(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
27 April 2017 (27.04.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/070094 A1

(51) International Patent Classification:
H05H 1/12 (2006.01) *H05H 1/02* (2006.01)

(21) International Application Number:
PCT/US2016/057494

(22) International Filing Date:
18 October 2016 (18.10.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/245,658 23 October 2015 (23.10.2015) US

(71) Applicant: **UNIVERSITY OF WASHINGTON** [US/US]; 4311 - 11th Avenue NE, Suite 500, Seattle, Washington 98105-4608 (US).

(72) Inventors: **JARBOE, Thomas, R.**; c/o University of Washington, 4311 11th Avenue NE, Suite 500, Seattle, WA 98105-4608 (US). **ROGERS, John, A.**; c/o University of Washington, 4311 11th Avenue NE, Suite 500, Seattle, WA 98105-4608 (US).

(74) Agent: **KAMLER, Chad, A.**; McDonnell Boehnen Hulbert & Berghoff LLP, 300 South Wacker Drive, Chicago, IL 60606 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: PLASMA CONFINEMENT SYSTEMS AND METHODS FOR USE

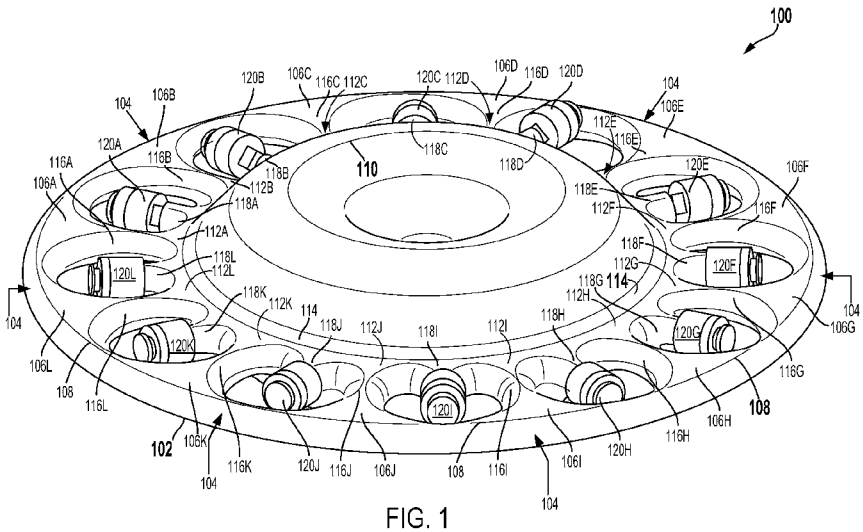


FIG. 1

(57) Abstract: In one example, a plasma confinement system includes a substantially torus-shaped outer manifold aligned on a mid-plane of the plasma confinement system. The outer manifold includes a first helicity injection port at an inner radius of the outer manifold. The plasma confinement system further includes a substantially torus-shaped inner manifold aligned on the mid-plane within the inner radius of the outer manifold. The inner manifold includes a second helicity injection port at an outer radius of the inner manifold. The plasma confinement system further includes a helicity injection tube on the mid-plane. The helicity injection tube connects the first helicity injection port to the second helicity injection port. Methods for using the plasma confinement system are also disclosed herein.

WO 2017/070094 A1

PLASMA CONFINEMENT SYSTEMS AND METHODS FOR USE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/245,658, filed on October 23, 2015, the contents of which are incorporated herein by reference in their entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Grant No. DE-FG02-96ER54361, awarded by the Department of Energy. The government has certain rights in the invention.

BACKGROUND

[0003] Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

[0004] Nuclear fusion is the process of combining two nuclei. When two nuclei of elements with atomic numbers less than that of iron are fused, energy is released. The release of energy is due to a slight difference in mass between the reactants and the products of the fusion reaction and is governed by $\Delta E = \Delta mc^2$. The release of energy is also dependent upon the difference between the attractive strong nuclear force between the reactant nuclei and the repulsive electrostatic force between electron clouds of the reactant atoms.

[0005] The fusion reaction requiring the lowest plasma temperature occurs between deuterium (a hydrogen atom having a nucleus with one proton and one neutron) and tritium (a hydrogen atom having one proton and two neutrons). This reaction yields a helium-4 atom and a neutron.

[0006] One approach for achieving nuclear fusion is to energize a gas containing fusion reactants inside a reactor chamber. The energized gas becomes a plasma via ionization. To achieve conditions with sufficient temperatures and densities for fusion, the plasma needs to be confined.

SUMMARY

[0007] In one example, a plasma confinement system includes a substantially torus-shaped outer manifold aligned on a mid-plane of the plasma confinement system. The outer

manifold includes a first helicity injection port at an inner radius of the outer manifold. The plasma confinement system further includes a substantially torus-shaped inner manifold aligned on the mid-plane within the inner radius of the outer manifold. The inner manifold includes a second helicity injection port at an outer radius of the inner manifold. The plasma confinement system further includes a helicity injection tube on the mid-plane. The helicity injection tube connects the first helicity injection port to the second helicity injection port.

[0008] In another example, a method for maintaining a plasma in a plasma confinement system is provided. The plasma confinement system includes a substantially torus-shaped inner manifold and a substantially torus-shaped outer manifold. The method includes flowing a gas into the plasma confinement system. The method further includes using a plurality of voltage coils to induce time-varying electric fields within respective sections of the outer manifold, thereby energizing at least a portion of the gas into a plasma having a toroidal current component within the outer manifold. The electric fields are mutually out of phase with each other. The method further includes using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold. The magnetic fluxes are mutually out of phase with each other and each of the magnetic fluxes is in phase with a respective electric field of the electric fields. The method further includes diverting portions of the plasma into respective helicity injection tubes that connect the outer manifold to the inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within the inner manifold.

[0009] In yet another example, a non-transitory computer readable medium is provided. The non-transitory computer readable medium stores instructions that, when executed by a controller, cause the controller to perform functions for maintaining a plasma in a plasma confinement system comprising a substantially torus-shaped inner manifold and a substantially torus-shaped outer manifold. The functions include flowing a gas into the plasma confinement system. The functions further include using a plurality of voltage coils to induce time-varying electric fields within respective sections of the outer manifold, thereby energizing at least a portion of the gas into a plasma having a toroidal current component within the outer manifold. The electric fields are mutually out of phase with each other. The functions further include using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold. The magnetic fluxes are mutually out of phase with each other and each of the magnetic fluxes

is in phase with a respective electric field of the electric fields. The functions further include diverting portions of the plasma into respective helicity injection tubes that connect the outer manifold to the inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within the inner manifold.

[0010] In yet another example, a computing device is provided. The computing device includes a controller and non-transitory computer readable medium storing instructions that, when executed by the controller, cause the controller to perform functions for maintaining a plasma in a plasma confinement system comprising a substantially torus-shaped inner manifold and a substantially torus-shaped outer manifold. The functions include flowing a gas into the plasma confinement system. The functions further include using a plurality of voltage coils to induce time-varying electric fields within respective sections of the outer manifold, thereby energizing at least a portion of the gas into a plasma having a toroidal current component within the outer manifold. The electric fields are mutually out of phase with each other. The functions further include using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold. The magnetic fluxes are mutually out of phase with each other and each of the magnetic fluxes is in phase with a respective electric field of the electric fields. The functions further include diverting portions of the plasma into respective helicity injection tubes that connect the outer manifold to the inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within the inner manifold.

[0011] When the term “substantially” or “about” is used herein, it is meant that the recited characteristic, parameter, or value need not be achieved exactly, but that deviations or variations, including for example, tolerances, measurement error, measurement accuracy limitations and other factors known to those of skill in the art, may occur in amounts that do not preclude the effect the characteristic was intended to provide. In some examples disclosed herein, “substantially” or “about” means within +/- 5% of the recited value.

[0012] These as well as other aspects, advantages, and alternatives will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings. Further, it should be understood that this summary and other descriptions and figures provided herein are intended to illustrate the invention by way of example only and, as such, that numerous variations are possible.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Figure 1 is a perspective view of a plasma confinement system, in accordance with example embodiments.

[0014] Figure 2A is another perspective view of a plasma confinement system, in accordance with example embodiments.

[0015] Figure 2B is another perspective view of a plasma confinement system, in accordance with example embodiments.

[0016] Figure 3 is a cross-sectional view of a plasma confinement system, in accordance with example embodiments.

[0017] Figure 4 is an exploded view of a plasma confinement system, in accordance with example embodiments.

[0018] Figure 5 is a block diagram of a method for maintaining a plasma in a plasma confinement system, in accordance with example embodiments.

[0019] Figure 6 is another cross-sectional view of a plasma confinement system, in accordance with example embodiments.

DETAILED DESCRIPTION

[0020] Known plasma confinement systems can generally sustain only a small variety of plasma perturbation modes and are not compatible with attractive reactors. The following disclosure describes, via example embodiments, plasma confinement systems and methods for use that can sustain a greater range of plasma perturbation modes and are compatible with attractive reactors.

[0021] It should be noted that various changes and modifications to the presently preferred embodiments described herein will be apparent to those skilled in the art. Such changes and modifications may be made without departing from the spirit and scope of the present invention and without diminishing its attendant advantages.

[0022] Referring now to the Figures, Figure 1 depicts a plasma confinement system 100. The plasma confinement system 100 may include an outer manifold 102, helicity injection ports 106A, 106B, 106C, 106D ,106E, 106F, 106G, 106H, 106I, 106J, 106K, 106L, 112A, 112B, 112C, 112D, 112E, 112F, 112G, 112H, 112I, 112J, 112K, and 112L, an inner manifold 110, helicity injection tubes 116A, 116B, 116C, 116D, 116E, 116F, 116G, 116H, 116I, 116J, 116K, and 116L, diagnostic ports 118A, 118B, 118C, 118D, 118E, 118F, 118G, 118H, 118I, 118J, 118K, and 118L, and sensors 120A, 120B, 120C, 120D, 120E, 120F, 120G, 120H, 120I, 120J, 120K, and 120L.

[0023] The outer manifold 102 may be used to confine and maintain a plasma and be

constructed from stainless steel, copper, or other metals (*e.g.*, non-magnetic metals). The outer manifold 102 may have a shape that is substantially similar to a torus. That is, the outer manifold 102 may be substantially donut-shaped or substantially ring-shaped, as shown in Figure 1. The outer manifold 102 may have an inner wall that defines a substantially ring-shaped area in which the plasma may be maintained and in which plasma currents may flow. The inner wall of the outer manifold 102 may be coated with an electrically insulating material to prevent current flow (*e.g.*, plasma discharge) between the inner wall and the plasma. For example, a ceramic material, such as alumina, may be spray-coated upon the inner wall of the outer manifold 102. The outer manifold 102 may be aligned on a mid-plane 104 of the plasma confinement system 100. As such, the outer manifold 102 (and the rest of the plasma confinement system 100) may have reflectional symmetry with respect to the mid-plane 104. In some examples, any or all surfaces making up the inner wall of the outer manifold 102 may form surfaces of revolution and/or have a bend radius of less than 2 centimeters.

