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Oct. 20, 1970 A. P. SABOL 3,535,586

CROSSED-FIELD MHD PLASMA GENERATOR/ACCELERATOR

Filed Jan. 24, 1969 2 Sheets-Sheet 1

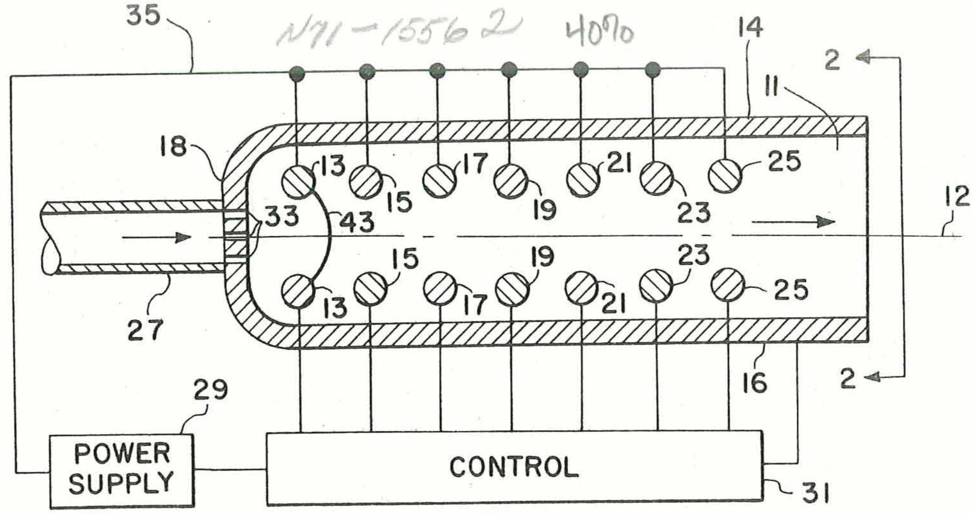

FIG. 1

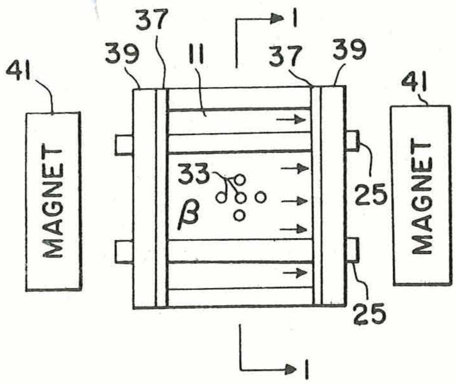

FIG. 2

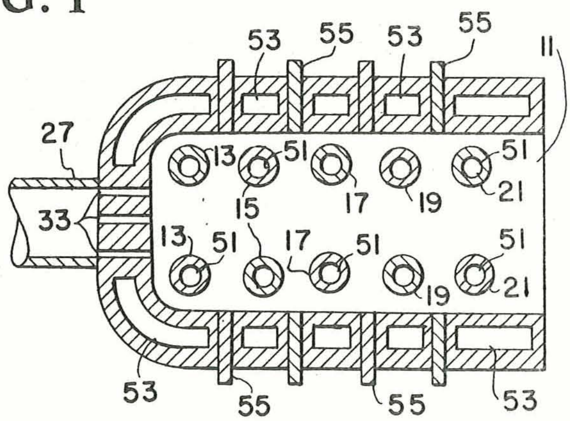

FIG. 4

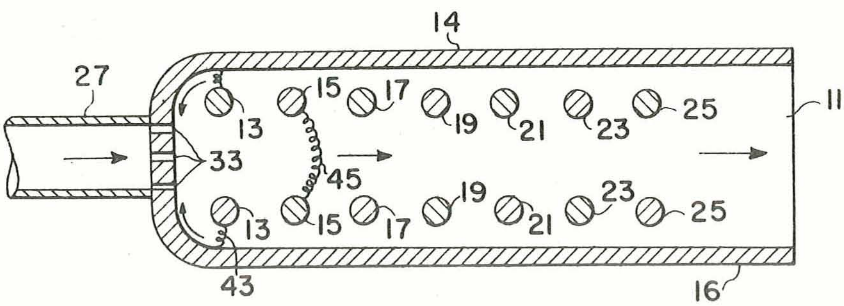

FIG. 3

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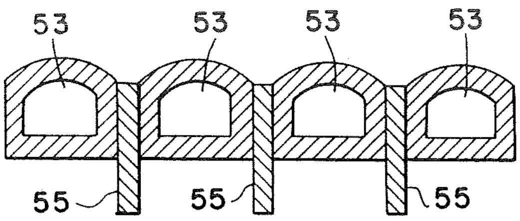

