Oct. 18, 1966 H. W. HENDEL ETAL 3,279,175

APPARATUS FOR GENERATING AND ACCELERATING CHARGED PARTICLES

Filed Dec. 19, 1962 2 Sheets-Sheet 1

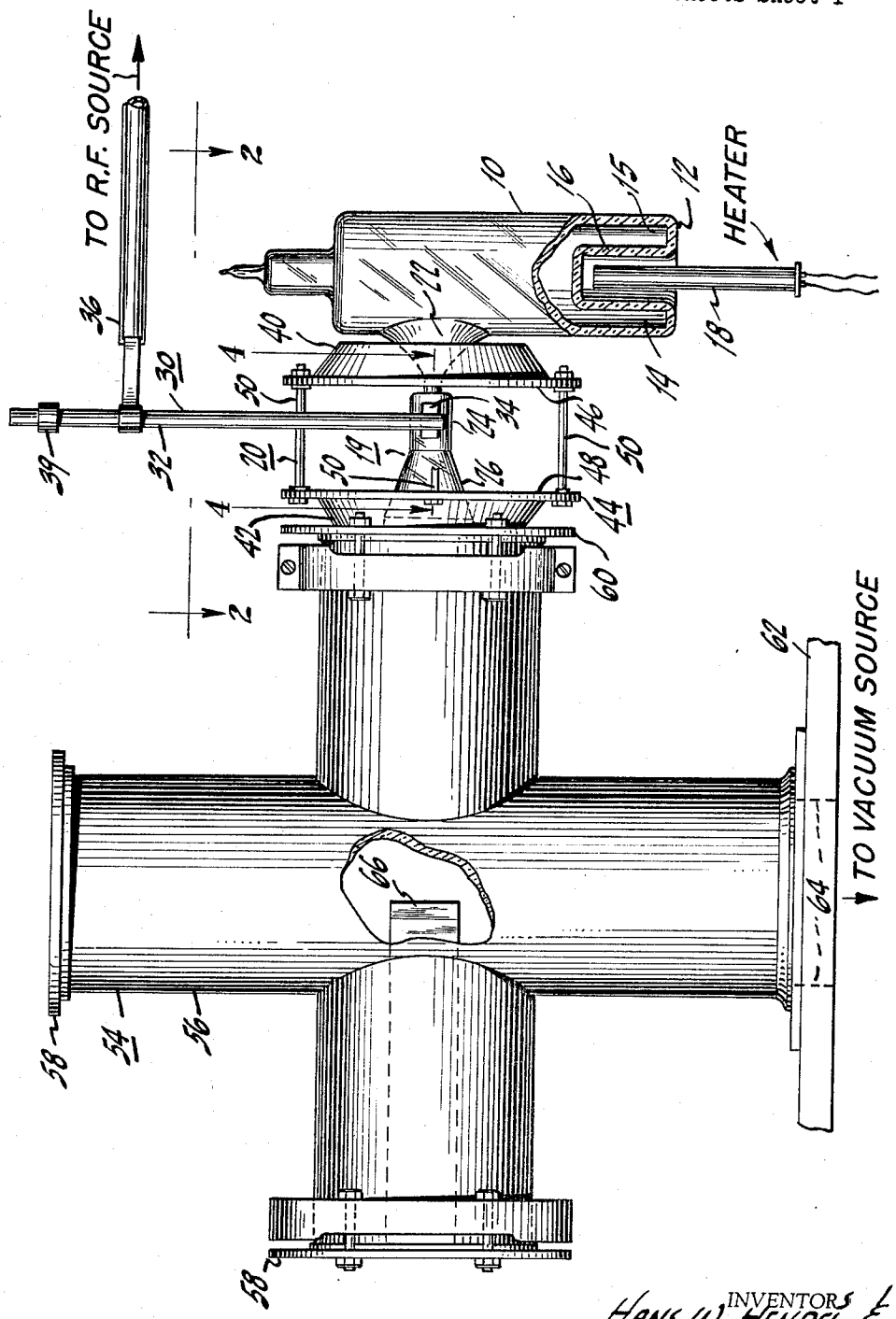


FIG. 1.