[0024] The helicity injection ports 106A-L may be located at respective azimuthal positions at the inner radius 108 of the outer manifold 102. The helicity injection ports 106A-L may include outlets at which the outer manifold 102 deviates somewhat from a torus-shape to provide fluid communication between the outer manifold 102 and the inner manifold 110 via the helicity injection tubes 116A-L and the helicity injection ports 112A-L. The helicity injection ports 106A-L may be made of any materials or insulating layers that make up the outer manifold 102. In some examples, any or all surfaces making up the helicity injection ports 106A-L may form surfaces of revolution and/or have a bend radius of less than 2 centimeters.

[0025] The inner manifold 110 may be used to confine and maintain the plasma and be constructed from stainless steel, copper, or other metals (*e.g.*, non-magnetic metals). The inner manifold 110 may have a shape that is substantially similar to a torus. That is, the inner manifold 110 may be substantially donut-shaped or substantially ring-shaped, as shown in Figure 1. As shown in Figure 1, the inner manifold 110 may have a major radius that is less than the major radius of the outer manifold 102. Also, the inner manifold 110 may have a minor radius that is larger than a minor radius of the outer manifold 102.

[0026] The inner manifold 110 may have an inner wall that defines a substantially ring-shaped area in which the plasma may be maintained and plasma currents may flow. The inner wall of the inner manifold 110 may be coated with an electrically insulating material to prevent current flow (*e.g.*, plasma discharge) between the inner wall and the plasma. For

example, a ceramic material, such as alumina, may be spray-coated upon the inner wall of the inner manifold 110. The inner manifold 110 may be aligned on the mid-plane 104 of the plasma confinement system 100. As such, the inner manifold 110 may have reflectional symmetry with respect to the mid-plane 104. The inner manifold 110 may be positioned within the inner radius 108 of the outer manifold 102. In some examples, any or all surfaces making up the inner wall of the inner manifold 110 may form surfaces of revolution and/or have a bend radius of less than 2 centimeters.

[0027] The helicity injection ports 112A-L may be located at respective azimuthal positions at the outer radius 114 of the inner manifold 110. The helicity injection ports 112A-L may take the form of outlets that provide fluid communication between the outer manifold 102 and the inner manifold 110 via the helicity injection tubes 116A-L and the helicity injection ports 106A-L. The helicity injection ports 112A-L may be made of any materials or insulating layers that make up the outer manifold 102 or the inner manifold 110. In some examples, any or all surfaces making up the helicity injection ports 112A-L may form surfaces of revolution and/or have a bend radius of less than 2 centimeters.

[0028] The helicity injection tubes 116A-L may be located at respective azimuthal positions between the outer radius 114 of the inner manifold 110 and the inner radius 108 of the outer manifold 102. The helicity injection tubes 116A-L may be made of any materials or insulating layers that make up the outer manifold 102 or the inner manifold 110. The helicity injection tubes 116A-L may provide fluid communication between the helicity injection ports 106A-L and the helicity injection ports 112A-L. In some examples, any or all surfaces making up the helicity injection tubes 116A-L may form surfaces of revolution and/or have a bend radius of less than 2 centimeters.

[0029] The helicity injection port 106A may be connected to the helicity injection tube 116A, and the helicity injection tube 116A may be connected to the helicity injection port 112A. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0030] The helicity injection port 106B may be connected to the helicity injection tube 116B, and the helicity injection tube 116B may be connected to the helicity injection port 112B. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0031] The helicity injection port 106C may be connected to the helicity injection tube 116C, and the helicity injection tube 116C may be connected to the helicity injection port 112C. This arrangement may provide fluid communication between the outer manifold 102

and the inner manifold 110.

[0032] The helicity injection port 106D may be connected to the helicity injection tube 116D, and the helicity injection tube 116D may be connected to the helicity injection port 112D. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0033] The helicity injection port 106E may be connected to the helicity injection tube 116E, and the helicity injection tube 116E may be connected to the helicity injection port 112E. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0034] The helicity injection port 106F may be connected to the helicity injection tube 116F, and the helicity injection tube 116F may be connected to the helicity injection port 112F. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0035] The helicity injection port 106G may be connected to the helicity injection tube 116G, and the helicity injection tube 116G may be connected to the helicity injection port 112G. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0036] The helicity injection port 106H may be connected to the helicity injection tube 116H, and the helicity injection tube 116H may be connected to the helicity injection port 112H. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0037] The helicity injection port 106I may be connected to the helicity injection tube 116I, and the helicity injection tube 116I may be connected to the helicity injection port 112I. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0038] The helicity injection port 106J may be connected to the helicity injection tube 116J, and the helicity injection tube 116J may be connected to the helicity injection port 112J. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0039] The helicity injection port 106K may be connected to the helicity injection tube 116K, and the helicity injection tube 116K may be connected to the helicity injection port 112K. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0040] The helicity injection port 106L may be connected to the helicity injection tube

116L, and the helicity injection tube 116L may be connected to the helicity injection port 112L. This arrangement may provide fluid communication between the outer manifold 102 and the inner manifold 110.

[0041] The diagnostic ports 118A-L may take the form of outlets at the outer radius 114 of the inner manifold 110 that provide access to the interior of the inner manifold 110 (*e.g.*, the plasma) for observational purposes. Each of the diagnostic ports 118A-L may be positioned between a respective pair of helicity injection tubes 116A-J. For example, the diagnostic port 118A may be positioned between the helicity injection tube 116A and the helicity injection tube 116B.

[0042] The sensors 120A-L may be mounted onto the respective diagnostic ports 118A-L. The sensors 120A-L may include pressure sensors or plasma probes.

[0043] Figure 2A is another depiction of the plasma confinement system 100. Some components of the plasma confinement system 100 that are identified and/or depicted in Figure 1 are not identified and/or depicted in Figure 2A for ease of illustration.

[0044] The plasma confinement system 100 includes voltage coils 122A, 122B, 122C, 122D, 122E, 122F, 122G, 122H, 122I, 122J, 122K, 122L, 126A, 126B, 126C, 126D (not shown), 126E, 126F, 126G, 126H, 126I, 126J, 126K, and 126L, and flux coils 124A, 124B, 124C, 124D, 124E, 124F, 124G, 124H, 124I, 124J, 124K, 124L, 128A, 128B, 128C, 128D, 128E, 128F, 128G, 128H, 128I, 128J, 128K, and 128L.

[0045] Each of the voltage coils 122A-L may be adjacent to the inner radius 108 of the outer manifold 102 and between a respective pair of helicity injection tubes of the helicity injection tubes 116A-L.

[0046] Referring to both Figures 1 and 2A, for example, the voltage coil 122A may be between the helicity injection tubes 116A and 116L. An example direction of current flow through the voltage coil 122A is depicted via arrows, but other examples are possible.

[0047] The voltage coil 122B may be between the helicity injection tubes 116A and 116B. The voltage coil 122C may be between the helicity injection tubes 116B and 116C. The voltage coil 122D may be between the helicity injection tubes 116C and 116D. The voltage coil 122E may be between the helicity injection tubes 116D and 116E. The voltage coil 122F may be between the helicity injection tubes 116E and 116F. The voltage coil 122G may be between the helicity injection tubes 116F and 116G. The voltage coil 122H may be between the helicity injection tubes 116G and 116H. The voltage coil 122I may be between the helicity injection tubes 116H and 116I. The voltage coil 122J may be between the helicity injection tubes 116I and 116J. The voltage coil 122K may be between the

helicity injection tubes 116J and 116K. The voltage coil 122L may be between the helicity injection tubes 116K and 116L.

[0048] The voltage coils 122A-L may be configured to induce respective toroidal electric fields within the outer manifold 102 as described in more detail below with reference to Figure 6. Each of the voltage coils 122A-L may include a coil of wire or another type of conductor that is configured to carry a current that induces a toroidal electric field within the outer manifold 102.

[0049] A controller 250 may cause such currents to flow into a first terminal of the respective voltage coils 122A-L and out of a second terminal of the respective voltage coils 122A-L. The controller 250 may be any computing device or hardware configured to execute instructions stored on a computer readable medium 260. The instructions stored on the computer readable medium 260 may include instructions for providing currents to the voltage coils 122A-L as described in more detail below.

[0050] Each of the voltage coils 126A-L may be between the inner radius 108 of the outer manifold 102 and the outer radius 114 of the inner manifold 110. Each of the voltage coils 126A-L may also be adjacent to a respective helicity injection tube of the helicity injection tubes 116A-L.

[0051] Referring to both Figures 1 and 2A, for example, the voltage coil 126A may be adjacent to the helicity injection tube 116A. An example direction of current flow through the voltage coil 126A is depicted via arrows, but other examples are possible.

[0052] The voltage coil 126B may be adjacent to the helicity injection tube 116B. The voltage coil 126C may be adjacent to the helicity injection tube 116C. The voltage coil 126D may be adjacent to the helicity injection tube 116D. The voltage coil 126E may be adjacent to the helicity injection tube 116E. The voltage coil 126F may be adjacent to the helicity injection tube 116F. The voltage coil 126G may be adjacent to the helicity injection tube 116G. The voltage coil 126H may be adjacent to the helicity injection tube 116H. The voltage coil 126I may be adjacent to the helicity injection tube 116I. The voltage coil 126J may be adjacent to the helicity injection tube 116J. The voltage coil 126K may be adjacent to the helicity injection tube 116K. The voltage coil 126L may be adjacent to the helicity injection tube 116L.

[0053] The voltage coils 126A-L may be configured to induce electric fields along a longitudinal axis of the respective helicity injection tubes 116A-L as described in more detail below with reference to Figure 6. Each of the voltage coils 126A-L may include a coil of wire or another type of conductor that is configured to carry a current that induces a

corresponding electric field along a longitudinal axis of a helicity injection tube.

[0054] The controller 250 may cause such currents to flow into a first terminal of the respective voltage coils 126A-L and out of a second terminal of the respective voltage coils 126A-L. The instructions stored on the computer readable medium 260 may include instructions for providing currents to the voltage coils 126A-L as described in more detail below.

[0055] Each of the flux coils 124A-L may be wrapped around a respective section of the outer manifold 102 that is between a pair of helicity injection tubes of the helicity injection tubes 116A-L.

