

May 7, 1957

J. S. FOSTER, JR., ET AL
RADIO FREQUENCY ION PUMP

2,791,371

Filed Jan. 9, 1956

2 Sheets-Sheet 1

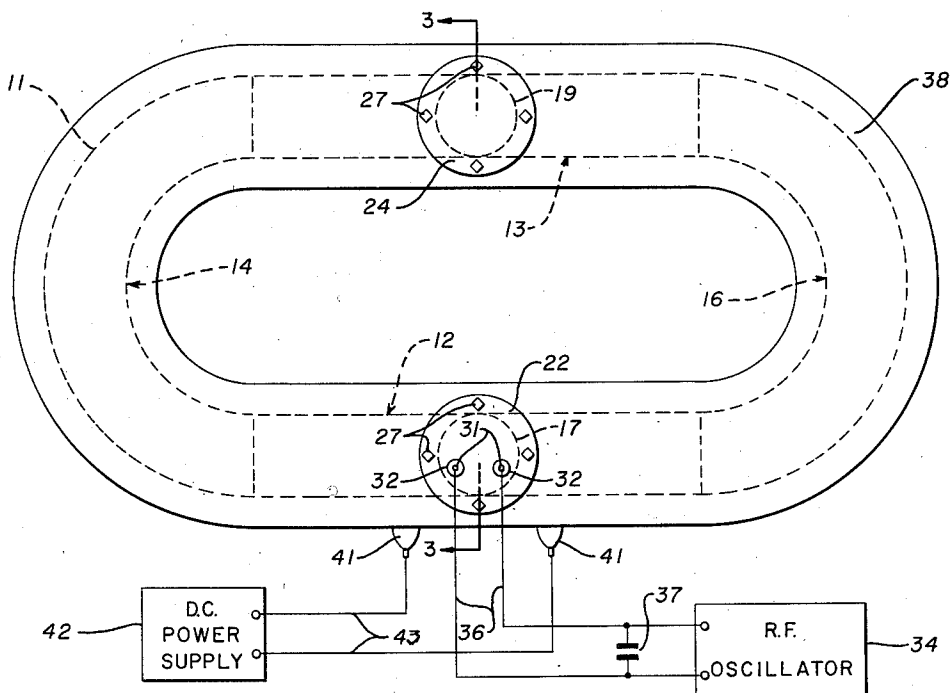


Fig. 1.

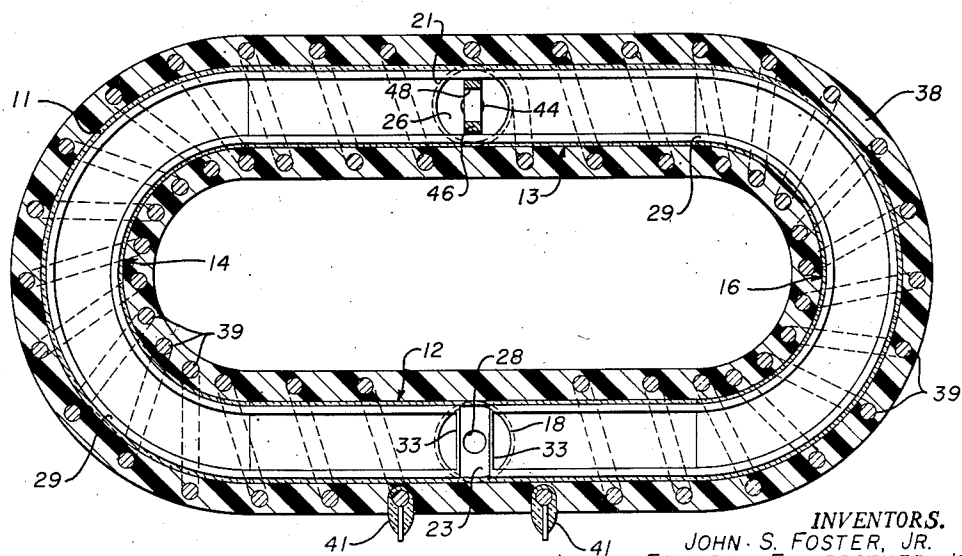


Fig. 2.

INVENTORS.
JOHN S. FOSTER, JR.
FORREST FAIRBROTHER, JR.
BY

Richard A. Anderson
ATTORNEY.

May 7, 1957

J. S. FOSTER, JR., ET AL

2,791,371

RADIO FREQUENCY ION PUMP

Filed Jan. 9, 1956

2 Sheets-Sheet 2

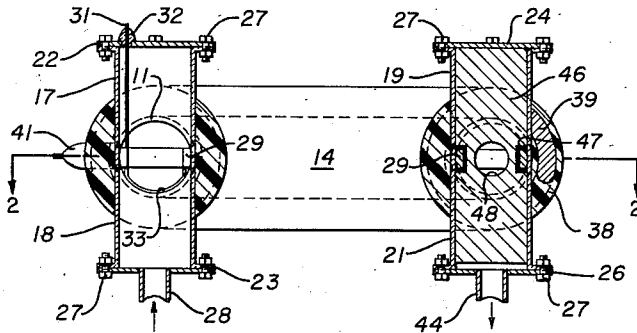


Fig. 3.

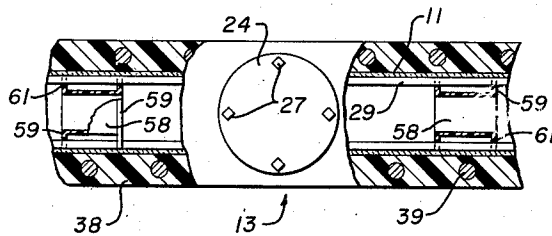


Fig. 5.

