United States Patent [19]
Bahr

[11] 3,757,518
[45] Sept. 11, 1973

[54] ION ENGINE

[75] Inventor: Alfred Bahr, Munich, Germany

[73] Assignee: Messerschmitt-Bolkow Blohm Gesellschaft mit beschrankter Haftung, Munich, Germany

[22] Filed: Oct. 20, 1971

[21] Appl. No.: 190,981

[30] Foreign Application Priority Data

Nov. 3, 1970 Germany.................. P 20 53 929.1

[52] U.S. Cl........................ 60/202, 313/63, 315/39, 315/111

[51] Int. Cl.. F03h 1/00

[58] Field of Search 60/202; 313/63, 231; 315/39, 111

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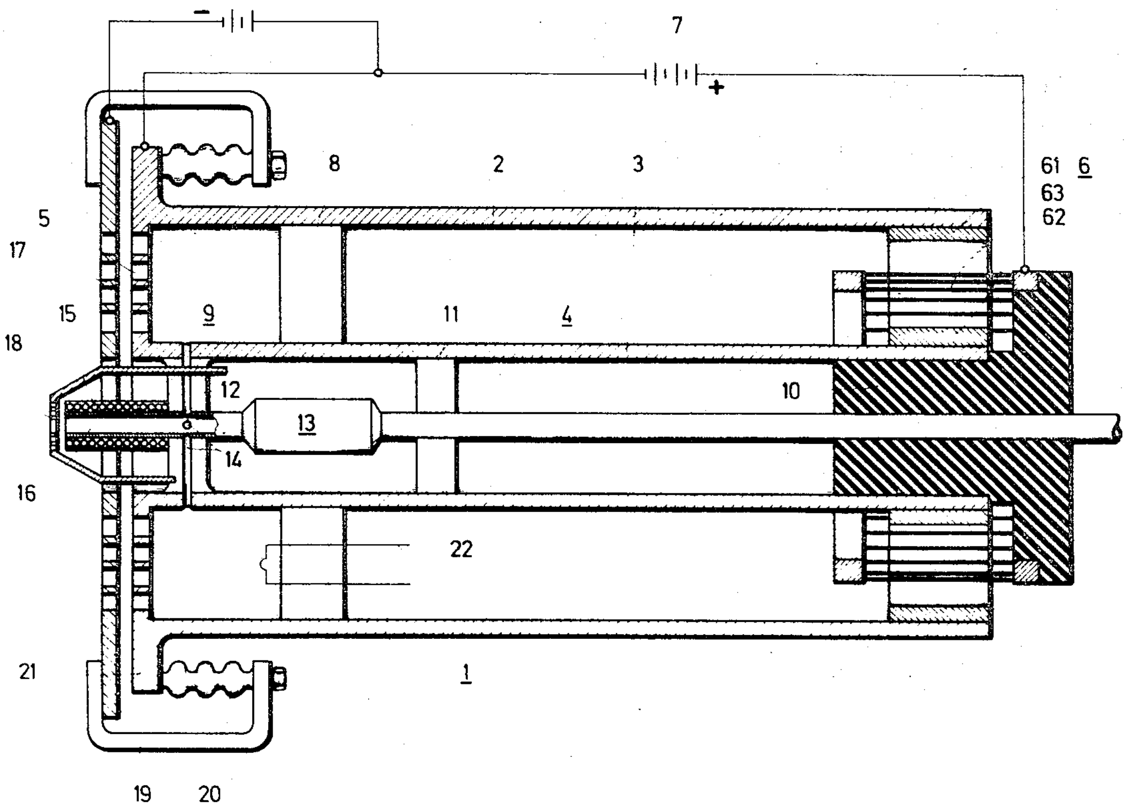
Primary Examiner—Carlton R. Croyle
Assistant Examiner—Robert E. Garrett
Attorney—John J. McGlew et al.

[57] ABSTRACT

An ion engine has a propellant supply system, means, including a high frequency generator, for the ionization of the electrically neutral propellant present in gaseous form in a discharge chamber closed off by a perforated bottom, an acceleration electrode, and means for the neutralization of the accelerated ion beam. The discharge chamber forms part of a high frequency resonator with the perforated bottom closing off one end of this resonator and with the resonator generating a standing electric wave having a node at the bottom. The resonator is a λ/4 resonator, where λ is the wave length of the electric wave, and the high frequency generator is arranged inside the resonator at the end opposite the bottom. The high frequency generator preferably is a disk seal triode or a Farnsworth tube.

