

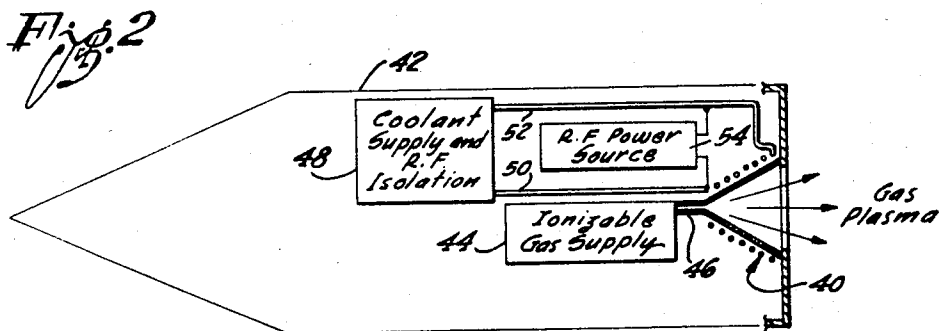
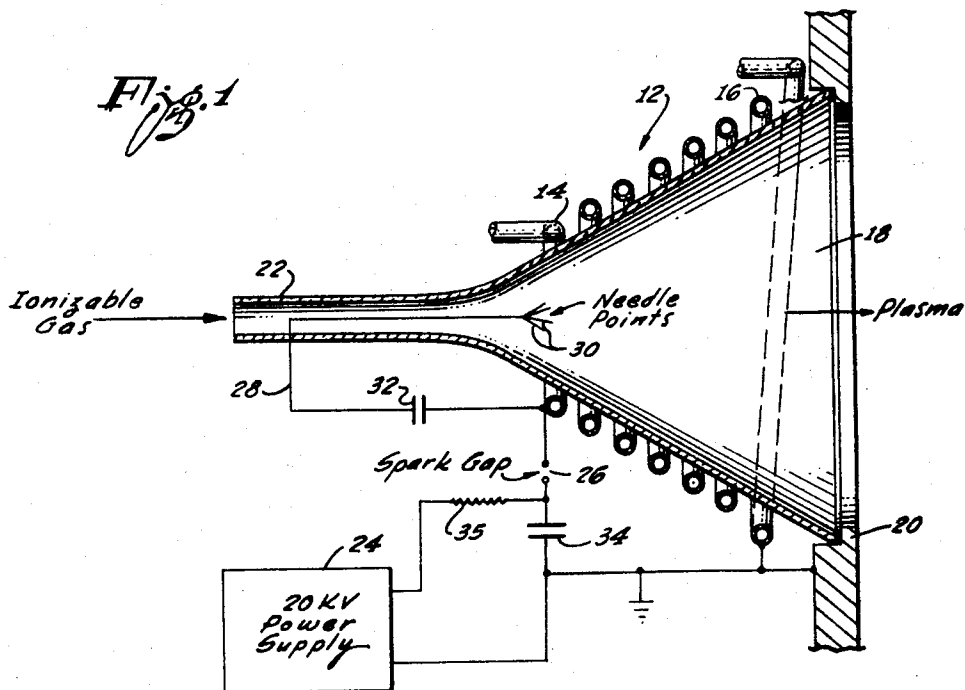
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IONIZATION AND PLASMA ACCELERATION APPARATUS

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IONIZATION AND PLASMA ACCELERATION APPARATUS

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The present invention relates to apparatus for ionizing gas and for accelerating the resultant gas plasma.

A number of systems have been proposed heretofore for ionizing gas and for accelerating the plasma produced thereby, some of these systems being described in the article entitled "A Comparison of Ion and Plasma Propulsion" by S. W. Kash which appeared at pages 458 through 465 of the Proceedings of the Institute of Radio Engineers, April 1960, volume 48, No. 4. In some of the disclosed electrostatic systems, the electrodes are in contact with gas discharge, and therefore tend to be eroded and ejected as part of the fuel. In addition, these systems are generally not adapted for continuous operation.

