Aug. 9, 1966 A. B. WITTKOWER 3,265,918

ION SOURCE HAVING PLASMA CONTROL MEANS

Filed June 18, 1962 3 Sheets-Sheet 1

Fig. 1

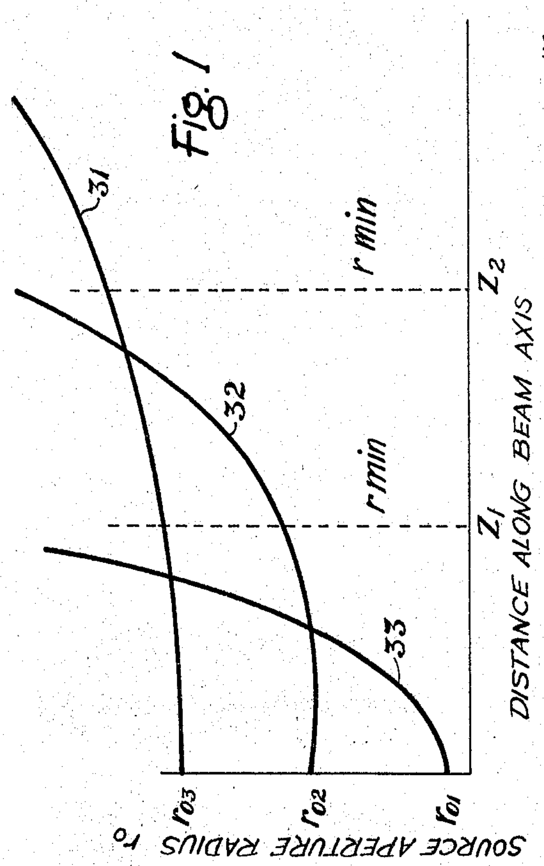
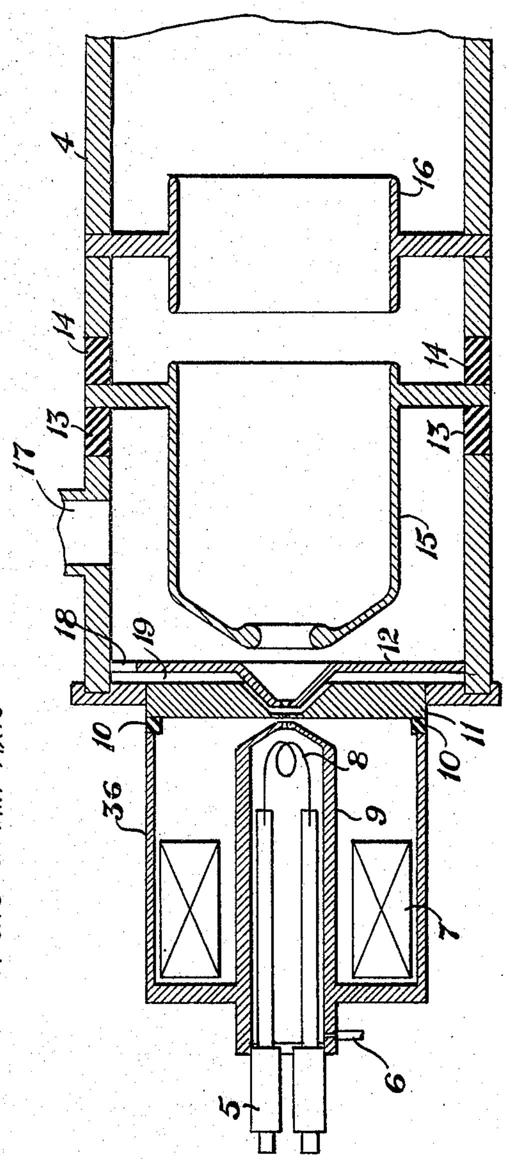



