NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO ATTN OF: GP

June 30, 1971

MEMORANDUM

TO: KSI/Scientific & Technical Information Division
Attn: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned U.S. Patents in STAR

In accordance with the procedures contained in the Code GP to Code USI memorandum on this subject, dated June 8, 1970, the attached NASA-owned U.S. patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U.S. Patent No.	:	3,238,413
Corporate Source	:	Langley Research Center
Supplementary Corporate Source	:	
NASA Patent Case No.	:	XLA-00327

Gayle Parker

Enclosure:
Copy of Patent

MAGNETICALLY CONTROLLED PLASMA ACCELERATOR

Filed May 31, 1962

N71-29184 40%

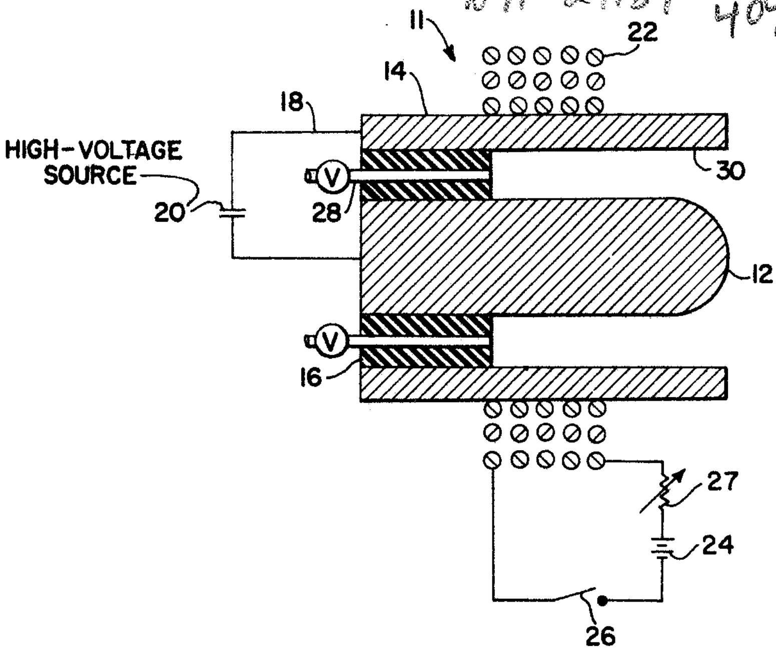

FIG. 1

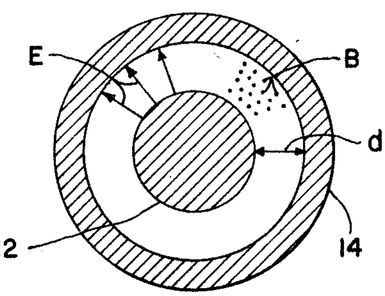

FIG. 2

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1837

United States Patent Office

3,238,413

Patented Mar. 1, 1966

3,238,413

MAGNETICALLY CONTROLLED PLASMA ACCELERATOR

Karlheinz Thom, Hampton, and Joseph Norwood, Jr., Williamsburg, Va., assignors to the United States of America as represented by the Administrator of the National Aeronautics and Space Administration

Filed May 31, 1962, Ser. No. 199,199
6 Claims. (Cl. 315—111)
(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by and for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

This invention relates generally to a plasma accelerator, and more particularly to a magnetically ignited, electromagnetic plasma accelerator capable of ignition in a low density gaseous environment.

Plasma accelerators, or plasma guns, have in recent times become valuable tools for space age research, and have also become the object of extensive development for practical applications. One primary area of research in the plasma physics field is in the simulation of outer atmospheric conditions in a laboratory environment for experimental purposes. Such conditions are essential to the study and solution of such problems as shock wave formation and extreme heating of space vehicles upon atmospheric reentry, and also the telemetry difficulties in communicating with space vehicles due to the ionized gas or plasma sheath which is formed about the space vehicle during its reentry into the atmosphere. In addition, plasma propulsion systems utilizing electromagnetic principles of operation have reached the stage of advanced development. Such systems, which utilize a very low mass of propellant and have a very high specific impulse, are visualized as possible future propulsion systems for travel outside of the Earth's environment. A further expanding application of an electromagnetic plasma gun is in the field of controlled thermonuclear fusion research and technology.

