United States Patent

Post

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[54] ION SOURCE WITH MOSAIC ION EXTRACTION MEANS

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[51] **Int. Cl.** **H05h 1/00**

[58] **Field of Search** 315/111; 313/63, 231, 230

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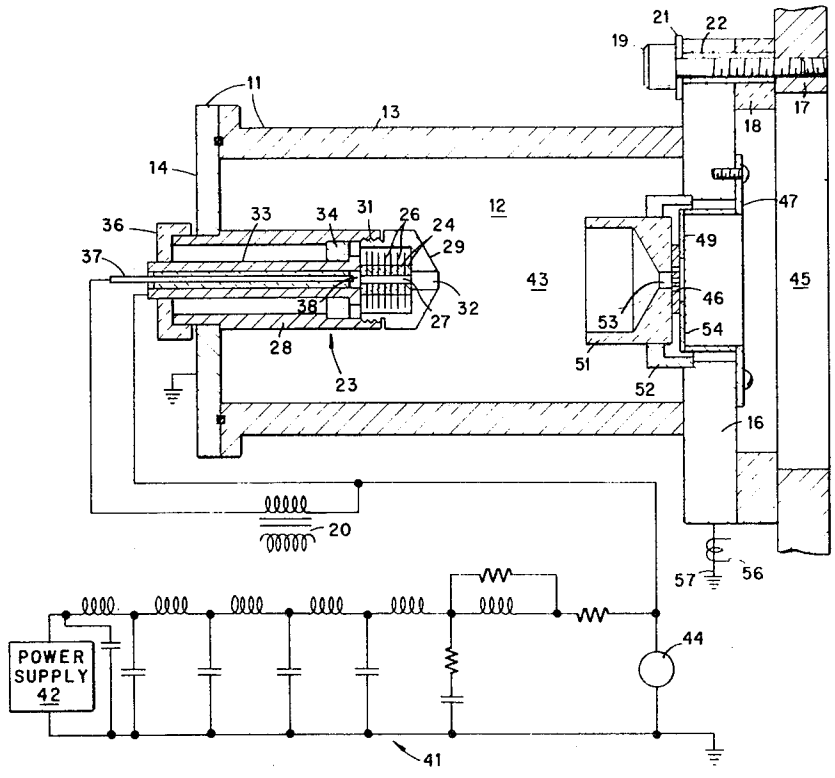
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[57] **ABSTRACT**

An ion source including means for producing a directed stream of ionized gas or plasma wherein a polycellular channeled mosaic element is positioned to transect the path traversed by the plasma so that a potential sheath is established in the plasma. The channel diameter is made less than the Debye length of the ions in the plasma wherefor the ions are accelerated out of the plasma, pass through the channels of the mosaic element and emerge as an ion beam on the other side of the matrix.

