Ion Sources for Ion Machining Applications

Harold R. Kaufman*
Colorado State University, Fort Collins, Colo.

and

Paul D. Reader† and Gerald C. Isaacson‡
Ion Tech, Inc., Fort Collins, Colo.

Ion sources with beam diameters of 2.5, 10, and 20 cm have been developed for ion machining applications. All three of these sources use carbon grids to minimize accelerator grid sputtering. A new starting circuit is also employed that uses only passive components for initiation of the discharge. The two larger sources use a flat multipole chamber with multiple cathodes to generate a very uniform beam. The multipole magnetic field is integrated into the anode, which greatly reduces the required number of insulating supports.

I. Introduction

THE broad-beam electron-bombardment ion source was introduced in 1960.[1] As the result of an extensive development program since then, a large body of technology exists for this source.[2] The main performance objectives for electric thrusters have been, and are, high electrical efficiency, high propellant utilization, light weight, and an unattended operating lifetime on the order of a year. The major propellants investigated for electric propulsion have been heavy elements such as mercury, cesium, and xenon. The major objectives for similar ion sources used in ground applications are high ion-current density and uniformity of the ion-beam profile, with argon the usual source of ions. This paper describes 2.5, 10, and 20 cm ion sources developed for ion machining applications. This development included technology from the space electric propulsion program, as well as the development of original concepts primarily suited for ion machining sources.

II. Ion-Source Design

Argon is the usual source of ions in ion machining applications because it is inert, economical, and readily available. A design ion energy of 500 eV was selected as a compromise of accelerator-system and sputtering-process requirements. The sputtering yields of various materials, given by Laegreid and Wehner[3] and Southern et al.,[4] are shown in Fig. 1. Silicon is typical of most materials of interest, with the ratio of yield to ion energy maximizing in the 300-500 eV range. Target heating for a given amount of material removal is therefore minimized by using ions in this energy range. Because current density in an electrostatic accelerator system varies as voltage to the 3/2 power, the upper end of the 300-500 eV range was selected as a design value.

Specific applications can require a range of ion energies. For sputter deposition, heating of the ion beam target is often unimportant. Higher accelerator-system voltages can therefore be useful, both to increase the yield per ion and to increase the ion beam current. If the ion beam current is increased less rapidly than the 3/2 power of voltage, then it may be desirable to increase the spacing between grids to maintain good collimation. On the other hand, lower ion energies can be useful as a final machining step to reduce surface damage. MacDonald and Haneman[5] found damage depths in germanium of 8, 13, 17, and 25 atomic atomic layers for 400, 600, 800, and 1000 eV argon ions (2.8 Å per atomic layer). The sputtering dose to reach equilibrium was found to be quite small – less than 20 sec for 1 mA/cm^2 of 1000 eV argon ions. Designing for 500 eV ions, though, usually results in a minimum grid spacing, so that lower voltages require ion beam currents to be reduced as the voltage to the 3/2 power.

Design for a 500 eV argon ion energy results in a high current desnity at lower ion energies, while an increased spacing can be used at higher energies. The 500 eV value thus appears to be the optimum single value design choice.

Discharge Chamber

During normal operation the discharge chamber is filled with a low-density plasma. Because of the low density, magnetic fields are required to contain and efficiently use energetic electrons to produce ions. Discharge voltages of 40 to 50V are normally used with argon. At 40V the production of doubly ionized atoms is usually negligible, while the discharge losses are usually slightly less at 50V (at a cost of several percent doubly ionized atoms). Discharge losses are measured in eV/ion, and equal to discharge voltage times discharge current, divided by the extracted ion-beam current.

The discharge plasma in which the ions originate is usually several volts positive of the anode, so that anode potential approximates the origin potential for ions. The plasma potential is nearly constant throughout the discharge chamber, resulting in a negligible energy spread for singly

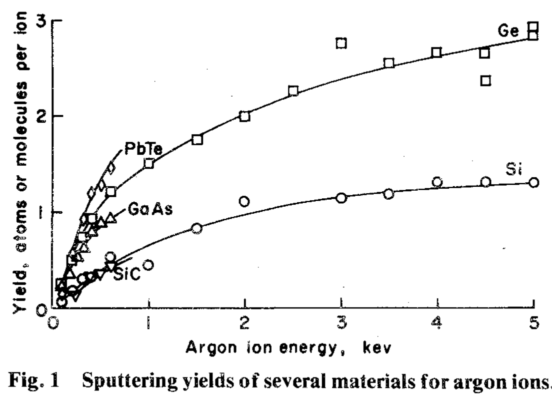

Fig. 1 Sputtering yields of several materials for argon ions.

