March 18, 1969 C. D. CORNISH **3,433,705**

STELLARATOR HAVING MULTIPOLE MAGNETS

Filed Feb. 28, 1968

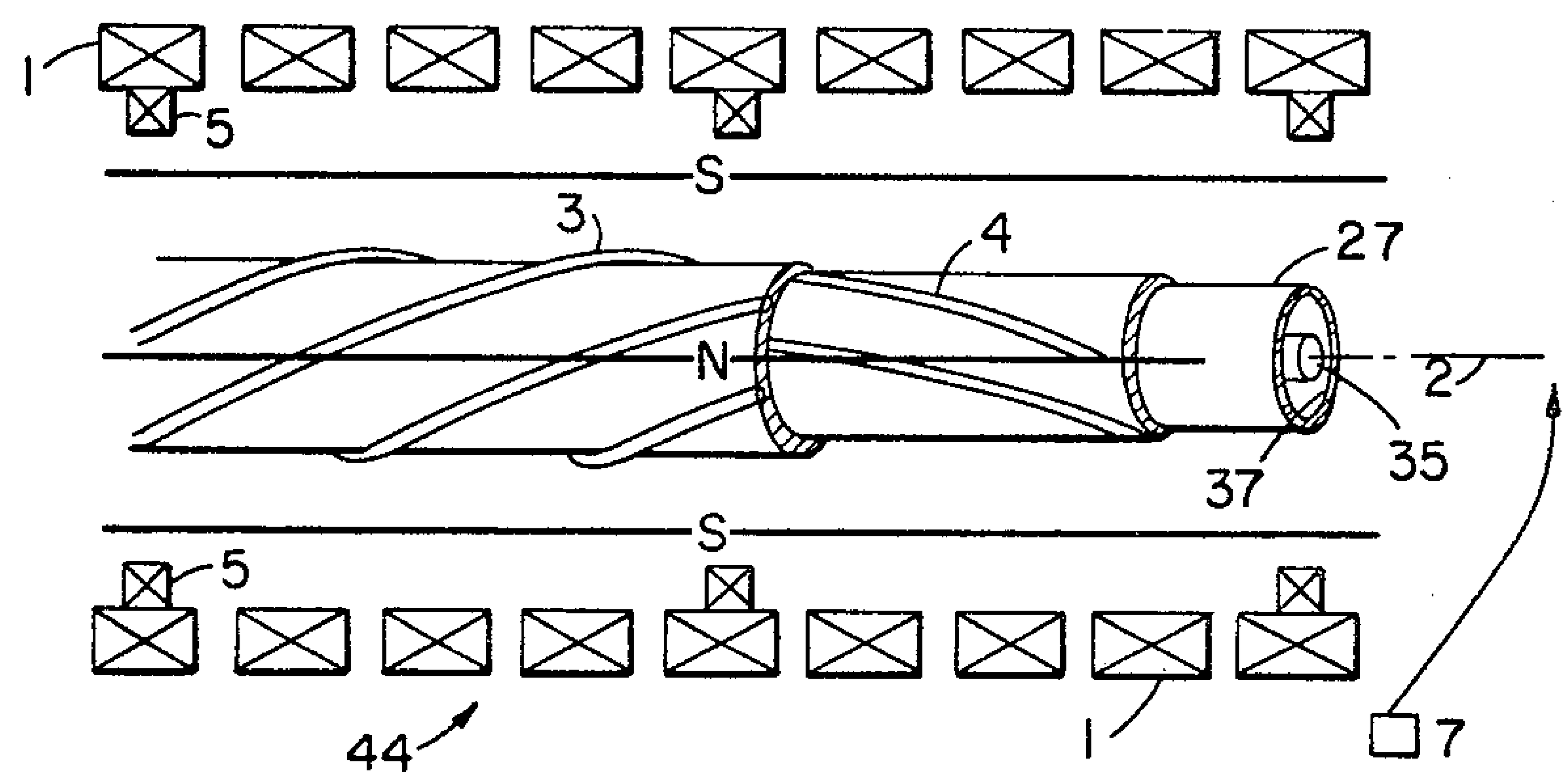

Fig. 1

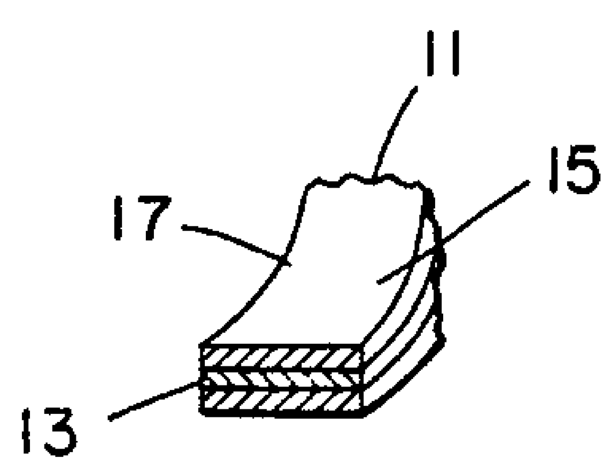

Fig. 2

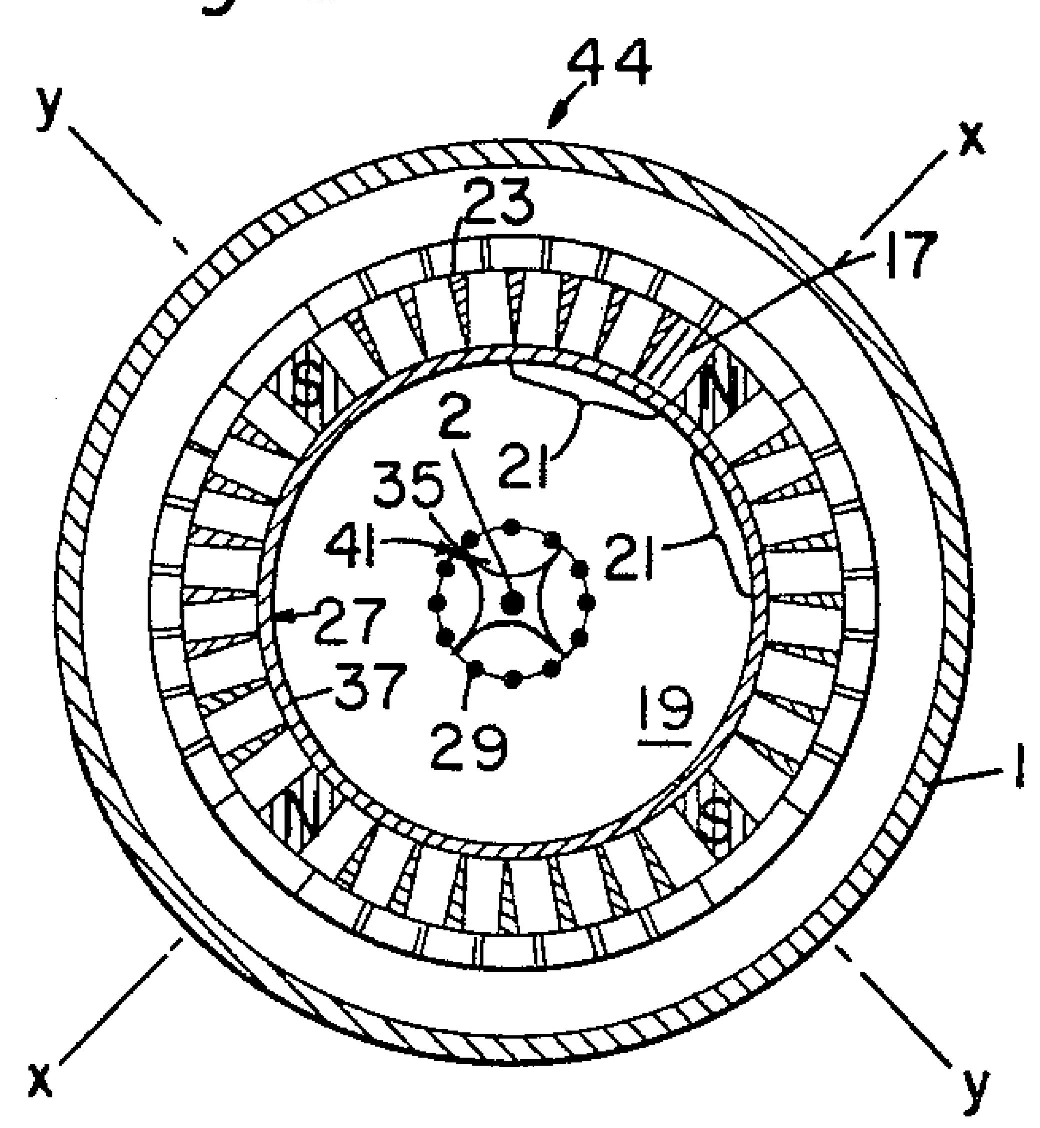

Fig. 3

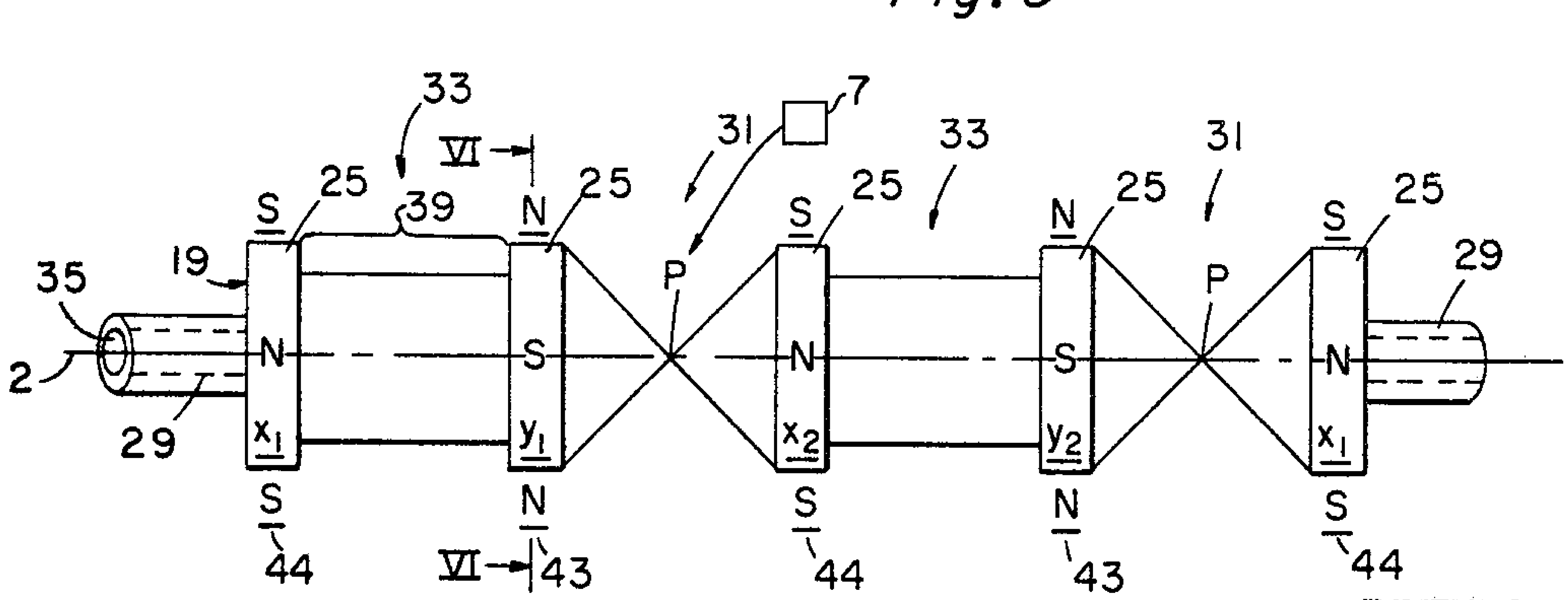

Fig. 4

INVENTOR.
CORNELL D. CORNISH
BY
Roland A. Anderson

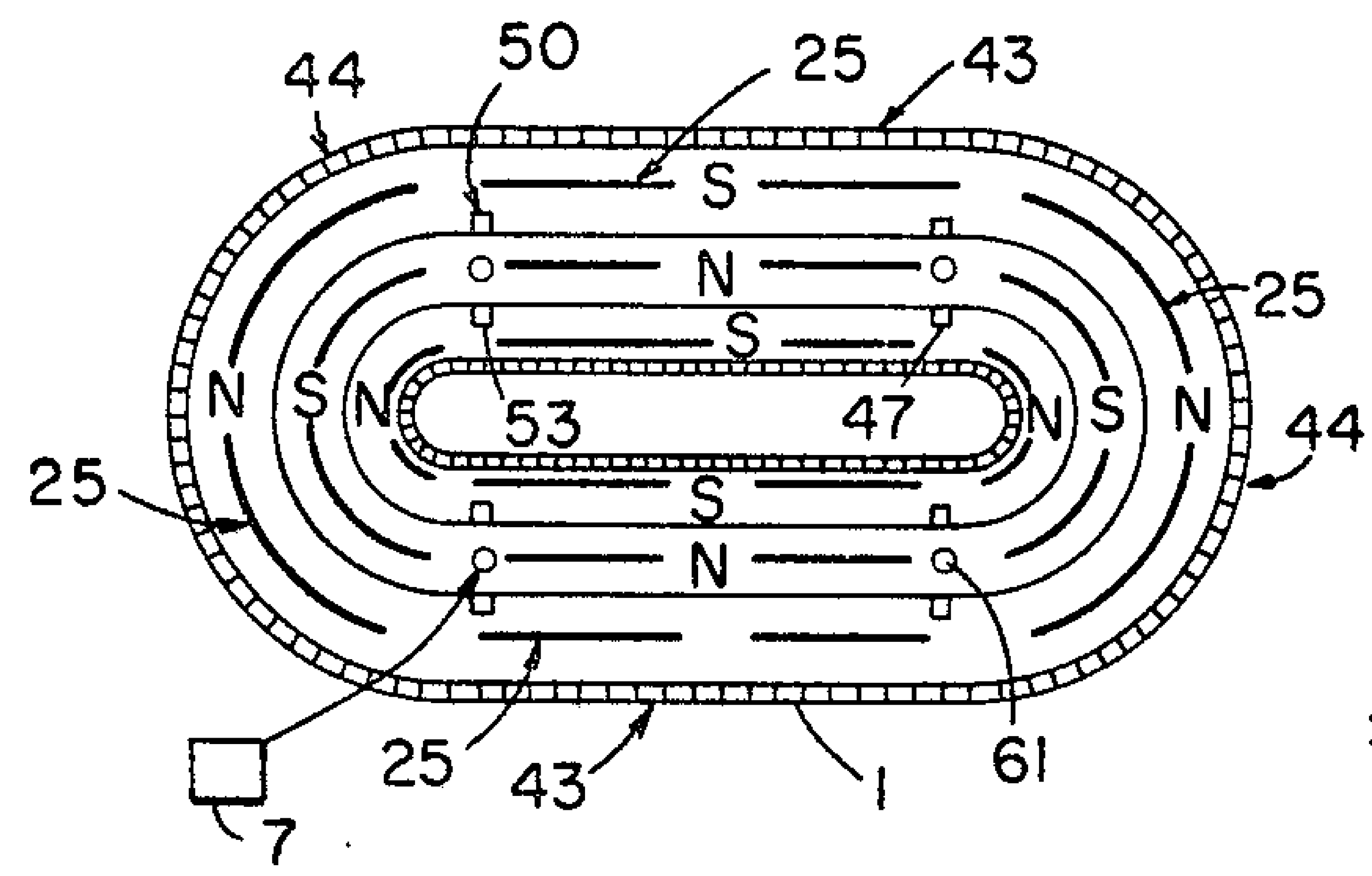

Fig. 5

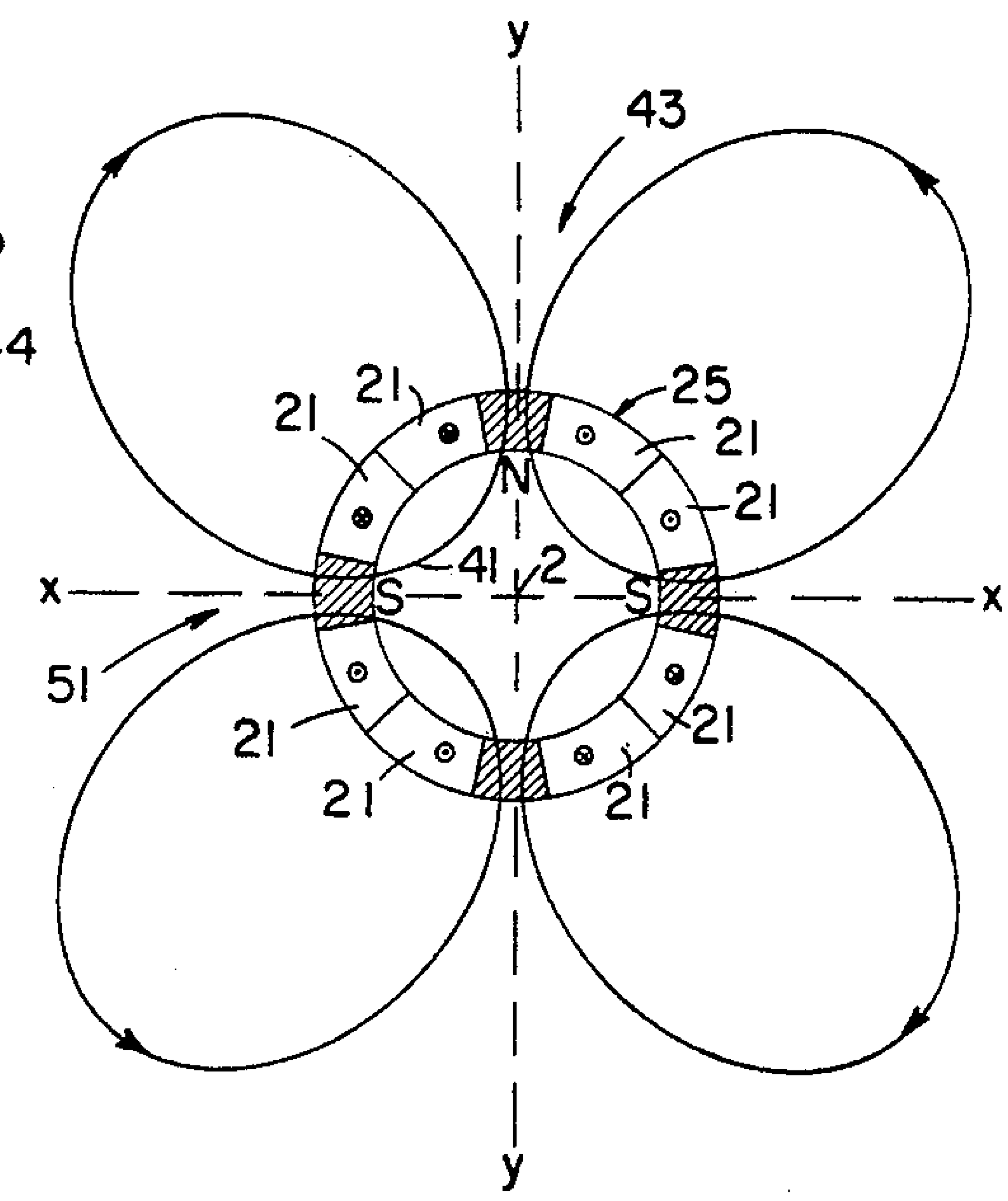

Fig. 6

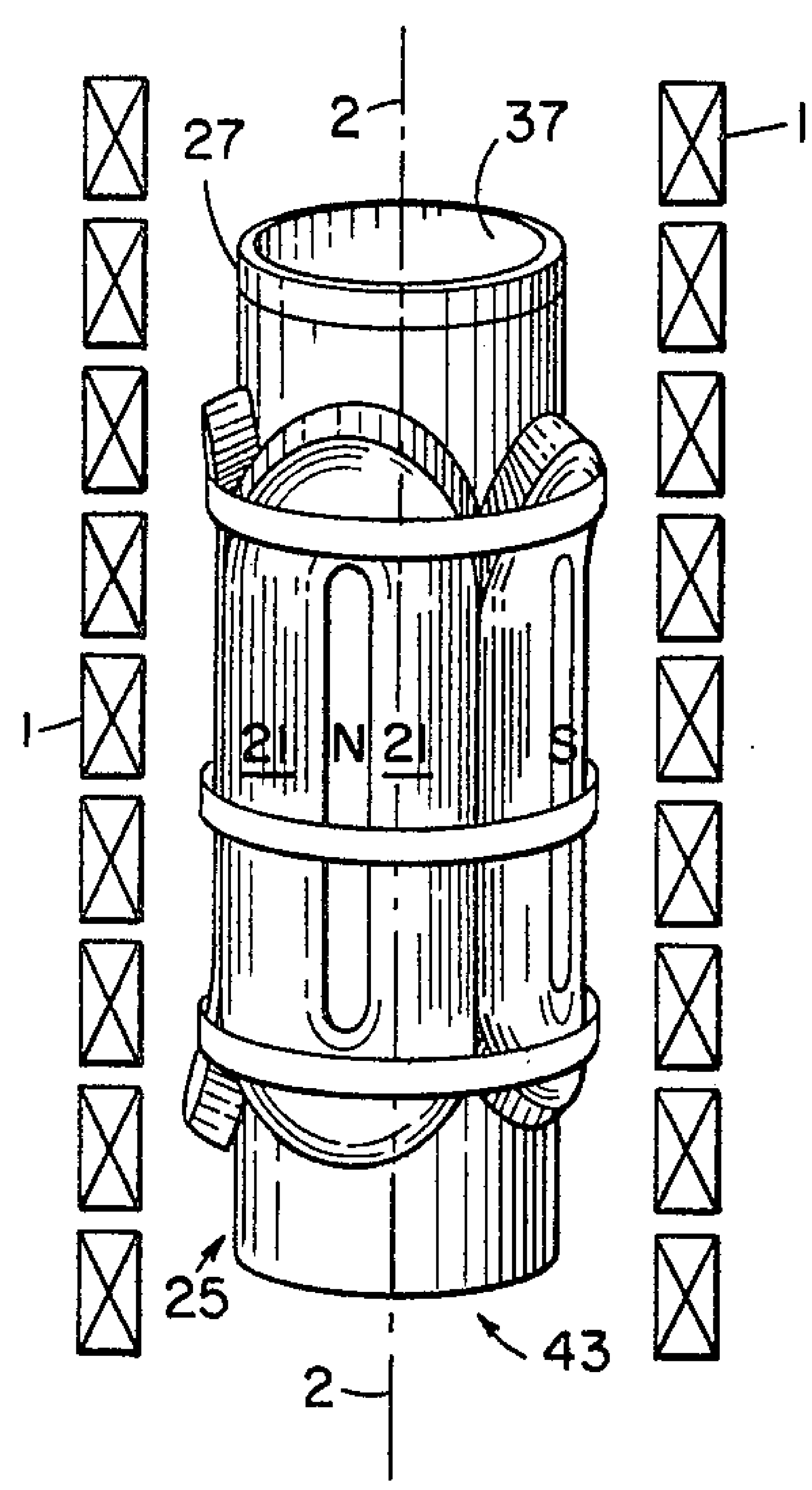

Fig. 7

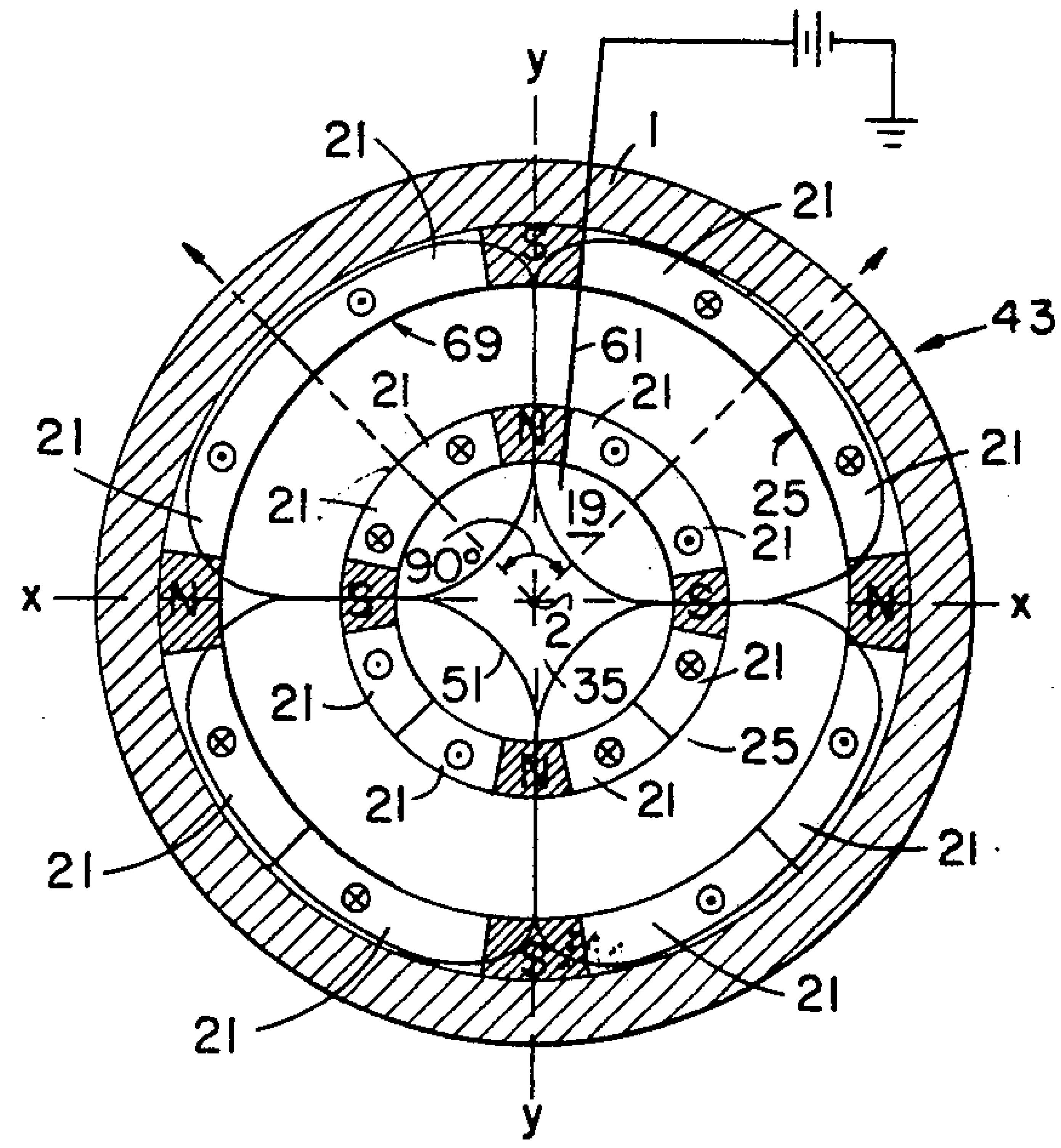

Fig. 8

INVENTOR.
CORNELL D. CORNISH

BY

Roland A. Anderson

United States Patent Office

3,433,705
Patented Mar. 18, 1969

1

3,433,705
STELLARATOR HAVING MULTIPOLE MAGNETS

Cornell D. Cornish, Port Jefferson, N.Y., asisgnor to the United States of America as represented by the United States Atomic Energy Commission

Filed Feb. 28, 1968, Ser. No. 709,080
U.S. Cl. 176—3 9 Claims
Int. Cl. G21b *1/00;* H01j *1/50;* G21j *1/00*

ABSTRACT OF THE DISCLOSURE

Multipole magnetic system having stabilized superconductors that provide for injecting and confining a high density, high temperature plasma along an endless axis in a stellarator. A particular stellarator configuration and method are provided for receiving and transporting the plasma particles in successive stages rotated between focusing and defocusing positions to provide a uniform velocity distribution in a central plasma column along an endless axis and a decreasing density gradient in the column radially outwardly from the axis and radially outwardly from the column to an endless tube wall.

