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Abstract

High current density ion sources have been used to heat plasmas in controlled thermonuclear reaction experiments. High beam currents imply relatively high emission currents from cathodes which have generally taken the form of tungsten filaments. This paper describes a hydrogen ion source which was primarily developed to assess the emission current capability and design requirements for hollow cathodes for application in neutral injection devices. The hydrogen source produced ions by electron bombardment via a single hollow cathode. Source design followed mercury ion thruster technology, using a weak magnetic field to enhance ionization efficiency. A 1.3-cm diameter hollow cathode using a low work function material dispenser performed satisfactorily over a discharge current range of 10-90 A. Cylindrical probe measurements taken without ion extraction indicate maximum ion number densities on the order of 10^{12} cm^{-3}. Discharge durations ranged from 30 seconds to continuous operation. Tests with beam extraction at 2.5 keV and 30 A discharge current yield average ion beam current densities of 0.1 A cm^{-2} over a 5-cm extraction diameter. Results of this study can be used to supply the baseline information needed to scale hollow cathodes for operation at discharge currents of hundreds of amperes using distributed cathodes.

Introduction

High current density ion sources are being used to produce energetic neutral beams for heating of plasmas in controlled thermonuclear reaction experiments. Ion source modules which produce deuterium beams at 40 keV and ion current densities of 0.5 A/cm^2 have advanced to a rather sophisticated state of development.[1] Next generation fusion test reactors require multi-megawatt neutral beam lines each of which is comprised of many ion source modules.[2,3] Anticipated neutral beam injection pulses will be approximately 0.5 seconds duration at 5 minute intervals. The ion source modules will also be exposed to the radioactive environment of the fusion reactor. Thus, highly reliable ion sources operating at rather high duty cycles are required to expedite and simplify remote maintenance, handling and adjustment.[4]

In order to satisfy the neutral injection requirements for high beam currents, discharge currents ranging from 10 to 40 times the beam current are required. Present generation ion sources for neutral injection attain the desired discharge currents by employing a rather large number of filament cathodes which operate at temperatures approaching 3000° K.[5] Potential life limiting problems that exist with filaments operating in this regime are high thermal stresses, sublimation[6] and ion sputtering.[7] The filament radiant heating may also produce undesirable thermal loads on critical ion source components (e.g. the ion optics). Investigation of other cathode approaches appears warranted based on filament cathode reliability considerations such as: (1) the large number of filaments generally required; (2) filament sublimation and sputtering; and (3) potential difficulties due to filament replacement in a radioactive environment.

The hollow cathode is an alternate approach that offers propects of reproducible characteristics and long life.[7] Hollow cathodes also allow a high degree of independent optimization and control of the cathode emission and discharge plasma parameters by proper selection of cathode geometry and operating conditions. Thus, there exists more freedom in discharge plasma control which may potentially provide improvement in beam purity and possibly charge state control.

This paper presents a preliminary investigation of hollow cathodes for use with high ion current density hydrogen ion sources. The hydrogen hollow cathode design was aided by the existing technology of electron bombardment mercury and inert gas ion sources.[7-10] Mercury hollow cathodes of this type have demonstrated lifetimes in excess of 18,000 hours.[11-13] The effort described herein was directed toward the determination of the cathode scaling requirements and constraints for high discharge current operation (up to 100 A) with hydrogen. Relevant discharge and beam parameters which result from hollow cathode discharge operation are presented. Cathode integrity and ion source performance were assessed with the intent to better define design requirements for deuterium ion sources with distributed cathodes operating at discharge currents of hundreds of amperes.

Ion Source

A section view of the hydrogen ion source used to evaluate the hollow cathodes is shown in figure 1. No attempt was made to optimize the ion source to obtain high gas or power efficiencies. Major elements of the ion source are the hollow cathode, pulse ignitor, cylindrical anode, magnetics and ion optics. Source design followed mercury ion thruster technology,[7] using a weak magnetic field to enhance ionization efficiency. For convenience, ion beam neutralization was accomplished by vacuum facility ground return.