13 Claims, 4 Drawing Figures



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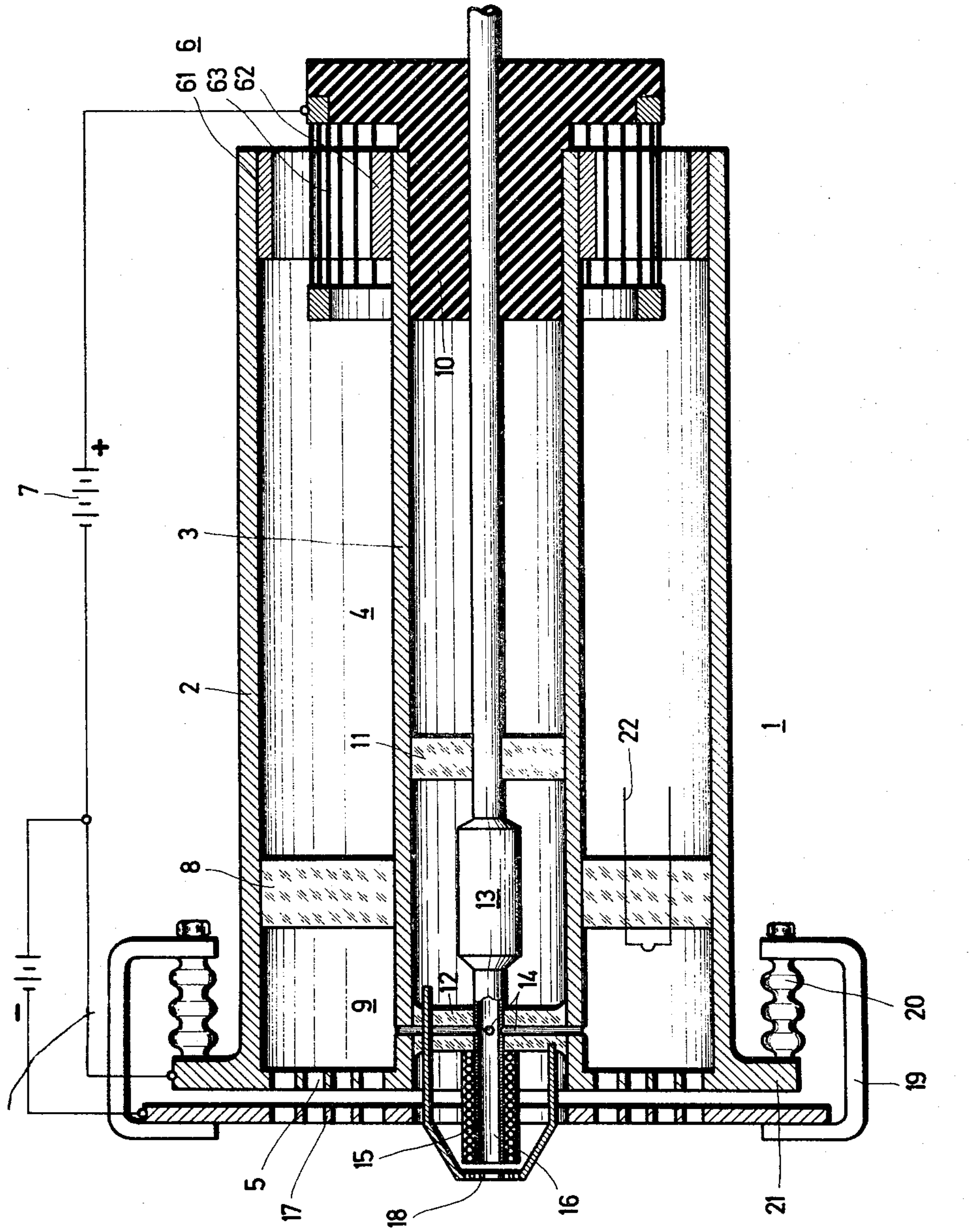