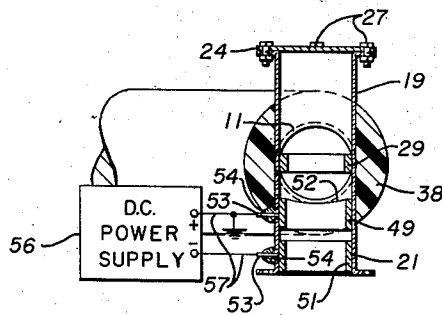


Fig. 4.

INVENTORS.
JOHN S. FOSTER, JR.
FORREST FAIRBROTHER, JR.
BY

Richard A. Anderson

ATTORNEY.

1

2,791,371

RADIO FREQUENCY ION PUMP

John S. Foster, Jr., and Forrest Fairbrother, Jr., Livermore, Calif., assignors to the United States of America as represented by the United States Atomic Energy Commission

Application January 9, 1956, Serial No. 558,173

19 Claims. (Cl. 230—69)

The present invention relates to the ionization and transport of molecules and/or charged particles in an evacuated system.

Devices employing the principle of ionizing gas molecules and transporting the ions so formed have a variety of diversified applications which are well known within the art. In ionic vacuum pumps, for instance, pumping action is provided by ionizing molecules of a gas to be evacuated and transporting the ions to an outlet region where they are neutralized thereby building up a gas pressure due to the accumulation of gas molecules therein. Evacuation means effective in this exit region then exhaust these molecules to the atmosphere, nearly all molecules of the gas to be evacuated being eventually exhausted in this manner. Conventional ionic vacuum pumps generally have an ionization chamber including a thermionic cathode to provide a source of electrons and an anode electrode for attracting electrons emitted by the cathode. Gas molecules appearing in the ionization chamber are ionized by impact of the electrons therewith as the electrons move from the cathode to the anode. The ionized molecules are attracted toward the cathode and tend to accumulate in the region thereof where they are neutralized, thereby building up a gas pressure at this point of the system sufficient to permit their removal by a mechanical vacuum pump.

One serious disadvantage with an ionic pump of the type described above is that the electrons traverse the gas-discharge path in the ionization chamber only once in their movement from cathode to anode. As a result there is a substantial number of electrons that do not strike gas molecules and, therefore do not contribute to the desired pumping action. Recent developments in ionic pumping techniques, however, have provided means for overcoming the foregoing limitation and consequently raising pumping speeds to a practical level. A particular device which advantageously incorporates many such recent developments has been disclosed in a copending application of Ernest O. Lawrence et al., Serial No. 333,928, filed January 29, 1953, which issued as U. S. Patent No. 2,726,805 on December 13, 1955. The latter device in general comprises means for establishing a magnetically collimated oscillating electron discharge between negatively charged electrodes and means for admitting gas to the center of the discharge whereby the gas is ionized to produce an arc plasma having a voltage gradient between the center and the ends thereof. The ionized gas thus travels in the arc plasma to the ends thereof, where it is neutralized at the electrodes and limiter or constriction tubes disposed about the arc adjacent each end electrode force gas diffusing back toward the inlet to pass through the arc where it is re-ionized and redelivered to the electrodes. The high electron current in the arc plasma is a very good ionizing agent in that nearly all of the electrons therein strike gas molecules so that large volumes of gas are ionized and, in addition, the arc plasma provides a unidirectional longitudinal path for ionized particles away from the arc center so that gas is removed therefrom and

2

delivered to the ends of the arc to produce a pumping action. Due to the relatively large degree of ionization effected in the above device as compared to that in previously related devices, far superior pumping speeds are achieved than had been theretofore realized. The referenced device overcomes many existing practical limitations and possesses advantages over prior art devices. However, such improved device is not easily adapted to continuous operation, since the life of the cathode is limited and must be frequently replaced.

The present invention provides a superior ionic pumping device capable of relatively continuous highly efficient operation. The ion pump of the present invention comprises means for establishing a radio frequency field within a substantially toroidal shaped low pressure envelope to excite free electrons normally occurring therein and thus establishing an oscillating electron discharge, magnetic field means collimating the electron discharge within the envelope, inlet means for admitting gas to the electron discharge whereby same is ionized to produce an arc plasma having voltage gradients symmetrically disposed along the electron discharge in the envelope bilaterally from the gas inlet, and gas outlet means disposed at a point in the envelope corresponding to a point along the arc plasma voltage gradient bearing opposite symmetry to the point of gas inlet. The arc plasma voltage gradient between the inlet and outlet means in either direction around the toroidal shaped envelope is therefore equal, thus the arc plasma provides a bifurcated path for ionized particles away from the inlet means to the outlet means where they may be neutralized and exhausted. Consequently, gas is removed from the inlet means and is delivered to the outlet means to produce a pumping action. Therefore, the present invention utilizes to great advantage the principle wherein free electrons existing in normal atmosphere excited by a radio frequency field to establish an electron discharge are effective in ionizing the admitted gas and to establish the necessary voltage gradient in the resultant plasma. The present invention, then, eliminates the thermionic cathode and hence overcomes the aforementioned limitations associated therewith as well as obtains other advantages.

Variously, the device of the present invention is useful for the ionization and transport of molecules and/or charged particles in a low pressure system. It is especially useful as an improved ionic vacuum pump capable of relatively long uninterrupted periods of very efficient operation, as an ion source device having utility as a source of charged particles for use in various instruments, and as a recycling means for exhausting and reinjecting gaseous materials in sundry particle acceleration devices.

Accordingly, it is an object of the present invention to provide improved methods and means of ionizing and transporting molecules and/or charged particles in a low pressure system.

It is another object of the invention to provide radio frequency means for ionizing a gas and transporting same as ions in a low pressure system.

A very important object of the present invention is to provide improved means for pumping gas utilizing a radio frequency field established in an axially symmetric magnetic field to ionize the gas and move same as ions to a remote point where the gas is neutralized and exhausted.

It is another object of the present invention to provide an improved ionic vacuum pump capable of long uninterrupted periods of operation.