Hollow Cathodes

Hollow cathodes used in this investigation are similar to those developed for thirty centimeter diameter mercury ion thrusters.[13] Figure 2 defines the basic elements of the hollow cathode assembly. A porous tungsten insert impregnated with barium calcium aluminate was placed inside a molybdenum tube on which an orifice plate and radiation flange were attached. The insert was wrapped with molybdenum foil which fixed the insert position and provided electrical contact to the tube. The downstream end of the cathode tube was surrounded by a swaged tantalum heater which was used for cathode starting. Radiation shielding made of 0.015 mm tantalum foil was wrapped around the cathode heater. The cathode was started by preheating to approximately 1100° C, introduction of hydrogen through the cathode (5-20 torr liter/sec) and application of a 3 kV - 6 μsec pulse to the cathode ignitor. The ignitor electrode consisted of a 1.5 mm diameter molybdenum wire located 2 mm downstream of the orifice plate.

Two hollow cathode tube sizes were used in this investigation. Preliminary tests at low discharge currents (<40 A) were conducted with cathodes fabricated from 6.4 mm diameter molybdenum tubes. These cathodes are designated 1A and 1B and pertinent dimensions are indicated in table I. Both cathodes had a radiation flange which was electron beam welded to the

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end of the tube. The insert was positioned against the orifice plate.

Tests at high discharge currents (>40 A) were conducted with a 1.27 cm diameter cathode which is designated cathode 2 (fig. 2, table I). A 0.53 cm diameter hole was located in a 0.38 mm thick tantalum orifice plate which was mechanically attached to the cathode tube. A large diameter porous tungsten insert was positioned against the orifice plate. The insert contained approximately 0.4 gm of barium calcium aluminate. A swaged heater and radiation shielding were also used. Rationale for this cathode design was based on a wealth of lifetime data for mercury hollow cathodes.[7] All ion source performance data were obtained with cathode 2.

Discharge Chamber

The discharge chamber is of the Penning type. The magnetic field (≈40 gauss) causes electrons to take spiral trajectories on their traverse to the anode, thereby increasing residence time and ionization efficiency. Ionization is produced both by primary electrons with energies near the anode-cathode potential drop and also Maxwellian electrons.[7]

The discharge chamber consists of the following elements: baffle region, anode and magnetic circuit which was comprised of electromagnets and two cylindrical iron pole pieces (fig. 1). The ion source exit aperature diameter was chosen to be approximately 5 cm in order to obtain relatively high ion densities taking into consideration power supplies available for this investigation.

The radiation cooled discharge chamber contained the plasma by a stainless steel shell, a backplate, iron pole pieces and the ion optics. Discharge electrical impedance was controlled by the geometry of the tantalum baffles, the magnetic circuit and the flow rate. The baffles also served to reduce cathode self heating due to ion bombardment.[7] Refractory metal baffles were required due to severe local heating in the cathode-baffle region.

The ion source shell, anode and pole pieces were covered with tantalum radiation shields (0.001 cm thick) to allow the magnets to operate at temperatures much lower than the anode or shell whose temperatures exceeded 1000° C during continuous operation. The relatively massive pole pieces along with radiation shielded components yield a rather large thermal time constant for magnetic circuit components. The cathode thermal time constant was small by comparison. Operation at discharge currents of 100 A could easily be accomplished for periods the order of a few minutes without affecting the integrity of the electromagnets.

Discharge chambers of this type operating with mercury, xenon and argon have been probed and found to contain 3-10 eV Maxwellian electrons and primary electrons which have energies the order of the discharge voltage.[7,14] Plasma densities are approximately an order of magnitude lower than the neutral density. For mercury and inert gas discharge chambers the plasma potential is generally near anode potential with sheaths occurring at the cathode, baffles and at the ion optics screen grid.

Plasma potential and electron temperature measurements could not be accurately made for the hydrogen ion source where discharge currents exceeded 20 A because of severe probe heating at biases near plasma potential.

Ion Optics

The ion optics were comprised of screen and accelerator grids which were dished away from the discharge chamber with a radius of curvature of 40 cm. The dished ion optics provided the required thermal stability for interelectrode gaps of 0.5 mm.[15] The screen grid was biased positively between 1000 and 2500 V and the accelerator grid 400 to 800 V negatively with respect to ground.

An ion optics design which has a screen grid transparency of 0.67 was selected based on investigations with argon[10] and mercury[16] ion sources. The 0.38 mm thick screen grid consisted of a hexagonal array of 0.19 cm diameter aperatures. The 0.51 mm thick accelerator grid had 0.15 cm diameter aperatures. Aperature center to center spacing was approximately 0.22 cm. The ion optics hole pattern was photochemically etched from arc cast molybdenum. The screen grid hole pattern was sized down (compensated for ion beamlet vectoring due to the dish shape of the ion optics) by 0.5 percent relative to the accelerator grid hole array. The compensation of the dished ion optics will yield a more paraxial beam as discussed in references 7 and 16.