FIG. 5

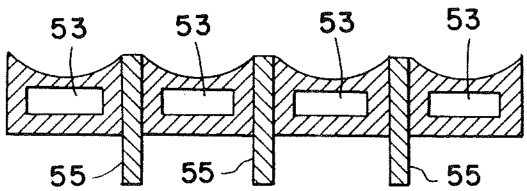

FIG. 6

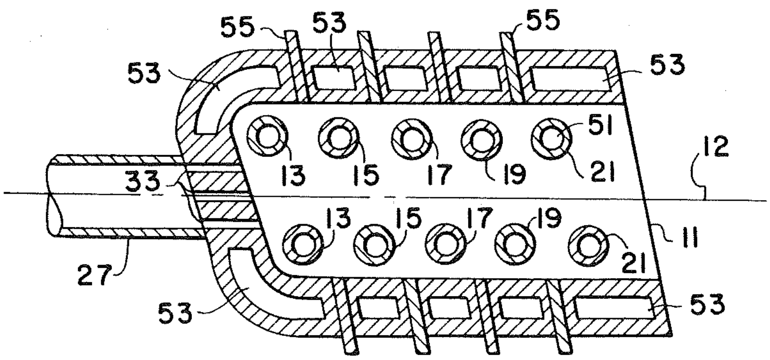

FIG. 7

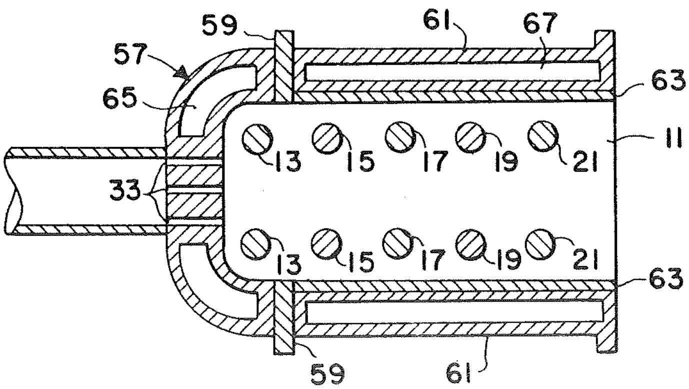

FIG. 8

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CROSSED-FIELD MHD PLASMA GENERATOR/ACCELERATOR

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U.S. Cl. 315—111 **10 Claims**

ABSTRACT OF THE DISCLOSURE

This disclosure describes a crossed-field MHD plasma generator and/or accelerator wherein a plurality of electrode pairs are mounted in a closed channel and a constant magnetic field is applied across the channel. The sides of the rectangular shaped channel parallel to the electrode pairs forms an idler (electrically floating) electrode. A working gas is introduced at one end of the channel. In operation, a main arc, supplied by a continuous source of power, is created across the pair of electrodes adjacent to the point of gas introduction. As it is being acted on by MHD forces, the main arc moves to the next pair of electrodes and so on downstream. Each time a main arc moves to the next pair of electrodes, side arcs are formed between each of the two electrodes of the prior electrode pair and the idler electrode. The side arcs move upstream in the outer sections of the channel and reconnect the electrode pair to form more main arcs. The reconnected main arcs then move downstream because of being acted on by MHD forces. Due to an electrical shorting action, the main arcs extinguish at the last electrode pair. The action of the main arcs accelerates plasma which is emitted from the channel.

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

BACKGROUND OF THE INVENTION

The prior art discloses various types of plasma accelerators and generators such as the crossed-field plasma generator, for example. One prior art crossed-field plasma generator includes a plurality of segmented electrodes mounted perpendicular to a magnetic field so as to provide a smooth channel. The sides of the channel are electrically insulated from the surrounding environment. The primary disadvantage of a crossed-field plasma generator of this nature is that the arc discharge is created and remains attached to each pair of segmented electrodes during the entire operation of the generator. This arc or electrical discharge attachment causes two undesirable results. First, severe erosion of the downstream face of the anode electrode and its adjoining insulator occurs. Secondly, "blow-out" frequently occurs; that is, the shape of the discharge balloons downstream and bears against both electrode surfaces, resulting in poor efficiency.