It is still another object of the present invention to provide a radio frequency ion pump having a high pumping speed and capable of attaining a very high vacuum.

It is yet another object of the present invention to provide a radio frequency ion pump having means for

3

limiting return gas flow to the low pressure inlet region.

It is an important object of the present invention to provide a source of ions and electrons.

It is a further object of the present invention to provide means for reionizing and reinjecting particles into various and sundry particle acceleration devices.

The invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood by reference to the following specification taken in conjunction with the accompanying drawings, of which:

Figure 1 is a plan view of the ion pump of the present invention;

Figure 2 is a horizontal cross sectional view of the device taken along the plane 2—2 of Fig. 3;

Figure 3 is an elevational view partially in section taken along the line 3—3 of Fig. 1 and illustrating details of the intake and exhaust portions of the ion pump, as adapted to yield the exhausted gas in a molecular form;

Figure 4 is a vertical cross sectional view of exhaust portions of the ion pump as adapted to yield the exhausted gas in the form of accelerated ions, taken in similar relation to Fig. 1 as is Fig. 3; and

Figure 5 is a partial horizontal view, with portions broken away, illustrating a superior arrangement of exhaust portions of the ion pump of Fig. 1.

Briefly, the device of the invention with reference to the accompanying drawings may be seen to include a low pressure envelope having intake and exhaust regions joined by a bifurcated path. Gas which enters the intake region is ionized by radio frequency means forming an arc plasma along the said bifurcated path and magnetic collimating field means are employed to delineate the arc plasma into the axial region therein, whereby the ionized gas is transported from said intake to the exhaust portion of the envelope. Thereafter, the exhausted gas may be discharged in either a neutral gaseous or in an accelerated ionic form by modifications in the exhaust structure employed.

More explicitly, an evacuated envelope structure 11 of a preferred embodiment of the device of the invention is constructed, as shown in various figures of the drawing, with parallel linear tubular sections 12, 13 joined terminally by arcuate tubular sections 14, 16. The material of construction may be any magnetically pervious non-conductor which is suitable for vacuum service, e. g., boro-silicate glass or glazed ceramic. In order to facilitate construction and assembly as well as to accommodate intake region structure, one or more flanged openings are provided in the linear envelope section 12. These preferably take the form of flanged side arms 17 and 18 (see Fig. 3), which are axially aligned and project upwardly and downwardly, respectively, from the mid length region of the linear section 12. The intake region includes the space enclosed by the side arms 17 and 18 as well as the intervening space of the bore of envelope section 12.

Similarly, the exhaust or discharge region of the envelope 11 is constructed by providing flanged side arms 19 and 21 (see Fig. 3), axially aligned and projecting upwardly and downwardly, respectively, from the mid length region of linear envelope section 13. When so constructed the envelope 11 possesses bilateral symmetry about a transverse vertical plane which bisects either the linear or arcuate envelope sections. Moreover, there exists a first path from the intake region through the first half of linear section 12, arcuate section 14 and a half of section 13, connecting with the discharge region which is similar to a second path which includes the second half of section 12, arcuate envelope section 16 and the remaining half of section 13; i. e., a bifurcated path joins the intake and exhaust regions of the envelope.

Closure of the outwardly projecting intake side arms 17 and 18 and exhaust side arms 19 and 21 is effected by attaching coverplates 22, 23 and 24, 26, respectively, 75

4

thereto as by means of flange bolts 27 or other suitable clamping means. Such coverplates may be of either metallic, vitreous or ceramic material and conventional gasketing or sealing means (not shown) may be employed therewith to assure an adequate vacuum seal. Coverplate 22 or, preferably, coverplate 23, is perforated and adapted for attachment of a vacuum conduit 28 which is coupled with a gas source, e. g., a system to be evacuated. However, high pumping speeds and a more compact arrangement can often be obtained by dispensing with the coverplate 23 and attaching the side arm 18 directly to suitable flanged fittings provided in the vessel to be evacuated. Pumping speeds may be further increased for some applications by dispensing with the flanged intake side arms 17, 18 and incorporating the system to be evacuated as integral intake structure of the pump.

The oscillating electric field which is required to ionize the gas in envelope 11, by the excitation of stray electrons therein, may be applied by electrodes formed of a good conductor such as copper and disposed along said bifurcated path. More particularly, there is employed at least one loop electrode 29 (see Fig. 2) which is disposed adjacent the wall surfaces within the bore of envelope 11 and is collinear with said bifurcated path. The electrode 29 is made discontinuous in the intake region of the envelope whereby terminals are provided for the attachment of paired lead-in conductors 31 (see Figs. 1 and 3) which are vertically disposed in side arm 17 and lead exteriorly through insulated feed-through bushing vacuum seals 32 provided in coverplate 22 to terminate thereat in conventional connector terminals in the manner indicated in Fig. 3. In the event that more than one electrode 29 is employed, the additional electrodes are disposed in equidistant radially spaced relation and the ends are joined as by radial strap connectors 33 to form either a paralleled circuit, as shown in various figures of the drawings, or a transposed circuit. The electrodes 29 may be supported either by fused attachment to the bore walls of envelope 11 or by annular insulator spacers (not shown) radially disposed therein.

Energy supplied by a radio frequency oscillator 34 (see Fig. 1) is coupled by means of paired conductors 36 to the terminals of the bushings 32 whereby the electrodes 29 are energized. In operation the electrodes 29 constitute a resonant circuit having characteristics determined by the distributed inductance, capacitance and resistance thereof, as well as certain electrical characteristics of the ionized gaseous discharge established. The electrode characteristics may be fortuitously chosen to provide the proper operating frequency. However, a capacitor 37 shunted across either the oscillator 34 terminals or the terminals of bushings 32 may be employed to adjust the resonant frequency to the proper value. It will be appreciated that maximum efficiency will be obtained when the resonant frequency of the load of electrodes 29 and the gaseous discharge is equivalent to that of oscillator 34.

