

April 21, 1959

W. R. BEAM ET AL

2,883,568

APPARATUS FOR PRODUCING THERMALLY-COOL CHARGED PARTICLES

Filed June 25, 1957

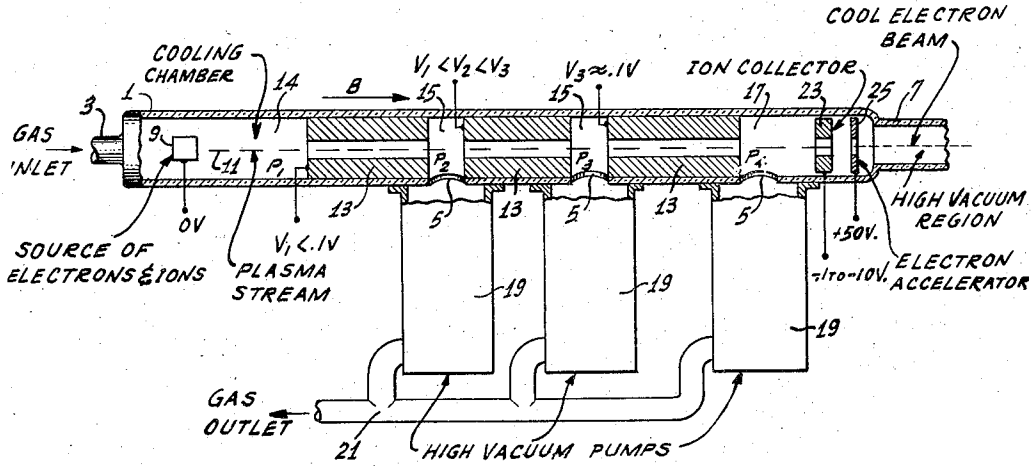


Fig. 1.

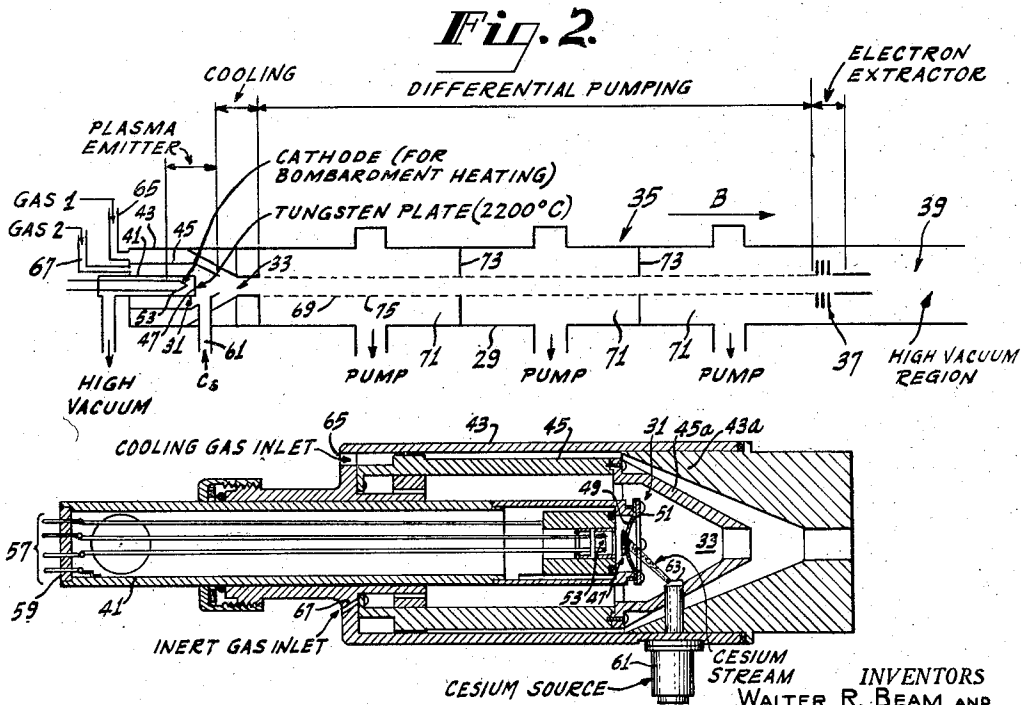


Fig. 3.

