Dec. 29, 1970 R. F. STENGEL 3,551,828

PLASMA CONTAINMENT APPARATUS AND METHOD

Filed July 1, 1968 3 Sheets-Sheet 1

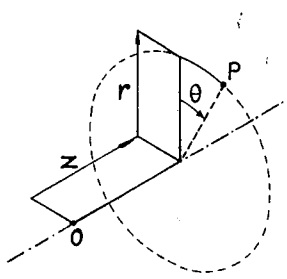

FIG 1a.

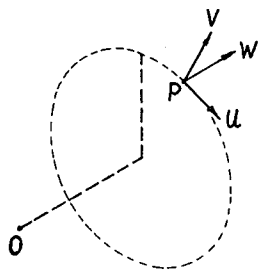

FIG 1b.

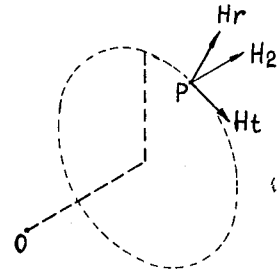

FIG 1c.

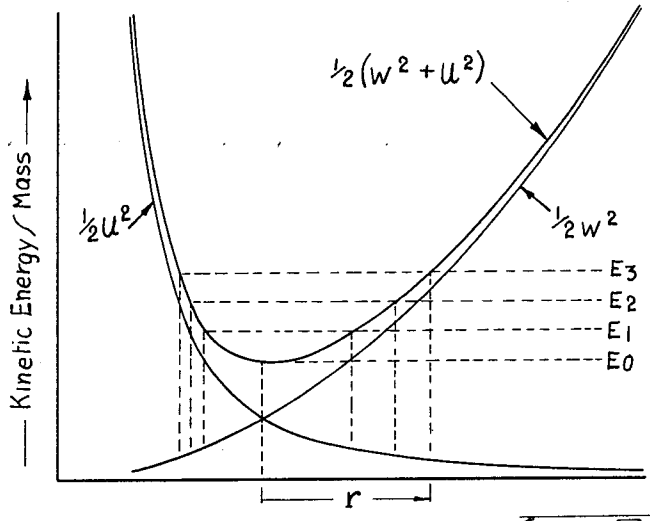

FIG 2a.

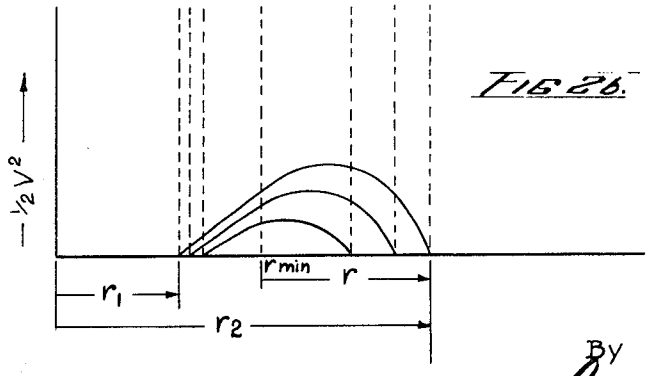

FIG 2b.

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PLASMA CONTAINMENT APPARATUS AND METHOD

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FIG 3a.

