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DEVICE HAVING HIGH-GRADIENT MAGNETIC CUSP GEOMETRY

Filed June 23, 1961

3 Sheets-Sheet 1

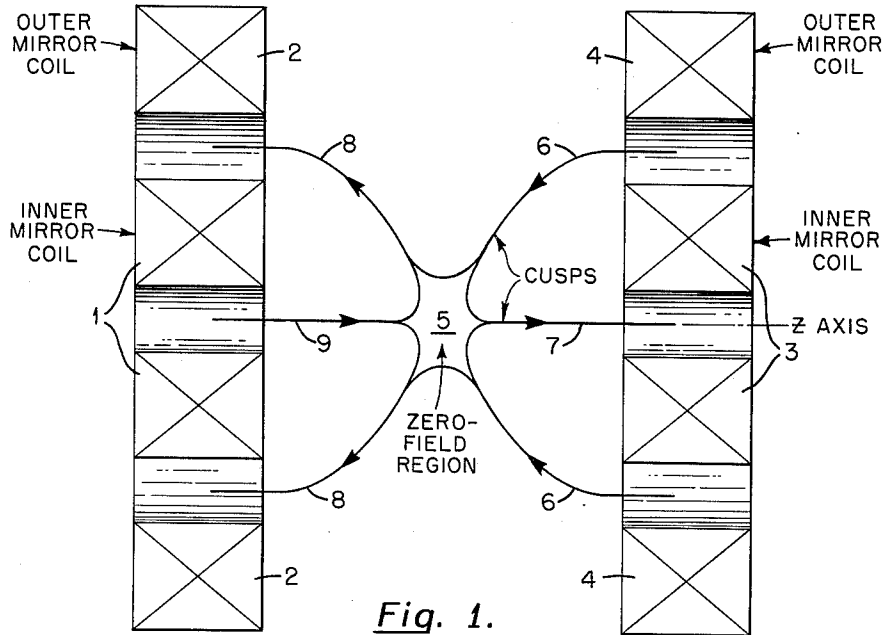


Fig. 1.

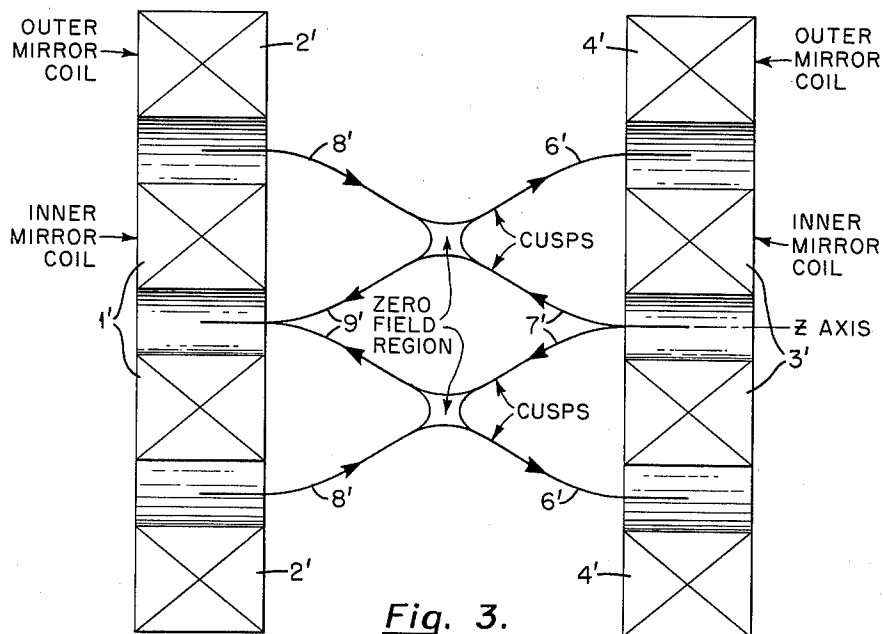


Fig. 3.

