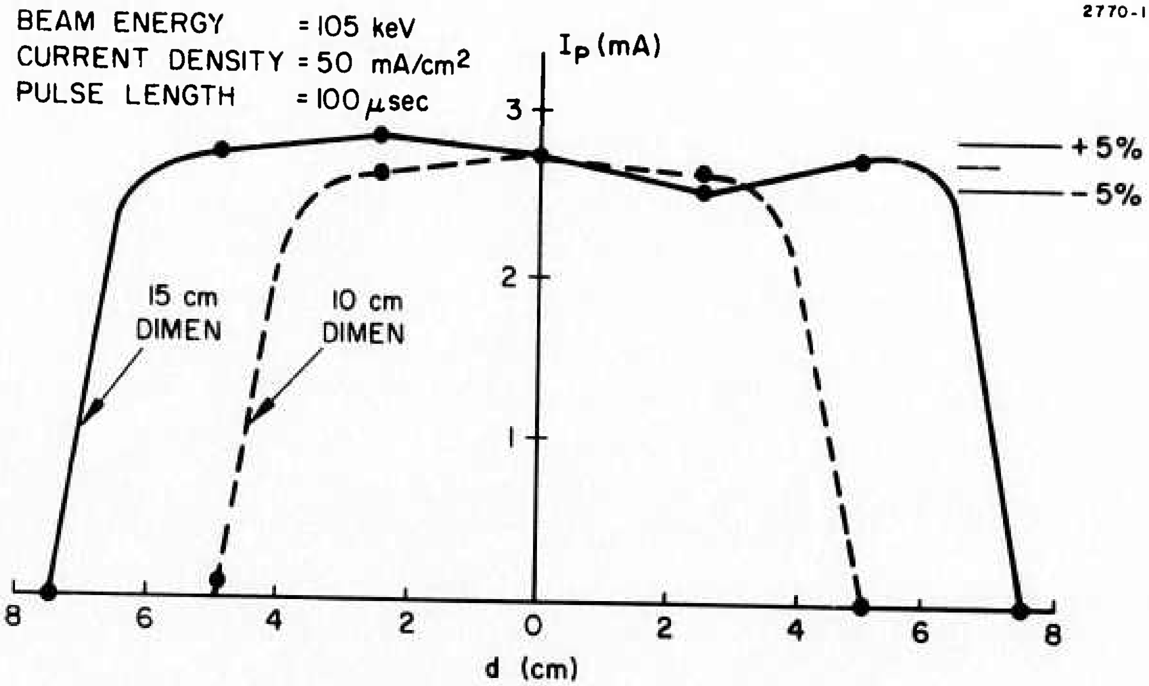

Fig. 7. Electron beam current density distribution with 10 x 15 cm device.

C. The 4 x 40 cm Coaxial Test Device

Although the 10 x 15 cm device has permitted verification of the applicability of the plasma cathode to large area electron beam production, its design is awkward to extend to very large area devices due to its parallelepiped geometry. It is clear that a cylindrical coaxial design, such as shown in Fig. 8, will more easily fulfill the simultaneous requirements for a uniform high voltage electrode spacing to prevent Paschen and vacuum breakdown, simplicity of construction, lightweight vacuum envelope, and ease of integration with practical lasers. In this design, the beam length is simply increased by increasing the length of the coaxial cylinders. Increasing the width required a proportional increase in the diameter of the device.

In order to evaluate this design, a test device having a configuration similar to that shown in Fig. 8 has been built and tested. The major objective was to assess the electron beam current density distribution, and to determine if any special techniques were necessary in order to achieve good beam uniformity. Since the current density distribution is only a function of the plasma density distribution (assuming beam focusing effects can be controlled), the insulating electrical components were designed for voltages only up to 25 kV. Aside from the absence of a high voltage feedthrough and field shaping electrodes which would be required for high voltage operation, all other aspects of this device were consistent with operation at beam energies in excess of 200 keV. Thus, for the expected hollow cathode operating pressure of 30 to 50 mTorr, the gap between the two cylinders was 4 cm. The foil window structure was replaced by a probe plate supporting 33 Faraday probe current collectors in order to facilitate measurements of the beam current distribution. Figure 9 shows the inner cylinder, and Fig. 10 shows the outer cylinder prior to welding the probe plate in position. Figure 11 shows the final assembly mounted on a diffraction pump station.

