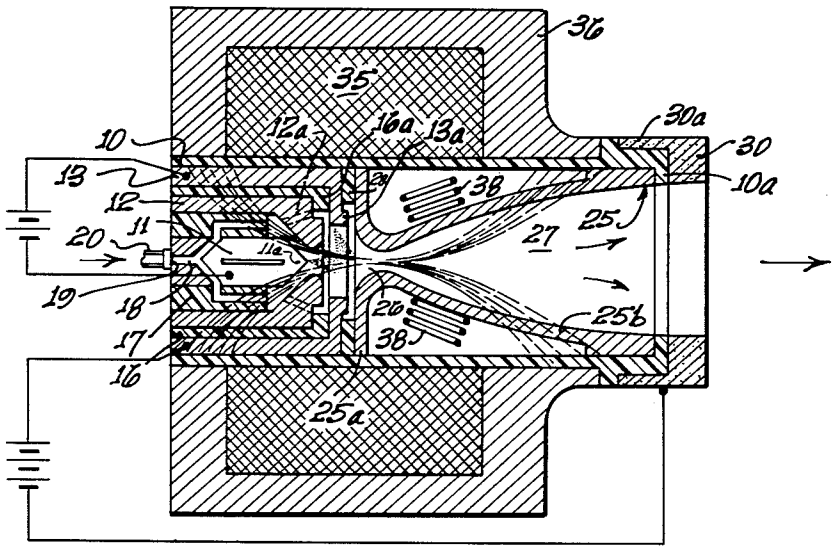
April 5, 1966 G. L. CANN 3,243,954

PLASMA ACCELERATOR USING HALL CURRENTS

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FIG. 1.



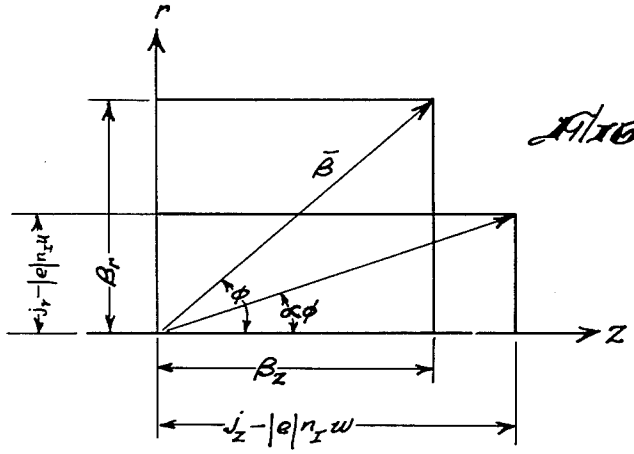


FIG. 2.

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PLASMA ACCELERATOR USING HALL CURRENTS

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FIG. 3.

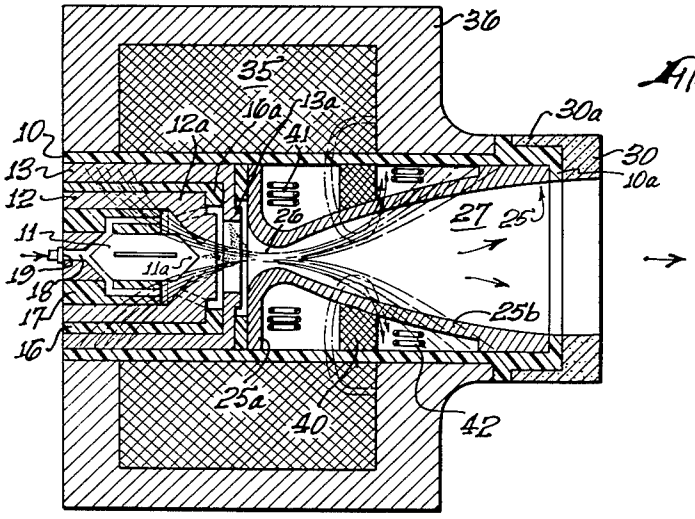
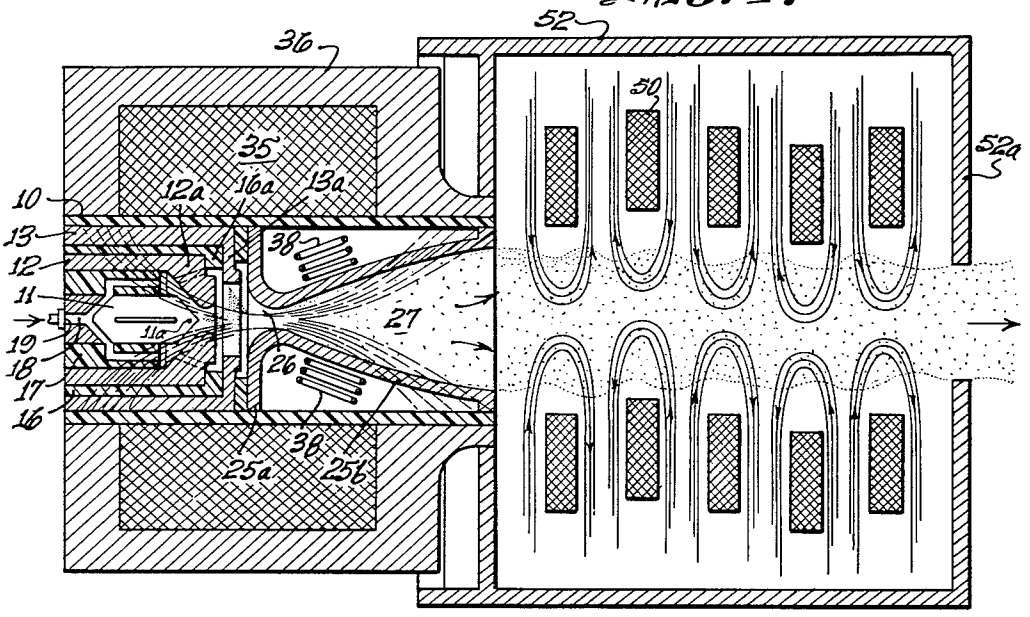


FIG. 4.



