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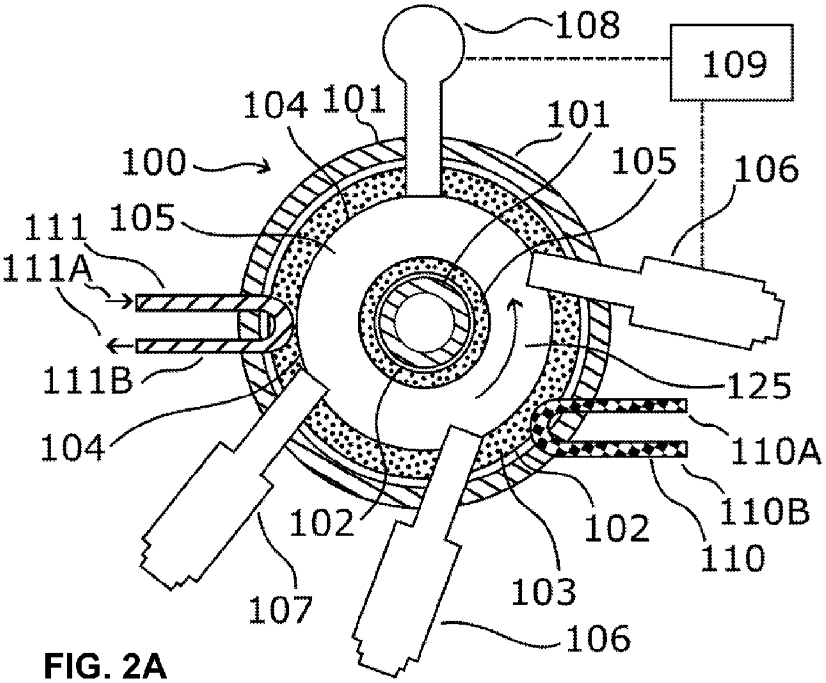

FIG. 2A

(57) **Abstract:** The present disclosure is directed to systems for generating neutrons, the systems including a stellarator optimized for fast particle finement. In some embodiments, the stellarator optimized for fast particle confinement is selected from a quasi-axisymmetric stellarator, a quasi-symmetric stellarator, a quasi-isodynamic stellarator, or a quasi-omnigenous stellarator. The present disclosure is also directed to methods of generating neutrons using the systems of the present disclosure and, in particular, systems incorporating a stellarator optimized for fast particle confinement.

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SYSTEM AND METHOD FOR STELLARATOR NEUTRON SOURCE

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0001] This invention was made with government support under Grant No. DE-AC02-09CH11466 awarded by the Department of Energy. The government has certain rights in the invention.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] The present disclosure claims the benefit of the filing date of United States Provisional Patent Application No. 63/319,588 filed on March 14, 2022, the disclosure of which is hereby incorporated by reference herein in its entirety.

FIELD OF THE DISCLOSURE

[0003] The present disclosure is generally directed to neutron sources and, in particular, systems for generating neutrons which include a stellarator capable of fast particle confinement.

BACKGROUND OF THE DISCLOSURE

[0004] Neutron sources, devices that can release neutrons, allow for the synthesis of useful isotopes. There are many types of neutron sources, from hand-held radioactive sources to research reactors and fission sources in neutron research facilities. Fusion neutron sources have been described for several applications. A common early concept was to use a blanket of fission fuel such as uranium or plutonium to generate energy. Lehnert (1975) and Kolesnichenko *et al.* (1976) present this possibility as a first logical step in fusion power (*see* Lehnert, B. 1975. Nuclear Instruments and Methods 129 (1): 27–30; *see* Kolesnichenko, Ya I., and S. N. Reznik. 1976. Nuclear Fusion 16 (1): 97). Hendel and Jassby (1990) list this application in their review on tokamak neutron source experimental results (*see* Hendel, H. W., and D. L. Jassby. 1990. Nuclear Science and Engineering 106 (2): 114–37).

[0005] The concept of using a beam of ions (sometimes injected as neutral atoms) and a plasma target to cause fusion events was developed in the 1970s as the "wet wood burner" concept, evoking the image that, if a plasma cannot ignite, an exterior source of heat can produce combustion. An early article describing the concept was authored by Dawson *et al.* (1971) (*see* Dawson, J. M., H. P. Furth, and F. H. Tenney. 1971. Physical Review Letters 26 (19): 1156–60). Dawson describes a system in which deuterium is injected via neutral beam into a cold tritium plasma, for the purpose of generating thermonuclear energy. Dawson's target plasma is contained in a torus, and the paper describes that the tokamak is the most practical choice for magnetic confinement.

[0006] Variations in the "wet wood burner" concept envision different types of devices for magnetic confinement of the plasma. Dawson *et al.* (1971), Jassby (1977), and Hendel and Jassby (1990) describe the use of a tokamak (*see* Jassby, D. L. 1977. Nuclear Fusion 17 (2): 309). Others describe less conventional plasma targets such as magnetic mirrors and screw taps. Lehnert (1975) describes high-density, low-temperature screw traps. Price *et al.* (1986) describe a high-pressure linear device like a magnetic mirror (*see* Price, Robert E., Geoffrey W. Shuy, and James T. Woo. 1986. Fusion Technology 10 (3P2B): 1412–17). Forest *et al.* (2020) describe a high-magnetic-field magnetic mirror (*see* Forest, Cary, *et al.* 2020. PPPL Colloquium, Princeton Plasma Physics Laboratory, Princeton, NJ, USA, October 14). SHINE technologies and Heikken (1988) describe systems in which the target is not in the plasma state, such as a solid-state target or a gas target (*see* SHINE Technologies, https://www.shinefusion.com/; *see* Heikkinen, D. W. 1988. UCRL-98946; CONF-881151-13. Lawrence Livermore National Lab., CA (USA). SHINE, Kolesnichenko *et al.* (1976), and Hendel *et al.* (1986) have recommended the injection of deuterium beams into a deuterium target, because of the greater availability and safety of deuterium.

[0007] The Large Helical Device (LHD), operated by the Japanese National Institute for Fusion Science and described by Seki *et al.* (2019) is a plasma physics experiment *see* (Seki, Ryosuke, *et al.* 2019. Plasma and Fusion Research 14: 3402126–3402126). The LHD has been configured to include negative ion-based neutral beam injectors, whereby the negative ion-based neutral beam has been injected into a deuterium plasma contained by a stellarator. While this reaction produced neutrons, this stellarator was not optimized for fast particle confinement and, as a result, the neutron generation rate was impractically low for any economic purpose. Furthermore, the purpose of the experiment was to support models of plasma physics to create a thermonuclear energy power plant, rather than the economic generation of neutrons.

[0008] SHINE's commercial fusion neutron sources have produced rates of $5x10^{11}$ neutrons per second (n/s) for deuterium ions into a gaseous deuterium target and $3x10^{13}$ n/s for deuterium ions into a gaseous tritium. The TFTR tokamak was configured to introduce deuterium beams into a deuterium plasma and, as a result, was in principle able to produce D-D neutrons at a rate of $1x10^{17}$ n/s for brief pulses as part of a plasma physics experiment according to Hendel and Jassby (1990).

[0009] To-date, the creation of useful isotopes via neutron bombardment isa very costly process. Indeed, the isotopes produced according to such a process are incredibly expensive to manufacture and/or purchase in useful quantities. For example, tritium currently costs tens of thousands of dollars per gram on the open market. Future estimates for fusion power production indicate that about 300 grams of tritium would be required per day to produce about 800 MW of electrical power, which would require millions of dollars per day just of tritium.

[0010] It would be useful to develop a system that was able to produce a large quantity of neutrons to facilitate economical isotope production.

BRIEF SUMMARY OF THE DISCLOSURE

[0011] Disclosed herein are systems and methods for generating neutrons. In particular, the disclosed systems and methods disclosed herein utilize one or more stellarators optimized for fast particle confinement. Ions, such as deuterium ions, are accelerated via negative ion-based neutral beams to energies at which the deuterium-deuterium ("D-D") fusion cross-section is significant (e.g., greater than at least 100 millibarns); and injected (as neutral atoms) into a stellarator that has been optimized for fast ion confinement to generate a flux of neutrons. These neutrons can be used to bombard one or more target materials (e.g., solid targets, liquid targets, gaseous targets) to generate a desired isotope.

[0012] A first aspect of the present disclosure is a system comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing high energy neutral atoms into the plasma in a second angular direction;

and (vi) an electron heater adapted to heat electrons in the plasma. In some embodiments, the plasma is a deuterium plasma.

[0013] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0014] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0015] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0016] In some embodiments, the system further comprises at least one material transfer system. In some embodiments, a first of the at least one material transfer system is in communication with the first volume. In some embodiments, the first of the at least one material transfer system is communicatively coupled to a material isolation system. In some embodiments, a second of the at least one material transfer system is in communication with the second volume. In some embodiments, the second of the at least one material transfer system is communicatively coupled to a material isolation system. In some embodiments, the second of the at least one material transfer system is adapted for introducing a flowable target into the second volume. In some embodiments, the second of the at least one material transfer system is adapted for introducing a solid target into the second volume.

[0017] In some embodiments, the electron heater is communicatively coupled to a controller.

[0018] In some embodiments, the stellarator optimized for fast particle confinement is a quasi-axisymmetric stellarator. In some embodiments, the stellarator optimized for fast particle confinement is a quasi-symmetric stellarator. In some embodiments, the stellarator optimized for fast particle confinement is a quasi-isodynamic stellarator. In some embodiments, the stellarator optimized for fast particle confinement is quasi-omnigenous stellarator.

[0019] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (b) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0020] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.

[0021] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0022] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0023] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

[0024] A second aspect of the present disclosure is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the blanket is positioned between the stellarator and the casing; (iv) at least a first negative ion-based neutral beam injector for introducing a first beam of high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second beam of high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma.

[0025] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0026] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0027] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0028] In some embodiments, the system further comprises at least one material transfer system. In some embodiments, a first of the at least one material transfer system is in communication with the first volume. In some embodiments, the first of the at least one material transfer system is communicatively coupled to a material isolation system. In some embodiments, a second of the at least one material transfer system is in communication with the second volume. In some embodiments, the second of the at least one material transfer system is communicatively coupled to a material isolation system. In some embodiments, the second of the at least one material transfer system is adapted for introducing a flowable target into the second volume. In some embodiments, the second of the at least one material transfer system is adapted for introducing a solid target into the second volume.

[0029] In some embodiments, the electron heater is communicatively coupled to a controller.

[0030] In some embodiments, the stellarator optimized for fast particle confinement is a quasi-axisymmetric stellarator. In some embodiments, the stellarator optimized for fast particle confinement is a quasi-symmetric stellarator. In some embodiments, the stellarator optimized for fast particle confinement is a quasi-isodynamic stellarator. In some embodiments, the stellarator optimized for fast particle confinement is quasi-omnigenous stellarator.

[0031] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (b) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0032] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.

[0033] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0034] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0035] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

[0036] A third aspect of the present disclosure is a method for generating neutrons, comprising: generating a negative ion neutral beam, such as to accelerate neutral atoms to an energy at which the D-D cross section is significant; and injecting the generated negative ion neutral beam into a stellarator optimized for fast particle confinement and controlling the electron temperature so that the beam-slowing down time is long enough for the fast ions to generate neutrons at a desired flux. In some embodiments, the method further comprises forming tritium by bombarding deuterium using the generated neutrons. In some embodiments, the method further comprises capturing and filtering plasma from the stellarator to isolate any tritium that has been formed. In some embodiments, the stellarator optimized for fast particle confinement is a quasi-isodynamic stellarator. In some embodiments, the stellarator optimized for fast particle confinement is quasi-omnigenous stellarator.

[0037] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.

[0038] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0039] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0040] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

BRIEF DESCRIPTION OF THE FIGURES

[0041] For a general understanding of the features of the disclosure, reference is made to the drawings. In the drawings, like reference numerals have been used throughout to identify identical elements.

[0042] FIG. 1 illustrates a block diagram of a system for generating neutrons in accordance with one embodiment of the present disclosure.

[0043] FIG. 2A illustrates a cross-section of a system for generating neutrons in accordance with one embodiment of the present disclosure.

[0044] FIG. 2B illustrates a cross-section of a system for generating neutrons in accordance with one embodiment of the present disclosure.

[0045] FIG. 3 illustrates a negative ion-based neutral beam injector in accordance with one embodiment of the present disclosure.

[0046] FIG. 4A illustrates a stellarator for use in the systems of the present disclosure in accordance with one embodiment of the present disclosure.

[0047] FIG. 4B illustrates a stellarator for use in the systems of the present disclosure in accordance with some embodiments of the present disclosure. In particular, FIG. 4B illustrates a plurality of planar encircling coils encircling the field-shaping coil system and hence the plasma.

[0048] FIG. 4C illustrates a top-down view of a stellarator for use in the systems of the present disclosure in accordance with some embodiments of the present disclosure.

[0049] FIG. 4D illustrates a cross sectional view of a stellarator for use in the systems of the present disclosure in accordance with some embodiments of the present disclosure.

[0050] FIG. 5 provides a flowchart of a method for generating neutrons in accordance with some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0051] It should also be understood that, unless clearly indicated to the contrary, in any methods claimed herein that include more than one step or act, the order of the steps or acts of the method is not necessarily limited to the order in which the steps or acts of the method are recited.

[0052] As used herein, the singular terms "a," "an," and "the" include plural referents unless context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise. The term "includes" is defined inclusively, such that "includes A or B" means including A, B, or A and B.

[0053] As used herein in the specification and in the claims, "or" should be understood to have the same meaning as "and/or" as defined above. For example, when separating items in a list, "or" or "and/or" shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as "only one of or "exactly one of," or, when used in the claims, "consisting of," will refer to the inclusion of exactly one element of a number or list of elements. In general, the term "or" as used herein shall only be interpreted as indicating exclusive alternatives (i.e., "one or the other but not both") when preceded by terms of exclusivity, such as "either," "one of," "only one of" or "exactly one of." "Consisting essentially of," when used in the claims, shall have its ordinary meaning as used in the field of patent law.