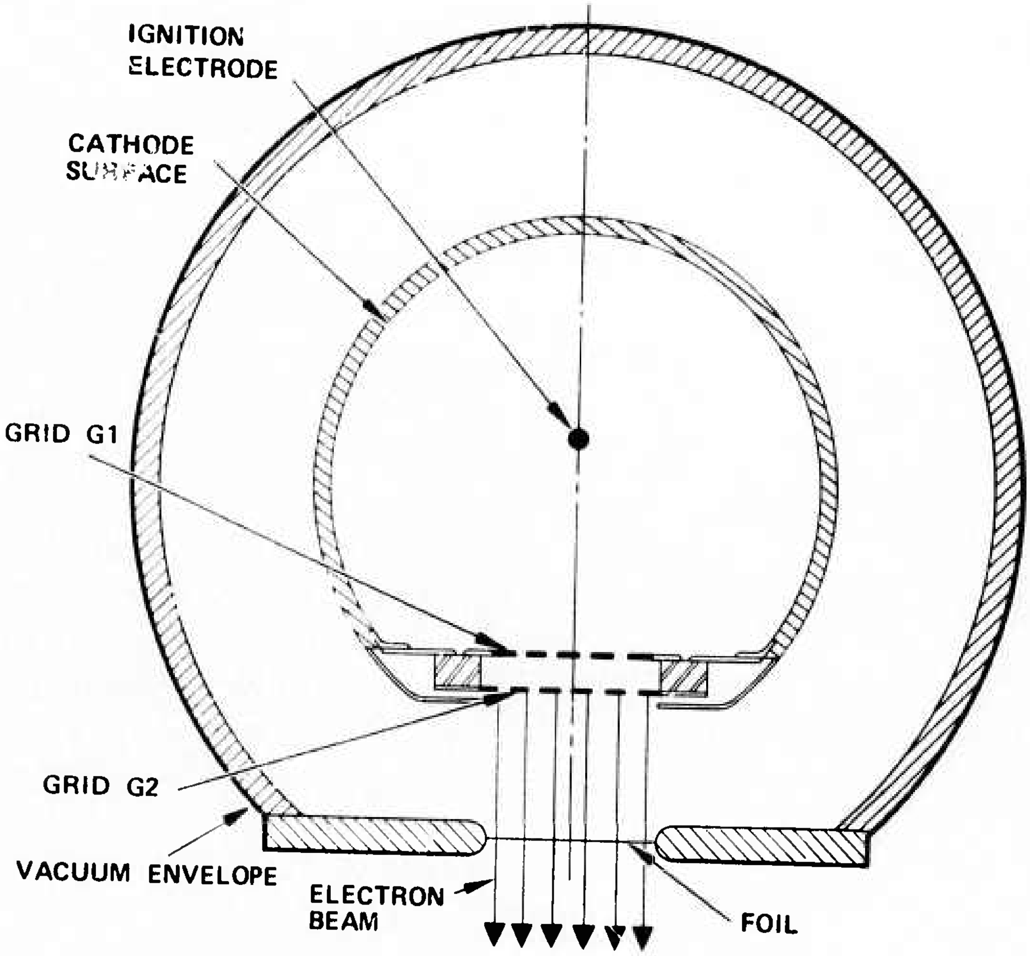

Fig. 8. Cross-section of the coaxial E-gun design.

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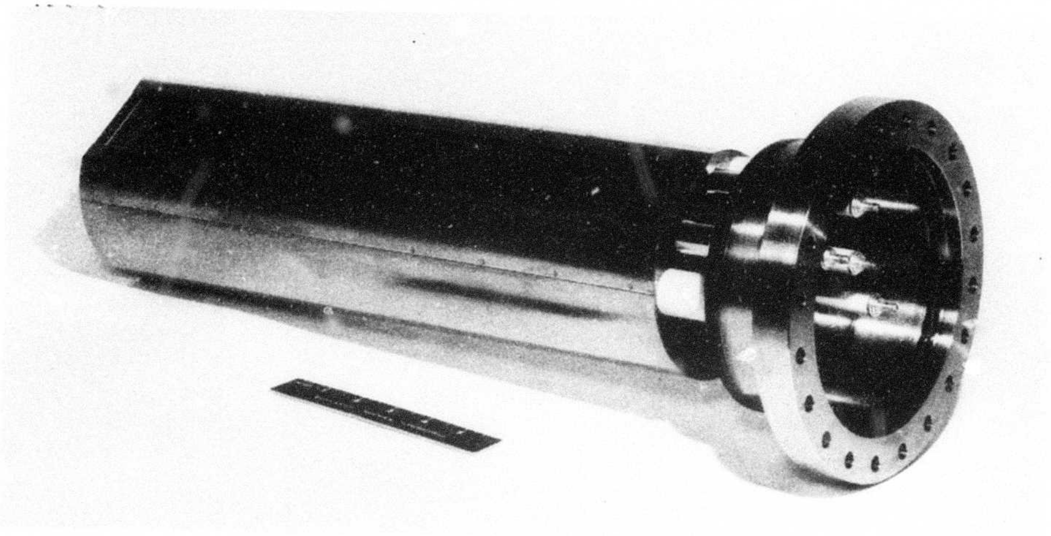

Fig. 9. Plasma cathode assembly.

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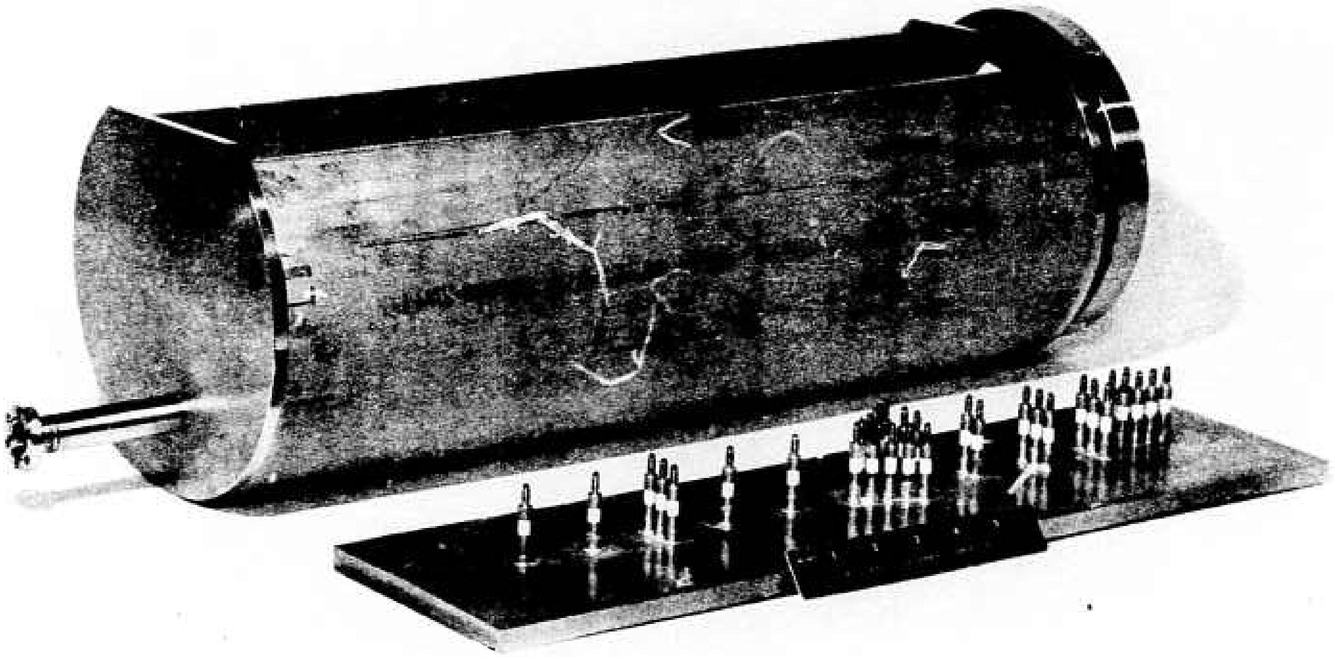

Fig. 10. Plasma cathode collector electrode showing the current density probe assembly prior to welding.

