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PLASMA GENERATOR

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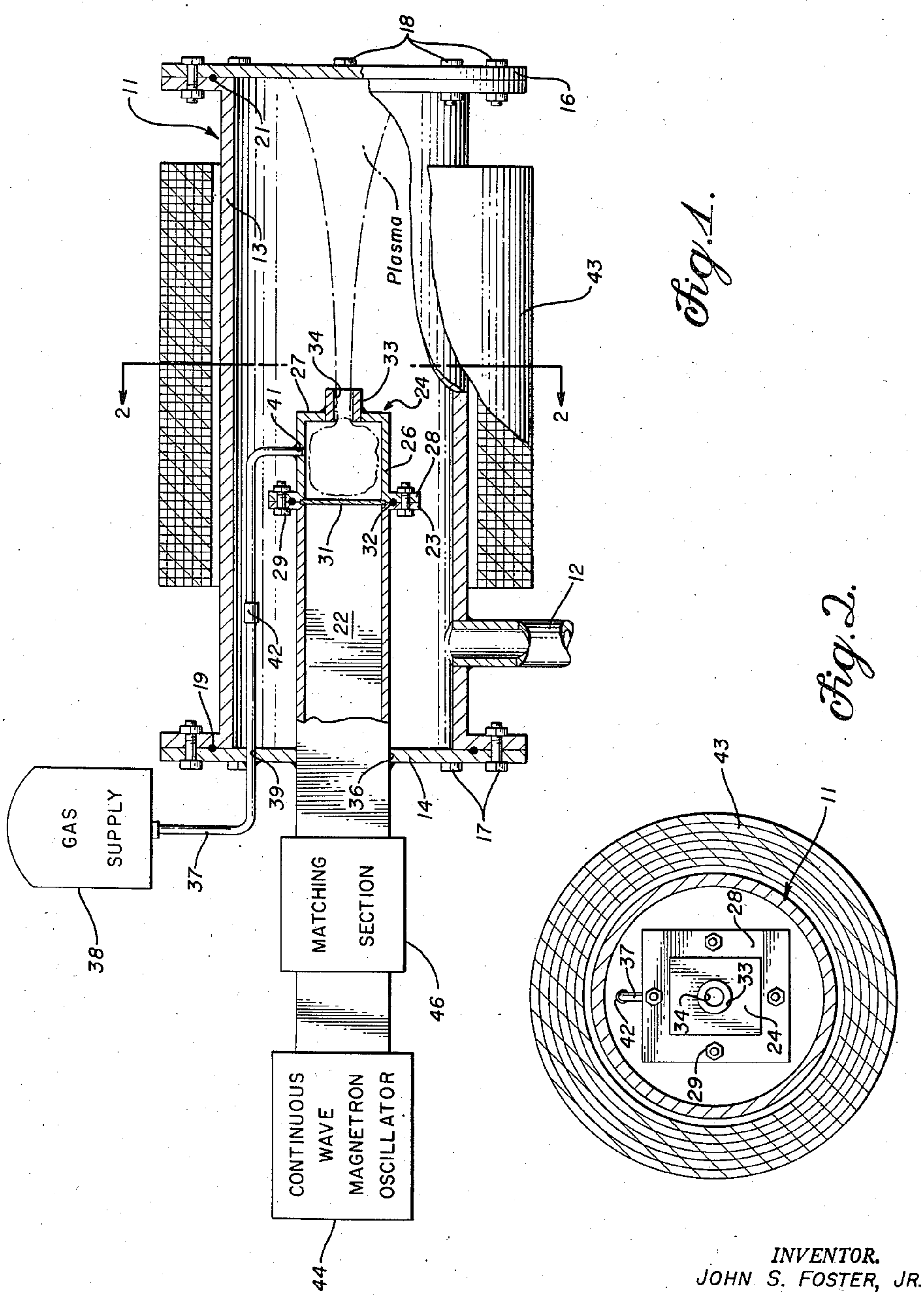

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PLASMA GENERATOR

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This invention relates to apparatus for producing ionized gas and, more specifically, to a generator for providing an electrically neutral ionized gas discharge.

Such electrically neutral ionized gas discharge is conventionally termed a plasma, i. e., a space charge neutralized ion gas and may be used in a variety of accelerators, mass spectrometers, high temperature chemical reactors, and other electrical devices. As employed herein the term "plasma" is intended to indicate such an electrically neutral ionized gas unless context indicates otherwise.