7 Claims, 2 Drawing Figures



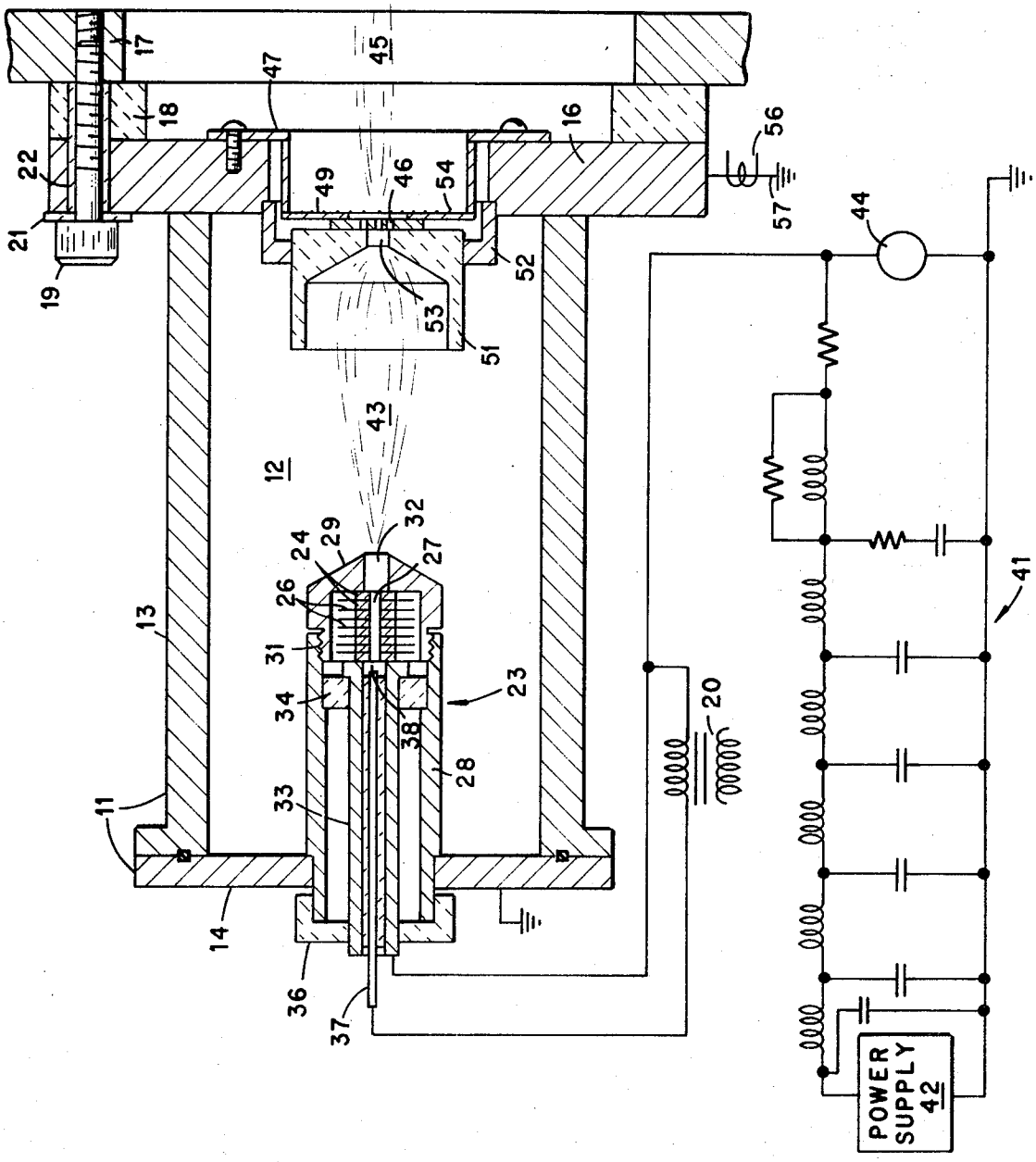


Fig. 1

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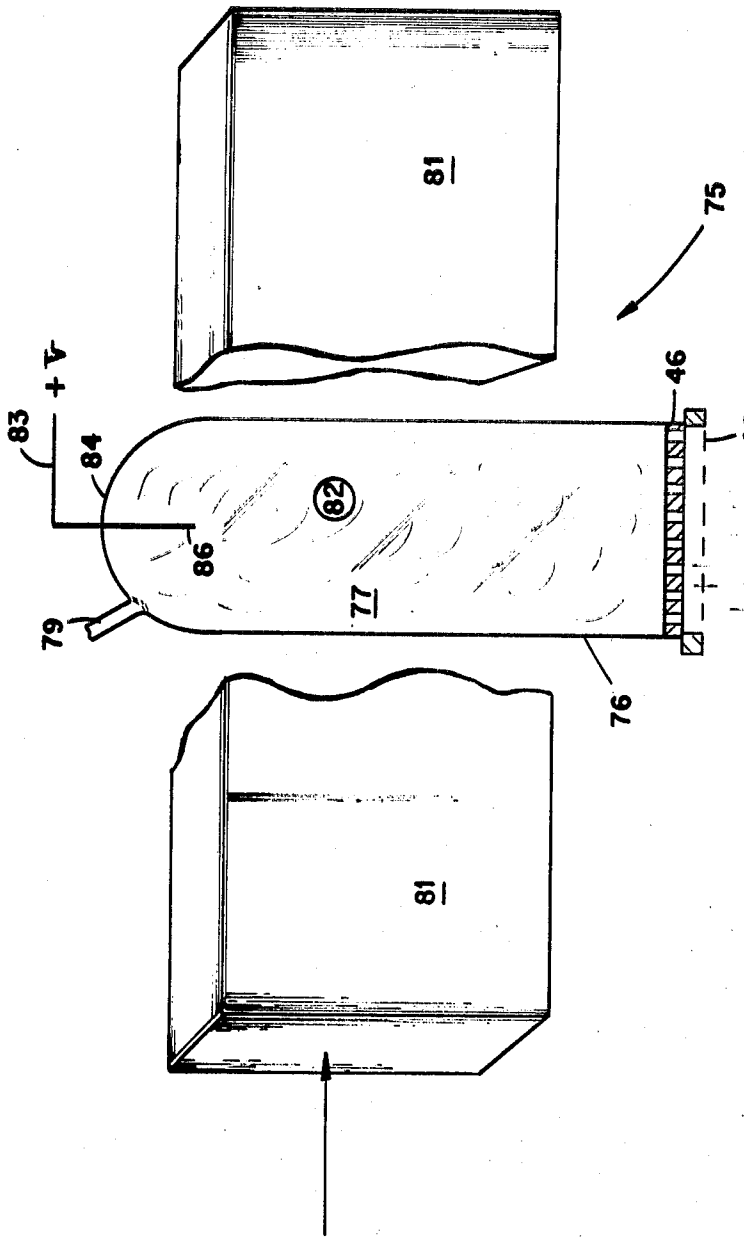