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*Professor. Associate Fellow AIAA.
†President.
‡Scientist. Member AIAA.

ionized atoms that are accelerated into the beam. Large energy spreads in the ion beam, when found, are the result of either a significant double-ion production or a high background pressure that gives collisional energy losses downstream of the accelerator system.

Discharge-chamber diameters of 3.8, 12.5, and 22.5 cm were selected for the beam diameters of 2.5, 10, and 20 cm. The plasma near the outside edge of the discharge chamber has a lower density. An accelerator system with a diameter smaller than the discharge chamber is used to mask this low density region, which would otherwise produce trajectories far from the beam axis.

The design used for the 2.5 cm discharge chamber is shown in Fig. 2, and is quite similar to an earlier 5 cm design by Wasserbauer.[6] A small source is normally used at distances that are large compared to beam diameter. The radial variation in plasma density at the accelerator system is therefore not critical. Except for the masking described above, no modifications were made to improve uniformity.

The 10 and 20 cm sources, shown in Figs. 3 and 4, are both often used at distances roughly equal to ion beam diameter. The radial uniformity of ion current density at the accelerator system is very important at such short distances, and a number of features were employed in both ion sources to improve this uniformity. These features included a flat discharge chamber with multiple cathodes and a multipole magnetic field, as well as the masking described earlier.

Both the 10 and 20 cm sources use a continuous cathode held by four evenly spaced supports from the side (cylindrical)

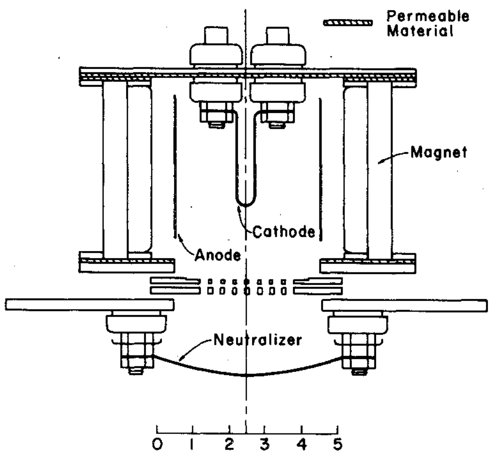

Fig. 2 Cross section of 2.5 cm ion source.

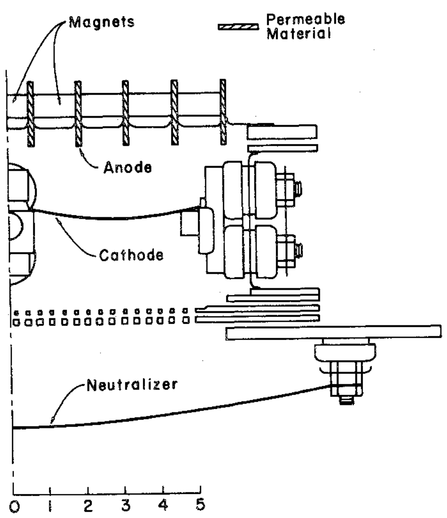

Fig. 3 Cross section of 10 cm ion source.

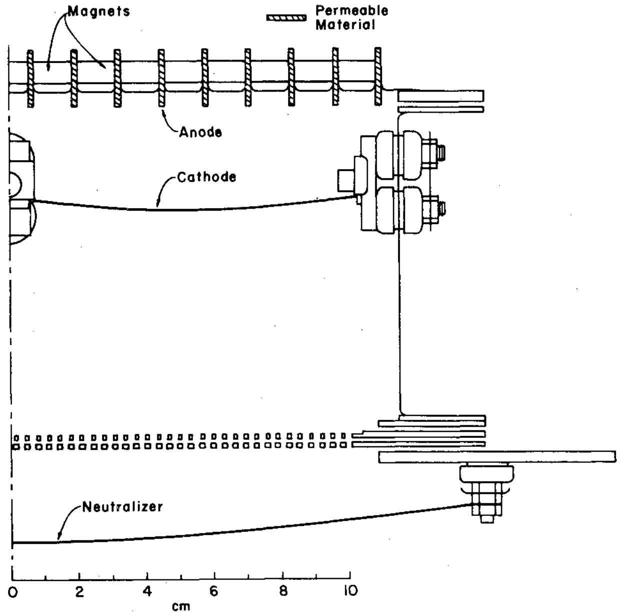

Fig. 4 Cross section of 20 cm ion source.