[0054] The terms "comprising," "including," "having," and the like are used interchangeably and have the same meaning. Similarly, "comprises," "includes," "has," and the like are used interchangeably and have the same meaning. Specifically, each of the terms is defined consistent with the common United States patent law definition of "comprising" and is therefore interpreted to be an open term meaning "at least the following," and is also interpreted not to exclude additional features, limitations, aspects, etc. Thus, for example, "a device having components a, b, and c" means that the device includes at least components a, b, and c. Similarly, the phrase: "a method involving steps a, b, and c" means that the method includes at least steps a, b, and c. Moreover, while the steps and processes may be outlined herein in a particular order, the skilled artisan will recognize that the ordering steps and processes may vary.

[0055] As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently "at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[0056] Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

[0057] The present disclosure is directed to systems for generating neutrons, the systems including a stellarator optimized for fast particle finement. The present disclosure is also directed to methods of generating neutrons using the systems of the present disclosure and, in particular, systems incorporating a stellarator optimized for fast particle confinement.

[0058] **SYSTEMS**

[0059] FIG. 1 provides an overview of the systems **100** of the present disclosure. In some embodiments, the system **100** includes a casing **104** defining a first volume **105**, a blanket **102** defining a second volume **103** which envelops the casing **104**, and a stellarator **101** adapted to confine a plasma within the first volume **105**, wherein the stellarator **101** encompasses the blanket **102**. The stellarator **101** utilized in the disclosed systems **100** is optimized for past particle confinement. Suitable stellarators **101** that are optimized for past particle confinement are described further herein.

[0060] In some embodiments, the system **100** further includes at least a first negative ion-based neutral beam injector **106** for introducing first high energy neutral atoms into the plasma in a first angular direction; optionally at least a second negative ion-based neutral beam injector **107** for introducing second high energy neutral atoms into the plasma in a second angular direction. In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors **106** and **107**, respectively, are in communication, such as fluidic communication, with the first volume **105**. In some embodiments, the system **100** includes at least one of the optional second negative ion-based neutral beam injectors.

[0061] In some embodiments, the system **100** further includes at least one electron heater **108** adapted to heat electrons in the plasma. In some embodiments, the system **100** includes one electron heater **108**. In other embodiments, the system **100** includes two or more electron heaters **108**. In some embodiments, the electron heater **108** is in communication with the first volume **105**. In some embodiments, the electron heater **108** is communicatively coupled to a controller **109**.

[0062] In some embodiments, the system further comprises one or more heat transfer systems **110** to regulate the thermal properties of the blanket **101**, the second volume **103**, and/or the casing **104**. In some embodiments, the system **100** further includes a material transfer system

111 to introduce one or more target materials into the second volume **103** and/or to remove synthesized materials from the second volume **103**. In some embodiments, the material transfer system **111** is coupled to a material isolation system **112** such that one or more synthesized materials may be isolated from one another and/or such that one or more synthesized materials may be isolated from one or more target materials.

[0063] FIGS. 2A and 2B further depict the system **100** of the present disclosure. The systems **100** of the present disclosure incorporates a stellarator **101** optimized for fast particle confinement. In some embodiments, the stellarator **101** optimized for fast particle confinement is configured to confine at least 85%, at least 90%, at least 95%, at least 96%, at least 97%, at least 98%, at least 98.5%, at least 99% of fast particles in a plasma that includes fast particles. Any stellarator **101** may be used as part of the systems of the present disclosure provided that the stellarator is optimized for fast particle confinement. Non-limiting examples of suitable stellarators **101** optimized for fast particle confinement are described further herein.

[0064] In accordance with one embodiment of the present disclosure, a stellarator **101** optimized for fast particle confinement is shown in FIGS. 2A and 2B as encompassing a blanket **102**, the blanket defining a second volume **103**. In some embodiments, the blanket **102** protects the components of the stellarator **101** from the high heat and high energy neutrons produced by fusion reactions within the plasma. As the neutrons are slowed by the blanket **102**, their kinetic energy is transformed into heat energy and collected by a heat transfer system **110** in communication with the blanket **102** and/or the second volume **103**.

[0065] The second volume **103** defined by the blanket **102** envelops a first volume **105** defined by a casing **104**. The first volume **105** is adapted to enclose a plasma, wherein the plasma enclosed in the first volume **105** is confined by the stellarator **101**. In some embodiments, the plasma is configured to flow in an angular direction **125** (see FIG. 2A). While the angular direction **125** of the plasma within the first volume **105** is depicted in FIG. 2A as counterclockwise, the skilled artisan will appreciate that the angular direction may be clockwise depending on the configuration of the magnetic field introduced onto the plasma by the stellarator **101**. In some embodiments, the angular direction may depend on the heating system and/or fueling system incorporated within the disclosed systems.

[0066] In some embodiments, the second volume **103** is configured to hold one or more targets comprised of a target material which may be reacted with neutrons to provide a synthesized material. In this regard, the target material is a precursor to the synthesized material. In some embodiments, the one or more targets are solid targets, e.g., ceramic targets. Ceramic target materials may include, for example, metal oxides or metal hydrides. Other target materials include molybdenum (where a material synthesized from the molybdenum target material is, for example, ^{98}Mo). In other embodiments, the target material is lithium. Other examples of target materials and the material synthesized therefrom include: a target material containing lithium-6 isotope (^{6}Li) which produces tritium upon neutron capture; and a target material containing molybdenum-98 (^{98}Mo) which produces molybdenum-99 (^{99}Mo) upon neutron capture.

[0067] In some embodiments, the target material is a precursor for a pharmaceutical radioisotope. In some embodiments, the one or more targets are liquid targets. In some embodiments, the liquid target includes a dispersion or slurry comprising the target material. Examples of such liquid targets include, but are not limited to, molten lithium metal (Li), heavy water (D_2O), or a molten salt such as fluorine lithium beryllium (FLiBe). In some embodiments, the one or more targets are in a gas, or are themselves gases.

[0068] In some embodiments, the systems of the present disclosure include one or more material transfer systems and/or one or more material isolation systems. In some embodiments, the systems of the present disclosure include two different material transfer systems. In some embodiments, a first material transfer system **111** is in communication with the second volume **103**; while a second material transfer system **113** is in communication with the first volume **105**. In some embodiments, the system **100** of the present disclosure includes two separate material isolation systems **112** and **114**, whereby a first material isolation system **112** is in communication with a first material transfer system **111**; and a second material transfer system **113** is in communication with a second material isolation system **114**. In other embodiments, the first and second material transfer systems **111** and **113** are in communication with a single material isolation system.

[0069] In some embodiments, target materials are introduced into the second volume **103** through one or more material transfer systems **111** in communication with the second volume **103**. In some embodiments, each material transfer system **111** includes an inlet **111A** (for introducing the target material into the second volume **103**) and an outlet **111B** (for removing synthesized material and/or remaining target material from the second volume **103**). In the case of a liquid target material or a target material dispersed within a liquid, the liquid and/or target material may be flowed into and out of the second volume **103** via the material transfer system **111**. In some embodiments, the material transfer system **111** is in communication with a material isolation system **112** adapted to capture and/or separate synthesized material from a target material. In some embodiments, the material isolation system **112** is adapted to capture and/or separate a target material from one or more synthesized materials and/or to separate two different synthesized materials from each other, where the materials were synthesized within the second volume **103**. For instance, the material isolation system **112** may be utilized to process materials from the second volume **103** after target material present within the second volume **103** have been bombarded by generated neutrons.

[0070] In some embodiments, the material transfer system **113** and the material isolation system **114** are used to introduce, remove, and/or separate at least one isotope of hydrogen (e.g., deuterium or tritium) or helium (e.g., helium-3) from the plasma confined within the first volume **105.** For example, if a gas comprising helium-3 has been synthesized within the first volume **105**, the helium-3 may be separated from the rest of the plasma and gas within the first volume using the material transfer system **113** and/or material isolation system **114114**.

[0071] In some embodiments, the system **100** includes one or more negative ion-based neutral beam injectors (*see* **106** and **107** in FIGS. 2A and 2B). In some embodiments, the one or more negative ion-based neutral beam injectors are configured to introduce high energy neutral atoms into the plasma contained within the first volume **105**. In some embodiments, the one or more negative ion-based neutral beam injectors introduce neutral atoms in the same angular direction as the angular direction of flow of the plasma within the first volume **105**. In other embodiments, the one or more negative ion-based neutral beam injectors introduce neutral atoms in the opposite angular direction as the angular direction of the flow of the plasma within the first volume **105**.

[0072] In some embodiments, the system **100** includes one negative ion-based neutral beam injector. In other embodiments, the system **100** includes two negative ion-based neutral beam injectors, where each of the at least two negative ion-based neutral beam injectors may be configured to introduce neutral atoms in any angular direction. In yet other embodiments, the system **100** includes three negative ion-based neutral beam injectors, where each of the at least three negative ion-based neutral beam injectors may be configured to introduce neutral atoms in any angular direction. In further embodiments, the system **100** includes four negative ion-based neutral beam injectors, where each of the at least four negative ion-based neutral beam injectors may be configured to introduce neutral atoms in any angular direction. In yet further embodiments, the system **100** includes five negative ion-based neutral beam injectors, where each of the at least five negative ion-based neutral beam injectors may be configured to introduce neutral atoms in any angular direction. In yet even further embodiments, the system **100** includes six or more negative ion-based neutral beam injectors. In some embodiments, the system **100** includes ten or more negative ion-based neutral beam injectors, where each of the at least ten negative ion-based neutral beam injectors may be configured to introduce neutral atoms in any angular direction. In some embodiments, the system **100** includes twenty or more negative ion-based neutral beam injectors, where each of the at least twenty negative ion-based neutral beam injectors may be configured to introduce neutral atoms in any angular direction.

[0073] In some embodiments, the system **100** includes at least two negative ion-based neutral beam injectors wherein a first negative ion-based neutral beam injector **106** introduces neutral atoms in a first angular direction; and wherein a second negative ion-based neutral beam injector **107** introduces neutral atoms in a second angular direction, wherein the first and second angular directions are opposite or substantially opposite each other. In some embodiments, the system **100** includes two or more negative ion-based neutral beam injectors **106**, where each of the two or more negative ion-based neutral beam injectors **106** are configured introduce neutral atoms in a first angular direction (such as the same angular direction of the flow of plasma in the first volume **105**); and at least negative one ion-based neutral beam injector **107** configured to introduce neutral atoms in a second angular direction, wherein the first and second angular directions are opposite or substantially opposite each other. In some embodiments, the system **100** includes three or more negative ion-based neutral beam injectors **106**, where each of the two or more negative ion-based neutral beam injectors **106** are configured introduce neutral atoms in a first angular direction (such as the same angular direction of the flow of plasma in the first volume **105**); and at least one negative ion-based neutral beam injector **107** configured to introduce neutral atoms in a second angular direction, wherein the first and second angular directions are opposite or substantially opposite each other.

[0074] In some embodiments, the system **100** includes four or more negative ion-based neutral beam injectors **106**, where each of the two or more negative ion-based neutral beam injectors **106** are configured introduce neutral atoms in a first angular direction (such as the same angular direction of the flow of plasma in the first volume **105**); and at least one negative ion-based neutral beam injector **107** configured to introduce neutral atoms in a second angular direction, wherein the first and second angular directions are opposite or substantially opposite each other (depicted in FIG. 2A). In some embodiments, the system **100** includes four or more negative ion-based neutral beam injectors **106**, where each of the two or more negative ion-based neutral beam injectors **106** are configured introduce neutral atoms in a first angular direction (such as the same angular direction of the flow of plasma in the first volume **105**); and two or more negative ion-based neutral beam injector **107** configured to introduce neutral atoms in a second angular direction, wherein the first and second angular directions are opposite or substantially opposite each other.

[0075] In some embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma, where the neutral atoms have an energy of at least about 100 keV. In other embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 150 keV. In other embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 200 keV. In other embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 250 keV. In yet other embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms having an energy of at least about 300 keV. In further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 400 keV. In even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 500 keV. In yet further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 600 keV. In yet even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 700 keV. In yet even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 800 keV. In yet even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 900 keV. In yet even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 1000 keV. In yet even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 1200 keV. In yet even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 1500 keV. In yet even further embodiments, each of the negative ion-based neutral beam injectors are configured to inject high energy neutral atoms into the plasma having an energy of at least about 2000 keV.

[0076] Any negative ion-based neutral beam injector may be utilized as part of the presently disclosed systems, provided that the negative ion-based neutral beam injector is capable of injecting high energy neutral atoms into a plasma. An exemplary negative ion-based neutral beam injector is illustrated in FIG. 3. In this particular embodiment, each negative ion-based neutral beam injector **300** may include an external housing **302** having a first end **304** and a second end **306** opposite the first end. The injector **300** may also include an ion source **310**, an accelerator **320**, and a neutralizer **330**. In some embodiments, the negative ion-based neutral beam injector may also include other components, including but not limited to, a residual ion dump **340**, and one or more controls **350**, such as a valve and/or a shutter. In some embodiments, the ions **315** (such as deuterium ions or tritium ions) are accelerated from the ion source **310** by the accelerator **320** and are passed through the neutralizer **330** where they become neutral atoms (such as deuterium atoms or tritium atoms) before eventually exiting the injector at the second end **306**.

[0077] Another suitable negative ion-based neutral beam injection is described in PCT Publication No. WO2014039579, the disclosure of which is hereby incorporated by reference herein in its entirety. Another suitable negative ion-based neutral beam injector is the Heating Neutral Beam (HNB) for the ITER experiment, described in Hemsworth *et al.* (2017) (Hemsworth, R. S., *et al.* 2017. New Journal of Physics 19 (2): 025005), the disclosure of which is hereby incorporated by reference herein in its entirety.