Other systems involving the use of coils have been proposed, one such system being disclosed in copending application Serial Number 723,018, of Siegfried Hansen, now Patent Number 2,992,345, granted July 11, 1961, which is assigned to the assignee of the present patent application. This system includes circuitry and coil structure for providing an accelerating field to accelerate the gas plasma.

A principle object of the invention is to simplify and reduce the weight of ionization and gas plasma acceleration apparatus. Collateral objects include the avoidance of electrode disintegration and electrical circuit complexity. An additional object of the invention is to optimize the "specific impulse" of plasma acceleration propulsion systems.

These objects are achieved, in accordance with the present invention, by the provision of a funnel-shaped coil which is energized at high power levels with high frequency electric signals. In addition, arrangements are provided for introducing gas into the coil near its apex. Simple single phase electrical signals may be used. In accordance with a suggested theory of operation, the gas is believed to be ionized cumulatively by the expanding and contracting cloud of electrons formed near the apex of the funnel, as explained in detail below. The flaring nature of the funnel produces an outward component of velocity to the gas plasma formed within the coil. This predominant effect is supplemented by thermal effects, and causes the forceable ejection of the plasma and the gas which is not ionized from the flared end of the funnel.

In accordance with an important feature of the invention, therefore, a gas ionization and plasma acceleration apparatus includes a generally funnel-shaped electric coil, with a flared mouth from which the plasma is ejected, circuitry for supplying high frequency electrical signals to the coil, and apparatus for supplying ionizable material to the apex of the coil.

In accordance with additional feature of the invention, apparatus may be provided for preventing flow of gas from the coil except at its flared mouth, and supplemental apparatus may be provided for enhancing the ionization of the gas near the apex of the funnel. The coil may be hollow, thus permitting water cooling. As will be disclosed in more detail hereinbelow, the included angle for the flared coil is preferably about 60°, although satisfactory performance may be obtained with coils having included angles of from 30 to 90°.

Other objects, features and advantages of the invention will become apparent from a consideration of the

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following detailed description and from the drawing, in which:

FIG. 1 is a schematic diagram of one form of ionization and plasma acceleration device in accordance with the invention; and

FIG. 2 is a schematic drawing in which the flared coil of FIG. 1 is shown mounted in a space vehicle.

With reference to FIG. 1 of the drawings, the funnel-shaped electric coil 12 includes the smallest turn 14 toward its apex, and several additional turns of progressively increasing diameter up to the outer turn 16 toward the open mouth of the coil. The coil 12 is closely wrapped around a funnel 18. The funnel 18 may be made of any heat-resistant material, such as a high silica glass, for specific example. The funnel 18 may be a conventional commercially available "Vycor" funnel having a diameter at its flared end of 4 inches, and an included angle of 60 degrees. The outer support 20 forms part of the vacuum-tight chamber wall. Gas to be ionized is supplied to the space within the funnel-shaped coil 12 through the stem 22 of the funnel 18.

With regard to the electrical system as shown in FIG. 1, power is supplied to the coil 12 from the power supply 24. In the particular apparatus shown in FIG. 1, a spark gap 26 is employed to generate intermittent high frequency pulses. The wire 28 terminates in a group of needle points 30 within the funnel 18 near the apex of the coil 12. These needle points 30 are energized through the capacitor 32 which is connected to the spark gap 26 in parallel with the coil 12. In the particular apparatus of FIG. 1, the 7000 micromicrofarad condenser 34 was selected to resonate with the 1.6 microhenry coil 12 to produce the desired resonant frequency of about 1.5 megacycles per second. The charging circuit for capacitor 34 includes resistor 35.