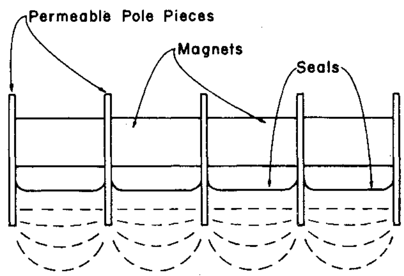

Fig. 5 Detail of combination anode and pole piece. Magnetic field shown by dashed lines.

wall of the discharge chamber. Two opposing supports were used to introduce the cathode heating current in the 10 cm source, so that the four cathode elements were effectively arranged with two parallel paths of two elements each. For the 20 cm source, all four elements were made parallel. The discharge-chamber depth was made equal to about half the ion-beam diameter for both the 10 and 20 cm sources.

A flat discharge chamber with multiple cathodes was used by Reader[7] with mercury propellant to obtain the first fairly uniform beam from an electron-bombardment thruster. The discharge chamber was 50 cm in diameter and only 13 cm deep, which was the smallest length-to-diameter ratio used up to that time. The relatively small cylindrical side wall was believed to contribute to the ion-beam uniformity. The use of multiple cathodes by Reader was another contributing factor to this uniformity. In comparison, a skewed profile was obtained when only three of the four cathodes were operating.

The multipole magnetic field was combined with the anode to minimize the number of insulating supports and their exposure to the discharge chamber plasma. As shown in Fig. 5, the pole-piece structure consists of thin (0.6 mm) permeable strips, separated by permanent magnets (1.2 cm long). This pole-piece structure is also the anode. Because of the magnetic field, only high-velocity (primary) electrons that approach from particular directions can pass through the magnetic field and reach the anode. The low-velocity (Maxwellian) electrons, on the other hand, readily diffuse across the magnetic field to reach the anode. In the multipole approach the magnetic field is weak, except near the pole pieces. This means that the motion of the ionizing electrons is essentially unrestrained by the magnetic field throughout most of the discharge-chamber volume, making the ion production more uniform. In comparison, the axial magnetic field of the original single cathode thruster has an inherent tendency to generate an ion-beam profile that is peaked at the center, with this tendency becoming more severe in larger thruster diameters.

The multipole design used herein was a further development of the multipole design introduced by Moore[8] and Ramsey.[9] The major difference between these designs is that Moore and Ramsey used anodes between the pole pieces, instead of using the pole pieces themselves as anodes. Also, Moore and Ramsey used permanent magnets as pole pieces, instead of between the pole pieces. The magnetic field used by Reader in the 50 cm source was, in effect, an intermediate step between the early axial field design and the later multipole design. Although this magnetic field was nominally axial, it was produced by a very short solenoid. As a result, the magnetic field strength was much higher near the anode (the cylindrical wall) than it was in the rest of the chamber. Some of the uniformity obtained was therefore probably the result of this low field strength throughout most of the discharge chamber volume.

Accelerator System

It is customary in accelerator system design to use an accelerator grid (the downstream grid in a two-grid system) biased below target (ground) potential. This means that the ions are first accelerated, then decelerated, to reach the final beam velocity. The amount of deceleration is indicated by the net-to-total voltage ratio. The ions originate at close-to-anode potential, so that a net-to-total voltage ratio of 0.5 would be one where the accelerator grid is as negative relative to ground as the anode is positive. A small amount of deceleration (net-to-total voltage ratio slightly less than 1.0) is required to prevent beam electrons from back-streaming through the accelerator system. The smallest beam divergence is also obtained with this minimum amount of deceleration. On the other hand, maximum ion-beam current density at a given grid spacing and a given ion beam velocity is obtained with a low net-to-total voltage ratio. If a small divergence and a large ion current density are desired at the same time, then a net-to-total voltage ratio near 1.0 must be used together with a very small spacing between the positive and negative grids. This small spacing is often a critical problem in accelerator-system design.