INVENTORS
WALTER R. BEAM AND
RONALD C. KNECHTLI
BY

William A. Galenk
ATTORNEY

1

2,883,568

APPARATUS FOR PRODUCING THERMALLY-COOL CHARGED PARTICLES

Walter R. Beam, Trenton, and Ronald C. Knechtli, Cranbury, N.J., assignors to Radio Corporation of America, a corporation of Delaware

Application June 25, 1957, Serial No. 667,920

13 Claims. (Cl. 313-7)

The present invention relates to apparatus for reducing the temperature of charged particles, and especially to apparatus for producing an ultra low noise low temperature electron beam in high vacuum.

When electrons are emitted from a thermionic emitter or cathode they leave, not at a uniform velocity, but with a thermionic velocity spread. Since such a velocity spread is typical of a heated gas, the electron stream may be said to possess a temperature. This temperature is substantially equal to the temperature of the emitter. The factors determining the noise figure (a measure of the noise introduced by the device) of a microwave beam amplifier device, such as a traveling-wave tube, are mainly the current and velocity fluctuations in the beam. The current fluctuations are independent of the temperature. However, the mean square value of the velocity fluctuations is proportional to the emitter temperature. Thus, if one could find some way to reduce the temperature of the emitter, or of the electron beam itself, a new way to reduce the noise figure of microwave amplifiers would be available. Reducing the temperature of the emitter below a certain point is not possible, because of the way in which thermionic emitters operate, and because of the non-existence of emissive materials with very low work function. One method of reducing the thermal velocity spread of the electrons in a beam is that of velocity selection, e.g. utilizing magnetic deflection. In velocity selection, only electrons within a narrow part of the Maxwellian velocity distribution are used. Also, space charge effects defeat attempts to realize a velocity selector capable of yielding appreciable currents or current densities. Typical orders of magnitude of room temperature electron currents obtainable with velocity selectors are of the order of 10^{-10} ampere.

In accordance with the present invention, a stream of electrons is "cooled" by means of thermalizing non-ionizing collisions of the electrons with the molecules of a cool gas, such as ammonia or hydrogen, in the presence of sufficient positive ions to neutralize the space charge of the electrons and thereby permit the production of substantial beam currents at low electron drift velocities. The temperature of the cooling gas may be of the order of room temperature, or less. The pressure of the gas in the cooling region may be between 10^{-5} and 10^{-1} mm. of Hg, and is preferably about 10^{-3} mm., or 1μ of Hg. In order to obtain a good vacuum in the region at the output end of the apparatus where the cooled electrons are to be utilized, evacuating means are provided for progressively reducing the pressure of the cooling gas along the stream. A magnetic field axial to the stream is provided to confine the electrons and ions to the stream throughout the cooling and evacuating regions. Means are provided at the output end for extracting the cool electrons from the stream and accelerating them uniformly along a desired path.

The positive ions can be produced independently of the electrons to be cooled, for example at the other end of the apparatus. However, in the preferred embodiment of

2

the invention, the electrons are produced by bombardment heating a tungsten plate to electron emitting temperature, and the ions are produced by contact ionization of atoms of an alkaline metal vapor, such as cesium, at the hot surface of the tungsten plate. The electrons and ions thus produced are caused to drift slowly, in the same general direction, through a cooling region containing the cooling gas and a pumping region to the output end of the apparatus where the cooled electrons are separated from the positive ions and formed into a cool ultra low noise, high-vacuum beam.

The low temperature electron beam produced by the invention can be used for any electron tube requiring appreciable electron current with low velocity spread, such as ultra low noise microwave tubes, or for basic physical research.

An object of the invention is to provide means for reducing the temperature of charged particles.

Another object of the invention is to provide means for producing a low temperature plasma stream.

A further object of the invention is to provide means for producing a low temperature, low noise electron beam in high vacuum.

Still another object is to provide a new and improved source of a plasma made up of electrons and positive ions.

In the annexed drawing:

Fig. 1 is a side view, partly in axial section, of one embodiment of apparatus for producing a low temperature beam of electrons in high vacuum according to the present invention;

Fig. 2 is a schematic view similar to Fig. 1 of another embodiment of the invention; and

Fig. 3 is an axial sectional view of the plasma emitter and gas inlet assembly of Fig. 2.

The invention provides means for greatly reducing the thermal velocities of electrons emitted from a thermionic source by mixing them with a cooler gas. By providing positive ions for neutralizing the space charge of the electrons, transporting the electrons and ions, pumping away the cooling gas and finally extracting the cool electrons from the plasma, the resulting electron stream is the equivalent of a thermionic cathode operated near room temperature but capable of delivering enough current to operate low-noise microwave amplifiers and similar devices. By this means the noise figure of beam type amplifiers can theoretically be reduced to 3 decibels or less. Conventional low noise microwave amplifiers without electron cooling have noise figures of about 5 decibels, at best, and more commonly about 7 decibels.

