Feb. 4, 1964 R. F. POST 3,120,481

MEANS FOR PRODUCING HIGH DENSITY PLASMAS

Filed April 25, 1962

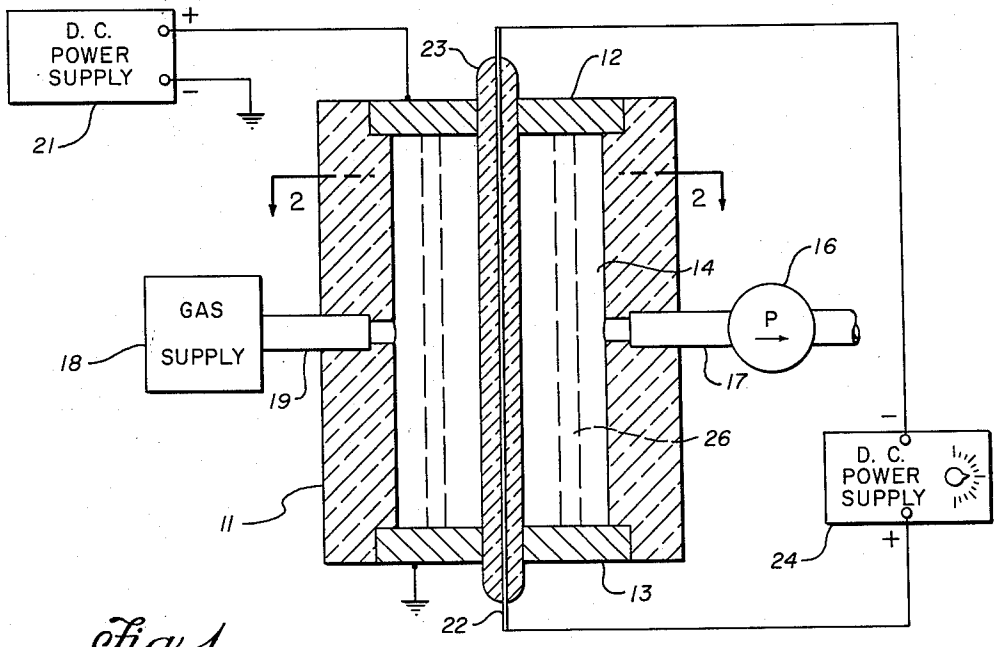


Fig. 1.

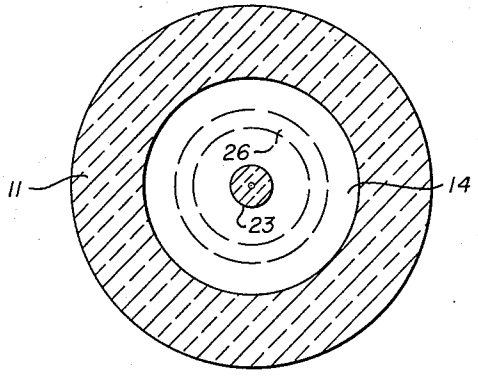


Fig. 2.

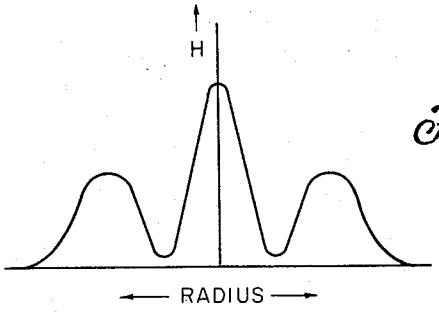


Fig. 3.

INVENTOR.
RICHARD F. POST

BY

ATTORNEY.

United States Patent Office 3,120,481
Patented Feb. 4, 1964

3,120,481

MEANS FOR PRODUCING HIGH DENSITY PLASMAS

Richard F. Post, Walnut Creek, Calif., assignor to the United States of America as represented by the United States Atomic Energy Commission

Filed Apr. 25, 1962, Ser. No. 191,680
5 Claims. (Cl. 176—8)

The present invention relates in general to method and means for compressing plasma discharges and employing stabilized pinch effects to this end.

