

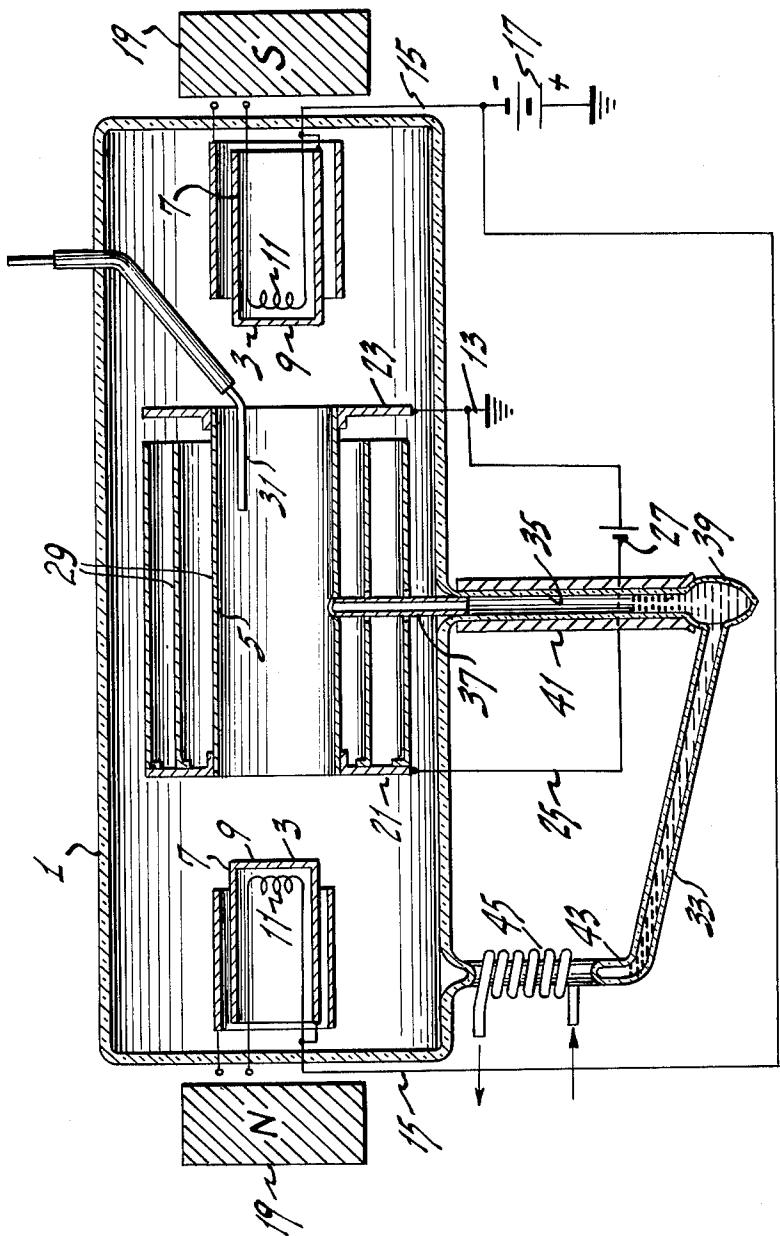
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HIGH DENSITY PLASMA GENERATOR

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HIGH DENSITY PLASMA GENERATOR
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The present invention relates to the generation or pro-
duction of a plasma having a very high ion density and
very high percent ionization. The invention provides
means for producing a plasma having an ion density
greater than 10^{14} ions/cm.³ and an ionization greater than
10 percent. Plasmas have been produced by using the
invention having densities greater than 10^{15} and ioniza-
tions greater than 50 percent.

A plasma is a region in space in which there are essen-
tially equal densities of positive and negative charges
carried by the particles, at least one type of particle hav-
ing random thermal motion. In a gas discharge plasma,
both types of charged particles and the neutral gas atoms
are mobile. High density gas plasmas have many uses,
including the generation or amplification of electrical os-
cillations in the millimeter and sub-millimeter regions by
the interaction of electron beams with such plasmas. In
order to generate 1 mm. signal waves (300 kmc.) by this
method, the critical ion density n_c of the plasma must be
such that the plasma frequency ω_p is equal to the angular
frequency, ω_s , of the signal waves. The plasma frequency

$$\omega_p = \sqrt{n_c e^2 / m \epsilon_0} \tag{1}$$

where e is the electron charge, m is the electron mass, and
 ϵ_0 is the dielectric constant of free space. Thus, for
beam-plasma interaction,

$$\omega_s = 2\pi f_s = \sqrt{\frac{n_c e^2}{m \epsilon_0}} \tag{2}$$

or

$$n_c = \frac{4\pi^2 m \epsilon_0 f_s^2}{e^2} = 1.24 \times 10^{10} f_s^2 \tag{3}$$

where f_s is the signal frequency in kmc. For 1 mm.
waves, n_c must be about 1.1×10^{15} ions/cm.³.