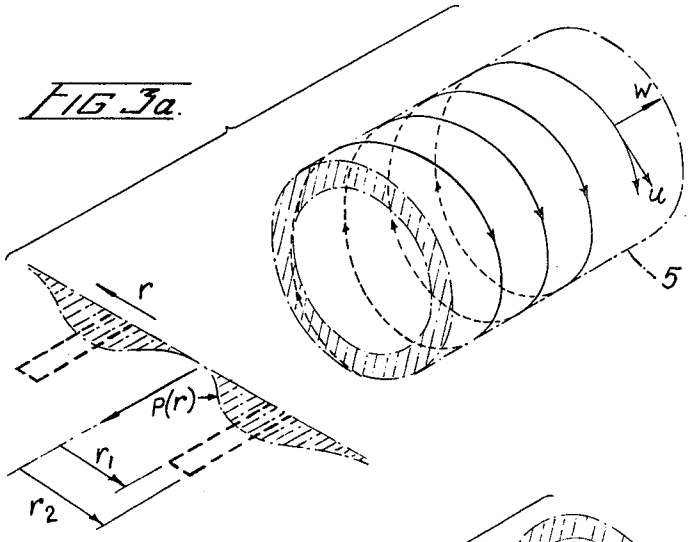
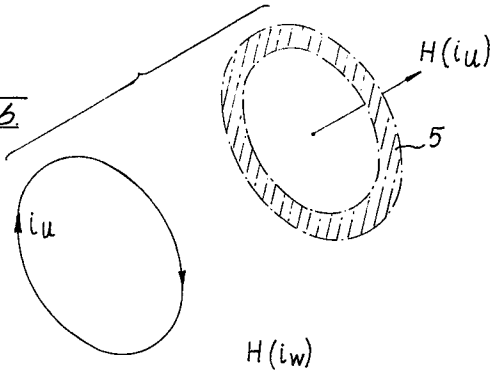


FIG 3b.



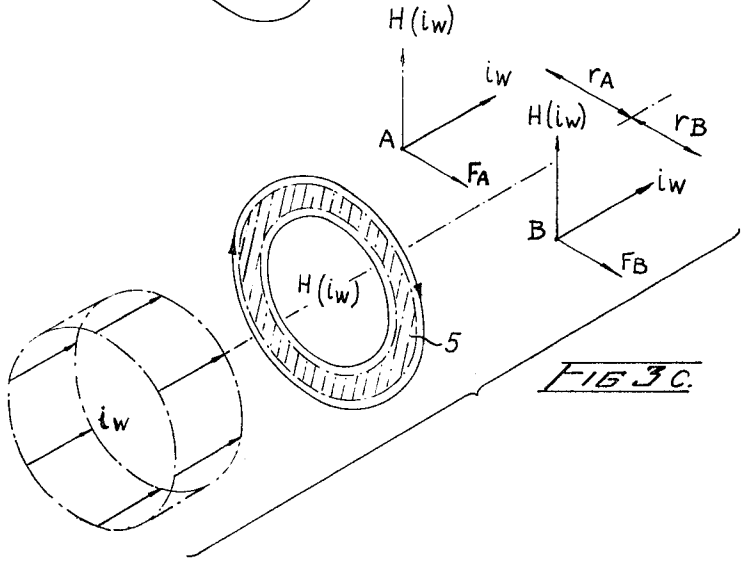


FIG 3c.

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PLASMA CONTAINMENT APPARATUS AND METHOD

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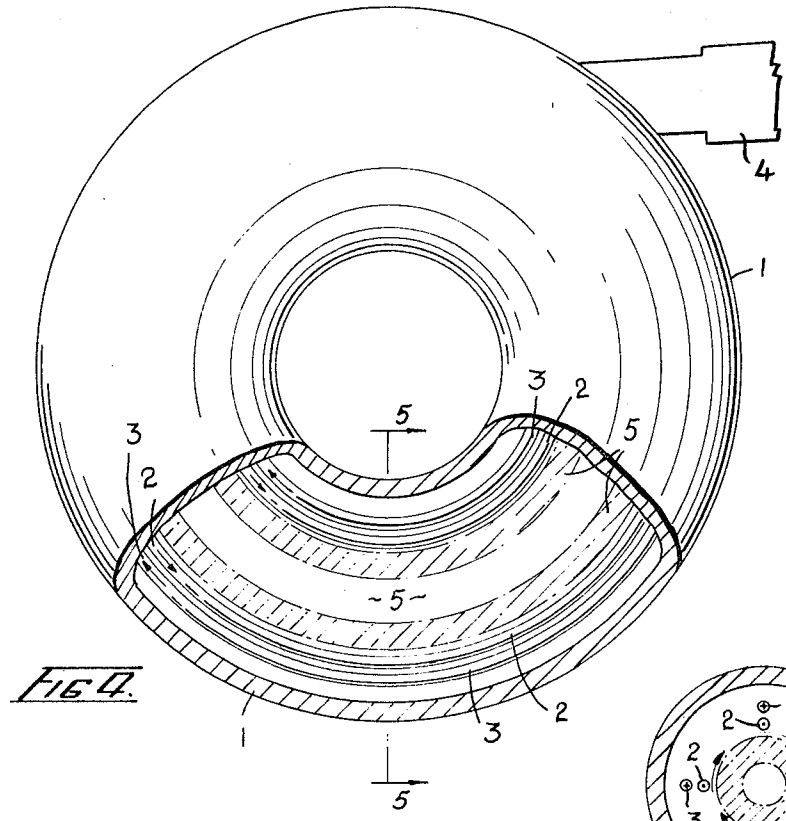

FIG 4.