The grid plates were spaced at the periphery using a 0.5 mm thick mica spacer. The mica was simply sandwiched between the grids and the assembly was clamped together with a ring to the downstream polepiece. The mica spacer was adequate for short term, low voltage (3 kV) operation and also simplified the mounting of the ion optics.

The screen grid was masked to an exit aperature of 5.1 cm (fig. 1) to increase chamber pressure and also provided an extraction area consistent with available power supply capability.

The screen grid of the ion optics system (fig. 1) was operated at cathode potential. The cathode and discharge chamber were run at positive high voltage.

Results and Discussion

Selection of Hollow Cathode Design

In previous investigations of mercury hollow cathodes[7,13,17], it was found that the proper choice of materials and cathode dimensions were necessary to insure low cathode erosion. It was also shown that the thermal environment of the cathode insert strongly affected lifetime. Factors that affect erosion and cathode thermal environment for a hydrogen hollow cathode are addressed herein.

All hollow cathodes used in this investigation employed barium compound inserts and were operated at discharge voltages in the range 35-55 V. A guideline for the selection of cathode orifice diameter for a given discharge current is given in figure 3. Results from long term tests of mercury hollow cathodes provide a guideline for cathode design which avoids erosion.[7] Long lifetime mercury hollow cathodes generally yield a discharge current to orifice diameter ratio which does not exceed about 12 A/mm.[7] Data from short term tests with argon hollow cathodes display approximately the same cathode orifice criteria[10] (fig. 3). Preliminary tests with hydrogen were conducted in an attempt to verify the cathode design criteria (fig. 3). For these tests cathodes 1A and 1B (table I) were utilized. Both cathodes exhibited severe orifice erosion in the form of orifice notching after testing at 40A discharge current. This result is consistent the cathode design guidelines of figure 3.

Subsequent tests were carried out with cathode 2 (table I) which was designed according to the criteria of reference 7. This cathode was tested at discharge currents from 20 to 40 A for periods up to 30 hours after which there was no observable change in cathode orifice dimensions. Cathode orifice erosion rates are rapid if the orifice size is insufficient.[7,17] Therefore, short term testing is generally sufficient to ascertain whether a cathode design is adequate. Cathode 2 also exhibited reproducibility of starting and discharge characteristics with time which are indicators of cathode integrity.[17] Thus the cathode design criteria of reference 7 are satisfactory for hydrogen hollow cathodes in terms of avoidance of orifice erosion.

Cathode thermal design is also an important factor in cathode lifetime. It has been shown that the lifetime of a cathode and the efficiency of the generation of plasma discharges depend heavily on the dispensing rate of low work function material contained in the cathode insert.[13] The efficiency of the generation of a plasma discharge improves with elevated temperature because of the increase in the barium dispensation rate. However, the lifetime of the cathode is limited by excessive emissive material depletion if insert temperatures exceed 1300° C.[13] Mercury hollow cathodes have been successfully endurance tested for 18,000 hours at insert temperatures in the range 800-900° C.[13] The equilibrium temperature of the hydrogen cathode 2 insert was between 950-1000° C for 40 A operation. Cathode insert temperatures were inferred by thermocouple measurements taken on the cathode tube over the insert. Thus, it is expected that cathode 2 should exhibit more than adequate lifetime at 40 A discharge currents because of modest self heating, reproducible performance and orifice dimensional integrity after short term tests.

Hollow cathode 2 was operated at discharge currents up to 90 A for purposes of obtaining discharge chamber ion current fluxes. For the 90 A condition, the cathode was operated for a period of approximately one minute to limit cathode self heating and prevent discharge characteristic hysteresis. From figure 3 one can see that cathode 2 may be a marginal design for continuous operation at 90 A because of the potential of orifice erosion. The cathode self heating, however, might easily be countered by more appropriate radiation and conduction cooling.