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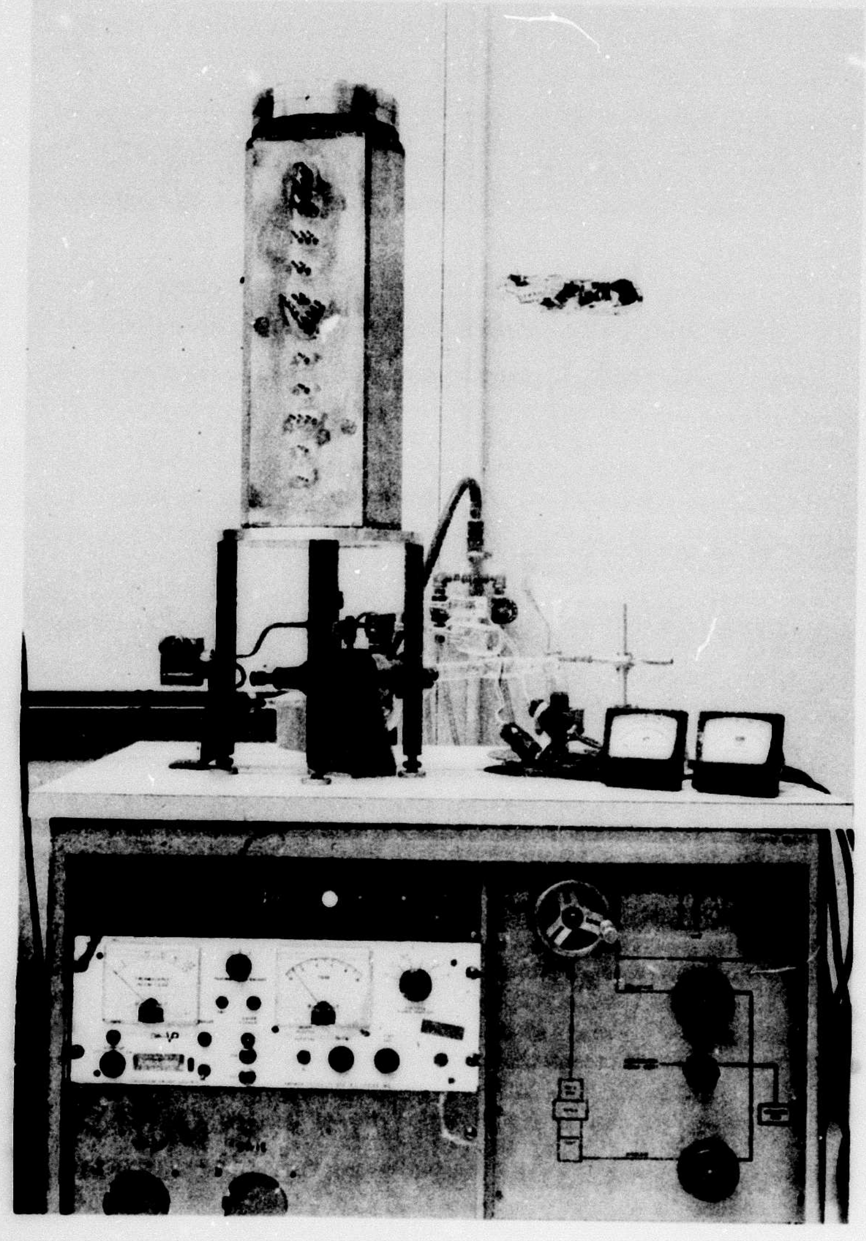

Fig. 11. Completed low-voltage plasma cathode device mounted on vacuum station.

This device has been operated at pulsed beam current densities up to 800 mA/cm^2 and at cw levels in excess of 1 mA/cm^2. In all cases the output current level was easily controlled.

Figure 12 illustrates the beam current density distribution obtained at 30 mA/cm^2 and 23 keV. A similar distribution was obtained for cw operating conditions. The uniformity in the long dimension (y) was characteristically ±5%. Similar uniformity in the short dimension (x) was also obtained except for a narrow peak in the center. This is believed to be due to either the presence of the igniter wire or to focusing of primary electrons from the curved cathode surface opposing the anode grid.

For pulsed operation the pulse risetime was typically 2 μsec with anode grid modulation and <0.2 μsec for control grid modulation. Beam current pulses were reproducible to better than 1% from shot to shot.

These results demonstrate the efficacy of the coaxial design to produce controlled, uniform E-beams. The tests indicate that relatively large area beams can be satisfactorily produced without requiring partitioning of the hollow cathode discharge chamber. We will see later that a simple form of partitioning will be necessary in order to maintain this uniformity for very large devices.

D. Compact High-Voltage Feedthrough Development

The high-voltage insulator design required for application to the plasma cathode E-gun must satisfy rather specialized requirements. In addition to the usual constraints imposed by vacuum and dielectric breakdown, there now exist constraints due to Paschen breakdown.

