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Highly Efficient, Inexpensive, Medium Current Ion Source

ROBERT L. HIRSCH AND GENE A. MEEKS
ITT Farnsworth Research Corporation, a subsidiary of International Telephone and Telegraph Corporation, Fort Wayne, Indiana 46803

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A newly designed ion source has provided deuterium ion currents up to 10 mA at input powers of about 100 W. The device utilizes a diffuse, filament-excited dc discharge produced in the 10^{-3} Torr pressure region and incorporates an ion extractor as a part of the plasma chamber. The extractor and discharge chamber exit aperture form a converging lens that shapes the ions into a small diameter beam, which exits the chamber through a small orifice in the extractor. The combination of low operating pressure and small diameter exit orifice results in low neutral gas leakage. Simplicity of design and operation renders the unit relatively inexpensive to build and maintain. Because the discharge is diffuse, it can be readily scaled up or down in size and modified for the extraction of a variety of beam shapes.

INTRODUCTION

IN the course of our work with ionized gases, a source of deuterium ions with the following properties was required:

(a) dc output,
(b) current capability up to 10 mA with low impurity level,
(c) simple and inexpensive to build and operate,
(d) high enough power efficiency so that water cooling would not be required,
(e) low neutral gas leakage, and
(f) small size.

The duoplasmatron[1] has been widely utilized [2–5] to fill similar requirements. However, because it is not particularly inexpensive, efficient, or compact, we decided to develop an ion source specifically for our purposes, using the duoplasmatron for comparison.

The design of a plasma type ion source involves two general considerations: the formation of the plasma and the extraction of the ions from the plasma. In the duoplasmatron the plasma is produced in the 10^{-1} Torr pressure range by a concentrated arc discharge immediately adjacent to a small exit aperture. On the high vacuum side of this aperture an extractor accelerates ions from the plasma and concentrates them into a beam, which is then formed and accelerated. The use of a concentrated arc produces a high degree of ionization near the exit aperture. This minimizes neutral particle flow, resulting in a high gas efficiency, i. e., a high ion current to neutral gas flow ratio. However, the high energy densities in the chamber also result in intense wall heating and bombardment with associated impurity liberation.

An alternative to this design philosophy has been adopted in the device described herein. Our experience with filament excited discharges in the 10^{-3} Torr pressure range served as a starting point. Because these discharges are relatively diffuse, the energy density at the walls is relatively low. To extract a large number of ions from these plasmas, a large exit aperture must be provided in the plasma chamber. In order to limit neutral particle leakage, the extractor was made a part of the plasma chamber and provided with a small exit orifice. By providing appropriate electrostatic focusing, the ions which are removed from the plasma are drawn into a fine beam, which leaves the source through the orifice in the extraction electrode. A low neutral gas flow, i.e., a good gas efficiency, is thus achieved by utilizing a low chamber pressure and by incorporating the extractor with its small orifice as an element of the source chamber. Due also to the low operating pressure, no discharge will occur between the extractor and the plasma chamber.

CONSTRUCTION

The resultant ion gun is shown in Fig. 1. Built on modified 7 cm Varian flanges, the principal structure material is 304 stainless steel with all joints heliarc welded. Situated at the rear of the 4.45 cm diam plasma chamber, the thoriated tungsten filament (0.3 mm diam) is positioned in a cup which is connected to one lead. The purpose of the cup is to restrict the discharge to the forward part of the chamber and to provide a degree of electrostatic focusing. The whole assembly is mounted on two Alite cable end seals, which are themselves mounted on the rear flange. The filament-cup assembly is typically operated at 50 to 200 V negative and of the order of hundreds of milliamperes.

Permanent magnets are situated around the outside of the plasma chamber. Typical field strengths within the chamber are of the order of a few hundred gauss. It is

[1] M. Von Ardenne, *Tabellen der Elektronenphysik, Ionenphysik, und Übermikroskopie* (V. E. B. Deutscher Verlag der Wissenschaften, Berlin, 1956).
[2] C. D. Moak, H. E. Banta, J. N. Thurston, J. W. Johnson, and R. F. King, Rev. Sci. Instr. **30**, 694 (1959).
[3] E. M. Kellogg and K. E. Eklund, Rev. Sci. Instr. **33**, 1338 (1962).
[4] M. J. Kofoid, C. M. Broams, and P. Zieske, Rev. Sci. Instr. **36**, 1415 (1965).
[5] M. S. Livingston and J. P. Blewett, *Particle Accelerators* (McGraw-Hill Book Company, Inc., New York, 1962).

