

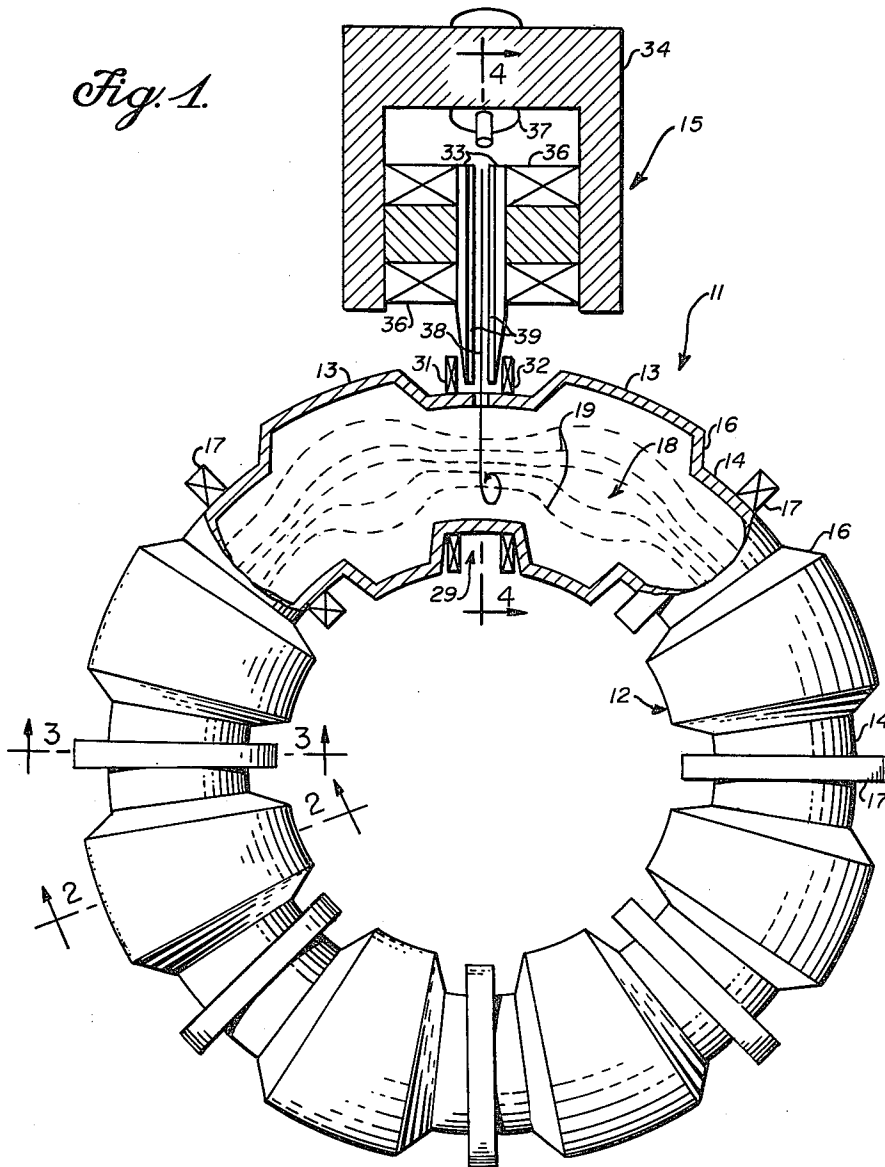
April 9, 1963 **G. GIBSON ETAL** **3,085,173**
APPARATUS FOR TRAPPING ENERGETIC CHARGED PARTICLES
AND CONFINING THE RESULTING PLASMA
Filed Aug. 17, 1961 2 Sheets-Sheet 1

63 G. GIBSON ETAL 3.0
APPARATUS FOR TRAPPING ENERGETIC CHARGED PARTICLES
AND CONFINING THE RESULTING PLASMA
7 1961

3,085,173

Filed Aug. 17, 1961

2 Sheets-Sheet 1



INVENTORS
GORDON GIBSON
WILLARD C. JORDAN
EUGENE J. LAUER

BY

Richard G. Spence

ATTORNEY

April 9, 1963

G. GIBSON ET AL
 APPARATUS FOR TRAPPING ENERGETIC CHARGED PARTICLES
 AND CONFINING THE RESULTING PLASMA

3,085,173

Filed Aug. 17, 1961

2 Sheets-Sheet 2

Fig. 2.