Discharge Characteristics Without Ion Extraction

Discharge chamber diagnostics were performed without ion extraction to evaluate trends in ion density with discharge current and also determine the spatial uniformity of the plasma density profile. The discharge chamber was fitted with a 47 percent transparent grid to simulate the ion optical system. The grid was slotted to allow Langmuir probe radial surveys. Cold flow tests indicated that the discharge chamber pressure was 2×10^{-2} torr while the vacuum facility pressure was 7×10^{-4} torr for the discharge chamber diagnostic tests. The hydrogen ion currents were obtained by a negatively biased cylindrical probe (0.5 mm dia. × 0.67 cm long) located on the discharge chamber centerline near the grid.

Figure 4 shows that the ion arrival rate to the cylindrical probe was nearly linear with respect to discharge current from 10 to 90 A. An order of magnitude calculation of ion number density yields 4×10^{11} cm^{-3} and 1.5×10^{12} cm^{-3} at discharge currents of 10 A and 90 A respectively. The electron temperature was measured to be 8-10 eV at the 10 A discharge current; an electron temperature of 15 eV was assumed for the 90 A condition. Ion source parameters for the 90 A condition are shown in table II.

Probe radial surveys (fig. 5) were obtained approximately 0.7 cm upstream of the grid. For these profiles, the average to peak ion current varies from 0.78 to 0.74 at discharge currents of 10 A and 70 A respectively.

In this series of tests, the discharge voltage was determined by the choice of baffle geometry, magnetic field (15-50 gauss) and flow rate (5-14 torr liter/sec). By selecting the appropriate parameters, the discharge voltage could be varied from 40-60 V for currents ranging from 10-90 A. Judicious choice and control of the discharge voltage may be important to minimize the degree of discharge chamber sputtering and thus enhance beam purity.

Ion Source Performance with Ion Extraction

The purpose of tests with ion extraction was to determine the beam current trend with discharge current which is important for scaling considerations. Also documented are the ion beam uniformity and ion optics perveance. Figure 6 shows that the hydrogen ion beam current was approximately linear with discharge current over the range tested with a discharge to beam current ratio of 15. Approximately 670 electron volts of energy was expended per beam ion. No attempt was made to operate at beam current levels greater than 2 A because of interelectrode arcing across the mica spacer. Operation at higher beam and voltage levels would require a more sophisticated ion optics' mounting system which was beyond the scope of this investigation.

Table II displays the parametric data for the 2 A beam current level. The beam current density on center line (2 cm downstream of the ion optics) was approximately 0.15 $\mathrm{A/cm^2}$. Average ion beam current density was 0.1 $\mathrm{A/cm^2}$. The gas efficiency was 7 percent. Further gains in gas efficiency would be expected by (1) operation at higher discharge currents, (2) magnetic circuit optimization, and (3) use of an accelerator grid with transparency less than 0.43 to present higher impedance to atomic and molecular species.[18]

Figure 7 shows the ion optics extraction capability for the 5 cm diameter ion source. The dished grid plates were separated by 0.5 mm. The maximum beam current at any given total voltage was based on the onset of high accelerator grid impingement currents. The beam current increased with total extraction voltage in agreement with the childs law exponent. The perveance at a 2 A beam current was approximately 1.5×10^{-5} $\mathrm{A/V^{3/2}}$.

Figure 8 is a plot of the beam current density profile for discharge currents of 10 and 20 A. The ratio of average to peak beam current density was approximately 0.7 in both cases. Further improvements in beam uniformity might be made by using distributed cathodes located near the discharge chamber periphery and a central anode[6] or by using a multipole chamber design.[7,14]

Based on the results of testing the 5 cm diameter source with a single hollow cathode, scaling ion source modules for multiple cathode operation at a 15 A beam current level, which is currently of interest[2], may be accomplished as follows: The 5 cm diameter source performance yielded 670 eV per beam ion. Assuming the 15 A ion beam current module operates between 700 and 1000 eV/ion, discharge currents between 230 and 330 A are required. This implies no more than eight of the hollow cathodes (of the type reported herein) are required with margin available for higher emission current operation which might be desirable to improve the gas efficiency.

Concluding Remarks

A hydrogen ion source was fabricated as a test vehicle for hollow cathodes in order to assess the emission current capability, design requirements and plasma characteristics for application to neutral injection devices. Significant test results with a single hollow cathode include:

1. Hollow cathodes have the potential for satisfying component requirements for neutral beam injection devices.

2. Hydrogen hollow cathodes with potential for long lifetime may be designed according to criteria established for operation with mercury and argon.