Carbon was selected for the accelerator-system grids. Of the various materials tested for electric-propulsion grids by Kerslake and Pawlik,[10] carbon has the lowest sputtering yield and lowest thermal expansion. Kerslake and Pawlik found that carbon grids could be operated safely at conditions that would have badly warped any metal grids. Only the launch vehicle environment prevented serious consideration of carbon in place of the usual molybdenum for flight programs. The advantages of carbon were further enhanced for the ion sources described herein by the use of pyrolytic graphite. With the proper grain orientation, pyrolytic graphite gives higher strength, higher modulus of elasticity, and lower thermal expansion in the plane of the grids. These properties are all important if close grid spacings are to be used.

For the 2.5 cm source, screen and accelerator thicknesses were 0.4 and 1.0 mm, while the hole diameters were both 2.1 mm. The gap between grids was 0.5 mm and the holes in the grids were arranged in a hexagonal pattern with 2.5 mm between centers. A net-to-total voltage ratio of 0.8 was used at design conditions.

For the 10 cm source, screen and accelerator hole diameters were 2.1 and 1.7 mm, while the corresponding thicknesses were 0.4 and 1.0 mm. The gap between grids was 0.6 mm and the holes were arranged in a hexagonal pattern with 2.5 mm between centers. A net-to-total voltage ratio of 0.9 was used at design conditions.

For the 20 cm source, screen and accelerator hole diameters were 3.3 and 2.6 mm, while the corresponding thicknesses were 0.5 and 1.0 mm. The gap between the grids was 1.0 mm and the holes were arranged in a hexagonal pattern with 4.2 mm between centers. A net-to-total voltage ratio of 0.67 was used at design conditions.

The design current densities were 2.0 mA/cm^2 for both the 2.5 and 10 cm sources and 1.5 mA/cm^2 for the 20 cm source. The net-to-total voltage ratios were made as high as possible to minimize ion-beam divergence. The ion-beam current density therefore falls off slowly with distance. The ion optics calculations were originally made from information given by Kaufman.[2] More complete theoretical[11] and experimental[12] studies have since been published. From the theoretical studies of three-grid systems,[11] a third grounded grid would not reduce beam divergence at the net-to-total voltage ratio used for the 2.5 and 10 cm sources. There would be some improvement, though, at the lower net-to-total voltage ratio used for the 20 cm source.

In a low-pressure environment, the accelerator impingement will be on the order of one percent of beam current at good operating conditions. If a high-pressure environment is used (with facility pressure about equal to discharge-chamber pressure), charge exchange of beam ions with background gas can easily increase the accelerator grid current to 10 or 20 percent of beam current.

Cathodes

Tantalum wire, 0.25 mm in diameter, was used for both discharge-chamber and neutralizer cathodes. The typical heater current for this wire size of tantalum was about 5A and the typical voltage was about 1V per cm of cathode length. Both cathodes used 60 Hz sources. The center tap of the discharge-chamber cathode was connected to the negative side of the discharge power supply, while the center tap of the neutralizer was grounded.

Tantalum was used rather than tungsten because it is much more ductile and therefore easier to install. In an argon atmosphere, tantalum also remains ductile after operation, as opposed to the glass-like brittleness of tungsten after operation. Other tests, however, suggest tungsten might be a better choice when oxygen is used for reactive sputtering.

The most complete tests of tantalum and tungsten cathodes in the discharge chamber were conducted by Milder and Kerslake.[13] These tests permit design lifetimes up to 1000 hours in inert atmospheres. The cathode lifetime, however, was found to be very dependent on small amounts of impurities present. The normal sputtering environment has many impurities present, so that cathode lifetime is often limited by these impurities. For the 0.25 mm cathodes employed, lifetime was typically 30 hours. A longer lifetime could have been obtained with a heavier cathode, but was not felt to be required.

Much fewer data are available for neutralizer design. Kemp et al.[14] found minimum lifetimes of 2-3 hours for both tantalum ribbons (2.5×0.05 mm) and tantalum wires (0.25 mm diam) in a 1.4 mA/cm^2 of 3000 eV mercury ions. Sputtering data indicate that lifetimes with 500 eV argon ions should be roughly 5 times longer. This agrees with observed lifetimes of about 15 hours for the cathodes employed herein. Ion beam sputtering is the major limitation on lifetime for the immersed neutralizers employed on these sources when argon ions are used, so that previous experience with ion thrusters appears to be a useful design guide. As with discharge chamber cathodes, neutralizer lifetime is sharply reduced in the presence of oxygen.