In conventional practice the plasma is usually accompanied by an energetic electron beam, and the plasma is highly contaminated with neutral gas particles. Collision processes of the neutral gas particles and other attendant phenomenon seriously alter the behavior of the plasma and may render such a plasma unfit for various uses. Power requirements in conventional methods of plasma production are high and plasma production efficiency is low. In conventional practice a plasma may be generated by electron bombardment of gas molecules as in an arc discharge. However, an electrically neutral ionized gas discharge has been very difficult to obtain.

The device of the present invention provides an uncontaminated palsma not associated with an electron beam and accomplishnes this result by inducting ionization of gas particles in a restricted region and selectively extracting the plasma particles through an orifice of limited size. Since the plasma is selectively extracted, contamination by neutral particles is largely eliminated and there is no association with an electron beam. The selective extraction is effected by utilizing an axially symmetric magnetic field acting in cooperation with a pressure differential established through said orifice whereby the probability of a plasma particle escaping through this orifice is high compared to that of a neutral particle. High ionization efficiency and maximum power transfer is obtained by utilizing very high radio frequency generating means efficiently coupled to a plasma generation chamber by establishing and maintaining certain critical relationships between the electron plasma frequency, cyclotron frequency of the electrons in the generating chamber, and the operating frequency of the radio frequency energizing source.

It is therefore an object of the present invention to provide methods and apparatus for generating a plasma.

Another object of the invention is to provide a generator capable of producing a plasma uncontaminated by an electron beam or neutral particles.

An additional object of the invention is to provide a plasma generator wherein radio frequency energy is employed in the production of ions of a plasma.

A further object of the invention is to provide a generator consuming minimum power in the production of a plasma.

A still further object of the invention is to provide a plasma generator utilizing an axially symmetric magnetic field acting in cooperation with a pressure differential to selectively extract and focus a plasma through an orifice.

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The invention, both as to its organization and method of operation, together with further objects and advantages thereof, will best be understood by reference to the following specification taken in conjunction with the accompanying drawing, of which:

Figure 1 is a longitudinal cross sectional view of a preferred embodiment of the invention; and

Figure 2 is a cross section taken along plane 2—2 of Figure 1.

The plasma generator of the invention is considered suitable for providing a plasma to be utilized in a variety of devices characteristically similar in that a plasma, i. e., ionized gas, is employed therein for sundry purposes. Electrically neutral plasmas are of interest in the thermonuclear fields and for experimental purposes; while charged plasmas, i. e., ion beams which may be produced by charge separation and/or charged particle acceleration treatment of neutral plasmas, may be used in charged particle accelerators, mass spectrometers and the like. In the event that the plasma generator is not to be employed with existing vacuum equipment, the plasma generator of the invention will include an evacuated system into which the plasma is discharged and utilized for diverse experimental purposes.

In brief, therefore, the plasma generator of the invention includes means providing an evacuated system in which there is contained a region wherein the plasma is to be utilized and also a plasma generation chamber having an orifice communicating with the evacuated system. In this chamber there is produced an impure plasma contaminated by neutral molecules. For producing said impure plasma there is provided means for introducing a suitable gas to the plasma generation chamber and thereby establishing a gas pressure differential across said orifice, means for establishing an axially symmetric magnetic field normal to said orifice, and very high radio frequency generating means adapted to energize the plasma generation chamber causing ionization of the gas therein. The magnetic field serves to constrain the charged particles to an axial region in said chamber and focus the plasma along a path most favorable for extraction through the orifice. The extraction of an electrically neutral uncontaminated plasma is accomplished by the focusing action of the magnetic field cooperating with the pressure differential established across the orifice, as will be more fully disclosed hereinafter.

More particularly, referring to the accompanying drawing, the means providing an evacuated system may comprise an elongated evacuated cylindrical housing **11** coupled as by a conduit tube **12** to a conventional vacuum pump (not shown). Conveniently, such a housing **11** is constructed of a tubular section **13** flanged at the extremities for the attachment of end cover plates **14** and **16** as by means of flange bolts **17** and **18**. Annular vacuum sealing elements **19** and **21** are disposed between the end plates and the flanged extremities of the housing **11** to provide a vacuum seal therebetween. The housing **11** should be constructed of material pervious to a magnetic field as will be apparent from the context of the specification.