In operation, the gas is ionized to a preliminary extent by the needle points 30 as the gas is introduced into the funnel. Additional ionization occurs as a result of the high frequency supplied to the coil 12. It may be noted in this regard that successful devices have also been built in which no special supplemental ionization arrangements, such as the needle points 30, were provided. The ionization becomes cumulative as a result of the interaction of the electric and magnetic fields provided by the flaring or funnel-shaped coil 12.

The nature of the electric and magnetic field within the funnel plays an important part in the gas ionization and in the plasma acceleration operation of the funnel apparatus. More specifically, the magnetic field in the center of the funnel is generally axial, while the electric field is circular and provides electric field patterns coaxial with the funnel. Thus, the initial electrons generated within the funnel are accelerated by the electric field toward a circular trajectory; the axial magnetic field, however, imparts inward and outward components of motion to the electrons, as the direction of the magnetic field reverses.

These inward and outward radial forces on the rotating electrons are a result of the "motor" forces of a magnetic field on a "current" flowing perpendicular to the field. In the present case, of course, the "current" is the electron stream. The alternate inward and outward pulsing forces on the electrons produce a contracting and expanding cloud of electrons which ionizes the gas introduced into the apex of the funnel through collisions. The probability of collisions is increased by the action of the contracting electrons on the gas in the region of highest gas density near the apex of the funnel. Additional electrons will, of course, be generated along with heavier charged particles. However, it is the high speed electrons which are believed to play a predominant part in the ionization of the incoming gas to form the desired gas plasma.

The flaring configuration of the coil provides an inner zone near the apex of the coil where the magnetic field diverges gradually and is of high density, and an outer region near the mouth of the funnel where the field diverges rapidly. The high density region permits relatively complete ionization, while the highly divergent field accelerates the plasma from the mouth of the coil.

In the operation of the apparatus of FIG. 1, gas was supplied through the stem 22 to the apex of the coil at a rate of about 2×10^{-3} grams per second. The gas was discharged into an evacuated space in which the ambient pressure was approximately 4×10^{-4} millimeters of mercury. In the tests of the device of FIG. 1 and other similar constructions, a visible plasma could be seen for approximately two meters from the mouth of the funnel.

Through the use of several photographs with probes in various positions, in which the camera was triggered by onset of ionization, the velocity of the plasma was measured to be about 5×10^4 meters per second.

One figure of merit for propellants and propulsion systems is the "specific impulse." The "specific impulse" is equal to the velocity divided by the acceleration of gravity, if 100 percent of the fuel is ejected at a given velocity. This may be expressed mathematically by the following expression:

$$I_{sp} = \frac{V}{g} \quad (1)$$

where:

I_{sp} is the specific impulse,
 V is the velocity of ejected "fuel," and
 g is the acceleration of gravity.

In the present case, where the velocity of the plasma is about 5×10^4 meters per second and the acceleration of gravity is 9.8 or approximately 10 meters per second per second, the resultant specific impulse would be about 5,000 seconds, assuming 100 percent ionization. This is in comparison with the specific impulse of the better chemical fuels which may reach 300 or 400 seconds.

The optimum specific impulse depends on many factors. Thus, for example, the energy required to eject fuel is roughly proportional to $\frac{1}{2}MV^2$, where V is the velocity of the fuel and M is its mass. Thus, to increase the specific impulse by a factor of two, where the specific impulse is a direct function of velocity, the power input must be quadrupled. In general, however, it has been determined that, with currently available power supplies, a specific impulse of between 5,000 and 10,000 seconds represents approximately optimum operating conditions, for presently contemplated space missions.

In a ballistic target experiment, a sheet of aluminum foil was suspended by a pair of threads in front of the open end of the funnel. It was found that three spark discharges were sufficient to cause the center of mass of the aluminum foil to have a maximum deflection of 0.087 centimeter from its rest position. Analyzing this on a mathematical basis:

$$T = 2\pi\sqrt{\frac{L}{g}} = 2 \text{ seconds} \quad (2)$$

where:

T represents the period of oscillation of the aluminum sheet pendulum,
 $\pi = 3.1416 \dots$,
 L equals the length of the pendulum, and
 g is the acceleration of gravity.