The basic insulator design employed with the 10 x 15 cm device, as shown in Fig. 4, exists as a proven approach which could be modified for adaption to the coaxial E-gun configuration. However, it can be expected that this approach would result in an excessively large and complicated design. Thus, work was undertaken to develop

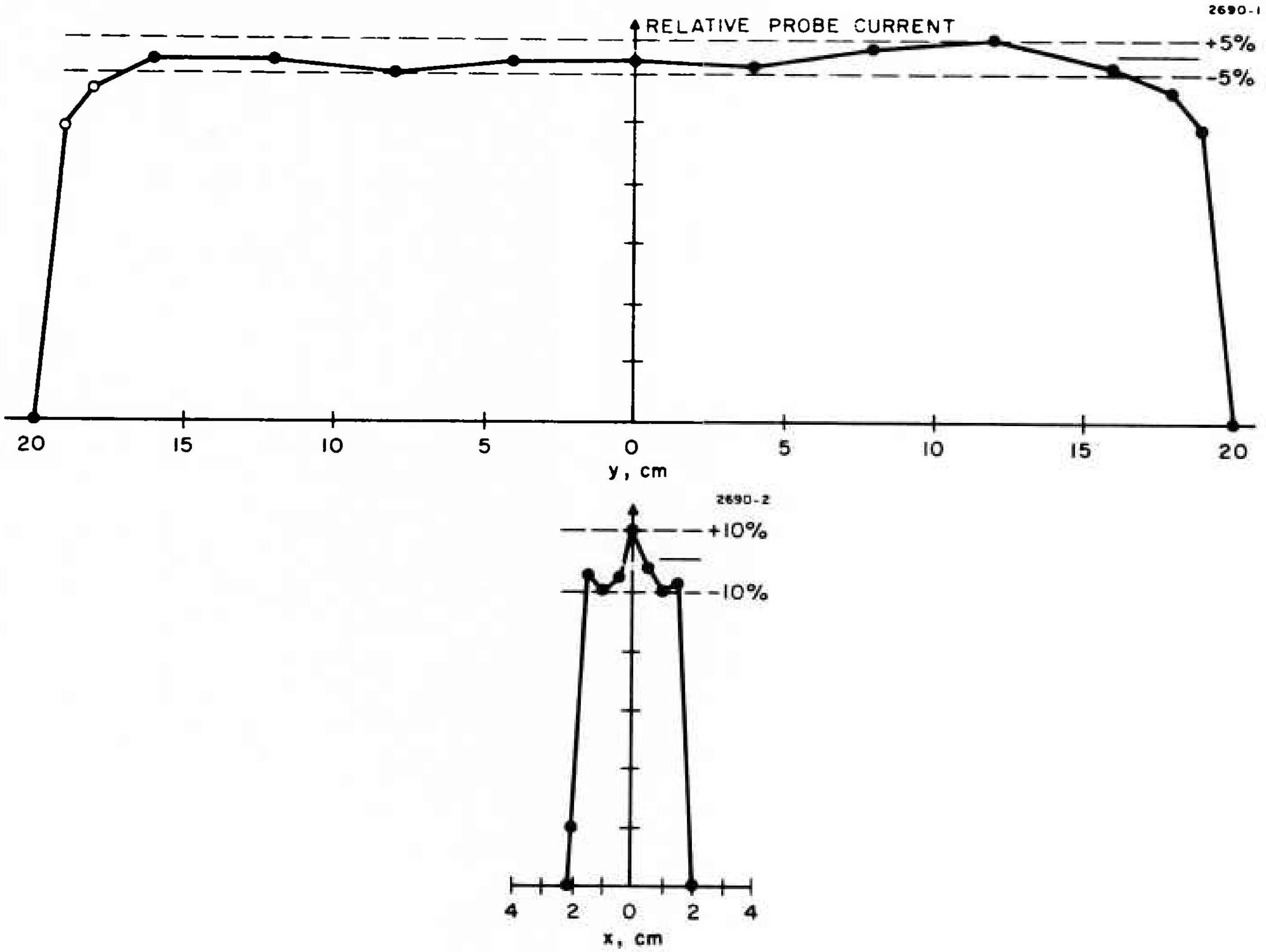

Fig. 12. Current density distribution with 4 x 40 cm coaxial device.

a high-voltage (150 kV) insulator design which would have attributes including: (1) the high-voltage should be completely enclosed by grounded surfaces in order to eliminate flash-overs in air and improve safety, (2) small and lightweight, (3) capable of using a readily available ceramic insulator; the ceramic required for the external high-voltage design (Fig. 4) is much larger, more expensive, and involves a lead-time in excess of six months, and (4) adaptability to any size E-gun without redesign.

The resultant design, as embodied in a test vehicle, is shown in Figs. 13 and 14. High voltage is supplied to the inner structure by a coaxial cable which is connected within a field shaping structure containing pressurized SF_6. The gap between inner and outer structures is equivalent to the plasma cathode E-gun acceleration region. In application to an E-gun this design would be separated at plane A-A and the hollow cathode would be inserted.

For evaluation the test vehicle was assembled with care to ensure exact electrode spacing, smooth electrode surfaces, and cleanliness. The device was then installed on a diffusion pump station, as shown in Fig. 15. Voltages of up to 200 kV were applied while the following parameters were monitored: (1) voltage, (2) current, (3) gap pressure, (4) SF_6 pressure, and (5) x-ray emission.

During testing the tube was initially evacuated to less than 10^{-4} Torr while the voltage was increased to 185 kV over a period of two hours. A current-limiting 2 MΩ resistor was placed in series with the high voltage power supply. As the voltage was increased the current and x-ray emission increased and then decreased irregularly after each voltage increment. The tube was operated for 4 min at 185 kV with very little activity.

Helium was then added and the Paschen characteristics were measured. Initially the results were not reproducible; however, after conditioning for several hours, the points shown in Fig. 16, for operation with a 2-MΩ resistor, were obtained. The current and x-ray activity, as expected, were lower with gas present than when the tube was evacuated. With a helium pressure of 56 mTorr and a voltage of 200 kV, the leakage current was less than 3 μA.