[0056] Referring to both Figures 1 and 2A, for example, the flux coil 124A may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116A and 116L. An example direction of current flow through the flux coil 124A is depicted via arrows, but other examples are possible.

[0057] The flux coil 124B may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116A and 116B. The flux coil 124C may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116B and 116C. The flux coil 124D may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116C and 116D. The flux coil 124E may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116D and 116E. The flux coil 124F may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116E and 116F. The flux coil 124G may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116F and 116G. The flux coil 124H may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116G and 116H. The flux coil 124I may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116H and 116I. The flux coil 124J may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116I and 116J. The flux coil 124K may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116J and 116K. The flux coil 124L may be wrapped around the outer manifold 102 at an azimuthal position that is between the helicity injection tubes 116K and 116L.

[0058] The flux coils 124A-L may be configured to induce respective toroidal magnetic fluxes within the outer manifold 102 as described in more detail below with reference to

Figure 6. Each of the flux coils 124A-L may include a coil of wire or another type of conductor that is configured to carry a current that induces a toroidal magnetic flux within the outer manifold 102.

[0059] The controller 250 may cause such currents to flow into a first terminal of the respective flux coils 124A-L and out of a second terminal of the respective flux coils 124A-L. The instructions stored on the computer readable medium 260 may include instructions for providing currents to the flux coils 124A-L as described in more detail below.

[0060] Each of the flux coils 128A-L may be wrapped around a respective helicity injection tube of the helicity injection tubes 116A-L.

[0061] Referring to both Figures 1 and 2A, for example, the flux coil 128A may be wrapped around the helicity injection tube 116A. An example direction of current flow through the flux coil 128A is depicted via arrows, but other examples are possible.

[0062] The flux coil 128B may be wrapped around the helicity injection tube 116B. The flux coil 128C may be wrapped around the helicity injection tube 116C. The flux coil 128D may be wrapped around the helicity injection tube 116D. The flux coil 128E may be wrapped around the helicity injection tube 116E. The flux coil 128F may be wrapped around the helicity injection tube 116F. The flux coil 128G may be wrapped around the helicity injection tube 116G. The flux coil 128H may be wrapped around the helicity injection tube 116H. The flux coil 128I may be wrapped around the helicity injection tube 116I. The flux coil 128J may be wrapped around the helicity injection tube 116J. The flux coil 128K may be wrapped around the helicity injection tube 116K. The flux coil 128L may be wrapped around the helicity injection tube 116L.

[0063] The flux coils 128A-L may be configured to induce magnetic fluxes along longitudinal axes of the respective helicity injection tubes 116A-L as described in more detail below with reference to Figure 6. Each of the flux coils 128A-L may include a coil of wire or another type of conductor that is configured to carry a current that induces its corresponding magnetic flux.

[0064] The controller 250 may cause such currents to flow into a first terminal of the respective flux coils 128A-L and out of a second terminal of the respective flux coils 128A-L. The instructions stored on the computer readable medium 260 may include instructions for providing currents to the flux coils 128A-L as described in more detail below.

[0065] Figure 2B is another depiction of the plasma confinement system 100. Some components of the plasma confinement system 100 that are identified and/or depicted in Figure 1 are not identified and/or depicted in Figure 2B for ease of illustration.

[0066] In the example of Figure 2B, the plasma confinement system 100 includes voltage coils 127A, 127B, 127C, 127D, 127E, 127F, 127G, 127H, 127I, 127J, 127K, and 127L.

[0067] Each of the voltage coils 127A-L may be adjacent to the inner radius 108 of the outer manifold 102, between a pair of respective helicity injection tubes 116A-L, and adjacent to both of the respective pair helicity injection tubes.

[0068] Referring to both Figures 1 and 2B, for example, the voltage coil 127A may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116A and 116L, and adjacent to both of the helicity injection tubes 116A and 116L.

[0069] The voltage coil 127B may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116A and 116B, and adjacent to both of the helicity injection tubes 116A and 116B. The voltage coil 127C may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116B and 116C, and adjacent to both of the helicity injection tubes 116B and 116C. The voltage coil 127D may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116C and 116D, and adjacent to both of the helicity injection tubes 116C and 116D. The voltage coil 127E may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116D and 116E, and adjacent to both of the helicity injection tubes 116D and 116E. The voltage coil 127F may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116E and 116F, and adjacent to both of the helicity injection tubes 116E and 116F. The voltage coil 127G may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116F and 116G, and adjacent to both of the helicity injection tubes 116F and 116G. The voltage coil 127H may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116G and 116H, and adjacent to both of the helicity injection tubes 116G and 116H. The voltage coil 127I may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116H and 116I, and adjacent to both of the helicity injection tubes 116H and 116I. The voltage coil 127J may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116I and 116J, and adjacent to both of the helicity injection tubes 116I and 116J. The voltage coil 127K may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116J and 116K, and adjacent to both of the helicity injection tubes 116J and 116K. The voltage coil 127L may be adjacent to the inner radius 108 of the outer manifold 102, between helicity injection tubes 116K and 116L, and adjacent to both of the helicity

injection tubes 116K and 116L.

[0070] The voltage coils 127A-L may be configured to induce respective toroidal electric fields within the outer manifold 102 as described in more detail below with reference to Figure 6. Each of the voltage coils 127A-L may include a coil of wire or another type of conductor that is configured to carry a current that induces electric fields within the outer manifold 102, the inner manifold 110, and/or the helicity injection tubes 116A-L.

[0071] A controller 250 may cause such currents to flow into a first terminal of the respective voltage coils 127A-L and out of a second terminal of the respective voltage coils 127A-L. The controller 250 may be any computing device or hardware configured to execute instructions stored on a computer readable medium 260. The instructions stored on the computer readable medium 260 may include instructions for providing currents to the voltage coils 127A-L as described in more detail below.

[0072] Figure 3 is a downward looking cross-sectional view of the plasma confinement system 100. As shown, the outer radius 114 of the inner manifold 110 may encircle a radius r_1 of approximately 0.32 meters (m). In other examples, r_1 may range in value from about 0.288 m to about 0.352 m. Other examples are possible as well.

[0073] An outer radius of the outer manifold 102 may encircle a radius r_1+r_2 of approximately 0.48 m. In other examples, r_1+r_2 may range in value from about 0.432 m to about 0.528 m. Other examples are possible as well.

[0074] An inner diameter d_1 of any of the helicity injection tubes 116A-L may be substantially equal to 0.12 m, or within the range of 0.018 m to 0.132 m. An inner diameter d_2 of the outer manifold 102 may be substantially equal to 0.12 m, or within the range of 0.018 m to 0.132 m.

[0075] Figure 4 is an exploded view of the plasma confinement system 100. Referring to Figure 1 and Figure 4, the outer manifold 102, the helicity injection ports 106A-L, and the helicity injection tubes 116A-L may be made of 24 pre-formed components 402, 404, 406, 408, 410, 412, 414, 416, 418, 420, 422, 424, 426, 428, 430, 432, 434, 436, 438, 440, 442, 444, 446, and 448.

[0076] For example, the pre-formed component 402 together with the pre-formed component 426 may form a portion of the outer manifold 102, the helicity injection port 106A, and the helicity injection tube 116A. The pre-formed component 404 together with the pre-formed component 428 may form a portion of the outer manifold 102, the helicity injection port 106B, and the helicity injection tube 116B. The pre-formed component 406

together with the pre-formed component 430 may form a portion of the outer manifold 102, the helicity injection port 106C, and the helicity injection tube 116C. The pre-formed component 408 together with the pre-formed component 432 may form a portion of the outer manifold 102, the helicity injection port 106D, and the helicity injection tube 116D. The pre-formed component 410 together with the pre-formed component 434 may form a portion of the outer manifold 102, the helicity injection port 106E, and the helicity injection tube 116E. The pre-formed component 412 together with the pre-formed component 436 may form a portion of the outer manifold 102, the helicity injection port 106F, and the helicity injection tube 116F. The pre-formed component 414 together with the pre-formed component 438 may form a portion of the outer manifold 102, the helicity injection port 106G, and the helicity injection tube 116G. The pre-formed component 416 together with the pre-formed component 440 may form a portion of the outer manifold 102, the helicity injection port 106H, and the helicity injection tube 116H. The pre-formed component 418 together with the pre-formed component 440 may form a portion of the outer manifold 102, the helicity injection port 106I, and the helicity injection tube 116I. The pre-formed component 420 together with the pre-formed component 444 may form a portion of the outer manifold 102, the helicity injection port 106J, and the helicity injection tube 116J. The pre-formed component 422 together with the pre-formed component 446 may form a portion of the outer manifold 102, the helicity injection port 106K, and the helicity injection tube 116K. The pre-formed component 424 together with the pre-formed component 448 may form a portion of the outer manifold 102, the helicity injection port 106L, and the helicity injection tube 116L.

[0077] Figure 5 is a block diagram of a method 500 for maintaining a plasma in a plasma confinement system that includes a substantially torus-shaped inner manifold and a substantially torus-shaped outer manifold.

[0078] At block 502, the method 500 includes flowing a gas into the plasma confinement system. For example, gas may be flowed into the plasma confinement system 100 via one or more inlet ports and gas flow meters (not shown). The gas may include a combination of fusion reactants, such as atomic or molecular hydrogen, deuterium, tritium, or helium, for example. The gas flow into the plasma confinement system 100 may be controlled by the controller 250 executing instructions stored on the computer readable medium 260. Alternatively, the gas flow into the plasma confinement system 100 may be controlled manually.

[0079] At block 504, the method 500 includes using a plurality of voltage coils to

induce time-varying electric fields within respective sections of the outer manifold, thereby energizing at least a portion of the gas into a plasma having a toroidal current component within the outer manifold.

[0080] For example, the controller 250 may pass respective currents through the voltage coils 122A-L and 126A-L. Referring to Figure 6, the currents passed through the voltage coils 122A-L may induce the respective electric fields 132A, 132B, 132C, 132D, 132E, 132F, 132G, 132H, 132I, 132J, 132K, and 132L. The currents passed through the voltage coils 126A-L may induce the respective electric fields 136A, 136B, 136C, 136D, 136E, 136F, 136G, 136H, 136I, 136J, 136K, and 136L. The electric fields 132A-L may be mutually out of phase with each other and the electric fields 136A-L may be mutually out of phase with each other.