In order to carry out the desired cooling of the electrons and end up with a substantial beam current in a region of high vacuum, there are certain basic requirements. First, the sizable beam currents needed for microwave devices require ion neutralization if the electrons are to pass through the cooling region at slow enough speed to be cooled to nearly the temperature of the gas, which may be room temperature, or less. The neutralizing ions should not contribute an appreciable amount of energy to the system, and must not recombine at an excessive rate with the electrons or with the cooling gas. Second, since the cooling gas must be present at a moderate pressure it is necessary to evacuate the gas from the plasma stream after cooling in order to obtain a good vacuum in the output region. Third, since the electron drift velocity must be very small, and the electrons must be accelerated by appreciable voltages in the region where they are used, means must be provided for carrying the electrons slowly through the cooling and pumping regions, and accelerating them when they reach the high vacuum region. At the same time, the ions must be carried from their point of origin to

the opposite end of the plasma stream so that they are at all times in position to neutralize the electronic space charge. Finally, provision must be made for separating the electrons from the ions in the region where the electrons are accelerated.

The electrons are most conveniently produced by means of a thermionic emitter. An attractive means of positive ion supply is the phenomenon of contact ionization. If a metal surface is heated in the presence of atoms having an ionization potential less than the work function of the metal, atoms which impinge on the metal surface will be ionized by the affinity of the surface for their electrons. The heat of the surface will then drive off the ions, resulting in a source of positive ions having a temperature substantially equal to the emitter temperature. In the case of tungsten as the heated metal, the atoms of cesium, potassium and rubidium satisfy the condition for contact ionization. If the tungsten is heated to electron emitting temperature the surface becomes a source of both positive ions and electrons, or a plasma emitter.

Preferably, the gas is removed from the plasma stream after cooling by means of a plural-stage vacuum pumping arrangement in which several pumps reduce the gas pressure through a series of constrictions. This is a very effective method because of the fact that normal diffusion pumps have constant speed (volumetric) over a wide range of pressures, which means that a plurality of pumps can reduce the pressure in approximately a geometric progression. In cases where the low-temperature stream does not require a high vacuum, the differential pumping arrangement may be reduced to a single stage, or eliminated.

The electrons must pass from the emitter through the cooling and pumping regions to the high vacuum region. Although the positive ions must be present to substantially neutralize the space charge, between the electron emitter and the region where the electrons are accelerated to high velocity, one has a choice as to the direction of the ions. The ions may originate with the electrons and travel through the apparatus in the same direction. Alternatively, the ions may originate at a separate ion source at the opposite end of the apparatus, in which case the ions and electrons travel in opposite directions. The electrons are drawn through the gas by a weak axial electric field set up by a low positive potential on an electron extractor electrode in the high vacuum region. Where electrons and ions travel in the same direction, due to their opposite charge, the ions must be transported by some means other than the axial electric field. In the preferred practice of the invention, the ions are carried through the cooling and pumping regions by the flow of the cooling gas itself. If the cooling gas is incapable of transporting the ions, a separate chemically-inactive gas, such as nitrogen or argon, for example, may be passed through the apparatus, in addition to the cooling gas, for transporting the ions. If the cooling gas has adverse effects on the plasma emitter, an inactive gas can be used to prevent excessive quantities of the cooling gas from reaching the emitter. Both of these functions can be performed by the same inactive gas.

In order to cool electrons efficiently it is necessary to use a gas which is either very light in mass or one which has a great many molecular degrees of freedom, enabling the molecules to be spun or vibrated by collision with electrons. Examples of such gases are ammonia, carbon dioxide, pentane and benzene. However, the more complex molecules, while making very effective cooling media, are very easy to dissociate into undesirable components. Therefore, ammonia is preferred. The only light-weight molecule with satisfactory cooling properties is hydrogen, which is practically harmless even when dissociated.