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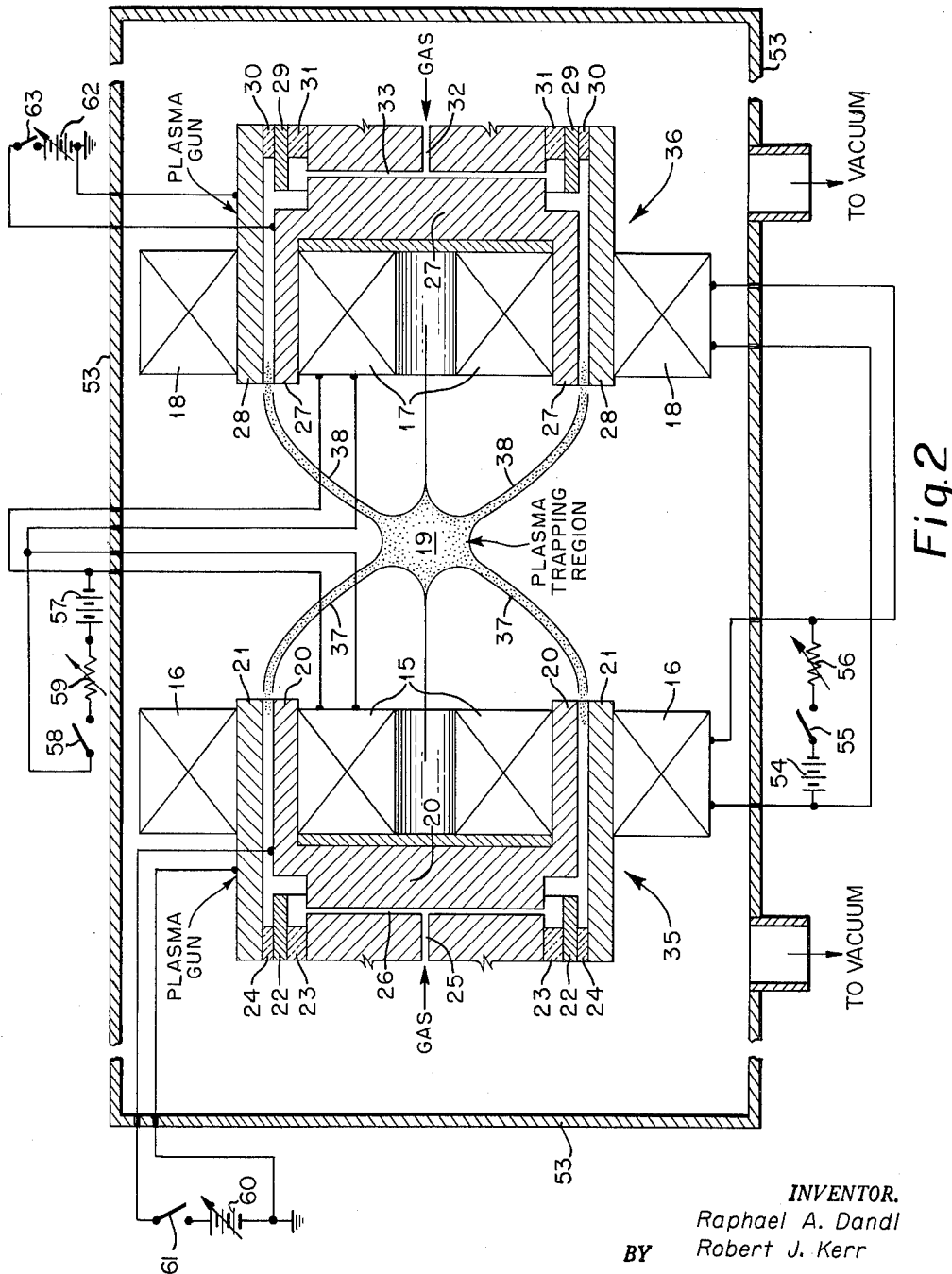