Fig. 2

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ION SOURCE WITH MOSAIC ION EXTRACTION MEANS

BACKGROUND OF THE INVENTION

The invention disclosed herein was made under or in the course of Contract No. W-7405-ENG-48 with the United States Atomic Energy Commission.

Ion sources for producing beams of ions used, e.g., in various types of energetic particle devices such as particle accelerators, ion bombardment devices, controlled fusion reactors, etc., generally employ electrically biased extractor electrodes for separating ions from a plasma to form the ion beam. Occluded gas ion sources of this type are described in "Controlled Thermonuclear Reactions," Glasstone and Lovberg, D. Van Nostrand Company, Inc., 1960, beginning at page 145. In these as well as in other types of ion sources the ions are extracted from relatively large orifices or surfaces of a plasma body of relatively large dimension and extraction is obtained by electrostatic attraction which often requires the application of relatively high potentials. Difficulties ensue due to electrical discharges between the electrodes, disruption of the plasma and the structures are complicated by the geometries required.

SUMMARY OF THE INVENTION

The invention relates, in general, to the production of ion beams for use in various charged particle devices and, more particularly, to an ion source wherein extraction of ions from a plasma body is accomplished by means of a passive mosaic element, defining a plurality of critically dimensioned cellular channels, disposed in proximity to the plasma body.

An ion source suitable for practice of the invention includes a means for producing a defined body of plasma generally in accord with various means well-known in the art. Such means usually include a means for supplying a suitable gas together with means for ionizing and heating the gas to provide the plasma body. One such suitable plasma producing means is that utilized in the above-referenced occluded gas ion source, i.e., an arrangement of hydrided metallic elements across which an electrical discharge is applied to release and ionize hydrogen gas to form the plasma. Other suitable devices may produce a plasma by instituting a continuous or pulsed electrical discharge in a suitable gas, for example, between electrodes positioned therein, by means of radio frequency energy applied thereto, or the like. Usually the plasma will be produced in a chamber defined by enclosure wall surfaces. Moreover, the plasma body may be constrained within a magnetic field as discussed more fully hereinafter.

For extraction of ions from such a plasma body, in accordance with the invention, a porous mosaic element formed of either insulating or conductive material is placed in proximity to the plasma, for example, as a portion of the enclosure wall, at a location from which extraction of the ions is desired. For effective extraction to occur, certain critical conditions must be satisfied. The mosaic element should define a large plurality of reasonably uniform diameter capillary channels passing in substantially straight line relation therethrough. Various polycellular or honeycomb type materials are satisfactorily provided that the channel diameter is smaller than the Debye length of the plasma. Furthermore, the plasma body dimensions must be at least one order of magnitude and preferably at least several orders of magnitude greater in extent that the Debye length thereof.