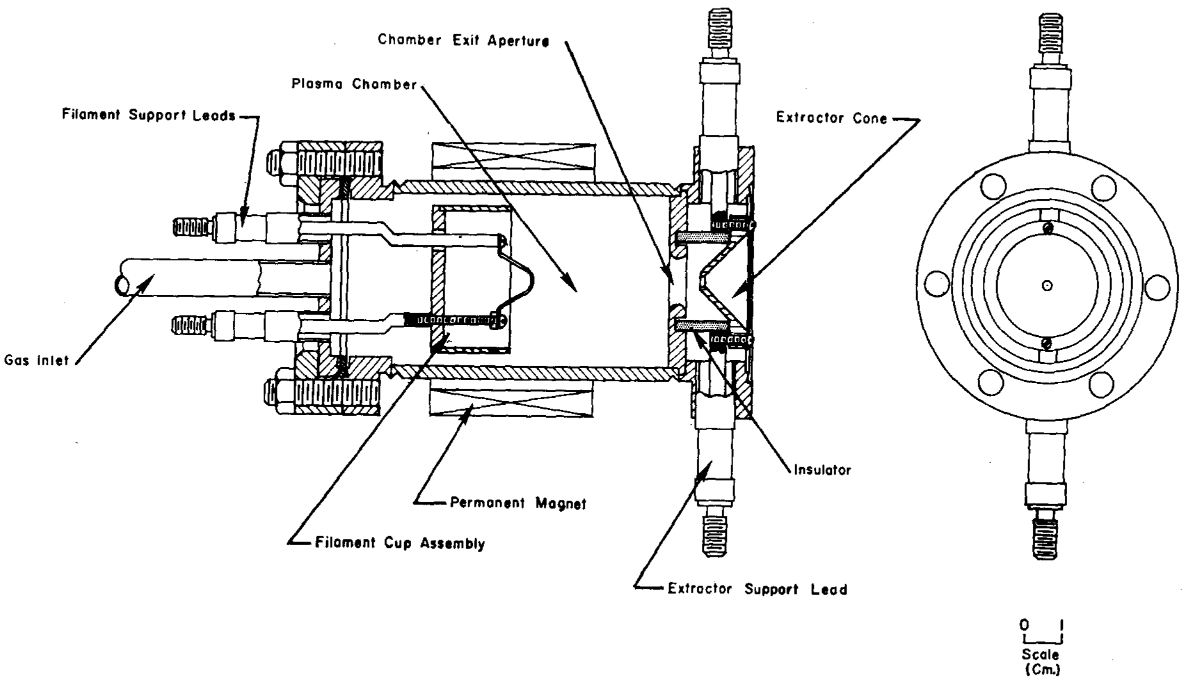

FIG. 1. General arrangement of the ion source.

worth noting that the gun operates without the magnets, but the resultant ion output is found to be reduced by about two-thirds. Since the magnets are inexpensive, require no power, and have only a minor effect on the convective cooling of the chamber, their use is more than justified.

The extraction assembly was built in a modified Varian double Conflat flange. The chamber aperture plate contains a 1.26 cm exit port beyond which the extraction electrode is located. The exit orifice on the extractor was 1.78 mm diam. For this particular ion optical configuration, this diameter permitted a large fraction of the ion beam to pass through the extractor. A cylindrical aluminum oxide insulator positions the extractor and acts as a gas barrier. Two side-mounted electrical leads connected to the extractor provide the force to hold the assembly together as well as the means of applying the negative accelerating voltage. Since gas leakage between the ceramic and the adjacent parts was found to be quite small, a more elaborate ceramic-to-metal seal was not required.

Up to 10 kV can be applied to the extractor with this arrangement. Above that voltage breakdown along the outside surface of the side-mounted insulators is encountered. By adding an epoxy coating over a portion of the insulated electrode, the outside surface distance between the electrodes can be increased so that extraction voltages to 15 kV and higher are possible. The test unit utilized such an epoxy coating to increase the usable upper extractor voltage to 12 kV.

The auxiliary equipment required to operate the source was as follows: a 6 V, 12 A filament supply with an output insulated for a few hundred volts, a plasma supply to bias the filament to 200–300 V negative at 1 A maximum, an extractor supply capable of 12 kV at 10 mA. For the tests described below, a dc filament supply was utilized to minimize 120 cycle modulation of the output (the filament is operated emission limited). For many applications, a simple filament transformer is sufficient. A voltage regulated supply for the plasma power was found convenient but not necessary. Because the dissipated power is of the order of 100 W, cooling other than natural convection is not required.

For the tests to be described, the output ion beam was directed into a Faraday cage biased at the extractor voltage to reduce secondary electron effects. Both the extractor and cage currents were recorded. Gas flow through the chamber was regulated by a variable leak while the cage chamber was evacuated with a mercury diffusion pump.