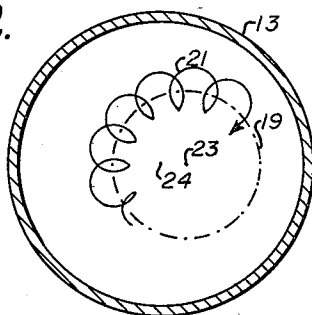


Fig. 3.

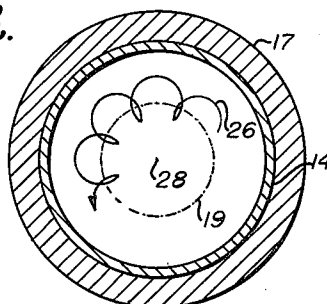


Fig. 2.a

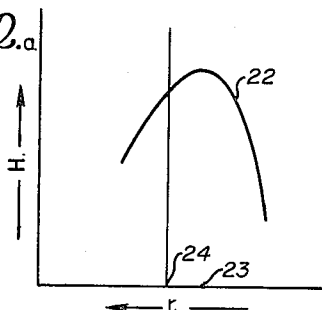


Fig. 3.a.

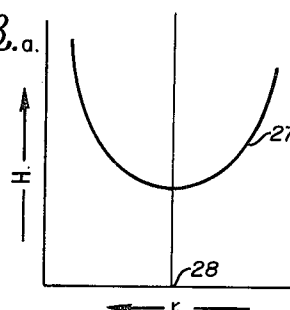


Fig. 4.

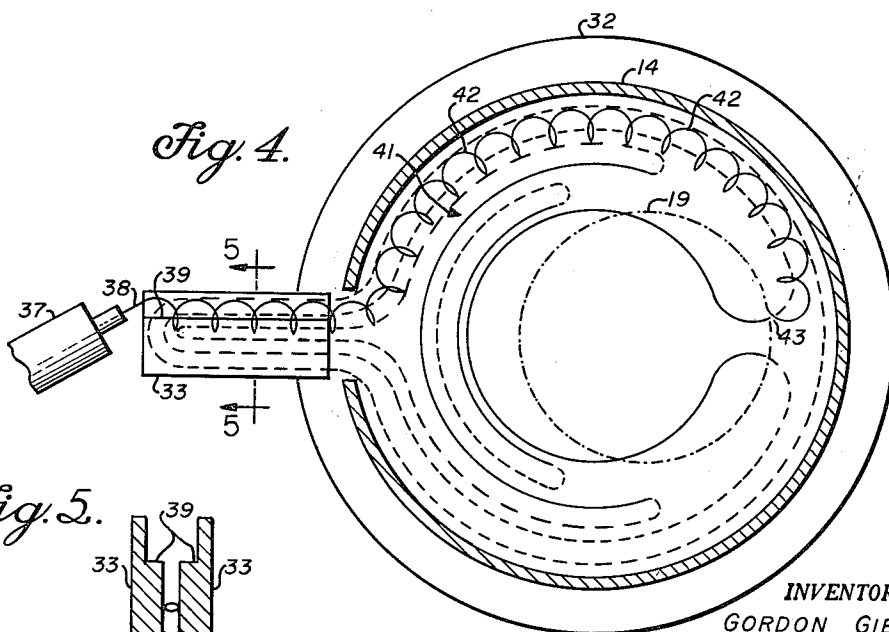
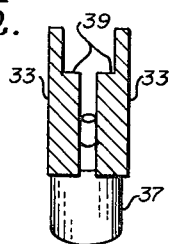


Fig. 5.



INVENTORS

GORDON GIBSON

WILLARD C. JORDAN

EUGENE J. LAUER

BY

Roland A. Anderson
 ATTORNEY

1

3,085,173

**APPARATUS FOR TRAPPING ENERGETIC
CHARGED PARTICLES AND CONFINING
THE RESULTING PLASMA**

Gordon Gibson, Hayward, Willard C. Jordan, Livermore,
and Eugene J. Lauer, Alamo, Calif., assignors to the
United States of America as represented by the United
States Atomic Energy Commission

Filed Aug. 17, 1961, Ser. No. 132,247

5 Claims. (Cl. 313-161)

The present invention relates to plasma-confining devices and a particle injector therefor, and, in particular, to a plasma-confining device of toroidal configuration wherein the magnetic fields therein are tailored to the operation of the specific injector.

