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March 14, 1967 E. A. PINSLEY 3,308,621

OSCILLATING-ELECTRON ION ENGINE

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FIG. 1

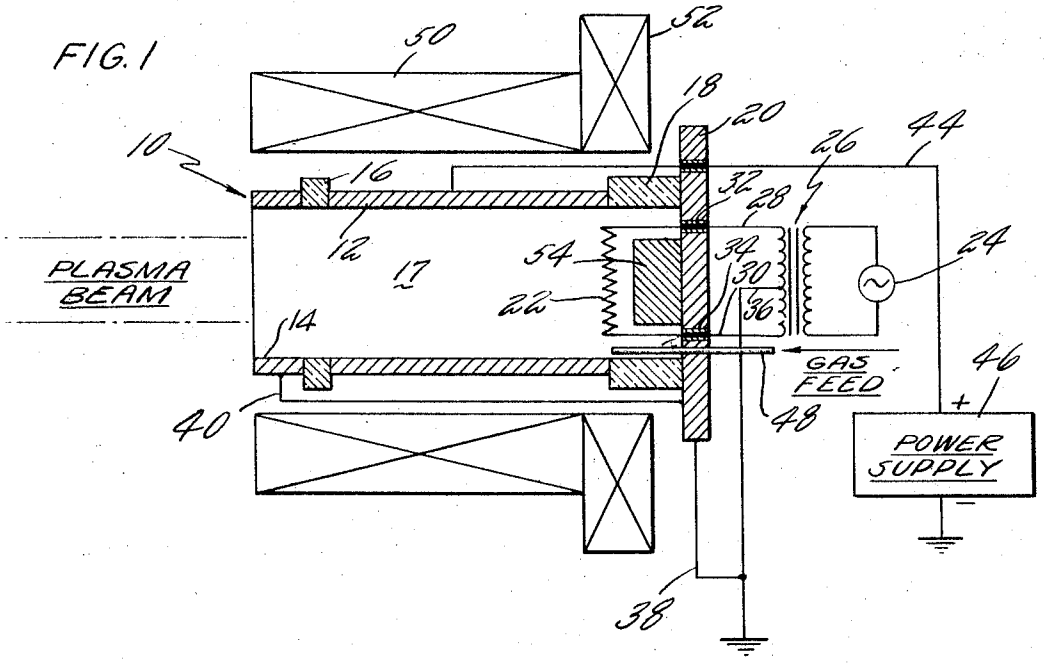
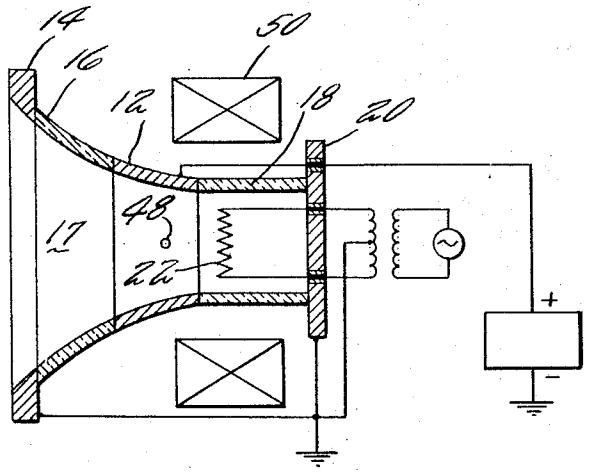