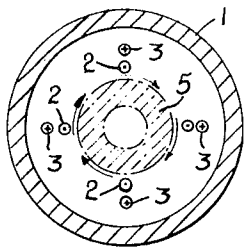

FIG 5.

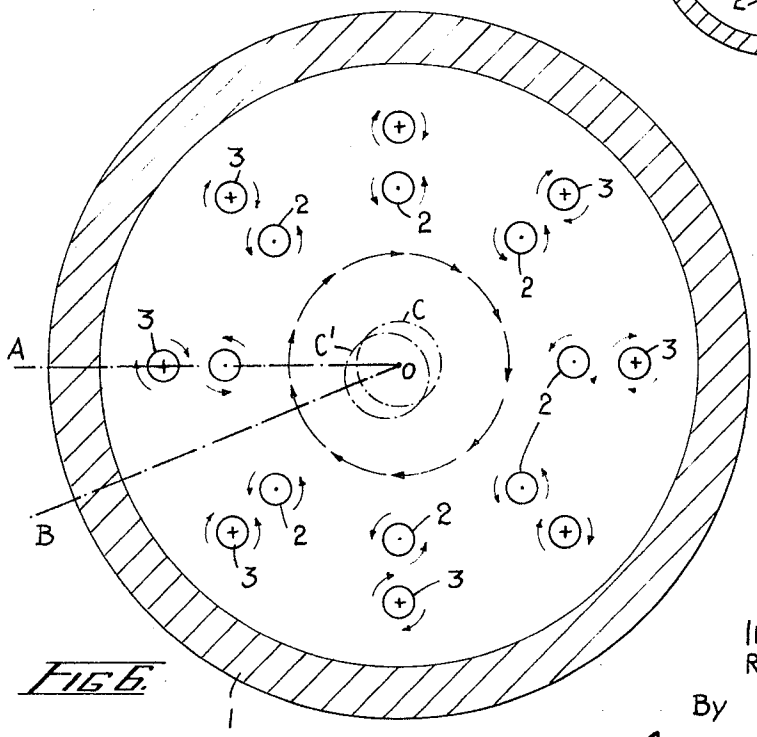

FIG 6.

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3,551,828

PLASMA CONTAINMENT APPARATUS AND METHOD

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Filed July 1, 1968, Ser. No. 741,540
Int. Cl. H01j 1/50; H05h 1/02
U.S. Cl. 328—233 6 Claims

ABSTRACT OF THE DISCLOSURE

A hollow toroidal enclosure for plasma containment comprising a plurality of current-carrying assemblies operable to generate an electromagnetic field within the enclosure, said electromagnetic field being directed substantially tangentially to a circle disposed in the plane of each cross-section of the enclosure and unidirectionally about said circle at every point thereof, each current-carrying assembly comprising two parallel current-carrying conductors in close, radially-spaced proximity to each other and in perpendicular orientation to said cross-section.

BACKGROUND OF THE INVENTION

Field of the invention

This invention relates to an improved apparatus and method for electromagnetic plasma containment. In the context of the present disclosure, the term "plasma" shall refer to a gas in which at least a fraction of the gas particles (e.g., molecules) is electrically charged to form ions through the loss or gain of at least one electron.

Description of the prior art

The present invention recognizes the advantages of prior plasma containment proposals. Two such proposals which may be singled out in particular are U.S. patent application Ser. No. 635,585, filed on May 2, 1967 by Wesley H. Bateman, and now abandoned, and U.S. application Ser. No. 679,311, filed on Oct. 31, 1967 by Jacques P. Drabier et al. In fact, the present inventor contemplates advantageous simultaneous a application of the invention disclosed herein conjunction with one or both of these prior art inventions.