Some earlier plasma accelerators which have been developed in the art, based on an electromagnetic principle of operation, have similar geometrical characteristics to the instant invention. These accelerators consist of a pair of coaxial electrodes upon which an electric potential is imposed for creating an electrical discharge therebetween. A magnetic field is set up transverse to the electrical field imposed on the electrodes by the applied potential. A fluid working medium may then be introduced into the space between the pair of electrodes and ionized upon passage through the electrical discharge struck therebetween.

The crossed electromagnetic field of these accelerators has been employed to perform various functions; such as, axially accelerating the charged particles, and rotating the working medium in the electrical discharge so as to increase the transfer of energy from the discharge to the working medium. Also, the crossed fields have been used to constrict or shape the ionized particles into a beam or column for more efficient utilization.

The present stage of development of the above described electromagnetic plasma accelerators may be viewed as one wherein an intensive effort is being made both to increase the efficiency and effectiveness of the accelerator structure, and to improve the performance characteristics and method or mode of operation of the accelerator.

Accordingly, one object of the present invention is to provide a new and improved electromagnetic plasma accelerator.

Another object of the present invention is to provide a magnetically ignited plasma accelerator wherein the necessity for switching means in the high-voltage circuit is eliminated.

A further object of the instant invention is to provide an improved electromagnetic plasma accelerator capable of controlled ignition in a very low density gaseous environment.

The foregoing and other objects are attained in the instant invention by providing a pair of coaxial electrodes across which a high-voltage electrical energy source is connected. The high-voltage electrical energy source is connected directly to the electrodes by an electrical circuit so as to eliminate any intervening switch means. A coil is positioned about the pair of electrodes to create an axial magnetic field, transverse to the electrical field created between the electrodes by the applied voltage. The ignition or triggering of the electrical discharge in the plasma gun is controlled by this axial magnetic field under predetermined conditions of electrode spacing and prevalent gas pressure therebetween.

Previous research in gaseous electronics has determined that the application of a transverse magnetic field to a system of electrodes carrying an electrical potential acts in such a way as to decrease the breakdown voltage under certain predetermined conditions of low environmental pressure and close electrode spacing. To utilize this principle, the accelerator electrodes of the instant invention are initially spaced apart at a selected distance dependent upon the gas pressure conditions under which the accelerator will be operating, so that the preselected requisite breakdown voltage of the system is greater than the magnitude of the applied voltage. Therefore, the accelerator is inoperative until the coil is energized to create an axial magnetic field sufficient in strength to decrease the system breakdown voltage to the magnitude of the applied voltage, at which time an electrical discharge will be triggered and the gaseous working medium between said electrodes ionized.

The magnetic ignition of an electrical discharge in a plasma gun has the advantage of omitting a switching device from the high-voltage circuit in plasma accelerators; the elimination of a switch represents an improvement, first, because the lower resistance and lower inductance of the high-voltage electrical energy circuit results in a shorter rise time for the current, higher obtainable currents, and greater transfer of electrical energy to the plasma. Second, the magnetic ignition causes controlled breakdown under predetermined electrode spacing and very low gas pressure, where, according to known theory, breakdown does not ordinarily occur at the voltage applied. Additionally, the incorporation of a triggering means and accelerating system into a single unit eliminates an additional component subject to malfunctioning from the plasma gun, thereby increasing reliability.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings, wherein:

FIG. 1 is a schematic diagram of the plasma accelerating apparatus according to the instant invention; and

FIG. 2 is an end view of the embodiment of FIG. 1 illustrating the coaxial arrangement of the electrodes, and the crossed electromagnetic field, of the instant invention.

Referring now to the drawings, wherein like reference numerals designate identical or corresponding parts throughout the several views, the plasma accelerator **11** is shown as comprising a pair of coaxially spaced electrodes **12, 14** and an electrical circuit **18** connecting high-voltage electrical energy source **20** directly across the electrodes **12, 14** for energizing an electrical discharge between the electrodes. The center electrode **12**, extending along the accelerator axis, is shaped as a cylindrical rod having a rounded end. It will be apparent that other electrode shapes may be employed, depending upon the desired electrical field configuration. The high-voltage electrical energy source **20** may consist of a bank of low inductance capacitors connected by coaxial cable means to electrodes **12, 14**. Obviously, other energy sources of high voltage may be substituted for the capacitor bank. As shown best in FIG. 2, a radial electrical field E is created between the coaxial electrodes by the applied voltage.