The magnetic collimating field which is required to restrict ionized gaseous particles produced within the envelope 11, as described in more detail hereinafter, to the central axial region of the envelope, is applied by a generally continuous solenoid 38 disposed coaxially with respect to the longitudinal axis of said envelope such that a substantially axially symmetric magnetic field is established longitudinally therethrough. More particularly, such solenoid 38 is provided as at least one continuous conductor 39 wound in the form of a helix coaxial with the longitudinal axis of the envelope 11 and disposed in equidistant radially spaced relation with respect to the periphery thereof. The longitudinal spacing between adjacent turns of the helix is made generally constant except in the intake and exhaust regions of the envelope where such spacing may be advantageously increased for purposes of providing relatively less intense magnetic field portions within such regions. The helix

5

is insulated and secured to the periphery of the envelope by any one of well known conventional methods; e. g., wrapping each turn of the helix with magnetically pervious electrical insulating tape and then applying and securing the conductor to form a helix structure about the periphery of the envelope, or, preferably, laminating the helix with an appropriate electrical insulating material such as fiber glass and establishing a bond between such insulated helix and the envelope with a suitable thermosetting plastic material, such as epoxy resin.

The conductor 39 of solenoid 38 is made discontinuous in the intake region of envelope 11 for the provision of electrical connector terminals to permit energization of solenoid 38 by a suitable source of external power. The ends of the conductor are conventionally attached, as by soldering, to insulated connector terminal lugs 41 which lead exteriorly through the insulating material encompassing the helically wound conductor. It is to be appreciated that in order for the magnetic field in the intake region to be continuous, the terminal ends of conductor 39 must be oriented such that each is the termination of a different one of diametrically opposed portions of adjacent turns of the helix (e. g., if one terminal end is the termination of an upper turn portion, the other terminal end must be the termination of a lower turn portion). The solenoid 38 is then suitably energized by coupling a conventional D. C. power supply 42 to the terminals of said connector lugs 41, by means of paired conductors 43.

Gas which is transported from the intake region to the discharge or outlet region of the ion pump as described more fully hereinafter, can be exhausted or extracted from the pump outlet region in either a normal gas or ionized gaseous form. For purposes of describing the outlet region structure it suffices to state that the gas molecules being exhausted will enter the outlet region situated between side arms 19 and 21, from the envelope 11, in an ionized form (i. e., as a plasma) wherein the individual particles are directed along helical paths centered about magnetic lines of force established by the solenoid 38, i. e., with the ion paths having an axis which is generally parallel to the longitudinal axis of said envelope.

In the event that it is desired to discharge the exhaust gas in the ordinary gaseous form (e. g., when the device is used as a vacuum pump) means for electrically neutralizing the ionized gaseous exhaust material is provided in the outlet region, whereby the ionized material is converted to the ordinary gaseous form and is thenceforth exhausted by auxiliary vacuum pump means (not shown). Preferred structure for accomplishing this purpose is illustrated in Figs. 1, 2, and 3 of the drawings. As illustrated therein, the coverplate 26 of side arm 21 is adapted to receive a vacuum conduit 44 connected to a conventional vacuum pump (not shown) which is capable of establishing a vacuum of forevac or "roughing" vacuum dimensions.

An electrically conducting collector electrode 46 is disposed in the outlet region of envelope 11 (i. e., the space enclosed by side arms 19, 21 as well as the intervening space of the bore of envelope section 13) transverse with the longitudinal axis of the envelope. Electrode 46 is formed as a rectangular block or plate of metal having one side dimension substantially equal to the diameter, and the other side dimension substantially equal to the combined overall length, respectively, of side arms 19 and 21 so as to partition the outer region of envelope 11 into two equal portions. Such electrode is supported by rigid insulated attachment to coverplate 24. Insulated slots 47 (see Fig. 3) are employed to permit traversal of electrode 46 by radio frequency loop electrodes 29.

A central circular bore 48 is provided in electrode 46 coaxial with the longitudinal axis of the bore of envelope 11. The diameter of bore 48 is made slightly less than the diameter of the arc plasma emerging from

6

the bore of envelope 11. Consequently, the outer annular portion of the plasma traversing the envelope bore is intercepted by the collector electrode 46, the remaining portions of the plasma traversing bore 48 uninterrupted. Since collector electrode 46 is thus subjected to intensive ion bombardment, a material such as tungsten, stainless steel, etc., which is resistant to erosion under these conditions is implied in the construction thereof.

For the purpose of the invention, electrode 46 is grounded or may be allowed to "float" electrically, or maintained at a negative potential with respect to the arc plasma with no substantial difference in operating efficiency. For purposes of establishing a ground or negative potential, a conductor (not shown) may be led in through one of said outlet side arms. As the plasma impinges upon the electrode 46 the ions thereof undergo recombination reactions with electrons yielding neutral molecules which diffuse into the side arm 21 and are exhausted by the mechanical vacuum pump of previous mention, thereby providing an overall means of obtaining a very high vacuum at the intake region of the ion pump.

For some purposes it is desirable to discharge the exhaust gas, entering the outlet region of envelope 11, in the ionized gaseous form (e. g., when the device is used as an ion source or as a recycling means) in which case conventional ion extracting means are provided in said outlet region whereby the ionized material is exhausted directly. It is to be appreciated that many complex structures may be provided for accomplishing this purpose depending on the requirements posed by a particular device utilizing the ionized particles so derived. For purposes of description, however, the simplified ion extracting structure illustrated in Fig. 4 of the drawings should suffice. As illustrated therein, the side arm 21 is adapted for extracting ionized gaseous particles, from the outlet region of the envelope 11, by providing a suitable array of ion accelerating electrodes within said side arm. More explicitly, two generally cylindrical tubular accelerating electrodes 49 and 51 are disposed in spaced relationship circumjacent the interior walls of the side arm 21 and coaxial with the longitudinal axis thereof. The inner end 52 of the first electrode 49 is advantageously conformed to the plasma volume as by removing a portion which intersect the cylindrical volume of envelope 11 as such electrode 49 projects into the interior portions of the envelope 11, which are disposed between the outlet side arms 19 and 21. The electrodes 49 and 51 are fabricated from a good electrical conducting material (e. g., copper) and are supported either by fused attachment to the interior walls of said side arm 21 or by annular insulator spacers (not shown) radially disposed therein.