Although the present invention deals with a preferably toroidal plasma containment volume, the functioning of the invention will be more readily understood by reference to a cylindrical rather than a toroidal containment volume. A cylinder may then be thought of as a portion of a torus which has an arbitrarily large toroidal radius. Any error which is introduced by the finite character of the toroidal radius does not significantly affect the subsequent arguments. For the discussions to follow, it is useful to define three mutually orthogonal directions z (along the cylinder axis), r (along a cylinder radius), and $r\theta$ (referring to an angular displacement at constant r and z).

The basic object of plasma containment in a cylindrical volume is to provide an electromagnetic field such that any charged particle moving in a $(+r)$-direction (i.e., toward the cylinder wall) experiences a force tending to deflect its trajectory in an axial (z) or gyrating ($r\theta$) direction or both. A considerable number and variety of electromagnetic field configurations claimed to be appropriate for this purpose have been disclosed previously.

One advantage of the present invention is that it provides a novel electromagnetic field configuration tending to deflect radially outwardmoving particles back toward the interior of the containment volume.

A further advantage of the present invention is that

it imposes upon the plasma a nonisotropic distribution of kinetic energies such that, on the average, the total kinetic energy of the plasma is necessarily allocated to axial and gyrating motion, thereby reducing the kinetic energy available for radially outward motion to the amount resulting from upward deviations from the average kinetic energy.

It is yet another advantage of the present invention that it imposes upon the plasma a combined axial and gyrating motion such that the electromagnetic field associated with such combined motion assists in the task of plasma containment.

SUMMARY OF THE INVENTION

The present invention provides a hollow, endless enclosure for electromagnetic plasma containment, comprising tangential field generating means operable to generate an electromagnetic field within the enclosure, said electromagnetic field being directed substantially tangentially to a closed geometric figure disposed in the plane of each cross-section of the enclosure and unidirectionally about said closed geometric figure at every point thereof, whereby the tangential field will cause an enclosed plasma to form a hollow plasma configuration within said tangential field, both the outer and inner cross-sectional peripheries of said plasma configuration being in substantially spaced parallel relation to said tangential field.

In the context of the present invention, a "hollow endless enclosure" shall include many enclosure configurations (e.g., toroidal, helical with the ends joined, and the like); however, it is preferred that the configuration be a hollow torus.

The present invention further provides a method for enclosing and maintaining a plasma, comprising the steps of:

(a) continuously injecting single-polarity charged particles into a hollow, endless enclosure;

(b) concurrently with (a) generating a tangential magnetic field, said tangential field being directed substantially tangentially to a closed geometric figure disposed in the plane of each cross-section of the enclosure and unidirectionally about said closed geometric figure at every point thereof;

(c) terminating the injection of charged particles when the plasma within the enclosure attains a pre-selected plasma density;

(d) maintaining said tangential magnetic field after the termination of injection of charged particles into the enclosure;

whereby the tangential field will cause the enclosed plasma to form a hollow plasma configuration within said magnetic field, both the outer and inner cross-sectional peripheries of said plasma configuration being in spaced, substantially parallel, relation to said tangential field.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention and its many advantages, reference may be had to the following detailed description of a preferred embodiment of the present invention taken in conjunction with the appended drawings in which:

FIG. 1*a* defines the coordinates (θ, r, z) of a point P with respect to a coordinate orgin O located on the axis of a cylindrical space;

FIG. 1*b* defines the velocities (u, v, w) in the coordinate directions at point P;

FIG. 1*c* defines the components (H_t, H_r, H_z) of the electromagnetic field at P in the coordinate directions;

FIG. 2*a* is a representative plot of kinetic energies per unit mass: $\frac{1}{2}w^2$, $\frac{1}{2}u^2$ and $\frac{1}{2}(w^2+u^2)$, for a single particle in an electromagnetic field having a constant H_t-component only, as a function of radius r;

FIG. 2*b* is a plot of kinetic energy per unit mass, $\frac{1}{2}v^2$, for the particle of FIG. 2*a* as a function of radius r for different total energy levels E_i (i=0, 1, 2, 3);