[0081] In other examples, the controller 250 may pass currents through the voltage coils 127A-L to induce the respective electric fields 132A-L, 136A-L, and 140A-L. For instance, the voltage coil 127A may be used to induce or affect the electric fields 132A, 136A, 140A, and/or 136L. The voltage coil 127B may be used to induce or affect the electric fields 132B, 136B, 140B, and/or 136A. The voltage coil 127C may be used to induce or affect the electric fields 132C, 136C, 140C, and/or 136B. The voltage coil 127D may be used to induce or affect the electric fields 132D, 136D, 140D, and/or 136C. The voltage coil 127E may be used to induce or affect the electric fields 132E, 136E, 140E, and/or 136D. The voltage coil 127F may be used to induce or affect the electric fields 132F, 136F, 140F, and/or 136E. The voltage coil 127G may be used to induce or affect the electric fields 132G, 136G, 140G, and/or 136F. The voltage coil 127H may be used to induce or affect the electric fields 132H, 136H, 140H, and/or 136G. The voltage coil 127I may be used to induce or affect the electric fields 132I, 136I, 140I, and/or 136H. The voltage coil 127J may be used to induce or affect the electric fields 132J, 136J, 140J, and/or 136I. The voltage coil 127K may be used to induce or affect the electric fields 132K, 136K, 140K, and/or 136J. The voltage coil 127L may be used to induce or affect the electric fields 132L, 136L, 140L, and/or 136K.

[0082] For example, the electric fields 132A-L and 136A-L may take the following form:

132A	$E_A \sin(\omega t)$
132B	$E_B \sin(\omega t + n\pi/6)$
132C	$E_C \sin(\omega t + n\pi/3)$

132D	$E_D \sin(\omega t + n\pi/2)$
132E	$E_E \sin(\omega t + 2n\pi/3)$
132F	$E_F \sin(\omega t + 5n\pi/6)$
132G	$E_G \sin(\omega t + n\pi)$
132H	$E_H \sin(\omega t + 7n\pi/6)$
132I	$E_I \sin(\omega t + 4n\pi/3)$
132J	$E_J \sin(\omega t + 3n\pi/2)$
132K	$E_K \sin(\omega t + 5n\pi/3)$
132L	$E_L \sin(\omega t + 11n\pi/6)$
136A	$E_a \sin(\omega t)$
136B	$E_b \sin(\omega t + n\pi/6)$
136C	$E_c \sin(\omega t + n\pi/3)$
136D	$E_d \sin(\omega t + n\pi/2)$
136E	$E_e \sin(\omega t + 2n\pi/3)$
136F	$E_f \sin(\omega t + 5n\pi/6)$
136G	$E_g \sin(\omega t + n\pi)$
136H	$E_h \sin(\omega t + 7n\pi/6)$
136I	$E_i \sin(\omega t + 4n\pi/3)$
136J	$E_j \sin(\omega t + 3n\pi/2)$
136K	$E_k \sin(\omega t + 5n\pi/3)$
136L	$E_l \sin(\omega t + 11n\pi/6)$

[0083] E_A-E_L may refer to the respective amplitudes of the electric fields 132A-L, E_a-E_l may refer to the respective amplitudes of the electric fields 136A-L, ω may refer to the angular oscillation frequency of the electric fields 132A-L and 136A-L, t may refer to time, and n may refer to a perturbation mode (*e.g.*, n=1, 2, 3, 4, 5, or 6). As described above, the electric fields 132A-L may be mutually out of phase by n*π/6 radians, and the electric fields 136A-L may be mutually out of phase by n*π/6 radians.

[0084] At block 506, the method 500 includes using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold.

[0085] For example, the controller 250 may pass respective currents through the flux

coils 124A-L and 128A-L. Referring to Figure 6, the currents passed through the flux coils 124A-L may induce the respective magnetic fluxes 134A, 134B, 134C, 134D, 134E, 134F, 134G, 134H, 134I, 134J, 134K, and 134L. The currents passed through the flux coils 128A-L may induce the respective magnetic fluxes 138A, 138B, 138C, 138D, 138E, 138F, 138G, 138H, 138I, 138J, 138K, and 138L. The magnetic fluxes 134A-L may be mutually out of phase with each other and the magnetic fluxes 138A-L may be mutually out of phase with each other. The magnetic fluxes 134A-L may be in phase with the respective electric fields 132A-L and the magnetic fluxes 138A-L may be in phase with the respective electric fields 136L. Other examples are possible.

[0086] For example, the magnetic fluxes 134A-L and 138A-L may take the following form:

134A	$B_A\sin(\omega t)$
134B	$B_B\sin(\omega t + n\pi/6)$
134C	$B_C\sin(\omega t + n\pi/3)$
134D	$B_D\sin(\omega t + n\pi/2)$
134E	$B_E\sin(\omega t + 2n\pi/3)$
134F	$B_F\sin(\omega t + 5n\pi/6)$
134G	$B_G\sin(\omega t + n\pi)$
134H	$B_H\sin(\omega t + 7n\pi/6)$
134I	$B_I\sin(\omega t + 4n\pi/3)$
134J	$B_J\sin(\omega t + 3n\pi/2)$
134K	$B_K\sin(\omega t + 5n\pi/3)$
134L	$B_L\sin(\omega t + 11n\pi/6)$
138A	$B_a\sin(\omega t)$
138B	$B_b\sin(\omega t + n\pi/6)$
138C	$B_c\sin(\omega t + n\pi/3)$
138D	$B_d\sin(\omega t + n\pi/2)$
138E	$B_e\sin(\omega t + 2n\pi/3)$
138F	$B_f\sin(\omega t + 5n\pi/6)$
138G	$B_g\sin(\omega t + n\pi)$
138H	$B_h\sin(\omega t + 7n\pi/6)$
138I	$B_i\sin(\omega t + 4n\pi/3)$

138J	$B_j \sin(\omega t + 3n\pi/2)$
138K	$B_k \sin(\omega t + 5n\pi/3)$
138L	$B_l \sin(\omega t + 11n\pi/6)$

[0087] B_A-B_L may refer to the respective amplitudes of the magnetic fluxes 134A-L and B_a-B_l may refer to the respective amplitudes of the magnetic fluxes 138A-L. As described above, the magnetic fluxes 134A-L may be mutually out of phase by n*π/6 radians, and the magnetic fluxes 138A-L may be mutually out of phase by n*π/6 radians.

[0088] The magnetic fluxes 134A-L and 138A-L may serve to inject helicity into the plasma maintained within the plasma confinement system 100 and to direct the plasma away from interior surfaces of the plasma confinement system 100. For example, a plasma current may circulate around the magnetic flux 134A as the plasma current flows along the electric field 132A, resulting in a current that flows in both the toroidal and poloidal directions within the outer manifold 102. The magnetic fluxes 134B-L and the electric fields 132B-L may also facilitate respective plasma current components that flow in both the toroidal and poloidal directions at various regions of the the outer manifold 102.

[0089] In another example, a plasma current may circulate around the magnetic flux 138A as the plasma current flows along the electric field 136A, resulting in a current that flows through the helicity injection tube 116A without contacting interior surfaces of the helicity injection tube 116A. The magnetic fluxes 138B-L and the electric fields 136B-L may also facilitate respective plasma current components that flow through the respective helicity injection tubes 116B-L without contacting interior surfaces of the helicity injection tubes 116B-L.

[0090] At block 508, the method includes diverting portions of the plasma into respective helicity injection tubes that connect the outer manifold to the inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within the inner manifold.

[0091] For example, the voltage coils 126A-L and the flux coils 128A-L may be used to divert plasma from the outer manifold 102 into the inner manifold 110, via the helicity injection tubes 116A-L. Alternatively, the voltage coils 127A-L may be used to divert plasma from the outer manifold 102 into the inner manifold 110, via the helicity injection tubes 116A-L.

[0092] The current that flows into the inner manifold 110 via the helicity injection tubes

116A-L may continue to circulate within the inner manifold 110. For example, plasma current may flow along the toroidal electric fields 140A, 140B, 140C, 140D, 140E, 140F, 140G, 140H, 140I, 140J, 140K, and 140L. These plasma currents may circulate around the toroidal magnetic fluxes 142A, 142B, 142C, 142D, 142E, 142F, 142G, 142H, 142I, 142J, 142K, and 142L, resulting in plasma currents having toroidal and poloidal components flowing within the inner manifold 110. The magnetic fluxes 142A-L may direct plasma currents away from interior surfaces of the inner manifold 110.

[0093] In some examples, the voltage coils 126A-L (or voltage coils 127A-L) and the flux coils 128A-L may inject helicity from the outer manifold 102 into the inner manifold 110 at a substantially constant rate. This may result in a spheromak equilibrium being present within the inner manifold 110.

[0094] While various example aspects and example embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various example aspects and example embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

CLAIMS

1. A plasma confinement system comprising:

a substantially torus-shaped outer manifold aligned on a mid-plane of the plasma confinement system, wherein the outer manifold comprises a first helicity injection port at an inner radius of the outer manifold;

a substantially torus-shaped inner manifold aligned on the mid-plane within the inner radius of the outer manifold, wherein the inner manifold comprises a second helicity injection port at an outer radius of the inner manifold; and

a helicity injection tube on the mid-plane, wherein the helicity injection tube connects the first helicity injection port to the second helicity injection port.

2. The plasma confinement system of claim 1, further comprising:

a third helicity injection port at the outer radius of the inner manifold; and

a diagnostic port at the outer radius of the inner manifold, wherein the diagnostic port is between the second helicity injection port and the third helicity injection port.

3. The plasma confinement system of any of claims 1 or 2, further comprising a plasma sensor coupled to the diagnostic port.

4. The plasma confinement system of any of claims 1-3, wherein the helicity injection tube is a first helicity injection tube, the plasma confinement system further comprising:

a third helicity injection port at the outer radius of the inner manifold;

a fourth helicity injection port at the inner radius of the outer manifold;

a second helicity injection tube on the mid-plane, wherein the second helicity injection tube connects the third helicity injection port to the fourth helicity injection port; and

a voltage coil that is adjacent to the inner radius of the outer manifold and between the first helicity injection tube and the second helicity injection tube.

5. The plasma confinement system of claim 4, wherein the voltage coil is configured to induce a toroidal electric field within the outer manifold between the first helicity injection tube and the second helicity injection tube.

6. The plasma confinement system of any of claims 1-5, wherein the helicity injection tube is a first helicity injection tube, the plasma confinement system further comprising:

a third helicity injection port at the outer radius of the inner manifold;

a fourth helicity injection port at the inner radius of the outer manifold;

a second helicity injection tube on the mid-plane, wherein the second helicity injection tube connects the third helicity injection port to the fourth helicity injection port; and

a flux coil that is wrapped around a section of the outer manifold that is between the first helicity injection tube and the second helicity injection tube.

7. The plasma confinement system of claim 6, wherein the flux coil is configured to induce a toroidal magnetic flux within the outer manifold between the first helicity injection tube and the second helicity injection tube.

8. The plasma confinement system of any of claims 1-7, further comprising a voltage coil adjacent to the helicity injection tube and between the outer manifold and the inner manifold.