A neutralizer cathode is required for most sputter machining applications. Without this source of electrons, the more random processes of background gas ionization, secondary electrons from the target, and sparks from nearby hardware will result in 50 to 200 V variations in beam potential. These variations might not be important for a multi-keV beam, but they can have substantial beam spread effects at the ion energies used in sputter machining. Proper neutralizer heater current is usually obtained by adjusting this current until there is zero net current to a probe at ground potential in the center of the beam. This procedure results in an ion beam that is about 5 to 10 V above ground potential.

The neutralizer is usually the largest single contributor to contamination from the ion source. An analog of the plasma-bridge neutralizer (used with mercury or cesium propellant) would therefore be valuable for ion sources used in sputtering applications. However, plasma-bridge neutralizers that operate well on argon are not yet available.

Starting Circuit

The usual starting procedure with an electron-bombardment ion source is to increase the discharge voltage above the normal value or, if an electromagnet is used, to turn off the magnet current. Such a starting procedure is required because discharge-chamber surfaces other than the anode are usually near cathode potential. The potential of these surfaces presents no problem during normal operation because the plasma conductivity permits adequate coupling to the anode. Before a discharge is initiated, however, the space-charge-limited emission of the cathode is adversely affected by these surfaces.

The starting circuit employed herein is indicated in Fig. 6. Surfaces other than the anode and cathode are connected to anode potential through resistor R. This resistor is sufficiently small that the potential drop across it is small during the initial space-charge-flow phase. At the same time, the potential drop approaches the discharge voltage during normal operation. In practice, a value of 5k to 10k ohms works well. Rapid and reliable starting is obtained over the entire operating range with a resistance value in this range and a discharge voltage of 50v. At the same time, the power dissipated in the resistor is small during normal operation. At no time was it necessary to turn off high voltage in order to start the discharge.

III. Experimental Results

Experimental ion-beam profiles are shown in Figs. 7 through 9 for the 2.5, 10, and 20 cm sources. The argon ion energy was 500 eV for all three sources. The data for the 10 cm source were also published in an earlier paper.[15] The 10 and 20 cm sources were operated with the argon introduced into the surrounding vacuum chamber at pressures high enough (5×10^{-4} and 3×10^{-4} torr) to operate the ion source at design conditions without any flow direct to the discharge chamber. Operation with this mode of propellant introduction simulated the adverse environment of a facility with a marginal pumping capacity. Good pumping capability,

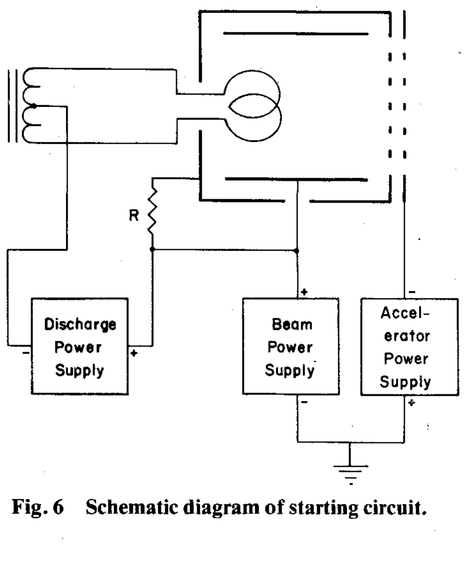

Fig. 6 Schematic diagram of starting circuit.

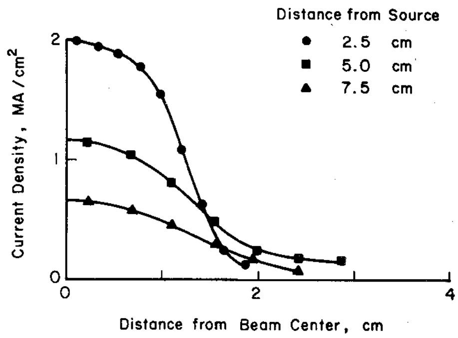

Fig. 7 Beam profiles for 2.5 cm source at ion beam current of 10 mA and bell-jar pressure of 5×10^{-4} torr.