The instant application is a continuation-in-part of my prior copending application, Serial No. 701,942, filed December 10, 1957, and hereby incorporates by reference pertinent subject matter disclosed therein.

Before proceeding with even a general description of the present invention, it is of importance to define certain terms employed in this following description. In this respect, the term "plasma" is herein taken to mean a space-charge neutralized ion cloud containing substantially equal numbers of positive ions and negative electrons. A further term employed throughout the following disclosure is "pinch effect." This term is employed with respect to discharges, such as plasma discharges noted above. A definition of this term, or more properly an explanation of the phenomenon to which it pertains, is best obtained by an analogy to a plurality of parallel conductors carrying currents in the same direction. It will be appreciated from basic electrical theory that such electrical conductors induce magnetic fields surrounding each, and that these fields tend to attract each other so that the conductors are acted upon by a magnetic force tending to move same together. This same phenomenon is to be found in electrical discharges wherein individual charged particles passing through space approximate electrical conductors in that an effective electrical current flows therethrough. A difference is found in this instance, however, for the particles of an electrical discharge, when acted upon by a magnetic force or pressure such as that noted above, are moveable, and this movement is in the general direction of each other so that a constriction or pinching of the discharge results from the self-induced magnetic field thereof. This constriction or pinching of an electrical discharge is termed the "pinch effect," and such definition is herein employed.

The present invention as noted above is directed to method and means for producing a stabilized, compressed plasma, and, as to the ultimate use of such a plasma, a variety of different applications thereof is possible; however, at the present time the most interesting lies in the field of nuclear physics. More specifically, it has been found that certain nuclear binary reactions may be made to occur between various light element plasma constituents such as deuterons, tritons, and the like. These light element plasma ions may be made to collide with each other, each colliding pair thereof undergoing a binary or pair reaction productive of various other nuclear constituents. Where, for example, a deuterium plasma is employed, each colliding pair of plasma deuterons undergoes the binary reaction:

$$D + D \rightarrow \begin{cases} He^3\ (0.8\ mev.) + n\ (2.5\ mev.) \\ T\ (1.0\ mev.) + p\ (3.0\ mev.) \end{cases}$$

Where a large number of the DD pair reactions occur in the plasma, a copious quantity of neutrons are produced useful for manifold purposes.

It has been found heretofore that very high density plasmas may be employed in this respect, as it is required that the deuterium, for example, must be very dense and, further, that the atoms thereof must have an extremely high temperature in order that a large number of pair reactions will occur. In order for a reaction of this type to be controlled, it is necessary that the system in which the reaction occurs provides the requisite density and temperature continuously or successively as in some sort of pulsed operation. It is contemplated by the present invention that a pulsed operation shall be employed. Although various approaches are possible to the provision of proper circumstances to the production of the nuclear binary reactions, the particular circumstance herein chosen in this invention employs the pinch effect wherein a plasma is constricted to increase the density and temperature of the ions therein, and to thereby attain the conditions requisite for reaction. In this respect, it is herein noted that pinch discharges may be employed in various configurations; in other words, they may be extremely elongated, they may be curved back upon themselves, they may be toroidal, or any of various other possible configurations. In the following disclosure of the present invention, only the simple situation of a linear discharge constricted radially by the pinch effect of the discharge is considered. However, it is to be appreciated that the same principles disclosed herein are equally applicable in machines or devices providing plasma discharges of other than linear configuration.