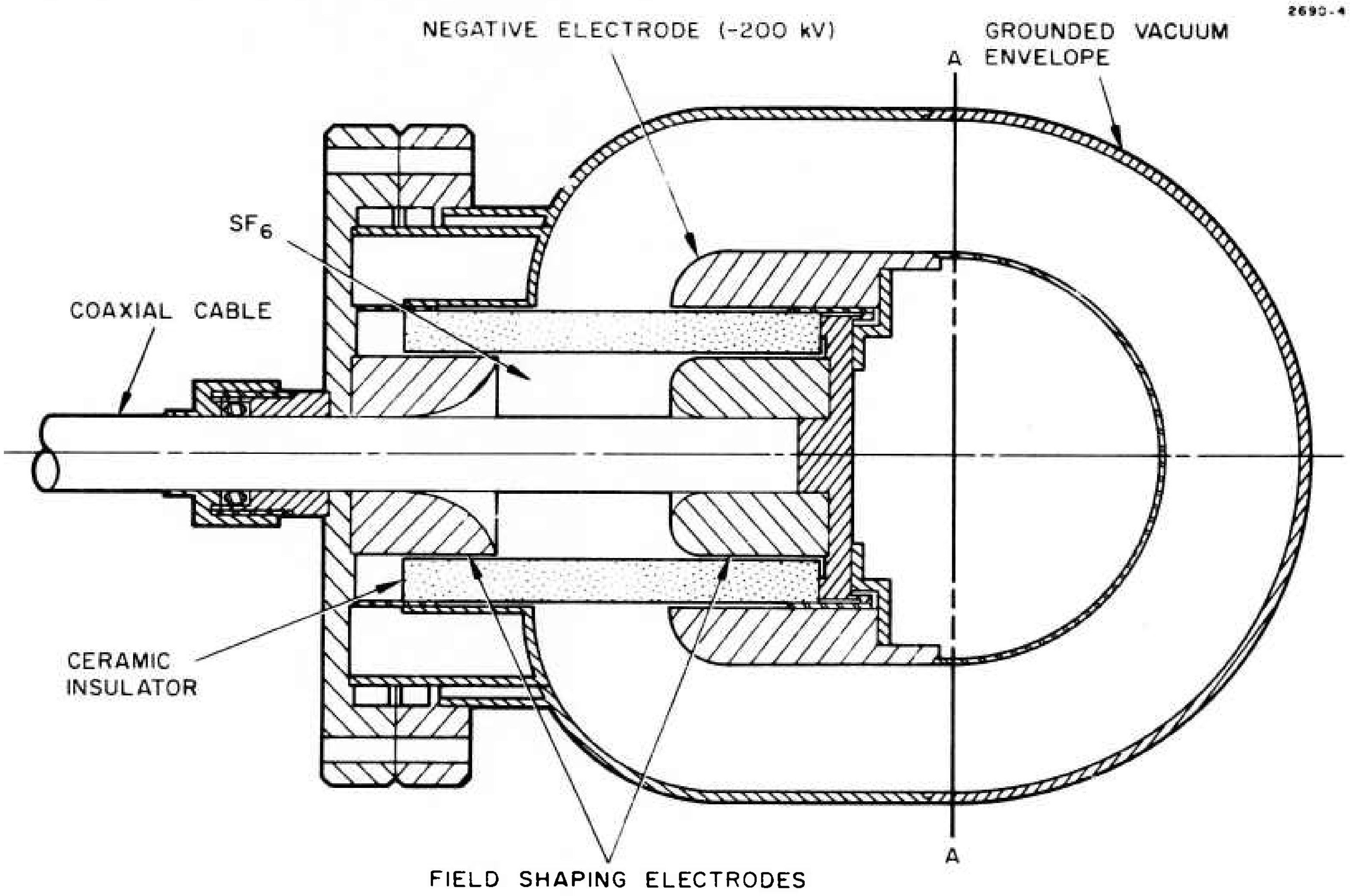

Fig. 13. High-voltage feedthrough test vehicle.

M10000

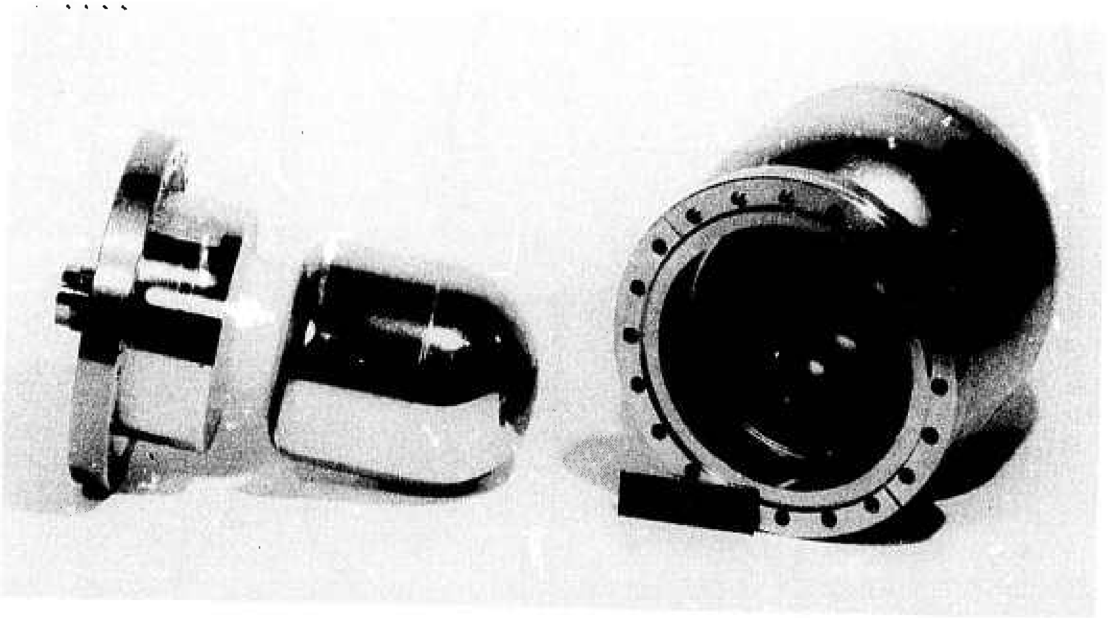

Fig. 14. Disassembled high-voltage feedthrough test vehicle.