FIG. 2



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FIG. 3

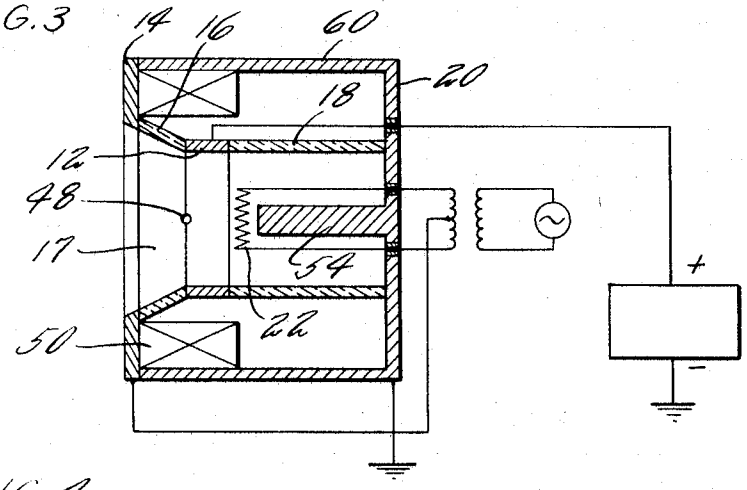


FIG. 4

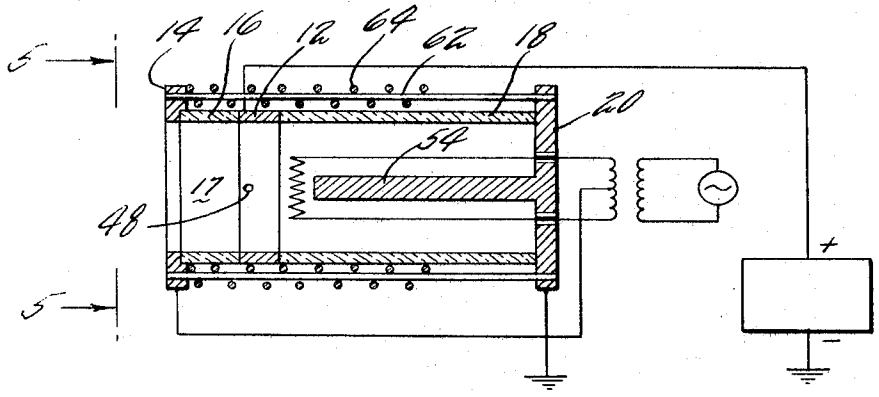
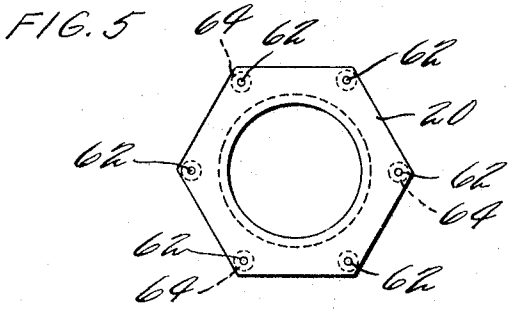


FIG. 5



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FIG. 6

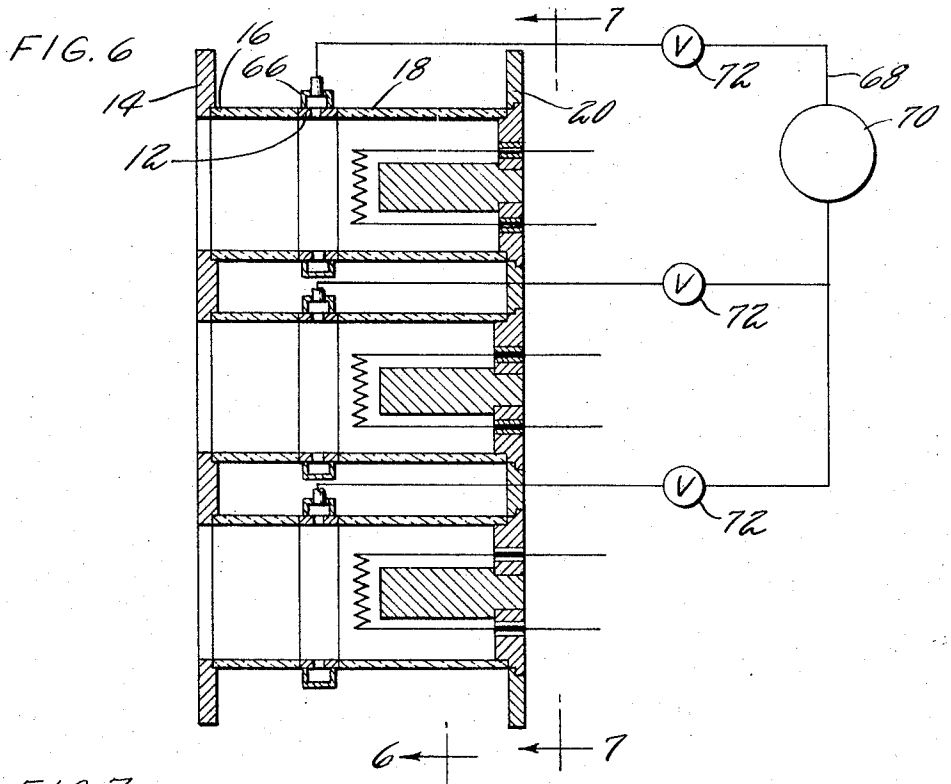
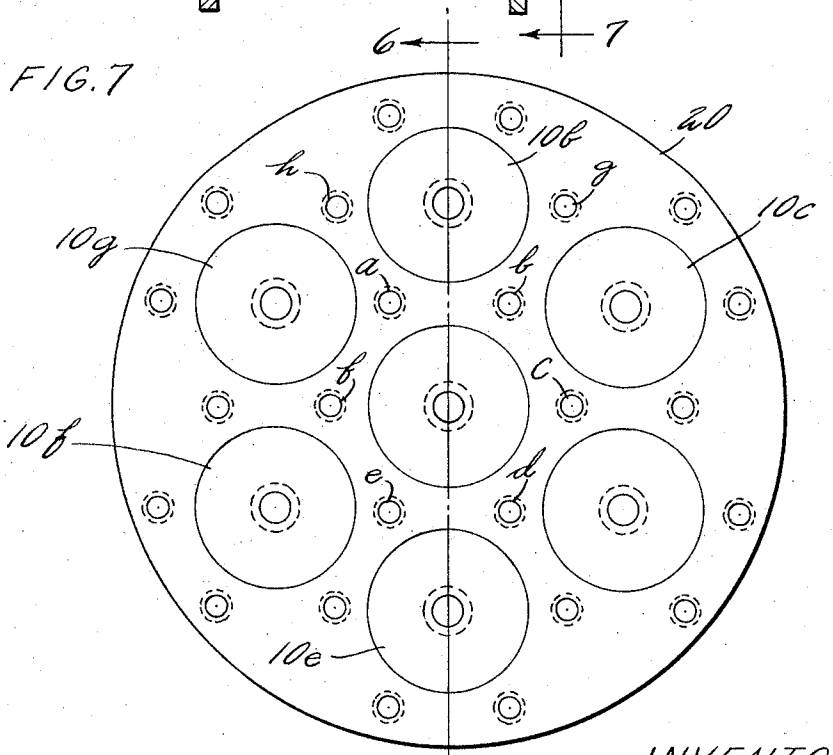