Transverse constraint of the plasma will prevent loss of any appreciable number of electrons or ions to the surrounding walls. This constraint may be obtained by

the provision of a strong axial magnetic field extending along the length of the plasma stream. This field limits the electrons to movement in tight circles in a transverse plane, which means that the greatest distance by which they can move outward, per collision, is the diameter of this circular path. The field is made strong enough that this diameter is several orders of magnitude smaller than the stream diameter, so that the electrons cannot move transversely to any appreciable extent in the length of the cooling region. The ions, because of their much greater mass, are not so constrained but, if a number of ions leave the region containing the electrons, the potential on the axis is depressed and a natural ion trap is formed. In order to prevent excessive depression of the plasma stream potential, an alternative consists in raising the potentials on the walls surrounding the stream by a small fraction of a volt.

In the preferred type of operation in which the electrons and ions drift in the same direction, the electrons must be separated from the ions at the high vacuum end of the apparatus. This may be accomplished by means of a cylindrical ion-collecting electrode, closely surrounding the plasma stream, at approximately the potential of the edge of the stream or slightly negative with respect thereto, followed by the electron accelerating electrode. As the number of ions in the stream is reduced, there would normally be a drop in stream potential. However, this drop will be approximately compensated by the accelerating electrode, and the electrons will be accelerated to high velocities only in the region beyond the ion-collecting electrode.

Fig. 1 shows, for example, an embodiment of the invention comprising an elongated tubular enclosure 1, which may be of glass, having a cooling gas inlet tubing 3 at the left end, a plurality of exhaust holes 5 spaced along the side thereof and an output tubing 7 at the right end adapted to be vacuum-sealed to a device for utilizing the low temperature electron beam produced within the enclosure 1.

A source 9 of electrons and positive ions is mounted within the enclosure 1 near the gas inlet tubing 3 to provide a plasma stream 11 directed toward the outlet tubing 7. The source 9, schematically shown in Fig. 1, is preferably of the contact ionization type shown in Fig. 2. Spaced from the source 9 is the first of three tubular constricting members 12, which form parts of a differential, three-stage pumping system.

The space between the source 9 and the first member 13 constitutes a cooling chamber 14 wherein electrons and ions from the source 9 are cooled by non-ionizing collisions with the molecules of the cooling gas. The cooling gas is preferably ammonia, in pure form, at room temperature and at an initial pressure of about 1μ of Hg. In order to cool the electrons down close to the gas temperature, it is necessary that the drift velocity of the electrons in the cooling region be about two orders of magnitude less than their initial mean thermal velocity, which is determined by the emitter temperature. This means a drift velocity of the order of 10^5 cm./sec. This drift velocity corresponds to an electron velocity of less than 3×10^{-6} volts, which is far below the ionization potential of the gases used in the apparatus. To obtain a desired current density of a few ma./cm.² with such a low drift velocity requires electron densities of the order of 10^{10} to 10^{11} electrons/cm.³, which makes it necessary to use positive ion space charge neutralization.

The constricting members 13 are positioned along the enclosure 1 to provide pumping chambers 15 and 17 registering with the holes 5. Each of these chambers opens into one of three high vacuum pumps 19 which are sealed by suitable means (not shown) to the enclosure 1 around the holes 5. The high pressure sides of the three pumps 19 may be connected together, as shown, by a gas outlet tubing 21, which may be connected to a mechanical

5

fore pump (not shown). Alternatively, the same cooling gas may be used over again by connecting the outlet tubing 21 directly to the inlet tubing 3.

The pumping system shown in Fig. 1 produces a pressure differential in the regions indicated in which $P_1 > P_2 > P_3 > P_4$. The pressure is substantially constant across each region, with a gradual pressure gradient along each of the constricting members 13. The final pressure in chamber 17 should be 10^{-6} mm. of Hg, or less, in order to produce a high vacuum at the output end 7 of the apparatus.

If desired, potentials V_1 , V_2 and V_3 may be applied to the constricting members 13 such that $V_1 \leq 1$ volt, $V_3 \approx 1$ volt, and $V_1 \leq V_2 \leq V_3$, as shown in Fig. 1, to prevent excessive depression of the plasma stream potential.

After passing through the pumping system, the plasma stream enters an electron extraction region where the positive ions are collected by a cylindrical ion collector 23 at a potential of -1 to -10 volts, and the electrons are accelerated by an annular accelerating electrode 25 at a substantial positive potential, of the order of $+50$ volts, relative to the source 9.

An axial magnetic field B for transversely constraining the plasma may be produced by any suitable means, such as one or more electromagnets coaxially surrounding the enclosure 1.