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United States Patent Office

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PLASMA ACCELERATOR USING HALL CURRENTS

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Filed Aug. 17, 1962, Ser. No. 217,631
13 Claims. (Cl. 60—35.5)

This invention relates to plasma accelerators and more particularly to electromagnetic accelerators utilizing Hall currents to achieve extremely high gas velocities.

Plasma generating and accelerating devices in which an ionized gas plasma is accelerated to high velocities are recognized by science to possess great potential in certain applications. A particular application in which such devices could be of particular importance is in the field of space propulsion. The thrust of a space propulsion system is dependent upon the product of the propellant mass flow rate and the exhaust velocity relative to the vehicle. The current use of chemical rocket fuels entails a limitation on space flights because the propellant exit velocities are relatively low and large masses of propellant must be carried aloft. Considerable thought has been given to the use of an ionized gas plasma in space propulsion systems with a view toward increasing the exhaust velocity of the propellant, together with a substantial reduction in propellant weight and space requirements as compared with chemical propellants.

The standard present art method for accelerating an ionized gas plasma to high velocities is to pass the plasma through a crossed field channel accelerator in which electric and magnetic fields are maintained at right angles to each other and transverse to the "channel" into which the ionized gas is longitudinally injected. It is known that an electric field transfers energy to charged particles and that a magnetic field exerts a force on charged particles in motion relative to the magnetic field. When a magnetic field is established at right angles to a moving stream of electrically conductive fluid, an electric field is induced perpendicular to both the stream direction and the field lines. If an electric field is now applied in the same direction as the induced electric field, but stronger than the induced electric field, then a current flows in the conductive fluid in the direction of the applied electric field, which current interacts with the magnetic field to produce a force which is in the direction of the moving stream. In accordance with commonly used vector notations, the net current density is denoted by "j" and the magnetic flux density denoted by "B." Hence, the crossed-field channel accelerator is also known in the art as a "$j\times B$" channel accelerator.

However, in a $j\times B$ channel accelerator, the electrical current does not actually flow perpendicular to the electrodes, but rather flows at some angle due to the phenomenon known as Hall effect. When the Hall potential is zero, the net resultant current is the combination of the "ordinary" currents (current due to the applied electric field plus current induced by movement of electrons through the magnetic field) and the Hall currents. Because of the angularity of the net resultant current flow between the electrodes, a force is applied to the gas stream deflecting the flow in the direction of the applied electric field, the angle of deflection changing with variations in gas pressure and in the strength of the applied magnetic field. Thus, acceleration of a plasma jet in accordance with present art practices results in deflection as well as spreading of the jet, these characteristics being undesirable for use of the jet as a space propulsor because maximum thrust is obtainable only from a sharply focused jet containing no angular velocity components.

Also, in the present art $j\times B$ channel accelerators, energy is initially transferred from the electric field to the electrons and must then be transferred by collisions to the heavier particles. Due to the slow rate of energy transfer between electrons and heavy particles by elastic collisions, the electrons usually are heated until they can collide inelastically and ionize the atoms, thereby transferring a large fraction of the input electrical energy into a form of potential energy that is not easily recoverable. There is also a very high heat flux into the electrodes, causing them to erode at a relatively high rate.

The present invention is directed toward obviating the aforementioned disadvantages of present art channel accelerators by accelerating an ionized gas plasma without causing deceleration or spreading of the jet while maintaining the electrodes at a relatively low temperature, the joule heating of the gas being converted into axial jet energy in the same region where the acceleration is occurring. The spiraling forces of the ordinary currents are minimized and the Hall currents utilized to provide an axial accelerating force.

Accordingly, it is an object of the present invention to provide improved plasma accelerators.

It is also an object of the present invention to accelerate an ionized gas plasma without any significant spreading or deflection of the jet.

It is another object of the present invention to provide an electromagnetic plasma accelerator in which the electrodes are maintained at a relatively low temperature to minimize electrode erosion and sputtering.

It is a further object of the present invention to provide a steady state plasma accelerator in which Hall currents are used to provide an additional measure of acceleration.

It is yet another object of the present invention to provide an improved plasma accelerator in which the joule heating of the gas plasma is converted into axial jet energy.

It is a still further object of the present invention to provide an improved plasma accelerator in which tangential velocities are effectively cancelled by clockwise and counterclockwise acceleration components.

It is also an object of the present invention to provide methods and means for focusing a plasma jet and eliminating the angular momentum of the jet while accelerating it to high velocities.

The objects of the present invention are accomplished by partially ionizing a gas stream, accelerating the jet to supersonic velocities through a nozzle, and accelerating the jet through axisymmetric fringe magnetic fields and a secondary electrical discharge extending axially downstream throughout the length of the fringe magnetic fields. Tangential Hall currents are generated by the current density lines crossing the magnetic field lines, the Hall currents then interacting with the radial components of the magnetic field to impart axial acceleration to the gas. The Hall electric field is effectively eliminated due to the impossibility of maintaining a tangential electric field. In the accelerating discharge, the electrons are forced to spiral due to the radial component of the applied fringe magnetic fields, the rotational force applied to the electrons upon entering the fringe field being oppositely directed from the rotational force applied on leaving the fringe field. Hence, the rotational forces cancel each other, thereby leaving only the axial Hall force for acceleration of the jet. By establishing a series of separate axisymmetric magnetic fringe fields along the discharge path, even greater exhaust velocities can be achieved since the jet is accelerated by the axial Hall forces created within each magnetic field. Although the electrons spiral within the fringe magnetic field the ions, being of much greater mass, are unaffected by the rotational forces and

so carry the current and pick up momentum and energy directly from the electric fields. The ions simultaneously collide with the atoms and hence accelerate the plasma as a whole.