INVENTORS
HANS W. HENDEL &
THEOPHILE T. REBOUL III

BY Morris Rabkin

Attorney

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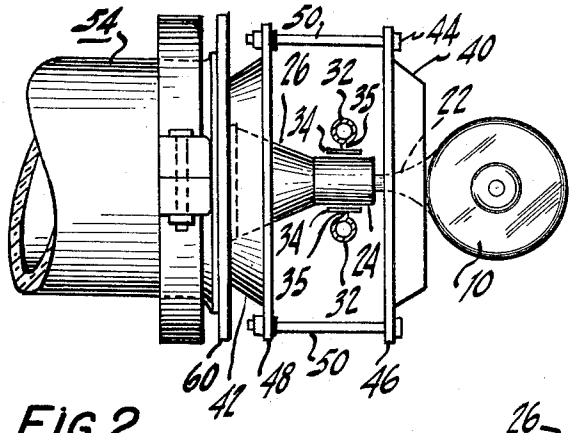


FIG. 2.

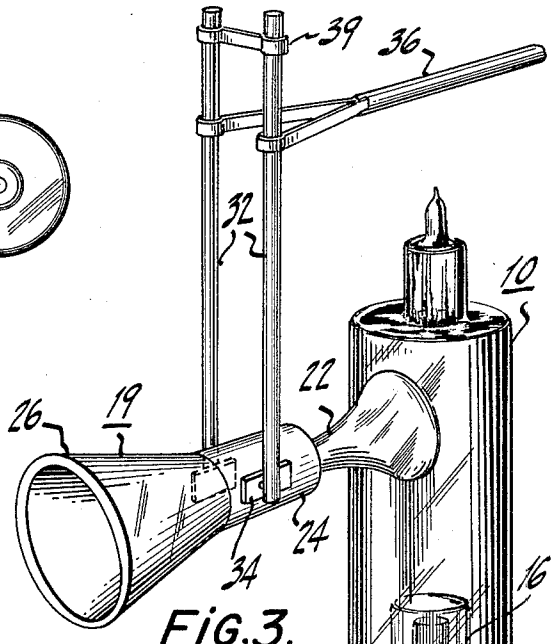


FIG. 3.