In the attempt to study the confinement of plasma within magnetic-bottle configurations, various coil arrangements are being employed by scientists the world over. However, each of the various coil arrangements presently employed exhibit certain loss regions within their configuration, whereby particles are allowed to escape. For example, in the well known magnetic mirror coil configuration, if the velocity vector of a charged particle makes a sufficiently small angle with the confining magnetic field, the particles escape as end losses through a confining mirror of the device. Such end losses, in turn, are avoided by employing a second type of confining magnetic-field configuration such as the uniformly wound torus, wherein there are no ends and thus no end losses. However, the uniformly wound torus configuration introduces its own type of loss due to drift of the charged particles therewithin, such drift resulting from the gradient of the magnetic field passing there-through. The drift causes the particles to impinge rapidly upon the walls of the toroid. This problem of particle drift to the walls is reduced by introducing a rotational transform in the magnetic field disposed thereabout, such as is found in a third type of magnetic configuration known as the stellarator device. However, the stellarator device is extremely complicated in construction and operating theory, with various limitations therein associated with the attainment of a respectable containment time.

The present invention eliminates the disadvantages of the magnetic mirror device and also of the uniformly wound torus by eliminating the respective losses from end effects and from particle drift to the walls. A charged particle which would normally escape from a conventional mirror field is now transferred into another mirror field along a closed precessional surface which is established, in turn, by a magnetic gradient created by means of a special, toroidal, magnetic field configuration. Since the torus is endless, the particles with small velocity angles to the magnetic field are transferred from one mirror field to another with no conventional end losses. The magnetic field configuration of the present invention is created by a continuous array of circular, mirror field coils, disposed side by side, in particularly spaced relation, to form an endless, toroidal loop. The resulting magnetic field created therein has the appearance of a "bumpy" torus, from which the informal designation of the tube is derived (i.e., "Bumpy Torus").

Efficient particle injection necessary for practical operation of the present invention is provided by splitting one of the aforementioned coils of the Bumpy Torus tube, and injecting a beam of particles in the plane between the halves of such modified coil so that the guiding centers of the particles follow a constant magnetic field in the plane for a particular distance within the torus. The particles then move out of this plane onto a precessional surface which does not intersect the point of injection.

2

Thus, the injected particles are prevented from striking the nozzle of the injector until they have made a large number of transits in the torus. The combination of the injector and Bumpy Torus tube, as set forth in the present invention, provides a practical, operable system for trapping and studying a plasma.

Therefore, it is an object of the present invention to provide a magnetic field configuration for containing a dense plasma at sufficiently high temperatures and containment times to allow behavior studies thereof.

It is another object of the present invention to provide a method of injecting charged particles into a magnetic field, wherein the injected particles do not promptly strike the injector nozzle.

It is still another object of the present invention to provide a device for injecting and trapping charged particles therein with a minimum of losses to the walls of the device.

It is a further object of the present invention to provide a method for injecting energetic, charged particles into a magnetic containment geometry to thereby raise the kinetic temperature of the initially cold particles therein due to interactions therebetween.

Other objects and advantages will be apparent in the following description and claims, considered together with the accompanying drawings, of which:

FIGURE 1 is a partially broken-out view of the Bumpy Torus tube and injector through the plane of symmetry thereof;

FIGURE 2 is a cross-sectional view taken along line 2-2 of FIGURE 1;

FIGURE 2a is a plot of the relative, magnetic field intensity along the line of intersection between section 2-2 and the plane of symmetry containing the torus;

FIGURE 3 is a cross-sectional view taken along line 3-3 of FIGURE 1;

FIGURE 3a is a plot of the relative, magnetic field intensity along the line of intersection between section 3-3 and the plane of symmetry containing the torus;

FIGURE 4 is a cross-sectional view taken along line 4-4 of FIGURE 1 wherein the Bumpy Torus tube cross section is enlarged; and

FIGURE 5 is a magnified, cross-sectional view taken along line 5-5 of FIGURE 4.