Fig. 2

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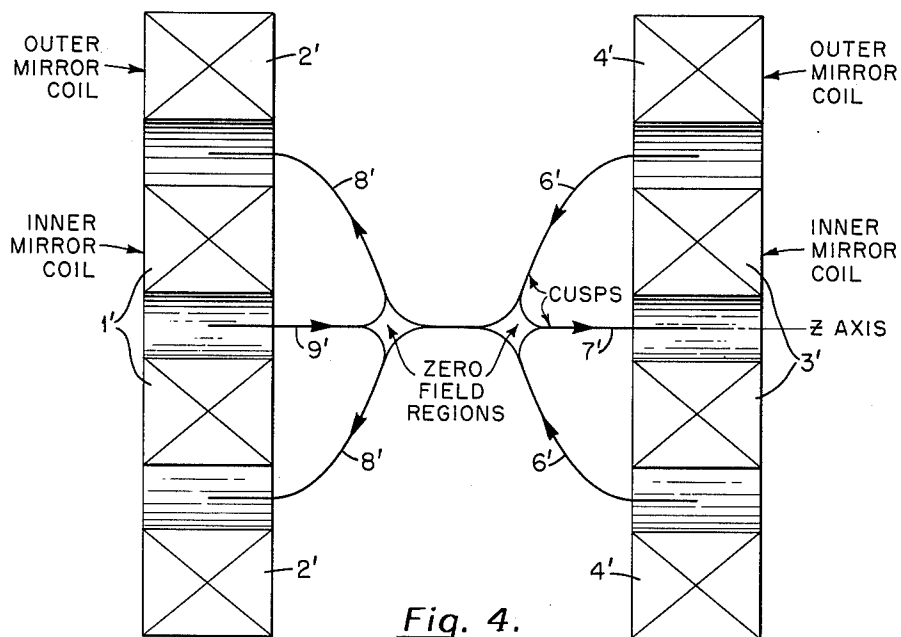


Fig. 4.

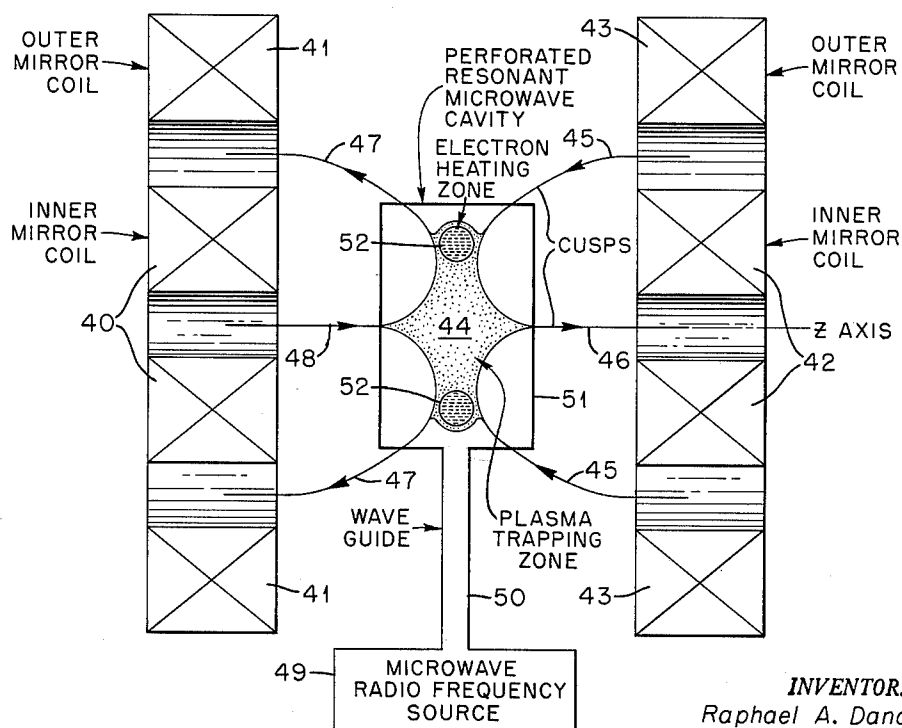


Fig. 5.

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DEVICE HAVING HIGH-GRADIENT MAGNETIC CUSP GEOMETRY

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7 Claims. (Cl. 315-111)

This invention relates to a device for providing an improved magnetic field configuration possessing cusps for the containment of plasmas. Contained plasmas are desired in experimental study of controlled thermonuclear reactions, in experimental devices for study of the physics of plasmas, and as sources of neutrons, among other uses.