FIG. 3*a* shows a simplified distribution and mode of motion of an assembly of such particles;

FIG. 3*b* shows a current and electromagnetic field component associated with the angular ($r\theta$) component of such particle assembly motion;

FIG. 3*c* shows a current and electromagnetic field component associated with an axial (z) component of such particle assembly motion;

FIG. 4 shows a toroidal magnetic enclosure having a portion of the wall thereof cut away for illustrative purposes, in accordance with one embodiment of the present invention;

FIG. 5 is a schematic cross-sectional view of the toroidal enclosure of FIG. 4 along line A—A;

FIG. 6 is a schematic cross-sectional view of another preferred arrangement of conductive members for generating an approximation to an electromagnetic field having an H_t-component only.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the nomenclature defined in FIGS. 1*a*, 1*b*, and 1*c*, consider a single particle of mass m and charge q in an electromagnetic field having a constant component H_t only. While q can be positive or negative, in the ensuing discussion it shall be assumed that q is positive. In the absence of any other forces (such as gravity), the particle velocities are found to be

$$w=w_0+(r-r_0)\ (q/m)H_t \tag{1}$$

(Newton's second law)

$$u=u_0(r_0/r) \tag{2}$$

(conservation of angular momentum)

$$v=(2E-w^2-u^2)^{1/2} \tag{3}$$

(conservation of energy)

where E denotes the total kinetic energy of the particle and the subscript $(\ )_0$ denotes an initial or reference state.

In particular, it may be noted that the kinetc energy per unit mass associated with axial motion (e.g., $\frac{1}{2}w^2$) increases as the square of r, whereas the kinetic energy per unit mass associated with gyrating motion (e.g., $\frac{1}{2}u^2$) decreases as r^{-2} with increasing radius, due to conservation of angular momentum. In other words, the radially outer particles have greater axial or circumferential velocities (relative to the cylinder or torus) than the radially inner particles, while the radially outer particles have smaller gyrating velocities than the radially inner particles.

This situation is schematically depicted in FIG. 2*a*, showing particularly that the sum $\frac{1}{2}(w^2+u^2)$ has necessarily a well-defined minimum at some radius. Given a finite total energy E, Eqn. 3 shows that the kinetic energy available for radial motion is itself finite. In particular, FIG. 2*b* depicts the available kinetic energy for radial motion $\frac{1}{2}v^2$ as a function of radius r and several values of the total kinetic energy E (e.g., E_0, E_1, E_2, E_3). As E decreases the range of possible values of r for the particle decreases correspondingly, until at $E=E_0$ the particle is restricted to a single radius r_{min} while simultaneously performing a gyrating motion and an axial motion, which motions taken together result in helicoidal motion concentric with the cylinder axis. Since E is finite, then by appropriate choice of injection conditions (e.g., of the magnitude and direction of velocity at which a particle is initially introduced into the cylindrical containment volume) in relation to the strength of the electromagnetic field H_t, a single charged particle can therefore be constrained to such helicoidal motion.

Passing now to the more general case of an assembly or aggregate of charged particles, collisions between such

particles cause the energy levels E_i of individual particles to deviate from the average energy level E of the aggregate. However, the *averages* of the kinetic energies in (u, v, w) directions nevertheless must vary with r as required by Eqns. 1–3.

In the case of previously proposed containment geometries involving solenoidal fields (as produced, e.g., by coil windings around the containment volume—see page 26 of "Progress Toward Fusion Power," T. K. Fowler and R. F. Post, pages 21 to 31, No. 6, Scientific American, December 1966) the H_z-component of the field merely induces the particle to gyrate at a frequency proportional to H_z. Conservation of angular momentum causes $\frac{1}{2}u^2$ to vary as r^{-2}, but there is no necessary *increase* in any other energy component with increasing r.

It is a novel feature of the present invention to employ a tangential field component H_t and to prescribe injection conditions such that the sum of kinetic energies for axial and gyrating motion has a necessary minimum at some finite radius r, and that the kinetic energy available for radial outward motion is therefore greatly restricted for particle aggregates compared to previously disclosed concepts.