M9999

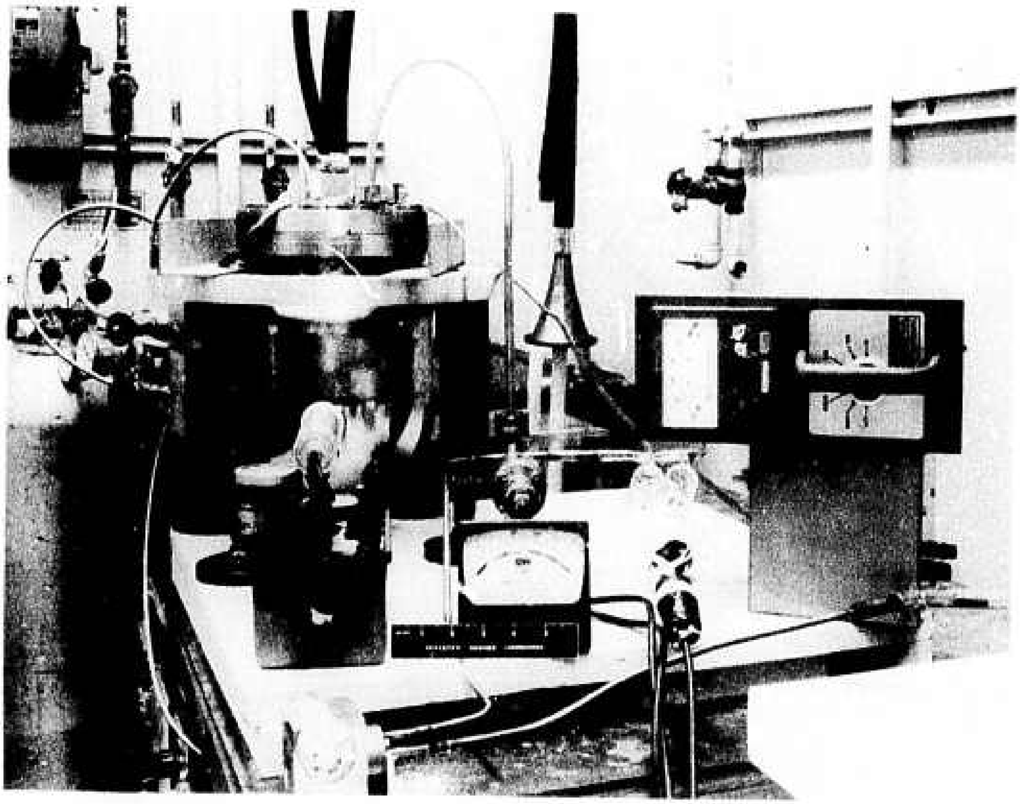

Fig. 15. Experimental arrangement for evaluation of the high-voltage feedthrough.

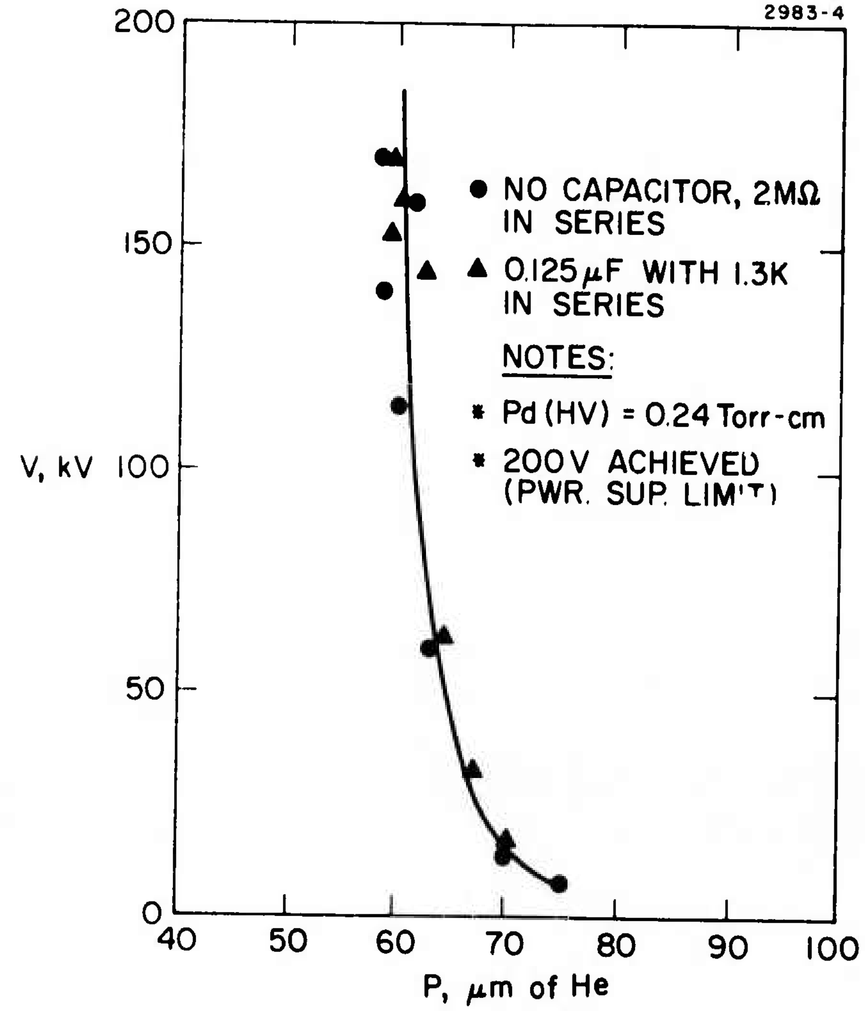

Fig. 16. High-voltage feedthrough test results (Paschen curve).

The final evaluation was performed with a power supply capacitance of 0.125 μF and a 1.3 kΩ series resistor which permitted a current of 100 A to flow for a discharge occurring at a voltage of 130 kV. These measurements of the Paschen breakdown voltage, as a function of pressure, were essentially identical to the previous measurements as shown in Fig. 16.

The above experiments include all factors, which would be encountered for operation with a plasma cathode E-gun, except an electron beam. However, by incorporating this feedthrough so that the insulator is removed some distance from the acceleration region, it can be expected that similar performance will be attained with a beam present. Thus, by incorporating this insulator configuration, plasma cathode operation at up to about 200 keV can be expected.* This design will be applied to the 5 x 125 E-gun to be discussed in paragraph III-F.

