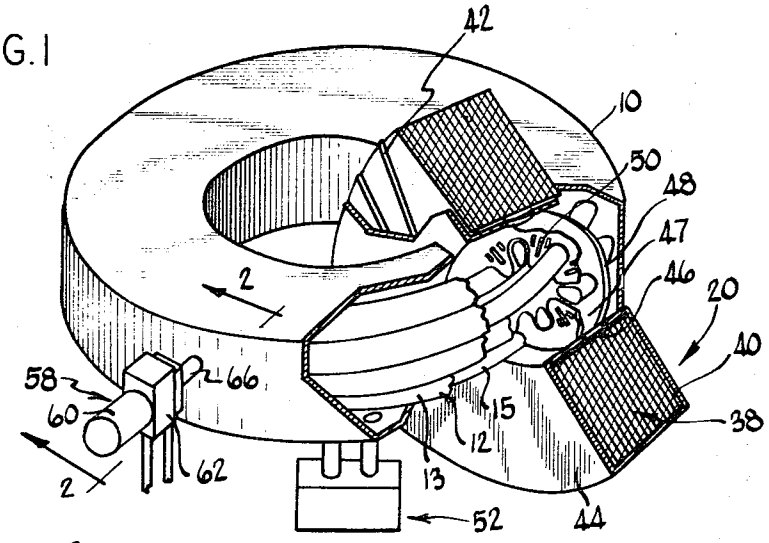
Aug. 4, 1970 TIHIRO OHKAWA ET AL 3,523,209