As depicted schematically in FIG. 3*a*, the probability $p(r)$ of encountering a particle at a particular radius r will therefore be zero at r=0, exhibit a maximum at some finite radius, and decrease asymptotically to zero as the radius becomes arbitrarily large. To simplify discussion of the resulting plasma configuration, $p(r)$ is replaced by a rectangular distribution between r_1 and r_2, as schematically indicated in FIG. 3*a* by broken lines. The plasma particles may then be viewed as occupying a volume **5** in the shape of a hollow cylinder having a wall thickness (r_2-r_1) wherein they describe helicoidal motion paths with finite values of w and u, whereas their radial velocities v appear only as perturbations.

As shown schematically in FIG. 3*b*, the gyrating motion of the charged particles is equivalent to a current i_u associated with a corresponding electromagnetic field $H(i_u)$. The field $H(i_u)$ is constant with respect to r and confined to the interior of the plasma volume **5** provided that the plasma actually moves within a torus (instead of moving within a cylindrical containment space, as heretofore assumed for purposes of simplifying the discussion).

As shown schematically in FIG. 3*c*, the axial motion of the charged particles is equivalent to an axial current sheath i_w associated with a corresponding electromagnetic field $H(i_w)$. Viewed in w-direction, the field direction is clockwise exterior to the sheath, and counterclockwise interior to the sheath, assuming positively charged particles. In view of the well-known Biot-Savart law, the interior field decreases with increasing plasma density, while the exterior field increases in strength, thereby forcing the charged plasma particles or ions radially inward even more strongly.

Consider in particular a charged particle at point A in FIG. 3*c*, somewhat radially exterior to the volume occupied by the majority of the plasma. The particle represents a current i_w and experiences a field $H(i_w)$ having a direction as indicated, due to the motion of all other particles. The particle at A therefore experiences a force F_A tending to reduce its radius r_A and to return it toward the majority of the plasma particles. Conversely, a particle momentarily at B and somewhat radially interior to the volume occupied by the majority of the plasma particles will experience a force F_B tending to increase its instantaneous radius r_B, unless with increasing plasma density the interior field becomes ineffective and vanishes.

It is another novel feature of the present invention to impose upon the plasma aggregate an ordered helicoidal motion, whereof the axial component and its associated electromagnetic field tend to counteract radial excursions of individual plasma particles from a plasma volume or sheath **5** of finite radius, thereby actively aiding in the confinement task.

It is a further novel feature of the present invention that it permits containment of plasma aggregates having predominently or exclusively a single electrical charge polarity. The counteracting force hereinbefore described is suitable, at comparatively lower plasma densities, for balancing the electrostatic repulsion forces experienced by particles of like electrical charge polarity, which in the case of a sheath-like plasma volume **5** would otherwise tend to cause plasma particles to accelerate in a radially outward direction. As is well known, it was heretofore deemed necessary to prevent not only gross, but also local deviations from a balanced spatial distribution of particles having positive and negative electrical charge polarity, respectively.

It will also be apparent that the charged plasma particles (e.g., protons) should be introduced into the toroidal enclosure at sufficiently high injection energies to overcome the electrostatic repulsion of the sheath of plasma particles which are already within the enclosure. Once the newly-injected plasma particles enter the plasma sheath **5**, the electromagnetic field forces described hereinabove will then act to retain these particles within the plasma sheath configuration. Accordingly, it is desirable that the ions or plasma particles be injected at energies of about 1 mev. or more, and in a narrow, preselected range of velocities and directions. For example, the ions can be injected into the hollow containment space through the exit port of a low energy linear accelerator.

The aforementioned arguments, conclusions, and advantages of the present invention are, of course, contingent upon means to generate at least an approximation of an electromagnetic field having a tangential component H_t.

A preferred arrangement for this purpose is schematically shown in FIGS. 4, 5, and 6. FIG. 4 schematically illustrates a suitable toroidal enclosure with a section of the walls cut away to show the plasma volume or configuration **5**.