The equation of motion of the aluminum sheet is:

$$s = S \sin wt$$

where:

s equals the instantaneous position of the target,
 S is the maximum displacement of the target,

w is equal to $2\pi f$, f being the frequency of oscillation of the pendulum, and
 t represents time.

$$\frac{ds}{dt_{max}} = V_{max} = S \frac{2\pi}{T} = 0.087 \times \frac{2\pi}{2} = 0.273 \text{ cm./sec.} \quad (4)$$

where V_{max} is the maximum velocity.

The momentum of the target at impact is given by the following expression:

$$MV = 5.8 \times 0.273 = 1.58 \text{ gm.-cm./sec.} \quad (5)$$

where M , the mass of the target, is equal to 5.8 grams.

The mass of the plasma per discharge may now be calculated by conservation of momentum as follows:

$$nM_p V_p = M_t V_t \quad (6)$$

where:

the mass and velocity of the plasma per discharge are given by M_p and V_p , respectively,

the mass and velocity of the target are given by M_t and V_t , respectively, and

where n represents the number of discharges required to produce the measured displacement mentioned above.

The mass of the plasma per discharge may now be calculated by substitution in equation (6) as follows:

$$M_p = \frac{M_t V_t}{V_p n} = 10^{-7} \text{ grams} \quad (7)$$

The energy per plasma pulse is equal to: $\frac{1}{2}MV^2 = 0.13$ joules.

The energy stored on the capacitor 34 prior to discharge is equal to: $\frac{1}{2}CE^2 = 1.4$ joules.

The efficiency of converting electrical power to the kinetic energy of the plasma was therefore equal to 9%. The foregoing experiment was conducted with a conical coil in which the pre-ionization needle points 30 were not employed. Through the use of photographs indicating the timing of the spark discharge, it was found that the gas did not start ionizing until 75 percent of the capacitor energy was used up in heating, or I^2R losses. Considering only that portion of the cycle from the time of ionization, therefore, the efficiency figure is raised to 35%. The use of a pre-ionization device such as the needle points, or more continuous modes of operation, reduces or eliminates the ionization time losses and thus increases efficiency.

Through additional computations, the maximum force supplied by the plasma accelerator was found to be approximately 0.26 lb. per pulse.

FIG. 2 shows the flared coil 40 of FIG. 1 mounted at the rear of a space vehicle 42, indicated in schematic outline form in the drawing. The conveyance 42 may be any known form of space vehicle such as one of the satellites which is now encircling the globe, for example. It is contemplated that additional conventional power arrangements, such as rockets, would also be provided to place the vehicle 42 into orbit or into space beyond the forceful pull of the earth's gravitational field.

With reference to FIG. 2, ionizable gas is supplied from the storage chamber 44 through the tube 46 to the apex of the coil 40. The coil 40 is hollow, and coolant is provided from the supply 48 through the tubes 50 and 52 to the hollow coil. The radio frequency power source 54 is connected between the copper tubes which are connected to the inner and outer turns of the coil 40. Radio frequency isolation is provided by plastic or rubber tubes which may be 5 or 10 feet in length when a water coolant is employed. This apparatus avoids short circuiting of the radio frequency power supply through the coolant.

With regard to the power source 54, it may be operated either on a pulsed basis as described above in connection with FIG. 1, or on a continuous basis. Continuous operation is desirable to avoid the necessity for re-ionization during successive pulses.

As mentioned above, the present ionization and plasma acceleration apparatus is primarily intended for use as a space vehicle propulsion unit. However, it may also be employed for other purposes in which high velocity gas streams and moderately high volumetric flow rates are desired. One such application is supersonic wind tunnels for simulating conditions at very high altitudes.

Considering the pressures and voltages to which the present system is applicable, the foregoing description has been on the basis of conditions approaching a vacuum and a power input of up to about 25 kilowatts. With higher power levels, operation could be successfully carried on at somewhat higher pressures.