9. The plasma confinement system of claim 8, wherein the voltage coil is configured to induce an electric field along a longitudinal axis of the helicity injection tube.

10. The plasma confinement system of any of claims 1-3 and 6-9, wherein the helicity injection tube is a first helicity injection tube, the plasma confinement system further comprising:

a third helicity injection port at the outer radius of the inner manifold;

a fourth helicity injection port at the inner radius of the outer manifold;

a second helicity injection tube on the mid-plane, wherein the second helicity injection tube connects the third helicity injection port to the fourth helicity injection port; and

a voltage coil that is adjacent to the inner radius of the outer manifold, between the first helicity injection tube and the second helicity injection tube, and adjacent to both the first helicity injection tube and the second helicity injection tube.

11. The plasma confinement system of claim 10, wherein the voltage coil is configured to induce a toroidal electric field within the outer manifold between the first helicity injection tube and the second helicity injection tube and configured to induce electric fields along respective longitudinal axes of the first helicity injection tube and the second helicity injection tube.

12. The plasma confinement system of any of claims 1-11, further comprising a flux coil wrapped around the helicity injection tube.

13. The plasma confinement system of claim 12, wherein the flux coil is configured to induce a magnetic flux along a longitudinal axis of the helicity injection tube.

14. The plasma confinement system of any of claims 1-13, wherein the outer radius of the inner manifold defines a circle with a radius substantially equal to 0.32 meters.

15. The plasma confinement system of any of claims 1-14, wherein an outer radius of the outer manifold defines a circle with a radius substantially equal to 0.48 meters.

16. The plasma confinement system of any of claims 1-15, wherein all interior surfaces of the plasma confinement system form a surface of revolution or have a bend radius of less than 2 centimeters.

17. The plasma confinement system of any of claims 1-16, wherein an inner diameter of the helicity injection tube is substantially equal to 0.12 meters.

18. The plasma confinement system of any of claims 1-17, wherein an inner diameter of the outer manifold is substantially equal to 0.12 meters.

19. The plasma confinement system of any of claims 1-18, wherein the plasma confinement system comprises 12 helicity injection tubes.

20. The plasma confinement system of claim 19, wherein the outer manifold and the 12 helicity injection tubes are collectively made up of 24 pre-formed components.

21. The plasma confinement system of any of claims 1-20, wherein all interior surfaces of the plasma confinement system are coated with an insulating material.

22. A method for maintaining a plasma in a plasma confinement system comprising a substantially torus-shaped inner manifold and a substantially torus-shaped outer manifold, the method comprising:

flowing a gas into the plasma confinement system;

using a plurality of voltage coils to induce time-varying electric fields within respective sections of the outer manifold, thereby energizing at least a portion of the gas into a plasma having a toroidal current component within the outer manifold, wherein the electric fields are mutually out of phase with each other;

using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold, wherein the magnetic fluxes are mutually out of phase with each other, and wherein each of the magnetic fluxes is in phase with a respective electric field of the electric fields; and

diverting portions of the plasma into respective helicity injection tubes that connect the outer manifold to the inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within the inner manifold.

23. The method of claim 22, wherein the plasma within the outer manifold is directed away from interior surfaces of the outer manifold via the time-varying magnetic fluxes.

24. The method of any of claims 22-23, wherein the plasma within the inner manifold is directed away from interior surfaces of the inner manifold via the time-varying magnetic fluxes.

25. The method of any of claims 22-24, wherein the plasma within the inner manifold is at a spheromak equilibrium.

26. The method of any of claims 22-25, wherein diverting the portions of the plasma into the respective helicity injection tubes comprises injecting helicity from the outer manifold into the inner manifold at a substantially constant rate.

27. The method of any of claims 22-26,

wherein each electric field of the electric fields is out of phase with another electric field of the electric fields by $n*\pi/6$ radians,

wherein each magnetic flux of the magnetic fluxes is out of phase with another magnetic flux of the magnetic fluxes by $n*\pi/6$ radians, and

wherein n is an integer that represents a perturbation mode and m is an integer that represents the number of electric fields included within the electric fields and the number of magnetic fluxes included within the magnetic fluxes.

28. The method of claim 27, wherein n is greater than 0 and less than 7.

29. The method of any of claims 22-28, wherein at least one voltage coil of the plurality of voltage coils is adjacent to an inner radius of the outer manifold and between a first helicity injection tube and a second helicity injection tube of the respective helicity injection tubes.

30. The method of any of claims 22-29, wherein at least one voltage coil of the plurality of voltage coils is adjacent to a helicity injection tube of the respective helicity injection tubes and between the outer manifold and the inner manifold.

31. The method of any of claims 22-28, wherein at least one voltage coil of the plurality of voltage coils is adjacent to an inner radius of the outer manifold, between a first helicity injection tube and a second helicity injection tube of the respective helicity injection

tubes, and adjacent to both the first helicity injection tube and the second helicity injection tube.

32. A non-transitory computer readable medium storing instructions that, when executed by a controller, cause the controller to perform functions for maintaining a plasma in a plasma confinement system comprising a substantially torus-shaped inner manifold and a substantially torus-shaped outer manifold, the functions comprising:

flowing a gas into the plasma confinement system;

using a plurality of voltage coils to induce time-varying electric fields within respective sections of the outer manifold, thereby energizing at least a portion of the gas into a plasma having a toroidal current component within the outer manifold, wherein the electric fields are mutually out of phase with each other;

using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold, wherein the magnetic fluxes are mutually out of phase with each other, and wherein each of the magnetic fluxes is in phase with a respective electric field of the electric fields; and

diverting portions of the plasma into respective helicity injection tubes that connect the outer manifold to the inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within the inner manifold.

33. The non-transitory computer readable medium of claim 32, wherein the plasma within the outer manifold is directed away from interior surfaces of the outer manifold via the time-varying magnetic fluxes.

34. The non-transitory computer readable medium of any of claims 32-33, wherein the plasma within the inner manifold is directed away from interior surfaces of the inner manifold via the time-varying magnetic fluxes.

35. The non-transitory computer readable medium of any of claims 32-34, wherein the plasma within the inner manifold is at a spheromak equilibrium.

36. The non-transitory computer readable medium of any of claims 32-35, wherein diverting the portions of the plasma into the respective helicity injection tubes comprises injecting helicity from the outer manifold into the inner manifold at a substantially constant rate.

37. The non-transitory computer readable medium of any of claims 32-36,

wherein each electric field of the electric fields is out of phase with another electric field of the electric fields by $n*\pi/6$ radians,

wherein each magnetic flux of the magnetic fluxes is out of phase with another magnetic flux of the magnetic fluxes by n*π/6 radians, and

wherein n is an integer that represents a perturbation mode and m is an integer that represents the number of electric fields included within the electric fields and the number of magnetic fluxes included within the magnetic fluxes.

38. The non-transitory computer readable medium of claim 37, wherein n is greater than 0 and less than 7.

39. The non-transitory computer readable medium of any of claims 32-38, wherein at least one voltage coil of the plurality of voltage coils is adjacent to an inner radius of the outer manifold and between a first helicity injection tube and a second helicity injection tube of the respective helicity injection tubes.

40. The non-transitory computer readable medium of any of claims 32-39, wherein at least one voltage coil of the plurality of voltage coils is adjacent to a helicity injection tube of the respective helicity injection tubes and between the outer manifold and the inner manifold.

41. The non-transitory computer readable medium of any of claims 32-38, wherein at least one voltage coil of the plurality of voltage coils is adjacent to an inner radius of the outer manifold, between a first helicity injection tube and a second helicity injection tube of the respective helicity injection tubes, and adjacent to both the first helicity injection tube and the second helicity injection tube.

42. A computing device comprising:

a controller; and

a non-transitory computer readable medium storing instructions that, when executed by the controller, cause the controller to perform functions for maintaining a plasma in a plasma confinement system comprising a substantially torus-shaped inner manifold and a substantially torus-shaped outer manifold, the functions comprising:

flowing a gas into the plasma confinement system;

using a plurality of voltage coils to induce time-varying electric fields within respective sections of the outer manifold, thereby energizing at least a portion of the gas into a plasma having a toroidal current component within the outer manifold, wherein the electric fields are mutually out of phase with each other;

using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold, wherein the magnetic fluxes

are mutually out of phase with each other, and wherein each of the magnetic fluxes is in phase with a respective electric field of the electric fields; and

diverting portions of the plasma into respective helicity injection tubes that connect the outer manifold to the inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within the inner manifold.

43. The computing device of claim 42, wherein the plasma within the outer manifold is directed away from interior surfaces of the outer manifold via the time-varying magnetic fluxes.

44. The computing device of any of claims 42-43, wherein the plasma within the inner manifold is directed away from interior surfaces of the inner manifold via the time-varying magnetic fluxes.

45. The computing device of any of claims 42-44, wherein the plasma within the inner manifold is at a spheromak equilibrium.

46. The computing device of any of claims 42-45, wherein diverting the portions of the plasma into the respective helicity injection tubes comprises injecting helicity from the outer manifold into the inner manifold at a substantially constant rate.

47. The computing device of any of claims 42-46,

wherein each electric field of the electric fields is out of phase with another electric field of the electric fields by $n*\pi/6$ radians,

wherein each magnetic flux of the magnetic fluxes is out of phase with another magnetic flux of the magnetic fluxes by $n*\pi/6$ radians, and

wherein n is an integer that represents a perturbation mode and m is an integer that represents the number of electric fields included within the electric fields and the number of magnetic fluxes included within the magnetic fluxes.

48. The computing device of claim 47, wherein n is greater than 0 and less than 7.

49. The computing device of any of claims 42-48, wherein at least one voltage coil of the plurality of voltage coils is adjacent to an inner radius of the outer manifold and between a first helicity injection tube and a second helicity injection tube of the respective helicity injection tubes.

50. The computing device of any of claims 42-49, wherein at least one voltage coil of the plurality of voltage coils is adjacent to a helicity injection tube of the respective helicity injection tubes and between the outer manifold and the inner manifold.

51. The computing device of any of claims 42-48, wherein at least one voltage coil of the plurality of voltage coils is adjacent to an inner radius of the outer manifold, between a first helicity injection tube and a second helicity injection tube of the respective helicity injection tubes, and adjacent to both the first helicity injection tube and the second helicity injection tube.