It will be noted here, in the event the plasma generator is used in an apparatus such as an accelerator or the like, that the housing **11** may be eliminated and an evacuated region of such apparatus may provide the hereinbefore mentioned means providing an evacuated system. It will also be appreciated that the plate **16** located at the forward extremity of the housing **11** may be eliminated to enable the housing to be secured directly to such apparatus when the plasma generator is used therewith. For particular applications of the invention other means providing an evacuated system will be obvious.

To provide a most convenient and simplified construction the plasma generation chamber may be constructed as an integral extension portion of a tubular wave guide 22 whereby the wave guide is made to serve the multiple purposes of providing structural portions of the said chamber and means for coupling the ionization energy source thereto. More specifically, the wave guide 22 is provided with a terminal flange 23 for the attachment of a cup-shaped terminal chamber member 24 having a tubular wall portion 26 of size and shape similar to said wave guide, an end face 27, and provided with a flange 28 attachable as by means of bolts 29 to the terminal flange 23 of the wave guide 22. The periphery of a gas tight partition 31 formed of electrically non-conductor material is disposed between said flanges 23 and 28 so as to separate the plasma generation chamber proper 24 from the remainder of the wave guide 22, and a sealing element 32 may be disposed outwardly therefrom between the flanges to provide a more positive vacuum seal.

The end face 27 of the chamber member 24 is centrally apertured to receive an exit tube 33 provdiing an orifice 34 axially aligned with said wave guide 22. Several structural arrangementse may be employed whereby said orifice is made to communicate with the interior of said housing 11. For structural convenience it is preferred that the wave guide be disposed so as to pierce or be supported in vacuum tight fashion by one of said cover plates, e. g., plate 14, whereby the wave guide 22 and orifice 34 are in approximate axial alignment with the housing 11. For the most compact arrangement the wave guide 22 is disposed in vacuum tight relation within an aperture 36 provided in said plate 14 and extending within the housing 11; however, if desired the plasma chamber 24 may be terminated at the plate 14 and with only the tube 33 piercing said plate.

For the purposes of the invention, the wave guide 22 is constructed and proportioned in accordance with conventional practice with regards to tubular transmission lines. While a rectangular guide is shown other tubular guides may also be employed. However, for reasons apparent hereinafter the material employed while being necessarily an electrical conductor must also be pervious to a magnetic field, i. e., a non-magnetic electrical conductor is employed in constructing the wave guide and plasma chamber. Also, to minimize heating of the partition 31 the partition is disposed at a minimum current node in the wave guide 22, i. e., the longitudinal length of the plasma generation chamber 24 is preferably made a half-wave length or multiple thereof.

The hereinbefore mentioned means for introducing gas to the plasma generation chamber may comprise a conduit 37 communicating with an external gas supply 38 and terminating in the plasma generation chamber 24 whereby a pressure differential is established across the orifice 34 by introducing gas therethrough. Gaseous material such as hydrogen, hydrogen isotopes or any other desired gaseous material may be employed, as required for the desired purpose. The conduit 37 as shown in Figure 1 transpierces the plate 14 in gas tight fashion through an aperture 39 and terminates in an aperture 41 formed in the wall of plasma generation chamber 24. An expansion joint 42 is provided in a section of the pipe 37 to allow for differential expansion of the mechanical structure.

The means for establishing an axially symmetric magnetic field normal to said orifice may comprise a solenoid 43 disposed coaxially about the housing 11 and extending along the longitudinal axis thereof a distance sufficient to provide an axially symmetric magnetic field in both the plasma generation chamber 24 and tthe evacuated region of the housing 11. Specific boundaries of the magnetic field will become more apparent hereinafter. A D. C. power supply (not shown) is provided to energize the solenoid 43.

Very high radio frequency energy required to energize said plasma generation chamber can be supplied by various conventional means and may comprise a continuous wave magnetron oscillator 44 coupled to the wave guide 22 as through a matching wave guide section 46. It will be appreciated that any appropriate electrical oscillatory apparatus operating in the microwave region may also be employed such as klystrons and the like. The electromagnetic waves propogating within the wave guide 22 energize the free electrons in the plasma generation chamber 23. Stray electrons always exist in such a system and it is well known in the art that an energetic electron moving in a magnetic field will follow a helical path, the axis of which lies perpendicular to the direction of rotation. Thus the energized electrons will describe a roughly tight helical path and produce ionization as they collide with the gas molecules and a plasma will be thereby formed in the plasma generation chamber 24. Moreover, the ionized gas molecules being positively ionized will describe generally similar paths, with opposite direction of rotation to the electrons and will form with the electrons an electrical neutral plasma in the chamber.