PLASMA DEVICE INCLUDING PLASMA INJECTION STRUCTURE AND METHOD

Filed June 29, 1967 3 Sheets-Sheet 1

FIG. 1



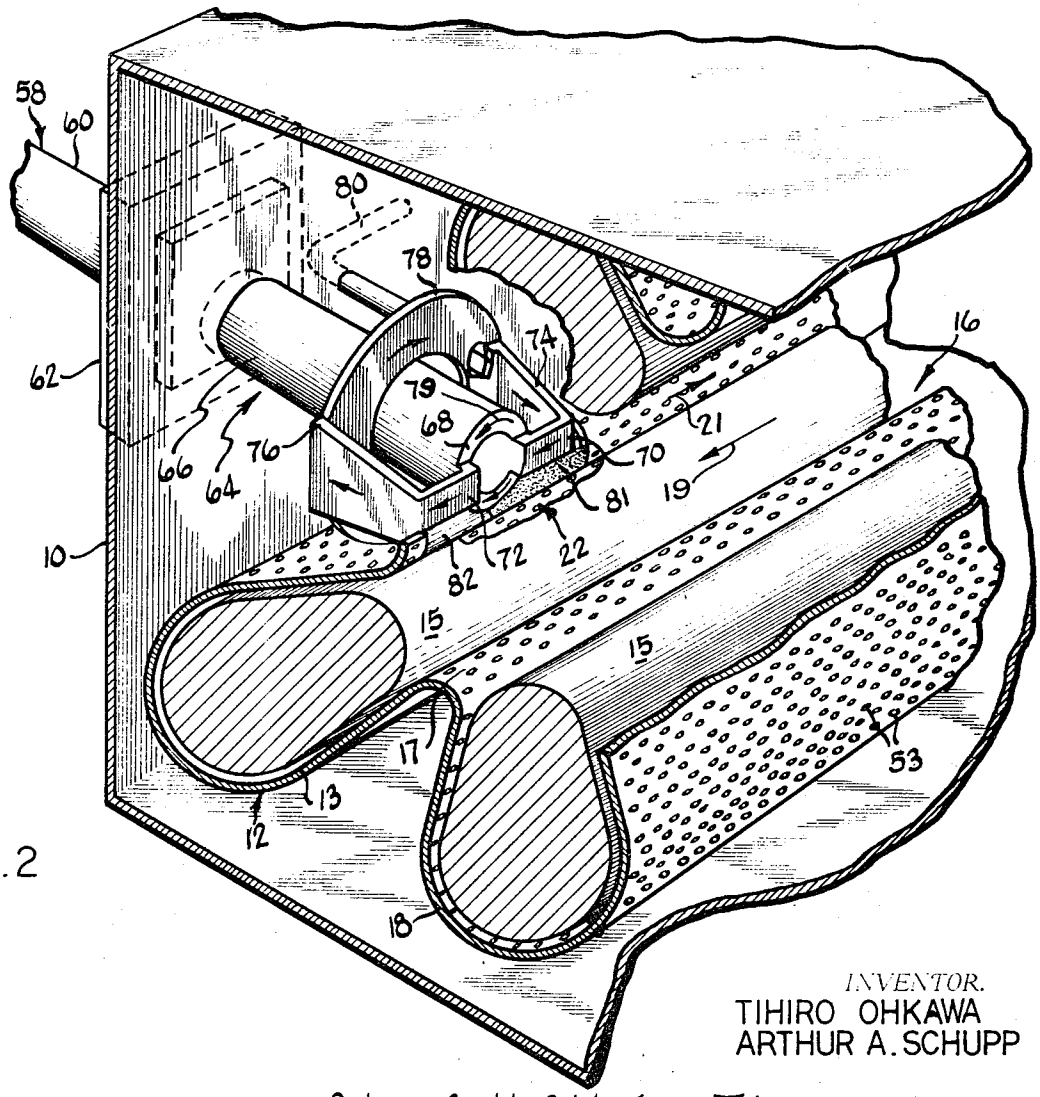


FIG. 2

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PLASMA DEVICE INCLUDING PLASMA INJECTION STRUCTURE AND METHOD

Filed June 29, 1967 3 Sheets-Sheet 2

FIG.3

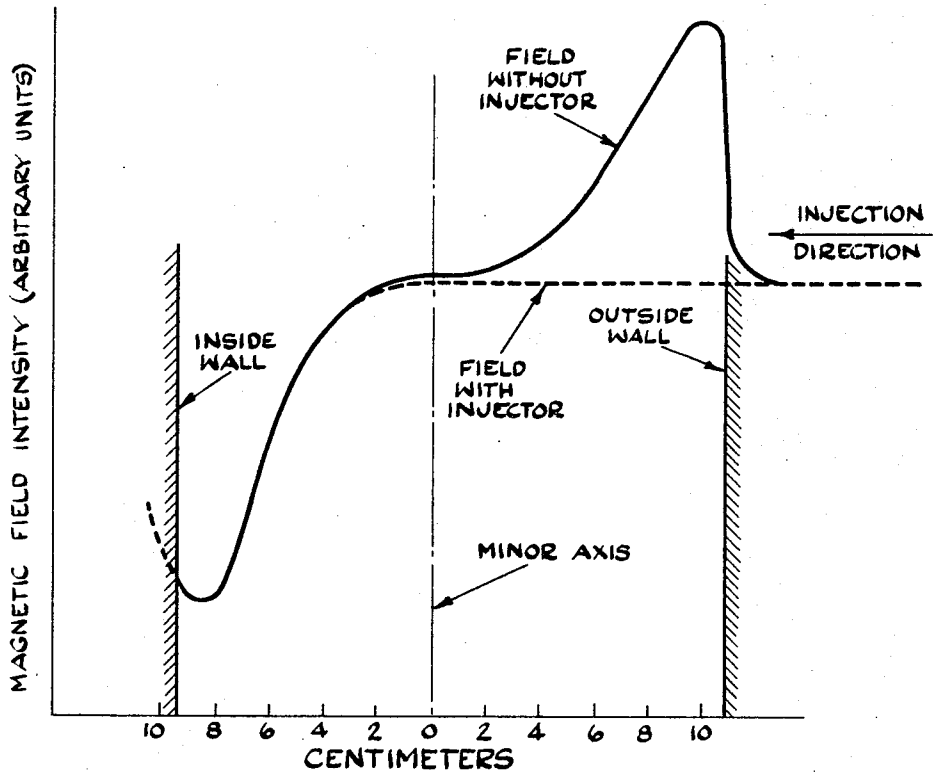


FIG.4

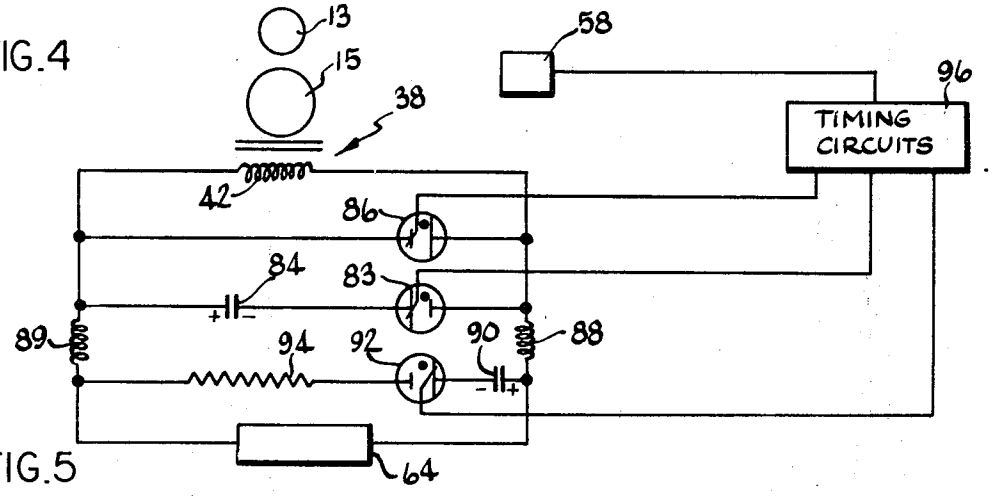
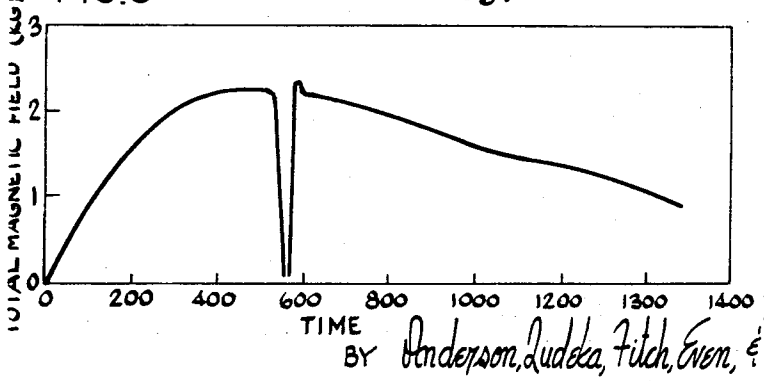