With these conditions satisfied a potential sheath is produced in the plasma as if the porous mosaic element was a solid wall similar to the remainder of the enclosure. The potential sheath is of a polarity and the potential thereacross is of a magnitude sufficient to accelerate positively charged ions out of the plasma body. The ions having a velocity vector sufficiently parallel to the axis of the mosaic channels pass therethrough to emerge on the opposite side of the mosaic element as an ion current or ion beam.

If the first condition noted above is not satisfied, i.e., if the channel diameter exceeds the Debye length the potential sheath necessary to effect extraction of the ions will not form as if the capillary channels were not present. If the second condition is not satisfied a true and appropriate plasma body will not be present.

Accordingly it is an object of the invention to provide an ion source in which extraction of ions from a plasma body is effected without the use of electrically energized extraction electrodes.

Another object of the invention is to provide an ion source including means for producing a confined plasma body wherein extraction of ions from the plasma body is effected by means of a passive channeled mosaic element disposed in proximity to the plasma.

Still another object of the invention is to provide an ion source including means for producing a plasma body wherein a mosaic element is disposed with one surface thereof in proximity to the plasma body, said mosaic element having a plurality of straight line capillary channels formed therein, which channels have a diameter less than the Debye length of the plasma so that a potential sheath is developed in the plasma effective to accelerate and extract ions therefrom to pass through said channels to provide an ion beam emerging at a second surface of said element.

Other objects and advantageous features of the invention will be apparent in the following description and accompanying drawing of which:

FIG. 1 is a longitudinal cross-sectional view of an ion source, utilizing a channeled mosaic element for extracting an ion beam in accordance with the invention; and

FIG. 2 is a schematic illustration of a second embodiment of the ion source of the invention.

DETAILED DESCRIPTION OF THE INVENTION

A plasma body such as that produced in the ion source of the invention is an electrically neutral collection of charged particles, i.e., a collective mass of electrons and positive ions in which the ions and electrons generally have a Maxwellian distribution in velocity space but in which the ion and electron temperature may be different. The ion temperature is generally less than or equal to the electron temperature, usually less. With a hydrogen plasma the random ion current is at most about one-fortieth of the random electron current [(mass electron/mass proton)$^{1/2}$ = 1/42.]

However, if such a plasma is confined within a container or enclosure with solid walls, the electron and ion currents reaching the boundary wall must be equal otherwise an absurdly high positive charge would be continuously built up in the plasma. The phenomenon that equalizes the ion and electron currents escaping from the plasma is termed "the plasma sheath." When the plasma is formed in the container more electrons than ions are initially lost resulting in the accummulation of a positive charge in the plasma which slows escape of electrons and accelerates loss of positive ions until the escape currents are equal. The main effect is to reduce the electron current.

The magnitude of the potential difference between the plasma body and the wall, "the sheath potential drop" is of the order of a few times kTe/e. This potential drop occurs over a characteristic distance which is of the order of the Debye length which is defined as follows:

$\lambda^D = (kTe/4\pi ne^2)^{1/2}$ (cgs units) wherein Te is the electron temperature in °K, ne is the electron density, k is the Boltzman Constant and e is the electron charge. Substituting numerical values:

$\lambda_D = 6.9\,(Te/ne)^{1/2}$cm

The Debye length is a measure of the distance into the plasma wherein variations in the potential can occur.

Now it may be noted that, if a section of wall having openings therein extending normal to the plasma surface is substituted for a solid section of the plasma container wall, a potential sheath forms in the plasma in proximity thereto as long as the openings or pores in the wall section are smaller

than the Debye length of the plasma. Ions are accelerated out of the plasma by such potential and impinge upon the wall and enter the openings therein. Provided that the openings are in the form of straight channels extending through the wall section, ions having a sufficiently large velocity vector parallel to the axis of said channels will pass therethrough and appear as an ion beam on the opposite side thereof. With a plasma having a density of the order of 10^{12} particles/cc, the requisite channel diameter is of the order of 10 microns. With lower density plasmas, the Debye length is larger, and a larger channel size can be used. Generally speaking, channel sizes of less than about 50 microns can be used and the porous wall section can be conveniently provided as a mosaic element.