The novel features which are believed to be characteristic of the present invention, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawing in which the invention is illustrated by way of example. It is to be expressly understood, however, that this description and the drawing are for the purposes of illustration and description only, and that the true spirit and scope of the invention is defined by the accompanying claims.

In the drawing:

FIGURE 1 is an elevation view, in section, of a first embodiment of a plasma accelerator;

FIGURE 2 is a schematic diagram defining the various angles used in the mathematical analysis presented in the specification;

FIGURE 3 is an elevation view, in section, of a second embodiment of a plasma accelerator; and,

FIGURE 4 is an elevation view, in section, of a third embodiment of a plasma accelerator.

In general, electric discharges in gases tend to operate most satisfactorily in an axial symmetric configuration. Hence, the present invention concepts are applied to a gas confined to a channel having an applied axisymmetric magnetic field and through which an electric discharge is maintained in an axial direction. With reference now to the drawings, wherein like or corresponding parts are designated by the same reference characters throughout the several views, there is shown in FIGURE 1 a basic accelerator structure of the aforementioned type. According to FIGURE 1, an arc gap device is disposed within a tubular casing **10** of an insulating material. Coaxially disposed within the tubular casing **10**, near one end thereof, are a cathode **11**, an intermediate shaping electrode **12**, and an anode **13**. The intermediate electrode **12** and the anode **13** are maintained in coaxial alignment and electrically insulated from each other by a tube **16** of an electrical insulating material. The cathode **11** is mounted within a cylinder **17** of insulating material.

The cathode **11** is cylindrical in shape and defines a pointed end portion **11***a*. The cathode is constructed of a suitable metal, tungsten being presently preferred. The cathode **11** is coaxially encased within the insulating cylinder **17** with its pointed end portion **11***a* extending past the end of the insulating cylinder. A multi-branch gas inlet passageway **18** extends coaxially into the cathode **11** from an inlet port **19**, with the various branches of the passageway extending radially outward and into the insulating cylinder **17** and then longitudinally within the cylinder to its innermost end. One end of a gas feedpipe **20** is coupled to the inlet port **19**, the other end of the pipe being coupled to a suitable source of gas pressure, not shown.

The intermediate electrode **12** defines an angular end portion **12***a* projecting radially inward past the pointed end portion **11***a* of the cathode **11** for the purpose of directing gas emerging from the multi-branch passageway **18** radially inward past the pointed end portion **11***a* and through the aperture defined by the angular end portion **12***a*. The insulating tube **16** defines a radially inwardly directed flange **16***a*. The generally tubular anode **13** defines a radially inwardly directed flange portion **13***a*, the flange portion **13***a* extending past the flange **16***a* to define a ring anode. The intermediate electrode **12** and the anode **13** are constructed of a suitable electrically conductive material, copper being presently preferred.

Also disposed within the tubular casing **10** is a generally tubular conduit means **25** having a transversely extending end section **25***a* and a divergent frusto-conical section **25***b*. The end section **25***a* defines a sonic orifice **26** in coaxial alignment with the pointed end portion **11***a* of the cathode **11**. The frusto-conical section **25***b* defines a super-sonic expansion nozzle **27**. The end section **25***a* of the conduit means **25** is positioned adjacent the flange portion **13***a* defining the ring anode and separated therefrom by an insulating ring **28**.

The open volume defined between the pointed end portion of the cathode **11** and the end section of the conduit means **25** forms a gas chamber. Plasma is produced within the chamber by pumping gas under pressure through the inlet passageway **18** into the chamber and through an arc maintained between the cathode **11** and the anode **13**, the plasma then passing through the sonic orifice **26** and expanded in the supersonic nozzle **27**. The design and construction of such arc gap devices are well known in the art and hence will not be discussed in detail.

The end of the tubular casing **10** adjacent the outlet of the nozzle **27** defines a radially inwardly extending flange **10***a*, the flange terminating flush with the mouth of the nozzle. Disposed adjacent the flange **10***a* is a ring cathode **30** fabricated of copper or other suitable electrically conductive material. The cathode **30** has a tubular extension **30***a*, by means of which the ring cathode is securely maintained in coaxial alignment on the tubular casing **10**. Wound about the tubular casing **10** is a magnetic field coil **35**, the field coil comprising multiple layers of coil windings wound circumferentially about the tubular casing **10** and extending throughout the length of the arc gap device within the casing and past the orifice of the expansion nozzle. The field coil **35** is encased within a ferromagnetic shield **36** which serves to establish the axisymmetric flux path shown by the dotted lines in FIGURE 1.

Since the radial component of the magnetic field drops to zero along the axis of the device, there might be a tendency for the plasma current to concentrate itself into a filament along the central axis with the result that little happens except local heating of the gas along the axis. In order to prevent this occurrence, a transverse rotating magnetic field is established along the length of the accelerator, the field strength being merely adequate to prevent a current filament from forming along the axis. The transverse rotating magnetic field is provided by a plurality of coils **38** circumferentially disposed about the expansion nozzle.

In the operation of the device shown in FIGURE 1, an arc jet is utilized to heat and partially ionize a gas flow which is then passed through the sonic orifice **26** and expanded in the supersonic nozzle **27**. A second electric discharge is maintained along the length of the nozzle by striking a discharge from the ring cathode **30** at the nozzle outlet to the anode **13** of the first arc. An axisymmetric magnetic field is applied throughout the volume of the nozzle such that the field strength drops to a very small value at the nozzle outlet. A tangential Hall current will be induced that will interact with the applied magnetic field to produce axial and radial forces on the gas. There will also be a positive axial accelerating force on the gas due to the interaction of the radial component of the current with the tangential magnetic field induced by the axial current. There are four accelerating mechanisms acting upon the plasma passing through the accelerator structure of FIGURE 1. First, there is supersonic joule heating with expansion. Second, there is an expansion of the current density in the secondary electric discharge. Third, an axial volume force is created due to the Hall currents. Fourth, there is a conversion of rotational kinetic energy to axial kinetic energy through radial expansion. To facilitate a mathematical analysis of this apparatus, it will be assumed that the tangential magnetic field is negligibly small. As long as the applied field is over several hundred gauss, this is a reasonable assumption when the axial current is of the order of a few hundred amperes.