Fig.1

Fig. IA

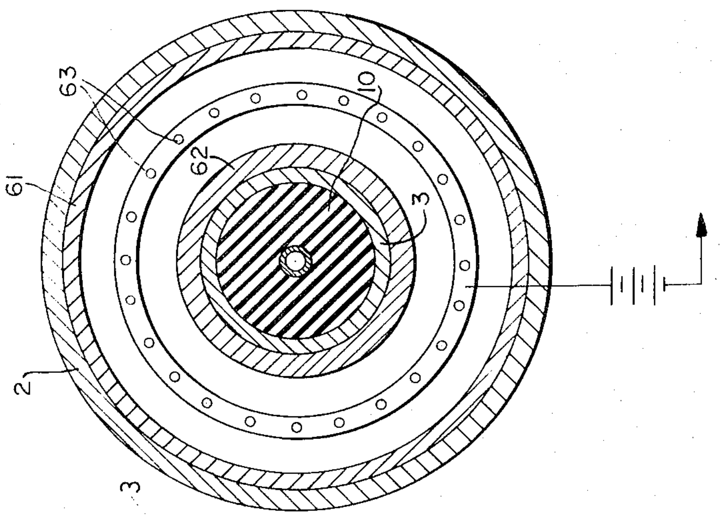
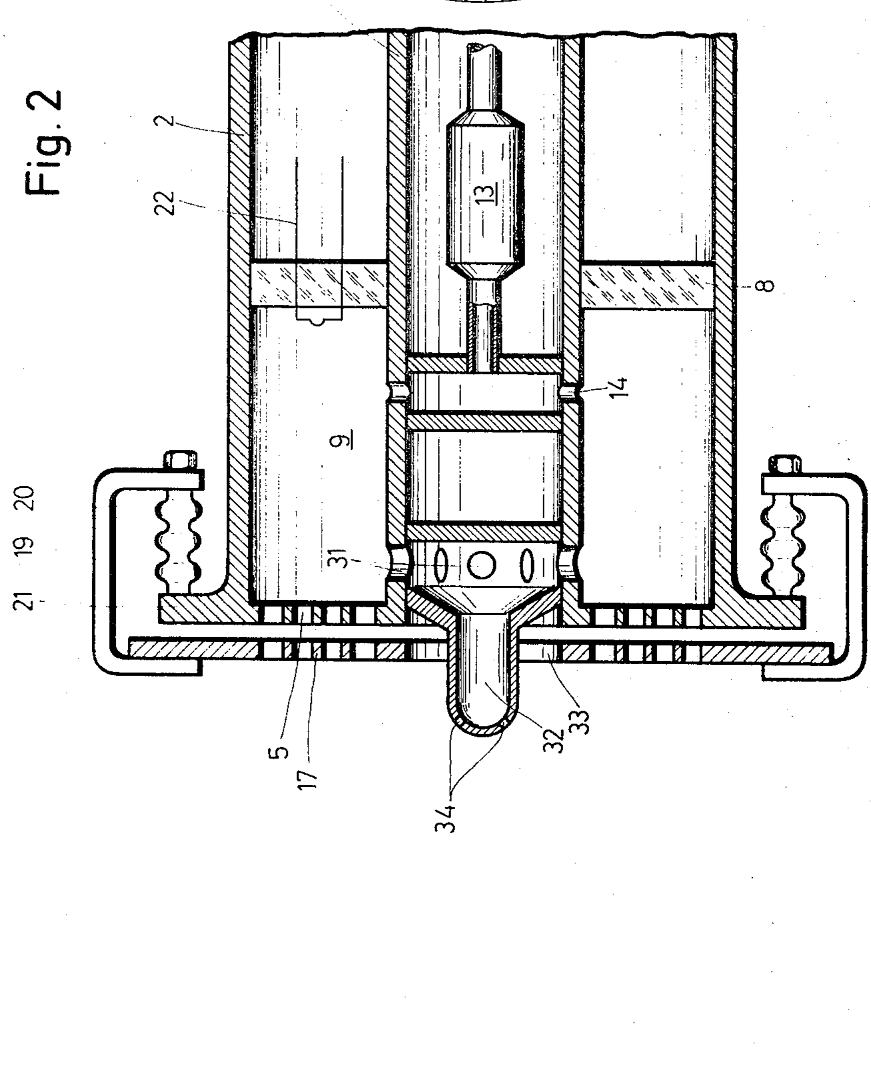