In addition to the high ion density requirement for 1
millimeter waves, it is necessary that the percent ioniza-
tion of the gas in the plasma be high in order to minimize
scattering of electrons out of the electron beam due to
collisions with neutral gas or vapor atoms. For example,
in a gas plasma with 3 percent ionization and 10^{15}
ions/cm.³, the density of neutral atoms would be above
 3×10^{16} /cm.³, which would mean a gas pressure of about
1 mm. of Hg at 0° C. The beam power requirement for
overcoming the effects of beam scattering at this pressure
would be prohibitive.

It can be shown that when a large diameter electron
beam interacts with a dense plasma the gain G , in db, is:

$$G = 17.4 [k_0 \delta - 1 - \log (k_0 \delta)] \tag{4}$$

where k_0 is the gain constant for an unattenuated beam
and δ is the mean free path of the beam electrons. The
gain is positive when $k_0 \delta > 1$, thus δ should be maximized.
For a given beam voltage

$$\delta \sim \frac{1}{n_t} \tag{5}$$

where n_t is the total density of the plasma, including the
neutral or non-ionized atoms of the gas or vapor. For a
given ion density, n_c , the higher the percent ionization of
the plasma is, the lower n_t will be, and hence, the higher
 δ will be. Lower n_t means lower vapor pressure. The

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relation between β and n_t for constant n_c is shown in the
following table:

β (percent):	n_t (particles/cm. ³)
1	100 n_c
5	20 n_c
10	10 n_c
20	5 n_c
50	2 n_c
100	n_c

Thus, for highest gain, the percent ionization of the plas-
ma should be as high as possible.

Ion densities as high as 10^{14} to 10^{15} ions/cm.³ have been
produced in continuous mercury discharges, but the per-
cent ionization there has been only a few percent, and
hence, it is impractical to use such plasmas to generate
oscillations at frequencies above about 100 kmc.

Another type of discharge which produces ion densities
of the order of 10^{14} ions/cm.³ but with low percent ioniza-
tion is that of the well-known "PIG" or Penning discharge
tube, in which two cathodes are mounted opposite the
ends of a ring anode and an axial magnetic field is estab-
lished between the two cathodes. A voltage applied be-
tween the two cathodes and the central anode accelerates
electrons toward the anode, ionizing part of the gas or
vapor in the tube. The electrons emitted from the cath-
ode and those created by impact ionization are trapped
radially by the axial magnetic field. In this tube, the
electrons entering the anode build up a negative space
charge therein establishing a potential trough which limits
the ion density to about 10^{14} ions/cm.³ and the ionization
to values much less than 10 percent.

The object of the present invention is to provide means
for producing a plasma having a very high ion density
(greater than 10^{14} ions/cm.³) and also a high percent
ionization (greater than 10 percent).

In accordance with the invention, a highly ionized, high
density, confined vapor plasma is produced by combining
contact or resonance ionization of a vapor at a hot metal
surface of sufficient work function with injection of elec-
trons from an external source. The vapor used is pref-
erably cesium, but other metals may be used, such as
rubidium and potassium.

The single figure in the drawing is an axial sectional
view of a Penning type discharge tube modified in ac-
cordance with the invention.

The tube shown in the drawing comprises a gas tight
envelope 1, of dielectric or non-magnetic metal, contain-
ing two spaced thermionic cathodes 3 and an interme-
diate hollow anode 5. As shown, the anode 5 is a hollow
cylindrical tube coaxially positioned centrally in the en-
velope 1, and the two cathodes 3 are coaxially positioned
opposite the open ends of the anode 5. Each cathode 3
may comprise a cup-shaped member 7 having an emis-
sive surface 9 of the barium-impregnated-tungsten type
facing the anode 5, and a heater 11. The various elec-
trodes may be supported within the envelope by any suit-
able means (not shown). The anode 5 and cathodes 3 are
provided with external terminals or leads 13 and 15, re-
spectively, which are shown connected to a voltage source
17, for establishing an accelerating electric field between
each cathode and the anode. Suitable means, such as a
magnet including the pole pieces 19 shown opposite each
of the cathodes 3, are provided for establishing an axial
magnetic field in the region between the two cathodes.