3 Probe measurements taken without ion extraction indicate discharge chamber ion number densities the order of 10^{12} cm^{-3}.

4 The beam current was linear with discharge over the range tested. An average ion beam current density of 0.1 A/cm^2 was obtained; higher levels could be achieved with an improved ion optics mounting system.

Results of this study are pertinent to the baseline information needed to scale for operation at discharge currents of hundreds of amperes using distributed hollow cathodes.

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TABLE I. - HOLLOW CATHODE DIMENSIONS

Cathode number	Cathode[a] tube diameter, cm	Tube wall, mm	Orifice plate thickness, mm	Orifice diameter, mm	Radiation[a] flange outside diameter, cm	Porous tungsten insert		
						Outside diameter, cm	Inside diameter, cm	Length cm
1A	0.64	0.25	[a]1.3	0.76	1.7	0.56	0.28	2.5
1B	0.64	0.25	[a]1.3	1.02	1.7	0.56	0.28	2.5
2	1.27	1.6	[b]0.38	5.3	---	0.79	0.53	2.5

[a] Material, molybdenum
[b] Material, tantalum

TABLE II. - ION SOURCE PARAMETERS

	Without beam extraction	With beam extraction
Gas	H_2	H_2
Ion extraction diameter, cm	6.5	5.1
Screen grid transparency, percent	---	67
Accelerator grid transparency, percent	[a]47	43
Maximum axial magnetic field strength, gauss	40	40
Discharge chamber pressure, torr	2×10^{-2}	1×10^{-2}
Flow rate, torr liter/sec	10	5.7
Discharge duration, sec.	30	CW
Discharge current, A	90	30
Discharge voltage, V	45	43
Beam current, A	---	2.0
Beam ion energy, eV	---	2500
Beam current density,[b] C/L, A/cm^2	---	0.15
Perveance, A/V$^{3/2}$	---	1.5×10^{-5}
Gas efficiency, percent	---	7