PERFORMANCE

Discussion of the operation of the source is divided into two parts: plasma chamber operation and extractor performance. The plasma chamber exhibits two modes of operation, designated as ignited and unignited. A minimum gas pressure of 10^{-3} Torr and a minimum filament bias of -50 V are required to ignite a discharge. Below either of these minimum conditions, a discharge does not occur, and the device acts as an emission saturated thermionic diode. Above these minimum conditions, a discharge occurs in which the current is determined by the electron emission from the filament. Currents in the ampere range are possible, the principal limitation being filament lifetime.

The key elements of the extractor section are the extractor itself and the chamber exit aperture. The shape and diameter of both elements and the separation between them determines the ion optics in this section. The particular geometry shown in the figure was determined empirically in an effort to optimize for 5–10 mA of ion output. As will be seen below, an optimum extractor voltage exists for each output current.

In Figs. 2 and 3 the performance of the extractor section is shown. Both figures represent operation of the filament assembly at -100 V and 2×10^{-3} Torr of deuterium in the plasma chamber. The extractor voltage and discharge current were varied while the output current and the extractor current were measured. Figure 2 shows that at a given chamber current the output current-extractor voltage characteristic has an "S" shape. Notably there exists a range of extractor voltages for which the output current rapidly increases. In Fig. 3, the percent ion transmission through the extractor orifice is shown versus the same variables. A minimum is evident at 100 mA and 200 mA and suggested at 300 mA. This minimum represents a maximum ion transfer from the tube and a minimum of ion heating of the extractor. The shape of the curves can be simply explained. The portion to the left represents insufficient field to form a beam which can pass through the aperture. The right hand side is characteristic of ion crossover short of the aperture. The actual transmissions are less than one-half[6] those shown because these data have not been corrected for the ion-induced emission from the extractor.

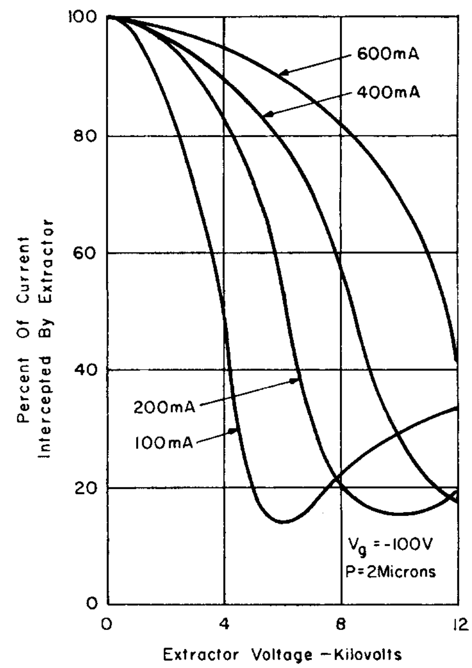

FIG. 3. Effect of extractor voltage on extractor transmission.

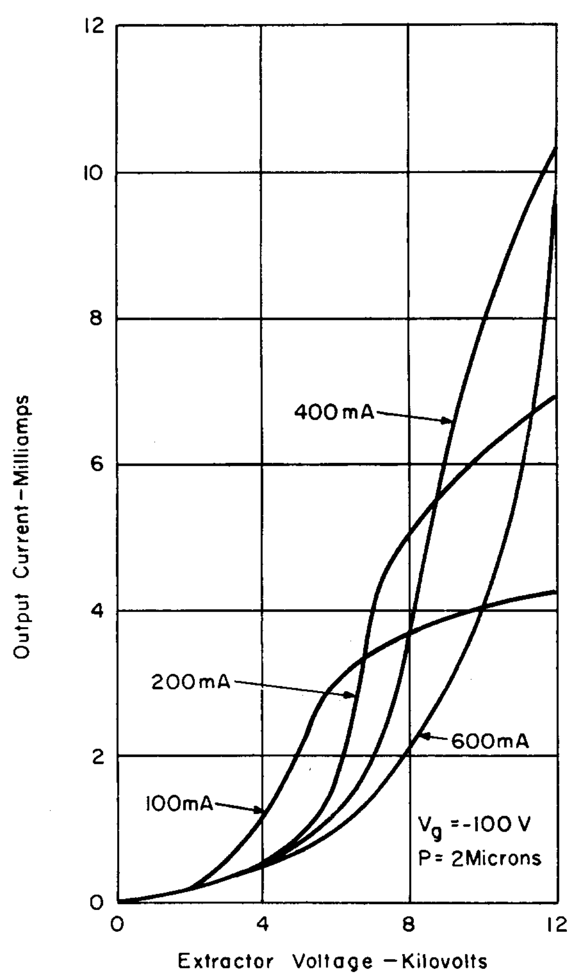

FIG. 2. Effect of extractor voltage on output current.

Each minimum in Fig. 3 represents an optimum operating point. They also correspond to definite output currents as shown in Fig. 2. Therefore, although a wide range of currents can be efficiently drawn at any given operating condition, an optimum operating condition does exist for any given output current.