[0078] The system **100** also includes an electron heater **108** configured to regulate the temperature of electrons within the plasma confined within the first volume **105**. In some embodiments, the electron heater **108** is an electron cyclotron resonance heater In some embodiments, the electron heater **108** is another neutral beam injector. In some embodiments, the electron heater **108** is a radiofrequency heater operating at a harmonic of the electron cyclotron resonance. In some embodiments, the electron heater **108** ensures that a significantly higher electron temperature is maintained in the plasma as compared with an ion temperature in the plasma by at least a factor of about 2, such as at least a factor of about 2.25, at least a factor of about 2.5, at least a factor of about 2.75, at least a factor of about 3, etc. In some embodiments, the ion temperature may be kept low by ensuring that particle fueling leads to a broad density profile. It is believed that a low ion temperature ensures that the electron density and beam particle density can be higher than otherwise, as they contribute less to the plasma pressure. By way of example, a low ion temperature could be about 2 keV, at which the thermonuclear D-D reaction rate is negligible.

[0079] In some embodiments, the electron heater **108** is communicatively coupled to a controller **109**. In some embodiments, the controller **109** commands the electron heater **108** to adjust the power it delivers to the plasma. Greater power, for example, about 1 MW, causes the electron temperature of the plasma to become elevated over the temperature that the electrons in the plasma would otherwise be. For example, without power to the electron heater, the electron temperature might be about 10 keV; while with about 1 MW of heating from the electron heater, the electron temperature might be about 13 keV. In some embodiments, the electron heater **108** is commanded by the controller **109** to deliver the amount of power which causes the temperature of the electrons in the plasma to be at the value which causes the highest neutron production rate within the plasma while satisfying all operational constraints. An example of this required electron heating power might be about 1 MW. A plausible range of electron heating powers might be between 0.5 MW and 10 MW, depending on the size of the stellarator, the strength of the magnetic field, and other parameters. An example of this optimal electron temperature might be about 13 keV. A plausible range of optimal electron temperatures might be between 10 keV and 50 keV, depending on the size of the stellarator, the strength of the magnetic field, and other parameters. An example of the neutron rate might be about 2×10^{17} neutrons / second. A plausible range of optimal neutron rates might be between 5×10^{16} neutrons / second and 1×10^{18} neutrons / second, depending on the size of the stellarator, the strength of the magnetic field, and other parameters. An example of an operational constraint might be that the density of high-energy beam-injected deuterium ions be below about 10^{18} ions/m^3. The neutron production rate increases with electron temperature, but so too does the density of high-energy beam-injected deuterium ions. At some maximum density of high-energy beam-injected deuterium ions, the plasma becomes unstable.

[0080] In some embodiments, the system further comprises a heat transfer system **110** to regulate the thermal properties of the stellarator **101**. In some embodiments, the heat transfer system **110** includes an inlet **110A** such that cool air or a liquid or gaseous coolant may be flowed into a portion of the second volume **103**; and an outlet **110B** such that warmer air or warmed coolant may be flowed out of the second volume **103** to effectuate removal of excess heat from the second volume **103**, the blanket **102**, and/or the stellarator **101**.

[0081] **Stellarators**

[0082] As noted herein, the systems **100** of the present disclosure include a stellarator **101** that is optimized for fast particle confinement. Any stellarator may be utilized having any coil configuration provided that the stellarator is optimized for fast particle confinement.

[0083] With reference to FIG. 4A, stellarators generally include an array of magnetic coils 410 which function to define a magnetic field that is capable of confining a plasma, such as confining a plasma within the first volume **420** described herein. In some embodiments, stellarators include additional coils external to the magnetic coils; and may further include one or more structural supports.

[0084] A stellarator is said to be "optimized" when its magnetic field fulfills a property known as omnigeneity, or quasi-omnigeneity ("QO"). This property and several subcategories are described by Helander (*see* Helander, Per. 2014. Reports on Progress in Physics 77 (8): 087001, the disclosure of which is hereby incorporated by reference herein in its entirety). Plasma particles on an omnigenous or QO field do not drift across the magnetic field and out of the stellarator. This property is a property of the geometry of the magnetic field that the stellarator produces. Omnigeneity is a rigorous mathematical property – a magnetic field is either omnigenous or not. Because of various considerations including finite engineering tolerance, it is impossible to build a perfectly QO stellarator. Stellarators have been built which are so approximately QO such that the plasma that they confine has been observed to behave substantially in the way that QO plasmas are predicted to behave (*see* Dinklage, A., *et al.* 2018. Nature Physics 14 (8): 855–60).

[0085] A subset of QO configurations are so-called quasi-symmetric configurations, also described in Helander (2014). Quasi-symmetric stellarators exhibit another specific property of the magnetic field, namely that the amplitude of the magnetic field exhibits a symmetry in a coordinate system which follows the direction of the magnetic field. Again, quasi-symmetry is a rigorous mathematical quantity and it is nearly impossible to construct a stellarator which produces a perfectly quasi-symmetric magnetic field. Stellarators, however, have been built which are so approximately quasi-symmetric that the plasma that they confine has been observed to behave substantially in the way that quasi-symmetric plasmas are predicted to behave (*see* Canik, J. M., *et al*. 2007. Physical Review Letters 98 (8): 085002). Quasi-symmetric magnetic fields can be further subdivided into quasi-helically symmetric ("QH") and quasi-axisymmetric ("QA") fields, both rigorously defined in Helander (2014). The quasi-omnigeneity and/or quasi-symmetry of a magnetic configuration can be assessed by someone skilled in the art.

[0086] Fast particle confinement refers to the ability of a magnetic field to contain charged particles where a mean gyroradius is not small compared to the scale length of the magnetic field amplitude. An example of a fast particle is a about 1 MeV deuterium ion in a stellarator whose magnetic field is about 6 Tesla (gyroradius about 2 cm) and whose magnetic field amplitude scale length is about 20 cm. QO, QH, and QA stellarators could all be said to be "optimized for fast particle confinement," though QH and QA are thought to be superior in this respect (*see* Landreman, Matt, and Elizabeth Paul. 2022. Physical Review Letters 128 (3): 035001). Landreman and Paul (2022) describe several more designs for QH and QA stellarators.

[0087] In some embodiments, the stellarator **101** optimized for fast particle confinement is quasi-omnigenous stellarator. An example of a suitable quasi-omnigenous stellarator Wendelstein 7-X ("W7-X") described by Dinklage *et al.* (2018).

[0088] In some embodiments, the stellarator **101** optimized for fast particle confinement is a quasi-axisymmetric stellarator. No QA stellarator has been built, but one device which was designed and modeled was the National Compact Stellarator Experiment ("NCSX") described in Williamson *et al.* (2005) (*see* Williamson, D., *et al.* 2005. Fusion Engineering and Design, Proceedings of the 23rd Symposium of Fusion Technology, 75–79 (November): 71–74).

[0089] In some embodiments, the stellarator **101** optimized for fast particle confinement is a quasi-symmetric stellarator or a quasi-helically symmetric. An example of a quasi-helically symmetric stellarator is the Helically Symmetric Experiment ("HSX") described in Canik *et al.* (2007).

[0090] In some embodiments, the stellarator **101** optimized for fast particle confinement is a quasi-isodynamic stellarator.

[0091] Stellarators Including One or More Encircling Coils and One or More Shaping Cols

[0092] In some embodiments, a suitable stellarator **101** comprises: (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more planar shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of planar encircling coils which encircle the field-shaping coil system.

[0093] In other embodiments, a suitable stellarator **101** comprises: (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.

[0094] In yet other embodiments, a suitable stellarator **101** comprises: (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0095] In yet further embodiments, a suitable stellarator **101** comprises: (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0096] In even further embodiments, a suitable stellarator **101** comprises: (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

[0097] In some embodiments, and with reference to FIGS. 4B – 4D, stellarators **101** for use in the systems of the present disclosure comprise a field shaping system **203** which surrounds a void **201** that confines a plasma **200**. In some embodiments, the void **201** is configured such that a largest dimension from a plasma axis **205** of any contained plasma **200** to an outer edge of the contained plasma (not shown) is less than 20 meters, such as less than 10 meters, such as less than 5 meters, such as less than 4 meters, such as less than 3 meters, such as less than 2 meters, such as less than 1 meter, such as less than 0.5 meters, etc.

[0098] In some embodiments, the plasma **200** has a topology which substantially approximates that of a torus. In some embodiments, the plasma **200** is centered around a "plasma axis" **205**, which is a magnetic field line that maps onto its own origin after one toroidal rotation. In some embodiments, the plasma axis **205** has a topology of a loop or one that substantially approximates a loop.

[0099] The field shaping system **203** comprises a plurality of field shaping units **210**. In some embodiments, the field shaping system **203** may comprise at least 2, at least 4, at least 6, at least 8, at least 10, at least 12, at least 16, at least 20, at least 24, at least 30, at least 36, at least 48, at least 54, at least 60, at least 70, at least 80, at least 90, at least 100, at least 110, at least 120, at least 130, at least 150, at least 170 field shaping units **210**. Each of the field shaping units **210** includes one or more structural mounting elements **211** having a surface **215**. In some embodiments, the surface **215** of each field shaping unit **211** faces the the void **201**. In some embodiments, each field shaping unit **210** further includes one or more additional components **216**. The one or more additional components include, but are not limited to, a first wall to handle plasma flux, a structure which mounts to the first wall, a breeding blanket to breed radioisotopes from the fusion neutron flux, a cryostat, and/or neutron shielding.

[0100] In some embodiments, each field shaping unit **210** comprises a single structural mounting element **211**. In other embodiments, each field shaping unit **210** comprises two structural mounting elements **211**. In yet other embodiments, each field shaping unit **210** comprises three structural mounting elements **211**. In further embodiments, each field shaping unit **210** comprises four or more structural mounting elements **211**. In some embodiments, the structural mounting element **211** is comprised of steel. In some embodiments, the structural mounting element **211** comprises a metal. In some embodiments, the structural mounting element **211** comprises a composite material such as G-10.

[0101] The field shaping unit **210** may have any size and shape. In some embodiments, the field shaping unit **210** defines an extruded circular annulus cross section structure. In other embodiments, the field shaping unit **210** has an arbitrary shape, such as a shape having a non-constant crosssection. For example, and as illustrated in FIG. 4C, in some embodiments, the field shaping unit **410** has a wedge shape (as seen from a perspective perpendicular to the plasma axis and the direction of curvature, arranged such that the narrower portion of the wedge faces the direction of plasma axis curvature, and the wider portion of the wedge faces opposite the direction of plasma axis curvature). In some embodiment, the field shaping unit **410** has substantially a wedge shape. In other embodiments, the field shaping unit has a similar or the same cross sectional shape as the plasma at that location. In other embodiments, the field shaing unit has**210** has a shape similar or the same as a cross sectional shape of the plasma, with some constant normal offset distance.

[0102] In some embodiments, one or more shaping coils **212** are disposed on the surface **215** of each of the one or more structural mounting elements **211**. It is believed that the one or more shaping coils **212** of the present disclosure are relatively easy to manufacture, assemble, and integrate into a field shaping unit. Moreover, it is beleved that the one or more field shaping coils **212** allow precise control over the shape of the plasma.

[0103] Each of the one or more shaping coils **212** are planar coils. A "planar" coil is one whose shape substantially lies within one flat plane. In some embodiments, each of the shaping coils **212** individually do not encircle the plasma axis **205**. Said another way, any one shaping coil **212** does not encircle the plasma **200** or the plasma axis **205**. While any individual shaping coil **212** does not encircle the plasma axis **205**, collectively an array including a plurality of shaping coils **212** mounted on the surfaces **215** of one or more structural mounting elements **211** would encircle the plasma axis **205**. In some embodiments, individual shaping coils may be positioned on opposite sides of the plasma or on different faces of the void.

[0104] Each of the one or more shaping coils **212** do not interlock with any other shaping coil, such as illustrated in at least FIG 4B. Additionally, each of the one or more shaping coils do not interlock with any of the encircling coils **230** described herein (see FIG. 4B). In some embodiments, the one or more shaping coils **212** are removably coupled to the surface **215** of the one or more surface mounting elements **211**.

[0105] In some embodiments, the planar shaping coils have a mean coil radius which is smaller than a major radius of the plasma and smaller than a minor radius of the plasma. As used herein, the "major radius" of the plasma is the mean distance between the plasma axis and the geometric center of the stellarator **101**. As used herein, the "minor radius" of the plasma is the mean closest distance between each point on the plasma boundary and the plasma axis. The plasma boundary is sometimes represented by a set of toroidal Fourier amplitudes; for this case, the major radius is represented by the amplitude of the mode with toroidal mode number 0 and poloidal mode number 0, and the minor radius is represented by the amplitudes of the mode with toroidal mode number 0 and poloidal mode number 1.

[0106] The shaping coils **212** may have different sizes and shapes. In some embodiments the shaping coils may be circular or substantially circular. In other embodiments, the shaping coils may be rectangular or substantially rectangular. In yet other embodiments, the shaping coils may be rectangular with rounded corners or substantially rectangular with rounded corners. In some embodiments, each field shaping unit may comprise one or more coils having different shapes. For instance, a field shaping unit **210** may comprise 10 shaping coils where 3 of the shaping coils may have a substantially circular shape, 4 of the shaping coils may have a substantially rectangular shape, and 3 of the coils may have a substantially rectangular shape with rounded corners (not depicted).

[0107] In some embodiments, stellarators **101** for use in the systems of the present disclosure may include between about 10 and 10,000 shaping coils. In other embodiments stellarators **101** for use in the systems of the present disclosure may include between about 50 and 5,000 shaping coils. In yet other embodiments, stellarators **101** for use in the systems of the present disclosure may include between about 100 and 5,000 about shaping coils. In further embodiments, stellarators **101** for use in the systems of the present disclosure may include between about 100 and 4,000 about shaping coils. In yet further embodiments, stellarators **101** for use in the systems of the present disclosure may include between about 100 and 3,000 about shaping coils. In even further embodiments, stellarators **101** for use in the systems of the present disclosure may include between about 100 and 2,000 about shaping coils. In even further embodiments, the stellarator of the present disclosure may include between about 100 and 1,000 about shaping coils.