Fig. 2



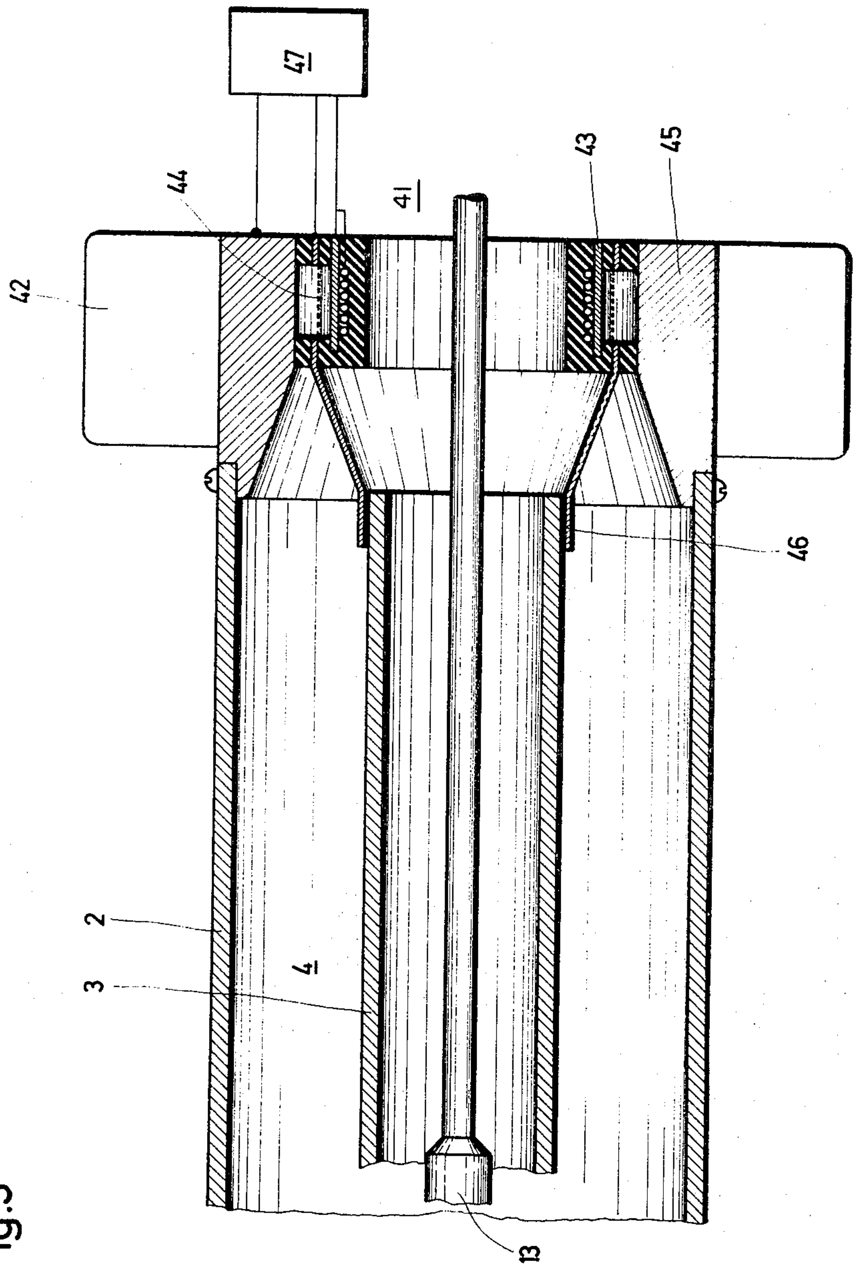


Fig.3

ION ENGINE

FIELD OF THE INVENTION

This invention relates to ion engines and, more particularly, to an ion engine which is of a simple mechanical construction and wherein, by a novel design of the discharge chamber, a plasma density, which improves the efficiency of the ion engine, is attained.

BACKGROUND OF THE INVENTION

In ion engines of the mentioned type, as used in spacecraft, neutral gas is ionized inductively by collision ionization in a discharge chamber consisting of dielectric material, for example, quartz. The ionization is effected by an induction coil surrounding the discharge chamber and supplied by a high frequency generator. For reference see, for example, H. W. Loeb, "State of the Art and Recent Developments of the Radio Frequency Ionmotors," AIAA Paper 69–285, 1969. The ions are accelerated electrostatically by means of an acceleration electrode, and neutralized by injection of electrons after passing the acceleration electrode.

While it is true that, in the ionization of the neutral gas with high frequency alternating fields, the problems occurring with conventional ion sources and related to the life of cathodes and anodes are eliminated, on the other hand, the mechanical construction of known high frequency engines, as well as the electronic circuits for the generation and control of the high frequency energy, are complicated and burdensome. The operational safety and, actually, the effective life of these ion engines thereby are reduced.

Another problem, occurring in known high frequency engines and in electrostatic ion sources, is the more or less irregular plasma density distribution in the radial direction as well as in the axial direction. This causes, in addition to high wall losses and diffusion losses, a low efficiency of these ion engines.

SUMMARY OF THE INVENTION

The objective of the invention is to provide an ion engine, of the kind mentioned above, which is of simple mechanical construction and wherein, by a novel design of the discharge chamber, a plasma density, which improves the efficiency of the ion engine, is attained. In accordance with the invention, this problem is solved in that the discharge chamber is part of a high frequency resonator closed off, on one end, by the perforated bottom, this resonator serving for the generation of a standing electric wave having a node at the bottom.