RELATED APPLICATIONS

S.N. 591,056, filed Oct. 28, 1966, by William B. Sampson et al.; S.N. 662,207, filed Aug. 21, 1967, by Richard A. Beth; and S.N. 626,674, filed Mar. 27, 1967, by Richard A. Beth.

BACKGROUND OF THE INVENTION

In the field of plasma physics a need exists for confining a plasma along an endless axis in a stellarator. Various proposals have been made and used to accomplish such confinement, including the arrangements shown and described in U.S. Patents 3,002,912; 3,012,955; 3,015,618; 3,016,341; and 3,278,384. While these arrangements are useful and have accomplished the desired confinement in the Model C stellarator at Princeton, N.J., they have been difficult to build, expensive to operate, or the field pressure has been low or imprecise. For example, they have required complicated and expensive normal resistance conductors, which have been limited to low fields or have been difficult to fabricate precisely, or they have employed superconductors requiring complicated supports or field shaping means, which have been subject to saturation or other undesirable effects. It has additionally been desirable to inject ionized materials into a stellarator to produce high density plasmas therein.

SUMMARY OF THE INVENTION

This invention overcomes the difficulties and shortcomings of these devices by providing a practical and effective stabilized superconductor configuration. More particularly, this invention involves the use of a system of stabilized, superconductors forming axial and multipolar magnetic means for confining the plasma along an endless axis in a particular stellarator configuration. This configuration is arranged in one embodiment, to receive and transport the plasma in successive stages rotated between focusing and defocusing positions to provide a uniform velocity distribution along the endless axis and a decreasing density gradient radially outwardly therefrom. In another aspect,

2

this invention provides curved and straight multipolar magnets and the injection of plasma and/or plasma producing materials therebetween. With the proper selection of components, as described in more detail hereinafter, the desired injection and plasma confinement are achieved.

The above and further novel features of this invention will appear more fully from the following detailed description when the same is read in connection with the accompanying drawings. It is to be expressly understood, however, that the drawings are not intended as a definition of the invention but are for the purpose of illustration only.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a partial schematic view of longitudinally extending, curved, multipoles produced by equally spaced, longitudinal extending conductors curved along the end loops of an endless stellarator tube;