FIG. 7



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3,308,621

OSCILLATING-ELECTRON ION ENGINE

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20 Claims. (Cl. 60—202)

This invention relates to an electrical propulsion system. More particularly, this invention relates to an improved oscillating-electron type of ion engine.

In the oscillating-electron ion engine, positive ions are produced by electron bombardment of neutral gas molecules. These ions are accelerated by self-generated potential gradients maintained in an essentially space-charge neutral plasma. The basic principle of the operation of the engine involves the establishment of an axially symmetric electrostatic "potential well" on which electrons are axially trapped and from which ions are axially accelerated. The radial drift of electrons is inhibited by the presence of a confining magnetic field.

The oscillating-electron ion engine utilizes many of the features of the Penning discharge. A discussion of the basic principles of the Penning discharge as adapted for use in accelerating ions and plasmas can be found in "High Current Ion Source" by R. G. Meyerand, Jr., et al., in the Review of Scientific Instruments, vol. 30, No. 2, February 1959. In the Penning discharge, electrons are emitted by a cathode and are accelerated electrostatically toward a hollow cylindrical anode. The electron drift motion in the radial direction toward the anode is constrained by a confining D.C. magnetic field generated by a solenoid which encircles the anode. Hence, the electron trajectory is a spiral along a magnetic field line contained within the anode cavity. This spiral terminates at the extremities of the "potential well," and the electron thus oscillates between these extremities.

When the Penning discharge is to be used as an ion or plasma, a hollow electrode is positioned downstream of the anode and is maintained at the same potential as the cathode. During operation of the Penning device, a self-generated electrostatic potential gradient will be set up in the vicinity of the downstream electrode in a fashion described in "Electrostatic Potenial Gradients in a Penning Discharge" by F. Salz et al., Physical Review Letters, May 15, 1961. The electrons are reflected back through the anode cavity by this potential gradient, and are thus trapped and forced to oscillate in the "potential well" formed between the cathode and the downstream electrode. The expellant gas is admitted into the source and diffuses as a free molecular flow through the anode region. Ions are formed by the impact of electrons upon the expellant gas molecules thereby forming a neutral plasma.

In the above-described oscillating-electron ion engine utilizing the Penning discharge principle, it can be shown that a large portion of the thrust is transmitted to the engine through impingement of ions on the cathode. This impingement of ions on the cathode is undesirable because it represents a source of energy loss and also results in deterioration of the cathode by sputtering action.