The excitation of the high frequency resonator, which is preferably a $\lambda/4$ resonator, is advantageously effected in that, in accordance with the preferred embodiment of the invention, the high frequency generator is a disk seal triode or a Farnsworth tube and is arranged within the resonator, namely at the end opposite the perforated bottom, so that the resonator and the high frequency generator form an organic unit.

As such an engine consists only of metal and comprises no electronic components such as resistors, condensers, transistors, etc., whose circuitry is susceptible to fault and breakage points, its mechanical and electrical construction is simple and strudy.

Another advantage of an ion egine embodying the invention is that, by the standing high frequency electric wave in the discharge chamber, Lorentz forces act on the ions and electrons of the gas discharge. These forces, as will appear hereinafter, accelerate the electrons and ions to the node of the standing wave located at the bottom. By virtue of this, the plasma density increases in the vicinity of the bottom, and furthermore, by the high concentration of the charge carriers and their axial velocity component at the perforated bottom, a reater current density is attained. In addition, the wall and recombination losses are smaller, since electrons and ions are accelerated immediately after their formation by the high frequency electric wave, and in the direction of the bottom of the resonator.

For these reasons, the efficiency of the ion engine is increased as compared with known ion engines so that, for example, at a certain acceleration voltage per unit time, more ions are extracted from the discharge chamber and accelerated by the acceleration electrode than is possible in known ion engines. Consequently, a thrust augmentation of the ion engine is attainable. The electrons remaining inside the discharge chamber after the electrostatic acceleration of the ions, and released during the ionization, are injected, in a known manner, into the accelerated ion beam through a neutralizing electrode.

In another preferred embodiment of the invention, the high frequency resonator comprises two concentrically arranged hollow cylinders which together form a coaxial $\lambda/4$ Lecher line, so that the device for the neutralization of the accelerated ion beam, and parts of the propellant supply system, can be arranged in the inner hollow or tubular cylinder. In addition to the saving of space, this arrangement has the further advantage that the device for the neutralization of the ion beam lies in the center of the accelerated ion beam, whereby an unfavorable effect on, and irregular neutralization of, the ion beam is avoided.

The device for the neutralization of the ion beam may, in a manner already known, be a hollow cathode, which injects the electrons remaining in the discharge chamber after the ionization into the ion beam through a plasma bridge produced by a gas discharge in the hollow or tubular cathode. However, the arrangement can be greatly simplified, namely by an also centrally arranged tubular hollow body which comprises, toward one end, apertures associated with the discharge chamber and, toward its other end, apertures in the direction of the accelerated ion beam.

With this arrangement and construction of the device for the neutralization of the accelerated ion beam, a plasma bridge to the accelerated ion beam is formed from the point inside the discharge chamber with high plasma pressure near the perforated bottom through the hollow body passed through the acceleration electrode, without the necessity of producing an additional gas discharge. By this procedure, all hollow or oxide cathodes, which would shorten the life of an engine, are avoided. By the elimination of the heated hollow or tubular cathode and of the respective energy supply and control, the engine is further simplified, by virtue of which the operational safety is further increased.

An object of the invention is to provide an improved ion engine which is of simple mechanical construction.

Another object of the invention is to provide such an ion engine in which, by a novel design of the discharge chamber, a plasma density, which improves the efficiency of the ion engine, is attained.

A further object of the invention is to provide such an ion engine in which the discharge chamber is part of a high frequency resonator closed off at one end by a perforated bottom, and serving for the generation of a standing electric wave having a node at the bottom.

For an understanding of the principles of the invention, reference is made to the following description of typical embodiments thereof as illustrated in the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing:

FIG. 1 is an axial or longitudinal sectional view of one embodiment of an ion engine in accordance with the invention.

FIG. 1A is a sectional end view through the Farnsworth tube of FIG. 1.

FIG. 2 is a partial axial or longitudinal sectional view illustrating another embodiment of an ion engine in accordance with the invention.

FIG. 3 is a partial axial or longitudinal sectional view illustrating a further embodiment of an ion engine in accordance with the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, an ion engine 1 comprises two concentrically arranged hollow or tubular metal cylinders 2 and 3, which conjointly form a coaxial λ/4 Lecher line, and whose cavity 4, defined between cylinders 2 and 3, is closed off at one end by a perforated bottom 5 designed as a multi-hole diaphragm. At the end of the resonator, formed by cylinders 2 and 3, opposite the end having bottom 5, a Farnsworth tube 6 is arranged. Tube 6 comprises two dynodes 61, 62 of a material with a secondary electron emission greater than 1, for example, nickel or silver, and a cylindrical grip type anode 63 arranged between dynodes 61 and 62. A source 7 of electric potential is connected between bottom 5 and anode 63, so that anode 63 has a positive potential relative to dynodes 61 and 62.