E. Scaling Experiments

A major question remaining with regard to the applicability of the plasma cathode to large laser systems, concerns the extent to which it can be scaled while good uniformity is maintained. E-gun length is of most importance in this respect since future designs ranging between 40 and 400 cm are likely while present data only extend to 40 cm. Experiments with the 10 x 15 cm device, on the other hand, have already provided data indicating that scaling to widths on the order of 10 to 20 cm are possible; this covers the range of interest for most future devices.

Since the beam current in an E-gun is dependent primarily on discharge plasma uniformity, it is expected that a valid investigation can be based on discharge studies alone. On this basis experimentation has been undertaken with the 200-cm long hollow cathode discharge device shown schematically in Fig. 17. The cathode of this device

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*Under a Hughes IR&D program the low-voltage 4 x 40 test device and the above high-voltage feedthrough will be combined to form a high-voltage E-gun.

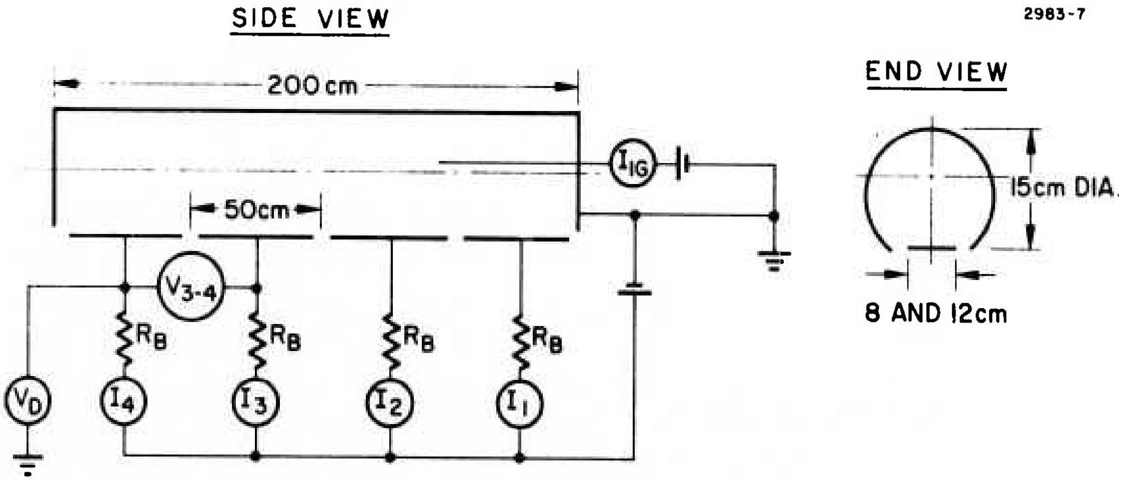

Fig. 17. 200 cm hollow cathode discharge device.

is formed by a 15-cm diameter stainless-steel tube which is closed at both ends. The anode is divided into four sections, each of which has dimensions of either 8 x 50 cm or 12 x 50 cm. The current to each anode was measured in order to assess uniformity. The voltage between anodes was monitored when ballast resistors R_B were used. The igniter consisted of a 10 cm length of 0.025-cm diameter wire which was biased at about 300 V for both cw and pulsed operation. The entire assembly was placed within a glass tube vacuum system.

Experiments were performed under both pulsed and cw conditions with similar results. Figure 18 illustrates the current-voltage characteristics of the discharge for various helium pressures. As usual, the discharge voltage is a weak function of current, and increases as the pressure decreases. Figure 19 illustrates the cw voltage-pressure characteristics for anode widths of 8 and 12 cm which correspond to area ratios (anode area + cathode area/anode area) of 5.9 and 3.9, respectively.

These data can be applied to transverse scaling considerations as discussed below. Assuming an E-gun with a 4-cm acceleration gap width and Pd = 0.24 Torr-cm for Paschen breakdown within the gap at high voltage, the maximum operating pressure would be 60 mTorr, as shown in Fig. 19. Thus, it is seen that the allowable operating pressure range for a maximum discharge voltage of 800 V is about 50% larger for the higher area ratio. Based on a desirability for a large operating pressure range (a factor of 2 or more is considered desirable) and a small device size, it is seen that an area ratio on the order of 6 is desirable.

Measurements of the anode currents under both pulsed and cw conditions indicated a ±10 to 15% current density variation with no ballast resistance. By adding a small amount of ballast which consumed typically less than 10% of the discharge power, the uniformity improved to ±3%. This occurred due to the close coupling between the four discharge sections. In other words, only a small voltage difference between anodes leads to large differences in collected current.