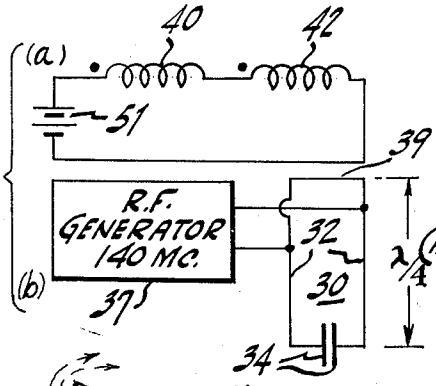


FIG. 5

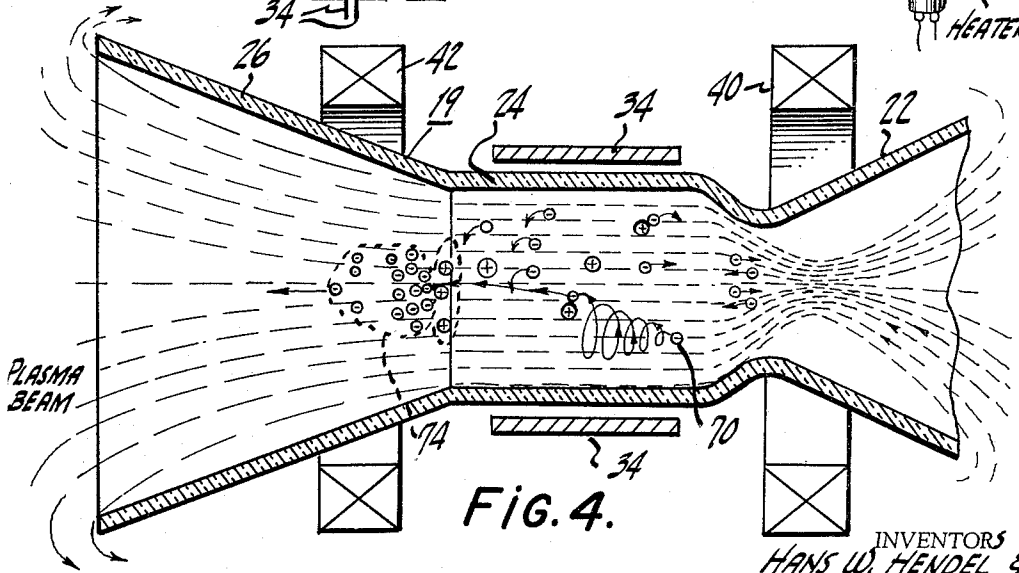


FIG. 4.

INVENTORS
HANS W. HENDEL &
THEOPHILE T. REBOUL III

By Morris A. Rabin
Attorney

United States Patent Office

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APPARATUS FOR GENERATING AND ACCELERATING CHARGED PARTICLES

Hans W. Hendel, Manasquan, and Theophile T. Reboul III, Princeton, N.J., assignors to Radio Corporation of America, a corporation of Delaware

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14 Claims. (Cl. 60—202)

This invention relates to methods of and apparatus for electromagnetically accelerating charged particles, and particularly for generating a plasma and for accelerating that plasma.

By a "plasma" is meant a gas including a mixture of positively and negatively charged particles, such as electrons and ions, in which gas the concentrations of positively and negatively charged particles are approximately equal.

The invention is especially useful for the propulsion of space vehicles. However, the invention may also be useful for studying thermonuclear reactions and aerodynamic effects.

Ion and plasma propulsion techniques have been proposed wherein ions or a plasma are produced and electrostatically and/or electromagnetically accelerated. Chief difficulties in ion acceleration are that (1) specific thrust (thrust per unit area of the cross-section of the beam in a plane perpendicular to the direction of the thrust) is limited by space charge effects, (2) the ion beam must be neutralized to maintain charge neutrality of the vehicle which is propelled by the beam, and (3) low efficiency at low specific impulse (velocity of the beam over the acceleration due to gravity). Various plasma accelerators have been suggested. These accelerators mainly use electrical pulses to drive the plasma and suffer from disadvantages of low duty cycle and produce low average specific thrust. Complex apparatus has been used in continuously operating plasma accelerators.

It is an object of the present invention to provide a method of and apparatus for plasma acceleration wherein the foregoing difficulties and disadvantages are eliminated.

It is a further object of the present invention to provide an improved method of and improved apparatus for generating and continuously accelerating a plasma.

It is still further object of the present invention to provide a method of and apparatus for plasma generation and acceleration which are less complicated and lower in cost than known plasma and ion acceleration schemes.

The foregoing objects and advantages may be obtained, according to the invention, in a plasma generator and accelerator wherein plasma is generated by introducing a neutral gas into a region where there are established combined magnetic and radio frequency electric fields, preferably at the electron cyclotron resonance frequency. The gas is ionized by the radio frequency electric field and a plasma is generated in the region. An externally generated plasma may be alternatively injected into this region. The combined fields selectively transfer radio frequency energy to the electrons of the plasma. The magnetic field extends beyond the first-mentioned region into a second region. The high energy electrons collide and expand in the direction of the magnetic field into this second region and are confined by the magnetic field. A space charge field forms which accelerates the ions in the plasma out of the first region and through the second region. The electrons thereby transfer their high energy to the ions and a high energy plasma beam of electrons and ions is expelled for propulsion or other purposes. Since the combined fields act primarily on the electrons, the magnetic field strength may be low as compared to the magnetic field strength used in ion devices and thus may

readily be generated and applied without difficulty. Ionic erosion also does not present a serious problem.