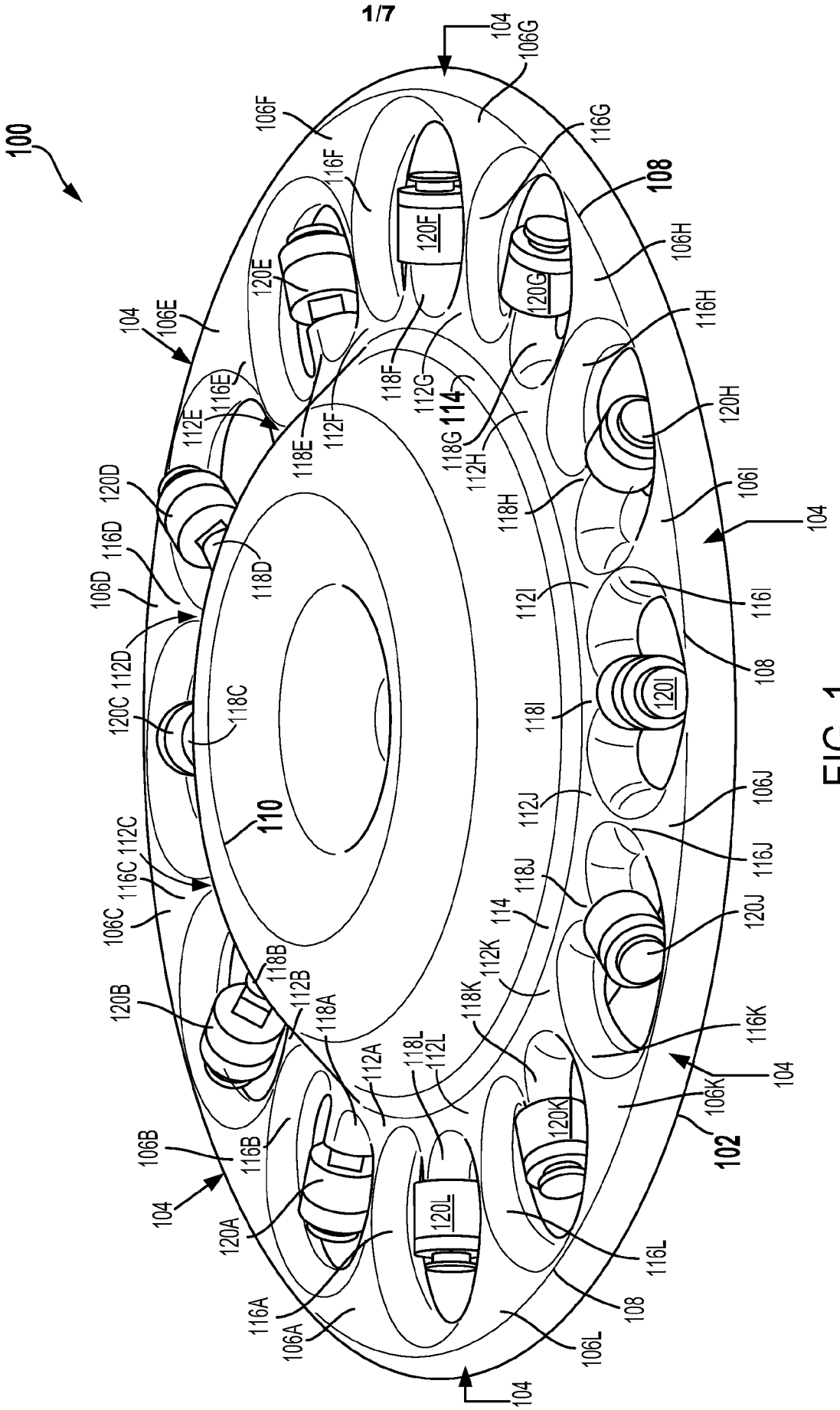

100
102
104
106A
106B
106C
106D
106E
106F
106G
106H
106I
106J
106K
106L
108
110
112A
112B
112C
112D
112E
112F
112G
112H
112I
112J
112K
112L
114
116A
116B
116C
116D
116E
116F
116G
116H
116I
116J
116K
116L
118A
118B
118C
118D
118E
118F
118G
118H
118I
118J
118K
118L
120A
120B
120C
120D
120E
120F
120G
120H
120I
120J
120K
120L

FIG. 1

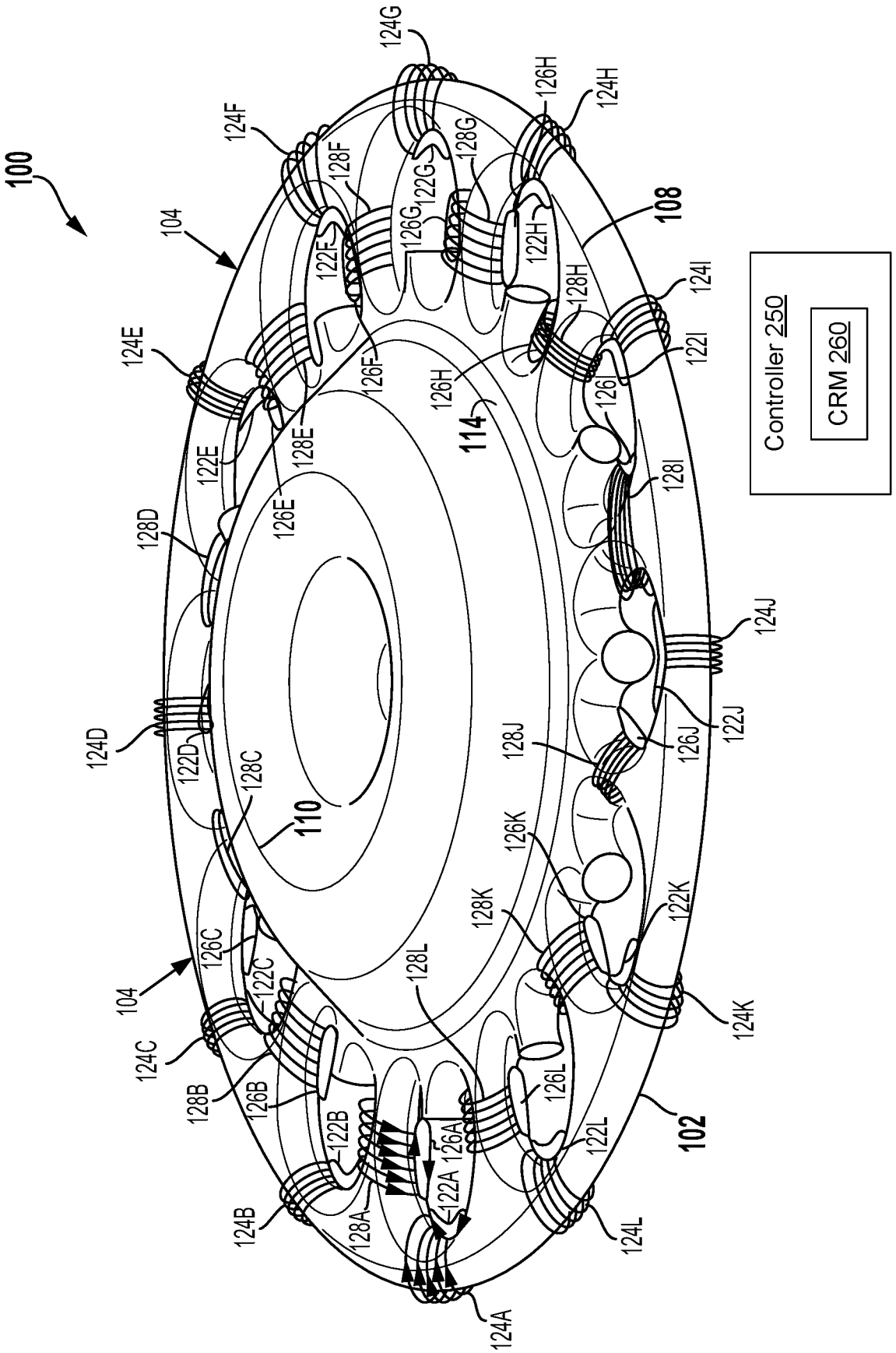

100
104
102
108
110
114
Controller 250
CRM 260
124A
124B
124C
124D
124E
124F
124G
124H
124I
124J
124K
124L
122A
122B
122C
122D
122E
122F
122G
122H
122I
122J
122K
122L
126A
126B
126C
126E
126F
126G
126H
126I
126J
126K
126L
128A
128B
128C
128D
128E
128F
128G
128H
128I
128J
128K
128L