The equations describing the current density are as follows:

$$j+\frac{\omega_e\tau_e}{|B|}j\times B-\frac{\omega_e\tau_e\omega_I\tau_I}{|B|^2}(j\times B)\times B\approx\sigma F_1 \quad (1)$$

$$\frac{\omega_e\tau_e}{|B|}=\frac{\sigma}{|e|n_I}=\frac{|e|}{kT}D_{ea}\frac{nq_{ea}f_{ea}^{(2)}}{n_Iq_{eI}f_{eI}^{(2)}+n_aq_{ea}f_{ea}^{(2)}} \quad (2)$$

$$\frac{\omega_I\tau_I}{|B|}=\frac{|e|}{kT}D_{Ia}\frac{nn_a}{(n_a+n_I)^2} \quad (3)$$

$$F_1=E+\mu\times B+\frac{kT}{|e|}(\nabla\ln p_e+K_e\nabla\ln T) \quad (4)$$

Where,

j=current density
ω=particle cyclotron frequency
τ=collision time of particle
B=magnetic field strength
σ=electrical conductivity of the gas
F=electromagnetic force per unit volume applied to gas generalized electric field term
n=particle density
e=charge on the electron
k=Boltzmann's constant
T=temperature in degrees Kelvin
D=diffusion coefficient
q=cross-section of interaction
f=force coefficient
E=electric field
μ=permeability of free space
p=pressure

and where the subscripts *e*, *I*, *a*, respectively refer to electrons, ions, and atoms.

It is possible to solve exactly for the three components of the force per unit volume of gas by defining the angles as shown in FIGURE 2 of the drawing, wherein ϕ represents the angle of the magnetic field with respect to the axis. It is seen that as long as $\alpha\phi\ll1$, a good solution will be obtained. The ideal solution is obtained when $\alpha\phi=0$. The results are shown below:

$$F_z=\frac{(\omega_e\tau_e)^2\sin^2\phi\left(1-\frac{\tan\alpha\phi}{\tan\phi}\right)|e|n_I(E_z-E'_z)}{(1+\omega_e\tau_e\omega_I\tau_I)\left[1+\left\{\frac{(\omega_e\tau_e)^2}{1+\omega_e\tau_e\omega_I\tau_I}+\omega_e\tau_e\omega_I\tau_I\right\}\sin^2\phi\left(1-\frac{\tan\alpha\phi}{\tan\phi}\right)\right]} \quad (5)$$

$$-E'_z=\frac{kT}{|e|}\left(\frac{\partial\ln pe}{\partial_z}+K_e\frac{\partial\ln T}{\partial_z}\right)-vB\sin\phi-\frac{(1+\omega_e\tau_e\omega_I\tau_I\sin^2\phi)}{\omega_e\tau_e}wB+\omega_I\tau_I\sin\phi\cos\phi uB \quad (6)$$

$$Fr=-\cot\phi\,F_z \quad (7)$$

$$F_\theta=\frac{(1+\omega_e\tau_e\omega_I\tau_I)}{\omega_e\tau_e\sin\phi}F_z+|e|n_I\sin\phi wB\left(1-\frac{u}{w}\cot\phi\right) \quad (8)$$

In these equations, u, v, and w are the components of the mass velocity vector in the representative r, θ and Z directions. The expression F_z can be greatly simplified if it is assumed that the pressure and magnetic field are chosen so that

$$\left|\left\{\frac{(\omega_e\tau_e)^2}{1+\omega_e\tau_e\omega_I\tau_I}+\omega_e\tau_e\omega_I\tau_I\right\}\sin^2\phi\left(1-\frac{\tan\alpha\phi}{\tan\phi}\right)\right|>>1 \quad (9)$$

and

$$\omega_e\tau_e\omega_I\tau_I>1 \quad (10)$$

then

$$F_z=\frac{|e|n_I}{1+(\omega_I\tau_I)^2}(E_z-E'_z) \quad (5a)$$

when E'_z is the rather complicated back E.M.F. term shown in the Equation 6. Subject to the conditions indicated in Equations 10 and 9, a number of important conclusions can be drawn from Equation 5*a*.

(1) The axial acceleration is always in the direction of the applied electric field and is proportional to the potential drop of the discharge through the nozzle.

(2) The axial acceleration is independent of the direction of the applied magnetic field subject to the restriction of Equation 9.

(3) As long as $\omega_I\tau_I<1$, the magnitude of the axial acceleration is independent of the magnitude of the applied magnetic field. However, the magnetic field must be strong enough so that the conditions specified in Equations 10 and 9 are maintained. Thus, magnetic field interactions, rather than gas dynamic forces, will develop the main axial accelerating force for the gas plasma. Therefore, it can be seen that the desired predominance of magnetic field interactions can be achieved by maintaining $\omega\tau$ greater than unity for the electrons in the plasma and less than unity for the ions in the plasma.

In addition to the axial acceleration, there are radial and tangential forces on the gas as indicated by Equations 8 and 7. When cot $\phi>0$, the radial force on the charged particles is directed inward when the axial force is accelerating the gas. In practice, this signifies that the beam of charged particles would contract when emerging from an axisymmetric magnetic field and would expand when entering such a field. The tangential component of the body force will induce a considerable amount of rotation in the gas. When the gas is continually expanding, some of this rotational energy will be recovered due to the necessity of conserving angular momentum.