Therefore, it is an object of this invention to provide a new and improved crossed-field plasma generator.

It is also an object of this invention to provide a new and improved crossed-field plasma generator that has improved erosion characteristics over prior art crossed-field plasma generators.

It is still a further object of this invention to provide a new and improved plasma generator wherein "blow-out" is less likely to occur than in prior art plasma generators.

It is a still further object of this invention to provide a new and improved plasma generator that continuously generates plasma out one end as gas in continuously injected into the other end.

It is a still further object of this invention to provide a new and improved plasma generator that has greater efficiency of operation than prior art plasma generators.

SUMMARY OF THE INVENTION

In accordance with a principle of this invention, a new and improved magnetohydrodynamic (MHD) crossed-field plasma generator is provided. The generator comprises a plurality of pairs of electrodes mounted in a channel. The channel forms an idler electrode. As gas is injected into one end of the channel and, a main arc, formed across a first pair of electrodes, creates a plasma region which flows down the channel as the main arc proceeds from electrode pair to electrode pair. The main arc moves due to the presence of an applied magnetic field. More specifically, as the main arc moves downstream from electrode pair to electrode pair, it accelerates the plasma region with it. The main arc is extinguished at the last electrode pair and the accelerated plasma passes out of the opposite end of the channel. As the main arc moves from electrode pair to electrode pair, secondary arcs form between each electrode of a prior electrode pair and idler electrode and move upstream to form a new main arc across the prior electrode pair. There is a continuous movement of a plurality of main arcs down the channel with each main arc accelerating a plasma region with it.

In accordance with a further principle of this invention, cooling means are provided for cooling the electrodes and the portion of the channel forming the idler electrode and any other portion of the device requiring cooling.

In accordance with a still further principle of this invention, means are provided for segmenting the idler electrode into a plurality of segments to prevent a Hall potential from axially shorting the electrodes.

In accordance with a still further principle of this invention, means are provided for controlling the application of electric potentials to the idler electrode and the electrodes so that predetermined potentials and electrode current flows are applied to those elements.

In accordance with an alternative principle of this invention, the idler electrode is insulated from the pairs of electrodes downstream from the first pair of electrodes so that secondary arcs only occur around the first pair of electrodes.

It will be appreciated from the foregoing summary of the invention that a new and improved MHD crossed-field plasma generator is provided. The generator of the invention is more efficient than prior generators, because there is a continuous movement of plasma down the channel which exhausts from the end of the channel. Hence, there is no interruption of plasma generation as occurs in prior art devices. In addition, the discharge does not remain fixed to any particular spot on the electrodes; hence, electrode erosion is reduced. Further, because a multiplicity of discharges exist simultaneously, plasma acceleration is improved. Moreover, undesirable blow-out or ballooning at any particular electrode is reduced due to the proper extinguishment of the arc at the end of the channel. Hence, the invention provides numerous advantages over prior art plasma generators. In addition, the invention is uncomplicated to manufacture.

BRIEF DESCRIPTION OF THE DRAWINGS

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

FIG. 1 is a cross-sectional diagram of one embodiment of the invention;

FIG. 2 is a front view of the channel of the embodiment of the invention illustrated in FIG. 1;

FIG. 3 is a cross-sectional diagram similar to the diagram of FIG. 1 utilized to describe the operation of the invention;

FIG. 4 is a cross-sectional diagram of an alternative embodiment of the invention.

FIG. 5 is a cross-sectional diagram of a portion of the embodiment of the invention illustrated in FIG. 4 illustrating one modification thereof;

FIG. 6 is a cross-sectional diagram of a portion of the embodiment of the invention illustrated in FIG. 4 illustrating a second modification thereof;

FIG. 7 is a cross-sectional diagram of a further embodiment of the invention; and

FIG. 8 is a cross-sectional diagram of a still further embodiment of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a cross-sectional view along lines **1—1** of FIG. 2 of one embodiment of the invention, and FIG. 2 is a front view along lines **2—2** of FIG. 1 of that embodiment. The embodiment of the invention illustrated in FIGS. 1 and 2 comprises: a closed channel **11**; first through seventh electrode pairs **13—13**, **15—15**, **17—17**, **19—19**, **21—21**, **23—23**, and **25—25**; a working gas supply pipe **27**; an electrical direct current power supply **29**, and a control **31**. The electrode pairs **13—13** through **25—25** are long tubular members and are mounted in parallel at right angles to the axis of the channel **11** at spaced apart points. The spacing between the electrodes is preferably equal, but precise spacing will depend upon operational requirements. In addition, the electrodes are equally spaced from the longitudinal axis **12** of the channel **11**, but can be altered to suit conditions. Moreover, the electrodes are approximately equally spaced from the sides of the channel.