FIG. 2A

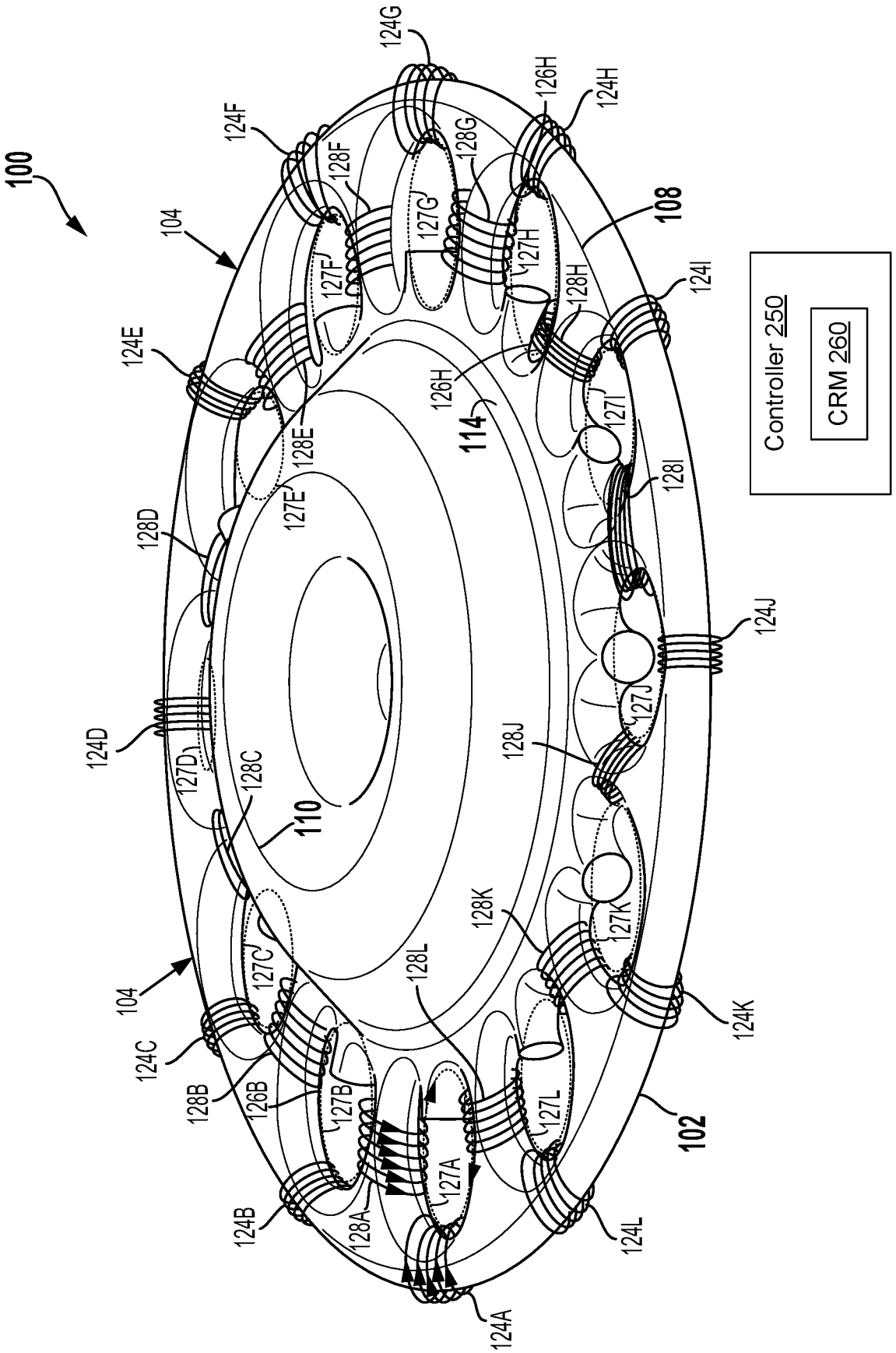

100
104
102
108
110
114
124A
124B
124C
124D
124E
124F
124G
124H
124I
124J
124K
124L
126B
126H
127A
127B
127C
127D
127E
127F
127G
127H
127I
127J
127K
127L
128A
128B
128C
128D
128E
128F
128G
128H
128I
128J
128K
128L
Controller 250
CRM 260

FIG. 2B

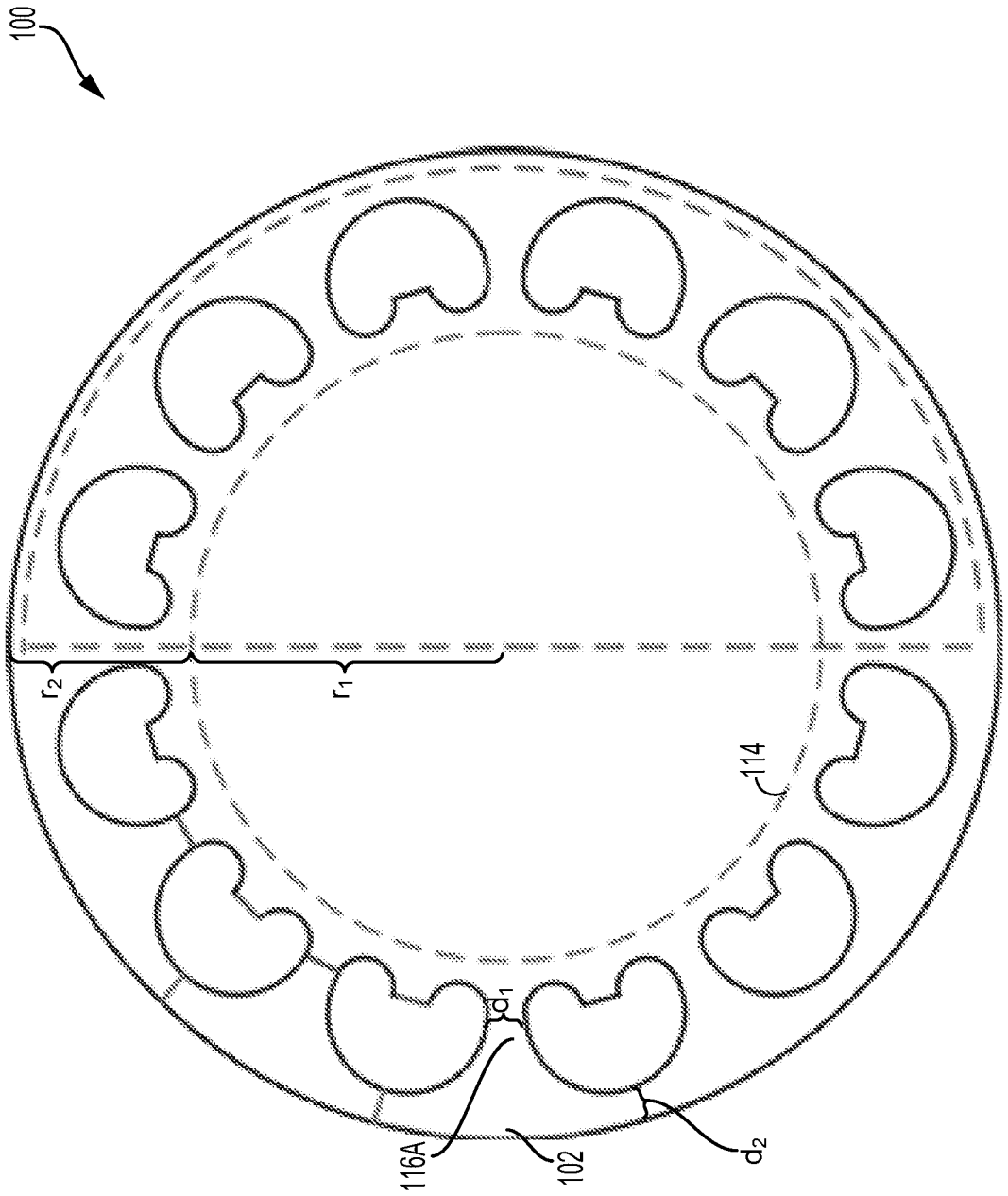


FIG. 3

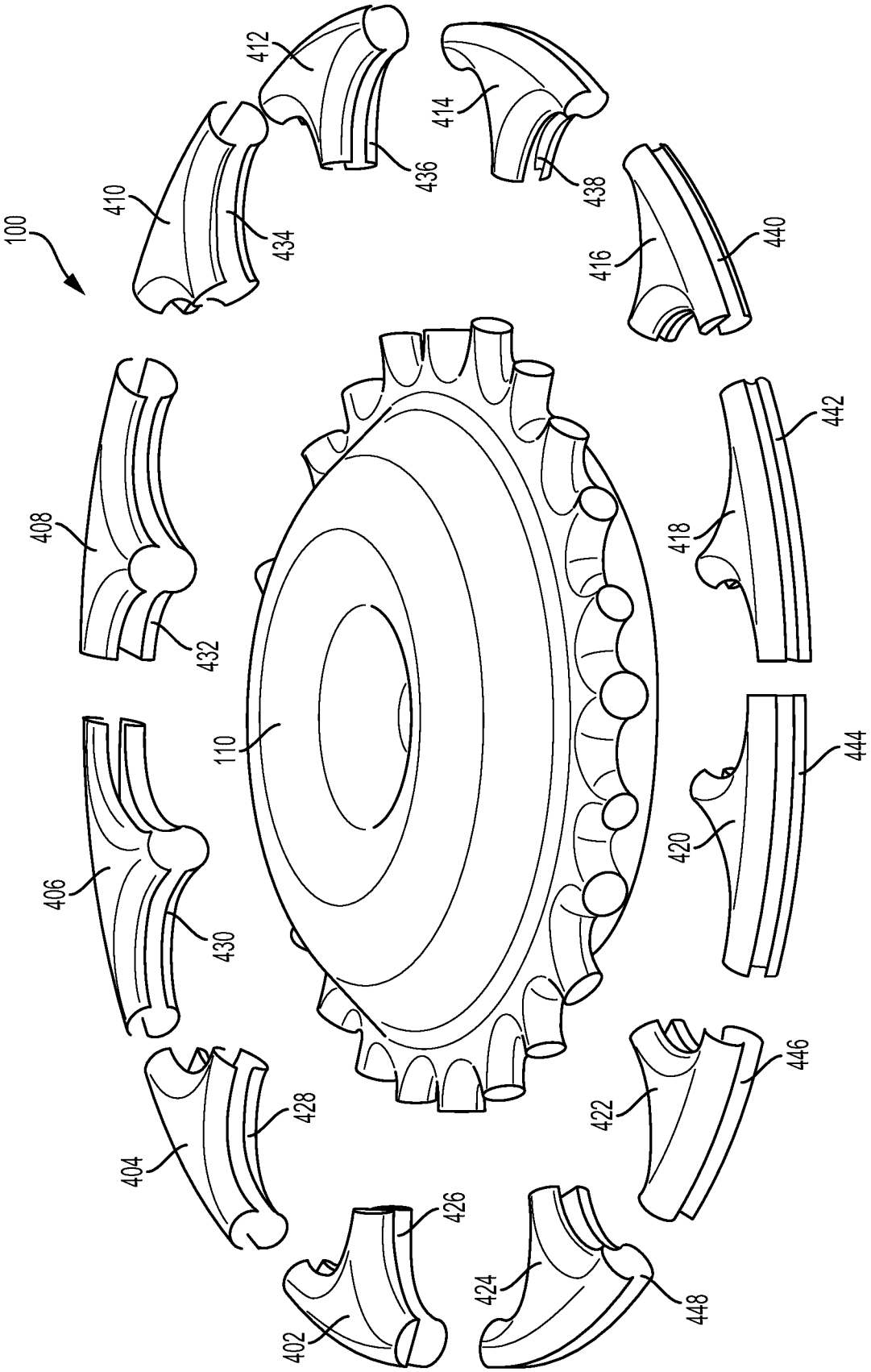

100
110
402
404
406
408
410
412
414
416
418
420
422
424
426
428
430
432
434
436
438
440
442
444
446
448