Fig. 2 schematically shows another apparatus, incorporating the basic principles of the present invention, including the preferred contact ionization type of plasma emitter in combination with an improved differential pumping system that is disclosed and claimed in a copending application of Ronald C. Knechtli, Serial No. 667,943, filed concurrently herewith, now Patent No. 2,841,726, issued July 1, 1958. The apparatus shown in Fig. 2 comprises an elongated enclosure 29 containing a plasma emitter 31, a cooling chamber 33, a differential pumping system 35, an electron extractor structure 37, and a high vacuum region 39.

The plasma emitter and gas inlet assembly of Fig. 2 is shown in detail in Fig. 3 and comprises an inner tubular member 41, on which the plasma emitter 31 is mounted, and a concentric outer tubular member 43 which forms an end portion of the enclosure 29. Concentrically mounted between the members 41 and 43 is a third tubular member 45 which separates the cooling gas from the transport gas, when the latter is used, and serves to keep the cooling gas cool by minimizing heat transfer from the hot plasma emitter 31.

The plasma emitter 31 comprises a tungsten plate 47, having a thickness of about 20 mils, transversely mounted at the right hand end of the member 41 by means of a thin apertured disc 49 of tantalum, to which the plate 47 is welded, clamped in substantially vacuum-tight relation to the end of member 41 by a ring 51. A cathode 53 is positioned behind the tungsten plate 47 for heating the latter by electron bombardment. The cathode 53 is mounted in insulated relation within a tubular accelerating electrode 55. Leads 47 for the cathode and accelerating electrode extend through an insulating end closure 59 vacuum sealed to the opposite end of the member 41.

A cesium evaporator 61 is mounted on one side of the member 43 with a cesium supply tube 63 extending through the tubular members 43 and 45 in position to direct a stream of cesium vapor atoms through the ring 51 toward the front surface of the tungsten plate 47.

The cooling gas, which may be ammonia or hydrogen, for example, is supplied at 65 to the annular space between the two outer tubular members 43 and 45. The right hand ends of the members 43 and 45 include converging conical members 43a and 45a which provide a converging annular passage therebetween leading to the cooling chamber 33. The structure shown may be used with an inactive gas, in which case the inactive gas is supplied at 67 to the space between the two inner tubular members 41 and 43 and flows past the plasma emitter 31

6

carrying the ions through the cooling and pumping regions. The ions will usually have sufficient initial velocities due to their temperature to reach the cooling chamber 33. If the cooling gas flow can effectively transport the ions and if its dissociation products at the hot tungsten plate are not harmful, the separate gas can be dispensed with.

The differential pumping system shown schematically in Fig. 2 comprises an elongated perforated metal tube 69 extending within the enclosure 29 from the cooling chamber 33 to the electron extractor 37. The space between the tube 69 and enclosure 29 is separated into three pumping chambers 71 by means of two annular partitions 73. Each of the chambers 71 is connected to a high vacuum pump (not shown). The pumps may be connected to a mechanical fore pump or to the cooling gas inlet 65, as described in connection with Fig. 1. The apertures 75 in the tube 69 may be distributed around and along the tube in either random or systematic order. However, it is preferred that the number of apertures or their size, or both, be chosen so that the total aperture area per unit axial length will increase along each pumping chamber 71 in the manner described in said copending application. In this pumping system the pressure in each chamber 71 outside the tube 69 will be substantially uniform at a value approximately equal to the pressure inside the tube 69 at the low pressure end of the part of the tube within that chamber, whereas the pressure within the tube 69 will progressively decrease throughout its entire length.

The electron extractor 37 and high vacuum region 39 may be the same as in Fig. 1.

What is claimed is:

1. Apparatus for cooling electrons comprising: a source of electrons having a mean thermal velocity determining a given initial electron temperature; a chamber containing a cooling gas having a temperature substantially lower than said initial electron temperature; means independent of said cooling gas for providing positive ions in said chamber; and means for causing said electrons to drift through said chamber at a drift velocity substantially less than said mean thermal velocity, whereby said electrons are cooled to a temperature substantially lower than said initial electron temperature as a result of non-ionizing collisions with the molecules of said gas.

2. Apparatus for producing a low temperature plasma stream comprising: a common source of electrons and positive ions, said electrons having a mean thermal velocity determining an initial electron temperature substantially higher than room temperature; a chamber containing a cooling gas having a temperature substantially lower than said initial electron temperature; and means for causing said electrons and ions to drift through said chamber in the same general direction at velocities substantially less than said mean thermal electron velocity, whereby said electrons are cooled to a temperature substantially below said initial electron temperature as a result of non-ionizing collisions with the molecules of said cooling gas.