Referring now to FIGURE 1, there is shown the present invention 11 comprising a generally toroidal tube 12 (herein termed a Bumpy Torus) and a particle injector 15 mounted normal thereto. Toroidal tube 12 comprises, in turn, a plurality of large diameter tubes 13 disposed end to end in alternate succession with an equal plurality of relatively smaller diameter tubes 14. Tubes 13 are rigidly connected to tubes 14 by annular members 16 to form a continuous cylindrical toroid of alternately large and small diameter portions. Each of the small diameter tubes 14 has a solenoidal coil 17 wound about its outer circumference; such coils to create a generally toroidal-shaped magnetic field within the tube 12 when energized by current flow. The generated magnetic field produced by the coils 17 in accordance with the theory of the present invention are herein generally designated by dashed lines 18. As may be seen from the drawing, field lines 18 are constricted within the smaller diameter tubes 14 and allowed to bulge outwardly within the larger diameter tubes 13. The geometry of the magnetic field lines 18, generated by the particular spaced coils and established within the varying-tubes configuration, has the inherent advantage of the formation therewithin of a closed, precessional surface 19, as seen by an injected energetic particle. Particles injected within and confined by the magnetic field 18, move along such precessional surface 19 within magnetic field 18 and do not encounter the walls of the toroidal tube 12.

Referring now to FIGURE 2, there is shown in diametric cross-section of the tube 12, a helical path 21 of an injected particle moving along the precessional surface 19 of previous mention. Although the particle path 21 is herein shown for purposes of description as having no axial velocity component, it is to be realized that such particle in general has axial velocity components and travels along the precessional surface 19 of tube 12. The precessional surface 19 and the helical path 21 therealong are determined by the degree and proportion of the magnetic field intensity created by the coils 17 (FIGURE 2A). As shown by a curve 22, the maximum field intensity is found at a point 23 which is closer to the center of the toroidal tube 12 than a center 24 of the perpendicular cross section taken along the length thereof.

Referring now to FIGURE 3, there is shown a helical path 26 along the precessional surface 19 of previous mention, which path is assumed by a charged particle in the plane of section 3—3 of the tube 12 and depicted herein with no axial velocity component, again for purposes of illustration only. Section 3—3 is taken transversely through one of the solenoidal coils 17 where the precessional surface 19 is at its minimum diameter, as compared to its largest diameter in section 2—2. In FIGURE 3a, curve 27, which is a plot of the magnetic field intensity along the plane of symmetry containing the tube 12, shows a minimum intensity at about the center 28 of the tube.

In operation, in keeping with the theory of the magnetic configuration of the Bumpy Torus, the magnetic field intensity as shown by curve 27 creates a magnetic field gradient which is directed essentially radially outward from point 28 towards the tube walls in the plane of section 3—3. Similarly, a field gradient directed essentially radially inward towards point 23 is created in the plane of section 2—2. These radial gradients cause the charged particles to assume paths on a closed surface within the tube, rather than drift to the walls as in the case of the uniformly wound torus. Thus, the particles remain on their closed, precessional surface 19 throughout the whole length of the tube 12 as they move axially therewithin. It is to be noted that the direction of particle movement as shown by helical paths 21 and 26, and also the magnetic field strengths and direction are herein shown only for purposes of illustration and have arbitrary values and polarities.

With regards to the injector 15 of the present invention 11 as shown in FIGURE 1, one of the coils 17 is modified to comprise a special injection coil 29. Such special injection coil 29, in keeping with the theory of injection herein specifically applicable to the present invention 11, is in actuality composed of two coils hereinafter termed split injection coils 31 and 32. The separation of the split injection coils 31 and 32 is somewhat less than one coil radius; the separation at the injection point being less than the separation at a point 180° away in angular relation thereabout. That is, at the point of injection, the split coils 31 and 32 must be closer together than they are at their opposite circumference. Two magnetic pole tips 33 are arranged between the injection point of the split coils 31 and 32, and normal to the containment field lines 18. A magnetic field is supplied between the facing surfaces of the pole tips 33 by means of a suitable iron yoke 34 and solenoidal coils 36 wound thereabout. An accelerator 37 supplies a charged particle beam which is injected into the tube 12 by means of the injector 15.