The transmitted particle beam comprises accelerated ions and decelerated electrons. A important advantage to be gained by use of a porous wall section, i.e., the mosaic element for extracting the ions is evidenced by the following consideration. Any device that is used to a accelerate charged particles incurs the limitations imposed by the Child-Langmuir Law (c.f. "Electric Phenomena in Gases" Papoular, R. Iliffe Books, Ltd., London 1965, p. 102) which gives the maximum current density, j_m, that can be accelerated by a potential difference, V, between two grids a distance, d, apart, as follows:

$$j_m = \frac{1}{9\pi}\left(\frac{2e}{m}\right)^{1/2}\frac{V^{3/2}}{d^2}$$

where m = mass of the ion.

By using the mosaic element to create a sheath potential for accelerating ions out of the plasma body, the distance over which acceleration occurs is of the order of the Debye length which is a very small distance, of the order of up to a few tens of microns in a relatively dense plasma, i.e., with a density of the order of 10^{12} particles/cc. With denser plasmas the distance, d, is even shorter. Accordingly, an ion beam of high current density can be produced even with a sheath potential of a few volts using such a mosaic element. The limit would be the ion current reaching the walls of the container and the transmissivity of the matrix element. A preponderance of ions pass through the element. The energy thereof will depend on the sheath potential as well as the initial kinetic energy of the particle in the plasma. Various means are known in the art for increasing such a sheath potential and accordingly the ion energy of the emergent ion beam may range upwardly from a few electron volts determined by the kinetic energy (temperature) of the ions in the plasma added to the energy supplied by the sheath potential. The ion current emerging from the mosaic element may reach densities at which charged particle repulsion causes the beam to "blow up" in which case low energy electrons may be introduced for space charge neutralization to offset the repulsive forces. Current densities of the order of about 0.1 to above about 1.0 amps sq cm may easily be obtained.

DESCRIPTION OF AN EMBODIMENT

An ion source utilizing an occluded gas source means for producing a plasma from which ions are extracted to form an ion beam in accordance with the teachings of the invention is illustrated in the FIG. 1 of the drawing. As illustrated therein the ion source is constructed within a generally cylindrical housing **11** defined an evacuable chamber **12**. Housing **11** may be constructed with a cylindrical section **13** of stainless steel, glass, ceramic or other tubing material suitable for vacuum service and with a hermetically sealed cover plate **14** attached, e.g., by flanges or the like to one end of section **13**. The other end of cylindrical section **13** may be provided with an annular base plate **16**, i.e., centrally apertured plate **16**, which can serve as means for attaching the ion source in vacuum tight relation to a part of a vacuum housing **17** of a device, e.g., particle accelerator, fusion reactor, etc., in which the ion beam is to be employed. While such source mounting plate might be attached directly to housing **17**, in order to facilitate making certain measurements, an electrically insulated mounting may be used. For this purpose, an annular member **18**, of insulating material, e.g., polymerized acrylic resin or the like, is interposed between plate **16** and housing **17** and the plate **16** is attached thereto by means of flange bolts **19** insulated from plate **16** by means of a washer **21** and an insulating sleeve **22**.

The occluded gas plasma source **23** used herein, is generally constructed with an assembly comprising a plurality of annular metallic washers **24** interleaved with and separated by means of thin insulating annular washers **26**, typically of mica and of larger diameter, stacked and arranged concentrically along an axial passage **27**. With this arrangement a series of gaps exist between the inner margins of the washers extending across the inner margin of the intervening mica washer. The aforesaid stack assembly may be disposed within a mounting housing including a metallic cylindrical body portion **28** and a conical nozzle cap portion **29** affixed thereto, e.g., by a threaded joint **31**. Conical cap portion **29** is provided with an orifice **32** axially aligned with channel **27** of the washer assembly and is in direct electrical contact with a washer **24** at one end of said assembly. Support for the opposite end of said washer assembly is provided by means of a tubular conductor **33**, retained concentrically within the cylindrical body portion **28**, by an annular insulating member **34** fitted into a stepped portion of the interior wall of body portion **28**. The interior end of conductor **33** abuts in direct contact with a washer **24** at the second end of the stacked washer assembly while the second end of conductor **33** projects beyond the free end of cylindrical body **28**. An insulating sealed cap **36** affixed to the free end of body **28** may be used to support the conductor **33** thereat.