In most systems in which a plasma is confined by a magnetic field that surrounds it smoothly, i.e., without a discontinuity, there will be a tendency toward instability. The reason is that the lines of force, which may be thought of as being stretched around the plasma, can shorten themselves by burrowing into the gas and thus force it outward. However, confinement which is substantially stable against arbitrary deformation can be achieved if the field lines everywhere curve away from a diamagnetic plasma, i.e., the field-plasma interface is everywhere convex on the side toward the plasma. In order to satisfy this curvature requirement, the magnetic field configuration must possess cusps, i.e., points or lines (or both), through which the field lines pass outward from the center of the confinement region. A discussion of the energy principle for hydromagnetic stability is contained in the "Proceedings of the Royal Society," Series A, vol. 244, pp. 17-40, 1958.

Cusp geometries which have been developed in the past include the "picket fence" geometry and the "chalice" geometry. A discussion of these types of geometries is contained in the book by Samuel Glasstone and Ralph H. Lovberg entitled "Controlled Thermonuclear Reactions," D. Van Nostrand Company, Inc., Princeton, New Jersey, pp. 421-427 (1960).

Two important features of any magnetic field configuration for the containment of plasmas are the inherent stability of the plasma and the adequate confinement of the plasma by the magnetic field. Prior art cusp configurations have in general been substantially stable devices. However, some of the plasma particles would not be confined by these configurations since they would leak out by squeezing between the lines of the radial components of the magnetic field. Even with a plasma of high density, the leakage rate would be excessive.

Under experimental thermonuclear conditions, a plasma behaves much like an ordinary gas, and exerts an outward pressure whose magnitude increases directly with the temperature and density. If a plasma is to be confined, its outward pressure P_p must not exceed the inward pressure P_B which the magnetic field is capable of exerting. Since the plasma acts like a normal gas, $P_p = nkT$, where n is the particle density, T is the temperature in $^{\circ}K$, and k is Boltzmann's constant. The maximum inward pressure, P_B , the magnetic field is capable of producing is given by $B^2/8\pi$, where B is the magnetic field strength in gauss. The ratio of these two pressures is denoted by β , where $\beta = nkT/(B^2/8\pi)$.

In order to provide a magnetic field configuration in which there are no radial components of the magnetic field, and such that a high value of β (approaching unity) could be realized, the present invention was conceived. By a unique arrangement of magnetic mirror coils, an improved cusp configuration is provided in which there

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is obtained a positive field gradient without radial field components. This feature of the present invention substantially lowers the leakage rate of plasma particles which is inherent in conventional prior art cusp configurations. Thus, a higher density plasma may be magnetically contained with the devices of the present invention and the contained plasma is confronted with an increasingly greater positive field gradient without radial components as it exerts a pressure thereagainst such that a high value of β may be realized.

The improved cusp geometry of the present invention is oriented in such a manner as to permit injection of a plasma along the field lines into the low field region provided by this geometry, where the plasma will be trapped by collision with neutral gas molecules or with trapped ions. Plasma trapping in the low field region may also be achieved by providing high energy electrons in the vicinity of this region. These electrons will then generate a plasma by ionization of the background gas.

It is the primary object of this invention to provide a positive high-gradient magnetic cusp field configuration possessing hydromagnetic stability for the containment of plasmas.

It is another object of this invention to provide a device for producing a positive high-gradient magnetic cusp geometry in combination with means for forming a plasma in the low field region of the cusp geometry.

These and other objects and advantages of this invention will become apparent from a consideration of the following detailed specification and the accompanying drawings wherein:

FIG. 1 is a schematic drawing of the arrangements of magnetic coils for this invention and a plot of one form of the resultant magnetic cusps;

FIG. 2 is a schematic drawing of an arrangement of components for producing a plasma in the magnetic field geometry of FIG. 1;

FIG. 3 is a schematic drawing of a variation of the magnetic field configuration of FIG. 1;

FIG. 4 is a schematic drawing of another variation of the magnetic field configuration of FIG. 1; and

FIG. 5 is a schematic drawing of another arrangement of components for producing a plasma in the magnetic field geometry of FIG. 1.

The above objects have been accomplished in the present invention by providing a pair of concentric coils spaced from another pair of concentric coils. Each outer coil is energized to provide a magnetic field reinforcing the other while the inner coils are energized to provide a magnetic field directed opposite to that of the outer coils. The field configuration provided by the coils may be thought of as two opposing magnetic mirrors. The resultant magnetic field produces point cusps and line cusps. With a proper adjustment of coil current, one or more low field regions can be achieved in the center of the device between the pairs of concentric coils. Means are provided for injecting a plasma into the low field region for trapping therewithin, or for forming and trapping a plasma within this region by the use of energetic electrons for ionizing the background gas.