FIG.5



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FIG.6

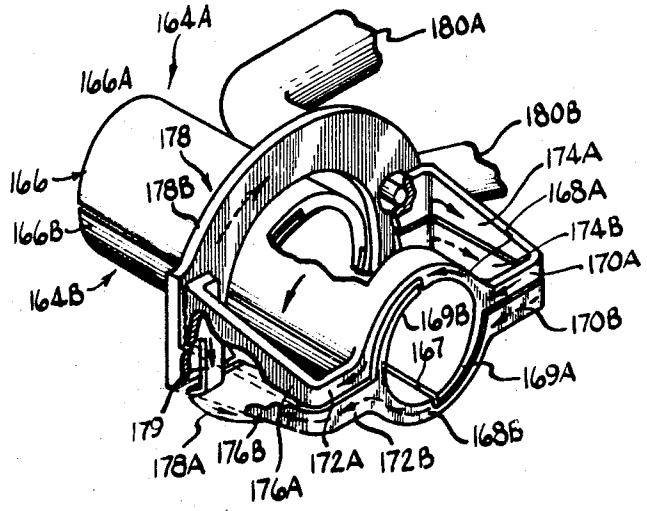
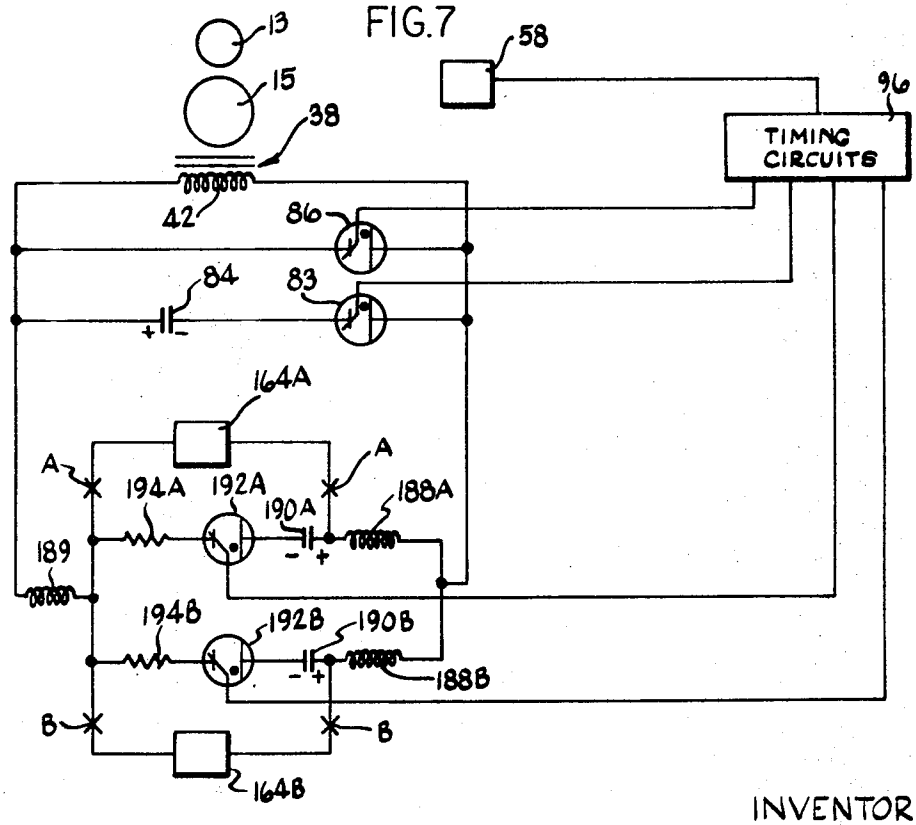


FIG.7



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United States Patent Office 3,523,209 Patented Aug. 4, 1970

3,523,209

PLASMA DEVICE INCLUDING PLASMA INJECTION STRUCTURE AND METHOD

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Int. Cl. H01j 1/50, 17/26; H01h 1/02
U.S. Cl. 315—111 19 Claims

ABSTRACT OF THE DISCLOSURE

A method and apparatus for injecting plasma into a confining magnetic field is provided with which the confining field is eliminated adjacent the entry point during the time while the plasma is injected and is reinforced adjacent the entry point at other times. The plasma may also be guided to the entry point using one form of the method and apparatus.

This invention relates generally to methods of and apparatus for manipulating plasma and, more specifically, to an improved device with which a plasma may be injected into plasma confining magnetic fields and an improved method of injecting plasma into such fields.

In recent years methods and apparatus have been developed for producing, manipulating and confining electrical plasmas, which plasmas are ionized gases comprising approximately equal numbers of positively charged ions and free electrons at high temperatures. Such plasmas may be utilized as sources of electrons for electron beams which in turn may be used in processing, forming or joining materials as well as in a variety of other useful applications. Plasmas may also be utilized to produce positive or negative ion beams which may be used, for example, to clean or etch surfaces without destructive heating. In addition, if a plasma is formed from a suitable gas such as deuterium or a mixture of gases such as deuterium and tritium, fusion reactions may occur within the plasma body. Such fusion reactions may produce highly energized protons or neutrons or other particles, thus providing a source of neutrons or protons or such other particles at high energy. If the proper conditions are realized, the energy obtained from the fusion reactions may exceed the input energy and provide useful power.

In order to achieve many of these results, it is necessary to provide a suitable means of confining the plasma in a given region at high temperature for an appreciable period of time. Such confinement of plasma is difficult to achieve with ordinary solid walled containers, since contact of the plasma ions with the walls of such a container cools the plasma. Consequently, external magnetic fields having a variety of configurations have been utilized to confine the plasma in a selected space. In some systems an un-ionized gas is injected into the confinement space and therein ionized to produce the plasma, but in many systems it is preferred first to produce the plasma outside, then to accelerate it into the confinement space through an injection window or aperture and finally to trap it there by means of the magnetic fields.

Injection of plasma into a confining field presents certain problems, however. Charged particles moving in a magnetic field tend to be reflected from regions of higher than average field strength. A magnetic field which is strong enough to confine the plasma ions may also be strong enough to exclude ions which are propelled toward the field. Conversely, plasma ions which have sufficient energy to penetrate into the confinement space will also tend to immediately escape therefrom. The problem is aggravated by the fact that magnetic field configurations providing relatively stable confinement of plasma are usually strongest at the periphery of the confinement space so that the equilibrium position of the plasma is at the center of the space. As a result, the plasma accelerated toward such a confining field must pass through a region of increasing magnetic strength and through the region of the strongest magnetic field to enter the confinement space.

Penetration of plasma into a confining field in some cases is aided by the creation of a polarization of charge in the plasma being injected due to motion of the plasma transversely of the magnetic field. This polarization causes a local electric field in the plasma which is transverse to the magnetic field and in turn results in a drift velocity of the plasma into the confining field. The plasma will nevertheless be decelerated as it moves into the magnetic field because the plasma is not a perfect conductor and the separation of charges which causes the drift velocity is not complete. Hence the drift velocity in many instances is not great enough to overcome the plasma excluding effects of the magnetic field to confine the plasma. As a result the entering plasma stagnates without reaching the center of the confinement space and may interact with the solid members of the device creating the magnetic field to produce a gas cloud near the point of entry.

In the present invention the problem of injection of plasma into an confining field is solved by creating a component of magnetic field in the confinement space adjacent the injection window, which component of field momentarily suppresses the confining field so that the plasma propelled through the window can enter the confinement space. After the plasma has entered the space, the confining field is restored adjacent the injection aperture so that the plasma will not leak out of the confinement space along the path by which it entered.