FIG. 2 is a partial three dimensional view of a stabilized superconductor winding for producing the multipoles of FIG. 1;

FIG. 3 is a partial cross-section of a $2n$ pole, stepped function, multipole magnet made with the stabilized superconductor of FIG. 2;

FIG. 4 is a partial schematic view of a pair of the magnets of FIG. 3 rotated between focusing and defocusing positions;

FIG. 5 is a partial top view of a stellarator incorporating the magnet pair of FIG. 4;

FIG. 6 is a partial cross-section through VI—VI of one of the magnets of the magnet pair of FIG. 4 illustrating the increasing field gradient of each magnet of this magnet pair and in which current flow in the direction normally upwardly from the plane of the paper is illustrated by circles with dots therein and the opposite current flow is illustrated by crosses in a circle;

FIG. 7 is a partial three dimensional view of a practical embodiment for producing the equally spaced poles of FIG. 5;

FIG. 8 is a partial cross-section of another embodiment of the magnet of FIG. 7.

DESCRIPTION OF THE PREFERRED EMBODIMENT

This invention is useful in confining a wide variety of plasma particles in a magnetic field of up to 100 kilogauss or more with magnetic field pressures of up to 500 pounds per square inch or more over a wide range of densities, temperatures and velocities. For example, the constituents comprise charged particles such as electrons and ions of the same or different species with densities up to 10^{18} particles/cm.^{3} or more. One suitable species of ions, comprises deuterium nuclei alone but ions of deuterium, tritium or heavier materials, such as He^3 nuclei, may also be used alone or in combination. Accordingly, this invention is useful for the wide variety of applications over the wide range of plasma particle velocities, densities, temperatures and confinement times to which the previously employed stellarator techniques have been applied.

As described on pages 16 and 17 in "Project Sherwood—The U.S. Program in Controlled Fusion" by Amasa Bishop, Addison-Wesley, 1958, if a homogeneous (uniform) magnetic field is applied to plasma particles in a tube the paths of these particles will be bent in tight helixes encircling the lines of force of the magnetic field in the tube. As a result, the particles are not free to move across the magnetic field lines to the walls of the tube and each is "tied" to a line of force about which it revolves at a radius that depends inversely upon the magnetic field strength. While particle collisions cause the particles to diffuse across the magnetic field the rate of diffusion is inversely proportional to the square of the magnetic field strength (i.e., it varies as $1/B^2$, where B denotes the magnetic field strength). As stated in this reference, this relationship is extremely significant, for it shows that if a hot plasma is confined in a stable way by a magnetic field, the rate of particle diffusion towards the tube wall may be greatly reduced by increasing the magnetic field strength.