FIG. 1 illustrates one embodiment of this invention in which the principles thereof may be carried out. An inner annular mirror coil 1 is encompassed by an outer annular mirror coil 2 in spaced relation thereto. Spaced from coils 1 and 2 are another pair of concentric, annular mirror coils 3 and 4. The coils 1, 2, 3 and 4 are energized with sources of D.C. current in the same manner as are the coils 15, 17 and 16, 18 of FIG. 2. The inner coils 1 and 3 are energized with about three times as much current as the outer coils 2 and 4 to provide a null or low

field region 5 as shown on the drawing. Each of the outer coils 2 and 4 is energized in such a way as to provide a magnetic field reinforcing the other, while the inner coils 1 and 3 are energized to provide a magnetic field directed opposite to that of the outer coils. The magnetic field lines are shown partially by the lines 6, 7, 8 and 9. It can be seen that the resultant magnetic field configuration produces two point cusps along the field Z axis and line cusps that follow approximately along 45° lines from the Z axis and the magnetic field lines forming the line cusps will pass between the inner and outer coils, as shown.

The device of FIG. 1 will have a positive field gradient in a plane which passes through the center of region 5 and which is parallel to the inner faces of coils 1, 2 and 3, 4. This field gradient does not have any radial components beyond the region 5 and the presence of such a gradient will provide for the containment of a high density plasma in a manner such as set forth in FIG. 2, to be described below.

The device of FIG. 1 is enclosed in any suitable vacuum chamber, such as shown in FIG. 2, which is evacuated to a pressure of about 3×10^{-7} mm. Hg. This pressure is not critical, but is given only as an example. The magnetic field at the outer convex boundaries of the region 5 is maintained at an average flux density of about 3500 gauss, for example. This flux density may be made higher, if desired, by adjusting the current flow to the coils 1, 2, 3 and 4.

The device of FIG. 1 may be used as a means for the confinement of a concentrated, energetic plasma in the low field region. FIG. 2 illustrates one embodiment in which energetic, high density plasma may be injected into the magnetic volume of FIG. 1. In FIG. 2, an inner annular magnetic mirror coil 15 is encompassed by an outer annular magnetic mirror coil 16. A plasma gun 35 is coaxially positioned between the coils 15 and 16, as shown. The plasma gun 35 includes an anode 20, a cathode 21, and an electrically floating electrode 22. An annular insulator 23 is positioned between the electrode 22 and anode 20, and an annular insulator 24 is positioned between the electrode 22 and the cathode 21. The anode 20 and cathode 21 are connected across an adjustable source of operating potential 60 by means of a switch 61. Gas, from a source not shown, is fed to the arc discharge chamber manifold of the gun 35 through passageways 25 and 26. The details of the operation of the ion gun are fully set forth in the application of Raphael A. Dandl, Serial No. 18,461, filed March 29, 1960, now U.S. Patent No. 3,005,931, issued October 24, 1961. As set forth in the aforementioned application, the ion gun will produce a plasma of about 3×10^{11} particles/cc. in a 3000 gauss magnetic field and with an operating voltage of about 1800 volts between the anode and cathode. The plasma from the ion gun is uncontaminated by neutral particles. The plasma density of the plasma provided by the ion gun varies nearly proportionally to the square of the magnetic field strength. For a more complete description of the ion gun and its operation, reference is made to the aforementioned application.

Spaced from the coils 15 and 16 and the ion gun 35 are a second pair of concentric inner and outer magnetic mirror coils 17 and 18 and a second ion gun 36 disposed in the space between the inner and outer coils 17 and 18. The ion gun 36 includes an anode 27, a cathode 28, and an intermediate, electrically floating electrode 29. An annular insulator 31 is positioned between electrode 29 and anode 27, and an annular insulator 30 is positioned between electrode 29 and cathode 28. The anode 27 and cathode 28 are connected across an adjustable source of operating potential 62 by means of a switch 63. Gas from a source, not shown, is fed to the manifold of the ion gun 36 through passageways 32 and 33. The ion gun 36 operates in the same manner as the ion gun 35

and as more fully set forth in the aforementioned application.