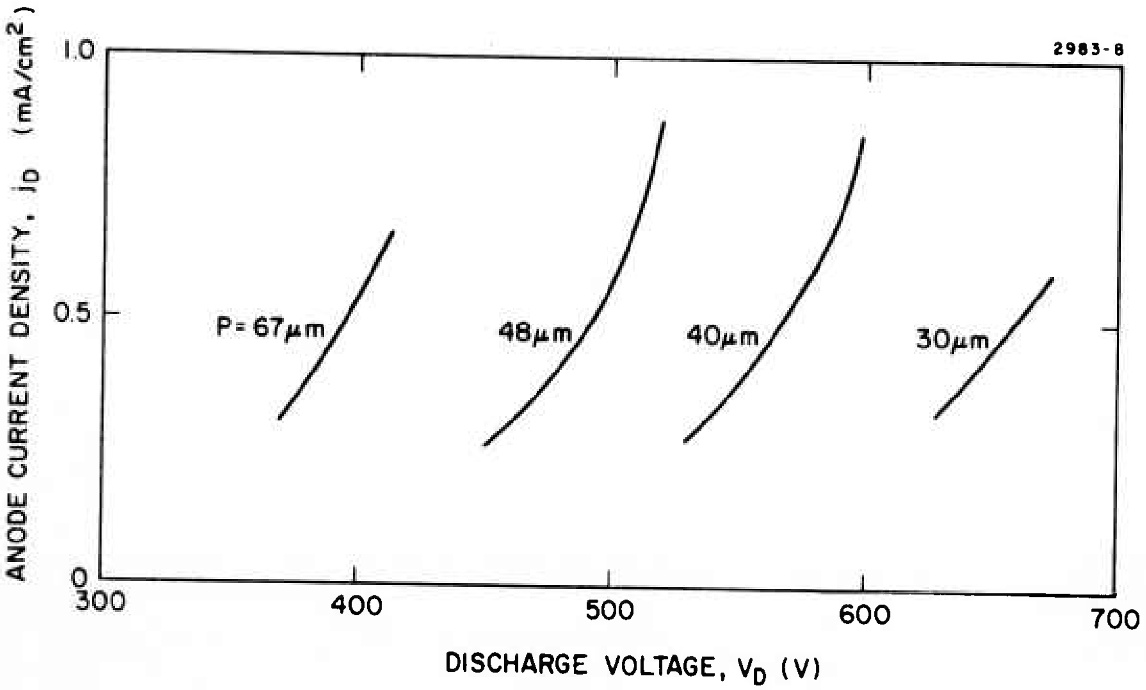

Fig. 18. CW discharge I-V characteristics.

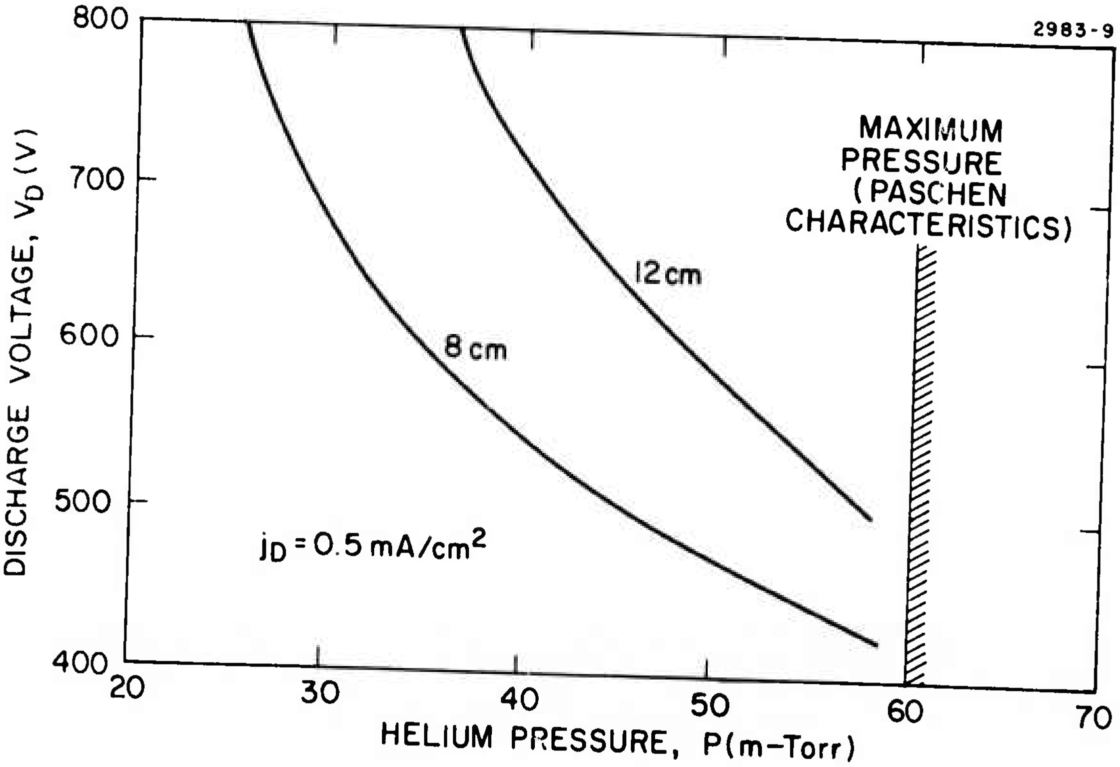

Fig. 19. CW voltage-pressure characteristics for 200 cm device.

For uniform operation the voltage between anodes was typically 0.1 V. This measurement indicates that, although separately ballasted anode sections are desirable for long devices, a common control grid can be used. This is because the anode-to-control grid voltages are not sufficient to result in significant current density variations.

The net result of these experiments is that the plasma cathode concept is quite scalable. The necessity of using ballast resistors involves little added design complexity since the small size of the required resistors means that they can be placed within the E-gun.

F. The 5 x 125 cm E-Gun

Design of a 5 x 125 cm E-gun, which will be constructed during the first half of 1974, is now underway. This gun will be configured specifically for cw operation although simple modifications will allow it to be operated with high efficiency in the pulsed mode. The design will be very similar in cross section to that shown in Fig. 8, except that weak focusing will be included so that the beam will be 4.2-cm wide at the foil window where it will have an 8° convergence half-angle. This will help to compensate for scattering by the foil.

IV. CONCLUSIONS AND FUTURE PLANS

During the past six months, major advances have been accomplished toward demonstrating and perfecting the plasma cathode for use with larger laser systems. This work has included: (1) uniform operation of the 10 x 15 cm device at energies up to 150 keV, (2) successful operation of a 4 x 40 cm E-gun at low energies, (3) development of a compact high-voltage feedthrough used to support and electrically isolate the hollow cathode discharge chamber from the vacuum envelope, (4) successful demonstrations of the capability for scaling to large E-gun sizes, and (5) preliminary design of a 5 x 125 cm high energy E-gun. The combination of proven performance, as demonstrated by this and previous work, with a number of advantages over other types of E-guns indicates that the plasma cathode electron gun is a very desirable device for use with high power lasers.

During the remaining six months of this program, work will be completed in the following areas:

- Evaluation of the high energy 4 x 40 E-gun, which is now being constructed under a Hughes in-house program, will be undertaken for both pulsed and cw operation.
- The 5 x 125 cm E-gun will be completed and evaluated on the Hughes (Culver City) Peacemaker Laser System.

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