It is therefore an important object of this invention to provide an improved method of and apparatus for injecting plasma into a plasma confining field.

Another object of the invention is to provide an improved method of and apparatus for suppressing a plasma confining field in the path of plasma being injected into a confinement space.

Still another object of the invention is to provide an improved method of and apparatus for maintaining a magnetic confining field adjacent to the plasma injection aperture during periods when injection is not taking place.

A further object of the invention is to provide an improved method of and apparatus for momentarily suppressing a plasma confining field during plasma injection and for subsequently restoring such field.

A still further object of the invention is to provide a method and apparatus for injecting plasma into a plasma confining field in which the amount of interaction of the injected plasma with portions of the apparatus is optimized.

Yet another object of the invention is to provide an apparatus for injecting plasma into a confining field which can guide the plasma and suppress or reinforce the confining field as desired.

Other objects and advantages of the invention will become apparent from the following description when considered in conjunction with the accompanying drawings, in which:

FIG. 1 is a diagrammatic perspective view of a plasma apparatus with which the present invention may be utilized with portions being broken away to show certain features thereof;

FIG. 2 is an enlarged diagrammatic perspective view of a portion of the apparatus shown in FIG. 1 showing various features of the invention;

FIG. 3 is a graph showing the magnetic field configuration as a function of distance from the injection aperture at two different times;

FIG. 4 is a circuit diagram of the apparatus shown in FIGS. 1 and 2;

FIG. 5 is a graph showing the magnetic field near the injection aperture as a function of time;

FIG. 6 is an enlarged diagrammatic view of another form of a portion of the apparatus shown in FIG. 2; and

FIG. 7 is a diagram of a circuit adapted for use with the apparatus shown in FIG. 6.

Generally, as shown in the drawings, a plasma apparatus with which the present invention may be utilized includes a vacuum sealed casing **10** within which is positioned means **12** for producing a plasma confining magnetic field within the casing. The invention may be utilized in conjunction with a variety of such apparatus but for clarity and ease of description it will be described in conjunction with the specific illustrated apparatus.

In the structure illustrated in FIG. 1, the vacuum sealed casing **10** is in the shape of a toroid and formed of a conductive material such as copper. It encloses, in spaced relationship and suitably insulated therefrom, a toroidal jacket **13**. The jacket, in turn, encloses a plurality of endless rods or members **15**, of conductive material such as copper, spaced about the minor circumference of a toroidal confinement space **16**. The jacket **13** is internally fluted or corrugated around its minor circumference to provide a plurality of alternate ridges **17** and grooves **18** each of which extends around the major circumference of the jacket. One each of the rods **15** is received in each groove **18** in spaced relationship to the wall thereof. A current is induced in each of the rods in the direction of the arrow **19** by a power source **20**, as hereinafter described in detail. When a current passes longitudinally through each rod **15**, an oppositely directed current in the direction of the arrow **21** is induced in the jacket **13**. These currents in combination provide a magnetic field in the confinement space **16** which is concave between the rods **15** and the wall of the grooves **18** and convex in the space adjacent the ridges **17** relative to the minor axis of the toroidal confinement space. Plasma is injected into the space **16** through a window or aperture **22** in the jacket **13**.

As previously indicated, current is induced in each rod **15** and, in turn, in the jacket **13** by a power source **20**. As shown in FIG. 1, the power source **20** includes a toroidal core transformer **38** which is disposed so that the rods **15** pass through the center hole or major axis thereof, and thereby act as short circuited secondary windings of the transformer. The transformer **38** includes a core **40** of iron laminations, and a primary winding or coil **42** of wire wrapped about the core **40**. The primary winding **42** of the transformer **38** is connected to a source of pulsatory power such as will be described in detail below.

As also shown in FIG. 1, the transformer is provided with a toroidal housing **44** of conductive material, such as copper, which is disposed about the primary winding **42**. An annular gap **46** is provided in the housing **44** adjacent the major axis thereof. The transformer housing **44** is suitably insulated from the casing **10** and is connected to a transverse gap **47** in the jacket **13** by a pair of spaced apart flanges **48** of conductive material, such as copper, which extend between the ends of the jacket **13** and the ends of the transformer housing **44**. By this means the jacket is prevented from acting as a shorted turn of the transformer and hence from excluding magnetic flux from its interior so that current may be induced in the rods **15**.

Because of the toroidal shape of the apparatus, the rods **15** have different lengths or major circumferences. When a current is passed through the primary winding **42**, each rod **15**, because it is a shorted turn of the transformer, generates the same magnetic flux. Therefore, the current density required in the jacket **13** around the short rods **15** is higher than the current density required in the jacket wall **13** around the longer rods. If the proper current density is not available locally to match the current density required, a transverse magnetic field will be set up at the gap **47** between the ends of the jacket **13**. Therefore, the turns of the primary winding **42** are preferably distributed on the core **40** so that the flow pattern of the currents on the surface of the flanges **48** goes generally directly in toward the grooves **18** which surround the longer rods and does not cross the whole flange **48** to the grooves **18** surrounding the shorter rods **15**.

Preferably, to insure proper distribution of the current, the gap between the flanges **48** is tapered toward the major axis of the confinement space **16** so that the width of the gap is inversely proportional to the distance of the point on the flange **48** from the major axis of the toroid. Moreover, perforations **50** are preferably provided in the flanges **48** to aid in the proper distribution of current flow on the surface of the flanges **48**.

So that plasma trapped in the confinement space does not exchange its charge with neutral gas, and thereby cause hot ions to be neutralized and escape across the magnetic confining fields, the plasma region **16** is maintained at as high a vacuum as possible (i.e., as free as possible from neutral atoms and molecules). In the illustrated embodiment, means **52** such as a conventional vacuum pump is connected to the casing **10** for rapidly evacuating the plasma region. In this connection, a substantial number of small apertures **53** are provided in the jacket **13** providing communication between the space enclosed by the casing **10** and the space enclosed by the jacket **13**.