The magnetic field configuration of FIG. 2 is established in the same manner as in FIG. 1 described above, that is, each of the outer coils 16, 18 is energized to provide a magnetic field reinforcing the other, while the inner coils 15, 17 are energized to provide a magnetic field directed opposite to that of the outer coils. The outer coils 16, 18 are each connected to a battery 54 and an adjustable resistor 56 by means of a switch 55. The inner coils 15, 17 are each connected to a battery 57 and an adjustable resistor 59 by means of a switch 58. By adjustment of the adjustable resistors 56 and 59, the inner coils 15, 17 are energized with about three times as much current as the outer coils 16, 18. The device of FIG. 2 is enclosed in a suitable vacuum chamber 53 which is connected to vacuum pumps, not shown, through the openings shown in the chamber 53. A dense, neutralized plasma 37 is injected from the ion gun 35, and this plasma follows the field lines into the plasma trapping region 19. Also, a dense, neutralized plasma 38 is injected from the ion gun 36, and this plasma follows the field lines into the plasma trapping region 19. The region 19 of FIG. 2 is the low-field region established by the coils 15, 16, 17 and 18. The plasma trapped in the region 19 will be substantially stable against arbitrary deformation because of the field lines everywhere curving away from the plasma in this region. The positive field gradient beyond region 19 in a plane through this region, as discussed for FIG. 1 above, will provide for containment of a high density plasma within this region. Since there are no radial components to this positive field gradient, the plasma will be adequately contained within region 19 without any serious losses through the cusps, and the plasma will be hydromagnetically stable with a high value of the ratio β . The resultant plasma confined in region 19 may then be useful as a breakup center for molecular ions or for other uses common to such plasmas. When used as a breakup center for molecular ions, the particle density and the particle energy will then be sufficient for producing a quantity of neutrons in the region 19. The device of FIG. 2 is also useful in the experimental study of controlled thermonuclear reactions.

Variations of the basic axial cusp configuration of FIG. 1 and FIG. 2 may be produced by changing the current in one of the sets of mirror coils to change the location and shape of the low or null field region. FIG. 3 and FIG. 4 are examples of such variations. Concentric inner and outer magnetic mirror coils 1' and 2' are spaced from concentric inner and outer magnetic mirror coils 3' and 4'. A partial showing of the magnetic field lines is shown by the lines 6', 7', 8' and 9'. In FIG. 3 current in the inside mirror coils 1' and 3' has been increased above that used in FIG. 1 while the current in coils 2' and 4' remains the same as in FIG. 1, such that the null or low field is now a circle or torus centered on the Z axis. In FIG. 4 the current in the outer mirror coils 2' and 4' has been increased above that used in FIG. 1, while the current in coils 1' and 3' remains the same as in FIG. 1, such that there are two regions of null or low field on the Z axis equidistant from the midplane of the mirror coils. In either of these alternative field configurations, it will be possible to create and maintain a plasma in the same manner as set forth for FIG. 2 above.

FIG. 5 illustrates another embodiment in which a plasma may be formed. In FIG. 5, an inner annular mirror coil 40 is encompassed by an outer annular mirror coil 41 in spaced relation thereto. Spaced from coils 40 and 41 are another pair of concentric, annular mirror coils 42 and 43. The coils 40, 41, 42 and 43 are energized with sources of D.C. current in the same manner as are the coils 15, 17 and 16, 18 of FIG. 2. The inner coils 40 and 42 are energized with about three times as much current as the outer coils 41 and 43. Each of the outer coils 41 and 43 is energized in such a way as to

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provide a magnetic field directed opposite to that of the inner coils 40, 42 to form a low field region 44.