[a] Single grid used to simulate ion optics
[b] Planar beam probe

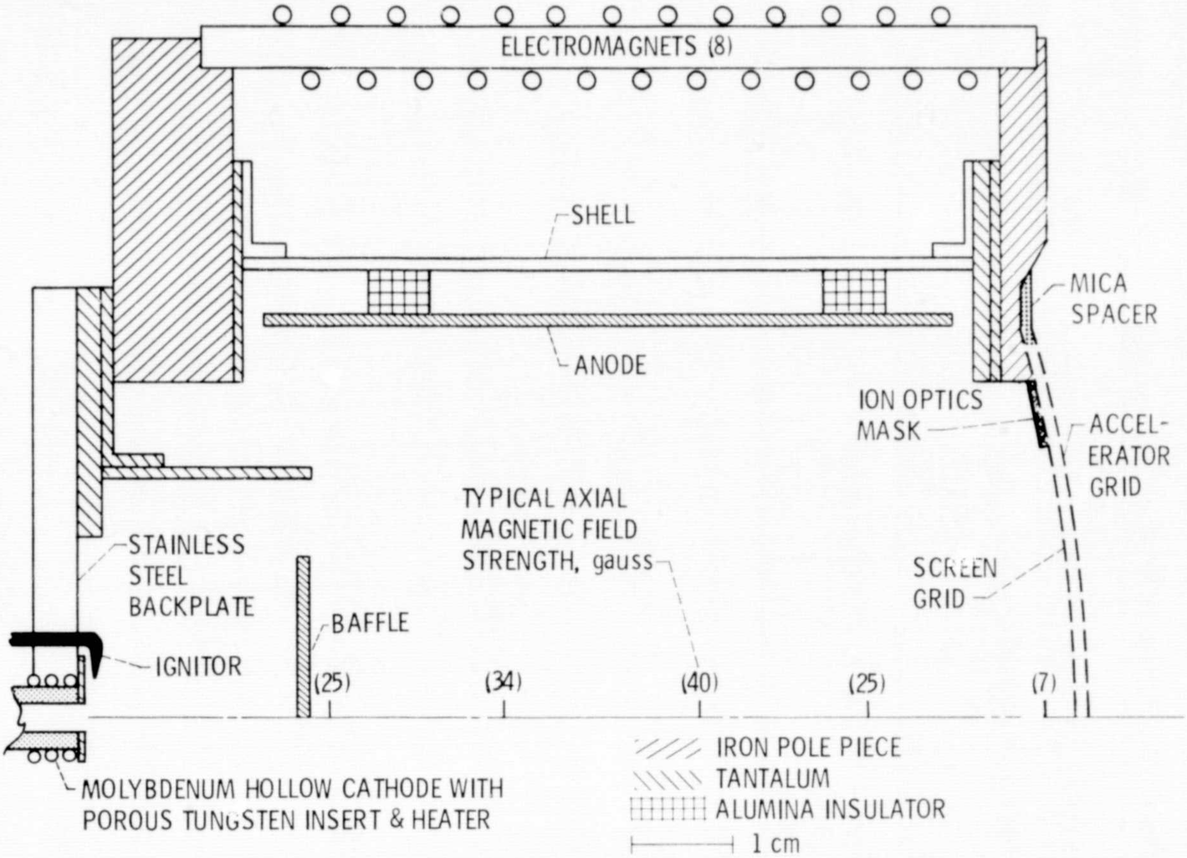

Figure 1. - Sketch of hydrogen ion source.

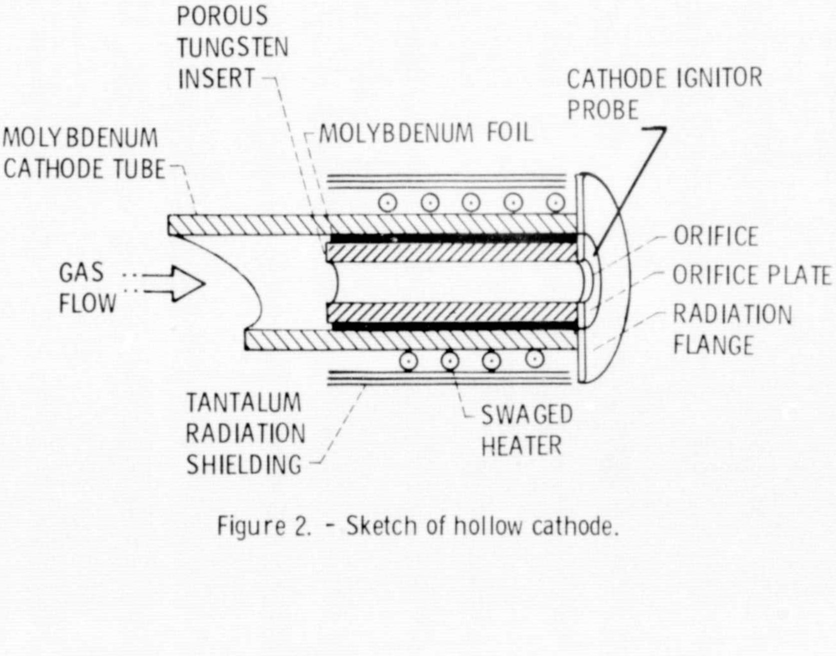

Figure 2. - Sketch of hollow cathode.

	GAS	PROJECTED CATHODE LIFETIME, hr	
—	Hg	>10 000 REF. 7	MINIMUM ORIFICE DIAMETER FOR A GIVEN DISCHARGE CURRENT
○	Ar	>100 REF. 10	PERMISSIBLE DISCHARGE CURRENT
●	Ar	<100 REF. 10	EXCESSIVE DISCHARGE CURRENT
△	*H_2 NO. 2	>10	PERMISSIBLE DISCHARGE CURRENT
▲	*H_2 NO. 1A, 1B	<10	EXCESSIVE DISCHARGE CURRENT

*TABLE I.