The invention itself, both as to its organization and method of operation, as well as additional objects and advantages thereof, will become more readily apparent from a reading of the following description in connection with the accompanying drawings in which:

FIG. 1 is an elevational view, partly broken away, showing a plasma generator and accelerator embodying one form of the invention;

FIG. 2 is a fragmentary plan view, partly in section, of the apparatus shown in FIG. 1 taken along the line 2—2 of FIG. 1 and viewed in the direction of the appended arrows;

FIG. 3 is a fragmentary, perspective view of parts of the apparatus shown in FIG. 1;

FIG. 4 is an enlarged, fragmentary, sectional view of the plasma confinement vessel of FIG. 1 taken on the line 4—4 of FIG. 1 and showing the charged particles and their movements diagrammatically; and

FIGS. 5*a* and 5*b* are schematic diagrams of the circuits used in the apparatus shown in FIG. 1.

Referring more particularly to FIGS. 1 to 3, there is shown a vessel **10** having a reentrant base **12** which defines an annular trough **14** wherein a vaporizable material **15**, such as mercury, may be located. The reentrant base **12** also defines a cylindrical tube **16** open externally at the bottom and closed at the top. An electric heater element **18** is inserted in the cylinder **16** and may be energized for heating and volatilizing the mercury to form a vapor or gas. This gas is introduced into a plasma confinement vessel **19** of a plasma generator and accelerator **20** through a conical inlet nozzle **22**. The plasma confinement vessel **19** includes a cylindrical tube **24**. The tube **24** is somewhat tapered or necked inwardly at one end which joins the nozzle **22**. This tube **24** defines a chamber in which the plasma is generated and in which the energy of the electrons of the plasma is raised, as is explained hereinafter. The confinement vessel **19** also includes a conical outlet nozzle **26** joined to the tube **24**. The flared outlet end of the nozzle **26** may be flanged. The vessel **10**, the inlet nozzle **22**, the tube **24**, and the outlet nozzle **26** are desirably of a non-magnetic, insulating material, such as glass. Glass of the type sold under the trade name "Pyrex" or ceramics may be suitable.

A transmission line **30**, including a pair of conductors **32**, extends perpendicularly to the axis of the confinement vessel **19**. Two plate electrodes **34** are individually connected by means of conductive stubs **35** to different ones of the conductors **32** of the line **30**. The electrodes **34** are disposed diametrically opposite and facing each other adjacent the wall of the tube **24**. The electrodes may be disposed internally of the tube, if desired. The conductors **32** may be connected to a transmission line **36**, such as of the adjustable coaxial type. A radio frequency generator **37** may be connected to the coaxial line **36** (see FIG. 5*b*). A shorting stub **39** is connected between the conductors **32** of the line **30** at a distance from the electrodes **34** equal to one-quarter wavelength of the radio frequency waves produced by the generator **37**. The coaxial line is connected to the transmission line **30** at a position between the electrodes **34** and stub **39** where the best impedance match is obtained. A radio frequency electric field may therefore be established between the plate electrodes **34**. This field is transverse to the axis of the confinement vessel **19**.

A pair of coils **40** and **42**, which may be of the solenoidal type, are located around the inlet nozzle **22** and the outlet nozzle, respectively. The coils are coaxial with the axis of the confinement vessel **19** (i.e., the axis of the nozzles **22** and **26** and the cylindrical tube **24**). The coils may be equidistant from the plate electrodes **34**.

The plate electrodes **34** are parallel to the axis of the coils **40** and **42**. The coil **40**, around the inlet nozzle **22**, may have a larger number of turns than the other coil **42** around the outlet nozzle **26**. A structure **44** for mounting the coils may include a pair of flanges **46** and **48** spaced from each other by bolts **50** and associated nuts. The coils **40** and **42** may be cemented or strapped to their respective flanged cylinders **46** and **48**. A cradle (not shown) may be used to support the coils **40** and **42** and their mounting structure in spaced relationship from the cylindrical tube **24** and the other elements of the plasma confinement vessel **19**.