Fig. 2



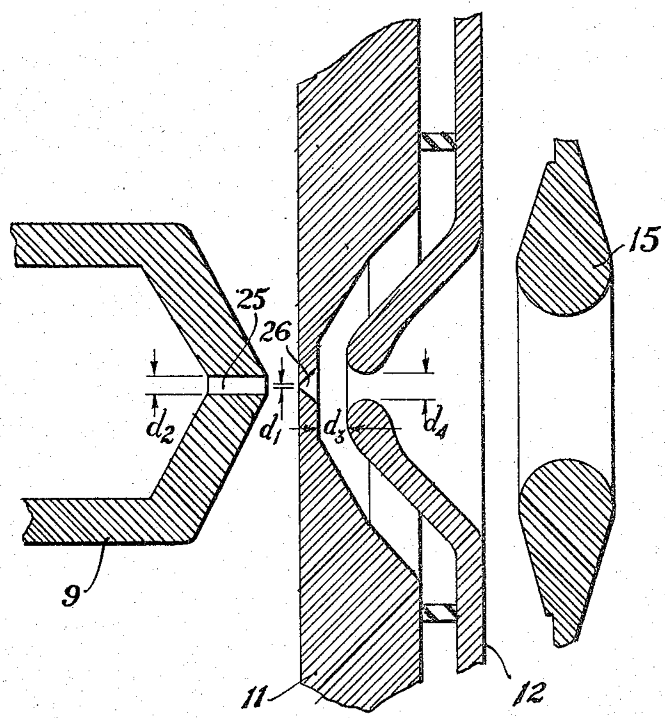



Fig. 3

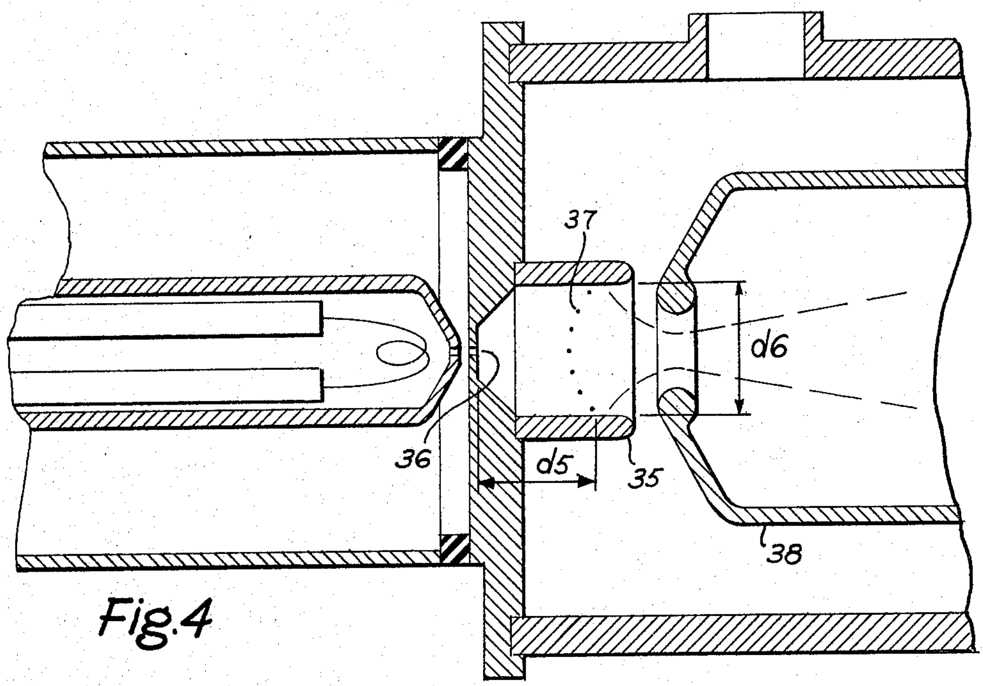



Fig.4

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# ION SOURCE HAVING PLASMA CONTROL MEANS

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6 Claims. (Cl. 313—230)

This invention is a continuation-in-part of my co-pending patent application S.N. 158,206 filed December 11, 1961 (now abandoned) and relates to an improved ion source and more particularly to novel concepts and structure directed toward more effective control of plasma emanating from the source aperture thereof.