The anode 5 is made of a metal, such as tungsten,
molybdenum, tantalum or alloys thereof, having an elec-
tron work function higher than the ionization potential
of the vapor used in the tube. Cesium, for example, has
an ionization potential lower than any of the anode metals
named. Means are provided for heating and maintaining
the anode at a temperature of at least 1300° C. For

example, the anode 5 may be made very thin, about .0005", and be directly heated by passing an electric current therethrough, by means of metal rings 21 and 23, leads 13 and 25, and voltage source 27. Instead, the anode 5 may be indirectly heated by radiation from one or more heater coils positioned around the outside thereof (not shown). The anode 5 may be provided with one or more heat shields, such as the double shield 29 shown, to minimize heat loss therefrom. A Langmuir type probe 31 may be provided inside the anode cylinder 5 and near the inner wall thereof to measure the saturated ion current from the plasma, for determining the ion density. The probe is heated by radiation to nearly the anode temperature.

The drawing also shows a convenient means for supplying cesium vapor within the envelope 1 and for controlling the vapor pressure. This means comprises a generally U-shaped tubular extension 33 of the envelope 1 having one leg 35 joined to the envelope centrally of the anode 5 and connected thereto by an extension tube 37. The lower end of leg 35 is enlarged to form a cesium reservoir or well 39. A heater element 41, e.g., an insulated tape coil, is provided around the leg 35 for adjusting the cesium vapor pressure by adjusting the temperature of the cesium in the leg 35. The other leg 43 is surrounded by a water cooling pipe 45 for condensing cesium therein. One advantage of this arrangement is that cesium is supplied directly to the interior of the anode 5, where the high density plasma is produced, and withdrawn from another part of the tube.

The tube illustrated is operated in a manner similar to a Penning discharge tube. The cathodes 3 are heated by heaters 11 to normal electron emitting temperature, e.g., about 1100° C. for impregnated cathodes, and an accelerating voltage of 3 to 10 volts is applied between the cathodes 3 and anode 5. If this voltage is above the ionization potential, 3.9 volts, of cesium, some positive ions will be produced in the cathode-anode regions by impact ionization, as in the conventional Penning tube. In addition, the anode 5 is heated to a temperature of at least 1500° C., and positive ions are produced within the hollow anode 5 as a result of cesium atoms coming into contact with the hot anode surface. When a cesium atom contacts a hot surface of tungsten, for example, it is at least momentarily bound thereto by a shared electron, and when the atom is driven from the hot surface by heat energy it gives up the bound electron to the high work function surface and becomes a positive ion. This phenomena is known as "contact" or "resonance" ionization. The cesium ions formed at the anode wall move into the plasma if a sufficient number of electrons are present to neutralize the space charge created by the ions. The ions produced by contact ionization not only greatly increase the percent ionization within the anode, but also neutralize the negative space charge that normally builds up within the anode in the conventional Penning discharge tube. Because of this neutralization, the plasma region can and will accept a larger number of electrons from the two cathodes 9, and thereby maintain charge neutrality in the region. Moreover, a plasma in which both types of charged particles are mobile can exist in equilibrium only if the temperature of the surroundings and of the plasma itself is sufficiently high for the creation of new charge pairs to compensate for the charges which leave the system by random motion. Thus, the hot anode not only produces positive ions by contact ionization but also maintains a high temperature within and around the plasma. The combination of all of these interrelated factors produces a plasma having an ion density greater than 10¹⁴ ions/cm.³ with an ionization greater than 10 percent. Although plasmas having ion densities of 10¹⁵ can be produced in a Penning discharge without the hot anode by using high vapor pressures, the degree of ionization of such plasmas is much less than 10 percent.

In the operation of the tube, the principal function of

the two cathodes and the accelerating voltages is to supply sufficient electrons to neutralize the positive ions produced in the anode. The accelerating voltage must be sufficiently high to overcome space charge effects at the cathode surface in order to achieve this result. In order to produce the maximum density and percent ionization, this accelerating voltage must also be greater than the ionization potential of the vapor used.