[0108] In some embodiments, a field shaping unit **210** may include between about 5 and about 150 shaping coils **212**. In other embodiments, a field shaping unit **210** may include between about 5 and about 100 shaping coils **212**. In yet other embodiments, a field shaping unit **210** may include between about 5 and about 80 shaping coils **212**. In further embodiments, a field shaping unit **210** may include between about 5 and about 70 shaping coils **212**. In even further embodiments, a field shaping unit **211** may include between about 5 and about 60 shaping coils **212**. In yet even further embodiments, a field shaping unit **210** may include between about 5 and about 50 shaping coils **212**. In yet even further embodiments, a field shaping unit **210** may include between about 5 and about 45 shaping coils **212**. In yet even further embodiments, a field shaping unit **210** may include between about 5 and about 40 shaping coils **212**. In yet even further embodiments, a field shaping unit **210** may include between about 5 and about 35 shaping coils **212**. In yet even further embodiments, a field shaping unit **210** may include between about 5 and about 30 shaping coils **212**. In yet even further embodiments, a field shaping unit **211** may include between about 5 and about 25 shaping coils **212**.

[0109] With reference to FIG. 4B, stellarators **101** for use in the systems of the present disclosure also includes a plurality of encircling coils **230** which encircle the plasma axis **205**. Each of the encircling coils **230** are arranged around an exterior of the field shaping system **203** and encircle it. Each encirlcing coil **230** of the plurality of encircling coils are planar. Moreover, each encircling coil **230** of the plurality of encircling coils are non-interlocking with any other encircling coil **230**. Additionally, each encircling coil **230** of the plurality of encircling coils are do not interlock with any of the shaping coils **212**. Said another way, any encirlcing coil **230** does not interlock with any other planar encircling coil **230** or with any other shaping coil **212**, such as depicted in FIGS. 4B and 4C. In some embodiments, each encircling coil **230** is supported by a structural component **231**. In some embodiments, the structural componnent **231** and the field shaping units **210** may be coupled to other structural members which react to unbalanced forces and torques.

[0110] In some embodiments, the encircling coils do not exhibit the N-fold rotational symmetry of toroidal field (TF) coils. If the encircling coils are N-fold rotationally symmetric, like TF coils in the prior art, then the planar shaping coils require some irreducible quantity of current length (Amperes*meters) in order to correct this field. If the encircling coils are allowed to not be N-fold rotationally symmetric, the current-length requirements of the planar shaping coils can be reduced by a large factor. Our analysis shows that this requirement may be reduced by nearly a factor of 10 by allowing the encircling coils to be positioned more favorably.

[0111] In some embodiments, stellarators **101** for use in the systems of the present disclosure include between about 3 and about 150 encircling coils. In other embodiments, stellarators **101** for use in the systems of the present disclosure include between about 3 and about 100 encircling coils. In yet other embodiments, stellarators **101** for use in the systems of the present disclosure include between about 3 and about 75 encircling coils. In further embodiments, stellarators **101** for use in the systems of the present disclosure include between about 3 and about 50 encircling coils. In yet further embodiments, stellarators **101** for use in the systems of the present disclosure include between about 3 and about 25 encircling coils. In even further embodiments, stellarators **101** for use in the systems the present disclosure include between about 3 and about 15 encircling coils. In yet even further embodiments, stellarators **101** for use in the systems of the present disclosure include between about 3 and about 10 encircling coils. In some embodiments, the spacing between each encircling coil may range from between abhout 10cm to about 1m.

[0112] The shaping coils **212** and the encircling coils **230** may be comprised of one or more superconducting materials. A superconductor is a material that achieves superconductivity. Superconductivity is the property of certain materials to conduct direct current (DC) electricity without energy loss when they are cooled below a critical temperature (referred to as T_c). An electric current in a superconductor can persist indefinitely. Exemplary superconducting materials include, but are not limited to, Nb-Ti, Nb_3Sn, MgB_2, $LaBaCuO_x$, LSCO (e.g., $La_{2-x}Sr_xCuO_4$, etc.), YBCO (e.g., $YBa_2Cu_3O_x$ or $YBa_2Cu_3O_7$), REBCO, bismuth-based cuprate superconductors (BSCCO) (including $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223), TBCCO (e.g., $Tl_2Ba_2Ca_2Cu_3O_{10}$ or $Tl_mBa_2Ca_{n-1}Cu_nO_{2n-m+2+\delta}$), $HgBa_2Ca_2Cu_3O_x$, and other mixed-valence copper-oxide perovskite materials. In some embodiments, the shaping coils and the encircling coils may be comprised on the same materials. In other embodiments, the shaping coils and the encircling coils may be comprised on different materials.

[0113] In some embodiments, stellarators **101** for use in the systems of the present disclosure further include one or more additional coils, such as one or more control coils and/or one or more saddle coils. In some embodiments, the control coils and/or the saddles are planar. In some embodiments, the control coils and/or the saddles are non-planar. In some embodiments, the control coils and/or the saddles are superconducting. In some embodiments, the control coils and/or the saddles are non-interlocking and, in particular, they do not interlock any other of the disclosed coils (e.g., encircling coils, shaping coils) or the plasma axis. In some embodiments, the control coils and/or the saddle coils are disposed between the plasma boundary and the field shaping system. In some embodiments, the control coils and/or the saddle coils are disposed outward of the field shaping system, on the non-plasma-axis-facing side. Control coils are coils included as a contingency against unexpected sources of error. These errors may arise from errors in assembly of the magnet system, or from unexpected plasma physics. Before the error is measured, the correct electrical current for the control coils is not known. During normal operation of the stellarator **101**, if the stellarator **101** and plasma are operating at their design points, the control currents have zero electric current. The design of the stellarator magnetic field does not include contributions from the control coils.

[0114] METHODS

[0115] The present disclosure is also directed to methods of generating neutrons and/or synthesizing one or more materials using the systems **100** of the present disclosure and, in particular, systems incorporating a stellarator **101** optimized for fast particle confinement.

[0116] With reference to FIG. 5, the method **500** may include generating **510** a negative ion-based neutral beam (such as with one or more negative ion-based neutral beam injectors) to accelerate ions (such as deuterium ions) to energies at which the ion-ion fusion cross-section (which, in the context of deuterium ions, is an energy at which the D-D cross section is significant) is high, such as 100 millibarns or higher.

[0117] In some embodiments, the method **500** may include injecting **520** the negative ion-based neutral beam into a stellarator **101** optimized for fast particle confinement (such as using the one or more negative ion-based neutral beam injectors **106**). In some embodiments, the stellarator **101** optimized for fast particle confinement is a quasi-axisymmetric stellarator. In some embodiments, the stellarator **101** optimized for fast particle confinement is a quasi-symmetric stellarator. In some embodiments, the stellarator **101** optimized for fast particle confinement is a quasi-isodynamic stellarator. In some embodiments, the stellarator **101** optimized for fast particle confinement is quasi-omnigenous stellarator. In some embodiments, the stellarator **101** optimized for fast particle confinement comprises (a) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (b) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis. In some embodiments, the stellarator **101** optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials. In some embodiments, the stellarator **101** optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis. In some embodiments, the stellarator **101** optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis. In some embodiments, the stellarator **101** optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

[0118] In some embodiments, the method **500** may include injecting **520** the negative-ion-based neutral beam into a stellarator **101** optimized for fast particle confinement (including any of those described above) and controlling **530** the electron temperature so that the neutron flux is at its maximum value while still satisfying operational constraints (such as with an electron heater **108**). Operational constraints include the maximum injected power (e.g., about 2 MW) and the maximum fast particle density (e.g., about 10^{18} ions/m^3) to maintain stability.

[0119] The method may also include, within the plasma of the stellarator and/or in the blanket **102**, forming **540** tritium by bombarding deuterium using the generated neutrons. The method may include capturing **550** and filtering/processing plasma from the stellarator to isolate any tritium that has been formed (such as using any one of the material transfer and/or isolation systems described herein). The method may also include allowing **560** the generated neutrons to enter a volume, such as a second volume **103**. The method may also include cooling **570** the internal volume of space.

[0120] The method may also include forming **580** a modified material by allowing the neutrons to bombard a target material located outside the first volume and within an internal volume of space, such as a second volume **103**. The target material should be a precursor for the desired synthesized material. In some embodiments, the target material is a ceramic. In some embodiments, the target material is molybdenum and the synthesized material is an isotope of molybdenum. In some embodiments, the isotope of molybdenum is ^{98}Mo. In some embodiments, the target material is hydrogen, helium, or deuterium. In some embodiments, the target material is a precursor of a pharmaceutical drug. The method may also include removing **590** the modified material from the internal volume of space.

[0121] ADDITIONAL EMBODIMENTS

[0122] A first additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume; (iii) a stellarator is adapted to confine a plasma within the first volume, and wherein the blanket is positioned between the stellarator and the casing; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises (a) a field-shaping coil system including one or more field shaping units, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more planar shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of planar encircling coils which encircle the field-shaping coil system. Since the field-shaping coil system defines a void which confines the plasma, and since the planar encircling coils encircle the field-shaping coil system, the planar encircling coils therefore encircle the plasma confined within the void. In some embodiments, the stellarator does not include any non-planar coils.

[0123] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0124] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0125] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0126] In some embodiments, the stellarator further comprises one or more controllers. In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddles coils are communicatively coupled to a controller.

[0127] In some embodiments, each of the one or more of planar shaping coils are superconducting coils. In some embodiments, each of the plurality of planar encircling coils are superconducting coils. In some embodiments, both the plurality of planar shaping coils and the plurality of planar encircling coils are superconducting coils.

[0128] In some embodiments, the stellarator includes between about 3 and about 100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils. In some embodiments, the plurality of planar encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of planar encircling coils do not interlock with each other. In some embodiments, the plurality of planar encircling coils do not interlock with each other and do not interlock with any of the shaping coils.

[0129] In some embodiments, the stellarator comprises at least 4 field shaping units. In some embodiments, each of the one or more field shaping units comprises one structural mounting element. In some embodiments, the one structural mounting element is wedge shaped. In some embodiments, each of the one or more field shaping units comprises two or more structural mounting elements.

[0130] In some embodiments, the one or more planar shaping coils do not interlock with each other. In some embodiments, the one or more planar shaping coils do not interlock with each other and do not interlock with any of the planar encircling coils.

[0131] In some embodiments, each of the one or more field shaping units comprises between about 5 and about 100 shaping coils. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 50 shaping coils. In some embodiments, the surface of the one or more structural mounting elements faces the void.

[0132] In some embodiments, a shape of each planar shaping coil of the one or more planar shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular.

[0133] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0134] In some embodiments, the system further comprises a material transfer system.

[0135] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0136] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0137] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0138] A second additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume; (iii) a stellarator is adapted to confine a plasma within the first volume, and wherein the blanket is positioned between the stellarator and the casing; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises (a) a field-shaping coil system including one or more field shaping, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials. In some embodiments, each of the one or more shaping coils disposed on the surface of the one or more structural mounting elements does not encircle the plasma. In some embodiments, the one or more shaping coils are planar. In some embodiments, each encircling coil of the plurality of encircling coils are planar.

[0139] In some embodiments, a shape of each of the one or more shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 100 shaping coils. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 50 shaping coils. In some embodiments, the one or more planar shaping coils do not interlock with each other.

[0140] In some embodiments, each of the one or more field shaping units comprises one structural mounting element. In some embodiments, the one structural mounting element is wedge shaped. In some embodiments, each of the one or more field shaping units comprises two or more structural mounting elements.

[0141] In some embodiments, the plurality of encircling coils encircle the plasma confined within the void. In some embodiments, the stellarator includes between about 3 and about 100 encircling coils. In some embodiments, the stellarator comprises at least four encircling coils.

[0142] In some embodiments, the plurality of encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of planar encircling coils do not interlock with each other.

[0143] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddles coils are communicatively coupled to a controller.

[0144] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0145] In some embodiments, the system further comprises a material transfer system.

[0146] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0147] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0148] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0149] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0150] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0151] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0152] A third additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume; (iii) a stellarator is adapted to confine a plasma within the first volume, and wherein the blanket is positioned between the stellarator and the casing; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles a plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis. In some embodiments, each of the plurality of planar shaping coils are superconducting coils. In some embodiments, each of the plurality of planar encircling coils are superconducting coils. In some embodiments, both the plurality of planar shaping coils and the plurality of planar encircling coils are superconducting coils. In some embodiments, the plasma is a deuterium plasma.

[0153] In some embodiments, the plurality of planar shaping coils do not interlock one another. In some embodiments, the plurality of planar shaping coils do not interlock with one another and do not interlock with any one of the plurality of encircling coils.

[0154] In some embodiments, plurality of planar encircling coils do not interlock one another. In some embodiments, the plurality of planar encircling coils do not interlock with one another and do not interlock with any one of the plurality of planar shaping coils.

[0155] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddle coils are not superconducting coils.

[0156] In some embodiments, a shape of each planar shaping coil of the one or more planar shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular.

[0157] In some embodiments, the stellarator comprises between about 10 and about 10,000 shaping coils. In some embodiments, the stellarator comprises between about 100 and about 2,000 shaping coils. In some embodiments, the stellarator includes between about 3 and about 100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils.

[0158] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0159] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0160] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0161] A fourth additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume and having at least two faces; (ii) a blanket defining a second volume; (iii) a stellarator is adapted to confine a plasma within the first volume, and wherein the blanket is positioned between the stellarator and the casing; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises at least two planar shaping coils, wherein a first of the at least two planar shaping coils is positioned near a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is positioned near a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0162] In some embodiments, the at least two faces are on opposite sides of the confined plasma.