Ion sources of the type comprehended by my invention generate ions through the discharge of a thermionic filament in the presence of hydrogen or other suitable ionizing gas. The conventional arrangement includes an ionization chamber and means for supplying thereto a sufficient quantity of gas to be ionized. A probe or intermediate electrode, having the filament disposed therein, is positioned in close proximity to an anode, said anode comprising the end wall and source aperture plate of the ionization chamber. Axially aligned apertures in the probe and anode together with appropriate potentials impressed thereon, provide arc discharge between filament and anode, ionization of gas residing therebetween, and emission of the ions thus formed through said anode aperture. An extractor electrode having a relatively high potential with respect to the anode (commonly in the 10 kv. to 60 kv. range) pulls ions in quantity through the anode aperture into an evacuated ion source housing and directs such ions to a focussing electrode. The focussing electrode in turn forms the ions into a beam which is made to focus at its point of application.

One undesirable characteristic that appears to be inherent in such an ion source is the space charge effect of the ions as they emerge from the source aperture. There results therefrom critical limitations to the formation of a well collimated, high density, ion beam and to the projection of such a beam over any appreciable distance. In the absence of a continuous focussing force, the component ions, having like electrical charges, mutually repel each other to the extent that the beam formed thereby quickly diverges and loses its identity. This problem becomes particularly acute when it is desired to produce high current density beams having current densities of greater than 500 milliamperes/cm.$^2$. While the so-called duoplasmatron ion source can deliver an ion beam of this order of magnitude and greater, such a beam cannot be maintained in the ion source accelerator-extractor section, even at the highest gradient normally available for well-polished electrodes in vacuum, because of the space charge forces. As a result, it has heretofore been impossible to scale up prior art ion sources and obtain high density ion beams without destroying the focussing capabilities.

The effectiveness of an electrostatic lens is limited by a loss in beam quality due to spherical aberration which depends in part upon a function $\omega^3$ where $\omega$ is the angle of divergence of the beam as it enters the lens. The focussing quality can, however, be materially increased for any ion beam of given parameters, if the diameter and divergence of such beam is a minimum when introduced to the focussing lens. This is accomplished by more effectively controlling the ions emanating from the source aperture, which control, in addition to achieving increased focussing range, results in more efficient beam generation, fewer ions lost to the extractor electrode, and less gas flow into the ion source vacuum system.

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I have determined, and it is fundamental to my invention, that, at any given distance from the source aperture electrode, the tendency of the ion beam to diverge is an inverse function of the aperture size. That is, within certain calculable limits, in an ion beam of given energy and intensity, an increase in source aperture size results in a commensurate decrease in beam divergence at a given distance from said aperture. There is, then, a particular value of source aperture radius for which the beam radius at a particular distance is a minimum. I have further developed equations relating source aperture size to the axial distance and radius of the beam for any given set of beam parameters whereby ion source geometry adapted to provide optimum beam configuration may be reliably predicted.

The above recited approach towards more effectively controlling plasma emanating from the source aperture, of course, introduces two further problems. A large source aperture will obviously permit the passage therethrough of a large amount of gas, thus contaminating the vacuum system. Furthermore, the minimum current which can be extracted from such an enlarged aperture may be greater than the system can handle. It is, however, another feature of my invention to provide novel structure adapted to effectively obviate these problems.

Accordingly, it is a principal object of my invention to provide a new and improved ion source.

It is another object of my invention to provide, in an ion source of the class described, a novel source aperture electrode adapted to effect optimum ion beam configuration and to restrict the flow of gas through said aperture to a minimum.