For purposes of applying operating potential to electrodes 49 and 51, radially disposed lead-in conductors 53 are attached to the electrodes in a conventional manner, as by soldering, and are led exteriorly through insulated feed-through bushing vacuum seals 54 provided in the walls of the side arm 21 to terminate thereat in conventional terminals in the manner indicated in Fig. 4. A conventional high potential D. C. power supply 56 is then coupled to the terminals of said bushings 54, by means of paired conductors 57, the positive terminal of said power supply being so connected to the proximal electrode 49 and to ground, and the negative terminal thereof to the distal electrode 51. As an alternate mode of connection producing no appreciable difference in operating efficiency, the positive terminal of the power supply 56 may be grounded and the negative terminal connected to the distal electrode 51 while the proximal electrode 49 is allowed to "float" electrically. The axially symmetric electrostatic field established by either of the above modes of connection is then negatively increasing along the longitudinal axis of the side arm 21 in a direction away from the interior of the envelope 11 such that positively charged ionized particles existing in the

arc plasma are extracted and accelerated through the side arm 21.

In order to provide an unobstructed path for ionized particles accelerated through the side arm 21, the cover-plate 24 heretofore terminally secured thereto is eliminated. The flanged extremity of said side arm 21 then provides an advantageous means for direct attachment to suitable flanged fittings provided at the source end of any desired particle accelerator or other apparatus such that ionized particles may be directly injected thereinto.

The efficiency of the ionization process occurring within the envelope 11 is increased by providing means therein to insure that randomly moving neutral gas molecules, formed from ionized particles by various recombination processes described more fully hereinafter, cross the longitudinal axis of said envelope at least once, and in so doing are re-ionized. Preferred structure for accomplishing this purpose is illustrated in Fig. 5 of the drawings. As illustrated therein, the envelope 11 is modified to include several bore constrictions having diameters approximating the diameter of the plasma which traverses the bore of said envelope and disposed within said bore in symmetrical spaced relationship with the mid point region of the linear tubular section 13 of the envelope 11.

In order to facilitate construction and assembly of said bore constrictions, a pair of like linear tubular sections 58 each provided with outwardly flanged end faces 59 engaging the bore walls of the envelope 11 and having bores effecting the desired construction, may be appropriately disposed within the linear tubular section 13. The tubular sections 58 may be supported in a vacuum tight manner as by fused attachment of flanged end faces 59 to the engaged bore walls of the envelope or by other conventional mechanical means. Since these elements are subjected to ion bombardment and it is desirable that recombination processes will not occur thereat, a material such as ceramic or plastic, which is electrically nonconducting and resistant to erosion under these conditions is implied in the construction thereof. Since the flanged end faces 59 are traversed by said electrode 29, such end faces are provided with insulated pressure sealed slots 61 to accommodate said electrodes.

Considering now in particular detail the means by which gas entering the inlet region of the device of the present invention is ionized and transported to the exhaust region thereof, the device is first appropriately energized and connected to a source of gas as hereinbefore described by means of the conduit 28 communicating with the interior of said side arm 18 of the evacuated envelope 11. The oscillating electric field established axially through the bore of the envelope 11 causes naturally occurring stray electrons therein to oscillate spirally and travel axially therethrough. The oscillating electrons so provided are restricted to the central axial region of the bore of the envelope 11 due to the collimating action of the strong magnetic field established axially therethrough. Gas molecules supplied by said gas source, diffuse by random motion into the intake region enclosed by the side arms 17 and 18 as well as the intervening space of the bore of the envelope 11, said molecules will at some time, however, randomly traverse the paths of oscillating electrons whereby it is highly probable that these molecules will be ionized by collision, i. e., in general, a positive ion and an additional electron are formed from each molecule. As more gas molecules are ionized, the ionization process becomes cumulative and an arc discharge is established axially through the bore of the envelope. Ions, as well as electrons, being both electrically charged, are consequently responsive to the oscillating electric field and magnetic field, and therefore the arc discharge is restricted to the central axial region of the bore of envelope 11 forming a constrained plasma.

Inherently, essentially all of the region occupied by an arc discharge or plasma of the character involved herein is essentially equipotential or force-free, being occupied

by ionized gaseous particles having as many positive as negative charges closely constituting a space charge neutralized plasma. Such plasma acts virtually as a continuous conducting gaseous element, of constant resistance per unit length, having positive and negative particle currents (i. e., currents due to the migration of electrically charged particles) passing therethrough. The positive and negative particle currents are each constant in magnitude along the entire length of the plasma and thus as many positive ions or electrons enter one side of a section of plasma as leave by the other. It is this characteristic of a plasma that is utilized to effect the transport of ionized gas from the intake to the exhaust portion of the envelope 11.

The plasma of the arc discharge established within the envelope 11 traverses the central axial region of the bore through said envelope and communicates with the intake region, enclosed by the side arms 17 and 18, and exhaust region, enclosed by the side arms 19 and 21. Positively charged ions are extracted from the plasma in said exhaust region by means disposed therein adapted to discharge gas in either the ordinary gaseous or ionized gaseous forms, as described more fully hereinafter. Since ions leave the plasma in this exhaust region, an equal number of ions are produced and enter the plasma at the inlet region to maintain a constant ion current flow through said plasma. Because of the bilateral symmetry of the envelope 11 with respect to the inlet and outlet regions, the space charge potential distribution of the plasma assumes a similar symmetry, indicating a bifurcated particle current path between the intake and exhaust regions of said envelope. Consequently, gas entering the intake region is continuously ionized and transported in an ionized gaseous form along the bifurcated plasma path through the envelope 11 to the exhaust region thereof.