To begin operation of the plasma generator of the invention, the housing 11 is continuously evacuated by said vacuum pump whereby continuous evacuation of the plasma generation chamber also is effected. Gas such as deuterium, tritium, and the like from which the plasma is to be generated is then continuously introduced into the generation chamber 24 from the gas supply 38 and at a rate correlated with the ratio of evacuation to establish the desired operating pressure in said chamber and to establish and maintain a gas pressure differential across the orifice 34.

Actuation of the radio frequency energizing means 44 then supplies radio frequency energy to the wave guide 22 wherein the electromagnetic waves propagate to the plasma generation chamber 24. Electrons present therein are caused to accelerate in the aforesaid helical paths by the interaction of electric fields produced by said radio frequency energy and the constraint of said axially magnetic fields producing copious ionization of the gas molecules thereby forming an impure plasma, i. e., neutral atom contaminated electrically neutral gas in the chamber. Also, both the electrons and positive ions are constrained by said axially symmetric magnetic field to helical paths of which the axes are parallel to the axis of the chamber 11 and said orifice 34.

Several parameters are mutually interrelated and tend to be interdependent in the operation of the plasma generation chamber. For maximum efficiency the magnetic field that passes through the plasma generation chamber 24 is adjusted so that the cyclotron frequency for electrons (Fc) in the chamber is equal to that of the operating frequency (Fm) of the magnetron as given by the following relation:

$$Fc=\frac{eH}{2\pi m_e c}=Fm$$

where:

e=electron charge
m_e=mass of electron
π=3.14
H=intensity of the magnetic field
c=speed of light

Under these conditions, electrons in the plasma generation chamber 24 receive the major portion of the energy from the electrical field, and a plasma can be produced with the least energy. With appropriately adjusted power input and gas pressure, the ion density (n) in the plasma, will increase until the electron plasma frequency (F_p) approaches the magnetron frequency (F_m) as indicated by the following relation:

$$F_m \geq F_p = \left(\frac{ne^2}{\pi m_e}\right)^{1/2} = 8980n^{1/2}$$

For example: if $F_m = 3000$ mc./sec. ($\lambda = 10$) then $n_{max} = 10^{11}$ ions/cc.

Thus it can be seen that the density of the plasma to be produced by the plasma generator can be varied while maintaining maximum power transfer and efficient ionization by correlatively adjusting the intensity of the magnetic field, the gas pressure, and the magnetron frequency until the condition wherein [$F_m = F_p = F_c$] is satisfied for the desired density of plasma.

The plasma thus formed in the plasma generation chamber **24**, wherein the total pressure is approximately 10^{-2} to 10^{-3} mm. is extracted through the orifice **34** by the focusing effect of the axially symmetric magnetic field acting in cooperation with the flow of gas through the orifice caused by the lower pressure (below approximately 10^{-5} mm.) in the evacuated region contained by the housing **11**. The gas flow is essential to the production of the electrical neutral plasma since the electrical extraction methods employed conventionally cause charge separation and the production of a positive ion beam. It will be appreciated that the short section of tubing **33** is provided to reduce the rate of gas flow from the plasma generation chamber **24** establishing the indicated pressure differential thereacross. Due to the constraint afforded by the magnetic field the orifice structure will have little effect on the plasma.

It will be noted that the aforementioned extraction method effectively screens out most of the neutral particles as the plasma is selectively focused and flows through the orifice **34**. The probability that a neutral particle following its usual random path has of escaping through such an orifice is small compared to that of a plasma particle focused as described by an axially symmetric magnetic field. The few gas molecules that escape through the orifice will diffuse randomly into the evacuated region as they are not effected by the magnetic field therein, and thus the extracted focused plasma is further freed from contamination by neutral particles as it emerges from the orifice into the housing. In addition, the electron beam usually associated with the production of a plasma is eliminated in the present invention by the extraction method employed; nevertheless, the electrons required to provide electrical neutrality are entrained and carried along by the positive ion content of the plasma. Hence, in the low pressure region of the housing **11** there is provided a low temperature uncontaminated plasma, focused along the axis of the magnetic field, without the presence of an electron beam or neutral particles and which can be utilized for various purposes therein.

While the invention has been disclosed with respect to a single preferred embodiment, it will be apparent to those skilled in the art that numerous variations and modifications may be made within the spirit and scope of the invention and thus it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. A plasma generator comprising in combination a plasma generation chamber having an exit orifice, a source for introducing gas to said chamber, means for ionizing gas in said chamber wherein a plasma is formed, magnetic field means for focusing said plasma, and means for establishing a pressure differential across said orifice whereby said plasma is focused and extracted through said orifice by said magnetic field in cooperation with said pressure differential.