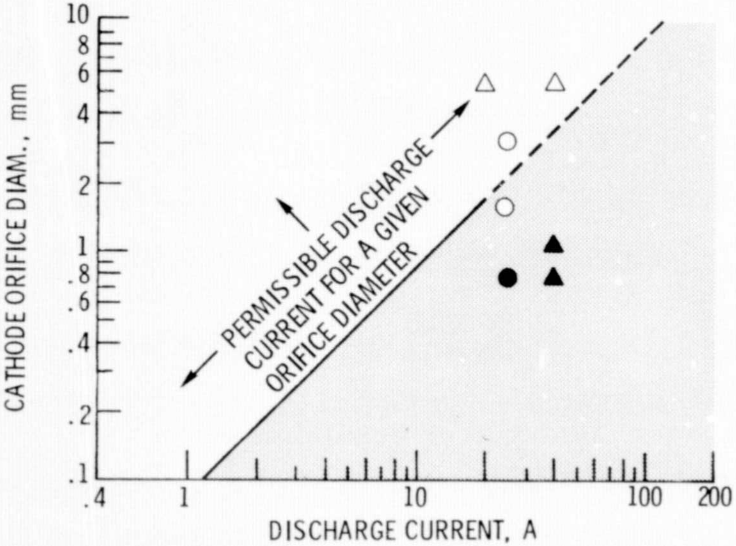

Figure 3. - Permissible discharge currents for various hollow cathode designs. Discharge voltage: 35 to 55 V.

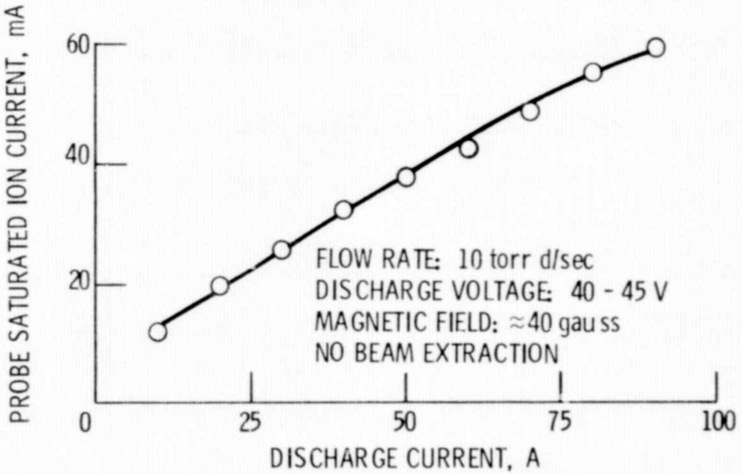

Figure 4. - Ion arrival rate to cylindrical probe versus discharge current. Data obtained on discharge chamber centerline near ion optics.

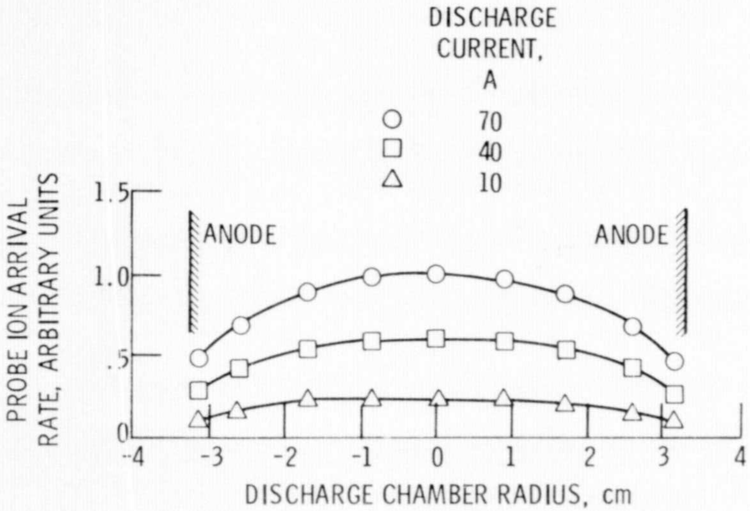

Figure 5. - Ion arrival rate to cylindrical probe versus discharge chamber radius. Biased probe located near screen grid. No ion extraction.