The coils **40** and **42** may be connected in series with a source of direct current, such as a battery **51** (see FIG. 5*a*). Each coil produces a solenoidal magnetic field in the same direction. The combined fields of both coils are illustrated by the dashed lines in FIG. 4. The field extends axially through the confinement vessel **19** and is essentially uniform and homogeneous within the tube **24**. The field is pinched or concentrated (i.e., has a higher flux density) inwardly in the plane of the rearwardly located coil **40** so as to define a "magnetic mirror" to prevent escape of the plasma from the rear of the vessel **19**. This mirror effect occurs since the rearward coil **40** may have more turns than the forward coil **42** and therefore generates a stronger field. Alternatively, the coils **40** and **42** may be of equal numbers of turns and separately energized, the coil **40** with more current than the other coil **42**.

When the accelerator **20** is used for vehicle propulsion in free space (for example, over approximately 200 miles from the surface of the earth), the air pressure in the plasma confinement vessel **19** may be relatively low so that evacuation is unnecessary. For laboratory test purposes and where the plasma beam is to be used for purposes other than propulsion, the confinement vessel **19** is desirably evacuated, as by a vacuum pump.

A structure **54** is used for maintaining a vacuum in the confinment vessel **19** when desired. This structure includes a tube cross-joint **56** made of glass. Closure plates **58** seal the open upper and rear tube ends of the cross-joint **56**. The front tube end of the cross-joint **56** is closed by a closure plate **60** having an aperture. The flanged end of the exhaust nozzle **26** is disposed against the closure plate **60** around the aperture thereof. A suitable ring gasket may be placed between the flanged end of the nozzle **26** and the plate **60**. The lower tube end of the cross-joint **56** is located on a platform **62** having an opening **64** therein. This opening is in communication with a vacuum source, such as a pipe leading to a vacuum pump of the type known in the art. Measurement apparatus may be inserted through the upper and rear tube ends into the vacuum structure **54**. For example, a Faraday cage **66** for ion measurement is attached to the rear closure plate **58**.

The operation of the apparatus illustrated in FIGS. 1 to 3 may be best explained in connection with FIG. 4. This explanation is, in part, theoretical and is intended to provide a clearer understanding of the invention without restricting the invention to any particular mode of operation. The gas (for example, mercury vapor) enters the tube **24** through the nozzle **22**. The gas may be ionized to form a plasma by the radio frequency electric field established by the electrodes **34**, which field penetrates the chamber formed by the tube **24** into the plasma therein. The positive ions or neutral atoms comprising this plasma are represented by circles inscribed with a "plus" (+) sign and the electrons are represented by a smaller circle inscribed with a "minus" (−) sign. The particles of the plasma initially have a velocity component in a direction towards the outlet nozzle **26** since there is a pressure gradient in the tube **24** from the inlet nozzle **22** to the outlet nozzle **26**. This pressure gradient is produced by the vacuum source (see FIG. 1). The ions and electrons come under the influence of the combined magnetic and radio frequency electric fields which are established in the chamber formed by the tube **24**. The radio frequency electric field is preferably at the electron cyclotron resonance frequency of the plasma. For example, the radio frequency field may have a frequency of 140 megacycles per second for a magnetic field of 50 gauss.