Thus, in the accelerator embodiment shown in FIGURE 1 of the drawing, the tangential component of the body force, when the gas is expanded through the nozzle, is utilized to increase the total axial force or thrust developed. There is, however, a much better method of increasing the total axial thrust. As shown by Equation 7, it is possible to reverse the angular acceleration by reversing the angle ϕ. As long as

$$\frac{u}{v}\ll1$$

then it should be possible to accelerate the gas axially and impart very little angular velocity to it by utilizing an axisymmetric magnetic field that fringes strongly at both the inlet and the outlet, i.e., an axisymmetric magnetic field in which the total radial components of the magnetic lines of force greatly predominate over the axial components. A plasma accelerator utilizing this principle is illustrated in FIGURE 3. The accelerator embodiment of FIGURE 3 utilizes the basic arc gap device and expansion nozzle of FIGURE 1, together with the axisymmetric field created by the field coil 35 and the ferromagnetic shield 36. To this basic structure has been added a fringe field coil 40 and a plurality of coils 41 and 42. The coils 41 are circumferentially spaced around the conduit means 25 between the end section 25*a* and the fringe field coil 40. The coils 42 are circumferentially spaced around the conduit means 25 on the other side of the fringe field coil 40. The flux lines of the fringe field produced by the field coil 40 are shown in FIGURE 3 as a series of dot-dash lines. The magnetic field created by the coils 41 and 42 are fields which rotate around the circumference of the conduit means 25.

As the plasma enters the fringe magnetic field, there are components of acceleration in the following directions:

(1) A positive axial acceleration.
(2) A radial outward acceleration.
(3) A counterclockwise angular acceleration. As the plasma leaves the fringe magnetic field, it again receives a positive axial acceleration. However, now the radial force is directed inwardly and the tangential acceleration is clockwise. By proper adjustment of the fringe and

rotating magnetic fields, it is possible to focus the plasma into a well-defined jet at the mouth of the nozzle with negligible angular velocity components in the jet. Thus, the fringe magnetic field created by the field coil **40** provides an axial velocity increment to the plasma jet. An extension of this principle would be to utilize a plurality of fringe field coils to obtain an axial velocity increment from each of the fields. FIGURE 4 of the drawings shows such an accelerator embodiment.

The accelerator of FIGURE 4 is the basic embodiment of FIGURE 1 to which it has been added a plurality of magnetic field coils **50** encased within a metal tube **52**, the tube **52** forming an extension of the channel through which the plasma is accelerated and replacing the ring cathode **30** of FIGURE 1. The coils **50** are relatively closely spaced and are cyclically displaced from the central axis of the device in 90° steps to prevent a region of very low radial magnetic field from occurring along the center line to thereby prevent formation of a current filament along the central axis. Thus, the coils **50** provide the dual function of a plurality of fringing magnetic fields and rotating magnetic fields. The metal tube **52** defines a radially inwardly extending flange *52a* to provide an outlet nozzle for the device and a ring cathode for establishing the aforementioned second electric discharge to the anode **13**.

The hereinabove-described accelerator embodiments possess a number of practical advantages over the channel $j \times B$ accelerator and other steady state accelerating devices:

(1) The present invention structures obviate the problem of introducing a plasma into a magnetic field of an accelerator and then removing it from the field without causing deceleration or spreading of the jet.

(2) The joule heating of the gas is converted into axial jet energy in the expansion nozzle in the same region where the acceleration is occurring.

(3) The tangential velocities are cancelled by both clockwise and counterclockwise acceleration, hence, the back E.M.F. is minimized. In any case, independent of the magnitude of the back E.M.F., the axial electric field can adjust itself to maintain the axial discharge at all times. Hence, it should be possible to give an arbitrarily large velocity increment to the gas plasma by using multiple stages of acceleration.

(4) The current from the accelerating discharge enters the anode where the gas is comparatively cool and the pressure is high. For this reason, the electron energy at the anode surface is only a fraction of an electron volt. Moreover, the anode point of attachment is rotating rapidly due to the axial magnetic field in this region of the arc. All of these factors tend to prevent local heating of the anode surface, and hence anode erosion and sputtering is minimized.

(5) The plasma jet is axially focused and angular momentum components are minimized, thereby rendering these accelerators especially suited for space propulsion.

The gases utilized in the present invention accelerators should possess several distinct characteristics. The gases should have a relatively low ionization potential (less than about 16 volts) and a molecular weight greater than about 40. The gases should be non-corrosive, non-oxidizing, i.e., gases which will not attack metallic surfaces whether the gases are in ion or atomic form. Examples of gases possessing these desirable characteristics are argon, nitrogen, cesium, and lithium. Alternatively, a combination of gases may be used. The radians per collision of the ions must be practically insignificant when compared to the radians per collision of the electrons. For example, the ions should typically be within the range of 0.1 to 1.0 radian per collision while the electrons are typically within the range of 100 to 1,000 radians per collision. It is readily apparent that when utilizing a suitable mixture of gases, one of the gases is almost completely ionized while the other gas is non-ionized. The ionized gas is preferably derived from an alkali metal, such as sodium or potassium.

In practical examples of the hereinabove illustrated plasma accelerator embodiments the potential difference between the anode **13** and the first cathode **11** is on the order from 40 to 150 volts, the power in the pre-ionizing arc being within the range from about 2 to 50 kw. The primary purpose of the first arc is to ionize rather than to heat the gas. As stated hereinabove, there is no potential applied to the intermediate shaping electrode **12**, its function being merely to channel the gas. The second cathode (ring cathode **30** in FIGURES 1 and 3 and cathode **52** in FIGURE 4) is maintained within the range of from about 200 to 1,000 volts below the anode, and therefore below the first cathode. The second cathode is at the outlet end in all of the embodiments and is insulated from the remainder of the charge. The discharge set up by the potential between the second cathode and the anode extends along the conducting channel, the current of this discharge being carried by the ions. The ions are being axially accelerated through the electrostatic potential and are being tangentially accelerated in a spiralling pattern by the radial component of the magnetic fields, the direction of the spiral depending upon the direction of the radial component of the magnetic fields which varies from coil to coil. Therefore, the tangential velocity component is cancelled out. An exhaust velocity of from 20,000 to 50,000 meters per second, or higher, is therefore obtained.