The significant variable in the plasma chamber is the current, and not the filament bias. This is shown in Fig. 4 where the ion output is plotted at various currents versus filament bias voltage. The outputs are seen to be linear and to increase only slightly with increasing bias. From the viewpoint of power consumed, the lower voltages are therefore preferable.

The relative independence of the plasma chamber and the extractor section is shown in Fig. 5 where extractor transmission has been plotted versus filament bias and chamber current. At both 100 mA and 200 mA the beam transmission ratio is nearly independent of the input to

[6] M. Kaminsky, *Atomic and Ionic Impact Phenomena on Metal Surfaces* (Academic Press Inc., New York, 1965).

the plasma. At 400 mA the characteristic decreases with increasing filament bias, indicating a slight interdependence (probably plasma geometry) between the two sections.

Pressures of two or three times the ignition pressure have negligible effect on performance. Therefore, where high gas efficiency is required, operation slightly above the ignition pressure is optimum. A variety of other gases can be utilized in this source with similar results. Tests with nitrogen and oxygen have shown similar ignition pressures as well as comparable output current.

From these data, a 10 mA ion output can be efficiently generated and extracted at -50 V and 400 mA in the chamber with 12 kV on the extractor. Since these conditions require of the order of 5 V and 10 A to the filament, the total power required for this output is of the order of 100 W. This compares favorably with the order of 1000 W required for the same current from the duoplasmatron.[3] Since the parts for the source do not require extensive machining, the device is relatively simple and comparatively inexpensive to construct in this rugged, bakable configuration. Maintenance has been confined to filament replacement, and at operation below about 1 A, no filament replacement has been required to date. The exit orifice of 1.78 mm utilized here represents one hundred times the area of the 0.178 mm diam orifices typical of the duoplasmatron. However, the factor of about two hundred difference in the respective operating pressures results in decreased neutral gas leakage. After chamber outgassing, the principal source of impurities is ion bombardment of the extractor near the exit aperture. Sputtering from this region can in principle be reduced by improved ion optics as well as the judicious selection of a low sputtering material for the extractor.

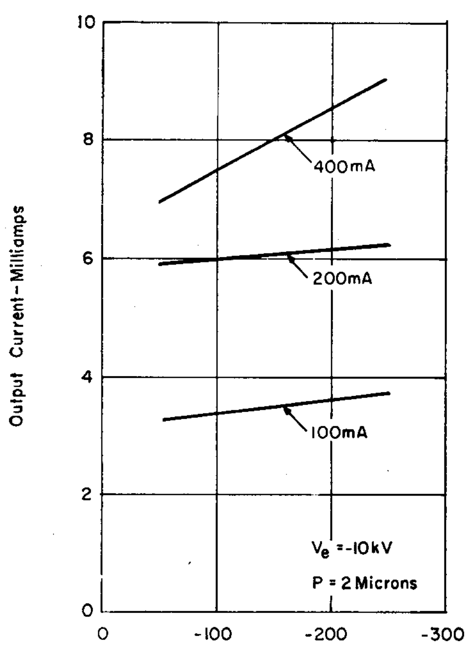

FIG. 4. Effect of filament bias on output current.

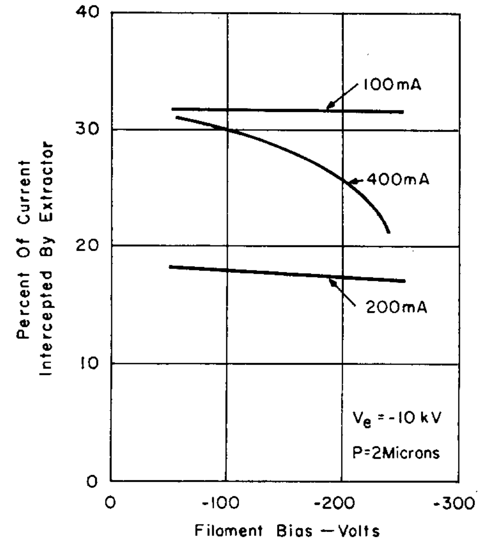

FIG. 5. Effect of filament bias on extractor transmission.

To date no experiments have been performed to determine the ionic composition of the beam. At these low operating pressures, however, concentrations of 10% D^+, 80% D_2^+, and 10% D_3^+ might be expected.[7]

The device can be scaled to larger and smaller sizes. A 10 cm diam model was tested and found to exhibit characteristics very similar to the unit described above. In a larger version, more than one aperture can be incorporated, and multiple beams can be extracted because the discharge is diffuse. Further, sheet and hollow beams can be produced using suitably shaped apertures and extractors.

ACKNOWLEDGMENTS

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[7] F.-Marcel Devienne and Jean-Claude Roustan, Compt. Rend. Acad. Sci. Paris **262**, 616 (1966).