FIG. 4

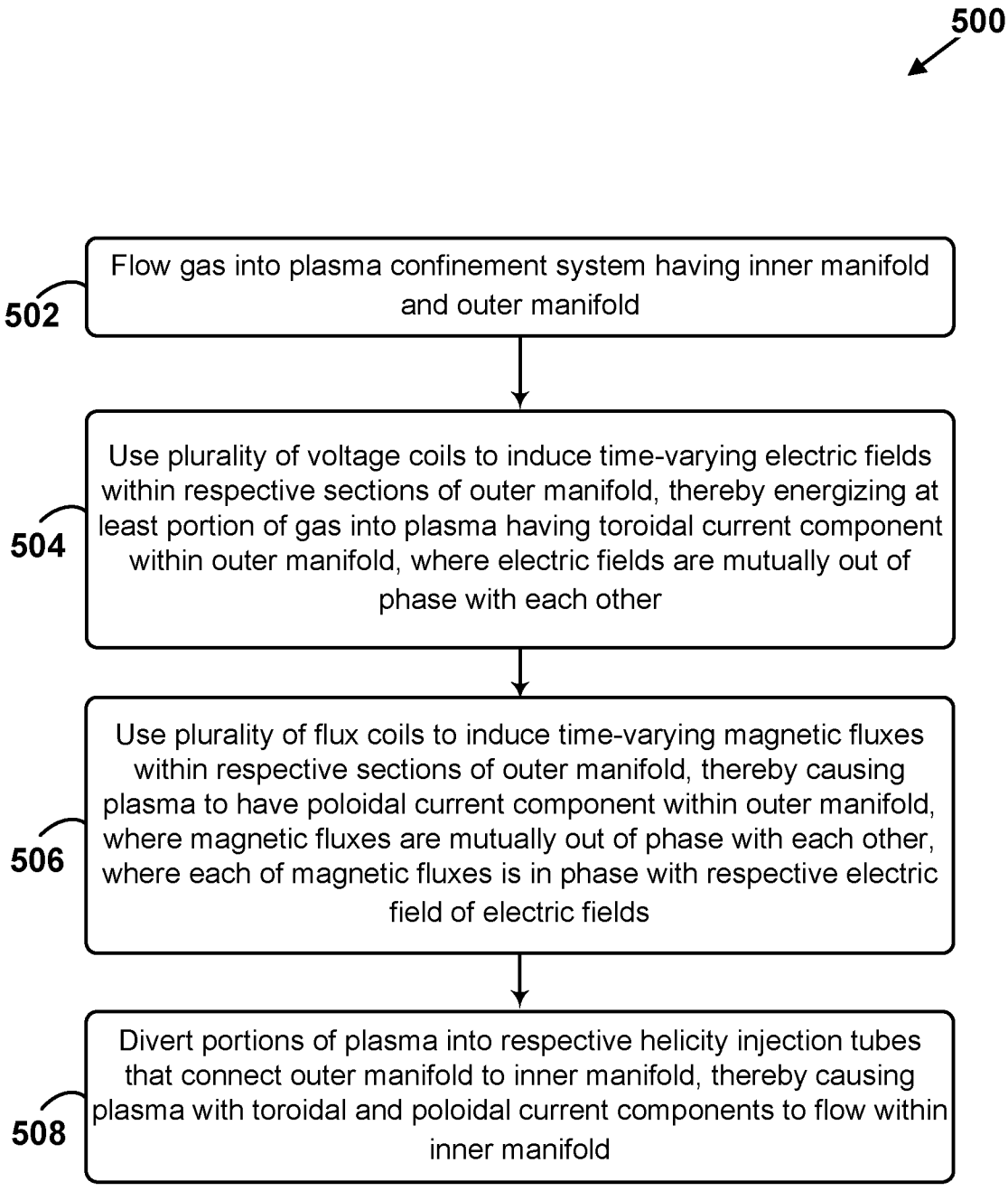

500
502
Flow gas into plasma confinement system having inner manifold and outer manifold
504
Use plurality of voltage coils to induce time-varying electric fields within respective sections of outer manifold, thereby energizing at least portion of gas into plasma having toroidal current component within outer manifold, where electric fields are mutually out of phase with each other
506
Use plurality of flux coils to induce time-varying magnetic fluxes within respective sections of outer manifold, thereby causing plasma to have poloidal current component within outer manifold, where magnetic fluxes are mutually out of phase with each other, where each of magnetic fluxes is in phase with respective electric field of electric fields
508
Divert portions of plasma into respective helicity injection tubes that connect outer manifold to inner manifold, thereby causing plasma with toroidal and poloidal current components to flow within inner manifold

FIG. 5

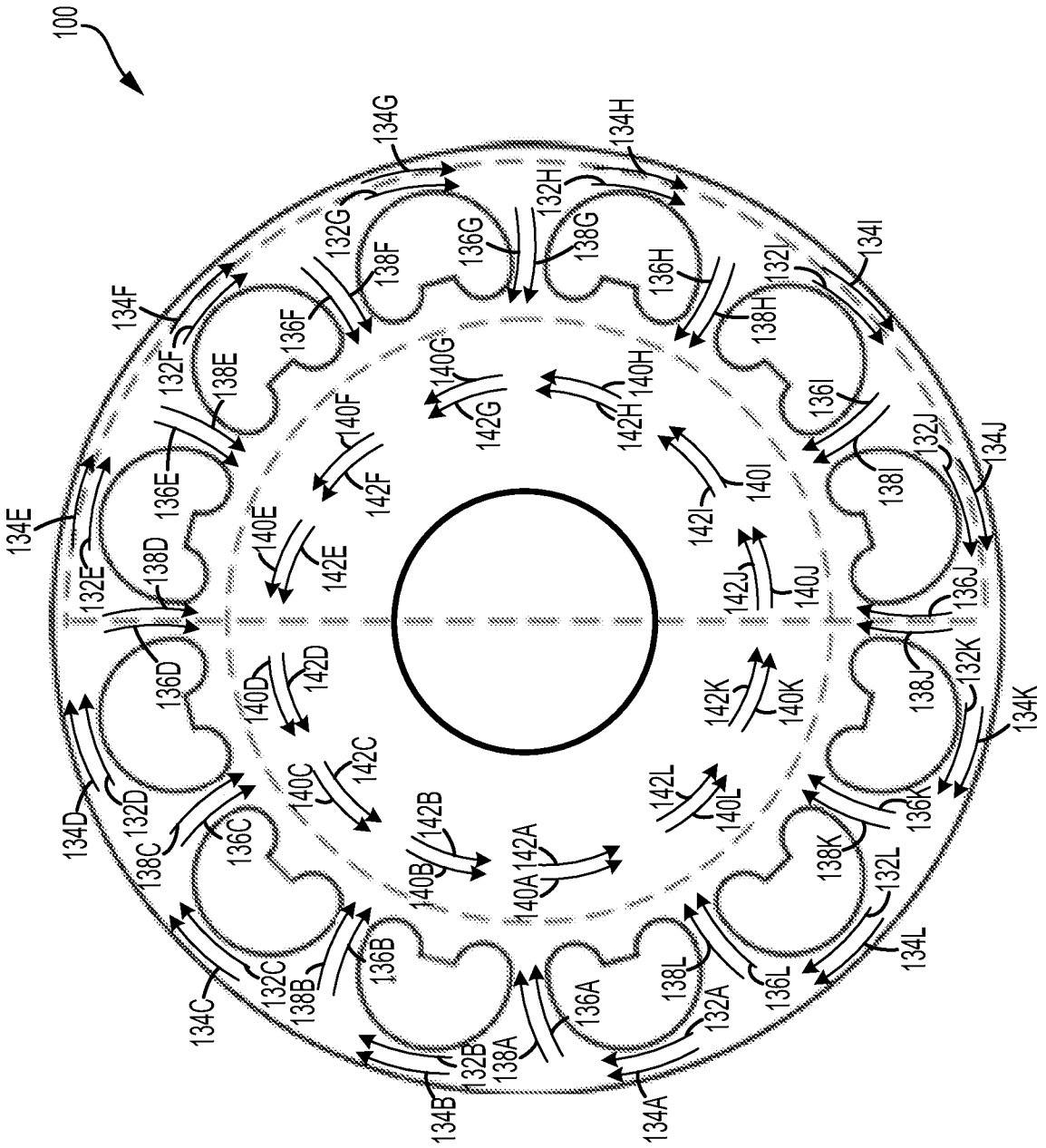

100
134A
134B
134C
134D
134E
134F
134G
134H
134I
134J
134K
134L
132A
132B
132C
132D
132E
132F
132G
132H
132I
132J
132K
132L
136A
136B
136C
136D
136E
136F
136G
136H
136I
136J
136K
136L
138A
138B
138C
138D
138E
138F
138G
138H
138I
138J
138K
138L
140A
140B
140C
140D
140E
140F
140G
140H
140I
140J
140K
140L
142A
142B
142C
142D
142E
142F
142G
142H
142I
142J
142K
142L

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/057494

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H05H 1/12; H05H 1/02 (2017.01)
CPC - H05H 1/12; G21B 1/05; H01J 37/32935 (2017.01)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC - G21B 1/00; G21B 1/05; G21B 1/11; H05H 1/02; H05H 1/12
CPC - G21B 1/05; H01J 37/32935; H05H 1/12; Y02E 30/122; Y02E 30/126

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 216/59; 216/67; 376/128; 376/133; 376/142; 376/143 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Patents, Google Scholar
Search terms used: plasma, confinement, sensor, diagnostic, port, helicity, injection

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2015/0055739 A1 (UNIVERSITY OF WASHINGTON THROUGH ITS CENTER FOR COMMERCIALIZATION) 26 February 2015 (26.02.2015) entire document	1-3
Y	US 2014/0321587 A1 (UNIVERSITY OF WASHINGTON THROUGH ITS CENTER FOR COMMERCIALIZATION) 30 October 2014 (30.10.2014) entire document	1-3
Y	US 2012/0074951 A1 (CHEN et al) 29 March 2012 (29.03.2012) entire document	2, 3
A	US 2005/0194099 A1 (JEWETT JR et al) 08 September 2005 (08.09.2005) entire document	1-3

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 January 2017	07 FEB 2017
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/057494

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 4-21, 25-31, 35-41, 45-51
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See supplemental page

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-3

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Continued from Box No. III Observations where unity of invention is lacking

Linking language: a plasma confinement system comprising: a substantially torus-shaped outer manifold; a substantially torus-shaped inner manifold; a helicity injection tube

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-3, drawn to a plasma confinement system.
Group II, claims 22-24,32-34,42-44, drawn to maintaining a plasma in a plasma confinement system.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: a first helicity injection port at an inner radius of the outer manifold; a second helicity injection port at an outer radius of the inner manifold; wherein the helicity injection tube connects the first helicity injection port to the second helicity injection port; aligning a manifold on a mid-plane of the plasma confinement system as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: wherein the electric fields are mutually out of phase with each other; using a plurality of flux coils to induce time-varying magnetic fluxes within the respective sections of the outer manifold, thereby causing the plasma to have a poloidal current component within the outer manifold, wherein the magnetic fluxes are mutually out of phase with each other, and wherein each of the magnetic fluxes is in phase with a respective electric field of the electric fields as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of a plasma confinement system comprising: a substantially torus-shaped outer manifold; a substantially torus-shaped inner manifold; a helicity injection tube, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2005/0194099 A1 (JEWETT, JR et al) 08 September 2005 (08.09.2005) teaches a plasma confinement system comprising (Para. 11): a substantially torus-shaped outer manifold (Para. 23 and Fig. 1); a substantially torus-shaped inner manifold (Para. 23 and Fig. 1); a helicity injection tube (Paras. 31-32 and Fig. 5).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.