A wall 8, consisting of dielectric material, preferably quartz, is arranged between bottom 5 and Farnsworth tube 6 and divides off, from high bottom frequency generator 6, a discharge chamber 9 defined between bottom 5 and wall 8.

When one of the dynodes 61 or 62 or Farnsworth tube 6 emits electrons, for example by brief heating, there are acelerated toward anode 63 by the positive potential applied thereto, and decelerated after passage through the anode. The potential of anode 63 is rated so that the electrons impinge on one of the dynodes at a certain residual velocity after the deceleration, and release from this dynode its secondary electrons. In turn, these secondary electrons like the returning primary electrons, are accelerated toward anode 62 and, as they impinge, they knock additional secondary electrodes out of the opposite dynode, so that the initially present primary electrons are multiplied in avalanche fashion. In this manner, very large current density and voltage amplitudes can be produced.

To make possible the operation of this high frequency generator 6, which is designed as a Farnsworth tube, the length of the λ/4 resonator connected between the two dynodes and the anode, and comprising the two cylinders 2 and 3, must be matched so that the natural period thereof is matched to the electron transit time between diodes 61 and 62. In resonator zone 4, there is thereby formeda standing high frequency electric wave whose node lies at the bottom 5 and whose antinode lies on the high frequency generator 6.

Production of the high frequency wave is, of course, possible by other means, such as, for example, avalanche diodes, commercial disk seal triodes, such as the Telefunken tube 2 C 40, or by means of transistor circuits.

In inner cylinder 3, there is arranged a propellant vaporizer 13 electrically insulated from cylinder 3 by supporting elements 10, 11 and 12. In vaporizer 13, liquid mercury is evaporated, and passes through several channels 14 into discharge chamber 9. A small portion of the vaporous mercury passes into a hollow or tubular cathode 16 provided with a heating coil 15. Cathode 16 extends through a central opening of acceleration electrode 17, which is designed as a multi-hole diaphragm. In front of cathode 16, there is arranged, in insulated relation, a starting electrode 18. A DC voltage is applied between bottom 5 and acceleration electrode 17, with the negative terminal of the DC source being connected with acceleration electrode 17. Acceleration electrode 17 is connected mechanically, by straps 19 and insulators 20, with a flange 21 arranged on outer cylinder 2.

Ion engine 1 operates in a manner which will now be described. In discharge chamber 9, by means of a starting electrode 22, a gaseous discharge of mercury is initiated at a pres-sure of 10^{-2} to 10^{-3} Torr, and this discharge is thereafter maintained by the high frequency alternating field, so that the mercury stays ionized.

The electric field E, acting on the charge carriers formed during ionization, is, written in cylinder coordinates,

$$E(r,z,t) = E_o\,(r,z) \cdot \cos(wt) \tag{1}$$

In this equation, r is the radial coordinate, z is the axial coordinate, both referred to the two cylinders, and t is the time. The field component E_o, existing for $t=0$, can be represented, for a value U of voltage source 7, as

$$E(r,z,o) = U/[r\, ln(r_2/r_1)] \cdot \cos\,[(\pi/2\,l)\,z] \tag{2}$$

In equation (2), r_2 is the inner radius of the outer cylinder 2, and r_1 is the outer radius of the inner cylinder 3. $l = \lambda/4$ is the length of the cylinders 2 and 3.

The magnetic field B, induced by the high frequency electric wave, is associated with the electric field E through the first Maxwell equation which, taking into consideration the fact that there is present in the resonator only the radial component E_r of the electric field and the tangential component of the magnetic field, is simplified in cylindrical coordinates as

$$\delta\, E_r/\delta\, z = -\,(l/c)\,(\delta\, B_\theta\ \ /\delta\, t) \tag{3}$$

By inserting equations (1) and (2) into equation (3) and with subsequent partial integration with respect to time, there is obtained for the magnetic field

$$(l/w)\ (\pi/2\ l)\ [U/r\,ln(r_2/r_1)] \cdot \sin\ [\pi/2\ l\ z] \cdot \sin(wt) = (l/c)\ B_\theta \quad (4)$$

This equation can also be written, in analogy with equation (1), as

$$B_\theta(r,z,t) = B_{\theta o}\ (r,z) \cdot \sin(wt) \quad (4a)$$

A comparison with equation (1) shows that B_θ is phase-shifted by 90° with respect to the radial electric field E_r. However, the motions of the electrons and ions oscillating radially in the electric field E_r are also phase-shifted by 90° in relation to E_r, so that they are in phase with the magnetic field B_θ, as will be shown in the following. The equations of motion for the charged particles are

$$m_e \cdot (d\ V_{re}/dt) = -\ e\ E_r \quad (51)$$

$$m_i \cdot (d\ V_{ri}/dt) = -\ e\ E_r \quad (52)$$

In these equations, indices e and i indicate a quantity connected with an electron or with an ion, respectively, and V_r represents the respective radial velocity components.