One tube, for example, constructed as shown in the drawing with an anode 5 having a length of 2 cm. and a diameter of 0.5 cm., fabricated from a .001" thick sheet of 90 percent tantalum—10 percent tungsten alloy, and two impregnated tungsten cathodes 3 having a total effective emissive area of about 0.4 cm.², was operated with the cathodes at about 1100° F., and the anode at about 1700° C., about 9 volts applied between the cathodes and anode, an applied magnetic field of about 7,500 gauss, and a cesium well temperature of about 300° C., which corresponds to a vapor pressure of about 2.3 mm. of Hg, producing a stable continuous-discharge plasma within the anode 5 having a measured ion density of 10¹⁵ ions/cm.³ and an ionization of about 50 percent.

The hot Langmuir probe 31 was used to measure the saturated ion current from the discharge plasma within the anode. The saturated ion current *I* is related to the ion density *n* by the formula

$$I = 4\pi n e \sqrt{2KT_e/M} \quad (4)$$

where *e* is the electron charge, *K* is the Boltzman constant, and *M* is the ionic mass. Various measurements of the electron temperature indicate a maximum *T_e* of about 25,000° K. for the example given.

The total particle density in the anode was determined by measuring the electron emission from a hot tantalum Langmuir probe with no discharge and zero axial magnetic field. A plot of the saturated electron emission from the tantalum probe as a function of the reciprocal of the anode heater current yields an S-curve, similar to the published S-shaped emission-temperature curves for tantalum in cesium vapor, showing a minimum between 1400 and 2000° K. A comparison of this minimum with similar published S curves for tantalum in cesium in which cesium pressures and temperatures are known yields a measure of the cesium density. The ratio of the particle flux in the anode to that in the cesium well was found to be about one-tenth at well temperatures below 255° C., where the highest total particle density measurement was made. Use of this ratio at a cesium well temperature of 300° C. and well pressure of 2.3 mm. of Hg indicated that the ionization is 50 percent at a plasma density of 10¹⁵ ions/cm.³.

The function of the axial magnetic field in the operation of the device is to prevent lateral spreading of the Penning discharge from the two cathodes. It has been found that the ion density and percent ionization in the plasma increase with increasing magnetic field, at least in the region between 2000 and 7500 gauss. Theoretically, this increase should continue for still higher magnetic fields up to a value at which the field limits the diffusion of ions from the anode into the plasmas. For the tube illustrated, this field would be about 10,000 gauss.

Plasmas having ionizations about 50 percent can be produced. However, experiments have shown that if the density of neutral cesium atoms is less than 10¹⁵ neutrals/cm.³, large amplitude density waves of 100 kc. and 200 kc. frequency appear in the plasma. Thus, in order to minimize noise in the plasma, it is desirable to maintain a cesium vapor pressure in the plasma region of at least 0.5 mm. of Hg. Moreover, the power required to produce a given density plasma is about five times higher with density fluctuations present than without them. The density fluctuations are damped out when the neutral particle density increases above a critical value. At this

critical value the energy flowing into the ion-neutral collisions is greater than the kinetic energy of the ion density wave and thus the wave is damped. At neutral densities between 5×10^{14} and 10^{15} neutrals/cm.³, the 100 kc. waves are damped and only the 200 kc. waves are present. At neutral densities greater than 10^{15} neutrals/cm.³, all waves are damped and the plasma is very quiet.

While best results are obtained with two thermionic cathodes 3, one of the two cathodes may be a secondary emissive cold cathode. If desired, each cathode may be in the shape of a cone with the apex facing the center of the anode, or hollow and conical with the apexes outward. If desired, each cathode may be in the shape of several adjacent cones. Such shapes tend to damp undesired oscillations. Moreover, the anode 5 may have some other hollow shape than cylindrical.

The high density plasma produced by the present invention may be utilized in any manner known in the art. For example, the structure shown in the drawing can be converted to a beam-plasma interaction tube by substituting annular cathodes for the two cathodes 9, adding an electron gun and collector for projecting an electron beam axially through the two cathodes and the anode 5, and adding suitable means for coupling an RF signal into and out of the beam in the case of an amplifier, or out of the beam in the case of an oscillator.

What is claimed is:

1. Apparatus for producing a high density plasma comprising:

- (a) an envelope containing a hollow anode;
- (b) means for producing a metal vapor in said envelope;
- (c) means, including a thermionic cathode adjacent to said hollow anode, for producing positive ions in said anode by electron bombardment of said vapor; and
- (d) means for producing additional positive ions in said anode by emission from an interior surface thereof, comprising means for heating said anode.

2. Apparatus as in claim 1, wherein said interior surface of said anode has an electron work function higher than the ionization potential of said vapor, and said apparatus includes means for heating said surface to a temperature sufficient to ionize said vapor by contact with said surface and thus produce said emission.