As best shown in FIG. 2, plasma is injected radially into the confinement space **16** by means of a source **58** of plasma, which may include a conventional plasma gun **60**. Preferably, the plasma source **58** includes purifying apparatus **62** for trapping neutral particles and preventing them from entering the casing thus purifying the plasma before it enters the jacket. A suitable device for performing such purification is described in co-pending application Ser. No. 408,949, of Franklin R. Scott, et al., entitled Plasma manipulation method and apparatus, now Pat. No. 3,445,722, filed Nov. 11, 1964, and assigned to the assignee of the present invention.

It will be apparent that in order for the confining magnetic field to exist at its peak strength when the plasma reaches the confinement space it is necessary to initiate the confining magnetic fields prior to the time of injection. To enable the purified plasma to enter the magnetic fields, a plasma injection device **64** is provided adjacent the injection window **22**.

The injection device as illustrated in FIG. 2 includes a cylindrical injection tube or pipe **66** which is connected at its outer end to the plasma source **58**, extends through the wall of the casing **10**, and terminates at the window **22** in an annular inner face **68** adjacent to the inner wall of the jacket **13**. Although it is not necessary that the tube be such, the face **68** of the injection tube is formed of a conductive material such as copper and is connected to conductor plates **70** and **72** which are perpendicular to the axis of the tube **66** and parallel to the major circumference of the toroid **13**. Each plate **70** and **72** is connected at its outer end to a conductive member **74** and **76**, respectively, which extend away from the jacket **13** parallel to the axis of the tube **66**. The member **76** is connected at its outer end to a conductive annulus **78** which is spaced from and surrounds the tube **66**. The annulus **78** and the outer end of the member **74** are connected to the respective terminals of a coaxial cable **80** connected to a direct current power source through a circuit to be described below. (FIG. 4).

The entire assembly of the injection device may be securely fastened to the jacket **13** and the casing **10** by potting with a suitable epoxy resin **81** around the out-

side of the tube **66** so as to completely fill the injection aperture **22** outside of the end **68** of the pipe **66**. A layer of stainless steel foil **82** covers the epoxy resin to prevent the epoxy resin from accumulating a charge or evaporating into the confinement **16** space and contaminating the plasma. It also provides a continuous conductive surface at the inner surface of the jacket **13** except for the end of the tube. It will be apparent that current supplied through the coaxial cable **80** will flow along the member **74** and the plate **70** to the face **68** of the pipe **66** where it will divide and flow across the face **68** by going around both sides of the end of the pipe. The divided current will reunite in the plate **72** and flow through the member **76** and annulus **78** back to the coaxial cable. The direction of flow may, of course, be reversed.

The effect of this current on the magnetic field in the portion of the confinement space **16** adjacent the window **22** depends upon the direction of the current around the face **68** in relation to the current induced in the jacket **13**. When these currents are in generally opposite directions as shown by arrows **79** on the face **68** and arrow **21** on the jacket in FIG. 2, the confining magnetic field will be diminished due to the component of magnetic field caused by the current around the face. When the currents are in generally the same direction, the confining field will be increased due to the component of magnetic field caused by the current around the face. These effects are shown in FIG. 3, which is a graph of the magnetic field strength taken along the axis of the tube **66** extended from the window to the inner wall of the jacket **13**. The solid line shows the field when the currents in the jacket **13** and on the face **68** are in generally the same direction while the dashed line shows the field when the currents are in generally opposite directions.

In operation of the apparatus, the confining magnetic field is first initiated. This field is then momentarily suppressed by operation of the injection device at approximately the same time that plasma which has been accelerated along the pipe **66** from the plasma source **58** reaches the inner wall of the jacket **13**. After the plasma has entered the confinement space, the confining field adjacent the window is restored and reinforced by the injection device. This mode of operation is accomplished by means of the circuit shown in FIG. 4.

In the illustrated circuit the rods **15** are linked through the transformer **38** and an ignitron bank **83** to a capacitor bank **84**. A second ignitron bank **86** is connected across the primary **42** of the transformer **38** and functions to short circuit the primary of the transformer after a predetermined time so that the confining magnetic field will decay. The primary **42** of the transformer **38** and the capacitor bank **84** and ignitron bank **83** are also connected to the injector device **64** through suitable inductors **88** and **89** which are in series connection on each side of the injection device. An injection capacitor bank **90** in series with an injector ignitron bank **92** and a suitable resistor **94** is connected across the injection device. The ignitron banks **83**, **86** and **92** are fired at the desired times relative to the time of plasma injection by timing circuits **96**, which may be conventional. The polarities of the charges on the capacitors **84** and **90** and the connections to the transformer **38** and the injection device **64** are so arranged that the current in the face **68** caused by discharge of the injection capacitor bank **90** is opposite to that produced in the jacket **13** by discharge of the capacitor bank **84**.

In operation of the apparatus the capacitors **84** and **90** are charged with the polarities shown by conventional direct current power supplies (not shown). These capacitors may be charged through switching means which are opened when the capacitors are charged to the desired potential. The timing circuits **96** are then started by some initiating signal, which may be the closing of a switch. The timing circuits **96** thereupon apply a control signal to the ignitors of the ignitron bank **83** which is thereby rendered conductive.

The capacitor bank **84** discharges through the ignitron bank **83** so as to cause current flow through the primary **42** of the transformer **38** and also through the inductor **89**, the injector device **64** and the inductor **88**. As a result, the currents in the jacket **13** and face **68** flow in the same direction and the magnetic field adjacent the window **22** rises to a peak as shown in FIG. 5 and begins to decay.

The rise in the field represents a transfer of energy from the charged capacitor **84** to the field produced by the transformer **38**. The peak in the field represents the completion of the transfer and signifies the complete discharge of the capacitor **84**. At about this point in time, a control signal is supplied by the timing circuits **96** to the ignitor of the ignitron bank **86** which thereupon shunts the capacitor **84** and the ignitron bank **83**. This leaves the capacitor **84** discharged, while current continues to circulate in the winding **42** until the energy is dissipated.