It is another object of my invention to provide an ion source of the class described that is adapted to deliver a directed ion beam having a current density of greater than 500 milliamperes/cm.$^2$.

It is another object of my invention to provide an ion source of the class described that can be scaled up to provide a directed high current density ion beam.

It is still another object of my invention to provide an ion source of the class described having improved focussing capabilities.

It is yet another object of my invention to provide, in an ion source of the class described, a novel source aperture electrode, said electrode comprising a composite structure having first and second co-axially aligned apertured plates spaced apart to provide optimum divergence and intensity control of the ion beam emanating therefrom.

These objects, together with other features and advantages of my invention will become more clearly understood from the following detailed description. While such description makes frequent reference to the accompanying drawings of one presently preferred embodiment of my invention, it is not intended that any limitation as to scope or application of the novel concepts taught herein be inferred therefrom, the true nature and extent thereof being defined in the appended claims.

In the drawings:

FIGURE 1 is a graphical representation of the space-charge expansion of ion beams emanating from various source apertures;

FIGURE 2 illustrates a sectional view of an ion source embodying the principles of my invention;

FIGURE 3 is an enlarged view of the source aperture electrode of FIGURE 2; and

FIGURE 4 illustrates a sectional view of an alternate embodiment of my invention.

In an ion source as hereinbefore described the ion beam divergence is controlled dominantly by space-charge forces. If the current, voltage, and mass composition are kept constant, there is a particular value of the initial beam radius $r_o$ for which the beam radius $r$ at a particular distance $z$ is a minimum. The characteristics of three such beams are illustrated by curves **31**, **32**, **33** of FIGURE 1. The three beams, being of identical energy and current, each have a different initial radius $r_o$. It is readily apparent that the particular value of the initial radius $r_{o2}$ results in a minimum beam radius at the particular distance $z_1$. This is true also of $r_{o3}$ and $z_2$ or of any of an infinite number of curves and distances in a family of such curves. An optimum source aperture radius exists, then, for each application, in terms of the current, energy and minimum spot size at a specific distance from the source. I have determined that the relationships from which such an optimum source aperture may be reliably predicted can be described by the expression

$$\frac{z}{r_o}=2K^{1/2}\int_0^{\sqrt{\log_e \frac{r}{r_o}}} e^{t^2}dt$$

where

$$K^{1/2}=\frac{4.942V^{3/4}}{M^{1/4}I^{1/2}}$$

$z$=the axial distance from the source aperture;
$r/r_o$=the ratio of the beam radius at a distance $z$ to the initial radius;
$M$=the ion mass number;
$V$=the beam energy in kiloelectron volts;
$I$=the beam current in milliamperes; and the integral $e^{t^2}dt$ may be taken from tables in the publication "Table of Functions" by Eugene Janke and Fritz Emde.

Having thus disclosed means for determining the optimum source aperture geometry for any given ion source parameters, I have further developed a unique structural arrangement adapted to more effectively control the plasma emanating therefrom. Since the optimum source aperture will often be substantially larger than that of a conventional device, excessive current generation, together with the escape of prohibitive amounts of gas into the ion source vacuum system must be prevented. Said structural arrangement accomplishes this by providing a composite source aperture electrode adapted to restrict the gas flow while allowing the plasma to expand before extraction, and comprises first and second apertured members co-axially aligned and spaced apart to provide vacuum pumping therebetween. Such an electrode is illustrated as an integral part of an ion source in FIGURE 2 and again in greater detail in FIGURE 3. In order to establish various geometric relationships the following detailed description will have reference to such an ion source adapted to generate a hydrogen ion beam in the one to fifteen milliampere range. Although specific values and dimensions are given, they are understood to be by way of example only, the novel principles and structures being capable of extrapolation over a wide range of such devices. More specifically, as stated in the above recited objects, the novel structure of my invention may be scaled to provide directed ion beams ranging from one milliampere to an ampere and higher.