Consider a representative electron **70** in the plasma. This electron receives energy from the combined magnetic and electric fields and begins to gyrate. The radius of gyration becomes greater on each succesive orbit. Since the electron has an initial velocity in the axial directions towards the outlet nozzle **26**, the electron has as slight corkscrew path of movement, which may be exaggerated in the drawing. After a number of gyrations depending upon the density of the plasma and the angular frequency of gyration of the electron, the electron may collide with a positive ion or a neutral atom and be deflected, for example, in the axial direction towards the outlet nozzle. In the illustrated collision of the electron **70** with a positive ion, some of the radial velocity of the electron is converted to axial velocity. The electron may continue to gyrate after the collision and pick up more and more energy from the electric field. Eventually, the electron travels out of the resonance chamber defined by the tube **24** into a second region in the exhaust nozzle **26**. Desirably, but not necessarily, the concentration of particles is such that the electrons may execute on the average about one hundred gyrations before a collision. After a collision, the electron may have enough energy to travel out of the resonance chamber defined by the tube **24** without further interaction between the electron and the electric field, since the energy of the electron after collision may result in an electron velocity higher than the phase velocity of the electric field. The magnetic field extends in the axial direction into the exhaust nozzle. The electron **70** is confined by this magnetic field to drift in the axial direction.

Many collisions between ions and electrons occur within the tube **24**. In some of these collisions, the radial velocity of the electrons is converted to velocity along the axial direction towards the inlet nozzle **22**. Those electrons which enter the inlet nozzle **22** experience a magnetic force which deflects them back into the tube **24**. This force is produced by the interaction of the moving electrons and the pinched magnetic field in the inlet nozzle region which establishes a magnetic mirror. The electrons reflected by the magnetic mirror reenter the tube **24** and again begin to gyrate.

The mobility of the electrons in a radially outward direction is much lower than the mobility of the electrons in the axial direction. The radial mobility of the electrons is limited by the axial magnetic field which interacts with the moving electrons and exerts a force thereon. After collisions, the magnetic field tends to redirect the electrons towards the common magnetic field and tube **24** axis. Many of the electrons therefore travel in the axial direction into the exhaust nozzle. The exhaust nozzle then contains a group of electrons having a very high energy. This group is enclosed by the dash line **74**. Since the electrons are rapidly accelerated in the tube **24** and experience motion randomizing collisions, the "temperature" of the electrons is effectively increased by the combined fields at electron-cyclotron resonance. The ions, on the other hand, do not derive significant energy from the combined fields. Thus, the ions essentially remain at their initial temperature in the resonance chamber defined by the tube **24**. The energetic electron gas expands. This expansion is in the axial direction due to the confining magnetic field. The expanding electron gas sets up space charge fields which electrostatically attract and accelerate the positive ions in the resonance chamber defined by the tube **24** out of that chamber into the exhaust nozzle **26**. The acceleration of the ions by the space charge field occurs sub-

stantially instantaneously. The energy transfer from the electron group to the ions occurs without significant transfer of heat from the electrons to the ions by collision due to the high mass ratio of an ion to an electron. Thus, the energy transfer from the electrons to the ions is adiabatic and therefore very efficient.

The electric and magnetic fields operate almost exclusively on the electrons and continuously accelerate electrons in the axial direction out of the resonance chamber defined by the tube **24**. A plasma comprising a continuous flow of electrons and ions is continuously ejected from the nozzle **26**. The thrust of the plasma beam is much greater than the thrust which might be produced by the magnetic and electric field forces acting upon the ions alone. Accordingly, the result of a high velocity plasma beam which is provided by the invention is unobvious from the field-ion interactions.

In an exemplary case, for a radio frequency field of approximately 100 volts per centimeter, a thrust of 10 dynes per square centimeter may be measured on a mechanical vane suspended from the closure plate **58** (FIG. 1). The frequency of the radio frequency field in this exemplary case may be 140 megacycles per second and the magnetic flux density in the chamber **24** may be 50 gauss.

From the foregoing description, it will be apparent that there has been provided an improved method of and apparatus for charged particle and plasma acceleration. While a preferred embodiment of the accelerator is described above, other forms of accelerators embodying the invention (for example, with different electrode configurations for coupling R-F power into the plasma) will, no doubt, be apparent to those skilled in the art. Accordingly, the foregoing description should be taken as illustrative and not in a limiting sense.