At the same time that energy is transferred to the winding, part of the energy in the capacitor **84** is transferred to the fields of inductors **89** and **88** and the injector device **64** so that current also continues to circulate through the injector device **64** upon actuation of the ignitron bank **86**.

Shortly after the ignitron bank **86** is fired, the timing circuits **96** supply a control signal to the ignitron **92**. The injector capacitor bank **90** is then discharged by the injector ignitron bank **92** so as to cause current to flow through the resistor **94** and through the injector **64** in the direction opposite to the current in the injector **64** caused by discharge of the capacitor bank **84**. This results in a component of magnetic field adjacent the window **22** which opposes and tends to suppress the field created by the currents in the jacket **13**. The effect of the combined components of magnetic field is a momentary suppression of the field adjacent the window as shown in FIG. 5, so that plasma accelerated through the window **22** can enter the space **16**.

The discharge of the capacitor **90** is isolated from the rest of the circuit by the inductors **88** and **89**. Because there is little inductance in the discharge path for this current, there is little tendency to oscillate, and further oscillation is damped by the resistor **94**. There may be a slight overshoot as shown in FIG. 5. Resistor **94** also serves to determine the time constant with which the capacitor **90** discharges and hence the duration of the current pulse through the injector **64**.

Even after this current is dissipated, the current in the inductors **88** and **89** that was caused by discharge of the capacitor bank **84** continues flowing in the same direction in the face **68** as the current in the jacket **13** and causes a component of field adjacent the window which is in the same direction as and reinforces the confining field.

In one particular mode of operation the parameters of the circuit are so chosen that the confining field rises to a peak in 400μ sec. The transformer is shorted 500μ sec. after initiation of the current through the rods. This confining field has a decay time constant of about 5,500μ sec. About 50μ sec. after the primary is shorted the plasma is injected and the injection capacitor bank **90** is discharged so as to create a field component opposed to the confining field adjacent the injection window **22**. The confining field is suppressed for approximately 20μ sec. by this opposing field component. The persisting portion of the field produced by the currents in the injection device as produced by discharge of the capacitor bank **84** is in phase with and in the same direction as the confining field produced by the current in the jacket **13** and reinforces the latter field adjacent the injection window **22** as both field components decay. The resulting time dependence of the total field adjacent the window **22** is shown in FIG. 5.

In one embodiment of plasma research apparatus, a copper jacket **13** having a wall, 3 cm. thick, is formed so as to provide six ridges **17** and six grooves **18**. The wall

is perforated so that approximately 25 percent of its area is open and the jacket is disposed within a copper casing **10**. The ridges are made with a radius of 15 cm., and the grooves are made with a radius of 28 cm. Six oval shaped rods **15** are disposed in the grooves. The radius of the larger arcuate portion of each rod is 22 cm., and the radius of the smaller arcuate portion of each rod is 15 cm. The projection of the flat sides of the rods on the diameter is 7 cm., and a one cm. gap is provided between the flat side of the rod **15** and the jacket **13**. The copper pipe **66** has an inner diameter of 5 cm. and the window **22** is 12 inches in diameter.

The capacitor bank **84** is charged by an external power source so that a flux density of 15,000 gauss is created in the core of the transformer, and the length of the current pulse is 0.1 second. The confinement space **16** is maintained at a vacuum of 10^{-6} mm. Hg. Preferably, a plasma density of 10^{15} particles per cubic cm. is provided.

The capacitor bank **84** has a capacitance of 7,200 f., while the injection capacitor bank **90** has a capacitance of 150 mf. The peak flux density adjacent the jacket **12** is 5,000 gauss. The resistance of resistor **94** is 20 milliohms and the inductance of inductors **88** and **89** are each 10 μH.

Although the injection device **64** illustrated in FIG. 2 is highly useful in many applications and provides for greatly improved injection of low energy plasma, it has been found in practice that a gas cloud may be produced near the injection window which can contaminate the plasma. Such a gas cloud, it is believed, may be produced by interaction of the injected plasma with the inner surface of the injection tube **66**. Accordingly, in the embodiment illustrated in FIG. 6 means are provided for producing a longitudinal magnetic field in the tube which serves to guide the plasma along the center of the tube and prevent interaction of plasma with the tube surface.

Specifically, as shown in FIG. 6, the injection device is divided into two portions **164**A and **164**B which are insulated from one another and provide two separate but interconnected current paths. The device includes a cylindrical injection tube **166** having an upper portion **166**A and a lower portion **166**B substituted for the tube **66** of FIG. 2. The portions **166**A and **166**B are insulated from one another by electrical insulation **167** and terminate at the window **22** in semi-annular inner faces **168**A and **168**B, respectively. On each portion **166**A and **166**B, an overlapping sheet **169**A and **169**B is provided which masks the gap between the portions and fits into a mating depression in the inner surface of the other member so that the inner surface of the tube is cylindrical. The face **168**A of upper portion **166**A is connected to conductor plates **170**A and **172**A which are perpendicular to the axis of the tube **166** and are parallel to the major circumference of the toroid **13**. Similarly the face **168**B of lower portion **166**B is connected to conductor plates **170**B and **172**B which are parallel to and insulated from the plates **170**A and **172**A.

The plates **170**A, **170**B, **172**A and **172**B are each connected at their outer ends to respective conductive members **174**A, **174**B, **176**A and **176**B, which extend away from the jacket **13** parallel to the axis of the tube and are each insulated from the adjacent member. The outer ends of the members **176**A and **176**B are connected to a conductive annulus **178** which is spaced from and surrounds the tube **166**. The annulus **178** is divided into a semicircular lower portion **178**A and an upper portion **178**B which are insulated from one another. The member **176**A is connected to the lower portion **178**A of the annulus by means of a connecting member **179** while the member **176**B is directly connected to the upper portion of the annulus **178**B. The end of the lower portion **178**A of the annulus opposite the member **176**A and the outer end of the member **174**A are connected to the respective terminals of a coaxial cable **180**A connected to a direct current power source through a circuit to be described below (FIG. 7). Similarly the end of the upper portion **178**B of the annulus opposite the member **176**B and the outer end of the member **176**A are connected through a coaxial cable **180**B and to the power source.