The metallic washers **24** comprise a metal such as titanium or zirconium which have been treated to occlude a large amount of a gas such as hydrogen, deuterium, tritium, etc., from which it is desired to produce a suitable ion beam. More specifically, the titanium washers may be heated in high vacuum to outgas impurities therein and then contacted, e.g., with H_2, D_2, etc., at an elevated temperature to initiate a hydriding reaction therewith. Details of such a preparation are disclosed, for example, in Report No. UCRL-4496, issued by the University of California Radiation Laboratory, abstracted in Nuclear Scientific Abstracts, Aug. 31, 1955.

The plasma source **23** also includes a trigger electrode **37** disposed in insulated sealed relation within conductor **33** having an inner end disposed in proximity to the inner end of conductor **33** and the washer **24** abutting therewith and defining a spark gap **38** therebetween. A pulse power source is connected across the stacked washer assembly to furnish power for generating the plasma. Such a power source may comprise a pulse line **41** comprising a series of capacitors connected to a tapped inductor and including damping and current limiting resistors as in conventional practice. A direct current power supply **42** is connected to one end of the pulse line while the other end of the pulse line is connected between conductor **33** and the grounded mounted housing of the plasma source to establish a suitable potential across the stacked washer assembly. A means for generating a spark discharge across spark gap **38** is provided to initiate a discharge of pulse line **41** along the series of gaps between the washers in axial passage **27**. Such means may comprise a pulse transformer **20** having the secondary connected between conductor **33** and electrode **37**. A trigger pulse applied from a trigger generator (not shown) to the primary of said pulse transformer will then produce a spark discharge across gap **38** which discharge will initiate discharge of the pulse line energy across the washer gaps as noted above. Such a discharge causes gas to be released from the metallic washers **24** to be ionized and heated and be ejected from passage **27** through orifice **32** axially along housing section **13**, to form plasma body **43** therein. The plasma of body **43**, with a hydride source will generally comprise H^+ ions, electrons and a substantial proportion, e.g., 50 percent of Ti^+ ions. Flow of pulse current from pulse line **41** can be

terminated, for example, by short circuiting the output therefrom as by means of a triggered ignitron **44** or other switch connected across the output of the pulse line. A substantially square wave pulse of selected duration can then be applied to such source. Voltages in the range of a few KV to at least 20 KV can be employed with such a pulse line.

For purpose of extracting ions from plasma body **43** a mosaic element **46** is disposed to intercept or otherwise be disposed to be in closed proximity to plasma body **43**. The matrix element **46** may be formed of any material suitable for vacuum service and it may be either conductive or non-conductive. Suitable materials include glass, ceramic, metals such as stainless steel, nickel, etc. The element may take the form of a planar disk plate, as shown, or it may be a curved section corresponding to a cylindrical or spherical plasma body, or any other suitable shape. The element must be provided with a large plurality of very small channels, preferably, substantially parallel straight line channels transpiercing the mosaic element. The element is arranged preferably with such channels aligned with the path of the ions leaving plasma body **43**.

In the event that magnetic field, supplied, e.g., by solenoids wound about vessel section **13**, is used to combine or guide the plasma, the channels must also be aligned with the magnetic field line guiding centers for effective extraction to occur. Generally speaking the channel diameter must be below about 50 microns and usually below about 25–30 microns dependent, as indicated above, on the Debye length of the particular plasma. With particle densities of the order of 10^{12} particles/cc, channel diameters of the order of 10–15 microns or smaller yield satisfactory or superior results and are preferred. Such element extracts ions from the plasma body **43** to form a beam **45**, e.g., of H^+ ions emergent from the opposite side to enter housing **17**.