As viewed in FIG. 1, the channel has upper and lower sides **14** and **16** that come together at a closed end **18** to form a generally U-shaped cross-section. This portion of the channel is made of a suitable electrode material and forms, as hereinafter described, an idler electrode. The other end of the channel **11** is open. The closed end **18** of the channel is attached to the gas supply pipe **27** which supplies a suitable gas such as air, for example. A plurality of apertures **33** allow gas from the gas supply pipe **27** to flow into the closed end **18** of the channel. The upper electrodes of the electrode pairs are connected by a conductor **35** to one side of the power supply **29**. The other side of the power supply **29** is connected to the control **31**. The control **31** has a plurality of outputs that are connected to the lower electrodes of the electrode pairs and to the idler electrode. It will be appreciated that this manner of connection is merely illustrative. That is, the power supply could be formed of a plurality of separate independent power supplies connected across the various electrode pairs. Alternatively, the power supply could be a single power supply connected via a resistor network to the various electrode pairs. The primary requirement is that appropriate arc-creating voltages be applied across the various electrode pairs and between the electrode pairs and the idler electrode.

As best illustrated in FIG. 2, the two remaining sides of the channel are closed by insulating plates **37**. Mounted outside of the insulating plates are side plates **39**. The side plates have apertures through which the electrode pairs project with the electrodes being appropriately insulated from the side plates. Hence, the side plates and the insulating plates maintain the electrodes in their predetermined positions. Mounted outside of the side and insulating plates are magnets **41** mounted so as to create a crossed-magnetic field. That is, a magnetic flux passes between the magnets so as to provide a magnetic field perpendicular to the channel **11** as the channel is illustrated in FIG. 1. It will be appreciated that the magnets **41** are merely illustrative and can take on various forms. For example, they can be permanent magnets. It will further be appreciated by those skilled in the art that the direction of the magnetic field depends upon the polarity of the power applied to the electrode pairs. If desired, the strength of the magnetic field can be varied along the length of the channel by the use of any suitable control means or construction.

Also illustrated in FIG. 1 is a fine wire **43** connecting the first electrode pair **13—13**. This wire is placed across the first electrode pair **13—13** so that an initial arc can be created across that electrode pair when power is first applied to the invention. The wire **43** is such that it vaporizes when power is applied leaving an arc across the first electrode pair. It is to be noted that other suitable starting devices can also be employed.

Turning now to the operation of the invention: the control **31** applies power to the electrode pairs, while a properly controlled gas, such as air, is introduced into the channel **11** from the gas supply pipe **27** via the apertures **33** in the direction of the arrows. The application of power causes a current flow through wire **43**, which vaporizes, and an electrically conducting plasma (arc) is formed across the first electrode pair **13—13**. This arc or electrically conducting plasma moves in the direction of the second electrode pair **15—15** because of the externally imposed magnetic field. The movement of the arc accelerates gas and plasma with it in the direction of the arrows, i.e., from left to right. More specifically, the arc shape balloons outwardly toward the second electrode pair **15—15** until it makes contact with that electrode pair, whereupon the power supply **29** discharges through that arc now across electrode pair **15—15**. Thereafter, the main arc **45** is in the position illustrated in FIG. 3, i.e., across the second electrode pair.

Because of the MHD forces, the segments of the arc between both sides of the first and second electrode pairs **13—13** and **15—15** move into the area between the first electrode pairs **13—13** and the idler electrode sides **14** and **16**. These side arcs illustrated at **43** in FIG. 3 move in the direction of their arrows, i.e., toward the closed end **18** of the idler electrode. The arcs **43** continue to move until they join each other and move into the position of the starting conductor **43**. At this point, one cycle of arc rotation is completed for the first electrode pair **13—13**.

Meanwhile, the first main arc **45** is ballooning from the second electrode pair **15—15** toward the third electrode pair **17—17**. And, the same sequence of events takes place between the second and the third electrode pairs. That is, the third electrode pair **17** assumes the burden of moving the main arc **45** down the channel and two separate side arcs are formed about the second electrode pair **15**. However, this time the side arcs formed about the second electrode pair **15—15** join the second center arc that has been born in the meantime across the first electrode pair **13—13**. This process continues through the seven electrode pairs until the first main arc **45** reaches the end of the channel. The movement of the main arc accelerates the plasma within the arc in the direction of the arrows. At the last electrode pair **25—25**, the moving main arc balloons out to the channel until the side arcs make contact with the idler electrode side **14** and **16**. When the side arcs are created, the main arc is extinguished and only the plasma leaves the channel **11**.