Taking into consideration equation (1), there is attained from equations (51) and (52):

$$V_{re} = -\ (e/w\ m_e)\ E_o\ (r,z) \cdot \sin(wt) \quad (61)$$

$$V_{ri} = (e/w\ m_i)\ E_o\ (r,z) \cdot \sin(wt) \quad (62)$$

Since thus the magnetic field B_θ as well as the radial velocities of the electrons and ions vary sinusoidally and they are therefore in phase, there act, on the charge particles, Lorentz forces, which can be expressed by the product of the charge with the vector product from the velocity of the charge carriers and the magnetic field:

$$F_e = -\ e\ (V_{re} \times B_\theta) \quad (71)$$

$$F_i = e\ (V_{ri} \times B_\theta) \quad (72)$$

By inserting in equations (71) and (72) the expressions for the velocities and or the magnetic fields as derived from equations (61), (62) and (4a), there results

$$F_e = (e^2/w\ m_e)\ E_o\ (r,z) \cdot B_o\ (r,z) \cdot \sin^2\ (wt) \quad (71a)$$

$$F_i = (e^2/w\ m_i)\ E_o\ (r,z) \cdot B_o\ (r,z) \cdot \sin^2\ (wt) \quad (72a)$$

It will be seen that the Lorentz force acting on the electrons and ions is always positive, that is, it is directed toward the node of the standing wave.

Although the forces acting on the electrons and ions bring about different velocities in the axial direction, due to the different masses thereof, these velocity differences are eliminated by charge separation forces, so that the electrons and ions move at the same velocity V_z in the z-direction. From the movement equation of motion of the plasma.

$$m_i(dV_{zi}/dt) + m_e(dV_{ze}/dt) = -\ e(V_{re} \cdot B_\theta) + e(V_{ri} \cdot B_\theta) \quad (8)$$

there is obtained, therefore, for $V_{ze} = V_{zi} = V_z$

$$(m_i + m_e)\ (d\ V_z/dt) = -\ e(V_{re} - V_{ri})\ B_\theta \quad (8a)$$

Since V_{ri} is very small with respect to V_{re}, and also m_e is very small with respect to m_i, equaion (8a) is simplified to

$$m_i(d\ V_z/dt) = -\ e(V_{re} B_\theta) = (e^2/w\ m_e)\ E_o\ (r,z) \cdot B_o\ (r,z)\ \sin^2(wt) = (e^2c/w^2\ m_e)\ (\pi/2\ l)[U/r\ ln(r_2/r_1]^2 \cdot \sin[(\pi/2\ l)z] \cdot \cos[(\pi/2\ l)z] \cdot \sin^2\ (wt) \quad (9)$$

From equation (9), it is evident that the acceleration in the z-direction dV_z/dt is positive between $z = 0$ and $z = 1$, that is, up to the perforated bottom **5**. Expressed in other words, this means that the ions and electrons are pushed toward the bottom **5** so that immediately before this bottom a high plasma density and a high current density are formed.

The ions arriving at bottom **5** with the velocity V_z are pulled out of the discharge chamber **9** by acceleration electrode **17** in a known manner, and are further accelerated electrostatically. The electrons remaining in discharge chamber **9** are injected into the accelerated ion beam over the plasma bridge formed after ignition of cathode **16** by starting electrode **18**, so that the beam is neutralized.

As can be seen from equation (9), the velocity attained at bottom **5** by electrons and ions, and hence also the plasma density present at the bottom, can be adjusted by adjusting the length of the discharge chamber.

By virtue of the plasma density increasing in the direction of the perforated bottom, a further form of construction of the device for the neutralization of the accelerated ion beam is possible, as shown in FIG. **2**. In FIG. **2**, at its end toward bottom **5**, discharge chamber **9** has apertures **31** which connect discharge chamber **9** with a tubular hollow body **32**. This body **32**, which protrudes through an opening **33** of acceleration electrode **17**, is also provided with openings **34** at its end away from the engine. When the plasma in discharge chamber **9** is pushed against bottom electrode **5**, a small portion of the plasma will pass through openings **31** into hollow body **32**, and thence through opening **34** to the accelerated ion beam, thus forming a plasma bridge. The electrons remaining in the discharge chamber **9** are drawn across this plasma bridge into the accelerated ion beam, which represents, for the electrons, a positive anode. The ion beam is thereby neutralized.