In operation of the injector 15, a beam of charged particles 38 is directed perpendicular to the field in the mid-plane of the special injection coil 29 by the facing pole tips 33. The facing pole tips 33 provide a region of rapid transition from field-free space just outside the nozzle of the accelerator 37 into a field of appropriate strength between the pole tips 33 along which the charged particle beam 38 is directed. The value of the field is

such that the gyration radius of the particle is small with respect to the coil 17 radius. Iron pole tips 33 are constructed with a step 39 (FIGURE 5) causing a gradient of the field therebetween. Thus, the guiding centers of the particles comprising the beam 38 move across the flux lines between the pole tips 33, following a path along which the field magnitude is approximately constant. (See FIGURE 4.) The particles travel along between the pole tips 33 to enter a special injection, magnetic field configuration 41, which configuration results from the field of the split injection coils 31 and 32, as well as from the field of the other coils 17 of the Bumpy Torus 12.

In theory, the beam 38 could be injected into the tube 12, into the plane of a single coil rather than into the central region of the special injection coil 29. However, if such a beam injected into the plane of a single coil had the slightest axial component of velocity, it would, immediately upon entering the field configuration for single coil injection, begin to move away from the injection plane and along the axial length of the tube 12. That is, beam 38 is in a region of maximum field strength upon being injected within the plane of a single coil, and therefore could be described as being "balanced on a mountain top." If the particles of the beam are allowed to fall off the "mountain top" immediately upon entering the field configuration 18 of the Bumpy Torus, particle losses due to particles striking the injection apparatus or walls of the torus would result. Thus, by constructing the split injection coils 31 and 32, and injecting into the region of narrowest separation therebetween, the particles are in effect being injected into a small mirror region, such as is shown in cross section in FIGURE 4. This slight mirror effect keeps the particles within the injection plane as they precess along a curved path 42. In other words, the axial motion of the particle is stabilized along the first half of the torus circumference. Since the separation of the two coils 31 and 32 comprising the special injection coil 29 is not constant, but greater on the inside of the tube 12 than on the outside thereof, there results a horseshoe pattern for the lines of constant field of the injection field configuration 41. The tips of the horseshoes correspond to points near which the mirror effect disappears, and where the Z motion or axial motion becomes unstable, allowing particles to move in the axial direction along the tube 12 precessional surface 19.

Referring to the lines of constant field magnitude of field configuration 41, the dashed lines indicate the Z component of motion is stable, and the solid lines indicate that same is unstable. Thus, injected particles follow the path 42 along the dashed, stable lines until the point 43 where the solid, unstable lines begin. That is, at this point, the slight magnetic mirror effect due to the split coils 31 and 32 disappears and the particle is allowed to escape into the magnetic field 18 to move along the precessional surface 19 of the torus 12. As previously mentioned, precessional surface 19 does not intercept the point of injection at the corner of the pole pieces 33 at any point thereon, to thus prevent the immediate loss due to particles striking the injection nozzle.

To further explain the present invention, there follows a brief description of the theory of injection and containment thereof, along with a set of operating parameters for the integral combination.

In applying the theory of single particle motion in the magnetic field created by the circular array of circular current loops, such as employed in the tube 12 of the present invention, it is assumed that the following quantities are constants of the motion of the particle. W, the kinetic energy;

$$\mu = W_{\perp} / H$$

5

the magnetic moment; and

$$J = \oint p_{\parallel} dl$$

the action integral as evaluated over a period of the longitudinal motion; where H is the magnetic field,

$$p_{\parallel}$$

is the component of the momentum parallel to the field, and dl is the element of path length parallel to the field. These quantities are calculated in the symmetry plane, S , of the tube 12 for N equally spaced circular current loops with a ratio of major radius divided by current loops radius, R/r . Because of the symmetry, it is only necessary to investigate the region between a median plane and the plane of an adjacent current loop.

Taking account of the constancy of the kinetic energy and of the magnetic moment, the action integral may be written as:

$$J = mv \oint \sqrt{1 - \frac{H}{H_0} \sin^2 \delta} dl$$

where mv is the momentum, H_0 is the initial field magnitude, and δ is the initial angle that the velocity makes with the field direction. For a given value of μ , this integral is calculated as a function of the radial position of the starting point in the median plane, M . The integrals are stopped either at the turning point where

$$v_{\parallel}$$

has decreased to zero or at the plane of the adjacent coil if there is no turning point.