A coil **22** is positioned about the outer electrode **14** at the breech of the accelerator for creating an axial magnetic field B at said breech. The coil **22** is connected into a circuit which also includes an electrical power source **24**, such as a bank of storage batteries, a trigger-ing switch **26**, and a variable resistance **27**. The resistance **27** may be varied so as to vary the strength of the axial magnetic field created by coil **22**. It will be apparent that other electrical power sources may be substituted for the D.-C. storage batteries **24**, depending upon the desired mode of operation of the plasma accelerator, i.e., as a single pulse operation or in fast repetition.

The terminus **30** of the accelerator is shown as extending parallel to the plasma accelerator axis, however, the accelerator terminus may be formed in the shape of an expansion nozzle or in other chosen configurations. An insulating spacer member **16** is disposed at the forward end of the plasma accelerator **11** between electrodes **12, 14**. A valved conduit means **28** is employed to introduce a fluid working medium into the space between electrodes **12, 14**. The conduit means **28** is depicted as being ring-shaped and formed in the member **16**; however, alternate means for conveying the fluid working medium uniformly into the region between the electrodes may also be utilized. For example, the conduit means could be formed directly in the outer electrode **14** to conduct the fluid directly into the annular ionizing region rearward of member **16**.

Previous research in gaseous electronics has determined that the application of a transverse magnetic field to a system of electrodes carrying an electrical potential acts in such a way as to decrease the breakdown voltage under certain predetermined conditions of low environmental pressure and close electrode spacing. This effect is explained by the fact that in crossed electric and magnetic fields the electrons traveling between the negative and positive electrodes follow cycloidal paths in a direction perpendicular to both the electric and magnetic fields,

$$\vec{E} \times \vec{B}$$

If the electron mean free path between electrodes is larger than the electron cyclotron radius, the electrons will perform a cycloidal motion in the

$$\vec{E} \times \vec{B} \text{ direction}$$

between their collisions with the gas molecules. When a collision occurs, the electron loses a part of its energy, and then starts a new cycloidal motion on a new level which is closer to the positive electrode by approximately the distance of the cyclotron radius. Thus, in the direction of the electric field, the cyclotron radius is roughly the distance between collisions instead of the mean free path as is the case where no magnetic field is supplied, and consequently leads to an increased effective gas pressure between electrodes.

The relationship between breakdown voltage and the pressure p and spacing d existing between the electrodes, in the absence of a magnetic field, has been graphically presented in a series of curves known as the Paschen curves. These curves illustrate the fact that for a certain critical pd product, $pd=(pd)_{critical}$, a minimum breakdown voltage exists. Prior investigation has established

that for the product $pd=(pd)_{critical}$, a transverse magnetic field has no influence on the breakdown voltage. For pd values greater than $(pd)_{critical}$, the breakdown voltage was increased by the application of the magnetic field whereas, for pd less than $(pd)_{critical}$, it was decreased in the manner described above. A more detained theoretical study of the effect of an axial magnetic field on the breakdown voltage of a coaxial system of electrodes, including an analysis of the formative time lag of the electrical discharge as a function of the magnetic flux density, may be found in National Aeronautics and Space Administration Technical Note D–910, published in June 1961, titled "Magnetic Ignition of Pulsed Gas Discharges in Air of Low Pressure in a Coaxial Plasma Gun" by Karlheinz Thom and Joseph Norwood, Jr.

Since electromagnetic plasma guns work under conditions of low pressure p, and involve small enough electrode spacings d so as to provide a pd product less than the $(pd)_{citical}$ corresponding to a predetermined minimum breakdown voltage, the above principle of gaseous electronics is herein applied to magnetically ignite the plasma accelerating apparatus high-voltage electrical energy circuit.

Accordingly, the distance d between electrodes **12, 14** is selected so as to give a product of pd which is less than $(pd)_{critical}$ for the predetermined initial pressure of the plasma accelerator. The axial magnetic field created by coil **22** when actuated through switch **26** and variable resistance **27** increases the effective gas pressure between electrodes **12, 14** to increase the product pd to the minimum value required for breakdown; whereupon an electrical discharge is triggered between the electrodes for ionizing the fluid working medium therebetween. In operation, the variable resistance **27** may be set to produce the necessary magnetic field strength for triggering the electrical discharge upon closing of switch **27**, or alternately, the switch **26** may first be closed and the resistance **27** then adjusted to increase the magnetic field strength to the point at which breakdown occurs.