The gas is pumped in through the inlet port **19** under a pressure on the order from 2 to 3 atmospheres. The gas is ionized within the chamber and formed into a plasma and injected into the sonic nozzle with supersonic expansion. The plasma flows along the channel and is acted upon by the second discharge and the fringe magnetic fields. The discharge current is carried by the ions while the electrons are spiralling as they enter the channel. The direction of electron spiralling is reversed as the electrons traverse the channel, in accordance with the direction of the radial component of the alternating magnetic fields. Thus, although the ions are being axially accelerated through an electrostatic potential, they are also being tangentially accelerated in a spiral pattern by the radial component of the magnetic fields. The radial component of the magnetic field is adjusted to cancel the tangential velocity component.

Thus, there has been described a novel plasma accelerator concept wherein Hall currents are utilized to significantly increase the axial acceleration of a gas plasma. By injecting a plasma axially into a channel along which is maintained an axial electric field and a strongly fringing axisymmetric magnetic field, the plasma is subjected to axial and rotational forces as it passes through the channel. Interaction between the applied (axial) electric field and the fringe (radial) magnetic field produce tangential Hall currents. These tangential Hall currents provide an axial force on the gas plasma. Interaction betwen the tangential Hall currents and the radial components of the fringe magnetic fields provide rotational forces on the gas plasma. However, since the radial components of the magnetic lines of force at one end of the fringe field are oppositely directed from those at the other end of the fringe field, the rotational forces applied to the gas plasma as it enters the fringe field are oppositely directed from the rotational forces applied to the plasma as it leaves the fringe field. Hence, the rotational forces cancel out, thereby leaving only the axial forces for acceleration of the plasma. Various structural embodiments of accelerators utilizing this concept have been illustrated. Although the invention has been described with a certain degree of particularity, it is understood that the present disclosure has been made only by way of example and that numerous changes in the details of construction and the combination and arrangement of parts may be resorted to without departing from

the spirit and scope of the invention as hereinafter claimed.

What is claimed is:

1. A plasma accelerator comprising, in combination:
(a) a casing having an axisymmetric supersonic expansion nozzle therein extending longitudinally between a sonic orifice inlet and a nozzle outlet, the longitudinal axis of said nozzle defining a reference axis for the accelerator;
(b) means for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into the sonic orifice inlet of said nozzle;
(c) means for establishing an axisymmetric electric discharge extending axially through said nozzle to thereby establish a plasma jet defining an axial current flow through said nozzle; and
(d) means for establishing a magnetic field within at least a predetermined longitudinal portion of said nozzle, said magnetic field bing axisymmetric with respect to said reference axis and strongly fringing intermediate said sonic orifice inlet and said nozzle outlet so that the total radial components of the magnetic lines of force of said magnetic field greatly predominate over the axial components of the magnetic lines of force of said magnetic field and cross the current density lines of the axial current flow of said plasma jet through said accelerator channel.

2. A plasma accelerator comprising, in combination:
(a) a casing having an axisymmetric supersonic expansion nozzle therein extending longitudinally between a sonic orifice inlet and a nozzle outlet, the longitudinal axis of said nozzle defining a reference axis for the accelerator;
(b) an arc gap device disposed within said casing adjacent said sonic orifice inlet for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into said sonic orifice inlet, said arc gap device including a first cathode electrode and an anode electrode between which a first electric discharge is maintained to partially ionize said gas stream;
(c) means for maintaining a second electric discharge axially through said nozzle between said nozzle outlet and the anode of said arc gap device to thereby establish a plasma jet defining an axial current flow through said nozzle; and
(d) means for establishing a magnetic field within at least a predetermined longitudinal portion of said nozzle, said magnetic field being axisymmetric with respect to said reference axis and strongly fringing intermediate said sonic orifice inlet and said nozzle outlet so that the total radial components of the magnetic lines of force of said magnetic field greatly predominate over the axial components of the magnetic lines of force of said magnetic field and cross the current density lines of the axial current flow of said plasma jet through said nozzle, the field strength of said magnetic field being sufficiently strong with respect to the ambient pressure in said nozzle so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said nozzle.

3. A plasma accelerator comprising in combination:
(a) a casing having an axisymmetric supersonic expansion nozzle therein extending longitudinally between a sonic orifice inlet and a nozzle outlet, the longitudinal axis of said nozzle defining a reference axis for the accelerator;
(b) an arc gap device disposed within said casing adjacent said sonic orifice inlet for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into said sonic orifice inlet, said arc gap device including a first cathode electrode and an anode electrode between which a first electric discharge is maintained to partially ionize said gas stream;
(c) means for maintaining an axial second electric discharge through said nozzle between said nozzle outlet and the anode of said arc gap device to thereby establish a plasma jet defining an axial current flow through said nozzle, said means including a second cathode electrode positioned at said nozzle outlet and a source of electric potential connected between said second cathode electrode and said anode; and
(d) means for establishing a magnetic field within at least a predetermined longitudinal portion of said nozzle, said magnetic field being axisymmetric with respect to said reference axis and strongly fringing intermediate said sonic orifice inlet and said nozzle outlet so that the total radial components of the magnetic lines of force of said magnetic field greatly predominate over the axial components of the magnetic lines of force of said magnetic field and cross the current density lines of the axial current flow of said plasma jet through said nozzle, the field strength of said magnetic field being sufficiently strong with respect to the ambient pressure in said nozzle so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said nozzle.