In the present invention the efficiency of the engine is increased and sputtering damage to the cathode is reduced by generating part of the engine thrust through interaction between electrons and a magnetic mirror field whereby momentum from the oscillating electrons is transferred as thrust to the structure generating the magnetic mirror field. A nonuniform magnetic field is generated in the engine with a higher flux density in the vicinity of the engine cathode than elsewhere in the engine to form a magetic mirror in the vicinity of the cathode. The presence of the higher flux density magnetic field in the vicinity of the

cathode results in a significant interaction between the tangential component of velocity of the electrons and the radial component of the magnetic field. Electrons are reflected away from the cathode by this interaction and their momentum is transferred to the engine as thrust on the structure generating the magnetic field.

The generation of the magnetic mirror in the vicinity of the cathode can be accomplished in several ways. The ampere turns of the engine solenoid can be increased in the vicinity of the cathode; a ferromagnetic element can be inserted in the engine behind the cathode; ferromagnetic elements can be used to provide a desired path for the magnetic lines of flux; or combinations of these alternatives can be used. Furthermore, the envelope of the engine can be contoured to conform in a general manner with the shape of the magnetic field to minimize charged particle interception losses.

Accordingly, one object of the present invention is to provide a novel and improved electrical propulsion device.

Another object of the present invention is to provide a novel electrical propulsion device having a magnetic mirror which is utilized in the production of thrust.

Still another object of the present invention is to provide a novel electrical propulsion engine having greater efficiency and greater life expectancy than previous engines.

Other objects and advantages will be apparent from the specification and claims, and from the accompanying drawings which illustrate an embodiment of the invention.

FIGURE 1 is a schematic representation of an oscillating electron ion engine with a generalized showing of a magnetic mirror in accordance with the broad concept of the present invention.

FIGURE 2 is a showing of an oscillating-electron ion engine wherein the engine envelope is contoured to conform to magnetic field lines.

FIGURE 3 is a showing of a modified ion engine having a ferromagnetic casing to direct magnetic flux lines to form a magnetic mirror.

FIGURE 4 is a showing of another modified ion engine having ferromagnetic rods and structure.

FIGURE 5 is a showing along line 5—5 of FIG. 4.

FIGURE 6 is a view along line 6—6 of FIG. 7 and is a sectional elevation view of a cluster of engines of the type shown in FIG. 4.

FIGURE 7 is a view along line 7—7 of FIG. 6.

In the several figures of the drawings, similar parts will receive the same numbers.

Referring now to FIG. 1, the oscillating-electron ion engine **10** has an annular anode electrode **12** and an annular downstream electrode **14** separated from anode **12** by an annular insulating element **16**. Downstream electrode **14** defines the open end of the ionization region chamber **17** of the ion engine. Annular anode **12** is separated by another annular insulator **18** from backplate element **20** which closes off one end of chamber **17**.

A cathode element **22** is located in chamber **17** and is supplied with heating current from a current supply **24** through a transformer **26**. The end terminals of the secondary of transformer **26** are connected to cathode **22** via conductors **28** and **30** which pass through backplate **20** through insulating sleeves **32** and **34**, respectively. Cathode **22** is maintained at D.C. ground potential through the grounded center tap **36** of the secondary winding of transformer **26**; backplate **20** is connected to ground via conductor **38**, and the downstream electrode **14** is also connected to ground via conductor **40** connected to conductor **30** through a connection to backplate **20**. The description "ground" implies a common potential; in a space vehicle this will generally, but not necessarily, be

the vehicle potential. A positive acceleration voltage is supplied to anode **12** through a conductor **44** which is connected to the positive side of the power supply **46**.

The expellant or propellant gas which is to be ionized in chamber **17** is introduced into chamber **17** from a supply tank (not shown) through a tube **48** which passes through backplate **20**. It will be understood that the propellant gas feed can be accomplished at other locations such as radially inward through the anode as shown in succeeding figures of the drawings. Since ionization is achieved in chamber **17** through electron bombardment, any propellant gas may be used provided essentially only one charge-mass ratio species is obtained. By way of example, argon, neon, krypton, nitrogen, mercury, xenon or the alkali metals can be used as propellants.