[0163] In some embodiments, the at least two planar shaping coils do not interlock one another. In some embodiments, the at least two planar shaping coils do not interlock one another and do not interlock any one of the plurality of encircling coils.

[0164] In some embodiments, plurality of planar encircling coils do not interlock one another. In some embodiments, the plurality of planar encircling coils do not interlock one another and do not interlock any one of the at least two planar shaping coils.

[0165] In some embodiments, the at least two planar shaping coils are comprised of one or more superconducting materials. In some embodiments, the plurality of encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of encircling coils and the at least two planar shaping coils are both comprised of one or more superconducting materials.

[0166] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddle coils are not superconducting coils.

[0167] In some embodiments, shape of each planar shaping coil of the at least two planar shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular. In some embodiments, the stellarator includes between about 3 and about 100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils.

[0168] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0169] In some embodiments, the system further comprises a material transfer system.

[0170] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0171] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0172] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0173] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0174] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0175] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0176] A fifth additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume and having at least two faces; (ii) a blanket defining a second volume; (iii) a stellarator is adapted to confine a plasma within the first volume, and wherein the blanket is positioned between the stellarator and the casing; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and

(vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

[0177] In some embodiments, the stellarator includes between about 3 and about 100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils. In some embodiments, the plurality of planar encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of planar encircling coils do not interlock with each other.

[0178] In some embodiments, the stellarator comprises at least 4 field shaping units. In some embodiments, each of the one or more planar, surface-mounted shaping coils do not interlock with each other. In some embodiments, a shape of each planar shaping coil of the one or more planar, surface-mounted shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular.

[0179] In some embodiments, each of the one or more field shaping units comprises between about 5 and about 100 planar, surface-mounted shaping coils. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 50 planar, surface-mounted shaping coils. In some embodiments, the one or more planar, surface-mounted shaping coils are comprised of a superconducting material.

[0180] In some embodiments, the stellarator further comprises one or more controllers.

[0181] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddles coils are communicatively coupled to a controller. In some embodiments, each of the one or more shaping coils do not individually encircle the plasma.

[0182] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0183] In some embodiments, the system further comprises a material transfer system.

[0184] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0185] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0186] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0187] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0188] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0189] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0190] A sixth additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises (a) a field-shaping coil system including one or more field shaping units, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more planar shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of planar encircling coils which encircle the field-shaping coil system. Since the field-shaping coil system defines a void which confines the plasma, and since the planar encircling coils encircle the field-shaping coil system, the planar encircling coils therefore encircle the plasma confined within the void. In some embodiments, the stellarator does not include any non-planar coils.

[0191] In some embodiments, the stellarator further comprises one or more controllers. In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddles coils are communicatively coupled to a controller.

[0192] In some embodiments, each of the one or more of planar shaping coils are superconducting coils. In some embodiments, each of the plurality of planar encircling coils are superconducting coils. In some embodiments, both the plurality of planar shaping coils and the plurality of planar encircling coils are superconducting coils.

[0193] In some embodiments, the stellarator includes between about 3 and about 100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils. In some embodiments, the plurality of planar encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of planar encircling coils do not interlock with each other. In some embodiments, the plurality of planar encircling coils do not interlock with each other and do not interlock with any of the shaping coils.

[0194] In some embodiments, the stellarator comprises at least 4 field shaping units. In some embodiments, each of the one or more field shaping units comprises one structural mounting element. In some embodiments, the one structural mounting element is wedge shaped. In some embodiments, each of the one or more field shaping units comprises two or more structural mounting elements.

[0195] In some embodiments, the one or more planar shaping coils do not interlock with each other. In some embodiments, the one or more planar shaping coils do not interlock with each other and do not interlock with any of the planar encircling coils.

[0196] In some embodiments, each of the one or more field shaping units comprises between about 5 and about 100 shaping coils. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 50 shaping coils. In some embodiments, the surface of the one or more structural mounting elements faces the void.

[0197] In some embodiments, a shape of each planar shaping coil of the one or more planar shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular.

[0198] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0199] In some embodiments, the system further comprises a material transfer system.

[0200] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0201] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0202] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0203] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0204] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0205] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0206] A seventh additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises (a) a field-shaping coil system including one or more field shaping, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials. In some embodiments, each of the one or more shaping coils disposed on the surface of the one or more structural mounting elements does not encircle the plasma. In some embodiments, the one or more shaping coils are planar. In some embodiments, each encircling coil of the plurality of encircling coils are planar.

[0207] In some embodiments, a shape of each of the one or more shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 100 shaping coils. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 50 shaping coils. In some embodiments, the one or more planar shaping coils do not interlock with each other.

[0208] In some embodiments, each of the one or more field shaping units comprises one structural mounting element. In some embodiments, the one structural mounting element is wedge shaped. In some embodiments, each of the one or more field shaping units comprises two or more structural mounting elements.

[0209] In some embodiments, the plurality of encircling coils encircle the plasma confined within the void. In some embodiments, the stellarator includes between about 3 and about 100 encircling coils. In some embodiments, the stellarator comprises at least four encircling coils.

[0210] In some embodiments, the plurality of encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of planar encircling coils do not interlock with each other.

[0211] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddles coils are communicatively coupled to a controller.

[0212] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0213] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0214] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0215] A eighth additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles a plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis. In some embodiments, each of the plurality of planar shaping coils are superconducting coils. In some embodiments, each of the plurality of planar encircling coils are superconducting coils. In some embodiments, both the plurality of planar shaping coils and the plurality of planar encircling coils are superconducting coils. In some embodiments, the plasma is a deuterium plasma.

[0216] In some embodiments, the plurality of planar shaping coils do not interlock one another. In some embodiments, the plurality of planar shaping coils do not interlock with one another and do not interlock with any one of the plurality of encircling coils.

[0217] In some embodiments, plurality of planar encircling coils do not interlock one another. In some embodiments, the plurality of planar encircling coils do not interlock with one another and do not interlock with any one of the plurality of planar shaping coils.

[0218] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddle coils are not superconducting coils.

[0219] In some embodiments, a shape of each planar shaping coil of the one or more planar shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular.

[0220] In some embodiments, the stellarator comprises between about 10 and about 10,000 shaping coils. In some embodiments, the stellarator comprises between about 100 and about 2,000 shaping coils. In some embodiments, the stellarator includes between about 3 and about 100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils.

[0221] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0222] In some embodiments, the system further comprises a material transfer system.

[0223] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0224] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0225] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0226] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0227] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0228] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0229] A ninth additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises at least two planar shaping coils, wherein a first of the at least two planar shaping coils is positioned near a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is positioned near a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0230] In some embodiments, the at least two faces are on opposite sides of the confined plasma.

[0231] In some embodiments, the at least two planar shaping coils do not interlock one another. In some embodiments, the at least two planar shaping coils do not interlock one another and do not interlock any one of the plurality of encircling coils.

[0232] In some embodiments, plurality of planar encircling coils do not interlock one another. In some embodiments, the plurality of planar encircling coils do not interlock one another and do not interlock any one of the at least two planar shaping coils.

[0233] In some embodiments, the at least two planar shaping coils are comprised of one or more superconducting materials. In some embodiments, the plurality of encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of encircling coils and the at least two planar shaping coils are both comprised of one or more superconducting materials.

[0234] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddle coils are not superconducting coils.

[0235] In some embodiments, shape of each planar shaping coil of the at least two planar shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular. In some embodiments, the stellarator includes between about 3 and about

100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils.

[0236] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0237] In some embodiments, the system further comprises a material transfer system.

[0238] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0239] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0240] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0241] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0242] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0243] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0244] A tenth additional embodiment is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing first high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma; wherein the stellarator comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

[0245] In some embodiments, the stellarator includes between about 3 and about 100 planar encircling coils. In some embodiments, the stellarator comprises at least four planar encircling coils. In some embodiments, the plurality of planar encircling coils are comprised of one or more superconducting materials. In some embodiments, the plurality of planar encircling coils do not interlock with each other.

[0246] In some embodiments, the stellarator comprises at least 4 field shaping units. In some embodiments, each of the one or more planar, surface-mounted shaping coils do not interlock with each other. In some embodiments, a shape of each planar shaping coil of the one or more planar, surface-mounted shaping coils is substantially rectangular, substantially rectangular with rounded corners, or substantially circular.

[0247] In some embodiments, each of the one or more field shaping units comprises between about 5 and about 100 planar, surface-mounted shaping coils. In some embodiments, each of the one or more field shaping units comprises between about 5 and about 50 planar, surface-mounted shaping coils. In some embodiments, the one or more planar, surface-mounted shaping coils are comprised of a superconducting material.

[0248] In some embodiments, the stellarator further comprises one or more controllers.

[0249] In some embodiments, the stellarator further comprises one or more control coils and/or one or more saddle coils. In some embodiments, the one or more control coils and/or the one or more saddles coils are communicatively coupled to a controller. In some embodiments, each of the one or more shaping coils do not individually encircle the plasma.

[0250] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0251] In some embodiments, the system further comprises a material transfer system.

[0252] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0253] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0254] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0255] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0256] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0257] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0258] An eleventh additional embodiment of the present disclosure is a system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing first beam of high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing a second beam of high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma.

[0259] In some embodiments, the stellarator optimized for fast particle confinement is a quasi-axisymmetric stellarator. In some embodiments, the stellarator optimized for fast particle confinement is a quasi-symmetric stellarator. In some embodiments, the stellarator optimized for fast particle confinement is a quasi-isodynamic stellarator. In some embodiments, the stellarator optimized for fast particle confinement is quasi-omnigenous stellarator.

[0260] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (b) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0261] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.

[0262] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0263] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

[0264] In some embodiments, the stellarator optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

[0265] In some embodiments, the second volume is configured to hold one or more target materials. In some embodiments, the first angular direction is the same as the direction of a flow of the plasma. In some embodiments, the second angular direction is opposite the first angular direction.

[0266] In some embodiments, the system further comprises a material transfer system.

[0267] In some embodiments, the at least the first and the optional at least the second negative ion-based neutral beam injectors include a source of ions, an accelerator, and a neutralizer.

[0268] In some embodiments, the electron heater is an electron cyclotron resonance heating system. In some embodiments, the electron heater is communicatively coupled to a controller. In some embodiments, the controller is adapted to command the electron heater to heat the electrons in the plasma.

[0269] In some embodiments, the first and second high energy neutral atoms are deuterium atoms. In some embodiments, the plasma comprises a deuterium plasma.

[0270] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0271] In some embodiments, the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0272] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0273] A twelfth aspect of the present disclosure is A system comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing high energy neutral atoms into the plasma in a first angular direction; (v) at least a second negative ion-based neutral beam injector for introducing high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma.

[0274] In some embodiments, the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction. In some embodiments, the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.

[0275] In some embodiments, the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction. In some embodiments, the first and second angular directions are opposite angular directions.

[0276] All of the U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet are incorporated herein by reference, in their entirety. Aspects of the embodiments can be modified, if necessary to employ concepts of the various patents, applications, and publications to provide yet further embodiments.

[0277] Although the present disclosure has been described with reference to a number of illustrative embodiments, it should be understood that numerous other modifications and embodiments can be devised by those skilled in the art that will fall within the spirit and scope of the principles of this disclosure. More particularly, reasonable variations and modifications are possible in the component parts and/or arrangements of the subject combination arrangement within the scope of the foregoing disclosure, the drawings, and the appended claims without departing from the spirit of the disclosure. In addition to variations and modifications in the component parts and/or arrangements, alternative uses will also be apparent to those skilled in the art.

CLAIMS

1. A system comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume, the blanket enveloping the casing; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the stellarator encompasses the blanket; (iv) at least a first negative ion-based neutral beam injector for introducing high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma.
2. The system of claim 1, wherein the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.
3. The system of claim 1, wherein the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.
4. The system of claim 1, wherein the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.
5. The system of any one of claims 1 - 4, wherein the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction.
6. The system of claim 5, wherein the first and second angular directions are opposite angular directions.
7. The system of any one of claims 1 - 4, wherein the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction.
8. The system of claim 7, wherein the first and second angular directions are opposite angular directions.
9. The system of any one of the preceding claims, wherein the plasma is a deuterium plasma.
10. The system of any of the preceding claims, wherein the system further comprises at least one material transfer system.

11. The system of claim 10, wherein a first of the at least one material transfer system is in communication with the first volume.
12. The system of claim 11, wherein the first of the at least one material transfer system is communicatively coupled to a material isolation system.
13. The system of claim 10, wherein a second of the at least one material transfer system is in communication with the second volume.
14. The system of claim 13, wherein the second of the at least one material transfer system is communicatively coupled to a material isolation system.
15. The system of claim 13, wherein the second of the at least one material transfer system is adapted for introducing a flowable target into the second volume.
16. The system of claim 13, wherein the second of the at least one material transfer system is adapted for introducing a solid target into the second volume.
17. The system of claim 1, wherein the electron heater is communicatively coupled to a controller.
18. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement is a quasi-axisymmetric stellarator.
19. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement is a quasi-symmetric stellarator.
20. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement is a quasi-isodynamic stellarator.
21. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement is quasi-omnigenous stellarator.
22. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement comprises (a) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (b) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
23. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping

unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.

24. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
25. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
26. The system of any of the preceding claims, wherein the stellarator optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.
27. A system for generating neutrons comprising: (i) a casing defining a first volume; (ii) a blanket defining a second volume; (iii) a stellarator optimized for fast particle confinement, wherein the stellarator is adapted to confine a plasma within the first volume, and wherein the blanket is positioned between the stellarator and the casing; (iv) at least a first negative

ion-based neutral beam injector for introducing a first beam of high energy neutral atoms into the plasma in a first angular direction; (v) optionally at least a second negative ion-based neutral beam injector for introducing second beam of high energy neutral atoms into the plasma in a second angular direction; and (vi) an electron heater adapted to heat electrons in the plasma.