It will be appreciated by those skilled in the art and others that the number of electrodes in the channel is determined by the amount of acceleration desired. Preferably, the channel is designed so as to take advantage or aerodynamic and MHD requirements of a particular use of the invention. Hence, the invention is not limited to a generally rectangular cross-sectional channel of the type illustrated in FIGS. 1–3—the channel could have a conical cross-sectional shape, for example.

The sequence of events described above suggests that there are half as many main arcs simultaneously moving down the channel at any one time as there are numbers of electrode pairs. However, under some operating conditions there may be the same number of main arcs as there are electrode pairs. And, each discharge, because of MHD forces, accelerates part of the flow down the entire working section of the channel. In addition, it should be noted that the side arcs create a back flow that aids in the acceleration of the plasma flow in the direction of the arrows, i.e., from left to right. This back flow enters the channel about the electrode pair 13—13. It arrives there by passing through the regions between the electrodes on one side or the other as a consequence of the side arc motion. This pumping action can be controlled by a proper adjustment of the operating parameters, i.e., the location of the electrodes, the size of the channel, the viscosity of the incoming gas, etc.

It should also be noted that while the foregoing description has described both a gas and a plasma region about each arc as the main arcs move down the channel, the channel can contain only plasma if there is no complete or sudden division between the main arc discharge and the surrounding environment. Thus, the accelerator can operate from a plasma generator that replaces the first electrode pair 13—13.

It will be appreciated by those skilled in the art and others that the embodiment of the invention illustrated in FIGS. 1–3 will operate satisfactorily in many environments. However, in some environments it may have certain unsatisfactory characteristics. For example, the embodiment of the invention illustrated in FIGS. 1–3 may over-heat if operated continuously for long periods of time. Moreover, a Hall potential may be created because the idler electrode is continuous along the length of the channel. The embodiments of the invention hereinafter described overcome these disadvantages.

The embodiment of the invention illustrated in FIG. 4 comprises the gas input pipe 27 and five pairs of electrodes, 13—13, 15—15, 17—17, 19—19 and 21—21 mounted in a channel 11 generally similar to the channel illustrated in FIGS. 1–3. The primary difference between the embodiment illustrated in FIG. 4 and the embodiment illustrated in FIGS. 1–3 is that the electrodes each include central apertures 51 through which a cooling liquid, such as water, for example, can flow. In addition, the idler electrode is broken into a plurality of sections and each section includes an aperture 53 through which a cooling liquid can flow. The sections are separated by insulating separating members 55 which may be formed of boron nitride, for example. However. while the idler electrode is separated into a plurality of section, it will be appreciated that each pair of opposite sections are electrically connected together so that across the channel the idler electrode potential remains the same. The operation of the embodiment of the invention illustrated in FIG. 4 is identical to the operation of the embodiment of the invention heretofore described; hence. it will not be restated here.

FIGS. 5 and 6 illustrate modifications of the inner surface idler electrode sections suitable for use in the embodiment of the invention illustrated in FIG. 4. Specifically, FIG. 4 illustrates that the inner or channel surface of the idler electrode sections is flat. FIG. 5 illustrates that they can have a concave curvature, while FIG. 6 illustrates that they can have a convex curvature. The exact flatness or curvature utilized will depend upon the intended use of a specific embodiment of the invention.

FIG. 7 is a further alternative embodiment of the invention that is similar to the FIG. 4 embodiment of the invention, with the difference that the axes between the electrode pairs are not perpendicular to the main axis of the channel, as in the previously illustrated embodiments. Rather, the axes between the electrode pairs are angled with respect to the main axis 12. Hence, the invention does not require a right angular relationship with respect to the axis between the electrode pairs and the main axis. The operation of the FIG. 7 embodiment of the invention is identical to the previously described operation of FIGS. 1–3 embodiment of the invention and will not be restated here.