2. A plasma generator comprising in combination an evacuated housing, a plasma generation chamber having an exit orifice communicating with said evacuated housing, a source for introducing gas to said chamber, thereby establishing a pressure differential across said orifice, means establishing an axially symmetric magnetic field normal to said orifice, and means for establishing high frequency electrical fields in said chamber for ionizing gas in said chamber to form a plasma that is focused and extracted through said orifice by said magnetic field acting in cooperation with said pressure differential.

3. A plasma generator comprising in combination an evacuated housing, a plasma generation chamber having an exit orifice communicating with said evacuated housing, a variable pressure source for introducing gas to said chamber thereby establishing a pressure differential across said orifice, magnetic field means establishing an axially symmetric magnetic field normal to said orifice of controlled intensity, and means producing and coupling high frequency electromagnetic radiation into said chamber with the frequency thereof substantially equal to the cyclotron frequency of electrons in said chamber and to the electron plasma frequency for maximized ionization efficiency, whereby a plasma is formed in said chamber and is magnetically focused and pressure propelled through said orifice.

4. A plasma generator comprising in combination an evacuated housing, a plasma generation chamber having an exit orifice communicating with said evacuated housing, a source for introducing gas to said chamber thereby establishing a pressure differential across said orifice, a solenoid element adapted for energization to establish a magnetic field directed axially through said orifice, and wave guide means terminating in said chamber whereby very high radio frequency excitation applied to said wave guide excites and ionizes gas molecules in said chamber producing a plasma which thenceforth is focused and extracted through said orifice by said magnetic field acting in cooperation with said pressure differential.

5. A plasma generator comprising in combination an evacuated housing, a wave guide element having an exit orifice communicating with said evacuated housing, a gas tight partition pervious to radio frequency radiation disposed within said wave guide forming a plasma generation chamber proximal to said exit orifice, a source for introducing gas to said chamber thereby establishing a pressure differential across said orifice, means for establishing an axially symmetric magnetic field normal to said orifice, and high frequency generating means energizing said wave guide to cause ionization of gas in said plasma generation chamber wherein a plasma may be formed and thenceforth focused and extracted through said orifice by said magnetic field acting in cooperation with said pressure differential.

6. A plasma generator comprising in combination an evacuated housing, a wave guide transpiercing one wall of said evacuated housing, said wave guide having an exit orifice opening into said evacuated housing, a gas tight partition pervious to radio frequency disposed within the end region of said wave guide extending into said evacuated housing forming a plasma generation chamber proximal to said exit orifice, a source for introducing gas to said chamber thereby establishing a pressure differential across said orifice, magnetic field means for establishing an axially symmetric magnetic field normal to said orifice, and radio frequency generating means coupled to said wave guide for ionizing gas in said chamber wherein a plasma may be formed and thenceforth be focused and extracted through said orifice by said magnetic field acting in cooperation with said pressure differential.

7. A plasma generator comprising in combination an elongated cylindrical evacuated vessel, a wave guide element disposed coaxially with said vessel, said wave guide element having a centrally located exit orifice communicating with said vessel, a gas tight partition pervious to radio frequency disposed transversely within said

wave guide proximal to said exit orifice thereby forming a plasma generation chamber communicating with said vessel, a source for introducing gas to said chamber thereby establishing a pressure differential across said orifice, a solenoid disposed coaxially with said vessel to provide an axially symmetric magnetic field in said vessel and said chamber normal to said orifice, generating means for producing high frequency electromagnetic radiation coupled to said wave guide through a matching section whereby said wave guide is energized causing ionization of the gas molecules in said plasma generation chamber to establish a plasma therein, which plasma is focused and extracted through said orifice by said magnetic field acting in cooperation with said pressure differential.

8. In a method for providing an uncontaminated plasma, the steps comprising producing a contaminated plas-

ma in a defined region having an exit orifice, and extracting said plasma by focusing said plasma along the axis of said orifice with an axially symmetric magnetic field and simultaneously providing a decreasing gas pressure gradient across said orifice whereby said plasma is selectively extracted from said defined region through said orifice as a well defined plasma beam and any neutral gas particles emerging from said orifice diffuse in a randomly indiscrete manner so as to separate from said plasma beam.

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