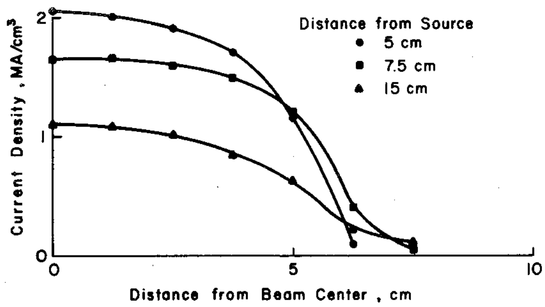

Fig. 8 Beam profiles for 10 cm source at ion beam current of 157 mA and bell-jar pressure of 5×10^{-4} torr.

together with argon introduction into the discharge chamber, would give higher current densities due to reduced charge-exchange and background scattering effects. The argon was introduced into the discharge chamber of the 2.5 cm source, so that the discharge chamber pressure was higher than the 5×10^{-4} torr bell-jar pressure shown. The small argon flow rates used with the 2.5 cm source make unlikely the use of a facility with marginal pumping capacity.

The uniformity of the 2.5 cm source is adequate for small samples, with a $\pm5\%$ variation over the center 1.25 cm diameter of the beam at the survey distances shown. The uniformity of the 10 cm source is sufficient for larger samples, with a $\pm5\%$ variation over the center 5 cm diameter of the beam at the survey distances shown. For the 20 cm source, the profiles at 10 and 15 cm from the source were uniform within $\pm5\%$ over the center 10 cm of the beam. Some beam spreading at the 10 and 15 cm distances is apparent for the 20 cm source, probably due to the lower net-to-total voltage ratio (0.67) used for this source.

The ion beam profiles were measured with 0.5 cm^2 (2.5 cm source) and 1 cm^2 (10 and 20 cm sources) probes biased -20V (relative to facility ground) to reflect electrons. Other tests, using sputtered layers with alternately contrasting colors, indicated some effects of individual beamlets at the 5 cm distance that were too small to be detected with the probes used. No such effects were observed at larger distances. At the high pressures used, the sputtering rate tended to be somewhat higher than indicated by current density at the larger distances. This discrepancy was assumed due to energetic neutrals resulting from charge exchange between beam ions and the background gas.

The discharge losses tended to be high compared to electric thruster experience. For the conditions shown in Figs. 7-9, the 2.5 cm source had a loss of 900 eV/ion (45V discharge), while both the 10 and 20 cm sources had losses of 800-900 eV/ion (50V discharges). The increase over electric thruster losses is believed due to the use of argon and the optimization for uniformity rather than efficiency. From operation of the same

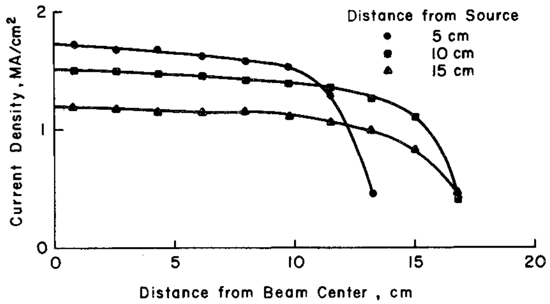

Fig. 9 Beam profiles for 20 cm source at ion beam current of 471 mA and bell-jar pressure of 3×10^{-4} torr.

sources on both mercury and argon, previous investigations have shown that argon losses can range from about the same to nearly twice that with mercury.[16-19] The masking of the outer edge of the beam will, of course, almost always increase discharge losses. Also, the use of multiple cathodes near the outer wall increases uniformity, but usually tends to increase discharge losses. In view of the ion-beam uniformity obtained with these sources – particularly the 10 and 20 cm sources – the discharge losses were felt to be reasonable.

IV. Concluding Remarks

Elements of ion thruster technology, together with some original concepts, have been used to design 2.5, 10, and 20 cm ion sources suited to ion machining applications. Among the original concepts are the use of pyrolytic graphite for grids, integration of the anode with magnetic pole pieces, and the starting circuit employed. All three sources produce beams of 500 eV argon ions with current densities in the 1-2 mA/cm² range at useful distances from the sources. At these useful distances, the three sources had beams uniform within ±5% over a diameter equal to half the beam diameter at the source.

The approach used for the two larger sources, with a flat multipole discharge chamber and multiple cathodes, appears applicable to much larger sources. From discharge-chamber scaling laws, the product of minimum chamber pressure and chamber depth should be nearly constant for larger beam diameters. Accelerator systems, though, will be more critical for these larger sources. The 1 mm gap appears to be near the minimum permissible for the 20 cm source. Experience has shown that the minimum ratio of gap to beam diameter is nearly a constant for a given accelerator system technology. This means that larger beam diameters will require larger gaps, and hence have lower ion current densities. Some of the effects of an increased gap could be offset by lower values of net-to-total voltage ratio, but this ratio was reduced to 0.67 for the 20 cm source described herein.

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