28. The system of claim 27, wherein the system comprises at least 2 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.
29. The system of claim 27, wherein the system comprises at least 4 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.
30. The system of claim 27, wherein the system comprises at least 6 first negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the first angular direction.
31. The system of any one of claims 27 - 30, wherein the system comprises at least one second negative ion-based neutral beam injector for introducing the high energy neutral atoms into the plasma in the second angular direction.
32. The system of claim 31, wherein the first and second angular directions are opposite angular directions.
33. The system of any one of claims 27 - 30, wherein the system comprises at least two second negative ion-based neutral beam injectors for introducing the high energy neutral atoms into the plasma in the second angular direction.
34. The system of claim 33, wherein the first and second angular directions are opposite angular directions.
35. The system of claim 27, wherein the plasma is a deuterium plasma.
36. The system of any one of claims 27 - 35, wherein the system further comprises at least one material transfer system.
37. The system of claim 36, wherein a first of the at least one material transfer system is in communication with the first volume.
38. The system of claim 37, wherein the first of the at least one material transfer system is communicatively coupled to a material isolation system.

39. The system of claim 37, wherein a second of the at least one material transfer system is in communication with the second volume.
40. The system of claim 39, wherein the second of the at least one material transfer system is communicatively coupled to a material isolation system.
41. The system of claim 39, wherein the second of the at least one material transfer system is adapted for introducing a flowable target into the second volume.
42. The system of claim 39, wherein the second of the at least one material transfer system is adapted for introducing a solid target into the second volume.
43. The system of claim 27, wherein the electron heater is communicatively coupled to a controller.
44. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement is a quasi-axisymmetric stellarator.
45. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement is a quasi-symmetric stellarator.
46. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement is a quasi-isodynamic stellarator.
47. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement is quasi-omnigenous stellarator.
48. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement comprises (a) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (b) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
49. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein

the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.

50. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
51. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
52. The system of any one of claims 27 - 43, wherein the stellarator optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.
53. A method for generating neutrons, comprising: generating a negative ion neutral beam to accelerate neutral atoms to an energy at which the D-D cross section is significant; and injecting the negative ion neutral beam into a stellarator optimized for fast particle confinement and controlling the electron temperature so that the beam-slowing down time is long enough for the fast ions to generate neutrons at a desired flux.

54. The method of claim 53, further comprising forming tritium by bombarding deuterium using the generated neutrons.
55. The method of claim 53, further comprising capturing and filtering plasma from the stellarator to isolate any tritium that has been formed.
56. The method of claim 53, wherein the stellarator optimized for fast particle confinement is a quasi-axisymmetric stellarator.
57. The method of claim 53, wherein the stellarator optimized for fast particle confinement is a quasi-symmetric stellarator.
58. The method of claim 53, wherein the stellarator optimized for fast particle confinement is a quasi-isodynamic stellarator.
59. The method of claim 53, wherein the stellarator optimized for fast particle confinement is quasi-omnigenous stellarator.
60. The method of claim 53, wherein the stellarator optimized for fast particle confinement comprises (a) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (b) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
61. The method of claim 53, wherein the stellarator optimized for fast particle confinement comprises (a) a field-shaping coil system including one or more field shaping units which define a void adapted to confine a plasma, wherein each field shaping unit comprises (i) one or more structural mounting elements; and (ii) one or more shaping coils disposed on a surface of the one or more structural mounting elements; and (b) a plurality of encircling coils which encircle the plasma and the field-shaping coil system, wherein the one or more shaping coils and the plurality of encircling coils are comprised of one or more superconducting materials.
62. The method of claim 53, wherein the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma having a plasma axis; (b) a plurality of planar shaping coils, wherein an array comprising the plurality of planar shaping coils encircles the plasma axis, but where any individual planar shaping coil of the plurality of planar shaping coils does not encircle the plasma axis; and (c) a plurality of planar

encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.

63. The method of claim 53, wherein the stellarator optimized for fast particle confinement comprises (a) a void adapted to confine a plasma, wherein the void comprises at least two faces; (b) at least two planar shaping coils, wherein a first of the at least two planar shaping coils is proximal to a first of the at least two faces but does not encircle the void, and wherein a second of the at least two planar shaping coils is proximal to a second of the at least two faces but does not encircle the void; and (c) a plurality of planar encircling coils, wherein each individual planar encircling coil of the plurality of encircling coils encircles the plasma axis.
64. The method of claim 53, wherein the stellarator optimized for fast particle confinement comprises (a) a plurality of structural supports; (b) one or more field shaping units operably connected to the plurality of structural supports, each field shaping unit comprising one or more planar, surface-mounted shaping coils; and (c) a plurality of planar encircling coils; wherein the plurality of structural supports, the one or more field shaping units, and the plurality of encircling coils collectively define a void adapted for confining plasma therein.

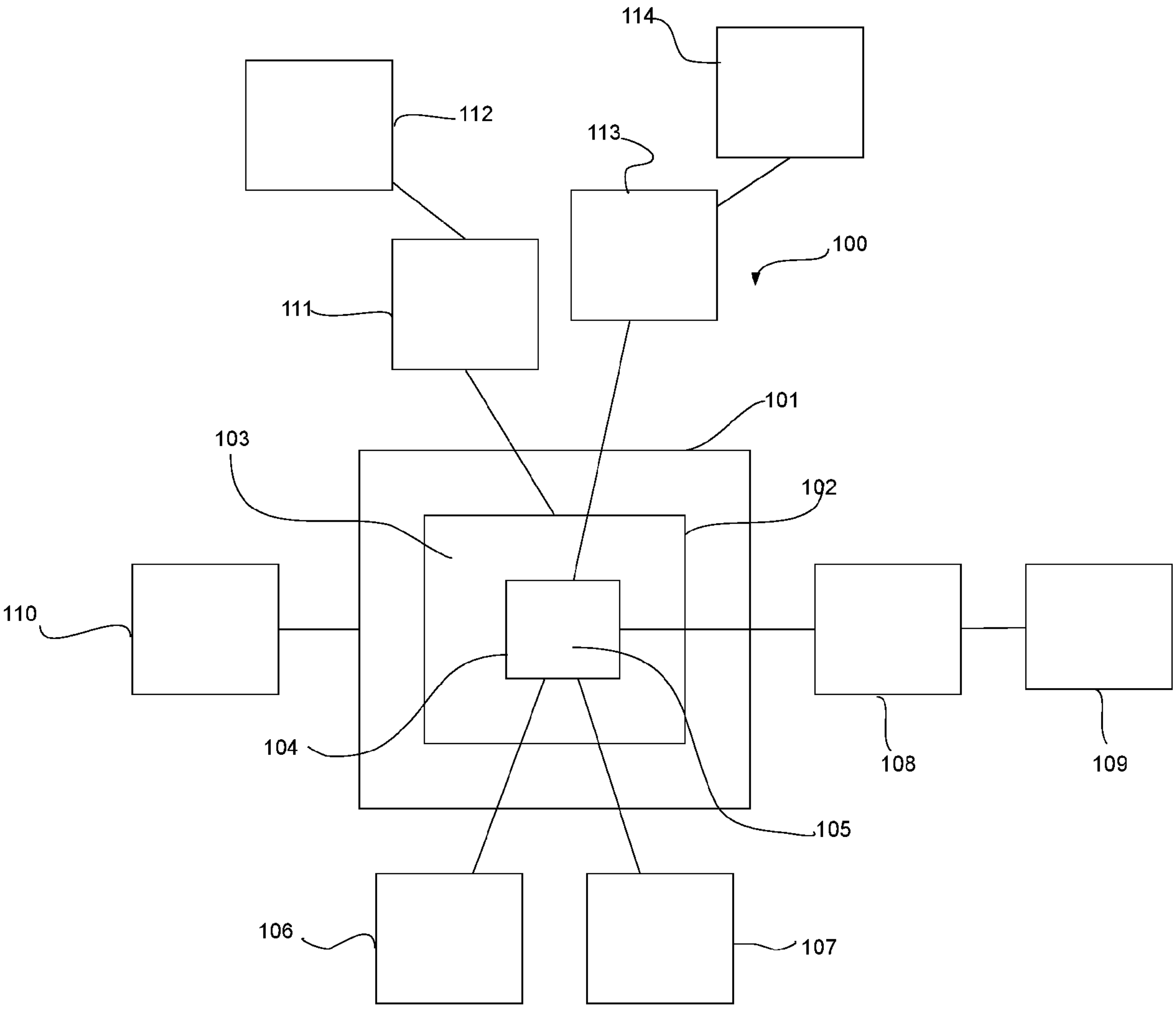

FIG. 1

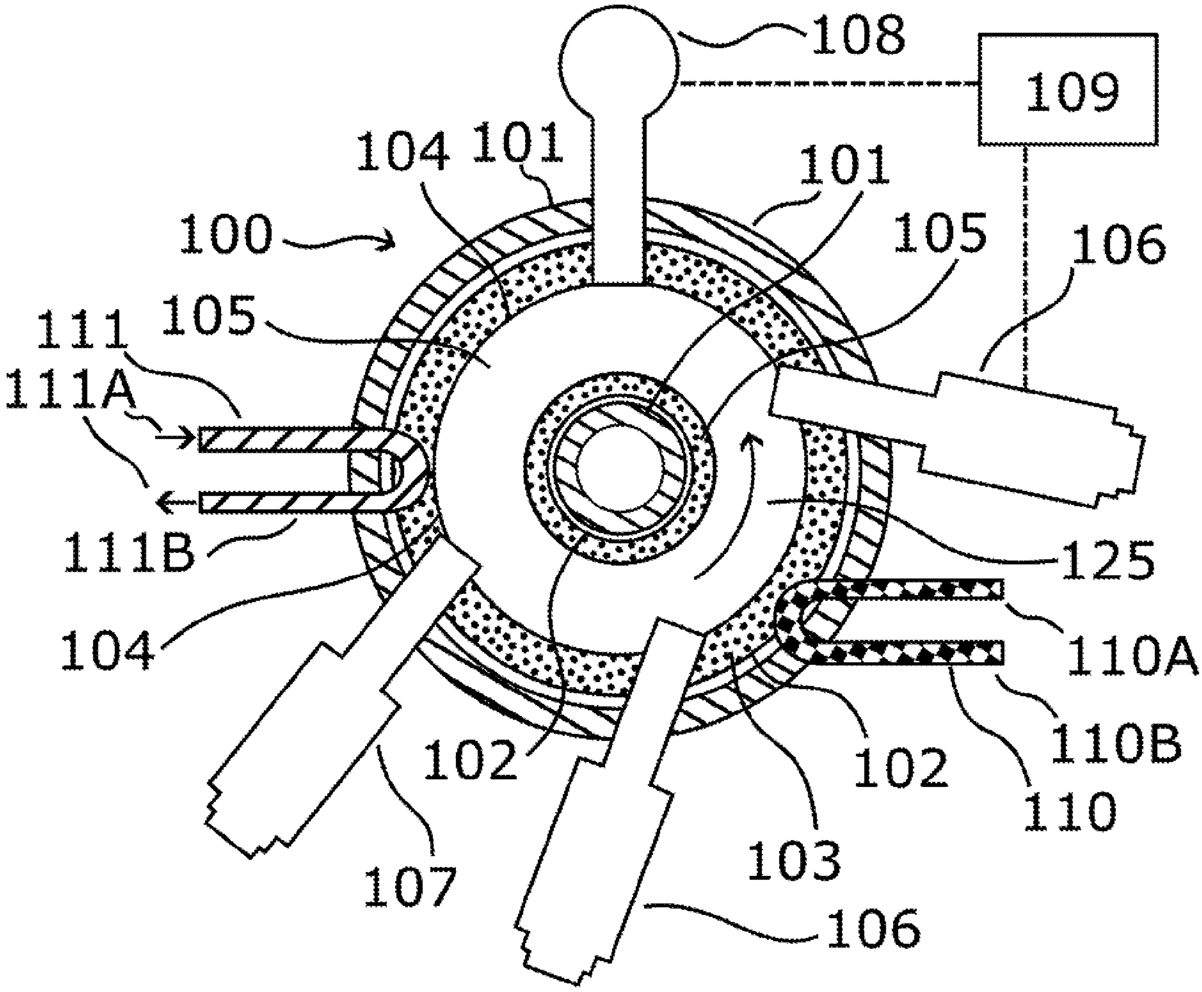
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FIG. 2A