In accordance with the above cited U.S. Patent 3,278,384 to Lenard et al., multipolar magnetic field configurations have been discovered for providing hydromagnetic stability. To this end, four curved, longitudinally extending multipolar conductors with current flowing in opposite directions in adjacent conductors are applied to mirror machine configurations to achieve hydromagnetic stability. This configuration, which is also reported to Nucl. Energy Pt. C5, 409 (1963), has been installed on the Model C stellarator, as described in Phys. Fluids 8, 118, (1965) and the references cited therein. The invention hereinafter described utilizes a stellarator configuration of the type described in the cited Lenard et al. patent to which are applied specific relatively rotated, straight and curved, multipolar stabilized conductors constructed in a manner described hereinafter in connection with this particular stellarator configuration. In this regard, the apparatus of this invention is incorporated into the existing stellarator configuration of U.S. Patent 3,278,384 so that use is made of the well known techniques for forming the plasma in the stellarator and for heating the plasma therein. Thus, standard well-known techniques, such as ion-cyclotron heating, magnetic pumping, ionization in-situ, and/or injection of a beam of excited neutrals, molecular ions, or separate species of particles are used to provide a hot plasma.

In understanding the principles of this invention, reference is made to FIG. 1, which is a partial three dimensional view of one of the stellarator end loops of the cited Lenard et al. patent, wherein a curved tube section is connected to another curved section by straight tube portions around an annulus. As shown in FIG. 10 of that patent the magnetic fields in the end loops are produced by five distinctly different sets of coils. An ordinary solenoid winding, coil **1**, produces the uniform axial field. Four equally spaced, curved, longitudinally extending conductors are applied to the curved end loops with current flowing in opposite directions in adjacent conductors to provide curved, longitudinally extending, equally spaced north and south poles N and S radiating around the curved portion of the endless axis **2** in the stellarator tube. Two sets of crossed conductors **3** and **4** are independent $l=\pm 2$ crossed multipolar windings with the same magnetic field periodicity along the curved axis **2** of the tube so that the fields resonate. Either set is similar to the $l=2$ multipolar field conductors installed in the U bend of the Model C stellarator. Coils **5** are ordinary mirror coils, again with the periodicity adjusted so that they resonate with the fields created by the multipole windings.

Should longitudinally extending, multipolar, stabilized superconductor magnets, such as shown in FIG. 2 of the above-cited co-pending application S.N. 591,056 by Sampson et al., or FIG. 1*c* of the above-cited co-pending application S.N. 662,207 by Beth, which are both assigned to the assignee of this invention, be curved and arranged along the end loops of the stellarator of FIG. 8 of the above-cited Patent 3,278,384 to Lenard et al. to produce the equally spaced north and south poles N and S shown in FIG. 1 herein, and should these magnets be combined with like magnets having straight axes arranged along the straight stellarator tube sections and rotated between focusing and de-focusing positions, in accordance with this invention, the desired precise, high and stable magnetic field confinement of the plasma is produced simply and effectively. Moreover, by providing these straight and curved multipolar, stabilized superconductor magnets, sequentially along the entire endless stellarator axis the plasma has a uniform velocity distribution along the entire endless axis and a decreasing density radially outwardly therefrom. Additionally, plasma particles of the same or different species may be injected into the tube by conventional injection means **7** between the rotated magnet positions to achieve high plasma density along the axis **2** of the tube, as described in more detail hereinafter.

Referring now to FIG. 2, the preferred embodiment of this invention incorporates a stabilized superconducting ribbon **11** forming the above mentioned conductors and curved, longitudinally extending multipoles. Advantageously, the superconductor **11** comprises a type II superconductor ribbon portion **13** of an intermetallic compound of niobium and tin coated with a normal resistance conductor **15**, such as copper. However, other type II superconductors **13** selected from the group consisting of the two metallic alloys of Nb-Zr and NbTi, may alternately be used. Also, other normal resistance coatings **15** may alternately be used, such as silver, gold, magnesium, iron, nickel and cobalt or suitable alloys. As described in U.S. Patent 3,356,976 and on page 118 of the March 1967 issue of Scientific American, the combination of type II superconductor ribbon and a normal resistance coating thereon provides a stabilized superconductor by preventing degradation, also referred to in the art as "flux jumping." The invention hereinafter described utilizes a stabilized superconductor of this type in which the superconductor is employed for providing all the mentioned conductors, and the described curved longitudinally extending multipoles. Thus, the axial field windings, which produce concentric endless toroidal field lines or "surfaces" as referred to in the cited stellarator art, the longitudinally extending, curved, multipoles along the curved end loops of the stellarator, the crossed conductors **3** and **4**, and the mirror coils **5** are provided by suitably wound stabilized superconductor ribbons **11**.

As described in the above-cited co-pending applications S.N. 591,056 by Sampson et al., and S.N. 662,207 by Beth, the stabilized superconductor ribbons **11** can be wound into annular, adjacent turns **17** forming an inner cylindrical aperture **19** and energized to produce the equally spaced or $2n$, alternating, north and south poles radiating around an axis (like the straight portion of axis **2**) in a plane through the center of the aperture **19** and with the poles radiating between the respective oppositely energized legs **21**, as shown in FIG. 3 herein. As shown in the above cited co-pending application by Sampson et al., the ribbons have their adjacent turns sequentially shim stepped by non-magnetic shims, such as shims **23** shown in FIG. 3 herein and that are arranged around cylindrical aperture **19**, so that the turns **17** have in cross-section periodically increasing and decreasing current density in a cylindrical current sheet that approximates a smoothly varying current sheet function and produces a constant gradient field in the aperture **19** radially outward from axis **2**. For example, a ribbon **11** that is 1.3 cm. wide by .010 cm. thick is positioned to equal or approximate the smoothly varying current function $I_\theta=I_0 \cos n\theta$ where n is the number of poles, e.g., $n=2$ in the case of a quadrupole. In the case of this quadrupole,

$$I=I_0 \cos (2\theta)$$

I_0 is the value of I at $r=r_0$ and $\theta=0$, and I is the total current between

$$-\frac{\pi}{4}$$

and θ and equals abamperes per centimeter on a current sheet of infinitesimal thickness and cylindrical geometry of radius r_0. The invention hereinafter described utilizes a $2n$ pole magnet **25** of the type described in the cited co-pending application by Sampson et al., in which the magnets **25** are rotated between focusing and de-focusing positions along an endless axis **2** in a stellarator tube **27** and in which a stabilized superconducting solenoid **1** produces concentric toroidal field lines **29**, as shown in FIG. 3. Also, stabilized superconducting crossed conductors **3** and **4** and mirror coils **5** are provided.