Exteriorally of the annular envelope defining chamber **17** is a solenoid **50** connected to a source of D.C. current (not shown) for generating a magnetic field substantially coaxial with the axis of engine **10**. Solenoid **50** has an increased number of turns **52** in the vicinity of the plane of cathode **22**. The increased number of ampere turns **52** serves to form a magnetic mirror by creating a magnetic field having a greater flux density in chamber **17** in the vicinity of cathode **22** than elsewhere in chamber **17**. The entire magnetic field generating structure is either supported on engine **10** or is attached to the vehicle of engine **10**. A ferromagnetic element **54** extending from backplate **20** toward cathode **22** is also shown forming part of the magnetic mirror. In accordance with the present invention, either the increased number of turns **52** or ferromagnetic element **54** can be used independently or in conjunction with the other to form a magnetic mirror in chamber **17** in the vicinity of cathode **22**; furthermore, any other means of creating a magnetic mirror in the vicinity of cathode **22** can be used as equivalents within the scope of the present invention. However, it is preferred that the varying flux density magnetic field extend throughout chamber **17** and vary from a maximum flux density in the vicinity of the cathode to a minimum flux density at the discharge end of the chamber **17**. That is, a magnetic mirror having a varying flux density throughout chamber **17** is preferred to one which only has a localized flux density variation in the vicinity of cathode **22**.

In the operation of the ion engine shown in FIG. 1, electrons are emitted from cathode **22**, and these electrons are accelerated electrostatically toward anode **12**. The electron drift motion in the radial direction toward anode **12** is constrained by the D.C. magnetic field generated by solenoid **50** so that the electron trajectories are spirals along axes substantially parallel to the magnetic field lines. As the electrons spiral down the ionization chamber they collide with neutral gas molecules of the propellant introduced into the chamber via tube **48**, thereby producing positive ions and forming a plasma. As explained in the above-referenced article by Salz et al., from Physical Review Letters, a self-generated electrostatic potential gradient will be set up in the plasma in the vicinity of downstream electrode **14**. This potential gradient produces a "potential well" which will accelerate ions in the vicinity of downstream electrode **14** toward the open or discharge end of chamber **17** while decelerating electrons. As the ions are ejected from the engine the discharge beam potential rises slightly, and this allows a sufficient number of cathode electrons whose mean free paths are very long to escape from chamber **17** along with the ions to form the essentially neutral plasma discharge beam necessary for propulsion.

In the standard type of oscillating-electron ion engine the thrust is transmitted to the engine through impingement of ions and electrons on the cathode. As has already been pointed out, the impingement of ions represents an energy loss which limits engine efficiency and also results in deterioration of the cathode through sputtering. The magnetic mirror construction of the present engine overcomes these shortcomings of the standard type of oscillating-electron ion engine by contributing to the generation of thrust through the interaction of electrons and the field of the magnetic mirror.

In the structure of FIG. 1, the increased number of ampere turns **52** and the ferromagnetic element **54** function to bunch the magnetic flux lines in the vicinity of cathode **22** so that flux density in chamber **17** is highest in the vicinity of cathode **16**. As has already been stated, it is preferable to form a magnetic mirror so that the magnetic lines of flux diverge from cathode **22** throughout chamber **17** to downstream electrode **14** so that the magnetic mirror extends throughout chamber **17**. As a result of the presence of the magnetic mirror in chamber **17** there is a significant interaction between the tangential component of electron velocity and the radial component of the magnetic field. Interaction between the ions and the field is small because of the relatively great weight of the ions with respect to the electrons. Electrons are reflected by this above-discussed interaction with the magnetic field and their momentum is transferred as thrust to the structure generating the magnetic field, i.e., on the solenoid **50** and the increased number of turns **52**. The solenoids are supported by the vehicle structure and hence this thrust is transmitted to the vehicle. As a result of the application of the magnetic field mirror, engine operating efficiencies are improved because the generation of thrust is not solely dependent on the backflow of ions, and engine life is lengthened by the reduction in cathode erosion.

Referring now to FIG. 2, the annular envelope of engine **10** is contoured, i.e., the inner surfaces of anode **12**, electrode **14**, and insulators **16** and **18** are shaped, along the lines of the magnetic field generated by solenoid **50**. The contouring is such that magnetic field lines which pass through the cathode **22** are not allowed to intercept any other electrode surface, and as a result charged particle interception losses are minimized. The contouring of the engine surface substantially conforms to the contour of the magnetic field from the axial station of cathode **22** so that the interior surfaces of electrode **14**, insulators **16** and **18**, and anode **12** are everywhere parallel to the magnetic field lines in their immediate vicinity. The configuration of the magnetic field throughout the length of chamber **17** constitutes a magnetic mirror in chamber **17** which functions as described above to transmit thrust through interaction between electrons and the magnetic mirror. The transmittal of thrust between electrons and ions is accomplished by electrostatic forces by the same principles as described by Salz et al. in Physical Review Letters.