4. A plasma accelerator comprising, in combination:
(a) a casing having an axisymmetric supersonic expansion nozzle therein extending longitudinally between a sonic orifice inlet and a nozzle outlet, the longitudinal axis of said nozzle defining a reference axis for the accelerator;
(b) an arc gap device disposed within said casing adjacent said sonic orifice inlet for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into said sonic orifice inlet, said arc gap device including a first cathode electrode and an anode electrode between which is established a first predetermined potential difference sufficient to maintain an electric discharge to partially ionize said gas stream, said arc gap device further including means for establishing a first magnetic field having its lines of force extending generally axially through said arc gap device and through said sonic orifice inlet;
(c) means for maintaining a second electric discharge between said nozzle outlet and the anode of said arc gap device to thereby establish a plasma jet defining an axial current flow through said nozzle, said means including a second cathode electrode positioned at said nozzle outlet and a second predetermined potential difference maintained between said second cathode electrode and the anode of said arc gap device, said second predetermined potential difference being substantially greater than said first predetermined potential difference; and
(d) means for establishing a second magnetic field within at least a predetermined longitudinal portion of said expansion nozzle, said second magnetic field being axisymmetric with respect to said reference axis and strongly fringing intermediate said sonic orifice inlet and said nozzle outlet so that the total radial components of the magnetic lines of force of said second magnetic field within said nozzle greatly predominate over the axial components of the magnetic lines of force of said second magnetic field and cross the current density lines of the axial current flow of said plasma jet through said nozzle, the field strength of said second magnetic field being sufficiently strong with respect to the ambient pressure in said nozzle so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said nozzle.

5. A plasma accelerator comprising in combination:
(a) a casing having an axisymmetric supersonic expansion nozzle therein extending longitudinally between a sonic orifice inlet and a nozzle outlet, the longitudinal axis of said nozzle defining a reference axis for the accelerator;
(b) an arc gap device disposed within said casing adjacent said sonic orifice inlet for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into said sonic orifice inlet, said arc gap device including a first cathode electrode and an anode electrode between which is established a first predetermined potential difference sufficient to maintain an electric discharge to partially ionize said gas stream, said arc gap device further including means for establishing a first magnetic field having its lines of force extending generally axially through said arc gap device and through said sonic orifice inlet;
(c) means for maintaining a second electric discharge between said nozzle outlet and the anode of said arc gap device to thereby establish a plasma jet defining an axial current flow through said nozzle, said means including a second cathode electrode positioned at said nozzle outlet and a second predetermined potential difference maintained between said second cathode electrode and the anode of said arc gap device, said second predetermined potential difference being substantially greater than said first predetermined potential difference; and
(d) means for establishing a second magnetic field within a first predetermined longitudinal portion of said nozzle, said second magnetic field rotating about said reference axis substantially transversely thereto; and
(e) means for establishing a third magnetic field within a second predetermined longitudinal portion of said nozzle, said third magnetic field being axisymmetric with respect to said reference axis and strongly fringing so that the total radial components of the magnetic lines of force of said third magnetic field greatly predominate over the axial components of the magnetic lines of force of said third magnetic field and cross the current density lines of the axial current flow of said plasma jet through said nozzle, the field strength of said third magnetic field being sufficiently strong with respect to the ambient pressure in said nozzle so that the magnetic field interactions within said nozzle predominate over the gas dynamic forces within said nozzle to axially accelerate said plasma jet through said nozzle.

6. A plasma accelerator comprising in combination:
(a) a casing having first and second ends and an axisymmetric supersonic expansion nozzle disposed therein intermediate said first and second ends and extending longitudinally between a sonic orifice inlet and a nozzle outlet, the longitudinal axis of said nozzle defining a reference axis for the accelerator;
(b) an arc gap device disposed within said casing between said first end and said sonic orifice inlet for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into said sonic orifice inlet, said arc gap device including a first cathode electrode and an anode electrode between which is maintained a first predetermined potential difference sufficient to maintain an electric discharge therebetween to partially ionize said gas stream, said arc gap device further including means for establishing a first magnetic field having its lines of force extending generally axially through said arc gap device and through said sonic orifice inlet;
(c) means for maintaining an axial second electric discharge between said second end of said casing and the anode of said arc gap device to thereby establish a plasma jet defining an axial current flow through said casing, said means including a second cathode electrode positioned at said second end of said casing and a second predetermined potential difference maintained between said second cathode electrode and the anode of said arc gap device, said second predetermined difference being substantially greater than said first predetermined potential difference, said second cathode electrode defining a circular opening therethrough coaxial with said predetermined axis; and
(d) means for establishing a plurality of fringe magnetic fields extending through predetermined adjacent longitudinal portions of said casing intermediate said nozzle outlet and said second cathode electrode, each of said fringe magnetic fields being axisymmetric with respect to an axis parallel to said reference axis and angularly displaced from the reference axes of the immediately adjacent magnetic fields, each of said fringe magnetic fields being strongly fringing so that the total radial components of the magnetic lines of force of each of said fringe magnetic fields greatly predominate over the axial components of the magnetic lines of force of each of said fringe magnetic fields and cross the current density lines of the axial current flow of said plasma jet through said casing, the field strengths of said fringe magnetic fields being sufficiently strong with respect to the ambient pressure in said casing so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said casing.

7. A plasma accelerator comprising in combination:
(a) a casing having a tubular channel therein extending longitudinally between an inlet and an outlet, the longitudinal axis of said channel defining a reference axis for the accelerator;
(b) means for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into the inlet of said channel;
(c) means for establishing an axisymmetric electric discharge extending axially through said channel between the inlet and outlet of said channel to thereby establish a plasma jet defining an axial current flow through said channel; and
(d) means for establishing a magnetic field within at least a predetermined longitudinal portion of said channel, said magnetic field being axisymmetric with respect to said reference axis and strongly fringing intermediate said inlet and said outlet so that the total radial components of the magnetic lines of force of said magnetic field greatly predominate over the axial components of the magnetic lines of force of said magnetic field and cross the current density lines of the axial current flow of said plasma jet through said accelerator channel, the field strength of said magnetic field being sufficiently strong with respect to the ambient pressure in said accelerator channel so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said accelerator channel.