In the event it is desired to utilize the device of the present invention as an ionic vacuum pump, the exhaust structure indicated in Fig. 3 of the drawings and hereinbefore described is incorporated in the outlet region enclosed by the side arms 19 and 21, as well as the intervening space of the bore of envelope 11. The collector electrode 46 disposed within the outlet region and projecting into the interior portions of the envelope 11 intercepts a portion of the plasma traversing the envelope bore, the remaining portion of the plasma traversing the central axial bore 43 of said electrode such that no appreciable discontinuity is effected in the plasma. The collector electrode 46, being at an electrically neutral, ground, or negative potential, constitutes an electrically attractive element with regard to both the positive ions and electrons which comprise the ionized gaseous material of the plasma. Relatively few electrons, however, are attracted to the extent that they impinge upon said electrode since electrons traverse the plasma path at relatively high velocities and are generally confined to the most central regions of said plasma by the magnetic collimating field. Positive ions, on the other hand, are relatively slow moving and occupy the peripheral regions of the plasma such that they are strongly attracted to the collector electrode 46 and impinge thereon. The impinging ions undergo recombination reactions with electrons of the collector material yielding neutral gas molecules, the majority of which diffuse into the side arm 21. The accumulation of gas molecules in the exhaust region establishes a pressure therein of proportions comparable to standard forevac dimensions whereby said gas molecules may be removed through the vacuum conduit 44 by a conventional vacuum pump. An overall pumping action is consequently achieved by the ion pump since gas entering the inlet region thereof from an external gas source (e. g., a vessel to be evacuated) is ionized and transported in ionized gaseous form to the exhaust region of the pump where the gas is discharged in the ordinary gaseous form. Ion gauges, and other equivalent means for determining vacuum pressures, which may be advan-

tageously disposed on the coverplates 22 and 24 of the envelope side arms 17 and 19, respectively, indicate an inlet pressure of below about 10^{-5} mm. of mercury and an exhaust pressure of above about 10^{-3} mm. of mercury for the foregoing ion pump structure constructed from conventional components and materials.

The exhaust structure depicted in Fig. 4 of the drawings may be incorporated in the side arm 21 of the envelope 11 to discharge gas in the ionized gaseous form; e. g., when the device of the present invention is utilized as an ion source unit or recycling means for sundry particle acceleration devices. It will be noted that positive ions in the plasma traversing the intervening space of the bore of envelope 11 enclosed by the sidearms 19 and 21 experience a strong attractive field applied by the accelerating electrodes 49 and 51 disposed within said side arm 21. The field in effect extends from the plasma axially through the side arm 21, the periphery of the plasma coinciding roughly with the contoured end face 52 of said electrode 49. Furthermore, the field is linearly increasing in negative magnitude in a direction away from the plasma. Positive ions are thus stripped from the plasma by the strong attractive force of the field and are accelerated through the side arm 21 and ejected through the open flanged end face thereof which is easily attached to a low pressure system of any device appropriately adapted to utilize such ions. Ions stripped from the plasma are continuously replenished by ionization of gas diffusing into the inlet region of the envelope 11 from a gas source communicating therewith whereupon the ionized particles so formed are transported to the exhaust region by the means hereinbefore described. In the event the foregoing ion source unit is utilized as a recycling device, the gas entering the inlet region of envelope 11 is supplied from the low pressure system of the device receiving ions from the exhaust region of said envelope. For use as an ion source, gas such as hydrogen or deuterium, etc., is introduced into the inlet region.

With respect to neutral gas molecules existing within the bore of the envelope 11 other than in the inlet and exhaust regions thereof, it is to be noted that such molecules are undesirable since they lower the efficiency of the device by flowing back towards the inlet region of the envelope, i. e., in a direction opposing normal gas flow. Such molecules may be variously formed by sundry recombination processes occurring within said envelope. For example, molecules associated with the outgassing of the internal elements of the device may be formed but are reduced to such a low order after a short period of operation as to be considered negligible. Molecules formed within the arc plasma as a result of electron-ion attachment are also considered negligible since this is normally a rare event in gaseous discharges of the density employed in the present invention. Molecules formed by ions falling out of the arc and becoming neutralized by striking the R. F. electrodes 29 are greatly minimized by the axial magnetic collimating field which restricts radial ion travel. Molecules formed by recombination processes with the materials of the various exhaust structures which may be employed within the exhaust region of the envelope 11, randomly diffuse through the envelope bore as well as advantageously into the side arm 21. It is the molecules formed by the latter named process that constitute the majority of all molecules existing within the envelope bore, although their existence is greatly minimized by the arcuate structure of envelope 11 whereby the paths of molecules rebounding off the walls thereof very probably pass through the plasma path such that a large percentage of said molecules are re-ionized and redelivered to the exhaust region of the envelope. Further minimization of the molecules flowing in a direction from the exhaust region to the inlet region of the envelope, and consequently an increase in efficiency of the device, may be achieved through the utilization of constriction tube structures 58 as depicted by Fig. 5 of the drawings and

hereinbefore described. Since said tubes have bores approximating the periphery of the plasma and are symmetrically disposed within the bore of the envelope 11 about the exhaust region thereof, molecules formed in the exhaust region and diffusing through said envelope bore toward the inlet region must pass through said constriction tube bores, and consequently the plasma, and are thus re-ionized and redelivered to the exhaust region.