Referring now to FIG. 3, a ferromagnetic sleeve **60** extends from downstream electrode **14** to backplate **20**, both electrode **14** and backplate **20** also being ferromagnetic. Sleeve **60** and backplate **20** are shown in FIG. 3 as being of one piece, which would be cup-shaped in construction, but it will be apparent that sleeve **60** and backplate **20** could be separate elements. Magnetic field generating solenoid **50** is housed in the annular chamber formed by the envelope of the engine and sleeve **60**. The ferromagnetic structure of sleeve **60**, backplate **20**, and element **54** provides a high permeability path for the lines of flux generated by solenoid **50**. This ferromagnetic structure acts to shape the magnetic field so that it is of very high flux density in the vicinity of cathode **22** and diverges toward downstream electrode **14** so that the necessary magnetic mirror is formed.

The embodiment shown in FIG. 4 is quite similar to that in FIG. 3 in that ferromagnetic structure is provided exteriorally of the engine envelope to provide a magnetic flux path. However, in the FIG. 4 embodiment the external ferromagnetic structure consists of a plurality of individual ferromagnetic rods **62** placed around the engine, preferably uniformly around the engine as shown in FIG. 5 and extending between ferromagnetic electrode **14** and ferromagnetic backplate **20**. In the FIG. 4 em-

bodiment the magnetic field generating elements are a number of separate small coils **64**, each of which surrounds one ferromagnetic rod **62**. The FIG. 4 embodiment functions in the same manner as the FIG. 3 embodiment, but the FIG. 4 embodiment realizes a significant weight savings in the use of the individual rods rather than an entire ferromagnetic sleeve, and further substantial savings are realized in the use of small individual coils rather than a massive solenoid winding.

A further significant advantage of the structure of FIG. 4 resides in the fact that it can be used in a building block concept. As can be seen in FIG. 5, by shaping the end plate **20** hexagonally a ready foundation is made for expansion by adding individual units together. The units would be butted together along hexagonal edges, and as will be more fully described in connection with FIGS. 6 and 7, the butting units can share common rods **62** to realize a further savings in weight and material.

FIG. 7 shows the end plate view of a cluster of seven elements of the FIG. 4 embodiment. As can readily be seen, each engine shares several rods with one or more neighboring engines. For example, central engine **10***a* has rods *a*, *b*, *c*, *d*, *e* and *f*; rods *a* and *b* are in common with engine **10***b*; rods *b* and *c* are in common with engine **10***c*; rods *c* and *d* are in common with engine **10***d*; rods *d* and *e* are in common with engine **10***e*; rods *e* and *f* are in common with engine **10***f*; and rods *f* and *a* are in common with engine **10***g*. It can also be readily seen that engine **10***b* shares rod *g* in common with engine **10***c* and rod *h* in common with engine **10***g*, and the commonality of the other rods will be readily apparent. The structure of FIG. 7 is shown having a single backplate **20**, but it will be understood that this multi-engine structure could as well be made by joining a number of the hexagonal units shown in FIG. 5 and using common rods as described.

FIG. 6 is a view along line **6—6** of FIG. 7 and shows the engines **10***b*, **10***a*, and **10***e* of FIG. 7. A manifold **66** surrounds each engine to supply the propellant through openings in the anode, and each manifold is fed through a conduit **68** by supply tank **70**. There is a valve **72** in the supply line to each engine, and any engine can be selectively turned on or off through the valves **72** to initiate or terminate propellant flow to any engine and thereby vary the thrust of the entire cluster of engines. Although only the supplies to three engines are shown in FIG. 6, it will be understood that a similar supply line **68** and valve **72** is provided for each engine if desired so that any engine or combination of engines of the cluster can be manipulated to vary the total thrust of the cluster. Variations in engine thrust might also be realized by control of the propellant flow rate through the individual engines or by control of the electric potential of individual engines.

It will be understood that in any of the embodiments of this invention the ferromagnetic element **54** can be incorporated or omitted as desired. It will also be understood that all or portions of the ferromagnetic elements may be formed of permanent magnets so that the solenoids **50** or the coils **64** may be eliminated to minimize engine weight and power requirements.

It is to be understood that the invention is not limited to the specific embodiment herein illustrated and described but may be used in other ways without departure from its spirit as defined by the following claims.