3. Apparatus as in claim 1, wherein said second-named means includes means for applying a voltage between said cathode and anode greater than the ionization potential of said vapor.

4. Apparatus as in claim 3, further comprising means for establishing a magnetic field in said hollow anode.

5. Apparatus for producing a confined plasma having an ion density greater than 10^{14} ions/cm.³ and an ionization greater than 10 percent, comprising:

- (a) a hollow anode;
- (b) a cathode facing each end of said anode, at least one of said cathodes being thermionic;
- (c) a gas-tight envelope enclosing said anode and cathodes;
- (d) means for producing a quantity of metal vapor in said envelope;
- (e) at least portions of the inner surface of said anode having an electron work function higher than the ionization potential of said vapor;
- (f) means for heating said anode surface to ionize said vapor by contact with said surface portions;
- (g) means for establishing an axial magnetic field in the region between said cathodes;
- (h) said anode and said cathodes having external terminals for applying potentials thereto.

6. Apparatus for producing a confined plasma having an ion density greater than 10^{14} ions/cm.³ and an ionization greater than 10 percent, comprising:

- (a) a hollow anode;

(b) a thermionic cathode facing each end of said anode;

(c) a gas-tight envelope enclosing said anode and cathodes;

(d) means for producing a quantity of metal vapor in said envelope;

(e) at least portions of the inner surface of said anode having an electron work function higher than the ionization potential of said vapor;

(f) means for heating said anode surface to ionize said vapor by contact with said surface portions;

(g) means for establishing an axial magnetic field in the region between said cathodes;

(h) said anode and said cathodes having external terminals for applying potentials thereto.

7. Apparatus for producing a confined cesium plasma having an ion density greater than 10^{14} ions/cm.³ and an ionization greater than 10 percent, comprising:

- (a) a hollow anode;
- (b) a thermionic cathode facing each end of said anode;
- (c) a gas-tight envelope enclosing said anode and cathodes;
- (d) means for producing cesium vapor in said envelope;
- (e) at least portions of the inner surface of said anode having an electron work function higher than the ionization potential of said vapor;
- (f) means for maintaining said anode surface at a temperature of at least 1,300° C., to ionize said vapor by contact with said surface portions;
- (g) means for establishing an axial magnetic field in the region between said cathodes;
- (h) said anode and said cathodes having external terminals for applying potentials thereto.

8. Apparatus for producing a low noise confined cesium plasma having an ion density greater than 10^{14} ions/cm.³ and an ionization greater than 10 percent, comprising:

- (a) a hollow anode;
- (b) a thermionic cathode facing each end of said anode;
- (c) a gas-tight envelope enclosing said anode and cathodes;
- (d) means for producing cesium vapor in said envelope;
- (e) at least portions of the inner surface of said anode having an electron work function higher than the ionization potential of said vapor;
- (f) means for maintaining said anode surface at a temperature of at least 1,300° C., to ionize said vapor by contact with said surface portions;
- (g) means for establishing an axial magnetic field in the region between said cathodes;
- (h) said anode and said cathodes having external terminals for applying potentials thereto;
- (i) said means for producing cesium vapor including means for adjusting the vapor pressure of said cesium to a value such that the neutral cesium density in said anode is at least 10^{15} neutrals/cm.³.

9. Apparatus for producing a confined cesium plasma having a density of about 10^{15} ions/cm.³ and an ionization of about 50 percent, comprising:

- (a) a hollow cylindrical anode;
- (b) a thermionic cathode facing each end of said anode in axial alignment therewith;
- (c) a gas-tight envelope enclosing said anode and cathodes;
- (d) means for producing cesium vapor in said envelope;
- (e) at least the inner surface of said anode comprising a metal having an electron work function higher than the ionization potential of cesium;
- (f) means for heating said anode surface to a temperature of about 1,700° C. to ionize said vapor by contact therewith;

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(g) means for establishing an axial magnetic field of about 7,500 gauss in the region between said cathodes; and

(h) means for applying a voltage of about 9 volts between said cathodes and said anode to ionize said vapor by electron impact. 5

10. Apparatus as in claim 9, wherein said anode is a tube of tantalum-tungsten alloy having a diameter of 0.5 cm. and a length of 2 cm., said cathodes are of the barium-impregnated-tungsten type having a total emissive area of 0.4 cm.² and operated at about 1,100° C. 10

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