With regard to the type of ionizable material which may be used, a number of gases have been successfully employed. These include carbon dioxide, air, nitrogen, argon, and helium. In addition, it is contemplated that lithium and other similar low-melting point metals may be employed, as well as other gases.

The funnel-shaped coil which is employed increases in diameter from its apex to the open mouth through which the gases are ejected. Various angles have been tried, from a 30° included angle through the preferred 60° cone shown in the drawing to a flat pancake style, similar in form to the heating elements found on electric stoves. In general, it is considered that an angle greater than 30° but less than 90° is most advantageous; however, positive results with somewhat lower efficiencies are found for flaring coils of somewhat smaller and larger included angles.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention. By way of example but not of limitation, it is possible to dispense with the funnel 18 of FIG. 1 without undue adverse effect, as the electrical and magnetic fields produced by the flaring coil tend to confine the plasma to the space within the coil. Thus, it is to be expressly understood that the present invention is to be limited only by the spirit and scope of the appended claims.

What is claimed as new is:

1. In a plasma accelerator, a flared generally conical coil having an included angle of approximately 60°, said coil being open at its larger end to permit the free and unrestrained ejection of high velocity plasma, means for introducing ionizable material into the smaller end of said coil, and means for applying high frequency signals to said coil on a steady-state basis to produce a continuous stream of plasma from the larger end of said coil.

2. In combination, a space vehicle, a propulsion system mounted in said vehicle, said propulsion system including a flared electrical coil having a plurality of turns mounted on said vehicle and defining a conical space, said space being open at its larger end toward the outside of said vehicle, a single phase source of high frequency electrical signals connected across the turns of said flared coil, means for cooling said coil, means for supplying ionizable material to a zone near the center of said conical space, and means for preionizing the material supplied to said conical space.

3. In combination, a space vehicle, a propulsion system mounted in said vehicle, said propulsion system including a flared electrical coil having a plurality of spaced turns mounted on said vehicle and defining a conical space, having an included angle of approximately 60° opening on the outside of said vehicle, a single phase source of high frequency electrical signals connected across the turns of said flared coil, means for cooling said coil, means for supplying ionizable material to said

conical space, and means for preionizing the material supplied to said conical space.

4. A plasma acceleration apparatus comprising: a coil structure consisting solely of a single coil having a series of turns of progressively increasing diameter, said coil being open at its larger end to permit the free and unrestrained ejection of high velocity plasma;

means for injecting ionized plasma through said coil near its center; and

means for energizing said coil at radio frequencies.

5. A plasma acceleration apparatus comprising: a coil structure consisting solely of a single coil having a series of turns of progressively increasing diameter, said coil being open at its larger end to permit the free and unrestrained ejection of high velocity plasma;

means for injecting ionized plasma through said coil near its center; and

means for energizing said coil on a steady-state basis at radio frequencies.

6. A plasma acceleration apparatus comprising: a coil structure consisting solely of a single coil having a series of turns of progressively increasing diameter, said coil having an included angle substantially greater than 30° and less than 90°, and being open at its larger end to permit the free and unrestrained ejection of high velocity plasma;

means for injecting ionized plasma through said coil near its center; and

means for energizing said coil at radio frequencies.

7. In combination, a space vehicle, a propulsion system mounted in said vehicle, said propulsion system including:

an electrical coil having a series of turns of continuously increasing diameter;

means for injecting ionized plasma through said coil near its center; and

means for energizing said coil at high frequencies.

8. In combination, a space vehicle, a propulsion system mounted in said vehicle, said propulsion system including:

a coil structure consisting solely of a single coil having a series of turns of continuously increasing diameter, said coil being open at its larger end to permit the free and unrestrained ejection of high velocity plasma;

means for injecting ionized plasma through said coil near its center; and

means for energizing said coil at radio frequencies.

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