The approach noted above of employing a pinch discharge to produce the circumstances wherein the nuclear reactions may be produced has received the attention of numerous workers in the field, and it has been determined by experiment and by theoretical calculations that certain basic difficulties face the production of a pinched plasma of sufficient density and temperature to produce nuclear reactions in large quantities. In this respect, it has been found that various instabilities are inherent in a linear pinched discharge. As regards the aforementioned instabilities of a high current discharge column or pinch column as it is hereinafter termed, by far the most serious is the so-called kink instability. This type of pinch instability is treated in a now classic paper by Kruskal and Schwarzchild, published in the Proceedings of the Royal Society, vol. 223 at page 48 (1954), and it is therein shown that a self-constricting current flowing in a plasma is unstable against kinking perturbations. That is to say, if the pinch column undergoes an infinitesimal localized lateral displacement, this displacement will grow exponentially with time until the column is disrupted. This instability arises physically from the fact that the magnetic field (and therefore the magnetic pressure) is greater near the concave side of a curved current-carrying conductor than it is on the convex side. It will be evident that the magnetic field lines become crowded together on the convex side of a pinch column and spread apart on the convex side so that there is a resultant lateral pressure upon the column which produces lateral displacement. Unless steps are taken to limit the extent of this instability or lateral column displacement, the column will become disrupted and the discharge extinguished. The present invention operates to preclude disrupting kinking perturbations of a pinch column by the provision of an auxiliary magnetic field limiting lateral displacement of the column.

As a further consideration in the establishment of a pinch column to the end of producing nuclear reactions is the fact that in a linear pinch discharge, there is no confinement at the ends of the discharge, but, instead, confinement is limited only to the lateral direction so that there are losses at the column ends. These losses will be seen to be appreciable so that it is necessary to produce a very fast pinch in order that the circumstances for a reaction may be produced before the end losses become

prohibitive. The present invention operates in a pulsed fashion with the individual energizing pulses of relatively short duration so that the problem of end losses is herein minimized.

A further consideration in the production of a pinch discharge to provide the circumstances for nuclear reactions in large quantity is the control of the column compression. In general, no control of the compression in a pinch discharge is possible because the pinching or constricting forces producing the compression are developed by the discharge itself, and thus are dependent upon other factors and are not independently variable without also affecting, for example, the discharge current or the rate of rise thereof. As noted above, the time within which a suitable circumstance may be provided for establishing a thermonuclear reaction is quite limited in a linear pinch column because of the end losses thereof, and thus the situation wherein no control of pinch column compression is allowed results in an unsatisfactory device. The present invention overcomes this noted difficulty in that the compression of the pinch column is controlled. Although the self-induced magnetic fields of the pinch column are employed to provide lateral compression, there is in the present invention provided an additional magnetic field of controlled strength and variation further compressing the pinch column whereby the rate of compression is controllable at the will of the operator. By these means and in this method, it is possible to produce particular results with a pinch column that are not generally available in an ordinary and conventional linear pinch device.

It is an object of the present invention to provide method and means for stabilizing a linear pinch discharge.

It is another object of the present invention to provide method and means for producing a high density plasma with controlled compression thereof.

It is a further object of the present invention to provide a method of stabilizing a pinch column by the introduction of auxiliary magnetic fields in the pinch area.

It is a further method of the present invention to control the compression of a plasma column by the application of time varying magnetic fields thereto.

Various other possible objects of the invention and advantages thereof will become apparent to those skilled in the art from the following description and accompanying drawings, wherein:

FIGURE 1 is a diagrammatic representation of one preferred embodiment of the means of the present invention for carrying out the objects set forth above;

FIGURE 2 is a sectional view taken at 2—2 of FIGURE 1; and

FIGURE 3 is a graphical representation of the magnetic field intensity in the vicinity of the plasma column of the present invention.

Considering now the improved method of the present invention for controlling a plasma, the first step of this method is the establishment of a cylindrical plasma column. It is desired to establish a hollow cylinder of plasma and various steps may be taken in this respect as, for example, the production of an electrical discharge through a gaseous atmosphere wherein a plasma is attained, and imposing insulation or an insulating member within the volume of this plasma discharge in order that the plasma shall be other than of uniform density in cross section. Alternatively to the foregoing steps to the end of producing a hollow plasma column, there may be established a discharge between annular electrodes whereby the discharge itself assumes a hollow cylindrical configuration and with the subsequent introduction of a selected gas into the discharge area produces a plasma. As to the particular gas selected for ionization by the discharge to produce the aforementioned plasma, same is discussed in some detail below as regards particular reactions that may be obtained and the advantages of different reactions.