For a suitable number of circular current loops having a suitable R/r value, a particular curve $\mu = \text{constant}$ and a chosen value of J , the (two) values of ρ , where the precessional surface intercepts the plane of symmetry, S , are uniquely determined. Although three-dimensional calculations have not been conducted, it is expected that the precessional surfaces are closed outside of the S plane.

For the particular case of precession in the plane M midway between adjacent pairs of coils 17, $J=0$ and the intercepts of the precessional surface are not defined. However, the precession for this special case is constrained to a path along which $H = \text{constant}$. When the coils are separated sufficiently, the plot of H vs. ρ/r in the plane S has a single maximum (this must be a maximum for displacements out of the plane S also). Thus, inner and outer intercepts for the precessional curve (which must be closed) with the plane of symmetry S may be found from the curve of H vs. ρ in the median plane. In the limit as μ approaches the value characteristic of a particle trapped in the median plane (holding the kinetic energy constant), the intercepts predicted by the J -curves approach those predicted by the median plane H -curve, as they should.

In the case where

$$v_{\parallel}$$

is zero at a mirror, J is not defined. Such a particle has

$$v_{\perp} = v = \text{constant}$$

and so follows a closed precessional curve for which $H = \text{constant}$ in the plane of the coil.

The above are two special cases where there is no longitudinal motion, i.e., the velocity vector remains normal to the field direction and, hence, the motion can be predicted without recourse to the longitudinal invariants.

In summation, the method of trapping particles as utilized and set forth herein is to inject a beam of such particles in the plane of a coil for a certain distance; allowing the particles to then move out of this plane with their guiding centers remaining on a μ, J, W surface which does not intersect the point of injection.

In steady state operation, the number of particles in-

6

jected per unit time will be balanced by the number lost from the plasma. Thus, the density of particles which can be obtained in the plasma contained in the apparatus depends upon the injection rate as related to the loss rate.

5 The fraction of particles in the primary beam which survive the initial injection process previously described herein and actually enter onto a precessional surface in the torus can be made to be approximately unity for properly chosen parameters of the beam and injector. 10 Thus, the injection rate is just equal to the flux of particles in the primary beam. Calculation of the loss rate is complicated, depending upon the energy of the plasma particles, the density of the plasma, and/or residual neutral gas molecules in addition to the other parameters of the torus-injector configuration. The mechanism which 15 results in the principal loss is assumed to be the scattering of particles as they pass the injector region with orientations such that they can become again "balanced on the mountain top" and precess out to strike the pole pieces 20 of the injector.

Although there are several methods of injecting particles into the Bumpy Torus coil configuration of the present invention, it is to be appreciated that efficient particle injection therein is practical (and results in a 25 useful plasma studying device) only by employing the injector configuration herein disclosed. Likewise, to utilize the injector configuration of above, there is need for the particular magnetic field configuration as set forth in the Bumpy Torus tube; that is, a tilted coil structure 30 must be employed.

It is to be noted that the present invention has been broadly described herein with respect to the injection and trapping of particles in general; wherein such particles may comprise, more particularly, electron or ion particles of varying densities and energies. The set of operating parameters included infra therefore comprise a particular 35 example of an electron model as taught by the present invention. Such preferred electron model is constructed with a Bumpy Torus tube comprising 64, 3.75" mean radius coils, wherein the major mean radius of the tube is 6.8'. The power required to properly operate such coils at a temperature of 60° C. equals $I^2 R = 290$ kw. for coils 1.6" thick and 2.2" long. The resulting magnetic field arising therefrom to create the confining magnetic field 40 described supra equals 2.20 kilogauss at the injection point (B_1), and 1.12 kilogauss in the mid-plane along the axis of the tube (B_m , where the latter is the minimum field of magnitude on the axis of the tube). For a chosen beam current value of 1 milliamp of 150 kev. electrons, 45 the final density ($n_{s.s.}$) is approximately 2.2×10^{11} electrons/centimeter³, and the mean containment time ($\tau_{s.s.}$) of an electron confined within the magnetic field of the tube is 3.5 seconds. β is approximately equal to 1, and the Debye distance approximately equals 1 centimeter 50 in the above electron model.