I claim:

1. An electrical propulsion engine including:
a chamber having positive and negative particles therein said chamber having an open end,
a cathode in said chamber removed from said open end for generating negative particles,
means for accelerating at least part of said positive particles through the open end of said chamber and for causing at least part of said negative particles to oscillate in said chamber,
and magnetic mirror means for introducing a magnetic field of non-uniform flux density into said chamber in the vicinity of said cathode for reflecting negative particles from the vicinity of said cathode toward the open end of said chamber.

2. An electrical propulsion engine including:
a chamber having positive and negative particles therein said chamber having an open end,
a cathode in said chamber removed from said open end for generating negative particles,
means for generating electric field gradients in said chamber,
means for generating a magnetic field in said chamber,
the electric field and the magnetic field being directed with respect to each other to cause at least part of said negative particles to oscillate in said chamber,
and means for accelerating at least part of said positive particles through the open end of said chamber,
said magnetic field generating means including means for generating a magnetic mirror in said chamber in the vicinity of said cathode for reflecting negative particles from the vicinity of said cathode toward the open end of said chamber.

3. An electrical propulsion engine as in claim **2** wherein the field of said magnetic mirror diminishes in flux density from the vicinity of said cathode toward said open end of said chamber.

4. An electrical propulsion engine as in claim **3** wherein said magnetic field generating means includes coil means around said chamber and extending along said chamber, said coil means having a greater number of ampere turns in the vicinity of said cathode than elsewhere.

5. An electrical propulsion engine as in claim **2** wherein said magnetic mirror means includes:
a ferromagnetic element on the side of said cathode removed from the open end of said chamber.

6. An electrical propulsion engine as in claim **2** wherein said magnetic mirror means includes a ferromagnetic element on the side of said cathode removed from the open end of said chamber and wherein said magnetic field generating means includes means for generating a magnetic field of greater strength in the vicinity of said cathode than elsewhere in said chamber, said greater magnetic field generating means forming part of said magnetic mirror.

7. An electrical propulsion engine including:
an annular member forming an ionization region chamber,
said annular member having first and second electrode elements, a first insulator between said electrode elements and a second insulator on the side of said first electrode removed from said first insulator,
said annular member terminating in an open end at said second electrode and having a closure member at the other end electrically insulated from said first electrode by said second insulator,
a cathode in said chamber adjacent said closure member,
means for causing said cathode to emit electrons,
means for introducing an electrically neutral gaseous propellant into said chamber,
means for imposing an electric potential on said first electrode to maintain said first electrode at a different potential than said cathode,
means for electrically connecting said second electrode and said cathode to maintain said second electrode and said cathode at the same potential,
and means substantially coaxial with said annular member for generating a magnetic field along at least part of the length of said chamber,
said annular member varying in diameter along at least part of the length thereof between adjacent said cathode and said second electrode,
the electric field gradients between said cathode, said first electrode and said second electrode coacting with

the magnetic field to cause electrons to oscillate in said chamber to ionize said gaseous propellant whereby ionized propellant is accelerated out of the open end of said chamber to produce thrust,

and said annular member and said magnetic field coacting to form a magnetic mirror throughout the extent of said chamber diminishing in flux density from said cathode toward said open end of said chamber for reflecting electrons from the vicinity of said cathode toward the open end of said chamber to generate thrust through interaction between electrons and said magnetic mirror.

8. An electrical propulsion engine as in claim 7 wherein said magnetic field generating means includes means for generating a magnetic field of greater strength adjacent said cathode than elsewhere in said chamber to form at least part of said magnetic mirror.

9. An electrical propulsion engine as in claim 7 wherein said varying diameter part of said annular member increases in diameter from adjacent said cathode toward said second electrode.

10. An electrical propulsion engine as in claim 7 including a ferromagnetic element between said cathode and said closure member, said ferromagnetic element forming part of said magnetic mirror.

11. An electrical propulsion engine including:

an annular member forming an ionization chamber,

said annular member having first and second electrode elements, a first insulator between said electrode elements, and a second insulator on the side of said first electrode removed from said first insulator,

said annular member terminating in an open end at said second electrode and having a closure member at the other end electrically insulated from said first electrode by said second insulator,

a cathode in said chamber adjacent said closure member,

means for causing said cathode to emit electrons,

means for introducing an electrically neutral gaseous propellant into said chamber,

means for imposing an electric potential on said first electrode to maintain said first electrode at a different potential than said cathode,

means for electrically connecting said second electrode and said cathode to maintain said cathode and said second electrode at the same potential,

means substantially coaxial with said annular member for generating a magnetic field along at least part of the length of said chamber,

the electric field gradients between said cathode, said first electrode and said second electrode coacting with the magnetic field to cause electrons to oscillate in said chamber to ionize said gaseous propellant whereby ionized propellant is accelerated out of the open end of said chamber,

and means, including ferromagnetic means extending between said second electrode and said closure member, to provide a magnetic flux path to increase flux density in the vicinity of said cathode to form a magnetic mirror for reflection electrons from the vicinity of said cathode toward the open end of said chamber to generate thrust through interaction between electrons and the magnetic mirror.