As shown in FIG. 4 herein, the apertures **19** of these alternating $2n$ pole magnets **25** are arranged along the endless axis **2** in the endless stellarator tube **27** around the concentric toroidal magnetic field lines **29** concentric with the axis **2** and rotated between focusing and defocusing positions **31** and **33** whereby the plasma particles are stably confined to circulate along the field lines **29** in a column **35** at the center of tube **27** to reduce the diffusion of the particles to the inside wall **37** of tube **27** when the particles are heated to high temperatures. A detailed description of rotated quadrupoles is provided in U.S. Patents 3,056,023 to Marshall and 3,171,025 to Collins and the references cited therein, but heretofore these quadrupoles have been used in mass separation of particles or in accelerators only and to rotate them and to combine them with a specific stellarator configuration having a solenoid **1** and a curved and straight endless axis **2**, as described herein or to operate them according to the method of this invention for the confinement of a plasma column, is new.

The rotation to produce the sequential focusing and defocusing is advantageously provided by like quadrupole magnets **25**, although like $2n$ pole multipole magnets of higher harmonics, for example, sextupoles, octapoles, etc., may be used as will be understood in the art. To this end the magnets **25** are disposed in pairs **39** along the endless axis **2** in the stellarator tube **27** with their equally spaced poles successively, relatively rotated 90° around axis **2**. Thus, as is understood in the art, the first quadrupole in each pair **39** has its north poles directed along a line vertical to the axis **2** and its south pole directed along a line horizontal to axis **2** whereas the second quadrupole has its north poles directed along a horizontal line and its south pole directed along a vertical line. Thus, each magnet **25** of each pair **39** tends to focus the particles in some particular transverse plane, such as either the X or Y plane, which are perpendicular to each other along a line of intersection coinciding with axis **2** in a conventional Cartesian coordinate system. Each pair **39** consists of two quadrupole magnets **25** to obtain focusing in all planes and the magnets **25** are matched at their ends at focusing end points P to provide a circuit along axis **2** in which magnet X_1 is the first and magnet Y_2 is the last magnet in the circuit. Thus, in the sequence shown in FIG. 4, magnet X_1 is shown twice in the sequence of magnets X_1, Y_1, X_2 and Y_2 for ease of explanation.

Consider a path of a particle that spirals along a concentric toroidal field line **29** produced in tube **27** under the influence of axial field winding **1**, as shown in FIG. 5 herein, which is the principal embodiment of the system of this invention, wherein each magnet **25** is represented schematically by equally spaced curved and straight longitudinally extending north and south poles arranged in the specific manner shown. It will be seen in this fig. which is a top view of a stellarator tube **27** like the one shown in FIG. 10 of the cited Lenard et al. patent and having the parameters cited therein, that equally spaced $2n$ (quadrupole) north and south poles are formed along the tube **27** and the fields are rotated between focusing and defocusing positions, as those terms are understood in the art. Also, the plasma particles may be injected into tube **27** at point P between the positions of the curved and straight poles of the magnets **25** from a suitable source **7**, as shown in FIG. 4, whereby a high density plasma can be produced in tube **27** due to the precision and field strength of the described stabilized superconducting magnets **25**, their relatively rotated positions and their focusing points P as described and shown herein.

As is understood in the art, the magnets **25** are adapted to produce a decreasing field gradient radially outwardly from the axis **2**. This field gradient confines the concentric toroidal magnetic field lines **29** produced by the conventional axial windings around the stellarator tube **27** to provide around column **35** a magnetic surface **41** that curves convexly toward the axis **2**, as shown by the cross-sectional view of aperture **19** in FIG. 6. Thus the density of the plasma particles tends to be most dense along the axis **2** and to decrease radially, outwardly from the axis **2** thereby to decrease the diffusion of the particles to the wall **37** of tube **27** while the velocity distribution of the plasma in column **35** remains uniform due to the collision of the particles with each other therein at high temperatures.

A practical embodiment of the magnet **25** for the described principal embodiment of FIG. 5, is shown in FIG. 7, which shows the details of one straight magnet **25** for producing the poles of FIG. 5. The parameters for the stellarator of FIG. 5 are given in the conceptual design, Princeton University Project Matterhorn report PM–529 (NYO–7899) (1957). For ease of explanation only one straight axis magnet **25** is shown, which is disposed along straight section **43**. Moreover, for ease of explanation, magnet **25** having a straight axis is shown in FIG. 7 with the solenoid **1** on a nonmagnetic supporting tube **27**. However, magnets **25** with curved axes are also disposed along the curved end loops **44**, which as described above have five distinctly different sets of coils comparable to those illustrated in FIG. 10 of the cited Lenard et al. Patent 3,278,384. Also, the conductors all comprise stabilized superconductors **11** as shown in FIG. 2 herein. The multipole sets of conductors equivalent to conductors **2** of FIG. 10 of the Lenard et al. patent are provided by curved $2n$ pole stepped function multipole magnets **25**, and straight multipole magnets **25**, which are rotated in successive stages between focusing and defocusing positions as shown in FIG. 4 herein, are combined therewith. Both the straight and curved magnets **25** have longitudinally extending conductor legs **21** in which ribbons **11** are stepped by shims **23**. Thus the current flows in opposite directions in legs **21** of both the curved and straight magnets **25** and these legs **21** are disposed on the opposite sides of the north and south poles N and S shown in FIG. 5 herein.

The assembly of coils and windings is built around an endless toroidal tube **27** formed by straight tube sections **43** and curved end loops **44** that are closed to form an evacuated, bakeable chamber for confining a high temperature plasma therein inside a magnetic surface **41** defining a plasma column **35** that is centered on the axis **2** of tube **27**. The various components of this configuration have been used individually or even with several present on the same device so that the techniques for designing, assembling and operating such a system are within the skill of the art based upon the disclosure herein. In this regard, the application of the stabilized superconductor **11**, and the rotated $2n$ pole magnets **25** of this invention to the round and/or elliptical plasma columns of the figures of the cited Lenard et al. patent, and the superimposed $l=\pm1$ and $l=\pm3$ multipolar fields and the other conductors thereof are well understood on the basis of this disclosure since $l=1$, $l=2$ and $l=3$ windings each correspond to $2n$ pole magnet legs **21** where $n=1$, 2 and 3 respectively to provide separate function dipoles, quadrupoles and sextupoles. Moreover, as will be understood from the above and the cited co-pending applications, these multipoles may be made to provide combined function dipoles and quadrupoles or higher harmonics.

In operation, a suitable pump evacuates tube **27** through outlet **45** to about 2×10^{-10} millimeters of mercury and the tube **27** is baked for about 12 hours at 450° C. to remove impurities from the tube **27**. Then particles from source **7**, having for example a suitable tritium and/or deuterium gas source, enters tube **27** through inlet **47** until the pressure in tube **27** is about 2×10^{-8} millimeters of mercury. A conventional current source **50**, such as described in U.S. Patent 3,088,894, ionizes and heats the gas in tube **27** and a suitable direct current source energizes the described magnetic field conductors, while they are kept in their superconducting state by suitable cryostatic means as are well known in the art. One suitable cryostat is shown and described in the above cited co-pending application S.N. 662,207 by Beth. A suitable divertor is also employed, as described in U.S. Patent 3,088,894. Advantageously, however, excited neutrals, molecular ions, or separate species of ions are efficiently injected into tube **27** from suitable source **7**. To this end the source **7** injects the plasma forming material between focusing and defocusing positions **31** and **33** having $2n$ pole magnetic fields **51** therein and produces a high density plasma, as described above, which may be heated to high temperatures by conventional means **53**, such as the ion cyclotron resonance heating as described in the above cited Stix Patent, 3,015,618, and/or U.S. Patent 3,052,614.