The plasma column established as set forth above will produce surrounding lines of magnetic force. These magnetic lines of force, inasmuch as they encircle the plasma, will thereby produce upon the outside of the plasma what may be termed as a magnetic constricter. Whatever the terminology employed, the consequence of the established magnetic field is to laterally constrict the plasma or to pinch same radially inwardly. This pinch effect, resulting from the self-induced magnetic field produced by the flow of charged particles in the plasma and as described above, is well known and with a sufficient current flowing in the plasma, the effect becomes quite marked in that the plasma diameter is materially reduced. In normal pinch devices wherein a solid plasma column is employed, this pinch effect is allowed to compress the plasma into a very small and dense column whereby particular temperatures and densities of ions within the plasma are achieved. The present invention differs from these conventional systems in that a hollow column or cylinder of plasma is initially produced. The pinch effect, however, is identical in that the self-induced magnetic field here again tends to laterally constrict or pinch the plasma. As a further step in the present invention, there is produced within the hollow cylindrical plasma column a further and auxiliary magnetic field. This additional or controlled magnetic field, as it will hereinafter be termed, may be produced by causing a current to flow axially of the hollow plasma column and in opposition to the current flow in the plasma column. The controlled magnetic field is thus composed of lines of force circling about the axis of the plasma column and directed in opposition to the self-induced magnetic field exteriorly of the plasma column and produced thereby. It will be appreciated that magnetic field strength decreases rapidly at increased distances from the current flow causing same, so that in close proximity to the axis of the plasma column, there is established a very strong control magnetic field which decreases rapidly radially outward therefrom toward the actual plasma itself. Also exteriorly of the plasma, there is produced by same an opposing magnetic field which falls off in intensity and rapidly away from the plasma column. As a consequence of these two above-noted magnetic fields, there is produced a magnetic field intensity variation across the plasma column somewhat as that shown in FIGURE 3 of the drawings. It will be seen from this figure that marked low intensity points occur at the conjunction of the control magnetic field and the self-induced magnetic field of the plasma. To the plasma, there are thus applied forces in opposition in that the control magnetic field tends to urge the plasma outward away from same, while the self-induced magnetic field of the plasma tends to constrict or pinch the plasma radially inward of same. With the proper field intensities, a balancing of forces results such that the plasma is laterally confined in a narrow elongated cylinder.

It will be readily appreciated that, inasmuch as the magnetic fields interiorly and exteriorly of the plasma column tend to act in opposition to the extent that they compress the wall of the plasma cylinder, it is possible by variation of the control magnetic field to vary the actual thickness of this plasma wall. Herein lies one of the great advantages of the present invention, for the control magnetic field is in this invention of a variable intensity such that it is possible to increase same at a controlled rate whereby the plasma is squeezed or pinches between this control field and its own self-induced field to a maximum density at the discretion of one carrying out the invention so that control is provided over the amount of plasma compression and also over the particular time of maximum plasma compression. It is herein contemplated that the aforementioned plasma column shall be established in a pulsed manner, i.e., the plasma shall be initiated and maintained only for a very short period of time

at the termination of which the energization originally provided to establish same will be terminated and the plasma will extinguish. Immediately following this extinguishment, the energization is again applied so that the plasma is again established. As a result of this type of operation, the plasma periodically builds up to its maximum intensity as regards the discharge current therethrough and periodically extinguishes. By this means, problems of long lived stability of linear pinch columns are obviated.