Considering now the operating frequency of the radio frequency oscillator of the device of the invention, it will be appreciated that optimum ionization by collision occurs for particles colliding at maximum velocity as determined by the frequency and intensity of the radio frequency field. The frequency must be such that electrons traverse the bore of envelope 11 for a distance of at least one mean free path equivalent to the average distance a particle travels before having a collision, in a time corresponding to a quarter cycle of field oscillation or an odd multiple thereof. Such time corresponds to the peaks of field potential which impart maximum electron velocity. This optimum frequency corresponds to the Larmor, or cyclotron frequency, of the electrons in the plasma, a value which can be calculated from conventional formulas or determined very easily in operation by merely varying the operating frequency while observing the increase in ionization as indicated by light output from the envelope and a lowering of pressure in the input region.

With respect to the relatively wider spacing between adjacent turns of the solenoid 38 in the inlet and outlet regions of the envelope 11, it is to be noted that the magnetic field intensities established in these regions are correspondingly of relatively low levels. The radial restraining force imparted by the magnetic field to particles within the plasma traversing the bore of the envelope is consequently reduced in the inlet and exhaust regions and therefore the plasma expands radially outward therein. A relatively large peripheral surface of plasma, serving as an ionization layer, is consequently exposed to gas molecules diffusing into the envelope bore through the side arm 18. A much increased pumping speed is thus provided, the pumping speed being proportional to the rate at which the gas is ionized. Similarly, a relatively large plasma surface in the exhaust region permits a large number of ionized particles to be collected by the collector electrode 46 without any appreciable interference with the plasma continuity in the event the exhaust structure for discharging gas in the neutral gaseous form is utilized, or permits a large number of positive ions to be extracted by the accelerating field applied by the exhaust structure for discharging gas in the ionized gaseous form thereby providing an increased ion extraction efficiency.

While the invention has been disclosed with respect to a single preferred embodiment, it will be apparent to those skilled in the art that numerous variations and modifications may be made within the spirit and scope of the invention and thus it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. A device for the ionization of molecules and subsequent transport thereof in the form of ions comprising an evacuated envelope including inlet and outlet regions, means coupled to said envelope establishing a radio frequency electric field longitudinally thereof to excite stray electrons therein and establish an oscillatory electron discharge between said inlet and outlet regions, means communicating with said inlet region for admitting gas to said electron discharge, said gas being ionized therein to establish a gaseous electrical discharge between said inlet and outlet regions of said envelope, magnetic field means coupled to said envelope for collimating said gaseous discharge therein, and means disposed within said outlet region for extracting ionized gaseous particles from said gaseous electrical discharge.
2. A radio frequency ion source comprising an evac-

uated envelope including inlet and outlet regions, means coupled to said envelope for establishing a radio frequency electric field longitudinally thereof to excite stray electrons therein and establish an oscillatory electron discharge between said inlet and outlet regions, means communicating with said inlet region for admitting gas to said electron discharge, said gas being ionized therein to establish a gaseous electrical discharge between said inlet and outlet regions of said envelope, magnetic field means coupled to said envelope for collimating said gaseous discharge therein, and means disposed within said outlet region for extracting ionized gaseous particles from said discharge and discharging said particles in an accelerated ionic form.

3. A radio frequency ion pump comprising an evacuated envelope including inlet and outlet regions, means coupled to said envelope establishing a radio frequency electric field longitudinally thereof to excite stray electrons therein and establish an oscillatory electron discharge between said inlet and outlet regions, means communicating with said inlet region for admitting gas to said electron discharge to establish an ionized gaseous discharge between said inlet and outlet regions, magnetic field means coupled to said envelope for collimating said gaseous discharge, an ion neutralizing element disposed within said outlet region for converting ionized gaseous particles from said gaseous discharge to a normal gaseous form, and exhaust pump means communicating with said outlet region for discharging the normal gaseous material.

4. In a radio frequency ion pump the combination comprising an evacuated generally toroidal envelope, means coupled to said envelope establishing a radio frequency electric field longitudinally thereof to excite stray electrons therein and establish an oscillatory electron discharge circumscribing the interior thereof, inlet means communicating with the interior of said envelope admitting gas to said electron discharge, said gas being thereby ionized to establish a gaseous electrical discharge circumscribing the interior of said envelope, magnetic field means coupled to said envelope restricting said gaseous discharge to the central axial regions of said envelope, and means communicating with the interior of said envelope at a point of bilateral symmetry with respect to said inlet means extracting ionized gaseous particles from said gaseous discharge.

5. The device as described in claim 4 wherein said means establishing a radio frequency electric field includes at least one electrically conducting loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope, and a radio frequency oscillator coupled in energizing relationship to said electrode.

6. The device as described in claim 4 wherein said magnetic field means comprises a solenoid disposed in insulated relationship about the periphery of said envelope and concentric with the longitudinal axis thereof, and a direct current power source connected in energizing relationship to said solenoid.

7. An ion source comprising an evacuated generally toroidal envelope having inlet and outlet regions disposed therein at points of bilateral symmetry, means coupled to said envelope establishing a radio frequency electric field longitudinally thereof to excite stray electrons therein and establish an oscillatory electron discharge longitudinally therethrough, means communicating with said inlet region admitting gas to said electron discharge, said gas being ionized therein to provide a gaseous electrical discharge longitudinally through said envelope, magnetic field means coupled to said envelope restricting said electrical discharge to the central axial region of said envelope, and ionized particle accelerating means communicating with said outlet region extracting and accelerating ionized gaseous particles from said electrical discharge.

8. The device as described in claim 7 wherein said means establishing a radio frequency field includes at least one electrically conducting loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope, and a radio frequency oscillator coupled to said electrode.

9. The device as described in claim 7 wherein said magnetic field means comprises a solenoid disposed in insulated relationship about the periphery of said envelope and concentric with the longitudinal axis thereof, and a direct current power source connected to said solenoid.