By way of example, one experimental apparatus utilizing the instant invention will now be described. The plasma accelerator consisted of a pair of electrodes, an outer stainless-steel cylinder 0.06 meter inside diameter, and a stainless-steel center electrode 0.04 meter in diameter, the spacing d between electrodes being 0.01 meter. The high-voltage electrical energy source consisted of a 36-microfarad capacitor bank charged to 48,000 volts. A pressure p of less than 10^{-4} mm. Hg was established in the accelerator. The magnetic field for triggering the accelerator was provided by a 1,500-turn coil fitting over the outer electrode, powered by a bank of storage batteries. The coil for producing the axial magnetic field was such as to generate a field strength having a magnitude of several thousand gauss at the breech of the electrodes. The battery coil circuit also included a remote controlled rheostat. The product pd for this experimental apparatus was thus fixed at $pd=(10^{-4}$ mm. Hg) (0.01 meter). A peak current of 1.3×10^{6} amperes was achieved with a current rise time of only 2 microseconds upon magnetic ignition of the plasma accelerator.

It will therefore be seen that a novel plasma accelerator has been provided wherein the switch connecting the high-voltage source to the electrodes has been eliminated, resulting in great improvement in the performance characteristics of the plasma accelerator. Further, the plasma accelerator may be controllably ignited under very low gas pressure conditions, which means, that the mass load of the accelerator in principle may be arbitrarily small, thus yielding a high efficiency in operation of the accelerator.

Obviously numerous modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as described herein.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. In an electromagnetic plasma accelerating apparatus comprising a pair of spaced electrodes, a high-voltage source for energizing an electrical discharge between said electrodes, conduit means for conveying a fluid working medium to the space between said electrodes, and a coil positioned about said electrodes for creating a magnetic field transverse to the electric field formed between said electrodes by said high-voltage source, the improvement consisting of: an electrical circuit connecting said high-voltage source directly to said electrodes; said electrodes being spaced apart a selected distance so that the magnitude of the requisite breakdown voltage of said electrodes is greater than the magnitude of the applied voltage from said high-voltage source; and circuit means for energizing said coil for creating a transverse magnetic field and consequently decreasing the magnitude of said requisite breakdown voltage, thereby magnetically triggering an electrical discharge between said pair of spaced electrodes without the necessity of switch means in said electrical circuit.

2. A magnetically ignited, electromagnetic plasma accelerating apparatus capable of ignition in a rarified gaseous environment comprising: a pair of spaced, coaxially extending electrodes; an electrical energy source for applying a voltage across said electrodes; means connecting said source directly to said electrodes; said electrodes being spaced apart a selected distance so that the value of the product of said distance and the gaseous pressure between electrodes is less than the critical value required for electrical breakdown at the magnitude of the applied voltage; a coil positioned about said electrode pair; circuit means for energizing said coil for creating an axial magnetic field, thereby increasing the effective gaseous pressure between electrodes and consequently the value of said product to said critical value, and magnetically triggering an electrical discharge to ionize the gaseous medium between said pair of electrodes.

3. An apparatus as defined in claim 2, said circuit means further including a variable resistance for varying the strength of said axial magnetic field.

4. A method for igniting an electromagnetic plasma accelerating apparatus in a very low density gaseous environment comprising: applying a first potential directly across the electrodes of the plasma accelerating apparatus lesser in magnitude than the requisite breakdown potential, applying a second potential less than said first potential to the accelerator coil to create a magnetic field transverse to the electric field created between said electrodes by said applied first potential; and increasing the strength of said transverse magnetic field so as to decrease the magnitude of the requisite breakdown potential to the magnitude of the applied potential; thereby magnetically triggering an electrical discharge between said electrodes and ionizing the gaseous medium therebetween.

5. A method for igniting an electromagnetic plasma accelerating apparatus in a very low density gaseous environment comprising: applying a potential directly across the electrodes of the plasma accelerating apparatus lesser in magnitude than the requisite breakdown potential; and applying a second potential to the accelerator coil for creating a magnetic field transverse to the applied electric field between said electrodes so as to decrease said requisite breakdown potential and consequently magnetically trigger an electrical discharge between said electrodes to ionize the gaseous medium therebetween.

6. A method for magnetically igniting an electromagnetic plasma accelerator in a very low pressure gaseous environment comprising: applying a high-voltage directly across the electrodes of the accelerator; spacing said electrodes a selected distance apart so that the product *pd*, gas pressure *p* between electrodes X electrode spacing *d*, is less than $(pd)_{critical}$ for breakdown at the applied high voltage; and creating a magnetic field transverse to the electric field between said electrodes to increase the product *pd* to $(pd)_{critical}$, and consequently magnetically trigger an electrical discharge between said electrodes to ionize the gaseous medium therebetween.

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