3. Apparatus according to claim 2, wherein said source of electrons and positive ions comprises a member having an electron emissive surface with a given work function, means for heating said member to electron emitting temperature, and means for supplying metal vapor atoms at said surface of said member for contact ionization thereof having an ionization potential less than said work function.

4. Apparatus according to claim 3, wherein said member is tungsten, and said metal vapor is cesium.

5. Apparatus for producing a low temperature plasma stream comprising: a first chamber and means for supplying a gas thereto having a temperature no higher than room temperature and an initial pressure between 10^{-5} and 10^{-1} mm. of Hg; means for supplying a stream of electrons and positive ions to said chamber, said

electrons having a mean thermal velocity determining an initial electron temperature substantially higher than room temperature; means for causing said electrons and ions to drift through said chamber in the same general direction at a drift velocity substantially less than said mean thermal electron velocity, whereby said electrons and ions are cooled to a temperature substantially below said initial electron temperature as a result of collisions with the molecules of said gas; a second chamber communicating with said first chamber through which said ions and electrons drift after passage through said first chamber; means for progressively reducing the gas pressure in said second chamber in the direction of drift to a pressure at the end remote from said first chamber substantially lower than said initial pressure; and means for minimizing loss of electrons and ions from said stream in said second chamber.

6. Apparatus according to claim 5, wherein said means for causing said ions to drift comprises said gas which by its flow through said apparatus imparts momentum to said ions.

7. Apparatus according to claim 5, wherein said means for causing said ions to drift comprises means for supplying and directing a separate inactive gas through said apparatus for imparting momentum to said ions.

8. Apparatus for producing a beam of low temperature electrons comprising: a source of electrons having a mean thermal velocity determining an initial electron temperature substantially higher than room temperature; a first chamber and means for supplying a gas thereto having a temperature substantially lower than said initial electron temperature and an initial pressure between 10^{-5} and 10^{-1} mm. of Hg; means for causing said electrons to drift through said first chamber at a drift velocity substantially less than said mean thermal electron velocity, whereby said electrons are cooled to a temperature substantially below said initial electron temperature as a result of collisions with the molecules of said gas; a second chamber communicating with said first chamber through which said electrons drift after passage through said first chamber; means for supplying positive ions to said chambers; means for progressively reducing the gas pressure in said second chamber in the direction of electron drift to a pressure at the end thereof remote from said first chamber substantially lower than said initial pressure; means for minimizing loss of electrons and ions in said second chamber; and means located at said remote end for separating said positive ions and said electrons and forming said electrons into a beam of low temperature electrons along a desired path.

9. Apparatus according to claim 8, wherein said means for causing said electrons to drift and said last-named means comprise an electron accelerating electrode located at said remote end of said second chamber.

10. Apparatus for producing a beam of low temperature electrons comprising: a first chamber and means for supplying a gas thereto having a temperature no higher than room temperature and an initial pressure between 10^{-5} and 10^{-1} mm. of Hg; means for supplying a stream of electrons and positive ions to said chamber, said electrons having a mean thermal velocity determining an initial electron temperature substantially higher than room temperature; means for causing said electrons and ions to drift through said chamber in the same general direction at a drift velocity substantially less than said mean thermal electron velocity, whereby said electrons and ions are cooled to a temperature substantially below said initial electron temperature as a result of collisions with the molecules of said gas; a second chamber communicating with said first chamber through which said ions and electrons drift after passage through said first chamber; means for progressively reducing the gas pressure in said second chamber in the direction of drift to a pressure at the end thereof remote from said first chamber substantially lower than said initial pressure; means for producing a confining magnetic field extending along said drift direction; and means located at said remote end for separating said positive ions from said electrons and forming said electrons into a beam of low temperature electrons along a desired path.

11. Apparatus according to claim 10, wherein said gas is ammonia at an initial pressure of about 1 micron of Hg, and said pressure at said remote end of said second chamber is not greater than 10^{-6} mm. of Hg.

12. A source of electrons and positive ions comprising a member metal having an electron emissive surface with a given work function, means for bombarding said member with electrons to heat said member to electron emitting temperature, and means for supplying at said surface of said member for contact ionization thereat metal vapor atoms having an ionization potential less than said work function, said atoms being provided by continuous evaporation of atoms from an alkaline metal.

13. A source according to claim 12, wherein said member is a plate of tungsten, and said alkaline metal is cesium.

References Cited in the file of this patent

UNITED STATES PATENTS

50 2,798,181 Foster ----- July 2, 1957