10. In an ionic pumping device adapted to produce a very high vacuum, the combination comprising a generally toroidal evacuated envelope having intake and exhaust regions disposed therein at points of bilateral symmetry, said intake region being adapted for attachment with a system to be evacuated, radio frequency oscillator means coupled to said envelope establishing an oscillatory electric field longitudinally of said envelope to excite stray electrons therein and thereby produce an oscillatory electron discharge longitudinally therethrough, said electron discharge ionizing gas entering said intake region from said system to produce a gaseous electrical discharge longitudinally through said envelope, magnetic field means coupled to said envelope to restrict said gaseous discharge to the axial regions of said envelope, an ion neutralizing element disposed within said exhaust region to convert ionized gaseous particles from said gaseous discharge to neutral gas molecules, and vacuum pump means communicating with said exhaust region for discharging said gas molecules therefrom.

11. The device as described in claim 10 wherein said radio frequency oscillator means includes at least one electrically conducting loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope, and a radio frequency oscillator coupled to said electrode.

12. The device as described in claim 10 wherein said magnetic field means comprises a solenoid disposed in insulated relationship about the periphery of said envelope and concentric with the longitudinal axis thereof, and a direct current power source connected to said solenoid.

13. A radio frequency ion pump comprising an evacuated generally toroidal envelope having inlet and outlet regions therein, at least one electrically conducting loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope and collinear with the longitudinal axis thereof, radio frequency means coupled to said electrodes to energize same with radio frequency power, a direct current energized solenoid disposed in insulated relationship about the periphery of said envelope and concentric with the longitudinal axis thereof, means attached to said inlet region to admit gas to said envelope whereby a collimated ionized gaseous discharge is established longitudinally therethrough, and means disposed within said outlet region to extract ionized gaseous particles from said gaseous discharge.

14. A radio frequency ion source comprising an evacuated generally toroidal envelope having inlet and outlet regions disposed therein at points of bilateral symmetry, at least one electrically conducting loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope and collinear with the longitudinal axis thereof, radio frequency means coupled to said electrodes energizing same with radio frequency power, a direct current energized solenoid disposed in insulated relationship about the periphery of said envelope and concentric with the longitudinal axis thereof, means attached to said inlet region to admit gas to said envelope whereby a collimated ionized gaseous discharge is established longitudinally therethrough, and ionized particle accelerating means communicating with said outlet region for extracting and accelerating ionized gaseous particles from said gaseous discharge.

13

15. A radio frequency ion pump comprising an evacuated generally toroidal envelope having inlet and outlet regions disposed therein at points of bilateral symmetry, at least one electrically conducting loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope and collinear with the longitudinal axis thereof, radio frequency means coupled to said electrodes energizing same with radio frequency power, a direct current energized solenoid disposed in insulated relationship about the periphery of said envelope and concentric with the longitudinal axis thereof, means attached to said inlet region admitting gas to said envelope whereby a collimated ionized gaseous discharge is established longitudinally through said envelope, an ion neutralizing element disposed within said outlet region intercepting said gaseous discharge to convert ionized gaseous particles existing therein to neutral gas molecules, and vacuum pump means communicating with said outlet region for exhausting said gas molecules.

16. In an ion source device, the combination comprising a generally toroidal evacuated envelope formed of two parallel linear tubular sections joined terminally by two diametrically opposed arcuate tubular sections, each of said linear sections having an outwardly projecting tubular sidearm communicating with the mid length interior thereof, at least one loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope and collinear with the longitudinal axis thereof, radio frequency means coupled to said electrodes energizing same with radio frequency power, a direct current energized solenoid disposed in insulated relationship about the periphery of said envelope having turns concentric with the longitudinal axis thereof, said turns being more widely spaced in the regions of said sidearms relative to turns uniformly spaced therebetween, a gas source terminally secured in pressure sealed relationship to a first one of said side arms, and an array of accelerating electrodes disposed within the second of said side arms and energized to establish an ionized particle accelerating electric field longitudinally therethrough, said second side arm being adapted for sealed attachment to a system in which accelerated ions may be employed.

17. An ion source device as defined in claim 16 where-

14

in said envelope is provided with a pair of like envelope constrictions disposed in symmetrical spaced relationship with the intersection of the longitudinal axis of said second side arm and the longitudinal axis of said envelope.

18. In an improved radio frequency ionic pumping device capable of evacuating a vessel to produce a very high vacuum therein, the combination comprising a generally toroidal evacuated envelope formed of two parallel linear tubular sections each having an outwardly projecting tubular side arm communicating with the mid length interior thereof and joined terminally by two diametrically opposed arcuate tubular sections, one of said side arms being adapted for sealed attachment to said vessel to be evacuated, at least one loop electrode disposed in insulated adjacent relationship with the inner wall surfaces of said envelope and collinear with the longitudinal axis thereof, radio frequency means coupled to said electrode energizing same with radio frequency power, a direct current energized solenoid disposed in insulated relationship about the periphery of said envelope having turns concentric with the longitudinal axis thereof, said turns being more widely spaced in the regions of said side arms relative to turns uniformly spaced therebetween, an ion neutralizing element disposed within the second one of said side arms transverse with the longitudinal axis of said envelope and having a central bore coaxial therewith, and vacuum pump means communicating with said second side arm to exhaust neutral gas molecules therefrom.

19. An improved ionic pumping device as defined in claim 18 wherein said envelope is provided with a pair of like envelope constrictions disposed along the longitudinal axis of said envelope in symmetrical spaced relationship with said ion neutralizing element.

References Cited in the file of this patent

UNITED STATES PATENTS

1,424,091	Fountain	July 25, 1922
2,460,175	Hergenrother	Jan. 25, 1949
2,526,618	Darrieus	Oct. 24, 1950
2,636,664	Hertzler	Apr. 28, 1953
2,726,805	Lawrence et al.	Dec. 13, 1955