The device of FIG. 5 is enclosed in any suitable vacuum chamber such as shown in FIG. 2 and evacuated in the same manner as the device of FIG. 2. A plasma 5 may be formed in the device of FIG. 5 in the following manner. A microwave cavity 51 is placed at the center of the field, as shown in the drawing, for heating the electrons therein at their cyclotron frequency. The walls of this cavity 51 are perforated. A microwave radio frequency source 49 is connected to the cavity 51 through a wave guide 50. The cavity 51 in combination with source 49 and the wave guide 50 will provide an annular resonance volume 52 as shown on the drawing. The resonance volume is an annulus because the magnetic field is cylindrically symmetric. The cross section of this volume 52 is not truly circular but is shown in this manner for the sake of illustration. The heated electrons at their cyclotron frequency are trapped within the resonance volume 52. These electrons process in circular orbits within the annular volume 52, such that there are two resultant circulating electric currents parallel to the axis of the volume 52. These currents are directed in opposite directions, one along the inner periphery of the volume 52 and the other along the outer periphery of the volume 52. Before the microwave source is energized, the magnetic field configuration of FIG. 5 is the same as the cusp configuration of FIG. 1 and is provided with a low field region 44. After the microwave source is energized to produce the annulus of trapped hot electrons, the field produced by the trapped electrons will modify the axial cusp configuration to provide a resultant field configuration with the low field region 44 being extended to encompass the annular resonance volume 52 as shown in FIG. 5. The low field region 44 which is extended to encompass the resonance volume 52 will be maintained partially by the mirror coils and partially by the diamagnetic plasma formed in region 44 by the ionization of the background gas by the heated electrons therein. The directions of the magnetic field lines of the resultant field configuration are shown partially by the lines 45, 46, 47 and 48. The magnetic field strength is so chosen that the electron cyclotron frequency in a zone inside the cavity 51 is the same as the injected radio frequency. The injected radio frequency may be about 2.25K mc., for example.

The energetic electrons in the resonance volume 52 will absorb an energy depending on their residence time and the applied field strength, and will ionize the background gas. The plasma thus formed is then contained in the cusped low field containment zone 44 encompassing the resonance volume. The above method of plasma formation and trapping can be used separately or in conjunction with the coaxial plasma guns of FIG. 2. When used together, the plasma guns and the resonant cavity method would supplement each other in the formation and containment of an energetic plasma in the containment zone 44 of FIG. 5.

This invention has been described by way of illustration rather than limitation and it should be apparent that this invention is equally applicable in fields other than those described.

What is claimed is:

1. An improved means for providing a magnetic field configuration possessing cusps comprising a first pair of concentric inner and outer magnetic mirror coils, a second pair of concentric inner and outer magnetic mirror

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coils, spaced apart and in alignment with said first pair of coils, said coils being enclosed within an evacuated enclosure, means for energizing each of said outer coils to provide a field reinforcing the other, and means for energizing said inner coils to provide a field directed opposite to that provided by the outer coils, the combined effects of said fields producing a resultant magnetic field with at least one low field region in the center of the space between the pairs of coils, said low field region being bounded by line cusps and point cusps.

2. The improved means set forth in claim 1, wherein said inner coils are energized with a first, predetermined magnitude of current, and said outer coils are energized with a second, predetermined magnitude of current to provide a magnetic field strength at the boundary of said low field region of about 3500 gauss average flux density.

3. The improved means set forth in claim 2, wherein said first current is about three times larger than said second current.

4. The improved means set forth in claim 3, wherein said first current is increased while said second current remains the same to increase the difference between said currents to thus provide said low field region in the form of a torus.

5. The improved means set forth in claim 3, wherein said second current is increased while said first current remains the same to decrease the difference between said currents to thus provide a pair of low field regions equidistant from the midplane of the pairs of concentric mirror coils.

6. The improved means set forth in claim 3, and further including a first ion gun disposed between the inner and outer magnetic mirror coils of said first pair of concentric coils, a second ion gun disposed between the inner and outer magnetic mirror coils of said second pair of concentric coils, means for actuating said ion guns to provide an energetic, neutral plasma with a density of at least 3×10^{11} particles/cc. from each of said guns, said plasma following the field lines provided by said coils into said low field region where said plasma is magnetically trapped, wherein said plasma in said region is substantially stable against arbitrary deformation.

7. The improved means as set forth in claim 3, and further including a microwave resonant cavity encompassing said low field region, a microwave radio frequency source, and a wave guide connected between said source and said cavity for providing an annular resonance volume within said cavity for heating electrons therein at a cyclotron frequency equal to the frequency of said source, said heated electrons producing a field which modifies the existing field configuration to provide a resultant low field region which encompasses said resonance volume, the electrons in said resonance volume ionizing the background gas within said cavity to thus form a plasma which is magnetically trapped within said resultant low field region.

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