As a further consequence of the introduction within the hollow plasma core of a control magnetic field that is in opposition to the self-induced magnetic field of the plasma, there is provided a stabilizing effect overcoming tendencies of the plasma to bow or kink. This kink instability, as noted above, operates to produce lateral perturbations that without counteraction rapidly extinguish the plasma before any appreciable compression thereof is possible. The effect whereby this stabilization is produced may be readily comprehended from a consideration of the relative magnetic fields in the plasma volume and surrounding same. Thus, the control magnetic field is actually in opposition to the self-induced magnetic field of the plasma so that should the plasma tend to move laterally at any point, it will actually encounter an increasing magnetic field. Considering further the magnetic field intensity across the area through which the plasma column extends, and referring in this respect to FIGURE 3 of the drawings, it will be appreciated that the points of minimum field intensity shown thereon occur at points wherein the exterior or self-induced plasma field and the interior control magnetic field are in opposition to such an extent that they are minimized. Although an outward movement of a portion of the plasma cylinder wall will, of course, likewise move outwardly the self-induced magnetic field thereof, this movement will then place this self-induced magnetic field at a greater distance from the origin of the central control magnetic field, so that less field cancellation will occur and the resultant exterior field will increase. As a consequence of this increasing of the surrounding magnetic field, there will thereupon be produced a magnetic pressure upon the exterior of the plasma tending to counteract any outward movement thereof. A similar explanation is applicable to an inward movement of the plasma wall in that the plasma will then encounter an increasing magnetic field from the central control field so as to be forced outward back into the original position thereof. In this respect, it will be clear that the actual radius of the plasma is determined in part by the magnitude of the current flow in the plasma that, in turn, determines the intensity of the field induced thereby about the plasma, and also in part by the magnitude of the interior control field. For any particular application, it is possible to vary these factors to provide the desired radius of plasma cylinder.

There has been set out above a new and novel method of plasma stabilization and concentration. This method, in short, may be summarized as comprising the steps of establishing a plasma discharge of a hollow cylindrical configuration and further by establishing within this discharge a control magnetic field in opposition to the field induced by the flow of current in the plasma itself. Although these steps are in themselves readily stated and, in fact, relatively easily accomplished, they produce a result of particular advantage and one long sought after by those skilled in the art. The particular field configuration produced by the present invention stabilizes the plasma against specific plasma instabilities as previously noted and further the steps set forth by the present invention provide for a control of the plasma compression. Thus the central control magnetic field noted above in the second general step of the invention is established to be of a variable nature so that the intensity thereof may be increased at a controlled rate. This controllable central magnetic field is available to and does operate to provide a particular desired compression of the walls of the plasma cylinder to the end of producing in a controlled fashion a desired plasma density and temperature. Although the method has been stated in connection with the establishment of a linear column or cylinder of plasma, it will be readily apparent that this column or cylinder may be other than linear and may, in fact, be of a generally circular extent or may alternatively be turned into the form of a figure 8, all to the end of reducing the aforementioned end losses of the plasma column. As to the particular results that may be attained by plasma compression, there is set forth below a brief description of same.

As regards the reactions that may be produced in a high temperature-high density plasma, reference is made to an article published by me in the Reviews of Modern Physics, September 1956, and relating to a survey of controlled fusion research. Suffice to say at this point that certain light elements such as deuterium, tritium, and lithium react under well-known conditions of density and kinetic temperature. Such reactions involve the fusion or combination of nuclei of the reactant elements with an attendant energy release in the form of neutrons and charged particles, inter alia. The aforesaid kinetic temperatures correspond to mean particle energies of tens or even hundreds of thousands electron volts. Note that a kinetic temperature of one thousand electron volts corresponds to 1.16×10^{7} Kelvin. It will be appreciated that in any system employing temperatures of the foregoing magnitude, all matter will be completely ionized, and thus it will be seen that a plasma wherein only ions and electrons are present is admirably suited to the furtherance of such reactions. As to the theory of binary reactions herein in question, the case of fusion reactions in a heated plasma is related to mutual collision processes involving the particles of the plasma and for a dissertation upon the theory of such reactions, reference is again made to the above-noted publication. Concerning the particular reaction parameter such as minimum temperature densities and the like necessary for producing thermonuclear reactions of the desired energy balance, reference is made to my copending application S.N. 433,447, filed July 14, 1954.

It should be noted at this point that the opposed orientations of the control field and self-induced field mentioned hereinbefore, which are productive of a depression in the overall resultant field, occur adjacent the inner boundary of the hollow plasma column. This is due to the plasma current adjacent the inner plasma boundary flowing in opposition to the central control current. However, the plasma current flow in regions of the plasma column radially outwardly displaced from the inner boundary is in the same direction as the control current. Thus, the self-induced field and control field are in aiding relation in such regions. Despite the reversed plasma current flow adjacent the inner boundary, the net flow of plasma current is in the same direction as the control current. Such condition is necessary in order that the plasma column be hydromagnetically stable, as will be subsequently explained more fully herein. Hence, the opposed field orientation terminology employed herein is to be taken as applying to the conditions that prevail adjacent the inner boundary of the plasma column, it being understood that in the other regions of the plasma column, the respective currents and fields are in the same directions.