The embodiment of the invention shown in FIG. **2** has the additional advantage that no thermally loaded electrodes are used. Naturally, the design of the neutralizer shown in FIG. **2** is possible also with other ion engines, as long as they have a sufficient plasma density in the region of the neutralizer.

In a further embodiment of the invention a conventional disk seal triode **41** with radiators **42** for radiation cooling is incorporated to produce the standing high frequency wave inside the cavity **4** of the λ/4 resonator. Triode **41** has a heated cathode **43**, grid **44** and anode **45**. Grid **44** is separated from the DC high voltage of the anode **45** by capacity **46**. Cathode **43**, grid **44** and anode **45** are supplied with DC voltages from a power supply **47**.

Triode **41** with capacity **46** and resonator consisting of the two cylinders **2** and **3** and the perforated bottom **5** is equivalent to a well known Colpitts-circuit.

By the so produced high frequency wave the evaporated mercury in the discharge chamber is ionized and accelerated towards the perforated bottom as described above.

While specific embodiments of the invention have been shown and described in detail to illustrate the application of the principles of the invention, it will be understood that the invention may be embodied otherwise without departing from such principles. What is claimed is:

1. In an ion engine having means defining a discharge chamber closed off by a perforated bottom, a propellant supply system communicating with the discharge chamber and supplying thereto electrically neutral propellant in gaseous form, a high frequency generator operable to ionize the gaseous propellant in the discharge chamber, a perforated acceleration electrode mounted, in electrically insulated relation, in outwardly spaced relation to the perforated bottom of the discharge chamber and pulling the ionized propellant out of the discharge chamber and accelerating the ionized propellant electrostatically to create an accelerated ion beam, and means operable to neutralize the accelerated ion beam, the improvement comprising, in combination, said discharge chamber forming part of a high frequency cavity resonator having a cylindrical wall closed at one end by said perforated bottom and having an open end, said cavity resonator containing said high frequency generator and said propellant supply system; said high frequency generator energizing said cavity resonator at its eigen frequency and producing, in said high frequency cavity resonator, a standing electrical wave having a node at said perforated bottom; and dielectric means mounting said acceleration electrode on said cylindrical wall.

2. In an ion engine, the improvement claimed in claim **1**, in which said high frequency resonator is a λ/4 resonator, wherein λ is the wave length of the electric wave.

3. In an ion engine, the improvement claimed in claim **1**, in which said high frequency generator is arranged inside said high frequency resonator at the open end of said high frequency resonator opposite said perforated bottom.

4. In an ion engine, the improvement claimed in claim **2**, in which said high frequency generator is arranged inside said high frequency resonator at the open end of said high frequency resonator opposite said perforated bottom.

5. In an ion engine, the improvement claimed in claim **1**, in which said high frequency generator is a Farnsworth tube.

6. In an ion engine, the improvement claimed in claim **5**, in which said Farnsworth tube is arranged inside said high frequency resonator at the open end opposite perforated said bottom.

7. In an ion engine, the improvement claimed in claim **1**, in which said high frequency generator is a disk seal triode.

8. In an ion engine, the improvement claimed in claim **7**, in which said disk seal triode is arranged inside said high frequency resonator at the open end opposite said perforated bottom.

9. In an ion engine, the improvement claimed in claim **1**, inwhich said high frequency resonator comprises two concentrically arranged tubular cylinders, the space intermediate said two cylinders forming a resonator chamber closed off at one end by an annular perforated bottom.

10. In an ion engine, the improvement claimed in claim **9**, in which said means for the neutralization of the accelerated ion beam, as well as parts of said propellant supply system, are arranged in the inner of said cylinders.

11. In an ion engine, the improvement claimed in claim **1**, in which said means for the neutralization of the accelerated ion beam comprises a hollow tubular body having, at one end, openings communicating with said discharge chamber and, at its other end, openings toward the accelerated ion beam.

12. In an ion engine, the improvement claimed in claim **5**, in which said means for the neutralization of the accelerated ion beam comprises a hollow tubular body having, at one end, openings communicating with said discharge chamber and, at its other end, openings toward the accelerated ion beam.

13. In an ion engine, the improvement claimed in claim **7**, in which said means for the neutralization of the accelerated ion beam comprises a hollow tubular body having, at one end, openings communicating with said discharge chamber and, at its other end, openings toward the accelerated ion beam.

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