Referring now to FIGURE 2, there is illustrated an ion source of the type comprehended by my invention. In operation, hydrogen gas is injected into ionization chamber **36** by means of gas input conduit **6**. Probe **9** (also referred to as an intermediate or Zwischen electrode) is centrally positioned in ionization chamber **36** and has disposed therein filament **8**. Filament supply **5** maintains the filament at about −200 volts with respect to anode **11**. Probe **9** is maintained at about −100 volts with respect to anode **11**. Magnet coil **7** shapes the discharge arc between filament **8** and anode **11**, and concentrates the ions, formed by such discharge in the presence of hydrogen, in the anode aperture region. Plasma control electrode **12** is positioned in close proximity to anode **11** and has its aperture in axial alignment with the anode and probe apertures. An evacuated space **19** is provided between anode **11** and plasma control electrode **12**, a vacuum being maintained therein by means of opening **18** and vacuum pumping system **17**. Anode **11** and plasma control electrode **12** are maintained at 0 volt and in combination comprise the novel structure whereby several of the objectives of my invention are accomplished. Such structure will be hereinafter described in greater detail with reference to FIGURE 3. Ions produced in ionization chamber **36** are drawn therefrom by extractor electrode **15**, said electrode being maintained at a negative potential in the 10 kv. to 50 kv. range with respect to anode **11** and aligned to direct ions extracted therefrom to focussing electrode **16**. Said electrodes are disposed within ion beam forming chamber **4** and are electrically isolated by insulators **10**, **13**, and **14**.



With respect to the anode-plasma control electrode arrangement, an enlarged sectional view thereof is illustrated in FIGURE 3. The relative dimensions are characteristic of an operable ion source in the ten milliampere beam class that has proved to successfully effect the objects and concepts of my invention. In the present instance, aperture **25** of probe **9** has a diameter $d_2$ of .09 inch. Aperture **26** of anode **11** has a diameter $d_1$ of .009 inch and is in axial alignment with aperture **25**. Finally, plasma control electrode **12** positioned a distance $d_3$ of .1 inch from anode **11** has therein aperture **27** with a diameter $d_4$ of .093 inch. It is pointed out that the physical dimensions referred to are in no way controlling and will, of course, vary with the parameters of any given ion source. The approximate relationships are significant, however, in that the essence of my invention resides in the combination of small aperture **26**, especially adapted to restrict gas flow and beam current intensity, a plasma travel distance $d_3$ to provide proper expansion of the plasma, and a discrete plasma control aperture diameter $d_4$ that provides optimum beam divergence.

FIGURE 4 illustrates an alternate embodiment of my invention that is particularly adaptable to the production of high density ion beams. In such an arrangement cylindrical member **35** provides a drift space $d_5$ wherein the plasma may expand to a diameter $d_6$. The plasma boundary in the present case may be established by a grid **37**, or the plasma may be allowed to form its own boundary curvature. While it has been found that for most applications the natural plasma boundary curvature is effective, the use of a grid is still desirable in that it provides a definite boundary upon which initial calculations may be based. The accelerating lens formed by the plasma boundary and extraction electrode **38** brings the beam to a minimum diameter at some discrete distance beyond the source and this distance may be varied by altering the plasma boundary curvature, the accelerating field configuration, or the aperture size. By way of example, it has been found that, by allowing the plasma from source exit aperture **36** to expand to greater than 3 cm. in diameter ($d_6$) prior to extraction, the space charge forces which disrupt the beam directivity at its inception are reduced by two or three orders of magnitude.

There has thus been divulged, in relation to an ion source, novel structure, together with design criteria and formulas adapted to provide a new and improved device whereby the several objects of my invention are accomplished. While many variations of structure and application may occur to those skilled in the art, such variations as fall within the spirit and scope of my invention are deemed to be included therein, the extent of said invention being limited and defined by the appended claims only.