It is also understood that plasma column **35** can be provided inside an outer annular rotating plasma column in tube **27** by the use of a positive electric field producing conductor **61** that intercepts outer magnetic surface producing outer concentric toroidal field lines **29** near the wall **37** of tube **27**. To this end the fields produced by the above described conductors provide the necessary field for confining the particle paths with the desired radially outwardly decreasing density gradient along axis **2** and plasma particle collisions produce the uniform velocity distribution in column **35**. Meanwhile an electric field is produced around column **35** by conductor **61** to circulate the plasma outside column **35** at high velocity. One electric field producing system, comprises an electrical conductor **61** having a positive potential of at least 200 volts with respect to tube **27**, that is applied to a longitudinally extending conductor **61** having an exposed area 1.3 mm. in diameter and 3 mm. long properly positioned and biased into the outside of the heated plasma transverse to the concentric toroidal field lines **29** in tube **27** to a position at least 10 mm. from axis **2** so as to intersect the conductor **61** with two or more outer magnetic surfaces around and concentric with surface **41** around the outside of column **35**. One suitable conductor **61** is described in U.S. Patent 3,171,788. In accordance with this invention, this circulating outer plasma column prevents the formation and radial inward transfer of instabilities into the central stable region in column **35** from the outside thereof.

In another embodiment, the magnet **25** has an outer $2n$ pole magnet **69** like magnet **25** that cancels the outer stray fields of the inner magnet **25** as described and shown in FIG. 3 of the above cited co-pending application S.N. 626,674 by Beth. As shown in FIG. 8 herein, the inner and outer $2n$ pole magnets **25** and **69** are coaxial, rotated 90° with respect to each other and arranged inside the axial field solenoid **1** which is concentric with the inner and outer magnet **25** and axis **2**. For ease of explanation in this and the other figures herein, the direction of the current in the current sheets formed by magnets **25** and **69** is referenced by a dot in a circle to indicate current out of the plane of the figures and a cross in a circle to indicate the opposite current flow.

It is understood from the above in connection with the cited disclosures that the stabilized superconductors **11** and rotated magnets **25** of this invention may be disposed along a stellarator tube **27** formed only by connected straight tube sections **43** as is understood in the art of accelerators where they have heretofore been provided as described in U.S. Patent 3,171,025 to Collins. Likewise, however, these stabilized superconductors **11** and rotated magnets **25** may be disposed along a stellarator tube formed only by curved tube sections **44**, as is understood in the art on the basis of this application. Advantageously, therefore, the curved and/or straight magnets **25** are displaced so that the axis **2** through their apertures **19** coincides with focal points P at ends of adjoining magnet **25** in pairs **39**, as is shown in FIG. 4.

This invention provides a stabilized superconductor system for effectively and efficiently confining a high temperature plasma by reducing the diffusion of the plasma to the walls of an endless stellarator tube and providing an efficient injection system. As such this invention has been described by reference to specific embodiments, but numerous modifications may be made by one skilled in the art without departing from the scope of the claimed invention. In particular several combinations of curved, straight, and rotated, stabilized superconductor magnets are described for producing the specific radially outwardly decreasing field gradients as well as more general shaping or minimum β fields, as will be understood by one skilled in the art. Moreover, the magnets of this invention are capable of containing currents of up to 630 amperes per turn or more and of efficiently producing a uniform magnetic field gradient of up to 8.6 kg./cm. or more for achieving long plasma confinement times effectively at high densities.

What is claimed is:

1. In a stellarator of the type having a column (**35**) of plasma particles confined in a toroidal system in a plane with concentric magnetic field lines (**29**) along an endless axis (**2**) for spiralling said plasma particles along said concentric magnetic field lines at high temperatures, the improvement, comprising successive stages of $2n$ pole magnets (**25**) extending longitudinally along said endless axis and having equally spaced alternating north and south poles radiating around said endless axis with said poles relatively rotated 90° between successive positions (**31** and **33**) along said axis whereby said plasma particles spiral along said concentric magnetic field lines in an endless column (**35**) with decreasing density radially outwardly from said endless axis to reduce the diffusion of said particles from said column due to the collision of said particles with each other at high temperature therein.

2. The stellarator of claim **1** having means (**7**) for injecting plasma into said column between successive stages (**31** and **33**) of said $2n$ pole magnets, which are quadrupoles.

3. The stellarator of claim **1** having means (**61**) for rapidly increasing the circulation of at least a portion of said plasma particles along said endless axis (**2**) for producing an inner stable column (**35**) having a uniform plasma particle velocity distribution and a radially outwardly decreasing plasma particle density gradient therein.

4. The stellarator of claim **1** having means for injecting a plasma of ions of different species into said column between successive stages (**31** and **33**) of said $2n$ pole magnets.

5. The stellarator of claim **1** in which said $2n$ pole magnets are spaced along the entire length of said endless axis (**2**).

6. The stellarator of claim **1** having $2n$ pole magnets displaced along said axis (**2**) that are combined function bending and focusing magnets adapted to focus and to bend the concentric magnetic field lines to coincide with said column (**35**).

7. The invention of claim **1** in which said $2n$ pole magnets receive said concentric magnetic field lines in successive stages between focusing and defocusing positions (**31** and **33**) along a plurality of connected straight tube portions (**43**).

8. The invention of claim **1** in which said plasma is received and transported in successive stages between focusing and defocusing positions (**31** and **33**) along a plurality of connected curved tube portions (**44**).

9. The invention of claim **1** in which said $2n$ pole magnets are formed from a continuous type II superconductor ribbon (**13**) that is stabilized by a normal resistance conductor (**15**) intimately bound around all the surfaces of the ribbon (**13**) for the efficient, continuous operation of said magnets at high magnetic field strengths.

References Cited

UNITED STATES PATENTS

3,088,894	5/1963	Koenig	176—1
3,177,408	4/1965	Mills et al.	317—123
3,278,384	10/1966	Lenard et al.	176—3
3,290,219	12/1966	Hurwitz	176—7 *X*
3,315,114	4/1967	Thonemann et al.	176—7 X

REUBEN EPSTEIN, *Primary Examiner.*

U.S. Cl. X.R.

176—1; 313—161; 317—158