Considering now one preferred embodiment of the means of the present invention as illustrated in FIGURES 1 and 2 of the drawings, there will be seen to be provided a housing or enclosure 11 formed in this instance as a cylinder of insulating material having open ends with metallic electrodes 12 and 13 disposed in closing relation to the cylinder. This housing, including the cylinder 11 and end electrodes 12 and 13, defines a reaction chamber 14 which is sealed against gas or air passage through the enclosure joints and which is adapted to

be evacuated. Suitable pumping means 16 are provided exteriorly of the enclosure and connected to the reaction chamber 14 thereof as by means of a pipe 17 extending through the cylinder wall for evacuating the reaction chamber. Additionally, a gas supply 18 is connected as by means of a pipe 19 through the cylinder wall to the interior of the enclosure for supplying thereto gas molecules of a selected material, as noted in some detail above. Appropriate controls are provided upon the pumping means and upon the gas supply in order that the final pressure within the reaction chamber may be closely regulated. The end electrodes 12 and 13 spaced apart by the cylinder 11 are adapted for electrical energization and, in this respect, electrode 13 may be electrically grounded and electrode 12 connected to one terminal of a pulsed direct current power supply 21. Grounding of the other terminal of this power supply thereby provides a complete electrical circuit between the electrodes 12 and 13. This power supply is designed to produce high voltage-high energy pulses between the electrodes 12 and 13 whereby the resultant electric fields established between these electrodes operate to accelerate free ions within the reaction chamber 14 and to thereby produce in a conventional manner an electron discharge between the electrodes 12 and 13 in a gaseous atmosphere as supplied from the gas supply 18. With the foregoing structure and electrical connections, it will be seen that periodically at the frequency of the pulsations of the direct current power supply, there will be produced a high intensity discharge through the reaction chamber 14 between the electrodes 12 and 13 at the ends thereof and that this discharge will ionize gas admitted to the reaction chamber so that a resultant plasma is produced. Insofar as the foregoing description of structure in operation is concerned, only conventional techniques have been employed and similar devices are to be found in various laboratories throughout the country. The present invention, however, is not limited to this conventional production of a strong plasma column as is herein produced between the electrodes 12 and 13 in the chamber 14, but instead operates also to stabilize and/or control this plasma.

There is additionally provided as a portion of the apparatus of this invention a central electrical conductor 22 disposed axially through the reaction chamber 14 and surrounded by an insulation 23 extending through the end electrodes 12 and 13. This axial conductor 22 is electrically connected to the terminals of a second pulsed direct current power supply 24 disposed exteriorly of the enclosure 11 and connection is made to this power supply for producing a current flow through the central conductor 22 in the same direction as the net current flow in the plasma established within the reaction chamber 14. As an example, the electrode 12 may be electrically connected to the positive terminal of the first direct current power supply 21 while the other electrode 13 and the negative terminal of the power power supply 21 are grounded, while the conductor 22 is connected at the top end adjacent the electrode 12 to the positive terminal of the second direct current power supply 24, and the lower end of this conductor 22 adjacent the electrode 13 is connected to the negative terminal of the direct current power supply 24.

As a consequence of the provision within the reaction chamber 14 of an axial insulator 23, it will be appreciated that the discharge between the electrodes 12 and 13 takes the form of a hollow cylinder surrounding this central insulator 23 and there is illustrated in FIGURE 1 by dashed lines a possible outline in cross section of such a plasma and identified by the numeral 26. This apparatus, therefore, operates to produce a hollow cylindrical plasma column and, as to the pinch effect related thereto, it will be seen that the flow of ions and electrons in the plasma column approximate electrically a plurality of electrical conductors in parallel carrying currents in the same direction whereby the magnetic fields induced about these conductors, or herein about the particle paths, result in magnetic lines of force encircling the plasma column exteriorly thereof. As is well known in electrical theory, the encircling magnetic field herein above described operates to apply a force against the conductors or herein against the particle in the plasma so as to urge same radially inward. This constricting force of the self-induced surrounding magnetic field produces the pinch effect of the present device. There is, however, in the present invention provided an additional effect operating upon the plasma and this results from the flow of current through the axial conductor 22. The pulsed current flow through conductor 22 produces encircling magnetic lines of force, which are disposed within the plasma column and which thereby tend to urge the plasma radially outward from the central conductor. The magnetic field due to this current flow through conductor 22 has a profound stabilizing effect on the pinched plasma column. More particularly, kink and other hydromagnetic instabilities inherent in a conventional plasma column are entirely eliminated upon appropriate adjustment of the control current through conductor 22. It can be shown, assuming a typical parabolic radial distribution of pressure in the plasma column, that the column is hydromagnetically stable where:

$$p_0 \leq \frac{I_0^2}{8\pi b^2} \cdot \frac{\left(1-\frac{a}{b}\right)^2}{\left[\left(1-\frac{a}{b}\right)-\frac{1}{24\pi}\left\{1-2\left(\frac{a}{b}\right)+2\left(\frac{a}{b}\right)^3-\left(\frac{a}{b}\right)^4\right\}\right]}$$

where:

p_0=plasma pressure in dynes per square centimeter,
I_0=control current in abamperes,
a=radius of inner wall in centimeters (outside radius of insulator 23),
b=radius of outer wall in centimeters (inside radius of envelope 11).

From the foregoing equation, the minimum value of control current for hydromagnetic stability in the plasma column can be easily calculated for a hollow plasma column having any given set of parameters. By way of illustration, consider the specific example of a hollow plasma column established between an enclosure 11 having an inner radius of 10 centimeters and an insulator 23 having an outer radius of 2.5 centimeters. The plasma has a temperature of 100 electron volts and equal ion and electron densities of 10^{14} particles per cubic centimeter. The net current flow in the plasma as established by power supply 21 is 4900 amperes. The corresponding plasma pressure for these parameters is 3.0×10^{14} dynes per square centimeter. Upon substitution of these plasma pressure and radius parameters in the equation, the minimum control current for hydromagnetic stability is derived as 10^5 amperes. Accordingly, where power supply 24 is set to establish a current of 10^5 amperes or greater in conductor 22, the plasma column of the foregoing example is rendered hydromagnetically stable. Inasmuch as kink and other instabilities do not therefore develop in the column, the plasma column is confined for a comparatively longer time than is a conventional pinch column.

Further to the foregoing, the control current supply 24 may be adjusted to produce a control current having a different rate of rise than that of the plasma current produced by supply 21 whereby the magnetic field internally of the plasma column increases at a different rate than the external self-induced field about the plasma column. Particular advantage lies in this situation for, by controlling the rate of rise and the maximum amplitude of the output of the second pulsed power supply 24, it is thus possible to control the rate of change of the thickness of the walls of the plasma column and to thereby control the time and extent of density increase in the plasma.

The increase in the self-induced magnetic field about the plasma column 26, producing the pinch effect upon the column and tending to constrict same radially inward as opposed to the magnetic field about the axial conductor 22 operating to force the plasma column wall outward, will be seen to provide a compressive force on the plasma and to thereby produce a very high density plasma. As the plasma column is compressed, the density and temperature increases as therefore does the plasma pressure. In order for the column to be hydromagnetically stable during compression, the control current must of course vary to at all times satisfy the previously noted equation relating pressure to control current.

Another equation useful in calculating the minimum control current for stability or the maximum plasma current for stability with a given control current is as follows:

$$I_T^2 - I_0^2 = p_0 \frac{b^2}{\left(1-\frac{a}{b}\right)^2}\left\{\left[1-\left(\frac{a}{b}\right)^4\right]-\frac{2}{3}\left[1-\left(\frac{a}{b}\right)^3\right]\left[1+\frac{a}{b}\right]\right\}$$

where:

$I_T = I_0 + I_P$

I_P = plasma current in abamperes,

I_T = total current in abamperes.

By substituting the known parameters for a given example in the above equation, the control current or the plasma current productive of stable condition may be readily derived.

It will be seen from the foregoing description that there is presented by the present invention an improved method and means for compressing a plasma column to the end of furthering conditions wherein thermonuclear reactions progress between ions within the plasma. Not only does the present invention provide for the stable confinement of plasma and compression thereof to raise the plasma density and temperature, but additionally, the invention provides for the control of this plasma compression. Although the invention has been described hereinbefore principally with reference to pulsed operation, the principles of the invention apply equally to operation under steady state conditions. It will thus be seen that the invention as described fulfills the objects set forth above, and it is not intended to limit the present invention by the foregoing description, but instead reference is made to the following claims for a precise definition of the scope of this invention.

What is claimed is:

1. A plasma control device comprising a vacuum-tight enclosure having spaced metallic electrodes forming a part thereof and insulated therefrom, means for evacuating said enclosure, means supplying a limited quantity of gas to said enclosure, power supply means connected between said electrodes for applying high voltage electrical energy therebetween for establishing a discharge through said enclosure whereby ions are formed therein to establish a plasma column between said electrodes, means limiting said plasma column to a cylindrical form, an electrical conductor extending axially through said plasma column within said enclosure and insulated from said electrodes, and power supply means applying electrical energy between ends of said electrical conductor for establishing a magnetic field surrounding same within said enclosure and within said plasma column for forcing same radially outward.

2. Plasma control means comprising a pair of spaced electrodes, insulating enclosure means defining an evacuated volume between said electrodes, means connected to said evacuated volume for supplying a limited amount of selected gaseous molecules thereto, a pulsed direct current power supply connected between said electrodes for producing a discharge between same whereby atoms within said volume are ionized to produce a discharge column extending between said electrodes and inducing an encircling magnetic field tending to constrict same radially thereof, an electrical conductor extending through said electrodes in insulated relationship thereto and axially of said plasma column, a second pulsed direct current power supply having a variable pulse rise time connected between the ends of said electrical conductor for producing a controlled current flow therethrough to establish a magnetic field thereabout whereby said plasma is constrained into cylindrical configuration.

3. A controlled fusion device comprising spaced electrodes, insulating means separating said electrodes and defining a reaction chamber therebetween, means supplying a limited amount of gaseous atoms of reactant to said reaction chamber, a pulsed direct current power supply connected between said electrodes for establishing a discharge through said reaction chamber whereby atoms therein are ionized to produce a plasma column between said electrodes, and electrical conductor extending axially through said plasma in insulated relationship through said electrodes, a second direct current pulsed power supply connected between opposite ends of said electrical conductor through said reaction chamber for applying thereto pulses of electrical energy of the same frequency as the pulsed energization of said electrodes and having a variable pulsed rise time for establishing a magnetic field surrounding said electrical conductor within said reaction chamber to constrain said plasma into a hydromagnetically stable cylindrical configuration in compression between the internal magnetic field and a magnetic field induced by the plasma discharge itself and surrounding same.

4. A controlled fusion device comprising means establishing a pulsed electric discharge through an atmosphere of gaseous atoms of a thermonuclear reactant for producing a pulsed plasma column composed of substantially equal numbers of ions of said reactant material and electrons, said plasma column inducing a surrounding and constricting magnetic field tending to pinch said column radially inward thereof, means insulated from said first named means and establishing an electric current flow axially through said plasma column for establishing a magnetic field within said column to urge same radially outward in opposition to the inward force of the self-induced magnetic field of said plasma column whereby said plasma is constrained into a cylindrical configuration with the cylinder wall thickness being dependent upon relative magnitudes of said constricting magnetic field and said central magnetic field.

5. A controlled fusion device as defined in claim 4 further characterized by said means establishing the current flow through said plasma column producing a current which is of a magnitude greater than a predetermined minimum magnitude at which the column is hydromagnetically stable for the particular magnetic pressure generated by the plasma of the column.

References Cited in the file of this patent

UNITED STATES PATENTS

3,031,396 Anderson ---------- Apr. 24, 1962