What is claimed is:

1. In apparatus for accelerating plasma located in a first region, a solenoidal magnetic field device positioned to provide a divergent field in a second region adjacent to and downstream from said first region, means for producing a mixture of electrons and positive ions in said first region, means for selectively driving the said electrons out of said mixture into said second region adjacent said first region to thereby establish electrostatic forces for attracting said positive ions into said second region and provide an accelerated plasma in said second region.

2. Apparatus for emitting a beam from a plasma including a mixture of positive ions and electrons comprising

(a) means for increasing the velocity of said electrons in said mixture without substantially increasing the velocity of said ions so that said electrons collide with said ions and are deflected,

(b) means for directing said deflected electrons out of said plasma in a predetermined direction into a region to thereby establish electrostatic forces which accelerate said ions in said predetermined direction to form a plasma beam, and

(c) a solenoidal magnetic field device positioned to provide a divergent field in said region.

3. Apparatus for providing a plasma beam including a mixture of electrons and positive ions comprising

(a) means for generating a plasma in a first region, said plasma including said mixture of electrons and positive ions,

(b) means for selectively transferring energy to said electrons in said mixture for driving said electrons out of said mixture into a second region adjacent to and downstream from said first region to thereby establish electrostatic forces in said second region for attracting said positive ions into said second region and provide an accelerated plasma in said second region, and

(c) a solenoidal magnetic field device positioned to provide a divergent field in said second region.

4. Apparatus for generating and accelerating a plasma comprising

(a) means for injecting a gas into a first region,

(b) means for ionizing said gas in said first region to provide a plasma including a mixture of electrons and positive ions,

(c) means for simultaneously and selectively driving said electrons out of said mixture into a second region adjacent to and downstream from said first region to thereby establish electrostatic forces for attracting said positive ions into said second region and thereby provide an accelerated plasma in said second region, and

(d) a solenoidal magnetic field device positioned to provide a divergent field in said second region.

5. Apparatus for accelerating a plasma located in a first region and including a mixture of electrons and positive ions comprising

(a) means for establishing a pressure gradient in said plasma directed from said first region to a second region adjacent said first region, and

(b) means for applying electric and magnetic forces on said plasma in said first region for cyclically driving said electrons in their cyclotron resonance mode of gyration out of said first region into said second region for attracting said positive ions into said second region and thereby providing an accelerated plasma in said second region.

6. Apparatus for accelerating a plasma located in a first region and including a mixture of electrons and positive ions comprising

(a) means for establishing a pressure gradient in said plasma directed from said first region to a second region adjacent said first region,

(b) means for applying to said plasma electric and magnetic fields thereby causing said electrons to gyrate in their electron cyclotron resonance mode of gyration into collisions with said ions in said first region, said electrons thereby being deflected into said second region, and

(c) means for confining said deflected electrons in said second region to form concentrated electrostatic forces for attracting said positive ions out of said first region into said second region to form a moving beam of plasma in said second region.

7. A plasma acceleration and generation apparatus comprising

(a) means for injecting a gas into a chamber,

(b) means for establishing through said chamber a homogeneous magnetic field of a certain density, which field extends beyond one of two opposite ends of said chamber and is concentrated near the other of said opposite ends,

(c) means for establishing in said chamber a radio frequency electric field at the electron cyclotron resonance frequency for said magnetic field flux density thereby ionizing said gas into a plasma and accelerating said plasma toward said opposite ends of said chamber, and

(d) means for reflecting said plasma entering said other, opposite end back into said chamber.

8. A plasma accelerator comprising

(a) means for establishing a plasma in a first region, said plasma including a mixture of electrons and positive ions,

(b) means for selectively driving said electrons out of said mixture into a second region downstream from and adjacent said first region for establishing electrostatic forces which attract said positive ions into said second region and providing an accelerated plasma in said second region, and

(c) a solenoidal magnetic field device positioned to provide a divergent field in said second region.