It will be apparent that current supplied through the cable **180**A will flow along the member **174**A and the plate **170**A, the pipe portion **166**A, the plate **172**A, the member **176**A, the vertical member **179**, and the lower portion **178**A of the annulus back to the axial cable. This flow is indicated by solid arrows. Similarly current supplied through the cable **180**B will flow along the various elements **174**B, **170**B, **166**B, **172**B, **176**B, and **178**B back to the cable. This flow is indicated by dashed arrows. Since the entire tube **166** is formed of a conductive material the current flow in each case is around the entire tube portion **166**A or **166**B rather than just the face portions **168**A and **168**B. Hence, a magnetic field is created in the tube itself as well as at its face. Where the respective overlapping sheets **169**A and **169**B are mated with the opposing portion **166**B and **166**A, respectively, an image current will be induced in the sheets which will have the same direction as the primary current on the inner surface of the tube. Thus the current distribution on the inner surface of the tube is made more uniform since the sheets cover the insulated gaps between the tube portions.

When the current in each of the members **174**A and **174**B has the same direction the effect on the magnetic field in the portion of the confinement space adjacent the window will be approximately the same as in the embodiment of FIG. 2. That is, when the currents across the face are generally opposite to the currents induced in the jacket **13**, the confining field is diminished and when such currents are in the same direction as those in the jacket the field is strengthened.

The current direction in either of the annular portions may, however, be reversed so that there is an effective closed current loop around the tube. Such a loop creates a longitudinal magnetic field which forces the plasma toward the center of the tube away from the tube surfaces and helps guide it. As a result there is less interaction between the plasma and the tube to create a gas cloud. Similar results may be achieved by simply having different magnitude currents in each portion of the annulus as well as by a change in their directions. Of course, in such a case the confinement field will not be completely canceled. This deficiency, however, in practice may be out-weighed by the lessening in the amount of contaminating gas produced.

The embodiment of FIG. 6 may be operated by the circuit of FIG. 7. As in the previous embodiment the rods **15** are linked through the transformer **38**, and the ignitron bank **83** to a capacitor bank **84**. A second ignitron bank **86** is connected across the primary **42** of the transformer **38** and functions to short circuit the primary of the transformer after a predetermined time so that the confining magnetic field will decay. The primary **42** of the transformer **38** and the capacitor bank **84** and ignitron bank **82** are also connected in series to the injector device **164** through suitable inductors **188**A and **188**B on one side and inductors **189** on the other side. Inductors **188**A and **188**B are in parallel with one another and in series with the respective portions of the injector **164**A and **164**B. An injection capacitor bank **190**A in series with an injector ignitron bank **192**A and a suitable resistor **194**A is connected across the portion of the injection device **164**A. Similarly an injection capacitor bank **190**B in series with an injector ignitron bank **192**B and a suitable resistor **194**B is connected across the other portion **164**B. The ignitron banks **83**, **86**, **192**A and **192**B are fired at the desired times relative to the time of plasma injection by timing circuits **96**, which may be conventional. The polarities of the charges on the capacitors **84**, **190**A and **190**B and the connections to the transformer **38** and the injection device **64** may be so arranged that the current in the faces **168**A and **168**B caused by discharge of the injection capacitor banks

190A and 190B is in the same general direction and opposite to that produced in the jacket 13 by discharge of the capacitor bank 84. The current in either portion 164A or 164B may be reversed by manually disconnecting at the points marked A or at those marked B and reversing the leads. The same result may be accomplished by switch means.

In operation of the apparatus the capacitors 84, 190A and 190B are charged with the polarities shown by conventional direct current power supplies (not shown). These capacitors may be charged through switching means which are opened when the capacitors are charged to the desired potential. The timing circuits 96 are then started by some initiating signal, which may be the closing of a switch. The timing circuits 96 thereupon apply a control signal to the ignitors of the ignitron bank 83 which is thereby rendered conductive.

The capacitor bank 84 discharges through the ignitron bank 83 so as to cause current flow through the primary 42 of the transformer 38 and also through the inductors 188A and 188B, the portions of the injector device 164A and 164B and the inductor 189. As a result, the current in the jacket 13 and the faces 168A and 168B flow in the same general direction and the magnetic field adjacent the window 22 rises to a peak as shown in FIG. 5 and bgeins to decay. If the direction of the currents in the tube 166 are such as to form a closed loop this effect will be reduced since the current in one face 168A or 168B will be opposite to the direction of the jacket current but a longitudinal guiding field will also be created in the tube. Reversal of the current in both parts of the tube as described in connection with the previous embodiment will reverse the direction but not the overall effect of the guiding field.

It should be realized that while the structure shown and described above is a toroidal construction, certain features of this invention may be employed in a linear or other geometrical form of plasma device. Moreover, instead of having the current induced in the rods by the illustrated circuits the rods may be separately excited by parallel leads extending through a wall of the jacket. In such a case, local magnetic fields generated about the parallel leads guard or protect the leads from the hot plasma.

Various other changes and modifications may be made in the above described plasma apparatus without deviating from the spirit or scope of the present invention, various features of which are set forth in the accompanying claims.

What is claimed is:

1. A method of injecting plasma into a space wherein a plasma confining magnetic field exists comprising the steps of accelerating the plasma in a path toward the space, momentarily suppressing the confining field in the path of the plasma so that the plasma enters the space, and creating a component of magnetic field in said path in the same direction as said confining field to restore the confining field in said path after the plasma has entered the space.

2. A method according to claim 1 wherein the field suppressing step comprises momentarily creating a component of magnetic field in said path, which component is opposed to said confining field.

3. A method according to claim 1 wherein said confining field is suppressed for approximately 20μ sec.

4. A method according to claim 1 including the step of synchronizing said plasma accelerating step and said field suppressing step so that the confining field is suppressed at the time that the plasma reaches the space.