12. An electrical propulsion engine as in claim 11 wherein said ferromagnetic means includes an annular sleeve coaxial with said annular member, said annular sleeve and said annular member defining an annular chamber therebetween, and wherein at least part of the magnetic field generating means is in said annular chamber.

13. An electrical propulsion engine as in claim 11 wherein said closure member is ferromagnetic, and including a second ferromagnetic element extending from said closure member into said ionization chamber toward said cathode.

14. An electrical propulsion engine as in claim 13 wherein said magnetic field generating means includes coil means around said second ferromagnetic element to generate at least part of said magnetic field.

15. An electrical propulsion engine including:

an annular member forming an ionization chamber,

said annular member having first and second electrode elements, a first insulator between said electrode elements, and a second insulator on the side of said first electrode removed from said first insulator,

said annular member terminating in an open end at said second electrode and having a closure member at the other end electrically insulated from said first electrode by said second insulator,

a cathode in said chamber adjacent said closure member,

means for causing said cathode to emit electrons,

means for introducing a gaseous propellant into said chamber,

means for imposing an electric potential on said first electrode to maintain said first electrode at a different potential than said cathode,

means for electrically connecting said second electrode and said cathode to maintain said cathode and said second electrode at the same potential,

a plurality of ferromagnetic rods extending between said second electrode and said closure member externally of said annular member,

and means for generating a magnetic field in said chamber,

the electric field gradients between said cathode, said first electrode and said second electrode coacting with the magnetic field to cause electrons to oscillate in said chamber to ionize said gaseous propellant whereby ionized propellent is accelerated out of the open end of said chamber,

and said magnetic field generating means providing a magnetic field of increased flux density in the vicinity of said cathode to form a magnetic mirror for reflecting electrons from the vicinity of said cathode toward the open end of said chamber to generate thrust through interaction between electrons and the magnetic mirror.

16. An electrical propulsion engine as in claim 15 wherein said magnetic field generating means includes coil means around each of said rods.

17. An electrical propulsion engine as in claim 15 wherein said closure member is ferromagnetic, and including a ferromagnetic element extending from said closure element into said chamber toward said cathode.

18. An electrical propulsion engine assembly including:

a cluster of ion engines, each ion engine of said cluster having

an annular member forming an ionization chamber,

said annular member having first and second electrode elements, a first insulator between said electrode elements, and a second insulator on the side of said first electrode removed from said first insulator,

said annular member terminating in an open end at said second electrode and having a closure member at the other end electrically insulated from said first electrode by said second insulator,

a cathode in said chamber adjacent said closure member,

means for causing said cathode to emit electrons,

means for introducing a gaseous propellant into said chamber,

means for imposing an electric potential on said first electrode to maintain said first electrode at a different potential than said cathode,

and means for electrically connecting said second

electrode and said cathode to maintain said cathode and said second electrode at the same potential,

a plurality of ferromagnetic rods around the annular member of each engine extending between the second electrode of each engine and the closure member of each engine, each engine of said cluster having at least one of said ferromagnetic rods in common with any adjacent engine,

and means for generating a magnetic field in the chamber of each of said engines, the electric field gradients between the cathode, the first electrode, and the second electrode of each engine coacting with the magnetic field in the chamber of each engine to cause electrons to oscillate in the chamber of each engine to ionize the gaseous propellant in each chamber whereby ionized propellant is accelerated out of the open end of each chamber,

and said magnetic field generating means providing a magetic field of increased flux density in the vicinity of the cathode of each engine to form a magnetic mirror in each engine for reflecting electrons from

the vicinity of each cathode toward the open end of each chamber to generate thrust in each engine through interaction between electrons and the magnetic mirror of each engine.

19. An electrical propulsion engine as in claim **18** wherein said magnetic field generating means includes coil means around each of said rods.

20. An electrical propulsion engine assembly as in claim **18** wherein the closure member of each engine is ferromagnetic, and wherein each engine has a ferromagnetic element extending from the closure element into the chamber toward the cathode.

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