One highly satisfactory mosaic element formed of a material, commercially available, comprises a glass Pyrex) element which on microscopic examination can be seen to be a polycellular or honeycomb mosaic in which the capillary channel walls have a hexagonal thin wall configuration leaving at least about 50 percent open channel space. Disks of such material having channel sizes such as 10 and 25 microns diameter are available. Versions having a metallic plating on one or both sides are also available and are suitable. Similarly suitable metallic polycellular mosaic materials can also be made as disclosed in U.S. Pat. No. 3,222,144 issued Dec. 7, 1965 to Donald E. Davenport. A thin matrix element is generally preferred since the shorter the channel length the higher the ion beam transmissivity, due to improved geometry, yielding larger ion currents. The current output can also be increased by increasing the ratio of open channel area present, by increasing the incident particle energy and by reducing the radial energy of the particles, i.e., the ratio of rotational energy to translational energy. The probability (Po) of passage through the channel of a particle at the center of the channel is $P(o) = \frac{1}{2}(Vz/Vr)^2 (R/L)^2$ where Vz = translational velocity along capillary axis, Vr = velocity transverse to axis, L = length of channel and R = radius of channel. Matrix elements of the order of 0.025 **inch thick for a** 25 micron hole size and 0.010 inch thick for a 10 micron hole size or less are satisfactory.

The mosaic element **46** may be mounted, for example, by means of a cup-shaped alumina mounting holder **47** secured to the base plate **16**, transverse to the axis of vessel **13** within the aperture defined by the annular base plate **16**. The bottom **49** of means **47** is apertured centrally and mosaic element is disposed to cover said aperture in bottom **49** of means **47**. The mosaic element **46** may be retained in position by a funnel-shaped guide element **51** secured to plate **16** by a mounting ring **52**, or by any other suitable retaining means. The walls of element **51** coverage on an axial aperture **53** therein which defines an area of mosaic **46** toward which the plasma body approaches or is in proximity to.

In usual applications, evacuation of chamber **12** may be provided by communication through the channels of the mosaic element to the region within vacuum housing **17** evacuated with the vacuum pump means (not shown) as customarily utilized. However, for other purposes, e.g., when making measurements of performance, etc., the housing **17** can be a vacuum tank evacuated to below 10^{-6} to 10^{-7} mm Hg or lower by a vacuum pump (not shown). In such a case current deposited on the mosaic element **46**, guide element **51** or grid **54** may be measured by a current detecting loop (, i.e., a bug) **56** disposed about a ground lead **57** connected to plate **16**. Collector grids, double probe detector means or the like may be provided in housing **17** to measure ion currents and other effects as in conventional practice. However when utilized as an ion source, e.g., in an accelerator, etc., plate **16** may merely be grounded.

Typical constructional details and operating parameters for such an ion source are set forth in the following illustrative example:

EXAMPLE

Vessel section **13**, 2 inches I.D. Pyrex glass tubing, 6 inches long

Source **10** hydrided titanium washers ¼ inch O.D. 3/32 inches I.D. ca. 1 mm thick

Pulse line: six 8.5 microfarad capacitors distributed along a 210 micro henry induction coil

Typical pulse lengths 5–175 microseconds

Charging voltage across pulse line 2 KV to 15 KV

Arc voltage drop across washer stack ca. 100 v. Evacuation pressure down to 5×10^{-7} mm Hg.

Source to mosaic spacing ca. 8 cm

Mosaic glass hexagonal channel 25 micron hole diameter 0.025 inch thick 10 micron hole diameter 0.010 inch thick (Gold plated bothsides and unplated)

Current density at least about 0.10 to 1.0 amp/cm^2

Plasma ion energy mean ca 1 ev

Ion energy (H^+) in ion beam about 50–150 ev

Results indicated that at 5 KV charge, productive of a higher density plasma, more current passed through the 10 micron mosaic than through the 25 micron mosaic. This is because the Debye length of such a plasma is about 25 microns and the 25 micron mosaic tends to defocus the plasma surface. With a 10 micron mosaic the plasma sheath forms much more evenly. With a 3 KV charge, the density is less and the Debye length longer so that defocussing no longer occurs. Moreover, in the first mentioned case the electron current is about five times as large as the ion current using the 25 micron mosaic. With the 10 micron mosaic, ion and electron currents are about equivalent.