5. A method of injecting plasma into a space wherein a plasma confining magnetic field exists comprising the steps of accelerating the plasma in a path toward the space, and momentarily suppressing the confining field in the path of the plasma so that the plasma enters the space wherein said plasma confining magnetic field is produced by a first current in a first conductor outside of the space, said conductor having an aperture in said path for the entry of plasma, and wherein said field suppressing step comprises producing a second current flowing along an annular second conductor positioned adjacent the aperture in a direction opposite to the direction of current flow in said first conductor.

6. A method according to claim 5 wherein said annular conductor surrounds the path of the plasma including causing said second current to flow around said path to produce a longitudinal magnetic field forcing the plasma away from said second conductor.

7. A method of injecting plasma into a space wherein a plasma confining magnetic field exists comprising the steps of accelerating the plasma in a path toward the space, momentarily suppressing the confining field in the path of the plasma so that the plasma enters the space, and creating a component of magnetic field in said path in the same direction as said confining field to restore the confining field in said path after the plasma has entered the space, including producing a substantially closed sheet of current surrounding the path of the plasma to create a longitudinal magnetic field directed along said path to guide said plasma toward said space.

8. A method of injecting plasma into a space wherein a plasma confining magnetic field exists comprising the steps of accelerating the plasma in a path toward the space, momentarily suppressing the confining field in the path of the plasma so that the plasma enters the space, and restoring the confining field in said path after the plasma has entered the space so that the plasma is confined in the space wherein said plasma confining magnetic field is produced by a current in a first conductor outside of the space, said conductor having an aperture in said path for the entry of plasma, and wherein said field restoring step comprises producing a current flowing along an annular second conductor positioned adjacent the aperture in the same direction as the direction of the current flow in said first conductor.

9. A method of injecting plasma into a space wherein a plasma confining magnetic field exists comprising the steps of accelerating the plasma in a path toward the space, and momentarily suppressing the confining field in the path of the plasma so that the plasma enters the space including the steps of passing current unidirectionally through a first conductor, the current in said first conductor creating a plasma confining field in the space, thereafter shunting the first conductor so that said current continues to pass therethrough, thereafter passing current momentarily through a second conductor in such direction as to create a component of magnetic field in said plasma path opposed to the plasma confining field, whereby the plasma confining field is momentarily suppressed.

10. A method according to claim 9 wherein simultaneously with the passage of current through said first conductor current is passed through said second conductor in a direction so as to create a second component of magnetic field in said plasma path in the same direction as the plasma confining field created by the current in said first conductor, whereby the plasma confining field is increased.

11. A method according to claim 9 wherein said first conductor has an inductance of such magnitude that said plasma confining field persists for a time which is long relative to the duration of said component of magnetic field opposed thereto.

12. A method of injecting plasma into a space wherein a plasma confining magnetic field exists comprising the steps of accelerating the plasma in a path toward the space, and momentarily suppressing the confining field in the path of the plasma so that the plasma enters the space including the steps of charging a first and second capacitor, thereafter discharging said first capacitor

through a first conductor so as to pass a current unidirectionally therethrough, the current in said first conductor creating a plasma confining field in the space, thereafter short circuiting said first conductor when said capacitor is substantially completely discharged so that said current continues to pass through said first conductor, thereafter discharging said second capacitor through a second conductor in such direction as to create a component of magnetic field in said plasma path opposed to the plasma confining field whereby the plasma confining field is momentarily suppressed.

13. A method according to claim **12** wherein simultaneously with the passage of current through said first conductor current from said first capacitor is passed through said second conductor in a direction so as to create a second component of magnetic field in said plasma path in the same direction as the plasma confining field created by the current in said first conductor whereby the plasma field is increased, said first conductor has an inductance of such magnitude that said plasma confining field persists for a time which is long relative to the duration of said component of magnetic field opposed thereto, said second conductor having inductance of such magnitude that oscillation of said current caused by discharge of said second capacitor is damped, and including the step of synchronizing said plasma accelerating step, said discharge of said first and second capacitors and said short circuiting of said first conductor so that the confining field is momentarily suppressed at the time that the plasma reaches the space.

14. Apparatus for injecting plasma into a space wherein a plasma confining magnetic field is produced by a first conductor outside of the space, said first conductor having an aperture therein for the entry of plasma, comprising means for accelerating plasma in a path toward the space, said plasma path passing through said aperture, and field suppressing means for momentarily suppressing the confining field adjacent said plasma path so that the plasma enters the space including an annular second conductor insulated from the first conductor and positioned adjacent the aperture around said plasma path.

15. Apparatus according to claim **14** including a first source of power linked with said first and second conductors, a second source of power linked with said second conductor, first switching means connected between said first power source and said first and second conductors for causing a first current to flow through each of said first and second conductors so that the current through each of said conductors produces respective first and second magnetic field components having the same direction, second switching means for shunting the first power source and the first switching means so that said first current continues to circulate through said first and second conductors, third switching means for causing current to flow through said second conductor so that the current through said second conductor produces a third magnetic field component opposed to the magnetic field component produced by the current in said first conductor, current damping means connected between said second power source and said second conductor so that said third magnetic field component decays rapidly relative to the decay of said first and second magnetic field components, and timing means for actuating said first, second and third switching means at predetermined times.

16. Apparatus according to claim **14** wherein said second conductor is connected to an electrical power source on opposite sides of said plasma path so that current divides and flows through said annular second conductor around each side of plasma path.

17. Apparatus according to claim **16** wherein said second conductor comprises two portions extending along the path of the plasma and insulated from one another, including means for causing different currents to flow in each of said portions so as to produce a longitudinal magnetic field forcing the plasma away from said second conductor.

18. Apparatus according to claim **16** including means for causing the current in said second conductor to flow momentarily in a direction opposite to the direction of current flow in the first conductor so that the plasma enters the space.

19. Apparatus according to claim **18** including means for causing the current in said second conductor to flow in th esame direction as the current in the first conductor so that the confining field is reinforced adjacent the aperture.

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CERTIFICATE OF CORRECTION

Patent No. 3,523,209 Dated August 4, 1970

Inventor(s) Tihiro Ohkawa and Arthur A. Schupp

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

Column 7, line 11, "12 inches" should read "2 inches".

[illegible]
[illegible]
NOV 3 1970

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents

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