As shown in FIGS. 4, 5, and 6, the tangential field generating means comprises a plurality of current-carrying assemblies which are circumferentially spaced along a closed geometric figure in a lateral cross-section of the hollow toroidal enclosure **1** and in perpendicular orientation to that cross-section. As shown in the drawings, each of the current-carrying assemblies comprises two parallel current-carrying conductors **2** and **3** in close, radially-spaced proximity to each other. These conductors or conducting members **2**, **3** are supported by members (not shown). While FIGS. 5 and 6 illustrate the use of four and eight such current-carrying assemblies, it will be apparent that at least three must be employed to define a closed geometric figure. It is desirable however that a large number of current-carrying assemblies be employed in order to define a more uniform tangential electromagnetic field. Moreover, while it is preferred that the current-carrying assemblies be arranged to define a discontinuous circle, any closed geometric configuration (e.g., triangle, square, hexagon, and the like) may be utilized in accordance with this invention.

Referring to FIGS. 5 and 6, dots in members **2** indicate current direction out of the plane of the drawing, whereas crosses in members **3** (which serve as return conductors for conducting members **2**) indicate current direction into the same plane. The power supply for conductors **2**, **3** is not shown and a suitable arrangement for same will be readily apparent to those skilled in the art.

Contemplating only a single conductive member **2**, the electromagnetic field associated with a current direction as indicated will be counterclockwise concentric to said member, and will decrease in intensity as s^{-1}, s being the distance from the center of said member. Despite the presence of a plurality of members **2**, the composite field in immediate proximity of an individual member is still approximately identical with the field generated by a single conductor only. This is schematically indicated in FIG. 6 by clockwise arrows arranged concentric to the center O.

A set of members **2** would suffer from a certain disadvantage, in that—going for example along line A–O—toward the center—a point is reached beyond which the influence of the other conductors outweighs that exerted by the single conductor located on A–O. The direction of the tangential field components would therefore reverse itself at some finite radius short of O.

This disadvantage is practically overcome by locating the return conductors **3** comparatively close to their respective conductors **2**. In proximity of individual members **2** and at points inward thereof, their associated field direction still prevails, while at greater distances from any pair (**2**,**3**) the respective effects of all pairs tend to cancel out.

The overall result of the arrangement depicted in FIGS. 4, 5 is a field having everywhere a clockwise tangetial direction. In deviation from the idealization made hereinbefore (i.e., a constant H_t throughout the torodial cross-section), the field intensity H_t increases with increasing radius, and exhibits at any constant radius a cyclic variation, being strongest along (e.g.) line A–O and weakest along (e.g.) line B–O. Neither deviation obviates or substantially modifies the arguments presented hereinbefore.

Whereas it had been assumed supra that the particles experience no forces other than electromagnetic ones, an actual toroidal device according to the present invention exposes the particles both to gravitational and to centrifugal forces. Circle C in FIG. 6 schematically represents the most probable locus of particles within a torus in absence of gravitational and centrifugal forces; circle C′ schematically depicts their most probable locus in presence of said forces. The shift of such circle downward and outward from the center of such torus cross-section does not invalidate the arguments presented hereinbefore.

With reference to FIGS. 5 and 6, it is also advantageous to dispose the current-carrying assemblies in uniformly spaced relation to each other and to the geometric center of the torus cross-section.

The current-carrying members **2**,**3** may be located inside or outside the physical enclosure of the plasma space.

In the present illustration, the current-carrying assemblies are located within the hollow space enclosed by the toroidal enclosure **1** in order that they define a tangential field path (e.g. C or C′ in FIG. 6) which is substantially spaced from the interior surface of the wall of the toroidal enclosure **1**. However, it shall be understood that the current-carrying assemblies may alternatively be located outside the hollow space of the toroidal enclosure **1**. Moreover, the material of the walls of the enclosure should preferably be magnetically permeable (e.g., brass, tungsten) and may have an interior coating of asbestos, ceramic, or a similar heat resistant material.

It is desirable that the toroidal enclosure **1** further include suitable ion injection means **4** operable to introduce ions into the hollow endless enclosure with controllable initial velocities and directions. The ion injection means **4** may consist of a low energy linear proton accelerator in communication with the interior of the torus. In order to overcome the electrostatic repulsion of an enclosed plasma configuration to the introduction of additional ions, the linear accelerator should be capable of introducing the additional ions at energies of 1 mev. or more.