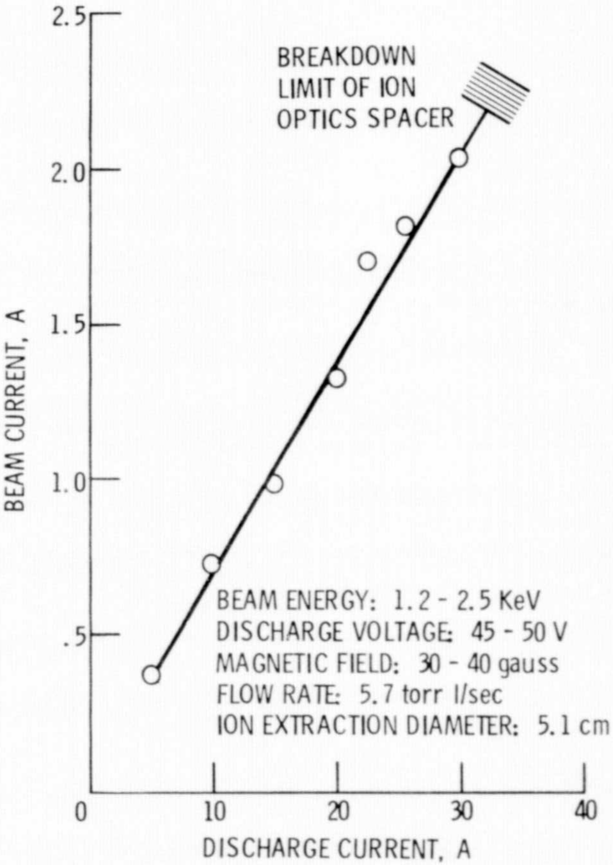

Figure 6. - Hydrogen ion source beam current versus discharge current.

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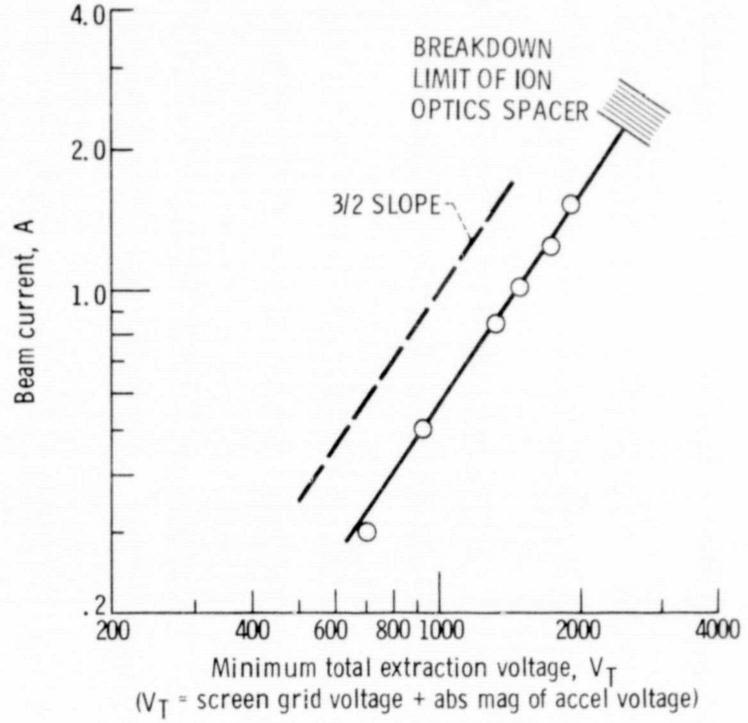

Figure 7. - Ion optics extraction capability for 5.1 cm diameter hydrogen ion source. Ion optics dished downstream and separated by 0.5 mm mica spacer.

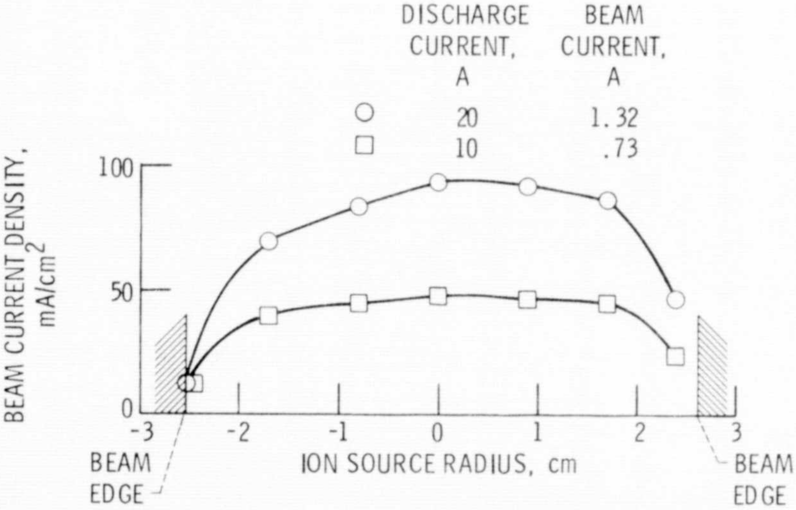

Figure 8. - Beam current density profile. Biased planar probe located 2 centimeters downstream of accelerator grid. Beam energy 1 to 2 keV.

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