B_1 , the magnitude of the magnetic field at the point of injection results in an orbit of $1/4''$. In the above exemplifying device, the distance between the wall thereof and the surface of the region of fast drift surface diffusion is about 3 orbit radii so that diffusion across the flux lines to the wall will take several mean randomization times. Hence, this loss is small. $I^2 R$ is the magnet power for the 64 coils assuming a 60° C. temperature and coils 1.6" thick and 2.2" long. The pole tips of the injector are constructed with a narrow separation of $1/4''$ and a wide separation of $1/2''$. The particle has a radius of $1/4''$ in the field magnitude approximately at the corner thereof.

Further understanding of the theory of containment 70 offered by the Bumpy Torus configuration disclosed herein may be obtained by referring to Gordon Gibson et al., Physical Review Letters, 4, 217 (1960), and A. I. Morozov et al., Soviet Physics—Technical Physics, 5, 241 (1960).

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

What is claimed is:

1. A device for containing a heated ionized plasma comprising a generally toroidal-shaped tube, said tube being formed of an alternate succession of relatively small and large diameter tube portions connected end to end, a solenoidal coil wound about each of said small diameter portions, one of said coils being split along the diametric cross section thereof to define two annular coils coaxially disposed about their respective small diameter tube portion forming a split injection coil thereof, said two annular coils having an average separation of slightly less than one coil radius with the separation between the coils being less on the outside circumference of the tube than the separation between the coils on the inside circumference of the tube, an energetic particle source means, injection means disposed between said tube and said source means to introduce a beam of energetic particles from said source means into the region between the split injection coil of said tube, and power means coupled to said coils to energize same.

2. A device for injecting and trapping charged particles comprising a generally toroidal-shaped hollow tube, said tube being formed of an alternate succession of relatively small and large diameter tube portions connected end to end, electrical coil means including a power source concentrically disposed about the small tube portions to create a magnetic field within said tube wherein the diametrical cross section thereof varies substantially in proportion to the inside diameters of the relatively small and large diameter tube portions, a split injection coil comprising two annular halves concentrically disposed about one of said small tube portions in axially spaced relation therealong wherein said charged particles are injected between said halves at an outermost point therebetween on a tangent to the plane of symmetry of the tube, said halves having an average separation of slightly less than one coil radius and wherein the separation at the injection point is less than the separation at a point 180° away in angular relation therewith, and particle beam injection means disposed between the halves of said split injection coil to introduce said charged particles into the magnetic field created by said electrical coil means and said split injection coil.

3. The combination according to claim 2 wherein said

particle beam injection means comprises a pair of magnet pole tips mounted in opposed relation between the injection point of the split injection coil, magnet yoke means disposed about the facing pole tips, solenoidal means disposed about said magnet yoke means, said facing pole tips having a stepped portion along matching portions of the facing surfaces thereof to provide a graded magnetic field therebetween upon energization of said solenoidal means, and particle source means for introducing an energetic particle beam into the graded magnetic field between said facing pole tips wherein said beam follows an approximately constant magnetic field path for subsequent entrance into said axial magnetic field within said tube.

4. An injector for injecting charged particles into a Bumpy Torus configuration comprising a split coil concentrically mounted about the ring axis of said Bumpy Torus, said split coil having a separation between the halves thereof somewhat less than one coil radius, said split coil halves having a separation on the inside of the torus greater than the separation on the outside thereof, magnet pole tips mounted on the outside circumference of the torus and between the halves of said split coil, said pole tips having a step formed along their length to vary the intensity of a magnetic field between said pole tips, and means for introducing particles between said pole tips wherein the particles are moved therebetween along an approximately constant field magnitude to enter a field region created by said split coil and said Bumpy Torus.

5. A device for injecting and trapping charged particles of an energetic beam comprising coil means including a toroidal tube structure for establishing a toroidal magnetic field of an alternate succession of relatively small and large diameter portions along the length thereof, a split injection coil comprising two halves concentrically disposed about one of the relatively small diameter portions of said toroidal magnetic field, said halves being separated in spacial relation to form a slight mirror field effect in a plane normal to the magnetic field passing axially there-through and in the region between said halves, and particle beam injection means disposed between and normal to said halves of said split injection coil to introduce the charged particles into the slight mirror field effect created between the split injection coil.

References Cited in the file of this patent

UNITED STATES PATENTS

50	3,015,618	Stix	Jan. 2, 1962
	3,052,617	Post	Sept. 4, 1962