FIG. 8 illustrates a still further alternative embodiment of the invention that operates in a slightly different manner than the previously described embodiments. Specifically, the FIG. 8 embodiment comprises five pairs of parallel electrodes 13—13, 15—15, 17—17, 19—19, and 21—21, mounted in a channel 11. The channel is generally U-shaped in cross section. A plurality of apertures 33 are located in the end of the end section 57 of the U to allow gas to pass from the gas input pipe 27 into the channel 11. Each leg of the U is broken by an insulating member 59. Elements 61, located adjacent to the insulating members 59, project outwardly to define a portion of the channel 11. Located on the inside of the elements 61 to form the inner face of the channel are inuslating surfaces 63 which may be formed of a refractory material such as boron nitrite, as may the insulating members 59. The mounting is such that a flat surface for the channel 11 is provided. The section 57 and the elements 61 each include cooling channels 65 and 67, respectively, through which a cooling liquid may flow, if desired.

The operation of the embodiment of the invention illustrated in FIG. 8 is generally similar to the operation of the previously described embodiments, except that no secondary arc is formed around any of the electrodes except the first electrode pair 13—13. The reason no secondary arc is formed around the second, third, fourth, and fifth electrode pairs is that the electrodes are mounted so that there is a portion of the insulating surface 63 located between each of them and the elements 61 which, if not for the insulating surfaces, would form a portion of the idler electrode.

The embodiment of the invention illustrated in FIG. 8 is operative in environments where secondary arcs are undesirable or dangerous. In general, a first arc is created across the first electrode pair 13—13, which balloons outwardly to the second electrode pair 15—15. Secondary arcs are created around the first electrode pair 13—13 and move upstream to reform a new center or main arc across the first electrode pair 13—13. Meanwhile, due to the influence of the magnetic field, the first main arc located across the second electrode pair 15—15 balloons outwardly and forms an arc across the third electrode pair 17—17. This operation continues until the first arc exhausts out the end of the channel 11 after being electrically shorted out by the following second arc. Other main arcs proceed down the electrode pairs in the same manner.

It will be appreciated from the foregoing description that the invention provides a crossed-field MHD plasma generator that accelerates plasma down the channel, as the plasma is formed, due to the influence of a magnetic field. The invention has certain advantages over the prior art devices. For example, the invention does not require a plasma generator as an addition, as do prior art crossed-field accelerators. Further, the discharge or arc continuously moves down the channel, thereby preventing any erosion of electrodes due to a constant arc existing across one pair of electrodes. In addition, a multiplicity of discharges exist simultaneously to accelerate the plasma. Moreover, the arcs do not balloon out at any one electrode or at the end electrode; rather, they are properly extinguished at the last electrode pair.

What is claimed is:

1. A crossed-field plasma generator/accelerator comprising:

a channel defined by an idler electrode on two opposing sides and by insulating plates on the other two opposing sides;

a plurality of pairs of cylindrical electrodes mounted in a predetermined spaced relationship in said channel;

a magnetic means for applying a crossed magnetic field to said channel; and

power supply means connected to said plurality of pairs of electrodes and to said idler electrode for energizing said plurality of pairs of electrodes and said idler electrode.

2 A crossed-field plasma generator/accelerator as claimed in claim 1 including gas supply means for applying a gas to one end of said channel

3. A crossed-field plasma generator/accelerator as claimed in claim 2, wherein said end comprises an end member having apertures therein and wherein said gas supply means includes a pipe connected to said end member whereby gas, introduced by said gas supply means, is allowed to pass into said channel.

4. A crossed-field plasma generator/accelerator as claimed in claim 3, wherein the two opposing sides of said channel forming said idler electrode are sectioned and including insulating means mounted between said sections for insulating said sections from one another.

5. A crossed-field plasma generator/accelerator as claimed in claim 4 including cooling means forming a part of said idler electrode for cooling said idler electrode.

6. A crossed-field plasma generator/accelerator as claimed in claim 5, wherein said cooling means includes apertures in said idler electrode to allow a cooling fluid to flow through said idler electrode.

7. A crossed-field plasma generator/accelerator as claimed in claim 6 including apertures in said plurality of pairs of electrodes to allow a cooling fluid to flow through said electrodes.

8. A crossed-field plasma generator/accelerator as claimed in claim 7, wherein the inner surface of said idler electrode sections are concave.

9. A crossed-field plasma generator/accelerator as claimed in claim 7, wherein the inner surface of said idler sections are convex.

10. A crossed-field plasma generator/accelerator as claimed in claim 7 including insulating means for insulating the inner sides of predetermined sections of said idler electrode for a predetermined distance along the length of said channel.

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