DESCRIPTION OF A SECOND EMBODIMENT

A second embodiment **75** of an ion source in accordance with the invention as illustrated in FIG. **2** is constructed with a tubular microwave permeable vacuum vessel **76** constructed, e.g., of ceramic or glass defining a chamber **77** therein. A mosaic element **49**, of the character described is disposed across the open end of such vessel **76** together with a grid **49**, as above. A conduit **79** may be used to supply a gas, e.g., hydrogen, deuterium, tritium, helium, etc., at the desired density to chamber **77**. The vessel **76** may be disposed within a waveguide **81** coupled to a microwave energy source (not shown) for application of microwave energy of a suitable frequency and at an appropriate level to ionize and heat the gas in chamber **77** to produce a plasma body **82** therein. To regulate the plasma potential an electrode **83**, e.g., of tungsten, etc., may be passed in sealed relation through the closed end **84** of vessel **76** with the inner end **86** thereof disposed in plasma body **82**. A positive potential, $\sqrt{+}$, applied from a D.C. power supply (not shown) applied to electrode **83** will regulate the plasma potential and thereby control the energy $\sqrt{}$ of ions emerging through mosaic **46** in ion beam **87**.

Certain relationships may be used to determine the operating parameters for such an ion source as follows:

The plasma frequency

$f_{plasma} = f\mu\lambda = 9\times10^3 \sqrt{ne}$ = frequency of microwave power to be applied. (Ne = plasma density particles/cc.) For exam-

ple, with $ne = 10^{12}$ particles/cc, $f\mu\lambda = 9\times10^{9}$ and $\lambda \cong 3$ cm microwaves $\sqrt{+}$ may be varied over a considerable range, e.g., up to at least to several hundred volts giving equivalent ion energies.

While there have been described in the foregoing what may be considered to a preferred embodiments of the invention, modifications may be made therein without departing from the teachings and scope of the invention and it is intended to cover all such as fall within the scope of the appended claims.

What I claim is:

1. An ion source comprising:

plasma source means including a stack of interleaved metallic annular and insulating material washers defining an axial channel therein, said metallic washers having a material selected from the group consisting of hydrogen, deuterium and tritium occluded thereon, and means for creating an electrical discharge between portions of said washer members within said channel so as to release, ionize and heat said occluded gas to generate a heated plasma stream containing electrons and ions which is ejected axially from said channel;

funnel guide element means including walls converging toward a central aperture which is axially aligned with said channel and arranged to collect and direct said plasma stream toward said central aperture; and

means including a substantially planar mosaic disk element disposed transversely across said aperture, said mosaic element defining a plurality of straight line channels substantially in alignment with the axil flow vector of said plasma stream through said aperture with the diameter of said channels being less then the Debye length of said plasma stream so that a plasma sheath potential is developed in the plasma in proximity to said mosaic element whereby electrons therein are decelerated and ions are accelerated therefrom at an energy above their initial kinetic energy in the plasma stream to pass through the channels in said mosaic element to form an energetic ion beam emergent therefrom.

2. Apparatus as defined in claim 1 wherein said plasma has a density of at least about 10^{12} particles/cc providing a Debye length below about 25 microns and wherein said channels have a diameter less than about 25 microns in magnitude.

3. Apparatus as defined in claim 2 wherein said plasma source means further includes a cylindrical housing disposed in insulated relation about said stack of interleaved washers said housing having a conical cup portion defining an orifice axially aligned with said channel through which said plasma stream is directed and wherein said metallic washers are formed of a material selected from the group consisting of titanium and zirconium.

4. Apparatus as defined in claim 3 further including a vacuum housing defining an evacuable chamber said housing including a central section to one end of which is attached to cover plate centrally apertured to receive and support said plasma source housing and to the opposite end of which is attached a base plate centrally apertured to receive and support said guide element means with the aperture in axial alignment with the washer stack channel as well as to support said means including said mosaic element with the channels thereof in axial alignment with the aperture of the guide element.

5. Apparatus as defined in claim 4 wherein said mosaic element comprises a disk of glass material, said glass material being disposed in a honeycomb configuration with thin wall portions defining said plurality of straight line channels, said straight line channels being in substantially parallel alignment.

6. Apparatus as defined in claim 4 wherein a charging voltage in the range of about 2 kilovolts to about 15 kilovolts is applied across said washer stack by said means for creating a discharge between said washer members, wherefor the plasma ions have an energy in the range of about 50 to 150 electron volts, wherein the channels of said mosaic elements have a diameter in the range of about 25 microns to about 10 microns and a thickness in the range of about 0.025 inches to about 0.010 inches.

7. Apparatus as defined in claim 6 wherein said mosaic disk element is provided with a metallic plating or at least one side thereof.

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