8. A plasma accelerator comprising in combination:
(a) a casing having a tubular channel therein extending longitudinally between an inlet and an outlet, the longitudinal axis of said channel defining a reference axis for the accelerator;
(b) means for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into the inlet of said channel;
(c) means for establishing a potential difference between the inlet and outlet of said channel sufficient to maintain an axial electric discharge therebetween to thereby establish a plasma jet defining an axial current flow through said channel;
(d) means for establishing a first magnetic field within a first predetermined longitudinal portion of said

channel, said first magnetic field rotating about said reference axis substantially transversely thereto; and

(e) means for establishing a second magnetic field within a second predetermined longitudinal portion of said channel, said second magnetic field being axisymmetric with respect to said reference axis and strongly fringing so that the total radial components of the magnetic lines of force of said second magnetic field greatly predominate over the axial components of the magnetic lines of force of said second magnetic field and cross the current density lines of the axial current flow of said plasma jet through said channel, the field strength of said second magnetic field being sufficiently strong with respect to ambient pressure in said channel so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said channel.

9. A plasma accelerator comprising in combination:

(a) a casing having a tubular channel therein extending longitudinally between an inlet and an outlet, the longitudinal axis of said channel defining a reference axis for the accelerator;

(b) means for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into the inlet of said channel;

(c) means for establishing a potential difference between the inlet and outlet of said channel sufficient to maintain an axial electric discharge therebetween to thereby establish a plasma jet defining an axial current flow through said channel; and

(d) means for establishing a plurality of magnetic fields extending through predetermined adjacent longitudinal portions of said channel, each of said magnetic fields being axisymmetric with respect to an axis parallel to said reference axis and angularly displaced from the reference axes of the immediately adjacent magnetic fields, each of said magnetic fields being strongly fringing so that the total radial components of the magnetic lines of force of each of said magnetic fields greatly predominate over the axial components of the magnetic lines of force of each of said magnetic fields and cross the current density lines of axial current flow of said plasma jet through said channel, the field strengths of said magnetic fields being sufficiently strong with respect to the ambient pressure in said channel so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said channel.

10. A plasma accelerator comprising in combination:

(a) a casing having a tubular channel therein extending longitudinally between an inlet and an outlet, the longitudinal axis of said channel defining a reference axis for the accelerator;

(b) an arc gap device disposed within said casing adjacent said channel inlet for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into the inlet of said channel, said arc gap device including a first cathode electrode and an anode electrode between which a first electric discharge is maintained to partially ionize said gas stream;

(c) means for maintaining an axial second electric discharge between the outlet of said channel and the anode of said arc gap device to thereby establish a plasma jet defining an axial current flow through said accelerator channel; and

(d) means for establishing a magnetic field within at least a predetermined longitudinal portion of said channel, said magnetic field being axisymmetric with respect to said reference axis and strongly fringing intermediate said inlet and said outlet so that the total radial components of the magnetic lines of force of said magnetic field greatly predominate over the axial components of the magnetic lines of force of said magnetic field and cross the current density lines of the axial current flow of said plasma jet through said accelerator channel, the field strength of said magnetic field being sufficiently strong with respect to the ambient pressure in said accelerator channel so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said accelerator channel.

11. The plasma accelerator device as defined in claim 10 wherein said means for maintaining said second electric discharge between the inlet and outlet of said channel includes a second cathode electrode positioned at said channel outlet and a source of electrical potential connected between said second cathode electrode and the anode electrode of said arc gap device.

12. A plasma accelerator comprising in combination:

(a) means for at least partially ionizing a gas stream and directing the resulting gas plasma along a reference axis past a first predetermined point;

(b) means for establishing a potential difference along said reference axis between said first predetermined point and a second predetermined point sufficient to maintain an electric discharge therebetween to thereby establish a plasma jet defining an axial current flow along said reference axis between said first and second predetermined points, said second predetermined point being spaced away from said first predetermined point in the direction of gas flow; and

(c) means for establishing a magnetic field axisymmetric with respect to said reference axis and strongly fringing intermediate said first and second predetermined points so that the total radial components of the magnetic lines of force of said magnetic field greatly predominate over the axial components of the magnetic lines of force of said magnetic field and cross the current density lines of the axial current flow of said plasma jet between said first and second predetermined points, the field strength of said magnetic field being sufficiently strong with respect to the ambient pressure along said reference axis between said first and second predetermined points so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet from said first predetermined point to said second predetermined point.

13. A plasma accelerator comprising in combination:

(a) a casing having a tubular channel therein extending longitudinally between an inlet and an outlet, the longitudinal axis of said channel defining a reference axis for the accelerator;

(b) an arc gap device disposed within said casing adjacent said channel inlet for at least partially ionizing a gas stream and injecting the resulting gas plasma axially into the inlet of said channel, said arc gap device including an anode a predetermined distance from said inlet and a first cathode electrode disposed adjacent said inlet, said first cathode electrode defining a circular opening therethrough coaxial with said reference axis, said arc gap device further including means for establishing a first magnetic field having its lines of force extending generally axially through said arc gap device and through the opening in said ring cathode;

(c) means for establishing an axisymmetric electric field extending axially between the outlet of said channel and the anode of said arc gap device to thereby establish a plasma jet defining an axial current flow through said channel, said means including a second cathode electrode positioned at said channel outlet and a source of electric potential connected between said second cathode electrode and said anode, said second cathode electrode defining a cir-

cular opening therethrough coaxial with said predetermined axis; and

(d) means for establishing a second magnetic field within at least a predetermined longitudinal portion of said channel, said second magnetic field being axisymmetric with respect to said reference axis and strongly fringing intermediate said inlet and said outlet so that the total radial components of the magnetic lines of force of said second magnetic field greatly predominate over the axial components of the magnetic lines of force of said second magnetic field and cross the current density lines of the axial current flow of said plasma jet through said channel, the field strength of said second magnetic field being sufficiently strong with respect to the ambient pressure in said channel so that the magnetic field interactions predominate over the gas dynamic forces to axially accelerate said plasma jet through said channel.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,243,954 April 5, 1966

Gordon L. Cann

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, after line 12, insert the following paragraph:

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568, (72 Stat. 435; 42 U.S.C. 2457).

Signed and sealed this 2nd day of December 1969.

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents