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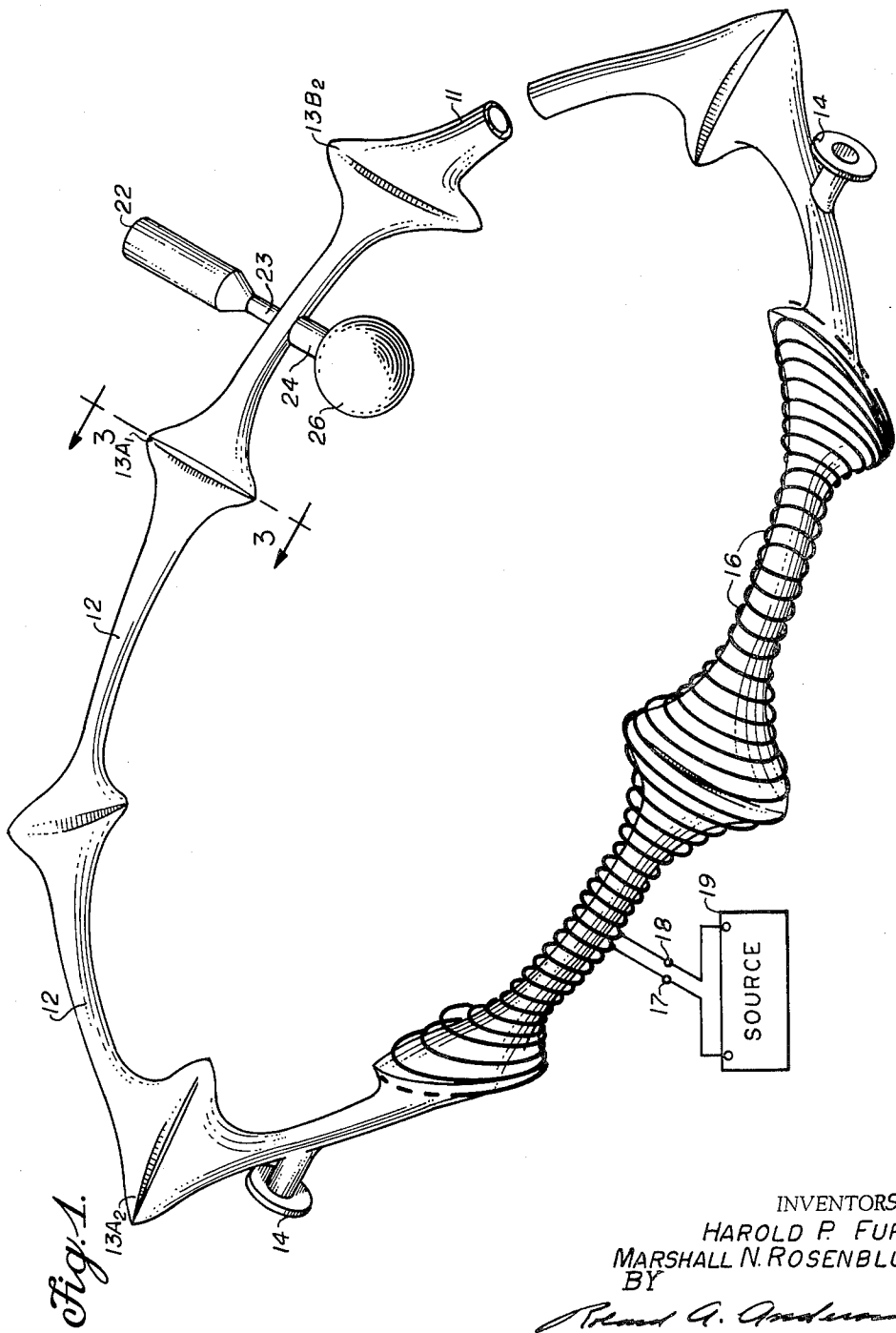
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3,230,145

APPARATUS FOR MAGNETICALLY CONFINING A PLASMA

Filed Nov. 4, 1963

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

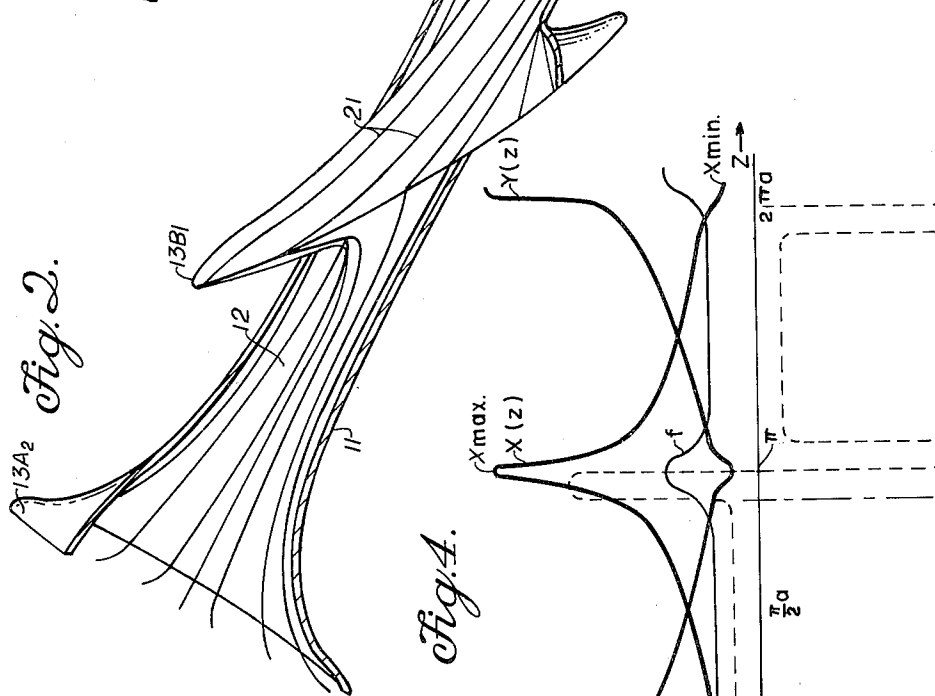
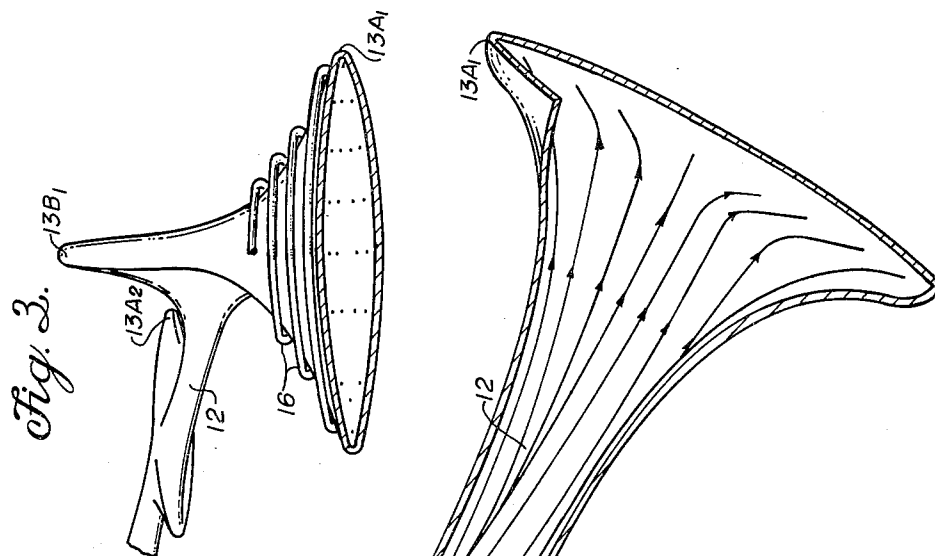
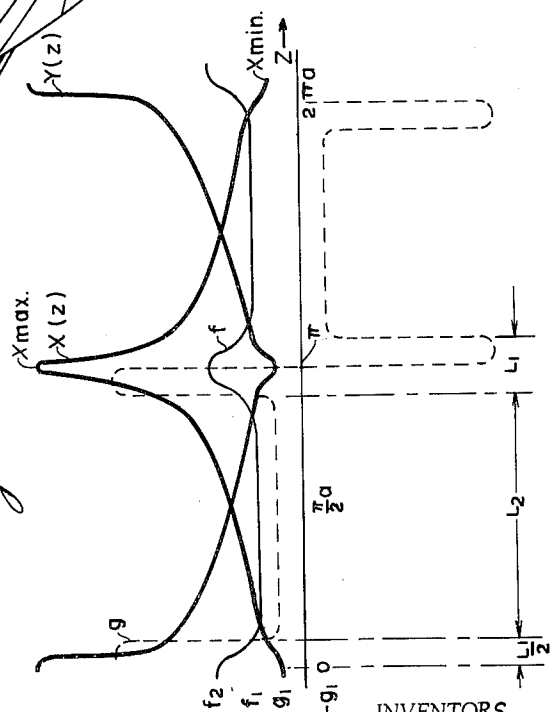


Fig. 4.



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3,230,145 APPARATUS FOR MAGNETICALLY CONFINING A PLASMA

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The present invention relates generally to magnetic confinement of a plasma. More particularly, it relates to magnetic confinement of a plasma of isotropic pressure in a magnetic field configuration having closed magnetic flux surfaces forming an annulus.

The production and confinement of a plasma for extended periods of time is useful for a variety of purposes, the most notable being the establishment of controlled fusion reactions. Because of the extreme plasma temperatures necessary for such reaction (kinetic temperatures of many millions of degrees) it has been recognized that means other than material walls are needed in order to confine the plasma. To this end much work has been devoted to confining a plasma by a magnetic field. The theory of plasma as relevant to the present subject has been extensively discussed in various publications, e.g., Controlled Thermonuclear Reactions, by Samuel Glasstone and Ralph H. Lovberg, D. Van Nostrand Co., Inc., New York (1960). In order to magnetically confine a plasma of isotropic pressure under equilibrium conditions it is necessary that the surfaces of constant plasma pressure coincide with magnetic flux surfaces and that the volume of every infinitesimal magnetic flux tube of magnetic flux $\delta\phi$ lying on the flux surface be the same for a particular $\delta\phi$. More specifically the equation

$$(I) \quad W = \int \frac{dl}{B}$$

must be constant along surfaces of constant plasma pressure where

W = the volume of a given infinitesimal magnetic flux tube $\delta\phi$ per magnetic flux $\delta\phi$

dl = the infinitesimal length measured along the magnetic flux tube

B = the magnetic field intensity.

In addition, as shown in the paper "Stability of Plasmas Confined by Magnetic Fields," M. N. Rosenbluth and C. L. Longmire, Annals of Physics, vol. 1, pp. 120-140, 1957, a plasma will be magnetically confined in a hydro-magnetically stable state of equilibrium if W decreases in the direction of diminishing plasma pressure while simultaneously satisfying the aforementioned plasma equilibrium condition. That is, by confining a plasma within nested magnetic flux surfaces such that surfaces comprised of infinitesimal magnetic flux tubes having larger volumes per unit flux are encircled by surfaces comprised of infinitesimal magnetic flux tubes having smaller volumes per unit flux, the plasma which is concentrated towards the center of such essentially coaxial magnetic flux surfaces will be hydromagnetically stably confined. This can be seen to be true by considering that for the plasma to be displaced towards a region wherein the magnetic flux tubes have smaller volumes per unit flux, the plasma would have to be compressed; thereby raising its energy. Hence it follows that such displacements could not be spontaneous in nature since such displacements could violate the conservation of energy principle. Consequently, these displacements, which generally lead to the plasma escaping to the material walls of the container and being destroyed, will be prevented.

Previous configurations utilized in attempts at achiev-

ing magnetic confinement of high temperature plasmas generally have been of two classes; closed toroidal and open-ended magnetic field configurations. Some closed toroidal field configurations have been constructed such that the closed magnetic flux surfaces of constant volume per unit flux coincide with constant pressure surfaces. However, in such closed toroidal field configurations, wherein the plasma pressure decreases outwardly from the central zone of confinement, W does not decrease uniformly in all directions. Therefore, the spontaneous outward displacement of the plasma is possible. Thus, these toroidal field configurations are susceptible to instabilities which lead to the destruction of the plasma as noted previously.

To overcome this instability problem, toroidal configurations wherein the magnetic field lines extend helically about the toroid to introduce a "shear" effect between overlying field lines have been advanced. However, because of the presence of plasma electrical resistivity, such configurations were found to have serious instabilities also.

Certain open-ended magnetic confinement field configurations are known to exhibit the desired volume-plasma pressure relationship. However it is recognized that such configurations permit only imperfect plasma confinement since those particles with velocities predominantly along the magnetic field lines can escape.

In accordance with the present invention a plasma is produced and magnetically confined in a closed configuration under conditions of stable equilibrium insensitive to the electrical conductivity of the plasma. The plasma is confined by a magnetic field whose locus of the centroids of transverse sections of the flux surfaces of constant volume flux tubes is a closed curve whereby the magnetic field lines are joined continuously to form an annular magnetic field configuration which is symmetric about the locus of the centroids. These magnetic field lines extend annularly through an evacuated region. The magnetic field is established by a coil wound in the form of a tubular annulus with the tubular cross section corresponding to the transverse section of the flux surfaces of the magnetic field. The transverse sectional area varies periodically along the centroid locus to include at least several periods of alternate area maxima and minima; the area minima being of elliptical configuration. The major axis of each area minimum is angularly displaced 90 degrees with respect to that of the preceding area minimum. The flux lines passing at the major axis extremities of a first area minimum elliptical transverse section pass at the minor axis extremities of the succeeding area minimum elliptical transverse section and conversely the flux lines passing at the minor axis extremities of the first elliptical cross section pass at the major axis of the next. This variation is periodic along the entire centroid locus with the length of a single period being the distance between successive similarly orientated area minima and further being substantially greater than the major axis dimension of the area minimum elliptical transverse section.

Furthermore, in accordance with the present invention, the volume of infinitesimal incremental magnetic flux tubes per constant unit magnetic flux decreases continuously in the direction of diminishing plasma pressure. It has been found that in the magnetic field configuration of the form noted hereinbefore, if the following inequality is satisfied for increasing R_0 , the above noted volume variance will be obeyed.

$$(II) \quad \int_0^{2\pi a} dz \left(e^{\left(\frac{2}{a} \int_{\pi a}^z dz_1 \frac{g}{f} \right)} \right) \left(\frac{df}{2dz} - \frac{g}{a} \right) \left(\frac{3df}{2dz} - \frac{g}{a} \right) < 0$$

where

R_0 =the radius of the transverse section of a flux surface where $x=y$ on the entire flux surface,
 z =a coordinate along the locus of the centroids of the flux surfaces of constant volume flux tubes,
 a =the scale factor of the length of one period,
 f =the variation of the magnetic field intensity along the z coordinate,
 $g=a(By-Bx)/2 \times B_0$ at all points where $x=y$

where

x and y are axes which orthogonally intersect simultaneously with z , the y axis extending in a plane which is simultaneously tangent to z and parallel to the principal axis of the annular magnetic field,

B_y =the magnetic field component in the y direction,
 B_x =the magnetic field component in the x direction,
 $B_0=Bz/f$.

where

B_z =the magnetic field component in the z direction.

Thus, it can be seen that a primary object of this invention is to magnetically confine a plasma under conditions of hydromagnetic stable equilibrium.

Further it is an object of this invention to provide plasma confinement in a closed annular magnetic field configuration whereby end-losses are averted.

More particularly, it is an object of this invention to provide an annular magnetic field configuration for confining a plasma wherein the volume of given infinitesimal magnetic flux tubes of constant magnetic flux is constant on surfaces of constant plasma pressure and decreases in the direction of diminishing plasma pressure.

Another object of this invention is to provide magnetic confinement of a plasma in a closed annular magnetic field which is insusceptible to instabilities arising out of the electrical resistivity of the plasma.

Yet another object of this invention is to provide apparatus for producing a stabilized high temperature plasma suitable for the establishment of controlled fusion reactions.

Additional objects and advantages of the present invention will become apparent from the following description considered together with the attached drawings in which:

FIGURE 1 is an illustration of a section of a preferred embodiment of the apparatus for producing and confining a plasma in accordance with the present invention.

FIGURE 2 is an enlarged cut-away of a section of FIGURE 1 showing a single period of the magnetic field variation.

FIGURE 3 is an enlarged cross-sectional view of FIGURE 1 taken along line 3—3.

FIGURE 4 is a graphical illustration of the variation of the parameters of the present invention.

Referring now to FIGURE 1 there is shown a section of an annular chamber 11. (Only a section is shown for ease of figure definition and illustration.) The tubular cross section of chamber 11 varies periodically along its central line to include alternate area maxima 12 and minima 13A and 13B. The cross sections of the area minima 13A and 13B are slender ellipses and substantially spaced from each other. With particular reference to FIGURE 3, each succeeding area minimum, e.g., 13B₁, is spacially orientated so that its major axis is angularly displaced 90 degrees with respect to that of the preceding area minimum, e.g., 13A₁. In progressing from a first to a second slender elliptical cross section, 13A₁ and 13B₁ respectively, the length of the major axis of the first slender ellipse, 13A₁, progressively decreases while that of its minor axis progressively increases. Thus, the elliptical cross section becomes thickset, then circular, and finally becomes progressively more slender in the coordinate of

the original major axis to eventually form the second slender elliptical cross section, 13B₁.

A plurality of ports 14 (two shown) are disposed about chamber 11 and provide the means for attaching conventional ultra-high vacuum pump systems (not shown) thereto in order to remove extraneous atmospheres therefrom.

A coil 16 is wound about the entire circumference of chamber 11. The principal axis of coil 16 is coincident with the central line of chamber 11. Terminals 17 and 18 provide the means of electrically connecting the coil 16 to power source 19. Power source 19 supplies the current to energize coil 16 and establish a magnetic field whose magnetic field lines are joined continuously to form an annular magnetic field configuration similar to the chamber configuration.

Considering now FIGURE 2, there is shown a single period of the magnetic field 21. Since the magnetic field configuration is similar to the chamber configuration, the transverse section of surfaces of constant magnetic flux varies periodically from a slender elliptical cross section, to become first thickset, then circular, and finally progressively more slender to eventually form another elliptical cross section whose major axis is angularly displaced 90 degrees with respect to that of the preceding slender elliptical cross section. The flux lines of magnetic field 21 passing at the major and minor axes extremities of a first area minimum, e.g., 13B₁, extend to become coincident with the minor and major axes extremities, respectively, of the succeeding area minimum, e.g., 13A₁. The flux lines further extend to the next elliptical area minimum, e.g., 13B₂ to become coincident with its major and minor extremities respectively.

Referring now to FIGURES 2 and 4, magnetic field 21 is described by the equations

$$(III) \quad Bx = -B_0x \left(\frac{df}{2dz} - \frac{g}{a} \right)$$

$$(IV) \quad By = -B_0y \left(\frac{df}{2dz} + \frac{g}{a} \right)$$

$$(V) \quad Bz = B_0 \frac{R_T}{R} \left[f - \frac{(x_2 + y^2)}{4} \frac{d^2f}{dz^2} + \frac{(x^2 - y^2)}{2a} \frac{dg}{dz} \right]$$

where

R_T is the radius of curvature of the central line

$R = x + R_T$ and R approaches R_T where the central line is straight.

And where $A, Z, f, g, x, y, B_0, B_y, B_x, B_z$ are defined as in Equation II. To insure the periodic behavior of magnetic field 21

$$(VI) \quad f(z) = f(z + \pi a)$$

$$(VII) \quad g(z) = -g(z + \pi a)$$

Additionally, to insure that W has the same variation in the x and y directions

$$(VIII) \quad f(z) = f(\pi a - z)$$

$$(IX) \quad g(z) = g(\pi a - z)$$

As noted previously, to insure stable confinement of a plasma the inequality expressed in Equation II must be satisfied. As can be seen from the inequality, the stability condition depends upon the relative variation in f and g along z . Considering now FIGURE 4 in detail, in the interval of one period there are six distinct regions to be considered;

$$0 \text{ to } \frac{L_1}{2}, \frac{L_1}{2} \text{ to } \left(L_2 + \frac{L_1}{2} \right), \left(L_2 + \frac{L_1}{2} \right) \text{ to } (L_1 + L_2), \\ (L_1 + L_2) \text{ to } \left(L_2 + \frac{3L_1}{2} \right), \left(L_2 + \frac{3L_1}{2} \right) \text{ to } \\ \left(2L_2 + \frac{3L_1}{2} \right), \left(2L_2 + \frac{3L_1}{2} \right) \text{ to } (2L_1 + 2L_2)$$

As a result of the nature of the periodicity of the variation of magnetic field 21 along the locus, the function of

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the parameter f from 10 to (L_1+L_2) is the same as from (L_1+L_2) to $(2L_1+2L_2)$. Furthermore the function of the parameter g from (L_1+L_2) to $(2L_1+2L_2)$ equals the negative of the function from 0 to (L_1+L_2) . The functions f and g are chosen in order that the modulation of the magnetic flux surface,

$$Q = \frac{X \max.}{X \min.} = \frac{Y \max.}{Y \min.}$$

is at least equal to 4 and are defined infra.

In the regions $0 < z < \frac{L_1}{2}$

and

$$(L_1+L_2) < z < \left(L_2 + \frac{3L_1}{2}\right)$$

$$f = f_2 - \frac{2z(f_2-f_1)}{L_2}$$

$$g = 2 \frac{(f_2-f_1)}{L_2} = -\frac{df}{dz}$$

In the regions $\frac{L_1}{2} < z < \left(L_2 + \frac{L_1}{2}\right)$

and

$$\left(L_2 + \frac{3L_1}{2}\right) < z < \left(2L_2 + \frac{3L_1}{2}\right)$$

$$f = f_1$$

$$g = g_1$$

$$e \int_{\pi a}^z dz_1 \frac{g}{f} > \frac{\sqrt{15} f_1^2}{f_2^2}$$

In the regions

$$\left(L_2 + \frac{L_1}{2}\right) < z < (L_1+L_2)$$

and

$$\left(2L_2 + \frac{3L_1}{2}\right) < z < (2L_1+2L_2)$$

$$f = f_1 + \frac{2\left(z - L_1 - \frac{L_2}{2}\right)(f_2-f_1)}{L_2}$$

$$g = 2 \frac{(f_2-f_1)}{L_2} = \frac{df}{dz}$$

where f_2 and f_1 are the maximum and minimum respectively of f and g_1 is the maximum magnitude of g .

Referring again to FIGURE 1, as a result of the annular configuration of chamber 11 and hence magnetic field 21, those magnetic field lines nearer the outer circumference of the annulus have a smaller curvature than those near the inner circumference. This results in the length of the flux tubes and the magnetic field intensity being longer and weaker respectively nearer the outer circumference. Hence from Equation I it is seen that curving of the magnetic field lines to form an annular configuration has tendency to adversely affect W . However by maintaining a large annular curvature, the effect on W will be insignificant. This can be achieved, for example, by insuring that the ratio of

$$\left(\frac{a}{R_T}\right)^2$$

is at least two (2) orders of magnitude less than one (1), where R_T is the radius of curvature of the centroid locus of the flux surfaces of magnetic field 21.

The annular configuration of magnetic field 21 may take various forms of a closed curve. For example, the centroid locus of the flux surfaces can be generally circular. Or, the closed curve could include a section of a magnetic field where the centroid locus of its flux

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surfaces is a straight line. With such an embodiment, the difference of curvature problem is eliminated over the straight section of the magnetic field, but it must be remembered that the curved sections have to satisfy the

$$\left(\frac{a}{R_T}\right)^2$$

criteria set forth above.

- 10 Injection of the particles forming the plasma may be accomplished for example by employing neutral injection techniques. In such cases injector 22 will include a conventional high energy ion source and neutralizer. The neutral atoms emerging from injector 22 are directed into magnetic field 21 through inlet 23 disposed on chamber 1. Trapping of the neutral atoms by magnetic field 21 arises from the fact that some of the injected neutral atoms are ionized by Lorentz dissociation, or by collisions with background particles. The ionized atoms (charged particles) are captured by magnetic field 21 with a majority of the charged particles trapped in less intensified magnetic field regions.

An outlet 24 is disposed on chamber 11 on the side opposite and coextensive with inlet 23. Outlet 24 provides an exit for those injected neutral atoms that are not ionized within magnetic field 21. Collector 26 is disposed at outlet 24 to collect the neutral atoms entering therein.

From the following analysis it will be shown that magnetic fields established in accordance with the present invention described hereinbefore will confine a plasma under conditions of hydromagnetic stable equilibrium.

Considering first a magnetic field configuration established in accordance with the present invention whose locus of the centroids of its flux surfaces is a straight line, its magnetic potential, x , is described by the following equation

$$(X) \quad x = B_0 \left[\int dz f - \frac{(x^2+y^2)}{4} \frac{df}{dz} + \frac{(x^2-y^2)g}{2a} \right]$$

Since the magnetic field configuration is long and narrow where power of x^2 and y^2 can be neglected, Equation X satisfies Maxwell's equation

$$(XI) \quad \frac{\partial^2 x}{\partial x^2} + \frac{\partial^2 x}{\partial y^2} + \frac{\partial^2 x}{\partial z^2} = 0$$

From the relation $\bar{B} = \Delta x$ and Equation X the magnetic field components expressed in Equations III, IV and V are derived. To determine if a magnetic field defined by Equations III, IV and V will confine a plasma under conditions of hydromagnetic stable equilibrium, the variation of W as defined in Equation I must be analyzed. In view of the periodicity indicated by Equations VI and VII it is sufficient to evaluate W over a single complete period. In terms of the B_z component of magnetic field, Equation I may be rewritten as

$$(XII) \quad W = \int_0^{2\pi a} \frac{dz}{B_z(X, Y)}$$

where B_z is to be evaluated along a magnetic field line having coordinates $x=X(z)$ and $y=Y(z)$ where

$$(XIII) \quad X = X_0 \left(\frac{f_1}{f}\right)^{1/2} e^{\left(\frac{1}{a} \int_{\pi a}^z dz_1 \frac{g}{f}\right)}$$

$$(XIV) \quad Y = Y_0 \left(\frac{f_1}{f}\right)^{1/2} e^{-\left(\frac{1}{a} \int_{\pi a}^z dz_1 \frac{g}{f}\right)}$$

and

$$X = X_0 \text{ and } Y = Y_0 \text{ at } z = \frac{\pi a}{2}$$

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From Equations V and XII

(XV)

$$W = \frac{1}{B_0} \int_0^{2\pi a} \frac{dz}{f} \left[1 + \frac{(x^2 + y^2)}{4} \frac{d^2 f}{f dz^2} - \frac{(x^2 - y^2)}{2a} \frac{dg}{f dz} \right]$$

which reduces to

(XVI)

$$W = \frac{1}{B_0} \int_0^{2\pi a} \frac{dz}{f} \left[1 + \frac{f_1 R_0^2}{f^2} e^{\left(\frac{2}{a} \int_0^z \frac{dz_1}{f} \right)} \left\{ \frac{d^2 f}{4 dz^2} - \frac{dg}{2 a dz} \right\} \right]$$

where

(XVII)

$$R_0^2 = X_0^2 + Y_0^2$$

The flux surfaces have a circular transverse section at the transverse planes

$$z = \frac{a\pi}{2}, \frac{a\pi}{2}, \dots, \frac{n a \pi}{2}$$

where n is an odd integer from $n=1$ to $n=4T-1$, with T being the total number of periods. At a fixed value of R_0 , the radius of the circular transverse section, W is constant on the flux surfaces which contain all those field lines specified by Equations XIII and XIV.

In order that such a magnetic field configuration be hydromagnetically stable, it must be shown that W decreases away from the locus of the centroids of the magnetic flux surfaces. That is to say, specifically that W decreases with increasing R_0 . In view of Equation XVI, the condition for hydromagnetic stability is seen to be

XVIII

$$\int_0^{2\pi a} \frac{dz}{f^3} e^{\left(\frac{2}{a} \int_0^z \frac{dz_1}{f} \right)} \left\{ \frac{d^2 f}{2 dz^2} - \frac{dg}{a dz} \right\} < 0$$

which reduces to Equation II. This condition will be satisfied if the interdependent functions f and g are selected in accordance with Equations VI, VII, VIII and IX.

It is to be noted that since the derivatives of g with respect to z do not appear in the stability condition expressed by Equation II, the degree of sharpness of variations in g is not critically important in respect to satisfying the stability condition. Furthermore, since the first derivative of f is the highest derivative of f that appears in Equation II, the degree of sharpness of variations in the rate of change of f is not important.

Considering now a magnetic field configuration established in accordance with the present invention whose locus of the centroids of its flux surfaces is a curved line, it can be shown that a large radius of curvature and

$$\left(\frac{a}{R_T} \right)^2$$

at least two (2) orders of magnitude less than one (1),

(XIX)

$$W = \frac{1}{B_0} \int_0^{2\pi a} \frac{dz}{f} \left[1 + \frac{f_1 \{ (X_0 - \Delta X_0)^2 + Y_0^2 \}}{f^2} e^{\left(\frac{2}{a} \int_0^z \frac{dz_1}{f} \right)} \left\{ \frac{d^2 f}{4 dz^2} - \frac{dg}{2 a dz} \right\} \right]$$

where ΔX_0 is the distance that the equilibrium pressure distribution is shifted outward along the major radius of

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the curved magnetic field lines and is defined by the equation

(XX)

$$\Delta X_0 = \frac{\frac{1}{R_T} \int_0^{2\pi a} \frac{dz}{f} e^{\left(\frac{2}{a} \int_0^z \frac{dz_1}{f} \right)}}{f_1 \int_0^{2\pi a} \frac{dz}{f^3} e^{\left(\frac{2}{a} \int_0^z \frac{dz_1}{f} \right)} \left\{ \frac{d^2 f}{4 dz^2} - \frac{dg}{2 a dz} \right\}}$$

Thus Equation XVII becomes

(XXI)

$$R_{00}^2 = (X_0 - \Delta X_0)^2 + Y_0^2$$

By combining Equations XIX and XXI and comparing the resultant equation with Equation XVI it is noted that the stability condition defined by Equation XVIII remains unchanged. Hence it is seen that a magnetic field configuration established in accordance with Equations III, IV and V will confine a plasma under hydromagnetically stable equilibrium conditions.

A particular example of parameters for establishing a magnetic field configuration for confining a plasma in accordance with the present invention is as follows:

Circumference of chamber 11 along the central line	40 m.
The length of a single period variation of magnetic field 21 ($2\pi a$)	2 m.
The inner diameter of the transverse section of chamber 11 at area maxima 12	5 cm.
The inner major diameter of the transverse section of chamber 11 at area minima 13A and 13B	18 cm.
The inner minor diameter of the transverse section of chamber 11 at area minima 13A and 13B	1.4 cm.
The ratio f_2/f_1	2.

$$\text{The inequality } e^{\left(\frac{2}{a} \int_0^z \frac{dz_1}{f} \right)} > \frac{\sqrt{15} f_1^2}{f_2^2} \dots 3.$$

The ratio L_2/L_1	5.
The modulation of the flux surface, Q	13.
The kinetic temperature	10 kev.
Plasma Density	10^{14} cm^{-3} .
$B_0 f_1$	50 kilogauss.

From the Equation $I=10B_0^2 a$, the following coil currents are:

	Amp./cm.
Current at area maxima 12	40,000
Current at area minima 13A and 13B	80,000

While the present invention has been hereinbefore described in detail with respect to a single embodiment it will be apparent that numerous modifications and variations are possible within the scope of the invention. For example, the annular configuration of the magnetic field can be in the form of alternate curved and straight sections with the radius of curvature in the curved sections being large in accordance with the conditions specified herein regarding the ratio

$$\left(\frac{a}{R_T} \right)^2$$

Furthermore, a high degree of curvature can be introduced periodically, i.e., $z=0, 2\pi a, 4\pi a$, etc., at regions where the radial dimension of the magnetic field is minimum and as long as the regions therebetween are substantially straight. In such a configuration, the net radius of curvature may be made smaller than the above noted

case in which the curvature is distributed uniformly in accordance with the limitation placed upon the ratio

$$\left(\frac{a}{R_T}\right)^2$$

However, it must be remembered that the length of one period must be substantially greater than the major axis dimension of the area minimum. By restricting the curvature to the regions specified, the destabilizing effect of the curvature is minimized. This can be seen by referring to Equations XIX and XX where it is noted that the contribution of curvature towards destabilization depends upon the functions f and x as well as

$$\frac{1}{R_T}$$

Hence the description of the present invention with respect to the embodiment shown is not intended to limit the invention except by the terms of the following claims.

What is claimed is:

1. Apparatus for magnetically confining a plasma comprising coil means wound in the form of an annular tube for establishing in an evacuated space a magnetic field extending longitudinally through said tube in an annular configuration, each of the flux surfaces of said magnetic field being closed and defining the locus of infinitesimal incremental flux tubes of constant volume per constant flux, the locus of the centroids of transverse sections of said flux surfaces being a closed curve, the area of said transverse sections varying periodically along said centroid locus to include at least several periods of alternate area maxima and minima, the distance between successive area minima being one-half period, said area minima being of slender elliptical transverse sections, the major axes of said slender elliptical sections being at least four times greater than the minor axes, the major axis of each area minimum being angularly displaced 90 degrees with respect to that of the preceding area minimum, the flux lines passing at the major axis extremities of each area minimum passing at the minor axis extremities of the succeeding area minimum, the flux lines passing at the minor axis extremities of each area minimum passing at the major axis extremities of the succeeding area minimum, the distance between successive similarly orientated area minima being substantially greater than the major axis dimension of the area minimum, and said volume of each said infinitesimal incremental flux tubes being defined by the equation:

$$W = \frac{1}{B_0} \int_0^{2\pi a} dz \left[1 + \frac{f_1 R_0^2}{f^2} e^{\left(\frac{2}{a} \int_{\pi a}^z dz_1 \frac{g}{f} \right)} \right] \left\{ \frac{d^2 f}{4 dz^2} - \frac{dg}{2 a dz} \right\}$$

where:

z = a coordinate along the locus of the centroids of the transverse sections of the flux surfaces,

a = the scale factor of one period,

f = the variation of the overall average magnetic field intensity along the z coordinate,

$g = a(B_y - B_x)/2 \times B_0$ at all points $x=y$ where x and y are axes which orthogonally intersect simultaneously with z , the y axes extending in a plane which is simultaneously tangent to z and parallel to the principal axis of the annular magnetic field,

B_y = the magnetic field component in the y direction,

B_x = the magnetic field component in the x direction,

$B_0 = B_z/f$ where B_z is the magnetic field component in the z direction,

R_0 = the radius of the transverse section of a flux surface where $x=y$ on the entire flux surface,

said volume decreasing with increasing radius R_0 .

2. Apparatus for magnetically confining a plasma as recited in claim 1 further defined by the length of the major axes of said transverse section area minima progressively decreasing and the length of the minor axes progressively increasing while advancing in the direction of the locus of the centroids of said transverse sections of said magnetic field flux surfaces to include regions between successive area minima wherein said slender elliptical transverse section becomes thickset and then circular at the area maximum and subsequently progressively more slender in the coordinate of the original major degrees with respect to that of said preceding area minimum, and the variation in the axis thereby forming an area minimum of slender elliptical transverse section having its major axis angularly displaced 90 degrees with respect to that of the elliptical transverse section of said preceding area minimum, and the variation in the magnetic field in the x and y directions being identical at distances spaced apart by one-half a period.

3. Apparatus for magnetically confining a plasma as recited in claim 2 further defined by said centroid locus being circular, and the relative magnitudes of the locus radius of curvature R_T and the length of one period selected to satisfy the ratio.

$$\left(\frac{a}{R_T}\right)^2 < 10^{-2}$$

where:

a = the scale factor of one period variation of the magnetic field,

4. Apparatus for magnetically confining a plasma as recited in claim 3 further defined by said magnetic field configuration including at least one period wherein said centroid locus is straight.

5. Apparatus for magnetically confining a plasma as recited in claim 2 further defined by said magnetic field configuration including alternate sections of straight and curved lengths, and the length of each period in every curved section selected to satisfy the ratio

$$\left(\frac{a}{R_T}\right)^2 < 10^{-2}$$

where:

a = the scale factor of one period variation of the magnetic field,

R_T = the locus radius of curvature in the curved section of said magnetic field.

6. Apparatus for magnetically confining a plasma as recited in claim 2 further defined by said locus comprised of a multiplicity of straight sections arranged in contiguous end to end relationship wherein each straight section is angularly bent with respect to its preceding straight section at a separate station along the locus, each said station demarking a said area minimum having the minor axis of its elliptical transverse section coinciding with said x coordinate.

No references cited.

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