9. Apparatus for generating a plasma beam comprising
(a) means for establishing a plasma including a mixture of positive ions and electrons,
(b) means operative upon said plasma for separately and selectively increasing the velocity of said electrons in said mixture so that said electrons travel at high speed and collide with said ions and are deflected out of said mixture into a region,
(c) means for directing said deflected electrons in a predetermined direction away from said plasma for establishing electrostatic forces for accelerating said ions toward said electrons in said predetermined direction to form a beam, and
(d) a solenoidal magnetic field device positioned to provide a divergent field in said region.

10. A plasma accelerator comprising
(a) a vessel,
(b) means for establishing in said vessel a plasma including a mixture of electrons and positive ions, and
(c) means for establishing magnetic fields in one direction through said vessel and electric and radio frequency electric fields in a direction transverse to said magnetic field in a predetermined portion of said vessel, said radio frequency electric fields selectively transferring energy to the electrons in said mixture and accelerating said electrons in the direction of said magnetic fields, said accelerated electrons establishing electrostatic forces for attracting said positive ions in the direction of said magnetic fields outwardly of said vessel.

11. A plasma generator and accelerator comprising
(a) a vessel defining an interaction chamber,
(b) magnetic and radio frequency electric field generating means for establishing a magnetic field in said vessel which extends through said chamber and an electric field at electron cyclotron resonance frequency for said magnetic field in said chamber, and
(c) means for injecting a gas into said chamber for ionization in said chamber into a plasma which is accelerated out of said vessel.

12. A plasma propulsion device comprising
(a) a vessel open at one end to provide an outlet and defining a chamber adapted to contain a plasma,
(b) a pair of electrodes disposed facing each other externally of said chamber,
(c) coil means for providing in said vessel a magnetic field of a certain flux density, which field is directed toward said outlet end, said field also being transverse to a line between said electrodes, and
(d) means for applying to said electrodes radio frequency energy at the electron cyclotron resonance frequency for said magnetic field flux density in said chamber.

13. A plasma generator and accelerator comprising
(a) a vessel defining a chamber and having inlet and outlet nozzles on opposite sides of said chamber,
(b) a pair of coaxial solenoidal coils each disposed around said vessel,
(c) a pair of plate electrodes disposed facing each other externally of said chamber between said coils, said electrodes being parallel to the axis of said coils,
(d) direct current means for energizing said coils to provide a concentrated magnetic field in said inlet nozzle, a homogeneous magnetic field of certain flux density in said chambers along said coil axis directed from said inlet to said outlet nozzle, and a field which extends into said outlet nozzle,
(e) means for applying radio frequency energy at the electron cyclotron resonance frequency for said certain magnetic field flux density in said chamber to said electrodes, and
(f) means for injecting a gas into said inlet nozzle for ionization in said chamber into a plasma which is accelerated out of said vessel through said outlet nozzle.

14. A plasma propulsion device comprising
(a) a tubular vessel defining a chamber and having inlet and outlet nozzles respectively at opposite ends of said chamber,
(b) a pair of solenoidal coils each disposed around said vessel and coaxial therewith,
(c) a pair of plate electrodes disposed facing each other externally of said chamber between said coils, said electrodes being parallel to the axis of said coils,
(d) means for energizing said coils to provide in said vessel an axial magnetic field of a certain flux density directed toward said outlet nozzle from said inlet to said outlet nozzle,
(e) means for reflecting a plasma entering said inlet nozzle into said chamber,
(f) means for applying radio frequency energy at the electron cyclotron resonance frequency for said certain magnetic field flux density in said chamber to said electrodes, and
(g) means for injecting a gas into said inlet nozzle for ionization in said chamber into a plasma which is formed into a beam, accelerated and emitted from said vessel through said outlet nozzle.

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MARK NEWMAN, *Primary Examiner.*

SAMUEL LEVINE, *Examiner.*

C. R. CROYLE, *Assistant Examiner.*