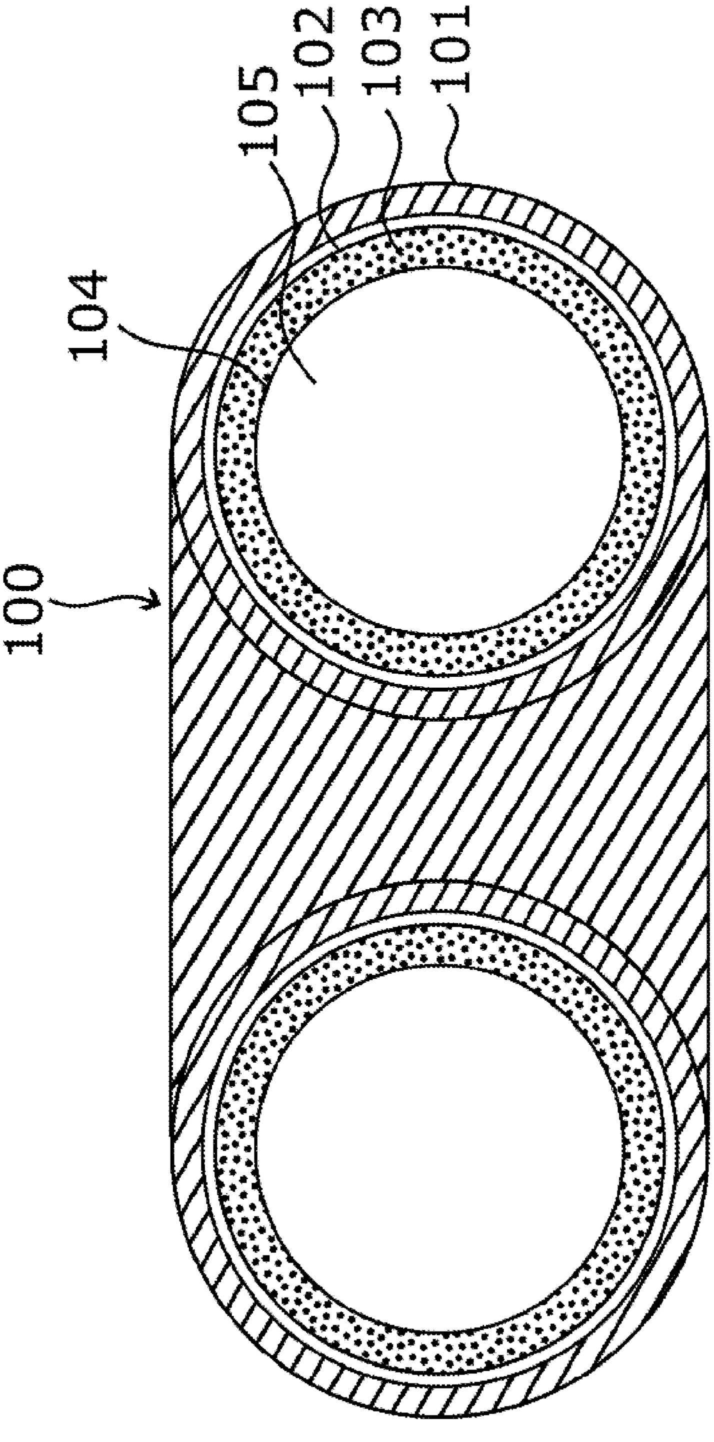

FIG. 2B

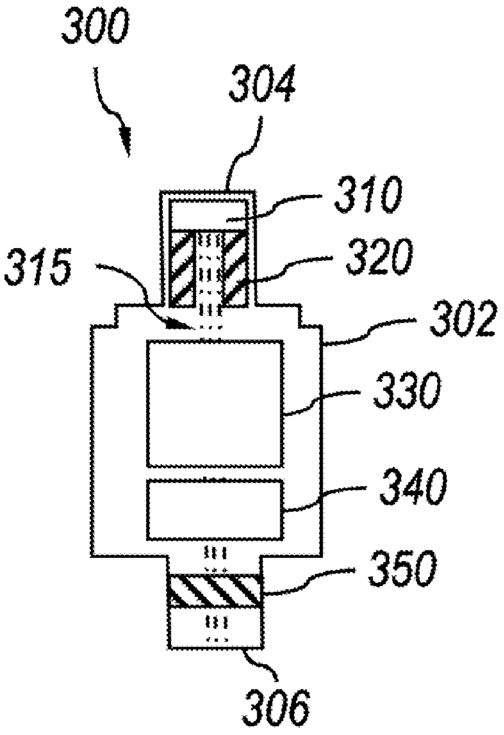

FIG. 3

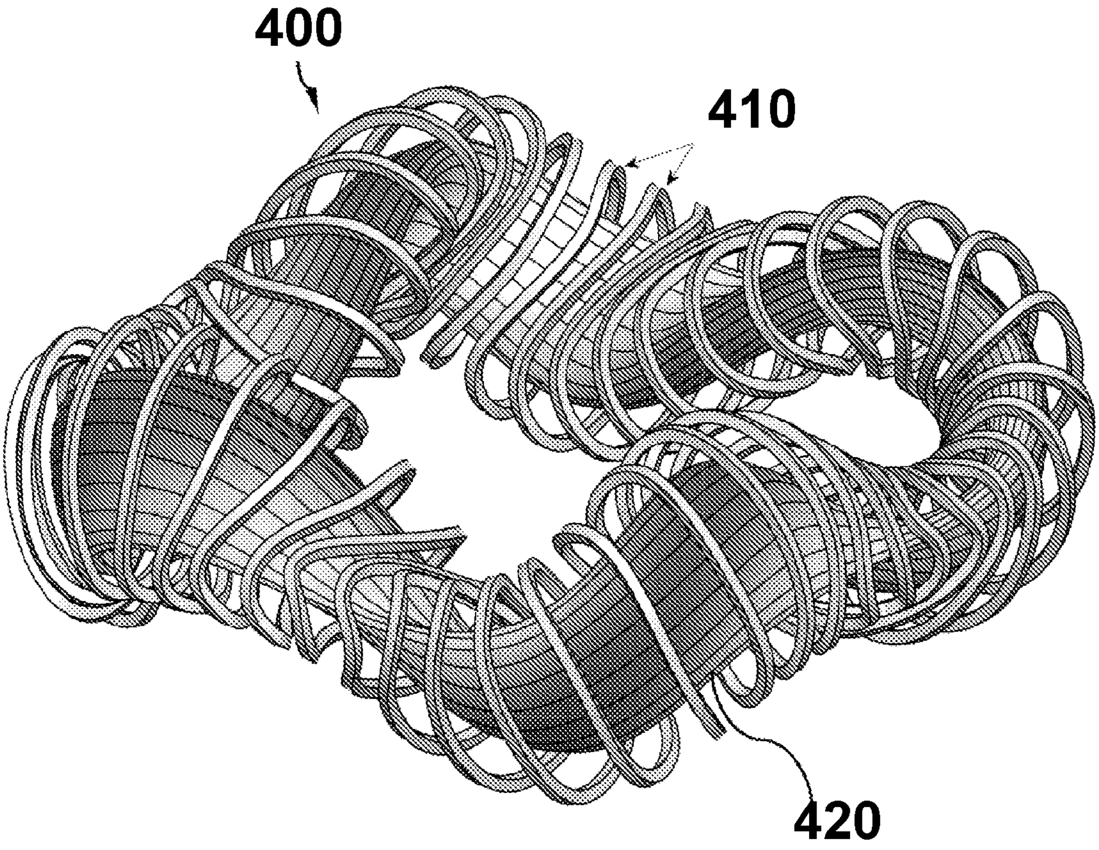

FIG. 4A

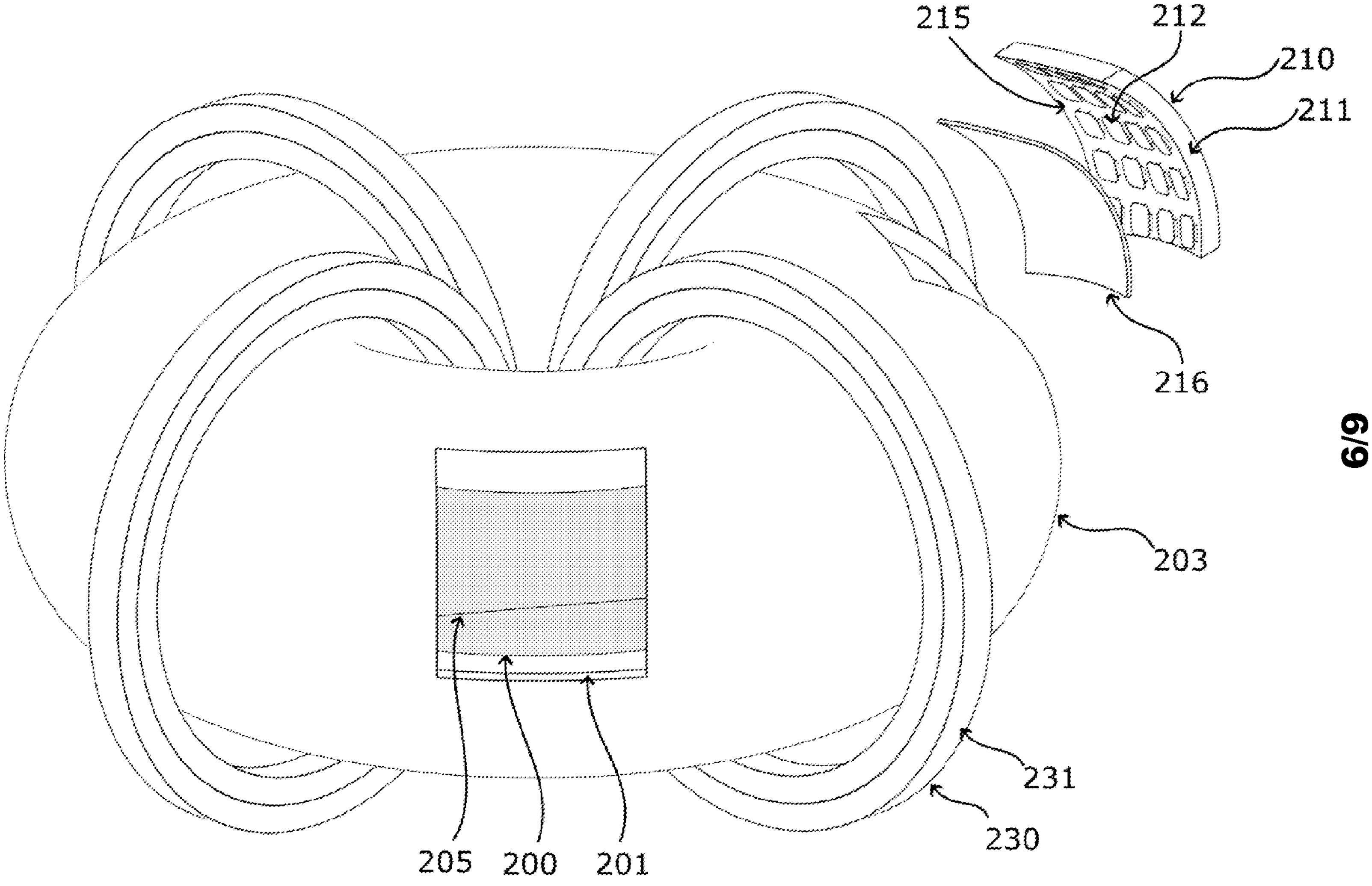

FIG. 4B

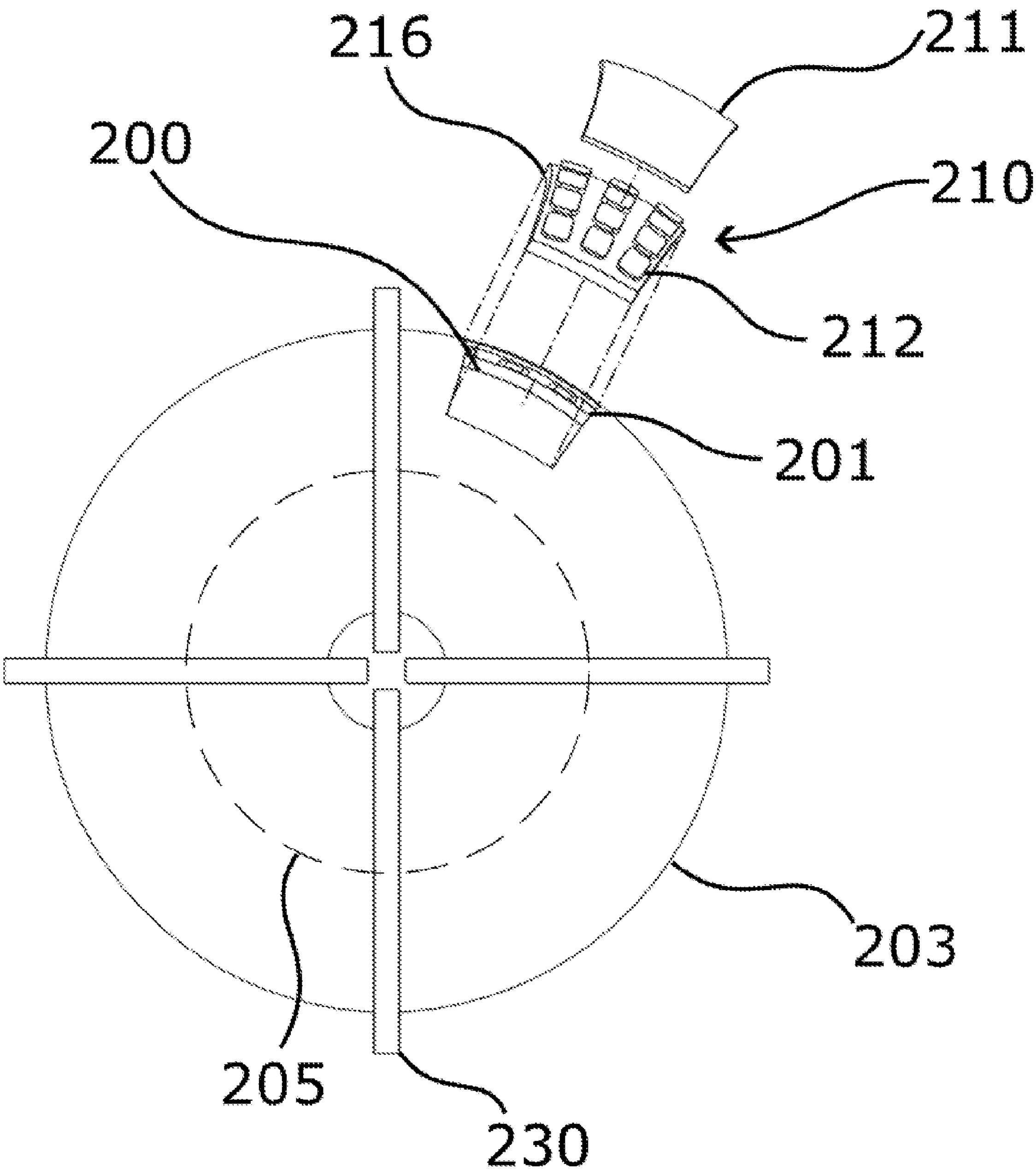

FIG. 4C

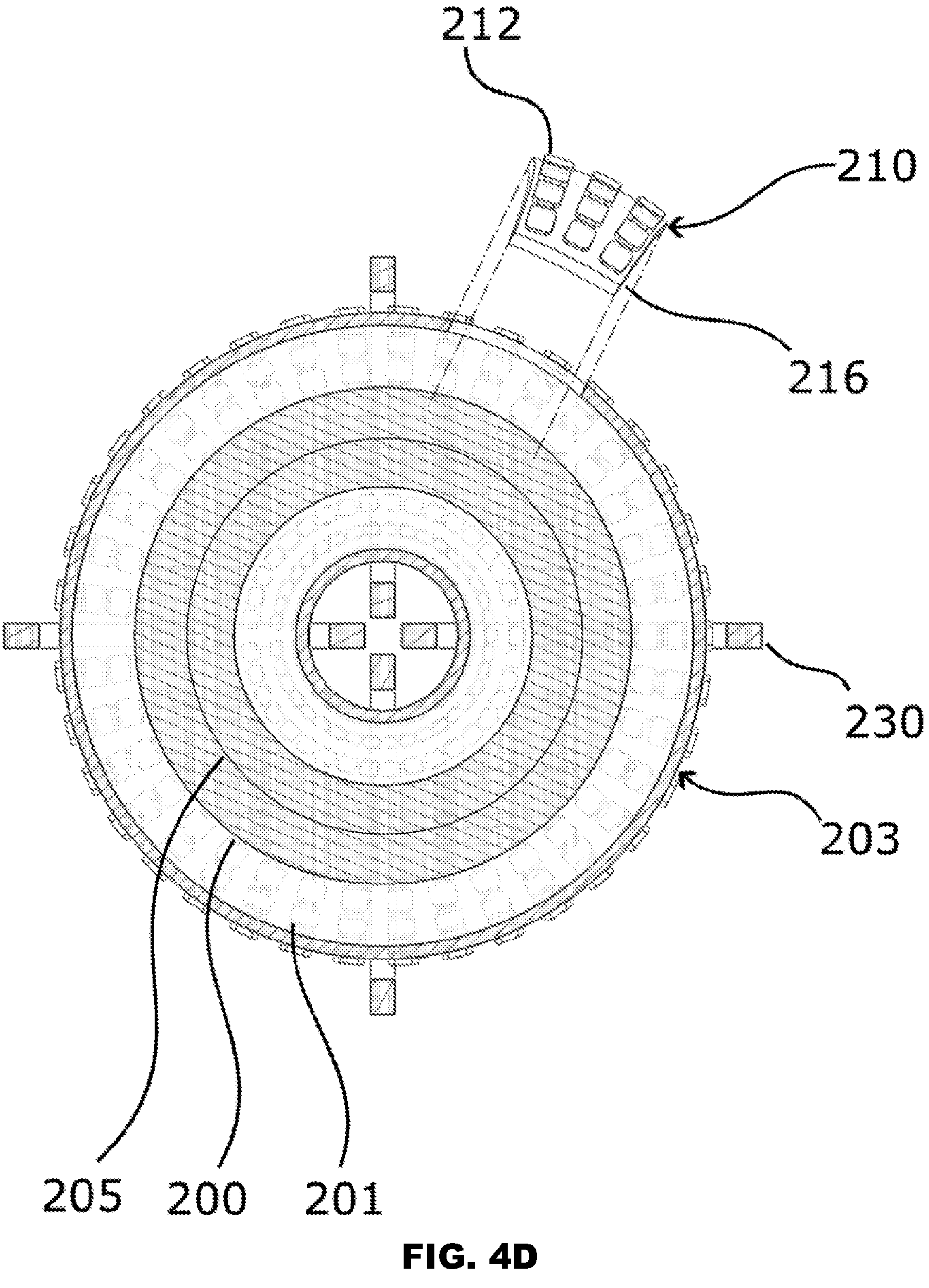

FIG. 4D

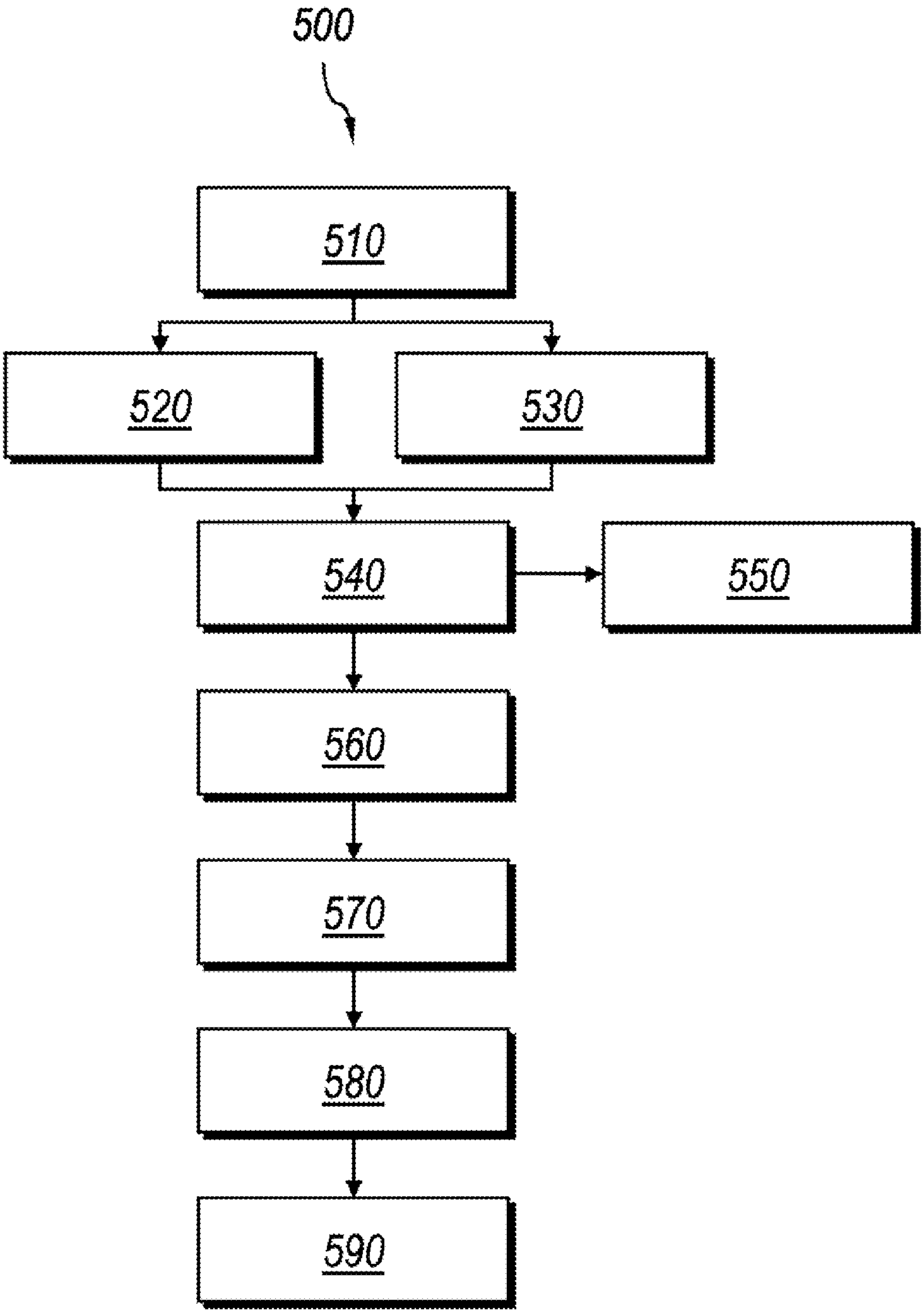

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2023/064025

A. CLASSIFICATION OF SUBJECT MATTER
INV. G21B1/05 G21G4/02
ADD.

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)
G21B G21G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TAKEIRI Y.: "Prospect Toward Steady-State Helical Fusion Reactor Based on Progress of LHD Project Entering the Deuterium Experiment Phase", IEEE TRANSACTIONS ON PLASMA SCIENCE., vol. 46, no. 5, 12 October 2017 (2017-10-12), pages 1141-1148, XP93046493, US ISSN: 0093-3813, DOI: 10.1109/TPS.2017.2771749 Retrieved from the Internet: URL:https://ieeexplore.ieee.org/ielx7/27/8354847/08122295.pdf?tp=&arnumber=8122295&isnumber=8354847&ref=aHR0cHM6Ly9pZWVleHBsb3JlLmllZWUub3JnL2Fic3RyYWN0L2RvY3VtZW50LzgxMjIyOTU=> the whole document ----- -/--	1-64

☒ 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 23 May 2023	Date of mailing of the international search report 05/06/2023
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Manini, Adriano

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Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2023/064025

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ISOBE M ET AL: "Fusion neutron production with deuterium neutral beam injection and enhancement of energetic-particle physics study in the large helical device", NUCLEAR FUSION, PUBLISHING SECTION. VIENNA, AT, vol. 58, no. 8, 29 June 2018 (2018-06-29), page 82004, XP020328963, ISSN: 0029-5515, DOI: 10.1088/1741-4326/AABCF4 [retrieved on 2018-06-29] the whole document -----	1-64
A	ZARNSTORFF M C ET AL: "Simpler optimized stellarators using permanent magnets", NUCLEAR FUSION., 25 June 2021 (2021-06-25), pages 1-4, XP93046600, AT ISSN: 0029-5515 Retrieved from the Internet: URL:http://ocs.ciemat.es/EPS2021PAP/pdf/P4.1055.pdf> the whole document -----	22-26, 48-52, 60-64
A	Zarnstorff M C: "Progress on the Stellarator Path to Fusion Power", Fusion Power Associates Meeting, 16 December 2021 (2021-12-16), pages 1-15, XP93046588, Washington DC Retrieved from the Internet: URL:http://www.firefusionpower.org/FPA21-28_Stellarator_Zarnstorff.pdf [retrieved on 2023-05-12] slides 10-12 -----	22-26, 48-52, 60-64

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2023/064025

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.: 1-64(partially)
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:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
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:

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 an 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.:

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.

Continuation of Box II.2

Claims Nos.: 1-64(partially)

Independent claims 1 and 27 are directed to a system comprising in particular a casing defining a first volume in which a plasma is confined (i.e. a vacuum vessel), a blanket (for breeding tritium) and a stellarator (cf. e.g. https://en.wikipedia.org/wiki/Stellarator). However, in view of both the present application (see in particular fig. 2A, 2B and 4A-4D) and of common general knowledge regarding the potential future use of a stellarator type device as nuclear fusion power generation reactor, such system definitions are inconsistent with both of them, as they convey the idea that the three claimed features are somehow independent from each other, while it is fully apparent that the casing and the blanket, together with other components such as a magnetic coil/magnet system, are in fact part of the stellarator per se. Hence, this inconsistency renders the matter for which protection is sought not clearly defined (Article 6 PCT). Independent claims 1 and 27 lack of clarity (Article 6 PCT) also for the following reasons. The claims define a generic " blanket", however without mentioning neither a specific function of such blanket, nor additional technical features allowing to clearly define such function. Hence, it is not clear whether the claimed blanket refers to a tritium breeding blanket (as discussed in para. 119), to a generic heat flux or neutron protection device (as discussed in para. 64) or for a further (but never mentioned) function. The claims also define that the stellarator is " optimized for fast particle confinement", however without further defining (i) any specific information about the energies of such fast particles, (ii) any specific degree (percentage? time?) of confinement and (iii) any further specific apparatus feature allowing to achieve such adaptation or even any specific way how the fast particles are supposed to be optimally confined. Hence, the claim merely attempts to define the result to be achieved, though, without clearly defining any apparatus feature allowing to indeed achieve such result. Independent claim 53 lacks of clarity (Article 6 PCT) for the following reasons. Same reason as mentioned above with regard to " optimized for fast particle confinement". Similar reason with regard to " controlling the electron temperature so that the beam-slowing down time is long enough for fast ions to generate neutrons at a desired flux" (result to be achieved with no further technical detail and specific method step for achieving the desired effect). Regarding the Article 6 PCT objections raised above, it is noted that the description does not provide any additional, specific, information about how the effects mentioned above are to be obtained. Hence, regarding these specific parts, the application does not comply with the requirements of Article 5 and Rule 5.1(a)(v) PCT, as the application does not set forth at least one mode contemplated by the applicant for

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

carrying out the invention claimed.

Regarding claims 22-26, 48-52 and 60-64, it is noted that they refer to the magnet structure shown in fig. 4A-4D and discussed in the corresponding descriptive text. However, even though some technical information about the magnet system is give, there is not one single example of a complete magnet configuration provided with also all operating parameters for obtaining in particular also the claimed confinement of fast particles. Hence, regarding this specific part as well, the application does not comply with the requirements of Article 5 and Rule 5.1(a)(v) PCT, as the application does not set forth at least one mode contemplated by the applicant for carrying out the invention claimed.

It is noted that a skilled person is also not able to put the invention into practice based only on its common general knowledge. The stellarator as claimed, partly discussed in description and drawings, seems to refer to a new type of stellarator (see in particular D3 and D4 in Item V) that has presently not even been built yet, so that the present disclosure can form the basis of very interesting and potentially useful experimental work to be performed in the context of basic science research to be evaluated within, and counter-proofed by, a scientific community. However, patentable inventions are required to be disclosed in a manner sufficiently clear and complete for the invention to be carried out by a person skilled in the art within the specific framework of the PCT. As such very specific type of stellarator has yet never been built and since the present application does not provide at least one, fully detailed, example of how the invention could be put into practice (i.e. no "detailed instructions" comprising all specific device components, materials, operational parameters to be used, etc.), a person skilled in the art is not in the position of being able to put the invention into practice without undue burden, i.e. e.g. without requiring undue additional experimentation.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guidelines C-IV, 7.2), should the problems which led to the Article 17(2) PCT declaration be overcome.