In operation, the hollow, toroidal enclosure **1** is first evacuated before the introduction of charged particles. By means of a linear accelerator or similar ion injection means, charged particles are then introduced into the hollow space defined by the toroidal enclosure **1**. While continuously injecting single-polarity ions, current is then passed through the current-carrying assemblies to generate a tangential magnetic field which is directed substantially tangentially to the circle C (see FIG. 6), there-

by causing the injected single-polarity ions to form a hollow plasma configuration **5** of annular cross-section. The injection of ions is terminated only after an adequate plasma density is attained within the torus **1**. The tangential magnetic field is continuously maintained by continuing to pass electric current through the conductors **2, 3** as indicated in FIGS. 5 and 6.

As mentioned hereinbefore, it may be advantageous to employ the apparatus of the present invention in conjunction with previously disclosed plasma containment methods (e.g., U.S. application Ser. No. 679,311, J. P. Drabier et al., and U.S. patent application Ser. No. 635,585, W. H. Bateman). In particular, it is preferred that the star-shaped assemblies of Drabier be utilized to contain the low density plasma immediately after initiating injection of plasma particles into the torus. The tangential field of the present invention would then be generated in order to cause the enclosed plasma to form a hollow plasma configuration (e.g., cylindrical) as additional ions are injected into the torus. Finally, when the axial component of the helical motion of the plasma particles within the cylindrical configuration attains a sufficiently high value, the wave-guide of Bateman would be brought into play in order to accelerate the plasma particles to high energies.

Since changes and variations in details can be made in practicing the invention without departing from the spirit thereof, it is intended to include in the scope of the appended claims all such modifications as will be obvious to those skilled in the art from the description given herein.

What I claim is:

1. A plasma confinement arrangement comprising: a hollow, endless enclosure for electromagnetic plasma containment; tangential field generating means operable to generate and maintain a steady-state electromagnetic field within the enclosure, said electromagnetic field being directed substantially tangentially to a closed geometic figure disposed in the plane of each cross-section of the enclosure and unidirectionally about said closed geometric figure at every point thereof; means injecting ions into the hollow, endless enclosure with controlled initial velocities and directions to form a confined plasma and means included with the said injecting means terminating the injection of the ions when the confined plasma attains a pre-selected plasma density, whereby said initial velocities and directions, in cooperation with said substantially tangential field causes the confined plasma to form a hollow plasma configuration, said confined plasma having a combined tangential and axial motion with respect to said enclosure.

2. An enclosure according to claim **1**, wherein said tangential field generating means comprises a plurality of current carrying assemblies which are circumferentially

spaced along said closed geometric figure in perpendicular orientation thereto.

3. An enclosure according to claim **2**, wherein each current carrying assembly comprises two parallel current-carrying conductors in close, radially spaced proximity to each other, the current direction in all radially inward conductors being opposite to that in all radially outward conductors.

4. An enclosure according to claim **3**, wherein the current carrying assemblies are uniformly spaced relative to one another.

5. An enclosure according to claim **4**, wherein the current carrying assemblies are located inside the hollow space defined by said hollow, endless enclosure.

6. A method of confining and maintaining a plasma comprising the steps of:

(a) continuously injecting single-polarity charged particles into a hollow, endless enclosure with controllable initial velocities and directions;

(b) concurrently with (a), generating and maintaining a steady-state tangential magnetic field, said tangential field being substantially tangential to a closed geometric figures disposed in the plane of each cross-section of the enclosure and unidirectionally about said closed geometric figure at every point thereof;

(c) terminating the injection of charged particles when the plasma confined within the enclosure attains a pre-selected plasma density;

(d) maintaining said tangential magnetic field after the termination of injection of charged particles into the enclosure;

whereby said initial velocities and directions, in cooperation with said substantially tangential field, causes the confined plasma to form a hollow plasma configuration, said confined plasma having a combined tangential and axial motion with respect to said enclosure.

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ROY LAKE, Primary Examiner

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U.S. Cl. X.R.

313—161, 231; 315—111.