I claim:

**1.** An ion source comprising an ionization chamber, means for supplying thereto a quantity of gas to be ionized, means for ionizing said gas, an evacuated plasma forming chamber, an apertured anode member, said anode member comprising a common partition between said ionization chamber and said plasma forming chamber, said anode member having an aperture therein of a size commensurate to the ion beam current requirements of said ion source, a plasma control electrode at the potential of said anode member, an extractor electrode at a high potential with respect to that of said anode member, said plasma control electrode being in operable relationship with and spaced apart from said anode member, said space therebetween being sufficient to form a region free of the influence of the extractor electrode for a distance over which the diffusion of the plasma permits expansion of the plasma to the size considered desirable for ion extraction therefrom, said plasma control electrode having an aperture therein, said aperture being large with respect to said anode aperture and axially aligned therewith, said plasma control electrode aperture being adapted to provide optimum ion beam divergence, and a focussing electrode.

**2.** In an ion source having a gas ionization chamber and an evacuated plasma forming chamber, plasma control means comprising, in combination, an anode, said anode constituting a common partition between said ionization chamber and said plasma forming chamber and having an aperture therein adapted to communicate a controlled quantity of ions therebetween, and a plasma control electrode at the potential of said anode member, an extractor electrode at a high potential with respect to that of said anode member, said plasma control member being in operable relationship with said anode, said plasma control electrode being spaced relative to said anode by an amount sufficient to form a region free of the influence of the extractor electrode for a distance over which the diffusion of the plasma permits expansion of the plasma to the size considered desirable for ion extraction therefrom, said plasma control electrode having an aperture adapted to provide optimum divergence characteristics of an ion beam passing therethrough.

**3.** An ion source comprising an ionization chamber, means for supplying thereto a quantity of gas to be ionized, means for ionizing said gas, an evacuated plasma forming chamber, an apertured anode member, an extractor electrode at a high potential with respect to that of said anode member, said anode member comprising a common partition between said ionization chamber and said evacuated plasma forming chamber, said anode member having an aperture therein of a size commensurate to the ion beam current requirements of said ion source, said ion source producing a concentration of ions at said aperture sufficiently great so that there would be a tendency for space charge repulsion to produce a highly divergent beam upon extraction of positive ions at that point,



a cylindrical member contiguous to and coaxially aligned with the aperture in said anode member and protruding into said ion beam forming chamber, said cylindrical member being at the same electrical potential as that of said anode member and being of sufficient length to form a region free of influence of the field effect of the extractor electrode until such time as said plasma has diffused to a sufficient extent to reduce space charge effects in the ion beam to be extracted therefrom, said cylindrical member thus providing a drift space adapted to allow expansion of plasma passing therethrough and having a diameter adapted to provide optimum divergence of the ion beam emanating therefrom, and a focussing electrode.

**4.** An ion source as defined in claim **3** including a plasma boundary forming grid disposed across said cylindrical member.

**5.** In an ion source having a gas ionization chamber and an evacuated plasma forming chamber, plasma control means comprising an anode, an extractor electrode at a high potential with respect to that of said anode, said anode constituting a common partition between said ionization chamber and said plasma forming chamber and having an aperture therein adapted to communicate a controlled quantity of ions therebetween, said ion source producing a concentration of ions at said aperture sufficiently great so that there would be a tendency for space charge repulsion to produce a highly divergent beam upon extraction of positive ions at that point, and an annular member contiguous thereto disposed in concentric relationship to said aperture, said annular member being at the same electrical potential as that of said anode and being of sufficient length to form a region free of influence of the field effect of the extractor electrode until such time as said plasma has diffused to a sufficient extent to reduce space charge effects in the ion beam to be extracted therefrom, said annular member thus providing a drift space and exit aperture for said plasma and having a geometry adapted to provide optimum divergence characteristics of an ion beam emanating therefrom.

**6.** Plasma control means as defined in claim **5** including a plasma boundary forming grid disposed across said annular member.


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